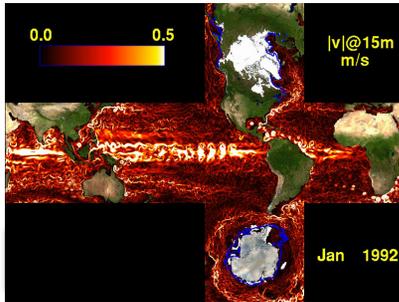


ECCO2 ocean surface carbon flux estimates

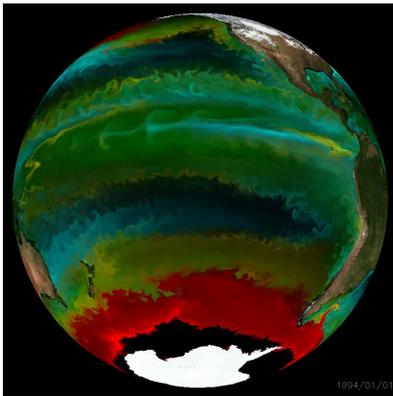
Carbon Monitoring System Flux-Pilot Meeting

NASA GSFC, October 20-21, 2010



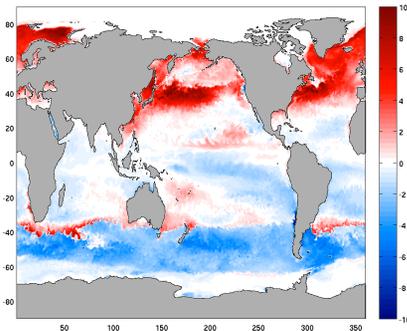
Dimitris Menemenlis

ECCO2 eddying ocean and sea ice state estimation



Chris Hill

Darwin: a self-organizing marine ecosystem model



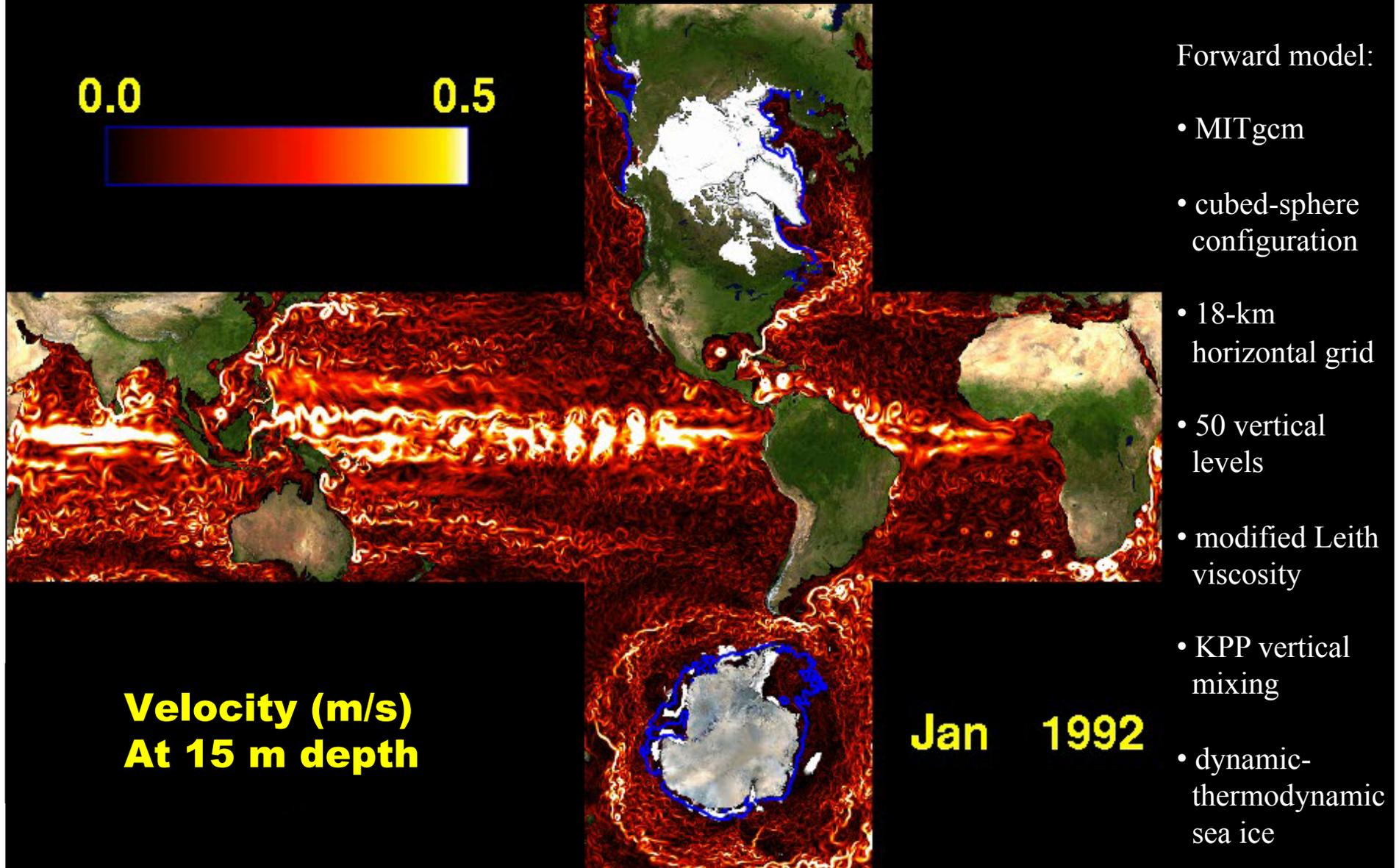
Holger Brix

ECCO2 eddying green ocean carbon fluxes - first results

ECCO2: High-Resolution Global-Ocean and Sea-Ice Data Synthesis

Objective: synthesis of global-ocean and sea-ice data that covers the full ocean depth and that permits eddies.

Motivation: improved estimates and models of ocean carbon cycle, understand recent evolution of polar oceans, monitor time-evolving term balances within and between different components of Earth system, etc.



