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"The Role of the Tropics in Abrupt Climate Changes"

FINAL TECHNICAL REPORT

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PI: Alexey Fedorov

This grant has generated results and led to eleven publications in several research areas, as described below. Some of the results were presented during the Fall 2006, 2007 and 2008 AGU meeting, at the Milankovitch meeting at University of Colorado (Boulder), and at invited seminars at Columbia University, New York University, University of Connecticut (Storrs), CSIRO (Australia), Woods Hole Oceanographic Institution, Scripps Institution of Oceanography, Stanford University and MIT, and in the UK at the Universities of Reading, Oxford, and East Anglia. The results were also shown during the meeting of the WGNE Workshop on Systematic Errors in Climate and NWP Models in San Francisco in February 2007, at the 3rd IPSL/NCAS Workshop held in May 2007 in Paris, France, and at the PRISM model intercomparison workshop at GISS / Columbia University in June 2008. In addition, the PI's contributions include review papers for the Encyclopedia of Ocean Sciences and Oxford Companion for climate change (Fedorov and Brown 2008a, Fedorov 2008).

Two postdoctoral associates were in part supported through this grant:
Jaclyn Brown (Ph.D. 2005, CSIRO, Australia)
Chris Brierley (Ph.D. 2007, University of Reading, UK)

Abrupt climate changes and ocean circulation in the tropics.

Studies of the effect of a freshening of surface waters in high latitudes on the oceanic general circulation usually focus almost entirely on the ocean deep thermohaline circulation and its poleward heat transport. Using a hierarchy of general circulation models (Fedorov *et al* 2007, Barreiro *et al* 2008), including idealized ocean GCMs and state-of-the-art ocean and coupled models (such as GFDL OM2.1 and CM2.1, Fig. 1), we have demonstrated that a similar freshening can also affect the shallow, wind-driven circulation of the ventilated thermocline and its heat transport from regions of heat gain (mainly in the upwelling zones of low latitudes) to regions of heat loss in higher latitudes. A freshening that decreases the surface density gradient between low and high latitudes reduces the ocean poleward heat transport, thus forcing the ocean to gain less heat in order to maintain a balanced heat budget. The result is a deepening of the tropical thermocline (Fig. 2) and a warming of the tropical Atlantic. The deeper the thermocline in equatorial upwelling zones is, the less heat the ocean gains. In effect, we have proposed a new mechanism by which a freshwater forcing in the Northern high latitudes can affect the tropics. The surface manifestation of such changes involves warmer tropical SSTs and a southward shift of the ITCZ.

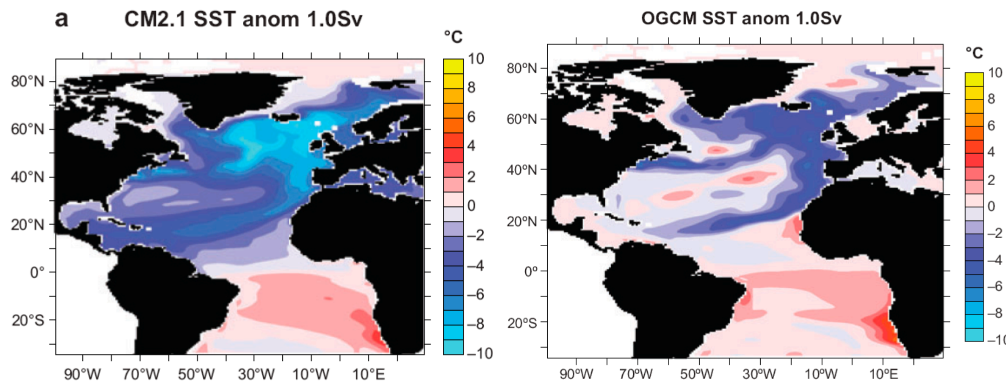

Fig.1: A comparison of the response of the Atlantic ocean SSTs to a freshening of surface waters in high latitudes in coupled and ocean-only models (left and right panels, respectively). Note the warming of the Atlantic south of the equator in both simulations. After Barreiro *et al* 2008.

