COLLABORATIVE PROJECT:
OCEAN-ATMOSPHERE INTERACTION FROM MESO- TO PLANETARY-SCALE: MECHANISMS, PARAMETERIZATION, AND VARIABILITY
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Summary

Most climate models are currently run with grid spacings of around 100km, which, with today's computing power, allows for long (up to 1000 year) simulations, or ensembles of simulations to explore climate change and variability. However this grid spacing does not resolve important components of the weather/climate system such as atmospheric fronts and mesoscale systems, and ocean boundary currents and eddies. The overall aim of this project has been to look at the effect of these small-scale features on the weather/climate system using a suite of high and low resolution climate models, idealized models and observations. This project was only possible due to the highly scalable aspect of the CAM Spectral Element dynamical core, and the significant resources allocated at Yellowstone and NERSC for which we are grateful.

The main results and achievements of the project have been as follows:

Computation results

A. The first century-long high-resolution fully coupled run with ~0.25° CAM version 5 and an ~0.1° eddy-resolving ocean model has been executed on Yellowstone supercomputer. The simulation has been used in many of the following Climate Science findings below, as well as by groups external to the project. The paper for the overall description of this simulation was published in the Journal of Advances in Modeling Earth Systems (Small et al. 2014a). This appears as a DOE BER Climate and Earth System Modelling research highlight: http://climatemodeling.science.energy.gov/research-highlights/new-synoptic-scale-resolving-global-climate-simulation-using-community-earth

B. In addition, subsidiary single component and lower resolution coupled runs were performed at NERSC and Yellowstone, which allowed for better attribution of improvements and degradations in the high-resolution coupled run.

C. A first global coupled simulation with a modified ocean-atmosphere coupling was performed. Specifically, this experiment "switched-off" the effects of mesoscale air-sea coupling by spatially smoothing out the eddy structure in the SST field used to compute air-sea fluxes. In-depth analysis of this simulation is ongoing in collaboration with other groups running regional versions of this type of experiment.

Climate science results

1. An idealized boundary layer model, completed under this and other related projects, was published (Schneider and Qiu 2015), and is currently being used to interpret CAM5 simulations, as well as to better understand the processes of mesoscale air-sea interaction.
2. The variability of the Kuroshio/Oyashio ocean fronts in the N. Pacific was documented from the high-resolution model. The relationship of atmosphere eddy heat flux to the state of the Kuroshio/Oyashio extension (meandering vs steady) was published by Bishop et al. (2015).
3. The relationship of the midlatitude storm tracks to ocean fronts was discussed in Kwon and Joyce (2013), and Small et al (2014b). A major finding was that transient eddy lateral heat flux was strongly sensitive to ocean fronts, and the regions of eddy heat flux divergence/convergence were exactly collocated with the warm/cold side of the ocean fronts respectively.
4. Lagrangian composite analysis of mesoscale air-sea interaction was carried out for the CESM run and compared to observations and higher resolution regional coupled models.
5. Two metrics of frontal scale air-sea interaction were studied in detail and compared between CAM5 and observations:
    i) The coupling coefficient between mesoscale SST features and wind speed
    ii) Surface convergence and Laplacian of sea level pressure.
6. The coupled sensitivity run (computational result C) led to modest changes in the atmosphere variability but large changes in the ocean eddy and frontal variability. Collaborative work on this is ongoing.
7. The mean and variability of the surface storm track and the various contributors in ocean and atmosphere are examined from the high-resolution coupled run and compared with the climate model simulations using GISS and GFDL climate models as well as various reanalyses (Small et al. 2015a).

In addition to the above mesoscale effects, significant improvements were seen in some aspects of the large scale circulation in the high-resolution coupled run as follows.

8. Notable improvements to the Nino3.4 SST power spectrum were found in the high-resolution run, compared to previous versions of the model, and lower resolutions.
9. The sea surface temperature in the Tropics was better represented in the high resolution run.
10. Sea surface temperature at western and eastern boundaries was improved in the high resolution coupled run, relative to standard resolution.

Frontal Scale Air-Sea Interaction Workshop

Another achievement of the project was the organization of an international workshop on Frontal Scale Air-Sea Interaction, held in year 2 (http://www.cgd.ucar.edu/events/fsasi-workshop/). This has led to a special collection in the American Meteorological Society journals: http://journals.ametsoc.org/page/climateimplications

1. Computation achievements

The first century-long high-resolution fully coupled run of the Community Earth System Model (CESM, Hurrell et al. 2013) has been executed. The model configuration used here has CAM version 5 (Neale et al. 2010) with a spectral element (SE) dynamical core (Mishra et al. 2011; Dennis et al. 2012), Community Ice Code version 4 (Hunke and Lipscomb 2008), Parallel Ocean Program version 2 (POP2, Smith et al. 2010), and Community land Model version 4 (Lawrence et al. 2011). In our simulation, CAM5 has a horizontal resolution of about 0.25° and the standard 30 levels in the vertical, with a model top of 3hPa. The POP2 model had a nominal grid spacing of 0.1° (decreasing from 11km at the Equator to 2.5km at high latitudes) in a tripole grid with poles in North America and Asia, with 62 levels in the vertical.

The simulation was run on the Yellowstone supercomputer, located at the NCAR-Wyoming Supercomputing Center, Cheyenne, Wyoming. The first 60 years of this CESM simulation was performed over a three-month time period of the "Accelerated Scientific Discovery" period, on 23404 cores and consuming 25 million CPU-hours. We performed the main coupled run on Yellowstone because we were given a large allocation of compute time as well as priority in the queue. In preparation for this, we used 3.6M hours at NERSC performing supporting atmosphere-only simulations with the same CAM5 configuration.

