The co-evolution of life and the planet *in silco*

Andy Ridgwell

THE ROYAL SOCIETY
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University of BRISTOL
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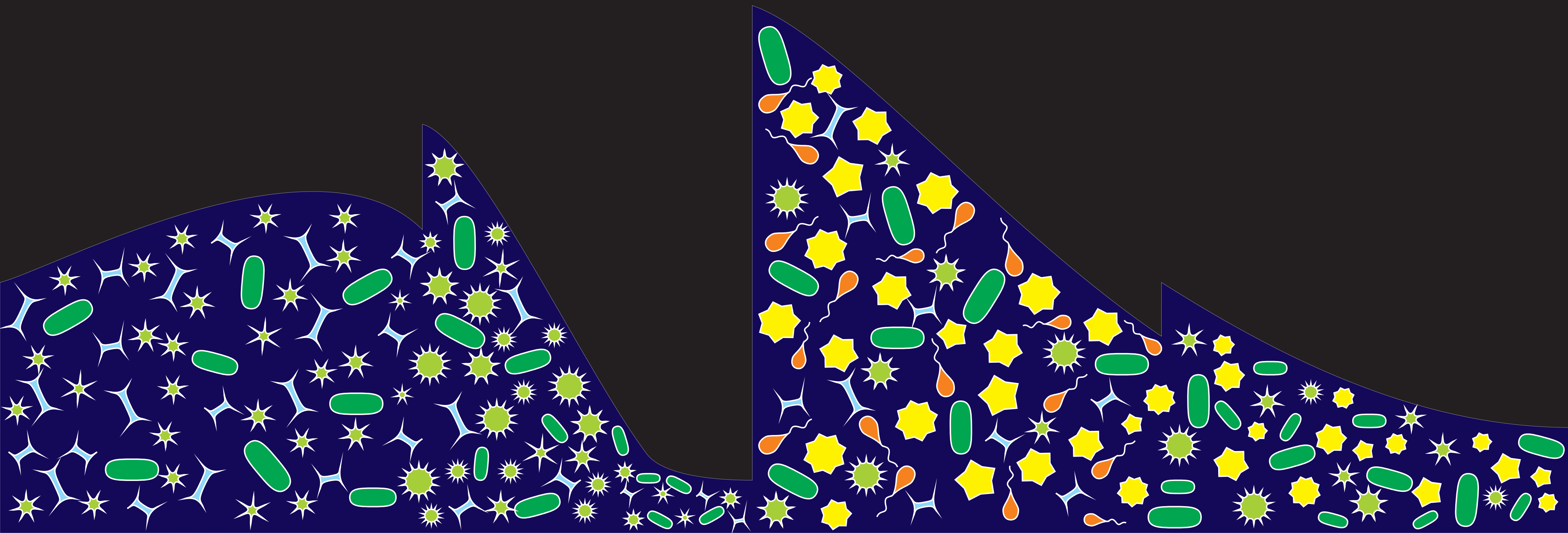
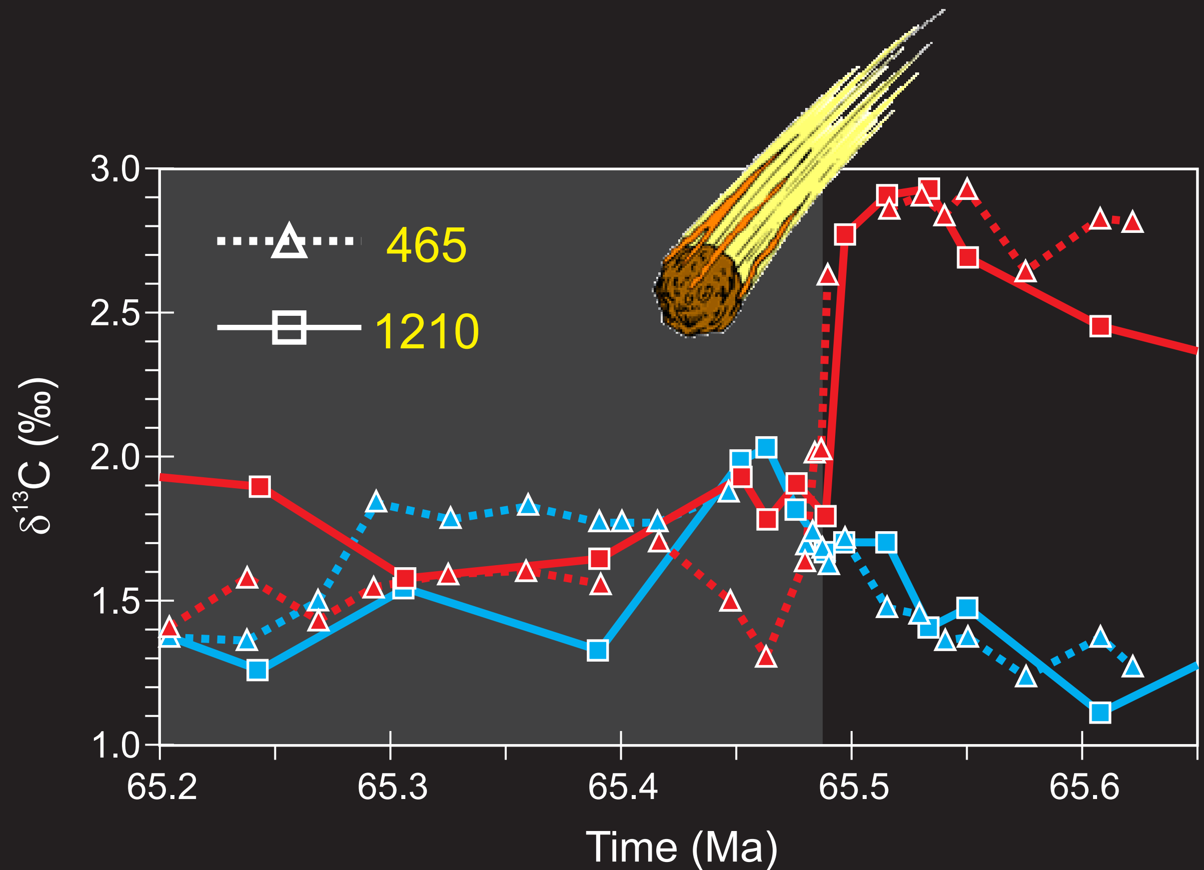
The co-evolution of life and the planet *in silco:* TALK OUTLINE

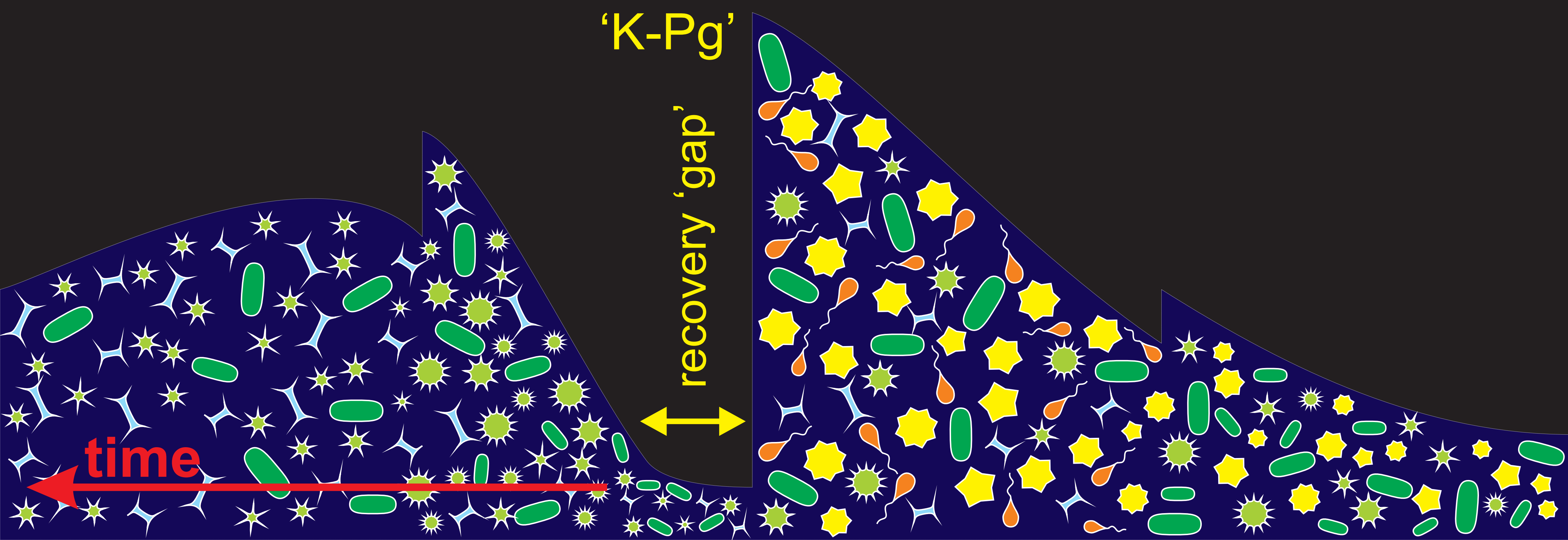
(1) Designing a novel synthetic (marine) ecological world with which to experiment and test hypotheses.

(2) 'Bio-geoengineering' and re-imagining the crop plant (applications to land-climate-terrestrial biosphere evolution and feedbacks)..

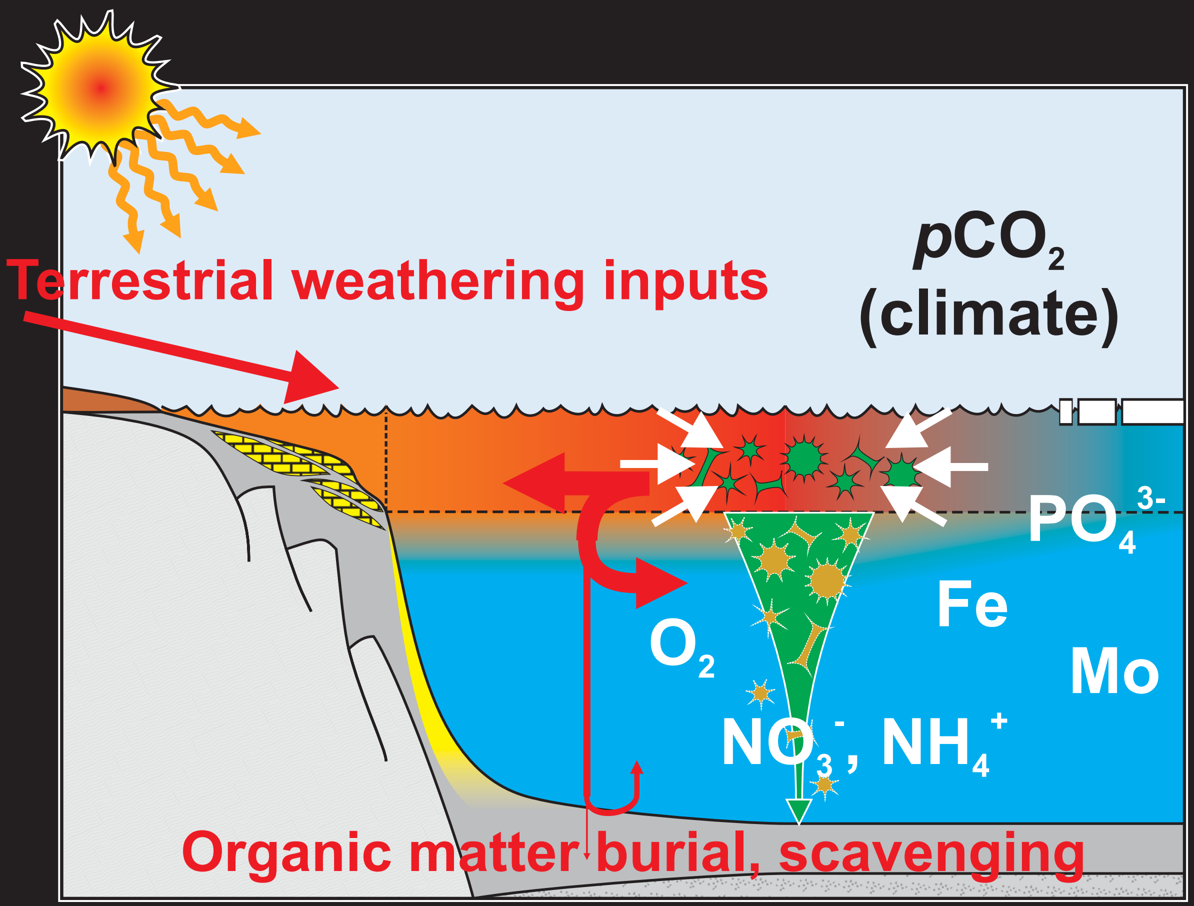


The co-evolution of life and the planet





The co-evolution of life and the planet



The nature marine ecosystems and strength of biological productivity and remineralization affects:

- Oceanic macros nutrient inventories, esp. P and the form of fixed N.
- Ocean oxygenation and hence micro nutrient inventories, esp. Fe – scavanged in an oxic ocean, and Mo – scavenged in a sulphidic ocean.
- Carbon burial and atmospheric pCO_2 and hence climate.

The co-evolution of life and the planet

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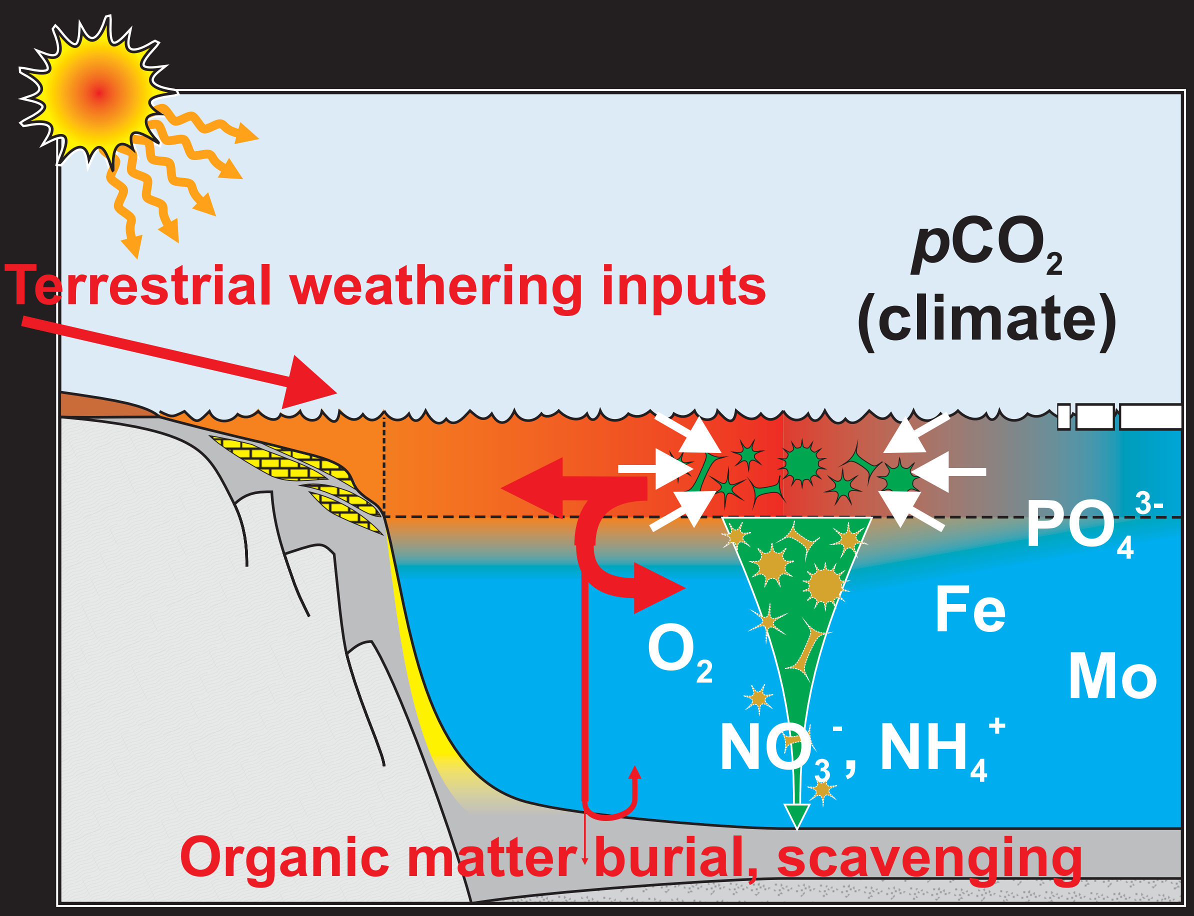
- Ocean oxygenation and hence micro nutrient inventories, esp. Fe – scavanged in an oxic ocean, and Mo – scavenged in a sulphidic ocean.
- Carbon burial and atmospheric pCO_2 and hence climate.

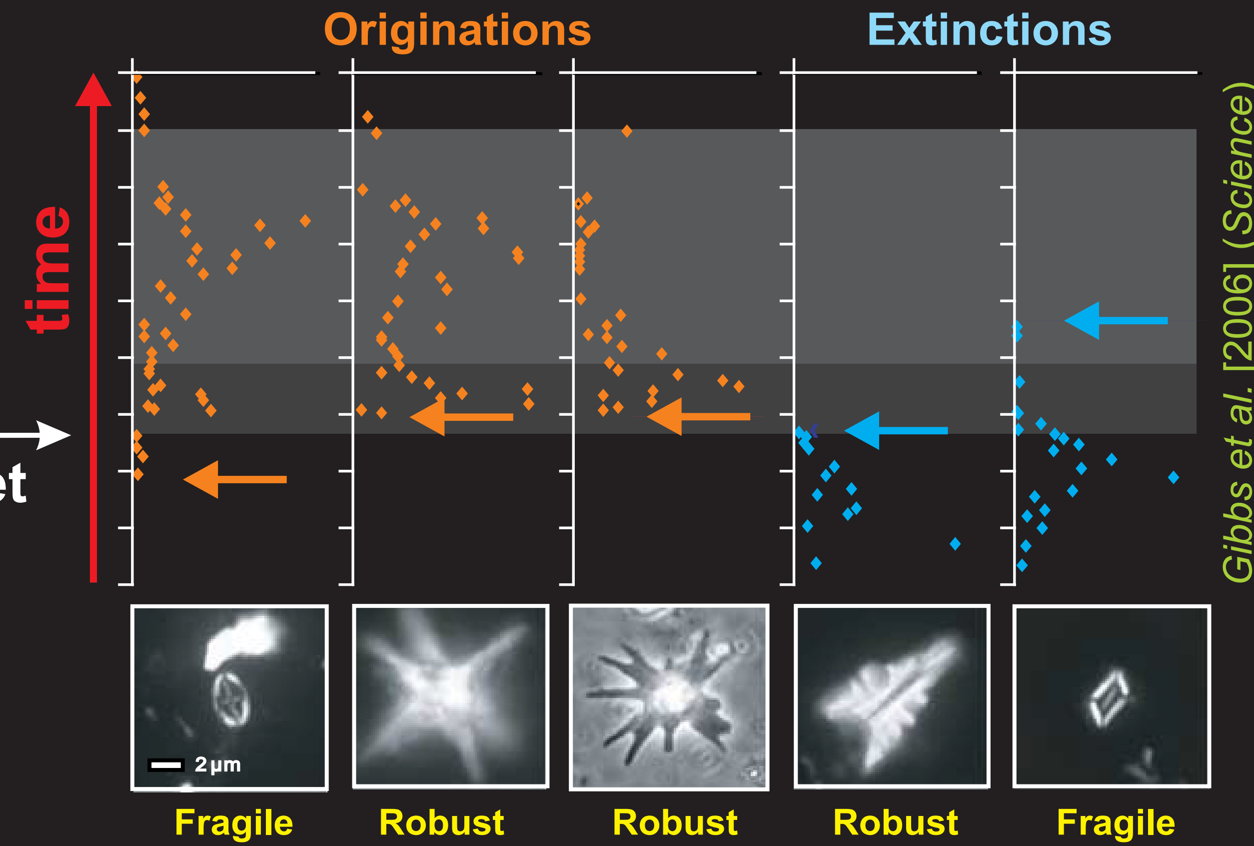
In turn, changes in the physical and biogeochemial (nutrient) environment will affect ecosystem composition and drive selection.

