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Ocean-atmosphere Interactions in Climate Models and the Real World

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Interpreting Climate Change Simulations: Capacity Building for Developing Nations

International Center for Theoretical Physics, Trieste, Italy

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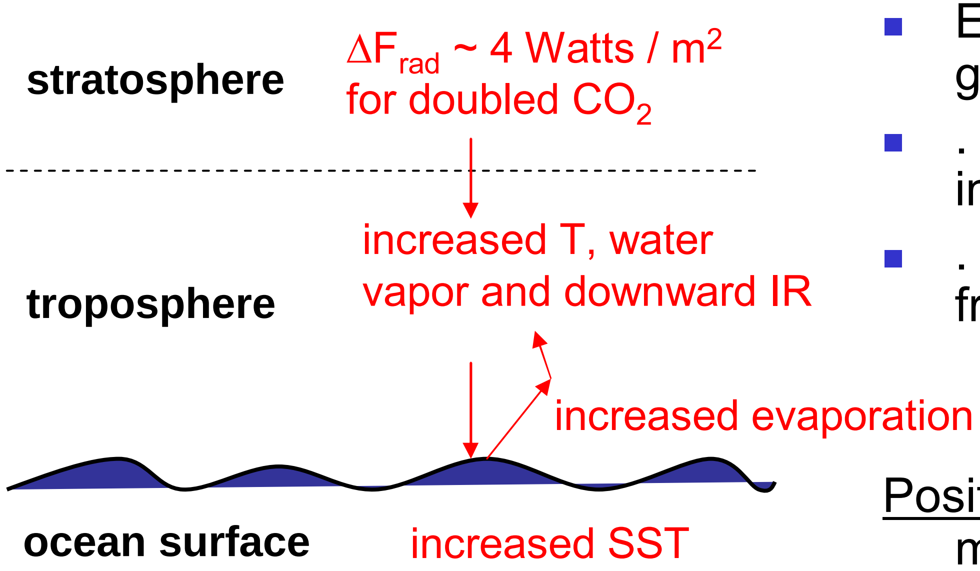
Surface energy and water balance



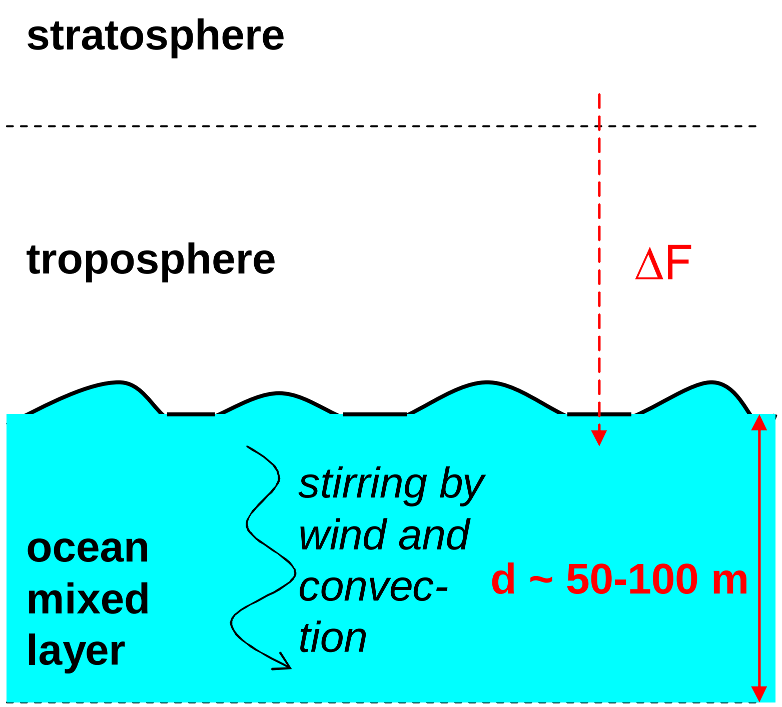
from V. Ramanathan (1981) “The Role of Ocean-Atmosphere Interactions in the CO2 Climate Problem” *Journal of the Atmospheric Sciences 38*: 918-930

- Enhanced IR to surface >> direct greenhouse heating
- . . . due to increased water vapor in atmosphere
- . . . due to increased evaporation from warmer ocean surface

Positive water vapor feedback in models and probably the real world: for 2 x atmospheric CO_2
$\Delta T_{equilibrium}$ ~ 1-3 K > $\Delta F_{rad} / (4\sigma T^3)$