It cost about 250K core hours per simulated year. The simulation was more computationally intensive than many previous CCSM simulations with similar resolution (e.g. McClean et al. 2011), largely because of the computational cost of prognostic equations for aerosols in the new CAM5 model (in CAM4 the aerosols were prescribed). (CAM5-SE was the most expensive component in this model run, accounting for 52% of the total cost.)

The core count was chosen to maximize the model throughput (in terms of number of model years that could be run in a single day), while also keeping the computational cost reasonable (so as not to adversely affect the number of model years completed). A throughput of two simulated model years per day was obtained by carefully load-balancing between the model components, some of which can largely run simultaneously (e.g. the ocean and atmosphere), while others couple more frequently. The input/output for the run was substantial, adding approximately 6.5% overhead to the run, and generating approximately one terabyte of data per compute day.

The simulation has been used in many of the following Climate Science findings below (section 2), as well as by groups external to the project (e.g. looking at the heat flux from ocean eddies, Abernathey and Wortham 2015). The paper was published in Journal of Advances in Modeling Earth Systems (Small et al 2014a). Data from the simulation is freely available to the public on the Earth System Grid.

In addition subsidiary single component and lower resolution coupled runs were performed at NERSC and Yellowstone, which allowed for better attribution of improvements and degradations in the high-resolution coupled run.

A first global coupled simulation with a modified ocean-atmosphere coupling was performed. Specifically, this experiment "switched-off" the effects of mesoscale air-sea coupling by spatially filtering the SST field used to compute air-sea fluxes so as to remove the eddy structure. The filtering was done with a 1000kmx1000km box-car smoother, at each time step. The smoother did not add significantly to the run time.

2. Frontal-Scale Air-Sea Interaction and Climate

2.1 Idealized Boundary Layer Model

An idealized boundary layer model, completed under this and other projects, was published, and is currently being used to interpret CAM5 simulations. The model of Schneider and Qiu (2015) approximates the lower troposphere by a reduced gravity model, and estimates its steady-state response to mesoscale SST variability in the presence of a large-scale geostrophic wind. The response to an SST perturbation is obtained by a linearization about a spatially homogeneous background Ekman spiral and constant air potential temperature. The heat budget of the active layer yields the vertically averaged temperature from the balance of background advection with air-sea heat exchange. The momentum and continuity equations include background advection, Coriolis acceleration, pressure gradient forces (including due to the back-pressure, Lindzen and Nigam 1987) and vertical mixing. The forcing on SST fronts through the 'vertical mixing' and 'pressure' effects naturally emerge. The model reproduces observed characteristics of the SST-induced responses of the wind speeds and direction, as well as the wind stress curl and divergence (Schneider and Qiu 2015). Full details of the model can be found in Schneider and Qiu (2015).

The boundary layer model and the "transfer function" analysis approach of Schneider and Qiu (2015) have been used to interpret the CAM5 high-resolution simulations. Two questions are being asked: i) how well does the idealized, linear model represent the full physics of the air-sea interaction processes and ii) what is the relative role of pressure gradients, vertical mixing, and spin down in the atmosphere response to SST fronts. As an example of this work, Fig. 1 shows the linear and full model response of the boundary layer vertical velocity to the fronts in the Agulhas return Current region. Understanding the vertical motion response is important as a link between the boundary layer and the free troposphere. (Schneider et al., in preparation)

2.2 Kuroshio/Oyashio system and climate variability

The variability of the Kuroshio/Oyashio ocean fronts in the N. Pacific was documented from the high-resolution model. The mean location and strength of the fronts based on the SST and sea-surface height (SSH) are very comparable to the observations. Furthermore, the monthly index time series for the Kuroshio Extension latitude and path lengths variability as well as the Oyashio Extension latitude variability (Fig. 2) compared reasonably with the corresponding index time series based on observations. The interannual variability in the Kuroshio Extension and Oyashio Extension are not well correlated, which is consistent with the observation. On the other hand, they are highly correlated in the multi-decadal time scale, which cannot be examined from the observation due to short SSH observational record.

These encouraging results allowed for an examination of how the ocean frontal variability affects the atmosphere. It was shown in Bishop et al. (2015), based on a composite analysis, that the meandering state of the Kuroshio Extension has important feedbacks on the atmospheric meridional heat transport (MHT). In this work it was first shown that the simulation of Kuroshio Extension exhibited decadal variability in its meandering states that had similar characteristics to what is observed. Then it was shown that when the Kuroshio Extension was in a weakly meandering state, it had a stronger cross-front temperature gradient than when it was in a strongly meandering state. This directly translated into stronger turbulent surface heat fluxes from the ocean to the atmosphere south of the front during the winter months (JFM). The enhancement of turbulent surface heat fluxes corresponded with an enhancement of atmospheric MHT (see Fig. 3). In contrast to the atmospheric MHT, the ocean had a weaker MHT during these weakly meandering states. The opposite effect on atmospheric and oceanic MHT was shown for the strongly meandering state of the Kuroshio Extension, pointing to a partial compensation between atmospheric and oceanic MHT during the winter months that is Bjerknes-like in nature.