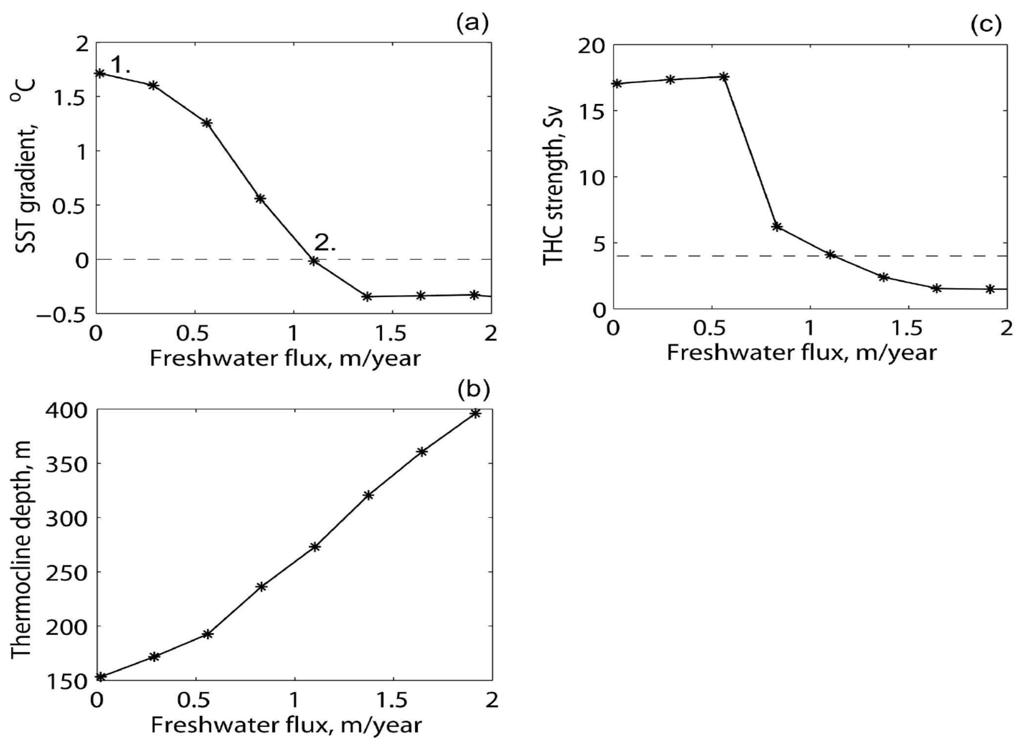

Fig. 2: A summary plot for several idealized GCM perturbation experiments for an Atlantic-size ocean basin. The horizontal axis indicates the strength of the imposed forcing in high latitudes (freshwater flux measured at 55°N). The connection between the high and low latitudes is established through the wind-driven circulation. After Fedorov *et al* 2007.

(a) Reduction of the zonal SST gradient along the equator in the tropical Atlantic.
(b) Deepening of the tropical thermocline.
(c) Reduction in the strength and the collapse of the THC.

Do abrupt climate changes involve primarily changes in the Atlantic thermohaline or wind-driven circulation? The answer to this question, which determines whether or not a climate transition has a large tropical signature, depends to a large degree on factors such as the model treatment of diffusive processes in the ocean, the model's resolution, and the spatial structure of the imposed freshwater forcing (Fedorov *et al* 2007).

What controls the ocean thermal structure in the tropics? A permanent El Niño in paleoclimates.

The early Pliocene, 5 to 3 million years ago, may provide some critical clues to the future evolution of the Earth's climate, even though the present generation of coupled climate models has difficulties in reproducing this period. During this time globally averaged temperatures were significantly higher than they are today, even though the key external factors that determine climate were essentially the same, including the atmospheric concentration of CO_2 (350-400ppm), location of continental boundaries, and continental topography. In the tropical Pacific the east-west gradient was permanently absent, suggesting that El Niño was continual (or ''permanent'') rather than intermittent. Major coastal upwelling regions of the world ocean were similarly warm (up to 10^{o}C warmer than today). The appearance of cold surface waters in oceanic upwelling zones in low latitudes (both coastal and equatorial), signaled the termination of those warm climate conditions and the end of "permanent" El Niño. A possible explanation is that the gradual shoaling of the oceanic thermocline reached a threshold around 3 million years ago, introducing strong feedbacks involving ocean-atmosphere interactions. Our paper in Science (Fedorov *et al* 2006) summarizes the available data, various approaches to model such warm conditions, and main implications for the contemporary global climate change. One of the major issues is whether a future melting of glaciers, changes in the hydrological cycle, and potential deepening of the ocean thermocline could restore the warm conditions of the early Pliocene. This problem is related to the question of what controls the thermal structure of the upper ocean in the tropics, which is one of the key questions of the current grant.

By analyzing new and recently published data, we have also established that the tropical ocean warm pool extended much farther poleward during that time (the meridional extent of the warm pool was ~50% larger than at present). We are currently investigating whether the contemporary global warming can cause a similar meridional expansion of the tropical warm pool, which would have huge climatic impacts.

The energetics of the tropical ocean.

The reliability of climate predictions by general circulation models strongly depends on the overall performance of those models. Even the best, state-of-the-art coupled models exhibit a wide range of behavior in the tropical Pacific, particularly when simulating ENSO, the mean state of the coupled system and decadal variations (Brown *et al* 2008b, Guilyardi *et a*l 2009). All these factors are critical for model's ability to simulate an abrupt climate change.

During this project we have proposed to use the energetics of ocean GCMs (and the oceanic component of coupled GCMs) as a metric to compare and contrast the performance of coupled GCMs in simulating tropical processes.

The energetics of the tropical ocean can be summarized as follows: Surface winds act on the ocean by generating the wind power (W), which is then converted to the buoyancy power (B). In turn, the buoyancy power modifies the slope of the isopycnals and changes the Available Potential Energy of the system (APE or E for simplicity), so that

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

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

Here, K stands for the kinetic energy of ocean zonal currents (usually small in comparison with E). Our initial focus was on the role of energy dissipation in this balance (Fedorov 2007). Several factors contributing to dissipation were considered, including turbulent mixing, energy fluxes away from the tropics, and ageostrophic processes. As the next step, we have tested the robustness of these equations by using a variety of ocean-only models and data-assimilation products, in order to establish a baseline for this relationship. With the baseline established, we have applied our method to a number of the IPCC coupled model simulations (Brown and Fedorov 2010, Brown *et al* 2011).

