Glacial-interglacial perturbations in the global carbon cycle

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Adapted from a remark attributed to Otto Von Bismarck,
1st chancellor of the German Empire, 1871-1890.
Abstract. A flexible representation of the global carbon cycle is developed for use on multi-millennial time-scales, based upon the cycling within the ocean of carbon and alkalinity, together with the essential nutrients; phosphate, silicic acid, and iron. The diagenetic alteration of calcium carbonate (CaCO₃) and opal in deep-sea sediments is explicitly considered, with primary biogeochemical interactions between oceanic and sedimentary reservoirs accounted for. Material preserved in the sediments is allowed to accumulate to form synthetic sediment records. This enables a wide variety of paleoceanographic observations to be directly employed in helping to constrain the processes driving the evolution of the carbon cycle over the course of the late Quaternary.

A test harness for use in the investigation of the observed glacial-interglacial variability in the concentration of atmospheric carbon dioxide (xCO₂) is constructed by marrying the biogeochemical framework developed here with a zonally-averaged representation of ocean circulation. Potential mechanisms are evaluated on a dynamic (i.e., time-stepping) basis by reconstructing variability in the relevant model boundary conditions over the past 400,000 years. Model results suggest that a key role is played in initial deglacial xCO₂ rise by declining aeolian iron supply to the Southern Ocean. With sea ice limits also varied in this region, it is also possible to account for the glacial-interglacial variability in much of the paleoceanographic record either side of the Antarctic Polar Front. However, none of the mechanisms considered here, even operating in concert, are able to reproduce the full magnitude of observed deglacial xCO₂ rise whilst simultaneously meeting constraints dictated by the sedimentary CaCO₃ record. It is, therefore, likely that any combination of changes in; equatorial up-welling, high latitude surface ocean stratification, and the oceanic nitrogen cycle, play an additional and important role.
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Introduction

There is abundant geological evidence on the Earth’s surface, particularly in characteristic landforms and drift sediments, that in the relatively recent geologic past global climate was very much colder than at present, with extensive ice sheets covering much of higher northern hemisphere latitudes [Imbrie and Imbrie, 1979]. In fact, such evidence points to there having been more than one cold episode, each punctuated by periods of relatively warm climatic conditions. Once this interpretation had become generally accepted during the 19th century, the search started for an explanation as to why these events should have occurred at all. On the basis that periods of low solar insolation would result in a cooling of the planet (thus allowing ice sheets to grow) variations in the amount of sunlight received was the obvious starting point. Initial explanatory theories included sun spot cycles, the existence of dust clouds in space through which the Earth might pass (therefore attenuating solar radiation) and in a similar vein, major sub-aerial volcanic eruptions. However, none of these could be reasonably tested at that time and had little supporting evidence. It was not until the French mathematician Joseph Adhémar, noting that the Earth’s orbit is elliptical rather than spherical that the first true astronomical theory was born. Adhémar proposed that the precession of the equinoxes would produce antagonistic variations in insolation received by the two hemispheres during winter with ice ages occurring alternately in each, a full cycle taking 22 thousand years (ka) to complete.

Later that same century, a Scotsman, James Croll, realized that Adhémar had overlooked the fact that the shape of the Earth’s orbit (eccentricity) varied over time, a detail which could potentially hold the key. Croll calculated orbital eccentricity for the past 3 Ma and determined a cyclicity of approximately 100 ka. The occurrence of ice ages was still linked to the precession of the equinoxes as postulated by Adhémar, but now the envelope of eccentricity modified the precessional cycle, such that when eccentricity was close to zero no ice age would occur in either hemisphere. However, since variations in eccentricity produced only very minor changes in the annual radiation budget of the Earth Croll considered that this was not sufficient to drive the ice ages, and therefore invoked positive feedbacks in the climate system through changes in surface albedo. Although widely welcomed at the time, this theory gradually fell out of acceptance as circumstantial geological evidence started to accumulate, with indications that the last ice age might have ended as recently as ~10 ka BP (Before Present), rather than the ~70 ka BP predicted by Croll.

No further progress was made with astronomical descriptions of the ice ages until during the first half of the 20th century when Milutin Milankovitch, a Serbian mathematician, constructed a theoretical framework for describing the distribution of insolation over the Earth’s surface as a function of three orbital properties (precession, obliquity, and eccentricity). Not only did Milankovitch apply this to the present-day but was also able to make calculations for any point in time during the past 650 ka. Noting that summertime melting appeared to be the key season in controlling the growth of modern glaciers, he suggested that it was insolation levels during this half of the year that was critical to the control of ice ages rather than the winter months as had previously been assumed. This received strong support through the remarkable match made between summer insolation calculated at 65°N and variability in the reconstructed terminal limits of Alpine glaciers.

It was not until the late ’60s and early ’70s with the advent of sufficiently-sensitive analytical techniques for determining isotopic composition that Milankovitch’s astronomical theory of the ice ages would be confirmed. Sediment cores recovered from the deep sea had already confirmed earlier geological evidence based upon glacial till sequences. Measurements of the abundance ratio of the stable isotopes 18O and 16O (δ18O) contained within foraminiferal calcite now revealed the occurrence of as many as 7 major ice age cycles (Figure 1). Location of the Brunhes-Matuyama magnetic reversal (then dated to around 730 ka BP) in particularly long sediment sequences allowed the period of the cycles to be estimated at around 100 ka, matching that of orbital eccentricity. Further support for the theory came with the realization that variations in δ18O, (particularly in benthic foraminifera) must reflect changes in global ice volume. Finally, spectral analysis of this ice volume proxy verified the presence of primary periods of variability occurring at 100 ka and 41 ka, corresponding to the orbital components of eccentricity and obliquity. Furthermore, the presence of not one but two precessional peaks (23 ka and 19 ka) was revealed by the sediment core data, an orbital feature not previously predicted by calculations.

From the very outset, the most problematic aspect of Milankovitch’s astronomical theory of ice ages has been that eccentricity, which appears to match the frequency of the glacial-interglacial cycles, is far weaker than either precessional or obliquity orbital components in terms of the spectral power of insolation variability. Indeed, variations in eccentricity alter annual radiation received by the Earth by less than 0.1% [Imbrie et al., 1993]. With the use of computers as a standard scientific tool in the mid 1970s, possible climatic mechanisms that could produce such a non-linear response began to be investigated with complex numerical models. The first such model calculated increases in global ice volume simply in proportion to an insolation (50°N summer) deficit [Calder, 1974]. Non-linearities in ice
An alternative approach brought to bear on the glacial-interglacial cycle question was to represent key feedbacks in this process [Deblonde and Peltier, 1991; Pollard, 1983; Oerlemans, 1980, 1982]. Having achieved this, the next area of deficiency in predicted ice volume (compared to the marine δ¹⁸O record) concerned the glacial terminations, which tended to be rather sluggish and with incomplete deglaciation occurring. Additional mass wasting parameterizations were therefore introduced to correct for this such as that of ice calving [Clark and Pollard, 1998; Deblonde and Peltier, 1990, 1991, 1993; Hughes, 1992; Oerlemans, 1991; Pollard, 1983]. In contrast, simulating glacial inception was much less problematic, with adequate representation of continental topology often sufficient to allow the initiation of ice sheets during periods of low summer insolation [Birchfield et al., 1982; Deblonde and Peltier, 1990, 1991, 1993; Ledley and Chu, 1995; Tarasov and Peltier, 1997]. Recent studies have also highlighted the potential importance of vegetation-albedo feedbacks in this process [de Noblet et al., 1996; Gallimore, 1991].

An alternative approach to the free-running oscillation driven by an inherent climatic instability [Berger et al., 1981; Saltzman and Maasch, 1988, 1990, 1991; Saltzman and Sutera, 1984, 1987; Saltzman and Verbitsky, 1992, 1993, 1994a,b; Saltzman et al., 1993], or through the existence of multiple thresholds prescribed within the system [Paillard, 1998]. Insolation forcing was still important in all of these, although in some cases its role in the glacial-interglacial cycles was reduced to little more than phase-locking of internal oscillations.

An alternative approach brought to bear on the glacial-interglacial cycle question was to represent key processes within the climate system in an explicit and mechanistic fashion. The element suspected to play the predominant role was that of the cryosphere [Calder, 1974] (including its interaction with other components of the climate system). On this basis, Weertman [1976] modelled the (northern hemisphere) cryosphere as a simple equilibrium ice sheet atop a plastic crust. Although significant changes in ice volume were found when this model system was forced with variable (summer 50°N) insolation, no clear 100 ka cycle was produced. Models comprising just atmospheric, ocean, or coupled ocean-atmosphere components similarly failed [Birchfield et al., 1991; Short et al., 1991; Suarez and Held, 1976], as did coupling an atmospheric component to the ice sheet [Pollard, 1978]. However, the introduction of a realistic time scale for isostatic bedrock adjustment, either explicitly or mechanistically through representation of mantle elasticity or viscoelasticity allowed an ice volume signal with a clear ~100 ka period to be obtained [Birchfield et al., 1981; Deblonde and Peltier, 1991; Pollard, 1983; Oerlemans, 1980, 1982].

One direction of development taken from these initial studies was in what were often highly abstracted models of the Earth system. In these, 100 ka cycles were various obtained through stochastic resonance [Matteucci, 1989], the selective frequency amplification of an internal oscillation [Le Treut and Ghil, 1983; Van der Sluijs et al., 1996], as a free-running oscillation driven by an inherent climatic instability [Saltzman, 1987, 1990; Saltzman and Maasch, 1988, 1990, 1991; Saltzman and Sutera, 1984, 1987; Saltzman and Verbitsky, 1992, 1993, 1994a,b; Saltzman et al., 1993] or through the existence of multiple thresholds prescribed within the system [Paillard, 1998]. Insolation forcing was still important in all of these, although in some cases its role in the glacial-interglacial cycles was reduced to little more than phase-locking of internal oscillations.

Figure 1-1 The SPECMAP stacked marine δ¹⁸O record [Imbrie et al., 1984], where increasing δ¹⁸O values approximately scale with increasing global ice volume. Labelled are the Marine Isotope Stages after Shackleton and Opdyke [1974] (with Stage 5 sub-divided ‘a’ through ‘c’) together with the location of the Brunhes-Matuyama magnetic reversal, taken at 730 ka BP [Imbrie et al., 1984]. Also marked are the last 7 major glacial terminations, labelled “I” through “VII”.

sheet response were represented by taking a different proportionality for melt-back than for growth. Remarkably, this model produces a distinct 100 ka cycle in spite of the relatively low power at the corresponding period inherent in the forcing. A similar formulation, but with non-linearities in ice sheet response now represented explicitly was presented by Imbrie and Imbrie [1980], proving a fruitful basis for further development [Pisias and Shackleton, 1984; Siedler, 1985]. This model improved upon the overall sawtooth shape of the glacial-interglacial cycles of that produced by Calder [1974]. Other simple methods were also found of accounting for much of the variance contained within the marine δ¹⁸O record directly from insolation, including multivarient regression [Berger et al., 1981] and astronomical climate index [Kukla et al., 1981] models, and through consideration of albedo-radiation feedbacks [Wigley, 1976].
Building upon the promising response obtained by interactions between ice sheets and the underlying bedrock models have gradually attained increasing complexity as additional climate components (such as full atmospheric energy balance models and representations of ocean heat transport and storage) have been added. In particular, considerable advances have been made in our understanding of glacial-interglacial climate dynamics through the development of models of ‘intermediate complexity’ such as those of Deblonde, Peltier and co-workers [Deblonde and Peltier, 1990, 1991, 1992; Peltier and Marshall, 1995; Tarasov and Peltier, 1997] and the LLN model of André Berger and co-workers [Berger and Loutre, 1997a,b; Berger et al., 1990, 1993, 1998, 1999; Li et al., 1998a,b; Loutre and Berger, 2000]. However, even relatively advanced models such as these fall noticeably short of being able to fully account for the 100 ka glacial-interglacial cycles. Clearly there must be some important climatic factor still missing.

The climatic fluctuations of the last ~800 ka are only a part of a longer-term evolution in the dynamics of the Earth’s climate, which has seen substantial change over the course of much of the late Cenozoic [Driscoll and Haug, 1998; Raymo and Ruddiman, 1992; Raymo and Ruddiman, 1988]. Figure 1-2 shows part of a marine δ18O record covering the last 5 Ma [Tiedemann et al., 1994]. Again taking (benthic) δ18O primarily as a proxy for global volume it can be seen that up until about ~3.1 Ma BP, climate appeared relatively stable, with little variability in global ice volume (probably similar to that of the present interglacial). After this point there was a clear downward trend, with the amplitude of fluctuations steadily increasing. This continued to around 2.5 Ma BP when the first major northern hemisphere glacial event occurred [Shackleton et al., 1984]. A relatively extended period ensued thereafter, with ice ages reoccurring with a period of about 41 ka and with maximum ice volume perhaps half that of the more recent 100 ka cycles [Clark and Pollard, 1998]. Finally, somewhere during the interval 1.5 to 0.7 Ma BP there was a transition to the establishment of 100 ka glacial-interglacial cycles. In an attempt to characterize the nature of this final transition a wide variety of spectral and statistical techniques have been brought to bear. These have ranged from relatively simple spectral [Mudelsee and Schultz, 1997; Pisias and Moore, 1981] and bispectral methods [Hagelberg et al., 1991; Rutherford and D’Hondt, 2000], through multitaper-based techniques [Birchfield and Ghil, 1993; Mann and Lees, 1996; Park and Maasch, 1993; Saltzman and Verbitsky, 1992], to probability density functions [Maasch, 1988; Matteucci, 1990; Mudelsee and Statterger, 1997] and more recently, wavelet analysis [Bolton et al., 1995; Lau and Weng, 1995]. However, these techniques have often been at odds with each other regarding the details of the rate of change and timing of the mid point of the transition. Statistical methods also generally fail to illuminate the underlying physical processes responsible for the change in the dynamics of the climate system at this time, although there have been suggestions that a key role was played by the tropics [Rutherford and D’Hondt, 2000].

Various explanations have been offered to account for aspects of the inferred evolution of the Earth’s climate system over the late Cenozoic. For the initial onset of ice age cycles around 2.5 Ma BP, favourite among these has been tectonic changes, particularly the emergence of the Isthmus of Panama with possible associated disruption of ocean circulation patterns [Hay, 1996], and the deepening of the Fram and Denmark Straits [Hay, 1993, 1996]. However, the timing of these events place them too early to have had a direct effect, with the results of ocean and atmospheric circulation models often not supporting a significant role [Hay, 1996; Maslin et al., 1998; Raymo and Ruddiman, 1992]. Uplift of the Tibetan plateau may also have had an influence in producing climatic conditions conducive to the growth of ice sheets through its distorting influence on atmospheric circulation in the northern hemisphere [Raymo and Ruddiman, 1992; Ruddiman and Raymo, 1992]. For the transition from 41 to 100 ka periodicity, a gradual

![Figure 1-2](https://example.com/image.png) The benthic δ18O record of Ocean Drilling Program site 659 [Tiedemann et al., 1994]. Shown at top are the approximate occurrences of the different magnetic polarity epochs over the length of this record.
transformation of continental regolith has been proposed, with the formation of ice sheets characterized by much greater height and volume only enabled by the eventual erosion of the underlying sediment substrate down to the bedrock [Clark and Pollard, 1998; Clark et al., 1999]. However, such explanations tend to be difficult to critically assess and are not entirely convincing as sole agents. Once again, one must suspect that an additional key component of the climate system has not yet been accounted for.

Past records of atmospheric composition, in the form of microscopic bubbles trapped within the crystalline structure of ice buried in the ice caps of both hemispheres, has sparked a revolution in thinking regarding the long-term dynamics of the climate system. Ice cores recovered from Greenland and Antarctica during the early 1980s and analysed for air bubble CO2 content showed that atmospheric CO2 levels at the time of last glacial were some ~30% lower than during the late Holocene [Nefel et al., 1988; Oeschger et al., 1984]. Cores were soon extracted from much greater depths, extending the record first back beyond the last interglacial period (the Eemian) [Barnola et al., 1987; Jouzel et al., 1993; Lorius et al., 1990] and then finally, four complete glacial-interglacial cycles were revealed by the Vostok core [Petit et al., 1999]. Results demonstrated that the pattern was regularly repeated, with relatively high CO2 levels (~280 ppmv) during interglacials and low levels (~190 ppmv) during the deepest glacial periods (Figure 1-3). On the basis that the presence of CO2 in the atmosphere effectively retards the loss from the Earth to space of radiation at infrared wavelengths [IPCC, 1990], it was immediately recognized that such past variability in CO2 concentrations might have played an important role in the ice age cycles [Barnola et al., 1987; Broccoli and Manabe, 1987].

The potential importance of variations in CO2 concentrations in determining the envelope of the ice age cycles has been demonstrated by numerous modelling studies. For instance, the addition of a CO2-dependent forcing to one of the earliest insolation-driven climate models produces a significant improvement in the evolution of simulated ice volumes [Pisias and Shackleton, 1984]. Other abstracted models confirmed that relatively realistic ~100 ka cycles could be generated by accounting for the influence of CO2 [Lindzen, 1986; Saltzman, 1987, 1990, Saltzman and Maasch, 1988; Saltzman and Verbitsky, 1994]. Mechanistic (intermediate complexity) climate models also exhibited an evolution in ice volume over the course of the 100 ka glacial-interglacial cycles significantly more in line with paleoclimate reconstructions upon the addition of external CO2 forcing [Berger et al., 1998, 1999; Li et al., 1998a; Loutre and Berger, 2000]. This improvement can be demonstrated more quantitatively through spectral analysis. Without applied variability in CO2 forcing, model spectral power
centred about a period of ~100 ka is in fact split into two peaks corresponding to periods of ~95 and ~125 ka [Ridgwell et al., 1999], closely following the character of eccentricity [Muller and MacDonald, 1997a,b,c]. There is also considerable (unwanted) power centred around the ~413 ka eccentricity component. In contrast, model response where changes in CO₂ levels are accounted for exhibit a single peak corresponding to ~100 ka with little power at lower frequencies, consistent with the spectral characteristics of marine δ¹⁸O records [Ridgwell et al., 1999].

The potential importance of CO₂ also extends to the evolution of the climatic system over the late Cenozoic. Uplift of the Tibetan plateau over this period may have resulted in increased chemical weathering and/or increased net organic carbon burial, producing a gradual draw-down in atmospheric CO₂ [France-Lanord and Derry, 1997; Raymo, 1994; Raymo and Ruddiman, 1992; Raymo et al., 1988]. This is illustrated once again by climate models driven by a long-term reduction in CO₂ forcing component, which are able to reproduce both the onset of ~41 ka ice age cycle around ~2.5 Ma BP, together with the transition between 41 and 100 ka periodicity with an associated increase in cycle amplitude [Saltzman and Maasch, 1991; Saltzman and Verbitsky, 1992, 1993, 1994].

What processes at work within the earth system then drive the observed glacial-interglacial variability in the concentration of atmospheric CO₂…?
2.1 Introduction

On time scales of decades and less the terrestrial biosphere exerts a significant control on atmospheric composition with a pronounced seasonal signal, primarily due to variability in the balance between uptake and release of CO₂ by the terrestrial biosphere \[\text{IPCC, 1990}\]. However, at some 39000 GtC the reservoir of dissolved carbon in the oceans is over 13 times that of the atmosphere and terrestrial biosphere put together \[\text{IPCC, 1994}\]. Thus, the mechanisms responsible for longer-term variability in the concentration of atmospheric CO₂ are more likely to involve the ocean. For this reason, models of the global carbon cycle used in the context of glacial-interglacial change are rooted in numerical representation of the oceanic carbon cycle.

Exchange of CO₂ between the ocean and atmosphere depends on the difference in molar fraction of gaseous CO₂ in the atmosphere (\(x_{\text{CO}_2}\)) and in the surface ocean (assumed to be equal to its fugacity (\(f_{\text{CO}_2}\))). In the absence of any significant change in terrestrial ecosystem carbon storage, in weathering rates of silicate rocks, or in volcanic out-gassing of CO₂, it is the mean ocean surface \(f_{\text{CO}_2}\) (area-weighted and modified by local wind speed) that determines the value of \(x_{\text{CO}_2}\). \(f_{\text{CO}_2}\) in turn is primarily a function of the concentration of total dissolved inorganic carbon (DIC), alkalinity (ALK), salinity (S), and temperature (T) at the ocean surface. \text{Volk and Hoffert [1985]} recognized three main cycles of transformation of state and translocation within the ocean system which act to vertically (and horizontally) partition DIC and ALK and thus determine surface ocean \(f_{\text{CO}_2}\). These three processes were termed ‘pumps’, and comprise:

- The ‘solubility pump’, whose action arises through the strong temperature-dependence of the solubility of gaseous CO₂ in water, with cold water exhibiting a much lower \(f_{\text{CO}_2}\) than warmer water. Thus, all other things being equal, warm oceanic regions will tend to be sources of CO₂ to the atmosphere and cold regions sinks. The concentration of atmospheric CO₂ is therefore related to mean sea surface temperature (SST).

- The ‘soft tissue pump’, whose effect is due to the removal of dissolved inorganic carbon from surface waters through its photosynthetic fixation by phytoplankton, and is subsequent export in the form of particulate organic carbon (POC) into deeper waters, where it is largely remineralized back into DIC. Through this action there is a vertical partitioning of DIC within the ocean with reduced surface concentrations. The concentration of atmospheric CO₂ is consequently inversely related to the strength of operation of this pump.

- The ‘carbonate pump’, whose effect arises in a similar way to that of the soft tissue pump, except that the particulate phase in question is calcium carbonate (CaCO₃). In the production of CaCO₃ by certain species of phyto- and zoo-plankton and subsequent export, alkalinity is changed in a 2:1 ratio with DIC. The resultant alkalinity partitioning in the ocean more than counteracts the effect on \(f_{\text{CO}_2}\) of that due to DIC. The concentration of atmospheric CO₂ therefore scales with the strength of the operation of this pump.

At a minimum, any description of the global carbon cycle must resolve these three separate ‘pumps’. However, the functioning of the real system is considerably more complicated than painted by this rather idealized picture. For instance, the soft tissue pump tends to ‘leak’, with a component of organic carbon primary production advected in a dissolved organic form as opposed to a pure vertical transport of particulates settling under the influence of gravity. The action of the soft tissue pump also results in a partitioning of alkalinity through the base capacities of the organic nutrients nitrate (NO₃⁻) and phosphoric acid (PO₄³⁻). This acts to slightly enhance the influence of the soft tissue pump on \(x_{\text{CO}_2}\). Regional variability in sea surface salinity (SSS) modifies the effect of the solubility pump, while regional differences in ocean surface wind speed and sea ice cover exert strong controls on the rate of gas transfer, thus influencing \(x_{\text{CO}_2}\). Finally, interactions between the ocean and underlying sediments plays an important role in influencing whole-ocean chemical and nutrient inventories on longer time scales.

Model structure is inevitably a trade-off between the degree of comprehensivity to which mechanisms within the global carbon cycle are represented, the spatial and temporal resolution of the model, simulation length, and actual model run-time. For a given requirement of simulation length together with practical and computational resource-driven limits on run-time, model structure is constrained by process complexity and spatial and temporal resolution. Additional constraints arise through deficiencies in our understanding of aspects of ocean biogeochemical cycling and in available data coverage and quality. Even so, there is no single solution in terms of a hypothetical ‘optimal’ model. Instead, model construction is inevitably a rather subjective ‘art’.
2.2 Model description

For investigation of potential mechanisms driving the observed glacial-interglacial variability in $xCO_2$, a new numerical description of the (oceanic) global carbon cycle is developed in this study; a model named “SUE”.

2.2.1 Framework overview

The model structure of SUE is shown schematically in Figure 2-1. SUE is essentially a biogeochemical framework of interactions important to the operation of the global carbon cycle operating on both an intra-ocean basis and across the interfaces linking atmosphere, ocean and deep-sea sediments. Ocean configuration and circulation are simply prescribed. As such, there is no feedback on the physical ocean from biogeochemistry and resulting atmospheric composition. Ocean-sediment interactions are described in Chapter 3. Typical model parameter values are summarized in Appendix IV. Full source code and example parameter files are attached on CD-ROM (Appendix V).

2.2.1.1 Ocean configuration and circulation

SUE is not tied to any particular ocean configuration but rather is developed as a flexible biogeochemical framework able to utilize any practical configuration of world ocean. In this, it is assumed that the ocean can be represented by a two-dimensional array of $c$ horizontal or vertical bands (hereafter referred to as ‘grid points’), divided vertically into $l$ vertical layers, giving a total of $c \times l$ distinct oceanic volumes (‘cells’). To fully define the model physical ocean structure all that remains are the areal extent and longitudinal boundaries (or alternatively the area) of each grid point region, together with the depth of the base of each ocean layer. Ocean circulation is defined by a set of mass flows between adjoining cells, from which the translocation of dissolved tracer species (such as DIC, ALK, and nutrients) can be calculated. Rather than prescribe entire ocean temperature (T) and salinity (S) fields as is usual in box model studies, temperature and salinity are advected along with other ocean tracers. Only SST and SSS boundary conditions must there be prescribed.

Many of the primary determinants of deep-sea sedimentary composition (such as CaCO$_3$ saturation state, and biogenic material rain rates) are depth-dependent. Assumption of a uniform depth for the ocean would then degrade the overall dynamics of ocean-sediment interaction [Keir, 1995]. In addition, the value of any comparison made between model sediments and observations will be reduced. The representation of deep-sea sediments therefore follows previous schemes where the ocean floor is defined at each grid point according to a hypsographic curve [Munhoven and Francois, 1994, 1996; Sundquist, 1990; Walker and Opdyke, 1995], derived from actual (inferred) topography [ETOPO5, 1988] on either a mean regional or global basis. These continuous bathymetric profiles are discretized into a series of $m$ separate depth bands at each grid point, with which an individual module handling ocean-sediment interactions is associated. The sediment module depth bands need not rigidly correspond to the depth intervals of ocean layers, with the result that changes in sea level can alter the depth in the ocean at which the sediments lie.

2.2.1.2 Overall biogeochemical cycling scheme

The model biogeochemical scheme is based around the cycling of three primary nutrients limiting to biological productivity: phosphate (PO$_4$), silicic acid (H$_4$SiO$_4$), and iron (Fe). Primary processes relating the intra-ocean cycling and ocean-sediment exchange of these nutrients in addition to dissolved inorganic carbon (DIC), alkalinity (ALK), and dissolved oxygen (O$_2$), are considered. Biogeochemical cycling is assumed to be representative of the ‘open ocean’ environment, with no explicit consideration of coastal or shelf processes (other than through highly parameterized representations of the accumulation and erosion of CaCO$_3$ and opal in neritic sediments – see 5.4.7). Carbon (as CO$_2$) and O$_2$ are exchanged with a ‘well-mixed’ atmosphere across the air-sea interface.

Nutrients, together with DIC and ALK, are taken out of solution in the sunlit surface ocean layer through biological action, and exported in particulate form (particulate organic matter (POM), CaCO$_3$, and opal) to deeper layers. As it settles through the water column, such material is subject to remineralization processes, resulting in the release of dissolved constituent species back to the ocean. Export of nutrients and carbon may also occur in the form of dissolved organic material (DOM). In this case, removal and transport is through ocean advection and mixing rather than gravitational settling. Dissolved iron in the ocean is considered in the form of a single species which is ultimately available for biological uptake at the ocean surface. In addition to surface biological removal dissolved Fe may also be taken out of solution throughout the ocean as a result of the scavenging action of settling particulate matter. Fe may therefore be subsequently released at depth back into solution not only through the normal operation of the ‘soft tissue pump’, but also liberated as the scavenging agents themselves are remineralized.

Biogenic and detrital material reaching the ocean floor may undergo diagenetic alteration (releasing further dissolved species to the ocean) and/or (semi-) permanent burial. The dissolution flux and thus fractional preservation of CaCO$_3$ and opal is represented mechanistically (Chapter 3). As an initial approximation, POM is preserved in a simple fraction, while Fe (whether in organic or inorganic form) reaching the sediments is assumed to be completely preserved along with detrital matter. Loss of material through burial in the sediments must be balanced over the long-term by supply to the ocean from continental weathering and geothermal processes (in the case of DIC, ALK, PO$_4$, and H$_4$SiO$_4$) together with aeolian input at the surface (Fe and H$_2$SiO$_4$).

The two stable isotopes of carbon ($^{12}$C and $^{13}$C) are treated separately, with all significant fractionation processes involving transformations of carbon state taken into account. However, many of the most important fractionation processes discriminating between the stable isotopes of oxygen ($^{16}$O, $^{17}$O, and $^{18}$O) are associated with the operation...
**Figure 2-1.** Schematic representation of the global carbon cycle model “SUE”. Solid biogeochemical fluxes are shown as solid lines, dissolved fluxes are dashed lines, and gaseous fluxes as dotted lines.
of the hydrological cycle and terrestrial ecosystems, neither of which are explicitly represented in SUE. $\delta^{18}O$ is therefore included only as a passive tracer. As such, it takes a (uniform) value throughout the ocean-atmosphere system set according to SPECMAP [Imbrie et al., 1984] for any point in time.

### 2.2.1.3 Carbonate system thermodynamics

In order to calculate important variables such as the fugacity of CO$_2$ in the surface ocean, or the degree of under-saturation of CaCO$_3$ in the deep sea, the equilibrium state of the aqueous carbonate system must be known. A solution for this is approximated numerically given the concentrations of DIC, ALK, H$_2$SiO$_4$, and PO$_4^{3-}$, together with ambient temperature, salinity, and pressure. The thermodynamical scheme is outlined in Appendix I.

### 2.2.1.4 Numerical scheme

The incarnation of SUE presented here is rooted in mean annual ocean circulation in common with many other carbon cycle models. Equations describing intra-ocean and ocean-atmosphere processes are solved numerically within a forward-time finite difference framework. However, while this and similar schemes are numerically stable for ocean models having a relatively thick ($\geq$150 m) surface ocean layer (e.g., Broecker and Peng [1986], Keir [1988]), instabilities in the air-sea exchange of CO$_2$ can arise if a much thinner surface ocean layer is assumed. The time step for intra-ocean and ocean-atmosphere processes is therefore allowed to take a value much shorter than 1 year. Problems can also arise with regards to the description of biological new production and ocean-atmosphere processes is therefore allowed to take a value much shorter than 1 year. Problems can also arise with regards to the description of biological new production.

### 2.2.2 Ocean-atmosphere gas exchange

In addition to being linked through ocean transport, surface ocean cells are geochemically coupled via the atmosphere. A single ‘well-mixed’ box is assumed on the basis of the relatively rapid rate of atmospheric mixing between the hemispheres compared with typical time scale of CO$_2$ concentration adjustment to changes in sources and sinks [IPCC, 1990]. Exchange of $^{12}$CO$_2$, $^{13}$CO$_2$, and O$_2$ between atmosphere and ocean across the air-sea interface is considered.

#### 2.2.2.1 Ocean-atmosphere CO$_2$ exchange

Carbon cycle models have often used a prescribed gas transfer coefficient, taken to be uniform over the entire ocean surface [Heinze et al., 1991, 1999; Maier-Reimer, 1993; Maier-Reimer and Hasselmann, 1987; Marchal et al., 1998b; Yamanaka and Tajika, 1996]. The value assumed for this coefficient (typically between 0.05 and 0.07 mol m$^{-2}$ atm$^{-1}$ a$^{-1}$) is taken consistent with $^{14}$C observations [Broecker et al., 1985]. Although wind speeds actually exhibit substantial spatial heterogeneity [Broecker et al., 1985], on the basis that the effect of sea ice cover at high latitude regions would act so as to largely cancel out the influence of the higher wind speeds found there Siegenthaler and Joos [1992] supported the use of this uniform coefficient. However, on glacial-interglacial time scales both wind speed and sea ice extent are likely to vary significantly and independently of each other. It has been suggested that changes in either or both of these ocean surface boundary conditions may account for much of the observed atmospheric CO$_2$ record [Keir, 1993; Stephens and Keeling, 2000]. For this reason the influence of wind speed and sea ice extent on the mean gas transfer coefficient is taken into account at each grid point. The gas transfer coefficient is represented as an explicit function of wind speed in a similar manner to Aumont et al. [1999], utilizing an empirical description of gas exchange coefficient [Wanninkhof, 1992]. This relationship is then corrected for the application of long-term mean rather than instantaneous wind speeds [Wanninkhof, 1992]. In this, the flux density across the air-sea interface of each cell is

\[ f_{\text{atm-oce}}^{CO_2} = K \left( p_{CO_2} - fCO_2 \right) \]  

where $p_{CO_2}$ is the partial pressure of CO$_2$ in the atmosphere, taken to be equal to its molar fraction ($x_{CO_2}$) for a mean atmospheric pressure of 1 atm, and $fCO_2$ is the fugacity of CO$_2$ in the surface ocean. $K$ is a gas transfer coefficient, expressed

\[ K = k_{sw} \cdot Q \]  

where $k_{sw}$ is the gas transfer velocity or piston velocity for appropriate for long-term average wind speeds (in m s$^{-1}$), and $Q$ is the Henry’s Law constant for CO$_2$ in seawater (calculated from Weiss [1974], and converted into units of mol m$^{-2}$ atm$^{-1}$). $k_{sw}$ is given by

\[ k_{sw} = l \left[ 2.5 \left( a + b \cdot T + c \cdot T^2 \right) + 0.38 \cdot u_{av}^2 \right] \left( \frac{Sc}{660} \right)^{0.5} \]  

where $a$, $b$, and $c$ are empirical constants, taking values of 0.5246, 1.6256 x 10$^2$, and 4.9946 x 10$^2$, respectively, $l$ is a scaling constant of value 2.778 x 10$^4$, $T$ is the temperature in $^\circ$C, $u_{av}$ is the long-term average wind speed (m s$^{-1}$), and $Sc$ is the Schmidt number for CO$_2$ in sea water, which can be approximated by

\[ Sc = a - b \cdot T + c \cdot T^2 - d \cdot T^3 \]  

where $a$, $b$, $c$, and $d$ are empirical constants, taking values of 2073.1, 125.62, 3.6267, and 0.043219, respectively [Wanninkhof, 1992].

In order to calculate the net exchange of CO$_2$ between the atmosphere and ocean, assuming that sea ice represents an impenetrable barrier to gaseous diffusion [Sarmiento et al., 1992] the flux density across the air-sea interface is simply multiplied by the ice-free area, and summed over all grid points.
\[
F_{\text{air-sea}}^{\text{CO}_2} = \sum_c \left( f_{\text{air-sea}(c)}^{\text{CO}_2} \left( A_{(c)} - A_{(c)}^{\text{ice}} \right) \right)
\]

(2-5)

Where \( A_{(c)} \) and \( A_{(c)}^{\text{ice}} \) are the appropriate total and sea ice areas, respectively, corresponding to grip point \( c \).

2.2.2.2 Ocean-atmosphere \( \text{O}_2 \) exchange

Unlike \( \text{CO}_2 \), dissolved oxygen concentrations \( [\text{O}_2] \) are not buffered by the presence of a complex chemical reservoir so that \( [\text{O}_2] \) in the surface ocean is often close to equilibrium with the atmosphere. The simplifying assumption is therefore often made in carbon cycle models that strict equilibrium is always maintained [Bolin et al., 1983; Maier-Reimer, 1993; Yamanaka and Tajika, 1996]. However, this doesn’t necessarily hold true in regions where vigorous convective overturning takes place such that the residence time of water at the surface may be too short for full equilibration with the atmosphere to take place [Heinze et al., 1999]. A simple restoring scheme is therefore adopted, weighted by the fractional ice-free area

\[
[\text{O}_2]_{\text{new}} = [\text{O}_2]_{\text{old}} + \frac{(A_{\text{tot}} - A_{\text{ice}})}{A_{\text{tot}}} \left([\text{O}_2]_{\text{eq}} - [\text{O}_2]_{\text{old}}\right) \frac{\Delta t}{\tau_{\text{O}_2}}
\]

(2-6)

where \( [\text{O}_2]_{\text{new}} \) is the new concentration of dissolved \( \text{O}_2 \) after exchange with the atmosphere, \( [\text{O}_2]_{\text{old}} \) is the old value before any exchange, and \( [\text{O}_2]_{\text{eq}} \) is the theoretical concentration of \( \text{O}_2 \) in the ocean in equilibrium with an atmospheric partial pressure \( (p\text{O}_2)_{\text{atm}} \) of 0.2096 atm, given by

\[
[\text{O}_2]_{\text{eq}} = Q_{\text{O}_2} \text{TS} \cdot p\text{O}_2\text{atm}
\]

(2-7)

where \( Q_{\text{O}_2} \text{TS} \) is the Henry’s Law constant for \( \text{O}_2 \) as a function of temperature and salinity in the surface ocean [Millero and Sohn, 1992]. The model time step is \( \Delta t \), with \( \tau_{\text{O}_2} \), the restoring time for \([\text{O}_2] \) assigned a default value of 30 days.

2.2.3 Biological new production

Numerous mechanistic schemes for representing biological productivity in the surface ocean based on a multi-component description of ecosystem structure and nutrient cycling have been developed to date [Aksnes et al., 1995; Andersen et al., 1987; Fasham et al., 1990]. These range in complexity from single nutrient and single phytoplankton component systems operating within a homogeneous surface ocean layer, to systems of multiple nutrients and trophic levels, all coupled to a 1D physical model. The export flux of particulate biogenic matter out of the surface layer in these models is derived from primary productivity taking into account various recycling and transformation processes within the euphotic zone. Although such schemes have been incorporated into global carbon cycle models their computational demands make their use in extended model runs problematic. In addition, they are often not particularly generalized and may require site-specific tuning [Hurt and Armstrong, 1996, 1998].

Much simpler is to attempt to estimate new (export) production directly from available surface nutrient concentrations, a tactic used in many carbon cycle models. Of limited use in addressing the glacial-interglacial question in this regard are schemes where export production is calculated to effectively ‘restore’ surface ocean nutrient concentrations to some pre-determined value (e.g., Marchal et al. [1998b], Murnane et al. [1999], Najjar et al. [1992]). Alternatively, export production may be parameterized as a function of a single nutrient (usually PO4), modified by terms representing Michaelis-Menten kinetic nutrient limitation, together with some or all of light, temperature, and mixed layer depth [Bacastow and Maier-Reimer, 1990; Heinze et al., 1991; Maier-Reimer, 1993]. Recently, the effect of additional limiting nutrients (H3SiO4 and Fe) have also been considered [Archer and Johnson, 2000; Archer et al., 2000; Heinze et al., 1999; Lefèvre and Watson, 2000; Watson et al., 2000]. However, common to all of these schemes is the calculation of a single value of whole-community organic carbon export. While this is sufficient in terms of the organic carbon pump alone, CaCO3 and opal production remain to be estimated. The magnitude of CaCO3 export flux together with its ‘rain ratio’ with respect to particulate organic carbon (POC), plays a critical role in controlling the alkalinity balance of the ocean and thus in determining xCO2 [Archer and Maier-Reimer, 1994]. For this reason it is undesirable to assume an invariant ratio of CaCO3:POC new production over the glacial-interglacial cycles. Not only is reproducing the observed spatial heterogeneity in rain ratios (at least to a first order) a precondition for effective simulation of Holocene sediments, being able to account for differences in this ratio during glacial times facilitates verification of the mechanism(s) assumed for glacial-interglacial change through comparisons between observed and model Last Glacial Maximum (LGM) sediment distributions. Similar arguments also apply for opal:POC. Unfortunately, since ecosystem structure is fundamental in determining such ratios there is no simple means of deriving their values from a total POC flux [Shaffer, 1993], although (highly parameterized) attempts have been made taking into account ambient nutrient and temperature conditions [Archer et al., 1999a,b, 2000; Heinze et al., 1999; Maier-Reimer, 1993].

A new computationally-efficient scheme for surface ocean biological production is presented here. In the manner in which it seeks to estimate export production out of the euphotic zone directly from surface physical and chemical conditions (as opposed to via a full ecosystem model) it is similar to that of Maier-Reimer [1993]. However, a significant departure is made in that production arising from two distinct classes of phytoplankton is considered; siliceous phytoplankton ("SP") and non-siliceous phytoplankton ("NSP"), following Egge and Aksnes [1992]. SP (typified by open ocean diatom species such as Thalassiosira oceanica) are assumed to be solely responsible for the production of opal, and as a result are limited by the availability of H3SiO4. In contrast, NSP (typified by open ocean coccolithophorids
such as *Emiliania huxleyi*, but including the bulk of pico- and nano-phytoplankton species), have no such silicic acid limitation and are assumed to be the sole producers of CaCO₃. Both classes are affected by ambient [PO₄] and [Fe], temperature, and light. In the absence of any nutrient limitation (and assuming a stable water column and adequate insolation levels) siliceous phytoplankton tend to dominate the phytoplankton community [Egge, 1998]. SP are therefore characterized in the model by a relatively high (export) productivity. NSP tend to generally comprise somewhat smaller species with productivity much more tightly controlled by grazing, and are therefore characterized by relatively low productivity. Obviously this is highly simplistic, with no explicit representation of the role played by zooplankton or the microbial loop [Taylor and Joint, 1990]. In addition, the important contribution made to PO₄ export in regions such as the Southern Ocean by high productivity non-siliceous bloom-forming species such as *Phaeocystis antarctica* [Elderfield and Rickaby, 2000] will not be captured. However, such a scheme is still able to capture the first order contrast in the observed CaCO₃:PO₄ mean ratio between different oceanic regions as will be demonstrated later (4.4.2).

Although the biological scheme is based around nutrient limitation by PO₄, H₂SiO₄, and Fe, present-day surface nutrient distributions suggest that the availability of nitrate (NO₃) is likely to be generally more limiting to phytoplankton growth than PO₄ [McElroy; Tyrrell, 1999]. However, considering the complexity of the oceanic NO₃ cycle no explicit representation is incorporated in SUE. A simple (normalized) insolation factor is made to alkalinity partitioning in the ocean by NO₃ cycled through the "soft tissue pump" [Broecker and Peng, 1982].

### 2.2.3.1 Phosphate uptake model

Net uptake fluxes (in units of mol PO₄ kg⁻¹ a⁻¹) within the euphotic zone by siliceous phytoplankton (\(u_{SP}^{PO₄}\)) and non-siliceous phytoplankton (\(u_{NSP}^{PO₄}\)) are based upon the 'law of the minimum' for multiple nutrient limitation [Aksnes et al., 1994], and described by

\[
u_{SP}^{PO₄} = u_{SP}^{PO₄} \cdot \text{MIN} \left( k_{SP}^{PO₄} \cdot h_{SP}^{PO₄}, k_{SP}^{Fe} \cdot h_{SP}^{Fe} \right) \mu_{(T)} \cdot \mu_{(T)}
\]

\[
u_{NSP}^{PO₄} = u_{NSP}^{PO₄} \cdot \text{MIN} \left( k_{NSP}^{PO₄} \cdot h_{NSP}^{PO₄}, k_{NSP}^{Fe} \cdot h_{NSP}^{Fe} \right) \mu_{(T)} \cdot \mu_{(T)}
\]

(2-8a) 

where \(u_{SP}^{PO₄}\) and \(u_{NSP}^{PO₄}\) are uptake rates (mol PO₄ kg⁻¹ a⁻¹) in the absence of any nutrient limitation for SP and NSP, respectively, and treated as optimizable parameters. \(\mu_{(T)}\) is a factor accounting for the effects of ambient insolation on primary production, and \(\mu_{(T)}\) is similar, but for temperature.

A realistic treatment of light limitation is complex, requiring consideration of the depth distribution of phytoplankton in the water column, effects of self-shading and photo-inhibition, and an estimate of the depth of the mixed layer [Andersen et al., 1987; Taylor et al., 1991; Tyrrell and Taylor, 1996], all of which are beyond the scope of the current model. A simple (normalized) insolation factor is therefore used (detailed in Appendix II), \(\mu_{(T)}\) is defined such that \(\mu_{(T)}\) takes a value of unity at a temperature of 0°C.

**A Q₁₀-type dependence is assumed, with the scalar \(a\) given by [Aksnes et al., 1995]**

\[
a = \ln \left( \frac{Q_{10}}{10} \right)
\]

(2-10)

Following *Eppley* [1972] \(Q_{10}\) for phytoplankton growth of 1.88 is assumed, giving \(a = 0.063\). No distinction is made between the two phytoplankton groups in terms of their temperature response [Aksnes et al., 1995].

The \(k'\) terms in (2-8a) represent Michaelis-Menten kinetic limitation of uptake [Aksnes and Egge, 1991; Dugdale, 1967]

\[
k_{SP}^{PO₄} = \frac{[PO₄]}{K_{SP}^{PO₄} + [PO₄]}
\]

(2-11)

\[
k_{SP}^{HSiO₄} = \frac{[H₂SiO₄]}{K_{SP}^{HSiO₄} + [H₂SiO₄]}
\]

(2-12)

\[
k_{SP}^{Fe} = \frac{[Fe]}{K_{SP}^{Fe} + [Fe]}
\]

(2-13)

where \(K_s\) values in the three equations are the half-saturation constants for the respective nutrients. The NSP terms are similar, except that there is no \(H₂SiO₄\) limitation.

Strictly speaking, Michaelis-Menten limitation kinetics and the associated use of half-saturation constants are not directly applicable to a model of this type. Reported constants are calculated on the basis of growth rate of individual phytoplankton cells, whereas SUE seeks to predict net nutrient removal throughout the euphotic zone (and with it, export production). It is likely that export production has no simple relationship with primary production. Indeed, a tendency for export production to increase more rapidly with increasing primary production than primary production itself has been reported [Aksnes and Wassmann, 1993]. However, for want of a suitable alternative, this concise and easily interpretable parameterization is adopted for the purpose of this recent study.

Integrating net uptake ((2-8a) and (2-8b)) over the depth of the euphotic zone (\(D_{euph}\)) and total ice free area gives the total net uptake rate from each oceanic region (in units of mol PO₄ a⁻¹)

\[
u_{SP}^{PO₄} = u_{SP}^{PO₄} \cdot 1027 \left( 1 - \left( A_{tot} - A_{icel} \right) \right) D_{euph}
\]

(2-14a)

\[
u_{NSP}^{PO₄} = u_{NSP}^{PO₄} \cdot 1027 \left( 1 - \left( A_{tot} - A_{icel} \right) \right) D_{euph}
\]

(2-14b)

where the mean density of sea water is assumed to be 1027 kg m⁻³. Finally, (steady state) export production out of the euphotic zone is simply equal to net uptake. Partitioning this export into particulate (POP) and dissolved organic phosphate (DOP) forms, gives
Model description

\[ F_{nP}^{POP} = \lambda_{SP} \cdot U_{SP}^{PO4} \]  
\[ F_{nP}^{POP} = \lambda_{NSP} \cdot U_{NSP}^{PO4} \]

and

\[ F_{nP}^{DOP} = (1 - \lambda_{SP}) \cdot U_{SP}^{PO4} \]  
\[ F_{nP}^{DOP} = (1 - \lambda_{NSP}) \cdot U_{NSP}^{PO4} \]

Where \( \lambda_{SP} \) and \( \lambda_{NSP} \) are the export partitioning coefficients for SP and NSP, respectively.

2.2.3.2 Nutrient half-saturation constants

Phytoplankton nutrient half saturation constants are derived from values observed in both incubation and whole-ocean ecosystem studies. These values are summarized in Table 2-1, and adopted on the following basis:

**Phosphate**

The PO\(_4\)\(_{1-4}\) half saturation constant for siliceous phytoplankton (\(K^{PO4}_{SP}\)) is taken from the diatom value used by Aksnes et al. [1995]. Coccolithophorids have been observed to exhibit a higher affinity for phosphate than do diatoms [Aksnes et al., 1994; Egge 1998]. The PO\(_4\) half saturation constant for non-siliceous phytoplankton (\(K^{PO4}_{NSP}\)) is therefore assigned a value some 50% lower than that assumed for siliceous phytoplankton in order to reflect this difference.

**Silicic acid**

The half-saturation constant for siliceous phytoplankton is taken to be 4 µmol kg\(^{-1}\), consistent with kinetic experiments on single and diatoms and natural assemblages suggest a value for \(K^{H_{2}SiO_{4}}_{SP}\) in the range 0.5-5.0 µmol kg\(^{-1}\) [Dugdale et al., 1995; Officer and Ryther, 1980].

**Iron**

Assigning globally representative half-saturation constant values for Fe is much more problematic than for the macro-nutrients. While Sunda and Huntsman [1995] reported \(K^{Fe}_{SP}\) values for several typical oceanic diatom species, their experimental system was heavily EDTA-buffered with results reported on a calculated dissolved Fe\(^{III}\) scale. It is unwise to utilize the results of such a system directly [Gerringa et al., 2000; Muggli et al., 1996]. More applicable are results of Fe additions made to natural systems when the concentration of Fe tends to be operationally defined and thus substantially equivalent to the total dissolved Fe scale considered in SUE. Incubation enrichment experiments on equatorial Pacific samples indicate a whole-community \(K^{Fe}_{SP}\) of 0.12 nmol kg\(^{-1}\) [Coale et al., 1996b; Fitzwater et al., 1996], while similar experiments conducted at the equator and 15°N are consistent with values of 0.035 and 0.22 nmol kg\(^{-1}\), respectively [Price et al., 1994].

