Ocean-Atmosphere Interactions & Modelling: A General Overview

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the Theory and Use of Regional Climate Models
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RICCARDO FARNETI
rfarneti@ictp.it

(ESP/ICTP)

Outline

1. Motivation for using coupled models
   - Ocean-atmosphere modelling
2. Posing the coupled model problem
   - Foundations
   - Resolving versus parameterizing: some numbers
3. Basics on (Low-Frequency) Variability
   - A few examples
4. Mesoscale/regional examples
   - Or how regional simulations can help overcome some issues

Outline

General motivational comments and challenges

- Climate model fundamentals and the use of climate models as a tool for science involves some of the most difficult problems in classical and computational physics.
  - turbulence closures and subgrid scale parameterizations
  - analysis and rationalization of massive datasets
  - efficient methods for discretizing continuous media.
- We are also touching on elements of the most important environmental and societal problem facing the planet.
  - Climate warming is happening and humans are the key reason.
  - The ocean's role in the earth climate is significant. ☺
  - Providing rational and robust models for understanding and predicting climate is a central element of climate science.

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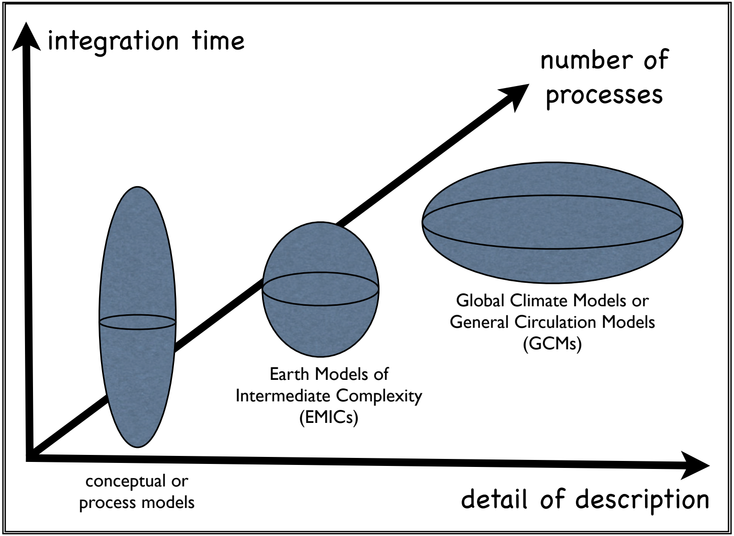
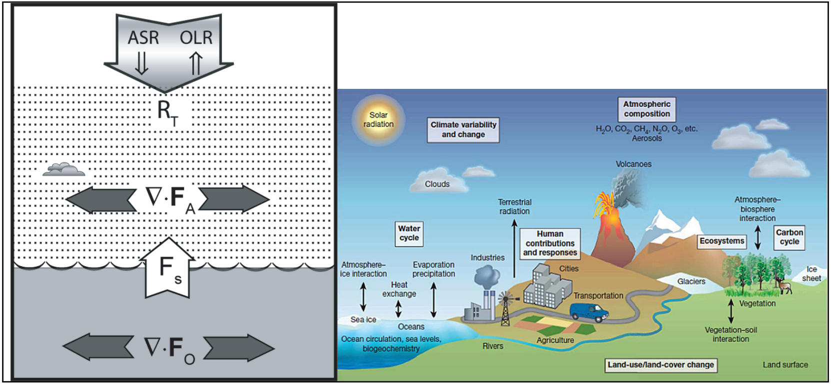
Types of climate models



Hierarchical approach

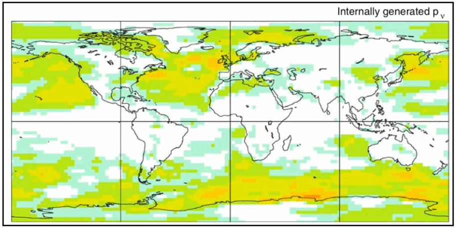
Hierarchical Ocean-Atmosphere Modelling

A hierarchy of models and simulations to understand and simulate the physics and dynamical mechanisms of climate

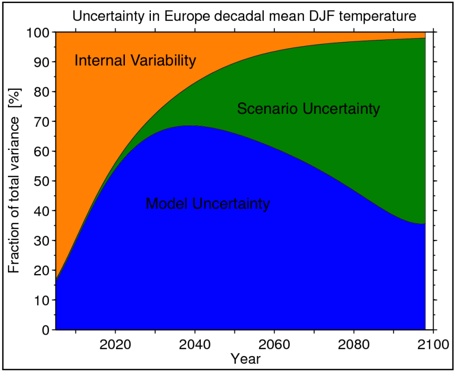


Hierarchical approach

Decadal Variability/Predictability lies in the Oceans

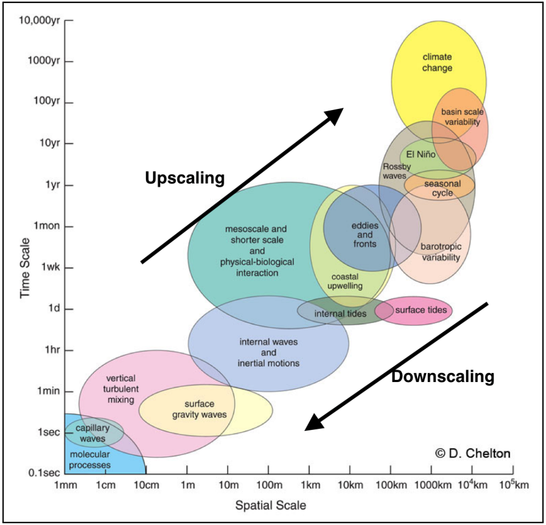


Internally generated potential predictability (From Boer et al, 2011)



