Feedbacks in the Earth System: Past changes in dust and iron fertilisation of the ocean

by A. Ridgwell

A climatic sub-system having the necessary properties for feedback has been found, with the marine iron cycle as its central component. This arises since CO_2 in the atmosphere, and therefore climate, may be responsive to dust due to iron 'fertilisation' and, in turn, dust supply depends on global climate. As the environmental sciences move towards a more holistic approach to understanding climate change on a range of time scales ("Earth System science"), it is becoming increasingly clear that 'feedbacks' are integral to the behaviour of the Earth System and its response to both natural and anthropogenic perturbations (see Box). Although the marine iron cycle feedback could be expected to play a role in the future climate response to anthropogenic change, it is more likely to have been important during past glacial periods when dust appears to be highly sensitive to small changes in climate.

A long-standing puzzle in oceanography has been why the primary producers of the open ocean (phytoplankton) do not always appear to fully utilise the major nutrients (such as phosphate and nitrate) that are supplied to them, since in certain regions of the world's oceans (most notably the eastern equatorial Pacific, North Pacific, and Southern Ocean), high concentrations of these nutrients remain in the surface waters in association with relatively low standing stocks of phytoplankton. Although physical (temperature, light levels, and the depth to which the surface ocean is mixed) and ecological (zooplankton grazing) regimes must all play a part in controlling phytoplankton standing stocks, open ocean iron 'fertilisation' experiments carried out first in the equatorial Pacific, and more recently in the Southern Ocean (e.g., [1], see Figure 1) and North Pacific, have demonstrated that insufficient iron availability limits phytoplankton growth.

A key source of this iron to the biota of the open ocean is via the deposition of mineral aerosol (dust)(Figure 2). Records of past dust deposition contained in ice, marine, and terrestrial records from around the world all suggest that during the last ice age the aeolian flux of iron to the surface ocean must have been much higher than at present (globally, some 2-3 times on average). This was also a time of much lower mixing ratios of CO_2 (CO_2) in the atmosphere (around 190 ppm [2]). This correspondence led John Martin to formulate the glacial 'iron hypothesis' [3], in which low atmospheric CO_2 is explained as a result of enhanced iron fertilisation of the biota. The results of numerical models of the ocean carbon cycle [e.g., 4] are consistent with the 'iron hypothesis' [5] although by itself dust cannot explain all of the observed ~90 ppm amplitude of glacial-interglacial CO_2 change, and different models of ocean biogeochemistry currently disagree as to what this fraction should be. Because of the radiative forcing on climate exerted by the presence of CO_2 in the atmosphere, climate will therefore also be sensitive to changes in the aeolian iron supply to the ocean.

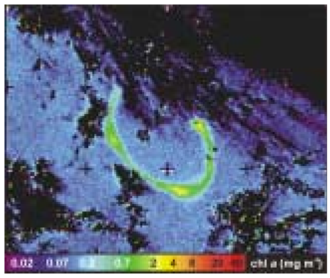

Figure 1.
Ocean colour satellite (SeaWiFS) image of concentrations of surface ocean chlorophyll (*a* phytoplankton photosynthetic pigment, whose concentration can be taken as a rough indicator of cell density), taken some 6 weeks after the deliberate release of iron in the Southern Ocean [1]. The contrast between the 'fertilised' area (green/yellow colour) and the surrounding ('unfertilised') waters (blue) can be clearly made out (note: black pixels in the image represent cloud cover). (SeaWiFS data provided by the NASA DAAC/ GSFC and copyright of Orbital Imaging Corps and the NASA SeaWiFS project, and processed at CCMS-PML.)

Figure 2. True colour satellite (SeaWiFS) image taken on February 11th 2001 of a massive sandstorm blowing off Northwest Africa and the Sahara Desert and out over the Canary Islands. Wind-blown dust is a key source of iron to biota in the open ocean, and is thought to be central to a climatic feedback system. (The SeaWiFS image was provided by NASA DAAC/GSFC and is copyright of Orbital Imaging Corps and the NASA SeaWiFS project).

