Interacciones Oceano-Atmosfera: Variabilidad Climatica (Decadal)

Workshop on the Science of Climate Change:
a focus on Central America and the Caribbean Islands
Antigua, Guatemala, 14-16 Marzo, 2017

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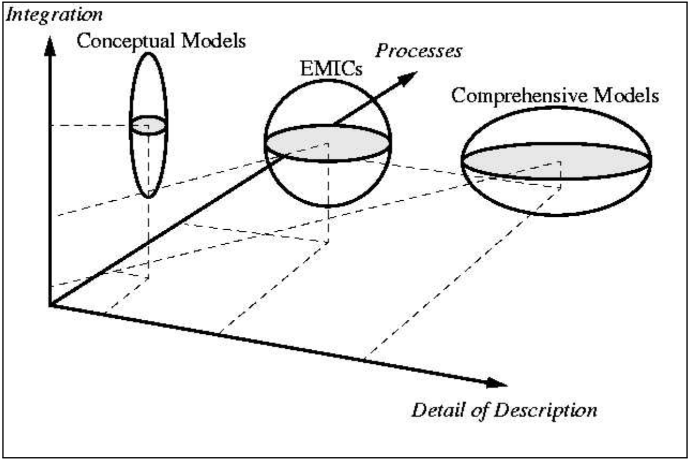
Too Much Too Fast

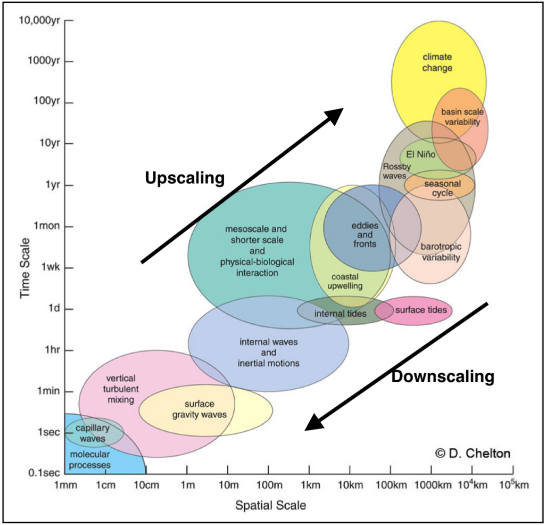
1. Modelos Acoplados
   - Reflexiones sobre el modelamiento del sistema Oceano-Atmosfera
   - El valor añadido de los modelos regionales
2. Interacciones Oceano-Atmosfera y Variabilidad a Baja Frecuencia
   - Variabilidad a baja frecuencia (LFV)
   - Variabilidad decadal e interdecadal en modelos

Outline

A variety of coupled climate models



Space-time diagram of motions

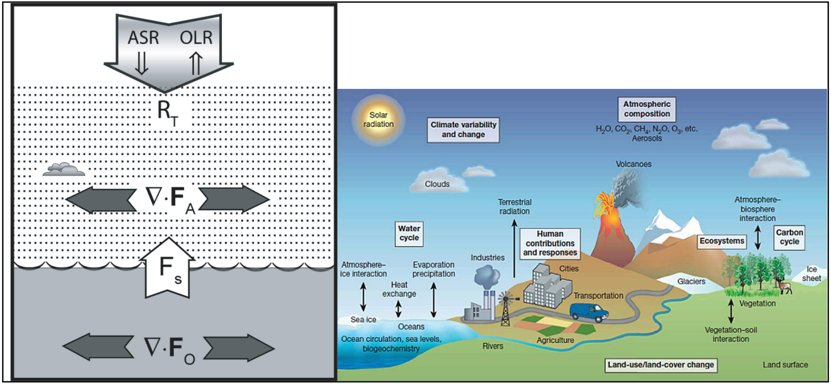


- Broad range of space-time scales
- NO spectral gap between phenomena.
- We can use EMICs or Downscale/Upscale to get information on smaller (larger) space-time scales.

Hierarchical approach

Hierarchical Ocean-Atmosphere Modelling

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

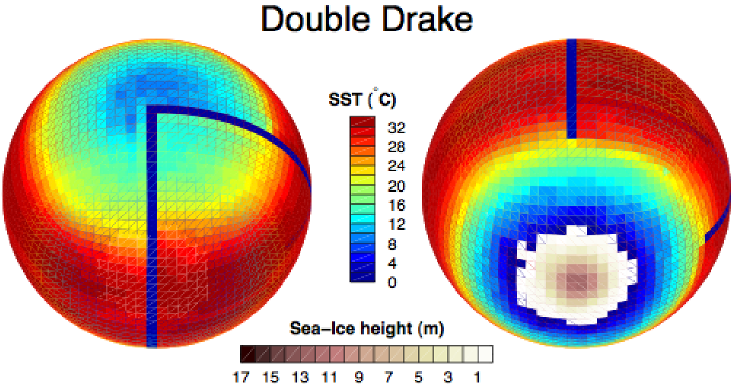


Hierarchical approach

or ... *"The Gap between Simulation and Understanding in Climate Modelling"*(Held, 2005)

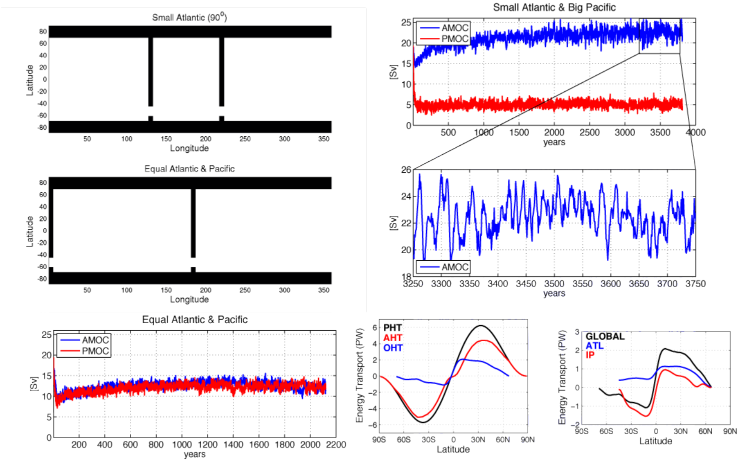
...A creative tension between simulation and understanding, between accepting complexity and searching for simplicity, is present in many challenging scientific problems. Climate science provides an excellent example of this tension. (Held, 2014)

What do I mean by hierarchical approach?



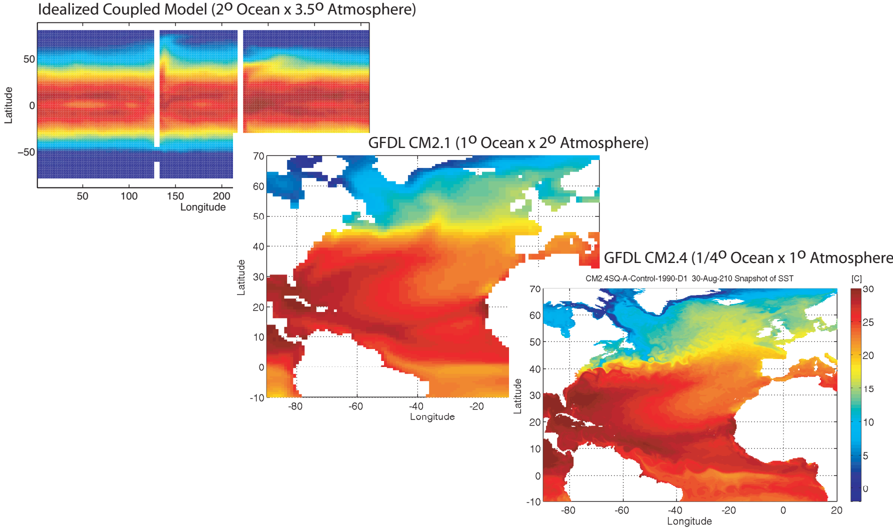
(Ferreira et al., 2001)

Hierarchical approach

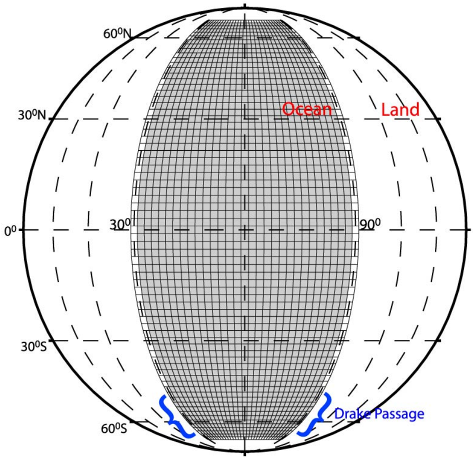


(Farneti and Vallis, 2009)

Hierarchical approach for a variety of (coupled) process studies



Intermediate Complexity Climate Model (ICCM)

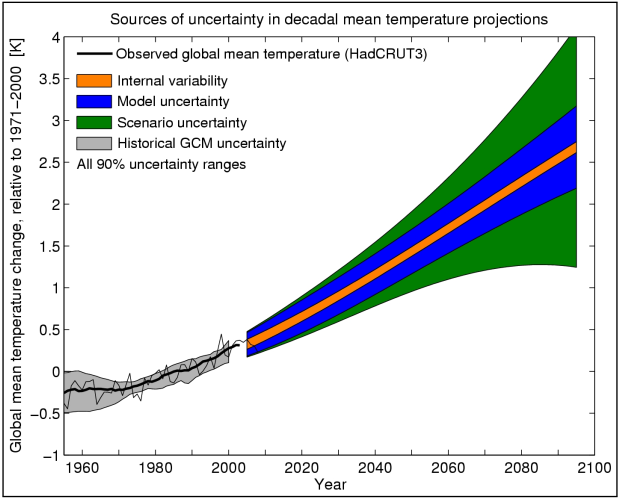


(Farneti and Vallis, 2009)

1. Based on PE ocean and atmosphere models. Reduced domain and single, two-hemisphere ocean basin.
2. The Atmosphere has simplified physics.
3. The Ocean is based on MOM with simplified geometry.
4. The Land model has simple hydrology.
5. 2x2^o Ocean ; 3.75x3^o - L7 Atm.

freely available within MOM repository (http://mom-ocean.org/)

Decadal Variability lies in the Oceans



(Hawkins and Sutton, 2009)

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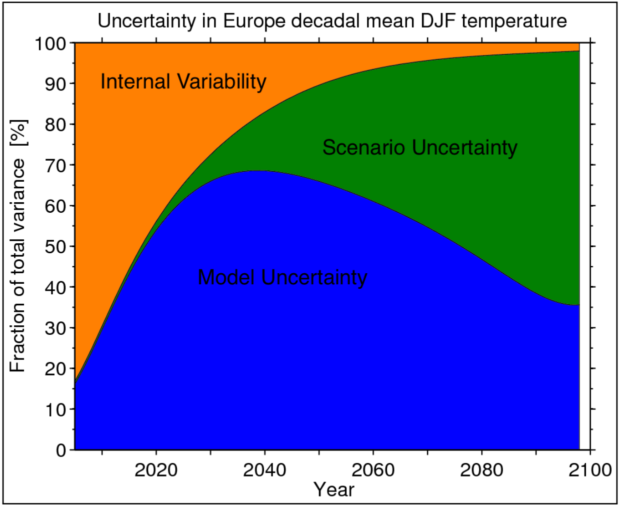
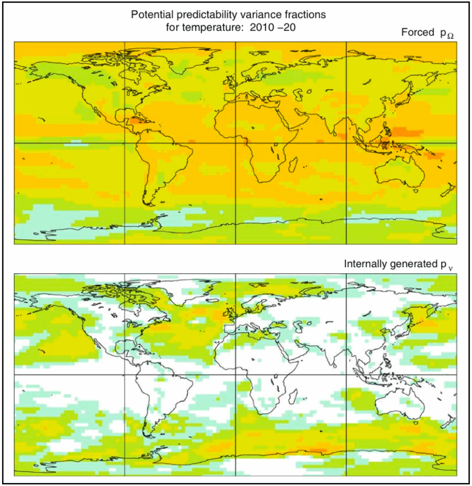


(Hawkins and Sutton, 2009)

Decadal Predictability lies in the Oceans



(Boer, 2011)

- concerns processes of 'long time scales' (usually in the ocean)
- External Forcing: aerosols, GHGs, Volcanoes, Solar
- Internal: Oceanic, Forced, Coupled

The evolution of any climate variable X (temperature, precip.,)

$$X = \mu + \Omega + (\nu + \epsilon) \tag{1}$$

where

- μ is the mean
- Ω is the externally-FORCED component. Essentially deterministic in simulations.
- ν is the internally generated component related to long time scales processes potentially predictable.
- ϵ is the internally generated component related to the short-time scales non-linearities ("noise").