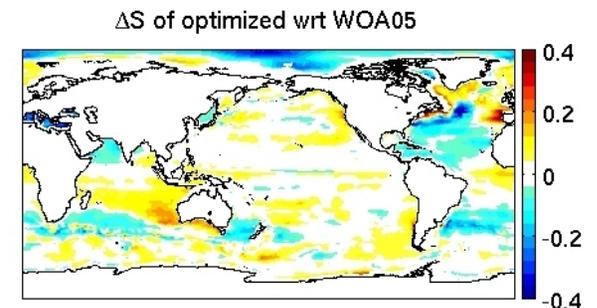
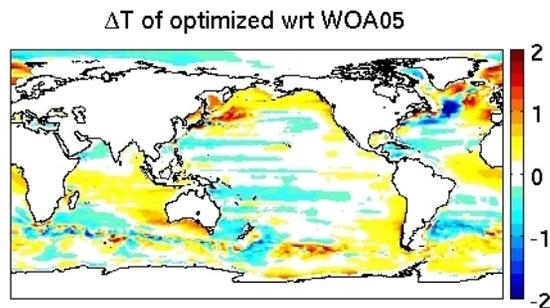
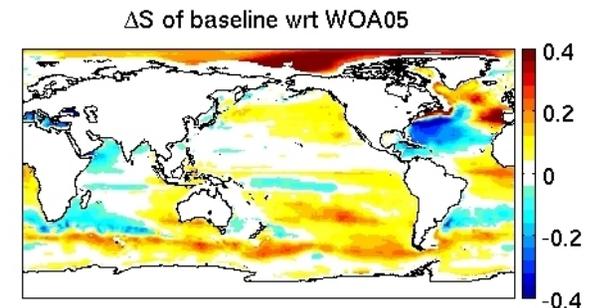
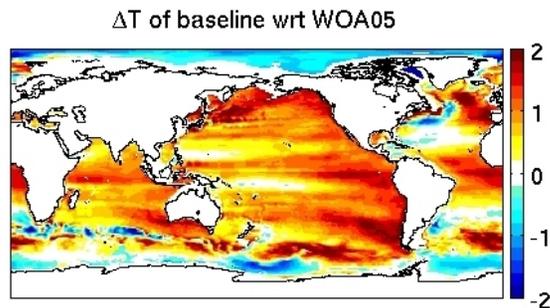
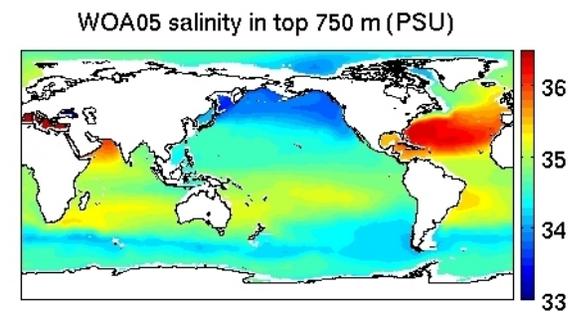
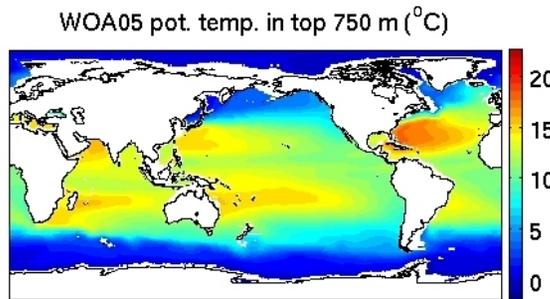
1992-present eddying global-ocean and sea-ice solution obtained using a Green's function approach

Data constraints:

- sea level anomaly
- time-mean sea level
- sea surface temperature
- temperature/salinity profiles
- sea ice concentration
- sea ice motion
- sea ice thickness

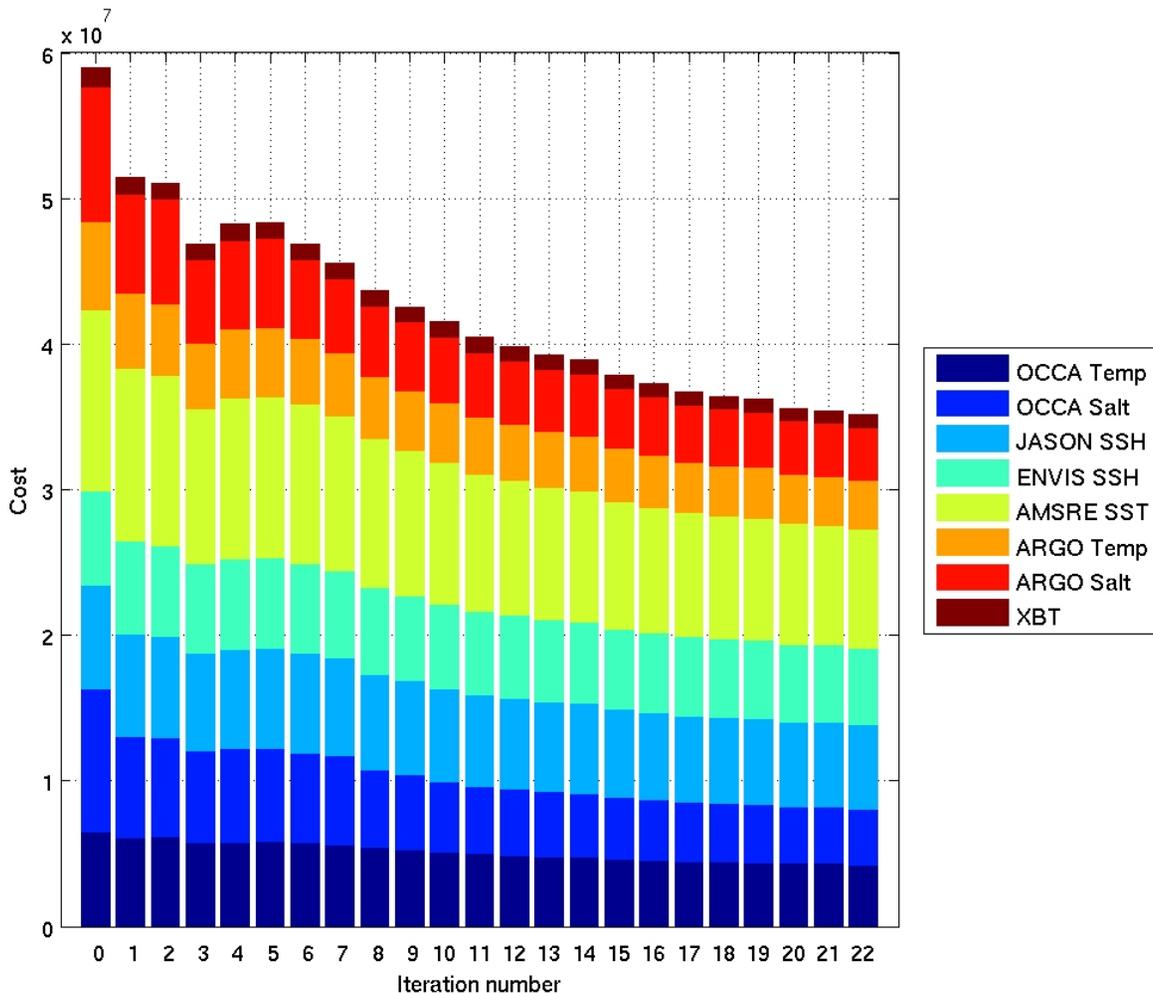
~80 control parameters:

- initial temperature and salinity conditions
- atmospheric surface boundary conditions
- background vertical diffusivity
- critical Richardson numbers for Large et al. (1994) KPP scheme
- air-ocean, ice-ocean, air-ice drag coefficients
- ice/ocean/snow albedo coefficients
- bottom drag and vertical viscosity



Eddying, global-ocean, and sea ice solution obtained using the adjoint method to adjust $\sim 10^9$ control parameters