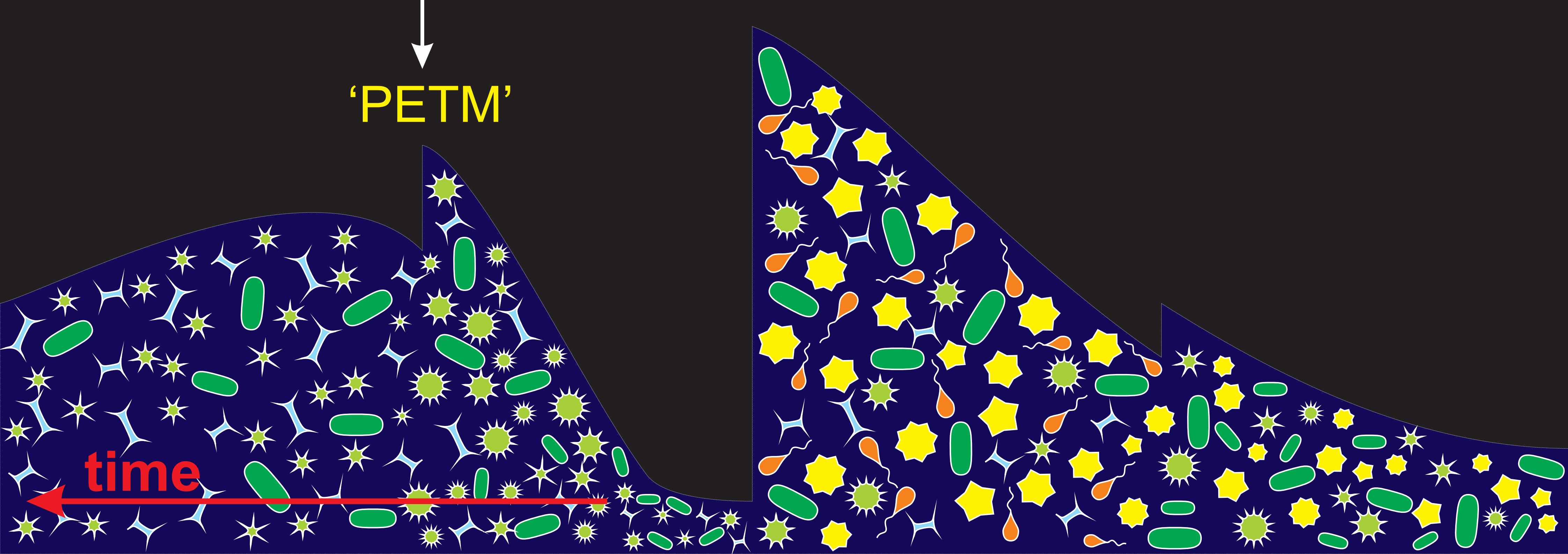
The approximate coincidence between plankton evolutionary time-scales and the residence time of many of the key ocean and atmospheric tracers raises the possibility of interesting dynamical behaviours of the full system.

/end speculation

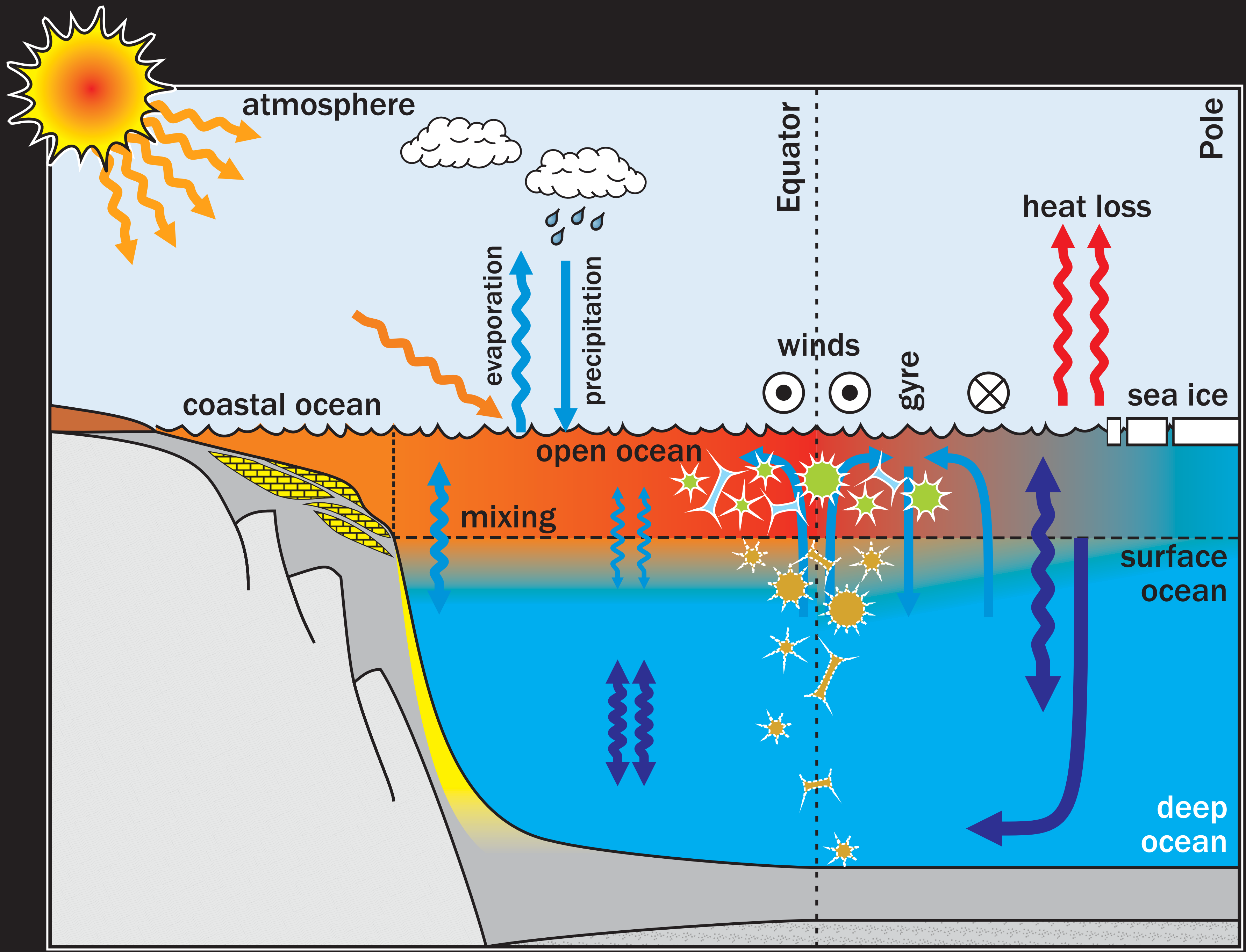


The co-evolution of life and the planet





Strategies for modelling complex marine systems



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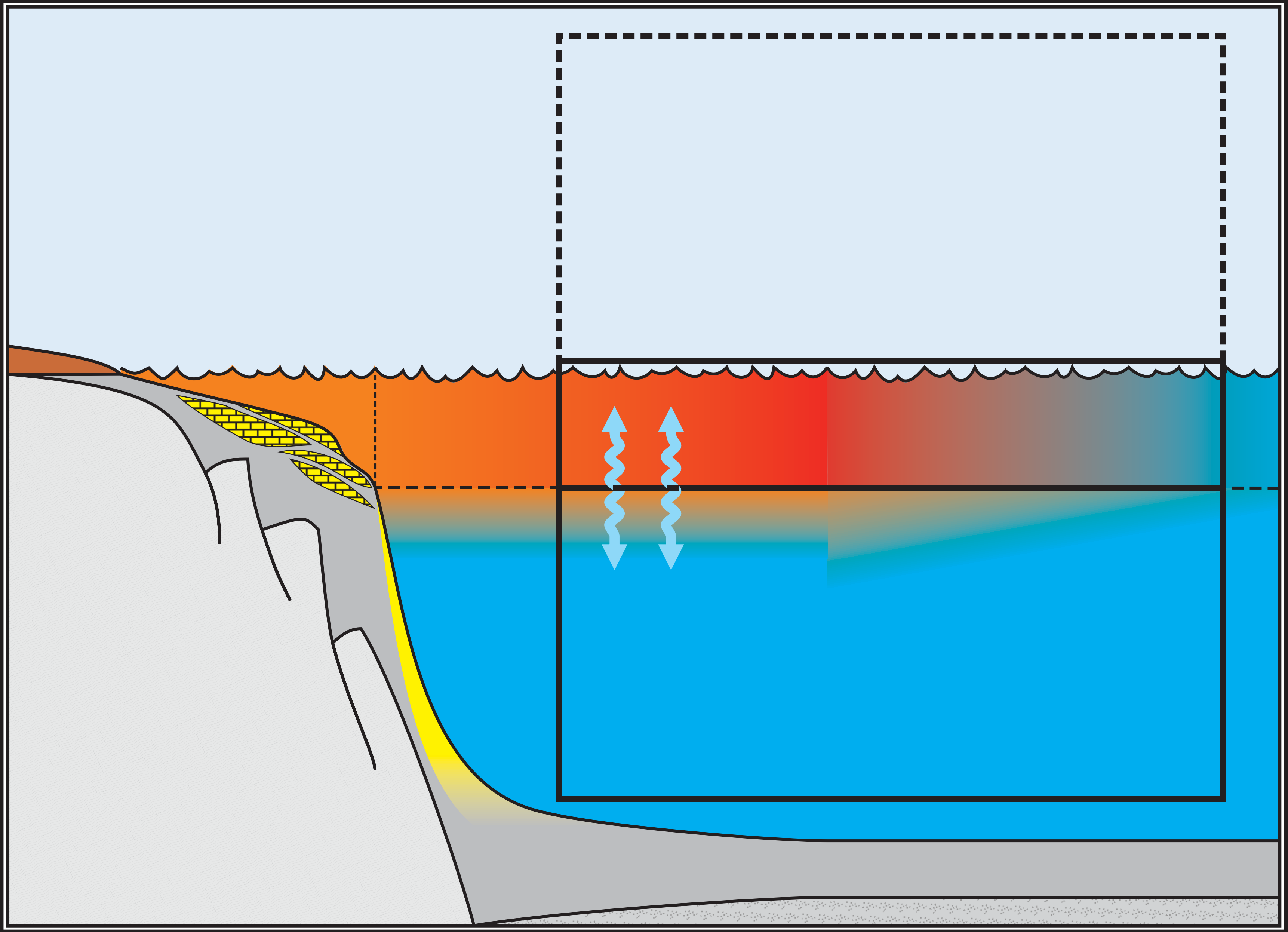
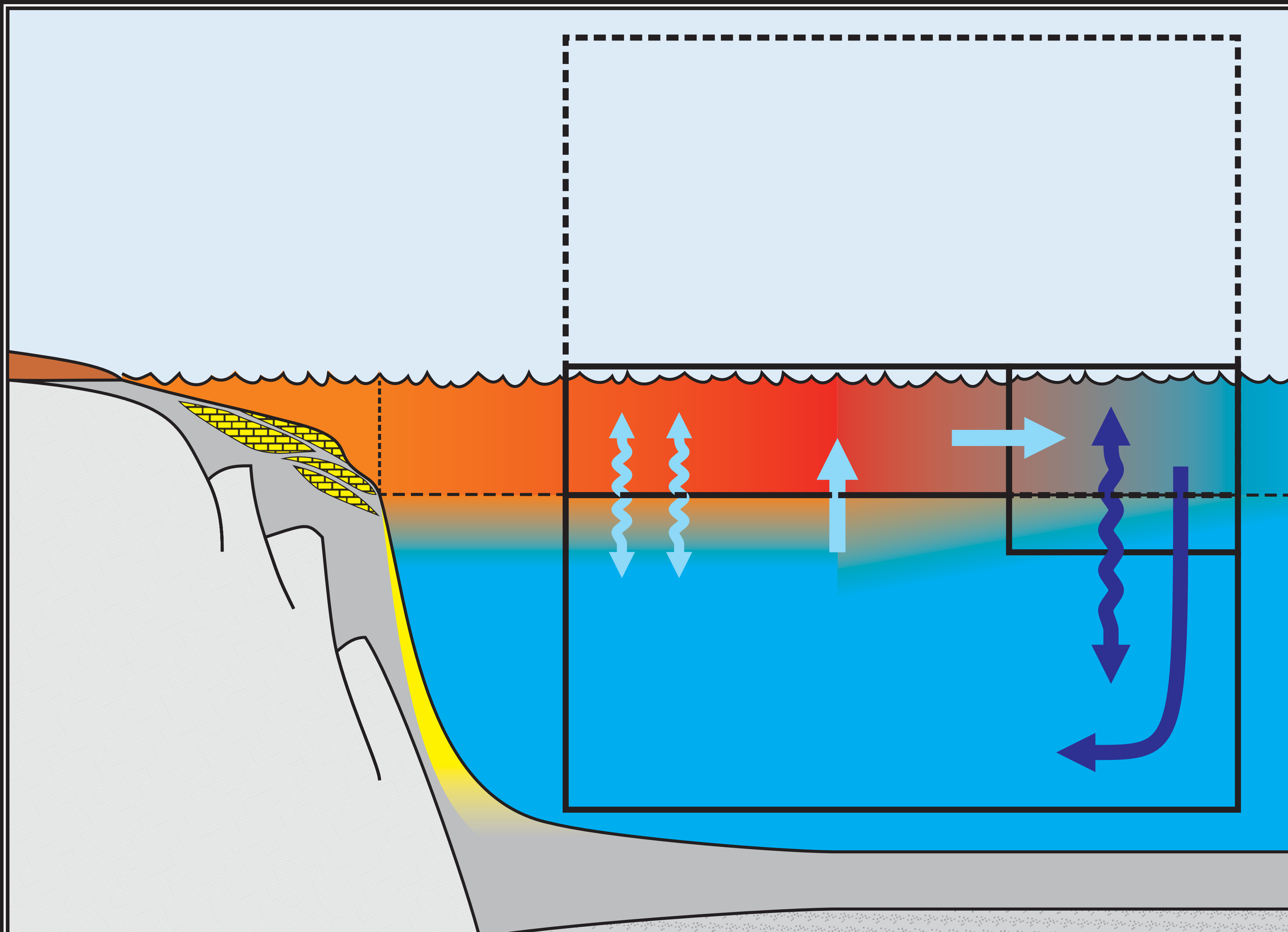


Creating models is effectively, the art of encapsulation of one's understanding (or preconceptions) of a system, numerically.

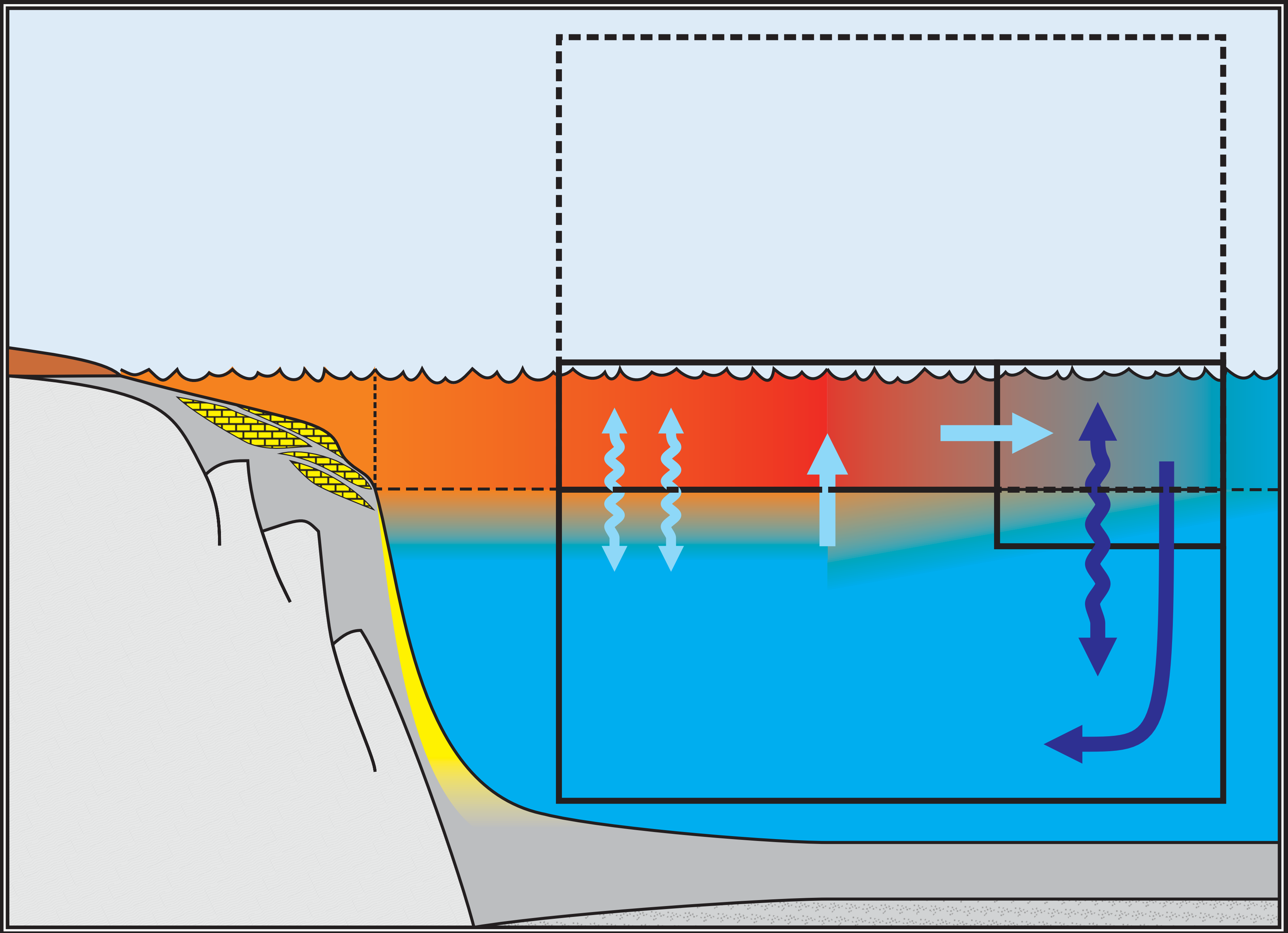
BUT ...



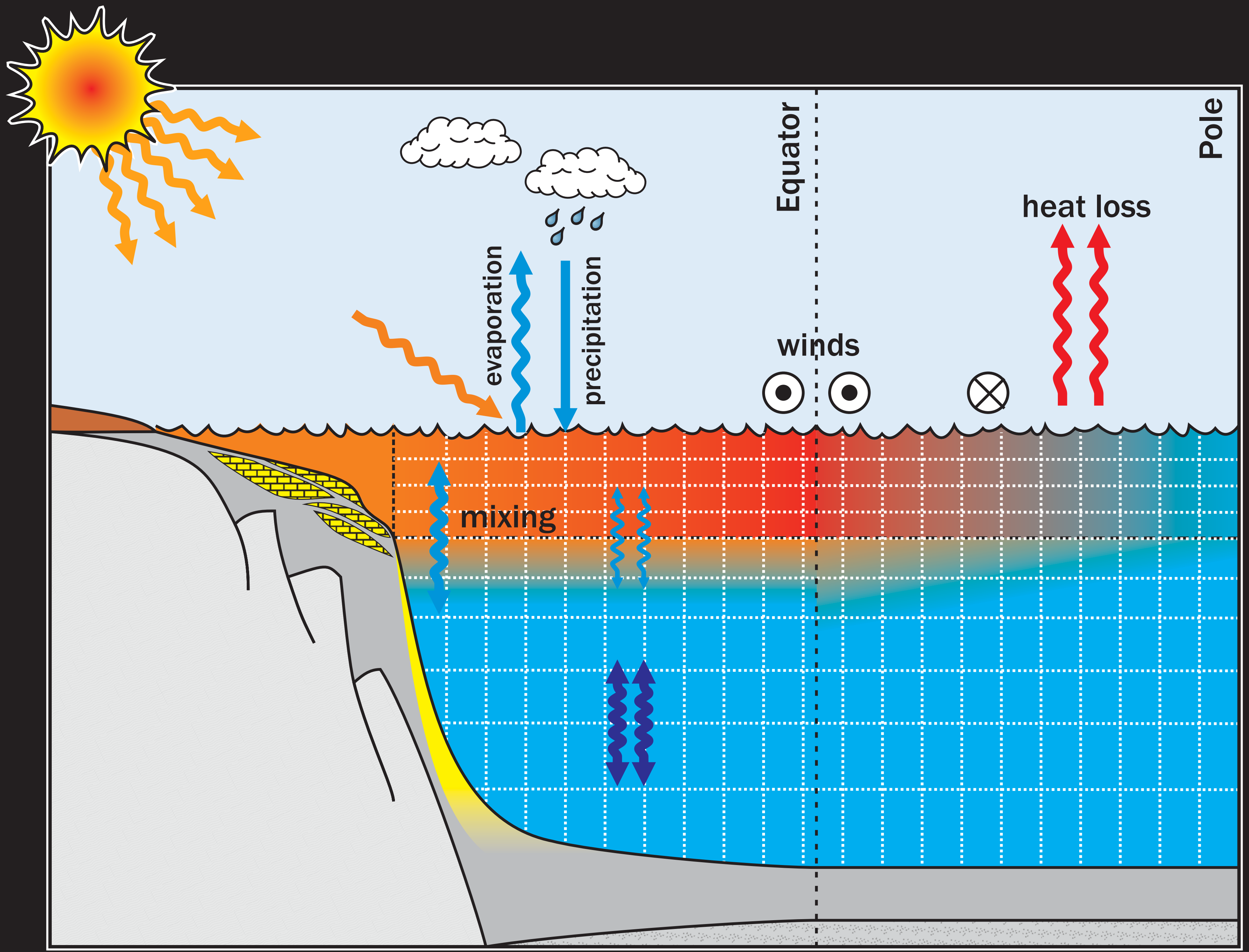
What happens under climate change?