Potential Predictability Variance Fraction is given by

$$p = (\sigma^2_\Omega + \sigma^2_\nu)/\sigma^2 = P_\Omega + P_\nu \tag{2}$$

Equilibration time scale problem

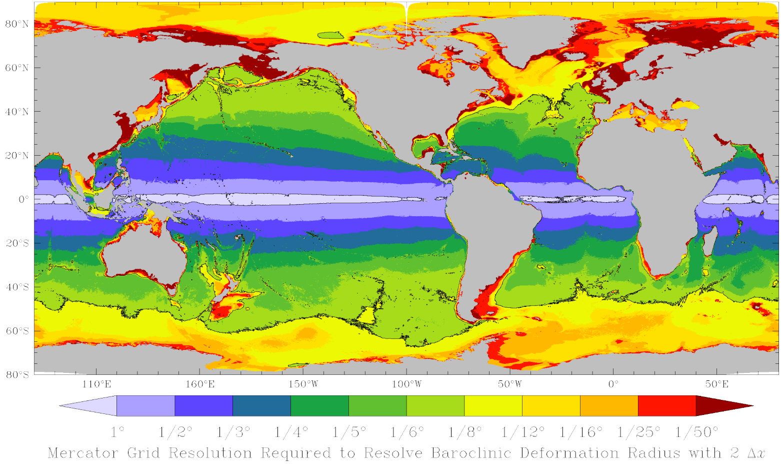
Scaling argument for deep adjustment time

$$H^2/\kappa = (2000\ m)^2/(2 \times 10^{-5}\ m^2/s) \quad (3)$$

$$= \mathcal{O}(5000\ years) \quad (4)$$

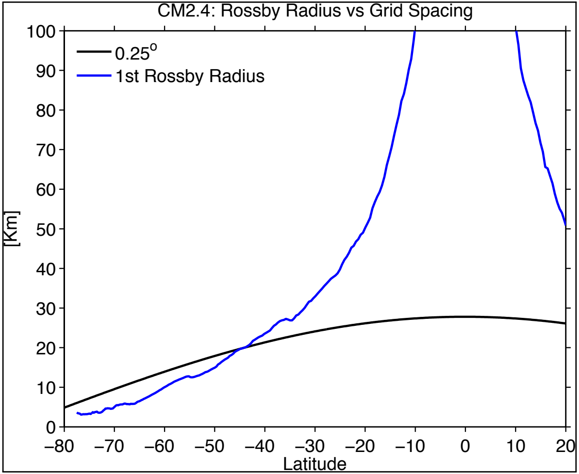
- Performing long (climate scale) simulations at eddy-resolving / permitting resolution are not practical.
- Must live with deep ocean not being at equilibrium in most simulations.
- Another good reason to use a hierarchy of climate models.

Oceanic Resolution problem



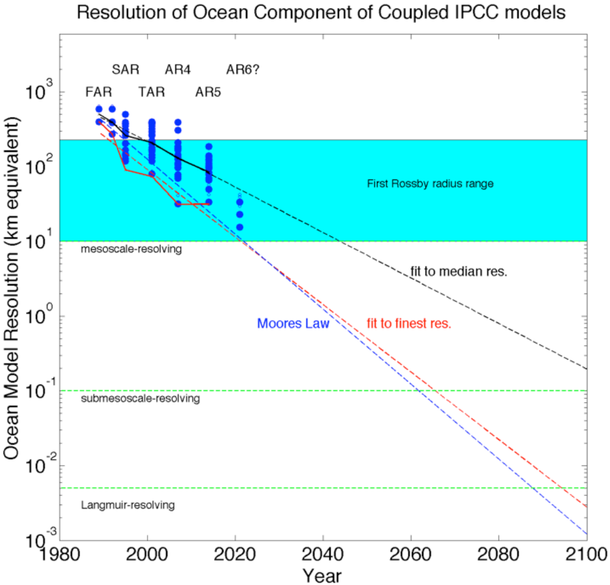
(Hallberg, 2013)

Spatial scale of mesocale and submesoscale eddies

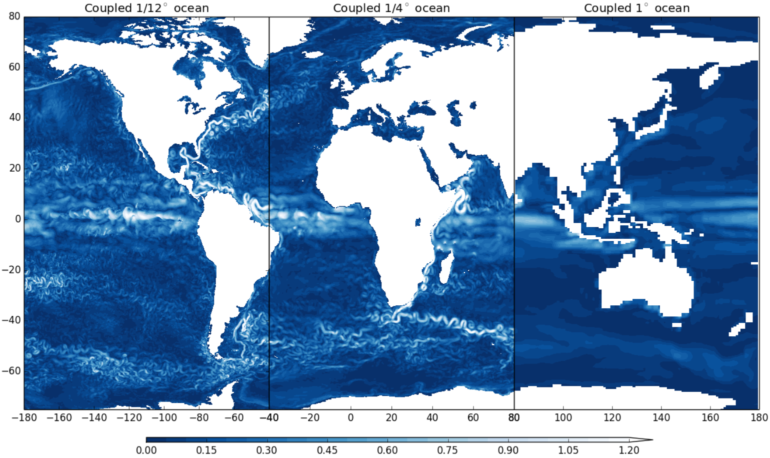


First baroclinic Rossby Radius $\lambda_m = c_m/|f|$, where $c_m \approx \frac{1}{m\,\pi} \int_{-H}^{0} N\,\mathrm{d}z$.

Ocean resolution in IPCC-class climate models

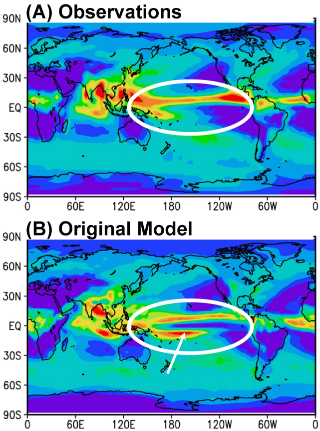


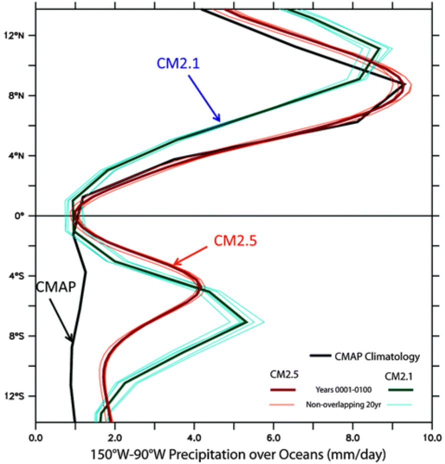
Nevertheless, progress is exciting!



HadGEM3 (courtesy of Malcolm Roberts)

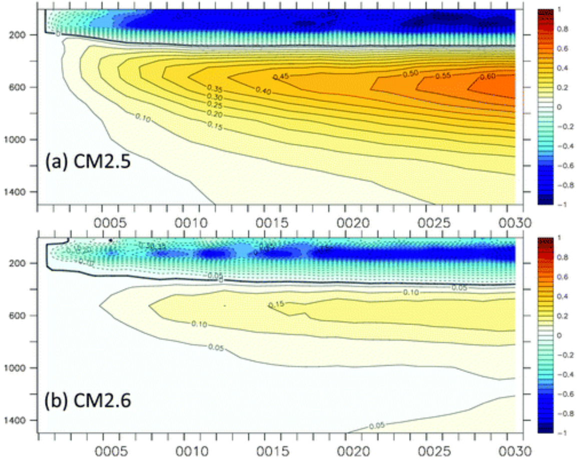
The double-ITCZ problem





Delworth et al. (2012)

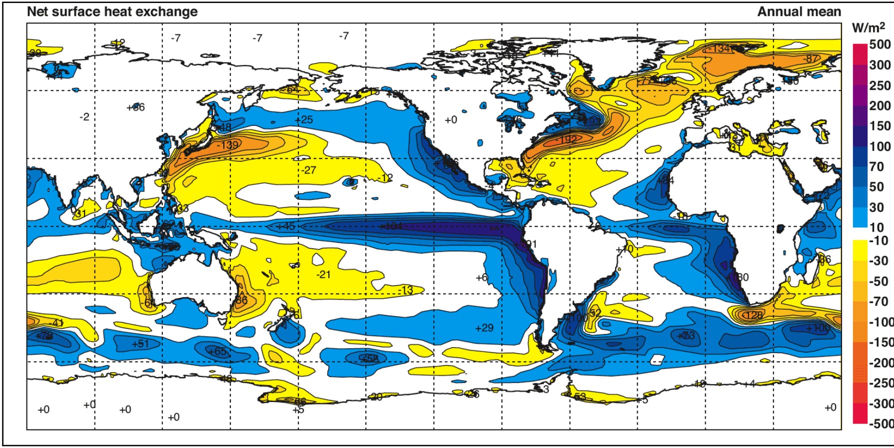
Drifts and biases



- Subsurface ocean temperature drift from initial conditions for (a) CM2.5 and (b) CM2.6.

