What Controls the Structure and Stability of the Ocean Meridional Overturning Circulation: Implications for Abrupt Climate Change?

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Summary of activities and research results
PI: Alexey Fedorov

Final technical report

The central goal of this research project is to understand the properties of the ocean meridional overturning circulation (MOC) – a topic critical for understanding climate variability and stability on a variety of timescales (from decadal to centennial and longer). Specifically, we have explored various factors that control the MOC stability and decadal variability in the Atlantic and the ocean thermal structure in general, including the possibility abrupt climate change. We have also continued efforts on improving the performance of coupled ocean-atmosphere GCMs. Particular results of the three years of the project are described in detail below.

At different stages our work involved two postdoctoral associates (Drs. Chris Brierley and Florian Sevellec), a research scientist (Dr. Patrick Haertel) and a graduate student (Melanie Parker funded outside of this grant). Collaboration with Profs. Kerry Emanuel of MIT and Eric Guilyardi of IPSL (France) was also an important component of this research.

This project has resulted so far in 14 manuscripts, including publications in *Nature*, *Science and the Bulletin of the American Meteorological Society*. Our *Nature* paper was featured on the journal's cover and also in an article by the Time magazine. Several new manuscripts are still at work. In addition, some of the results of this research are being incorporated into three classes currently taught by the PI at Yale University – "Climate Dynamics", "Physical oceanography" and "Geophysical Fluid Dynamics". These are graduate courses open to upper-level undergraduate students.

The results of this work have been presented at numerous invited seminars, including at International Center for Theoretical Physics (Italy), University of Paris (France), Stony Brook University, University of Rhode Island, Harvard University, Rutgers University, University of California San Diego, Woods Hole Oceanographic Institution, University of Washington, University of Bologna (Italy), and at several conferences and workshops, including the Workshop on Ocean-Atmosphere Energy Transport in Caltech (2009), CLIVAR workshop on new strategies for evaluating ENSO processes in climate models in Paris (2010), the 3rd International Summit on Hurricanes and Climate Change in Rhodes, Greece (2011), and the Workshop on Hierarchical modeling of climate in Trieste, Italy (2011). Our scientific results have been also presented during two AGU Fall meetings (2009, 2010), the US AMOC annual meetings (2009, 2010), and the DOE Integrated Science Team Meetings for Climate Change Modeling (2009, 2010).

Finally, the PI participated in the AR5 Scoping Meeting of the Intergovernmental Panel for Climate Change (IPCC) in Venice (2009).

Stability of the AMOC in a zonally averaged ocean model.

As the first step, we have reexamined the stability of the Atlantic meridional overturning circulation (AMOC), and its sensitivity to several types of forcing using a two-dimensional zonally averaged ocean model (Sevellec and Fedorov 2011). The basin of the model extends from northern high latitudes to Antarctica and includes an implicit representation of a periodic circumpolar channel in the South. The ocean circulation in the model is driven by a combination of surface buoyancy fluxes and wind forcing. In contrast to previous studies, our approach includes a careful treatment of both Eulerian and residual mean circulation in the Southern Ocean. Using boundary conditions consistent with present-day observations the model reproduces a realistic ocean thermal and salinity structure and realistic meridional overturning. The structure, intensity, and stability of the overturning is then extensively studied using three control parameters: the strength of westerly wind stress over the Southern ocean, the magnitude of surface freshwater fluxes imposed in the northern Atlantic, and the strength of diapycnal diffusion (Fig. 1).

Further, we estimate the AMOC sensitivity to changes in the Southern ocean winds at ~1Sv per 10% increase in the wind stress. The overturning also increases with diapycnal diffusivity, but the dependence is weaker than in the absence of the winds. The model can undergo a shut-down of the overturning (subject to a hysteresis) when either the freshwater forcing or the wind stress are gradually varied. The hysteresis loop disappears for large values of isopycnal diffusivity. Changes in the AMOC strength are accompanied by changes in the implied volume transport of the Antarctic Circumpolar Current (ACC). Ultimately, our calculations have produced stability maps (Fig. 2) for the overturning meridional circulation that can be used, for example, to interpret some of the differences between comprehensive general circulation models, and to understand abrupt climate change related to shifts in the AMOC.