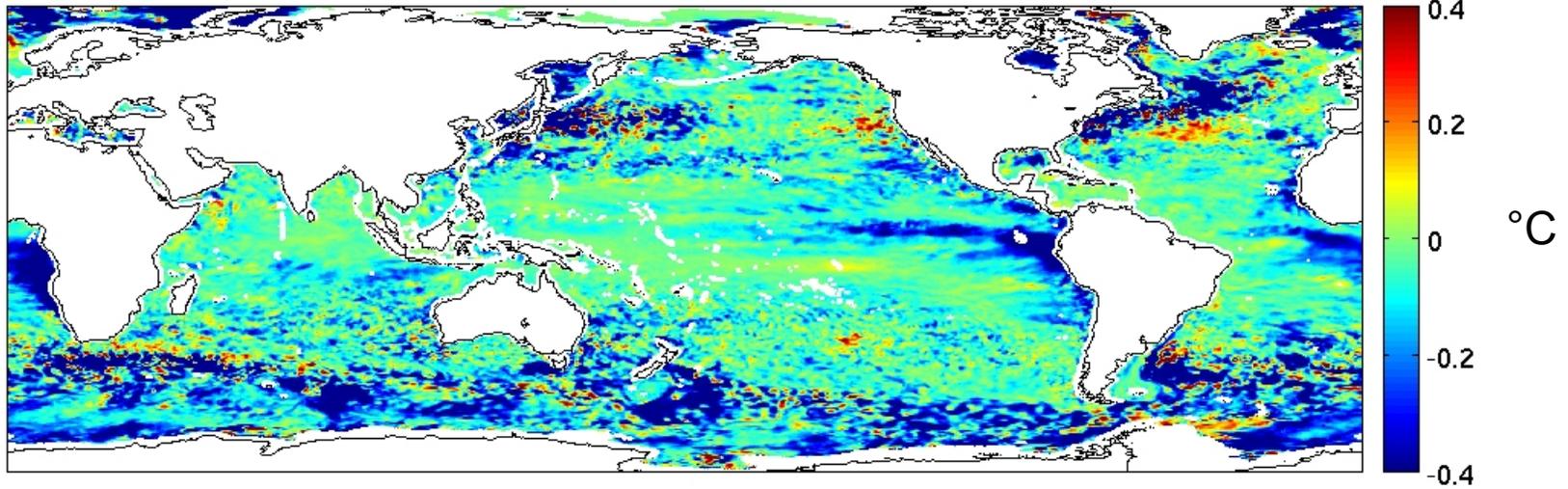
Cost functions reduction during first 22 forward-adjoint iterations



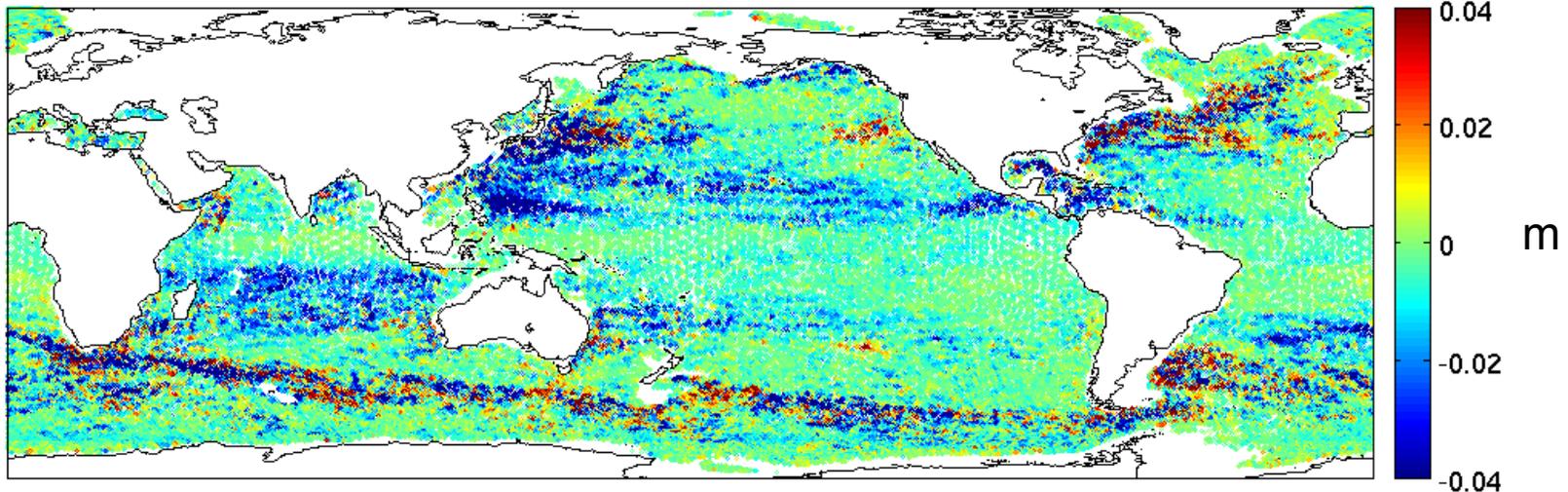
- Baseline solution derived from optimized Green's function solution and OCCA (Forget 2010) climatology
- Optimization period is beginning of ARGO-rich period (January 1994 to April 1995)
- Huge computation: ~ 1 week per forward-adjoint iteration on 900 CPUs and 3.6 TB of RAM
- 41% overall cost function reduction after 22 forward-adjoint iterations

Reduction of root-mean-square model-data residual

$\text{rms}(\text{Optimized} - \text{AMSRE SST}) - \text{rms}(\text{Baseline} - \text{AMSRE SST})$

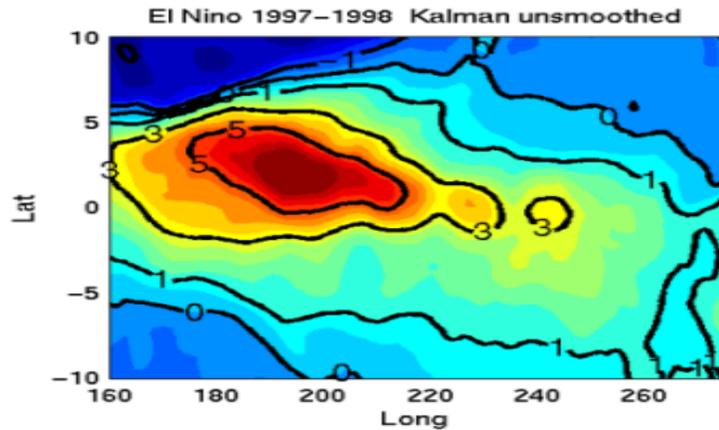


$\text{rms}(\text{Optimized} - \text{ENVISAT SSH}) - \text{rms}(\text{Baseline} - \text{ENVISAT SSH})$

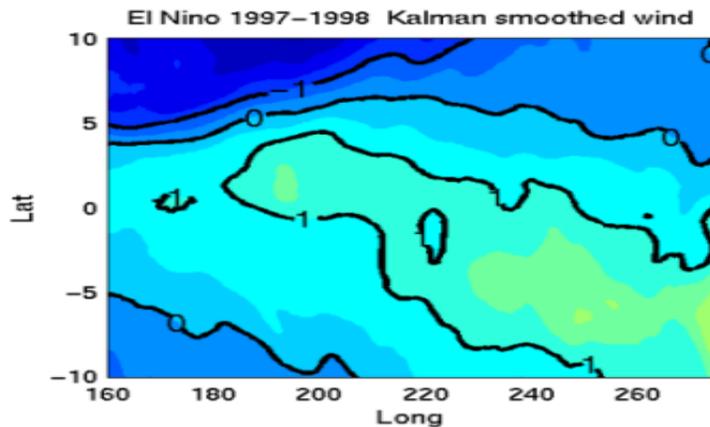


Importance of using physically consistent solutions for tracer studies

Estimate of CO₂ air-sea flux during 97-98 El Niño (mol/m²/yr) based on Kalman filter solution