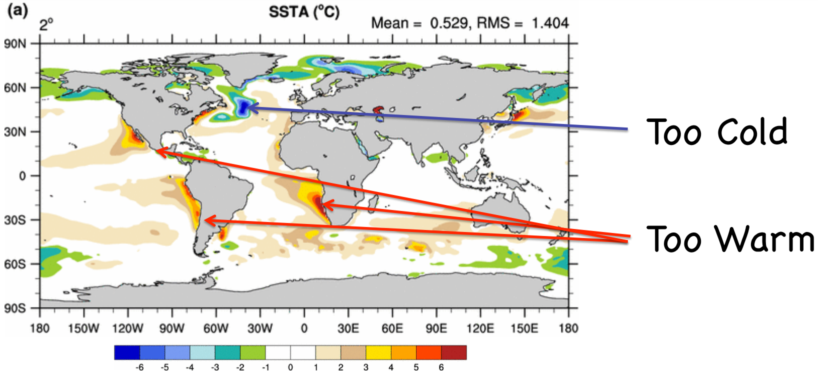
(Delworth et al., 2012)

Motivations for regional modelling



- Net Surface Heat Flux: Blue → Heat into the Ocean

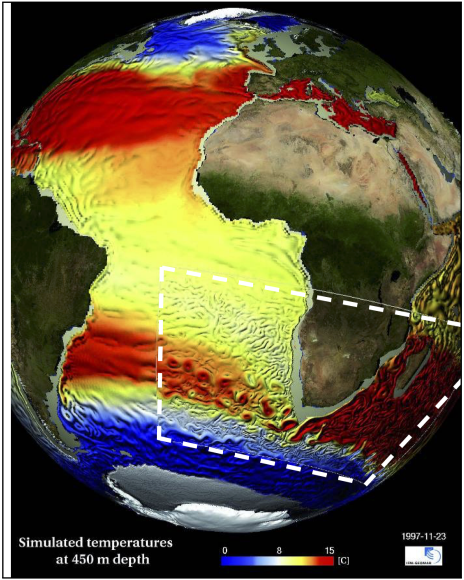
SST bias in Coupled Models



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

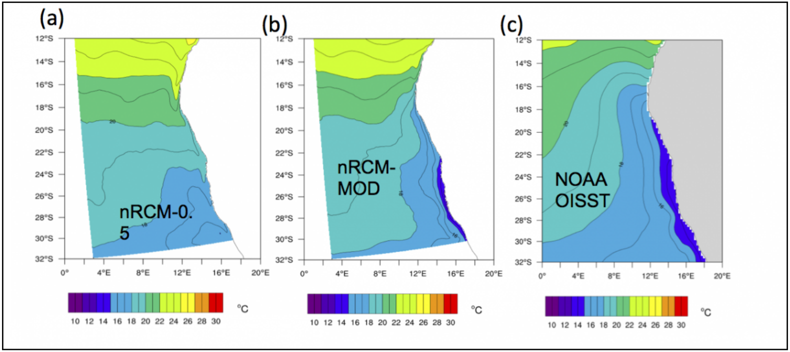
Randal et al., 2007.

Regional focus: Two-way nesting in the Agulhas region



Biastoch et al. (2012)

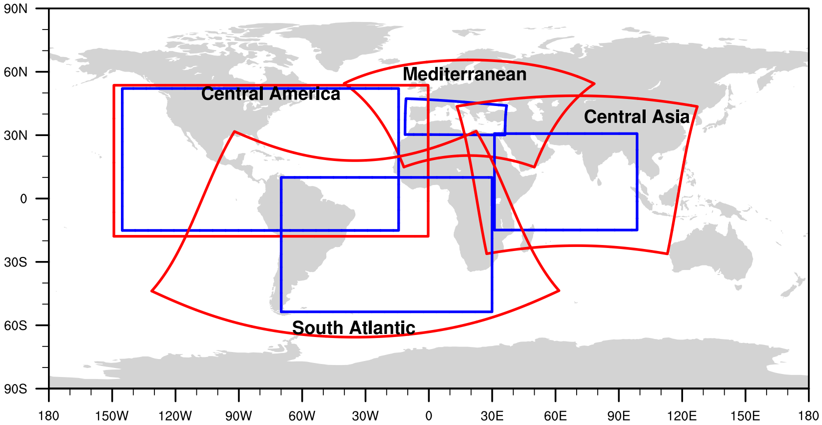
The Benguela Upwelling problem



Small et al. (2015)

- 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.
- a realistic wind stress curl at the eastern boundary, and a high-resolution ocean model, are required to well simulate the Benguela upwelling system. But they are not enough.

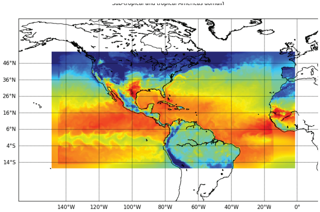
Regional Modelling (RegESM)



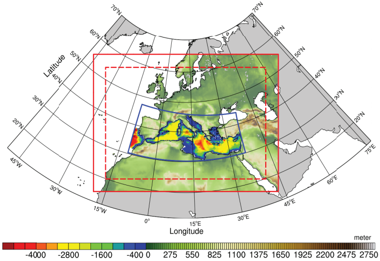
- RegCM + MITgcm (+ CLM + HD + bgc + ...)
- Available through the RegCM network.
- Mostly the work of {Sitz, Di Sante, Turuncoglu, Fuentes} @ICTP.

Regional Modelling

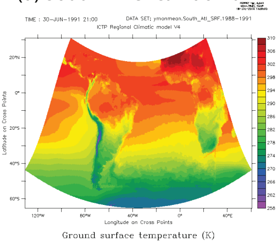
(b) Central American domain



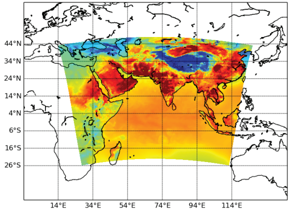
(a) Mediterranean domain



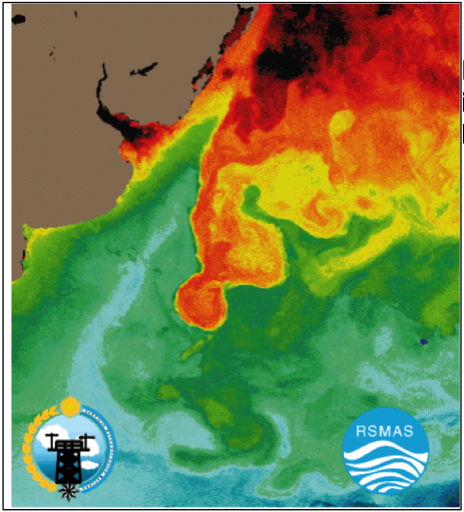
(d) South American domain



(c) Indian domain



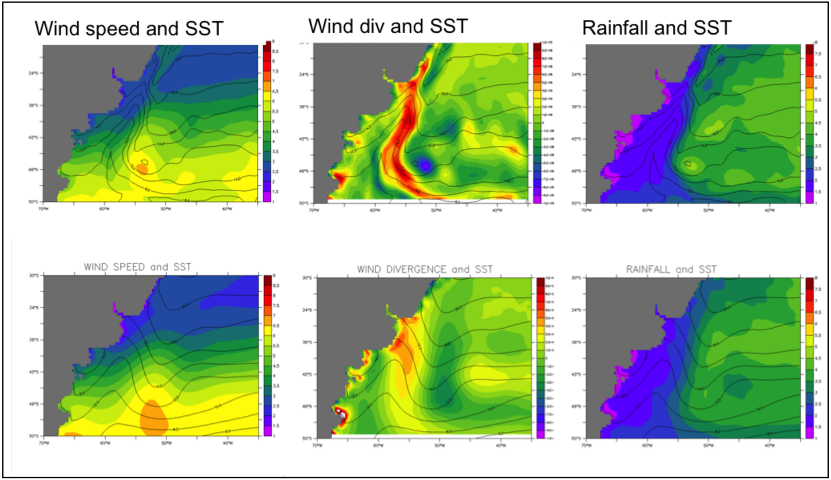
An example from the South American domain



Extratropical air-sea interactions in the Brazil Malvinas Confluence

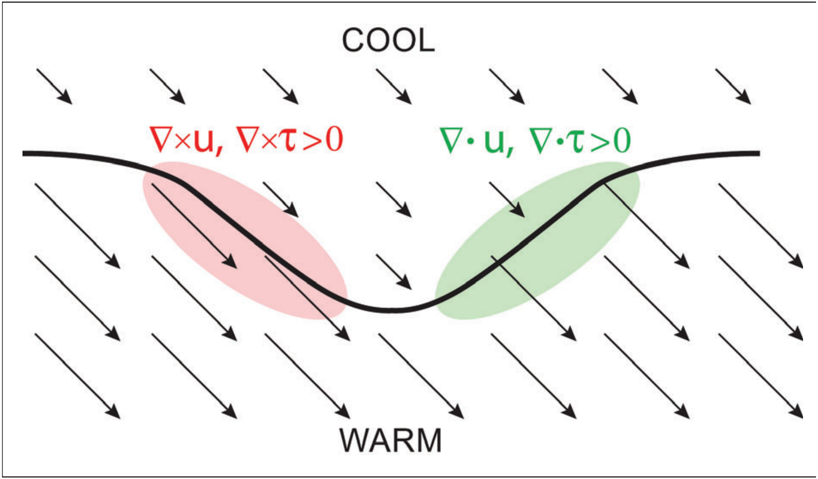
- Cold water enters the South Atlantic from the Pacific around the southern tip of South America.
- The Malvinas Current meets the warm poleward flowing Brazil Current in the B-M Confluence Zone.

An example from the South American domain

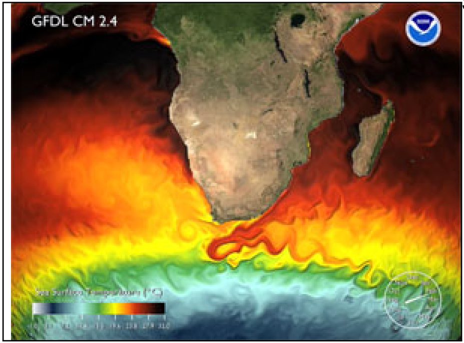


- The CPL model clearly shows air-sea coupling in the Brasil-Malvinas Confluence.
- Rainfall is enhanced (reduced) over regions of wind convergence (divergence).

How does it work?



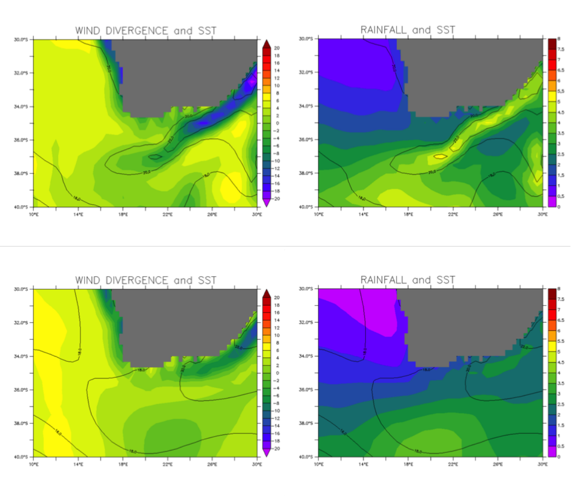
An example from the South American domain



Extratropical air-sea interactions in the Agulhas System

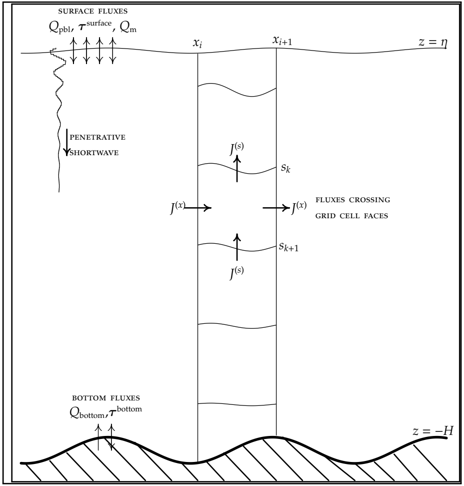
- The Agulhas Current in the Indian Ocean flows down the southeast coast of Africa and past the tip of South Africa then takes a sharp turn to the east.
- Large eddies called Agulhas Rings spin off this bend and carry huge bundles of warm salty Indian Ocean water west into the South Atlantic.

An example from the South American domain



- The CPL model shows a strong convergence of the surface winds surrounded by net divergence.
- Increased rainfall over the warm Agulhas current and its retroflection (consistent with the SST- induced vertical mixing mechanism for wind adjustment).