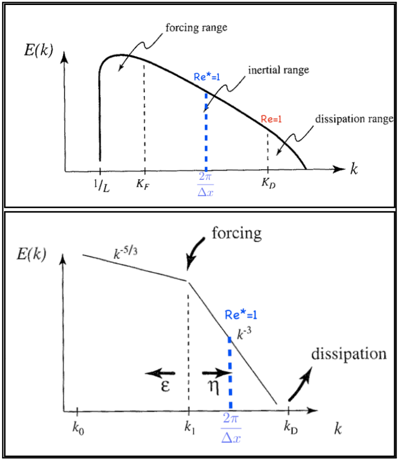
From Hawkins and Sutton, 2009

Space-time diagram of motions



- Broad range of space-time scales
- We see the absence of a clear spectral gap except for scales larger than 1000 km.
- We can use EMICs or Downscale to get information on smaller space-time scales.

Turbulent cascade of mechanical energy



Compliments of Baylor Fox-Kemper, Brown University, USA

- 3d turbulence: energy cascade to small scales
- 2d/QG turbulence: energy cascade to large scales (inverse cascade)
- Cascades act to couple space-time scales.

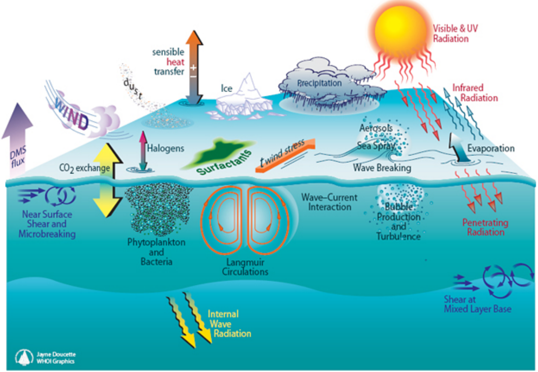
Outline

2 Posing the coupled model problem

Theoretical foundations for ocean-atmosphere models

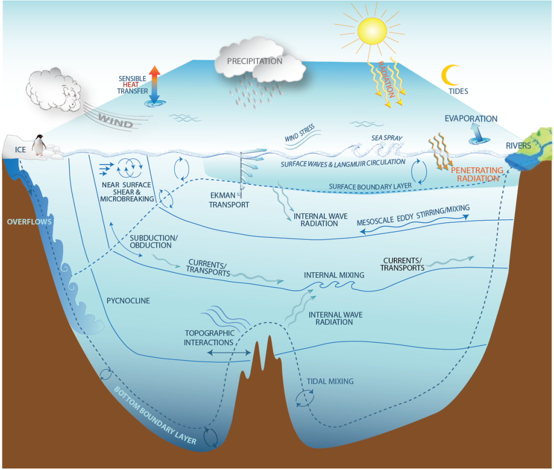
- Continuum thermo-hydrodynamical equations
  - Seawater mass conservation
  - Tracer mass conservation
  - Momentum conservation
  - Linear irreversible thermodynamics of seawater
  - Typically assume hydrostatic balance
- Boundary conditions
  - Air-sea interactions
  - Sea ice-ocean interactions
  - Ice shelf-ocean interactions
  - Solid-earth-ocean interactions
- Subgrid scale parameterizations
  - Momentum closure: frictional stress tensor
  - Tracer closure: transport tensor
  - Boundary layer parameterizations

A zoo of physical processes



- The ocean-atmosphere interface contains a zoo of physical processes!
- Strong coupling between processes ⇔ no spectral gap.
- Coupling means it is generally better to resolve than parameterize.
- Yet we cannot resolve everything

A zoo of physical processes in the Ocean interior



- What happens in the interior will affect the surface interacting with the atmosphere.
- ... The Ocean **is not** an SST ... ☺

Equilibration time scale problem

Scaling argument for deep adjustment time

$$H^2/\kappa = (2000\ m)^2/(2 \times 10^{-5}\ m^2/s) \quad (1)$$
$$= \mathcal{O}(5000\ years) \quad (2)$$

Bottom line for global climate:

- Performing long (climate scale) simulations at eddy-resolving / permitting resolution are not practical
- Must live with deep ocean not being at equilibrium in most simulations

Upper ocean boundary and wave interactions

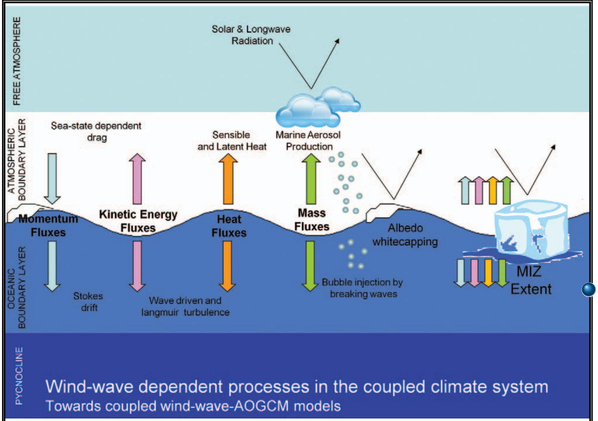
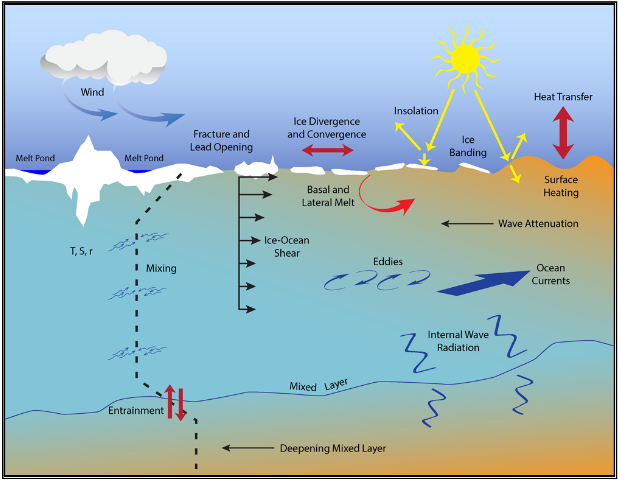


FIG. 1. A schematic view of the influence of waves on air–sea exchanges.