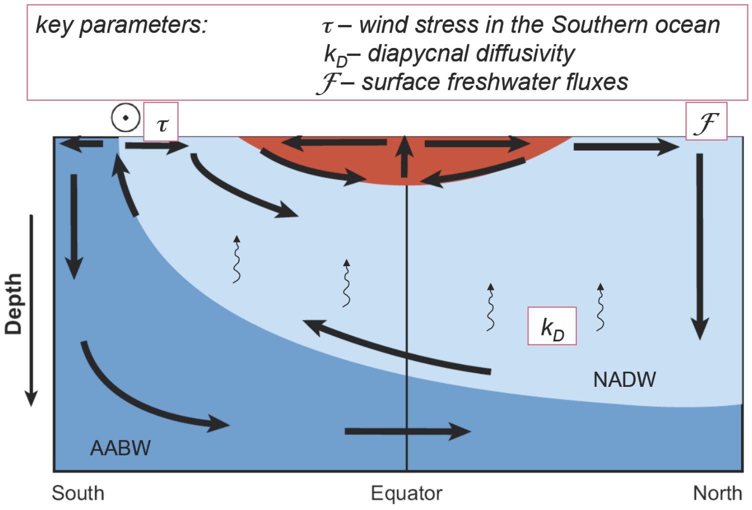

Fig. 1: A schematic of the AMOC. The overturning has several components (or cells): The first (light blue) is associated with the formation of deep waters in the northern Atlantic from where waters subduct, travel southward, and then upwell due to the effect of the wind in the Southern ocean or upward turbulent mixing elsewhere. Another component (dark blue) consists of bottom circulation where waters downwell in the southern polar regions, travel northward, and join the deep waters to upwell in the Antarctic polar front. The wavy arrows indicate the effect of mixing that contributes to bringing cold waters from depths back to the surface. The key parameters used in this study - freshwater flux $\mathcal{F}$, Southern Ocean wind stress anomaly τ, and diapycnal diffusivity k_d - are also shown. After Sevellec and Fedorov 2011.

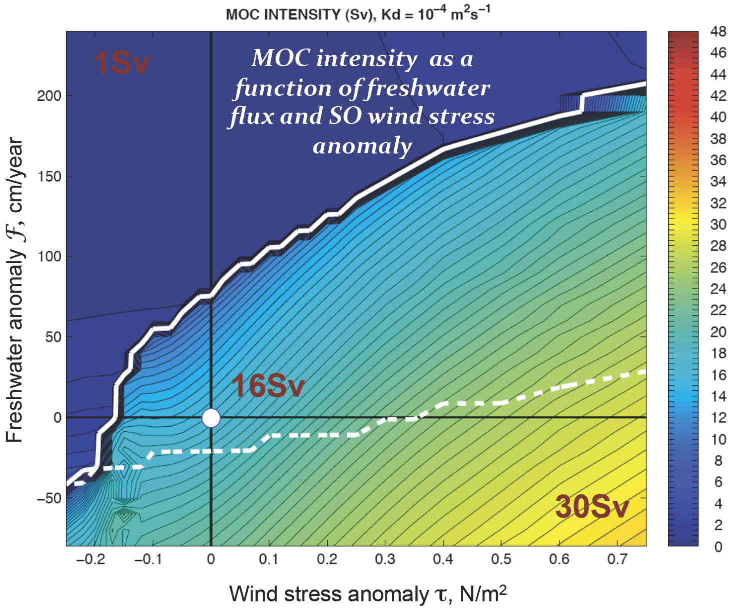

Fig. 2: A stability map for the AMOC. The map shows the AMOC intensity (Sv) as a function of freshwater anomaly in the northern Atlantic and wind stress anomaly in the Southern ocean. The white dot indicates the reference state (present-day conditions), whereas the white lines indicate the limits of the bistable regime. Contour intervals for AMOC intensity are 0.5 Sv. The solid white line indicates the collapse of the AMOC when the freshwater flux increases. The dashed white line indicates the resumption of the AMOC when the freshwater flux decreases.