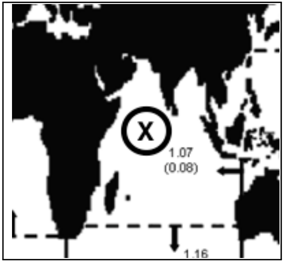
A regional model has surface and lateral fluxes



From Griffies and Treguier (2013)

- Boundary fluxes through surface and bottom, and all lateral sides.
- Transport convergence and all surface fluxes should be properly interpolated, balanced and corrected.

Conservation becomes an issue when coupled

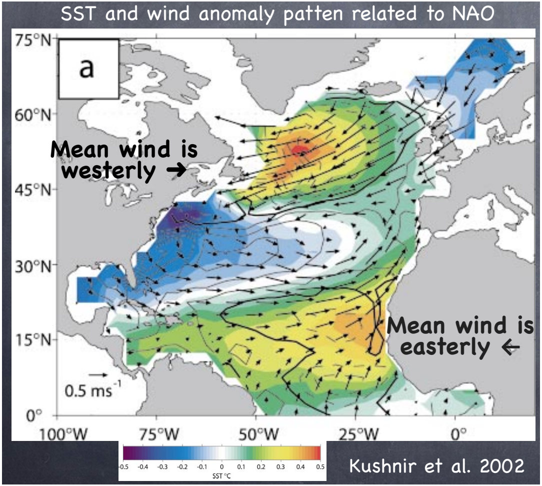


Take the vertically-integrated Temperature budget

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

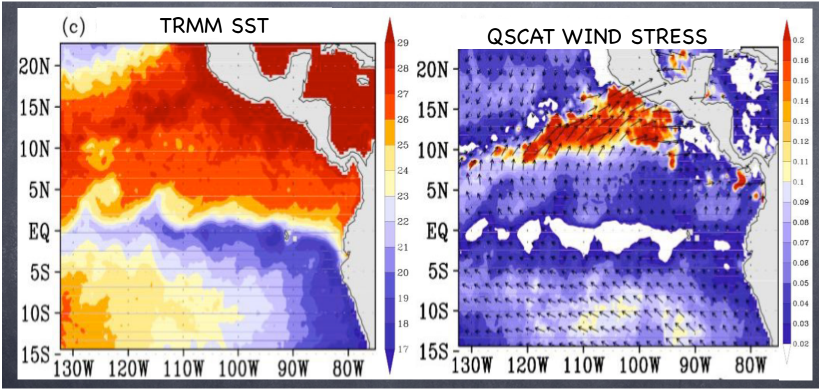
Air-Sea interaction at basin (slow and large) scales

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



Air-Sea interaction at meso (fast and short) scales

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

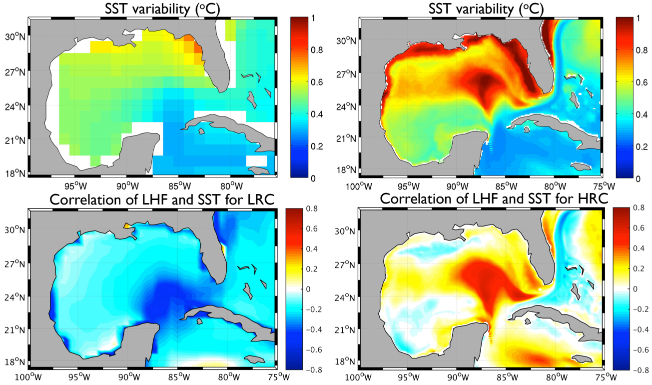


Resolution helps getting fluxes right

Community Climate Systems Model (CCSM3.5)

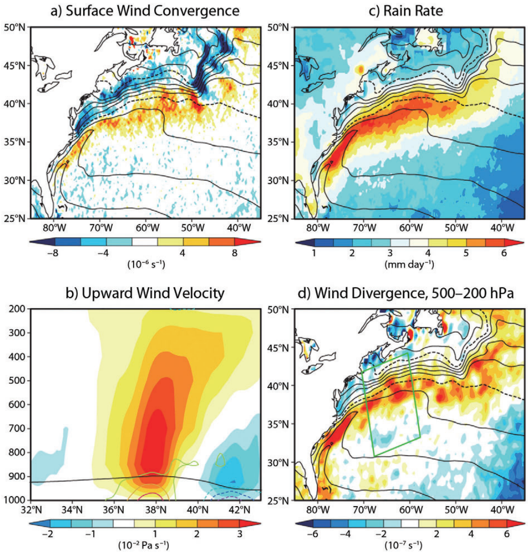
Low resolution (LRC):
- 1º ocean, 0.5º atm
- Model years: 35-88
- Fixed forcing (1990)

High resolution (HRC):
- 0.1º ocean, 0.5º atm
- Model years: 102-155
- Fixed forcing (1990)



Putrasahan et al., US CLIVAR Variations 2015

Effects on the Atmosphere



Chelton and Xie (2010)

A pause for thoughts

A movie from the ECCO model

Outline

2 Interacciones Oceano-Atmosfera y Variabilidad a Baja Frecuencia

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 have primarily an oceanic origin. Ocean variability might affect the atmosphere without the need for coupled modes.
- Climate variability might arise via coupled ocean-atmosphere modes (e.g. ENSO). Controversial in mid-latitudes.

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Frankignoul and Hasselmann (1977)'s Stochastic Climate Model

- An equation for the SST anomaly can be written as
  $\partial_t T' = -\lambda T' + F(t)$
  where λ represents dissipative and feedback mechanisms and F behaves as white noise for time scales longer than τ.
- SST anomalies behave like a first order Markov process and the spectrum is red
  $|T'(\omega)|^2 = \frac{|F'|^2}{\omega^2+\lambda^2}$
- for time scales shorter than λ^{-1}, the SST spectrum increases as the square of the period (ω^{-2}).
- for longer time scales SST are damped and the spectrum flattens.

The null hypothesis for climate variability

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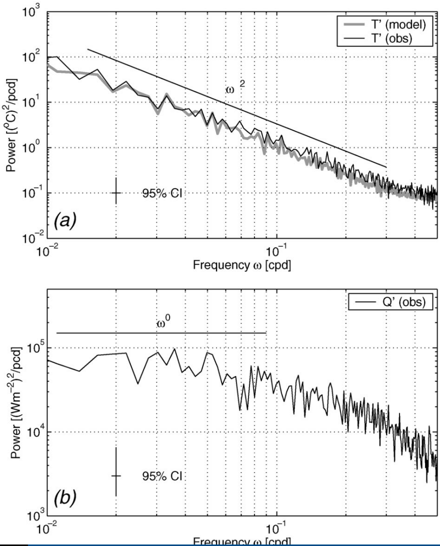
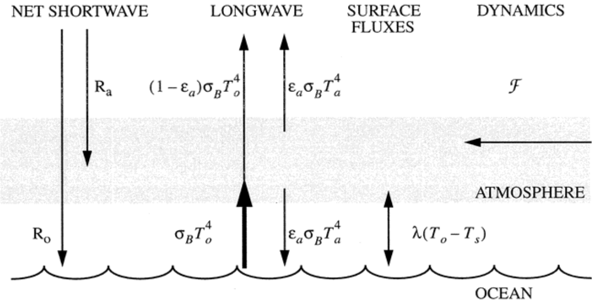
The null hypothesis for climate variability
The ocean mixed layer (the slow component), of much higher heat capacity, integrates atmospheric white noise (the fast component), giving rise to a red spectrum.



Barsugli and Battisti (1998)'s Stochastic Climate Model



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

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

Barsugli and Battisti (1998)'s Stochastic Climate Model

If we Fourier transform the two eqs. ($t \rightarrow \omega$)

$$i\sigma T_a = -aT_a + bT_o + F(\sigma) \quad (5)$$

$$i\beta\sigma T_o = cT_a - dT_o \quad (6)$$

- coefficients a and d represent damping of atmosphere and ocean
- coefficients b and c represent coupling between atmosphere and ocean
- $\alpha = bc$ is our coupling coefficient, representing feedbacks between O-A coupling of low-frequency thermal variance in the atmosphere.
- F is assumed to be white noise of unit amplitude.

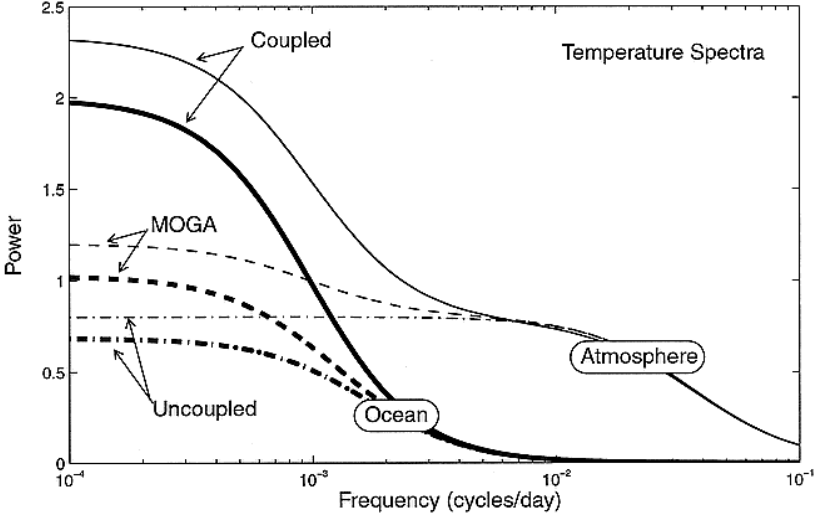
Barsugli and Battisti (1998)'s Stochastic Climate Model

TABLE 1. The standard parameter values as defined in the text and in appendix A.

Parameter	Value	Parameter	Value
γ_a	1×10^7 J m^{-2} K^{-1}	a	1.12
γ_o	2.0×10^8 J m^{-2} K^{-1}	b	0.5
λ_{sa}	23.9 W m^{-2} K^{-1}	c	1
λ_{so}	23.4 W m^{-2} K^{-1}	d	1.08
λ_a	2.8 W m^{-2} K^{-1}	β	20
λ_o	1.9 W m^{-2} K^{-1}	$\lvert N \rvert$	1
λ	20 W m^{-2} K^{-1}	$z \equiv \frac{ad}{\alpha} \equiv \frac{ad}{bc}$	2.42

- γ are the heat capacities
- λ_s are the linearized coefficient of combined latent, sensible and long wave heat flux
- λ_a, λ_o are the radiative damping to space.
- N white noise of unit amplitude

Barsugli and Battisti (1998)'s Stochastic Climate Model



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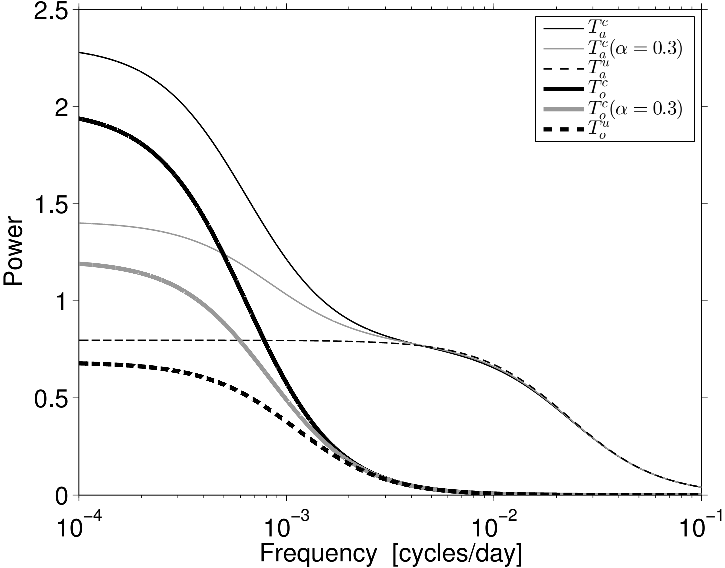


Basic effects of ocean-atmosphere thermal coupling

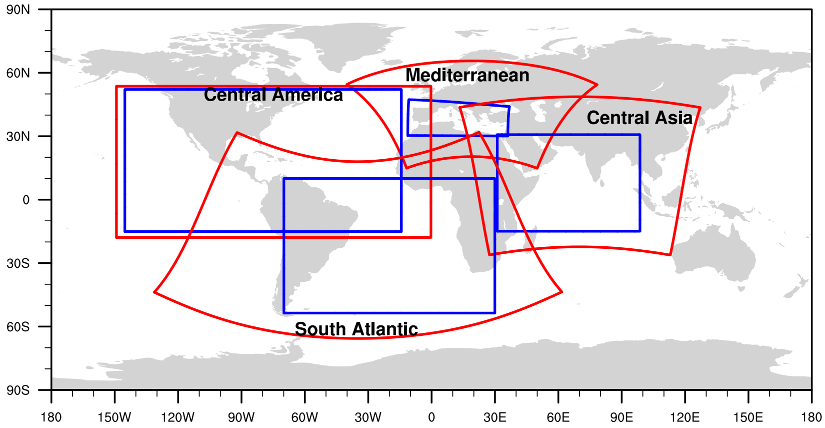
Coupling between the atmosphere and ocean in midlatitudes will

- increase the 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.