More recent enrichment incubation experiments carried out by Takeda [1998] are consistent with a value for \(K^{Fe}_{SP}\) of 0.25-0.75 nmol kg\(^{-1}\) for oceanic waters of all three main HNLC zones, while Hatches and Bruland [1998] suggest values characterizing the California coastal up-welling regime lie anywhere in the range 0.02-1.0 nmol kg\(^{-1}\) (depending on the precise details of the operational definition of [Fe] chosen). A value of \(K^{Fe}_{SP}\) of 0.125 nmol kg\(^{-1}\) is therefore chosen generally consistent with these estimates and assuming that most of the observed changes in primary production is due to diatoms. On the basis that Sunda and Huntsman [1995] observed half-saturation values for \(T. oceanica\) approximately twice that for \(E. huxleyi\), \(K^{Fe}_{NSP}\) is taken to be 50% lower than that of \(K^{Fe}_{SP}\).

2.2.3.3 ‘Redfield’ and derived chemical export ratios

While (2-15a) and (2-15b) together predict particulate PO\(_4\) export from the euphotic zone the export of other biogeochemically important nutrient and non-nutrient chemical species, such as H\(_2\)SiO\(_4\), Fe, CO\(_2\), and alkalinity (from Ca\(^{2+}\) and NO\(_3\)) must now be derived. The organic or inorganic components of particulate matter export are related directly (or via an intermediary) to phosphate export, by a series of characteristic ratios. For SP, these relationship are

\[ F_{nP}^{POC} = r_{SP}^{POC:POP} \cdot F_{nP}^{POP} \]  
\[ F_{nP}^{ALK} = -0.7 \cdot r_{SP}^{PON:POP} \cdot F_{nP}^{POP} \]  
\[ F_{nP}^{POFe} = r_{SP}^{POFe:POC} \cdot F_{nP}^{POC} \]  
\[ F_{nP}^{POFe} = r_{SP}^{POFe:POC} \cdot F_{nP}^{POC} \]

where \(r_{SP}^{x:y}\) is a molar ratio linking constituent \(x\) to \(y\). For NSP, they are

\[ F_{nP}^{POC} = r_{NSP}^{POC:POP} \cdot F_{nP}^{POP} \]  
\[ F_{nP}^{ALK} = -0.7 \cdot r_{NSP}^{PON:POP} \cdot F_{nP}^{POP} \]  
\[ F_{nP}^{POFe} = r_{NSP}^{POFe:POC} \cdot F_{nP}^{POC} \]  
\[ F_{nP}^{POFe} = r_{NSP}^{POFe:POC} \cdot F_{nP}^{POC} \]

where

<table>
<thead>
<tr>
<th>Phytoplankton group</th>
<th>Nutrient</th>
<th>(K_x) value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Siliceous</td>
<td>PO(_4)</td>
<td>0.1 µmol kg(^{-1})</td>
</tr>
<tr>
<td>Siliceous</td>
<td>H(_2)SiO(_4)</td>
<td>4.0 µmol kg(^{-1})</td>
</tr>
<tr>
<td>Siliceous</td>
<td>Fe</td>
<td>0.125 nmol kg(^{-1})</td>
</tr>
<tr>
<td>Non-siliceous</td>
<td>PO(_4)</td>
<td>0.05 µmol kg(^{-1})</td>
</tr>
<tr>
<td>Non-siliceous</td>
<td>H(_2)SiO(_4)</td>
<td>n/a</td>
</tr>
<tr>
<td>Non-siliceous</td>
<td>Fe</td>
<td>0.0875 nmol kg(^{-1})</td>
</tr>
</tbody>
</table>
The proportions of C and N to P in POM are characterized by observed mean ratios (the so-called 'Redfield' ratios), with \( r_{\text{POC}:\text{POF}} \) and \( r_{\text{POM}:\text{POF}} \) taking values of 106:1 and 16:1, respectively [Redfield et al., 1963]. The same ratios are assumed for POM derived from both SP and NSP. Net oxygen production in the euphotic zone is assumed to be in a fixed ratio to phosphate export, with \( O_2: P \) of 177:1.

Recent studies have indicated profound physiological effects on phytoplankton of iron availability aside from the direct influence on growth rate. For instance, phytoplankton have been observed to take up Fe in an apparent 'luxuriant' manner when ambient Fe availability is high [Sunda et al., 1991; Sunda and Huntsman, 1995]. A second physiological change manifests itself through the molar ratio of cellular carbon to frustular opal in diatoms, with the apparent efficiency of silicic acid utilization (per unit carbon fixed) increasing with iron availability. Where available \( H_4SiO_4 \) is limiting to diatom growth, therefore, enhanced iron supply may enable increased diatom organic export without any concurrent increase in opal export. This has important implications both for the operation of the global carbon cycle and for the paleoecological interpretation of sedimentary opal content and accumulation rates in deep sea sediment cores [Anderson et al., 1998; Boyle, 1998; Takeda, 1998; Watson et al., 2000]. The export ratios \( r_{\text{SP}}^{\text{POFe}:\text{POC}} \) and \( r_{\text{SP}}^{\text{POFe}:\text{POC}} \) are therefore defined as functions of Fe availability. Although Fe availability was previously thought to have relatively little influence on the ratios linking C, N, and P [Greene et al., 1991], nitrate utilization appears to be significantly greater per unit carbon fixed under Fe-replete conditions [Cullen, 1995; Hutchins and Bruland, 1998; Hutchins et al., 1998; Muggli et al., 1996; Takeda, 1998]. Since there is no explicit consideration of \( NO_3 \) in SUE and little quantitative information is currently available concerning changes in \( H_4SiO_4: P \) uptake, no dependence of \( [Fe] \) on \( r_{\text{POC}:\text{POF}} \) or \( r_{\text{POM}:\text{POF}} \) is considered.

**Export CaCO_3:POC ratio**

The export ratio of \( \text{CaCO}_3: \text{POC} \) from non-siliceous phytoplankton (\( r_{\text{NSP}}^{\text{CaCO}_3: \text{POC}} \)) is left as an optimizable parameter in the model. \( \text{CaCO}_3 \) in SUE is resolved in calcitic and aragonitic components. Although there is little available data for aragonite export, sediment trap measurements suggest that aragonite constitutes at least 12% of the total \( \text{CaCO}_3 \) sinking flux at a depth of 667 m in the equatorial Atlantic [Berner and Honjo, 1981], but can be as high as 24% at 100 m in the North Pacific [Berner et al., 1984]. Aragonite is therefore assumed to constitute \( \sim 5\% \) of \( \text{CaCO}_3 \) export production, equivalent to \( \sim 10\% \) at 1000 m depth as a result of rapid reduction in calcite fluxes through the mesopelagic zone (see 2.2.4.2).

While the value of \( r_{\text{CaCO}_3: \text{POC}} \) is itself invariant and spatially uniform the overall, \( \text{CaCO}_3: \text{POC} \) export ratio comprises export from both SP (contributing POC only) and NSP (contributing both POC and \( \text{CaCO}_3 \)). Temporal or spatial variability in the balance between SP and NSP productivity (for instance, due to changes in the availability of \( H_4SiO_4 \)) can thus give rise to variability in the net \( \text{CaCO}_3: \text{POC} \) export ratio.

**Export POC:POFe ratio**

Export \( \text{POFe}: \text{POC} \) ratios are related to Fe availability empirically in the model based on culture results reported by [Sunda and Huntsman, 1995]. Their theoretical free Fe\(^{II} \) (Fe\(^{II} \)) scale is converted to the equivalent in total dissolved iron \( [Fe] \) used in SUE by assuming that the half saturation constant for diatoms on the \( [Fe] \) scale of \( \sim 0.004 \text{nmol kg}^{-1} \) [Sunda and Huntsman, 1995], can be equated directly to the estimated value for NSP of 0.125 nmol kg\(^{-1} \) of \( [Fe] \) derived earlier (2.2.3.2). A simple power law function is used, with the observed behaviour of \( T. oceanica \) taken to be representative of SP, and \( E. huxleyi \) of NSP [Sunda and Huntsman, 1995]. Assuming that there is no fractionation between Fe and C components of POM primary production within the euphotic zone, Fe:C export ratios for the two phytoplankton groups are set equal to these cellular relationships. A threshold level is imposed and set at the maximum observed efficiency of iron utilization [Sunda and Huntsman, 1995]; a value of some 3 \( \mu \text{mol} \) Fe (mol C\(^{-1} \)) for both \( r_{\text{SP}}^{\text{POFe}:\text{POC}} \) and \( r_{\text{NSP}}^{\text{POFe}:\text{POC}} \). The relationships thereby obtained (Figure 2-3) are

\[
\frac{1}{r_{\text{SP}}^{\text{POFe}:\text{POC}}} = \frac{1}{\text{MIN}(333000, 150000 \times \frac{115623 - [Fe] + 0.125}{0.1805})} \tag{2-24a}
\]

and

\[
\frac{1}{r_{\text{NSP}}^{\text{POFe}:\text{POC}}} = \frac{1}{\text{MIN}(333000, 200000 \times 31805 - [Fe] + 0.125)} \tag{2-24b}
\]
where \([\text{Fe}]\) is the total dissolved iron concentration in units of nmol kg\(^{-1}\).

**Export opal: POC ratio**

Incubation and ocean patch studies have reported changes in the cellular uptake ratios of \(\text{HSiO}_4^+:\text{NO}_4^3-\) and \(\text{HSiO}_4^+:\text{C}_4^4\) by HNLC-type phytoplankton assemblages upon the addition of iron [Hutchins and Bruland, 1998; Takeda, 1998; Watson et al., 2000], summarized in Table 2-2. Fe-stressed diatoms are also visibly more heavily silicified [Hutchins et al., 1998; Leynaert et al., 1993]. This increase in diatom \(\text{HSiO}_4^+:\text{C}_4^4\) with decreasing Fe-availability has been suggested to be due to the order of cell cycle events, where silicic acid uptake only occurs in a phase just prior to cellular division [Pondaven et al., 1999]. If division is delayed through Fe-limitation, the length of time available for opal deposition is longer, thus resulting in a higher degree of diatom silicification. If this is the case, a reasonable starting point in relating \(\text{HSiO}_4^+:\text{C}_4^4\) uptake to ambient \([\text{Fe}]\) would be to assume that this ratio is proportional to Fe-stress as defined by the reciprocal of the relevant Michaelis-Menten kinetic term (2-16), to give

\[
\frac{r_{\text{HSiO}_4^+:\text{C}_4^4}}{r_{0,\text{HSiO}_4^+:\text{C}_4^4}} = \frac{1}{K_{\text{Fe}}}
\]  

(2-25)

where \(r_{0,\text{HSiO}_4^+:\text{C}_4^4}\) is the ratio of \(\text{HSiO}_4^+:\text{C}_4^4\) uptake under Fe-replete conditions. The singularity at \([\text{Fe}] = 0\) is removed by adding a fixed offset \([\text{Fe}]_{\text{off}}\) to the value of ambient \([\text{Fe}]\).

The observed decrease in diatom \(\text{HSiO}_4^+:\text{C}_4^4\) with increasing Fe availability (Table 2-3) can be reasonably reproduced with \(K_{\text{Fe}} = 0.25\) nmol kg\(^{-1}\), and applying an offset in ambient \([\text{Fe}]\) of 0.125 nmol kg\(^{-1}\).

Given their very different biogeochemical natures, a high degree of differential recycling between opal and POC within the euphotic zone is likely [Dugdale et al., 1995; Dugdale and Wilkerson, 1998]. Changes in the degree of diatom silicification may alter the magnitude of this differential, such as through changes in sinking rate [Boyle, 1998; Muggli et al., 1996], grazing susceptibility, or the ‘quality’ of frustuline opal (and thus solubility and/or dissolution rate). However, for simplicity the export opal:POC ratio \(r_{\text{SP}}^{\text{opal:POC}}\) will be assumed to scale linearly with the cellular \(\text{HSiO}_4^+:\text{C}_4^4\) uptake ratio. The export ratio can therefore be written

\[
\frac{r_{\text{SP}}^{\text{opal:POC}}}{r_{0,\text{SP}}^{\text{opal:POC}}} = \frac{K_{\text{SP}}^{\text{Fe}} + ([\text{Fe}] + [\text{Fe}]_{\text{off}})}{([\text{Fe}] + [\text{Fe}]_{\text{off}})}
\]  

(2-26)

where \(r_{0,\text{SP}}^{\text{opal:POC}}\) is now the export opal:POC ratio under Fe-replete conditions. The form of this relationship is shown in Figure 2-3. The magnitude of differential recycling within the euphotic zone represented by the implicit scale factor linking \(r_{\text{SP}}^{\text{opal:POC}}\) to \(r_{0,\text{SP}}^{\text{opal:POC}}\) is poorly quantified, and has been variously estimated to be in the range 1.25 to 3.0 depending on assumptions made regarding grazing [Dugdale et al., 1995; Dugdale and Wilkerson, 1998]. \(r_{0,\text{SP}}^{\text{opal:POC}}\) is therefore left as an optimizable parameter in the model.

**Table 2-2** Observed Dependence of Molar Uptake Ratios upon Iron Availability

<table>
<thead>
<tr>
<th>Identifier and location</th>
<th>Treatment</th>
<th>([\text{Fe}]) (nmol kg(^{-1}))</th>
<th>(\text{HSiO}_4^+:\text{NO}_4^3)</th>
<th>(\text{HSiO}_4^+:\text{C}_4^4)</th>
<th>Growth rate (d(^{-1}))</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1 - Big Sur 1997A</td>
<td>Control</td>
<td>0.1-0.5 (^1)</td>
<td>1.6</td>
<td>0.27</td>
<td>0.30</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fe addition</td>
<td>2.5</td>
<td>0.8</td>
<td>0.21</td>
<td>0.68</td>
<td>Hutchins and Bruland [1998]</td>
</tr>
<tr>
<td>#2 - Big Sur 1996</td>
<td>Control</td>
<td>0.06-0.3 (^1)</td>
<td>2.7</td>
<td>0.39</td>
<td>0.70</td>
<td>Hutchins and Bruland [1998]</td>
</tr>
<tr>
<td></td>
<td>Fe addition</td>
<td>10</td>
<td>1.1</td>
<td>0.24</td>
<td>0.94</td>
<td></td>
</tr>
<tr>
<td>#3 - Ano Nuevo 1995</td>
<td>Control</td>
<td>1.5-2.6 (^1)</td>
<td>1.0</td>
<td>n/a</td>
<td>0.44</td>
<td>Hutchins and Bruland [1998]</td>
</tr>
<tr>
<td></td>
<td>Fe addition</td>
<td>10</td>
<td>0.9</td>
<td>n/a</td>
<td>0.37</td>
<td></td>
</tr>
<tr>
<td>#4 - Southern Ocean</td>
<td>Control</td>
<td>0.16</td>
<td>2.3</td>
<td>n/a</td>
<td>0.13</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fe addition</td>
<td>1.2</td>
<td>0.95</td>
<td>n/a</td>
<td>0.43</td>
<td>Takeda [1998]</td>
</tr>
<tr>
<td>#5 - Subarctic North Pacific</td>
<td>Control</td>
<td>0.22</td>
<td>2.6</td>
<td>n/a</td>
<td>0.14</td>
<td></td>
</tr>
<tr>
<td>#6 - Equatorial Pacific</td>
<td>Control</td>
<td>&lt;0.05</td>
<td>1.3</td>
<td>n/a</td>
<td>0.06</td>
<td>Takeda [1998]</td>
</tr>
<tr>
<td></td>
<td>Fe addition</td>
<td>0.46</td>
<td>0.45</td>
<td>n/a</td>
<td>0.48</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fe addition</td>
<td>0.72</td>
<td>0.45</td>
<td>n/a</td>
<td>0.79</td>
<td></td>
</tr>
<tr>
<td>#7 - Southern Ocean</td>
<td>Control</td>
<td>0.06</td>
<td>n/a</td>
<td>0.36±0.015</td>
<td>n/a</td>
<td>Watson et al. [2000]</td>
</tr>
<tr>
<td></td>
<td>Fe addition</td>
<td>0.3-3.0 (^2)</td>
<td>n/a</td>
<td>0.18±0.1</td>
<td>n/a</td>
<td></td>
</tr>
</tbody>
</table>

\(^1\) Control Fe concentration are presented as a range of estimates, depending on the analytical method employed [Hutchins and Bruland, 1998].
2.2.4 Remineralization within the water column

Much of particulate biogenic material exported out of the euphotic zone is remineralized within the water column before it can reach the sediments. Material returned to solution in the mesopelagic zone has the potential to be rapidly returned to the surface, which in the case of nutrients such as PO₄, NO₃, H₂SiO₄, and Fe has obvious implications for surface productivity. The magnitude of the remaining particulate fraction reaching the sediments ultimately exerts an important control on oceanic inventories of nutrients, DIC, and ALK. An adequate representation of remineralization processes within the water column is therefore critical to any description of the global carbon cycle, particularly over glacial-interglacial time scales. In the following sections, a reference depth \( z_0 \) is defined at the base of the euphotic zone, where the settling flux of particulate constituent \( x \) is equal to the total export flux

\[
F_{\text{set}}(z_0) = F_{\text{np}} + F_{\text{np}}^{\text{res}}
\]

For dissolved organic matter, remineralization proceeds according to a simple characteristic decay rate [Marchal et al., 1998b; Najjar et al., 1992] as it is transported through the ocean. No distinction is made between semilabile and refractory components [Yamanaka and Tajika, 1997].

2.2.4.1 Particulate organic matter

The processes involved in the remineralization of particulate organic matter (POM) within the water column are extremely complex, including such factors as the repackaging and aggregation/dispersal of particles, bacterial and zooplankton ecology and the occurrence of rapid export events following phytoplankton blooms [Kriest and Evans, 1999; Shaffer, 1993]. Simple empirical functions are therefore utilized in global carbon cycle models. Various schemes have been proposed, typically based on exponential [Volk and Hoffert, 1985] or power law [Martin et al., 1987; Suess, 1980] functions in which the remaining (un-remineralized) fraction of the initial POM export flux is related directly to the depth in the water column. Of these, the parameterization of Martin et al. [1987], derived from a series of sediment trap measurements made during the ‘VERTEX’ programs and covering the uppermost 2000 m in the eastern equatorial Pacific tends to be fairly ubiquitous (e.g., Maier-Reimer [1993], Yamanaka and Tajika [1996]). However, sediment trap studies suggest that remineralization deeper than this is much less extensive than extrapolation of the Martin et al. [1987] function might suggest (Figure 2-4). Since any significant underestimation of POM rain rate to the sediments would reduce the component of CaCO₃ dissolution driven by in situ POM remineralization [Archer and Maier-Reimer, 1994] and thus disrupt global alkalinity, Archer et al. [1996, 1998] modified the Martin et al. [1987] function (Figure 2-4). Although this is in good agreement with deeper (> 2000 m) sediment trap observations, it tends to deviate a little from the VERTEX data at mesopelagic depths.

Table 2-3 Observed and Model-estimated Relative Changes in H₂SiO₄:C Uptake From Comparatively Iron-deplete to Iron-replete Conditions

<table>
<thead>
<tr>
<th>Identifier</th>
<th>( \text{HSiO}<em>4 )\text{C}</em>{\text{deplete}}</th>
<th>( \text{HSiO}<em>4 )\text{C}</em>{\text{replete}}</th>
<th>( \text{HSiO}<em>4 )\text{C}</em>{\text{deplete}}</th>
<th>( \text{HSiO}<em>4 )\text{C}</em>{\text{replete}}</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>1.29</td>
<td>1.27-1.92(^2)</td>
<td>1.27-1.92(^2)</td>
<td>1.27-1.92(^2)</td>
</tr>
<tr>
<td>#2</td>
<td>1.63</td>
<td>1.59-2.35(^3)</td>
<td>1.59-2.35(^3)</td>
<td>1.59-2.35(^3)</td>
</tr>
<tr>
<td>#3</td>
<td>1.00(^4)</td>
<td>1.10-1.15(^5)</td>
<td>1.10-1.15(^5)</td>
<td>1.10-1.15(^5)</td>
</tr>
<tr>
<td>#4</td>
<td>1.58(^3)</td>
<td>1.58</td>
<td>1.58</td>
<td>1.58</td>
</tr>
<tr>
<td>#5</td>
<td>1.42(^3)</td>
<td>1.43</td>
<td>1.43</td>
<td>1.43</td>
</tr>
<tr>
<td>#6</td>
<td>1.89(^3)</td>
<td>&gt;1.70(^4)</td>
<td>&gt;1.70(^4)</td>
<td>&gt;1.70(^4)</td>
</tr>
<tr>
<td>#7</td>
<td>2.00</td>
<td>2.03</td>
<td>2.03</td>
<td>2.03</td>
</tr>
</tbody>
</table>

\(^1\) (see Table 2-2)
\(^2\) Depending upon assumptions made regarding the exact value of [Fe] in the experimental control.
\(^3\) Estimated from published changes in H₂SiO₄:NO₃. Care must therefore be taken in using these values, since there is also a significant dependence of H₂SiO₄:NO₃ on [Fe].
\(^4\) Assuming control [Fe] < 0.05 nmol kg\(^{-1}\).

\[ F_{\text{set}}(z) = F_{\text{set}}(z_0) \quad z \leq z_0 \] (2.28a)
As shown in Figure 2-4, this gives a reasonable compromise solution, consistent with observations of both mesopelagic and bathypelagic flux profiles.

Constant ratios linking C, Fe, and N to P during the remineralization of POM are assumed throughout the water column, taking values equal to those characterizing mean export production (2-17 to 2-23). The remineralization of POM involves the oxidation of organic compounds, a process that requires the availability of oxygen (or an alternative electron donor). Dissolved oxygen is assumed to be depleted within the water column in a 177:1 molar ratio with the quantity of phosphate released. To prevent depletion of O₂ below zero in regions characterized by poor ventilation and/or high surface productivity, a minimum threshold is prescribed (taken to be 25 µmol kg⁻¹) below which no further depletion is allowed. POM continues to be remineralized in the model though, somewhat analogous to remineralization fuelled through denitrification (although nitrogen cycling is not explicitly represented).

2.2.4.2 Calcite

Calcite has been the only polymorph of CaCO₃ explicitly considered in global carbon cycle models to date. Its remineralization within the water column invariably proceeds in accordance with an exponentially decreasing flux profile, taking an e-folding depth sometimes as short as 2 km [Heinze et al., 1999; Maier-Reimer, 1993], although studies where model alkalinity fields are fitted to observed data suggest a higher value in the region of 3-3.5 km [Marchal et al., 1998b; Yamanaka and Tajika, 1996]. However, Milliman et al. [1999] concluded that 40-80% of CaCO₃ export dissolved at depths...
shallower than about 1 km, while dissolution was inconsequential below this, perhaps due to the rapid dissolution of coccoliths in the guts of grazing zooplankton. This can be parameterized by the assumption of a fixed fraction of calcite export production with reaches the deep ocean without alteration, with the remainder subject to remineralization \[\text{Archer et al., 1998}\]. The magnitude of the remineralizable fraction together with its remineralization scale length are chosen consistent with the general conclusions of \text{Milliman et al. [1999]}, and more specifically, with the sediment trap observations of \text{Martin et al. [1993]} over the upper-most 1000 m. The calcite settling flux is therefore defined

\[F_{\text{set,calcite}}(z) = F_{\text{set,calcite}}(z_0) \quad z \leq z_0 \quad (2-29a)\]

\[F_{\text{set,calcite}}(z) = F_{\text{set,calcite}}(z_0) \left( 0.4 + 0.6 \cdot e^{-\frac{(z - z_0)}{z_l}} \right) \quad z > z_0 \quad (2-29b)\]

2.2.4.3 Aragonite

The remineralization of aragonite within the water column is based on the analysis of \text{Byrne et al. [1984]}. Their theoretical profiles of flux decrease with depth below the aragonite saturation horizon can be reasonably well fitted with a simple power function (Figure 2-5)

\[f_{\text{aragonite}}(z) = f_{\text{aragonite}}(z_{\text{sat}}) \left( 1 - \left( \frac{z - z_{\text{sat}}}{z_l} \right)^{2} \right) \quad (2-30)\]

where \(f_{\text{aragonite}}\) is the aragonite flux at depth \(z\), \(f_{\text{aragonite}}(z_{\text{sat}})\) is the aragonite flux at the base of the photic zone, \(z_{\text{sat}}\) is the depth of the aragonite saturation horizon, and \(z_l\) is a scale depth for remineralization, depending on the initial size/settling rate. A net remineralization profile in the ocean can then be defined given the depth of the aragonite saturation horizon together with an estimate of the initial size distribution of sinking particles. Unfortunately, the latter piece of information is extremely poorly quantified. Aragonite export is therefore assumed to be comprised of a mixture of the four species considered by \text{Byrne et al. [1984]}, \text{Culierina columnella}, \text{Limaclina bullmoldes}, \text{Limacina helicina}, and \text{Limacina inflata}. The initial export flux is partitioned 2:2:3:3 (by mass) between these, giving 40% of the flux as > 1 mm diameter particles, and 60% as < 500 µm, reasonably consistent with observations of aragonite flux size distributions \text{Berner and Honjo, 1981; Byrne et al., 1984}. The remineralization of each initial class size is summed and the total flux fitted as a function of depth below the aragonite saturation horizon (Figure 2-5). The aragonite settling flux is therefore defined

\[f_{\text{aragonite}}(z) = f_{\text{aragonite}}(z_{\text{sat}}) \left( 1 - \left( \frac{z - z_{\text{sat}}}{z_l} \right)^{2} \right) \quad (2-30)\]
Model description

\[ F_{\text{set}} = F_{\text{set}}(z_0) \]

\[ F_{\text{set}} = F_{\text{set}}(z_0 \cdot 0.25 \left(1 - e^{-\frac{\left(\frac{z - z_{sat}}{1000}\right)}{0.25}}\right)) \]

2.2.4.4 Opal

In initial studies incorporating Si cycling into a global carbon cycle model the remineralization of opal within the water column was described with a simple exponential depth function, taking a somewhat arbitrary e-folding length of order 10 km [Heinze et al., 1999; Maier-Reimer, 1993]. More recently, noting the importance of temperature in the control of dissolution rates, Gnannadesikan [1999] proposed a more realistic scheme. In this, the dissolution rate of opal, \( r_{\text{opal}} \) (d\(^{-1}\)) was described by

\[ r_{\text{opal}} = 1.32 \times 10^{9} \cdot e^{-\frac{T}{0.225}} \]  

where \( T \) is the absolute temperature. Opaline particles were assumed to settle through the water column at a uniform rate of 50 m d\(^{-1}\). While Erez et al. [1982] concluded that variations in silicic acid concentrations were not the main control on opal dissolution rates, this was on the basis of first-order dissolution kinetics, an assumption which has now been called into question [Van Cappellen and Qiu, 1997b]. A new scheme is therefore developed here, able to account explicitly for the dependence of opal remineralization of both ambient temperature and concentration of \( \text{H}_4\text{SiO}_4 \).

Model formulation

The description of opal remineralization is based empirically on the thermodynamic studies of Van Cappellen and Qiu [1997a,b] (see 3.2.5.1 for more details). Primary controls are assumed to be ambient temperature and the concentration of silicic acid, together with the settling velocity of the material. No account is taken of changes in surface reactivity which may occur during transit down through the water column, such as may arise through a general reduction in surface roughness or the removal of reactive sites at surface defects [Van Cappellen and Qiu, 1997b]. Bacteria may also play an important role in controlling the dissolution rate of diatom frustules, which strongly depends on the presence or absence of a protective organic coating [Bidle and Azam, 1999; Kamatani, 1982]. However, since the bacterial degradation of this layer appears to be substantially complete within a matter of only 1-2 days [Bidle and Azam, 1999], bacterial influence may be confined to pelagic and mesopelagic regions.

The rate of release of silicic acid within an ocean layer \( l \) resulting from the dissolution of biogenic opal settling through the water column, \( F_{\text{dispol}}(l) \) (mol a\(^{-1}\)), is described by

\[ F_{\text{dispol}} = r_{\text{opal}} \cdot F_{\text{setpol}} \cdot \Delta t(l) \]

where \( k_{\text{pol}} \) is a base opal dissolution rate pertaining to ambient conditions of 0°C and complete under-saturation with respect to the solid phase, \( F_{\text{setpol}} \) is the settling flux of opal into the layer (mol a\(^{-1}\)), and \( \Delta t(l) \) is the residence time of this opal within the layer. \( r_{\text{pol}} \) is a normalized dissolution rate (described in 3.2.5.1) characterized by a \( Q_{\text{pol}} \) value of 2.3 for under-saturated conditions, consistent with the dissolution experiments of Kamatani [1982] and given by

\[ r_{\text{pol}} = 0.225 \left(1 + \frac{T(l)}{15}\right) \cdot u_{\text{pol}} \]

\[ 0.775 \left(1 + \frac{T(l)}{400}\right) \cdot u_{\text{pol}} \]

where \( u_{\text{pol}} \) is the degree of under-saturation of the solid phase (3.2.5.1).

The value for \( K_{\text{pol}} \) is derived from observed diatom dissolution rates. From laboratory studies, Nelson et al. [1976] found a mean dissolution rate in small centric diatoms under different growth conditions equivalent to 0.134 d\(^{-1}\) at 20°C, while two acid-washed coastal species (also measured at 20°C) dissolved at a rate of 0.074 d\(^{-1}\) [Kamatani, 1982]. Dissolution rates can also be estimated in the field from observations of the increase in sediment trap head-space \([\text{H}_4\text{SiO}_4] \). In this way, Brzezinski and Nelson [1995] calculated the dissolution rate of trapped material at 0.07 ± 0.03 d\(^{-1}\) at −19°C, while Blain et al. [1999] estimated rates of 0.068, 0.085, 0.075, and 0.065 d\(^{-1}\) from a series of four different deployment depths. If conditions of complete under-saturation (i.e., \( u_{\text{pol}} = 1.0 \)) are assumed, and dissolution rates corrected to \( T = 0°C \) (estimated from Levitus et al. [1994] where not reported) and taking a \( Q_{\text{pol}} \) value of 2.3, a mean value across all these studies of 0.019 d\(^{-1}\) is obtained.

Analysis of sediment trap series suggests settling rates of opal material ranging from 32 to 200 m d\(^{-1}\) [Blain et al., 1999; Honjo and Mangani, 1993; Takahashi, 1986]. In the absence of any tighter observational constraint a uniform sinking rate of 125 m d\(^{-1}\) is assumed following Pondaven et al. [1998]. The residence time \( \Delta t(l) \) (d) is then given by

\[ \Delta t(l) = \frac{\theta_l(l)}{125} \]

where \( \theta_l(l) \) is the thickness (m) of the \( l \)th ocean layer.

Model evaluation

A number of studies have reported opal settling fluxes at multiple depths measured at the same geographical location, which in theory could be used to validate the remineralization model. However, there are a number of serious complications in the interpretation of opal sediment trap observations which are likely to significantly reduce their utility in such validation:

- Since the ocean is everywhere under-saturated with respect to biogenic opal, opal caught in sediment traps will continue to dissolve throughout the period of trap deployment. While recent studies make use of traps that
have been filled with high density brine solution in order to help quantify in situ dissolution (Blain et al. [1999]; Brzezinski and Nelson [1995]; Honjo and Manganini [1993]), early studies took no account of such losses (Honjo [1980]; Noriki and Tsunogai [1986]; Takahashi [1986]). Thus, account must be taken of the potential for the underestimation of settling fluxes by less sophisticated trap designs.

- Sinking fluxes may be modified by the random mesoscale eddy field through which the particles settle [Siegel et al., 1990], an effect which can be manifested as an ‘inverted’ flux profiles (i.e., where measured fluxes increase with depth despite continued dissolution). Even where flux measurements have been made by free-floating traps (e.g., Blain et al. [1999]) there is likely to be some residual hydrodynamic distortion.

- Temporal variability in export production (such as associated with phytoplankton blooms) may cause problems in short term trap deployments. For instance, flux profiles which strongly increase with depth can arise should the traps be deployed at such a time that the uppermost trap samples post-bloom conditions while deeper ones still sample bloom conditions.

- In mesopelagic trap deployments, increased capture rates of radiolarians with depth may also produce inverted-type profiles [Blain et al., 1999].

- Any decrease in surface reactivity as opal dissolves in the water column may lead to the influence of surface to deep contrasts in ambient temperature and [H_4SiO_4] profiles in the water column for these locations are further considered.

Studies reporting opal settling flux profiles used in the validation of the water-column dissolution model are shown in Figure 2-6a. While some of the sediment trap data is consistent with this model over the upper most ~2500 m of the water column, there is a prominent negative trend with depth below this, contrary to observations. An improved fit is possible if a more rapid settling rate is adopted, although it is beyond this particular scheme’s capability to fit either of data sets #2 and #5, regardless of assumptions made regarding settling rate.

For comparison, the equivalent model predictions using the parameterization of Gnanadesikan [1999] are shown in Figure 2-6b. While some of the sediment trap data is consistent with this model over the upper most ~2500 m of the water column, there is a prominent negative trend with depth below this, contrary to observations. An improved fit is possible if a more rapid settling rate is adopted, although it is beyond this particular scheme’s capability to fit either of data sets #2 and #5, regardless of assumptions made regarding settling rate.

Predicted opal remineralization profiles for the same six locations (Table 2-4) are shown in Figure 2-7. It can be seen that there are interesting regional contrasts in the degree of remineralization which occurs within the water column. The lowest degrees of remineralization are predicted for regions characterized by relatively low temperatures and high concentrations of silicic acid throughout the water column, such as found in the north Pacific (#6) and the Southern Ocean (#1). In contrast, a relative high degree of remineralization occurs throughout the water column in the low- and mid-latitude Atlantic (#4 and #5) where, despite temperatures rapidly decreasing with depth below the

### Table 2-4 Biogenic Opal Flux Sediment Trap Data

<table>
<thead>
<tr>
<th>Identifier</th>
<th>Location</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>61.5°S, 150.5°E</td>
<td>Noriki and Tsunogai [1986]</td>
</tr>
<tr>
<td>#2</td>
<td>31.7°N, 124.6°W</td>
<td>Noriki and Tsunogai [1986]</td>
</tr>
<tr>
<td>#3</td>
<td>17.5°N, 117.0°W</td>
<td>Noriki and Tsunogai [1986]</td>
</tr>
<tr>
<td>#4</td>
<td>34°N, 21°W</td>
<td>Honjo and Manganini [1993]</td>
</tr>
<tr>
<td>#5</td>
<td>13°N, 54°W</td>
<td>Honjo [1980], Honjo et al. [1982]</td>
</tr>
<tr>
<td>#6</td>
<td>50°N, 145°W</td>
<td>Takahashi [1986]</td>
</tr>
</tbody>
</table>
Figure 2-6: Apparent opal settling fluxes recorded by arrays of sediment traps, normalized to the value recorded in the uppermost trap of each array (filled symbols) and compared with model-predicted opal fluxes, normalized in a similar way (solid lines of a corresponding colour). Model results are shown for both the scheme developed here (a), and that of Gnanadesikan [1999] (b).
surface, \([\text{H}_4\text{SiO}_4]\) remains comparatively low and thus conditions highly under-saturated. Low- and mid-latitude Pacific regions (#2 and #3) are also characterized by high temperatures and low \([\text{H}_4\text{SiO}_4]\) at the surface. However, little remineralization occurs below the mesopelagic zone despite cold, high \([\text{H}_4\text{SiO}_4]\) deep ocean conditions.

### 2.2.5 Iron biogeochemical cycling

The behaviour of iron in the ocean is highly complex, involving transformations between various particulate, dissolved, and complexed phases [Donaghay et al., 1991; Johnson et al., 1997; Gerrings et al., 2000]. The dynamic equilibrium state of such a system is strongly affected by such factors as pH [Jickells, 1999; Jickells and Spokes, in press; Kuma et al., 1996], temperature, insolation levels [Jickells and Spokes, in press; Kuma et al., 1996; Sunda and Huntsman, 1995], and the presence of organic compounds able to bind to Fe (ligands) [Johnson et al., 1997; Rue and Bruland, 1997; Sunda and Huntsman, 1995]. Qualitative knowledge regarding the role of these (and further) factors is currently still in its infancy. SUE therefore considers a single 'total dissolved' iron phase, substantially equivalent to the operational definition in ocean Fe measurements [de Baar and de Jong, in press]. In this way, the values of Fe-related variables and parameters in the model should be directly comparable to those measured in both the ocean and laboratory seawater systems.

On the basis of the similarity between observed profiles of dissolved iron and nitrate in the upper 2000 m of the water column, the first-order biogeochemical behaviour of iron in the ocean has been considered to parallel that of other organic nutrients (PO\(_4\) and NO\(_3\)) [Johnson et al., 1997]. That is to say, like PO\(_4\) and NO\(_3\), Fe is taken up in a set ratio with carbon by phytoplankton (2-20, 2-23), exported as a component of (particulate) organic matter from the euphotic zone, and subsequently released back into dissolved form during remineralization within the water column. In common with other model studies [Archer and Johnson, 2000; Lefèvre, and Watson, 1999; Watson and Lefèvre, 1999], therefore, the basic biogeochemical scheme used for Fe follows that for PO\(_4\). However, the extremely low solubility and high reactivity of free Fe in solution under typical seawater conditions results in it being readily scavenged out of

![Model-predicted opal dissolution profiles](image)

**Figure 2-7** Model-predicted opal dissolution profiles, for each of the site locations detailed in Table 2-4. Opal rain rates are normalized to the flux at 100 m depth.
solution by the rain of particulate debris settling through the water column [Johnson et al., 1997]. This scavenging has previously been represented by a simple characteristic residence time for dissolved Fe, assumed to be uniform in value throughout the ocean [Archer and Johnson, 2000; Johnson et al., 1997; Lefèvre and Watson, 1999]. Intuitively, though, the scavenging rate should be directly related to the flux density of settling particulate material. SUE therefore scales local residence times inversely with particulate flux densities. Previous studies have also considered the ubiquitous presence of a Fe-binding ligand [Archer and Johnson, 2000; Lefèvre and Watson, 1999; Watson and Lefèvre, 1999], which acts so as to effectively prevent any further scavenging when Fe concentrations fall below that of the ligand [Johnson et al., 1997]. While the action of ligands in retaining Fe in solution, particularly in the surface ocean is undoubtedly critical [Rue and Bruland, 1997], the exact nature, global distribution, and lifetime of these compounds is still far from being adequately elucidated. The presence of Fe-binding ligands is therefore omitted from the current model. Fe previously scavenged higher up in the water column is released back into solution if the host material is remineralized.

In the ocean interior the total change in the Fe inventory of each ocean cell (mol a⁻¹) can be written

\[ \Delta M_{Fe}^{tot} = \Delta M_{Fe}^{out} + \Delta M_{Fe}^{rem} - \Delta M_{Fe}^{scav} \] (2-36)

where \( \Delta M_{Fe}^{out} \) is the net change due to ocean advection, convective adjustments, and (horizontal and vertical) diffusivity, and \( \Delta M_{Fe}^{rem} \) represents Fe both liberated from organic compounds through the remineralization of POM and from Fe scavenged by particulate matter further up in the water column and subsequently released through the remineralization of the scavenger substrate. \( \Delta M_{Fe}^{rem} \) is defined

\[ \Delta M_{Fe}^{rem} = r_{POC:POM}^{Fe} \left( Fset_{POM}^{in} - Fset_{POM}^{out} \right) + \frac{Fset_{POM}^{in} - Fset_{POM}^{out}}{Fset_{in}^{POM}} \cdot Fscav_{POM,in} + \frac{Fset_{POM}^{in} - Fset_{POM}^{out}}{Fset_{in}^{POM}} \cdot Fscav_{POM,out} + \frac{Fset_{cal}^{POM} - Fset_{cal}^{POM}}{Fset_{cal}^{POM}} \cdot Fscav_{cal,in} + \frac{Fset_{arg}^{POM} - Fset_{arg}^{POM}}{Fset_{arg}^{POM}} \cdot Fscav_{arg,in} \] (2-37)

where \( r_{POC:POM}^{Fe} \) is the mean ratio of Fe:C in POM, and \( Fset_{POM}^{out} \) and \( Fset_{POM}^{in} \) are the settling fluxes of POC into and out of the cell, respectively (mol a⁻¹). \( Fscav_{POM,in} \) is the flux of scavenged Fe associated with POC into the cell, with the scavenged fluxes associated with opal (“opal”), calcite (“cal”), and aragonite (“arg”), similarly designated.

\( \Delta M_{Fe}^{rem} \) is the loss (mol a⁻¹) of Fe due to scavenging by settling particulate matter

\[
\begin{align*}
\Delta M_{Fe}^{scav} &= k_{scav}^{Fe} \cdot Fset_{POM}^{out} \cdot M_{Fe}^{POM} + \\
&= k_{scav}^{Fe,opal} \cdot Fset_{POM,opal}^{out} \cdot M_{Fe}^{POM} + \\
&= k_{scav}^{Fe,cal} \cdot Fset_{POM,cal}^{out} \cdot M_{Fe}^{POM} + \\
&= k_{scav}^{Fe,arg} \cdot Fset_{POM,arg}^{out} \cdot M_{Fe}^{POM} 
\end{align*}
\] (2-38)

where \( k_{scav}^{Fe,POC} \) is the scavenging rate of Fe by POC (a⁻¹ (mol m⁻² a⁻¹)), with scavenging rates associated with opal (“opal”), calcite (“cal”), and aragonite (“arg”), similarly designated, and \( M_{Fe}^{POM} \) the inventory of Fe within the cell (mol), \( Fset_{POM}^{out} \) is the particulate matter flux density out of the cell (mol m⁻² a⁻¹) defined by

\[ Fset_{POM}^{out} = \frac{Fset_{POM}^{in}}{A} \] (2-39)

where \( A \) is the horizontal cross-sectional area of the cell (m²).

For the surface ocean layer, the mass balance is

\[ M_{Fe}^{tot} = M_{Fe}^{in} + M_{Fe}^{aolian} - M_{Fe}^{scav} - M_{Fe}^{dep} \] (2-40)

where \( M_{Fe}^{aolian} \) is the aeolian input of dissolved Fe from dust deposited to the surface, and \( M_{Fe}^{scav} \) is the loss of Fe due to biological uptake (and subsequent export)

\[ M_{Fe}^{dep} = \rho^{POC:POM} \cdot Fnp^{POC} \] (2-41)

where \( Fnp^{POC} \) is the export flux of POC from the surface.

The aeolian input of dissolved Fe, \( M_{Fe}^{aolian} \), can be simply written

\[ M_{Fe}^{aolian} = \frac{1}{55.8} \cdot Fesor^{dust} \cdot Ffrac^{dust} \cdot Fdep^{dust} \] (2-42)

where \( Fesor^{dust} \) is the mass fraction of aeolian Fe soluble in sea water, \( Ffrac^{dust} \) is the mass fraction of Fe in aeolian dust, and \( Fdep^{dust} \) is the deposition flux of dust to the surface ocean (g a⁻¹). The mean relative atomic mass of Fe, used to convert between mass and molar fluxes is taken to be 55.8 g mol⁻¹. The mass fraction of Fe in aeolian dust (\( Ffrac^{dust} \)) can be reasonably assumed to be equal to the mean crustal abundance of 3.5% [Duce and Tindale, 1991]. However, estimating a representative global value for \( Ffrac^{dust} \) is much more problematic. Indeed, estimates reported for the solubility of aerosol Fe range over a full 3 orders of magnitude from <0.013 % to 55% [Tickells and Spokes, in press]. The most important controlling factor in determining overall solubility of Fe in sea water is likely to relate to the balance of aeolian material deposited between ‘wet’ and ‘dry’ deposition routes, as the solubility of Fe in rainwater (~14%) is considerably higher than that of Fe in seawater (0.1-1.0%) [Tickells and Spokes, in press]. However, the effective solubility of Fe in sea water via the ‘wet’ deposition route is reduced by the precipitation of insoluble iron.
(hydr-)oxide phases associated with the pH change, to perhaps \(-0.3-6.8\%\) [Jickells and Spokes, in press; Spokes and Jickells, 1996]. Final solubility is also likely to be affected by the degree of remoteness of an oceanic region from dust source area, as the solubility of iron in aerosols is enhanced through \(\text{pH}\) cycling within clouds [Spokes and Jickells, 1996]. Given these complications together with uncertainties regarding the balance between wet and dry dust deposition routes, \(F_{\text{Fe sol}}^{\text{dust}}\) is treated as an optimizable parameter, whose value(s) is chosen in order to be broadly consistent with the estimate of global mean solubility of Jickells and Spokes [in press] (0.8-2.1%).

A second important factor affecting overall aerosol iron solubility concerns the degree of system loading. For instance, Zhuang et al. [1990] showed that the soluble metal fraction decreased dramatically with increasing total iron content in seawater, while Spokes and Jickells [1996] found that solution concentrations were highly nonlinear with particulate loading. These effects may be related to (re-)adsorption of dissolved iron onto aerosol surfaces [Jickells et al., 1995b]. A degree of ‘self-scavenging’ by aerosols in the ocean surface layer is therefore implemented in SUE. This implicitly produces an apparent Fe solubility which exhibits an inverse dependence on both [Fe] and dust flux, qualitatively consistent with observations. The surface ocean Fe mass balance (2.42) is now modified

\[
\Delta M^\text{Fe}_{\text{scav}} = \frac{1}{55} F_{\text{Fe sol}}^{\text{dust}} \cdot F_{\text{Fe\,frac}}^{\text{dust}} \cdot F_{\text{dep}}^{\text{dust}} - k_{\text{sca} \text{Fe}}^{\text{dust}} \cdot f_{\text{dep}}^{\text{dust}} \cdot M^\text{Fe}
\]

where \(k_{\text{sca} \text{Fe}}^{\text{dust}}\) is a ‘self-scavenging’ rate constant (in units of \(\text{a}^{-1} \, \text{g m}^{-2} \, \text{a}^{-1}\)), and \(f_{\text{dep}}^{\text{dust}}\) is the dust deposition flux density (g m\(^{-2}\) a\(^{-1}\)) defined by

\[
f_{\text{dep}}^{\text{dust}} = \frac{F_{\text{dep}}^{\text{dust}}}{A}
\]

Finally, aeolian iron not dissolved in the surface ocean is assumed to pass through the water column without further dissolution.

2.2.6 Carbon-13

As an aid to elucidating the function of the present-day global carbon cycle together with the causes of glacial-interglacial change, all major \(^{13}\text{C}\) fractionation processes are represented within SUE. These relate to the dissolution equilibria within the aqueous carbonate system, biological fixation of both organic and inorganic carbon, and air-sea gas exchange.

In the subsequent sections, the following conventions will be adopted. From the ratio of the concentration of \(^{13}\text{C}\) to \(^{12}\text{C}\) in bulk matter

\[
R(C) = \frac{[^{13}\text{C}]}{[^{12}\text{C}]}
\]

a fractionation factor is defined for any process, \(\alpha\) where the chemical or physical state of carbon is transformed

\[
\alpha(C \rightarrow C') = \frac{R(C)}{R(C')}
\]

The fractionation associated with this process is more commonly written

\[
\epsilon = \alpha - 1
\]

where \(\epsilon\) is quoted in units per mil (‰).

2.2.6.1 Fractionation within the aqueous carbonate system

The equilibrium partitioning of \(^{13}\text{C}\) between the three primary reservoirs of the aqueous carbonate system is calculated explicitly (Figure 2-8). In this treatment, the net \(^{13}\text{C}\) isotopic signature of \(\text{CO}_2(\text{aq})\) \((\delta^{13}\text{C}\text{CO}_2(\text{aq}))\) is derived from bulk DIC \((\delta^{13}\text{C}\text{DIC})\) by considering the fractionation with respect to both \(\text{HCO}_3^-\) and \(\text{CO}_3^{2-}\) and calculated in proportion to their relative aqueous concentrations [Marchal et al., 1998b; Yamanaka and Tajika, 1996]. Although Zhang et al. [1995] suggested that the presence of iron complexes in seawater prevent this simple approach being valid, the error in this method is \(<0.2\\%\) under typical oceanic conditions. This scheme has the advantage over the use of a single empirical temperature-dependent function linking \(\delta^{13}\text{C}\text{CO}_3^{2-}\) and \(\delta^{13}\text{C}\text{DIC}\) (e.g., Mook et al. [1974]) in that it is able to additionally account for the influence on \(\delta^{13}\text{C}\text{CO}_3^{2-}\) of changes in ALK, DIC, and pressure (depth).