Oscillatory modes of the AMOC and decadal climate variability.

Variations in the strength of the Atlantic meridional overturning circulation (AMOC) are believed to be a major source of decadal and longer climate variability in the Atlantic. Coupled climate models, however, exhibit very different characteristics of the simulated AMOC variations, which is evident in the CMIP3/CMIP5 intercomparisons. Consequently, potential mechanisms of AMOC variability are still being debated.

Our focus has been on the pronounced AMOC variations with the period of about 20-30 years found in many of the coupled models. We have conducted a generalized stability analysis of a realistic ocean general circulation model (NEMO-OPA) and rigorously show the existence in the system of an interdecadal, weakly-damped mode of oscillation centered in the North Atlantic and related solely to ocean dynamics (Sevellec and Fedorov 2013a). The period of the mode is approximately 24 years, its e-folding decay timescale is in the range of 10-40 years, and the mode surface manifestation is evident in the westward propagation of temperature anomalies in the upper Atlantic ocean within the zonal band between 30°-60°N (Fig. 3). These temperature anomalies affect the ocean density field and hence, by thermal wind balance, ocean currents (mainly in the Subpolar gyre) which then affect the temperature field. Salinity variations tend to compensate the effect of temperature on density but, in general, have a smaller impact on the oscillation.

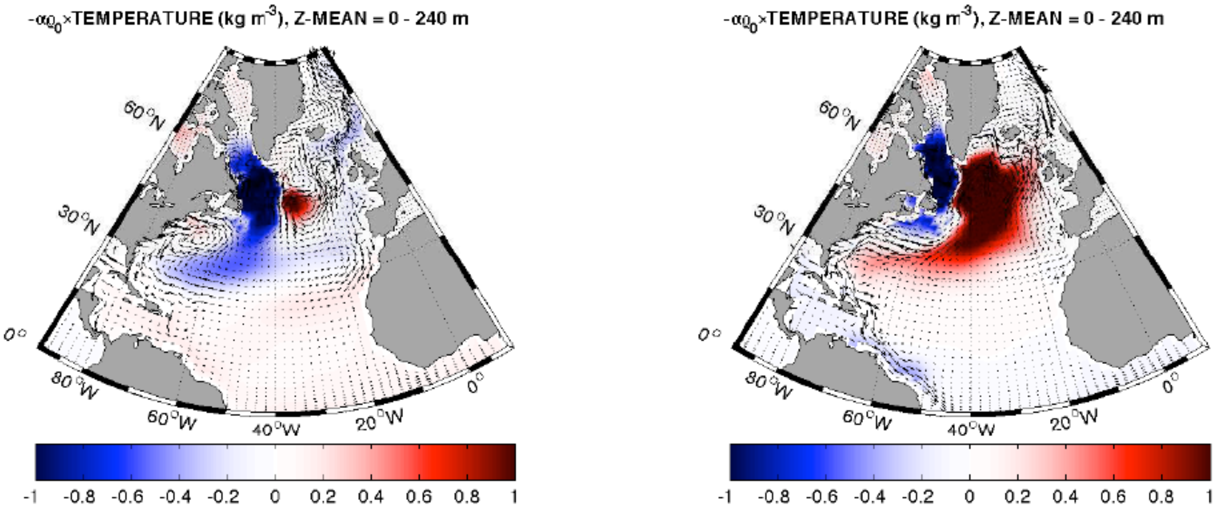

Fig. 3: Temperature variations associated with a dominant oscillatory AMOC mode (the patterns are separated by a quarter-period of the oscillation). Temperature variations are given in terms of density. The period of the mode is 24 years. After Sevellec and Fedorov 2013a.