What did the system look like in the past (e.g. Cretaceous)??

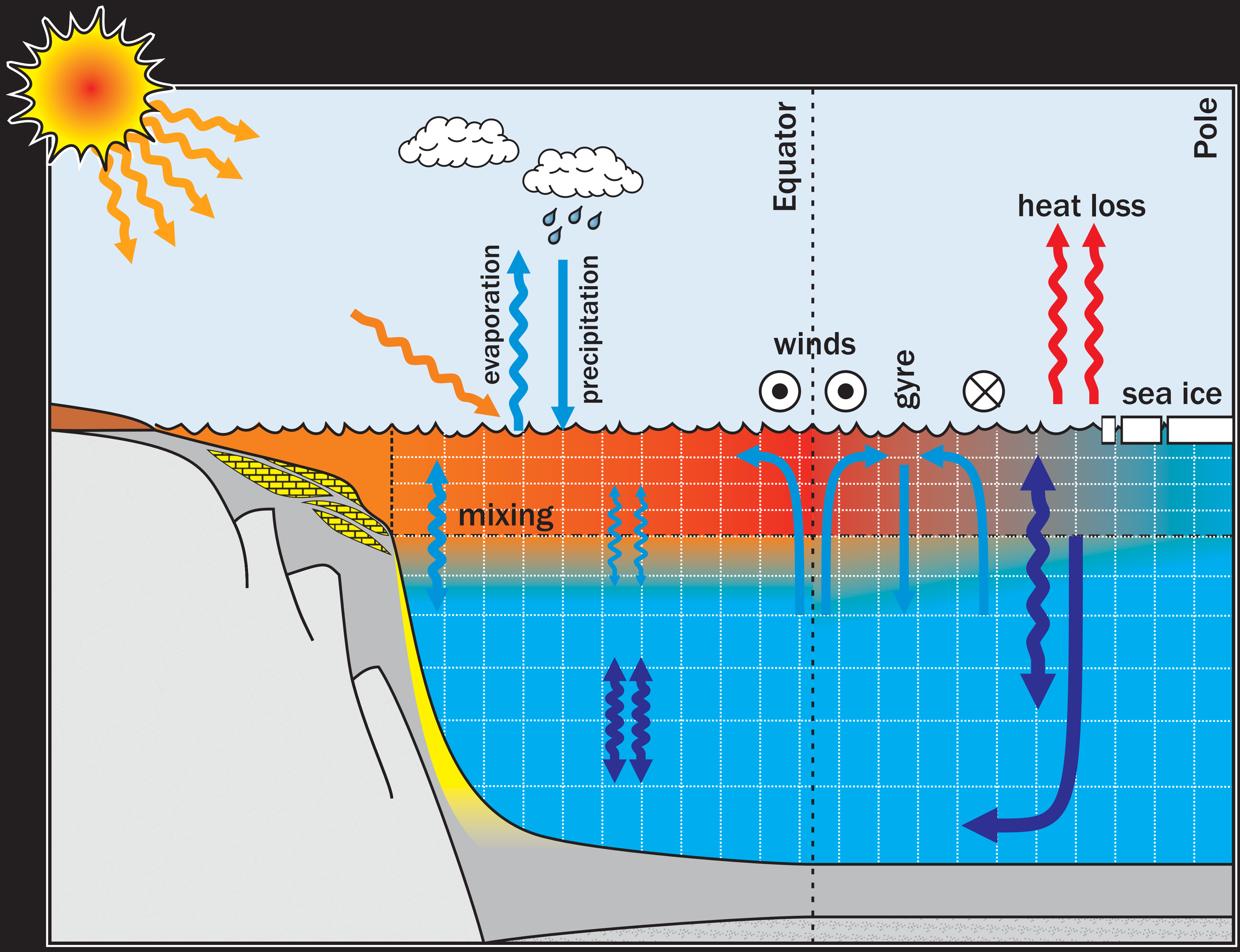
What if the structure of the system is not correctly understood???



(Ocean) General Circulation Models (O-GCMs)



Ocean circulation becomes an ***emergent*** *rather than prescribed property of the system.*



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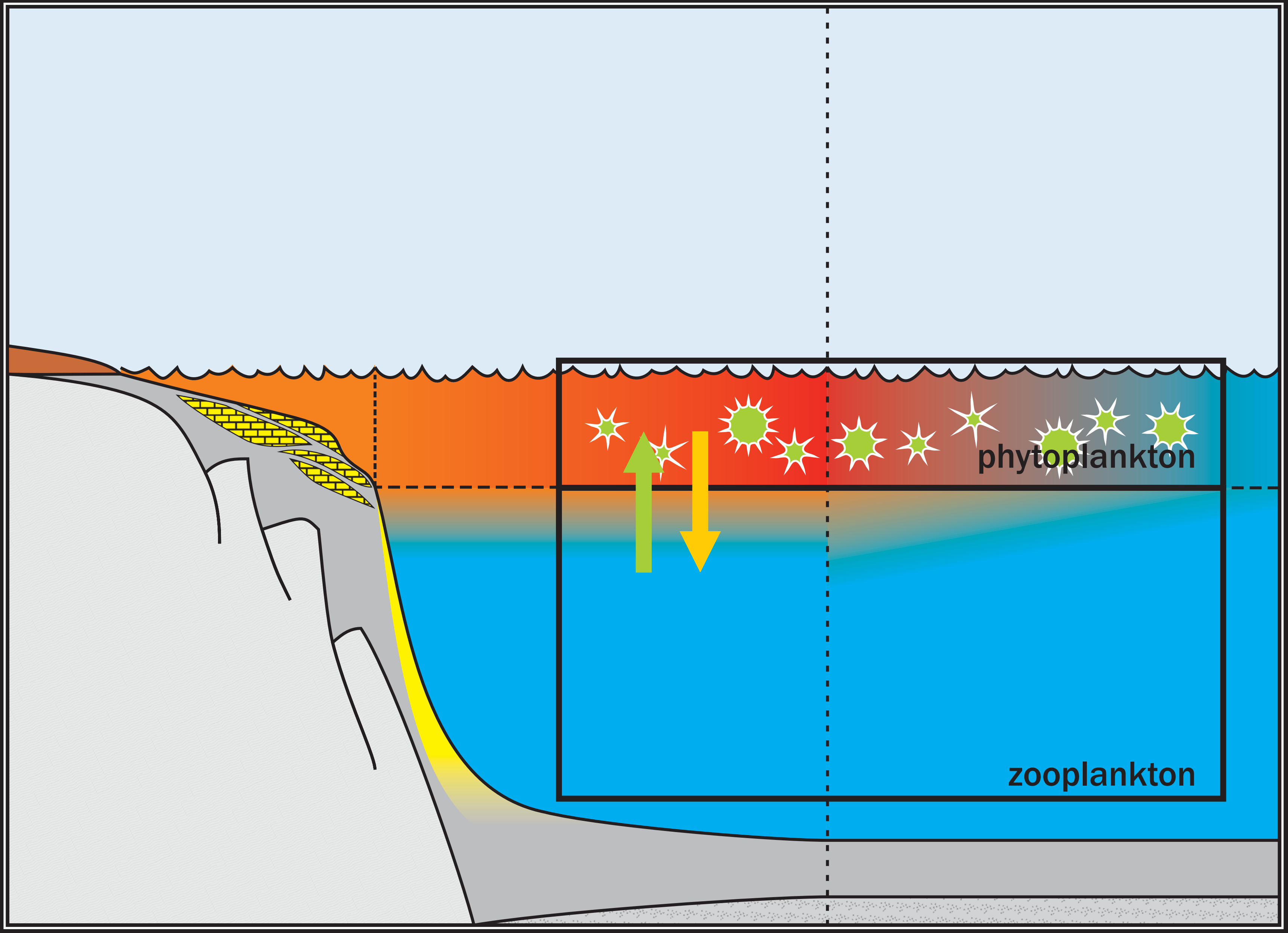
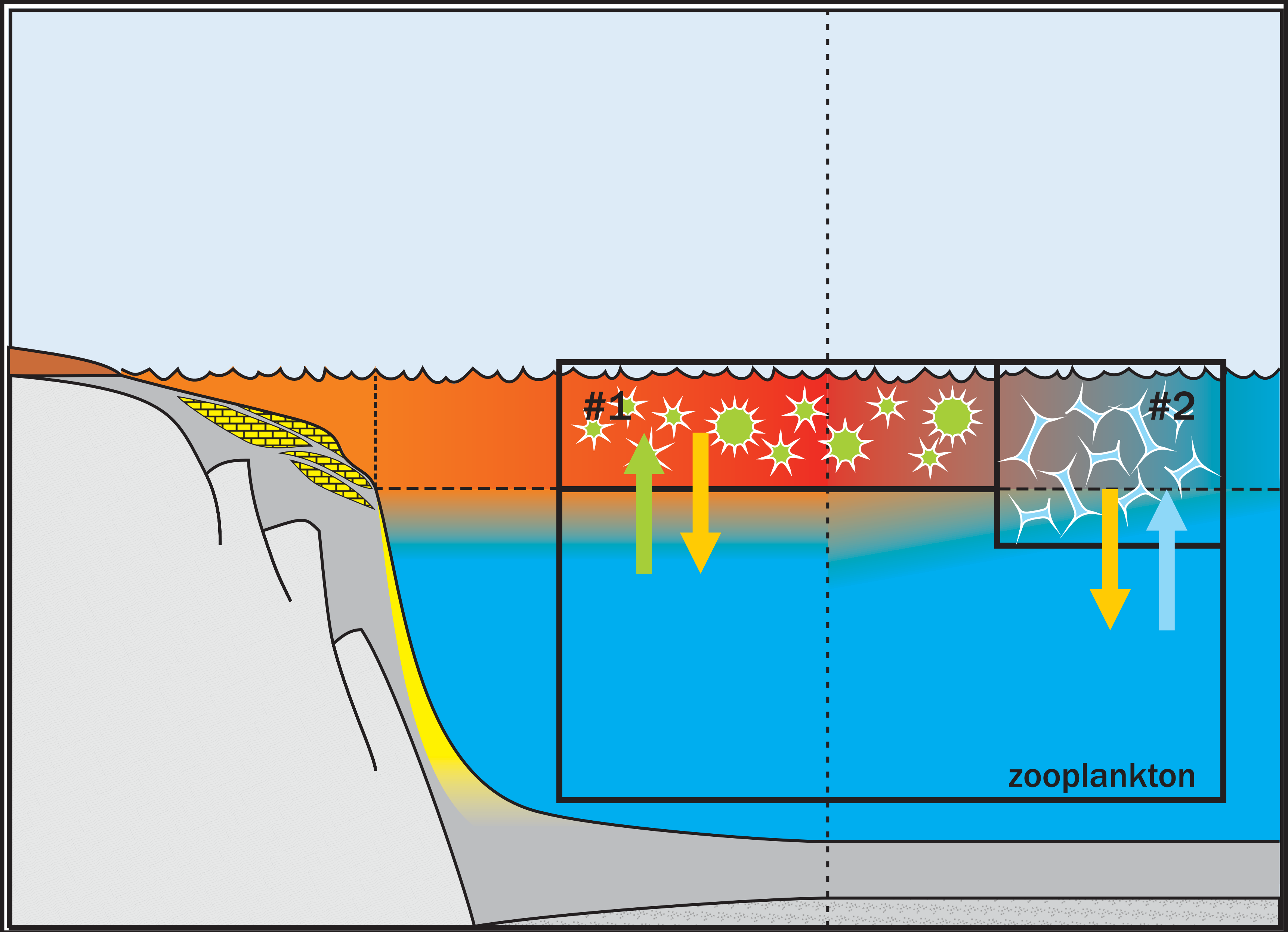


Creating models is effectively, the art of encapsulation of one's understanding (or preconceptions) of a system, numerically.

But additionally ...

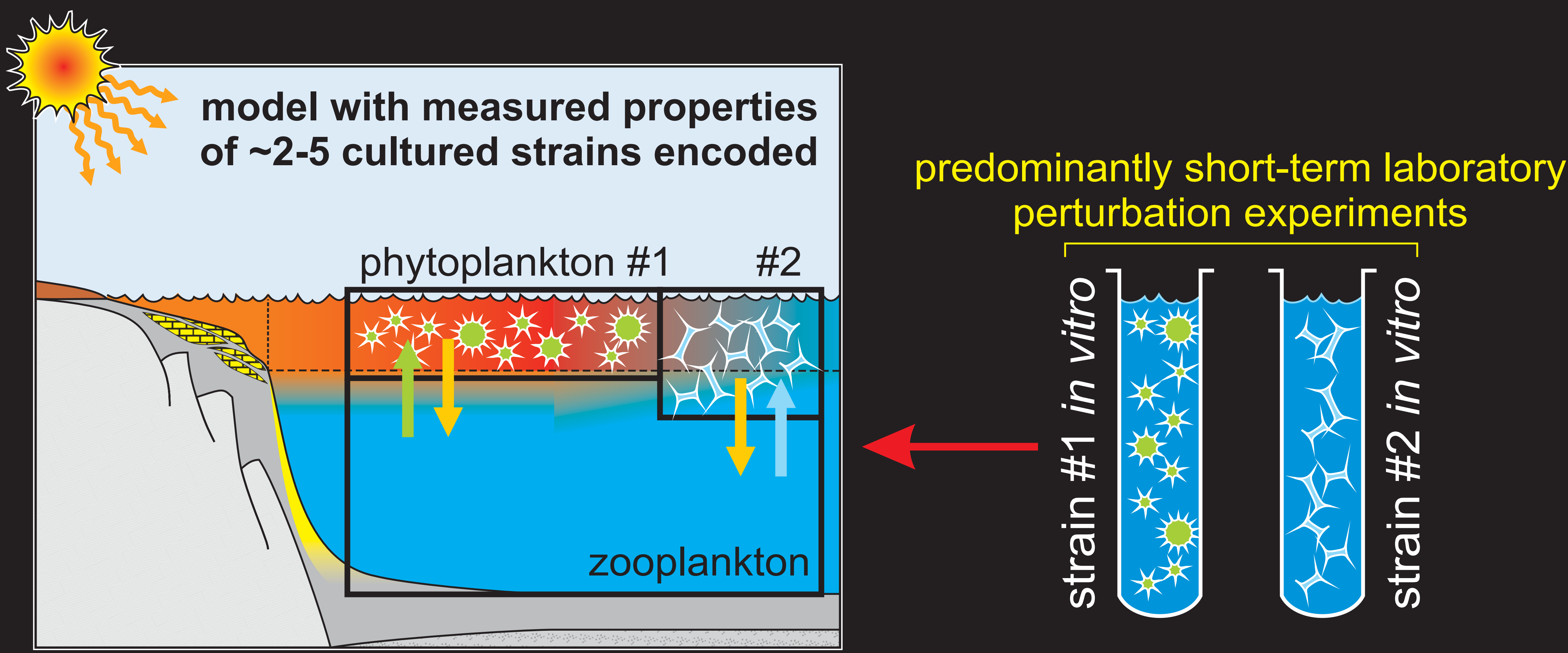


Again:

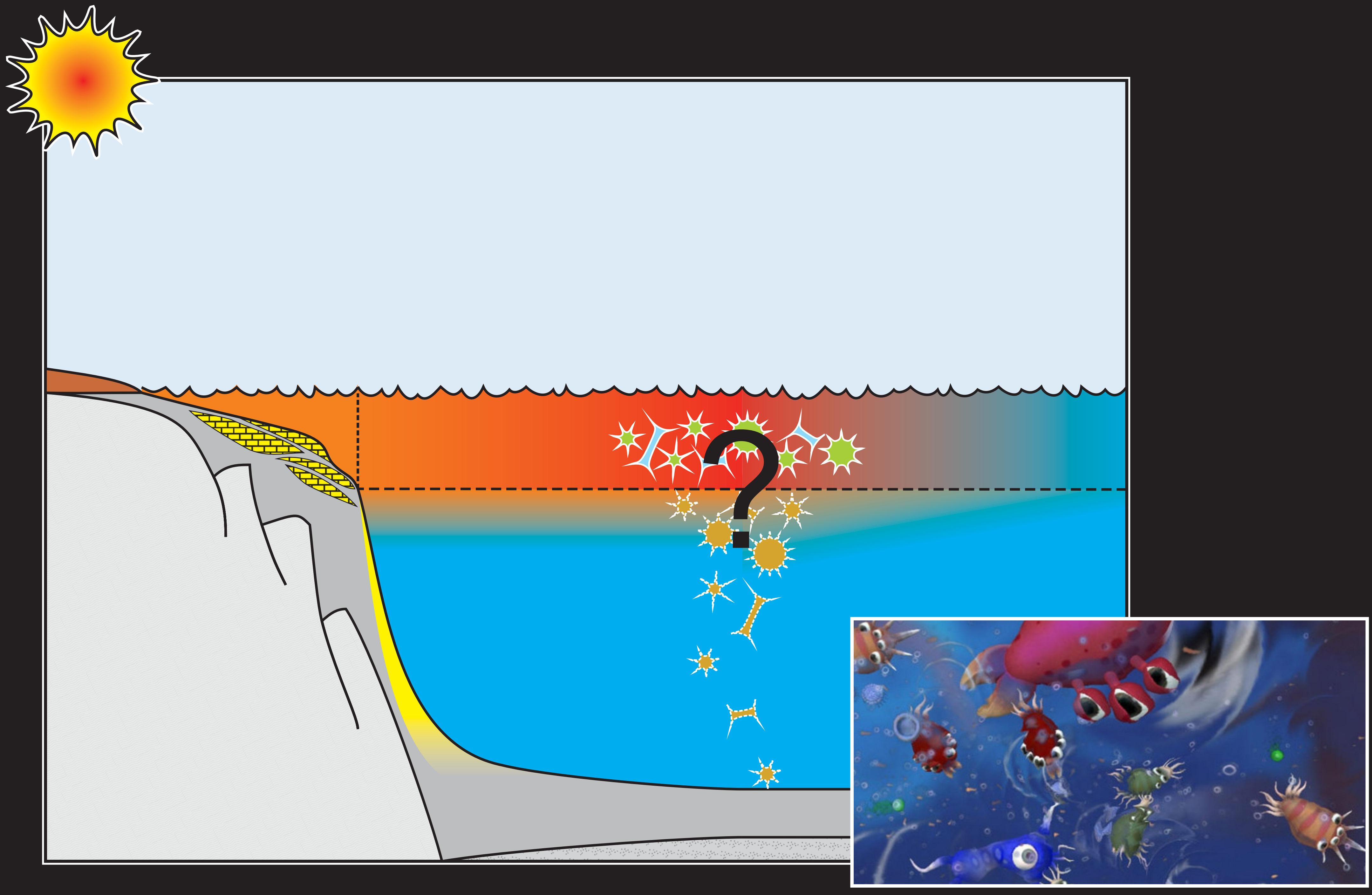
What happens under climate change?
What did the system look like in the past (e.g. Cretaceous)??
What if the structure of the system is not correctly understood???