Equilibrium fractionation factors within the surface ocean carbonate system are adapted from Zhang et al. [1995], with fractionations \(\alpha_1\) and \(\alpha_2\) derived by correcting the observed fractionations \(\text{HCO}_3^- \rightarrow \text{CO}_2(\text{aq})\) and \(\text{CO}_3^{2-} \rightarrow \text{CO}_2(\text{aq})\), respectively (Figure 2-8), to their relative aqueous concentrations \(\alpha_1\) (\(\alpha_2\)). Writing in per mil notation, these become

\[
\epsilon_1 = -41.92 + 0.114 \cdot T
\]

\[
\epsilon_2 = -24.07 + 0.057 \cdot T
\]

where \(T\) is the ambient temperature (K). The fractionation between DIC and \(\text{CO}_2(\text{aq})\) can then be estimated from

\[
\epsilon_\text{ao} = \frac{\epsilon_1 \cdot [\text{HCO}_3^-] + \epsilon_2 \cdot [\text{CO}_3^{2-}]}{[\text{CO}_2(\text{aq})] + [\text{HCO}_3^-] + [\text{CO}_3^{2-}]}\]

2.2.6.2 Fractionation during ocean-atmosphere gas exchange

The one-way ocean–atmosphere and atmosphere–ocean fractionation factors, \(\alpha_{\text{o} \rightarrow \text{ao}}\) and \(\alpha_{\text{ao} \rightarrow \text{o}}\), respectively (Figure 2-8) are defined [Siegenthaler and Munnich, 1981]

\[
\alpha_{\text{o} \rightarrow \text{ao}} = \alpha_\beta \cdot \alpha_k
\]

\[
\alpha_{\text{ao} \rightarrow \text{o}} = \alpha_\beta \cdot \alpha_k
\]

where \(\alpha_\beta\) is the equilibrium CO\(_2\) solubility fractionation factor [Zhang et al., 1995], equivalent to
\[ \varepsilon_\text{f} = -2.65 + 0.005 \cdot T \] (2-53)

and \( \alpha_{E} \) is the kinetic fractionation factor associated with CO\(_2\) diffusion across the boundary layer. A value of -0.88‰ is assumed for \( \varepsilon_\text{f} \), consistent with both the experimental measurements of Zhang et al. [1995] and theoretical calculation of Siegenthaler and Munnich [1981]. A (sea water) correction is made to \( \varepsilon_{\text{a-o}} \) [Zhang et al., 1995], to give final descriptions for one-way ocean–atmosphere and atmosphere–ocean fractionation.

\[ \varepsilon_{\text{a-o}} = \varepsilon_{\text{f}} - 0.88\% e \] (2-54)

\[ \varepsilon_{\text{a-o}} = \varepsilon_{\text{p}} - 1.08\% e \] (2-55)

2.2.6.3 Fractionation during biological fixation of organic carbon

The fractionation of 13C during the formation of organic material in the surface ocean is usually described by a fixed factor, typically assigned a value between -20 and -22‰ in global carbon cycle models [Heinze, 1994; Mäler-Reimer, 1993; Yamanaka and Tajika, 1996]. However, the isotopic signature of organic constituents in marine plankton appears to vary strongly as a function of both latitude and SST [Rau et al., 1989] against a background of relatively constant \( \delta^{13} \text{C}_{\text{DIC}} \). Recent field and experimental observations suggest that the ambient concentration of CO\(_2\) (itself a function of temperature) is a more important denominator [1997]. These parameters are therefore parameterized with an explicit dependence on [CO\(_2\)\(_{\text{aq}}\)]. The model of Rea et al. [1996] is adapted, assuming that the isotopic signature of exported POC reflects that of phytoplankton biomass. \( \delta^{13} \text{C}_{\text{POC}} \) is therefore defined

\[ \delta^{13} \text{C}_{\text{POC}} = \delta^{13} \text{C}_{\text{CO}_2\text{(aq)}} - \varepsilon_{\text{f}} + (\varepsilon_{\text{f}} - \varepsilon_{\text{a}}) \frac{Q}{D_r (1 + r / \eta)} + \frac{1}{P} \] (2-56)

where \( \varepsilon_{\text{f}} \) and \( \varepsilon_{\text{a}} \) are fractionation factors associated with enzymic intercellular C fixation and CO\(_2\)\(_{\text{aq}}\) diffusion, respectively, \( \varepsilon_{\text{f}} \) is the ambient concentration of CO\(_2\)\(_{\text{aq}}\) (in units of mol m\(^{-3}\)), \( r \) is the surface area equivalent cell radius, \( \eta \) is the reacto-diffusive length, \( Q \), the CO\(_2\)\(_{\text{aq}}\) uptake rate per cell surface area, \( P \) is the cell wall permeability to CO\(_2\)\(_{\text{aq}}\), and \( D_r \) is the temperature-sensitive diffusivity of CO\(_2\)\(_{\text{aq}}\) in seawater given by

\[ D_r = 5.019 \times 10^{-6} \cdot e^{\frac{E_D}{R T}} \] (2-57)

where \( E_D \) is the activation energy of diffusion, \( R \) is the gas constant, and \( T \) the temperature (K). Parameter values are those used by Rea et al. [1996], with the exception of \( r \) and \( Q \), which follow Rea et al. [1997]. These parameters are summarized in Table 2-5.

The description of \( \delta^{13} \text{C}_{\text{POC}} \) (2-56) can be simplified

\[ \delta^{13} \text{C}_{\text{POC}} = \delta^{13} \text{C}_{\text{CO}_2\text{(aq)}} - \varepsilon_{\text{f}} + (\varepsilon_{\text{f}} - \varepsilon_{\text{a}}) \frac{Q}{D_r (1 + r / \eta)} + \frac{1}{P} \] (2-58)

where

\[ K_Q = 1027 \cdot Q_t \cdot \frac{r}{D_r (1 + r / \eta)} + \frac{1}{P} \] (2-59)

and with [CO\(_2\)\(_{\text{aq}}\)] now in units of mol kg\(^{-1}\). Finally, \( K_Q \) is approximated assuming that factors such as cell size are invariant

\[ K_Q = 2.829 \times 10^{-10} - 1.788 \times 10^{-7} \cdot T + 3.170 \times 10^{-5} \cdot T^2 \] (2-60)

Despite the scheme of Rau et al. [1996,7] being able to successfully explain the main observational \( \delta^{13} \text{C}_{\text{POC}} \) trend in the ocean, variations in [CO\(_2\)\(_{\text{aq}}\)] alone cannot account for the residual scatter and the more extreme outlying values [Goericke and Fry, 1994, Rau et al., 1989, 1997]. Variability in vital factors such as cell size, growth rate, cell membrane
permeability, and diffusion rate will all affect the intercellular availability of CO₂(aq) and thus overall fractionation [Hinga et al., 1994]. Unfortunately, such parameters are not available in the simple biological model employed in SUE. However, since the biological scheme does differentiate between two distinct classes of phytoplankton (siliceous and non-siliceous) it is possible to represent species-specific factors, at least to a first order. While Rau et al. [1996, 1997] adopt an intermediate value of 25% for the enzymatic isotope fractionation factor associated with intracellular C fixation (εf), they note that it may actually range from 20 to 29%. Indeed, Hinga et al. [1994] observed that δ¹³C-POC in the diatom Skeletonema costatum was lower by some 8-10% compared to the coccolithophorid Emiliania huxleyi under identical growth conditions, possibly largely due to species differences in carbon fixation pathways [Falkowski, 1991]. Different values of εf associated with the two different classes of phytoplankton are therefore adopted, taking default values of 25% and 20%, for siliceous and non-siliceous classes, respectively.

2.2.6.4 Fractionation during the formation of calcium carbonate

The formation of the carbonate tests of coccolithophorids and foraminifera and the shells of pteropods typically involves a degree of $^{13}$C fractionation an order of magnitude less than that in the fixation of organic carbon. The ‘carbonate pump’ (2.1.1) therefore plays only a relatively less important role in determining spatial heterogeneity in the availability of CO₂(aq) and thus overall fractionation [Sundquist].

### Table 2-5 Parameters Used in the $^{13}$C POC Fractionation Model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>εf</td>
<td>20 to 29</td>
<td>%e</td>
</tr>
<tr>
<td>εd</td>
<td>0.7</td>
<td>%e</td>
</tr>
<tr>
<td>$Q_2$</td>
<td>1.62×10⁻⁷</td>
<td>mol C m⁻² s⁻¹</td>
</tr>
<tr>
<td>r</td>
<td>5.00×10⁻⁵</td>
<td>m</td>
</tr>
<tr>
<td>$E_d$</td>
<td>19510</td>
<td>J mol⁻¹</td>
</tr>
<tr>
<td>R</td>
<td>8.3143</td>
<td>J K⁻¹ mol⁻¹</td>
</tr>
</tbody>
</table>

1 $ε_d$ has a small temperature dependence in reality, but is assumed here to be constant.

In contrast, foraminiferal calcite is assumed not to contribute to the bulk sediment, but instead is treated as a tracer tied to bulk calcite (and as such does not contribute to mass transfer within the system). The simplest description of foraminiferal calcite $δ^{13}$C would be to assume an identical fractionation behaviour to bulk calcite. However, recent culture and modelling studies [Spero et al., 1997; Wolf-Gladrow et al., 1999a,b; Zeebe et al., 1999] suggest that the concentration of carbonate ions ([CO$_{3}^{−}$]) has an important controlling influence on fractionation. Empirically-determined relationships linking planktonic foraminiferal $δ^{13}$C to [CO$_{3}^{−}$] under conditions of constant DIC [Spero et al., 1997] are therefore adopted (with reported shell $δ^{13}$C corrected for experimental $δ^{13}$C-DIC). For the spinose Orbulina universa, $δ^{13}$C-cal is taken to be the mean of high light and dark responses (in a 50:50 proportion), while for the non-spinose Globigerina bulloides, $δ^{13}$C-cal is taken to be the mean of 12th and 13th chamber values [Spero et al., 1997]. For Orbulina universa the resulting DIC $→$ CaCO$_{3}^{form}$ fractionation can be written

$$e_{δ^{13}C} = 1.795 - 0.006 \times [CO_{3}^{−}] \%e$$ (2-62)

while for Globigerina bulloides it is

$$e_{δ^{13}C} = -0.135 - 0.013 \times [CO_{3}^{−}] \%e$$ (2-63)

where [CO$_{3}^{−}$] is the carbonate ion concentration in units of μmol kg$^{-1}$. As a default, Globigerina bulloides is assumed to represent the planktonic foraminiferal tracer in SUE. In the absence of comparable experimental data for benthic species the relationship for Globigerina bulloides is also used for the benthic foraminiferal tracer.
3.1 Introduction

Deep-sea sediments play a critical role in global biogeochemical cycles. Particulate material delivered to, or formed at the ocean surface and which is not removed whilst settling through the water column will eventually reach the ocean floor, forming a surficial ‘fluff’ layer at the ocean-sediment interface. Much of this material undergoes diagenetic alteration as it is gradually incorporated deeper into the sediments. Such post-depositional changes involve a multitude of interacting physical (diffusion, advection), biological (bioturbation, metabolism) and chemical (dissolution, oxidation, reduction) processes, often characterized by rapid rate constants and operating on a fine spatial scale. By nature of the extremely remote and hostile location of the benthic environment, many of these processes are poorly characterized. Modelling the diagenetic alteration of material within deep-sea sediments is therefore no easy task and can be numerically expensive. Global carbon cycle models have therefore often simply returned all settling material reaching the ocean floor instantaneously back to the ocean (in dissolved form). However, there are a number of compelling reasons for the explicit representation of the deep-sea sediment system, particularly for application to glacial-interglacial change;

- Dissolved chemical species formed through diagenetic alteration processes may escape the sediments by diffusing out across the sediment-water interface into the ocean. Solid material not transformed in this way will be eventually buried. This burial represents a ‘sink’ for the chemical constituents of that material. For the system as a whole to be at steady state, such sinks must be balanced by inputs to the ocean-atmosphere, such as via continental weathering or volcanic out-gassing. A simplified system where there are no sources or sinks of a species is considered to be ‘closed’ with respect to this species. The dynamical response of a closed system is found to be very different from that of an open one where there is a continual throughput [Hotinski et al., 2000; Kamp, 1993; Sigman et al., 1998]. Particularly where the species in question are potentially limiting nutrients, carbon, or alkalinity, a closed system may not capture the long-term dynamics of the global carbon cycle, and will thus not be capable of correctly accounting for the observed glacial-interglacial variability in atmospheric CO2.

- The explicit consideration of the diagenetic alteration of material delivered to the deep-sea floor allows for realistic estimation of the fractionation preservation of this material in the sediments, and therefore of surface sediment composition. Comparisons between model and observed distributions of major solid constituents (CaCO3, opal, detrital material) provides a powerful diagnostic for optimizing or validating components of the overall system model.

- Finally, representation of deep-sea sediments enables an extensive synthetic sedimentary record to be built up over the course of the model simulation. Perturbations to the system will be recorded as down-core variations in sediment solid and/or isotopic properties. Contrasting artificial sediment tracer signals with those derived from actual cores recovered from the ocean floor provides additional constraints for elucidating the mechanisms involved in glacial-interglacial change [Berger et al., 1996].

Deep-sea sediments and their biogeochemical interaction with the ocean are therefore included as a key component within SUE. However, although sediments in the model are considered at all depths (including the pelagic zone) the schemes used for ocean-sediment interaction are strictly applicable only to the benthic environment. As such, there is no explicit consideration of shelf sedimentary processes. The diagenetic alteration of CaCO3 (separately as both calcite and aragonite) and opal are all represented, with the first order effects of bioturbation and sediment compaction accounted for. However, there is no similar mechanistic representation of processes relating to the diagenetic alteration of particulate (or dissolved) organic matter or detrital particles.
3.2 Modelling deep-sea sediments

The deep-sea sediment module used in SUE is shown schematically in Figure 3-1. The system comprises a single surface layer underlain by a series of sub-layers. The surface layer represents the upper zone of the sediment where bioturbation effectively homogenizes solid composition with respect to depth, and where the most important diagenetic processes of interest to this present study take place. Solid material which is preserved and exported out of this surface layer (i.e., ‘buried’) is stored in sedimentary sub-layers lying immediately below. These sub-layers are prescribed a thickness of 1 cm, representing a trade-off between simulated down-core sediment resolution and computational running and storage costs. In addition to the advective transfer of solids between the surface layer and upper-most sediment stack sub-layer (arising from net sedimentary accumulation/erosion) a diffusive-like transfer is prescribed between adjacent sediment layers. This represents the vertical mixing of solids due to biological activity.

Sediment composition within the surface layer is calculated via a simple mass balance and operated asynchronously with the ocean-atmosphere module, such that at time $t = t + 1$

$$M_{S(t+1)}^S = M_{S(t)}^S + \Delta M_{S(t)}^S + F_{bal}^S$$

(3-1)

where $M_{S(t)}^S$ is the mass of solid component $S$ in the surface layer, and $\Delta M_{S(t)}^S$ is the change in mass of this component calculated as the net flux across the sediment-ocean interface

$$\Delta M_{S(t)}^S = F_{sed}^S - F_{dis}^S$$

(3-2)

where $F_{sed}^S$ is the sedimentation (or settling) flux of solid material at the ocean-sediment interface, and $F_{dis}^S$ is the flux to the ocean of dissolved species derived from the diagenetic alteration of $S$ within the surface layer. $F_{bal}^S$ is a balancing flux, calculated according to the criterion that there must be no net change in the thickness of the surface layer. Where a net flux across the sediment-water interface results in a volume surfeit of material in the surface layer, a correction is made by removing material from the surface layer and transferring it to the top sub-layer of the sediment stack. Conversely, where the net flux results is a volume deficit, material is removed from the top of the sediment stack and added to the surface layer. This is formally written

$$F_{bal}^S = -\frac{\sum_s \Delta V_{S(t)}^S}{\sum_s V_{(t)}^S} \left( M_{S(t)}^S + \Delta M_{S(t)}^S \right) \sum_s \Delta V_{S(t)}^S > 0 \quad (3-3a)$$

$$F_{bal}^S = +\frac{\sum_s \Delta V_{S(t)}^S}{\sum_s V_{(t)}^S} M_{S(t)}^S \sum_s \frac{V_{S(t)}^S}{\sum_s V_{S(t)}^S} \sum_s \Delta V_{S(t)}^S < 0 \quad (3-3b)$$

where $M_{S(t)}^S$ is the mass of component $S$ in the uppermost sediment stack sub-layer. Equivalent volumes ($V$) for the mass of each component are defined

Figure 3-1 Schematic representation of the sedimentary module within SUE.
The simulation of deep-sea sediments

\[ V^S = \frac{M^S}{\rho^S \cdot \phi} \]  

(3-4)

where \( \rho^S \) is the density of (solid) component \( S \), and \( \phi \) is the sediment porosity. This transferal procedure is more complicated in practice than this description suggests, since the uppermost sub-layer in the sediment stack has a finite capacity. The situation therefore arises that the effective volume of material to be added to this sub-layer is greater than its remaining (un-filled) capacity. In this case, the incomplete sub-layer is filled first, after which a new sub-layer is created immediately above, which accepts the remaining material. Conversely, when there is a surface deficit, the effective volume of material required may be greater than that remaining within the uppermost sub-layer. All the material in this sub-layer is therefore removed first and the sub-layer destroyed. The residual deficit is then made up by removing material from the new uppermost sub-layer. A simple alternative to this ‘open-topped’ stack arrangement would be that of an ‘open-bottomed’ stack [Heinze et al., 1999]. In this scenario all the sub-layers are always complete, with excess material permanently lost or gained from the base. However, this is not only more computationally demanding to implement but is numerically diffusive.

Solid components represented in the sediments include calcite, aragonite, and opal, who all share a biogenic origin in the surface ocean and whose fractional preservation in the sediments is represented explicitly (3.2.4 and 3.2.5). Detrital matter derived from aeolian deposition at the ocean surface is also represented, although it is assumed to act conservatively within the sediments, and no release either \( \text{H}_4\text{SiO}_4 \) (from silicates) or dissolved Fe (from Fe-bearing ore and silicate minerals) is considered. Finally, in order to allow glacial-interglacial variability in the isotopic composition of particulate organic carbon to be recorded, POM is simply added to the sediment in a fixed ratio with the flux of material reaching the sediment surface, acting conservatively thereafter. A mean fractional preservation of the POM settling flux of 5% is chosen, consistent with estimates of ~3-7% in deep-sea sediments [Archer et al., submitted; Tromp et al., 1995]. Since the system is not open with respect to \( \text{PO}_4 \), the carbon and phosphorous components of buried POM (together with associated alkalinity) are artificially returned in dissolved form to the overlying surface ocean.

In addition to the representation of solid sedimentary components, a number of isotopic and ‘colour’ tracers (both conservative and non-conservative) are considered in the sediment module. An isotopic composition for calcite and aragonite is considered, with \( ^{14}\text{C} \) added and removed in proportion to changes in the solid fraction. This proportionality takes a ratio whose value is determined by fractionation processes associated with formation in the ocean surface (2-61a and 2-61b) upon initial deposition to the sediments. Removal from the surface through dissolution or transfer between layers proceeds simply according to a ratio equal to the mean bulk isotopic composition in the layer(s) where the material resides. \( ^{14}\text{C} \) is treated in a similar manner, with the exception that it is decayed with a half life of 5.73 ka. \( ^{14}\text{C} \) in POC is treated in a similar manner to \( ^{14}\text{C} \) in \( \text{CaCO}_3 \). ‘Colour’ (artificial numerical) tracers are also considered, and used to represent properties such as the age of solid calcite, foraminiferal \( \delta^{18}\text{O} \) (with planktonic and benthic isotopic signatures considered separately), and foraminiferal \( \delta^{18}\text{O} \) (again resolved into planktonic and benthic species). These are tied to a solid fraction and treated in a similar manner to that for \( ^{14}\text{C} \), with the exception that the depositional value of benthic and planktonic foraminiferal \( \delta^{18}\text{O} \) follow (2-62) and (2-63), while benthic and planktonic foraminiferal \( \delta^{18}\text{O} \) take an isotopic value equal to mean oceanic \( \delta^{18}\text{O} \), itself prescribed according to the SPECMAP stack [Imbrie et al., 1984]. A final colour tracer is used to represent ash depositional events (3.2.1.2).

At the start of a model run, all sediment modules are initialized with the surface layer and 100 sub-layers entirely composed of detrital material. Steady state is typically reached throughout the ocean with respect to the solid composition in surface sediments on an order of 100 ka.

### 3.2.1 Bioturbation

The vertical (and horizontal) mixing of solid material in the surface zone of deep-sea sediments by the action of benthic organisms (termed ‘bioturbation’) plays an important role in the dynamical behaviour of the global carbon cycle. For instance, perturbations in ocean chemistry or biological export may lead to the erosion of surface \( \text{CaCO}_3 \). Previously buried material can then be exhumed from depth through bioturbational mixing, thus effectively replenishing the material in the sediment surface [Archer et al., 1998; Boudreau, 1994]. If the perturbation continues for an extended period a significant mass of material may eventually be brought to the surface and eroded in this way, thus affecting global ocean chemistry [Archer et al., 1998]. Bioturbation also has important consequences for the interpretation of paleoceanographic proxies [Dubois and Prell, 1988; Ruddiman et al., 1980; Schifferlein, 1984; Trauth, 1998]. Down-core tracer profiles (such as foraminiferal calcite \( \delta^{13}\text{C} \) or \( \delta^{18}\text{O} \)) associated with a perturbation event can be ‘smeared out’ by vertical mixing. This degrades the resolution of the phase information which can be obtained from recovered cores, complicating the analysis of causal links between different processes operating within the system [Boudreau, 1994; Hutson, 1980]. The apparent magnitude of a perturbation event can also be significantly diminished. Implementation of an adequate sedimentary bioturbation scheme is therefore desirable both for realism in model-generated sediment cores and in capturing system dynamics.

#### 3.2.1.1 Bioturbation model description

The mechanistic action of benthic organisms leads to the movement of solid material within the surface zone of the sediment. This transfer can occur in both horizontal and vertical planes, may be highly selective in terms of size fraction or chemical composition, and take place throughout a large range of spatial and temporal scales, from an almost
continuous local transport to highly episodic occurrences over an extended distance. The nature of individual disturbances will depend on the animal species involved through behavioural characteristics such as mode of feeding, locomotion, and shelter [Soetaert et al., 1996; Wheatcroft et al., 1990; Wheatcroft, 1992]. The abiotic benthic environment also has an important influence, particularly in terms of food source availability [Legeleux et al., 1994; Trauth et al., 1997]. Various detailed mechanistic treatments of bioturbation have been proposed [Soetaert et al., 1996; Wheatcroft et al., 1990; Trauth, 1998]. However, such schemes are computationally expensive and require knowledge of benthic ecology which cannot be prognostically provided by SUE. A highly simplified representation of bioturbational mixing in deep sea sediments is therefore required.

The simplest possible treatment is to assume the presence of a relatively thick surface layer, homogeneous in composition over its entire depth [Berger and Heath, 1968; Munhoven and Francois, 1996]. Such schemes typically assume a thickness of 10 cm for this layer, representing the approximate depth to which deep-sea sediments are often observed to be predominantly ‘well-mixed’ [Boudreau, 1994; Ikehara et al., 2000; McManus et al., 1995]. However, vertical resolution can be improved by assuming that the effect of bioturbation can be modelled as an quasi-diffusional process [Pope et al., 1996; Wheatcroft et al., 1990] and therefore ignoring the effects of non-local mixing [Boudreau, 1994; Legeleux et al., 1994; Soetaert et al., 1996; Wheatcroft, 1992]. In this, the surface sediment zone is discretized into a series of sub-layers with mixing between adjacent layers characterized by a prescribed biodiffusion coefficient [Archer, 1991; Guinasso et al., 1975; Officer and Lynch, 1983; Walker and Opdyke, 1995].

A variety of simple bioturbational schemes are evaluated here for application in SUE. Potential parameterizations are constrained by the configuration of the sediment module (Figure 3-1) to comprise a homogeneous surface layer overlying a sequence of 1 cm thick stacked layers. The mixing rate between pairs of sub-layers is determined by a biodiffusion coefficient which decreases with depth determined by a profile which can be varied in both shape and magnitude. In the following sections the results from just two of these schemes are presented. The first (designated “10 cm only”) is the simplest, consisting of just a 10 cm thick surface layer with no deeper mixing. The second (“5 cm plus deep mixing”) is adapted from Peng et al. [1979], and comprises a 5 cm thick surface layer with deeper mixing below this. This deep mixing follows an exponentially-decreasing profile of e-folding length 1 cm, with a maximum mixing rate (at the base of the surface layer) of 16 cm² ka⁻¹.

3.2.1.2 Inert tracer profile simulation

Sub-aerial volcanic events tend to produce airborne ejecta such as ash and pumice in discrete rather transitory pulses. Since the time scale for its deposition to the deep-sea floor is short compared to the residence time of material in the bioturbated zone, the input to the sediments of ash and pumice can be assumed to be effectively instantaneous. An additional advantage of such material as a bioturbation tracer is that it is relatively inert, thus acting conservatively. If a constant sediment accumulation rate is assumed, down-core profiles of ash and pumice concentration will depend only on the details of bioturbational mixing. Modelling such profiles allows different bioturbation schemes to be evaluated.

Table 3-1 details a number of deep-sea sediment cores taken from the Pacific and Indian oceans where down-core concentrations of (62-125 μm) volcanic ash and pumice have been measured [Ruddiman et al., 1980]. The sediment module is run once for each of these cores with bulk-matter deposition fluxes chosen to give the appropriate observed sediment accumulation rate. After sediment ‘spin-up’, an impulse addition of a ‘colour’ tracer (representing the input of volcanic material) is made to the sediment surface. Figure 3-2 shows the results of this exercise for the “10 cm only” and “5 cm plus deep mixing” mixing schemes. It can be seen that while the first scheme can reproduce tracer profiles in cores characterized by relatively high sedimentation rates (>2 cm ka⁻¹), it tends to over-estimate peak concentrations at lower rates. The second scheme, however, produces a reasonable fit under all sedimentation conditions. There is a general failure in both these and other schemes evaluated (not shown) to produce adequate mixing of tracer deeper than the level of impulse addition (the observed ‘tail’ to the right of the maximum tracer concentration). While prescribing stronger biodiffusion at depth can partly alleviate this mis-match it also seriously reduces peak concentrations. The inability to reproduce this feature highlights one of the deficiencies of a simple quasi-diffusional model, that of the role of non-local mixing events.

3.2.1.3 ¹⁴C age profile simulation

A second test of mixing scheme involves the use of down-core measurements made of ¹⁴C age. Core ERDC-92 is chosen for this analysis, having already been extensively characterized in terms of mixing and accumulation regime by Peng et al. [1979]. The sediment sub-model is run assuming apparent (i.e., ¹⁴C age-derived) sedimentation rates of 2.3 cm ka⁻¹ before 6 ka BP and 1.2 cm ka⁻¹ thereafter [Peng et al., 1979]. No dissolution of CaCO₃ is prescribed, consistent with the shallow location of this core. CaCO₃ deposited to the

<table>
<thead>
<tr>
<th>Core</th>
<th>Tracer</th>
<th>Sediment accumulation rate (cm ka⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>V19-28</td>
<td>Ash</td>
<td>7.00</td>
</tr>
<tr>
<td>V19-29</td>
<td>Ash</td>
<td>7.00</td>
</tr>
<tr>
<td>V29-39</td>
<td>Ash</td>
<td>0.50</td>
</tr>
<tr>
<td>V29-40</td>
<td>Ash</td>
<td>0.50</td>
</tr>
<tr>
<td>RC17-126</td>
<td>Ash</td>
<td>2.00</td>
</tr>
<tr>
<td>E48-23</td>
<td>Pumice</td>
<td>2.50</td>
</tr>
</tbody>
</table>
Model down-core ‘colour’ tracer profiles (solid and dotted red lines, corresponding to the schemes “5 cm plus deep mixing” and “10 cm only”, respectively) compared to observed ash and pumice concentrations (filled circles). All tracer concentrations are shown normalized to unit integrated volume.
sediment surface in the model is assigned a $^{14}$C age of 0.4 ka, in order to account for surface water aging [Keir and Michel, 1993; Oxburgh, 1998; Peng et al., 1979]. The results from the same two bioturbation schemes as presented before are shown in Figure 3-3, and compared to observations. While both correctly reproduce the observed core-top $^{14}$C age, the simple “$10$ cm only” scheme is noticeably less successful in reproducing the deeper age profile.

The “$5$ cm plus deep mixing” scheme is also evaluated against four $^{14}$C profiles presented by Broecker et al. [1991], with corrections made for the surface ocean $^{14}$C reservoir age as before. Core details, including apparent accumulation rates used to constrain the sediment module are listed in Table 3-2. The results of this exercise are shown in Figure 3-4, demonstrating that the mixing scheme is able to capture core-top $^{14}$C ages and down-core profile of core FAM527-3, while introducing only a relatively small age offset (~0.5 ka) in cores EN66-21 and ERDC-92. However, the model significantly under-predicts $^{14}$C ages in TT154-5. This apparently somewhat mixed success might be a direct consequence of the different oceanographic locations of the cores; while the other three cores come from either relatively shallow depths or from the Atlantic, TT154-5 is from the mid-depth Pacific. As such, it is likely to be bathed in water under-saturated with respect to CaCO$_3$ [Archer, 1996a]. A significant fraction of the (young $^{14}$C age) CaCO$_3$ rain is therefore likely to dissolve upon reaching the surface and before being incorporated into the well-mixed layer, leading

![Figure 3-3](image_url) Model down-core CaCO$_3$ $^{14}$C age tracer profiles (solid and dotted red lines, corresponding to the schemes “$5$ cm plus deep mixing” and “$10$ cm only”, respectively) compared to observations from core ERDC-92 [Peng et al., 1979] (filled circles with error bars).

### Table 3-2 Radiocarbon Profile Sediment Core Details

<table>
<thead>
<tr>
<th>Core</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Depth (m)</th>
<th>Sediment accumulation rate (cm ka$^{-1}$)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>FAM527-3</td>
<td>36.8°N</td>
<td>33.3°W</td>
<td>2600</td>
<td>2.9</td>
<td>Nozaki et al. [1977]</td>
</tr>
<tr>
<td>ERDC-92</td>
<td>2.2°S</td>
<td>157.0°E</td>
<td>1598</td>
<td>1.8</td>
<td>Berger and Killingley [1982], Peng et al. [1979]</td>
</tr>
<tr>
<td>EN66-21</td>
<td>4.2°N</td>
<td>20.6°W</td>
<td>3995</td>
<td>1.4</td>
<td>DuBois and Prell [1988]</td>
</tr>
<tr>
<td>TT154-5</td>
<td>10.3°S</td>
<td>111.3°W</td>
<td>3225</td>
<td>0.8</td>
<td>Broecker et al. [1991]</td>
</tr>
</tbody>
</table>
to a higher-than expected $^{14}$C age [Broecker et al., 1991, 1999b; Oxburgh, 1998]. That the simple test used here assumes that no dissolution of CaCO$_3$ takes place is the probable cause of this discrepancy. A secondary effect contributing to model-observation mismatch may be insufficient elapsed time since the LGM for a new steady-state to have been established. This is supported by an anti-correlation between the degree of $^{14}$C age mis-match and sediment accumulation rate. Only for the fastest sediment accumulation rate (FAM527-3) would it have been possible for virtually all trace of LGM conditions to have been erased over the entire depth of the observed profile.

3.2.1.4 Scheme choice
Although carrying an additional computational burden associated with it, the “5 cm plus deep mixing” scheme appears to perform better than the simpler “10 cm only” parameterization. However, the performance of both of these is significantly better than that of other schemes tested, such as the power law mixing parameterization of Walker and Opdyke [1995]. The “5 cm plus deep mixing” scheme is therefore adopted as default in SUE. Although some models have introduced a dependence of sediment mixing rates on ocean depth or POM rain rates [Archer et al., in press; Muhoven and Francois, 1996], the chosen parameterization is applied uniformly to all sediments throughout the model ocean as an initial step.

3.2.2 Porosity
The porosity of deep-sea sediments can affect diagenetic behaviour through scaling the vertical accumulation rates (which in turn determines the mean time spent by material in the sub-surface zone of intense diagenetic alteration), and by controlling the diffusivity of dissolved species within the sediment matrix. Although there appears to be some dependence of porosity on sediment composition [Archer et al., 1979; Martin et al., 1991], for simplicity, a single empirically-derived sediment porosity profile is utilized in this study.

Figure 3-5 shows porosity profiles estimated from in situ microelectrode resistivity measurements in a number of
Assuming porosities at the surface of 0.95 and 0.70 cm$^3$ cm$^{-3}$ at depth, all these observations can be reasonably described by

$$
\phi(z) = 0.69 + 0.26 \cdot (1.0 + z)^{-1.2}
$$

where $\phi(z)$ is the porosity at depth $z$ (cm) in the sediment. This gives a mean porosity of $\sim 0.89$ cm$^3$ cm$^{-3}$ over the uppermost 0.5 cm, consistent with Hensen et al. [1998], and an overall profile similar to models use by Heinze et al. [1999] and Jahnke et al. [1997]. The 5 cm thick surface layer in the sediment module is therefore assigned a porosity of 0.776 cm$^3$ cm$^{-3}$, with 0.705 cm$^3$ cm$^{-3}$ applied uniformly to all sub-layers.

3.2.3 Numerical implementation of diagenesis

The diagenetic alteration of material in deep-sea sediments is in essence a 1-D reaction-diffusion system. Numerical stability considerations in the solution of such a system dictate a minimum time step for the required vertical resolution [Moldrup et al., 1996] such that explicit application over a global scale for extended time model runs is problematic. While elegant schemes have been developed for rapid approximation of a quasi-steady solution [Archer, 1991, Archer et al., in press], there are alternative methodologies for the efficient encapsulation of complex diagenetic behaviour.

On the basis of a set of simplifying assumptions, Sigman et al. [1998] successfully reduced the dimensionality of a complex model of CaCO$_3$ diagenesis to a system defined by only 2 independent variables. A multi-variate polynomial fit was derived from this and subsequently employed within a global carbon cycle model. However, if the number of variables considered essential for a reasonable representation of system behaviour exceeds this, it becomes difficult to construct an equivalent regression surface. Alternatively, a representation of the solution surface can be obtained by training a neural network on the underlying numerical model. Unfortunately, the protracted ‘training’ times required by neural networks will tend to curtail their use where the parameter space is large. A simple ‘look-up’ table approach is therefore introduced here for the

![Figure 3-5](image-url) Model sediment down-core porosity profile (continuous line) compared with observations.
representation of sedimentary diagenetic behaviour, whereby required values of state are obtained through linear interpolation on a regular grid of pre-calculated values within an \( n \)-dimensional space, where \( n \) is the number of parameters defining the system.

### 3.2.4 Sedimentary diagenesis of CaCO\(_3\)

Sedimentary diagenesis of CaCO\(_3\) follows Archer [1991]. In this model, the dissolution of CaCO\(_3\) within a 10 cm thick surface zone is considered, driven both by the overlying ocean chemistry and as a result of remineralization of POC within the sediments. The assumption is made that POC reaching the sediments is completely reduced under oxic conditions. Numerical solution is achieved via a relaxation method within a vertically discretized system. While no account is taken of anoxic conditions produced at depth or resulting from a high ratio of POC rain rate to ocean dissolved oxygen concentrations, this scheme has proved successful in a number of previous global carbon cycle models [Archer, 1996a; Archer et al., 1998; Heinz et al., 1999]. For application in SUE, several minor modifications are made. Firstly, to ensure internal model consistency, the same assumption is taken of anoxic conditions produced at depth or reaching the sediments is completely reduced under oxic conditions found in the benthic environment, with step intervals relaxed where \( f_{diss}^{CaCO_3} \) is only weakly non-linear with a particular parameter.

Since both forms of biogenic CaCO\(_3\) are resolved in SUE, two look-up tables must be generated, one for calcite and the other for aragonite. For the dissolution of calcite, parameter values are taken from Archer [1996a] for the order of dissolution (4.5) and dissolution rate constant (1.0 \( \text{d}^{-1} \)). The dissolution rate constant for aragonite is assumed to be the same, but a slightly lower value of 4.2 is used for the reaction order [Keir, 1980]. Artificially separating the dissolution of calcite and aragonite in this way presents the problem of how dissolution forcing due to POC remineralization is partitioned between the two polymorphs. As a crude approximation \( f_{diss}^{POC} \) is split between the calcite and aragonite diagenetic systems in proportion to their relative mass abundance in the sediments, giving

\[
f_{diss}^{calc} = L \left( D, dCO_3, c^{\text{calc}}, f_{diss}^{POC} \right)
\]

where \( L \) is a function for linear interpolation within an \( n \)-dimensional space. The dissolution of CaCO\(_3\) in the sediments is primarily a function of ocean depth (\( D \)), the bottom-water concentration of total dissolved inorganic carbon ([DIC]), alkalinity ([ALK]), and dissolved oxygen ([O\(_2\)]), the mass fraction of CaCO\(_3\) in the sediments (\( c^{\text{CaCO}_3} \)), and the flux density of particulate organic matter delivered to the sediment surface (\( f_{diss}^{POC} \)). The look-up table function for such as system can be written

\[
f_{diss}^{CaCO_3} = L \left( D, dCO_3, c^{\text{CaCO}_3}, [O_2], f_{diss}^{POC} \right)
\]

where \( L \) is a function for linear interpolation within an \( n \)-dimensional space. However, the six-dimensional space defined by these variables does not easily yield a manageable look-up table. Parameter space dimensionality can be reduced considering that it is carbonate ion concentration that directly determines CaCO\(_3\) dissolution rates rather than DIC and ALK individually. A variable representing the degree of under-saturation (\( dCO_3 \)) is therefore introduced following Sigman et al. [1998], defined as the difference between ambient \( [\text{CO}_3^{2-}] \) and the local saturation value for CaCO\(_3\). The spanning space is collapsed through the substitution of [DIC] and [ALK] by a single descriptive variable (\( dCO_3 \))

\[
f_{diss}^{CaCO_3} = L \left( D, dCO_3, c^{\text{CaCO}_3}, [O_2], f_{diss}^{POC} \right)
\]

A further dimensional reduction is made by assuming a uniform dissolved oxygen concentration throughout the ocean (taken to be 200 \( \mu\text{mol kg}^{-1} \)). This is justified on the basis of the relatively weak dependence of \( f_{diss}^{CaCO_3} \) on \([O_2] \) under typical benthic conditions (of order 0.01% (\( \mu\text{mol kg}^{-1} \)). The CaCO\(_3\) dissolution flux density is now a much simpler function of just four variables;

\[
f_{diss}^{CaCO_3} = L \left( D, dCO_3, c^{\text{CaCO}_3}, f_{diss}^{POC} \right)
\]

The spanning set of look-up table parameters are detailed in Table 3-3. Spanning ranges are generally chosen to cover conditions found in the benthic environment, with step intervals relaxed where \( f_{diss}^{CaCO_3} \) is only weakly non-linear with a particular parameter.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Spanning range</th>
<th>Spanning step</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>( dCO_3 )</td>
<td>-100 to 100</td>
<td>1</td>
<td>( \mu\text{mol kg}^{-1} )</td>
</tr>
<tr>
<td>( D )</td>
<td>0 to 10000</td>
<td>1000</td>
<td>m</td>
</tr>
<tr>
<td>( f_{diss}^{POC} )</td>
<td>0 to 50</td>
<td>1</td>
<td>( \mu\text{mol cm}^{2} \text{ a}^{-1} )</td>
</tr>
<tr>
<td>( c^{\text{CaCO}_3} )</td>
<td>10 to 100</td>
<td>10</td>
<td>%</td>
</tr>
</tbody>
</table>

### 3.2.4.1 Look-up table implementation

In the Archer [1991] model, CaCO\(_3\) dissolution flux density across the sediment-water interface (\( f_{diss}^{CaCO_3} \)) can be written

\[
f_{diss}^{CaCO_3} = L \left( D, [\text{DIC}], [\text{ALK}], c^{\text{CaCO}_3}, [O_2], f_{diss}^{POC} \right)
\]

The spanning set of look-up table parameters are detailed in Table 3-3. Spanning ranges are generally chosen to cover conditions found in the benthic environment, with step intervals relaxed where \( f_{diss}^{CaCO_3} \) is only weakly non-linear with a particular parameter.

Since both forms of biogenic CaCO\(_3\) are resolved in SUE, two look-up tables must be generated, one for calcite and the other for aragonite. For the dissolution of calcite, parameter values are taken from Archer [1996a] for the order of dissolution (4.5) and dissolution rate constant (1.0 \( \text{d}^{-1} \)). The dissolution rate constant for aragonite is assumed to be the same, but a slightly lower value of 4.2 is used for the reaction order [Keir, 1980]. Artificially separating the dissolution of calcite and aragonite in this way presents the problem of how dissolution forcing due to POC remineralization is partitioned between the two polymorphs. As a crude approximation \( f_{diss}^{POC} \) is split between the calcite and aragonite diagenetic systems in proportion to their relative mass abundance in the sediments, giving

\[
f_{diss}^{calc} = L \left( D, dCO_3, c^{\text{calc}}, f_{diss}^{POC} \right)
\]

\[
f_{diss}^{arg} = L \left( D, dCO_3, c^{\text{arg}}, f_{diss}^{POC} \right)
\]

### 3.3.4.2 The location of CaCO\(_3\) dissolution

In terms of CaCO\(_3\) mass balance it makes no difference from where in surface sediments material is dissolved. However, this is not true for qualities of CaCO\(_3\) that may vary with time such as \( ^{13}\text{C} \) and \( ^{14}\text{C} \) isotopic composition. A number of different end-member models have been proposed to qualitatively describe the effect of dissolution on such properties [Broecker et al., 1991; Oxburgh and Broecker, 1993], namely; “interface” dissolution, where the dissolution of CaCO\(_3\) takes place in the surficial fluff layer before any downwards mixing occurs; “homogeneous” dissolution, where settling CaCO\(_3\) is first homogenized into the intensely bioturbated zone prior to dissolution; and “sequential” or
“one pass” dissolution, where CaCO$_3$ is initially mixed into the surface layer, but ‘ages’, becoming less susceptible to dissolution with time. On the basis of observed $^{14}$C ages, the surface layer, but ‘ages’, becoming less susceptible to preservation of opal in deep-sea sediments are poorly proxies of past change, the factors determining the carbon cycle and in the interpretation of paleoceanographic Despite its importance to both the dynamics of the global 3.2.5 Sedimentary diagenesis of biogenic opal

Despite its importance to both the dynamics of the global carbon cycle and in the interpretation of paleoceanographic proxies of past change, the factors determining the preservation of opal in deep-sea sediments are poorly understood [Archer et al., 1993]. As a result, there have been few previous global carbon cycle models in which the ocean Si cycle has been comprehensively represented [Archer et al., 2000; Heinze et al., 1999]. A new description of sedimentary opal diagenesis is presented here, developed empirically from recent observations and laboratory analyses ofopal dissolution and thermodynamics in a series of cores taken from the Southern Ocean [Rabouille et al., 1997; Van Cappellen and Qui, 1997a,b].

3.2.5.1 A model for sedimentary opal diagenesis

The system for the diagenetic alteration of opal within deep-sea sediments can be restricted to the uppermost 10 cm since little net diffusion of H$_2$SiO$_4$ is observed below this depth [Rabouille et al., 1997; Sayles et al., 1996; Van Bennekom et al., 1988]. A further simplifying assumption is made in that the concentration of opal is constant with depth, again in line with observations [Rabouille et al., 1997; Schlüter and Sauter, 2000; Van Bennekom et al., 1988]. The system is vertically discretized into 0.2 cm thick sub-layers with down-core sediment porosity following (3-5), and solved on a finite-difference basis. However, considering that the relaxation time of solutes in the system is several orders of magnitude faster than for the solids [Rabouille and Gaillard, 1990], pore-water H$_2$SiO$_4$ concentrations are solved for in isolation. Steady-state is assumed to have been obtained when the dissolution flux across the sediment-water interface changes by less than 0.001% between time steps. The two individual components of the reaction-diffusion system are defined as follows.

**Diffusion of H$_2$SiO$_4$**

Correcting for tortuosity [Ullman and Aller, 1982] the in situ diffusion of H$_2$SiO$_4$ at depth $z$ in the sediment is described by

$$ D_{n}(z) = \left( \frac{\phi(z)}{\phi(\infty)} \right)^{(n-1)} D_{SW} $$ (3-10)

where $D_{SW}$ in the molecular diffusivity of H$_2$SiO$_4$ in free seawater, taken as $4.59 \times 10^{-6}$ cm$^2$ s$^{-1}$ at 0°C and adjusted for the actual bottom-water temperature after Hensen et al. [1998]

$$ D_{SW} = 4.59 \times 10^{-6} + 1.74 \times 10^{-7} \cdot (T_{SW} - 273.15) $$ (3-11)

where $T_{SW}$ is the temperature of the bottom-water (K), $\phi(z)$ is the porosity at depth $z$ (3-5), and $n$ is a correlation factor taking a value of 2.5 typical for deep-sea sediments [Hensen et al., 1998; Ullman and Aller, 1982]. Compared with molecular diffusion of H$_2$SiO$_4$, bioturbation and advection (due to sediment accumulation) play no significant role in aqueous transport within the sediment [Schink et al., 1975] and are thus omitted.

**Dissolution of biogenic opal**

Dissolution of opal (in units of mol cm$^{-3}$ opal a$^{-1}$) at depth $z$ in the sediment proceeds according to

$$ R_{opal}(z) = k_{opal}(z) \cdot \rho_{opal} \cdot \left( 1 - \phi(z) \right) \cdot c_{opal} $$ (3-12)

where $k_{opal}(z)$ is a dissolution rate constant (a$^{-1}$), $\rho_{opal}$ the density of opal (mol cm$^{-3}$), $\phi(z)$ sediment porosity (cm$^3$ cm$^{-3}$), and $c_{opal}$ the solid fraction of opal (cm$^3$ cm$^{-3}$) as a proportion of sediment solids. Traditionally, opal dissolution rate has been assumed to be a linear function of the degree of under-saturation [Archer et al., 1993, 2000; Rabouille and Gaillard, 1990; Rabouille et al., 1997; Schink et al., 1975]

$$ k_{opal}(z) = a \cdot u_{opal} $$ (3-13)
where $a$ is a constant and $u_{\text{opal}}$ is the degree of local pore-water under-saturation with respect to the solid phase

$$u_{\text{opal}} = \frac{[\text{H}_4\text{SiO}_4]_{\text{eq}(z)}}{[\text{H}_4\text{SiO}_4]_{\text{op}}(z)}$$

where $[\text{H}_4\text{SiO}_4]_{\text{eq}(z)}$ is the pore water concentration of silicic acid and $[\text{H}_4\text{SiO}_4]_{\text{op}}(z)$ the equilibrium (saturation) concentration with respect to opal. $[\text{H}_4\text{SiO}_4]_{\text{op}}(z)$ can be estimated empirically [Van Cappellen and Qiu, 1997a] by

$$\log_10\left(\frac{[\text{H}_4\text{SiO}_4]_{\text{op}}(z)}{\text{mol} \cdot \text{g}^{-1}}\right) = 6.44 - \frac{968}{T}$$

where $T$ is the absolute temperature (Figure 3-6). Although a dependence of $[\text{H}_4\text{SiO}_4]_{\text{op}}(z)$ on pH has also been observed [Van Cappellen and Qiu, 1997a], errors arising from omission of this effect are unlikely to be more than ~5% under typical pore-water conditions.

Contrary to the common assumption of linear dissolution kinetics (3-13) Van Cappellen and Qiu [1997b] found that the relationship describing dissolution rate appeared to become highly nonlinear as $u_{\text{opal}}$ approached unity. As shown in Figure 3-7, estimated and directly observed dissolution rates [Van Cappellen and Qiu, 1997b] can be crudely represented by an equation of the form

$$R_{\text{opal}} = 0.16 \left(1 + \frac{T}{15}\right) u_{\text{opal}}$$

$$+ 0.55 \left(1 + \frac{T}{400}\right)^4 u_{\text{opal}}^{0.25}$$

Figure 3-7 Opal dissolution rate as a function of degree of under-saturation ($u_{\text{opal}}$). Directly measured (at 5°C) dissolution rates are shown as filled (for core KYB05) and unfilled (KTB06) circles, respectively, together with estimated (at 0°C) dissolution rates marked by crosses [Van Cappellen and Qiu, 1997b]. Calculated dissolution rates using (3-16) are shown for temperatures of 5°C (top line) and 0°C (bottom line).
Early diagenetic alteration of opal also appears to affect dissolution rates, with rate constants inversely correlated with depth in the sediment [Van Cappellen and Qiu, 1997b] (Figure 3-8). This can be approximated

\[ R^{\text{opal}} = 0.068 + 0.0194 \cdot e^{(-\frac{z}{2})} \]  

(3-18)

Normalizing to a value of unity at the sediment surface (i.e., before any additional diagenetic alteration has occurred) gives a second scaling factor

\[ \eta_2^{\text{opal}} = 0.26 + 0.74 \cdot e^{(-\frac{z}{2})} \]  

(3-19)

The introduction of this factor is analogous to the decrease in kinetic ‘constant’ with depth employed by Rabouille et al. [1997].