From Cavaleri et al (2012)

- New research activities in boundary layer param prompted by refined atmos and ocean resolutions that admit new dynamical regimes (e.g., mesoscale eddies, tropical cyclones).
- An increased awareness in the climate community of the importance of surface ocean gravity waves. See also Ufuk's talk in a few minutes.

The marginal ice zone (MIZ)



From ONR Marginal Ice Zonal Project

- Questions about processes at the marginal ice zone are of prime importance as Arctic sea ice melts.

The marginal ice zone (MIZ)

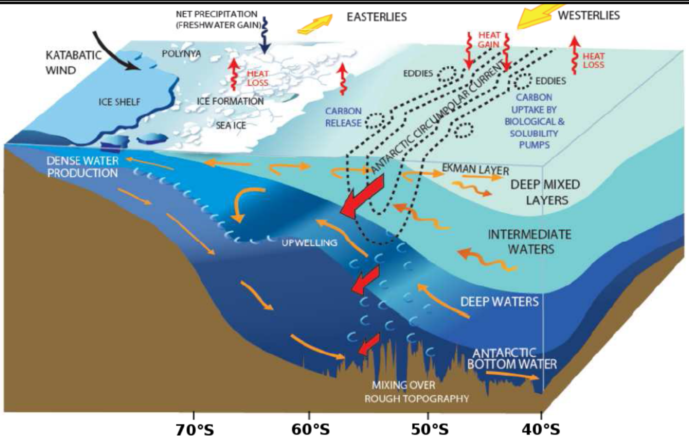
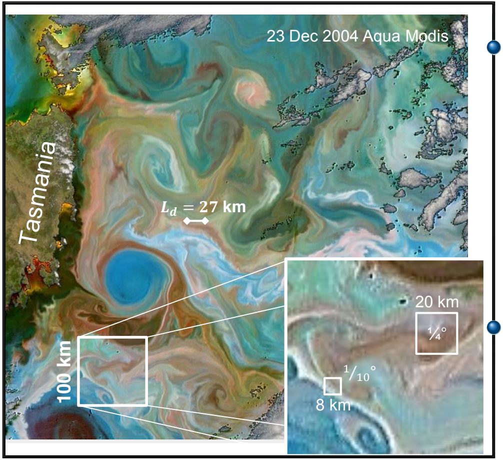


Fig. 1: Schematic of the Southern Ocean circulation, showing the numerous relevant physical and biogeochemical processes [courtesy of L. Talley].

Resolving versus parameterizing: some numbers

- Setting the model's grid scale to the Kolmogorov length $\Delta = 10^{-3}$m over a global (ocean) domain of volume 1.3×10^{18} m^3 requires 1.3×10^{27} discrete grid cells. This is roughly $10^4 \times$ Avogadro's number!
- Each model grid point has a velocity vector and tracer fields to time integrate.
- Conclude:
  - We will be dust long before DNS of global climate simulations.
  - We must use parameterizations to simulate, or regional simulations.

Spatial scale of mesocale and submesoscale eddies



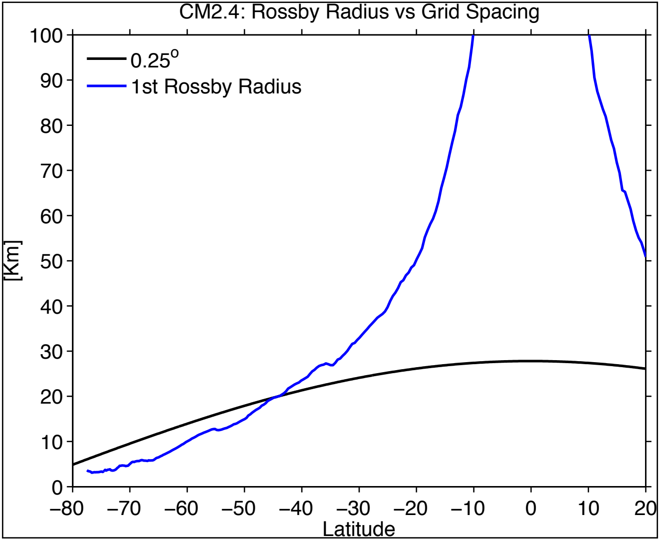
MODIS satellite w/ inserts by A. Adcroft (GFDL)

- Eddy size $\propto$ first baroclinic Rossby Radius $\lambda_m = c_m/|f|$, where the phase speed is approximated by (Chelton et al. 1998)

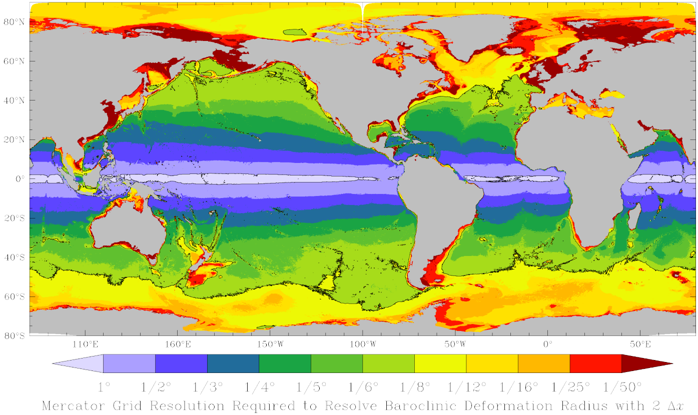
$$c_m \approx \frac{1}{m\,\pi} \int_{-H}^{0} N \, \mathrm{d}z.$$

- Global models are marginal at representing this scale; regional and process models can help reach into the submesoscale.