One particular factor was investigated in detail – the transfer of energy from surface winds to the ocean thermocline. We have found that the efficiency γ of this transfer (the ratio of B to W) varies between the models from 30 to 60% for ENSO variations, and from 10 to 20% for the mean state of the ocean. Such a large range explains, in part, differences in how the models simulate the mean state of the tropical Pacific ocean (Fig. 3)

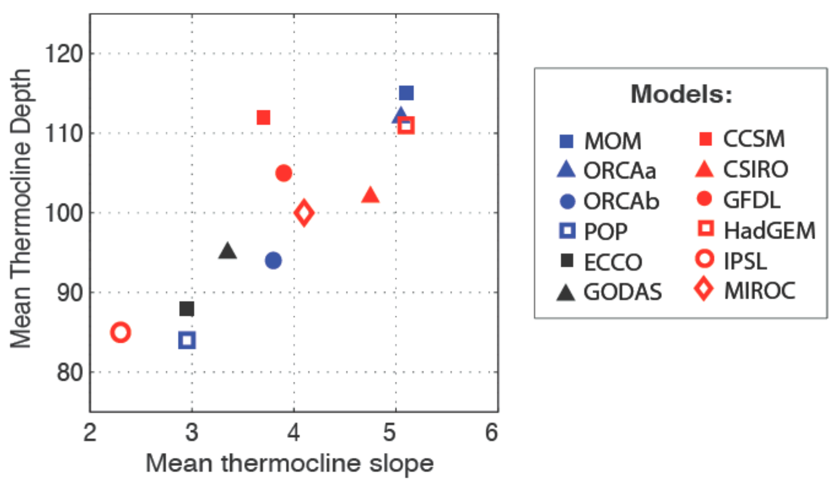

Fig. 3: The mean depth of the equatorial thermocline and mean thermocline slope along the equator as simulated in a number of ocean models (blue), data assimilations (black), and coupled GCMs (red). The thermocline slope is defined as a normalized difference between thermocline depths at 180ºE and 100ºW. The thermocline is defined as the depth of where $d\rho/dz$ is maximum. Note the large differences between the mean thermocline depth and, especially, the mean thermocline slope produced by the models. After Brown and Fedorov 2008b.

Another striking difference between coupled models is in the way they partition energy between the seasonal cycle and interannual variability, which is being investigated within the same framework.

Ultimately, we are developing the energy-based analysis into an effective diagnostic tool for assessing and improving the performance of coupled GCMs, and for quantifying climate changes. For example, our analysis emphasizes decadal climate variations that take place in the tropical Pacific. Fig. 4 shows a decrease in the mean wind power over the tropical Pacific ocean in the late 1970s that resulted in a reduction of the mean available potential energy of the tropical ocean (indicative of a reduction in the thermocline east-west tilt along the equator).

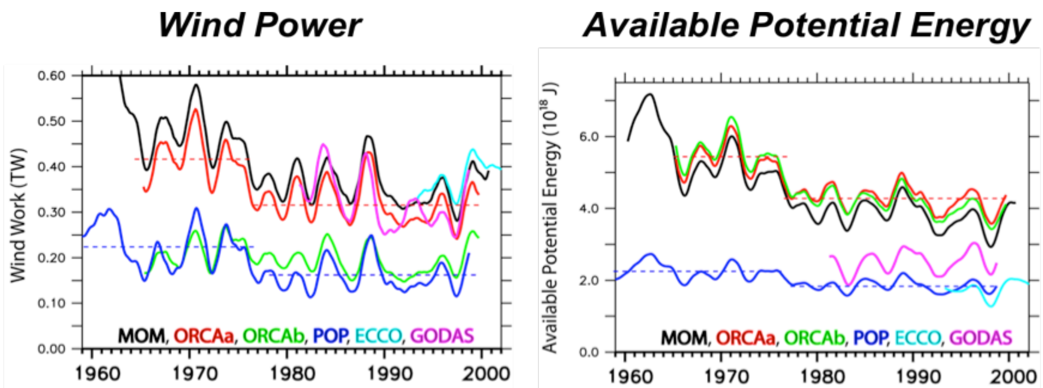

Fig. 4: Time series of the wind power (wind work rate) and the APE for different ocean models and data assimilations showing a reduction in the wind power and the APE in the late 1970's. Wind power is in TW (terawatts), the APE is Joules x10^{18}. Such a climate shift amounts to an abrupt climate change originating from the tropics. After Brown and Fedorov 2008b.

This flattening of the thermocline occurred around the time of the climate regime shift in the late 1970s and is associated with a weakening of the zonal winds along the equator. The flatter thermocline corresponds to a warmer mean state of the tropical Pacific and can potentially be the cause of stronger El Niño events in the 1980s and 1990s.

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