The most efficient way to excite this mode is via optimal initial perturbations in temperature and salinity with the spatial structure centered off the east coast of Greenland and Canada, south of the Denmark Strait (Sevellec and Fedorov 2013b, for details of the method also see Sevellec and Fedorov 2010). Simple estimates show that moderate changes in salinity or temperature in the upper ocean in this region (0.5psu or 1°C, respectively) can lead to AMOC variations with amplitude on the order of 10-20% of the mean meridional overturning. A stronger forcing can easily lead to a temporary collapse of the AMOC, causing an abrupt climate change with vast consequences for global climate.

Ocean thermal structure and tropical cyclones

Tropical cyclones are now believed to be an important component of the Earth's climate system. In particular, by vigorously mixing the upper ocean, they affect the ocean heat uptake, poleward heat transport, and hence global temperatures and climate. Changes in the spatial distribution, frequency and strength of tropical cyclones could become an important element of the climate response to global warming.

We have identified a positive feedback between hurricanes and the upper-ocean circulation in the tropical Pacific that may lead to warm, El Niño-like conditions and a deeper thermocline in the tropical Pacific. This feedback is based on the ability of hurricanes to warm water parcels that travel towards the equator at shallow depths and then resurface in the eastern equatorial Pacific as part of the ocean wind-driven circulation. In the present climate, very few hurricane tracks intersect the parcel trajectories; consequently, there is little heat exchange between waters at such depths and the surface. More frequent and/or stronger hurricanes in the central Pacific imply greater heating of the parcels, warmer temperatures in the eastern equatorial Pacific, warmer tropics and, in turn, even more hurricanes. Using a downscaling hurricane model, we show potential shifts in the tropical cyclone distribution that favours this feedback. Calculations with a coupled climate model generally support our conclusions. The proposed feedback should be relevant to past equable climates and potentially to contemporary climate change.

Some of the results are presented in Fig. 4. The effects of increasing ocean vertical mixing (due to tropical cyclones) in the subtropical bands include a warming of the eastern equatorial Pacific, a reduction of the east-west equatorial SST gradient (and a weakening of the atmospheric Walker circulation), and a deepening of the tropical thermocline. Another result is significant reduction (by ~50%) in the amplitude of the simulated ENSO (not shown here). The latter result was unexpected since the ocean mixing was increased only in the subtropics, and not in the equatorial region. These results were published in *Nature* (Fedorov *et al.* 2010); our paper was also featured on the magazine's cover.