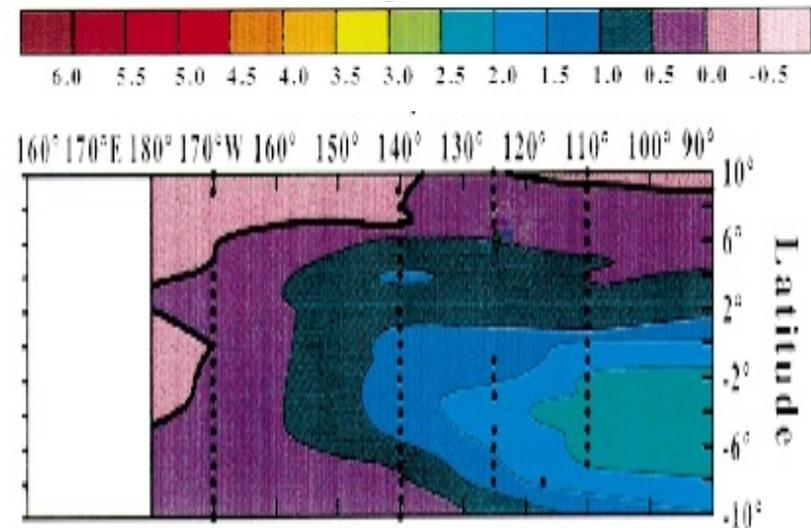


Estimate based on smoothed solution



McKinley, 2002

Observed estimate of CO₂ flux during 92-93 El Niño (mol/m²/yr)

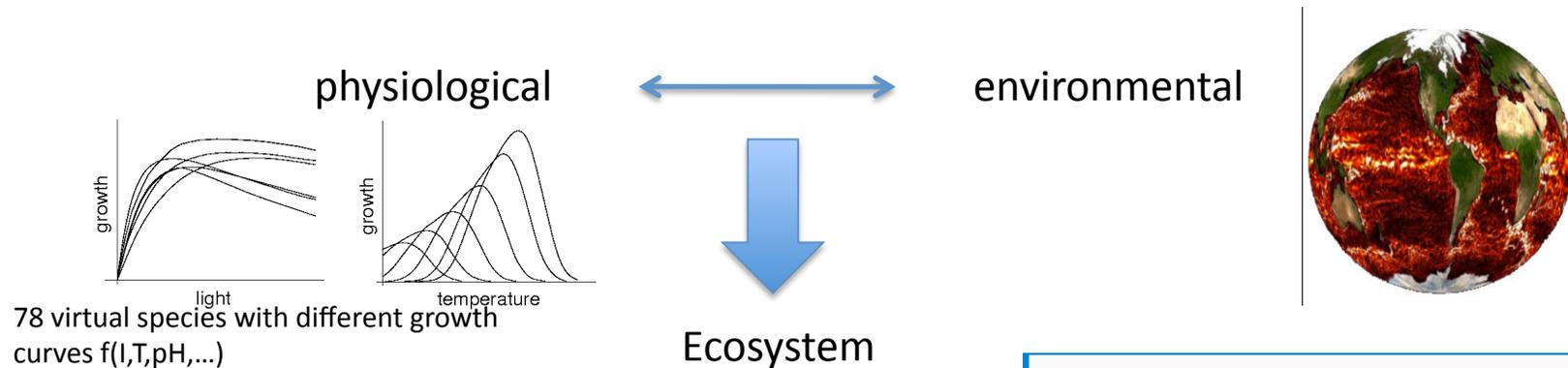


Feely et al., 1999

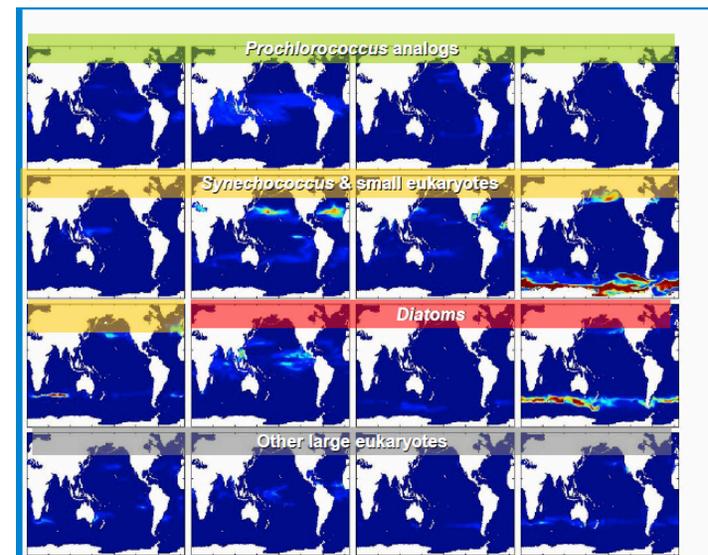
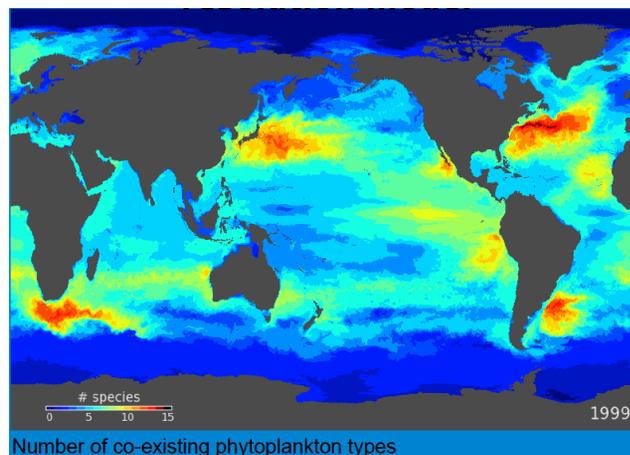
Darwin ecosystem model in ECCO2 cs510.

JPL
 Holger Brix
 Dimitris Menemenlis
 Hong Zhang
MIT
 Stephanie Dutkiewicz,
 Mick Follows,
 Oliver Jahn,
 David Wang,
 Chris Hill

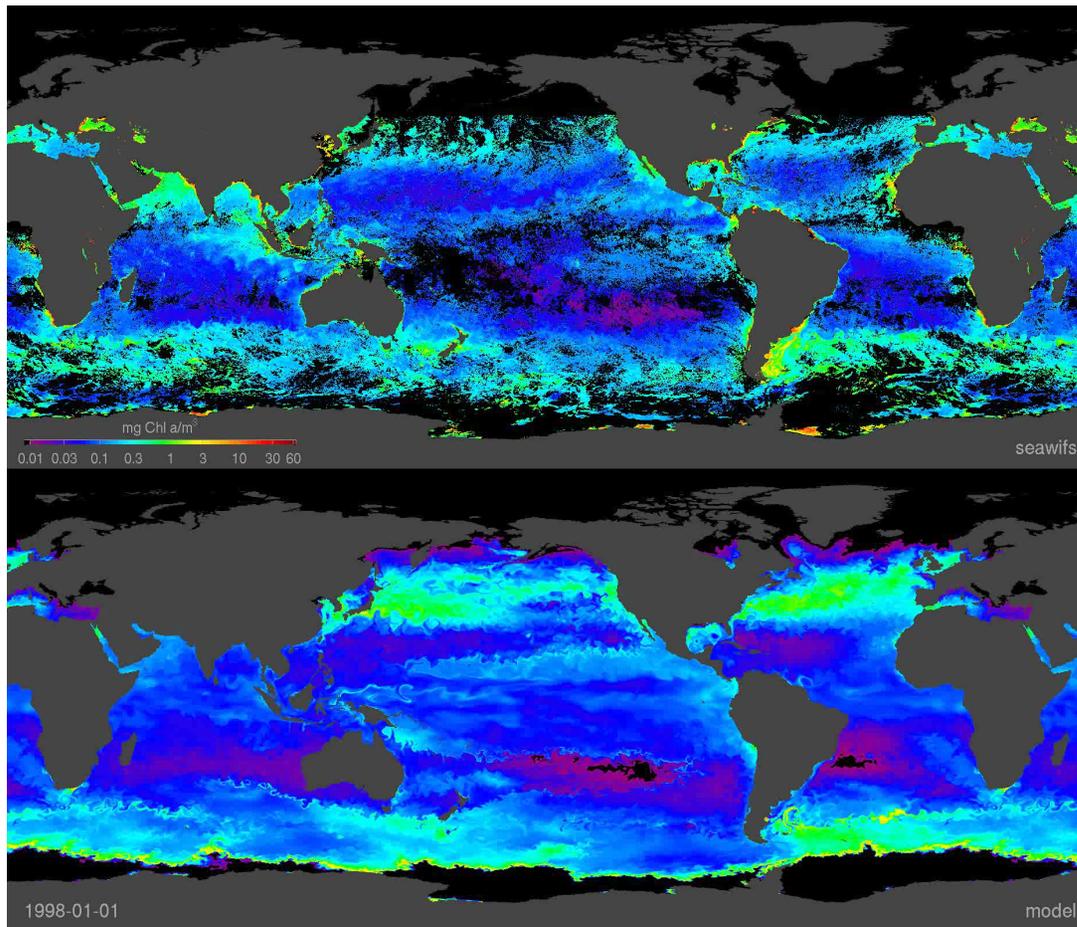
Biogeochemical approach based on “self-organizing” principle – *Follows et. al, Science, 2007.*