2.3 Storm Tracks

The storm track response to ocean fronts was examined in detail by Kwon and Joyce (2013) and Small et al. (2014b). The latter paper showed that the eddy transport of heat and moisture in the atmosphere is significantly sensitive to ocean fronts (Gulf Stream and ACC/Agulhas return current). It was also shown that the combination of strong sensible and latent heat fluxes over the warm side of ocean fronts gives rise to enhanced baroclinicity in the lower troposphere and boundary layer.

The transient eddy heat flux is important because its divergence is a major term in the atmosphere's heat budget. Kwon and Joyce (2013) found that the climatological mean spatial pattern of the lateral heat flux divergence very closely follows the ocean fronts in both basins, i.e. the Gulf Stream-North Atlantic Current and Kuroshio-Oyashio Extension, across the entire basins (Fig. 4, Kwon and Joyce 2013). The results implies the transient eddies (primarily around 850 hPa level) are impacted by ocean-to-atmosphere feedback along not only the strong ocean fronts in the western basins but also the relatively weaker ocean fronts in the eastern basin. In particular, these weaker ocean fronts in the eastern basins are co-located with the atmospheric blocking centers. The results were supported by Small et al (2014b), who showed that the spatial pattern of lateral heat flux divergence was strongly modified and damped when the SST field was smoothed out. This part of the research is primarily supported by a grant to Kwon from the NASA Physical Oceanography program and supplemented by the DOE support.

This work has now been used to interpret the high-resolution CESM experiments of section 1, as well as various climate models of differing resolutions (Small et al 2015a). A major result of this is that the inclusion of a high-resolution ocean model leads to only modest changes to the storm track. At first a surprising result (as the SST gradients are an order of magnitude larger in the high-resolution models, which should lead to changes in atmospheric baroclinicity), it is consistent with the finding of Small et al. (2014b) from corresponding atmosphere-only experiments: that large changes to storm tracks only occur when the SST is made much more smooth than that seen in a 1deg ocean model. (The reason is that horizontal temperature gradients in the atmospheric boundary layer very rapidly reduce with height, due to the advective-diffusive nature of the thermodynamic equation: such that the fine scale structure of the SST is not communicated to the free atmosphere. As an example, in Small et al (2014b), SST gradients that were 10 times as large as in a smooth-SST run became air-temperature gradients at 850hPa that were only 1.3 times as large as in the smooth run.) Secondly it was found that the strength of the surface storm track in CESM was comparable to that of the free troposphere storm track, whilst reanalysis and other climate models suggest a much weaker surface storm track, an issue that is currently being investigated.

2.4 Metrics of Frontal Scale Air-Sea Interaction

Two metrics of frontal scale air-sea interaction were studied in detail:

i) The coupling coefficient between mesoscale SST and wind speed improved with finer resolution of SST and/or vertical resolution of the atmosphere model, with less dependence on horizontal resolution of the atmosphere model. The coupling coefficients obtained from CAM5 using daily high-resolution SST forcing were comparable to those obtained from satellite observations (Tomas et al. 2014).

ii) A key factor governing the surface convergence over ocean fronts is the Laplacian of sea level pressure. Unfortunately this quantity is not observable on the fine spatial scales involved. To get round this problem, we compared against a related quantity (“proxy”) that is observed, namely the thickness between two pressure levels in the lower atmosphere (Shimada and Minobe 2011). Comparison of this quantity in CAM5 with observations revealed excellent agreement (Fig. 5). Further, the Laplacian of thickness correlated with the Laplacian of SST. A paper on this work is in preparation. An international discussion group organized by PI Small (following on from the Workshop – see section 4) is investigating these results and the new finding by other groups that the relationship between surface convergence and sea surface temperature breaks down on daily timescales.

2.5 Composite analysis of air-sea interaction over eddies.

The response of atmospheric flow to Gulf Stream eddies was explored using a Lagrangian eddy-tracking analysis. The analysis was carried out for satellite observations, the high resolution CESM run and two regional coupled model runs using WRF coupled to ROMS with even higher horizontal resolution (9km and 3km). A sea level anomaly gradient-based algorithm was used to identify anticyclonic and cyclonic eddies. Lagrangian composites were then computed for atmospheric properties like surface windspeed, boundary layer height and precipitation over the two types of eddies. Our results show that CESM reproduces the surface windspeed response to mesoscale eddies seen in observations (Figure 6). If anything, CESM response appears to be a bit stronger in this Lagrangian analysis than observed. The composites also identify a precipitation signal that indicates that the atmospheric response penetrates above the boundary layer into the free troposphere. Preliminary results from this study were presented at the AMS conference (Steinweg_Woods et al., 2015) and a manuscript is in preparation.

2.6 Effect of removing Frontal-Scale Air-Sea Interaction

The smoothed-SST coupled run (computational result C) led to modest changes in the atmosphere variability but large changes in the ocean eddy and frontal variability, relative to the control high-resolution run. In these simulations the ocean model was at 0.1deg resolution. The smoothing of SST was done to reduce the SST gradients to magnitudes similar to that seen in 1deg ocean simulations. The resulting modest changes to atmospheric storm tracks is consistent with the finding of Small et al (2014b), and the last paragraph of section 2.3. Regarding the ocean response, recall that the air-sea fluxes will be smoothed due to the use of smooth SST. Then the underlying ocean is significantly changed in response to these altered fluxes, with much less heat loss over warm eddies and currents, and less heat gain over cold eddies and currents. This reduction in damping changes the mean and variability of SST and mixed layer depth, particularly in the western boundary currents. Work on this is ongoing.

3. Other major results arising from the high-resolution CESM simulation

3.1 Large scale mean state and variability

In addition to the above mesoscale effects, significant improvement were seen in some aspects of the large scale circulation in the high-resolution coupled run as follows.