Spatial scale of mesocale and submesoscale eddies



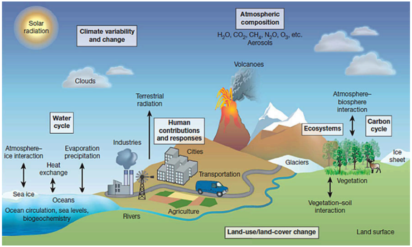
Resolution required to represent mesoscale eddies

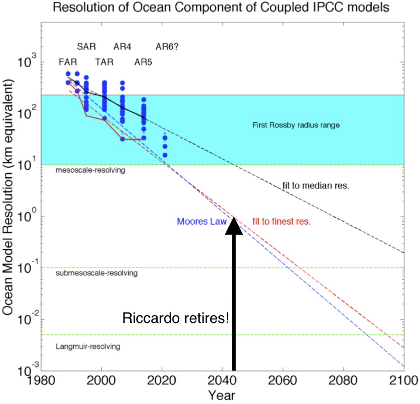


From Hallberg (2013)

- Hallberg (2013): $2\Delta \leq \lambda_1$ needed to resolve mesoscale eddies.
- Map indicates the necessary Mercator spacing for $2\Delta = \lambda_1$.

Ocean resolution in IPCC-class climate models



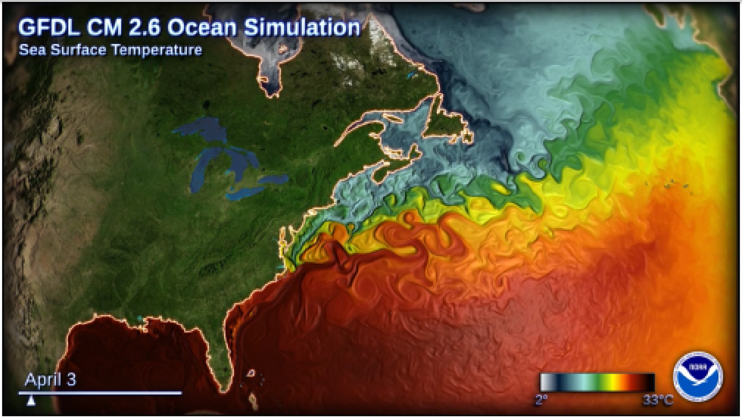


- The ocean is but one component amongst many within climate system models.
- Resolution refinement is painfully slow!
- This diagram is useful to target one’s career choices.

Nevertheless, progress is exciting!

Daily SST from the GFDL CM2.6, a 0.1° configuration for the ocean component, under a 50 km global atmosphere model

But with a big limitation...



Outline

Possible Mechanisms and sources of variability

- Climate variability might arise primarily from the atmosphere, independent of varying boundary conditions such as SST.
- Climate variability might be enhanced by the presence of an ocean with a large heat capacity, leading to a red spectrum. The null hypothesis for climate variability.
- Climate variability might arise via coupled ocean-atmosphere modes (e.g. ENSO). Controversial in mid-latitudes.
- Climate variability might have primarily an oceanic origin. Ocean variability might affect the atmosphere without the need for coupled modes.

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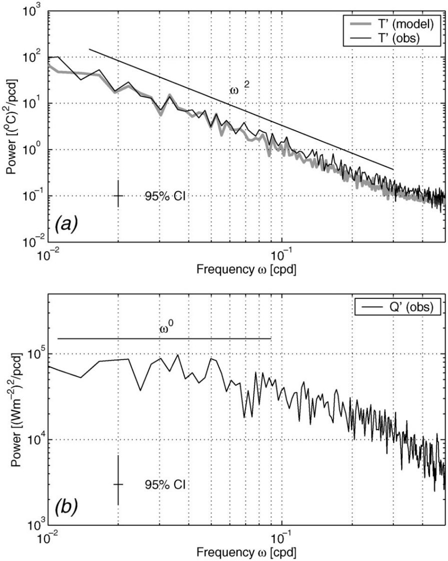
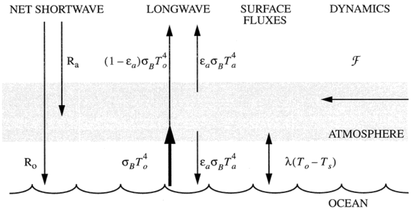
Hasselmann (1977)'s Stochastic Climate Model

- The ocean mixed layer (the slow component), of much higher heat capacity, integrates atmospheric white noise (the fast component), giving rise to a red spectrum.
- $\partial_t T' = -\lambda T' + F(t)$
- The variance spectrum is $|T'(\omega)|^2 = \frac{|F'|^2}{\omega^2 + \lambda^2}$
- and so the slope is ω^{-2}