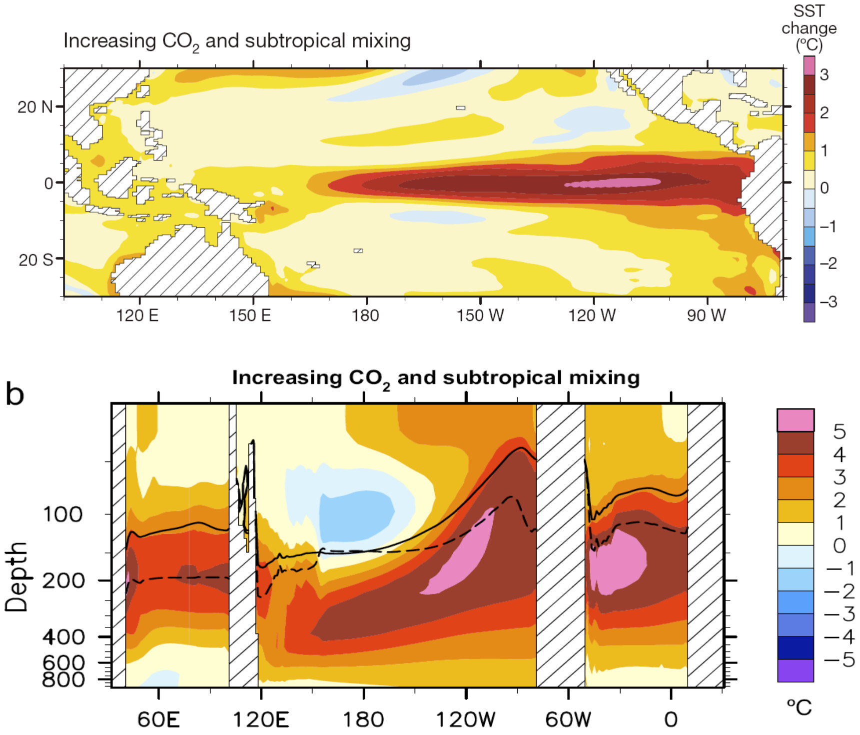

Fig. 4: Changes in (top) ocean SST and (bottom) temperature along the equator between two coupled simulations – one is a simulation with enhanced vertical mixing in the upper 200m of the ocean in the subtropical bands between 8-40°N/S, which mimics he effect of enhanced hurricane activity; the other simulation is control. The model used is CCSM3. Note the deepening of the tropical thermocline (dashed versus solid lines). After Fedorov *et al.* 2010.

Further, we have explored the effect of intermittent mixing induced by tropical cyclones on the ocean thermal structure and climate (including the atmospheric Hadley cells and the ocean shallow tropical cells - STCs) in a suite of experiments with different durations of subtropical mixing (Manucharyan *et al.* 2011). In particular, we have focused on changes in poleward heat transport by the ocean and the atmosphere induced by tropical cyclones (Fig. 5) and on whether those changes are favourable for maintaining warmer high latitudes.

In a complimentary paper (Brierley *et al.* 2009), we have also explored key factors that are responsible for changes in the meridional extent of the tropical ocean warm pool on longer timescales (a potential meridional expansion of the warm pool under global warming scenarios, and of the tropical belt in general, can have dramatic consequences for the ocean circulation and global climate).

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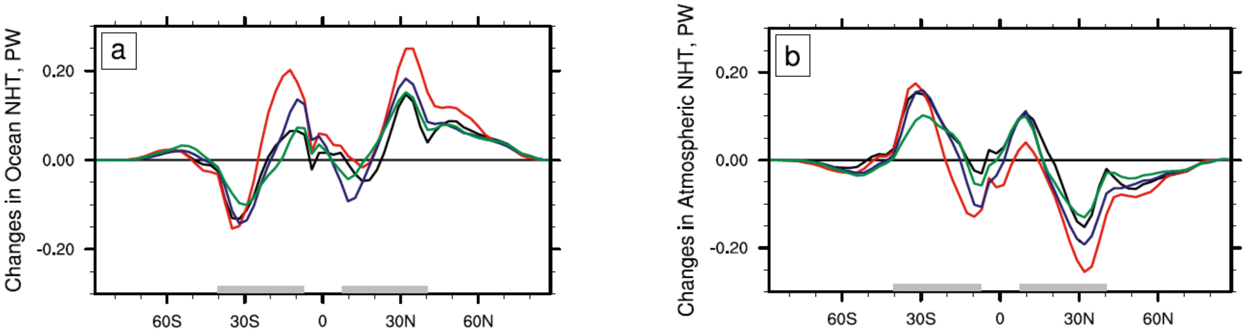

Fig. 5. Changes in oceanic (left) and atmospheric (right) northward heat transports when enhanced mixing is prescribed in the subtropical bands. Different lines correspond to slightly different parameterizations of the TC-induced mixing. Note that the ocean poleward heat transport increases but this increase is partially compensated by the atmosphere. After Manucharyan *et al.* 2011.

Theoretical studies of ocean stratification and overturning

In a recent theoretical study, we consider fundamental factors that control the thermal structure and meridional overturning circulation in the deep ocean (Haertel and Fedorov 2012). In particular, we explore adiabatic theories of the ocean thermal structure and the role of deep-ocean mixing using a Lagrangian ocean model (LOM), which simulates ocean motions by computing trajectories of water parcels (Fig. 6). This model has been developed recently by Patrick Haertel, a research scientist at Yale University working with the PI.