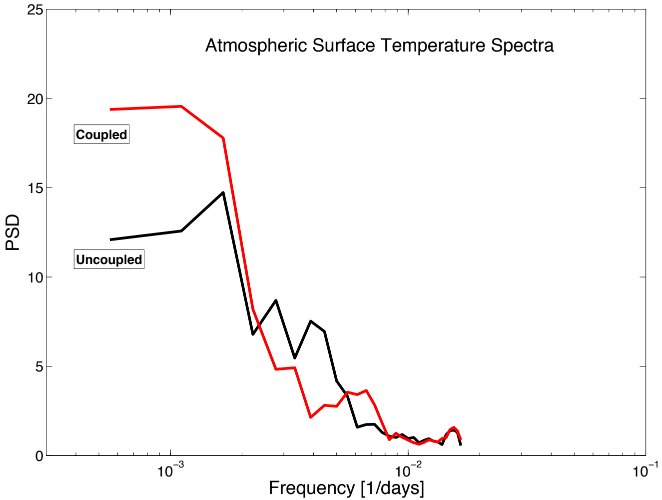
REDUCED THERMAL DAMPING

- **We need coupled ocean-atmosphere models ...**

Does this work?



Does this work? YES!



Is this ‘all there is’? ...

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

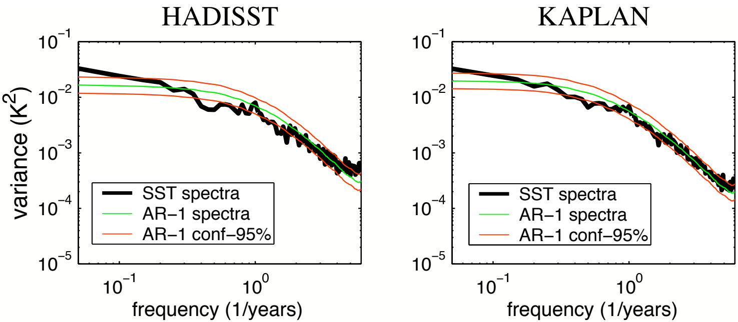
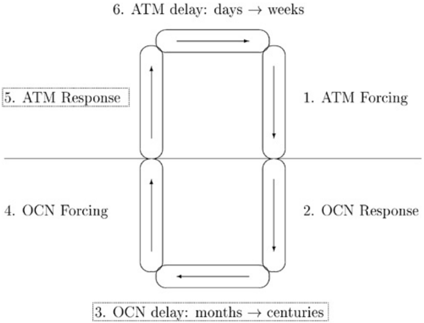


Figure 6. Mean spectra of midlatitude SST anomalies of the HADISST and Kaplan SST data sets (thick lines), along with the best fit spectra from an AR(1) process (thin central line) with 95% confidence levels (thin outer lines). Adapted from Dommenget

Midlatitude coupled O-A interactions

- The ocean integrates the atmospheric forcing, producing a red spectrum in the upper ocean to first order.
- Due to its large thermal inertia and long adjustment time scale, the ocean response to atmospheric forcing is delayed, producing a time scale of months to centuries.
- Provided the ocean response involves changes in SST, the ocean may force the atmosphere
- The atmosphere responds to the ocean forcing, with a delay time on the order of days to weeks before repeating the cycle.

Figure 1. Causal "chain" for a coupled oscillation in the midlatitudes



Midlatitude coupled O-A interactions (?)

- The two most limiting branches of the diagram involve details of the **ocean delay** and of the **atmospheric response** to ocean forcing.
- The first, involves ocean dynamics, which, in the mid-latitudes, tend to spatially confine and attenuate the oceanic response to atmospheric forcing. Theories for mid-latitude coupled mechanisms must account for this spatial confinement and signal attenuation.
- The second, is very sensitive to the structure, location, and amplitude of the ocean forcing.
- The atmosphere responds more readily to large-scale spatial forcing.
- The atmospheric response to ocean forcing is very sensitive to the location and amplitude of the forcing. In the mid-latitudes, the atmosphere is not sensitive to SST anomalies less than about 1C. Thus, the atmospheric response to ocean forcing is very weak. However, in the tropics, the atmosphere is quite sensitive to SST anomalies, implying a stronger response to a given temperature anomaly.
- Without any atmospheric response to ocean forcing, there can be no decadal atmospheric variability, due to the short time scale of intrinsic atmospheric variability.

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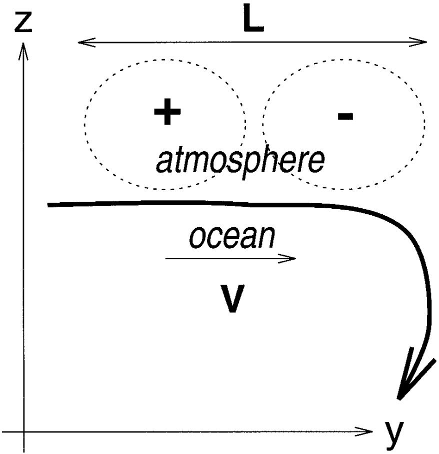
The model of Saravanan and McWilliams (1998)

- A simple 1-D stochastic model of the interaction between spatially coherent atmospheric forcing patterns and an advective ocean. The model may be considered a generalization of the 0-D stochastic climate model proposed by Hasselmann.
- A mechanism of decadal variability in the mid-latitude ocean atmosphere system that produces a defined time scale.
- For long time scales (greater than intraseasonal), mid-latitude atmospheric variability tends to be dominated by fixed spatial patterns that vary with no preferred time scale (stochastic) (e.g. NAO).
- Provided the ocean response involves changes in SST, the ocean may force the atmosphere.
- The atmosphere responds to the ocean forcing, with a delay time on the order of days to weeks before repeating the cycle.



The Stochastic Climate Model of Saravanan and McWilliams (1998)

$$\partial_t T_a = -\alpha T_a - \frac{Q}{C_a} + F_a(y,t) \quad (7)$$

$$\partial_t T_o = -V \partial_y T_o - \frac{Q}{C_o} \quad (8)$$

- where $Q = \kappa(T_a - T_o)$
- F denote stochastic forcing of the atmosphere.
- α is an intrinsic damping coefficient for the atmosphere representing all dissipative processes
- V = 1 cm s^{-1}, L = 5000 Km

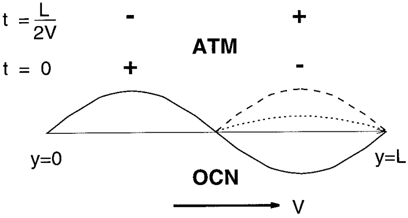
→For a white-noise forcing and after non-dimensionalizing, the following nondimensional parameter appears:

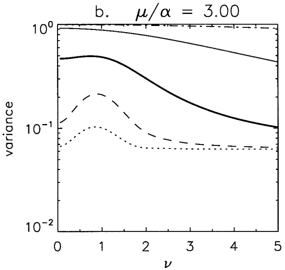
- $\Gamma = \omega_{adv}/\lambda_{eff}$
- $\omega_{adv} = 2\pi/T_{adv}$; $T_{adv} = L/V$
- λ_{eff} is the effective damping coefficient

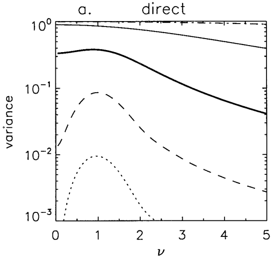
The model of Saravanan and McWilliams (1998)

ADVECTIVE RESONANCE MECHANISM

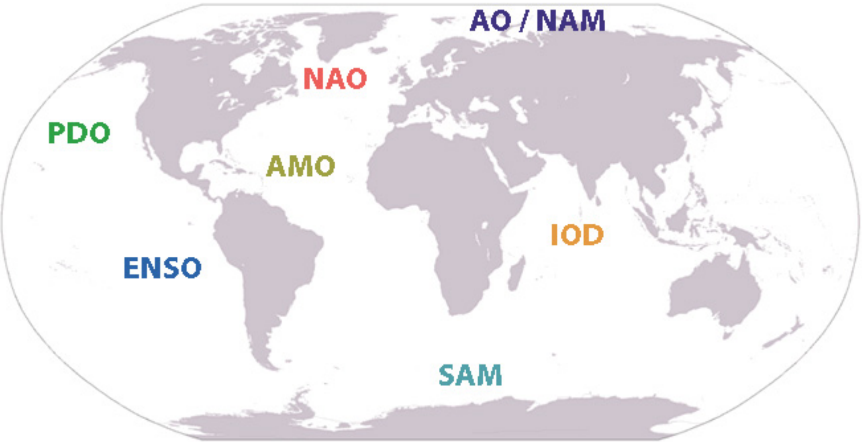
- **Slow-shallow regime:** $\Gamma \ll 1$. Where the depth of penetration of thermal anomalies is small and thermal damping effects dominate over advection (red-noise).
- **Fast-deep regime:** $\Gamma \gg 1$. Where thermal anomalies penetrate quite deeply and the ther- mal damping effects are weaker than advection







If we add spatial coherence in atmosphere and a dynamical ocean: Regional Basin Modes/Oscillations



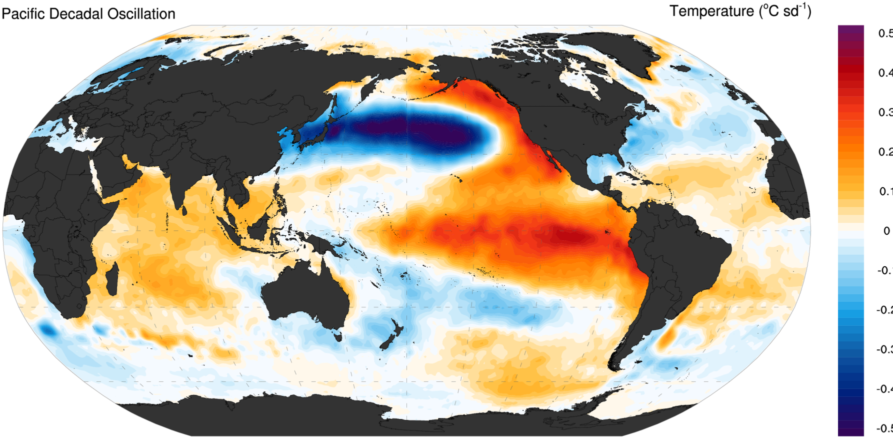
If we add spatial coherence in atmosphere and a dynamical ocean: Regional Basin Modes/Oscillations