What factors might influence aeolian iron supply? The entrainment of dust from the land surface is facilitated by low soil moisture levels (when the cohesive forces that exist between soil particles are minimal) and also by the absence of vegetation cover (which allows greater wind speeds to be reached at ground level). Dust transport out to the open ocean becomes more efficient under a less vigorous hydrological cycle (as a result of decreased dust removal by rainfall over land and coastal regions). CO_2 in the atmosphere can also have a direct 'fertilising' effect on vegetation growth. That climate (and CO_2) should exert a strong control on dust is consistent with information contained within ice cores [e.g., 2] which demonstrate that enhanced dust concentrations are associated with cold dry glacial periods.

Taking these two different linkages in the Earth System together; if changes in dust flux affect atmospheric CO_2, and therefore climate, and dust fluxes are in turn responsive to global climate (and CO_2), a positive 'feedback' loop is formed [5] (see Box). In this feedback system, any cooling of global climate (such as might arise due to orbitally-driven changes in insolation at the Earth's surface) will tend to produce an increase in dust availability and transport efficiency. This could, in turn, produce a decrease in atmospheric CO_2 (through iron fertilisation of the biota), causing additional climate cooling and thus further enhanced dust supply. Equally, the feedback loop could operate in the reverse direction to amplify a warming of climate. Preliminary calculations suggest that the operation of this feedback is not uniform in climate space, but exhibits a maximum effect during glacial conditions (when any perturbation of climate could be amplified by over 50%). This is because dust (as recorded at in the Vostok ice core [2]) appears to be relatively insensitive to small changes in climate during interglacials. In addition, CO_2 becomes insensitive to small changes in dust under times of extreme glacial conditions (and maximum dust supply rates) [4], when ocean productivity may no longer be responsive to further iron fertilisation (perhaps due to the onset of limitation by other nutrients [5]). It is possible that operation of this feedback could give rise to two distinct glacial states in the Earth System, one of 'high-CO_2 low-dust', and the other 'low-CO_2 high-dust'. This is consistent with developing views of the Earth System as being characterised by the presence of different quasi-steady

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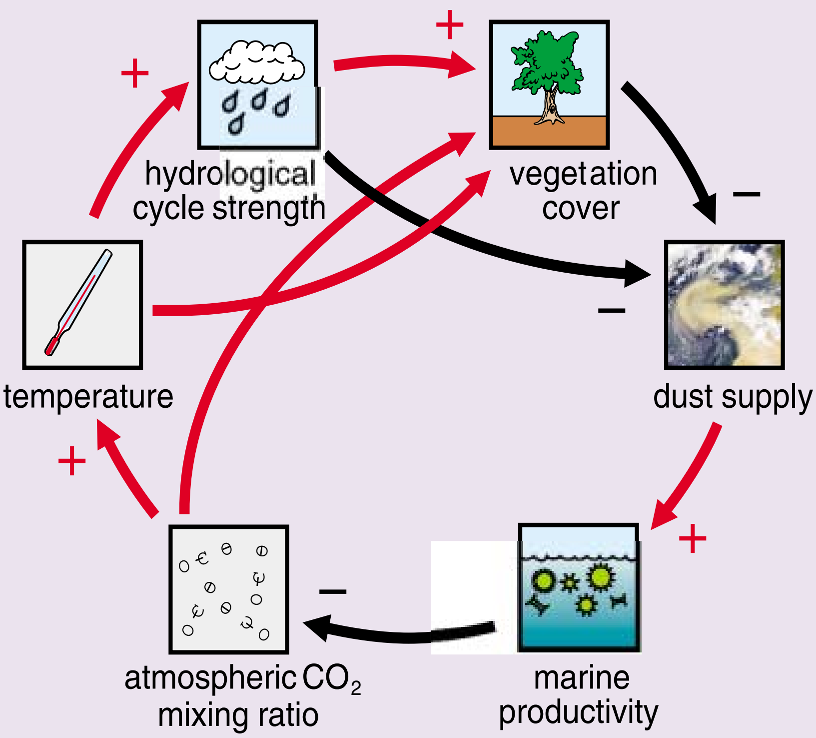
Box: What are 'feedbacks?

Different components of the Earth System can be connected in two different ways:

- with a positive correlation (i.e., an increase in the state of one component causes an increase in a second, or, a decrease in the state of one component causes a decrease in a second);
- with a negative correlation (i.e., an increase in the state of one component causes a decrease in a second, or *vice versa*);

If a path of successive connections can be traced from any given component back to itself, a closed or 'feedback' loop is formed (see Figure). An even number (including zero) of negatively correlated connections counted around the loop gives a positive feedback, which will act to amplify an initial perturbation in the state of any component within this loop. Conversely, an odd number of negative correlations gives a negative feedback, which will tend to dampen any perturbation, thus stabilising the system.