- Notable improvements to the Nino3.4 SST power spectrum were found in the high-resolution run, compared to previous versions of the model, and lower resolutions. This is discussed in more detail in (Small et al 2014a).
- The SST in the Tropics was better represented in the high resolution run. This is discussed in more detail in (Small et al 2014a).
- SST at western and eastern boundaries was improved in the high resolution coupled run (Small et al 2014a). Comparison with the single component runs and lower-resolution runs showed that high-ocean resolution lead to the improvement at the western boundary, whilst higher atmosphere resolution led to most of the eastern boundary improvements. However, results from another project have revealed that if the coastal wind stress is improved, high ocean resolution is essential to correctly model the mesoscale upwelling front and eddy system and the SST. See Small et al (2015b).
- The above listed desirable features of the high-resolution model make it a suitable tool for analyzing other aspects of the climate system, such as large-scale variability (decadal ENSO, PDO, NAO, Southern Annular Modes).
- The simulation also suffers from biases, of course, and principal among these are excessive precipitation in the ITCZ (a typical feature of high-resolution CAM5 in stand-alone mode, amplified by coupling to either a 1° ocean or a 0.1° ocean), and excessive wind stress in mid-latitudes, especially the Southern Ocean (a feature present in all resolutions of CESM). These biases are discussed in more detail in Small et al. (2014a).

3.2 Sensitivity of climate statistics to spatial resolution (climate objective 3)

At Texas A&M, a study comparing results from high-resolution CESM simulations to regional model simulations has been carried out. The study focused on the analysis of wind power density simulations over the continental U.S., as well as adjoining coastal regions, in existing model runs. Wind power density is an important factor determining the capacity for generating energy from wind. Due to the cubic dependence of power density on wind speed, this is a very sensitive metric for evaluating climate simulations.The global climate models, such as the CESM fail to reproduce the fine-scale features seen in the observations. The regional climate simulation using the WRF model does a better job of capturing the wind speed distribution, although it too exhibits significant biases. The study also found correlations between wind power density and modes of atmospheric variability and ENSO. A poster summarizing these results was presented the AMS Fourth Conference on Weather, Climate, and the New Energy Economy (Steinweg-Woods and Saravanan, 2014).

4. Workshop on Frontal Scale Air-Sea Interaction

The Workshop was held at NCAR on August 5-7 2013, in year 2 of the project. It brought together international and national collaborators to address the climate research topics of our SCIDAC project. Participants included several PhD and post-doctoral fellows, as well as more senior scientists, providing a good framework for interaction and learning. A major aim of the workshop was to bring together scientists working on idealized interpretation of air-sea interaction with the numerical modelling and the satellite observation community. The agenda of the workshop as well as the presentations are available at http://www.cgd.ucar.edu/events/fsasi-workshop/. This workshop has led to a special collection of papers in the American Meteorological Society journals: http://journals.ametsoc.org/page/climateimplications, which is still accepting papers on these topics.

5. Relationship of Achievements to original Objectives

The following lists the original Objectives and whether they were achieved.
The main computational objectives were;

i) to perform and assess Community Earth System Model (CESM) simulations with the new Community Atmospheric Model (CAM) spectral element dynamical core;
We ran simulations of ~100 years long, including the highest resolution of 0.25deg atmosphere, 0.1deg ocean. We did not attempt to run at higher atmosphere resolution (0.125deg), as we did not see a sensitivity of mesoscale air-sea coupling coefficient to horizontal resolution, and also the 0.125deg climate solutions were not sufficiently scientifically validated. See section 1 for details.

ii) use static mesh refinement to focus on oceanic fronts;
This was not done for the reason that we did not see a sensitivity of mesoscale air-sea coupling coefficient to horizontal resolution. The PI Small is currently involved in an NSF project that is using mesh-refinement to look at coastal upwelling.
iii) develop a new Earth System Modeling tool to investigate the atmospheric response to fronts by selectively filtering surface flux fields in the CESM coupler.
The aim here was achieved in CESM by spatially filtering the sea surface temperature from the ocean model before passing to the coupler: this was because the coupler does not have spatial connectivity information (all operations are done on a column), making the spatial filter impractical in the coupler. See section 1 for details.

The climate research objectives were

a) to improve the coupling of ocean fronts and the atmospheric boundary layer via investigations of dependency on model resolution and stability functions:
In section 2.4 it was noted that the coupling coefficients in CAM5 compared well with observations, especially with additional vertical resolution and daily high resolution SST. Therefore dependence on stability functions was not explored.

b) to understand and simulate the ensuing tropospheric response that has recently been documented in observations
As a first step the idealized boundary layer model was published and comparison experiments with CAM are being written up (section 2.1). Meanwhile responses of precipitation to eddies and the laplacian of sea level pressure are being examined (section2.4ii), iii)).

c) to investigate the relationship of ocean frontal variability to low frequency climate variability and the accompanying storm tracks and extremes in high resolution simulations.
The initial focus has been on local meridional heat transport, storm track and extremes response to low frequency ocean frontal variability. Sections 2.2, 2.3 and 3.2 discuss the storm track and extremes.