Diagenetic effects also appear to suppress solubility. Van Bennekom et al. [1988] found that low concentrations of Al markedly lower the solubility of biogenic and amorphous silica, with opal samples exhibiting a contraction of the lattice at relatively high Al/Si ratios suggesting a degree of substitution of Si by Al. This is supported by observations made by Van Cappellen and Qiu [1997a] regarding the asymptotic concentration of pore-water silicic acid \([H_2SiO_4]_{\text{sym}}\) reached in the sediment. They noted that \([H_2SiO_4]_{\text{sym}}\) correlated with the mass ratio of detrital material to opal, suggesting that interstitial incorporation of Al into opal surface layers during a process of continuous dissolution/recrystallization might lead to decreasing solubility. Reduction in \([H_2SiO_4]_{\text{sym}}\) with the ratio of detrital to opal content [Van Cappellen and Qiu, 1997a] (Figure 3-9) can be approximated

\[ [H_2SiO_4]_{\text{sym}} = 895 - \left( 5528 \cdot \frac{c^{\text{detrital}}}{c^{\text{opal}}} \right)^{0.58} \]  

(3-20)

where \(c^{\text{detrital}}\) and \(c^{\text{opal}}\) are the fractions (wt%) of detrital material and opal in the sediment, respectively. Although the highest sediment core %detrital/\%opal ratio considered by Van Cappellen and Qiu [1997a] was 4.8 (corresponding to a reduction in \([H_2SiO_4]_{\text{sym}}\) from ~880 to ~520 µmol kg\(^{-1}\)) values of \([H_2SiO_4]_{\text{sym}}\) as low as 150 to 300 µmol kg\(^{-1}\) have been observed in opal-poor cores outside of the Southern Ocean [Archer et al., 1993; Martin et al., 1991; McManus et al., 1995]. The observed relationship is therefore extrapolated to a maximum %detrital/\%opal ratio of 15, producing a potential minimum \([H_2SiO_4]_{\text{sym}}\) value of around 180 µmol kg\(^{-1}\) under typical abyssal temperatures. Despite the dependence of asymptotic silicic acid concentrations on sediment composition being accountable on a purely kinetic basis [Rabouille et al., 1997], to reduce the degrees of freedom in the model the assumption is made that the equilibrium saturation state of opal is directly affected (i.e., \([H_2SiO_4]_{\text{eq}}\)). A reduction factor (\(\gamma_{Al}\)) accounting for Al-inhibition is then defined

\[ \gamma_{Al} = 0.2 \frac{c^{\text{detrital}}}{c^{\text{opal}}} > 15 \]  

(3-21a)

\[ \gamma_{Al} = 1.0 - \left( 0.045 \frac{c^{\text{detrital}}}{c^{\text{opal}}} \right)^{0.58} \frac{c^{\text{detrital}}}{c^{\text{opal}}} \leq 15 \]  

(3-21b)

and used to modify \([H_2SiO_4]_{\text{eq}}\) (3-15), to give

\[ [H_2SiO_4]_{\text{eq}} = \gamma_{Al} \cdot 10^{\left( 6.44 - \frac{968}{\gamma_{Al}} \right)} \]  

(3-22)

A full description for the dissolution rate of opal within the sediments can now be written...
The simulation of deep-sea sediments

\[ R_{\text{opal}}^{(2)} = \eta_1^{\text{opal}} \cdot \eta_2^{\text{opal}} \cdot \rho_0^{\text{opal}} \cdot [1 - \phi \cdot c_0^{\text{opal}}] \]  

(3-23)

where \( k_0^{\text{opal}} \) is the dissolution rate constant (a\(^{-1}\)) for ‘fres’
opal delivered to the sediment surface (i.e., in a
diagenetically unaltered state) under conditions of complete
under-saturation and at a temperature of 0°C. All that
remains is then to determine a value for \( k_0^{\text{opal}} \).
Unfortunately, published estimates for the dissolution rate
constant of opal vary widely. Model fitting of a series of
Antarctic cores suggests a value at the sediment surface in
the range 0.016 to 0.315 a\(^{-1}\) [Rabouille et al., 1997]. Schink et al.
[1975] adopted a value of 0.032 a\(^{-1}\), but noted that
experimental determinations often give much higher values
than this, upwards of 0.063 - 0.252 a\(^{-1}\). A further complication
arises in that all these estimates are based on the assumption of
linear kinetics.

The value of \( k_0^{\text{opal}} \) is therefore optimized to reproduce
(under equivalent conditions) estimated opal dissolution
fluxes across the sediment-water interface (\( f_{\text{dis}}^{\text{opal}} \)) of each of
a series of Southern Ocean cores [Rabouille et al., 1997].
To achieve this, the model was run for each of the cores
detailed in Table 3-4, taking opal and detrital content from
observations and assuming a bottom-water \( H_2SiO_4 \)
concentration of 145 \( \mu \)mol kg\(^{-1}\) typical of that area [Conkright
et al., 1994]. Since laboratory analyses on these cores were
conducted at relatively elevated temperatures (2 to 4°C)
comparable to the abyssal Southern Ocean [Rabouille et al.,
1997] and there being a general likelihood of post-recovery
distortion in \( H_2SiO_4 \) profile [Martin et al., 1991; McMansus
et al., 1995], the adoption of a temperature characteristic of
the benthic location may not necessarily be appropriate.
Instead, an effective temperature of 3.5°C is assumed, giving
a good agreement between observed values of \( H_2SiO_4 \)\(_{\text{sym}}\)
[Rabouille et al., 1997] and \( H_2SiO_4 \)\(_{\text{opal}}\) predicted by (3-15).
However, even accounting for all these factors the estimated
value of \( k_0^{\text{opal}} \) still ranges from 0.07 to 0.3 a\(^{-1}\). That these are
all significantly lower than suggested by the kinetic
experiments of Van Cappellen and Quo [1997b] made on
samples taken from the same cores (0.66 nmol s\(^{-1}\) g\(^{-1}\),
equivalent to 1.25 a\(^{-1}\)) may be due to further differences between
experimental and in situ conditions. It is likely that
opal isolated from a sedimentary matrix behaves in a
thermodynamically different manner from that still in the
presence of detrital material, so that care must be taken in
the interpretation of laboratory analyses.

On the basis that the presence of detrital material appears
to exert an important control on asymptotic silicic acid
concentrations (Figure 3-9) \( k_0^{\text{opal}} \) is made a function of the
\%detrital/\%opal ratio. The relationship is defined consistent
with the individually fitted core-specific dissolution rates
(Table 3-4). An additional constraint is imposed of a value of
1.25 a\(^{-1}\) at a %detrital/\%opal ratio of 0.0, assuming that the
kinetic experiments of Van Cappellen and Quo [1997b] are
representative of conditions where there is no detrital matter
influence. This gives rise to the relationship (Figure 3-10)

\[ k_0^{\text{opal}} = 0.05 + 0.055 \left( \frac{c_{\text{detrital}}}{c_{\text{opal}}} \right)^{-0.75} \]  

(3-24)

3.2.5.2 Look-up table implementation

In an analogous manner to that for \( CaCO_3 \), the sedimentary
diagenesis of opal in SUE is represented via means of a
look-up table. The spanning set of parameters utilized for
this are shown in Table 3-5. As before, these represent
something of a compromise between the dimensionality and
resolution of the parameter space describing the processes,
and considerations of computational resource availability.
A look-up table function is defined for the \( H_2SiO_4 \) flux
density across the sediment-ocean interface resulting from
opal dissolution within the sediment

\[ f_{\text{dis}}^{H_2SiO_4} = L \left( T, [H_2SiO_4]_{\text{sym}}, c_{\text{opal}}, c_{\text{detrital}} \right) \]  

(3-25)

where \( T \) and \( [H_2SiO_4] \) are the bottom-water temperature
and silicic acid concentrations, respectively, while \( c_{\text{opal}} \) and

Table 3-4 Details of Sediment Core Observations Together With Fitted Model Dissolution Flux (\( f_{\text{dis}}^{\text{opal}} \))

<table>
<thead>
<tr>
<th>Core ID</th>
<th>opal (wt%)</th>
<th>( CaCO_3 ) (wt%)</th>
<th>detrital (wt%)</th>
<th>( H_2SiO_4 )(_{\text{sym}} ) (μmol kg(^{-1}))</th>
<th>( f_{\text{dis}}^{\text{opal} 1} ) (μmol cm(^{-2}) a(^{-1}))</th>
<th>( H_2SiO_4 )(_{\text{opal}} ) (μmol kg(^{-1}))</th>
<th>( f_{\text{dis}}^{\text{opal} 2} ) (μmol cm(^{-2}) a(^{-1}))</th>
<th>( k_0^{\text{opal} 2} ) (a(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>KTB05</td>
<td>75.5</td>
<td>12.8</td>
<td>9.2</td>
<td>0.12</td>
<td>875</td>
<td>132.0</td>
<td>835</td>
<td>146.3</td>
</tr>
<tr>
<td>KTB06</td>
<td>86.3</td>
<td>0.3</td>
<td>10.8</td>
<td>0.13</td>
<td>841</td>
<td>203.0</td>
<td>834</td>
<td>154.0</td>
</tr>
<tr>
<td>KTB11</td>
<td>36.7</td>
<td>33.8</td>
<td>26.5</td>
<td>0.72</td>
<td>768</td>
<td>66.0</td>
<td>761</td>
<td>65.4</td>
</tr>
<tr>
<td>KTB19</td>
<td>38.0</td>
<td>7.7</td>
<td>52.2</td>
<td>1.37</td>
<td>700</td>
<td>53.5</td>
<td>709</td>
<td>55.7</td>
</tr>
<tr>
<td>KTB26</td>
<td>17.5</td>
<td>28.0</td>
<td>53.3</td>
<td>3.05</td>
<td>629</td>
<td>31.0</td>
<td>608</td>
<td>30.3</td>
</tr>
<tr>
<td>KTB28</td>
<td>15.8</td>
<td>7.7</td>
<td>75.5</td>
<td>4.78</td>
<td>515</td>
<td>24.0</td>
<td>526</td>
<td>23.9</td>
</tr>
</tbody>
</table>

1 Rabouille et al. [1997]
2 model fitted (present study)
3 estimated
3.2.5.3 Model validation

The opal diagenesis model has been constructed empirically on studies utilizing cores taken from a single transect located in the Southern Ocean. It is therefore essential to validate the model against data from geographically, and more importantly, biogeochemically different locations. Rather than focus on the specifics of any one particular site for validation, since the diagenesis model is to be used within a global framework where only mean regional behaviour is under consideration, it is more appropriate to analyse general trends of response. A database of parameters having direct equivalence with model output is constructed (detailed in Appendix III), taken from studies carried out on cores located mainly in the tropical and sub-tropical Pacific and sub-tropical Atlantic. Conditions in these regions generally deviate substantially from those in the Southern Ocean, often characterized by much higher CaCO₃ sediment content (especially in the Atlantic), lower opal rain rates, higher (Pacific) or lower (Atlantic) silicic acid concentrations, and slightly warmer temperatures. Such data is thus able to provide a robust test of the model parameterization.

Model data is generated with SUE configured with the simple box structure, ocean circulation, and biological export production of the PANDORA box model [Broecker and Peng, 1986]. Remineralization of POM, CaCO₃, and opal takes place below the surface layer according to the schemes of Archer et al. [1998] for POM and CaCO₃, and Gnanadesikan [1999] for opal, with sediment modules employed at 100 m depth intervals. The model was run for a total of 300 ka with inputs to the system of DIC, ALK, and dissolved SiO₂ chosen to attain a steady-state consistent with the modern ocean [Yamanaka and Tajika, 1996]. It should be noted that since PANDORA considers only seven geographically distinct surface regions, reducing to as few as four at depth, spatial variability in actual ocean biogeochemical conditions is unlikely to be well represented. The exact correspondence between observed and model data must therefore be interpreted with some caution.

Model results are shown in Figure 3-11, demonstrating a number of trends in the ocean. Of particular importance is the clear non-linear increase of opal burial with rain flux (a). There are a number of obvious artefacts present, such as the apparent decrease in mean opal content (τopal) with increasing rain flux (b), and the decrease in dissolution flux (fdisopal) with increasing τopal (c). These are likely to be a consequence of unrealistic CaCO₃ sediment distributions produced by the overly-simple ocean configuration and biological schemes in PANDORA. Figure 3-12 shows the same model data, but now on an expanded scale and contrasted with observations. The main points that can be drawn from this exercise are:

1. The model successfully reproduces a number of observed trends, such as in τopal as a function of opal rain flux (fsetopal) as shown in plot (b) and asymptotic silicic acid concentrations in the sediment ([H₄SiO₄]asym) as a function of τopal (e). The correspondence between model predictions and the relationship deduced from observations relating [H₄SiO₄]asym with fsetopal [Archer et al., 2000] is particularly good (d).

2. The model is much less successful in predicting opal dissolution fluxes across the sediment-water interface (fdisopal), which are generally overestimated, as demonstrated in plots (c) and (f).

Overall, considering that the opal diagenesis model was developed from core data taken solely from the Southern Ocean, many aspects of its performance under completely different conditions are in good agreement with observations. That dissolution fluxes at low- and mid-latitude regions tend to be overestimated is much less important in terms of the global mass balance of Si since the Southern Ocean dominates the global sink. However, it will be shown subsequently that the use of a more ‘realistic’ ocean representation greatly enhances the apparent success of the model (4.5.2).

![Figure 3-10](image-url)

**Figure 3-10** Dependence of kopal on the ratio of detrital to opal sediment content. Model dissolution rates required to produce the estimated dissolution fluxes of Rabouille et al. [1997] are shown as filled circles, while the dissolution rate of free opal under ambient conditions of 0°C and complete under-saturation estimated from Van Cappellen and Qiu [1997b] is shown as a filled triangle.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>range</th>
<th>step</th>
<th>units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sedimentary opal content</td>
<td>2 to 100</td>
<td>2</td>
<td>%</td>
</tr>
<tr>
<td>Bottom-water [H₄SiO₄]</td>
<td>0 to 250</td>
<td>10</td>
<td>µmol kg⁻¹</td>
</tr>
<tr>
<td>Bottom-water temperature</td>
<td>270 to 280</td>
<td>1</td>
<td>K</td>
</tr>
<tr>
<td>Base dissolution rate, kopal</td>
<td>0.01 to 1.00</td>
<td>0.01</td>
<td>a⁻¹</td>
</tr>
<tr>
<td>Sedimentary %detrital/%opal</td>
<td>0 to 10</td>
<td>1</td>
<td>n/a</td>
</tr>
</tbody>
</table>
Figure 3-11  Combined response of the opal diagenesis model within SUE (configured following Broecker and Peng [1986]).
Figure 3-12  Combined response of the opal diagenesis model within SUE (small open circles) contrasted with the validation data, indicated by larger filled symbols; squares - McManus et al. [1995], diamonds - Archer et al. [1993], triangles - Martin et al. [1991]. The thick dashed grey line in (d) indicates the estimated trend of Archer et al. [2000].
3.3 Synthetic deep-sea sediment cores

Much of the available information regarding the glacial-interglacial cycles of the late Quaternary comes from sediment cores recovered from the benthic environment. Not only is there excellent global coverage afforded by such records but in addition they contain a large number of proxies relating to different aspects of the state and operation of the Earth system. However, to be of use in understanding glacial-interglacial change these proxies must be interpreted. This is often no easy matter, particularly where a number of separate nonlinear processes all contribute to the observed net change. It may then not be possible to unequivocally deduce the mechanism(s) responsible for this change.

An alternative but very much complementary approach to glacial-interglacial analysis is developed here - working forwards from a description of processes driving the change towards observations. The advantage of this methodology is that the processes operating are explicitly known, and as such can be isolated and fully characterized through sensitivity studies and similar analyses. The possibility of non-unique solutions remains; correctly simulating a paleoceanographic proxy can not prove unequivocally that the model processes involved were actually important. However, use of multiple paleoceanographic proxy indicators can provide powerful additional constraints to a chosen hypothesis.

3.3.1 Synthetic sediment core construction

The thickness of accumulating material that the sediment module can track is theoretically limitless. However, in the sediments integral to the model where there is one module associated with every depth interval at each of every ocean grid point, practicalities of data storage forces the maximum number of sub-layers represented to be restricted. Sub-layers at the bottom of the stack are now gradually ‘lost’ as sediment accumulates at the top of the stack. As long as the depth of sediment represented exceeds the maximum possible thickness that can be lost due to sediment erosion [Archer et al., 1998] the dynamical response of the model will be unaffected.

A second set of sediment modules is introduced, distinct from the ‘integral’ modules. These are prescribed only at key and/or representative locations in the ocean. This gives a much more manageable number of cores such that enough sub-layers can be represented to enable the entire history of sediment accumulation over the course of the model run to be tracked. Although the representations of sediment deposition, diagenetic alteration, and bioturbation are identical to those acting in the integral modules, these additional core systems are assumed to be completely passive in that there is no exchange of mass with the ocean.

Age scales (i.e., age as a function of depth in the sediment) are provided for these synthetic cores in order to allow direct comparisons to be made with actual cores recovered from the deep sea. A number of different approaches for this are provided for.

Oxygen isotope stratigraphy

Age scales for sediment cores recovered from the deep-sea are typically generated by a rather complex procedure involving tuning measured foraminiferal $\delta^{18}O$ stratigraphy to an orbital template [Berger, 1994; Berger et al., 1994, 1995, 1996; Imbrie et al., 1984]. The foraminiferal $\delta^{18}O$ colour tracer in SUE provides the raw information to allow this procedure to be followed. However, constructing orbitally-tuned age scales for the huge number of synthetic sediment cores which can be generated from multiple model runs is likely to be very time-consuming. This approach is therefore not adopted for routine use with SUE.

Single stratigraphic marker

The simplest approach for down-core age assignment is to assume constant sediment accumulation rates. A single stratigraphic marker is generated by applying an impulse of a conservative colour tracer to the sediment surface at the end of model spin-up (identical to inert tracer profile simulations - 3.2.1.2). The level at which the peak concentration of colour tracer occurs in the core is identified and assumed to have an age equal to that at which the impulse event occurred. Linear interpolation between the age at this depth level and zero at the sediment surface thus defines the sediment age scale. This method is analogous to the use of linear interpolation from the magnetic reversal at the Brunhes-Matuyama boundary to core-top [Raymo, 1997], a relatively common technique, particularly in cores lacking a reliable $\delta^{18}O$ stratigraphy [Farrell and Prell, 1991]. However, many potential mechanisms for glacial-interglacial change in the global carbon cycle lead to significant variability in sediment accumulation rates. This methodology is thus only of use either with a sub-set of glacial-interglacial hypotheses or for cores located in environments inhibitive to the preservation of calcite (upon which other age scales depend).

Carbon-14

Calcitic $^{14}C$ in the sediments is continuously decayed allowing radiocarbon ages to be calculated. However, this is of limited practical use in contrasting extended model and observed core signals. Uncertainties in past cosmogenic production rates, and changes in reservoir capacity [Stocker and Wright, 1996], together with analytical considerations all act so as to restrict the age interval over which radiocarbon dating is reliable to within the last full glacial cycle.

Depositional age tracer

The advantage of synthetic sediments is that the precise time at which material is deposited to the sediment surface is known. A (calcite-tied) colour tracer representing the time of deposition can be used to provide a mean age for each sediment sub-layer. In light of the various drawbacks associated with the three methodologies outlined above this simple internal age scale is adopted for all further analysis of synthetic sediment cores in the present study.
The application of synthetic sediment cores to paleoclimatic analysis

Three primary areas for application of synthetic deep-sea sediment cores to glacial-interglacial paleoclimatic investigation are identified: analysis of the global distribution of sediment composition, general down-core variability within individual cores, and changes in the character of the CaCO₃ lysocline transition zone. In the following sections these are exemplified with the aid of the results of a simple carbon cycle model. SUE is run in a ‘PANDORA’-type configuration (see 3.2.5.3) for a period of 500 ka following 50 ka of spin-up. The system is perturbed by varying the magnitude of the terrestrial carbon reservoir. The forcing signal for this is a square-wave; period 100 ka, amplitude 1000 GtC, and with a linear transfer of carbon between reservoirs taking place over an interval of 1 ka.

3.3.2.1 Sediment distribution analysis

Model-generated (core-top) sediment composition and isotopic signatures can be used to produce maps of global distributions. Contrasts with available data sets [Archer, 1996b; Catubig et al., 1998; Henze et al., 1999] can give essential diagnostics on the operation of the model carbon cycle and aid in the optimization of unconstrained parameter values. This analysis need not be restricted to the present-day and can be extended back in time, with characteristics extracted from buried sediments for any required period. Comparisons with paleoceanographic observations can then yield important clues as to the past operation of the global carbon cycle. For example, the belt of maximum opal accumulation in the Southern Ocean appears to have migrated northwards at the time of the LGM compared to the present-day [Anderson et al., 1998; Francois et al., 1997; Kumar et al., 1995]; any complete solution for glacial-interglacial change should therefore be able to reproduce such a shift.

Mapping global sediment distributions from results produced by SUE is complicated by the absence of a single ocean floor depth associated with each grid point (as is the case in 3D OGCMs). Instead, each model region has a series of sediment modules which span discrete intervals over the maximum depth of the water column. Distributions are therefore produced for each ocean region in turn by mapping the sediment composition characterizing each sediment module onto all ocean floor lying within the depth interval spanned by that module as defined by observed ocean bathymetry [ETOPO5, 1988]. To illustrate this Figure 3-13 shows the global distribution of core-top CaCO₃. While the prescribed export fluxes in PANDORA [Broecker and
of deep-sea sediments

Peng, 1986] clearly produce erroneously high $\text{CaCO}_3$ preservation in the Southern Ocean with little preservation in the northern Atlantic and Indo-Pacific, this exercise does highlight two important features. Firstly, the depth-dependence of $\text{CaCO}_3$ preservation (for instance, the topographic and therefore preservational high of the mid-Atlantic ridge can be picked out). Secondly, distinct regional differences in preservation arising from a combination of the specifics of ocean circulation and biological export can be generated. The boundaries differentiating between the various grid point regions can be seen as sharp linear transitions in $\%\text{CaCO}_3$, an artifact of the low spatial ocean resolution of PANDORA.

3.3.2.2 Single core analysis

Of particular interest in this present study of glacial-interglacial change are comparisons that can be made between variability in model and observed down-core sediment characteristics. Ideally, mismatches between model and observations should indicate deficiencies in the model representation of changes in the global carbon cycle. However, in practice such direct analysis is not possible. The information contained in synthetic model sediment cores is determined by processes and environments representing large temporal and spatial means. In contrast, sediment cores recovered from the deep sea may be influenced by local processes such as up-welling [Bertrand et al., 1996] and sediment redistribution by bottom currents [Bareille et al., 1994; Seidov and Haupt, 1999]. Moreover, in order to maximize core resolution locations are often deliberately chosen where such local processes result in enhanced sedimentation rates. As a result, the degree of bioturbational filtering in down-core variability is likely to differ substantially between model-generated and observed signals. The respective amplitudes and mean values of such variability cannot therefore be expected to closely correlate. Random events can further increase the specificity of recovered cores, particularly through non-local mixing (such as through burrow formation) and core damage during recovery, but also from turbidity events. These can all result in depth intervals characterized by intense distortion and hiatuses in proxy signals, factors which cannot be prognostically generated by the model.

Figure 3-14 Down-core variability in major sediment solid components, isotopic foraminiferal $\delta^{13}$C tracers, and overall sediment accumulation rate in a synthetic sediment core located at an intermediate depth in the Southern Ocean. The model is forced by a simple cyclical (square-wave) change in terrestrial carbon storage.
Although processes operating on smaller scales than those represented by the model exert an important control on the observed record there is no reason a priori why the timing and direction of change on glacial-interglacial time scales should not generally find a strong correspondence with synthetic proxies (that is where perturbations in the global carbon cycle are correctly represented in the first place). By contrasting the phase of model and observed signals information should be extractable regarding the mechanisms responsible for variability in the system. Visual inspection may often be sufficient for such analysis, although use of spectral methods can naturally provide a more quantitative assessment of the response (e.g., Hagelberg et al. [1991]; Lau and Weng [1995]; Mann and Lees [1996]).

Figure 3-14 shows a sub-set of the paleoceanographic proxy information extractable from a single synthetic sediment core generated by SUE. All are plotted as a function of sediment age for the past 400 ka (equivalent to a total core length of about 229 cm), defined according to the internal calcite-tied age tracer. The effect on the preservation of CaCO3 resulting from changes in ocean chemistry as carbon is alternately removed from and added to the ocean can be clearly seen, with the relative proportions of the other major solid phase responding in anti-phase. In this particular model run 13C fractionation in benthic and planktonic foraminifera is assumed to follow that for bulk calcite (2-61a), such that variability in δ13C foramin reflects only changes in the mean isotopic composition of the ocean as a whole. Finally, pronounced changes in sediment accumulation rate are apparent. Use of an age scale derived from a single stratigraphic marker with the assumption of constant accumulation rate (3.3.1) would obviously therefore produce a distorted picture were it to have been adopted in this example.

### 3.3.2.3 CaCO3 lysocline transition zone

Although there is no precise definition, the location of the calcium carbonate (as either calcite or aragonite) lysocline is often taken to mark the depth in the ocean at which the presence of CaCO3 starts to decline rapidly in surface sediments with increasing depth [Berger, 1968; Balsam, 1983; Broecker and Takahashi, 1978; Farrell and Prell, 1989]. A second characteristic feature of deep-sea sediment composition is the carbonate compensation depth. This is the point at which the CaCO3 dissolution flux is exactly balanced by the rain rate and is usually taken to be the depth where CaCO3 first disappears from the sediments [Farrell and Prell, 1989]. Between these lies the lysocline transition zone.

In any restricted region of the ocean, the depth and thickness of the lysocline transition zone will vary on glacial-interglacial time scales as a result of changes in ocean chemistry and/or particulate rain rates to the sediment surface. Analysis of past changes in this zone obtained by comparison of model simulation with observations can thus provide important information regarding the operation of the carbon cycle. Although a number of studies report past variability in the depth profiles of both calcite and aragonite sediment content [Balsam, 1983; Berger, 1977; Farrell and Prell, 1989, 1991; Karlin et al., 1992] there has only been one modelling attempt to date [Walker and Opdyke, 1995].

To reconstruct glacial-interglacial variability in the depth and shape of the calcite and aragonite lysocline transition...
zones a series of synthetic sediment cores are defined within the same grid point region and at closely spaced depths. Figure 3-15 shows how the shape of the CaCO₃ lysocline transition zone changes over the past 400 ka in response to the applied terrestrial carbon storage forcing. It can be seen that there is a pronounced cyclicity in both lysocline and carbonate compensation depths over this period, with a peak-to-peak amplitude of about 1 km. Pronounced preservation spikes during times of rapid carbon transfer out of the ocean-atmosphere system are also present.

Other sedimentary characteristics can be plotted in a similar manner. Figure 3-16 shows the distribution of the synthetic foraminiferal δ¹⁸O tracer over the CaCO₃ lysocline transition zone with time, together with contours of CaCO₃ content (see Figure 3-15).

![Figure 3-16](image)

Figure 3-16 Variability in the synthetic foraminiferal δ¹⁸O tracer over the CaCO₃ lysocline transition zone with time, together with contours of CaCO₃ content (see Figure 3-15).
Modelling the pre-industrial state

4.1 Introduction

The biogeochemical processes previously outlined delineate what is essentially a framework for representing the global (oceanic) carbon cycle. However, before SUE can be employed to test potential mechanisms behind the observed glacial-interglacial variability in the concentration of atmospheric CO$_2$, model ocean structure and circulation must be prescribed. Furthermore, the existence of a number of unconstrained parameter values within certain process parameterizations dictates that a degree of model 'optimization' must be carried out. The end-product of this optimization will be a steady-state representation of the modern (pre-industrial) carbon cycle which can be used to critically evaluate the model's performance against observational data.

Parameter optimization and model evaluation should ideally be undertaken within a rigorous statistical framework, with indicators of 'goodness of fit' defined and utilized in order to achieve some quantitatively optimal model solution. System characteristics such as atmospheric composition, fields of physical and chemical ocean properties, areal distributions of biological production and sediment composition are all important indicators of system operation and therefore need to be considered in constructing any hypothetical 'goodness of fit' statistic. However, in order to achieve this, weightings of relative importance to the overall system response of the carbon cycle must be assigned to all these individual components. Unfortunately it is not possible in the context of this present study for such an approach to be undertaken since these assignments cannot be made unobjectively. Furthermore, with the exception of a few predominantly global values such as the concentration of atmospheric CO$_2$ and its isotopic signature, there is a serious scale mismatch between the descriptors of model state and observational data. While model ocean properties are regional in character, typically representing zonal or even entire basin averages, much of available observational data is in the form of point measurements, for which system characteristics such as biological productivity (and to a lesser extent, sediment composition) are extremely patchy in their global coverage. Instead, a 'reasonable' model state is objectively judged through consideration of a basket of apparently important system characteristics. In any event, the modern ocean carbon cycle is likely to be far from steady state, even prior to the advent of the Industrial Revolution. The validity of an exact simile of the pre-industrial system obtained with a steady state model is thus questionable, particularly for subsequent application to long-term change.
4.2 Ocean structure and circulation

Historically, substantial progress in our understanding of the potential causes behind the relatively low concentration of atmospheric CO₂ (xCO₂) observed to have occurred during the Last Glacial Maximum (LGM) has been made with the use of global carbon cycle models where the representation of the world ocean is highly simplified. In some of the earliest of these models the ocean was partitioned into only two or three homogeneous volumes or ‘boxes’ with a prescribed ocean circulation (e.g., Knox and McElroy [1984], Sarmiento and Toggweiler [1984], Siegenthaler and Wenk [1984]), soon followed by slightly more complex ‘multi-box’ models utilizing up to a few dozen boxes (e.g., Broecker and Peng [1986], Keir [1988]). Despite their apparent oceanographic naivety they are advantaged by relative ease of interpretation and numerical efficiency [Joos et al., 1997; Sarmiento et al., 1988; Siegenthaler and Joos, 1992] which has led to them playing a central role in the development of many of the mechanisms for glacial-interglacial xCO₂ changes proposed to date. However, a number of problems in representing the ocean carbon cycle arise, particularly as a result of the low vertical and horizontal resolution inherent in ocean structures comprising no more than a few dozen distinct elements;

- The remineralization of particulate organic matter (POM), CaCO₃, and opal within the water column are unlikely to be adequately resolved. Vertical adjacency between boxes lying at the surface (where nutrients may be limiting to biological productivity) and at intermediate depths (where most POM remineralization and nutrient release occurs) can lead to ‘nutrient trapping’ problems (see 4.3.4).

- The scavenging of Fe from the water column is similarly likely to suffer from low vertical resolution. Low horizontal resolution may also distort the system, particularly where regions receiving high aeolian Fe supply incorrectly adjoin regions of low aeolian supply rather than being separated by a zone where scavenging can restrict Fe transfer.

- With relatively low (mainly horizontal) resolution model validation attempted between spatially-aggregated model descriptors and point observations taken from paleoceanographic sediment cores becomes difficult.

- Failure to resolve important regions of CO₂ ocean-atmosphere exchange (such as strong net out-gassing from equatorial up-welling zones) may distort the dynamical response of xCO₂ to perturbations, even if model tuning allows for a realistic pre-industrial value to be simulated at steady-state.

- Circulation fields generated by tuning to a single tracer such as radiocarbon (natural or bomb) may be in error when applied to other tracers [Joos et al., 1997; Kurz and Maier-Reimer, 1993; Siegenthaler and Joos, 1992].

Increasing the number of boxes beyond a few dozen in an attempt to alleviate these problems makes it difficult to construct a self-consistent and realistic ocean circulation. An alternative way of increasing vertical resolution is to use a diffusive box model [Oeschger et al., 1975; Shaffer, 1989, 1996; Shaffer and Sarmiento, 1995]. However, where there is no analytical solution, this improvement is achieved at the expense of computational efficiency and issues related to horizontal resolution still remain. A final possible trick is to sub-divide vertically and/or horizontally boxes in an existing box model whilst retaining the original advective field [Klepper et al., 1994].

In contrast to box models, Ocean General Circulation Models (OGCMs) represent the global ocean on a three-dimensional grid, with a typical horizontal resolution of order 3° and with upwards of 15-30 separate vertical levels resolved. Ocean circulation is calculated by consideration of forces generated through surface wind stress and ocean density contrasts (driven by heat and salinity gradients) [McGuffie and Henderson-Seller, 1996], with surface boundary conditions prescribed from observations or calculated through coupling with an (Atmospheric) General Circulation Model (GCM or AGCM). Although their grid spacing enables most major ocean biogeochemical provinces to be adequately resolved, the shear number of cells in the 3D structure results in a considerable computation requirement, even when run ‘off-line’ (i.e., utilizing a pre-calculated circulation [Bacastow and Maier-Reimer, 1990]). The simulation of entire glacial-interglacial cycles is therefore currently beyond the practical application of most OGCMs, particularly where extensive sensitivity analyses might be required. In addition, despite having an apparently strong semblance of reality about them OGCMs are far from perfect, for instance often exhibiting serious deficiencies in equatorial circulation which are highlighted when biogeochemical cycling is incorporated [Najjar et al., 1992]. Although such problems can be corrected with the use of a sufficiently fine grid spacing [Aumont et al., 1999], this adds further to the computational costs of running the model.

There is, however, something of a “third way”. Zonally-averaged OGCMs (also known as ‘2D’ or ‘2.5D’ models, but referred to as ‘ZOGCM’s hereafter) divide the ocean meridionally into a number of latitudinal bands with a typical resolution of 5-15°. The ocean is therefore zonally averaged although each basin is represented separately. The number of vertical levels is comparable to that of full (3D) OGCMs. As with OGCMs, ocean circulation is calculated from basic fluid physics, albeit in a more highly parameterized form [Wright and Stocker, 1992]. While they cannot represent sub-zonal features such as boundary currents they are successful in reproducing the global and basin-scale features such as the Atlantic thermohaline circulation [Hovine and Fichefet, 1994; Wright and Stocker, 1992]. Indeed, simple single-basin models have been successfully employed in investigating modes of variability in overturning circulation [Drbohlav and Jin, 1998; Yang and Huang, 1996; Yang and Neelin, 1993]. The relatively short integration times of ZOGCMs achieved through zonal averaging (compared to that possible with a true 3D grid) together with their ability to produce an interactive ocean circulation (as opposed to the fixed prescribed circulation of box models) has made them ideal candidates for integrating into complete Earth System Models (ESMs) [Ganopolski et al., 1998a,b; Sakai and Pelletier, 1997, 1998].
The flexibility in physical ocean structure enabled by SUE allows for implementation of a ZOGCM-type configuration as an alternative to a simple multi-box model format. While a number of different zonally-averaged global ocean circulation models have been developed (e.g., Fichefet et al. [1994], Hovine and Fichefet [1994], Sakai and Peltier [1996, 1997, 1998]), as an initial step the Bern 2D model is utilized [Stocker et al., 1992; Stocker and Wright, 1991a, 1996; Wright and Stocker, 1991, 1992]. This has an ocean structure slightly simpler than possible alternatives, consisting of three zonally-averaged ocean basins (Atlantic, Indian, and Pacific) with a variable meridional resolution of between 7.5 and 15.0° (Figure 4-1). The three basins are linked by a Southern Ocean component with meridional but no zonal structure. Ocean levels are considered in the vertical. It also has the advantage of arguably the longest application pedigree, having been previously used in contexts such as ocean thermohaline circulation sensitivity [Stocker and Wright, 1991b], anthropogenic CO\textsubscript{2} uptake [Stocker et al., 1994] and future feedbacks [Joos et al., 1999], deglacial changes in the ocean 14C reservoir [Stocker and Wright, 1996] and factors affecting surface ocean δ13C distributions [Lynch-Stieglitz et al., 1995]. Of obvious relevance to this present study is the fact that with the addition of a comprehensive carbon cycle [Marchal et al., 1998b] the Bern 2D model has been previously employed in exploring the influence of changes in ocean circulation on xCO\textsubscript{2} [Marchal et al., 1998a,b, 1999].

Although ocean circulation in the version of the Bern 2D model considered for application in SUE is annual [Stocker and Wright, 1996], important variability in the actual ocean system occurs seasonally. In particular, physical properties such as sea ice extent and mixed layer depth change markedly over the course of the year at high latitudes, leading to profound biogeochemical changes. The relatively sensitivity of CO\textsubscript{2} fugacity (fCO\textsubscript{2}) with respect to ocean-atmosphere exchange CO\textsubscript{2} in a surface ocean layer thickness of ~50 m dictates that for numerical stability, carbon transfer across the air-sea interface in SUE must operate with a time step of order one month as opposed to annually. Taking advantage of this, an extremely crude pseudo-seasonality for high latitude processes is introduced in conjunction with a calculated annual insolation cycle (Appendix II). Firstly, fractional sea ice coverage is varied at the monthly time step according to relative changes in insolation levels. Although the cryosphere actually tends to lag changes insolation maximum sea ice extent is assumed to coincide with the winter insolation minimum, while minimum sea ice extent coincides with the summer maximum

\[ A_{\text{ice}}(i) = A_{\text{min}} \left( A_{\text{max}}^{\text{ice}} - A_{\text{min}}^{\text{ice}} \right) \frac{I_{\text{max}} - I(i)}{I_{\text{max}} - I_{\text{min}}} \]  

(4-1)

where for each grid point, \( A_{\text{ice}}(i) \) is the sea ice-covered area at time \( t \), \( A_{\text{max}}^{\text{ice}} \) and \( A_{\text{min}}^{\text{ice}} \) are the maximum and minimum sea ice-covered areas, respectively, with insolation \( (I) \) variables, similarly designated. Secondly, a ‘winter’ season is defined (used subsequently in the representation of seasonal convection – see 4.2.3.1) at a particular grid point on the basis of mean monthly insolation falling below a prescribed threshold. This threshold is arbitrarily set at a value of \( I = 0.225 \), giving a plausible ‘winter’ season of length 4-6 months south of ~55°S.

For carbon cycle work, OGCMs are typically run in an ‘off-line’ mode where a previously calculated advective field is imposed on the ocean biogeochemistry [Archer et al., 2000; Bacastow and Maier-Reimer, 1990]. Such a configuration could virtually be considered a box model, albeit one with a huge number of boxes (in the range \( 10^3-10^4 \)). By defining a structure of meta cells in the ocean, each of which encompassing multiple cells of the original ocean model, and by integrating fluxes across each of the meta cells boundaries, a new model structure can be obtained [Michel et al., 1995]. While this ‘child’ structure will be characterized by lower vertical and/or horizontal resolution, ocean circulation should retain the basic characteristics of the ‘parent’ OGCM. Depending on to what extent resolution is degraded, a hierarchy of child models is possible based upon the same parent.

A new ‘pseudo-box’ model of the ocean carbon cycle for use over glacial-interglacial time scales is presented here (shown schematically in Figure 4-2) based upon the ocean configuration and circulation of the Bern 2D ZOGCM [Stocker and Wright, 1996]. Since its physical structure comprises 16 grid points horizontally with 8 levels in the vertical, it will hereafter be referred to as “SUE1608”.

### 4.2.1 Derivation of basic ocean structure

Ocean zonation results in a relatively uncomplicated model circulation field, with mass flow often in the same direction across a series of adjacent cell boundaries. This allows horizontal and vertical resolution to be degraded without any serious distortion of the overall circulation pattern. Grid points in the Bern 2D model are therefore amalgamated in
such a way that primary biogeochemically distinct surface regions and water masses are retained, the aim being to produce a minimum ‘reasonable’ representation of the ocean within the context of glacial-interglacial change and within constraints dictated by computational practicalities.

Taking the Bern 2D model, latitudinal boundaries are removed as indicated in Figure 4-1. A single grid point now represents the entire mid-latitude gyre zone (one for each hemisphere and for each of the ocean basins), the sub-polar zone of the Atlantic is enlarged, and both zones lying south of 50°S (the boundary which can be crudely taken to represent the location of the Antarctic Polar Front) in the Southern Ocean are merged. Since the spatial and seasonal complexity in Indian Ocean circulation north of 7.5°S is not reproduced in the parent model, both these regions are also amalgamated with little loss in realism. This leaves a total of 16 geographically distinct ocean regions.

In the vertical, the 50 m near-surface resolution is retained down as far as 150m, with layers amalgamated thereafter according to the apparent delineation of major water masses. A total of 8 vertical levels with lower boundaries at depths of 50, 100, 150, 500, 1000, 2500, 3500, and 4000 m are therefore retained. The overall reduction in the total number of cells by factor ~3 in SUE1608 results in a more than doubling in computational speed compared to that of the Bern 2D parent.

### 4.2.2 Physical boundary conditions

Physical ocean configuration in the Bern 2D model is highly idealized, assuming uniform zonal widths for each basin and with the longitudinal locations of the basin boundaries not specified in absolute terms [Stocker and Wright, 1996]. Regions associated with each model grid point are therefore prescribed as shown in Figure 4-3 for the purpose of deriving surface forcing data from observational fields. Forcing values for each region are then

\[
b_{\text{mean}}^x = \frac{\sum_{\text{lat,lon}} H(D_{\text{lat,lon}}) \cdot A_{\text{lat,lon}} \cdot b_{\text{lat,lon}}^x}{\sum_{\text{lat,lon}} H(D_{\text{lat,lon}}) \cdot A_{\text{lat,lon}}} \tag{4-2}
\]

where \(D\) is the depth of the ocean floor (m) taken from ETOPO5 [1988], \(A\) is the ocean surface area associated with each ETOPO5 5° x 5° pixel, \(H\) is the Heavyside operator (acting to exclude terrestrial regions as defined by topography lying above sea level) and \(b_{\text{lat,lon}}^x\) is the observed value of surface property \(x\). The physical boundary condition fields utilized are:

- Sea-surface temperature (SST) - from Levitus et al. [1994c] (taken at 30 m depth).
- Sea-surface salinity (SSS) - from Levitus et al. [1994b] (taken at 30 m depth), but modified in the southernmost grid cell (i.e., south of 55°S) to enable observed
deep-water values to be reproduced in that region [Stocker and Wright, 1996].
• Annual wind speed - calculated as an annual mean from individual monthly values [Trenberth et al., 1989].
• Maximum sea ice coverage - set equal to the maximum (winter) monthly value [CLIMAP, 1984].
• Minimum sea ice coverage - set equal to the minimum (summer) monthly value [CLIMAP, 1984].
• Maximum mixed-layer depth - set equal to the deepest mean monthly depth of the mixed layer [Levitus et al., 1994b,c].

Insolation is treated slightly differently, taking a value for each grid point region simply calculated at its mid-latitude (see Appendix II).

Unlike the meridional boundaries of each surface forcing region which have an exact correspondence with the physical ocean model, the longitudinal boundaries of the forcing regions are constrained in order to approximate actual basin topology. They therefore differ from those in the physical model. The resulting difference in area between the forcing and physical model grid point regions is a potential source of bias in terms of magnitude of mean global boundary conditions. However, even for surface properties that vary strongly with latitude such as SST, the area-weighted global mean surface temperature of the model is not significantly different (~0.1°C) from that derived directly from observations [Levitus et al., 1994c].

4.2.3 Derivation of basic ocean circulation

Ocean circulation is taken from the modern (pre-industrial) annual velocity field of the Bern 2D ZOOGCM [Marchal et al., 1998a]. Meridional and vertical components of velocity are converted to an equivalent mass flow before any cell amalgamation takes place. Both net advection and exchange (mixing) across each of the internal physical ocean boundaries in SUE1608 are calculated.

4.2.3.1 Convective processes

While the derivation of a new advective field is relatively straightforward, the limited spatial and temporal resolution of the Bern 2D model makes representation of non-advective circulation, such as (high latitude) convective processes extremely problematic. While convection in the actual ocean is a seasonal process operating on relatively fine spatial scales and occurring heterogeneously within a zonal region, in contrast, the Bern 2D model has no true seasonality and is characterized by extensive homogeneous zonal regions. SUE1608 suffers from an additional deficiency with regard to convective processes in that it lacks any thermodynamic consideration of sea ice formation. As a result, application of commonly-used algorithms for convective adjustment in regions of water column density instability (identified according to the equation of state polynomial approximation of Winton and Sarachik [1993]) produces an overly-ventilated and homogenized deep high latitude ocean [Stocker and Wright, 1996]. This situation is exacerbated if Levitus SSSs [Levitus et al., 1994b] are adjusted in order to produce more realistic deep-water salinities [Stocker and Wright, 1996]. Where water column instabilities do not extend all the way down to the ocean floor, pronounced hiatuses in temperature (T), salinity (S), and nutrient distributions can arise. Three highly parameterized processes are therefore introduced into the model in an attempt to capture (to a first order) observed high latitude behaviour – one for each of; seasonal mixed layer deepening, the formation of deep water masses characterized by low temperature, high salinity, and high dissolved O2 concentrations, and generally enhanced vertical

Figure 4-3 Prescribed ocean grid point regions in SUE1608.
mixing in the water column arising through convective and other sub-grid scale processes.

Mixed-layer dynamics

There is a pronounced seasonal cycle apparent at high latitudes. Summer months are characterized by high insolation levels and a stratification of the surface ocean, providing physical conditions suitable for rapid phytoplankton growth. In contrast, during winter months biological activity is suppressed by restricted light availability due to a combination of lower insolation levels incident at the surface ocean together with the presence of a relatively deep mixed layer. During winter, previously depleted surface nutrients are replenished through the entrainment of nutrient-rich deeper waters. This cycle is approximated by allowing deepening of the surface ocean mixed layer during the ‘winter’ season in SUE (as defined by mean monthly insolation being less than a prescribed threshold) with biological export effectively prohibited. If the water column becomes convectively unstable during this period, convective adjustments are made by pair-wise homogenization of cells down through the water column [Wright and Stocker, 1992]. To prevent excessive ventilation of the deep ocean occurring via this route, mixing depth is restricted according to the maximum observed mean mixed-layer depth (4.2.2).

‘Deep water’ formation

Realistic deep ocean T, S, and dissolved O$_2$ distributions are reproduced by transporting surface properties to depth via a conceptual sinking plume. Each ‘winter’ season, a water mass equal to that of the surface cell is allowed to sink until it reaches a cell with higher potential density (or the ocean bottom, whichever occurs first). T, S, and [O$_2$] properties are incorporated into the intervening cells in proportion to the mass of each call as a fraction of the total mass contained within the vertical interval over which the plume sinks. In order to further improve deep-water properties, the temperature of the sinking plume is reduced 4°C below mean annual SST (4.2.2) down to a minimum of -1°C.

Enhanced Southern Ocean mixing

Although between them the seasonal mixed-layer deepening and plume-generation go some way towards reproducing observed pelagic and benthic tracer fields, distributions at mesopelagic depths in the Southern Ocean, particularly of nutrients, are extremely poor. Lack of explicit vertical mixing in the ocean interior in this region due to convective and other sub-grid scale processes is counteracted by prescribing a mass exchange flux between layers lying at or below the maximum mixed-layer depth. This mixing is equivalent to a volumetric exchange of 50 Sv at 62.5°S and 10 Sv at 51.25°S.

4.2.3.2 Eddy diffusivity

The strength of vertical eddy diffusivity is varied down through the water column following Weaver and Sarachik [1991]. Use of a value for horizontal eddy diffusivity consistent with OGCMs and observational estimates of 1x10$^3$ m$^2$ s$^{-1}$ [Wright and Stocker, 1992] is found to result in overly-steep meridional gradients in T, [PO$_4$], [H$_2$SiO$_4$], and [O$_2$] tending to develop in the Pacific and Indian Ocean basins. In order to improve these tracer fields a coefficient of 1x10$^4$ m$^2$ s$^{-1}$ is adopted, comparable to values used in some ZOGCM [Hovine and Fichefet, 1994] and box models [Archer et al., in press; Rich et al., 1999]. This higher value can be justified on the basis that the effective diffusivity at a zonal scale is unlikely to be comparable to local rates [Marchal et al., 1998b] and will need to account for the large-scale meridional mixing processes not represented, such as through gyre circulation [Stocker et al., 1994].

4.2.4 The addition of deep-sea sediments

The Bern 2D model assumes a uniform ocean depth of 4000 m. However, in order to correctly represent the interaction between the ocean and deep-sea sediments a more realistic bathymetry must be prescribed [Keir, 1995]. As an initial step a mean global bathymetric profile (made on the basis of ETOP05 [1988] topography) is applied to each of the 16 grid points, imposing a maximum depth of 6000 m. Alteration of bathymetry in this way results in a slight reduction in total global ocean volume compared to the original model. In order to avoid biasing the residence time of water in each cell, global ocean volume is corrected by increasing the width of each ocean basin by ~9% and altering the depth of the base of each ocean layer. The lower boundary depths of the 8 vertical levels are now 47, 95, 144, 496, 1013, 2652, 3986, and 6000 m.

The depth resolution of the sediment modules employed to span the entire 6000 m depth of the ocean is chosen to maximize overall computational efficiency. Sensitivity analyses suggest that a depth interval of up to 500 m can be used with little distortion in the overall response of the global carbon cycle system to applied perturbations. However, since ocean layer thicknesses decrease and sedimenting fluxes increase as the ocean surface is approached, this resolution is progressively increased above 500 m depth in the ocean, to a minimum interval of 50 m.

4.3 Biogeochemical configuration

Final configuration of the global carbon cycle in SUE1608 requires the prescription of certain geochemical boundary conditions. In addition, there exist several unconstrained parameters associated with various biogeochemical processes that require a degree of optimization, with values chosen on the basis of achieving balanced model simulation ‘success’, as measured against a basket of present-day observational data. Such considered constraints include oceanic fields of [PO$_4$], [H$_2$SiO$_4$], and [Fe], particulate fluxes of POC, CaCO$_3$, and opal (and in particular the CaCO$_3$:POC rain ratio), and core-top CaCO$_3$ and opal sediment contents.

4.3.1 Geochemical boundary conditions

Since there is no explicit representation in SUE of processes lying outside of the atmosphere-ocean-sediment system (such
as terrestrial weathering) a number of geochemical boundary conditions need to be evaluated. Suitable values can be estimated on the basis of present-day observations, paleoclimate reconstructions, model simulations, or chosen simply to achieve a required system steady-state on an appropriate time scale.

4.3.1.1 Dissolved chemical input to the ocean

Coastal and continental shelf environments provide an important interface between terrestrial processes and the open ocean. In the absence of any explicit representation of these in SUE, dissolved chemical input to the ocean is simply applied directly to the surface ocean grid points in proportion to their relative surface area. Dissolved chemical inputs to SUE1608 are:

- Carbon and alkalinity (from $\text{Ca}^{2+}$) following Walker and Opdyke [1995]; some 20 and 40 Tmol a$^{-1}$ for DIC and ALK, respectively.
- The $^{13}$C isotopic signature of DIC is chosen in order to bring the system to a steady state characterized by an estimated pre-industrial mean oceanic $\delta^{13}$C$_{\text{DIC}}$ of -0.4‰ [Yamanaka and Tajika, 1996] over the long-term (>100 ka). A value for $\delta^{13}$C$_{\text{DIC}}$ of around -3.1‰ will achieve this.
- Global input of silicic acid arising from a combination of riverine influx, hydrothermal sources, and sea floor weathering (excluding the dissolution of biogenic opal) is taken to be 5.5 Tmol Si a$^{-1}$ following Tréguer et al. [1995]. There is little difference between the delivery of aeolian-derived dissolved Si (assumed to be some 0.5 Tmol Si a$^{-1}$ [Tréguer et al., 1995]) in proportion to dust deposition fluxes or simply in proportion to surface area. All (externally-derived) dissolved Si added to the ocean, a total of 6.0 Tmol Si a$^{-1}$, therefore follows the other dissolved inputs in being delivered in proportion to surface area.