The more prominent low-frequency modes

- The Pacific Decadal Oscillation (**PDO**)
- The Atlantic Multidecadal Oscillation/variability (**AMO/V**)
- The Southern Ocean Centennial Variability (**SOCV**)

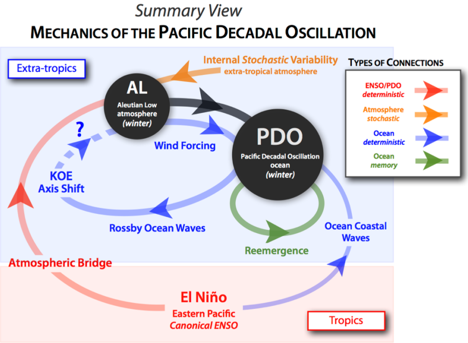
Pacific Decadal Oscillation (PDO)

- Leading pattern of monthly SST variability in the North Pacific (>20N), monthly global mean SST removed

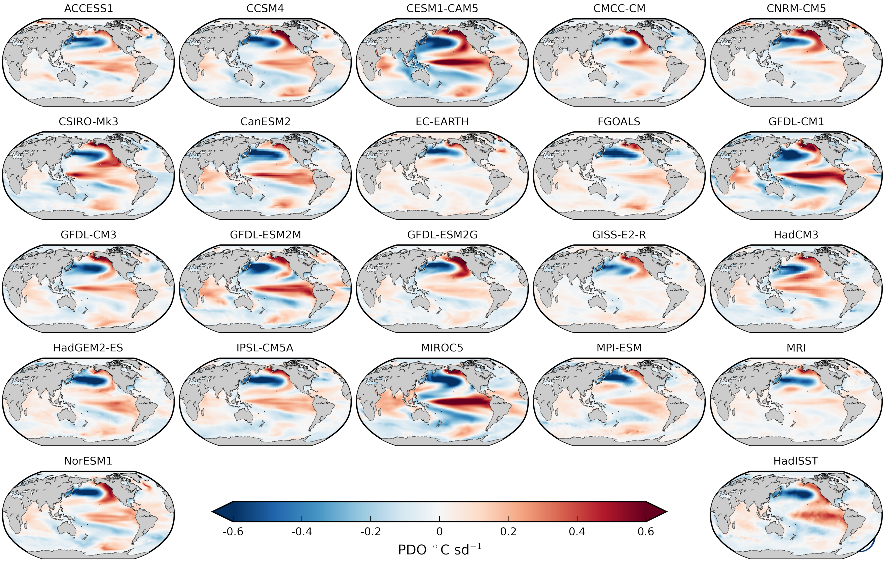


What is the PDO?

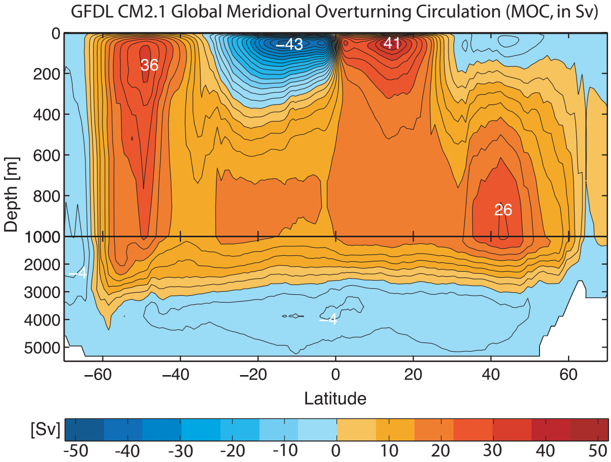
- The PDO is not a physical mode but rather is the sum of several physical processes
- North Pacific SST integrates weather noise
- SST anomalies provide reduced damping of atmospheric signals at low-frequency
- local and remote coupled feedbacks / teleconnections



PDO from CMIP5



The fundamental role of STCs for Eq. Pacific SST variability is well observed



(Zhang and McPhaden, 2006)

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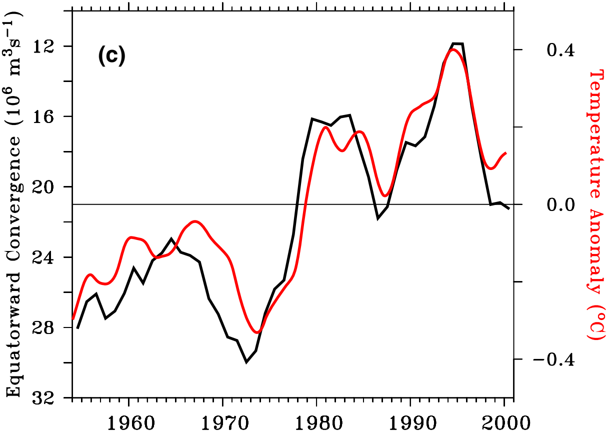


(Zhang and McPhaden, 2006)

An idealized model for the ENSO-STG-STC interactions leading to LFV

Let T be the SST anomaly in central equatorial Pacific, G and C the indices of the anomalies in the intensity of the Pacific sub-tropical gyre (G) and cells (C) [based on the ENSO delayed oscillator of Suarez and Schopf (1988)]:

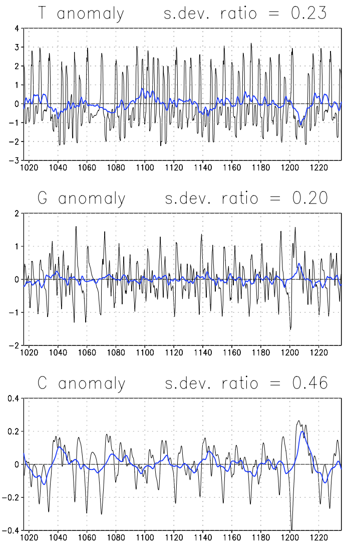
$$\frac{\mathrm{d}\,T}{\mathrm{d}\,t} = T - \alpha\,T(t-\delta) - r_1(T - T_0)^3 - E\,G \qquad (9a)$$

$$\frac{\mathrm{d}\,G}{\mathrm{d}\,t} = E\,T - \kappa\,G + \gamma\,r_2 \qquad (9b)$$

$$\frac{\mathrm{d}\,C}{\mathrm{d}\,t} = -\kappa\,(C - G) \qquad (9c)$$

where $T_0 = -\beta C$, γ = 0.25 and κ = 0.025 (because atmospheric response is 10$\times$faster than the G-C interactions).

An idealized model for the ENSO-STG-STC interactions leading to LFV



1. Time series for the three variables T (ENSO SST) , G (subtropical gyre) and C (subtropical cells) in the idealized model.
2. Decadal variability appears in T and C, which are anticorrelated by construction.

An idealized model for the ENSO-STG-STC interactions leading to LFV

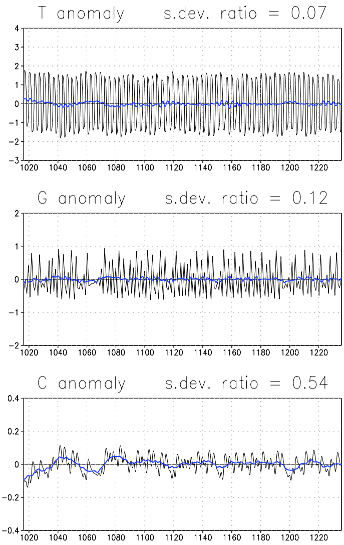
If there is no direct interaction between T and G, i.e. E = 0 & r_1 = const.

$$\frac{\mathrm{d}\,T}{\mathrm{d}\,t} = T - \alpha\,T(t-\delta) - r_1(T-T_0)^3 - \cancel{EG} \tag{10a}$$

$$\frac{\mathrm{d}\,G}{\mathrm{d}\,t} = \cancel{ET} - \kappa\,G + \gamma\,r_2 \tag{10b}$$

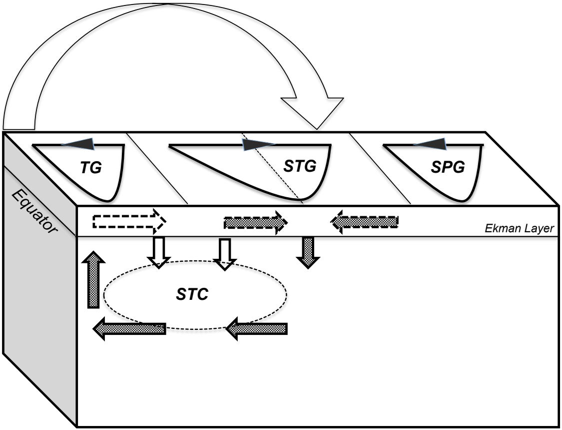
$$\frac{\mathrm{d}\,C}{\mathrm{d}\,t} = -\kappa\,(C-G) \tag{10c}$$

An idealized model for the ENSO-STG-STC interactions leading to LFV



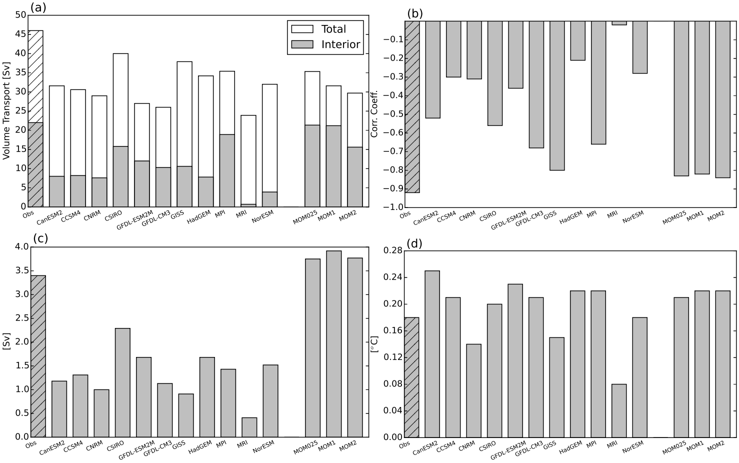
1. Much reduced variability in C and G and regular variations in T.
2. The gyre forcing by chaotically-modulated ENSO response is crucial.

Coupled tropical-extratropical feedbacks and the generation of low-frequency ENSO variability



(Farneti et al., 2014)

But CMIP5 (and CMIP3) models don't get STC variability right



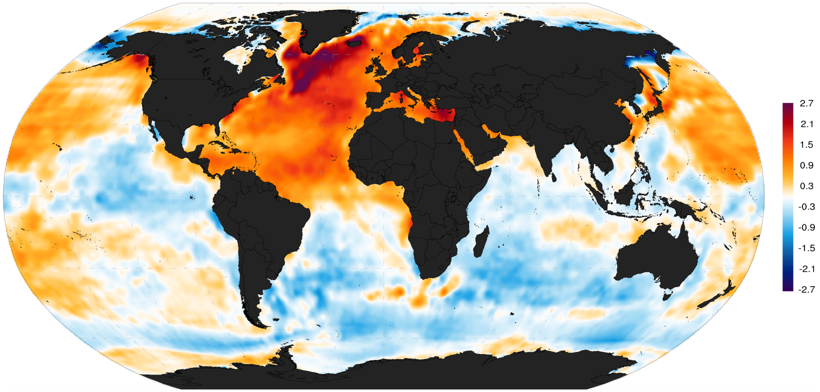
(a) Time-mean equatorward pycnocline volume transport convergence across 9°N and 9°S.
(b) Correlation between interior pycnocline volume transport convergence and tropical SST.
(c) Interior pycnocline transport standard deviations.