Species abundance from 78 possible types in environment set by interplay between circulation, nutrients and physiology.



Conventional, ocean color, view of solution v. SeaWIFS.

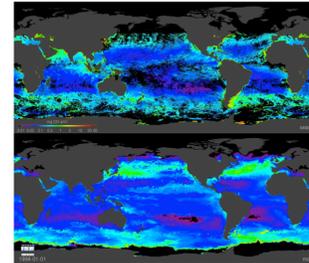
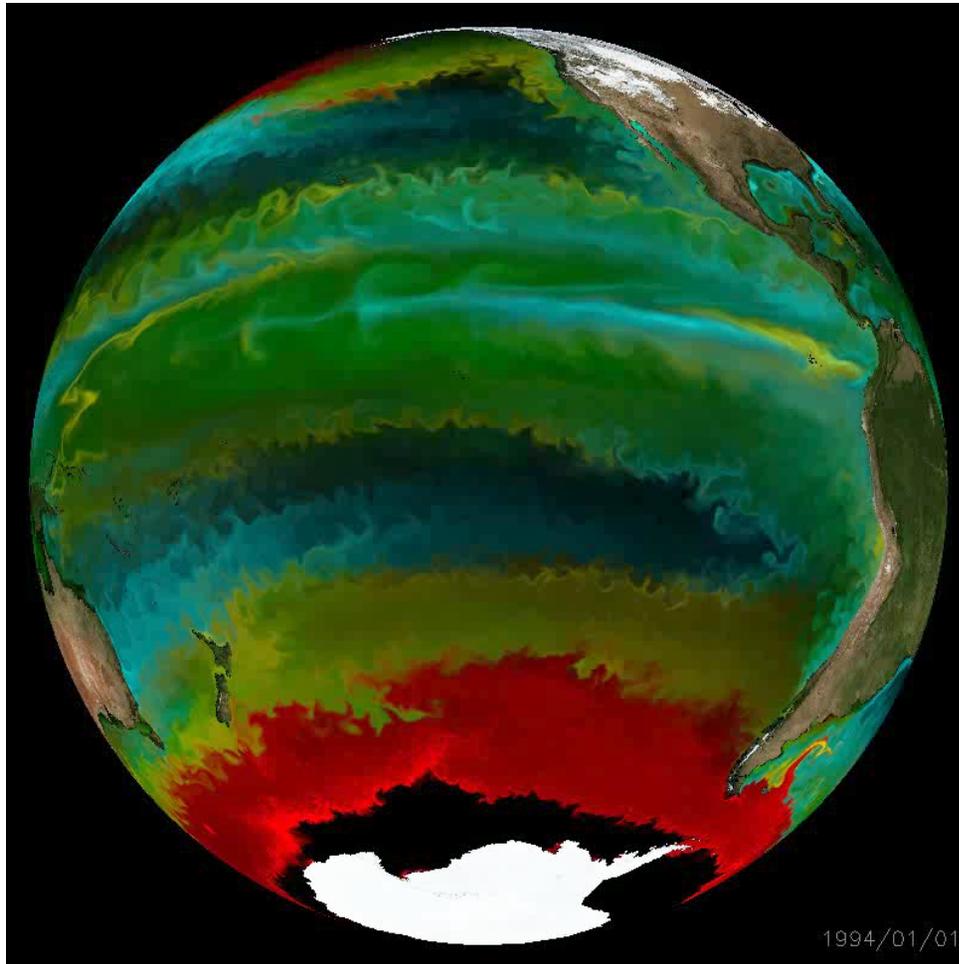


Top panel – SeaWIFS monthly composite Chl concentration 1998-1999.

Bottom panel – cube84 + 78 species self-organizing ecosystem model simulation for 1998-1999.

i.e can recover fields that are calculated in traditional NPZD approach... but can now look at what species are contributing to Chl where and when.

Species mix v. space and time – global view.



SeaWiFS Chl
comparison on previous slide is integral over multiple different species (both in real world and in model).

Movie shows concentration of different species categories as a function of space and time. Diatoms (red), prochlorococcus (green), picoplankton (blue), everything else (yellow) all contribute to the overall growth rate. At different times at some location different species may dominate. This is driven by relative fitness of the species wrt to local nutrient, light, temperature conditions – but it is also modulated by fluid transport.

ECOLOGY

Seasons and diversity

Phytoplankton form the foundation of the marine food web. In mass, these single-celled organisms take up large quantities of carbon dioxide from the atmosphere and, if not consumed near the surface, deliver it to the bottom of the ocean when they die.

Numerous studies have examined how nutrient levels affect phytoplankton abundance – a primary focus being the impact of iron additions. Less is known, however, about the factors regulating phytoplankton diversity. This is a potentially important omission, as the diversity of these populations could also influence the amount of carbon taken up by the oceans, given that ecosystem diversity is thought to affect function.

Using model simulations, Andrew Barton and colleagues show that phytoplankton diversity should be high in tropical and subtropical waters, as a result of the low seasonal variability at low latitudes (Science doi:10.1126/science.1184960, 2010). In their model, biodiversity declines toward the poles as seasonal variability becomes more pronounced. Indeed, observations of many terrestrial and marine organisms, including marine microbes, document such a pattern of declining diversity with increasing latitude.

quite happily for a thousand model-years or more when relatively weak temporal variations were imposed with a period of either years or days – in other words when they mimicked conditions in the tropical and subtropical oceans. But species died off rapidly under the influence of stronger oscillations with a period of months, typical of polar and subpolar waters.

Hotspots of diversity were superimposed on the latitudinal gradient, and coincided with areas of energetic circulation, such as the Gulf Stream. In these regions, ocean currents can replenish depleted phytoplankton stocks, and the continuous mixing of species from different regions probably prevents a single species from becoming locally extinct.

In the simplified model world, phytoplankton diversity is determined in any one location by the balance between the competitive elimination of species and the addition of nearby phytoplankton stocks by ocean currents. The suggestion is plausible, but only a comprehensive ocean survey across latitudes, spanning calm waters as well as locations of vigorous mixing, can confirm the idea.