Cloud feedback much more difficult to predict: positive or negative

Well-mixed upper ocean layer



from V. Ramanathan (1981) *op. cit.* **and** J. Hansen et al. (1981) "Climate Impact of Increasing Atmospheric Carbon Dioxide" *Science 213*, 957-966

- Heat capacity of even a thin layer greatly exceeds that of atmosphere (or land surface) :

  $\rho\ c\ d \sim (10^3\ \mathrm{kg\ m^{-3}})(4 \times 10^3\ \mathrm{J\ kg^{-1}\ K^{-1}})(50\ \mathrm{m})$

  $\sim 2 \times 10^8\ \mathrm{J\ K^{-1}\ m^{-2}}$

  $\gg c_p \times (p_{surface} / g)$

- Sets largest time scale of "transient" changes that can exclude deep ocean:

  $\rho\ c\ d\ (\Delta T / \Delta t) \sim \Delta F$

  $\Rightarrow \Delta t \sim \rho\ c\ d\ (\Delta T / \Delta F)$

- If $(\Delta T / \Delta F) \sim (\Delta T_{equilibrium} / \Delta F_{radiative})$

  $\Delta t \sim (2 \times 10^8\ \mathrm{J\ K^{-1}\ m^{-2}})(\ 2\ \mathrm{K} / 4\ \mathrm{J\ s^{-1}\ m^{-2}})$

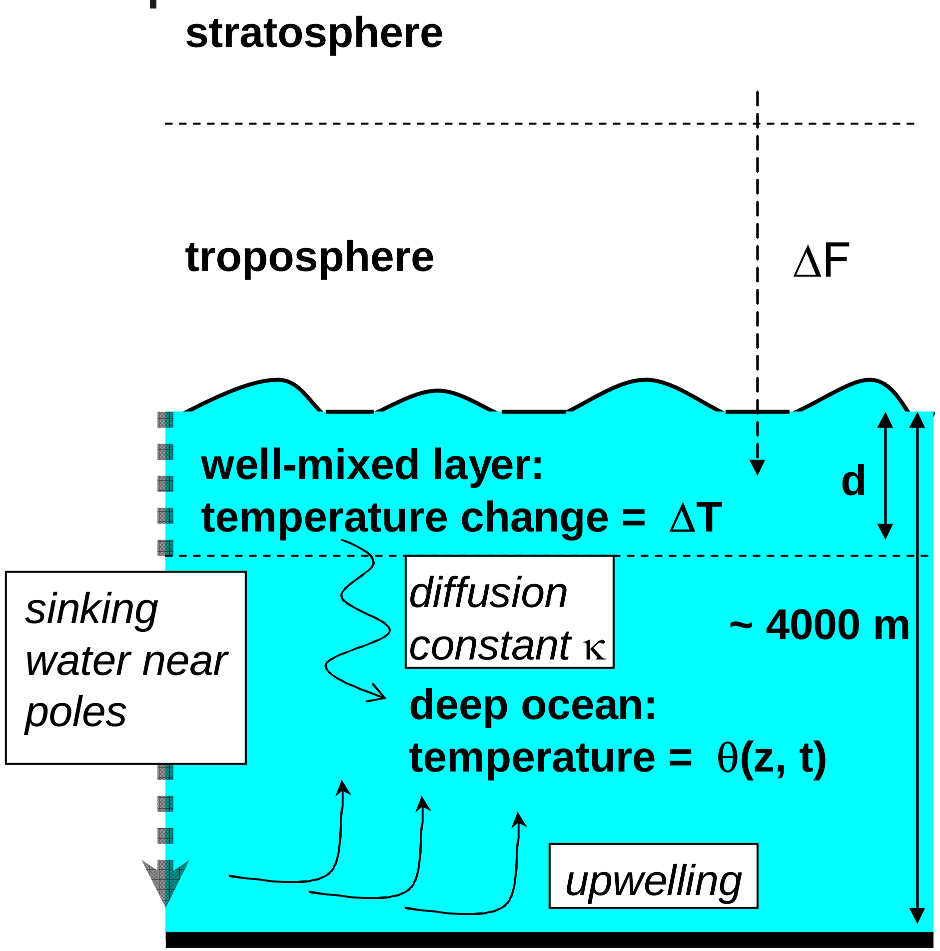
  $\sim 10^8$ seconds

  ~ a few years

Note: proportional to climate sensitivity

Deeper layers and thermohaline circulation

See M. Hoffert et al. (1980) “The Role of Deep Sea Heat Storage and in the Secular Response to Climate Forcing” *Journal of Geophysical Research 85*, 6667-6679 (www.cgd.ucar.edu/cas/wigley/magicc for downloadable model code) **and** T. M. L. Wigley and M. E. Schlesinger (1985) “Analytical Solution for the Effect of increaseing CO2 on Global Mean Temperature” *Nature 315*, 649-652