(d) SST standard deviations.

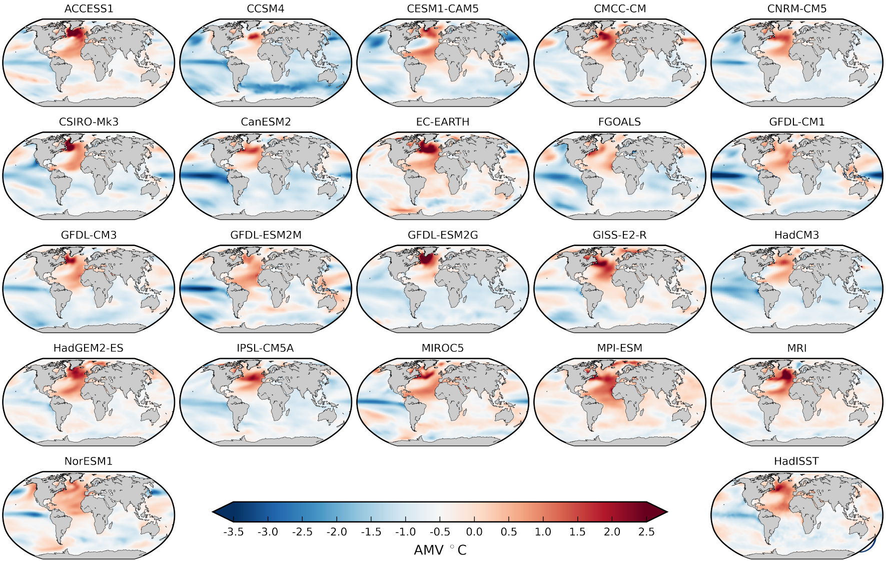
Atlantic Multidecadal Oscillation/Variability (AMO/V)

- The AMV is computed as the North Atlantic SSTa minus global SSTa. The AMV pattern is created by regressing global SSTa onto the index timeseries and smoothing with a 9-point spatial filter.

Atlantic Multidecadal Oscillation



AMO from CMIP5



The Bjerknes compensation mechanism

The atmospheric meridional energy flux (AHT) can be obtained by integrating the divergence of the zonally averaged surface and TOA fluxes

$$\nabla \cdot AHT = F^{TOA} - F^{SFC}, \tag{11}$$

where F^{SFC} and F^{TOA} are the surface and net TOA fluxes, respectively. In the ocean, the balance is between its heat content (OHC) tendency and the zonally integrated surface flux, so that the oceanic meridional heat transport (OHT) is given by

$$\nabla \cdot OHT = F^{SFC} - \partial_t OHC. \tag{12}$$

The total or planetary, energy transport (PHT) is then

$$\nabla \cdot PHT = \nabla \cdot OHT + \nabla \cdot AHT = F^{TOA} - \partial_t OHC. \tag{13}$$

The Bjerknes compensation mechanism (Bjerknes, 1964)

1. If we assume that on sufficiently long time scales $\partial_t OHC = 0$,

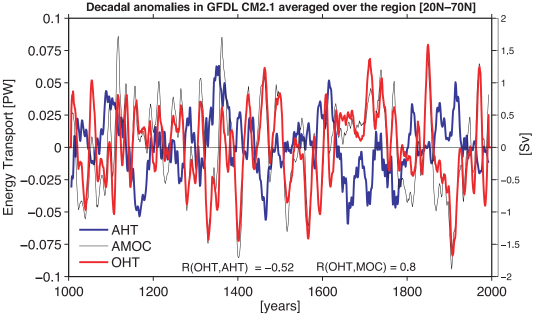
$$\nabla \cdot PHT = F^{TOA}. \quad (14)$$

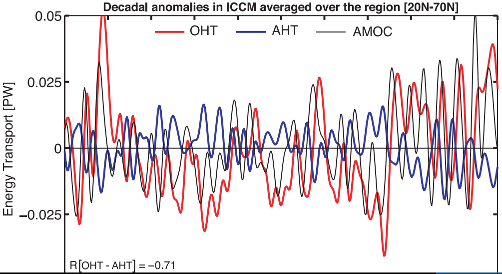
2. Further, if $\partial_t F^{TOA} = 0 \rightarrow$
one subsystem must compensate for variations in the other.

$$\nabla \cdot PHT = \nabla \cdot OHT + \nabla \cdot AHT \quad (15)$$

3. The hypothesis for Bjerknes compensation is that it doesn't work
   - at shorter time scales ($\partial_t F^{TOA} \neq 0$)
   - in the Tropics ($\partial_t OHC \neq 0$)
4. Bjerknes compensation was found in a couple of climate models, but without further explanation of mechanisms and origin.

The atmosphere and the AMOC

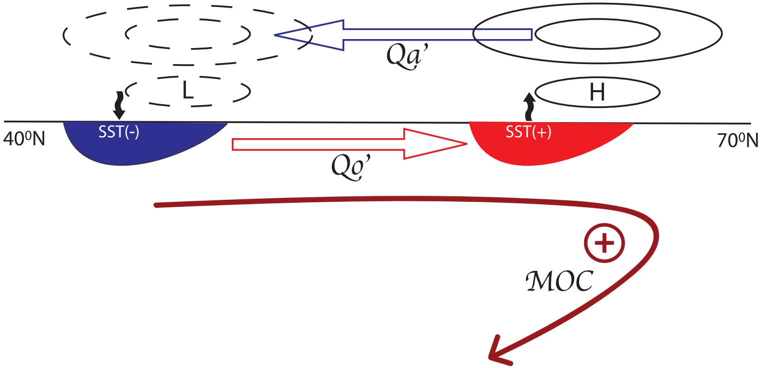




In both ICCM and CM2.1:

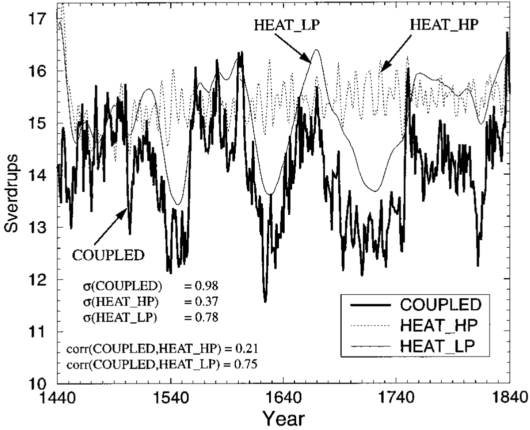
- AMOC leads the OHTa. AHTa tend to compensate
- Significant *negative* correlation between OHT and AHT

Mechanism for Variability (in the model)



- AMOC decadal variability generates OHTa, which drive ATHa, as the atmosphere tries to compensate and maintain a constant planetary transport (Farneti and Vallis, 2011) and (Farneti and Vallis, 2013).

It is the LFV part of the Atmosphere that excites AMOC variability

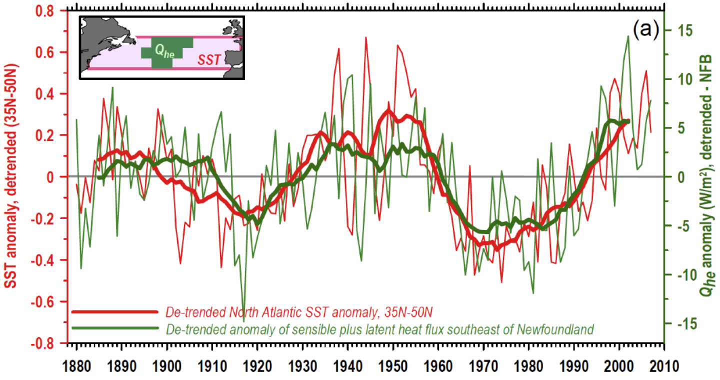


(Delworth and Greatbatch, 2000)

- But how is atmospheric LFV generated?

Reconstructed fluxes prove Bjerknes' conjecture

- on decadal timescales ocean drives mid-latitude SST and turbulent heat fluxes

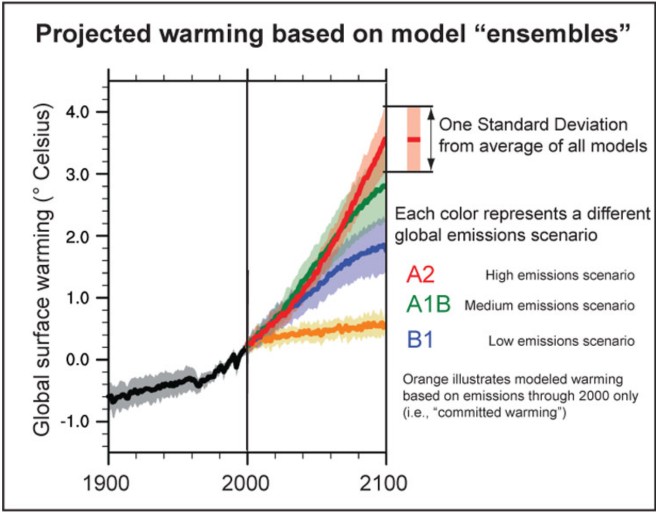


Gulev et al. (2013)

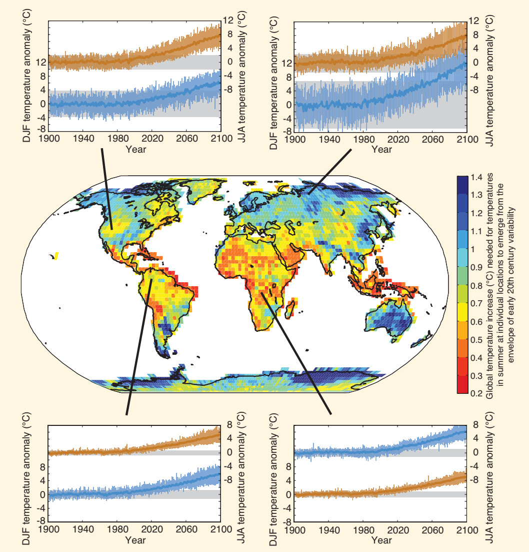
So what can we do with these coupled ocean-atmosphere models?