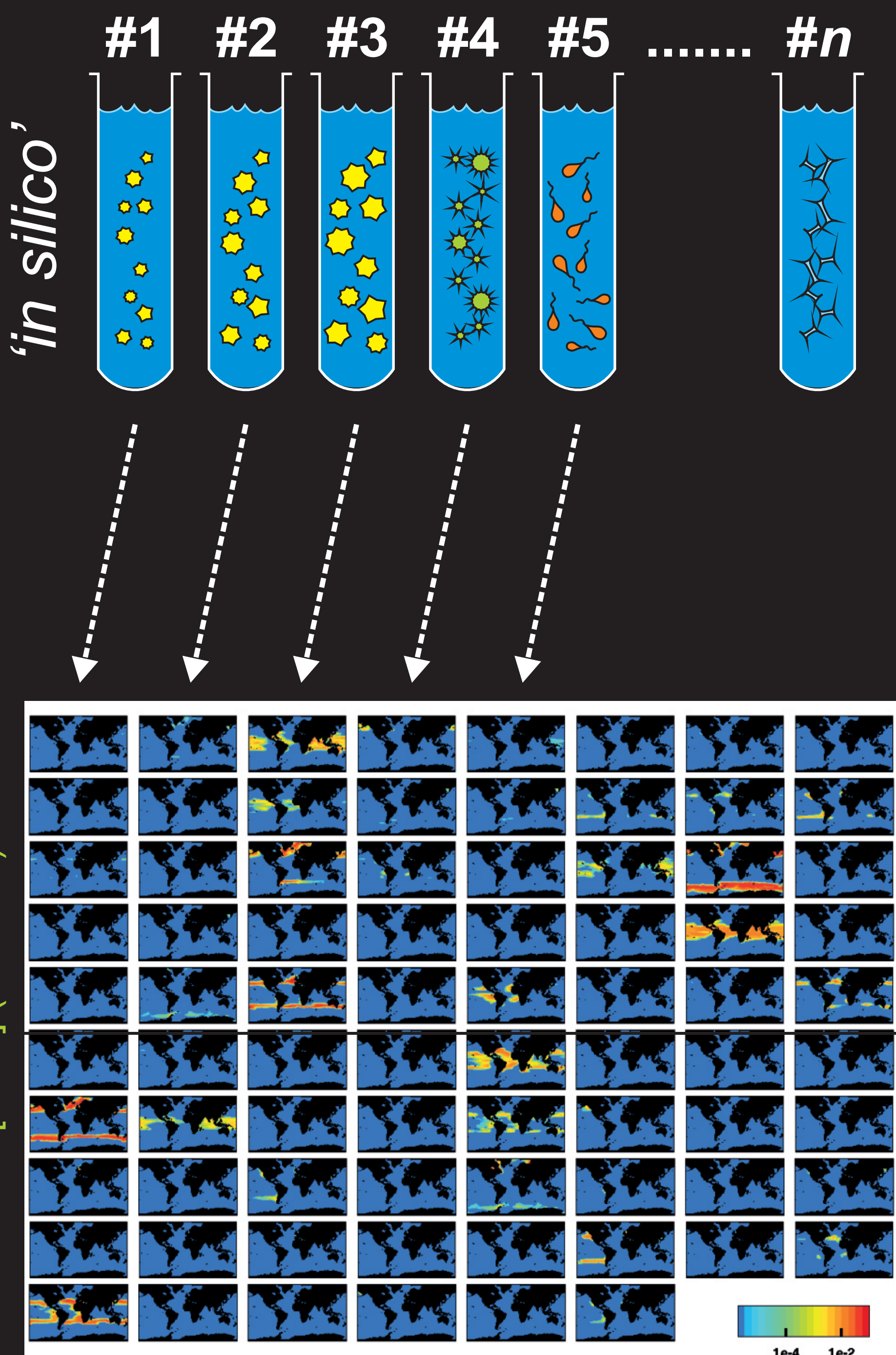
But also:

What about adaptation (or even evolutionary responses) to global change?



(Ocean) General Ecological Models? (O-GEMs?)



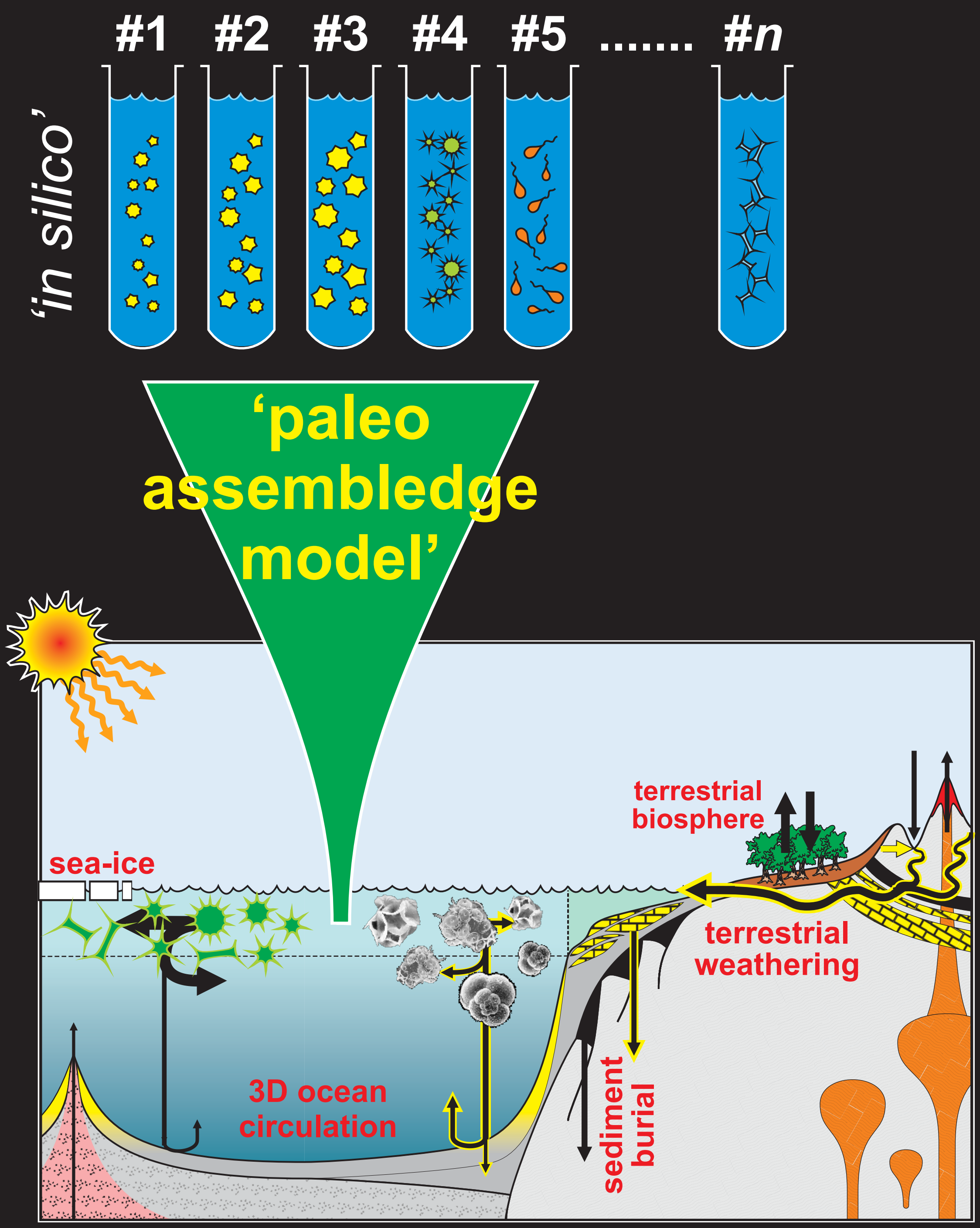


Follows et al. [2007] (*Science*)

Marine ecosystems *in silico*:

- The MIT ‘Darwin’ model typically considered ca. *n* = 76 randomly-generated trait vectors (’plankton’).
- Plankton trait vectors set according to physiological ‘rules’, e.g. larger cells have a higher nutrient limitation threshold, the ability to fixed N_2 comes at the expense of reduced growth rate, etc.
- Plankton compete and the ecosystem is an **emergent** rather than prescribed property.

But ...



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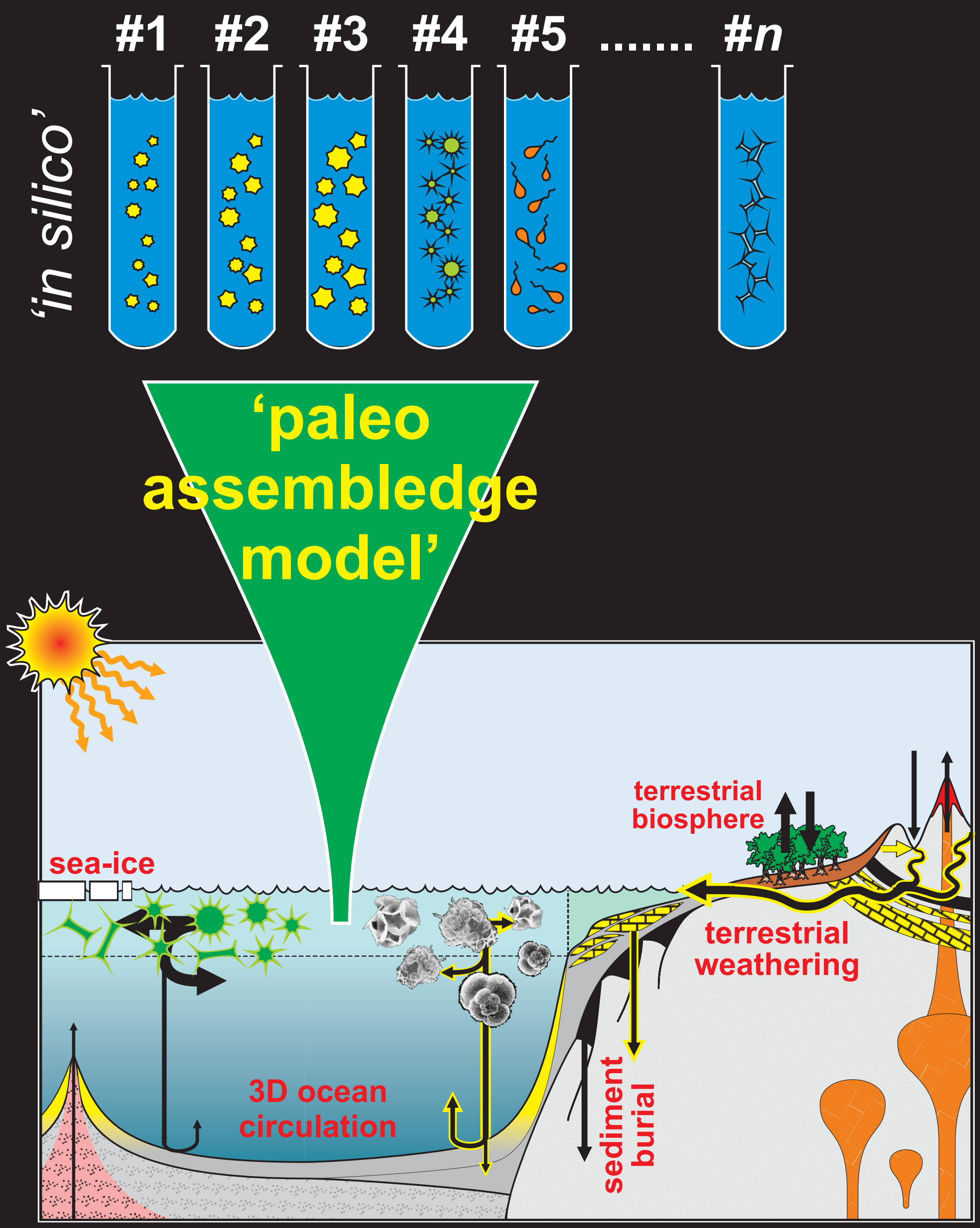
But ...

... *the geochemical environment and climate co-evolves as global nutrient cycles are modified*.

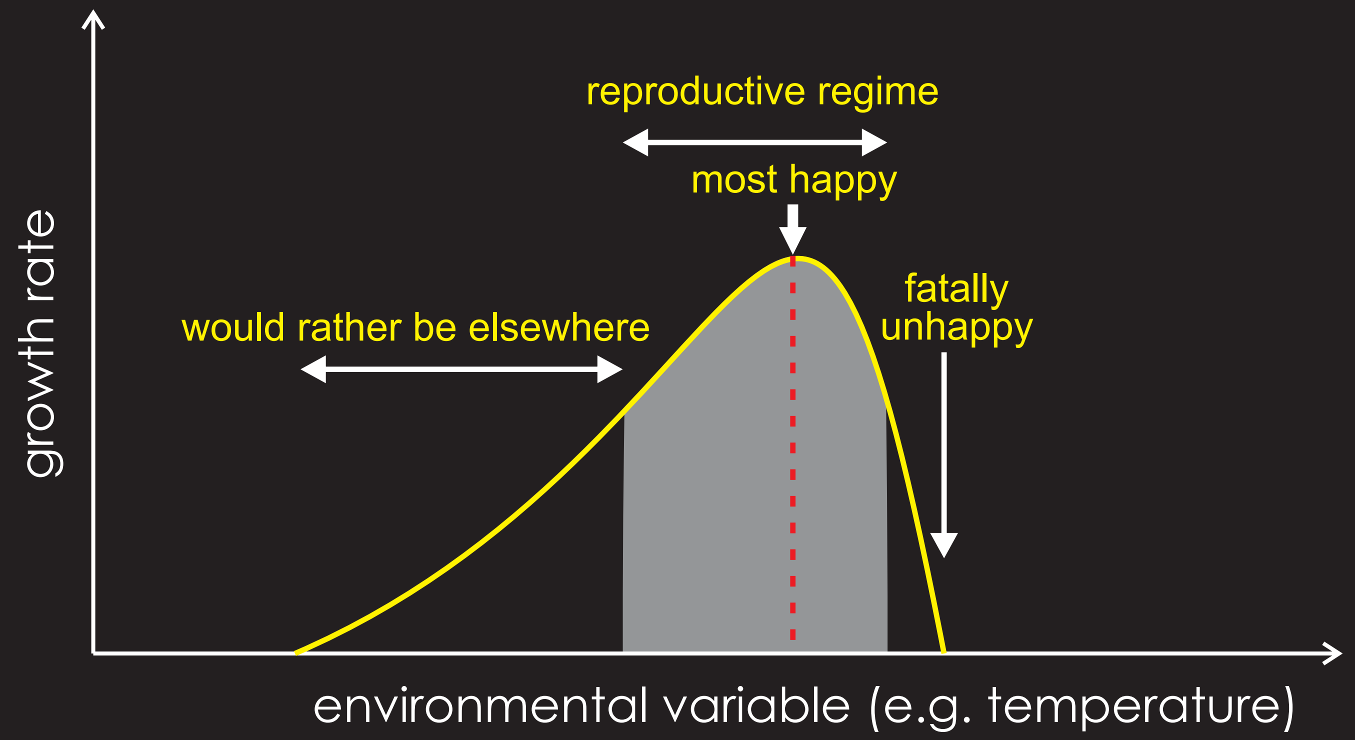
'PALEOGENiE'



Marine ecosystems *in silico*:

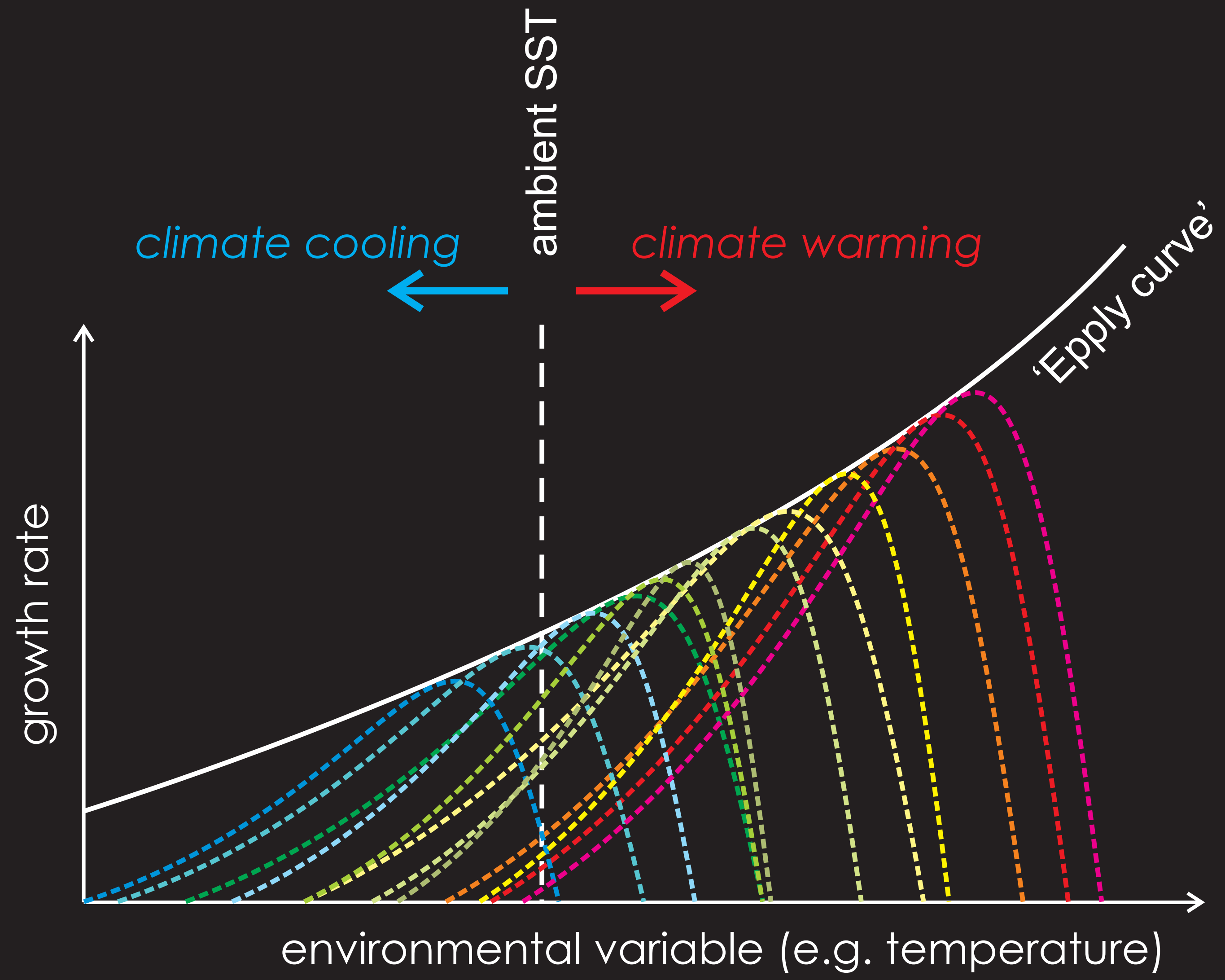
- *n* = 1,000-10,000 randomly-generated trait vectors ('plankton').
- Plankton trait vectors set according to physiological 'rules', e.g. larger cells have a higher nutrient limitation threshold, the ability to fixed N_2 comes at the expense of reduced growth rate, etc.
- Plankton compete and the ecosystem is an **emergent** rather than prescribed property.
  But ...
  ... *the geochemical environment and climate co-evolves as global nutrient cycles are modified*.
- At very high resolved diversity, we can explore questions of **adaptation** and rates of **evolutionary change** by spawning new plankton with perturbed characteristics.

