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An investigation of Bjerknes Compensation in the Southern Ocean in the CCSM4

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ABSTRACT

This project aims to understand the relationship between poleward oceanic and atmospheric heat transport in the Southern Ocean by analyzing output from the community Climate System Model Version 4 (CCSM4). In particular, time series of meridional heat transport in both the atmosphere and the ocean are used to study whether variability in ocean heat transport is balanced by opposing changes in atmospheric heat transport, called Bjerknes Compensation. It is shown that the heat storage term in the Southern Ocean has a significant impact on the oceanic heat budget; as a result, no robust coherences between oceanic and atmospheric heat transports could be found at these southern latitudes.

I. INTRODUCTION

Heat transport in the climate system has contributions from both the atmosphere and the ocean. This heat transport is mainly a poleward flow: air and water warmed by the Sun flows from the equator poleward. On a global scale, this flow is essentially symmetric with respect to the equator, despite there being different contributions from the atmosphere and the ocean in the separate hemispheres.

It has been proposed that variations in atmospheric (oceanic) heat transport can be compensated by an opposing change in oceanic (atmospheric) heat transport so that the total heat flux in the system remains constant, as balanced by top-of-the-atmosphere (TOA) heat loss [Bjerknes, 1964]. This balance, called Bjerknes Compensation, has been shown to hold in the Northern Hemisphere on decadal time scales [Shaffrey and Sutton, 2006; van der Swaluw et al., 2007]. Another requirement for Bjerknes Compensation to hold is that the variability of heat stored in the ocean, as well as the variability of heat lost to space from the TOA, must remain almost constant.

In the project, we investigate whether this Bjerknes Compensation holds in the Southern Ocean, the region south of about 50^{o}S. We approach this problem by investigating oceanic and atmospheric heat transports in the CCSM4. These transports and their various components are available to us in the form of 500 year time series, which are processed and then evaluated using several statistical methods.

The rest of this paper outlines the methods, results, and conclusions obtained from this study along with recommendations for future work.

II. METHODS

The Community Climate System Model, Version 4 (CCSM4) [Gent et al., 2001] is composed of four separate climate component models: the Community Atmosphere Model (CAM) and the Community Land Model (CLM) developed at the National Center for Atmospheric Research (NCAR) and the Parallel Ocean Program (POP) and Sea Ice Model

(CICE) developed at Los Alamos National Laboratory (LANL). The models exchange data only through the flux coupler, allowing them to be run either together or separately if forced by some external data set.

The model was run for 1300 years forced by forcing conditions representative of the year 1850; the data we have is from the last 500 years (801-1300) of this pre-industrial integration. The atmospheric heat transport was inferred from the difference between top and surface heat fluxes, which must balance the divergence of meridional atmospheric heat transport. These components included longwave and shortwave fluxes at both the TOA and the surface, as well as sensible and latent heat fluxes. Following Kay et al. (2012), we added an additional correction term to the latent heat flux to account for the thermodynamics of snow melt

The components of the divergence of atmospheric heat transport, *F* include

$$F = F_S - F_T \qquad (1)$$

where F_S is the surface heat flux and F_T is the heat flux at the top of the model.

The components of F_S and F_T include

$$F_S = -FSNS + FLNS + SHFLX + [(L_f \times \rho_w \times PRECSC) + LHFLX] \qquad (2)$$
$$F_T = -FSNT + FLNT$$

where *FSNS* and *FSNT* are shortwave, *FLNS* and *FLNT* are longwave, *SHFLX* is sensible heat, *LHFLX* is latent heat, L_f is latent heat of fusion, ρ_w is the density of water, and *PRECSC* is the water equivalent snow precipitation rate.