- New term in equation for mixed-layer temperature change:

  $\rho\ c\ d\ (d\Delta T / dt) = \Delta F - \lambda\ \Delta T$

  $+ K (\partial \theta / \partial z)_{\text{bottom of mixed layer}}$

  where $\lambda = (\Delta F_{radiative} / \Delta T_{equilibrium})$

- Advection-diffusion equation for $\theta(z, t)$

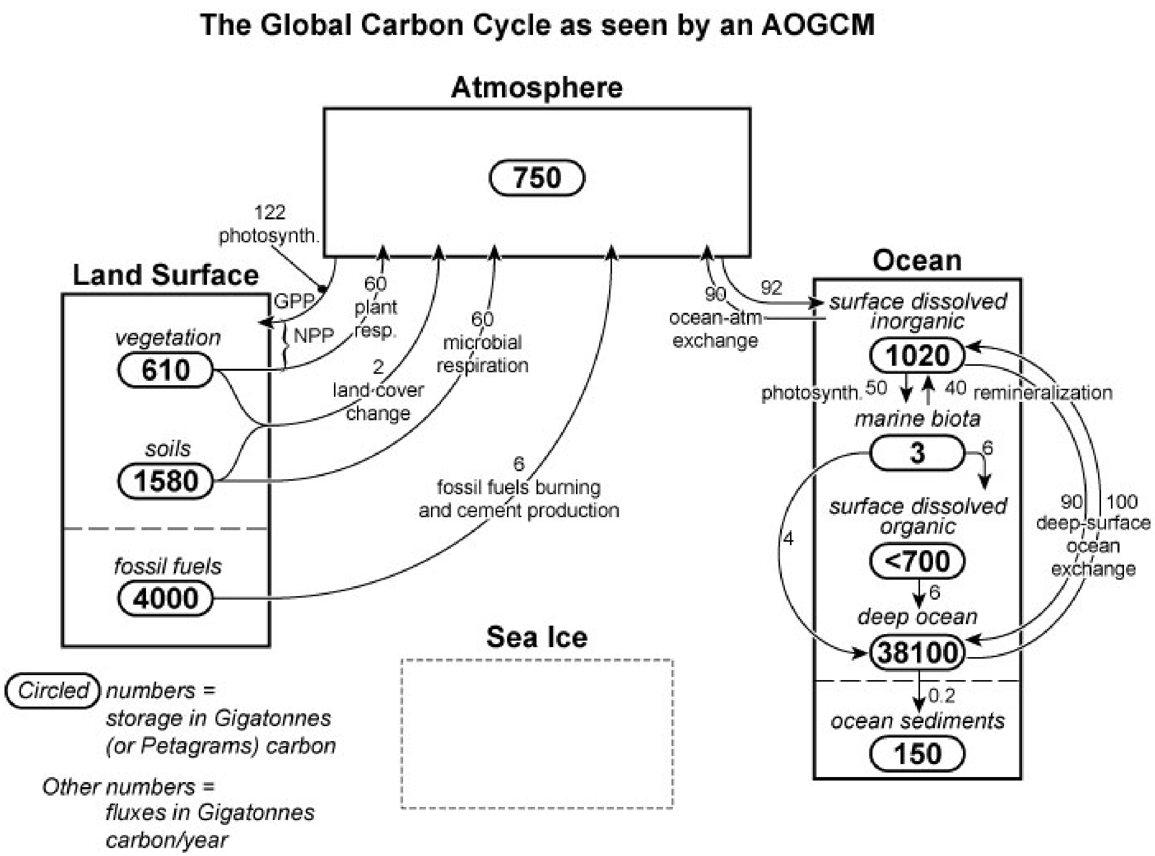
- Response time increases from $\rho\ c\ d / \lambda$ to $\sim \kappa\ (\rho\ c\ / \lambda)^2$