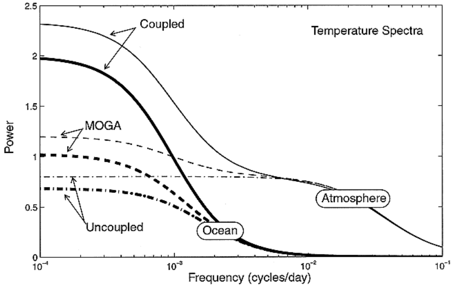


Barsugli and Battisti (1977)'s Stochastic Climate Model

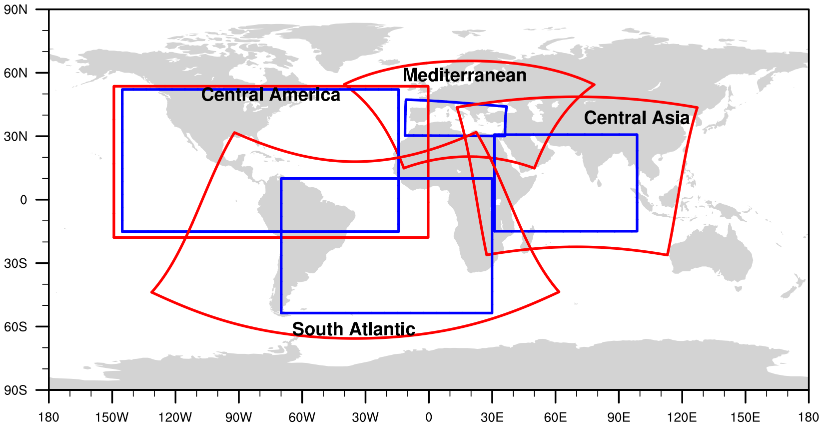


$$\gamma_a \partial_t T_a = -\lambda_{sa}(T_s - T_o) - \lambda_a T_a + F$$

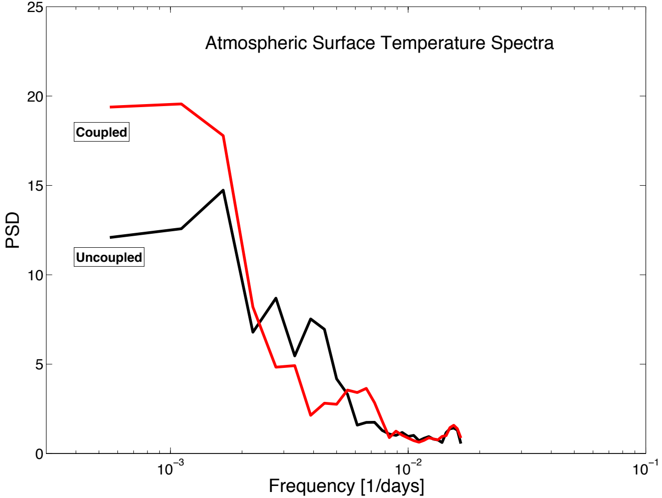
$$\gamma_o \partial_t T_o = -\lambda_{so}(T_s - T_o) - \lambda_o T_o$$



Does this work?



Does this work? YES!



Basic effects of ocean-atmosphere thermal coupling

- increases variance in both media.
- decrease energy fluxes between them.
- prescribing mid-latitude SSTs does not lead to a correct simulation of low-frequency thermal variance in the atmosphere.
- **We need a coupled ocean-atmosphere model ...**

Is this ‘all there is’? ...

- Is the integration of atmospheric variability by the oceanic mixed layer producing a red spectrum *all there is*?
- dynamical process can indeed produce variance at long periods

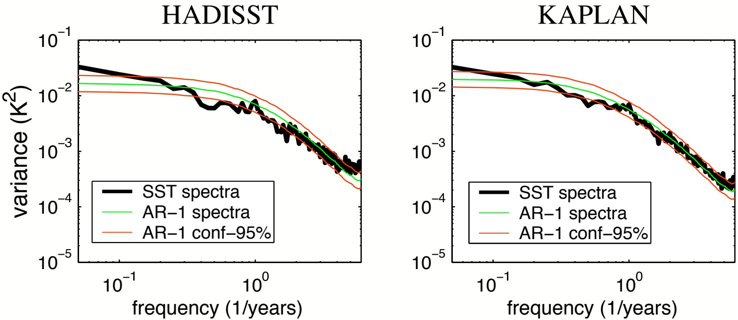
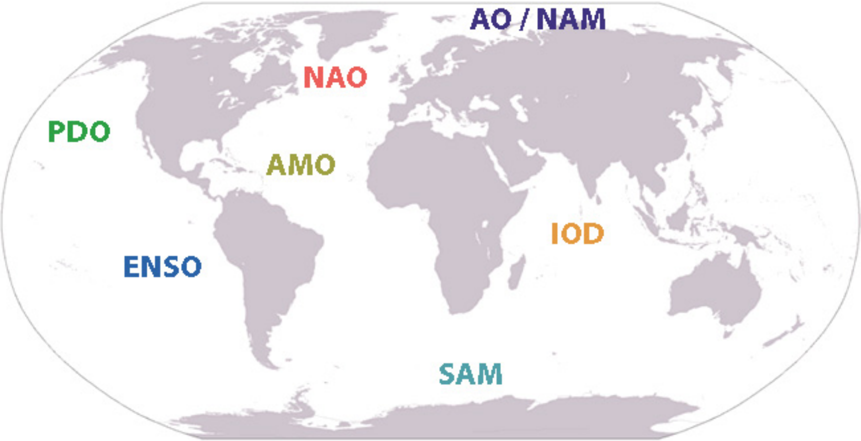


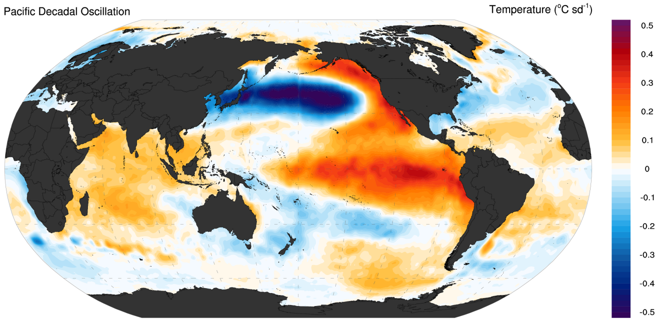
Figure 6. Mean spectra of midlatitude SST anomalies of the HADISST and Kaplan SST data sets (thick lines), along with the best fit spectra from an AR(1) process (thin central line) with 95% confidence levels (thin outer lines). Adapted from Dommenget & Latif (2002).