4.3.1.2 The delivery of aeolian material to the ocean

Supply of iron to the world ocean is thought to be dominated by riverine input [Duce and Tindale, 1991]. However, most of this iron is likely to be removed from the water column and sedimented in the neritic environment through a combination of low Fe utilization efficiency by coastal phytoplankton [Sunad and Huntsman, 1995] and high coastal productivity (with proportionally rapid scavenging). Indeed, the length scale of Fe penetration into the open ocean from coastal shelf areas has been estimated to be only ~16 km [Johnson et al., 1997]. Iron input to the (open) ocean in the model is therefore assumed to be derived exclusively from aeolian dust deposited to the ocean surface.

Dust deposition rates are taken from the coupled GCM tracer advection and terrestrial ecosystem model simulations of Mahowald et al. [1999]. Fluxes to each grid point are derived from gridded GCM depositional fields in a similar manner to that used for deriving the physical surface forcings (4.2.2). However, on the basis that Fe originating from elevated near-shore dust deposition will suffer a similar fate to that of riverine Fe, coastal areas are masked out [Fung et al., 2000]. Mean dust deposition fluxes ($f_{\text{dust}}^{\text{grid}}$) to each grid point region in the model are thus given by

$$f_{\text{dust}}^{\text{grid}} = \frac{\sum \sum H(D_{\text{lat,lon}} - 250) \cdot A_{\text{lat,lon}}^{\text{grid}} \cdot f_{\text{dust}}^{\text{grid}}}{\sum \sum H(D_{\text{lat,lon}} - 250) \cdot A_{\text{lat,lon}}^{\text{grid}}} \ (4-3)$$

where the Heavyside function $H$ excludes shelf areas defined by ocean depth <250 m.

Dust deposition tends to be a highly episodic process with a substantial proportion of the annual total being delivered in only a few individual events [Jickells and Spokes, in press; Rea, 1990, 1994]. However, the simple biological export scheme used in SUE is unlikely to gain much benefit from increased realism in this respect. Mean annual dust fluxes are therefore used.

Dettiral input to deep-sea sediments derived only from the overlying surface aeolian flux can cause $\text{CaCO}_3$ and opal preservation to be underestimated in regions of very low dust supply (particularly the Southern Ocean and much of the Pacific). Additional material derived from continental shelves and slopes and reworked by bottom currents [Bareille et al., 1994; Seidov and Haupt, 1999] may therefore play a significant role in such regions. To qualitatively account for these sources, neither of which are explicitly represented in SUE, detrital fluxes to deep-sea sediments are enhanced by 1.8 g m$^{-2}$ a$^{-1}$ [Archer et al., 1998].

4.3.1.3 Neritic sediment accumulation

Calcium carbonate in coral reefs has been estimated to have been accumulating at 7-10 Tmol C a$^{-1}$ over the last few thousand years [Milliman, 1993; Munhoven and Francois, 1996]. $\text{CaCO}_3$ is also deposited in non-reefal sediments within the neritic environment at a similar rate (~7.5 Tmol C a$^{-1}$ [Milliman, 1993]). During glacial periods, low sea level stands resulted in extensive exposure of continental shelves. Intuitively, it would therefore seem highly likely that total global $\text{CaCO}_3$ accumulation rates were lower during the LGM than at present [Berger, 1982a; Kleypas, 1997; Munhoven and Francois, 1994, 1996; Walker and Opdyke, 1995]. This presents a problem in constructing a modern simulation, since $\text{CaCO}_3$ in benthic sediments, with an adjustment time upwards of ~9 ka [Archer et al., 1998] is likely to be far from steady state following the recent deglacial transition centred around 12 ka BP. This is supported by the observations of anomalous $^{13}$C profiles in Pacific sediments [Berelson et al., 1997; Broecker et al., 1999b; Keir and Michel, 1993; Oxburgh, 1998; Stephens and Kadko, 1997]. For the purpose of generating a baseline simulation for parameter optimization, the carbonate system is assumed to be at steady state with respect to two thirds of the total estimated increase in $\text{CaCO}_3$ accumulation rate since the LGM, a net neritic sink of ~10 Tmol C a$^{-1}$. This is justified on the basis that following the rapid deglacial rise, sea level has been relatively stable for a period roughly equivalent to the e-folding time of the carbonate system.

An analogous situation might be expected to arise with respect to opal accumulation. That the global Si budget does not appear to balance at present, with an excess of loss
through deposition over dissolved inputs [Tréguer et al., 1995] supports this hypothesis. However, since processes controlling neritic opal accumulation are much more poorly understood than for CaCO₃, no significant increase in opal accumulation rate since the LGM is taken into account in the construction of the baseline scenario.

### 4.3.2 Biological productivity

With a time step for biological uptake set at 1 day, unconstrained parameter values for export production are adjusted both in isolation and in concert in the search for an ‘optimal’ solution. The rate of net PO₄ uptake by (nutrient-replete) siliceous phytoplankton \( r_{\text{PO}_4} \) is set sufficiently high so as to enable realistic seasonal nutrient draw-down in the Southern Ocean. The value for net PO₄ uptake by (nutrient-replete) non-siliceous phytoplankton \( r_{\text{PO}_4,\text{NSP}} \) is then chosen in conjunction with the CaCO₃:PO₄ export rain ratio \( (\text{CaCO}_3:\text{PO}_4) \) both to obtain a reasonable global rain field and to balance the ocean DIC and ALK budgets over the long-term. Organic matter production is assumed to be entirely in particulate form with no DOM formation. The opal:POC export ratio from siliceous phytoplankton under iron replete conditions \( (r_{\text{opal:POC}}) \) is chosen in order to obtain an oceanic inventory of dissolved Si consistent with Si:C uptake ratios reported under nutrient-replete non-siliceous phytoplankton \( (\text{nutrient-replete}) \) conditions. The value for \( r_{\text{opal:POC}} \) is chosen in order to obtain a reasonable seasonal cycle in \( [\text{H}_4\text{SiO}_4] \). Final optimized parameter values are summarized in Table 4-1. A degree of differential recycling is expected between opal and POC [Dugdale and Wilkerson, 1998] such that Si:C uptake ratios might be expected to be significantly different from the ultimate export ratio. However, the magnitude of this differential is highly dependent on assumptions made regarding grazing pressure, and can approach unity under conditions of low grazing intensity [Dugdale et al., 1995]. The value for \( r_{\text{opal:POC}} \) is therefore reasonably consistent with Si:C uptake ratios reported under Fe-enriched conditions in the Southern Ocean [Watson et al., 2000] and from incubation studies [Hutchins and Bruland, 1998] (Table 2-2).

### 4.3.3 Fe biogeochemical cycling

Initial constraints can be imposed upon basic aeolian Fe solubility in the surface ocean \( (\text{Fe}\text{solub}) \) through consideration of global dust input and estimated oceanic Fe residence times [Jickells and Spokes, in press]. Values for ‘self-scavenging’ and biogenic particulate scavenging rates \( (k_{\text{scav}}^{\text{Fe}}\text{dust} \text{ and } k_{\text{scav}}^{\text{Fe}}\text{POC}) \) are adjusted in order to obtain a reasonable \([\text{Fe}]\) field and produce surface ocean macro-nutrient concentrations (i.e., PO₄ and \( [\text{H}_4\text{SiO}_4] \)) approximately in line with observations. In the absence of any quantitative information regarding differential scavenging characteristics of the various materials comprising biogenic particulate matter, it is assumed that Fe is scavenged by POM, calcite, aragonite, and opal, in a 10:1:1:1 ratio (by molar flux density). Optimized values for Fe scavenging rate constants are summarized in Table 4-1. Aeolbian Fe solubilities range from 1% in regions proximal to dust source areas such as low and mid latitudes in the Atlantic and Indian Oceans, to 3% in remote high southern latitudes and much of the Pacific Ocean, giving a mean global solubility of 1.17%. The influence of ‘self-scavenging’ reduces effective solubilities by up to \(-70\%\) under the highest dust deposition fluxes and surface dissolved Fe concentrations. The effective global mean solubility is therefore reduced to 0.69%, slightly lower than the range 0.8-2.1% estimated by Jickells and Spokes [in press].

### 4.3.4 “Nutrient trapping”

A common problem afflicting carbon cycle models is that of ‘nutrient trapping’ [Najjar et al., 1992] — a positive feedback mechanism whereby nutrients released through the remineralization of particulate matter beneath highly productive up-welling regions are rapidly advected back to the surface, fuelling further productivity. This can lead to excessive nutrient concentrations and near-anoxic conditions at mesopelagic depths in such affected regions [Maier-Reimer, 1993; Marchal et al., 1998b; Najjar et al., 1992; Yamanaka and Tajika, 1996]. Distorted rain rates can also result in insufficient CaCO₃ preservation in the underlying sediments [Heinze and Crowley, 1997; Heinze et al., 1999].

A number of different solutions to this highly undesirable feature have been proposed. The most common of these being to partition a substantial fraction of new production into the form of dissolved organic matter (DOM), allowing nutrients to advectively ‘leak’ out of the up-welling system. This fraction can be either explicitly prescribed [Marchal et al., 1998b; Najjar et al., 1992; Paillard et al., 1993; Sarmiento et al., 1988; Yamanaka and Tajika, 1997] or derived internally as a result of grazing and cell lysis within a multi-trophic mechanistic biological scheme [Six and Maier-Reimer, 1996]. However, the DOM export fraction required in order to largely alleviate this problem is substantial, typically being more than 50% (Table 4-2).

Although biogeochemical ‘fixes’ have tended to be chosen in order to remove nutrient trapping from equatorial up-welling systems, it has been suspected that it is the representation of ocean circulation that is at fault [Yamanaka

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**Table 4-1 Parameter Values Resulting from Model Optimization**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( r_{\text{PO}_4} )</td>
<td>5.00 ( \mu )mol ( \text{kg}^{-1} \text{a}^{-1} )</td>
</tr>
<tr>
<td>( r_{\text{PO}_4,\text{NSP}} )</td>
<td>0.25 ( \mu )mol ( \text{kg}^{-1} \text{a}^{-1} )</td>
</tr>
<tr>
<td>( r_{\text{opal:POC}} )</td>
<td>0.175</td>
</tr>
<tr>
<td>( r_{\text{CaCO}_3:\text{PO}_4} )</td>
<td>0.300</td>
</tr>
<tr>
<td>( \lambda_{\text{SP}} )</td>
<td>1.0</td>
</tr>
<tr>
<td>( \lambda_{\text{NSP}} )</td>
<td>1.0</td>
</tr>
<tr>
<td>( k_{\text{scav}}^{\text{Fe}\text{dust}} )</td>
<td>0.0750 ( \text{a}^{-1} \text{(mol C m}^{-2} \text{a}^{-1})^{-1} )</td>
</tr>
<tr>
<td>( k_{\text{scav}}^{\text{Fe}\text{POC}} )</td>
<td>0.0025 ( \text{a}^{-1} \text{(mol C m}^{-2} \text{a}^{-1})^{-1} )</td>
</tr>
</tbody>
</table>
and Tajika, 1996]. Aumont et al. [1999] found that increasing meridional resolution in the Pacific can vastly improve the simulation of nutrient transport by the equatorial undercurrent (EUC) into the region of equatorial divergence and up-welling and result in very little nutrient trapping. Application of a numerical scheme with relatively low diapycnal diffusivity has also been found to lessen nutrient trapping in the equatorial Atlantic [Oschlies and Garcon, 1999]. There must be serious concerns regarding attempts made to correct for local problems in the representation of the physical ocean through what is effectively the distortion of global biogeochemical cycling. In any case, there is scant observational evidence to support the magnitude of the required DOM fraction, with some model results suggesting that DOC is unlikely to constitute more than 10% of the total organic carbon transport out of the equatorial Pacific [Aumont et al., 1999].

Nutrient trapping is muted in the Equatorial Pacific because the EUC (the primary source of up-welled nutrients) is tightly confined in the vertical so that the proportion of settling POM remineralized within it is low. Instead, nutrients are predominantly released at depths below the EUC and are thus prevented from feeding directly back into the equatorial divergence and up-welling. On this basis, an oceanographic topological ‘fix’ is employed in SUE1608. In this, the depth at which remineralization begins is artificially deepened: 400 m in the equatorial Atlantic and Pacific with 200 m in the equatorial Indian Ocean.

4.4 The ‘present-day’ in SUE1608

A modern (pre-industrial) baseline simulation is generated by running SUE1608 for 500 ka following an initial 50 ka spin-up, sufficient to bring even the slowest adjusting part of the system approximately into equilibrium (ocean $^{13}$C with an e-folding time of order 100 ka). Final model state is characterized by an atmospheric CO$_2$ concentration of 269 ppmv, slightly lower than pre-industrial estimates of 278 ppmv [IPCC, 1990], with a $^{13}$C isotopic signature of -6.2‰, some ~0.3‰ too high [Smith et al., 1999]. The reasons for the discrepancies in atmospheric composition probably lie mainly in a combination of the simplistic partitioning of biological export between just two phytoplankton groups, the representation of convective regimes at high latitudes, and lack of true seasonality. Since the primary focus of this study is on the dynamical behaviour of the system over an extended time period there is little to be gained from over-tuning model steady-state. Indeed, it would be detrimental to the ability of SUE1608 to produce a realistic glacial-interglacial response if deficiencies in physical ocean representation were to be entirely compensated for through the alteration of biogeochemical processes. Mean ocean DIC, ALK, POC, and H$_2$SiO$_4$ concentrations of 2234, 2370, 2.1, and 74.5 µmol kg$^{-1}$, respectively, are all in line with pre-industrial estimates [Tréguer et al., 1995; Yamanaka and Tajika, 1996], as is a mean ocean $^{8}$O of 0.37‰ [Yamanaka and Tajika, 1996]. Total POC export out of the euphotic zone is 8.8 GtC a$^{-1}$, similar to current model estimates of 7.5-10.0 GtC a$^{-1}$ as summarized in Table 4-2. CaCO$_3$ export is 1.3 GtC a$^{-1}$, giving a mean ocean CaCO$_3$:POC export ratio of 0.14, again consistent with estimates lying in the range 0.08-0.25. Global opal export is 137 Tmol a$^{-1}$, somewhat lower than previous model-derived estimates of 170-275 Tmol a$^{-1}$ but close to the value of ~120 Tmol a$^{-1}$ obtained by Tréguer et al. [1995] from mass balance considerations. Model parameter values are summarized in Appendix IV.

The degree of ‘success’ of this simulation in reproducing the characteristics of the modern state of the global ocean carbon cycle is now evaluated in more detail against a variety of ocean tracer, biogenic flux, and sediment compositional fields.

Table 4-2  Global New Production Estimates from Global Carbon Cycle Models

<table>
<thead>
<tr>
<th>Model class</th>
<th>$F_{np}^{POC}$ (GtC a$^{-1}$)</th>
<th>$F_{np}^{DOC}$ (GtC a$^{-1}$)</th>
<th>$F_{np}^{TOC}$ (GtC a$^{-1}$)</th>
<th>$\frac{DOC}{TOC}$</th>
<th>$F_{np}^{CaCO3}$ (GtC a$^{-1}$)</th>
<th>$F_{np}^{CaCO3}:POC$</th>
<th>$F_{np}^{opal}$ (Tmol a$^{-1}$)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>3D OGCM</td>
<td>10</td>
<td>0</td>
<td>10</td>
<td>0.00</td>
<td>0.80</td>
<td>0.08</td>
<td>n/a</td>
<td>Yamanaka and Tajika [1996]</td>
</tr>
<tr>
<td>3D OGCM</td>
<td>8</td>
<td>3</td>
<td>11</td>
<td>0.27</td>
<td>-</td>
<td>-</td>
<td>n/a</td>
<td>Yamanaka and Tajika [1997]</td>
</tr>
<tr>
<td>3D OGCM</td>
<td>9.4</td>
<td>1.7</td>
<td>11.1</td>
<td>0.15</td>
<td>-</td>
<td>-</td>
<td>n/a</td>
<td>Six and Maier-Reimer [1996]</td>
</tr>
<tr>
<td>3D OGCM</td>
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<td>0.0</td>
<td>8.9</td>
<td>0.00</td>
<td>1.80</td>
<td>0.20</td>
<td>170</td>
<td>Heinze et al. [1999]</td>
</tr>
<tr>
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<td>-</td>
<td>-</td>
<td>-</td>
<td>0.12</td>
<td>-</td>
<td>-</td>
<td>n/a</td>
<td>Aumont et al. [1999]</td>
</tr>
<tr>
<td>3D OGCM</td>
<td>7.5</td>
<td>0.0</td>
<td>7.5</td>
<td>0.00</td>
<td>1.65</td>
<td>0.22</td>
<td>n/a</td>
<td>Archer et al. [1998]</td>
</tr>
<tr>
<td>3D OGCM</td>
<td>-</td>
<td>-</td>
<td>12-15</td>
<td>0.80</td>
<td>-</td>
<td>-</td>
<td>n/a</td>
<td>Najjar et al. [1992]</td>
</tr>
<tr>
<td>3D OGCM</td>
<td>11.0</td>
<td>0.0</td>
<td>11.0</td>
<td>0.00</td>
<td>2.18</td>
<td>0.20</td>
<td>275</td>
<td>Archer et al. [2000]</td>
</tr>
<tr>
<td>ZOGCM</td>
<td>-</td>
<td>-</td>
<td>6.3-10.8</td>
<td>0.50</td>
<td>0.38-0.65</td>
<td>0.06</td>
<td>n/a</td>
<td>Marchal et al. [1998b]</td>
</tr>
<tr>
<td>Box</td>
<td>8.5</td>
<td>0.0</td>
<td>8.5</td>
<td>0.00</td>
<td>-</td>
<td>-</td>
<td>n/a</td>
<td>Rich et al. [1999]</td>
</tr>
<tr>
<td>(SUE)</td>
<td>8.8</td>
<td>0.0</td>
<td>8.8</td>
<td>0.00</td>
<td>1.3</td>
<td>0.14</td>
<td>137</td>
<td>This study</td>
</tr>
</tbody>
</table>
Figure 4-4  Ocean temperature field (°C); model results (top) compared with observations [Levitus et al., 1994c] (bottom).

Figure 4-5  Ocean salinity field (‰); model results (top) compared with observations [Levitus et al., 1994b] (bottom).
Figure 4-6  Ocean PO₄ field (μmol kg⁻¹); model results (top) compared with observations [Conkright et al., 1994] (bottom).

Figure 4-7  Ocean H₄SiO₄ field (μmol kg⁻¹); model results (top) compared with observations [Conkright et al., 1994] (bottom).
4.4.1 Ocean tracer fields

4.4.1.1 Temperature and salinity

The annual mean temperature field in the model (Figure 4-4) is generally quite realistic. However, there are several obvious deficiencies; the thermocline in all three ocean basins is too weak and high latitude temperature distributions tend to be poorly reproduced, particularly in the north Atlantic (associated with the formation of North Atlantic Deep Water (NADW)) and in the north Pacific where there appears to be inadequate up-welling and/or wintertime convective overturning. The weak thermocline structure may exacerbate nutrient trapping problems in the model, as a temperature overestimate of ~5°C (typical of much of the mesopelagic zone) will result in an overestimate in the dissolution rate of settling opal of ~50% (assuming a Q_{10} of 2.3).

Salinity fields (Figure 4-5) are much more poorly reproduced than those for temperature, with obvious problems associated with the formation and transport of NADW and Antarctic Intermediate Waters. Fortunately, with prescribed ocean circulation, salinity plays little part in controlling the global carbon cycle. Even where aqueous carbonate chemistry is moderately sensitive to salinity such as its influence on CO_{2} fugacity in the surface ocean, salinity values are restored to and thus always follow observations.

4.4.1.2 Phosphate

The ocean phosphate field is generally fairly well reproduced by the model (Figure 4-6) particularly in the upper water column (< 1000 m), although there is still some distortion of equatorial Pacific profiles associated with residual nutrient trapping. As with temperature, circulation-related problems occur at high latitudes although to a lesser degree, since remineralization processes within the water column dominate over advection in controlling vertical PO_{4} distributions. Contrary to observations there are no distinct mid-depth nutrient maxima in either the northern Indian or Pacific basins, suggesting potential deficiencies with the scheme used for POM remineralization. Lack of any explicit representation of the diagenetic alteration of particulate organic matter in deep-sea sediments may also play a role.

4.4.1.3 Silicic acid

As with phosphate, the model is reasonably successful in reproducing general trends in the H_{4}SiO_{4} field (Figure 4-7). However, again there is a failure to reproduce observed ocean interior nutrient maxima in both the Pacific and Indian basins. In addition, the degree of opal remineralization appears to be slightly too extensive in surface layers (above ~500 m), possibly associated with the weak thermocline structure as noted previously. The model also underestimates the gradient of the deep H_{4}SiO_{4} nutricline centred on the 75 μmol kg^{-1} contour. That the

Figure 4-8 Ocean dissolved O_{2} field (μmol kg^{-1}); model results (top) compared with observations [Levitus et al., 1994a] (bottom).
remineralization of POM and opal are represented and controlled in very different ways within SUE supports the notion that it is ocean structure and/or circulation that is predominantly to blame for such failures.

4.4.1.4 Dissolved oxygen

The dissolved oxygen field (Figure 4-8) is arguably the least successfully reproduced. That this should be so is perhaps not entirely surprising considering that its distribution is highly dependent on seasonal high latitude processes to delivering O$_2$ to the ocean interior, processes that are poorly-represented in the model. Despite this, [O$_2$] minima beneath the equatorial Atlantic and at intermediate depths in the northern Indian Ocean are simulated, although the northern Pacific minima is clearly too shallow and weak.

4.4.1.5 Total dissolved iron

Figure 4-9 shows the model field of total dissolved iron. Unlike other chemical ocean properties which have been routinely analysed for many years, measurements of [Fe] are a relatively recent innovation with the result that there is no comparable global data set available. The following comparisons can still be drawn between predicted and observed [Fe], although care must be taken since model values represent zonal and depth-averaged annual means while measurements are discrete in space and time:

- Fe concentrations appear to be over-estimated in the north Atlantic with the existence of a prominent mesopelagic maximum (>1.0 nmol kg$^{-1}$) whereas JGOFS data suggests a more steady increase down through the water column and not reaching a maximum (~0.7 nmol kg$^{-1}$) until a depth of 2000 - 3000 m [Martin et al., 1993].
- Relatively high Fe concentrations observed in the northeast Pacific [Martin and Gordon, 1988; Martin et al., 1989; Johnson et al., 1997] are not captured by the model with deep-water concentrations being too low. The existence of a mesopelagic maximum is predicted, however.
• The model matches observations at depths shallower than ~500 m in the equatorial Pacific [Coale et al., 1996; Gordon et al., 1997], although deeper concentrations are again underestimated.

• In the Southern Ocean there is generally good agreement between model and observed Fe concentrations at shallow and intermediate depths (< 1500 m) in the Drake Passage [Martin et al., 1990], the SE Pacific sector [de Baar et al., 1999], and the Australian sector [Sohrin et al., 2000]. However, once more, values in the deep ocean tend to be underestimated.

It is likely that SUE1608 fails to reproduce the enhanced Fe concentrations observed in the deep ocean due to the lack of any representation of the return to the ocean of dissolved Fe derived from material deposited to the sediments. This diagnostically-released Fe may be largely restricted to the deep ocean due to a constant downward scavenging pressure. If so, this omission may not significantly affect Fe supply to the surface ocean (a critical factor in controlling biological productivity).

4.4.1.6 δ13C DIC

Figure 4-10 shows the field for the 13C isotopic signature of total dissolved inorganic carbon (δ13C DIC). In the Atlantic basin model δ13C DIC distributions are reasonably similar to observations (not shown) [Yamanaka and Tajika, 1996]. However, surface values are generally too high across all three basins (responsible for the over-prediction in atmospheric δ13C). The strength of mid-depth minima underlying the equatorial Atlantic and northern Pacific are also incorrectly predicted.

4.4.2 The biological pump

Meridional distributions of annual mean nutrient concentrations and biological fluxes are shown in Figure 4-11 for each of the three ocean basins. It can be seen that observed zonally averaged surface ocean PO4 concentrations are reasonably reproduced, albeit slight too low. Observed trends in H4SiO4 concentrations with deplete conditions in much of the low- and mid-latitude world ocean but rising steeply south of the Antarctic Polar Front are also correctly predicted, although again there is a general slight under-prediction in concentrations. However, there is a complete failure to capture high [H4SiO4] values observed in the north Pacific, suggesting serious deficiencies in ocean circulation and/or biological representation in this region. The control that silicic acid availability exerts on the partitioning of POC between siliceous and non-siliceous phytoplankton in the biological model is exemplified by the export rain ratio of CaCO3:POC. For instance, in the Southern Ocean where H4SiO4 is not limiting to siliceous phytoplankton, export by this class dominates the biological system and net CaCO3:POC is extremely low.

The availability of iron exerts a number of different controls on export production. Excess PO4 remaining in the equatorial Pacific up-welling zone is a result of the high degree of Fe limitation there, while a combination of summertime Fe limitation and wintertime deep mixing act to limit annual production in the Southern Ocean and north Pacific. High concentrations of Fe present in surface waters in the mid and northern latitude Atlantic and Indian Oceans are due to their relative proximity to dust source regions, with concentrations declining sharply towards the south as the remote Southern Ocean is approached. Low dust deposition rates to the low- and mid-latitude Pacific restricts Fe availability preventing the complete utilization of PO4 advected from the equator and high latitudes. Iron also plays an important role in determining the efficiency with which H4SiO4 is utilized by siliceous phytoplankton per unit carbon fixed (2.2.3.3). For instance, while POC export derived from siliceous phytoplankton is slightly greater at the equator in the Atlantic compared to that in the Pacific, greater Atlantic Fe availability allows increased H4SiO4 utilization efficiency resulting in opal export being suppressed.

The meridional profile of (total) δ13C POC in each of the three basins is very similar, with a relatively constant degree of 13C fractionation in exported POC between -19 and -21‰ over mid and low latitudes. South of around 50°S, however, the isotopic signature decreases sharply to a value of around -28‰ by 60°S, while a less steep decrease with latitude is apparent north of 30°N, reaching a minimum of only about -25‰. These model distributions are consistent with measurements made on suspended particulate organic matter recovered from along meridional transects (not shown) [Bentaleb et al., 1998; Goering and Fry, 1994; Hofmann et al., 1999; Popp et al., 1999], sharing remarkably similar features and values. Differences do arise in the location and slope of the transition zone lying either side of the low- and mid-latitude δ13C POC ‘plateau’. This is probably simply an artifact of the low meridional resolution of SUE1608 rather than reflecting anything more fundamental regarding biological export or 13C fractionation. However, observed data do exhibit a significant degree of scatter with extreme values lying up to ±5‰ from the general trend. While this may be partly due to the high degree of spatial averaging inherent in the model it may also reflect variability in ecosystem assemblage and the physiological state of individual cells [Burkhardt et al., 1999; Hinga et al., 1994], both of which are poorly accounted for in the biological scheme employed in SUE.

There is a reasonable similarity between model-generated settling fluxes of POC and CaCO3 and observational data [Tsunoaga and Norki, 1991] (not shown). Water-column profiles of CaCO3 are well reproduced with little dissolution occurring in the water column below 500-1000 m, although observations indicate a greater degree of POC remineralization at depth than predicted by the model. Inter-regional contrasts are generally correctly simulated, with lowest POC fluxes in the ocean associated with mid-latitude gyre regions. However, problems in the representation of the equatorial Pacific up-welling zone results in a significant overestimation of POC fluxes. As CaCO3 fluxes here are of the correct magnitude, the CaCO3:POC rain ratio is then distorted.
Figure 4-11  Meridional profiles of ocean surface characteristic in each ocean basin in SUE1608. Shown (from top to bottom) are: mean annual PO4 concentrations (model values in green, observations (at 30 m depth) [Conkright et al., 1994] marked as filled triangles); mean annual H4SiO4 concentrations (model values in light blue, observations (at 30 m depth) [Conkright et al., 1994] marked as filled triangles); mean annual Fe concentrations (orange); POC export fluxes from siliceous phytoplankton (dark blue), non-siliceous phytoplankton (red), together with the total flux (black dotted); opal export (dark blue) and CaCO3 export (red) fluxes; CaCO3:POC rain ratio (black dotted); and δ¹³C of siliceous phytoplankton (dark blue), non-siliceous phytoplankton (red), together with the total flux (black dotted).
Figure 4-12  Modern steady-state distributions of surface sediment characteristics generated by SUE1608; wt% CaCO₃ (top), wt% opal (middle), and benthic foraminiferal $\delta^{13}$C (bottom) assuming the *Globigerina bulloides* $\delta^{13}$C fractionation relationship (2-63). Spatial resolution is gridded at 2.5°×2.5°.
4.4.3 Sediment composition

The composition of deep-sea sediments is controlled by a combination of benthic environmental conditions (physical and chemical) and particulate matter rain rates (in turn affected by a combination of ocean properties throughout the water column and surface ocean biological productivity). Since surface sediment properties effectively reflect an integrated state of ocean biogeochemical cycling, their global distribution can be used as a powerful diagnostic of model operation. Figure 4-12 shows predicted distributions of surface sediment CaCO₃ (as calcite) and opal content, together with benthic foraminiferal δ¹³C. Equivalent observational data (where available) is shown in Figure 4-13.

It can be seen that there is a good correspondence between predicted CaCO₃ contents and observations for many regions of the world ocean. In particular, the apparent depth of the calcite lysocline appears to be extremely well reproduced in the south Atlantic and south Pacific. However, there are a number of notable problem areas. Firstly, there is too little CaCO₃ preservation in the equatorial Pacific. This is most likely a result of an under-predicted CaCO₃:POC rain ratio, since the poor representation of biogeochemical cycling in this region produces excessive POC export which in turn drives enhanced CaCO₃ dissolution in the underlying sediments. This problem is not specific to SUE1608 and is apparent in 3D OGCM carbon cycle models [Heinze and Crowley, 1997; Heinze et al., 1999], although nutrient trapping tends to be much more localized in these. Similar arguments...
apply to the equatorial Atlantic. The other major areas of concern are the Indian Ocean and northern mid latitude Atlantic where the zonally-averaged nature of ocean circulation tends to overly-restrict nutrient supply and thus potential CaCO₃ export. That these two regions are both characterized by high dust deposition fluxes suggests that the influence of Fe availability on H₂SiO₄ utilization efficiency (2.2.3.3) may potentially be overstated, distorting the POC partitioning between the two phytoplankton groups and with it the net CaCO₃:POC rain ratio. The aragonite lysocline is predicted to lie at a depth of around 2000-3000 m in the Atlantic and <1000 m in the Pacific, both consistent with observations [Balsam, 1983; Berger, 1977].

Global distributions of core-top opal content are also generally reasonable. However, little opal accumulation is predicted for the Indian Ocean contrary to observations, whereas opal contents in the equatorial Atlantic and north Pacific are slightly over-estimated. The only other area of significant mismatch concerns the Southern Ocean, where a maximum in opal content occurs in the southernmost grid point region (centred on 62.5°S) in contrast to observations of a relatively tightly constrained circumpolar ‘belt’ of maximum opal accumulation further to the north at around ~55°S. This is likely to be primarily an artifact of the low meridional resolution in this region employed in the model.

The distribution of the benthic foraminiferal calcite isotopic signature (δ¹³C_{foram}) in the model is also shown (Figure 4-12c). A trend is visible across the ocean with maximum values of -0.6 ‰ in the north Atlantic, through -1.1 ‰ in the sub-polar Antarctic, to less than -1.5 ‰ in parts of the northwestern Pacific. This oceanic trend is comparable to that reconstructed from the analysis of deep-sea sediment cores [Matsumoto and Lynch-Stieglitz, 1999; Michel et al., 1995], although a few tenths of a per mill less in the total range spanned. It should be noted that due to vital differences between species used for observational analysis and those represented in the model, absolute values are not directly comparable.

4.5 An improved representation of the Southern Ocean and global Si cycling

One of the most noticeable deficiencies resulting from the ocean configuration adopted in SUE1608 was in the inability of the model to resolve the circumpolar opal maximum observed in the Southern Ocean. There is a danger that any significant failure in correctly representing what is the primary opal sink in the world ocean might distort the dynamics of the global silica cycle in the model and thereby degrade the applicability of SUE1608 to many of the mechanisms for glacial-interglacial variability. In addition, use of a single grid point region covering the entire polar Southern Ocean makes any attempt in a realistic representation of variability in sea ice extent (thought to be a key mechanism driving CO₂ changes [Stephens and Keeling, 2000]) problematic. An alternative configuration is therefore introduced to allow more detailed analysis of the global silica cycle and of mechanisms for glacial-interglacial change located in the Southern Ocean.

The ocean configuration of the improved model is derived from Bern 2D ZOOGCM [Marchal et al., 1998a; Stocker and Wright, 1996] as previously for SUE1608 (4.2.1). However, rather than amalgamating the two zonal regions in the parent model south of 55°S these are now kept discrete. Meridional resolution is further enhanced by sub-dividing these two 7.5° zones into sub-zones of width 2.5°. Ocean circulation in these regions is derived by assuming that each of the sub-zones is characterized by the same vertical velocity as its parent zone. Meridional velocities across the boundaries separating the sub-zones are obtained by linearly interpolating between velocities at 55°S and 62.5°S in the Bern 2D circulation, and extrapolating south of 62.5°S. A total of six zonal regions now replaces the single zone south of 55°S in SUE1608 – with a total of 21 grid points the new model is designated ‘SUE2108’. The same parameter values as optimized for SUE1608 (4.3.2) are adopted, resulting in a similar baseline model state.

4.5.1 Sedimentaryopal distributions

Figure 4-14a shows the global distribution of surface sediment opal content in SUE2108. It can be seen that a distinct circumpolar belt of maximum opal content is now resolved. The meridional location of this feature is centred on ~60°S with maximum opal contents reaching around 75 wt%, both reasonably consistent with observations [Archer, pers com; Broecker and Peng, 1982]. Preservation efficiencies in these high opal content sediments have been recently estimated at some 6.8% [DeMaster, 2000], comparable to model predictions of 7-9% (Figure 4-14c). There is an apparent southerly offset (~3-4°) in the latitude of maximum opal content relative to the location of peak surface ocean biogenic opal export rates (not shown). This is a result of the trend of increasing H₂SiO₄ concentrations at intermediate and shallow depths (< 4000 m) with southerly latitude (Figure 4-7), producing a similar trend in the preservation efficiency within the water column (Figure 4-14b) and displacing southwards peak opal fluxes reaching the sediment surface. Near to the Antarctic continental shelf, model sediment preservation efficiencies of 5-7% are also comparable to observational-based estimates in the Ross Sea of around 6% [DeMaster, 2000]. A consequence of the improved representation of the Southern Ocean silica cycle is a slight reduction in equatorial and north Pacific opal contents, bringing them more in line with observations. Primary observed variability in sedimentary opal distributions not captured by the model is now intra-zonal, beyond the ability of a zonally-averaged model to prognostically generate.

4.5.2 Re-evaluation of the opal diagenesis module

Previously, the opal diagenesis module was validated with the aid of a simple box model (3.2.3.5). Re-validation of this
Figure 4-14 Modern steady-state distributions generated by SUE2108 of: (a) sediment surface wt% opal, (b) opal preservation efficiency within the water column, and (c) opal preservation efficiency within the sediments. Spatial resolution is gridded at 2.5°x2.5°.
Figure 4-16 Combined response of the opal diagenesis model within SUE2108, shown by small filled circles colour-coded by ocean region; Southern Ocean (blue), Atlantic Ocean (green), Indian Ocean (yellow), Pacific Ocean (red). Sediments lying at depths shallower than 1000 m are excluded.
Figure 4-17  Combined response of the opal diagenesis model within SUE2108 shown by small filled circles colour-coded by ocean region; Southern Ocean (blue), Atlantic Ocean (green), Indian Ocean (yellow), Pacific Ocean (red). Sediments lying at depths shallower than 1000 m are excluded. Also shown is the validation data, indicated by larger filled symbols; squares - McManus et al. [1995], diamonds - Archer et al. [1993], triangles - Martin et al. [1991]. The thick dashed grey line in (d) indicates the estimated trend of Archer et al. [2000].
biogeochemically critical module is now carried out with SUE2108. Global functional (steady-state) relationships exhibited by the opal diagenesis module are displayed in Figure 4-16, with results from the four distinct ocean basins now differentiated. General trends are similar to before (3-11), although increased spatial resolution leads to trends being slightly better constrained with fewer prominent hiatuses. However, when model output is contrasted with the validation data set (Figure 4-17) the performance of the opal diagenesis module appears to be significantly better than suggested by the original analysis (3.2.3.5). Most striking is that the observed trend of opal burial flux with rain flux (a) is now extremely well reproduced whereas before, the slope was underestimated by a factor of >2. Interestingly, although the observational data delineating this trend is derived from cores mainly located in the eastern equatorial and temperate northeast Pacific [Archer et al., 1993; McManus et al., 1995], the matching model results come from equatorial Atlantic and Indian Ocean grid points. In the model both these regions are characterized by relatively high aeolian detrital fluxes to the sediments with low CaCO$_3$ contents. Such conditions are similar to those found at the core locations in the eastern equatorial and temperate northeast Pacific [Archer et al., 1993; McManus et al., 1995]. Thus, while there is a poor geographical correspondence between model regions and core locations, there is a much close match on the basis of prevailing biogeochemical conditions (which the diagenesis module appears to be correctly responding to). Observed relationships between both opal content and asymptotic $[\text{H}_3\text{SiO}_4]$ with rain flux (b) and (d), respectively, and also asymptotic $[\text{H}_2\text{SiO}_4]$ with opal content (c) are well reproduced as before. Although the observed trend of asymptotic $[\text{H}_4\text{SiO}_4]$ with dissolution flux (f) is slightly improved, it is obvious both from this and from the trends of dissolution flux with opal content (c) that dissolution fluxes are still somewhat over-predicted. Despite the continued existence of apparent deficiencies in several of the functional relationships characterizing opal diagenesis, behaviour critical to the global silica cycle such as the degree of fractional burial as a function of the flux of biogenic opal is still captured (Figure 4-18).

### 4.6 Summary

It is clear that significant deficiencies in the representation of global biogeochemical cycles arise out of zonalization of ocean circulation and structure. However, in spite of this SUE1608 is generally successful in capturing the characteristics of most of the key distinct biogeochemical provinces in the world ocean. Furthermore, SUE is designed to capture the dynamics of the carbon cycle on glacial-interglacial time scales, for which failure to accurately simulate the modern state is not necessarily a strict pre-requisite. Indeed, for long-term dynamical realism it is probably better to retain deficiencies arising from problems in the physical ocean representation rather than compensate for them by distorting biogeochemical cycling.
5.1 Introduction

Ice core records reveal that the concentration of CO₂ in the Earth's atmosphere (xCO₂) has undergone substantial fluctuations over the course of the late Quaternary [Petit et al., 1999]. That the climatic system in general has undergone parallel excursions, with glacial periods characterized by extensive northern hemisphere ice sheets occurring contemporaneously with low xCO₂ suggests that there is a fundamental causal link between the two. Should changes in xCO₂ be at least partly responsible for driving the global climate system there would be obvious repercussions for our predictions for the coming decades of the radiative forcing effects due to anthropogenic CO₂ emissions. Even if over the glacial-interglacial cycles atmospheric composition responded in a predominantly passive manner, then elucidation of the mechanisms involved is still vital to our understanding of key feedbacks operating in the present-day Earth system [Falkowski et al., 2000].

The sheer diversity and biogeochemical scope of mechanisms purporting to explain low glacial levels of CO₂ has made any comparative assessment within a single framework problematic, with models often customized around a single process. Hypotheses range from relatively simple changes in surface ocean biological productivity [Knox and McElroy, 1984; Martin, 1990; Rich et al., 1999; Sarmiento and Toggweiler, 1984], ocean circulation [Keir, 1988; Siegenthaler and Wenk, 1984; Toggweiler, 1999], and changes in the storage on continental shelves of nutrients and CaCO₃ [Berger, 1982a; Broecker, 1982; Opdyke and Walker, 1992; Shaffer, 1990], through subtle effects on deep-sea sediments exerted by changes in the particulate composition of biogenic material exported out of the euphotic zone [Archer and Maier-Reimer, 1994], to more exotic mechanisms such as transients in ocean pH driven by rapid manganese depositional events [Mangini et al., 1991] and CH₄ out-gassing [Loehle, 1993]. However, of the mechanisms forwarded to date, when taken in isolation all fall short of simultaneously meeting constraints dictated by the various marine, terrestrial, and ice core paleoclimatic records [Broecker and Henderson, 1998; Holligan and Robertson, 1995]. It is thus becoming increasingly obvious that in spite of the perhaps aesthetic desirability of a single mechanism yet to be discovered and able to completely solve the mystery, the solution to the observed glacial-interglacial variability in xCO₂ almost certainly lies in a combination of processes operating during the late Quaternary. The problem then lies in determining the important mechanisms involved and constraining their relative overall contribution to the dynamics of the system. A series of potentially important mechanisms will therefore be characterized in isolation within the same model framework (SUE) and then combined together in a ‘best guess’ scenario. Although a number of comparative studies have been carried out in the past, these all have shared a common approach, of contrasting two steady states of the system: one characterized by modern (pre-industrial) boundary conditions and the other by those thought to be representative of the Last Glacial Maximum (LGM). Partly as a consequence of this, many of these studies (particularly those based around simple box model representations of the ocean) have concluded that permutations which give rise to a simile of glacial atmospheric and ocean chemistry are relatively easy to construct [Hausman and McElroy, 1999; Keir, 1988; Marino et al., 1992; Toggweiler, 1999]. However, recent work based around a comprehensive OGCM-based global carbon cycle model has suggested that we are still far from solving the problem [Archer et al., 2000]. In an attempt to increase the utilization efficiency of information available from both ice cores and the paleoceanographic record in constraining the operation of the global carbon cycle, mechanisms are tested on a dynamical (i.e., time-stepping) basis. Changes in the boundary conditions of the global carbon cycle are reconstructed for multiple glacial-interglacial cycles so that the dynamical evolution of the system may be followed over that entire period. Special emphasis will be placed on the role of the Southern Ocean, particularly with respect to the inception of deglacial transitions in the system.
5.2 Evidence for glacial-interglacial variability of the global carbon cycle

The primary records of past change in the global carbon cycle over the course of the late Quaternary comes from ice cores. Material (both solid and gaseous) contained within the crystalline structure of accumulating ice in both low latitude glaciers [Thompson et al., 1995] and high latitude ice caps [Edwards et al., 1998; Jouzel et al., 1995; Petit et al., 1999; Smith et al., 1999] present us with a proxy record of past climate. While cores located in low latitude glaciers rarely extend back even as far as the LGM, the greater ice thickness afforded by high latitude ice caps generally allows a much longer record to be obtained, with records obtained to date spanning almost 250 ka in Greenland [Johnsen et al., 1997], but back as far as 420 ka BP in Antarctica [Petit et al., 1997, 1999]. With respect to the past state of the global carbon cycle the most important single indicator is the concentration of CO2 held within bubbles trapped within the ice. Such bubbles start to form in the firn relatively near the surface, effectively recording a snapshot of atmospheric composition at the time of occlusion [Deschger et al., 1984]. However, Greenland ice contains high concentrations of aeolian carbonate-rich dust, which can chemically denature over time thereby contaminating trapped air samples with CO2 produced in situ [Indermühle et al., 1999; Smith et al., 1997]. Therefore they cannot be relied upon as indicators of a changing carbon cycle. In contrast, the low carbonate content of Antarctic ice suggests that cores recovered there will record past CO2 concentrations with much greater fidelity [Smith et al., 1997]. The ice core record from Vostok (78°S, 106°E, elevation 3,488 m) covering the last ~400 ka [Petit et al., 1999] will be used to provide the model target for glacial-interglacial variability in xCO2.

A second property of atmospheric composition recorded in ice cores and of direct relevance to the state of the global carbon cycle at any point in time is the stable isotopic composition of CO2 (δ13CO2). The ~27 ka long record from Taylor Dome [Smith et al., 1999] will be used to provide the model target for variability in this. Visual inspection suggests that the age scales constructed for the Vostok and Taylor Dome cores do not exactly correspond. A simple linear age transformation (reduction in gas age of 7.5%) is therefore made to the Taylor Dome CO2 record so that it matches that at Vostok over the most recent deglacial transition (Figure 5-1a). As a result of considerable analytical difficulties inherent in measuring isotopic composition of ice core δ13CO2 [Lenzenberger et al., 1992; Smith et al., 1999] there is a considerable degree of uncertainty in the values obtained. Confidence in many of the major features of this record can be improved, however, through reference to estimates of past (atmospheric) isotopic composition made by an entirely independent method, based on preserved samples of the shrub Atriplex confertifolia [Marino et al., 1992]. The 14C-derived age scale for A. confertifolia is adjusted so that major transitions are in phase with recorded events at Taylor Dome, as shown in Figure 5-1b. It can be seen that while the magnitude of some of the events disagree, many of the general features are held in common between the two records. In particular, there is a pronounced negative δ13C anomaly during the initial stages of Termination I, with a second one around the time of the Younger Dryas (~12.8 ka BP [Blunier et al., 1997]). The presence of this first anomaly is also supported by planktonic foraminalifer δ13C records which exhibit contemporaneous features, similar in magnitude to cores located between the Antarctic polar and subtropical fronts in the Southern Ocean [Ninemmann and Charles, 1999] but slightly more muted than cores from the eastern tropical Pacific and tropical Atlantic [Curry and Crowley, 1987; Shackleton et al., 1983].

Another effective integrator of the state of the global carbon cycle for which there is extensive (paleoceanographic) information available concerns the CaCO3 lysocline transition zone. The CaCO3 content of benthic sediments is primarily a function of deep ocean pH together with particulate matter rain rates. Changes in the shape and depth of the CaCO3 lysocline transition zone, therefore, represents a powerful constraint upon the operation of the majority of mechanisms forwarded to explain the observed variability in xCO2. Sediment cores located in the Pacific Ocean indicate that CaCO3 was more abundant during glacial than interglacial times there; LGM time-slice reconstructions show a slightly greater areal extent of CaCO3-rich sediments [Cattabig et al., 1998] while lysocline sections detail glacial age lysolines lying of order 500 m deeper [Berger, 1978, 1982b; Farrell and Prell, 1989, 1991; Karin et al., 1992]. In contrast, distribution patterns of sediments in the Atlantic basin exhibit significantly lower CaCO3 abundances than during glacial periods [Balsam and McCoy, 1987; Cattabig et al., 1998]. This is supported by estimates made of the location of the calcite lysoline during glacial periods which suggest it was some 200-700 deeper [Berger, 1968; Crowley, 1983], although some estimates put this shoaling as large as 1500 m or more in the western north Atlantic [Balsam, 1983]. Variability in the depth of the carbonate compensation depth (CCD) appears to be generally much more muted when compared to the response of the lysoline in either basin [Balsam, 1983; Farrell and Prell, 1989]. Thus, not only the depth of the lysoline but the shape of the entire transition zone must be altering in response to perturbations of the global carbon cycle. That some mechanisms (such as whole-ocean changes in pH) will tend to alter the depth of both the lysoline and CCD to a similar extent while others (such as changes in the CaCO3:POC rain ratio [Archer and Maier-Reimer, 1994]) tend to shift lysoline depth whilst leaving the location of the CCD relatively invariant, may further aid in the elucidation of the key mechanisms involved.

There is a cornucopia of other paleoceanographic proxies reflecting changes in the earth system; for instance, in the relative abundance of solid sediment constituents (calcite, aragonite, opal, detrital material, organic matter), the isotopic (δ18O, δ13C, δ14C, δ15N) and Sr/Sr, 238U/230Th) and chemical (Cd/Ca, Ge/Si, and Mg/Ca ratios) composition of these solid components, together with phytoplankton and zooplankton species abundance, marine and terrestrial biomarkers, the degree of shell fragmentation,
and varied burial fluxes (³He, Ba, Fe, Al, Zn, authigenic U). However, many of these depend on individual processes operating with the ocean not accounted for in the model and can be more localized in scope than the resolution of SUE1608 reasonably allows for. The implications of such proxies for this present study will therefore only be discussed where especially relevant to a particular mechanism or region of glacial-interglacial change.

5.3 Uncertainties in model response to perturbations of the carbon cycle

Recent studies have questioned whether certain types of model can be relied upon to correctly predict the response of atmospheric composition to a perturbation applied to the system. In particular, attention has focussed on whether simple box-type models might over-estimate the sensitivity of xCO₂ to physical and biological changes located at high latitudes. The results of two independently-developed indices for the relative importance of low vs high latitude regions in controlling xCO₂ indicate a fundamental divide separating box models from OGCMs [Archer et al., in press; Broecker et al., 1999a]. It is important to establish what class of response the models developed from use in this present study fall into, before either SUE1608 or SUE2108 can be wholly relied upon to critically assess mechanisms for glacial-interglacial change.

5.3.1 The ‘Harvardton Bear Equilibrium Index’

Using an index (the ‘Harvardton Bear Equilibrium Index’, or ‘HBEI’) first devised by Bacastow [1996], Broecker et al. [1999a] found that global carbon cycle models based around a box-type representation of the ocean scored considerably lower (~0.11 for 2- and 3-box models and around 0.2 for ‘multi-box’ models) than those based around 3D OGCMs (up to 0.32). In this index (the ‘Warm Surface’ variant), higher values represent a greater relative equilibrium response of xCO₂ to a perturbation of the low latitude surface ocean. It was concluded from this that box models significantly overestimate the importance of high latitude
regions; the implication being that the results of early studies based upon such models, which suggested that low glacial xCO₂ is explicable through changes in Southern Ocean circulation and/or biological productivity, might be in error [Broecker et al., 1999a]. Somewhat worryingly, the parent model from which both SUE1608 and SUE2108 derive their ocean structure and circulation, the Bern 2D ZOGCM [Stocker and Wright, 1996], scored an HBEI value of just 0.14, putting its response into a similar class to (and in fact below) the box models. Rather surprisingly, however, SUE1608 gives an HBEI score of just under 0.39, making atmospheric composition slightly less sensitive to high latitude perturbations even than in OGCM-based models. This apparently anomalous behaviour of the Bern 2D model is now investigated.