Marine ecosystems *in silico*



're-drawn', with sincere apologies, from Schmidt et al. [2006]

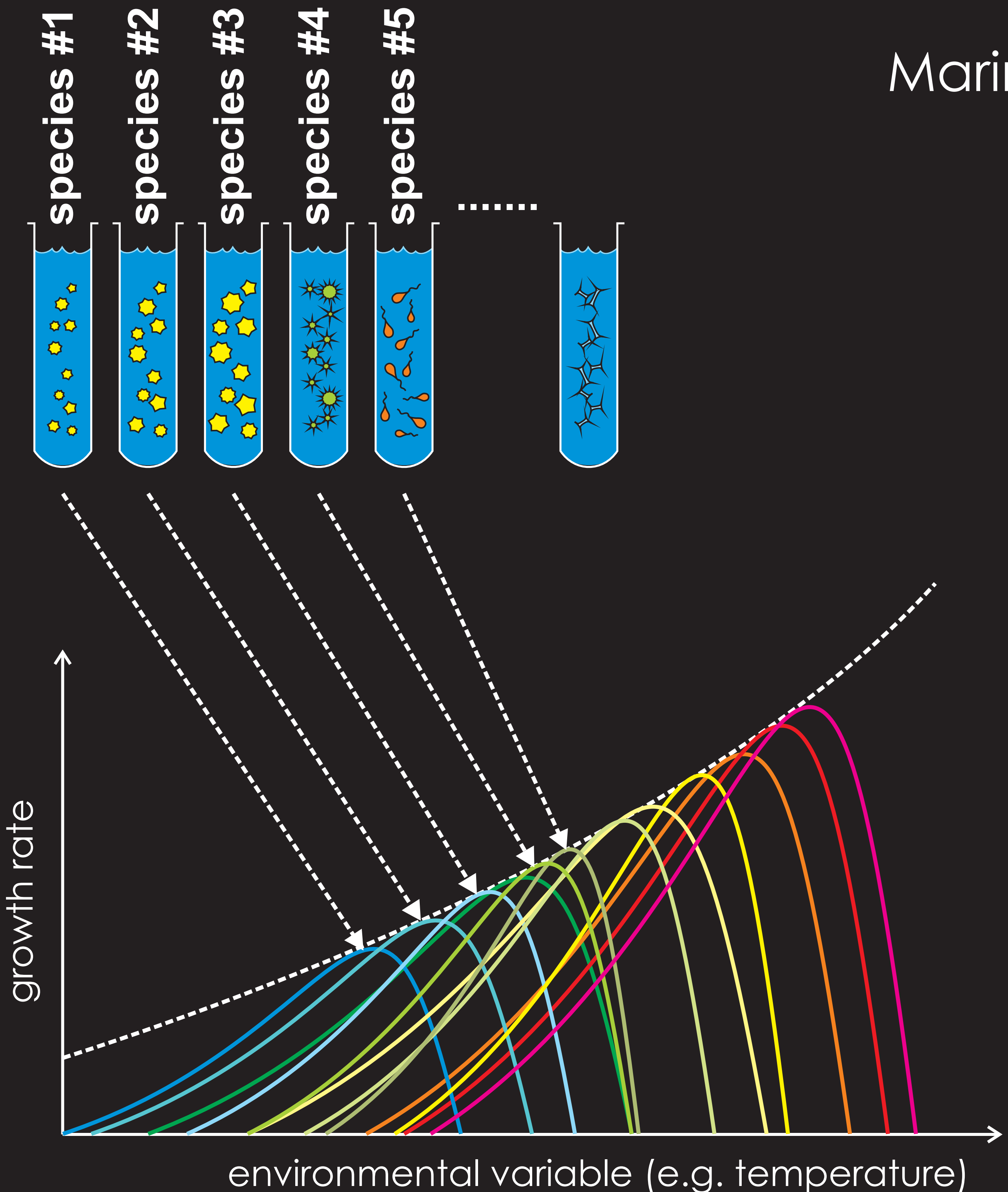
Marine ecosystems *in silico*



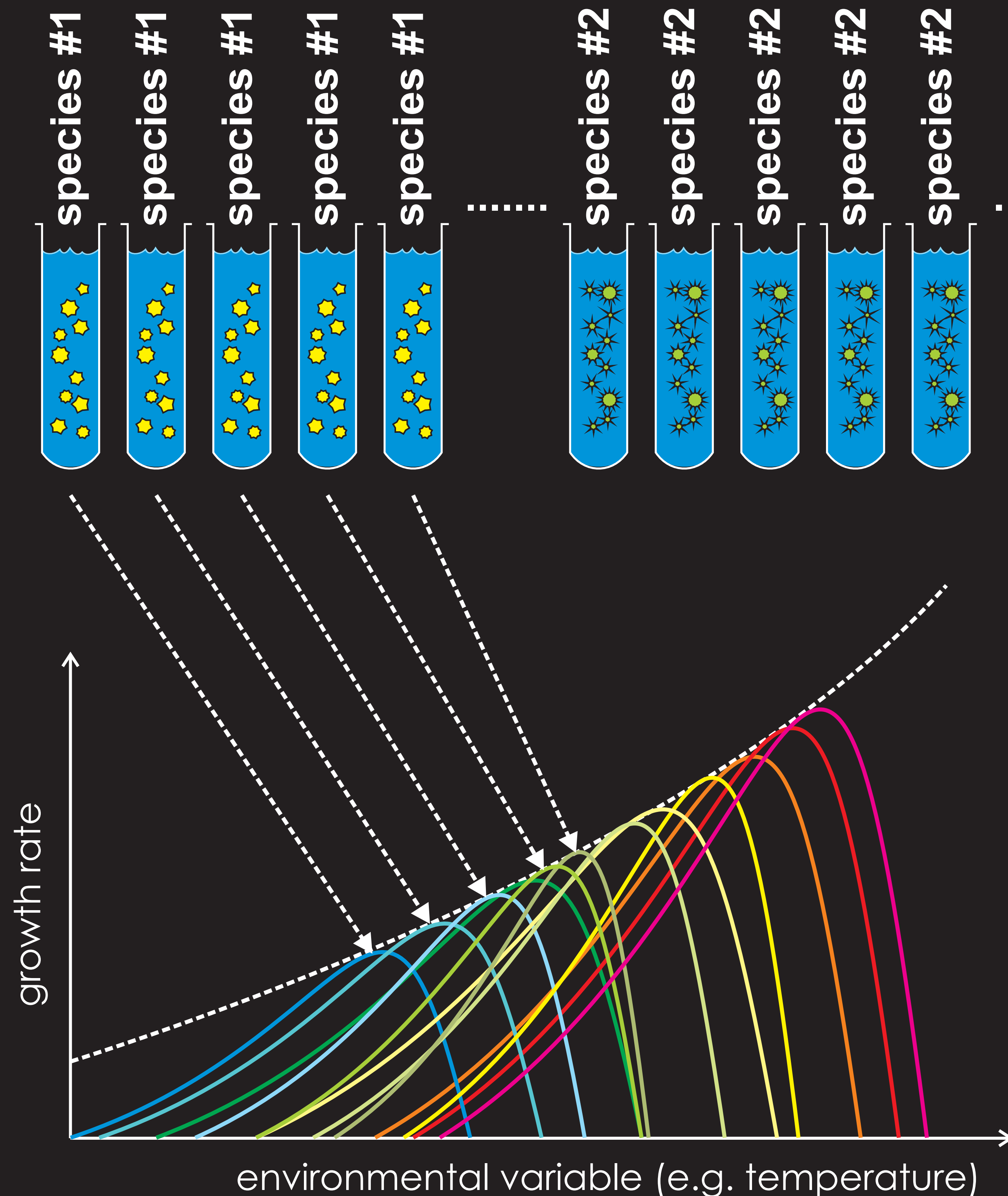
In traditional 'functional type' ecosystem models, diversity is not resolved, but instead its effects highly parameterized (e.g. the 'Epply curve').

The response to a change in climate is then instantaneous and fully reversible.

Marine ecosystems *in silico*



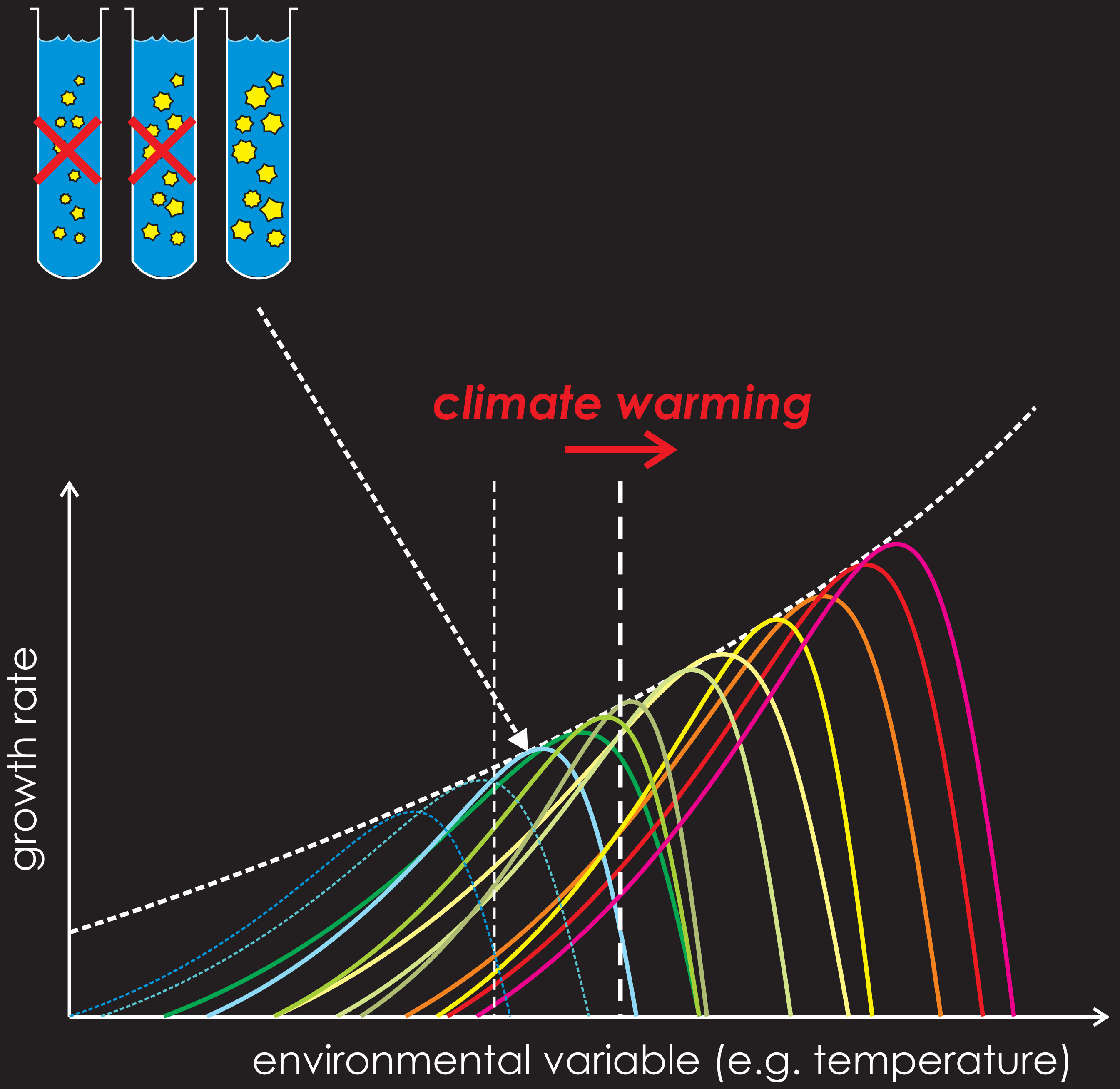
Instead, in a highly diverse model, the environmental response of individual ‘species’ can be resolved ...



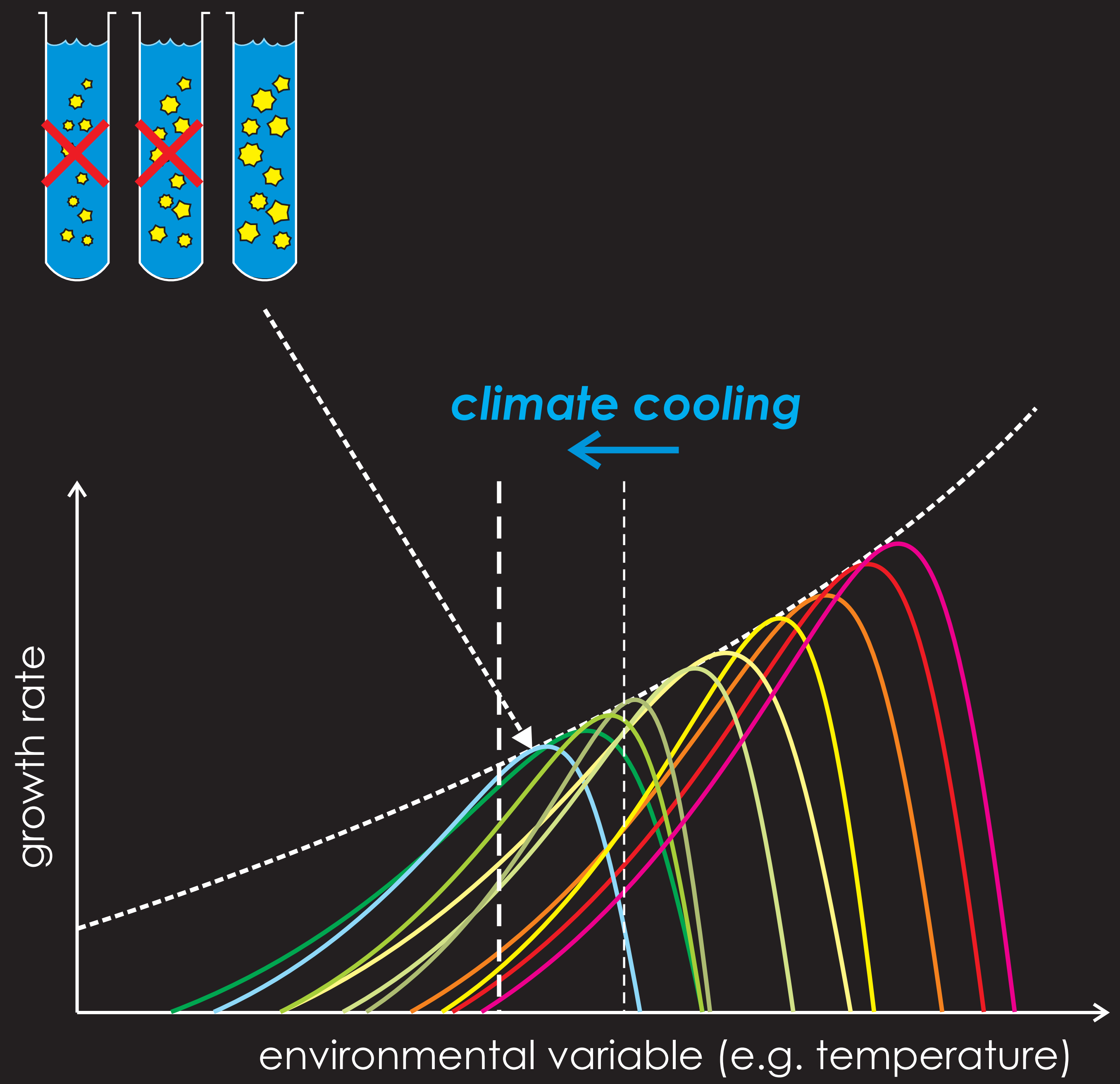
Instead, in a highly diverse model, the environmental response of individual 'species' can be resolved ...

... or instead, the capability for adaptation (environmental selection within existing genetic diversity) can be represented(?)

Marine ecosystems *in silico*



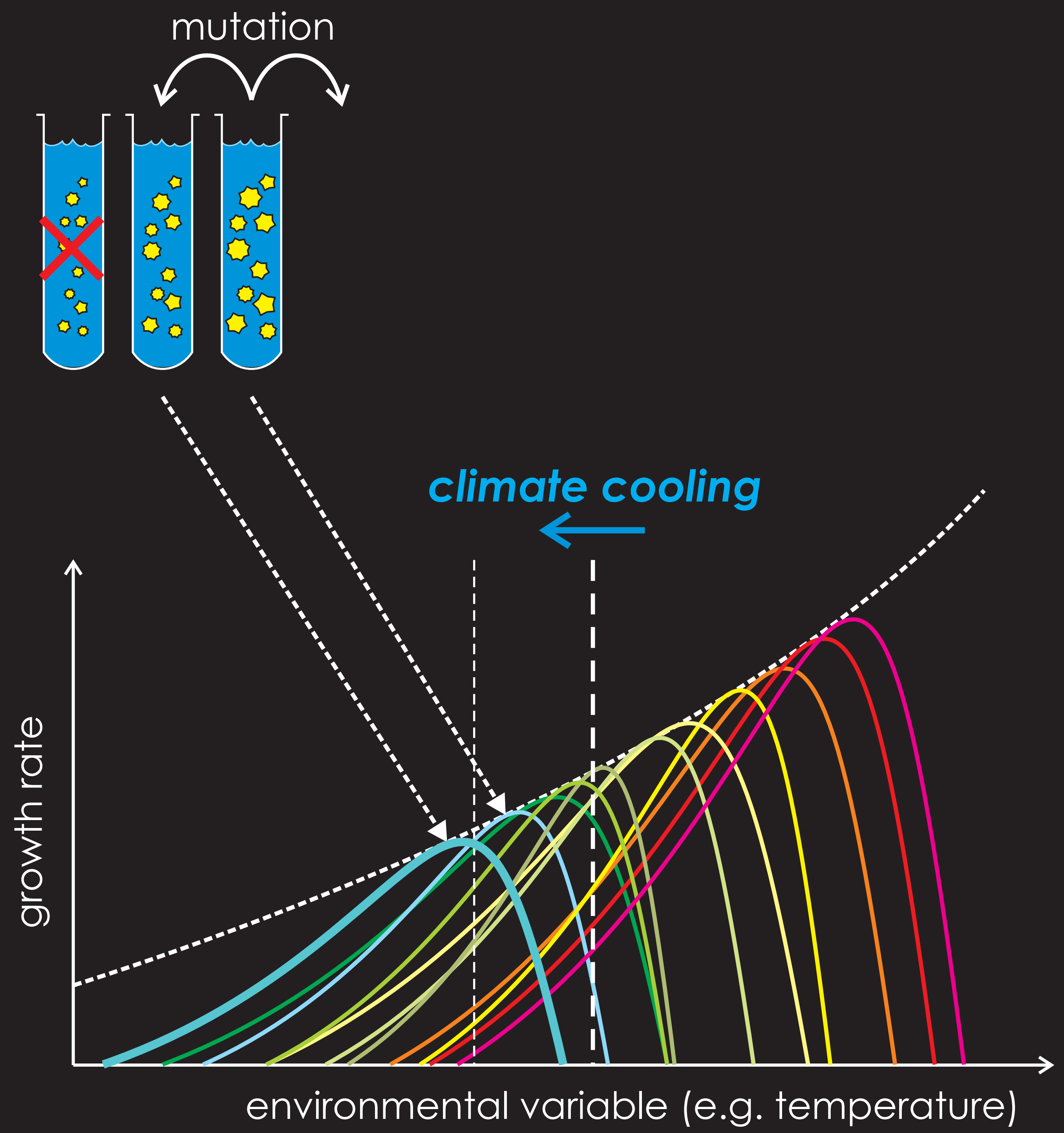
Marine ecosystems *in silico*



If climate cools, the low SST optimized species/varients no longer exist. Ecosystem dynamics are presumably different.

Niches are unfilled, so ...

Marine ecosystems *in silico*

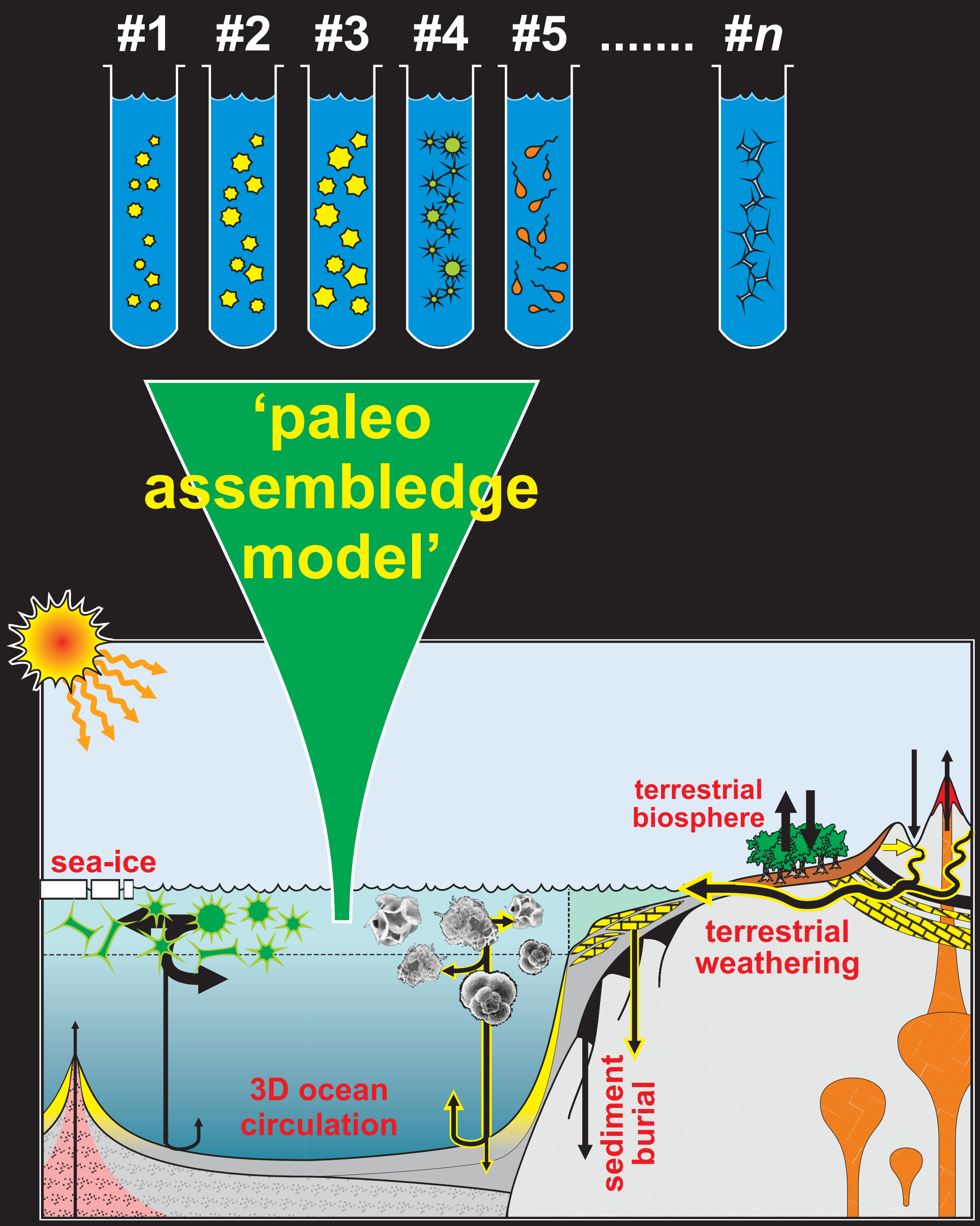


Allow non-viable plankton to be replaced with 'mutations' of surviving species, using the trait based trade-offs.