We can add spatial coherence in atmosphere and a dynamical ocean: Regional Basin Modes/Oscillations



Adding spatial coherence in atmosphere and a dynamical ocean: Regional Basin Modes/Oscillations

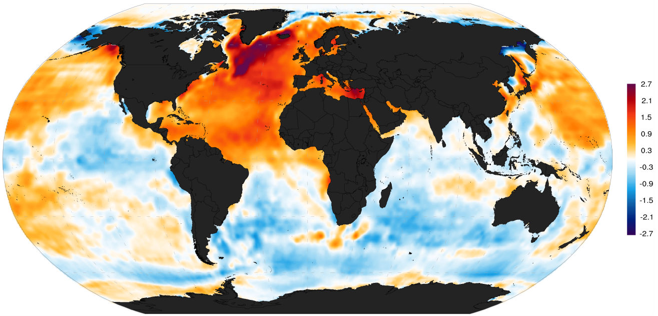
- The Pacific Decadal Oscillation **PDO**
- North Pacific SST integrates weather noise
- SST anomalies provide reduced damping of atmospheric signals at low-frequency
- local and remote coupled feedbacks



Adding spatial coherence in atmosphere and a dynamical ocean: Regional Basin Modes/Oscillations

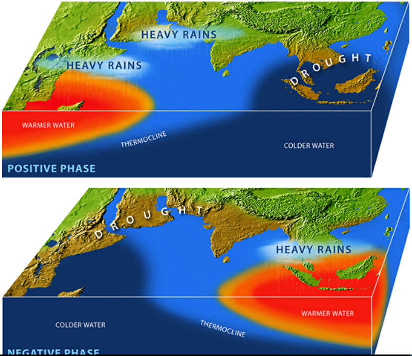
- The Atlantic Multidecadal Oscillation **AMO**
- AMOC variability forces AMO signal (most probably)
- AMO forces atmospheric response, e.g. negative NAO (maybe)
- trans-basin connections

Atlantic Multidecadal Oscillation



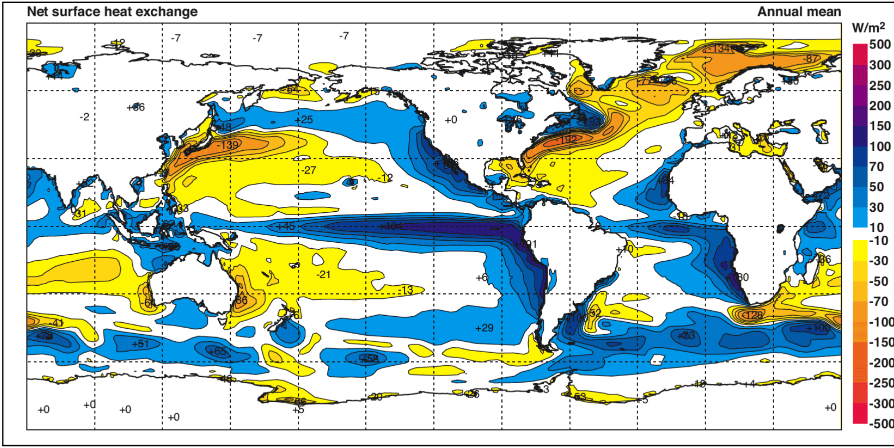
Adding spatial coherence in atmosphere and a dynamical ocean: Regional Basin Modes/Oscillations

- The Indian Ocean Dipole **IOD**
- ocean-atmosphere interaction causing interannual climate variability
- Oscillations of SSTs due to variability in trade winds
- Tropical $\rightarrow$ shorter time scale (interannual)