A new baseline model is constructed (designated ‘SUE1608’), taking the same physical structure and advective field as SUE1608 (outlined in 4.2) but otherwise configured following Marchal et al. [1998b], the main features being: 18 time steps of 20 days each with no seasonality, CO₂ air-sea gas exchange with a uniform transfer rate of 0.067 mol m⁻² a⁻¹ ppmv⁻¹, no sea ice cover, new production derived by restoring ocean surface [PO₄] towards observations at 30 m depth [Conkright et al., 1994] on a time scale of 100 days with export production split 50:50 between DOM and POM phases, uniform vertical and horizontal eddy diffusivities of 0.2 cm² s⁻¹ and 10⁻⁶ cm² s⁻¹, respectively, and with the system run entirely ‘closed’ (i.e., no sediment burial or weathering inputs). The HBEI value so obtained is 0.21, a little higher than that reported by Broecker et al. [1999a] for the full Bern 2D model, probably largely a result of remaining differences in model resolution and biogeochemical schemes. With total export production fixed, a number of changes are made to the details of ocean mixing in SUE1608’ and the HBEI value recalculated. These are summarized in Table 5-1.

From this sensitivity analysis it can be seen that the details of vertical and horizontal diffusivity have a relatively minor effect on the HBEI score (±0.04). However, there is a strong dependence on the details of high latitude convection, with the introduction of just 5% mixing to a stratified high latitude ocean surface almost halving the HBEI score. This suggests that much of the variability in values reported by Broecker et al. [1999a] might be attributed to differences in the representation of convective mixing. Indeed, whether mixing takes place seasonally or uniformly all year around (for the same mean annual rate) can account for much of the difference between the seasonal Hamburg [Maier-Reimer, 1993] and the annual circulation Princeton [Murnane et al., 1999] 3D OGCMs. Furthermore, the low HBEI value of the ‘PANDORA’ box model [Broecker and Peng, 1986] can be almost entirely explained by the relatively thick surface layer (~450 m) used. Other factors (not shown) such as the introduction of a wind speed dependency on air-sea CO₂ gas exchange, the presence of sea ice cover, and the absence of DOM production (equivalent to exacerbating nutrient trapping in equatorial up-welling regions) have relatively little effect.

<table>
<thead>
<tr>
<th>Model details</th>
<th>HBEI value</th>
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<tbody>
<tr>
<td>SUE1608’ (default)</td>
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</tr>
<tr>
<td>SUE1608’ - enhanced vertical diffusivity¹</td>
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<tr>
<td>SUE1608’ - enhanced (200×10⁻⁶ cm² s⁻¹ at depth) horizontal eddy diffusivity</td>
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<td>SUE1608’ - 10% intensity convective adjustment</td>
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</tr>
<tr>
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<tr>
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<tr>
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<tr>
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</tr>
<tr>
<td>SUE1608’ - depth of all convective adjustment completely restricted (i.e., none)</td>
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</tr>
</tbody>
</table>

¹ Following Weaver and Sarachik [1991]
5.3.2 The ‘Archer Abiotic $x$CO$_2$’ test

In a contemporary study, David Archer investigated the potential bias that simpler ocean models might exhibit [Archer et al., in press] in the relative strength of regional control on atmospheric composition. Various global carbon cycle models were run in an ‘abiotic’ mode and the steady state concentration of CO$_2$ in the atmosphere noted. A similar trend was apparent to that found by Broecker et al. [1999a], whereby 3-box and ‘multi-box’ models tended to cluster at one end of the scale with an abiotic $x$CO$_2$ value in the range $\sim$220-230 ppmv, while most 3D OGCMs exhibited high values in the range 250-290 ppmv. Archer et al. [in press] deduced that it was low latitude vertical diffusivity in 3D OGCMs (not present in box models) that went towards overcoming the control exerted by deep water formation at high latitudes. They therefore concluded, similarly to Broecker et al. [1999a], that the importance of high latitudes in glacial $x$CO$_2$ draw-down (such as through Southern Ocean Fe fertilization) deduced from box models has been overstated. However, contrary to the results of the HBEI test, abiotic $x$CO$_2$ exhibited by the Bern 2D model (289 ppmv) places it firmly into the same group as the 3D OGCMs, supported by tests made with SUE1608 (287 ppmv). The factors controlling the value of this second index are also further investigated.

SUE was configured following a number of different published configurations, detailed in Table 5-2. The results of the abiotic $x$CO$_2$ test closely follow those of Archer et al. [in press]. Small ($\leq$7 ppmv) differences do arise, possibly due to differences in the choices made for the carbonate dissociation constants. With the exception of the 3-box model (whose representation of only two surface boxes is a little too crude to translate to the real world), latitudinal and longitudinal boundaries are now assigned to each surface ocean region, chosen in order to both retain the surface areas of the original model and to be generally consistent with regional descriptions given of the surface boxes. SSTs are derived from Levitus et al. [1994c] using these boundaries (see 4.2.2) and the tests re-run. It can be seen (Table 5-2) that use of more realistic SSTs has a dramatic effect on multi-box model abiotic $x$CO$_2$ values, with that of ‘PANDORA’ now comparable to most (depth-coordinate) OGCMs, while ‘CYCLOPS’ only just falls short of isopycnic OGCMs [Archer et al., in press]. This suggests that the apparent divide between box and OGCM-based carbon cycle models dictated by this test may be partly an artefact of unrealistically low mean SSTs adopted in the original model definitions.

5.3.3 Implications for this present study

Under both the ‘HBEI’ and ‘Abiotic $x$CO$_2$’ tests of relative inter-regional control on atmospheric composition SUE1608 (as does SUE2108) scores similarly to carbon cycle models based upon 3D OGCMs. That the HBEI score is slightly on the high side suggests that the response of $x$CO$_2$ to perturbations occurring at high latitudes in SUE1608 may, if anything, be underestimated. There is thus little danger of seriously overstating the importance of high latitudes in this present study. In light of the strong control exerted by convective mixing regime on the sensitivity of the system to perturbations, it is important that convective adjustments are prevented from co-varying in order that the response of the atmosphere to specific mechanisms for low glacial $x$CO$_2$ might be isolated.

5.4 Model evaluation of mechanisms for glacial-interglacial $x$CO$_2$ variability

A variety of mechanisms purporting to explain the observed glacial-interglacial variability in the concentration of atmospheric CO$_2$ are now evaluated. However, there are several aspects of the operation of the global carbon cycle over the late Quaternary for which SUE1608 is not entirely suited for investigating. Changes in the balance between nitrogen supply (through its fixation from the atmosphere) and losses (through denitrification) are suspected to play an important role [McElroy, 1983; Shaffer, 1990]. However, the lack of explicit representation of the oceanic nitrogen cycle in SUE precludes such analysis. In addition, with the exception of the Atlantic overturning circulation, changes in ocean circulation will not be considered further in any detail.

One of the aims of the approach taken here is to consider the dynamical evolution of the global carbon cycle over the entirety of several glacial-interglacial cycles. For assessment of system response, the Vostok ice core provides a target record of fluctuations in the concentration of atmospheric CO$_2$ over the last $\sim$400 ka [Petit et al., 1999]. However, in

<table>
<thead>
<tr>
<th>Model</th>
<th>Number of boxes - original configuration</th>
<th>SUE configuration - (as columns=)(layers)</th>
<th>$x$CO$_2$ (ppmv); original SSTs</th>
<th>$x$CO$_2$ (ppmv); adjusted SSTs</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-box</td>
<td>3</td>
<td>2x2</td>
<td>218</td>
<td>n/a</td>
<td>Sarmento and Toggweiler [1984]</td>
</tr>
<tr>
<td>PANDORA</td>
<td>10</td>
<td>8x3</td>
<td>224</td>
<td>279</td>
<td>Broecker and Peng [1986]</td>
</tr>
<tr>
<td>CYCLOPS</td>
<td>13</td>
<td>6x3</td>
<td>230</td>
<td>249</td>
<td>Keir [1988]</td>
</tr>
<tr>
<td>Bern 2D ZOGCM</td>
<td>406</td>
<td>29x14</td>
<td>285</td>
<td>288</td>
<td>Stocker and Wright [1996]</td>
</tr>
</tbody>
</table>
order to generate a synthetic atmospheric record the model
must be informed of changes in boundary conditions (e.g.,
physical ocean surface conditions, dissolved chemical or
aerolain inputs) over a comparable period, i.e., the model
must be continuously ‘forced’ for the duration of the
simulation run. With the possible exception of the use of
benthic oxygen isotopes as a proxy for sea level change, there
is no continuous 400 ka record fully describing any suspected
forcing of the system. Indeed, for many glacial-interglacial
changes in boundary conditions such as SST, terrestrial
storage, or sea ice extent, there exist paleoclimatic
reconstructions for only isolated periods (‘time slices’) [Adams et al., 1990; CLIMAP, 1984]. Even then, the
magnitude of regional change is often highly controversial
[Crosta et al., 1998b; Crowley, 1995, 2000]. Forcings
(externally imposed changes in boundary condition) are
therefore devised with the aid of continuous records
sampling at least the last 400 ka which can taken to be
first-order proxies for the timing and rate of forcing
variability over this period. The absolute magnitude of
change spanning the last deglacial transition (i.e., 19–0 ka
BP) is taken directly from time slices reconstructed for
modern (pre-industrial) and glacial (LGM) conditions.
Model forcing over the complete 400 ka interval is then
derived by linearly transforming the proxy signal so that its
magnitude at 0 and 19 ka BP corresponds to the respective
values given by the two time slices. Forcing signals are
applied to the model at a resolution of 1 ka but subsequently
(lineally) linearly interpolated to an annual time step. As a
consequence, SUE is not particularly suited for detailed
investigation of millennial-scale changes such as
Dansgaard-Oeschger [Dansgaard et al., 1982] and Heinrich
[Bond et al., 1992] events, which will not be considered
further in this study. In light of the phase differences
exhibited by climatic changes as deduced from ice cores
taken from Greenland and Antarctica [Bunier et al., 1997,
1998; Broecker and Henderson, 1998; Kim et al., 1998; Sowers
et al., 1991], it may not always be appropriate to use the same
forcing template for both hemispheres. In such situations
different proxy templates are assigned to each polar region.
The relative influence of these signals is then diminished
away from each pole according to a pair of weighting
functions

$$
\gamma^N_{(\omega)} = \left( \cos \left( \frac{90 - \text{lat}}{2} \right) \right)^2 \quad (5-1 \ a)
$$

$$
\gamma^S_{(\omega)} = \left( \cos \left( \frac{90 + \text{lat}}{2} \right) \right)^2 \quad (5-1 \ b)
$$

where \( \gamma^N_{(\omega)} \) and \( \gamma^S_{(\omega)} \) are the weighting factors for changes in
boundary conditions of the Northern Hemisphere (NH) and
Southern Hemisphere (SH), respectively, both as a function
of (northern) latitude (lat).

In the model investigations that follow, following a spin-up
of 50 ka (sufficient to bring the sediment system largely into
steady state), SUE1608 is run for a total of 500 ka, a period
over which it is informed by a variable boundary condition
(the model ‘forcing’). Although the Vostok CO2 record
extends back only just beyond 400 ka BP [Petit et al., 1999],
the model is forced over the entire 500 ka run length. This
allows the initial 100 ka of model run to be treated as an
additional spin-up period, the aim of which is to allow the
model to relax towards a quasi-steady state (the long-term
mean about which the system oscillates over the course of
the glacial-interglacial cycles). Indeed, it is probably prudent
to regard half of the entire model run in this manner
(i.e., up until 250 ka BP), leaving the response to 3 individual
deglacial transitions and 2 glacial inceptions available for
comparison with observations. To avoid contaminating the
direct effects of the mechanisms being tested through
secondary perturbations arising through changes in
non-advective ocean circulation to which the system is
apparently extremely sensitive (see 5.3.3), convective regimes
produced by the steady-state baseline model are applied and
held invariant.

As a first-order assessment, four key indicators of the state
of the global carbon cycle will be considered: the
concentration of atmospheric CO2 together with its \(^{13}C\)
isotopic signature and the shape evolution of the calcite
lysocline in both the Atlantic and Pacific basins. All these
records are presented for the last 400 ka (with the exception
of \(^{13}C\)CO2, for which observational data is currently only
available back to \(~25\) ka BP [Smith et al., 1999]). The calcite
lysoclines are reconstructed with the aid of a series of
synthetic sediment cores separated in ocean depth by 100 m
(see 3.3.2.3); one set located in the south Atlantic and the
other in the south Pacific Ocean (both centred on 23.75°S).

5.4.1 Sea level

In response to the waxing and waning of ice sheets over
the course of the late Quaternary there was significant associated
variability in sea level height. Of all the processes suspected
to exert any significant perturbatory effect on the global
carbon cycle over this period, only past changes in sea level
can be reconstructed with any accuracy. However, while
these changes are reliably recorded by proxy indicators such
as coral terraces [Adkins et al., 1998; Fairbanks, 1989;
Lambeck and Nakada, 1992; Stein et al., 1993] and
transgressions of shallow marine environments [Yokoyama et
al., 2000], these are only primarily available for events
surrounding the two most recent glacial terminations. As an
alternative, changes in the oxygen isotopic composition of
benthic foraminiferal calcite has often been used as a proxy
for global ice volume and thus for sea level [Munhoven and
Francois, 1994, 1996; Walker and Opdyke, 1995].

There are three distinct effects on the (oceanic) global
carbon cycle arising from sea level change:

- Since the solubility ratio of CaCO3 is a sensitive function
  of pressure (Appendix I), glacial reduction in the ambient
  hydrostatic pressure at the surface of deep-sea
  sediments will drive enhanced CaCO3 preservation and
  thus lead to the removal of DIC and ALK from the
  ocean in a 1:2 ratio, driving xCO2 higher.
- During glacial periods of lower ocean volume, dissolved
  species such as DIC, ALK, and nutrients will all become
  more concentrated in the ocean. Increasing DIC and
Figure 5-2  Effects on the global carbon cycle of glacial-interglacial variability in sea level. Shown are; (a) the forcing signal (normalized to a value of unity at the LGM); (b) model \( xCO_2 \) response (red line) compared to the Vostok ice core record [Petit et al., 1999] (grey line with data points); (c) model \( \delta^{13}C_{\text{CO}_2} \) response (red line) compared to the Taylor Dome ice core record [Smith et al., 1999] (grey line with data points); (d) and (e) the response of the calcite lysocline in the (south) Atlantic and (south) Pacific basins, respectively.
ALK in a 1:1 ratio has the effect of driving $xCO_2$ up. However, complicating this response are further influences on $xCO_2$ related to increased export production and sedimentary opal preservation during glacial periods, both driven by the increased nutrient availability.

- Lastly, there is the effect of generally higher ocean salinity during glacials. This manifests itself (at least in terms of atmospheric composition) almost entirely through its influence on aqueous carbonate equilibria in the surface ocean, with an increase in salinity of 1%0 producing a typical increased in $CO_2$ fugacity ($fCO_2$) of order 10 ppmv. The control that glacial-interglacial changes in sea level may have exerted on atmospheric composition is now tested. The SPECMAP stacked $\delta^{18}O$ record [Imbrie et al., 1984] is used as a signal template for the reconstruction of sea level change over the last 400 ka. The magnitude of this signal is scaled by assuming that sea level just prior to Termination I was 117 m lower than at present [Fairbanks, 1989]. Since ocean volume is calculated directly from prescribed sea level in SUE and dissolved constituents in the ocean are considered inherently in mass unit terms, changes in oceanic tracer concentrations are automatically accounted for. Sea surface salinity (SSS) values are simply varied linearly with changes in sea level, resulting in a typical glacial enhancement in SSS of ~1‰.

The results of this exercise are summarized in Figure 5-2. Deglacial sea level rise produces a decrease in $xCO_2$ of some 13.8 ppmv over the period 19–$\pm$0 ka BP. This compares favourably with previous estimates for the magnitude of this effect of around 14 ppmv [Broecker and Peng, 1986]. Of the total change, decreasing SSSs are responsible for just under 50% via control exerted on surface ocean $fCO_2$, while the remaining processes tied to sea level change account for the rest. There is virtually no influence of sea level on $\delta^{13}CO_2$ (<0.02‰ over 19–$\pm$0 ka BP). Perturbations in the lysocline transition zones in both Atlantic and Pacific basins is relatively modest (Figure 5-2d,e), with glacial deepenings of ~300 and ~100 m, respectively. Around half of the Atlantic lysocline response and virtually the entirety of the Pacific response can be accounted for purely by changes in hydrostatic pressure. Although the sign of the change in the Atlantic basin is inconsistent with observations, the magnitude of the change is relatively small and thus could be easily masked by the operation of one or more additional mechanisms.

### 5.4.2 Ocean surface temperatures

Paleoclimatic reconstruction of the Earth’s climate at the time of the LGM suggests that sea surface temperatures (SSTs) were significantly lower than today [CLIMAP, 1984]. Since temperature exerts a strong control on both the fugacity of $CO_2$ in ocean surface waters and on the degree of $^{13}C$ fractionation during air-sea gas exchange, it has been suggested that rising SSTs over the course of a deglacial transition could potentially account for much of the observed increase in both $xCO_2$ and $\delta^{13}CO_2$ [Bacastow, 1996; Hofmann et al., 1999; Stephens and Keeling, 2000]. As an initial test of the role that glacial-interglacial changes in SSTs may have played in altering atmospheric composition, spatially uniform changes in temperature are applied to the ocean surface taking LGM SSTs to be some 1.7°C lower than at present, consistent with estimates of mean global change [Broecker and Peng, 1986; Guilerson et al., 1994]. Different signal templates are used to represent the differential climatic variability characterizing the two hemispheres. Northern latitudes are simply weighted via the SPECMAP curve [Imbrie et al., 1984], while southern latitudes take information regarding the timing and rate of change of events from the Vostok 3D record [Petit et al., 1999] on the basis that changes in local (air) temperatures in continental Antarctica are strongly coupled with Southern Ocean SSTs [Sowers et al., 1993].

The results of this exercise are summarized in Figure 5-3. The magnitude of the response of $xCO_2$ to the two separate forcings is comparable, with a 19–$\pm$0 ka BP increase of 9.5 ppmv for SH-weighted SST changes and 7.2 ppmv weighted towards the NH. Differences between these arise only as a result of the shapes of the respective forcing signals, and due to the imbalance in the distribution of ocean surface area between the hemispheres. The combined $xCO_2$ deglacial rise is thus some 16.5 ppmv, a value which falls comfortably within the range 14-21 ppmv estimated from box models and 3D OGCMs for a similar global temperature change [Broecker and Peng, 1986, 1989; Heinze et al., 1991]. Isotopic composition (Figure 5-3c) exhibits a 0.11‰ (19–$\pm$0 ka BP) increase associated with SST changes weighted towards the SH and 0.08‰ to the north. The net deglacial increase in $\delta^{13}CO_2$ is then 0.19‰. There is virtually no change in deep-sea sedimentary $CaCO_3$ (Figure 5-3d,e).

Glacial cooling at high latitudes was actually much more pronounced than nearer to the equator [CLIMAP, 1984]. A more realistic test of the effect of glacial-interglacial variability in SSTs on the global carbon cycle would be to consider inherent spatial heterogeneity in this change. The CLIMAP [CLIMAP, 1984] reconstructions of modern (pre-industrial) and LGM Earth surface conditions can be used to define this. However, recent studies based on paleoclimatic evidence from low latitudes such as from coral paleothermometers [Guilerson et al., 1994] and high altitude air temperatures [Thompson et al., 1995] suggest that the CLIMAP reconstruction may significantly underestimate glacial cooling in the tropics, although the precise degree of regional underestimation is highly controversial [Crowley, 2000]. A series of sensitivity tests are therefore carried out following Archer et al. [2000], with low latitude glacial SSTs progressively modified from their CLIMAP values. Three model runs are carried out. The first takes present-day and LGM ocean temperature distributions directly from CLIMAP. The second assumes tropical cooling at the time of the LGM was ~2°C greater than suggested by CLIMAP, implemented in SUE1608 by reducing temperatures in each equatorial grid point by 2°C, with a 1°C reduction in the adjoining mid-latitude gyre regions (designated ‘CLIMAP-2’). The third is similarly modified, but represents an end-member scenario of maximum likely change, with a
Figure 5-3  Effects on the global carbon cycle of glacial-interglacial variability in SST. Shown are; (a) the NH-weighted (green) and SH-weighted (blue) forcing signals; (b) model NH-weighted (green), SH-weighted (blue) and net (red) $x$CO$_2$ response compared to the Vostok ice core record [Petit et al., 1999] (grey line with data points); (c) model NH-weighted (green), SH-weighted (blue) and net (red) $\delta^{13}$C CO$_2$ response (red line) compared to the Taylor Dome ice core record [Smith et al., 1999] (grey line with data points); (d) and (e) the net response of the calcite lysocline in the (south) Atlantic and (south) Pacific basins, respectively.
4°C tropical cooling and 2°C in the sub-tropics (designated ‘CLIMAP-4’).

The difference between the three CLIMAP-based scenarios is relatively small, with the model exhibiting a sensitivity to tropical SST changes of ~2 ppmv °C⁻¹. This is slightly greater than the ~1 ppmv °C⁻¹ reported by Archer et al. [2000], which might reflect differences between the respective model sensitivities to low latitude surface perturbations as highlighted by respective ‘HBEI’ scores (5.3.1). Alternatively, it may simply be an artefact arising from differences in model resolution with respect to how additional cooling is prescribed adjacent to the equatorial zones.

A glacial SST scenario similar to ‘CLIMAP-2’ is consistent both with recent oxygen isotope analyses and coupled ocean-atmosphere modelling studies, which suggest that glacial temperatures in the tropics were likely to have been intermediate between that as reconstructed by CLIMAP and suggested by corals and snow lines [Crowley, 2000; Spero et al., 1997; Wolff et al., 1998]. The ‘CLIMAP-2’ scenario for glacial-interglacial SST change is therefore adopted as default. The results of this are summarized in Figure 5-4. The amplitude of \( x_{\text{CO}_2} \) variability is now much greater, with a 19–0 ka BP increase of 29.6 ppmv. The associated increase in \( \delta^{13} \text{CO}_2 \) is similarly enhanced at some 0.33‰.

5.4.3 Wind speed driven air-sea gas transfer

Variability in the air-sea gas transfer coefficient driven by changes in wind speed has been proposed as being an important control on atmospheric composition [Erickson, 1989; Keir, 1993a], with a simple box model being able to account for around 50 ppmv of the observed deglacial increase in atmospheric CO₂ [Keir, 1993b]. As a first-order test of the potential influence of glacial-interglacial changes in surface ocean wind speeds, the LGM climate is assumed to be characterized by mean annual wind speeds 50% higher than at present. Different forcing signals are used to characterize assumed differential variability between the two hemispheres. Northern latitudes are weighted using the SPECMAP curve [Imbrie et al., 1984], while southern latitudes take information regarding the timing and rates of change from the Na concentration record contained within the Vostok ice core [Petit et al., 1999], a proxy for wind speeds in Southern Ocean source areas of marine aerosol production [De Angelis et al., 1987; Petit et al., 1981].

The results of this exercise are summarized in Figure 5-5. Differences in the nature of the response between the two hemispheres are evident; while decreasing wind speeds weighted towards NH latitudes produce a noticeable increase in \( x_{\text{CO}_2} \) (3.6 ppmv over 19–0 ka BP), SH latitudes appear to have little influence (< 0.9 ppmv over 19–0 ka BP). In contrast, it is only SH wind speeds that exert any significant
Figure 5-5  Effects on the global carbon cycle of glacial-interglacial variability in surface ocean wind speed. Shown are: (a) the NH-weighted (green) and SH-weighted (blue) forcing signals; (b) model NH-weighted (green), SH-weighted (blue) and net (red) $\Delta$CO$_2$ response compared to the Vostok ice core record [Petit et al., 1999] (grey line with data points); (c) model NH-weighted (green), SH-weighted (blue) and net (red) $\delta^{13}$C$_{\text{CO}_2}$ response (red line) compared to the Taylor Dome ice core record [Smith et al., 1999] (grey line with data points); (d) and (e) the net response of the calcite lysocline in the (south) Atlantic and (south) Pacific basins, respectively.
control on $\delta^{13}$CO$_2$ – a deglacial increase of some $\sim$0.15%e. Global reduction in wind speed consequently produces a net rise in xCO$_2$ and $\delta^{13}$CO$_2$ of 4.4 ppmv and 0.16%e, respectively. Since only the rates of gas transfer across the air-sea interface are being modified through this test it comes as little surprise that there is virtually no detectable response in the shape and depth of the calcite lysocline (Figure 5-5d,e).

This subdued response in xCO$_2$ is at odds with previous box model results [Keir, 1993b]. One contributing factor is that a glacial enhancement in wind speed of only 50% is assumed (at the lower end of estimates derived from Antarctic ice cores [Petit et al., 1981]), substantially less than the 80-150% increase considered by Keir [1993]. However, the greatest difference is probably due to the global change applied in this present study where concurrent changes in gas transfer rates in warm low latitude regions will tend to offset the influence on xCO$_2$ of changes occurring at higher colder latitudes, although both will constructively combine in terms of the net $\delta^{13}$CO$_2$ response. Keir [1993b] restricted changes to a single high latitude box in a class of model ocean representation strongly suspected of significantly over-estimating the effect of high latitude perturbations [Archer et al., in press; Broecker et al., 1999a]. The results obtained with SUE1608, with relatively little response in the atmospheric CO$_2$ inventory but much greater change in isotopic composition are consistent with those obtained with 3D OGCMs [Sarmiento et al., 1992].

5.4.4 Sea ice extent

Reconstructions of the cryosphere at the time of the LGM suggest that seasonal sea ice cover was much more extensive than today, particularly during the summer months [CLIMAP, 1984]. A recent modelling study found that glacial-interglacial variability in Southern Ocean sea ice coverage had a profound effect on both the concentration of CO$_2$ in the atmosphere and on its isotopic composition [Stephens and Keeling, 2000]. To test this hypothesis, maximum (wintertime) and minimum (summertime) sea ice extent are varied, with the fractional coverage in each grid point region of the model taken from CLIMAP [1984]. Different forcing signals are used to represent the differential climatic variability characterizing the two hemispheres: northern latitudes are weighted using the SPECMAP curve [Imbrie et al., 1984] while Southern latitudes take information regarding the timing and rate of change of events from the Vostok 8D record [Petit et al., 1999] (assuming a first-order correspondence between sea ice cover and local air temperature).

The results of this exercise are summarized in Figure 5-6. While the response of xCO$_2$ to changes in sea ice cover weighted towards either hemisphere are of a similar magnitude, the signs of glacial-interglacial change are opposite. At high northern latitudes, increased sea ice cover acts so as to effectively ‘cap’ what is a strong CO$_2$ sink region, with its deglacial retreat driving xCO$_2$ down by 11.9 ppmv over 19$-$0 ka BP. This can be taken as a maximum likely response, since circulation patterns in the north Atlantic would have shifted further south during glacial periods in parallel with expanded sea ice cover. In the Southern Ocean, mean model annual surface ocean CO$_2$ fugacity is much more neutral with respect to atmospheric composition during interglacials such that capping this region has little direct effect. However, the overall response of the system to changes in Southern Ocean sea ice cover is more complicated than this. Increased sea ice cover suppresses biological productivity, resulting in an increased northwards advective transport of nutrients. These fuel increased export production and thus additional surface ocean CO$_2$ draw-down at lower latitudes, with the net effect of a deglacial reduction in sea ice cover being a 7.5 ppmv increase in xCO$_2$ over 19$-$0 ka. In contrast, Stephens and Keeling [2000] reported an increase of over 45 ppmv associated with a reduction of sea ice coverage of surface ocean boxes lying south of the Antarctic Polar Front (APF) in their model. Much of this inter-model contrast is probably due to the more highly idealized nature of their box model, where only 5 surface zones are resolved. A direct consequence of the lack of any representation of distinct equatorial up-welling zones (regions of intense CO$_2$ out-gassing in the modern ocean [Tans et al., 1990]) is that only the Southern Ocean is a significant source of CO$_2$ to the (modern) atmosphere. The strong response of xCO$_2$ to changes in Southern Ocean sea ice cover found by Stephens and Keeling [2000] could, therefore, largely be an artefact of an initially unrealistic distribution of surface ocean fCO$_2$. Indeed, with a reduction of ice-free area by a factor of 3 in the Southern Ocean of their ‘PANDORA’ multi-box model, Broecker and Peng [1986] reported a reduction in xCO$_2$ of only 2 ppmv. In SUE1608, the antagonistic influences of the two hemispheres produces a relatively small net response, with a 19$-$0 ka BP decrease in xCO$_2$ of just 4.9 ppmv.

As with CO$_2$ concentrations, the response of isotopic composition is also highly hemisphere-dependent with the NH playing little role in controlling $\delta^{13}$CO$_2$ (a 19$-$0 ka BP decrease of only 0.07%e). The degree of exposure of the atmosphere to the Southern Ocean has a much greater effect (primarily due to its larger surface area) with a 19$-$0 ka BP decrease of 0.30%e, virtually identical to that reported by Broecker and Peng [1986]. The net effect of global deglacial sea ice retreat is then 0.41%e. The magnitude of this change is comparable to the substantial transient excursion observed in $\delta^{13}$CO$_2$ at the onset of Termination I [Smith et al., 1999], supporting suggestions that it is sea ice retreat that is primarily responsible for this feature [Stephens and Keeling, 2000].

The re-organization of ocean nutrient cycles driven by changes in sea ice cover results in deepenings in the calcite lysoclines of $\sim$400 and $\sim$300 m in the Atlantic and Pacific basins, respectively (Figure 5-6d,e). Re-organization is most significant in the ocean Si cycle, with rain ratios and thus CaCO$_3$ dissolution distorted. Greatest CaCO$_3$ preservation occurs during interglacial periods when the oceanic H$_2$SiO$_4$ inventory is depleted.

Recent Southern Ocean reconstructions based upon the Modern Analogue Technique and applied to core-top and LGM diatom assemblages suggest that although the position
Figure 5-6  Effects on the global carbon cycle of glacial-interglacial variability in fractional sea ice cover. Shown are; (a) the NH-weighted (green) and SH-weighted (blue) forcing signals; (b) model NH-weighted (green), SH-weighted (blue) and net (red) $\Delta$CO$_2$ response compared to the Vostok ice core record [Petit et al., 1999] (grey line with data points); (c) model NH-weighted (green), SH-weighted (blue) and net (red) $\delta^{13}$C$_{CO_2}$ response (red line) compared to the Taylor Dome ice core record [Smith et al., 1999] (grey line with data points); (d) and (e) the net response of the calcite lysocline in the (south) Atlantic and (south) Pacific basins, respectively.
of maximum (winter-time) sea ice extent was shifted much further to the north during glacial times [Crosta et al., 1998a,b] in reasonable agreement with CLIMAP [1984], the position of minimum (summer-time) sea ice extent may have been little changed [Crosta et al., 1998b]. The rather crude representation of sea ice extent in SUE, where a fractional coverage is applied to a zonally homogeneous ocean region, makes quantitative assessment of alternative LGM sea ice regimes difficult. Even so, summer sea ice extent appears to have a substantial effect on model $\delta^{13}C_{CO_2}$, with the assumption of constant summer sea ice extent reducing the amplitude of glacial-interglacial isotopic variability by over 50%. This sensitivity suggests that ice core records of $\delta^{13}C_{CO_2}$ could potentially help in providing additional constraints on reconstructions of past sea ice extent.

### 5.4.5 Ocean circulation

Changes in ocean circulation have often been invoked as a key driving force behind glacial-interglacial variations in atmospheric composition. In particular, changes in the supply of nutrients together with DIC and ALK to the surface Southern Ocean, both through variability in convective regime and advective up-welling have been suspected to produce profound changes in $xCO_2$ through the solubility and biological pumps in this region [Knox and McElroy, 1984; Martin, 1990; Sarmiento and Toggweiler, 1984]. In particular, increased surface stratification has been proposed as the single most important driver of low glacial $xCO_2$ [Francois et al., 1997; Sigman et al., 1999a,b]. Variations in the solubility and biological pumps arising through changes in the strength and depth of the Atlantic thermohaline circulation and through wind-driven enhancement of equatorial up-welling rates could also have played important roles [Howard and Prell, 1994; Oeschger et al., 1984; Rich et al., 1999; Siegenthaler and Wenk, 1984; Toggweiler, 1999].

There are few unambiguous constraints on glacial ocean circulation, particularly with respect to the details of convective and advective regimes in the Southern Ocean. This present study is also limited in scope by the requirement of a prescribed advective field. While the baseline ocean configuration of SUE1608 is derived from a modern-type ocean simulation of the Bern 2D ZOGCM [Marchal et al., 1998b], there is currently no equivalent simulation available for the LGM. However, a glacial-type Atlantic circulation field is available, produced in an identical way to that for modern conditions with the exception that surface salinity in the northernmost Atlantic grid box (65°N-80°N) was restored to 34.2‰ [Marchal, pers. comm]. This leads to a maximum stream function in the Atlantic, approximately half that obtained in the modern simulation and with shallower NADW, allowing increased penetration of AABW into the north Atlantic in accordance with observations [Marchal et al., 1998a; Peltier and Marshall, 1995].

As a simple test of the influence of variability in Atlantic overturning circulation, the model is forced by a hybrid of modern and glacial circulations. A continuous 400 ka record is constructed assuming that the advective field at any point in time can be described as a linear combination of the two end-member advective fields, weighted via the SPECMAP curve [Imbrie et al., 1984].

The results of this exercise are summarized in Figure 5.7. There is a small 19-40 ka BP deglacial increase in $xCO_2$ of 6.3 ppmv accompanied by almost no change in $\delta^{13}C_{CO_2}$ (<1.03‰). However, altering the Atlantic thermohaline circulation produces a more substantial influence on the calcite lysolcne transition zone. In the Atlantic basin, increased northwards penetration of AABW (characterized by lower carbonate ion concentrations thus being more caustic to CaCO$_3$) during glacial periods clearly leads to decreased CaCO$_3$ preservation as compared with during interglacials [Broecker et al., 1993], resulting in a 600-700 m shoaling of the calcite lysolcne. Ocean chemistry is balanced on a global scale through antagonistic changes occurring in the Pacific, where glacial preservation is slightly enhanced with a lysolcne some ~200 m deeper. The respective sign of glacial-interglacial change in both basins is in agreement with paleoceanographic observations [Balsam, 1983; Cattiuq et al., 1998; Farrell and Prell, 1989; Howard and Prell, 1994; Karlin et al., 1992].

### 5.4.6 Terrestrial carbon storage

 Shackleton [1977] first proposed that glacial-interglacial changes in foraminiferal $\delta^{13}C$ might indicate that transfers of carbon had occurred between the ocean (and atmosphere) and terrestrial biosphere. From measurements made on deep-sea sediment cores which suggested ambient glacial $\delta^{13}C$ conditions around 0.7‰ lighter than during the Holocene, Shackleton [1977] estimated that some $10^{18}$ g of carbon (1000 GtC) must have been removed from the ocean since the LGM. This was consistent with what was suspected at that time regarding a deglacial increase in carbon stored in terrestrial ecosystems through the expansion of tropical rainforests and afforestation of high northern latitudes. Should a significant quantity of carbon have been removed from the ocean and atmosphere upon deglaciation, this would effectively increase the gross deglacial CO$_2$ rise that other mechanisms must together explain [Berger and Wefer, 1991; Martin, 1995]. The magnitude of the change in carbon storage is therefore of primary importance in accounting for glacial-interglacial change.

From an extensive survey of deep-sea sediment cores, Curry et al. [1988] concluded that an increase in mean ocean $\delta^{13}C_{DIC}$ of 0.46‰ had taken place during the last deglacial transition (19-40 ka BP), although this was subsequently reduced to 0.32‰ [Duplessy et al., 1988]. Further re-analysis of benthic $\delta^{13}C$ data now suggests a mean oceanic $\delta^{13}C$ increase intermediate between the two, perhaps ~0.40‰ [Crowley, 1995]. To translate this into an equivalent shift in terrestrial biospheric carbon requires an estimate to be made of the mean isotopic composition of terrestrial organic carbon. This lies in the range -22 to -25‰ for the pre-industrial biosphere [Bird et al., 1994]. However, the mean isotopic composition of land biota cannot be guaranteed to have remained invariant over the course of the late Quaternary, with a shift in the dominance of C$_4$ over C$_3$ species suspected to have occurred since the LGM [Crowley,
Figure 5-7  Effects on the global carbon cycle of glacial-interglacial variability in Atlantic overturning circulation. Shown are: (a) the forcing signal (normalized to a value of unity at the LGM); (b) model $x$CO$_2$ response (red line) compared to the Vostok ice core record [Petit et al., 1999] (grey line with data points); (c) model $\delta^{13}$C$_{CO_2}$ response (red line) compared to the Taylor Dome ice core record [Smith et al., 1999] (grey line with data points); (d) and (e) the response of the calcite lysocline in the (south) Atlantic and (south) Pacific basins, respectively.
Further complications arise as a result of recent culture studies, which have found a dependence on ambient carbonate ion concentrations ([CO$_3$$^2$]$_i$) of the degree of calcitic 13C fractionation in several planktonic foraminiferal species [Spero et al., 1997]. If benthic species were to behave in a comparable manner then changes in deep sea [CO$_3$$^2$]$_i$ might act to either amplify or diminish apparent variations in 13C/DIC recorded by foraminiferal tests [Russell and Spero, 2000]. Changes in foraminiferal 13C/DIC would therefore need to be interpreted in light of glacial-interglacial perturbations in oceanic DIC and ALK inventories, both of which are poorly constrained.

There are independent methods available for quantifying the deglacial change in carbon stored in the terrestrial biosphere, primarily through the reconstruction of terrestrial ecosystems (and their associated soils) both for LGM and modern (pre-industrial) conditions. This can be done either directly from terrestrial proxy evidence [Adams et al., 1990; Adams and Faure, 1998; Crowley, 1995; Faure et al., 1996; Maslin et al., 1995] or by means of climate-vegetation models [Esser and Lautenschlager, 1994; Francois et al., 1998, 1999; Friedlingstein et al., 1992; Peng et al., 1998; Prentice and Fung, 1990; Van Campo et al., 1993]. Estimates made by these two methods often do not entirely agree, however, either amongst themselves or when compared with estimates based on oceanic 13C/DIC changes [Bird et al., 1994; Crowley, 1991, 1995; Maslin et al., 1995] as summarized in Table 5-3. That reconstructions suggest increases ranging from -100 GtC to 1900 GtC puts a high degree of uncertainty on the importance to observed glacial-interglacial variability in atmospheric composition of the transfer of carbon between the terrestrial biosphere and ocean and atmosphere.

The perturbing effect that changes in terrestrial vegetation might have had on the global carbon cycle is now investigated by varying the magnitude of the terrestrial carbon reservoir. As an initial test, 500 GtC is assumed to have been removed from the atmosphere following the LGM; a value chosen to be consistent with the mid-point of the range of estimates made from observed foraminiferal 13C change and climate-vegetation models. The SPECMAP 18O stack [Imbrie et al., 1984] is taken as a first-order proxy for glacial-interglacial variability in the terrestrial reservoir.

The results of this exercise are summarized in Figure 5-8. It can be seen that the effect of an expansion of the terrestrial biosphere is to reduce xCO$_2$ by a total of 24.7 ppmv for the interval 19→0 ka BP, contrary to the sign of the observed change. The magnitude of this decrease is greater than suggested by other models that predict change in the range 12 to 17 ppmv [Archer et al., 2000; Broecker and Peng, 1986]. However, these all assume that a steady state with respect to deep-sea CaCO$_3$ has been reached (i.e., through 'carbonate compensation'). This process occurs with an e-folding time of ≈9 ka such that if the main transferal of carbon were to be centred around 10 ka BP then the reduction in oceanic DIC inventory will be far from having been fully compensated for. Indeed, Archer et al. [2000] reported that the uncompensated change in xCO$_2$ in response to a 500 GtC perturbation is almost 40 ppmv. Thus not only is the absolute magnitude of the change in terrestrial carbon storage of fundamental importance to the response of the system but so to is the rate of this change. Associated with the deglacial change in xCO$_2$, a gradual increase in 13C/C:CO$_2$ of ≈0.31‰.

The response of the calcite lysocline in both the Atlantic and Pacific basins is very similar, with weak preservational spikes characterized by a 200-300 m deepening, synchronous with the deglacial transitions. These transients of enhanced preservation are slightly greater in depth for the aragonite lysocline (not shown) than for calcite, and are consistent with observations of CaCO$_3$ preservation between the end of the LGM and early Holocene [Berger, 1977; Broecker et al., 1993, 1999b].

### 5.4.7 Neritic sediment storage

A number of hypotheses to explain glacial-interglacial variations in atmospheric CO$_2$ concentrations have been based upon the extraction from the ocean (during interglacial periods of high sea level) and temporary storage in continental shelf sediments of materials whose presence would otherwise tend to exert a negative pressure on xCO$_2$. The earliest of such schemes was the 'Phosphate Extraction Model', in which the removal of organic phosphate from the ocean resulted in the limiting of ocean productivity and thus higher xCO$_2$. During glacial times, PO$_4$ returned to the ocean through shelf sediment erosion fuels ocean productivity, leading to lower xCO$_2$ [Broecker, 1982; Broecker and Peng, 1982]. However, as a sole explanation for the magnitude of
Figure 5-8  Effects on the global carbon cycle of glacial-interglacial variability in terrestrial carbon storage. Shown are: (a) the forcing signal (normalized to a value of unity at the LGM); (b) model $\delta^{13}$CO$_2$ response (red line) compared to the Vostok ice core record [Petit et al., 1999] (grey line with data points); (c) model $\delta^{13}$CO$_2$ response (red line) compared to the Taylor Dome ice core record [Smith et al., 1999] (grey line with data points); (d) and (e) the response of the calcite lysocline in the (south) Atlantic and (south) Pacific basins, respectively.
glacial-interglacial change it fell foul of considerations such as observed changes in oceanic $\delta^{13}C$ [Keir and Berger, 1983; Knox and McElroy, 1984], Cd/Ca ratios [Boyle, 1988; Shaffer, 1990], dissolved oxygen concentrations [Knox and McElroy, 1984], and the tendency for $xCO_2$ rise to lag sea level change contrary to the observed sequence of events surrounding glacial terminations [Barnola et al., 1987; Sowers et al., 1991].

5.4.7.1 The ‘Coral Reef Hypothesis’

A variant on the phosphate extraction model that avoids many of the above-mentioned proxy violations considers the deposition of CaCO$_3$ in shelf sediments. This envisages that glacial-interglacial changes in the rate of accumulation of CaCO$_3$ in the neritic environment driven by sea level change would perturb global ocean chemistry and thus atmospheric composition [Berger, 1982a,b; Keir and Berger, 1983, 1985; Opdyke and Walker, 1992]. This is known as the ‘Coral Reef Hypothesis’ [Berger, 1982a], although accumulation of CaCO$_3$ can take place as both reefal (coral-derived) and non-reefal (unconsolidated sediments) components. Simple logic supports the notion that there must have been a significant degree of variability in CaCO$_3$ accumulation rates over the late Quaternary; reduced submerged continental shelf area during glacial periods would result in a lower global rate of CaCO$_3$ accumulation compared to interglacials. Indeed, erosion of carbonate-rich sediments from exposed shelves may even have produced a net transfer of CaCO$_3$ back during times of low sea level stand. Although deep-sea sediments will eventually counteract any perturbation in the magnitude of shelf accumulation rates via transient changes in the depth of the lysocline, this only occurs with an $e$-folding time of the order of 10 ka. Changes in sea level (and thus neritic accumulation rates) will therefore produce a degree of disequilibrium between benthic sediments and ocean chemistry. It is this disequilibrium that allows the oceanic inventories of DIC and ALK to be perturbed, affecting $xCO_2$ [Berger, 1982b]. As with the phosphate extraction model, such atmospheric changes will, at best, lag sea level change, invalidating the coral reef hypothesis as a sole explanation for the observed deglacial transition, for instance in counteracting the downward forcing pressure upon $xCO_2$ due to the buildup of carbon in the terrestrial biosphere (5.4.6) [Berger, 1982b; Broecker and Peng, 1993; Maslin et al., 1995].

Accurate estimation of the magnitude of glacial-interglacial change in neritic CaCO$_3$ accumulation is far from straightforward. Areal accumulation rates have previously been derived from estimates made of neritic CaCO$_3$ build-up over the course of the late Holocene [Mundhoven and Francois, 1996; Walker and Opdyke, 1995], taken to be $7 \times 10^{12}$ and $7.5 \times 10^{12}$ mol CaCO$_3$ a$^{-1}$ for reefal and non-reefal components, respectively [Milliman, 1993]. For reefal accumulation this figure is independently corroborated by process-based global models of coral reef growth [Kleypas, 1997]. Erosion rates are especially hard to quantify, with values previously either adapted from observed terrestrial weathering rates [Mundhoven and Francois, 1996] or simply treated as a model tuning parameter [Opdyke and Walker, 1992]. As an initial test of the potential role of this mechanism, the parameterization of Mundhoven and Francois [1996] is adopted. Sea level history is the same as assumed previously (5.4.1).

The results of this exercise are summarized in Figure 5-9. It can be seen that the coral reef hypothesis as formulated by Mundhoven and Francois [1996] has a very substantial influence on $xCO_2$, with a total 19–$\sim$0 ka BP increase of 45.9 ppmv. This is despite the concurrent effect of sea level change alone (i.e., excluding SSS changes) being some 7.7 ppmv in the opposite direction. Changes in the oceanic inventory of DIC and ALK in the ocean therefore drive a total deglacial increase of 53.6 ppmv, almost two thirds of the observed increase [Petit et al., 1999] and consistent with comparable models [Mundhoven and Francois, 1994, 1996; Opdyke and Walker, 1992; Walker and Opdyke, 1996]. There is virtually no associated change in atmospheric $\delta^{13}C$-CO$_2$ (<0.02‰).

Although this appears to offer a simple means of explaining much of the observed amplitude of glacial-interglacial change in $xCO_2$, there appears to be a serious problem with the magnitude of the perturbation in deep-sea sediments which it drives (Figure 5-9d,e). Both basins exhibit glacial deepenings in the depth of the calcite lysocline of between 1 and 2 km. Changes of this order in the Pacific are not supported by available data [Berger, 1978, 1982b; Farrell and Prell, 1989, 1991; Karin et al., 1992]. Furthermore, observed Atlantic changes are opposite in sign to that predicted by the model [Balsam, 1983; Berger, 1968; Crowley, 1983; Gardner, 1975]. It is unlikely that additional mechanisms might act so as to correct excess CaCO$_3$ preservation of this degree. Either the magnitude of changes in neritic CaCO$_3$ storage must have then been over-estimated, or deficiencies in the model CaCO$_3$ cycle artificially magnify the response of the system. In the latter case, the apparent under-estimation of CaCO$_3$ content in the equatorial zones of the ocean as well as in several mid-latitude regions (4.4.3) might reduce the overall buffering capacity of the deep-sea sediment system with respect to changes in neritic CaCO$_3$ accumulation rates. Variability in CaCO$_3$ preservation in other regions of the world ocean (coincidently the locations the synthetic sediments cores used for reconstructing the two lysocline sections) would thus be intensified.

A more plausible response of the CaCO$_3$ lysocline can be obtained by reducing the rate of neritic build-up and erosion (both reefal and non-reefal components) by 50%. This results in a maximum glacial-interglacial difference in deposition rates of $\sim 7 \times 10^{12}$ mol CaCO$_3$ a$^{-1}$. To re-balance ocean DIC and ALK inventories over the long term, the influence of CaCO$_3$ dissolution through the oxidation of organic carbon within the sediments (3.2.4) is reduced by 50%, thereby increasing deep-sea CaCO$_3$ preservation and making up the neritic shortfall. This has the desirable side-effect of generally improving the global distribution of CaCO$_3$-rich sediments in the model (not shown), with sedimentary CaCO$_3$ distributions much closer to
Figure 5-9 Effects on the global carbon cycle of glacial-interglacial variability in neritic CaCO$_3$ storage. Shown are: (a) the forcing signal (normalized to a value of unity at the LGM); (b) model $x$CO$_2$ response (red line) compared to the Vostok ice core record [Petit et al., 1999] (grey line with data points); (c) model $\delta^{13}$C$_{CO_2}$ response (red line) compared to the Taylor Dome ice core record [Smith et al., 1999] (grey line with data points); (d) and (e) the response of the calcite lysocline in the (south) Atlantic and (south) Pacific basins, respectively.
observations in the equatorial Atlantic and Pacific zones and in the Indian Ocean.

The peak-to-peak amplitude in $\Delta$CO$_2$ variability is now almost exactly 50% of that observed before, with a rise of 22.5 ppmv over the interval 19–40 ka BP. Importantly, changes in lysocline depth are much more modest. While Atlantic change is still in a direction opposite to that observed, it is no longer overwhelmingly so (~900 m). A glacial-interglacial amplitude of 400-600 m in the Pacific is consistent with observations.