The feedback system is, of course, much more complicated than portrayed in this simplified schematic. For instance, as a result of the optical properties of dust aerosol, the presence of dust in the atmosphere can drive a strong direct radiative forcing of climate. There are also potentially important influences of climate on dust via the growth of ice sheets – both through their ability to produce suitably sized mineral fragments, and in altering sea level (exposing shelf sediments to wind erosion) [5].

Figure. Some of the potential feedbacks involving dust and iron fertilisation in the climate system. Positively correlated connections are shown in red, and negative ones in black. Four main (positive) feedback loops exist in this system, each having a total of two negatively correlated connections within the loop;

(1) dust supply→productivity→CO_2→temperature→hydrological cycle→vegetation→dust supply,

(2) dust supply→productivity→CO_2→temperature→hydrological cycle→dust supply,

(3) dust supply→productivity→CO_2→vegetation→dust supply, and

(4) dust supply→productivity→CO_2→temperature→vegetation→dust supply

Examples of feedbacks

The well-known 'ice-albedo' feedback involves the reciprocal interaction between temperature and snow/ice cover. An increase in ice and/or snow cover increases surface albedo, resulting in a reduction in absorbed solar energy and a surface cooling, thus driving a tendency for a further increase in ice/snow cover.

Recent coupled climate-vegetation models have identified the existence of potentially important positive feedbacks between climate and the release of CO_2 from the terrestrial biosphere (particularly in the Amazon), and between climate and vegetation cover in the Sahelian region of North Africa [6,7 respectively]. Misunderstandings can arise in tightly coupled systems such as these since a climatic component may appear to be simultaneously both 'cause' and 'effect' (consider in the 'ice-albedo' feedback; snow cover affects temperature, but yet it is also affected by temperature). However, this situation is simply the basic property of a feedback system.

states with comparatively abrupt transitions between them.

Identifying and quantifying the role of feedback systems such as described here, in amplifying (or suppressing) climatic change may help us to understand not only how the climate system operated in the past (such as during the glacial-interglacial cycles of the past few million years), but how it may respond in the future to continuing greenhouse gas emissions.

Andy Ridgwell
School of Environmental Sciences and Tyndall Centre for Climate Change Research, University of East Anglia, Norwich NR4 7TJ, UK (http://www.tyndall.ac.uk)

Now at: Department of Earth Sciences, University of California - Riverside, Riverside, CA 92521, USA.
E-mail: A.Ridgwell@uea.ac.uk

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Climate-ecosystem interactions in montane meadows

by J. Harte

Climate change can alter ecosystems and thereby trigger feedback effects that can either enhance or retard the climate change. Such feedbacks are especially likely in montane and high-latitude ecosystems where soils are carbon-rich, sharp transitions in ecosystem community structure are prevalent as a result of topographic variability, vegetation is sensitive to climatic variables such as snowmelt date and length of growing season, and climate change is expected to be large due to snow-albedo feedback. Predicting the chronology and magnitude of such feedbacks is a major challenge in ecology today, as well as an important issue both for global climate change science and policy and, locally, for people whose livelihood is dependent upon montane climatic and ecological regimes.

To investigate montane climate-ecosystem interactions, we are conducting three types of field studies in subalpine meadow habitat. Central to the research is a climate manipulation experiment (Figure 1) that uses overhead electric heaters to continuously warm five 30m^2 Rocky Mountain meadow plots (matched with five control plots) by an amount anticipated from global warming models during the middle of this century. The site is at 2920 m, 38°53′N 107°02′W on the western slope of the Colorado Rockies in Gunnison Co. CO, USA. In 1988 we designed the experimental facility and in 1990 began collecting data. Since then we have been routinely monitoring effects of the manipulated climate change on soil microclimate, carbon and nitrogen fluxes and pool sizes, and plant growth, flowering success, physiological vigour, phenology, and species diversity.

The climate manipulation has lengthened the snow-free growing season (Figure 1b) by approximately two weeks at