F was then zonally integrated using the following definition:

$$\bar{F} = r_0 cos\vartheta \oint F d\varphi \qquad (3)$$

The meridional integral was then taken up to a certain latitude:

$$\bar{\bar{F}} = r_0 \int_{-90}^{\vartheta} \bar{F} d\vartheta' \qquad (4)$$

where φ is longitude, ϑ is latitude, and r_0 is the radius of the Earth. We now have our atmospheric heat transport across any latitude ϑ:

$$F_a(\vartheta) = \bar{\bar{F}} \qquad (5)$$

We derive ocean meridional heat advection and diffusion (collectively F_o) from their divergences, as provided by variables *ADVT* and *HDIFT*. These are the vertically integrated divergences of the heat advection and diffusion. We thus have:

$$F_o(\vartheta) = \overline{\overline{ADVT}} + \overline{\overline{HDIFT}} \qquad (6)$$

The separate components of oceanic transport from advection and diffusion are also defined as:

$$F_o^A = \overline{\overline{ADVT}}$$
$$F_o^D = \overline{\overline{HDIFT}} \qquad (7)$$

This oceanic heat transport across latitude ϑ must be balanced by the sum of net surface heat loss to the atmosphere:

$$S_{oa}(\vartheta) = \overline{\overline{SHF}} \qquad (8)$$

and the heat stored in the ocean south of this latitude, *S*:

$$S(\vartheta) = \rho c_p \overline{\overline{\int_{-H}^{0} \frac{dT}{dt} dz}} \qquad (9)$$

where ρ and c_p are the density and heat capacity of sea water, respectively, and *H* is the water depth.

Yearly averages were then taken in order to eliminate the seasonal cycles present in the data and to focus on interannual variability. A plot of the mean states of S_{oa}, F_o, S_{oa}+F_o, F_o^A, and F_o^D is shown in Figure 1. The sum of the surface and oceanic flux components nearly equal zero, indicating a balance existing between these two terms.

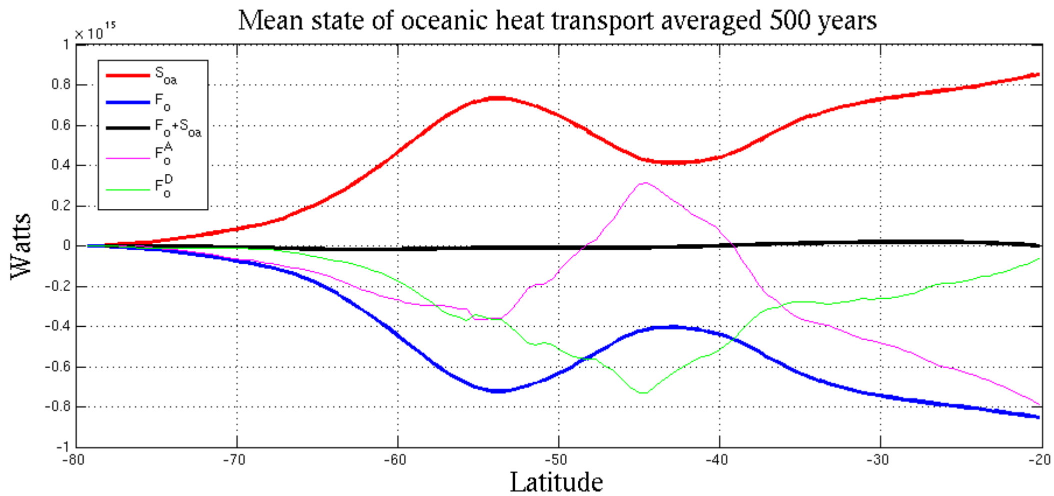

Figure 1: Mean state of surface heat flux (S_{oa}, red), oceanic heat transport (F_o, blue), the sum of those two (black), Eulerian component of the oceanic heat flux (F_o^A, magenta), and eddy-induced heat diffusion (F_o^D, green). The vertical axis is in watts and the horizontal axis is latitude.

Several statistical methods were then used on the data using MATLAB computational software. Standard deviations of the time series were calculated to investigate the overall variability of the data. Additionally, certain latitudes were selected from the Southern Ocean and were used for spectral and coherence analysis. The latitudes evaluated included 70^o, 60^o, 45^o, and 30^o S; coherences computed included the relationships between F_o and S_{oa}, F_o and F_S, and finally between F_o and S.