Q. How 'frequently' to mutate, and as a function of what?

Q. What 'step size' to take for mutation?

‘PALEOGEN*i*E’:



- A radical paleo model-data concept for theoretically exploring questions of marine plankton adaptation and evolution.
- Specific questions:
  Cause(s) of the delayed recovery (100s of kyr) from end Cretaceous extinction
  Determining which factor(s) best explain ecological responses to PETM carbon release.
- A tool for gaining understanding about future ecosystem stability (+ proof concepts for future models).

Marine ecosystems *in silico*:

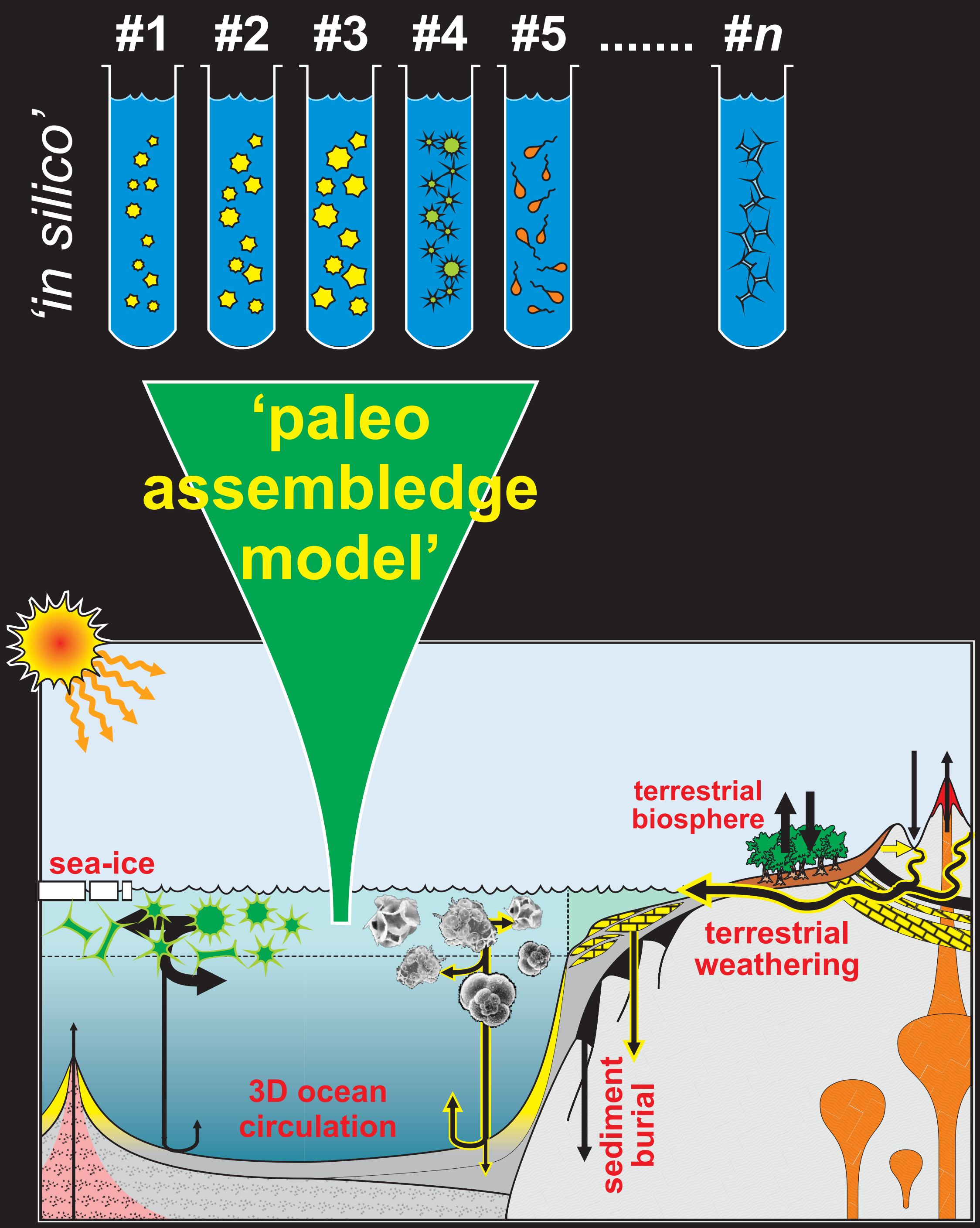
- *n* = 1,000-10,000 randomly-generated trait vectors ('plankton').

...

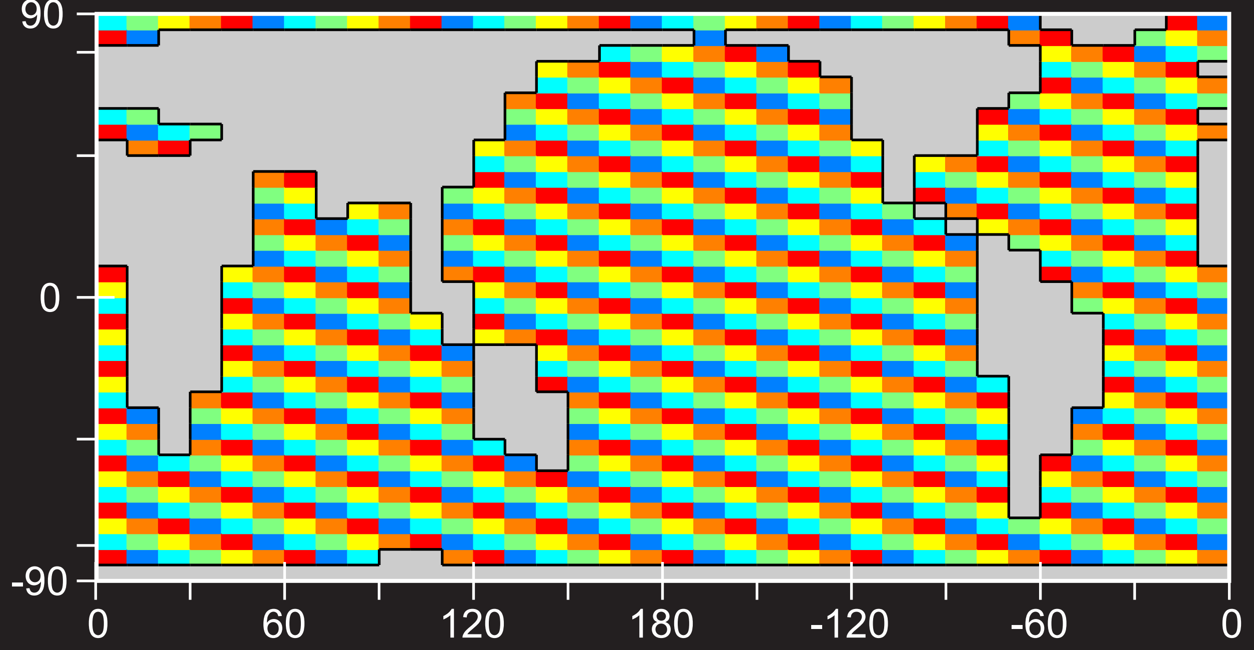
...

- At very high resolved diversity, we can explore questions of **adaptation** and rates of **evolutionary change** by spawning new plankton with perturbed characteristics.

There is clearly a very significant computational expense involved, even if using low resolution/efficient Earth system models such as 'GENIE'.



'Color' tracer pattern to unambiguously diagnose surface ocean transport



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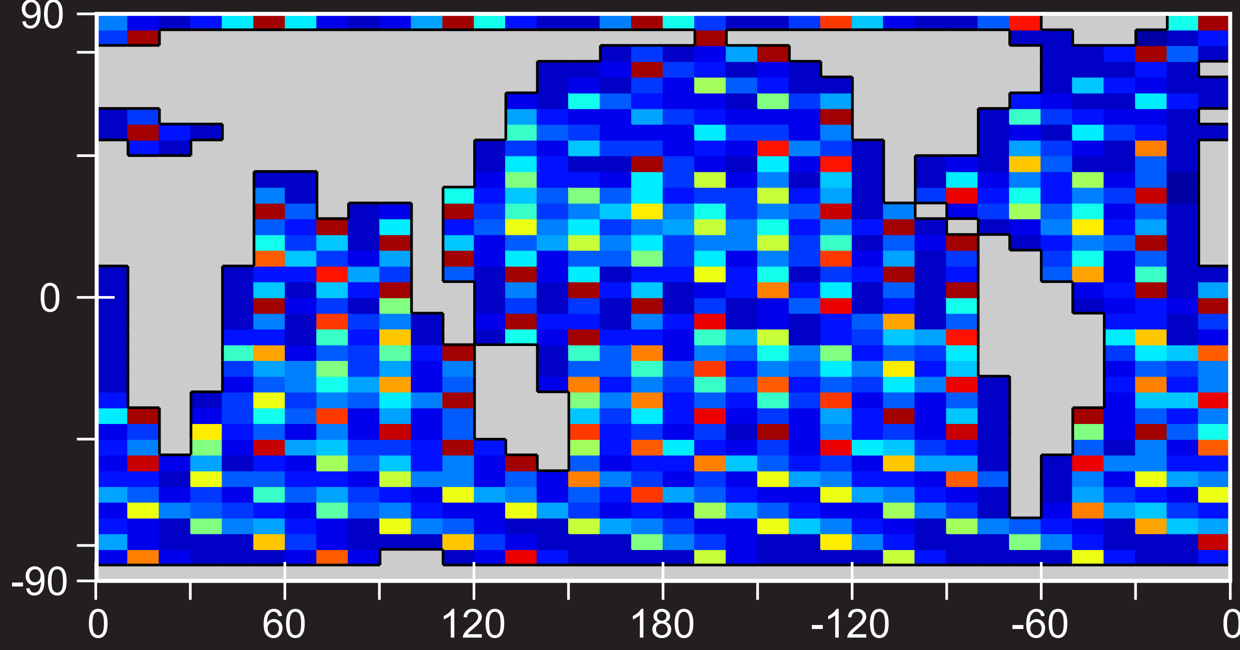
=> Calculate plankton transport separately from nutrients (and other dissolved tracers)?

Dispersal of a single 'color' after 1 year



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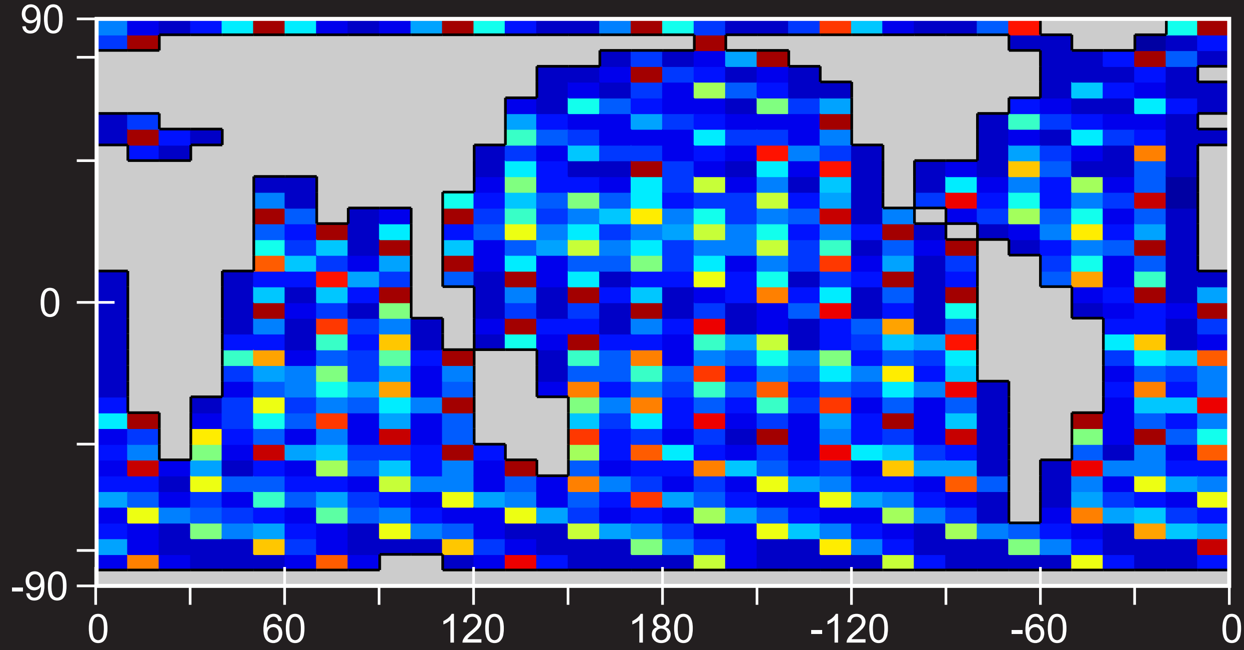
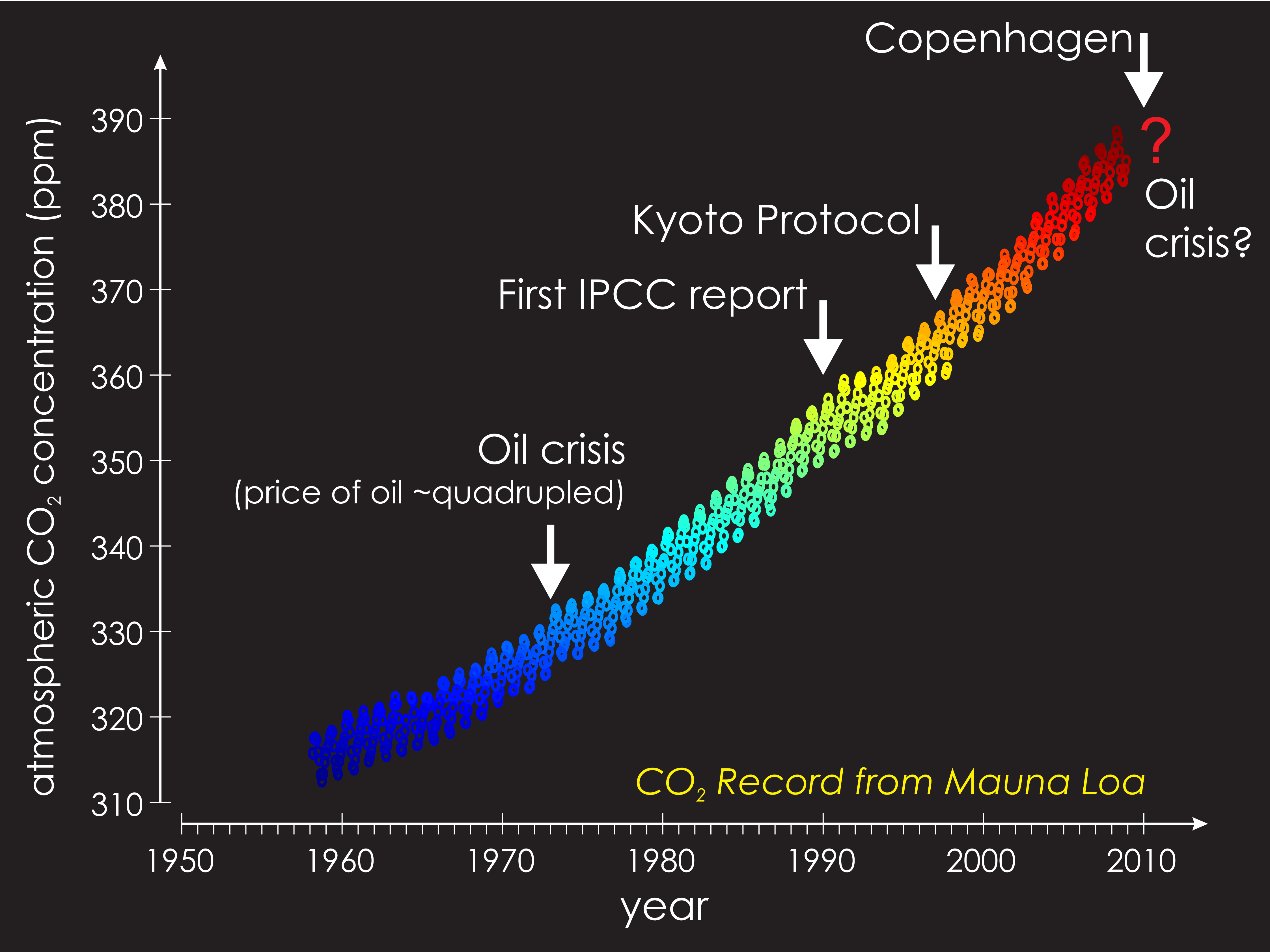


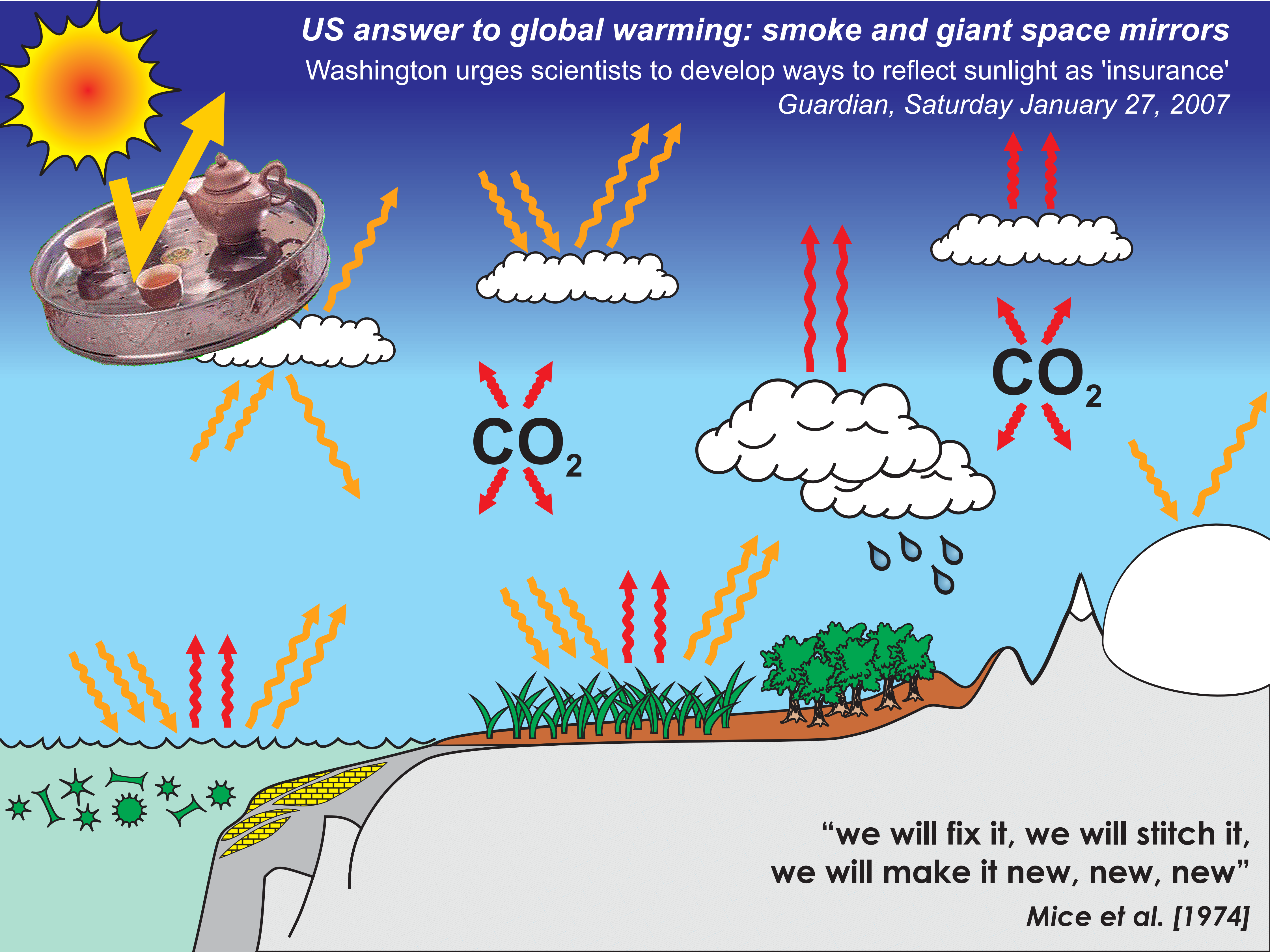
There is clearly a very significant computational expense involved, even if using low resolution/efficient Earth system models such as ‘GENIE’.