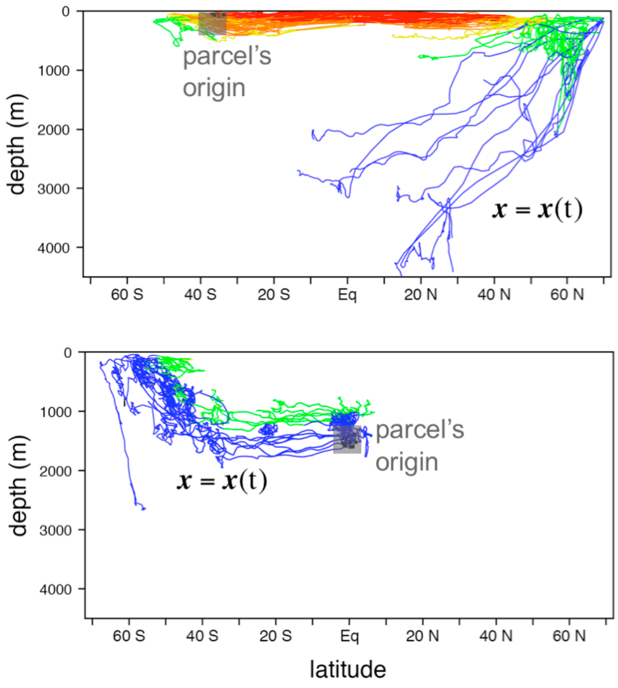

Fig. 6
Several examples of parcel trajectories obtained from the LOM. Colors indicate different water masses that the parcels contribute to. $x=x(t)$ are the parcel's coordinates as functions of time. Note the connections between the deep and upper oceans.

A unique feature of the LOM is its capacity to model ocean circulation in the fully adiabatic limit, in which water parcels exactly conserve their properties (temperature, salinity) when they are not in contact with the ocean surface. The main conclusion of our study is that the adiabatic limit for the ocean interior provides the leading-order solution for the ocean meridional overturning and density structure, with tracer diffusion contributing first-order perturbations. We can precisely quantify the changes in stratification and circulation that result from adding a moderate amount of tracer diffusion in the model, and these include an increase in the amplitude of the deep meridional overturning cell of several Sverdrups and a 10-20% increase in poleward heat transport.

Ocean energetics and coupled model improvement

We have now completed the study of the ocean energetics as applied to ocean and coupled GCMs and ocean data assimilations (Brown and Fedorov 2010, Brown *et al.* 2011) – a part of a larger project on improving the simulation of climate by coupled GCMs.

In brief, the energetics can be formulated in terms of four main variables – E, K, B, and W. Surface winds act on the ocean by generating wind power (W), affecting the buoyancy power (B), modifying the slope of the isopycnals and changing the Available Potential Energy (E) of the system (Fig. 7). The generated kinetic energy of ocean currents (K) turns out to be negligibly small. Integrating the primitive equations of motion, we combine these four variables into two equations of energy conservation:

$$\frac{dK}{dt} = W - B - Dissipation_1$$

$$\frac{dE}{dt} = B - Dissipation_2$$

The two additional terms on the right-hand-side of these equations - *Dissipation₁* and *Dissipation₂* - describe explicit turbulent viscous and diffusive energy losses, respectively. This energy description in terms of E, B, and W gives a basin-wide, integral approach ideal for model inter-comparison.