  Stronger dependence on climate sensitivity -- up to several decades

Full 3D ocean dynamics

- Needed for equator-to-pole heat transport
- 7 fundamental equations in 7 unknowns: u, v, w, ρ, P, T, S
  - Conservation of momentum (3 equations)
  - Conservation of energy (mainly thermal)
  - Conservation of mass
    - for water density ρ
    - for salinity S
  - Equation of state: $\rho = f(T, S)$
- Computer program that solves them = OGCM

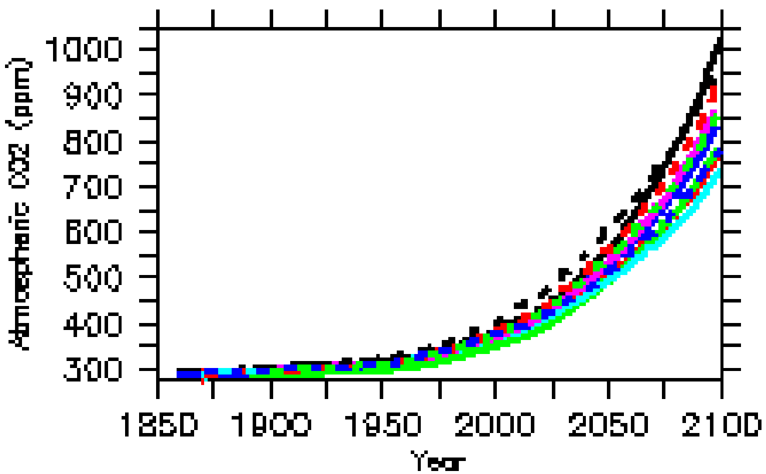
The carbon cycle and related "biogeochemistry" (for both ocean and land)



from D. Bader et al. (2008) *Climate Models, their Uses and Limitations,* US Climate Change Science Program Synthesis and Assessment Product 3.1

Why the carbon cycle matters

- Climate models usually *assume* a time history of atmospheric CO_2, CH_4, etc.
- . . . but actual amounts will depend on the climate, and may enhance global warming:



Each curve shows atmospheric CO2 calculated by a different model (P. Friedlingstein et al. (2006) “Climate-Carbon Cycle Feedback Analysis: Results from the C4MIP Model Intercomparison” *Journal of Climate 19*, 3337-3353).

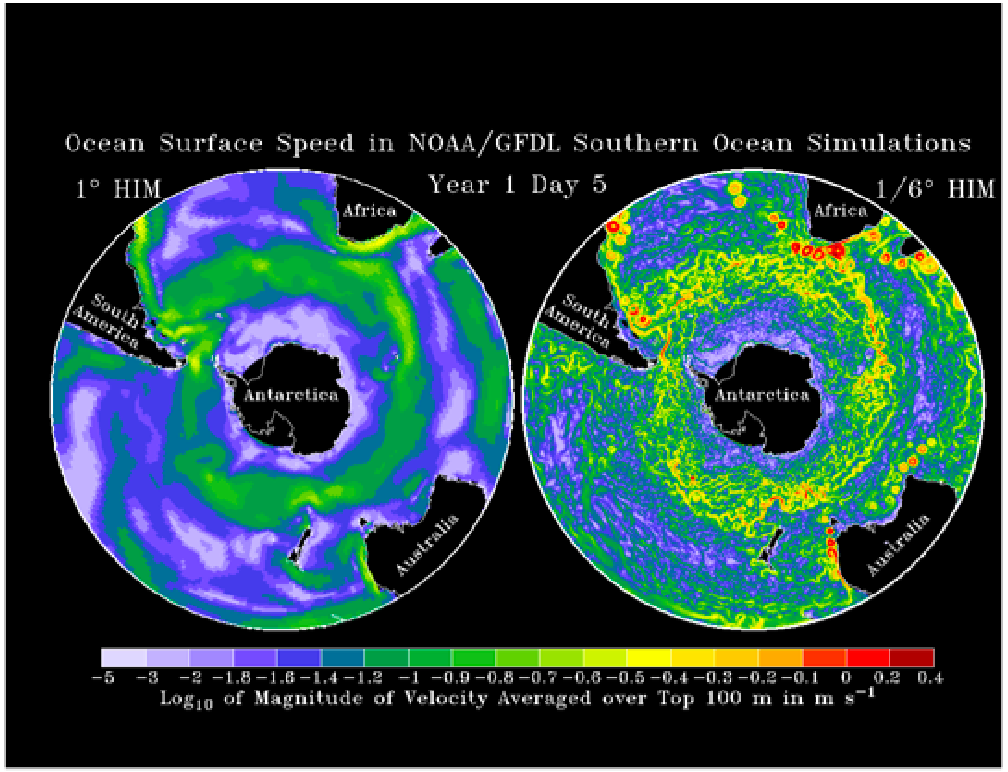
See also S. C. Doney and D. S. Schimel (2007) “Carbon and Climate System Coupling from the Precambrian to the Anthropocene” *Annual Reviews of Environment and Resources 32*.