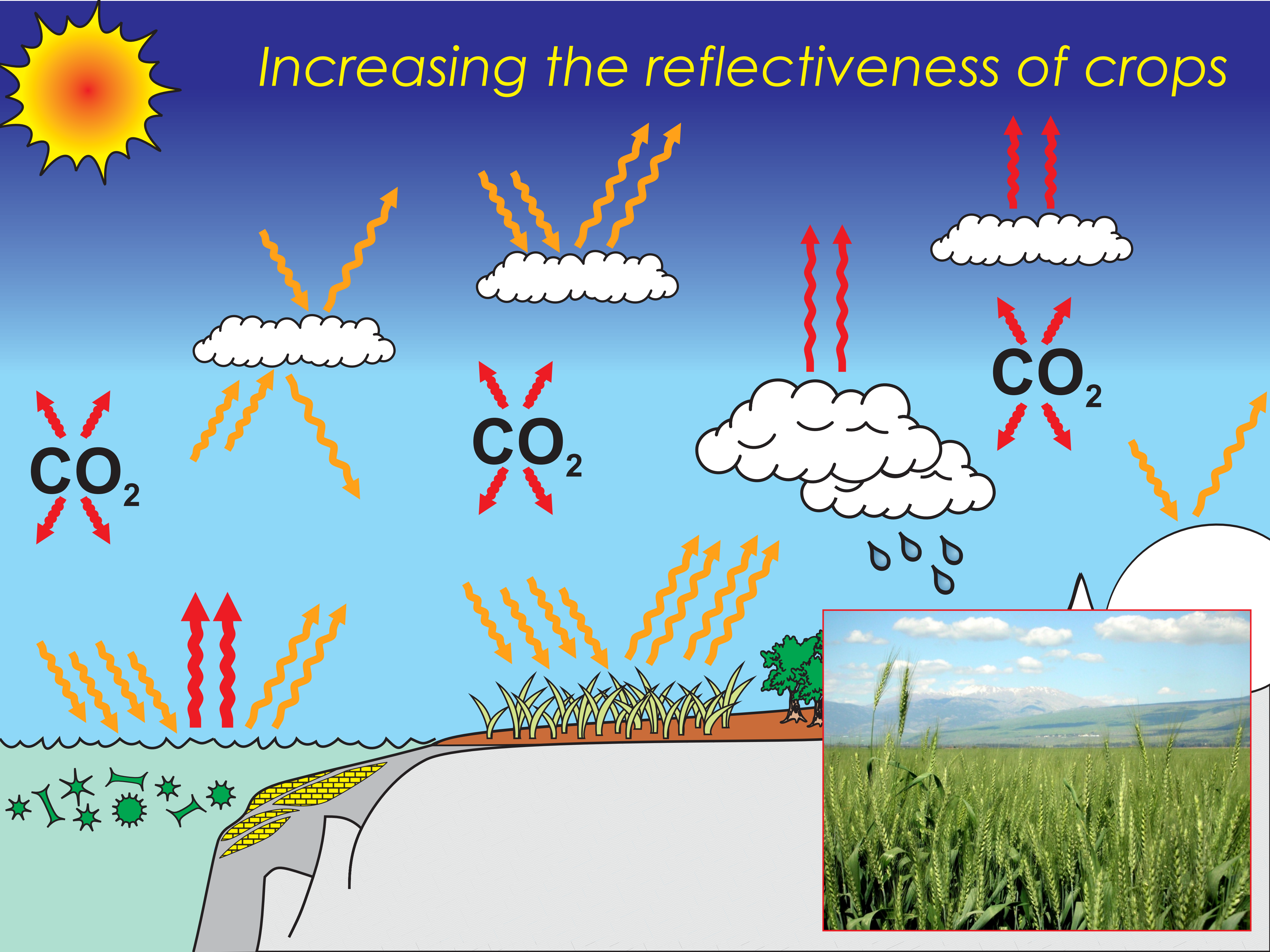
=> Calculate plankton transport separately from nutrients (and other dissolved tracers)?

=> Or, diagnose full 3D circulation, and employ (sparse) parallelized matrix multiplication or similar ...



Copenhagen
?
Oil
crisis?
Kyoto Protocol
First IPCC report
Oil crisis
(price of oil ~quadrupled)
CO_2 Record from Mauna Loa
atmospheric CO_2 concentration (ppm)
390
380
370
360
350
340
330
320
310
1950
1960
1970
1980
1990
2000
2010
year


US answer to global warming: smoke and giant space mirrors
Washington urges scientists to develop ways to reflect sunlight as 'insurance'
Guardian, Saturday January 27, 2007
CO_2
CO_2
“we will fix it, we will stitch it,
we will make it new, new, new”
Mice et al. [1974]


Increasing the reflectiveness of crops
CO_2
CO_2
CO_2

Cooling the Planet with Crops (background)

albedo ~ 0.23
(77% absorption)

albedo ~ 0.18
(82% absorption)

albedo ~ 0.16
(84% absorption)

Decreasing albedo

Increasing reflectivity

Cooling the Planet with Crops (background)

albedo ~ 0.26
(74% absorption)

sugar beet

albedo ~ 0.23
(77% absorption)

barley

Decreasing albedo

Increasing reflectivity

Cooling the Planet with Crops (background)

Controls on (intra) variety crop albedo:

leaf waxiness

leaf/stem hairs

canopy structure

Cooling the Planet with Crops (background)

albedo ~ 0.25
(75% absorption)

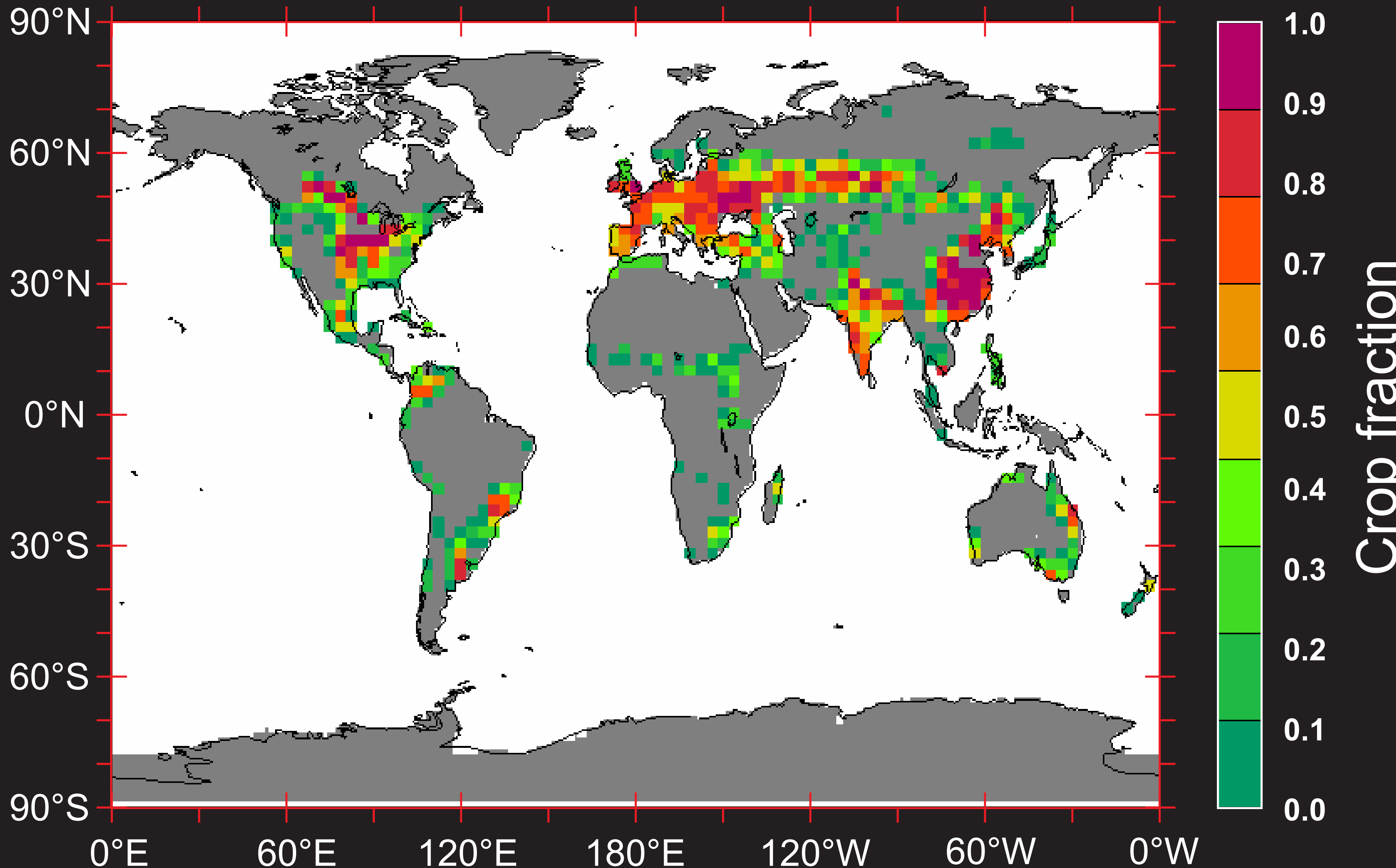
albedo ~ 0.23
(77% absorption)

albedo ~ 0.21
(79% absorption)

Decreasing albedo

Increasing reflectivity

Cooling the Planet with Crops (proof-of-concept)



Ridgwell et al. [2009] (*Current Biology* **19**)

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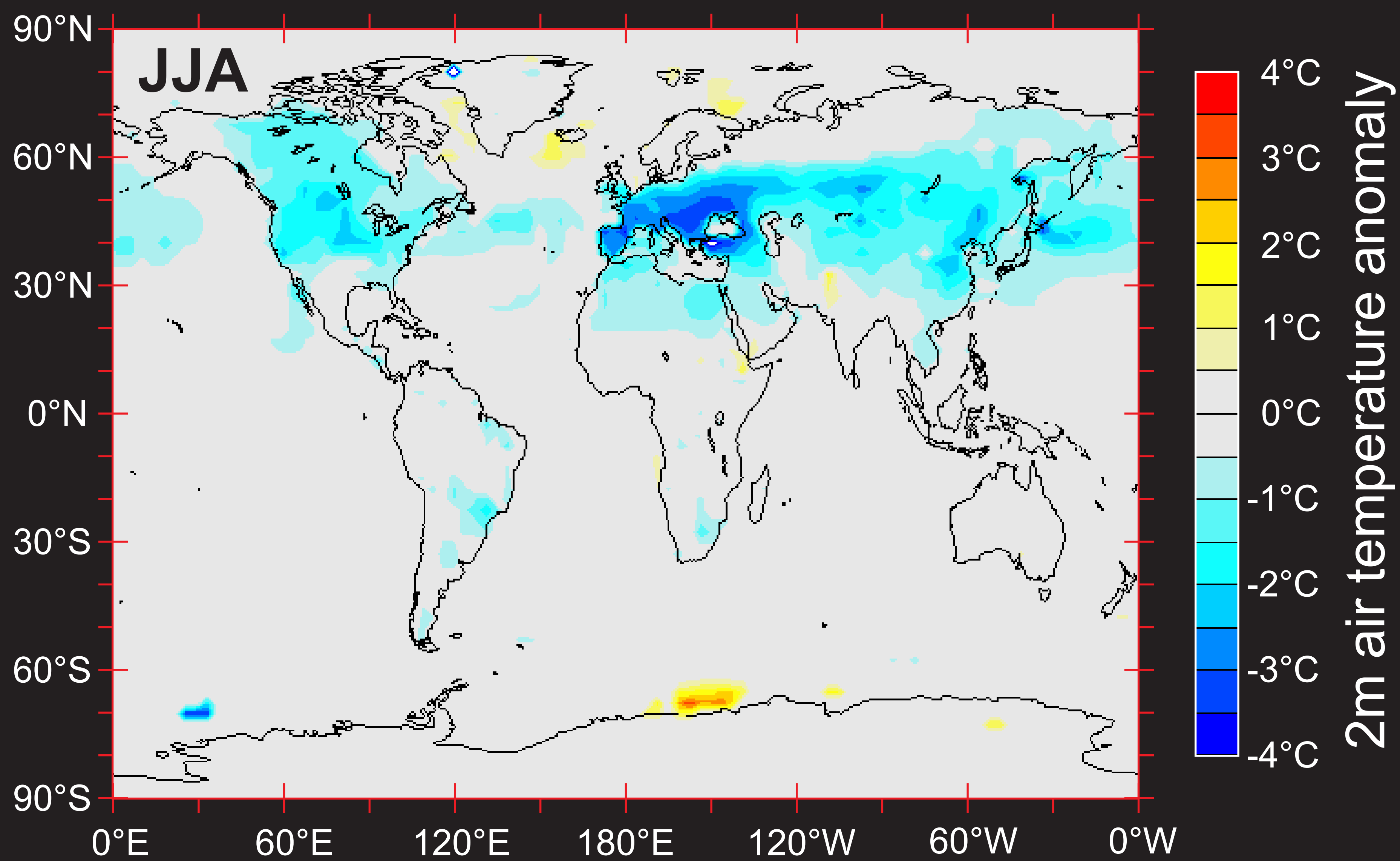

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Cooling the Planet with Crops (feasibility)

#1 Growing range of commercially available strains of wheat.

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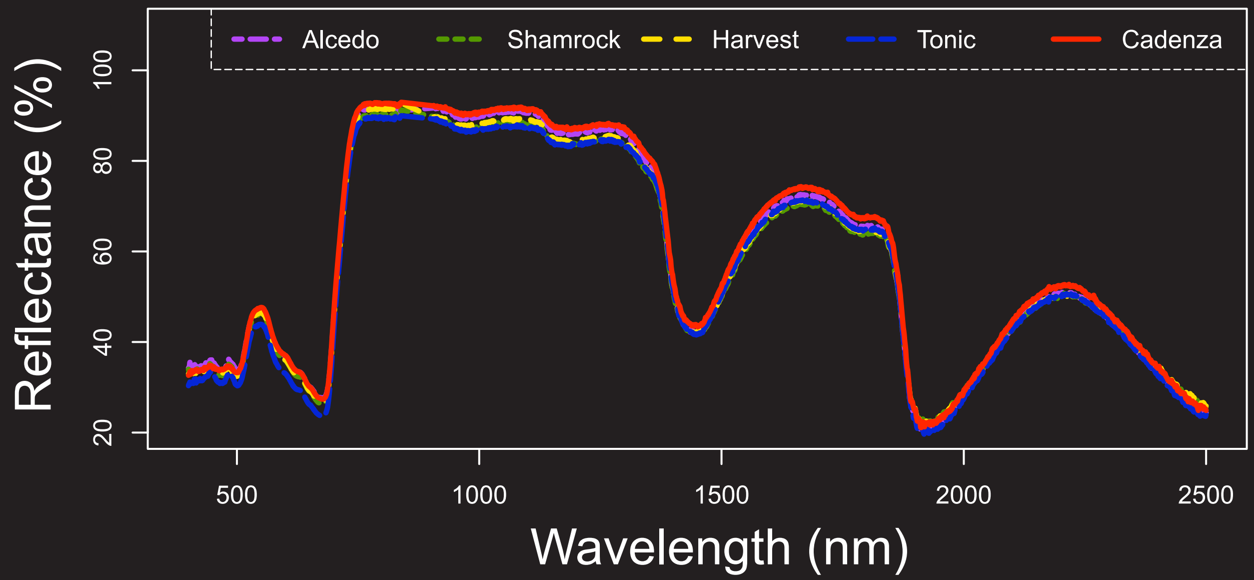
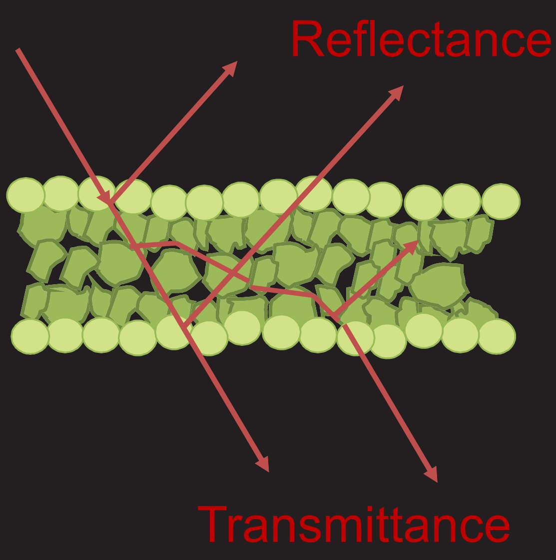
#2 Measuring reflectance and transmissivity of the leaves.





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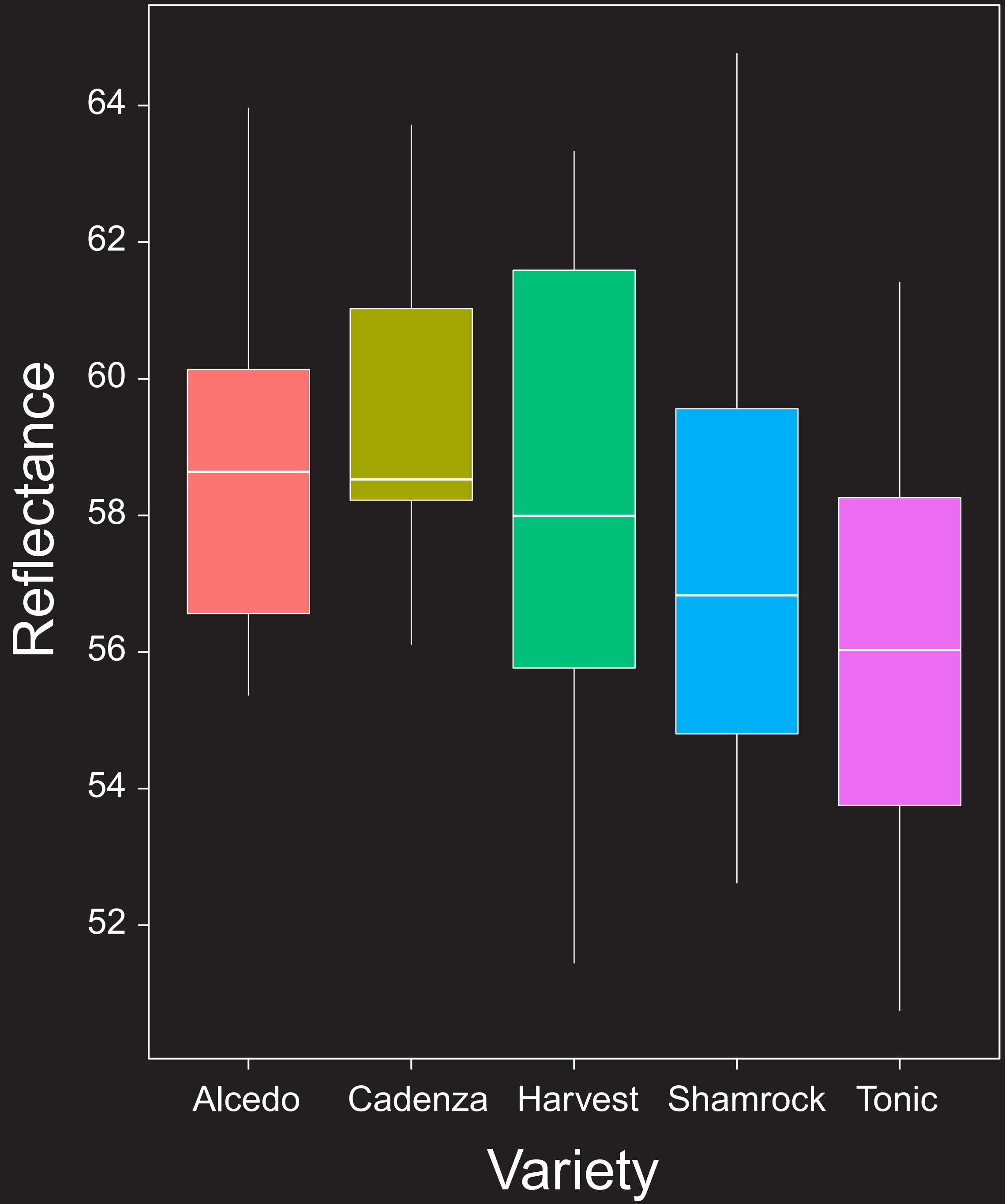


Cooling the Planet with Crops (feasibility)

#1 Growing range of commercially available strains of wheat.