Seasonal changes in the environment affect phytoplankton diversity via intermittent nutrient supplies. As a result, simulated diversity flourished in temporally changing environments, and those species able to grow fast during high-nutrient periods survived longer than the slow growers. But in the presence of more stable nutrient loads, a diverse community of microorganisms thrived.

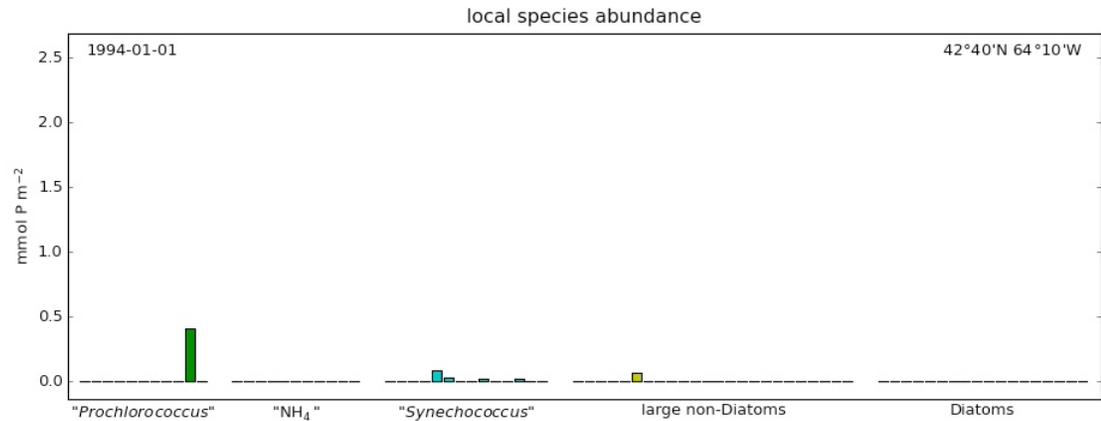
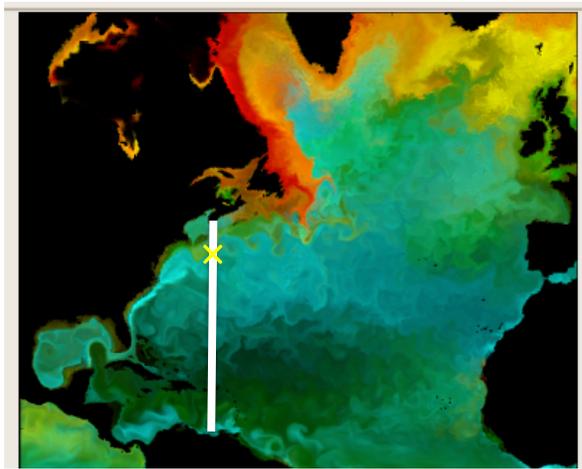
The frequency and strength of the oscillation in environmental conditions determined the time it took for species to die out. Multiple species co-existed

ANNA ARMSTRONG

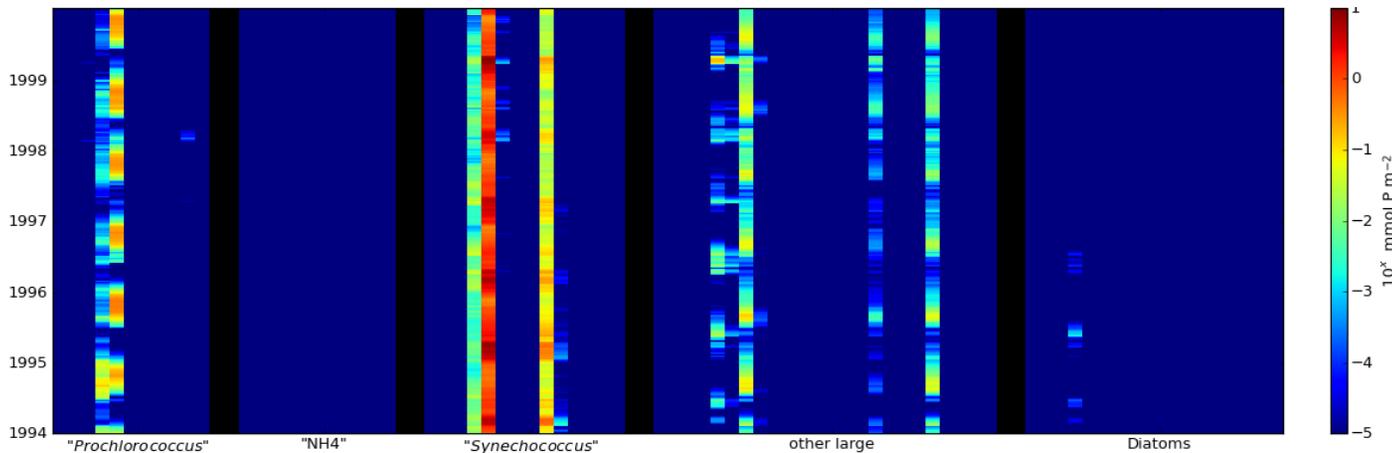
Armstrong, Nature Geoscience, 2010.

Species mix v space and time – local views.

Individual species abundance at yellow x as function of time.

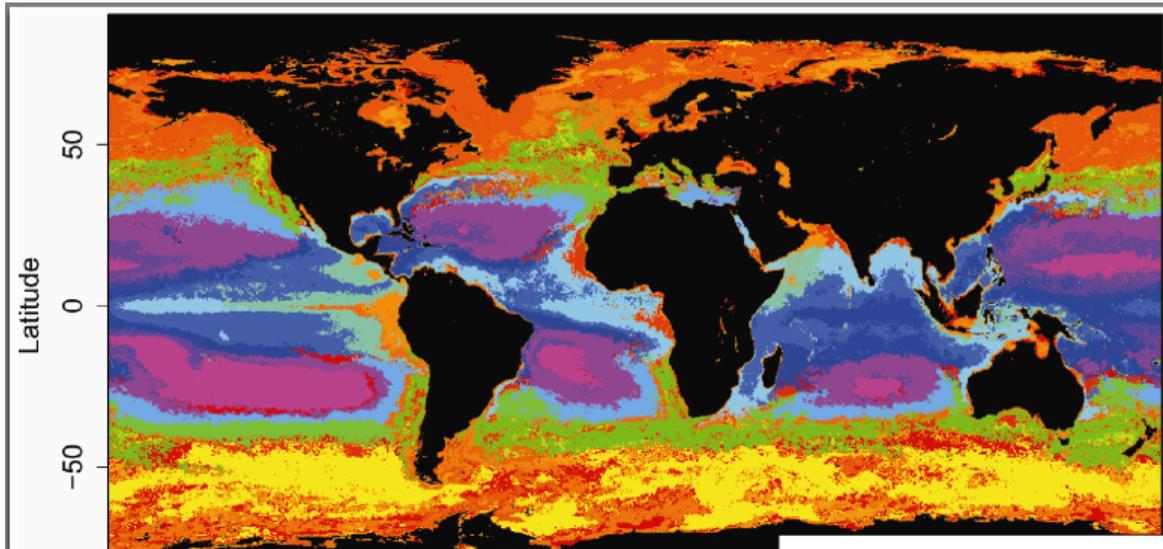


Hofmuller plots of individual species abundance at point on white line.



The plot and animation show views of abundance of individual species over time at an Eulerian point.