Several power spectral plots were also produced at the same latitudes in order to identify frequency bands that display enhanced energy, indicating timescales of climate modes which may have an increased effect on the time series being investigated. Spectra of F_o, the S_{oa}, $F_o + S_{oa}$, and the S were produced at both 45^o and 60^o S.

III. RESULTS

Figure 2 shows the coherence analysis between F_o and F_a at 60^o S latitude. While there is some coherence on timescales of 100 years, it is not very strong; nor is there significant coherence on interdecadal timescales, where we would expect for Bjerknes Compensation. Based on these initial negative results, we look further into the relationship between F_o and S_{oa} as well as F_o and S by investigating the coherence between these parameters as well as their variability to see which terms play important roles in the heat balance at these southern latitudes.

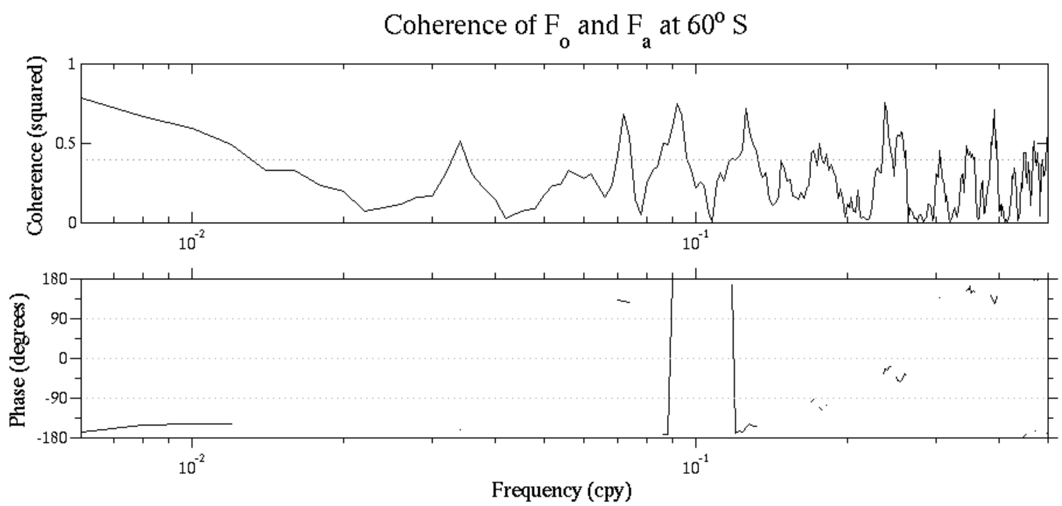

Figure 2: Coherence between oceanic heat transport (F_o) and atmospheric heat transport (F_a) at 60 S.

The mean states of F_o and S_{oa} do show a balance between these two terms in Figure 1, however, on shorter timescales the ocean tendency term shows a significant amount of variability that ruins the relationship between ocean heat transport and surface heat fluxes. These two parameters therefore were not found to have a very strong coherence, as can be seen in Figure 3. This figure shows the coherence between the F_o and S_{oa}, which ideally would be totally coherent if there were no additional heat source or sink terms. However, since the two parameters are not coherent at all timescales, then it is clear that there may be a larger than expected influence from heat storage at this latitude.