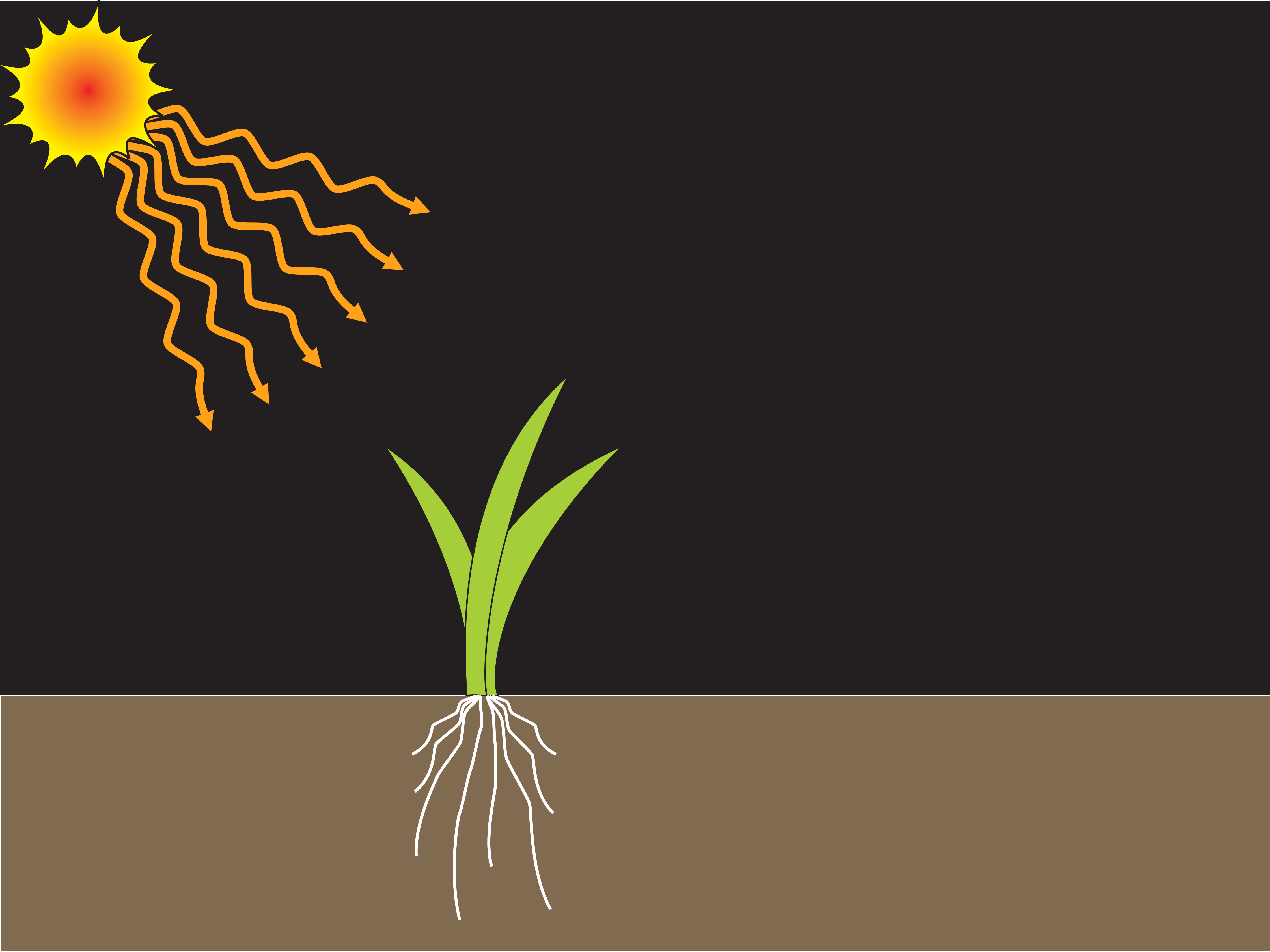
#2 Measuring reflectance and transmissivity of the leaves.

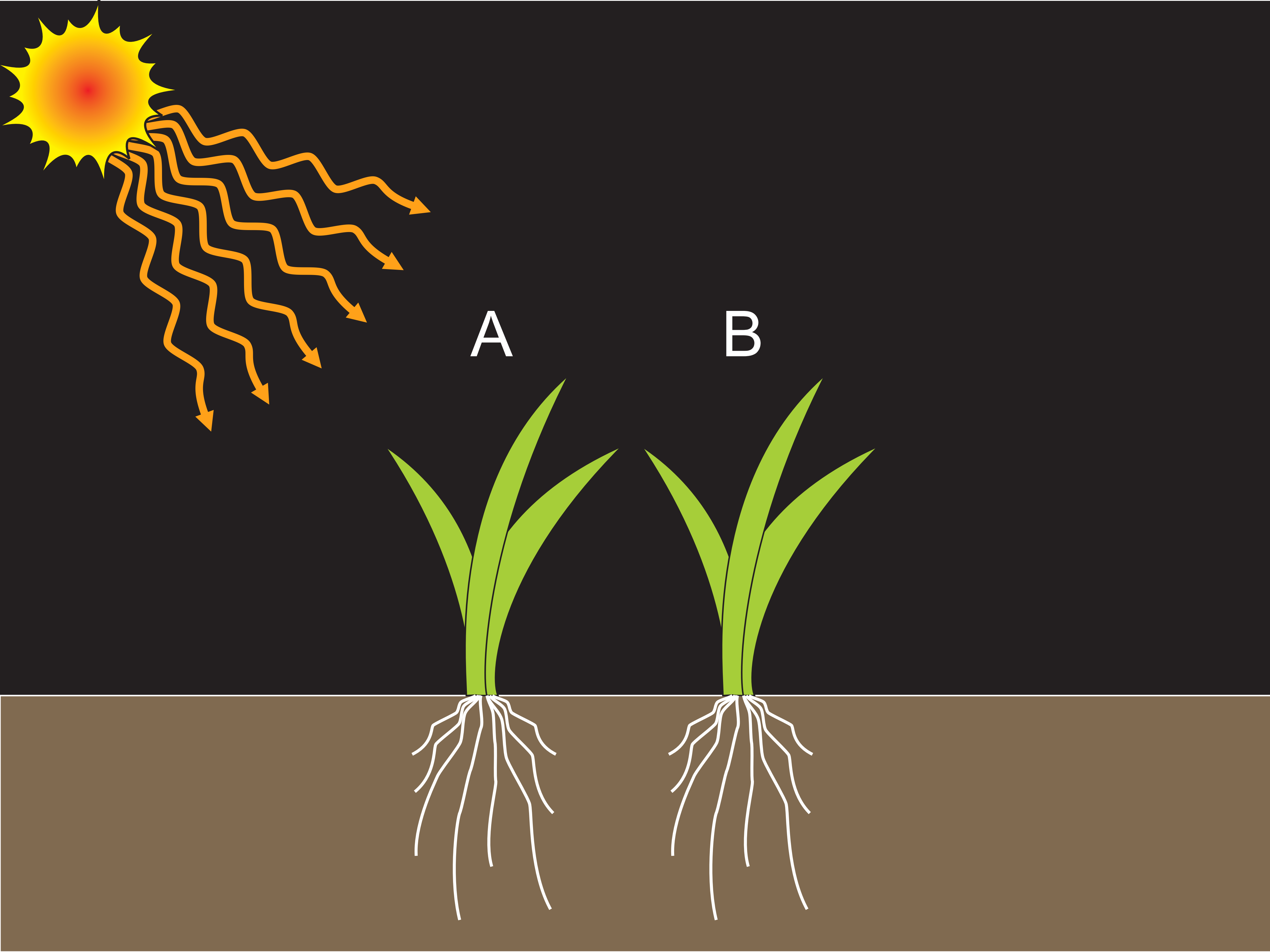
#3 Calculation of yield in crop models.

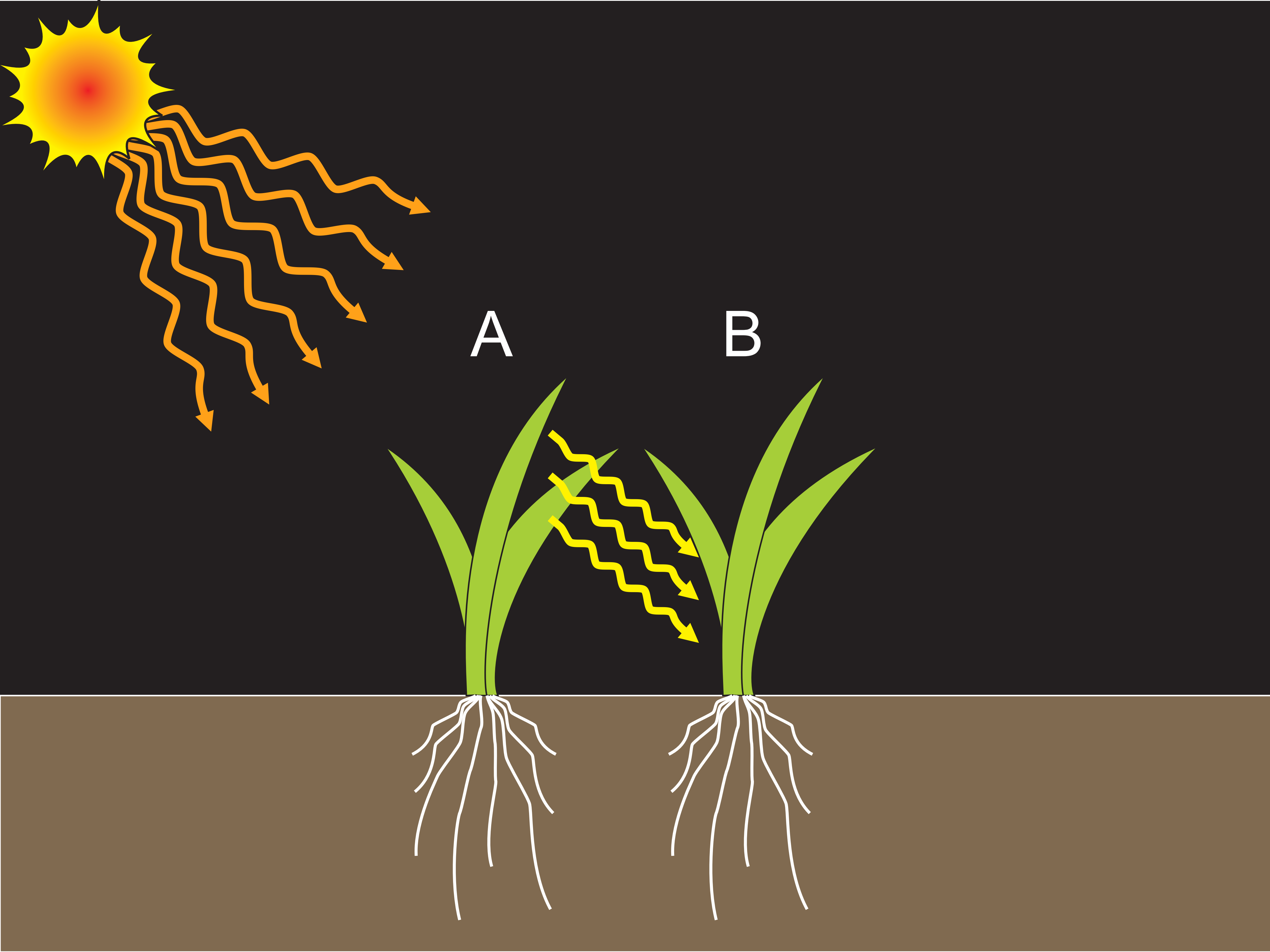
#4 Up-scaling to canopy level in climate models.

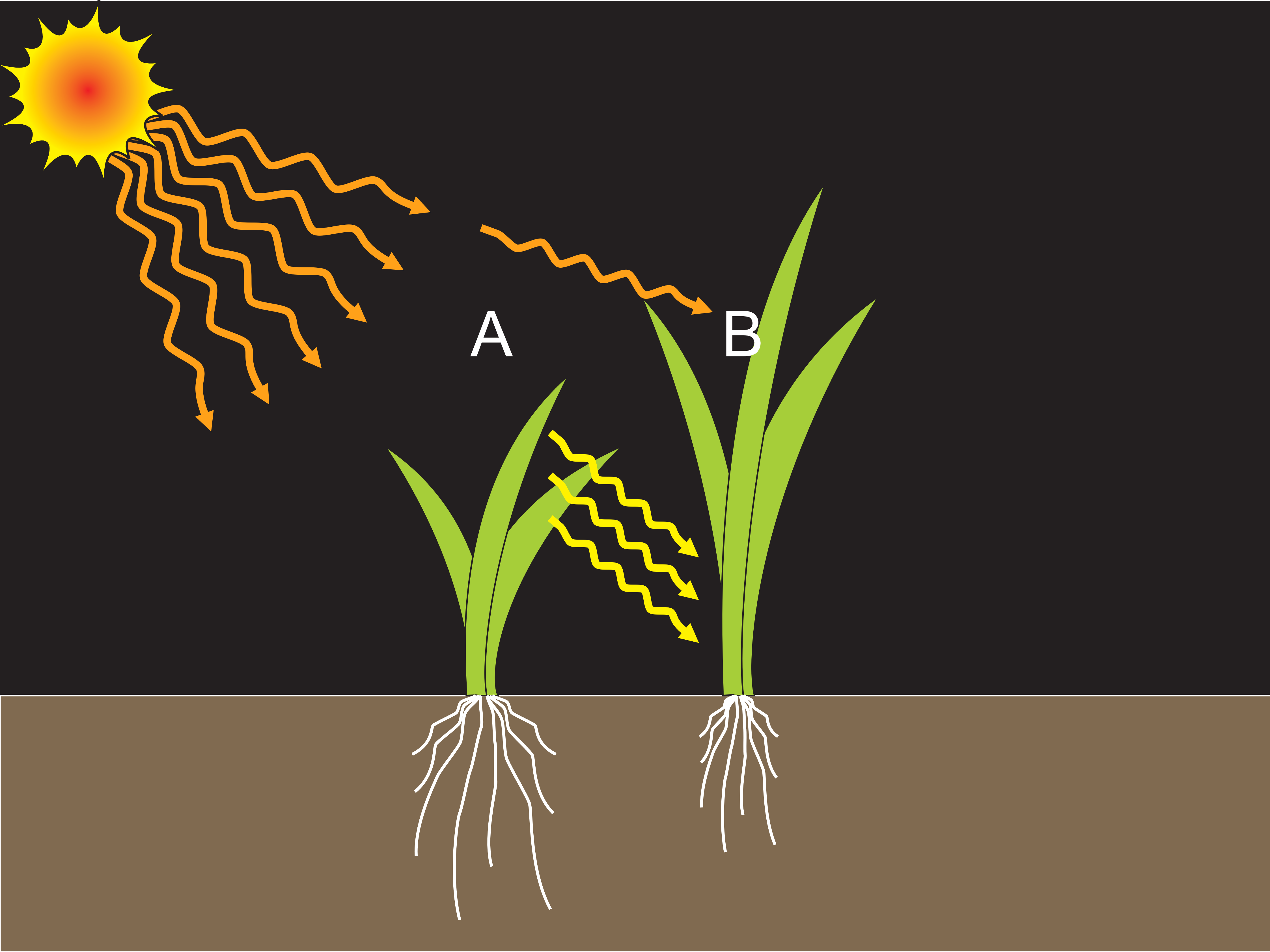
#5 Field measurements.

#6 ...




A
B

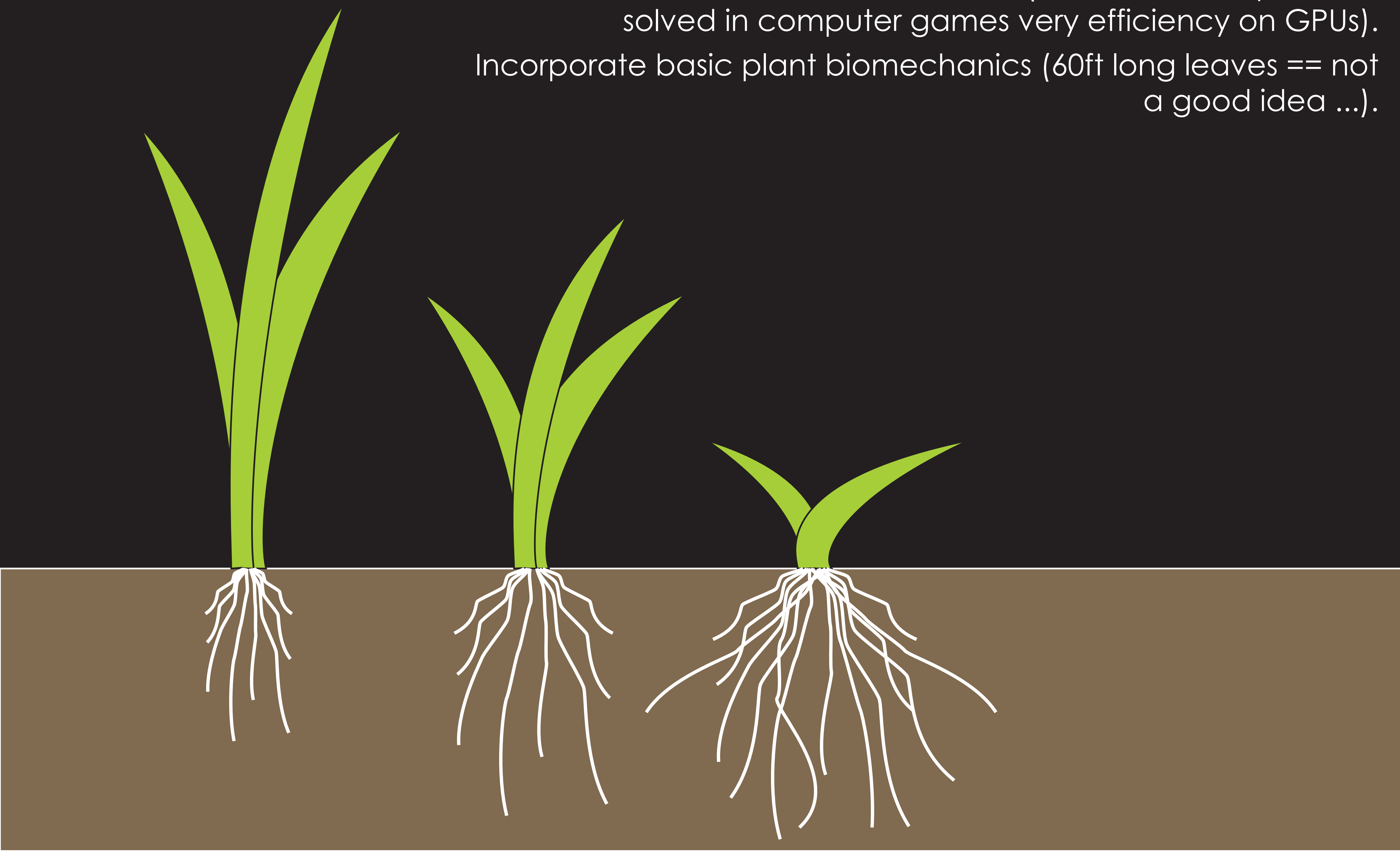

A
B

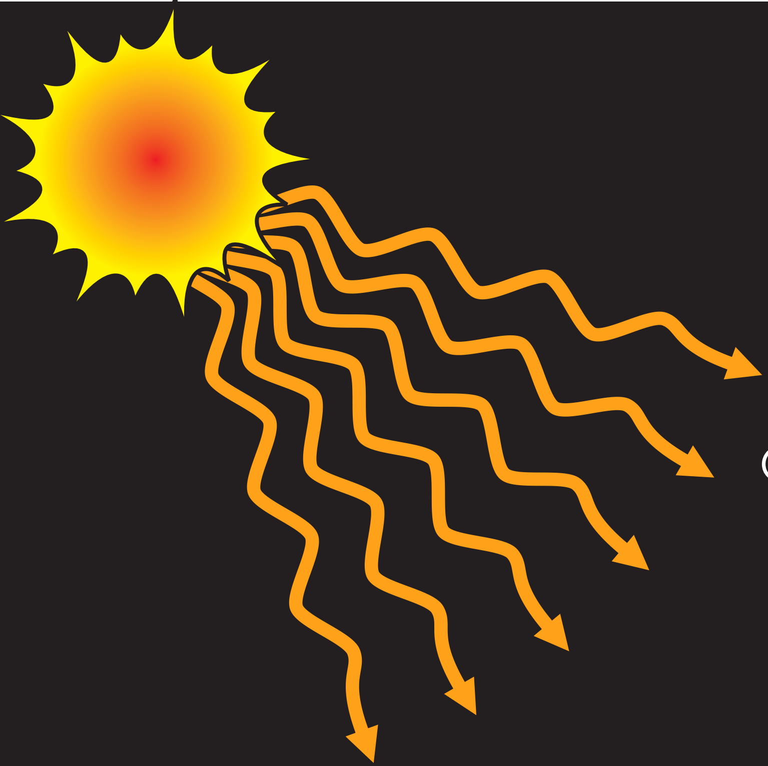

A
B

Create a crop (plant) model based on carbon resource allocation.

Incorporate a fully resolved canopy light transmission/reflection scheme (an established problem solved in computer games very efficiency on GPUs).

Incorporate basic plant biomechanics (60ft long leaves == not a good idea ...).





Mutate the plants across millions of generations and across millions of 'fields' on a massively parallel computing basis. Select for yield (but at the field scale, hence dealing with 'competition').

Can also select for e.g. water use efficiency, tolerance to gusty wind conditions, etc. etc.

Q. Would an 'optimal' crop plant have 6 triangular leaves that enables a hexagonal space-filling tessellation across the soil surface??

Rather than crops, such a model could be used to explore the coupled evolution of terrestrial plants and environment?