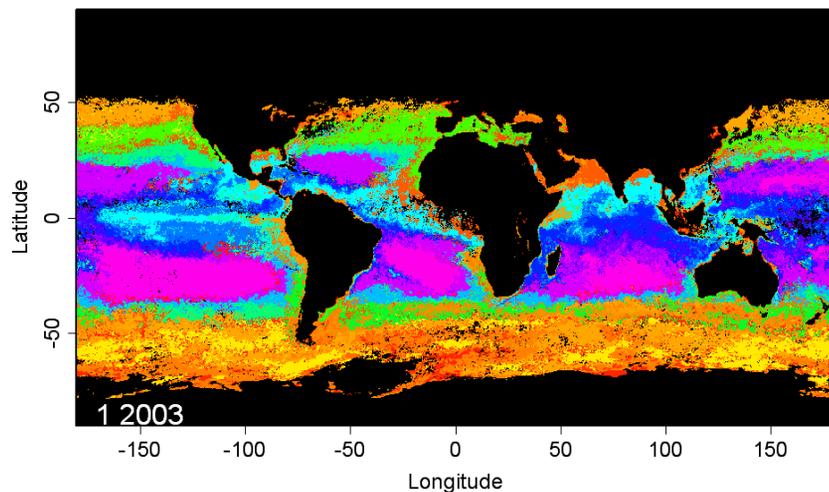
Can relate to ecological provinces.



Biological “provinces”, M. Oliver et. al (derived from color + SST obs)

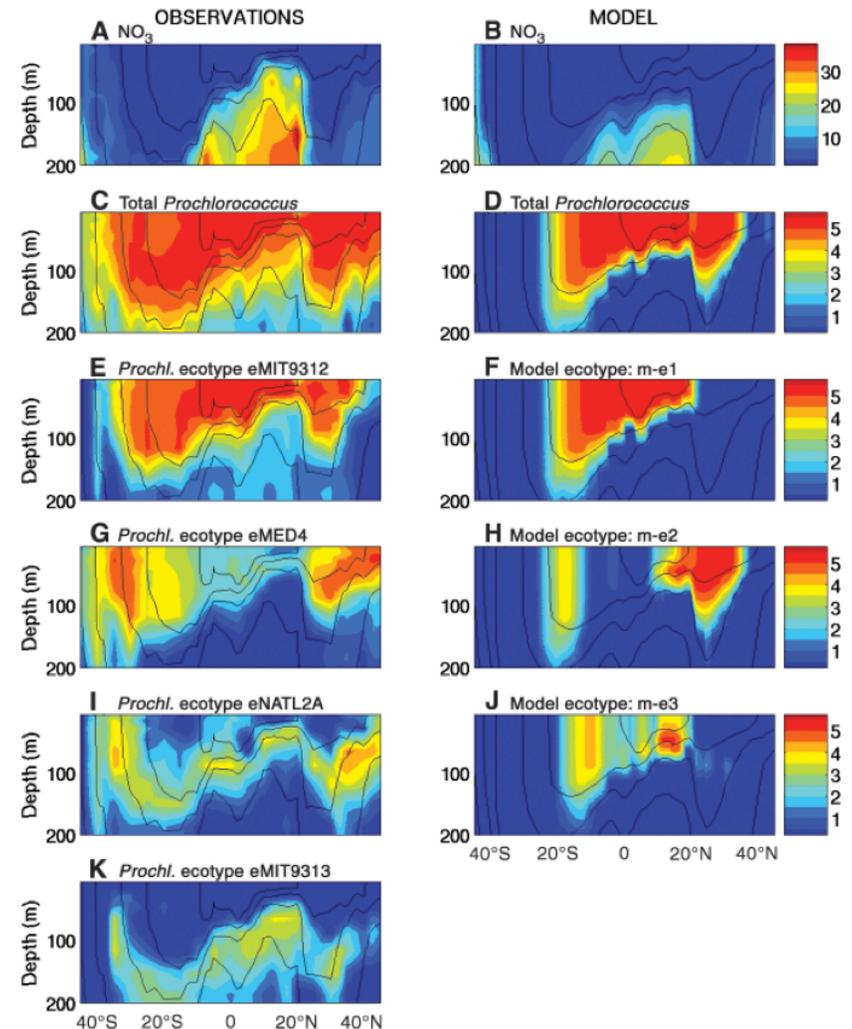
Model species abundance should be equivalent to “provinces” (Longhurst) – can be compared against observationally inferred provinces.

Role of flow can be understood through looking at local growth rate versus actual abundance (which includes fluid transport).



Connecting to CO₂ estimates

- cs510 + ecosystem → alternate perspective on biological activity, species diversity.
 - emergent virtual species analogs of ocean ecotypes.
 - for CMS nutrient source/sink terms include
 - carbon chemistry.
 - carbon exchange with organic pool for each species is function of growth/decay.
- provide a time evolving physical and biological environment for air-sea CO₂ flux estimates.
- also get information on what “virtual species” categories take up and where and when for free!



Follows et. al, Science, 2007.

ECCO2 eddying green ocean carbon fluxes - first results

Holger Brix

Dimitris Menemenlis, Chris Hill,
Oliver Jahn, Stephanie Dutkiewicz,
Mick Follows

$p\text{CO}_2_A$

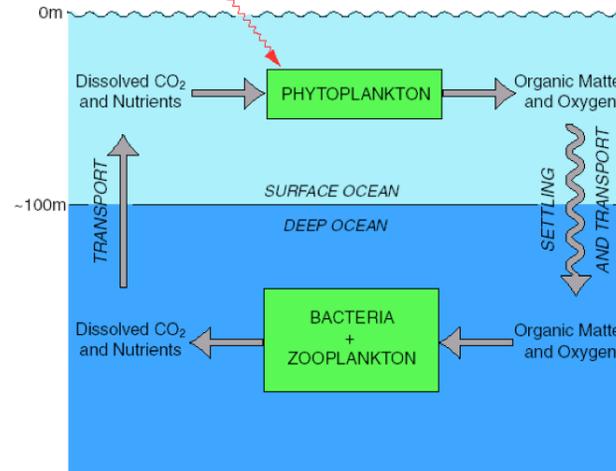
chemical exchange $f(T, pH, \Delta p\text{CO}_2)$

$p\text{CO}_2_o$

phyto₁ phyto₂ phyto₃ phyto_n

$$\frac{d\text{CO}_2_{\text{phyto}}}{dT} \approx \text{growth}$$

The "biological pump"