5.4.7.2 Introducing the 'Opal Extraction Model'

An analogue to the phosphate extraction model can be found in the limiting nutrient silicic acid, with variable accumulation rates of biogenic opal deposited on continental shelves in response to changes in sea level likely. Indeed, the potential significance of this mechanism to the global carbon cycle is highlighted by estimates made of the present-day ocean sink of H$_2$SiO$_4$ in neritic sediments equivalent to ~20% of the entire abyssal ocean sink (5.9 Tmol Si a$^{-1}$) [Treguer et al., 1995]. While the effect of glacial-interglacial variability in H$_2$SiO$_4$ may not significantly alter the absolute strength of the biological pump, the favouring of siliceous phytoplankton over non-siliceous species will alter the CaCO$_3$:POC rain ratio, driving changes in ocean chemistry and thus xCO$_2$ [Archer and Maier-Reimer, 1994; Harrison, 2000].

To test this hypothesis, a simple model is constructed based directly upon the neritic (non-reefal component) CaCO$_3$ sediment accumulation model of Mundhoven and Francois [1996]. Specific opal accumulation rates are chosen to reproduce estimated mean global neritic buildup during the late Holocene (1.2 Tmol Si a$^{-1}$) [Treguer et al., 1995]. Since little is known regarding possible rates of erosion of previously-deposited material, no erosional term is included. A variable oceanic sink for H$_2$SiO$_4$ of between 0.36 and 1.21 Tmol Si a$^{-1}$ thus arises as a function of sea level.

The action of this mechanism is to produce a small deglacial (19–40 ka BP) decrease in xCO$_2$ of 5.4 ppmv with virtually no associated effect on $\delta^{13}$C/CO$_2$. These results, together with the interglacial shoaling of the calcite lysocline (some ~300 m in the Atlantic basin), are practically indistinguishable from the effects of sea level change alone, suggesting that this mechanism has little influence on the global carbon cycle (at least in isolation).

5.4.8 Dissolved silica supply to the ocean

Interest has recently been stimulated in the role that changes in the dissolved Si input to the ocean may have had on glacial-interglacial xCO$_2$ variability. This has arisen out of the potential for the ocean Si cycle, with a residence time for dissolved Si of ~15 ka, to account for the lag of up to 8 ka that occurs between the start of dust decline towards the end of Stages 2 and 6, and the initial CO$_2$ rise that follows in each core [Broecker and Henderson, 1998]. On this basis, Harrison [2000] proposed a 'Silica Hypothesis', whereby increased glacial aeolian Si supply to the surface ocean enhances diatom productivity at the expense of calcium carbonate shell-forming species, thus affecting xCO$_2$ via the ‘rain ratio hypothesis’ [Archer and Maier-Reimer, 1994]. Harrison [2000] went further to suggest the entire glacial-interglacial xCO$_2$ difference might be explained in this way. Increases in dissolved Si supply to the oceans driven by changes in the weathering rate of continental (silicate) rock might further enhance this effect [Treguer and Pondaven, 2000]. The potential role of these mechanisms in perturbing the global carbon cycle are now individually assessed.

5.4.8.1 Aeolian flux

To test the hypothesis that glacial-interglacial changes in dissolved Si supply derived from aeolian silicates exert a strong control over atmospheric CO$_2$ levels, dust deposition to the surface ocean is varied. Modern dust deposition to the model ocean surface is some 6.85x10$^{14}$ g a$^{-1}$ [Mahowald et al., 1999]. Assuming that SiO$_2$ comprises 66 wt% of dust (mean upper continental crustal abundance [Taylor and McLennan, 1985]) gives a solid input of some 4.52x10$^{14}$ g SiO$_2$ a$^{-1}$, equivalent to 7.54 Tmol Si a$^{-1}$. To achieve a value for total aeolian dissolved Si input 0.5 Tmol Si a$^{-1}$ consistent with Treguer et al. [1995] therefore requires a solubility of ~6.6%, in line with experimental estimates [Wollast and Chou, 1985]. Dissolved (riverine) Si supply is reduced by an equivalent amount in the model in order to balance the (modern) ocean budget. For the LGM, the equivalent global dust deposition flux is 2.29x10$^{14}$ g a$^{-1}$ [Mahowald et al., 1999] giving a peak glacial aeolian dissolved Si flux of 1.67 Tmol Si a$^{-1}$, more than 3 times greater than at present. The temporal variability in the Vostok dust concentration record [Petit et al., 1999] is used as a proxy for relative changes in global dust deposition fluxes in order to reconstruct a record for the last 400 ka. Aeolian iron supply is held constant for the purpose of this experiment.

The results of this exercise are summarized in Figure 5-10. It can be seen that there is a rather minimal response in xCO$_2$ to this forcing with a glacial-interglacial amplitude of less than 2.2 ppmv and virtually no detectable change in $\delta^{13}$C/CO$_2$. Similarly, sedimentary CaCO$_3$ contents in both Atlantic and Pacific basins are little affected. Sensitivity analyses suggest that even by assuming a solubility for aeolian SiO$_2$ as high as 14.2% (sufficient to produce a 50% increase in total dissolved Si supply at the LGM over present-day rates) the 19–40 ka BP deglacial increase in xCO$_2$ is proportionally increased only to ~6 ppmv.

5.4.8.2 Riverine fluxes

To test the secondary hypothesis, that glacial-interglacial changes in riverine dissolved Si supply might have produced a significant effect on xCO$_2$, the riverine input to the ocean is varied. Glacial rates of supply were set some 1.0 Tmol Si a$^{-1}$ higher than at present, comparable in peak amplitude to the aeolian experiment (5.4.8.1). However, the SPECMAP $\delta^{13}$O stack [Imbrie et al., 1984] is now used as a proxy for relative changes in weathering-derived fluxes in order to reconstruct a forcing record for the last 400 ka.

As with aeolian Si supply, the response of atmospheric composition to the forcing is small, with a 19–40 ka BP increase in xCO$_2$ of 2.4 ppmv and no detectable change in
Figure 5-10  Effects on the global carbon cycle of glacial-interglacial variability in aeolian Si supply. Shown are; (a) the forcing signal (normalized to a value of unity at the LGM); (b) model CO₂ response (red line) compared to the Vostok ice core record [Petit et al., 1999] (grey line with data points); (c) model δ¹³CₐCO₂ response (red line) compared to the Taylor Dome ice core record [Smith et al., 1999] (grey line with data points); (d) and (e) the response of the calcite lysocline in the (south) Atlantic and (south) Pacific basins, respectively.
Despite substantial differences in the shape and integrated area of the forcing signal used for weathering rate change compared to that in the aeolian deposition experiment, the overall effect on the global carbon cycle is similar. There is slightly greater variability in the depth of the calcite lysocline, although a glacial shoaling of $\sim$100 m is still relatively minor. Sensitivity analyses again suggest that enhancing the strength of the forcing produces a proportional (but still small) atmospheric response.

5.4.8.3 Oceanic Si cycling and the ‘Silica Hypothesis’

Contrary to conceptual schemes purporting to explain glacial-interglacial change in atmospheric composition via increased dissolved Si supply to the world ocean during glacial times [Harrison, 2000; Treguer and Pondaven, 2000], the results of a mechanistic ocean silica cycle model suggest that there is little effect. This present study supports the conclusions of Archer et al. [2000] that attempting to change the oceanic inventory of $\text{H}_4\text{SiO}_4$ is a relatively ineffective way of altering $x\text{CO}_2$. However, it is an interesting question as to what processes operating within the system are responsible for the surprisingly damped response to what appear quite substantial perturbations in the supply of this key nutrient.

One contributing factor relates to the time-varying nature of the perturbations employed in this study. Some of the more prominent features in the Vostok dust concentration [Petit et al., 1999] and SPECMAP $\delta^{18}\text{O}$ [Imbrie et al., 1984] forcing signals (such as deglacial transitions) are characterized by time scales of only 2-5 ka. This is short compared to the residence time of $\text{H}_4\text{SiO}_4$ in the ocean which in SUE1608 is about 16 ka (consistent with estimates of 10-20 ka derived from modelling and mass balance considerations [Archer et al., 2000; Treguer et al., 1995]). Furthermore, when interactions between CaCO$_3$ and silica cycles within the carbon cycle as a whole are taken into account, the $\epsilon$-folding time of changes in atmospheric composition with respect to perturbations in dissolved Si supply is even longer, some $\sim$23 ka. Variability in the $x\text{CO}_2$...
response to changes in dissolved Si input are therefore highly damped. This is in contrast to that expected by Harrison [2000] and Treguer and Pondaven [2000] who implicitly assume a system at steady-state.

An equally important contributor to overall system response involves the dynamics of Si burial, with Archer et al. [2000] finding that since Si burial appeared to rise with the second power of H$_4$SiO$_4$ inventory it would be extremely difficult to significantly change the H$_4$SiO$_4$ inventory through increased Si supply in the first place. Results of sensitivity analyses carried out with SUE1608 and driven by (total) dissolved Si inputs to the ocean of between 3 and 42 Tmol Si a$^{-1}$ are shown in Figure 5-11. For this test, following a spin-up period, a step increase in dissolved Si input is applied and the system allowed to adjust for a further 50 ka (thus achieving ~95% of true steady state). The resulting model state is then compared to a control run forced continuously with the baseline dissolved Si input (6 Tmol Si a$^{-1}$). From this it can be seen that the oceanic H$_4$SiO$_4$ inventory is relatively insensitive to the dissolved Si input; a 14-fold increase in input is required to produce just over a 4-fold increase in inventory (Figure 5-11a). Export production of biogenic opal appears to be linear with H$_4$SiO$_4$ inventory over a range spanning plausible dissolved Si input rates to the ocean (3-12 Tmol Si a$^{-1}$) above which there is a rapid decline in slope with further increases in H$_4$SiO$_4$ availability (probably due to a maximum shift in species composition towards silicious phytoplankton having been approached). These effects, together with a scaling of sedimentary opal preservation efficiency with H$_4$SiO$_4$ inventory (Figure 5-11c) combine to produce a non-linear response of burial flux with H$_4$SiO$_4$ inventory (Figure 5-11d). This final relationship is consistent with results from 3D OGCM carbon cycle modelling work suggesting an approximately parabolic relationship [Archer et al., 2000]. However, in SUE1608 this relationship breaks down at an inventory of around 225 Pmol Si as a result of the saturation in export flux (Figure 5-11b).

The apparent failure of the ‘Silica Hypothesis’ in the model employed here can now be assessed in light of these two factors. In order to explain low glacial levels of CO$_2$, an increase in the oceanic H$_4$SiO$_4$ inventory of between about 10% and 67% (depending upon assumptions made regarding ecosystem composition and interaction) was suggested to be sufficient [Harrison, 2000]. Taking the absolute minimum requirement, a 10% increase in H$_4$SiO$_4$ inventory requires a 32% increase in dissolved Si input (Figure 5-11a), equivalent to an additional ~1.9 Tmol Si a$^{-1}$. This could be achieved with a solubility for aeolian silicates of about 11%, higher than available estimates allow for [Wollast and Chou, 1985] (but not unreasonably so). Given that the full width at half maximum (FWHM) of the Stage 2 dust peak in the Vostok core is only of order 10 ka, the 16 ka oceanic Si residence time suggests that solubility would have to be substantially greater in order to have attained the required increase in H$_4$SiO$_4$ inventory by the end of the LGM. Indeed, a peak aeolian influx of over 4.4 Tmol Si a$^{-1}$ corresponding to a solubility of SiO$_2$ of ~25% is required in SUE1608 to produce such an inventory. Solubilities of this order are highly unlikely. A further problem with this hypothesis concerns the uniform global distribution assumed of phytoplankton species abundance and thus of export ratio [Harrison, 2000]. With the exception of equatorial up-welling regions, most deep-sea sediment CaCO$_3$ accumulation tends to occur beneath regions where diatoms are responsible for a relatively minor proportion of POC export. In such regimes, a 10% increase in the POC export from silicious species would result in much less then a 10% decrease in non-silicious POC export and thus less than a 10% decline in CaCO$_3$ flux. The minimum increase needed in H$_4$SiO$_4$ inventory to achieve the required reduction in CaCO$_3$ export by Harrison [2000] would therefore be greater, further adding to the aeolian SiO$_2$ solubility requirement.

By similar arguments, the solubility requirement of an ocean nutrient cycle model [Tyrell, 1999] used in the variation of the hypothesis put forward by Treguer and Pondaven [2000] proves to be even worse. In this, model glacial xCO$_2$ levels are explained by a 48% increase in biogenic opal export. If a similar increase in H$_4$SiO$_4$ inventory is required as an absolute minimum, an additional dissolved Si input of 6.6 Tmol Si a$^{-1}$ is needed at steady state. The solubility requirement is now already 16% – this is before even the transitory nature of the input forcing or spatial heterogeneity in species composition have been taken into account.

Additional model experiments suggest that even a combination of aeolian supply and riverine influx fall far short of being able to account for the magnitude of observed xCO$_2$ changes. Indeed, with an assumption of 10% aeolian SiO$_2$ solubility together with a 50% LGM enhancement in riverine input, xCO$_2$ increases by only ~9 ppmv (19-30 ka BP). The response time of the system with respect to changes in dissolved supply is too long for any significant role to be played in the initial observed rapid rise in atmospheric CO$_2$ levels, with just ~2 ppmv occurring before Termination I is substantially complete by 10 ka BP. Despite this, changes in the global Si cycle may yet be important in driving declining xCO$_2$ as glaciations deepen, being responsible in this test for as much as 18 ppmv of the overall trend apparent between Stages 5a and 2.

5.4.9 The ‘Iron Hypothesis’

One of the great puzzles in oceanography has been the reason for the existence of certain areas of the world ocean, particularly the Southern Ocean together with the equatorial and north Pacific, where there is an abundance of unused macro-nutrients [de Baar and Boyd, 2000]. Although physical (solar insolation and ocean surface mixing) and grazing regimes must play a part in controlling phytoplankton standing stocks in these so-called ‘High-Nitrate Low-Chlorophyll’ (HNLC) regions, John Martin suggested that growth limitation through insufficient availability of the micro-nutrient iron (Fe) might also exert an important control [Martin and Fitzwater, 1988]. He furthermore proposed that stimulation of biological productivity through increased aeolian Fe delivery to the Southern Ocean at the height of the last ice age might have led to the concurrently low levels observed of atmospheric CO$_2$ [Martin, 1990]. The
IronEx II' open ocean Fe fertilization experiment demonstrated unequivocally the role that iron played in limiting phytoplankton growth (particularly of larger diatoms) in the equatorial Pacific [Coale et al., 1996a,b]. More recently, a similar experiment ('SOIREE') was carried out in the Southern Ocean. Here too, an unambiguous response of the phytoplankton standing stock to the addition of Fe was observed [Boyd et al., 2000].

To test the ‘Iron Hypothesis’ for low glacial xCO2 it should be sufficient to increase aeolian deposition rates in the model and record the results. However, there is a caveat to the use of SUE in predicting the atmospheric response to Fe fertilization. This concerns the nature of the scheme for biological productivity in which export production is estimated directly from ambient nutrient concentrations with the aid of Michaelis-Menten kinetics (2.2.3). A response of POC export upon relief of Fe limitation is, therefore, implicitly assumed. Although increased export production was indeed reported in the equatorial Pacific as a result of Fe fertilization [Coale et al., 1996b], there was no evidence during the 14-day course of SOIREE that POC export was similarly enhanced in the Southern Ocean [Boyd et al., 2000; Charette and Buesseler, 2000] in spite of a significant draw-down in surface ocean fCO2 having occurred [Boyd et al., 2000; Watson et al., 2000]. Furthermore, the apparent persistence of the bloom (on the basis of remotely-sensed elevated surface chlorophyll concentrations, as shown in Figure 5-12) for several months after the end of the experiment [Abraham et al., 2000] implies that losses of Fe must have been relatively restricted over this entire period and thus export constrained to be modest. A very different response, though, might be expected from a continuous enhancement of aeolian Fe supply over a period of thousands of years and across the entire Southern Ocean, as opposed to that obtained under the temporal and spatially-limited experimental conditions of SOIREE [Ridgwell, 2000]. Regardless of the specifics of Southern Ocean ecosystem dynamics, a more general response of the system to changes in aeolian Fe supply is to be expected. Accumulation rates of aeolian mineral material in deep-sea sediments around the world are generally higher during glacial periods than at present [Balsam et al., 1995; deMenocal, 1995; deMenocal et al., 1993; Pye, 1989; Rea et al., 1986; Ruddiman, 1997]. This is supported by AGCM modelling studies, which predict that in the drier, colder, and windier glacial climate, dust transport from terrestrial sources to the open ocean is more efficient [Andersen et al., 1998; Gent, 1992; Mahowald et al., 1999; Joussaume, 1993]. Furthermore, concurrent expansion of arid dust source areas [Adams et al., 1990; Iriondo, 2000] would act so as to further enhance the flux of material to the ocean [Andersen and Dittevorsen, 1998; Mahowald et al., 1999; Reader et al., 1999]. Although the primary impact of increased aeolian Fe supply is on the enhancement of productivity (in HNLC regions) there are more subtle secondary effects that may be equally important in affecting xCO2 over the longer term. Fe-replete conditions have been demonstrated to favour (predominantly larger) diatoms over pico- and nano-plankton [Boyd et al., 2000; Coale et al., 1996b; Watson et al., 2000]. Since CaCO3 is only produced by smaller phytoplankton (coccolithophorids), such a shift in species composition will reduce the CaCO3:POC rain ratio [Harrison, 2000; Watson and Leifèvre, 1999], driving enhanced accumulation of aeolian mineral material in deep-sea sediments around the world.

Figure 5-12 Image of the SOIREE bloom in the Southern Ocean in the region of 141°E 61°S, taken from the SeaWiFS ocean colour satellite on 23rd March 1999, some 6 weeks following initial Fe release [Abraham et al., 2000]. The SeaWiFS data, provided by the NASA DAAC/GSFC and copyright of Orbital Imaging Corps and the NASA SeaWiFS project, was processed at CCMS-PML.
CaCO₃ dissolution in deep-sea sediments and thus lower xCO₂ [Archer and Maier-Reimer, 1994].

To test the hypothesis that glacial-interglacial changes in aeolian Fe supply to the ocean exerted a strong control over atmospheric composition, dust deposition fluxes to the ocean surface were altered. Present-day and LGM distributions of dust flux were taken from Mahowald et al. [1999]. The Vostok dust concentration record [Petit et al., 1999] is used as a proxy for the timing and rate of change of deposition in order to reconstruct a record for the last 400 ka. Use of a signal template of dust deposition rates at Vostok (reconstructed using estimated snow accumulation rates [Petit, pers com]) as opposed to the dust concentration record makes very little difference.

The results of this exercise are summarized in Figure 5-13. The response of xCO₂ to this forcing is pronounced, with a 19–20 ka BP increase of 52.4 ppmv. There are several components that contribute to this: a fast response via the direct effects of changes in iron availability on export production (accounting for perhaps three quarters of the deglacial increase) together with a slower one, arising through adjustment of the deep-sea sediment system [Watson et al., 2000]. The first component is associated with total POC export during the LGM being some ~10% higher than at present. There is also a shift in species composition with siliceous phytoplankton favoured (via increased Fe-driven efficiency in H₂SiO₄ utilization), suppressing CaCO₃ export by 24%. The second component involves a reduction in the CaCO₃ inventory of deep-sea surface sediments driven by a lower CaCO₃:POC rain ratio [Archer and Maier-Reimer, 1994]. This takes place more gradually with an adjustment time scale of ~9 ka. There is also a third component, although this is only apparent in the response of the system to an artificial stepped transition in dust supply. This involves a gradual depletion in oceanic H₂SiO₄ inventory under the influence of enhanced biogenic opal export. This acts so as to partly reverse the influence on atmospheric composition of the first two components, taking place with an -folding time of ~25 ka (characteristic of direct perturbations made to the global Si cycle – see 5.4.8.3).

In addition to the model explaining slightly more than half the entire deglacial rise, there is an obvious marked similarity in shape between the time evolution of model and observed CO₂ concentrations. In particular, the model can explain virtually all the variability associated with full glacial periods (e.g., Stages 4 through 2). δ¹³C/CO₂ also exhibits a response consistent with early observed deglacial change, with a fall of some 0.19‰ over the interval 19–20 ka BP. However, an extremely marked response is exhibited by the calcite lysolines (Figure 5-13d,e). Associated with episodes of high dust deposition is intense dissolution and dilution (by increased detrital input) of calcite virtually throughout the depth of the water column, both in the Atlantic and Pacific basins. A perturbation of sedimentary composition of this magnitude is greater than can be supported by available paleoceanographic evidence, at least for the Pacific. There are a number of possible explanations for this mismatch:

- The simplistic zonally-averaged ocean circulation might lead to variability in mid-latitude export production being over-sensitive to changes in global Fe availability.
- The biological export scheme might be producing an unrealistic response of the CaCO₃:POC rain ratio to changes in Fe availability.
- The component of sedimentary CaCO₃ dissolution driven by the respiration of POC might be over-estimated.
- General deficiencies in the global CaCO₃ cycle, with insufficient burial of CaCO₃ in the benthic environment.

In light of these uncertainties the effect on atmospheric composition of whole-ocean changes in dust deposition should be considered as an upper limit of possible response.

5.4.10 The nitrogen hypothesis

Although it can’t be directly assessed in SUE, the oceanic nitrogen cycle has been suggested to be a potentially significant element in the dynamical evolution of the global carbon cycle over the late Quaternary. Various hypotheses have been forwarded to explain the observed glacial-interglacial variability in atmospheric composition, all envisioning in some way or other an oceanic NO₃ inventory higher during glacial periods than interglacials. Comparisons made between the predictions of ocean N cycle models and paleoceanographic δ¹⁵N proxy data go some way to supporting this assertion [Altabet and Curry, 1989].

Hypotheses forwarded for the rapid rise in xCO₂ at deglacial inception require the existence of a critical threshold within the oceanic nitrogen cycle. In this, during the descent into full glacial climate, dissolved O₂ concentrations in the ocean gradually fall until at some point widespread denitrification rapidly proceeds. Since the oceanic residence time of NO₂ is relatively short (3-10 ka [Codispoti, 1995]) the oceanic nitrate inventory could be quickly depleted, resulting in decreased biological productivity and thus a steep rise in atmospheric CO₂ [Knox and McElroy, 1984; Shaffer, 1990]. Declining [O₂] could be driven by increased productivity fuelled by nutrients (PO₄ and/or NO₃) eroded from shelf sediments exposed as sea level falls [McElroy, 1983; Shaffer, 1990].

A second hypothesis draws its basis from the likelihood that the modern ocean nitrogen cycle is far from steady state, with nitrogen losses from the ocean through denitrification (particularly on continental shelves) exceeding the combined input from rivers, atmosphere, and nitrogen fixation in the surface ocean [Berger and Vincent, 1986; Codispoti, 1995; McElroy, 1983]. With sea level fall, denitrification within neritic sediments ceases on the newly exposed shelf area. This leads to an increase in the oceanic N inventory, which fuels greater productivity leading to CO₂ draw-down [Altabet and Curry, 1989; Berger and Vincent, 1986; Codispoti, 1995; Ganeshram et al., 1995]. Although this mechanism can correctly generate CO₂ draw-down as glaciations intensify, deglacial CO₂ rise will lag sea level change contrary to observed temporal relationships, barring it from being a stand-alone explanation.
Figure 5-13 Effects on the global carbon cycle of glacial-interglacial variability in dust deposition to the world ocean. Shown are: (a) the forcing signal (normalized to a value of unity at the LGM); (b) model $xCO_2$ response (red line) compared to the Vostok ice core record [Petit et al., 1999] (grey line with data points); (c) model $^{13}C(CO_2)$ response (red line) compared to the Taylor Dome ice core record [Smith et al., 1999] (grey line with data points); (d) and (e) the response of the calcite lysocline in the (south) Atlantic and (south) Pacific basins, respectively.
Recently, a third variant has been suggested whereby increased Fe availability arising from aeolian dust deposition simulates the activity of diazotrophs such as *Trichodesmium* spp. in the surface ocean, thereby increasing the rate of N₂ fixation [Broecker and Henderson, 1998; Falkowski, 1997]. As a consequence, biological productivity and thus CO₂ draw-down follow (lagged) changes in aeolian dust supply, in general agreement with ice core records.

All these require as a minimum a detailed representation of the oceanic nitrogen cycle. However, this is still relatively poorly understood, particularly in terms of the rates and locations of nitrogen fixation and denitrification in the ocean. These in turn are critically dependent on seasonal and transient [O₂] and [Fe] distributions in the ocean, both of which are beyond the capability of the model configurations developed in the present study to reproduce sufficiently well for this purpose.

### 5.5 The role of the Southern Ocean

The Southern Ocean has long been regarded as a pivotal region for glacial-interglacial change in the global carbon cycle, with mechanisms relating to increased biological productivity [Knox and McElroy, 1984; Martin, 1990; Sarmiento and Toggweiler, 1984], decreased vertical mixing rates [Francois et al., 1997; Sigman et al., 1999a,b], increased wind speed [Keir, 1993a,b], and greater sea ice cover [Broecker and Peng, 1986; Moore et al., 2000; Stephens and Keeling, 2000] all having been proposed as playing important roles. The Southern Ocean achieves its climatic status both biochemically, as a result of the pool of excess nutrients found there [de Baar and Boyd, 2000], and through its physical oceanographic characteristics as a pathway of relatively low resistance linking the carbon reservoirs of the atmosphere and deep ocean [Sarmiento and Toggweiler, 1984]. Mechanisms influencing the carbon cycle relating to changes in biological productivity and sea ice extent in this region are now investigated in more detail with the aid of the higher resolution model implementation, SUE2108 (4.5), and constrained through consideration of additional paleoceanographic proxies.

#### 5.5.1 Glacial-interglacial variability in dust deposition

John Martin's glacial Fe fertilization hypothesis [Martin, 1990], formulated specifically with regards to the Southern Ocean is now tested. For this, dust deposition is only varied within the Southern Ocean, defined as ocean area south of 47.5°S (Figure 4-1). Restricting Fe fertilization in this way avoids many of the possible biases suspected to arise from whole-ocean dust forcing (5.4.9). Variability in atmospheric composition thereby obtained will now represent a minimum likely effect of whole-ocean change in dust deposition, particularly since the HBEI score of the model suggests that the role of the Southern Ocean in controlling xCO₂ may be underestimated (5.3.1). As before, the magnitudes of deposition flux under modern and LGM conditions is taken from Mahowald et al. [1999] with the forcing signal following Vostok dust concentrations [Petit et al., 1999].

The results of this exercise are summarized in Figure 5-14. The response of xCO₂ to declining dust fluxes in the Southern Ocean is an increase of 21.9 ppmv over the interval 19–40 ka BP with an associated decrease in δ¹³C(CO₂) of 0.15‰. Glacial draw-down in xCO₂ is a consequence of POC export being enhanced by ~100% south of about 54°S driven by increased Fe-availability. Although export from siliceous phytoplankton dominates this response (>95%), opal export increases by no more than ~35% due to greater Si utilization efficiency (enabled by higher ambient dissolved Fe levels). As a result of greater macro-nutrient utilization in the Southern Ocean there is decreased advective nutrient supply to the north, reducing POC export at lower latitudes. This slightly offsets xCO₂ draw-down driven by the Southern Ocean alone. In contrast to the significant response obtained in this study, box models of ocean Fe cycling have predicted that an increase in dust supply of order 1000 is required to produce a comparable decrease in xCO₂ [Lefèvre and Watson, 1999]. However, boundary conditions for this were taken from the Dupe et al. [1991] dust deposition field such that the supply of Fe to the modern surface Southern Ocean was almost entirely from below (~99%). Although adoption of a similar depositional field might diminish the response in SUE1608, aeolian Fe solubilities assumed here are relatively low and could be substantially increased (countering lower dust fluxes) without degrading the plausibility of model assumptions. This present study also differs from results obtained from of a coupled ecological and ocean box model which suggested that a realistic lifting of Fe limitation in the Southern Ocean would produce a draw-down in xCO₂ of only 12 ppmv [Popova et al., 2000]. However, this draw-down resulted from an increase in global new production of 1.7 GtC a⁻¹. That an increase in new production only slightly higher (2.2 GtC a⁻¹) obtained upon the lifting of physical constraints on productivity in the Southern Ocean in a 3D OGCM produced a draw-down of 34 ppmv [Kuz and Maier-Reimer, 1993] suggests that the relatively simple ocean model of Popova et al. [2000] may be overly insensitive to high latitude perturbations.

The general shape of the response of atmospheric composition over the course of the late Quaternary is noticeably different from that arising from whole ocean changes in dust flux (Figure 5-13). In particular, peak Holocene xCO₂ appears to be centred on ~7 ka BP. Since Fe-fertilization now takes place away from ocean regions overlying CaCO₃-rich sediments, there can be relatively little direct control exerted on CaCO₃ dissolution, with only modest changes in lysolme depth occurring (Figure 14d,e). The effect of the gradual recovery in oceanic H₂SiO₄ inventory following its previous glacial draw-down is now revealed – increasing H₂SiO₄ availability over the course of the Holocene shifts species composition towards siliceous phytoplankton which in turn produces a negative pressure on xCO₂, dominating the atmospheric response once the decline in dust flux has virtually ceased. The poor reproduction of the general trend observed in xCO₂ from Stage 5e through 2
Figure 5-14  Effects on the global carbon cycle of glacial-interglacial variability in dust supply to the Southern Ocean. Shown are: (a) the forcing signal (normalized to a value of unity at the LGM); (b) model $x$CO$_2$ response (red line) compared to the Vostok ice core record [Petit et al., 1999] (grey line with data points); (c) model $\delta^{13}$CO$_2$ response (red line) compared to the Taylor Dome ice core record [Smith et al., 1999] (grey line with data points); (d) and (e) the response of the calcite lysocline in the (south) Atlantic and (south) Pacific basins, respectively.
is partly due to the same effect, whereby a gradually decreasing $H_4SiO_4$ inventory works against CO$_2$ draw-down driven by increasing Fe availability in the Southern Ocean. The maximum glacial-interglacial contrast associated with Termination I is therefore some 27.7 ppmv (over 23/1747 k a BP) with 0.19‰ in $^{13}$C of CO$_2$.

Probably the most compelling aspect of the model atmospheric CO$_2$ response to dust variability concerns the timing of the major perturbations [Watson et al., 2000]. Figure 5-15 shows the events surrounding the last two glacial terminations on an expanded time scale. It can be seen that there is an excellent temporal match (within ~1 ka) between the onset of periods of rapid CO$_2$ rise in both modelled and observed signals. This is despite dust deposition fluxes having begun to decline at least 5 ka before this point, with little associated increase in CO$_2$. This lag has previously been interpreted by Broecker and Henderson [1998] as a powerful argument against John Martin’s hypothesis. That a system as complex as the global carbon cycle should be highly non-linear in this respect should hardly be surprising. Non-linearities arise in the model through a number of factors:

- Onset of (summer-time) $H_4SiO_4$ limitation in the more northerly reaches of the Southern Ocean.
- Through Michaelis Menten saturation kinetics in the biological export model, whereby further increases in export start to tail off rapidly with increasing Fe availability once half saturation concentrations have been surpassed.
- Increasing loss of Fe from the surface ocean through both ‘self-scavenging’ (2.2.5) and decreasing efficiency of Fe use by phytoplankton (i.e., increasing organic matter Fe:C ratios - see Figure 2-2).

These combine to produce the observed behaviour with POC export declining rapidly (and thus increasing CO$_2$) once dust deposition fluxes start to drop below a critical level. A degree of variability can still be observed even during peak glacial times. However, because the amplitude of the response during this time is highly dampened, an apparent lag is produced between the start of dust decline and significant CO$_2$ rise as observed by Broecker and Henderson [1988].

Paleoceanographic evidence from the Southern Ocean reveals a fundamental meridional divide, with glacial-interglacial changes in the opal content of deep-sea sediments either side of the position of the present-day Antarctic Polar Front (APF) being virtually opposite in sign. To the south, glacial-age sediments are characterized by a lower opal content than during interglacial periods, while to the north, it is interglacial sediments that are the more opal-rich [Anderson et al., 1998; Charles et al., 1991; De La Rocha et al., 1998; Francois et al., 1997; Kumar et al., 1995; Mortlock et al., 1991]. Although changes in preservation efficiency, sediment focussing, and the physiological effects

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**Figure 5-15** Temporal relationships surrounding glacial Terminations I and II between observed dust (thin black line, inverted at top) and CO$_2$ concentrations contained within the Vostok ice core (thick grey line with data points) [Petit et al., 1999] and model CO$_2$ (red line). The general decreasing trend in dust concentrations associated with the deglacial transition is highlighted in green, with the start of this dust decline marked by a dashed line, and the start of CO$_2$ rise by a dotted line.
of Fe availability on diatoms can all complicate the interpretation of this [Anderson et al., 1998; Boyle, 1998; Francois et al., 1997; Takeda, 1998], indicators of H_4SiO_4 utilization in the surface ocean such as opal Ge/Si ratios [Froelich et al., 1989; Mortlock et al., 1991] and δ^{30}Si [De La Rocha et al., 1998] are consistent at least with the sign of the observed change in opal content. This coupled antagonistic response presents us with an important validation target for proposed carbon cycle mechanisms operating in the Southern Ocean.

Figure 5.16 shows down-core variability in opal content in three cores spanning the APF in the Atlantic sector of the Southern Ocean [Mortlock et al., 1991]. Core RC13-259 (53°53'S) is located to the south of the APF while RC13-254 (48°34'S) and V22-108 (43°11'S) both come from further to the north. Also shown are records of down-core opal content contained within synthetic sediments cores located at the nearest equivalent model grid points. It can be seen that while deglacial increases in %opal are reproduced by the model for Terminations I and II in RC13-259 there is little other correspondence with this core. For the two cores located to the north of the APF the situation is far worse, with the model exhibiting a distinct anti-phase relationship with paleoceanographic observations. Low glacial opal content in these two synthetic cores is a direct consequence of local nutrient limitation, as macro-nutrients previously advected northwards across the APF are depleted under the influence of Fe-fertilization to the south. Clearly, either the effect of Fe fertilization in the Southern Ocean is being substantially overstated in the model, or one or more mechanisms important to the paleoceanographic record in the Southern Ocean have not been accounted for.

5.5.2 The role of changes in seasonal sea ice extent

It was shown earlier that, in isolation, changes in the maximum seasonal limits of sea ice extent in the Southern Ocean have little direct impact on the concentration of atmospheric CO_2. However, such changes might be critical in
explaining some of the observed paleoceanographic features of this region [Charles et al., 1991]. Fractional sea ice cover is, therefore, now varied in addition to changes in dust deposition. A record of sea ice cover is reconstructed for the past 400 ka as before (5.4.4), taking maximum (winter-time) and minimum (summer-time) coverage for each grid point region from the CLIMAP [1984] and taking Vostok /c100 D [Petit et al., 1999] as a signal template.

The response of atmospheric composition to this combined forcing is shown in Figure 5-17. During glacial periods, the presence of increased seasonal sea ice cover south of the APF results in much lower POC export, with a complete cessation south of about 62.5°S. Importantly, sea ice cover prevents escape of CO2 to the atmosphere during non-productive winter months. Previously utilized macro-nutrients are advected northwards, fuelling much greater (>100%) POC export just to the north of the APF in conjunction with higher Fe availability. The combination of these factors helps to enhance the glacial-interglacial contrast in xCO2 to 36.3 ppmv (19–0 ka BP). The overall form of the model xCO2 signal now bears a noticeably closer resemblance to the Vostok record than through Fe fertilization alone, particularly in the relative levels along the sequence of transitions Stage 5e through Stage 2. The full ~0.4‰ decrease observed in δ13C CO2 associated with deglacial inception can also now be accounted for.

The addition of varying sea ice extent brings about a remarkable change in the synthetic opal sediment records (Figure 5-18), with most of the major transitions in opal content reproduced extremely well (even the characteristic antagonistic variability either side of the APF). Although there is a substantial mismatch between model and observations during Stages 3 and 4 in RC13-259, this core has a known hiatus around this level [Anderson, pers comm], which could easily account for this. The correspondence in the timing of the changes are all the more surprising considering that the synthetic model age scale and that derived on the basis of /c100 18O stratigraphy in the observed records are unlikely to be equivalent. Indeed, by eye, RC13-254 appears to share an even greater similarity in opal variability with the paired synthetic model record than it does with core V29-105, located only 0°29' further to the north [Mortlock et al., 1991]. Absolute values of opal content do not correspond nearly so well, particularly for core RC13-254. However, this is not entirely unexpected since model sediments represent zonal means whilst individual deep-sea sediment cores record local conditions.

With regard to other paleoceanographic proxy evidence from the Southern Ocean, the model predicts generally lower glacial POM export well to the south of the APF compared to at present but becomes largely invariant with respect to the deglacial transition as the APF is approached.
This is consistent with organic matter export proxies such as $^{231}\text{Pa}/^{230}\text{Th}$ and $^{10}\text{Be}/^{230}\text{Th}$ ratios, authigenic U production, and Ba accumulation fluxes [Anderson et al., 1998; Francois et al., 1997; Kumar et al., 1995]. As a result, annual mean PO$_4$ concentrations are at their highest levels during the LGM, in line with lower PO$_4$ utilization suggested by Cd/Ca ratios [Elderfield and Rickaby, 2000; Rickaby and Elderfield, 1999]. In addition, the synthetic sediment record exhibits a deglacial ($19\rightarrow 0$ ka BP) rise in planktonic foraminiferal $^{13}$C of $\sim 1.0\%_o$ at 56.25°S (not shown), virtually identical to the change recorded in RC13-259 [Mortlock et al., 1991].

To the north of the APF the model also performs well against additional observational indicators. Substantially higher glacial POM export is again consistent with $^{231}\text{Pa}/^{230}\text{Th}$, $^{10}\text{Be}/^{230}\text{Th}$, authigenic U production, and Ba accumulation records, as well as with phytoplankton biomarkers [Anderson et al., 1998; Francois et al., 1997; Ikahara et al., 2000; Kumar et al., 1995]. Although temperature-corrected changes in sub-Antarctic Cd/Ca ratios have been interpreted as indicating a fairly minimal change in surface ocean PO$_4$ concentrations [Elderfield and Rickaby, 2000], uncertainties in this proxy allow for a reduction during the LGM of up to 0.5 µmol kg$^{-1}$, agreeing with a mean annual glacial draw-down in the model at 51.25°S and 43.75°S of $\sim 0.4$ and $\sim 0.3$ µmol kg$^{-1}$, respectively.

However, there is one further paleoceanographic indicator conspicuous by its absence in the discussion so far. Changes in the $^{15}$N isotopic composition of organic matter, a proxy for surface ocean nitrate utilization, is difficult to reconcile with the interpretation of other nutrient and export proxies in this region. Indeed, $^{15}$N suggests almost the complete opposite, with increased glacial nutrient utilization south of the APF and decreased or unchanged utilization to the north [Francois et al., 1997; Sigman et al., 1999a,b]. Factors controlling productivity proxies are therefore probably much less well understood than was previously assumed [Cullen et al., 1999; Sigman and Boyle, 2000]. In the case of $^{15}$N it is possible that the observed variability may be significantly affected by factors other than the degree of nitrate utilization. For instance, increased export production due to

\[ \text{Figure 5-18} \quad \text{Observed variability in sedimentary opal content from a transect spanning the approximate location of the modern Antarctic Polar Front in the Atlantic sector of the Southern Ocean [Mortlock et al., 1991] (blue) compared to synthetic model sediment core results (red) generated by SUE2108 and forced by glacial-interglacial variability in both dust deposition to the Southern Ocean and sea ice extent.} \]
pyrmenesiophytes such as *Phaeocystis antarctica* might radically alter N/P uptake ratios and thus decouple nitrate utilization from POC export, while the different $^{15}$N fractionation regime associated with sea ice algal communities might distort the mean $\delta^{15}$N signal [Elderfield and Rickaby, 2000].

5.6 Towards the complete picture

It is apparent, at least for the hypotheses tested in this present study that no single mechanisms can simultaneously fulfill the constraints dictated even by the limited paleoclimatic evidence considered so far. The explanation for the observed glacial-interglacial variability in the concentration of atmospheric CO$_2$ must therefore lie in a combination of processes at work together over the course of the late Quaternary. Indeed, it has already been shown that through combining changes in sea ice extent with dust deposition in the Southern Ocean it is possible to correctly account for a number of key paleoatmospheric and paleoceanographic features. Although in this case the influence on xCO$_2$ of sea ice in isolation is limited, its addition to dust deposition forcing is evidently non-linear, producing a marked improvement in the amplitude and overall character of the resulting xCO$_2$ signal. Mechanisms that in isolation appear to have little impact may therefore actually play an essential role as a component of wider change in the global carbon cycle. It is therefore important that even effects that are superficially ‘unhelpful’ in reproducing the observed atmospheric signal, such as CO$_2$ draw-down forced by deglacial increases in terrestrial carbon storage, must be included in order to build up a complete picture of the evolution of the system. All the separate mechanisms tested so far are now combined.

SUE2108 is run with the ocean carbon cycle forced by the following perturbations:

- sea level change (117 m 19–0 ka BP rise with a 1.05‰ decrease in ocean salinity) and following SPECMAP
- ocean surface temperature changes (19–0 ka BP difference taken from CLIMAP, but with LGM tropical temperatures cooler by an additional 2°C), with the NH weighted according to SPECMAP and the SH to Vostok $\delta^D$.
- wind speed changes in the SH only, weighted to Vostok Na concentrations
- variability in sea ice extent (19–0 ka BP difference taken from CLIMAP) in the SH only, weighted to Vostok $\delta^D$
- changes in Atlantic overturning circulation (19–0 ka BP difference taken from the two alternative circulations of the Bern 2D ZOGCM [Marchal, pers comm]) and following SPECMAP
- changes in terrestrial carbon storage (500 GtC 19–0 ka BP increase) following SPECMAP
- changes in neritic CaCO$_3$ storage (50% strength of the parameterization of Manhoven and Francois [1996])
- 6.6% solubility of SiO$_2$ (present at 66 wt%) in aeolian dust deposited to the ocean surface, and a variable sink in neritic opal accumulation rate (19–0 ka BP increase of ~0.8 Tmol Si a$^{-1}$)
- variability in aeolian Fe deposition to the Southern Ocean (19–0 ka BP decrease from Mahowald et al. [1999]) and following Vostok dust concentration changes.

In order to account for the fact that by simply ‘poisoning’ NADW formation (in order to produce the alternative circulation in the Bern 2D model) north Atlantic circulation does not shift southwards, sea ice extent is not extended in this composite scenario. To prevent overall glacial gas transfer rates in this region from then being overestimated wind speeds are also held invariant. The ocean carbon cycle is configured with a reduced POC-driven dissolution component to deep-sea sediment CaCO$_3$ diagenesis (5.4.7.1).

The results of this exercise are summarized in Figure 5-19. It can be seen that when combined these mechanisms can explain around two thirds of the observed variability in xCO$_2$ with a deglacial (19–0 ka BP) increase of some 61.1 ppmv. However, there are a number of specific areas where the model noticeably falls short with respect to the Vostok record. In particular, the initial rapid deglacial increase in xCO$_2$ surrounding Terminations I through III is significantly underestimated, there is too little intra-glacial variability (e.g., Stages 4 through 2), and the magnitude of the overall decline from interglacial to full glacial is lacking. A deglacial minimum in $\delta^13$C$_{CO_2}$ around ~15 ka BP is successfully predicted by the model, although it is less than half of the observed magnitude.

What are the reasons for the model-observation mismatches? Dealing with deglacial inception first, a critical aspect of combining together different model forcings which has not yet been fully considered is the relative phase between them [Henderson and Slowey, 2000]. The temporal evolution of boundary conditions of the northern hemisphere have, until now, been assumed to mirror changes in the SPECMAP $\delta^18$O stack [Imbrie et al., 1984]. However, this record is a composite of mainly planktonic foraminifera and is not corrected for changes in ocean temperature. Rates of change predicted by this record and the timing of the mid-point of the deglacial transition, while sufficient for the investigation of the magnitude of glacial-interglacial change and to define long-term trends arising from single mechanisms, is unlikely to be adequate in a composite environment. Of particular concern in this regard is when (and how rapidly) increases in carbon stored in terrestrial ecosystems occur, since this acts so as to oppose the general trend of deglacial CO$_2$ increase. Indeed, it is noticeable that the model is more successful in predicting observed xCO$_2$ variability further back than ~250 ka BP, a period when the SPECMAP and Vostok time scales appear to be significantly out of sync.

An improved temporal framework for forcing the composite scenario over the course of Termination I can be devised by deriving signal templates for NH-weighted change from proxy signals taken from the GRIP Greenland ice core in lieu of SPECMAP. Following Blunier et al. [1997], the GRIP ice core is placed onto the same age scale as the Vostok CO$_2$ target by matching changes in CH$_4$ concentrations surrounding the Younger Dryas event as
Figure 5-19  Effects on the global carbon cycle of a composite scenario for glacial-interglacial change. Shown are; (a) model $x$CO$_2$ response (red line) compared to the Vostok ice core record [Petit et al., 1999] (grey line with data points); (b) model $\delta^{13}$C$_{\text{CO}_2}$ response (red line) compared to the Taylor Dome ice core record [Smith et al., 1999] (grey line with data points); (c) and (d) the response of the calcite lysocline in the (south) Atlantic and (south) Pacific basins, respectively.
recorded in these two cores. The \( \delta^{18}O_{isc} \) record [Johnsen et al., 1997], a proxy for local (air) temperature, is adopted to describe the evolution of NH-weighted SSTs over the last 20 ka together with changes in the Atlantic overturning circulation. The deglacial evolution of sea level is taken from Fairbanks [1989] and placed onto a common chronology with the other forcing records by linearly transforming \( ^{14}C \) ages so that the period separating meltwater pulses 1A and 1B corresponds with the Younger Dryas, as defined by GRIP \( \delta^{18}O_{isc} \). Estimating the past history of changes in the size of the terrestrial biosphere carbon reservoir is much more difficult. While variations in atmospheric CH\(_4\) concentrations relate to changes in terrestrial ecosystems, much of the magnitude of \( xCH_4 \) variability over the deglacial period is thought to relate to changes in low latitude wetland extent [Blunier et al., 1995] and thus predominantly reflect rapid changes occurring in local (tropical) hydrological regime rather than global biomass. Sea level rise (Fairbanks [1989]) is instead taken as a proxy for global biospheric state, but lagged with an \( e \)-folding time of 2 ka to account for the time taken for climax ecosystems to develop and soil carbon levels to stabilize. The maximum deglacial (19\textendash}0 ka BP) change is scaled to 500 GtC as before (5.4.6).

The effect on atmospheric composition of the new Termination I forcing chronologies is shown in Figure 5-20. It can be seen that the model now explains slightly more of the initial rapid increase in \( xCO_2 \) with the hiatus in \( CO_2 \) rise surrounding the Younger Dryas reproduced. However, even with this improved inter-hemispheric chronology the model still only accounts for almost 50\% of \( CO_2 \) rise surrounding deglacial inception. With respect to \( \delta^{13}C_{CO_2} \) the improvement is also partial. Again, the hiatus of the Younger Dryas period is reproduced but the initial transient is shallower than observed. It is likely that the relative chronologies of the forcings may still not reflect the real sequence of events. In particular, it is possible that collapse in sea ice extent was either slightly earlier or much more rapid than changes recorded by local temperature (as indicated by Vostok \( \deltaD \)). This would enable a much more pronounced early minimum in \( \delta^{13}C_{CO_2} \). Changes in convective regime, particularly if resulting in a greater degree of exposure of the atmosphere to the deep ocean would also enhance the respective responses in both \( xCO_2 \) and \( \delta^{13}C_{CO_2} \). In addition, buildup in carbon stored in the terrestrial biosphere might be more sluggish still.

A second aspect of apparent deficiencies in predicted \( xCO_2 \) concerns the inherent sensitivity of model response. It has already been seen that according to indices of inter-regional control of levels of \( xCO_2 \) (5.3), SUE2108 has a tendency to under-estimate the importance of that high latitude regions of the world ocean. At least part of the missing response at deglacial inception and in intra-glacial variability (especially Stages 4 through 2) might then be due to an underestimation of mechanisms such as Fe fertilization in the Southern Ocean. Likewise, the model may be too insensitive to changes in fractional sea ice cover, particularly should the Southern Ocean actually be a stronger source of \( CO_2 \) to the atmosphere under interglacial conditions than it predicts. There is also the question of the real effect of whole ocean aeolian deposition as opposed to the minimum case (i.e., Southern Ocean only) imposed in the composite scenario. It would not be unreasonable to assume that Fe fertilization could account for the missing intra-glacial variability in \( xCO_2 \), particularly since no other potential forcings share a similar pattern over this period. This would imply an additional \( \sim 15 \) ppmv at deglacial inception taking the initial rise to around 40 ppmv (only 10 ppmv short of that observed). The deficit in total \( CO_2 \) increase since the LGM would then be reduced to \( \sim 15 \) ppmv. Aside from model sensitivity to Fe availability, the temporal evolution of the global silica cycle also plays a role. Since the onset of \( H_2SiO_4 \) limitation in parts of the Southern ocean appears to be a key factor in the degree of \( CO_2 \) draw-down obtained, if the ice ocean inventory of dissolved Si is incorrectly predicted at the LGM then the magnitude of the effect of Fe fertilization may also be in error. Unfortunately, there are no reliable quantitative constraints available as to the state of the global silica cycle over the late Quaternary, leaving this as an unknown factor.