6. Papers published and presentations

Bishop, S. P., F. O. Bryan and R. J. Small, 2015. Bjerknes-like compensation in the wintertime North Pacific. J. Phys. Oceanogr., online release, http://dx.doi.org/10.1175/JPO-D-14-0157.1

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Steinweg-Woods, J., R. Saravanan, 2014: Wind Resource Assessment Utilizing Time-Averaged Community Earth System Model data. Talk presented at AMS Annual meeting, Atlanta, February 2014

Steinweg-Woods, J., J.-S. Hsieh, R. Saravanan, and P. Chang, 2015: A Lagrangian view of midlatitude air-sea interaction associated with mesoscale oceanic eddies. Talk presented at AMS Annual meeting, Phoenix, January 2015

Tomas, R., R. J. Small and F. O. Bryan, 2014. Sensitivity of Frontal Scale Air-Sea Coupling in CAM5 to Model and SST Resolution. Poster presented at Ocean Sciences, Honolulu, February 2014. See http://www.cgd.ucar.edu/ccr/tomas/data2/oce2/posters/robert_tomas_ocean_sciences_Feb14.pdf

Papers in preparation

Small, R. J., R. A. Tomas, F. O. Bryan, S. Minobe, and F. Inoue. The response of near surface convergence to Laplacian of sea level pressure over ocean fronts revisited.

Schneider, N., R. J. Small, R. A. Tomas, and F. O. Bryan. Dynamics of lower tropospheric vertical velocity induced by sea surface temperature fronts.

Small, R. J., R. Msadek, Y.-O. Kwon, and J. Booth. Storm tracks in high resolution climate models.

Booth, J., Y.-O. Kwon, R. Msadek, and R. J. Small. The surface storm track in modern era climate models and reanalysis.

Steinweg-Woods, J., J.-S. Hsieh, R. Saravanan, and P. Chang: The atmospheric response to mesoscale ocean eddies in the Gulf Stream separation region

7. Other References

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8. Figures

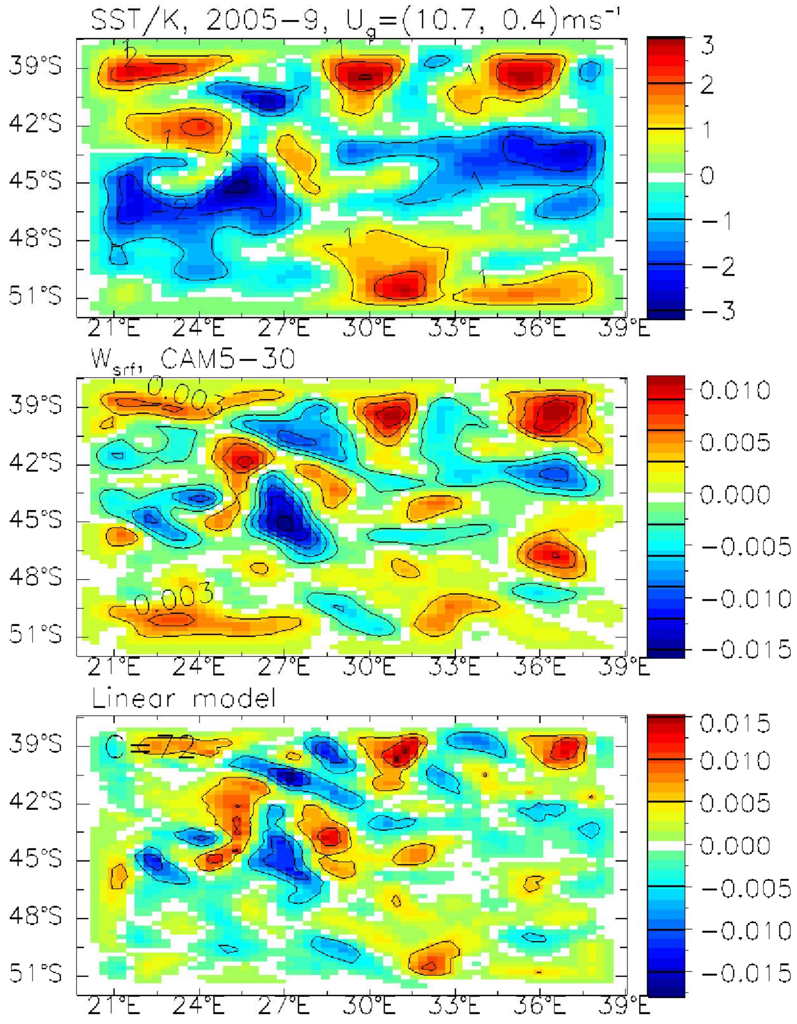


Figure 1: *Example of SST (top), near surface vertical velocity from CAM5 (center) and its prediction by linear model (bottom) for September 2005 in the Agulhas region. The linear model is forced by the SST, and near surface geostrophic winds of CAM5, and use a vertical momentum mixing and its linearized dependence on the air-sea temperature difference that mimics CAM5. Spatial correlation of CAM5 and the linear model are 0.72, and vary, for the Agulhas retroflection area, between 0.5 and 0.9, with higher correlation for stronger background winds.*