A new frontier in ocean modeling:

Resolving baroclinic disturbances (meso-scale eddies in ocean, “weather” in atmosphere)

- (horizontal scale / vertical scale) ~ (buoyancy frequency / planetary rotation rate)
- For the ocean, horizontal scale ~ 50 km
  - Much less than for atmosphere because vertical scale ~ mixed-layer d << atmospheric scale height (~ 10 km)
- *What it costs:* a lot of computer time
- *What it gains:* most of the kinetic energy in the ocean’s circulation

An example of conventional (left) and eddy-resolving (right) ocean simulation

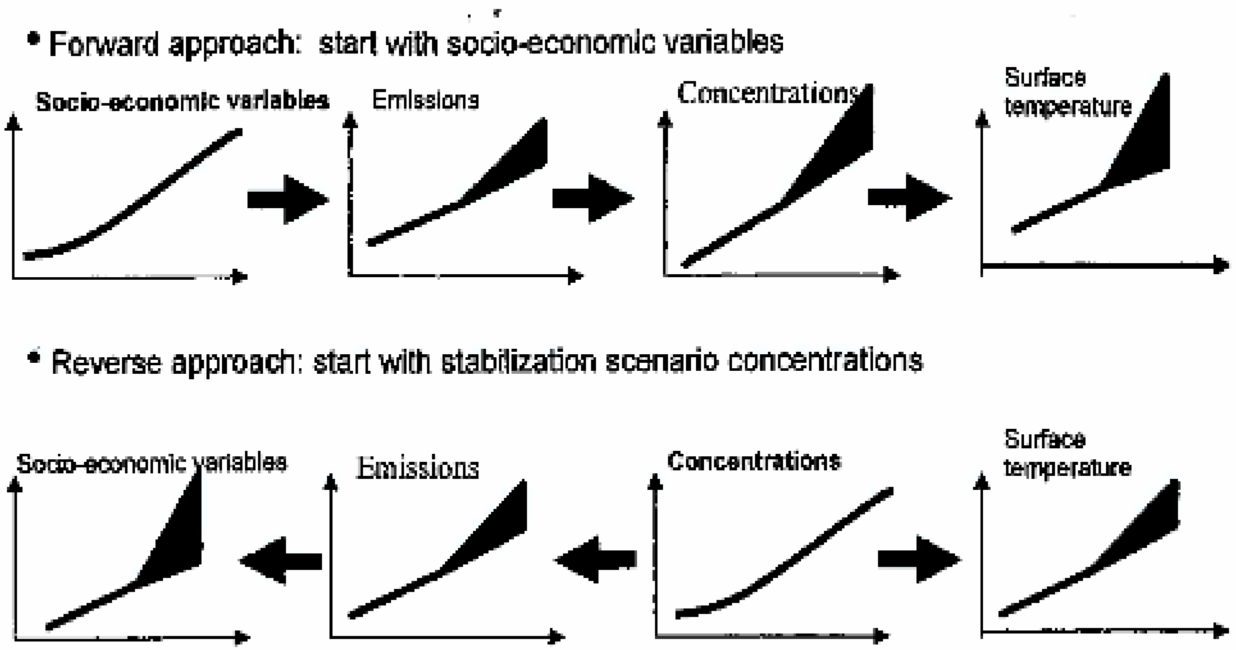


In the Southern Hemisphere meso-scale ocean eddies may be particularly important in equator-to-pole heat transport.

A new frontier in ocean-atmosphere-biosphere modeling:

from *A Strategy for Climate Change Stabilization Experiments with Agamas and ESMs*, World Climate Research Program Informal Report 3 / 2007

- Assume atmospheric concentrations of CO_2, CH_4, etc. as a function of time (e.g. a CO_2-stabilization scenario) instead of the usual "forward approach"



- Shows what the world has to do to attain a particular stabilization scenario -- and the resulting climate