Figure 5-20 Evolutions of atmospheric composition surrounding Termination I as a result of the composite scenario with improved temporal relationships of northern hemisphere forcing with respect to change in the southern hemisphere; (a) model \( \delta^{13}C_{CO_2} \) (red line) with observations from the Taylor Dome ice core record [Smith et al., 1999] (grey line with data points), (b) model \( xCO_2 \) (red line) with observations from the Vostok ice core record [Petit et al., 1999] (grey line with data points).
Perhaps more problematic to the composite scenario is the response of deep-sea sedimentary CaCO3. Preservation of CaCO3 during glacial periods is over-predicted in the Pacific with a deepening of the calcite lysol ine of ~1 km. Increased aeolian detrital supply to the deep ocean during glacial periods (e.g., Stages 2, 4, and 6) has a significant diluting effect on CaCO3 content, indicated by a sharp shoaling of the depth of the lysol ine. That this feature is not apparent in the lysol ine evolution reconstruction of Farrell and Prell [1989] (if not an artefact of their relatively low core resolution and interpolation algorithm) may be a consequence of zonal averaging in the model. Mean detrital deposition to ocean zones in the model will be biased by a component of elevated dust fluxes near ocean margins, and thus will not be representative of the more remote location of many of the sediment cores used in lysol ine reconstructions. Similarly, accepting some of the glacial lysol ine shoaling as an artefact of model resolution places reconstructed sedimentary CaCO3 changes in the Atlantic in first-order agreement with observations. The comparatively muted response of the CCD in both Atlantic and Pacific basins is in accordance with observations.

Interestingly, periods of peak detrital input aside, the thickness of the lysol ine transition zone in the Pacific appears to be relatively invariant compared to that in the Atlantic. This suggests that Pacific CaCO3 sediments are responding primarily to changes in ocean pH rather than being controlled by changes in the CaCO3:POC rain ratio. The excessive excursions in lysol ine depth in the Pacific together with over-estimated glacial CaCO3 preservation thus indicates too great a change in deep ocean pH, which at the equator is some ~0.12 pH units higher (3300 depth) during glacial times. This is in contrast to the increase of ~0.3 pH units deduced via the ³¹B ‘paleo-acidity’ proxy in this region [Sanyal et al., 1995, 1997]. If this proxy were to be correct then an even greater excursion in lysol ine depth than that predicted would be expected. This apparent contradiction between evidence for glacial-interglacial changes in ocean chemistry deduced from sedimentary CaCO3 and from boron isotopes has been a considerable puzzle in paleoceanography [Archer et al., 2000; Sanyal et al., 1995; Sigman et al., 1998]. However, there is a substantial inter-specific vital influence on ³¹B fractionation upon calcite deposition [Sanyal et al., 1996; Vengosh et al., 1991] . Benthic foraminiferal ³¹B measurements are made on mixed assemblages because of the analytical requirements of this method [Sanyal et al., 1996, 1997]. Therefore, there is no guarantee that changes in bulk ³¹B represent changes in ambient ocean pH as opposed to changes in species composition or even of the sedimentary environment [Berger and Vincent, 1986; Mackensen et al., 1993; Palmer et al., 1998]. If, for the sake of argument, the interpretation of ³¹B is taken to be correct, then deep waters in the Pacific during the last glacial were characterized by a carbonate ion content some ~100 µmol kg⁻¹ higher than at present [Sanyal et al., 1995]. However, applying the least [CO₃]⁻ sensitive dependence of foraminiferal ¹³C fractionation observed by [Spero et al., 1997] (2.2.6.4) would suggest that glacial ocean ¹³C-DIC was actually some ~0.6‰ higher than observed, giving a net deglacial decrease in ³¹C-DIC of ~0.3‰. This completely contradicts all that is currently accepted regarding increased storage of carbon in the terrestrial biosphere since the LGM (5.4.6). Given that both proxies extrapolate planktonic fractionation behaviour to the benthic environment [Spero et al., 1997], it would be difficult to entirely accept one whilst disregarding the other. It is, therefore, concluded that the ³¹B paleo-acidity proxy may well overestimate the magnitude of glacial-interglacial pH change, perhaps by a factor of three. [CO₃]⁻ dependent ¹³C fractionation may be similarly overstated for the benthic environment.

In light of its poorly quantified envelope of operation, it is tempting to remove the ‘coral reef hypothesis’ from the composite scenario in order to meet criteria laid down by the paleoceanographic CaCO3 record. Indeed, without this mechanism both modern and LGM-age CaCO3 distributions in the model are consistent with reconstructions (not shown). However, intuitively it seems unlikely that rates of neritic CaCO3 accumulation should have been largely invariant with respect to substantial changes in sea level and shelf area. However, it is possible that these effects were offset by decreased riverine supply of DIC and ALK (derived via continental weathering) during glacial periods. Although the ‘coral reef hypothesis’ produces a lagged response in xCO2 at deglaciation, it is an important component in setting the overall sawtooth form of the glacial-interglacial cycles. It would therefore appear that a mechanism is required that enhances the underlying decline of xCO2 as glacials deepen but does not drive deep ocean pH overly high. Such a solution might lie in the long-overlooked phosphate extraction model. As an explanation for the entire magnitude of glacial-interglacial change this fell foul of timing issues together with considerations of oceanic ¹³C-DIC and dissolved oxygen changes [Keir and Berger, 1983; Knox and McElroy, 1984; Shaffer, 1990]. However, none of these need be violated if only a proportion of the total CO2 draw-down is required. In the absence of parallel changes in the dissolved Si inventory of the ocean, only non-siliceous phytoplankton might generally be expected to be able to take advantage of increased PO4 availability. This would lead to increased CaCO3 export and thus the removal of DIC and ALK from the ocean, exerting a negative pressure on pH. Unfortunately, little is currently quantitatively understood with regards to deposition in the neritic environment and less still reliably known about the fate of interglacial-age sediments deposited there when sea level falls.

Finally, considering the problems discussed above regarding adherence to ocean chemical constraints, even in order to achieve only two thirds of the observed amplitude of glacial-interglacial xCO2 variability, it is difficult to envisage a substantially larger change in terrestrial carbon inventory than the 500GtC considered so far, as has been proposed by some authors [Adams et al., 1990; Adams and Faure, 1998; Maslin et al., 1995].
5.7 The sequence of events surrounding Termination I

In light of the results from both the individual mechanisms tested and from the composite scenario, a conceptual sequence of events perturbing the global carbon cycle at deglaciation is proposed. Termination I is chosen for illustration. A sequence of transitional stages between the end of the LGM and the present-day (pre-industrial) is defined on the basis of identifiable paired trends in both $xCO_2$ and $\delta^{13}CO_2$ with additional constraints taken from the timing of The Antarctic Cold Reversal (ACR) and Younger Dryas (as delineated by observed variations in Vostok and GRIP CH4 concentrations [Blunier et al., 1997], and from the recent results presented from DOME C by Monnin et al. [2001]). Marine Isotope Stage 1 is subdivided for illustration, something akin to that for Stage 5. The proposed sequence of events surrounding Termination I is as follows (Figure 5-21):

**Stage 2.** Full glacial conditions. High rates of dust supply to the Southern Ocean (although already starting to decline towards the end of this period). Generally iron replete conditions with a dominance of siliceous phytoplankton in the determination of POC export production. Low levels of $xCO_2$ and intermediate $\delta^{13}CO_2$.

**Stage 1g.** Dust deposition to the Southern Ocean decline rapidly and iron starts to limit export production leading to a rise in $xCO_2$. A combination of decreased productivity together with a shift in ecosystem composition towards non-siliceous species (which fractionate $^{13}$C in organic matter less strongly) results in a drop in $\delta^{13}CO_2$ concurrent to the $xCO_2$ rise. The negative trend in atmospheric isotopic signature is exacerbated by a collapse of the maximum seasonal limits of sea ice extent in the Southern Ocean, perhaps driven by a combination of increasing local temperature and relatively high austral summer insolation levels at 65°S at this time [Jouzel et al., 1987, 1995; Laskar et al., 1993]. Slightly offsetting the negative excursion in $\delta^{13}CO_2$ but enforcing the $xCO_2$ rise during this stage are increasing SSTs in the southern hemisphere.

**Stage 1f.** Dust decline is virtually complete, with Southern Ocean productivity at near-interglacial levels. There is a much slower rise in $xCO_2$ levels, perhaps due to increases in carbon stored in the terrestrial biosphere, particularly in the tropics and in the SH offsetting the effect of increasing SSTs. Together these two effects constructively interfere to force $\delta^{13}CO_2$ to start to rise.

**Stage 1e.** Bölling/Alleröd. The northern hemisphere now starts to deglaciate, with substantial ice sheet collapse. Rapidly rising SSTs in the NH together with an intensification of the Atlantic overturning circulation drive $CO_2$ levels higher. This is later compensated for by lower SH SSTs during the ACR [Blunier et al., 1997; Smith et al., 1999] producing a slight decline towards the end of this stage. Initial continuing increases in $\delta^{13}CO_2$ also reflect the sudden change in NH climate and increases in terrestrial biome carbon storage (although it is not immediately obvious what might subsequently produce the slight decline observed).

**Stage 1d.** Younger Dryas. Return to near-LGM conditions in the North Atlantic region. Atmospheric $CO_2$ concentrations increase again following the end of the ACR event. Reductions in carbon stored in the terrestrial biosphere could produce further increases in $xCO_2$ while reducing $\delta^{13}CO_2$, as observed.

**Stage 1c.** Deglaciation restarts. Similar initial forcings on the system as per Stage 1e. Global climate attains typical interglacial conditions. Further increases in $\delta^{13}CO_2$ throughout this stage driven by higher SSTs in both hemispheres together with greater terrestrial biome carbon storage. After the initial rise the is a gradual reduction in $xCO_2$ possibly a result of the continued expansion of terrestrial ecosystems, particularly in northern subtropical regions [Brovkin et al., 1998; Claussen and Gayler, 1997; Indermühle et al., 1999].

**Stage 1b.** Collapse of sub-tropical ecosystems with a slight cooling in climate, leading to a significant fall in $\delta^{13}CO_2$ over the course of this stage, with reduced terrestrial biomass dominating over SST effects to bring about an increase in $xCO_2$ [Indermühle et al., 1999].

**Stage 1a.** Slight decrease in $xCO_2$ with an increase in $\delta^{13}CO_2$ despite no significant climatic change occurring during this interval, perhaps as a result of the expansion of northern hemisphere peatlands [Klinget al., 1996]. Changes in the oceanic ${CaCO}_3$ system (i.e., ‘carbonate compensation’ and neritic CaCO3 storage) and dissolved Si cycles have not been discussed in the above. While these have time constants of change too long for them to be directly involved in some of the observed rapid variations in the sign of change of atmospheric composition, they will be important in determining the overall deglacial trend.

Supporting the causal linkage between dust supply and $\delta^{13}CO_2$ suggested to account for part of the Stage 1g anomaly are records presented by Ninnemann and Charles [1999] of planktonic foraminiferal $\delta^{13}$C from the Southern Ocean. Not only do these exhibit a prominent negative excursion consistent with the Taylor Dome record [Smith et al., 1999] following the dust decline at the end of Stage 2, but also a (slightly smaller) negative excursion at around 60 ka BP, apparently synchronous with the earlier substantive drop-off in dust deposition (as recorded in the Vostok core [Petit et al., 1999]). Additional palaeoceanographic evidence that changes in productivity drive at least part of the Stage 1g $\delta^{13}CO_2$ excursion comes from benthic foraminiferal $δ^{18}C$ records from the South Atlantic [Charles et al., 1996]. These show prominent negative anomalies, synchronous both with initial rise in local SSTs (itself synchronous with Vostok $δD$) and again, also with the Stage 3/4 boundary.
5.8 What ultimately drives the deglacial rise in atmospheric CO2?

Should the onset of Fe limitation in the Southern Ocean brought about by a decline in dust deposition to this region be the primary driving force behind the initial deglacial increase in atmospheric CO2 levels, what might cause dust to decline in the first place? The mechanisms driving dust variability are especially intriguing since at each glacial termination the decline appears to precede significant changes in other indicators of southern hemisphere climate (such as ice core δD and δ13C CO2) by some ~5 ka. The interval is as great as 10 ka with respect to northern hemisphere ice sheet collapse [Broecker and Henderson, 1998]. A clue comes from the apparent correlation between periods of rapid sea level fall and peak dust deposition fluxes (Figure 5-22), at least over the last ~250 ka (before which the SPECMAP and Vostok time scales diverge). Furthermore, dust starts to decline slightly prior to the stabilization of sea level at local minima.

Mineralogical and isotopic analysis suggest that the primary source area for dust deposited at Vostok during the LGM was Patagonia [Grousset et al., 1992]. The effective land area of this region would have been substantially enhanced during glacial periods of low sea level stand through the exposure of the adjoining continental shelves [Iriondo, 2000]. Unconsolidated shelf sediments could have been easily deflated and transported by the prevailing winds out across the Southern Ocean [Iriondo, 2000]. The simplest explanation for the apparent relationship between sea level and Vostok dust fluxes would then be that dust supply is directly related to exposed shelf area. However, assuming dust fluxes in proportion to this area (derived from mean ocean bathymetry lying between 20°S and 70°S [ETOPO5, 1988], encompassing the Patagonian region [Basile et al., 1997]) produces a response that bears little resemblance to the Vostok record. On the basis that dust source regions have a finite lifetime after which they become effectively completely deflated [Pyr, 1989; Rea, 1994], the source strength of each portion of shelf newly exposed is relaxed. With a characteristic decay rate of 0.1 ka⁻¹, a series of sharp peaks is obtained lying atop of a background (not shown).

Figure 5-21 Conceptual transition stages in the global carbon cycle surrounding Termination I; (a) observed atmospheric CO2 concentration records from the Vostok [Petit et al., 1999] (circles) and Taylor Dome [Smith et al., 1999] (triangles) ice cores placed on the Vostok chronology as described previously (5.2), with suggested general trends indicated by the orange line, (b) observed δ13C CO2 record from the Taylor Dome [Smith et al., 1999] (triangles) ice core, with suggested general trends again indicated.
Although the timing of these peaks is in excellent agreement with Vostok, since their heights relate directly to the rate and overall magnitude of each fall in sea level, the strongest dust peak is predicted to occur with the Stage 5e/5d transition, contrary to the Vostok record. One final adjustment is now made to the model: since a warm wet climate is conducive to vegetation cover and will hinder atmospheric dust transport [Yung et al., 1996], account must be taken of the gradual climatic transition into cold dry glacial conditions. Model dust fluxes are therefore arbitrarily weighted by the square of SPECMAP (normalized to a value of unity at 19 ka BP). The result of this final model is shown in Figure 5-22. It can be seen that not only can the relative heights and timing of the major dust peaks be reproduced, so can background trends. For the Stage 4 and 2 dust peaks in particular, the respective phases of declining dust fluxes between model and observations correspond to within ~1 ka.

Despite the surprising success of such a simple model, recent studies of the provenance of dust deposited in Antarctic ice casts some doubt on this shelf dust source hypothesis. Detailed geochemical analyses based on the Rb-Sr and Sm-Nd isotopic systems put the primary source regions of dust deposited in East Antarctica as Patagonian loess rather than sediments lying on the Argentine continental shelf [Basile et al., 1997]. Although this suggests that sea level fall cannot directly control dust sources through shelf exposure, the apparent linkage between periods of rapid change as delineated by the SPECMAP δ¹⁸O record [Imbrie et al., 1984] and peak dust concentrations still requires an explanation. A second hypothesis is therefore advanced, in that during periods of ice sheet advance the supply of glacially-eroded material (particularly fines such as rock flour) fuels the overall rate of dust deflation from Patagonia. In such a scenario, supply falls off as active erosion of new regions ceases with the stabilization of ice extent, with the result that dust fluxes start to decline just as peak glacial conditions are attained, as observed.

Sudden increases in the concentration of atmospheric CO₂ in the atmosphere could thus be a consequence of glacio-geological dynamics. That deglaciation occurs following Stage 2 rather than Stage 4 may be due to a critical glacial extent having been attained in Patagonia, analogous to the ‘excess ice’ hypothesis [Paillard, 1998; Raymo, 1997; Ridgwell et al., 1999], with the catastrophic collapse of dust supply at the end of Stage 2 perhaps occurring as glaciers reach the ocean margin or extend beyond regions rich in erodible

![Figure 5-22](image_url)
material. Whatever the ultimate cause of dust variability, declining deposition rates to the Southern Ocean is the only mechanism that clearly precedes $x\text{CO}_2$ rise, strongly implicating it in the initial deglacial perturbation of the global carbon cycle and thus in the dynamics of the 100 ka ice age cycles of the late Quaternary.
Conclusions

The following main conclusions can be drawn from the study presented herein;

(i) simulation of the modern carbon cycle
The framework for biogeochemical cycling developed here, when used in conjunction with a zonally-averaged representation of ocean circulation enables a reasonable simile of the modern ocean carbon cycle to be produced. However, a number of apparent deficiencies arise as a result of the simplified two dimensional circulation, particularly that of ‘nutrient trapping’ in equatorial up-welling zones. There are also associated problems manifested ‘down-stream’; as a consequence of the strong control on total nutrient supply to mid-latitude gyre regions exerted by the equatorial zones, biogeochemical changes at the equator (such as through iron fertilization) are amplified to produce unrealistically large changes in biological productivity at higher latitudes. To retain model biogeochemical integrity, a simple topological fix is employed to lessen the degree of nutrient trapping. This has the advantage of avoiding any serious distortion of global nutrient cycles, such as might occur through the prescription of an excessive dissolved organic matter component to export production.

Despite the obvious first-order importance of the depth at which nutrients are released back into the ocean, the remineralization of biogenic particulates within the water column has been a relatively neglected area of model development. In particular, only recently has account been taken of important influences on opal remineralization such as that of ambient temperature. A new scheme for the remineralization of biogenic opal within the water column developed here, when contrasted with available opal sediment trap data, is demonstrated to offer a significant improvement on previous schemes. However, serious deficiencies in the reproduction of some observations remain, suggesting that further progress will require additional sediment trap observations to be made and the dissolution of biogenic opal more fully (experimentally) characterized. The development and inclusion of mechanistic schemes able to take into account factors determining particulate matter settling rates (including the representation of rapid export events such as those associated with phytoplankton blooms in the surface ocean) would be likely to result in a substantial improvement in overall model realism.

While indices of differential regional control exerted on atmospheric composition are difficult to interpret in terms of the underlying processes responsible, the wide range of sensitivities exhibited to perturbation in key regions (such as the Southern Ocean) amongst different models suggests that more care needs to be taken in model interpretation. Generation of a standard ‘benchmark’ of response, perhaps obtained through the one-off use of a state-of-the-art model could form the basis for subsequent quantitative assessment of predictions made by different model formulations.

(ii) simulation of the dynamic evolution of the system
The use of a representation of world ocean circulation derived from a zonally-averaged ocean general circulation model has important computational advantages over its three-dimensional counterpart, enabling easy access to multi-millennial time scales. Fully dynamic (i.e., ‘time-stepping’) model simulations made over multiple glacial-interglacial cycles provides a means for more fully utilizing the information contained within ice core records. Consideration of both the phase and amplitude of observed variability provides an important constraint on the underlying mechanisms. Ideally, model assessment would be made quantitatively via statistical and spectral methodologies, with system forcings taking into account spatial heterogeneity in the timing and magnitude of changes in boundary conditions. However, full global reconstructions are currently available only for discrete time-slices. An alternative might be to generate continuous time series of spatially-explicit boundary conditions from within a suitable Earth System Model. Forcings on the carbon cycle produced by such a model would have the advantage of being internally consistent, in contrast to paleoclimatic reconstructions made from sediment and ice cores for which there is no precise common chronology. As demonstrated here, even on a simple visual basis, it is still possible to make better use of the Vostok record, with the likely type of mechanism(s) missing from a composite scenario deduced through consideration of the timing of periods of greatest model-observation mismatch.

There is considerable interplay between the various biogeochemical cycles on glacial-interglacial time scales. Central to these is that of the ocean silicic acid cycle, which exerts important controls upon atmospheric and sediment composition through its influence upon biological productivity (particularly in determining the export ratio of calcium carbonate (CaCO₃) to organic carbon). With an adjustment time of order ~15 ka for the oceanic silicic acid inventory and ~9 ka for the calcite lysocline, it is not necessarily safe to rely upon steady-states when considering glacial-interglacial change. Indeed, the interaction between these two cycles produces an even slower response in the atmospheric concentration of carbon dioxide (xCO₂) with respect to perturbations of the global silicic acid cycle in the model, characterized by an e-folding time of ~23 ka. The traditional methodology of contrasting pairs of time slices made at steady state either side of the last deglacial transition (an interval of less than 18 ka) may, therefore, result in an...
erroneous assessment of the magnitude of the predicted change in $xCO_2$.

(iii) simulation of paleoceanographic proxies

Comparisons made between synthetic sediment cores and paleoceanographic proxy records can provide important additional constraints in the elucidation of the processes involved in glacial-interglacial change. For example, although in isolation, reduced aeolian iron supply to the Southern Ocean could explain a significant fraction of the initial observed deglacial increase in $xCO_2$, the paleoceanographic proxy record in this region clearly indicated an important omission. The anti-phase relationship exhibited by glacial-interglacial changes in sedimentary opal content in cores located either side of the Antarctic Polar Front suggested the presence of contrasting meridional variability in boundary conditions. The substantial glacial expansion of seasonal sea ice limits south of the Antarctic Polar Front, with little change to the north, represents such a contrast. The generation of synthetic sediment records driven by this additional forcing does indeed confirm sea ice extent as a vital element of glacial-interglacial change in this region.

(iv) the role of the neritic environment in the global carbon cycle

Changes in the neritic environment have the potential to account for much of the amplitude of observed $xCO_2$ variability, particularly through changes in the accumulation rate of CaCO$_3$ and of organic matter (including its associated nutrients). There is, therefore, a compelling need to understand the role that the coastal system plays in the global carbon cycle. Mechanistic descriptions need to be developed for this environment and coupled with existing carbon cycle models (which tend to represent just the open ocean system).

(v) the role of the Southern Ocean in the global carbon cycle

Results from this study suggest that changes in the surface boundary conditions of the Southern Ocean played a key role in perturbing the global carbon cycle, at least at the time of deglacial inception. Rapid reductions in aeolian iron supply and in maximum seasonal sea ice extents can, between them, explain much of the initial rise in $xCO_2$ together with the concurrent decrease in its stable isotopic signature. In addition, these two processes produce a response in the ocean surface consistent with the bulk of paleoceanographic observations made in this region. Crucially, even the apparently antagonistic response of the system either side of the Antarctic Polar Front can be accounted for. It is likely that changes in convective regime in the Southern Ocean (not tested here) will have enhanced the effect on the atmosphere.

(vi) glacial-interglacial perturbations in the global carbon cycle

None of the mechanisms considered in this study when considered in isolation are able to simultaneously meet all the constraints dictated by the paleoclimatic record. With the mechanisms applied in concert, though, over two thirds of the amplitude of $xCO_2$ variability can be explained. However, the component of $xCO_2$ change due to the ‘Coral Reef Hypothesis’ may be overstated (on the basis of deficiencies in the synthetic model paleoceanographic CaCO$_3$ record) which would reduce the effective magnitude of $xCO_2$ which can be accounted for consistent with paleoceanographic observations. Model results suggest that perturbations located in the Southern Ocean (aeolian Fe supply, sea ice extent) could potentially account for all of the observed glacial variability in $xCO_2$ together with the initial deglacial rise. However, longer-term changes in the system routed in oceanic CaCO$_3$ and silicic acid cycles probably play an important role in defining the envelope of gradual $xCO_2$ draw-down immediately following each interglacial period. Driving mechanisms for this probably include decreasing neritic CaCO$_3$ (‘Coral Reef Hypothesis’) and organic matter (‘Phosphate Extraction Model’) accumulation rates (as sea level falls), together with increasing dissolved Si supply. Considering the difficulties in generating a sufficient amplitude of $xCO_2$ variability without contravening paleoceanographic CaCO$_3$ constraints, it is not easy to reconcile deglacial increases in the carbon inventory of the terrestrial biosphere substantially more than the 500 GtC assumed here.

(vii) dust supply and the ice age cycles

Solely on the basis of its being the only boundary condition to substantially change prior to initial deglacial rise in $xCO_2$ variability in dust deposition rates to the world ocean would seem likely to be a key element in glacial-interglacial change. This is supported by model results presented here of the effect on $xCO_2$ of variable aeolian iron supply, either to the Southern Ocean or to the ocean as a whole. These results demonstrate that the apparent lag observed in ice cores between the start of declining aeolian deposition rates and initial deglacial $xCO_2$ rise can be accounted for as a result of non-linearities inherent in the ocean biogeochemical system. If variability in aeolian iron supply to the ocean does play such a critical role in glacial-interglacial change then it is important that processes controlling dust sources, atmospheric transport, and deposition (including issues of iron solubility) all be understood more fully. It is suggested here that the decline in aeolian deposition rates in the Antarctic towards the end of Stage 2 is inexorably linked to a maximum in global (or local) ice volume having been obtained. Understanding the determinants of dust supply could potentially reveal the reasons for the timing of deglaciation, thus unlocking the secrets of the 100 ka ice age cycles.
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Appendix I

Carbonate system thermodynamics

The inorganic aqueous carbonate system in the ocean comprises four dissolved species, \( \text{CO}_2, \text{H}_2\text{CO}_3, \text{HCO}_3^-, \) and \( \text{CO}_3^{2-} \), characterized by the following series of reactions

\[
\begin{align*}
\text{CO}_2(0) & \leftrightarrow K_0 \text{CO}_2(0) \\
\text{CO}_2(0) + \text{H}_2\text{O} & \leftrightarrow K_1 \text{H}_2\text{CO}_3 \\
\text{H}_2\text{O} + \text{CO}_2(0) & \leftrightarrow K_2 \text{HCO}_3^- + \text{H}^+ \\
\text{HCO}_3^- & \leftrightarrow K_3 \text{H}^+ + \text{CO}_3^{2-}
\end{align*}
\]

where \( K_0 \) is the solubility coefficient of \( \text{CO}_2 \), \( K_1 \) is the dissociation constant of \( \text{H}_2\text{O} \), and \( K_1 \) and \( K_2 \) are the first and second dissociation constants of carbonic acid, respectively, all referenced to seawater. Given the total dissolved inorganic \( \text{CO}_2 \) (\( \Sigma\text{CO}_2 \)) and carbonate alkalinity (\( A_C \)) concentration in seawater, this system can be defined \([\text{Millero and Sohn, 1992}]\) by solving for three of the dissolved carbonate species

\[
\begin{align*}
[\text{CO}_2] &= \Sigma\text{CO}_2 - A_C + \\
A_C & \cdot K - \Sigma\text{CO}_2 \cdot K - 4 \cdot A_C + Z \\
& \frac{2}{(K - 4)} \\
[\text{HCO}_3^-] &= \frac{\Sigma\text{CO}_2 \cdot K - Z}{K - 4} \\
[\text{CO}_3^{2-}] &= \frac{A_C \cdot K - \Sigma\text{CO}_2 \cdot K - 4 \cdot A_C + Z}{2 \cdot (K - 4)}
\end{align*}
\]

where

\[
K = \frac{K_1}{K_2}
\]

and

\[
Z = \left( (4 \cdot A_C + \Sigma\text{CO}_2 \cdot K - A_C \cdot K)^2 + 4 \cdot (K - 4) \cdot A_C^2 \right)^{0.5}
\]

The total alkalinity (\( A_T \)) of seawater is defined as the “concentration of all the bases that can accept \( \text{H}^+ \) when a titration is made with \( \text{HCl} \) to the carbonic acid endpoint” \([\text{Millero and Sohn, 1992}]\). However, in order to improve overall model computational efficiency, the exact definition of \( \text{Dickson [1981]} \) is simplified by omitting the relatively minor contributions made by S, F, and N species. In addition, since the contribution from phosphoric acid to total alkalinity is relatively small and exhibits very little temperature or pressure dependence, this is approximated by a simple linear dependence on ambient \( \text{PO}_4^{3-} \) concentration (producing an additional error in \( A_T \) of \( \leq 0.01\% \)). \( A_T \) is therefore written

\[
A_T = [\text{HCO}_3^-] + 2[\text{CO}_3^{2-}] + [\text{H}_2\text{BO}_4^-] + [\text{H}_3\text{SiO}_4^-] + [\text{OH}^-] + 1.1[\text{PO}_4^{3-}]
\]

Carbonate alkalinity (\( A_C \)) is defined as

\[
A_C = [\text{HCO}_3^-] + 2[\text{CO}_3^{2-}]
\]

and thus can be approximated by

\[
A_C = A_T - \left( [\text{H}_2\text{BO}_4^-] + [\text{H}_3\text{SiO}_4^-] + [\text{OH}^-] + 1.1[\text{PO}_4^{3-}] \right)
\]

The concentrations of \( \text{HCO}_3^- \), \( \text{CO}_3^{2-} \), \( \text{OH}^- \), \( \text{H}_2\text{BO}_4^- \), and \( \text{H}_3\text{SiO}_4^- \) are calculated via their respective dissociation constants, \( K_1, K_2, K_1', K_2' \) and \( K_0 \), defined by

\[
\begin{align*}
K_1 &= \frac{[\text{H}^+][\text{HCO}_3^-]}{[\text{H}_2\text{O}][\text{CO}_2]} \\
K_2 &= \frac{[\text{H}^+][\text{CO}_3^{2-}]}{[\text{HCO}_3^-]} \\
K_B &= \frac{[\text{H}^+][\text{H}_2\text{BO}_4^-]}{[\text{H}_2\text{O}][\text{H}_2\text{BO}_3]} \\
K_H &= \frac{[\text{H}^+][\text{OH}^-]}{[\text{H}_2\text{O}]} \\
K_{SS} &= \frac{[\text{H}^+][\text{H}_3\text{SiO}_4^-]}{[\text{H}_2\text{SiO}_4^-]}
\end{align*}
\]

where \( [\text{H}_2\text{O}] = 1 \). Dissociation constants are typically written as empirically-determined multi-variate regressions of temperature and salinity (or total ionic strength), detailed in Table I-1. All calculations assume the same seawater pH scale (\( \text{pH}_{\text{SW}} \)) \([\text{Millero, 1995}]\). It is therefore necessary to make a correction to \( K_0 \) to account for its being determined
on the total pH ($pH_{tot}$) scale. Rather than make an explicit conversion from a $pH_{tot}$ to $pH_{HSWS}$ basis, which requires consideration of the dissociation of HF and $H_2SO_4$ [Millero, 1995], since there is little dependence on salinity a simple linear dependence on temperature is made. A correction must also be made to $K_{aq}$ since it was not determined in seawater. The concentration of silicic acid and phosphoric acids are taken directly from the ocean tracer field, while that of boric acid in seawater is simply estimated from salinity [Millero, 1982].

The fugacity of CO$_2$ in seawater ($f$CO$_2$) rather than the partial pressure ($p$CO$_2$) is calculated as the CO$_2$-seawater system exhibits considerable non-ideality, with the value of $f$CO$_2$ in air about 0.3% lower than that of $p$CO$_2$ at pressures of order of 1 atm. $f$CO$_2$ is given by Weiss [1974]

$$f$CO$_2 = \frac{[CO_2]}{Q_{CO_2}} (I-18)$$

The thermodynamics of the solid-aqueous system are defined by the solubility products for the two solid phases of calcium carbonate (CaCO$_3$), calcite ($K_{calc}$) and aragonite ($K_{arg}$), and calculated using empirical functions of temperature and salinity [Mucci, 1983] (given in Table I-1). From these, the saturation state of CaCO$_3$ in seawater can be obtained, which is defined in terms of a solubility ratio ($\Omega$) for each phase

$$\Omega_{cal} = \frac{[Ca^{2+}][CO_3^{2-}]}{K_{calc}} (I-19)$$

$$\Omega_{arg} = \frac{[Ca^{2+}][CO_3^{2-}]}{K_{arg}} (I-20)$$

### Determination of pH

It remains to determine the hydrogen ion concentration ($[H^+]$) and thus the pH of the system. Since there is no analytical solution, this is estimated by means of an iterative numerical approximation. The sequence of stages in this is as follows:

1. An initial guess made of $[H^+]$; at model spin-up this is taken to be $7 \times 10^{-9}$, otherwise the equilibrium value from the previous time step is assumed.
2. $CO_2$ alkalinity is estimated from the current value of $[H^+]$, from which the concentrations of $HCO_3^-$, $CO_3^{2-}$, and $CO_2$ are calculated.
3. $[HCO_3^-]$, $[CO_3^{2-}]$, and $[CO_2]$ calculated in (2) are used in conjunction with the two dissociation constants of carbonic acid ($K_1$, $K_2$) to produce two different estimates for $[H^+]$

$$[H^+]_1 = K_1 \frac{[CO_3^-]}{[HCO_3^-]} (I-21)$$

$$[H^+]_2 = K_2 \frac{[HCO_3^-]}{[CO_3^{2-}]} (I-22)$$

4. A new estimate of $[H^+]$ is then made by combining the two estimates made above

### Table I-1  Empirical Descriptions of Aqueous Carbonate System Dissociation Constants

<table>
<thead>
<tr>
<th>Constant</th>
<th>Thermodynamic approximation</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_1$</td>
<td>$\ln(K_1) = 2.18867 - 2275.036 / T - 146859.1 \cdot \ln(T) +$</td>
<td>Millero [1995]</td>
</tr>
<tr>
<td></td>
<td>($-0.138681 - 9.33291 / T \cdot S^{0.5} + 0.0726483 - S - 0.00574938 \cdot S^{1.5}$)</td>
<td></td>
</tr>
<tr>
<td>$K_2$</td>
<td>$\ln(K_2) = -0.84226 - 37411.288 / T - 1437319 - \ln(T) +$</td>
<td>Millero [1995]</td>
</tr>
<tr>
<td></td>
<td>($-0.128417 - 24.41239 / T \cdot S^{0.5} + 0.1195308 - S - 0.0912840 \cdot S^{1.5}$)</td>
<td></td>
</tr>
<tr>
<td>$K_B$</td>
<td>$\ln(K_B) = 148.0248 + 137.1942 \cdot S^{0.5} + 1.62142 \cdot S +$</td>
<td>Dickson [1990]</td>
</tr>
<tr>
<td></td>
<td>($-8966.90 - 2890.53 \cdot S^{0.5} - 77.942 + S + 1.728 \cdot S^{1.5} - 0.0996 \cdot S^2 / T +$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>($-24.4344 - 25.085 \cdot S^{0.5} - 0.2474 \cdot S \cdot \ln(T) + 0.053105 \cdot S^{0.5} / T$)</td>
<td></td>
</tr>
<tr>
<td>$K_H$</td>
<td>$\ln(K_H) = 148.9802 - 13847.26 / T - 23.6521 \cdot \ln(T) +$</td>
<td>Millero [1992]</td>
</tr>
<tr>
<td></td>
<td>($-5.977 + 118.67 / T + 1.0495 \cdot \ln(T) \cdot S^{0.5} - 0.01615 \cdot S$</td>
<td></td>
</tr>
<tr>
<td>$K_{Si}$</td>
<td>$\ln(K_{Si}) = 117.40 - 8904.2 / T - 19.334 \ln(T) +$</td>
<td>Millero [1995]</td>
</tr>
<tr>
<td></td>
<td>($3.5913 - 458.79 / T \cdot I^{0.5} + (-1.5998 + 188.74 / T) \cdot I + (0.07871 - 12.1652 / T) \cdot I^2 \cdot I$</td>
<td></td>
</tr>
<tr>
<td>$K_{calc}$</td>
<td>$\log_{10}(K_{calc}) = -1719065 - 0.077993 \cdot T + 2839.319 / T + 71.595 - \log_{10}(T) +$</td>
<td>Mucci [1983]</td>
</tr>
<tr>
<td></td>
<td>($-0.77712 + 0.0028426 \cdot T + 178.34 / T \cdot S^{0.5} - 0.07711 \cdot S + 0.0041249 \cdot S^{1.5}$)</td>
<td></td>
</tr>
<tr>
<td>$K_{arg}$</td>
<td>$\log_{10}(K_{arg}) = -1719450 - 0.077993 \cdot T + 2903.293 / T + 71.595 - \log_{10}(T) +$</td>
<td>Mucci [1983]</td>
</tr>
<tr>
<td></td>
<td>($-0.068393 + 0.0017276 \cdot T + 88.135 / T \cdot S^{0.5} - 0.10018 \cdot S + 0.0059415 \cdot S^{1.5}$)</td>
<td></td>
</tr>
</tbody>
</table>

$I$ is the ionic strength, defined [Millero, 1982]; $I = 19.92 \cdot S / (10000 - 1.005 \cdot S)$
If the difference between new and old estimates of $[\text{H}^+]$ is greater than 0.1% (equivalent to an error in $f\text{CO}_2$ of 0.6 ppmv under typical oceanic conditions), steps #2 through #5 are repeated until an approximate convergence is obtained.

**Pressure-dependence of system thermodynamics**

Pressure correction of dissociation constants is carried out assuming a conversion between depth and pressure of 1 dbar m\(^{-1}\). The error in this is no more than ~3%, even at the deep ocean depths (10000 m). Corrections are applied to all of $K_1$, $K_2$, $K_{oH}$, $K_{oB}$, and $K_{oSi}$. However, the influence on the carbonate system as a whole of pressure effects on the dissociation constants of HF and H\(_2\)SO\(_4\) (used in converting between different pH scales) are insignificant, and as such are omitted. The general form of the pressure correction factor is [Miller, 1979]

\[
\ln \left( \frac{K_{(P)}}{K_{(0)}} \right) = \left( \frac{\Delta V}{RT} \right) \cdot P + \left( \frac{0.5 \Delta \kappa}{RT} \right) \cdot P^2
\]

(1-24)

where $P$ is the applied pressure in bars, $T$ is the temperature (\(^{\circ}\)C), $\Delta V$ and $\Delta \kappa$ are the molar volume and compressibility change for the dissociation reactions, respectively, and $R$ is the gas constant (83.145 bar cm\(^3\) mol\(^{-1}\) K\(^{-1}\)). For each dissociation reaction the values of $\Delta V$ and $\Delta \kappa$ in seawater are approximated as function only of temperature (assuming a salinity of 35‰) by

\[
\Delta V = a_0 + a_1 \cdot T + a_2 \cdot T^2
\]

(1-25)

\[
10^3 \cdot \Delta \kappa = b_0 + b_1 \cdot T
\]

(1-26)

with the coefficients $a_0 \ldots b_1$ given in Table I-2. There is no available relationship describing the effect of pressure on the dissociation of silicic acid. The same pressure effect as for boric acid is therefore assumed.

**Table I-2** Coefficients for Describing Dissociation Constants as a Function of Pressure

<table>
<thead>
<tr>
<th>Acid</th>
<th>$a_0$</th>
<th>$a_1$</th>
<th>$a_2$</th>
<th>$b_0$</th>
<th>$b_1$</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{H}_2\text{CO}_3$</td>
<td>-2.55E+01</td>
<td>+1.27E-01</td>
<td>+0.00E+00</td>
<td>-3.08E+00</td>
<td>+8.77E-02</td>
<td>[Miller, 1995]</td>
</tr>
<tr>
<td>$\text{HCO}_2$</td>
<td>-1.58E+01</td>
<td>-2.19E-02</td>
<td>+0.00E+00</td>
<td>+1.13E+00</td>
<td>-1.47E-01</td>
<td>[Miller, 1995]</td>
</tr>
<tr>
<td>$\text{H}_2\text{BO}_3$</td>
<td>-2.86E+01</td>
<td>+1.21E-01</td>
<td>-3.21E-04</td>
<td>-3.00E+00</td>
<td>+4.27E-02</td>
<td>[Miller, 1982]</td>
</tr>
<tr>
<td>$\text{H}_2\text{O}$</td>
<td>-2.00E+01</td>
<td>+1.12E-01</td>
<td>-1.41E-01</td>
<td>-5.13E+00</td>
<td>+7.49E-02</td>
<td>[Miller, 1982]</td>
</tr>
<tr>
<td>CaCO(_3) (calcite)</td>
<td>-4.88E+01</td>
<td>+5.30E-01</td>
<td>+0.00E+00</td>
<td>-1.18E+01</td>
<td>+3.69E-01</td>
<td>[Ingle [1975], Miller [1979]]</td>
</tr>
<tr>
<td>CaCO(_3) (aragonite)</td>
<td>-4.60E+01</td>
<td>+5.30E-01</td>
<td>+0.00E+00</td>
<td>-1.18E+01</td>
<td>+3.69E-01</td>
<td>[Miller [1979]]</td>
</tr>
</tbody>
</table>
Light limitation of new production is parameterized in a similar manner to Bacastow and Maier-Reimer [1990], based on a normalized incident light factor, calculated from estimated solar elevation summed over each day [Holtslag and van Ulden, 1983]. However, no account is taken of the reduction of radiation incident at the ocean surface with increasing solar elevation due to reflectance at the air-sea interface.

Incoming solar radiation at the ocean surface assuming clear sky conditions, is given by

$$K = a_1 \cdot \sin \phi + a_2$$  \hspace{1cm} (II-1)

where $\phi$ is the solar elevation, and $a_1$ and $a_2$ are empirical coefficients, taking values of 1041 and -69 W m$^{-2}$, respectively [Holtslag and van Ulden, 1983]. Solar elevation follows Holtslag and van Ulden [1983];

$$\sin \phi = \sin \delta \cdot \sin \psi + \cos \delta \cdot \cos \psi \cdot \cos h$$  \hspace{1cm} (II-2)

where is $\psi$ the latitude of the location (radians), $\delta$ the solar declination

$$\delta = \arcsin(0.398 \cdot \sin(SL))$$  \hspace{1cm} (II-3)

where $SL$ is the the solar longitude

$$SL = 4.871 + 0.0175 \cdot d + 0.033 \cdot \sin(0.0175 \cdot d)$$  \hspace{1cm} (II-4)

with $d$, is the day number. Finally, $h$, the hour angle is described by

$$h = -\lambda_w + 0.043 \cdot \sin(2 \cdot SL) - 0.033 \cdot \sin(0.0175 \cdot d) + 0.262 \cdot t - \pi$$  \hspace{1cm} (II-5)

where $\lambda_w$ is the western longitude (radians) of the location and $t$ is the universal time (hours).

For each time step in the biological scheme ($\Delta t$), the reduction in new production due to sub-optimal insolation is calculated by

$$I_{t, lat} = \sum_{t-\Delta t/2}^{t+\Delta t/2} H(K_{t, lat})$$  \hspace{1cm} (II-6)

where the mean hourly insolation is summed over the length of the new production time step at the mean latitude of each grid point, and $H$ is the Heavyside function. $I$ is then normalized to a value of unity at the time and location of maximum calculated insolation on Earth to give $\mu_{(t,y)}$. No account is taken of past variations in the Earth’s orbital parameters.
## Appendix III

### Opal diagenesis core data

<table>
<thead>
<tr>
<th>Core ID</th>
<th>opal (wt%)</th>
<th>CaCO₃ (wt%)</th>
<th>opal rain rate (μmol cm⁻² a⁻¹)</th>
<th>opal burial rate (μmol cm⁻² a⁻¹)</th>
<th>opal dissolution rate (μmol cm⁻² a⁻¹)</th>
<th>opal preservation (%)</th>
<th>[H₄SiO₄]_{asym} (μmol kg⁻¹)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>HAP</td>
<td>3</td>
<td>21</td>
<td>6</td>
<td>4.32₁</td>
<td>1.08₁</td>
<td>72</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>NAP</td>
<td>0</td>
<td>6</td>
<td>4</td>
<td>0.04₁</td>
<td>3.96₁</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>2</td>
<td>28</td>
<td>5</td>
<td></td>
<td></td>
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<td>1</td>
<td></td>
</tr>
<tr>
<td>MFZ</td>
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<td>1.21₁</td>
<td>9.79₁</td>
<td>11</td>
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<td></td>
<td></td>
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<tr>
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<td>8.80₁</td>
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<td>20</td>
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</tr>
<tr>
<td>MW</td>
<td>6</td>
<td>1</td>
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<td>12.04₁</td>
<td>14</td>
<td>1</td>
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</tr>
<tr>
<td>G</td>
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<td>25</td>
<td>5</td>
<td>0.20₁</td>
<td>4.80₁</td>
<td>4</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>H</td>
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<td>7</td>
<td>0.28₁</td>
<td>6.72₁</td>
<td>4</td>
<td>1</td>
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<tr>
<td>M</td>
<td>11</td>
<td>15</td>
<td>12</td>
<td>0.48₁</td>
<td>11.52₁</td>
<td>4</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>S</td>
<td>16</td>
<td>1</td>
<td>3</td>
<td>0.03₁</td>
<td>2.97₁</td>
<td>1</td>
<td>1</td>
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References: 1, Archer et al. [1993]; 2, Martin et al. [1991]; 3, McManus et al. [1995].

₁ Calculated from published opal rain rates and percentage opal preservation.

₂ Estimated from similarly located cores.
<table>
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<th>Core ID</th>
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<th>CaCO₃ (wt%)</th>
<th>opal rain rate (µmol cm⁻² a⁻¹)</th>
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<th>opal dissolution rate (µmol cm⁻² a⁻¹)</th>
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# Appendix IV

## Model parameter values (baseline scenario)

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<th>Parameter Description</th>
<th>Symbol</th>
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<td>Model time step: primary (ocean-sediment) interactions</td>
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<td>1 year</td>
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<td>Model time step: intra-ocean and ocean-atmosphere interactions</td>
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<tr>
<td>Maximum (at depth) vertical eddy diffusivity</td>
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<td>$Q_{10}^{PO4}$</td>
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<td>PO$<em>4$ uptake rate $Q</em>{10}$ temperature dependency (NSP)</td>
<td>$Q_{10}^{NSP}$</td>
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<td>1.88</td>
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<td>Base PO$_4$ uptake rate (SP)</td>
<td>$u_{SP}^{PO4}$</td>
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<td>5.0 μmol kg$^{-1}$ a$^{-1}$</td>
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<td>Base PO$_4$ uptake rate (NSP)</td>
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<td>Particulate organic matter export partition coefficient (NSP)</td>
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<td>Particulate organic matter C:P export ratio (SP)</td>
<td>$r_{POC:POP}^{SP}$</td>
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<td>Particulate organic matter O$_2$:P export ratio (SP)</td>
<td>$r_{POC:POP}^{SP}$</td>
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<td>Opal:POC export ratio value under Fe-replete conditions (SP)</td>
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<td>Opal:POC export ratio function [Fe] half-saturation constant</td>
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<td>Opal:POC export ratio function [Fe] off-set</td>
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<td>Particulate organic matter N:P export ratio (NSP)</td>
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<td>Opal water-column base dissolution rate constant</td>
<td>$k_{0}^{opal}$</td>
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<td>Minimum allowed oceanic O$_2$ concentration</td>
<td>-</td>
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<td>25.0 μmol kg$^{-1}$</td>
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| Fe scavenging rate: by POC | $k_{scav}^{Fe_{POC}}$ | 2-38 | 0.00025 a$^{-1}$ (mol C m$^{-2}$ a$^{-1}$)$^2$
| Fe scavenging rate: by opal | $k_{scav}^{Fe_{opal}}$ | 2-38 | 0.00025 a$^{-1}$ (mol C m$^{-2}$ a$^{-1}$)$^2$
| Fe scavenging rate: by calcite | $k_{scav}^{Fe_{cal}}$ | 2-38 | 0.00025 a$^{-1}$ (mol C m$^{-2}$ a$^{-1}$)$^2$
| Fe scavenging rate: by aragonite | $k_{scav}^{Fe_{arg}}$ | 2-38 | 0.00025 a$^{-1}$ (mol C m$^{-2}$ a$^{-1}$)$^2$
| Fe ‘self-scavenging’ rate (by dust) | $k_{scav}^{Fe_{dust}}$ | 2-43 | 0.0750 a$^{-1}$ (mol C m$^{-2}$ a$^{-1}$)$^2$
| Fe abundance in dust | $Fe_{frac}^{dust}$ | 2-43 | 3.5% |

**Note:** All values and equations are provided in SI units, where applicable.
<table>
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<th>Parameter Description</th>
<th>Symbol</th>
<th>Equation number</th>
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<td>Enzymic $^{13}$C fraction factor (SP)</td>
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<td>Surface area equivalent cell radius</td>
<td>$r$</td>
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Prescribed POC sedimentary preservation efficiency: - 5%
Prescribed additional sedimentary rain flux of detrital material: - 0.167 g cm$^{-2}$ ka$^{-1}$
Thickness of ‘well mixed’ surface sediment layer: - 5 cm
Porosity of ‘well mixed’ surface sediment layer: $\phi$ 3-4 0.776 cm$^3$ cm$^{-3}$
Thickness of (complete) sedimentary stack layers: - 1 cm
Porosity of sedimentary stack: $\phi$ 3-4 0.705 cm$^3$ cm$^{-3}$
Bioturbation rate at top of sedimentary stack: - 120 cm$^3$ ka$^{-1}$
Calcite dissolution rate constant: - 20 % d$^{-1}$
Calcite dissolution power: - 4.5
Aragonite dissolution rate constant: - 20 % d$^{-1}$
Aragonite dissolution power: - 4.2
Riverine input of carbon: - 15 Tmol a$^{-1}$
$^{13}$C isotopic signature of riverine carbon: - 3.1‰
Volcanic input of carbon: - 5 Tmol a$^{-1}$
$^{13}$C isotopic signature of volcanic carbon: - 3.1‰
Riverine input of alkalinity: - 40 Tmol eq a$^{-1}$
Total input of dissolved silica: - 6 Tmol a$^{-1}$
Accumulation rate of neritic CaCO$_3$: - 10 Tmol a$^{-1}$
$^{13}$C isotopic signature of neritic CaCO$_3$: - 3.1‰