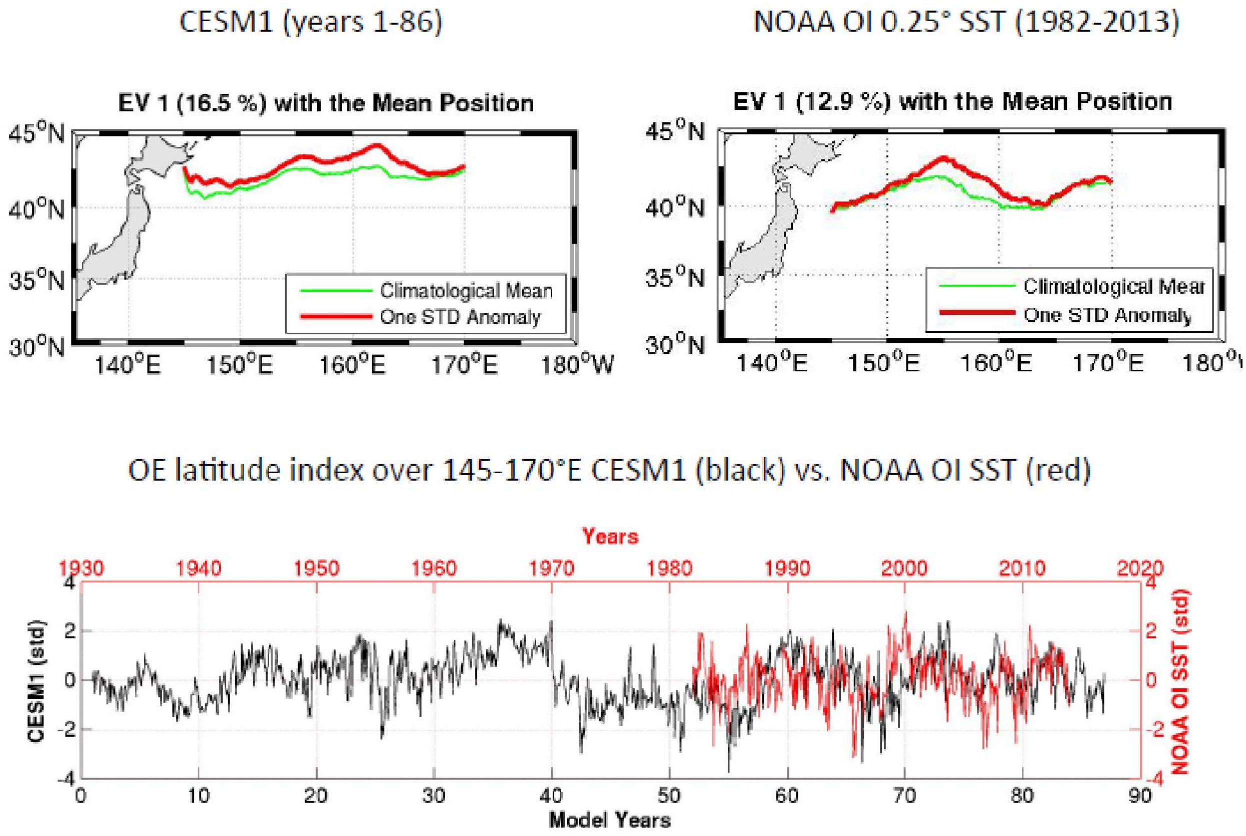


Figure 2. *Index of Oyashio Extension. Top: mean location of maximum SST gradient, and one standard deviation anomaly of first EOF. of maximum SST gradient, added to mean position . Bottom: timeseries of the first EOF. Top left is from high-resolution CESM: top right from observations. In the bottom panel the timeseries of observations and model are arbitrarily lined up (the model simulation does not correspond to actual years).*