- STUDY CLIMATE CHANGE
- STUDY CLIMATE VARIABILITY

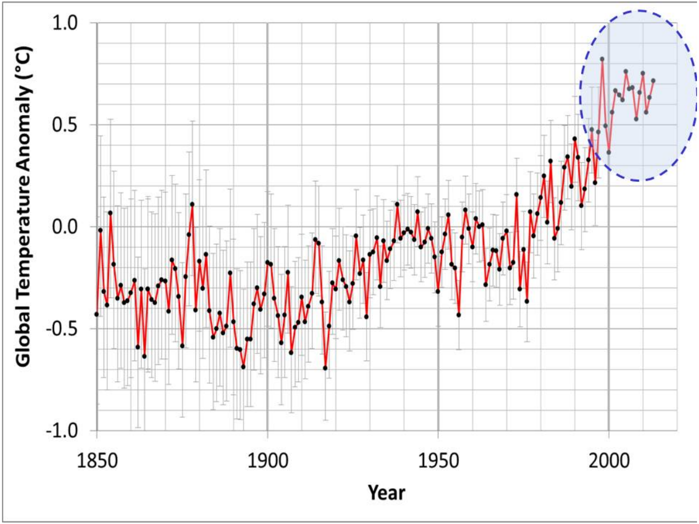
Climate Change at the global scale (IPCC AR5)



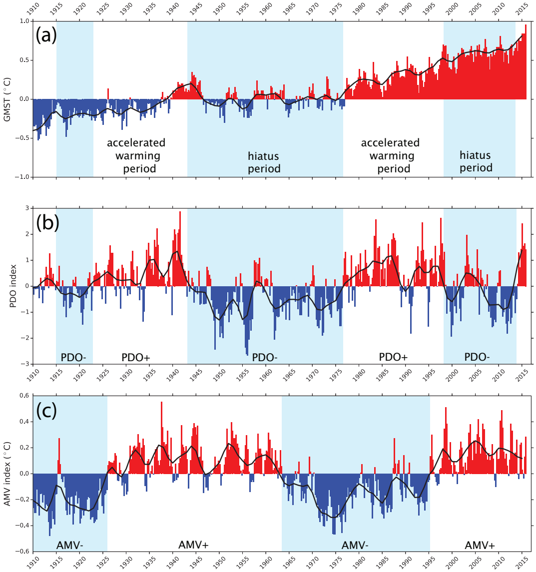
Climate Change at the regional scale (IPCC AR5)



Climate Variability at low frequency



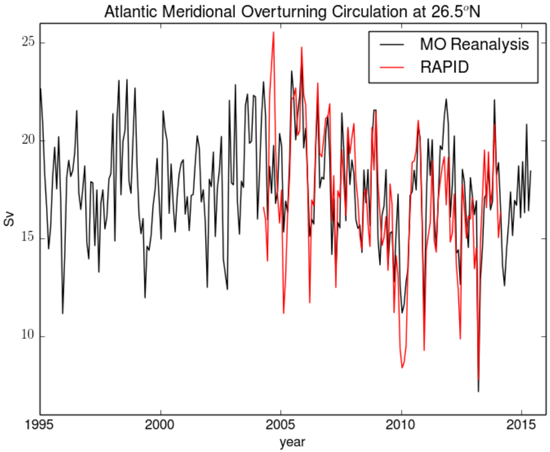
The warming hiatus & natural variability



Do we robustly simulate AMOC LFV?

- If decadal predictability depends on slow modes of variability rooted in the ocean, we need to understand the mechanisms giving rise to decadal variability
- What sets the internal variability in the models? why 20-30 years in AMOC variability? what is the relevance for predictability?
- Is the simulated internal variability robust? how sensitive is to resolution, formulation, parameterizations, ...?

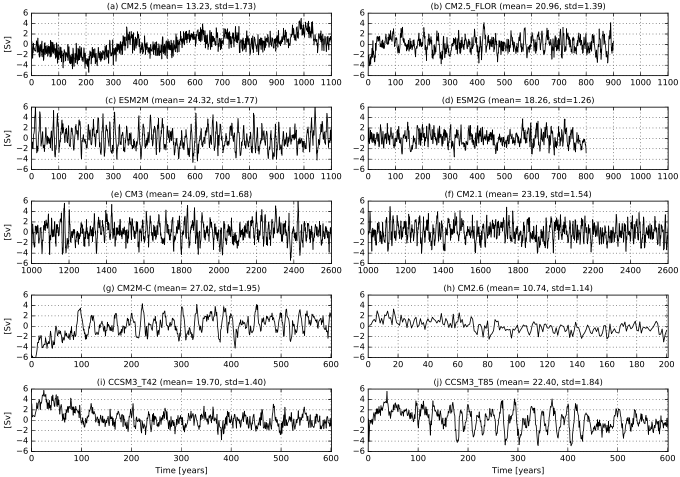
AMOC: observations of variability



Jackson et al. (2016)

- Ocean reanalysis that combines ocean and satellite observations since 1989 with a state-of-the-art eddy-permitting ocean model.

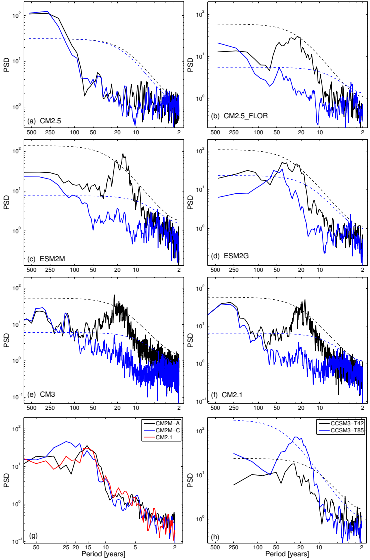
AMOC



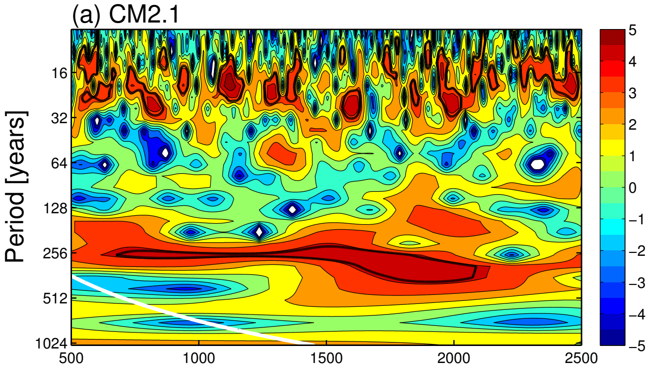
- Annual-mean AMOC time series anomalies for a suite of GFDL and NCAR models. All data are from a pre-industrial simulation with greenhouse gases fixed at 1860 levels, and thus only natural internal variability is simulated.

AMOC Spectra: multidecadal and centennial variability

- Power spectral densities for annual-mean AMOC time series at 27N.
- Blue lines in (a-f) are for the AMOC spectra computed at 30S.
- CM2M-A and CM2.1 use the same parameterization of mesoscale eddy-induced transport whereas CM2M-C uses a different scheme.
- In (h) two NCAR coupled models with the same ocean but using an atmosphere which differs in horizontal resolution (T42 and T85) are compared.



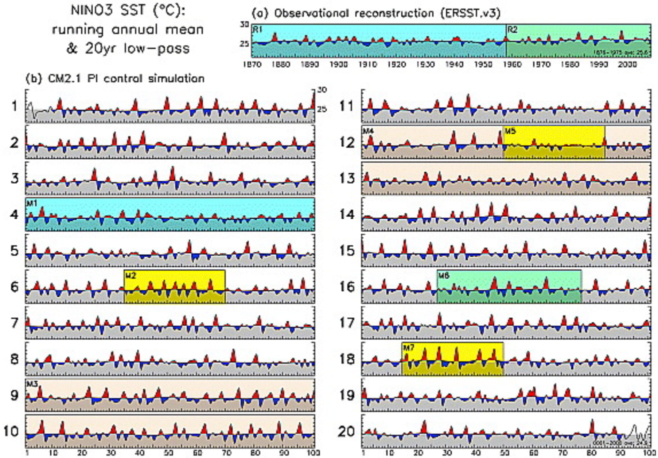
AMOC modulation



(Farneti, 2017)

- strong interdecadal and intercentennial modulation of AMOC

ENSO modulation



(Wittenberg, 2009)

- strong interdecadal and intercentennial modulation of ENSO

Stochastically-driven internal decadal variability

stochastic climate model hierarchy

1. **Atmosphere drives the ocean, but a feedback from the ocean on the atmosphere can exist**
   - Local model (heat flux and momentum)
   - Spatial coherence in atmosphere, with and without oceanic advection
   - Spatial coherence in atmosphere, dynamical ocean models (wind-driven or thermohaline)

Some personal suggestions:

- Use a variety of models (coupled, global, regional, nested, ..)
- Use a hierarchy of models (ESMs, EMICs, toy models, ...)

References

Barsugli, J. J. and D. S. Battisti, 1998: The basic effects of atmosphere-ocean thermal coupling on midlatitude variability. *J. Atmos. Sci.*, **55**, 477–493.

Bjerknes, J., 1964: Atlantic air-sea interaction. *Advances in Geophysics*, **10**, 1–82.

Boer, G. J., 2011: Decadal potential predictability of twenty-first century climate. *Climate Dyn.*, **36 (5)**, 1119–1133.

Delworth, T. L. and R. J. Greatbatch, 2000: Multidecadal thermohaline circulation variability driven by atmospheric surface flux forcing. *J. Climate*, **13**, 1481–1495.

Delworth, T. L., et al., 2012: Simulated climate and climate change in the GFDL CM2.5 high-resolution coupled climate model. *J. Climate*, **25 (8)**, 2755–2781.

Farneti, R., 2017: Modelling interdecadal climate variability: the role of the ocean. *WIREs Clim Change*, **8**, doi: 10.1002/wcc.441.

Farneti, R., F. Molteni, and F. Kucharski, 2014: Pacific interdecadal variability driven by tropical-extratropical interactions. *Climate Dyn.*, **42 (11-12)**, 3337–3355.

Farneti, R. and G. K. Vallis, 2009: An intermediate complexity climate model (ICCMp1) based on the GFDL Flexible Modelling System. *Geosci. Model Dev.*, **2 (2)**, 73–88.

Farneti, R. and G. K. Vallis, 2011: Mechanisms of interdecadal climate variability and the role of ocean-atmosphere coupling. *Climate Dyn.*, **36 (1)**, 289–308.

Farneti, R. and G. K. Vallis, 2013: Meridional energy transport in the coupled atmosphere-ocean system: Variability and compensation. *J. Climate*, **26 (18)**, 7151–7166.

Ferreira, D., C. Frankignoul, and J. Marshall, 2001: Coupled ocean-atmosphere dynamics in a simple midlatitude climate model. *J. Climate*, **14**, 3704–3723.

Frankignoul, C. and K. Hasselmann, 1977: Stochastic climate models. Part II: Application to sea-surface temperature variability and thermocline variability. *Tellus*, **29**, 289–305.

Hallberg, R., 2013: Using a resolution function to regulate parameterizations of oceanic mesoscale eddy effects. *Ocean Modelling*, **72**, 92–103.

Hawkins, E. and R. Sutton, 2009: The potential to narrow uncertainty in regional climate predictions. *Bull. Amer. Meteor. Soc.*, **90 (8)**, 1095–1106.

Held, I. M., 2005: The gap between simulation and understanding in climate modeling. *Bull. Amer. Meteor. Soc.*, **86**, 1609–1614.

Held, I. M., 2014: Simplicity amid complexity. *Science*, **343 (6176)**, 1206–1207.

Saravanan, R. and J. C. McWilliams, 1998: Advective ocean-atmosphere interaction: an analytical stochastic model with implications for decadal variability. *J. Climate*, **11**, 165–188.

Suarez, M. and P. S. Schopf, 1988: A delayed action oscillator for ENSO. *J. Atmos. Sci.*, **45**, 3283–3287.

Wittenberg, A. T., 2009: Are historical records sufficient to contrain ENSO simulations? *Geophys. Res. Lett.*, **36 (L12702)**, doi:10.1029/2009GL038 710.

Zhang, D. M. and J. McPhaden, 2006: Decadal variability of the shallow Pacific meridional overturning circulation: Relation to tropical sea surface temperatures in observations and climate change models. *Ocean Modelling*, **15 (3–4)**, 250–273.