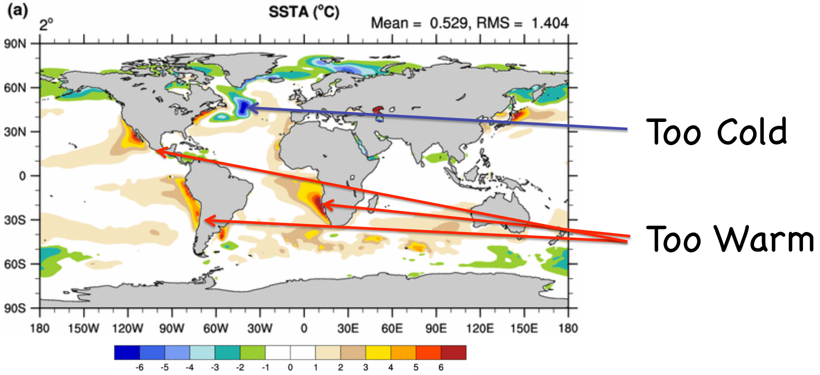
Outline

Net Surface Heat Flux



- Blue → Heat into the Ocean

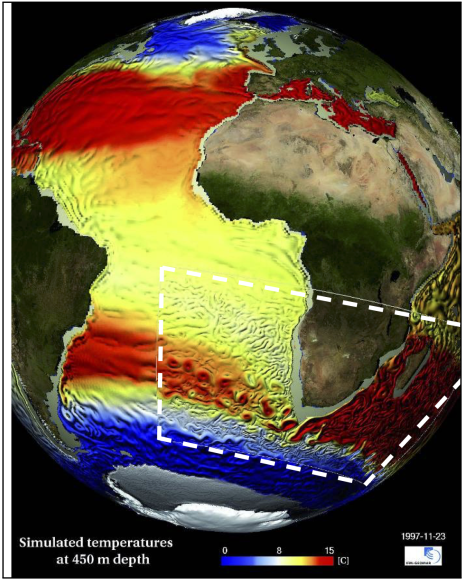
SST bias in Coupled Models



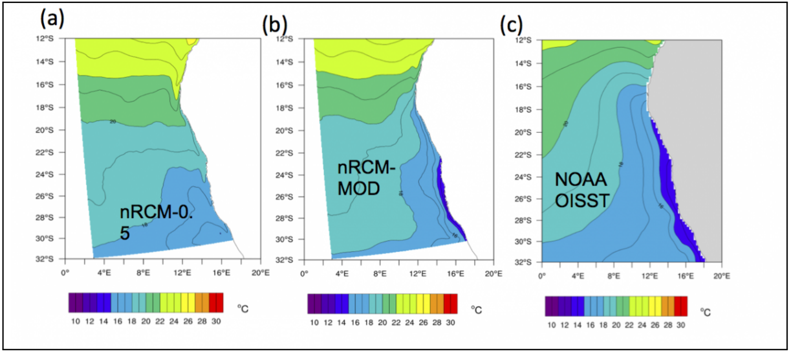
"Models still show significant errors … The ultimate source of most is that many important small-scale processes are not represented explicitly in models …"

Randal et al., 2007.

Two-way nesting in the Agulhas region

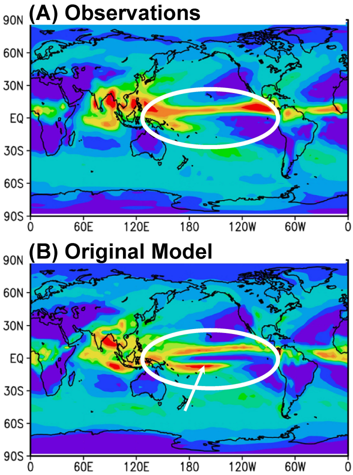


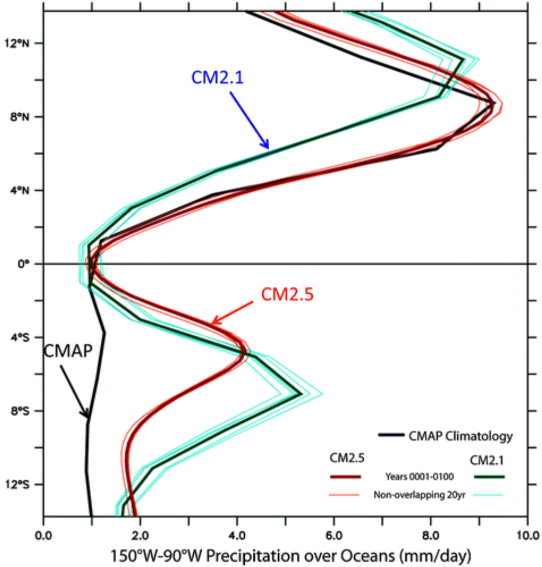
The Benguela Upwelling problem



- Of all the major coastal upwelling systems in the World's ocean, the Benguela, located off south-west Africa, is the one which climate models find hardest to simulate well.
- Increasing both oceanic and atmospheric resolutions (and shifting winds towards the coast) improves the simulation.

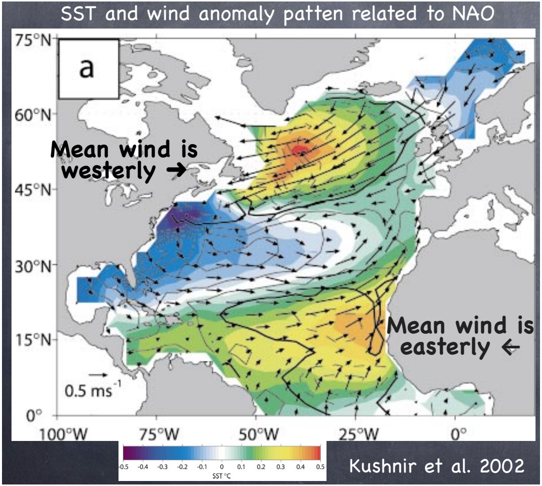
The double-ITCZ problem





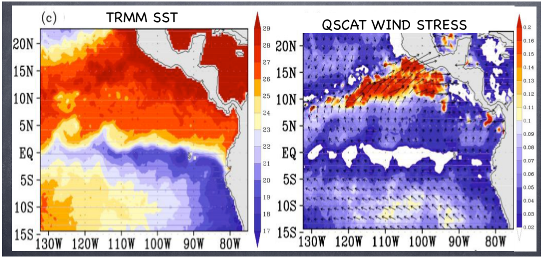
Air-Sea interaction at basin (slow and large) scales

- Stronger wind speed $\rightarrow$ lower SST via mixing and turbulent flux
- **Negative Correlation** $\rightarrow$ Atmosphere drives the Ocean



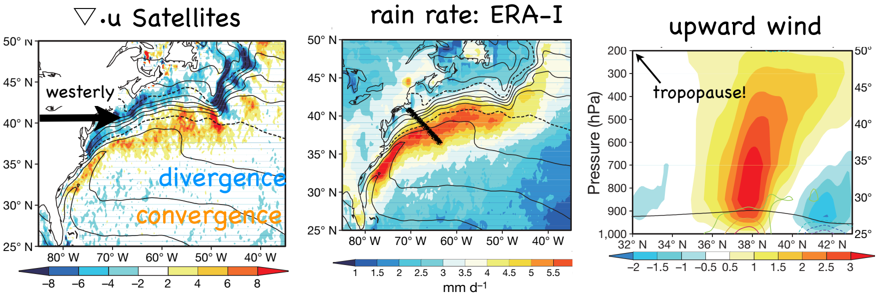
Air-Sea interaction at mesoscales (fast and short)