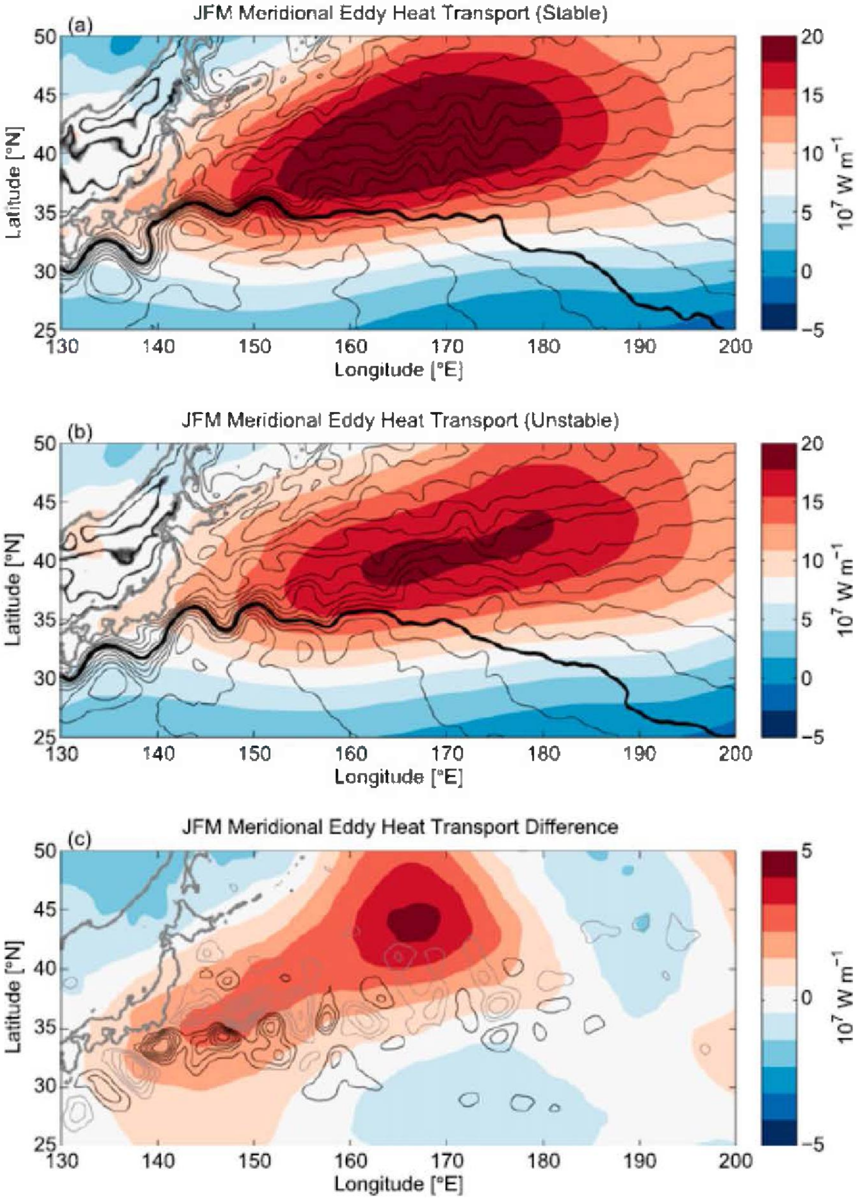
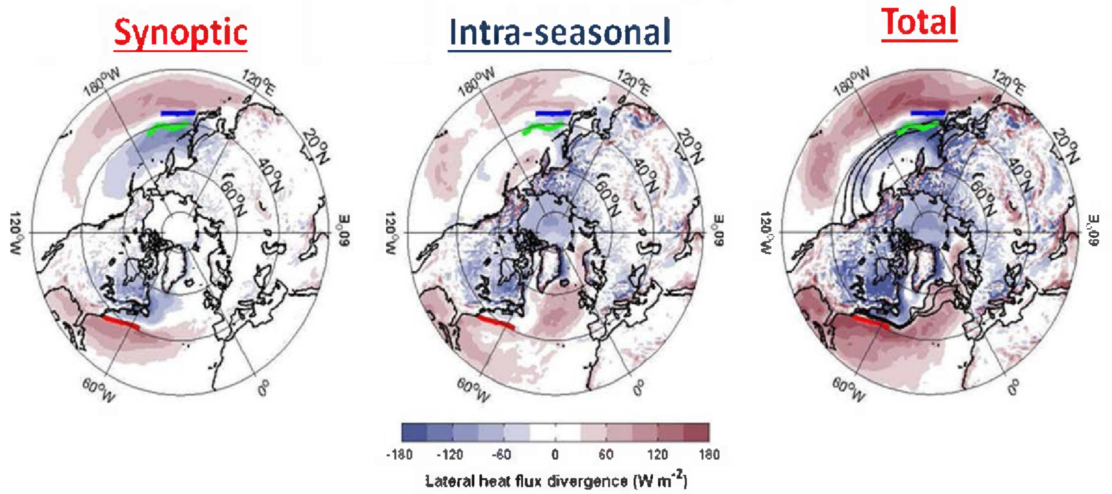


Figure 3. Stable vs unstable wintertime (JFM) atmospheric meridional eddy heat flux. Composite of vertically integrated meridional eddy heat flux (color contours, ci = 0.25×10^7 W m^{-1}) and SSH contours (black contours, ci = 10 cm) for model years 45–86 for the (a) stable and (b) unstable meandering regimes. (c) Composite difference (stable minus unstable).

Lateral divergence of transient eddy heat fluxes

(Vertically integrated climatological mean for JFM)

$$\frac{1}{g}\int_{50\,hPa}^{p_{surface}} (C_p < \frac{\partial u'T'}{\partial x} + \frac{\partial v'T'}{\partial y} > + L < \frac{\partial u'q'}{\partial x} + \frac{\partial v'q'}{\partial y} >)dp$$


Synoptic

Intra-seasonal

Total

Figure 4. Lateral divergence of transient eddy heat fluxes from MERRA data, from Kwon et al. (2013). Left: for synoptic band, Middle: intra-seasonal band. Right: sum of synoptic and intra-seasonal. The mean WBC positions are marked: : – Gulf Stream / – Kuroshio Extension / – Oyashio Extension (from Joyce et al. 2009 & Frankignoul et al. 2011). Black contours on right panel: SST isotherms for 6, 8,10°C.

From Kwon and Joyce 2013.

