What drives ocean heat content variability in CESM in the extra-tropics, and at what scales?

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Recap: Relationship between SST and surface turbulent heat flux

Data from observational product:
J-OFURO-v3 years 2002-2012

Strong positive correlations in ocean frontal/eddy regions (red circled) and also weaker ocean forcing in open ocean (e.g. blue circles) and Tropics
From Bishop et al 2017

Stochastic model of air-sea interaction
Frankignoul, Hasselmann 1977
Barsugli and Battisti 1998
Wu et al. 2006
Zhang et al 2017

\[ \frac{dT_a}{dt} = \alpha(T_o - T_a) - \gamma_a T_a + N_a, \quad \text{and} \]
\[ \frac{dT_o}{dt} = \beta(T_a - T_o) - \gamma_o T_o + N_o, \]

where \( T_a \) is the near-surface atmospheric temperature, \( T_o \) is the SST, \((\alpha, \beta)\) are exchange coefficients normalized by the respective heat capacities of the atmosphere and ocean with \( \beta \ll \alpha \), \((\gamma_a, \gamma_o)\) are radiative damping coefficients, and \((N_a, N_o)\) represent stochastic forcing arising from weather or turbulent eddies in the atmosphere and ocean, respectively.

Fig. 1. Lagged correlations from solutions to the local energy balance model [Eqs. (1) and (2)]. (a) Lagged correlation between SST and SHF (blue) and between SST tendency and SHF (green) with variability driven by atmospheric noise. (b) As in (a), but with variability driven by oceanic noise. Lagged correlation between (c) SST and SHF and (d) SST tendency and SHF as a function of the forcing frequency \( \omega_o \) of the stochastic ocean forcing \( N_o \) on a logarithmic scale. Black and gray contours are positive and negative correlations respectively [contour interval (ci) = 0.25] and the black dashed contour is the zero correlation contour. See appendix for details on the solutions to Eqs. (1) and (2).
Left panels: correlation of SST and surface latent heat flux. Right panels: correlation of SST tendency and surface latent heat flux. Low resolution CESM much too atmosphere-driven.
From Doney et al. 2007, analysis of hindcast simulations, **interannual variability**. Switched sign convention to right-hand-panels on previous slide.

Hindcast model is too much atmosphere-driven

**Positive values: atmosphere forces ocean**
Initial interpretation

• High-resolution model appears to be dominated by SST forcing of surface turbulent heat flux (THF)
  – Consistent with Barsugli&Battisti 98 model with incorporated strong ocean noise (Wu and Kirtman 2006, Bishop et al 2017)

• Low-resolution model appears to be dominated by a passive response of SST to THF
  – Consistent with B-B 98 model with strong atmosphere noise

• Is this the whole story? And what about deeper ocean heat content?
Overview

• Approach
  – Here we focus on short-term, monthly variability
  – The monthly climatology and the linear trend is removed from the data, as are regressions on Nino3.4 SST.
  – Will not consider low-frequency variability (e.g. Yeager et al. 2012, Clement et al. 2015, Zhang et al. 2017, Cane et al. 2017 etc.)
  – Extratropics
  – Spatial maps of pointwise correlation or regression are shown
  – Two depth-averages chosen: to 50m, to 400m
  – The ocean temperature budget is analyzed
  – Results from a spatial smoother of budget terms shown

• Observations
  – SSH from AVISO
  – SST from Reynolds et al. 2007

• Models
  – CESM-HR. Coupled simulation with 0.1deg. ocean model.
  – CESM-LR. Coupled simulation with 1deg. ocean model.
  – Short (5-10 year) segments analyzed with full budget terms.
Ocean heat budget to 50m

\[ \rho c \int_{-D}^{0} \left( \frac{\partial T}{\partial t} + U \cdot \nabla T - H_{diff} \right) \, dz = Q_S - Q_D \]

- Following Doney et al. 2007, we regress the budget terms onto the total tendency
  - Values near +1 show a dominance of the term
  - Negative values counteract tendency
  - Positive values reinforce tendency
Fig. 14 Left panels: Regression of vertical diffusion including surface heat flux on heat content tendency and $\varepsilon$ to 50m. Right panels: Heat content tendency and advection (or Ocean Heat Flux Convergence, OHFC) $\varepsilon$ to 50m.
Correlation, temperature tendency to 50m and Ekman heat transport anomaly

Ekman heat transport anomaly is written as

$$\frac{\rho c_p}{\rho f} \left( \bar{\frac{\partial SST}{\partial x}}' \tau_y - \bar{\frac{\partial SST}{\partial y}}' \tau_x \right) - \frac{\rho c_p}{\rho f} \left( \frac{\partial SST'}{\partial x} \tau_y - \frac{\partial SST'}{\partial y} \tau_x \right)$$

Where overbars are climat. means, primes are deviation. I start from monthly data. The first set of brackets dominates. The whole expression is negated to be on RHS of temperature equation.

Figure 15. Role of Ekman advection
Ocean Heat budget to 400m
Fig. 16. As Fig. 14 but for a depth-integral to 426m.