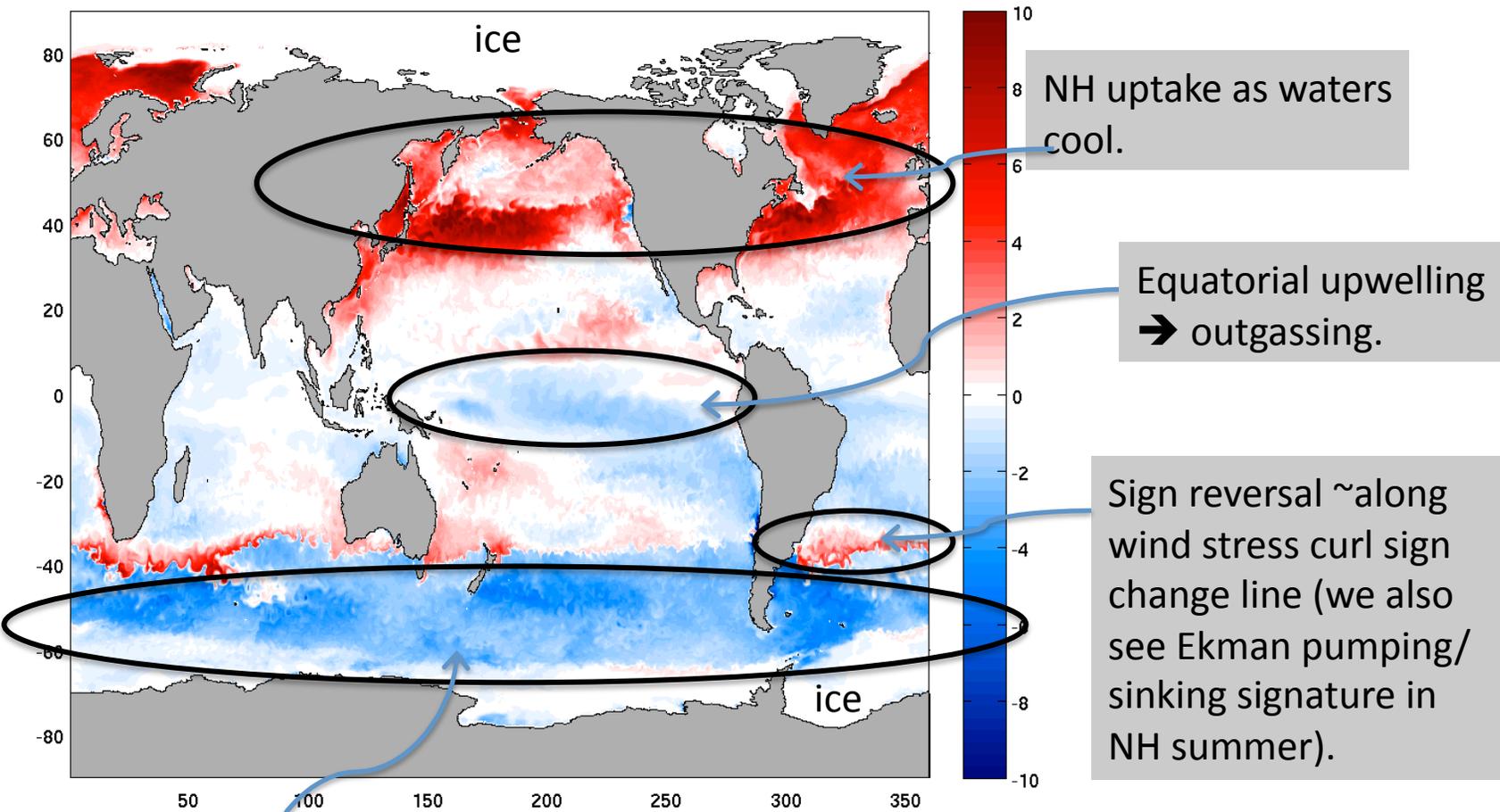


- Photosynthesis**
- Depletion of carbon and nutrients
 - Enhancement of oxygen

- Respiration**
- Depletion of oxygen
 - Regeneration of carbon and nutrients

remineralize at depth.....

Example Northern Hemisphere (NH) winter, monthly mean surface CO₂ flux map (molC/m²/yr, from cyclic year spin-up phase).



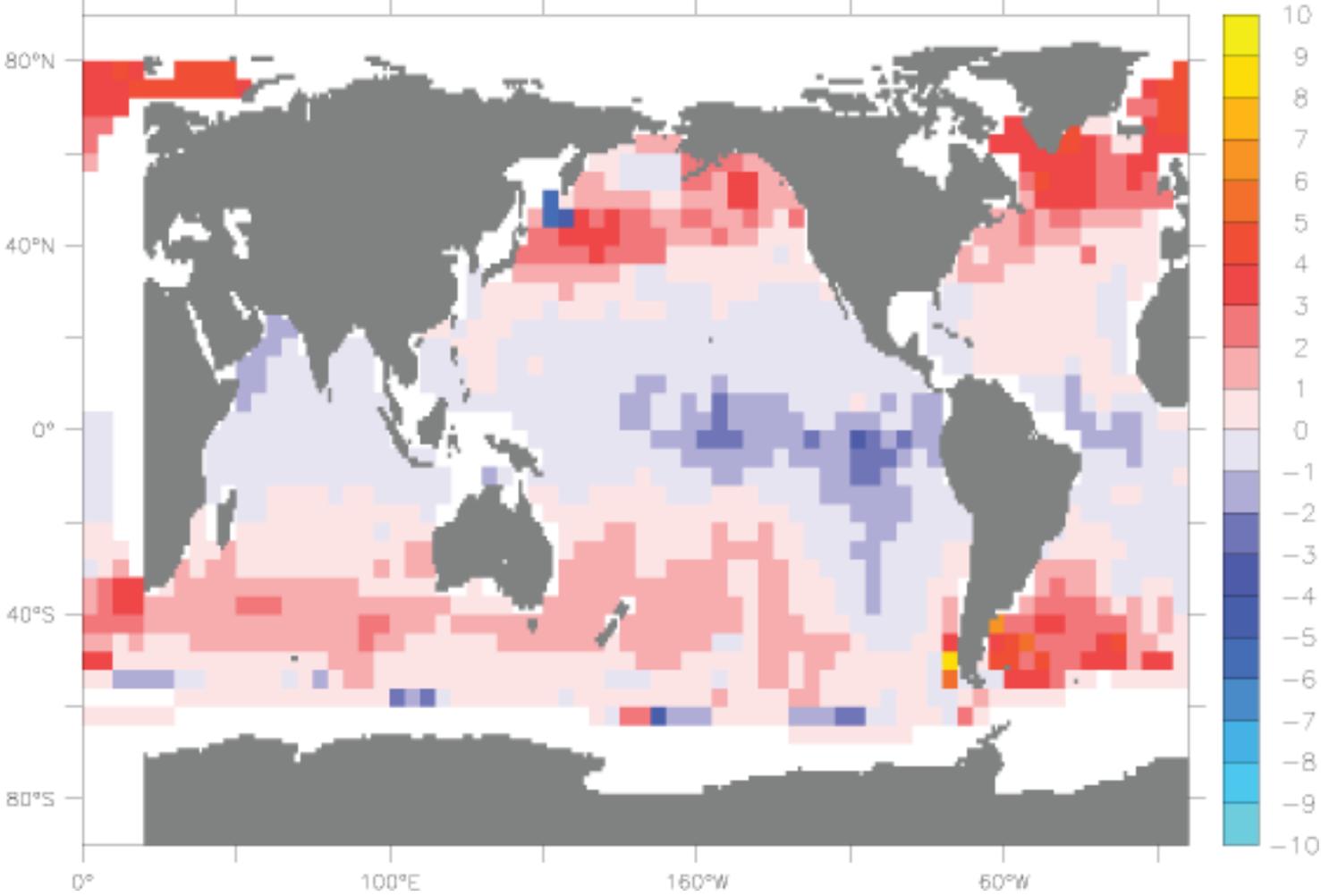
NH uptake as waters cool.

Equatorial upwelling → outgassing.

Sign reversal ~along wind stress curl sign change line (we also see Ekman pumping/sinking signature in NH summer).

Southern Ocean outgassing in SH summer.

Example Northern Hemisphere (NH) winter, monthly mean surface CO₂ flux map (molC/m²/yr, from Takahashi climatology).



Requirements for interfaces

- Atmospheric CO₂ values
 - Fixed value?
 - Variable fields?
- Physical variables? Problematic as ECCO₂ solution is optimized for particular set of forcing fields/parameters