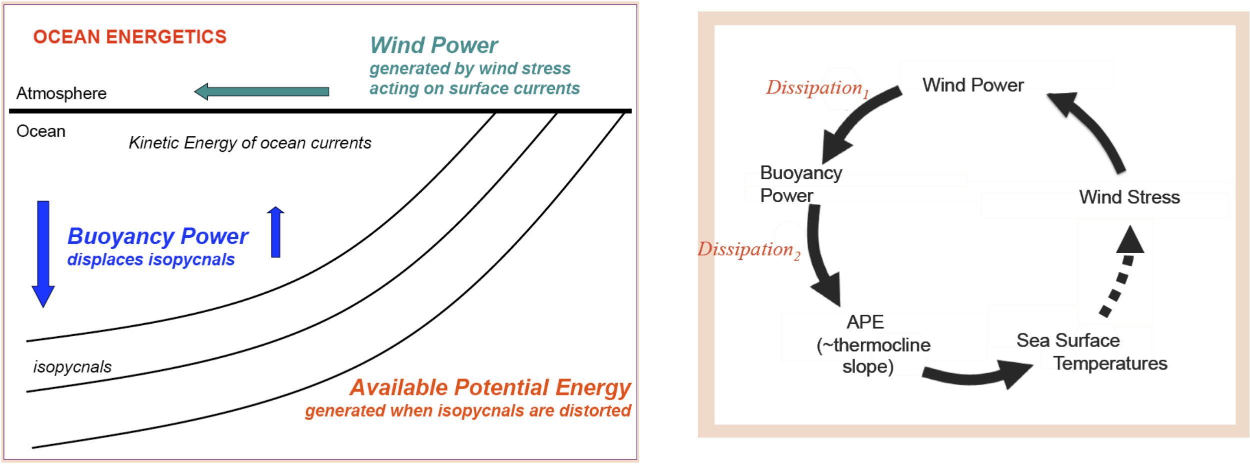

Fig. 7. Schematics of energy transformations in the tropical ocean: (a) Energy transfer from the winds to the thermocline; (b) the cycle of mechanical energy in the coupled ocean-atmosphere system. After Brown *et al.* 2011.

Our focus has been on two critical issues - (a) the overall energy balance and (b) the role of energy dissipation in this balance. Several factors contributing to dissipation were considered, including turbulent mixing, and ageostrophic processes.

We tested the robustness of the energy equations using a variety of ocean-only models and data-assimilation products, in order to establish a baseline for this relationship (Brown *et al.* 2011). With the baseline established, we have applied our method to a number of IPCC coupled model simulations. In fact, net energy loss to dissipation varies greatly from one model to the next, for a number of physical reasons - some related to the details of ocean mixing schemes, some to the behavior of the model atmospheric components (e.g. different simulated wind stress patterns). We have proposed to use the ocean energetics for evaluating dissipative properties of the ocean component of general circulation models. As part of the ongoing community efforts, this method can be used to improve the performance of coupled GCMs.

Further, in an article in the *Bulletin of American Meteorological Society* (Guilyardi *et al*. 2009), we have summarized the progress in the development of coupled GCMs, some of the persistent problems and challenges, and potential strategies to address them.

Dynamics of ENSO and tropical decadal variability in simple models

A complimentary component of this work involves studies of processes in the tropical Pacific, including ENSO and decadal climate variability originating from the tropics. In particular, we have developed in a framework, referred to as the low-frequency approximation (Fedorov 2010, Parker and Fedorov 2011), that allows a simplified but rigorous treatment of ENSO and decadal climate dynamics. Physical processes that control ENSO are relatively fast. For instance, it takes only several months for a Kelvin wave to cross the Pacific basin ($T_k \approx 2$ months), while Rossby waves travel the same distance in about half a year. Compared to such short timescales the typical periodicity of El Niño is much longer ($T \approx 2$-7 years). Thus, ENSO is fundamentally a low-frequency phenomenon in the context of these faster processes. We take advantage of this and use the smallness of the ratio $\varepsilon_k = T_k / T$ to expand solutions of the ocean shallow-water equations into power series (the actual parameter of expansion also includes the oceanic damping rate). Using this expansion we relate thermocline depth anomalies to temperature variations in the eastern equatorial Pacific via an explicit integral operator.

Our method allows a simplified formulation of ENSO dynamics based on an integro-differential equation. Within this formulation, we showed how the interplay between wind stress curl and oceanic damping rates affects (1) the amplitude and periodicity of El Niño and (2) the phase lag between variations in the equatorial warm water volume and SST in the eastern Pacific. A simple analytical expression is derived for the phase lag. Ultimately, this approach provides a rigorous framework for deriving simple models of ENSO (the delayed and recharge oscillators), highlights limitations of such models, and can be also used for describing decadal climate variability.

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