Left panels: Regression of vertical diffusion including surface heat flux on heat content tendency. Right panels: Heat content tendency and advection (or Ocean Heat Flux Convergence, OHFC)
Scale-dependence

- The heat budget in the high-resolution model is clearly very different from that of the low-resolution model.
  - Is one of the models wrong, are both wrong, or is it a question of spatial scale dependence?
- The heat budget terms from the high-resolution model are spatially smoothed with a box-car filter. Results are compared with low-resolution case.
Regression between heat content tendency and **vertical diffusion including surface heat flux**: to 50m.

Plots show HI-RES, LOW-RES, and HI-RES with various amounts of box-car smoothing. The full width of smoothing is labelled (1deg, 3deg etc).

After about 7deg smoothing, high-res looks like low-res.
Regression between heat content tendency and **advection**: to 50m.

After about 7deg smoothing, high-res looks like low-res, and shows the structure of Ekman heat advection.
Regression between heat content tendency and **vertical diffusion including surface heat flux** to 400m.

After about 10deg smoothing, high-res looks like low-res, except in frontal regions.
Regression of Heat content tendency and **advection**: to 400m

After about 10deg smoothing, high-res looks like low-res, except in frontal regions
Regression of Heat content tendency and vertical diffusion including **surface heat flux**: to 426m

Regression of Heat content tendency and **advection**: to 426m

After about 10deg smoothing, high-res looks like low-res, except in frontal regions
Ocean intrinsic scales

10deg. Smoothing is not enough to reduce high-resolution model to atmosphere-driven in WBCs. But 10deg. Is much larger than typical eddy-scales – see plots on this page.

Chelton and deSzoeke et al 1998
First Linear baroclinic Rossby radius

Chelton et al 2007
Eddy tracking method

Hallberg 2013. Model grid spacing required to “resolve” Rossby radius
Conclusions Initial interpretation

- High-resolution model is dominated by SST forcing of THF
  - SST is driven by unforced advection variability on small scales of 5-10 deg. or less
  - On larger scales it is similar to low-res, including the Ekman advection part
  - Excepting strong eddying regions in 400m depth-average
- Low-resolution model is a combination of a passive response of SST to THF and to Ekman (wind) variability
  - THF forcing dominates in 50m average
  - Advection (probably Ekman) dominates at 400m
- Stochastic Barsugli-Battisti type model is limited as it does not include Ekman advection effect on ocean temperature
Background literature

• Stochastic models of air-sea interaction
  – Frankignoul, Hasselman 1977
  – Barsugli and Battisti 1998
  – Wu et al. 2006
  – Zhang et al 2017 – Bishop et al 2017

• Intrinsic ocean variability
  – (e.g. Serazin et al 2015, Nonaka et al 2016)

• Role of ocean heat transport convergence in observed ocean variability

• Role of local Ekman heat transport
  – (e.g. Doney et al 2007, Buckley et al. 2014, 2015, Larson et al., submitted)
Heat content tendency = Heat transport convergence + Net surface heat flux

Roberts et al 2017
Observational study where C is computed as a residual.

Obtained from forced ocean simulations, with either climatological forcing or time-varying forcing.
From Larson et al. 2018, submitted

Mechanically decoupled CESM – ocean does not feel wind stress variability but does feel variability in air-sea buoyancy fluxes (Larson pers. comm. 2017)

Variance is significantly reduced when wind stress variability removed – Ekman advection removed – except in some subtropical regions.

Figure 1. a) Unfiltered SSTA variance ratio $\text{Var}(\text{SST}_{MD}) / \text{Var}(\text{SST}_{Control})$ calculated as the variance of SSTA in the mechanically decoupled (MD) CESM divided by that of the CESM fully coupled control. Variance is computed over time at each grid point. Values $> 1$ (pinks) indicated increased variance in the MD.
Correlation, temperature tendency to 50m and Ekman heat transport anomaly

Correlation, full advection to 50m and Ekman heat transport anomaly

Ekman heat transport anomaly is written as

\[
\frac{\partial \xi'}{\partial t} - \frac{\partial \xi}{\partial t} = -\frac{\rho c_p}{\rho_f} \left( \frac{\partial \xi'}{\partial x} - \frac{\partial \xi}{\partial x} \right) - \frac{\rho c_p}{\rho_f} \left( \frac{\partial \xi'}{\partial y} - \frac{\partial \xi}{\partial y} \right)
\]

where overbars are climatological means, primes are deviation. I start from monthly data. The first set of brackets dominates. The whole expression is negated to be on RHS of temperature equation.

Figure 15. Role of Ekman advection
Low-res advection at 50m

Low-res advection at 400m
Recap: Correlation of SST and latent surface heat flux

a) OAFLUX 1993-2014

b) OAFLUX 2002-2012

c) J-OFURO-v3 2002-2012

d) SEAFLUX 2002-2012

Positive values denote the ocean is not responding to surface heat fluxes: it is driving the surface heat fluxes.

Strong positive correlations in ocean frontal/eddy regions (red circled) and also weaker ocean forcing in open ocean (e.g. blue circles) and Tropics.

Correlation of SST and surface latent heat flux in **observational products**. Based on monthly data for period shown. Sign convention: positive surface heat flux is out of ocean.
SSH as a proxy for ocean heat content

Correlation SSH and THF

Correlation HC(400m) and THF

• Qualitative agreement in vicinity of WBC, ACC and other frontal regions