- Enhanced (Reduced) wind speed over warm (cold) SST
- **Positive Correlation** $\rightarrow$ Ocean drives the Atmosphere



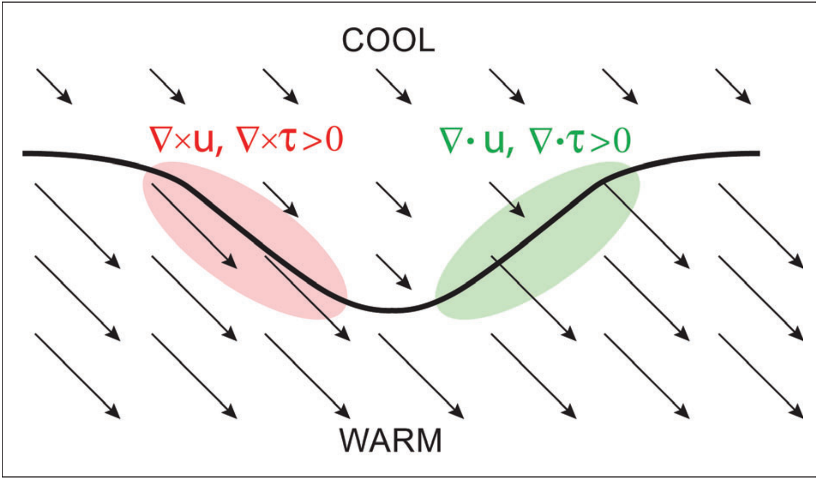
Effects on the Atmosphere

- Enhanced (Reduced) wind speed over warm (cold) SST
- **Positive Correlation** → Ocean drives the Atmosphere

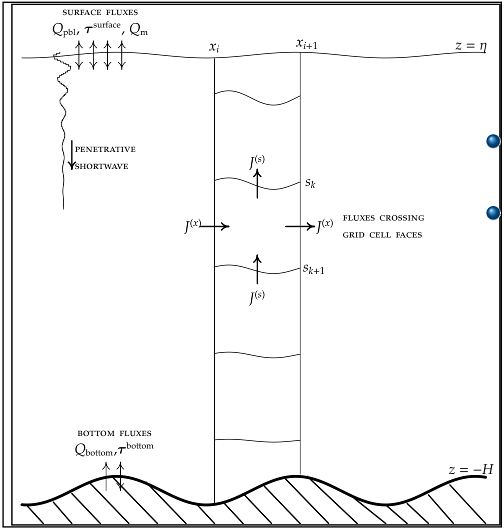


Minobe et al. 2008

How does it work?

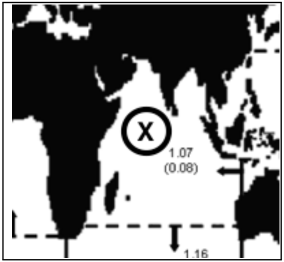


Discretizing a column of ocean fluid



- Boundary fluxes through surface and bottom.
- Transport convergence (advective and subgrid scale), body forces (gravity, Coriolis), contact forces (pressure, friction), and penetrative radiation render time tendency for mass, tracer, and momentum.

Conservation is important



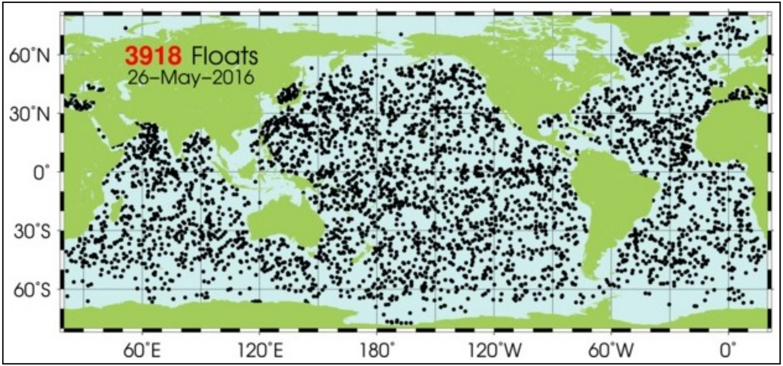
Take the vertically-integrated Temperature budget

- $\partial_t \left(\int_{-H}^{\eta} dz\, \theta \right) = -\nabla \cdot \left(\int_{-H}^{\eta} dz\, (\mathbf{u}\theta + \mathbf{F}_{sgs}) \right) + Q_{heat}/(\rho C_p)$
- Assuming steady state and a basin: $\rho C_p \int dx \int_{-H}^{\eta} dz (v\theta + F^y) = \int_{y_s}^{y_n} dy \int dx\, Q_{heat}$
- A meridional ocean heat transport is thus **implied** by the net surface forcing.

Lateral BCs for regional ocean models

Near-global observations are pushing models to improve.

Argo + satellites provide high quality near-global information.
These data sources are now assimilated into global ocean models.
These products could generate the BC's for our coupled regional models.



Summary

Where the envelope can be pushed

1. **Role of resolution in climate**
    - How/will climate sensitivity, variability, predictability be modified with eddying ocean simulations and higher atmospheric resolution?
    - Coupled ocean-atmosphere models are still too coarse to resolve mesoscale SST influence on the atmosphere.
    - This can readily be achieved with regional coupled models.
2. **Regional and Global Coupled Models**
    - There is a clear motivation for the development of both regional and global coupled models.
    - and for a comparison and feedback between the two.