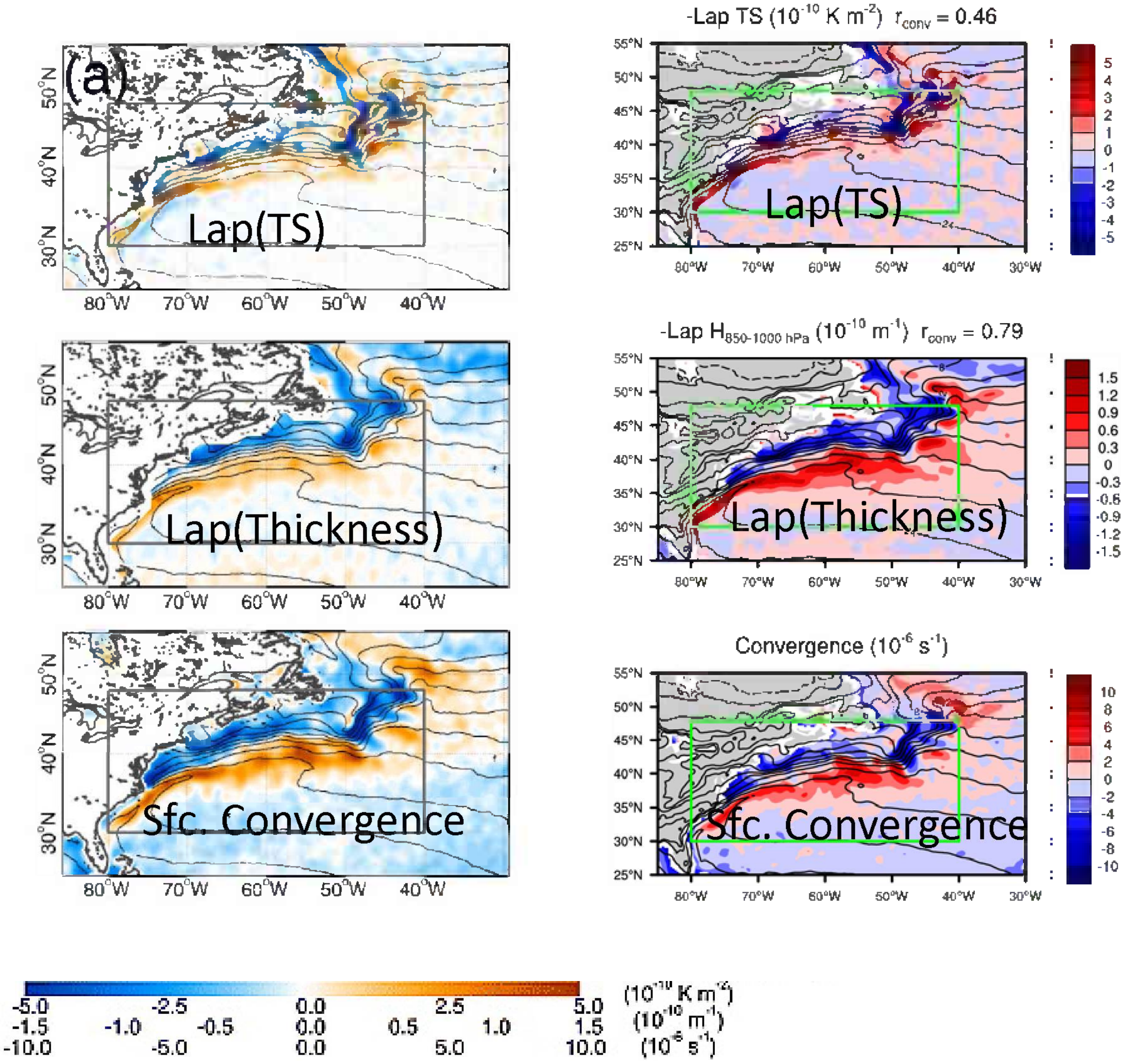


Figure 5. Annual mean fields of (top) SST Laplacian ($-\nabla^2 SST$), (middle) thickness Laplacian ($-\nabla^2 H$), and (bottom) surface wind convergence for the North Atlantic. Left panels: AIRS/Aqua data (Shimade and Minobe, 2011). Right panels: CAM5 atmosphere model, 0.25deg grid, 0.25deg Reynolds SST. Color bars for left panels are shown at bottom in same vertical ordering as the panels: color bars for right panels are shown at the side of each panel and use the same units and range as corresponding left panels. Note that thickness is used here as a variable related to sea level pressure which is measurable from satellite at fine scale (Shimada and Minobe 2011).

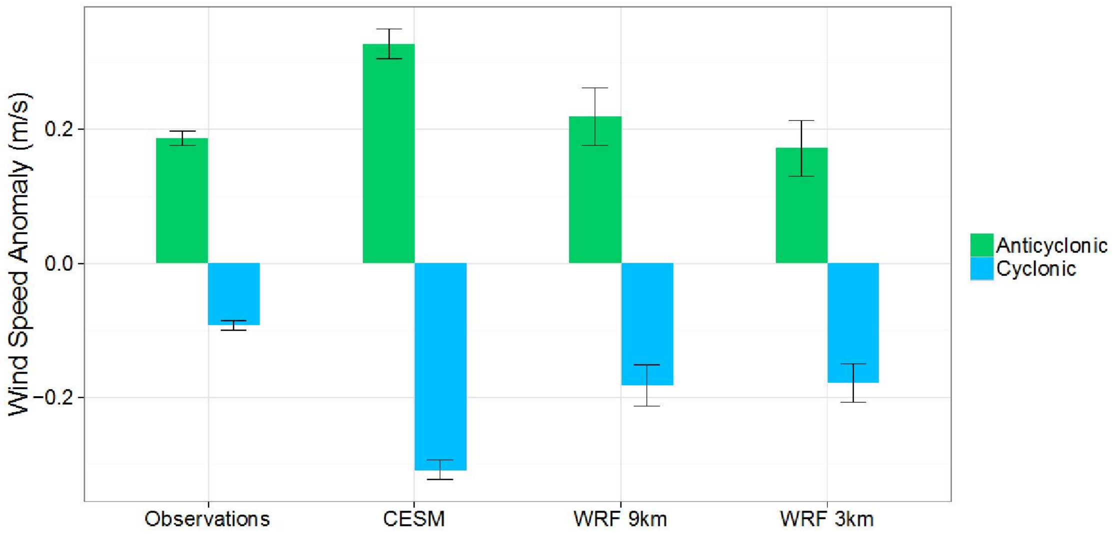


Figure 6. Results from Lagrangian composite analysis of the wintertime surface windspeed response to cyclonic and anticyclonic eddies in the Gulf Stream separation region, comparing scatterometer observations to the CESM control integration and two regional coupled model integration using ROMS and WRF (at 9km and 3km horizontal resolution respectively).