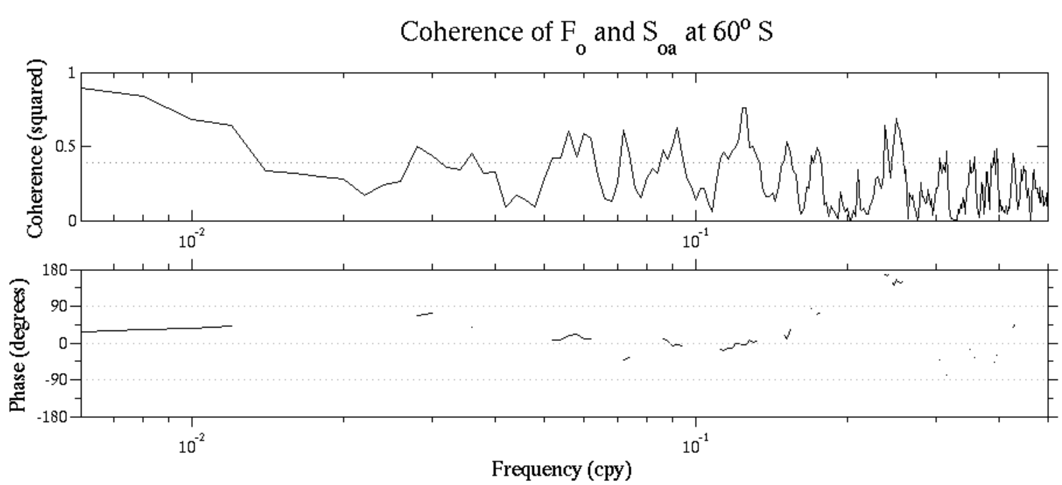

Figure 3: Coherence between oceanic heat transport (F_o) and ocean surface heat flux (S_{oa}) at 60^o S.

Figure 4 shows the variability of F_o, S_{oa}, F_o+S_{oa}, and S. The discrepancy between the F_o and S_{oa} variability is found in the S term. The variability of S nearly equals the sum of F_o and S_{oa}; this large is surprising for yearly averaged time series, but it explains the low coherence between F_o and S_{oa}.

To further support this, a coherence analysis between the oceanic heat transport and the heat storage term was performed at 60^o S and can be seen in Figure 5 below. It is clear that there is a high correlation between F_o and S, especially at larger timescales (hundreds of years) down to about three years. The correlation is nearly perfect (equal to one) down to ten years, and then it tapers off to noncoherence after three years.

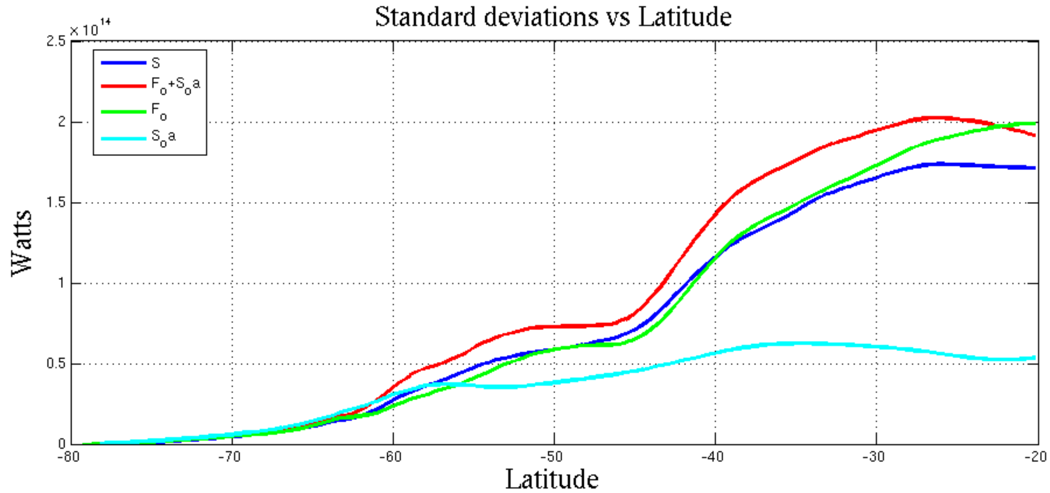

Figure 4: Standard deviation of oceanic heat storage (S, blue), sum of oceanic heat transport and surface transport ($F_o + S_{oa}$, red), oceanic heat transport (F_o, green), and surface heat flux (S_{oa}, cyan).

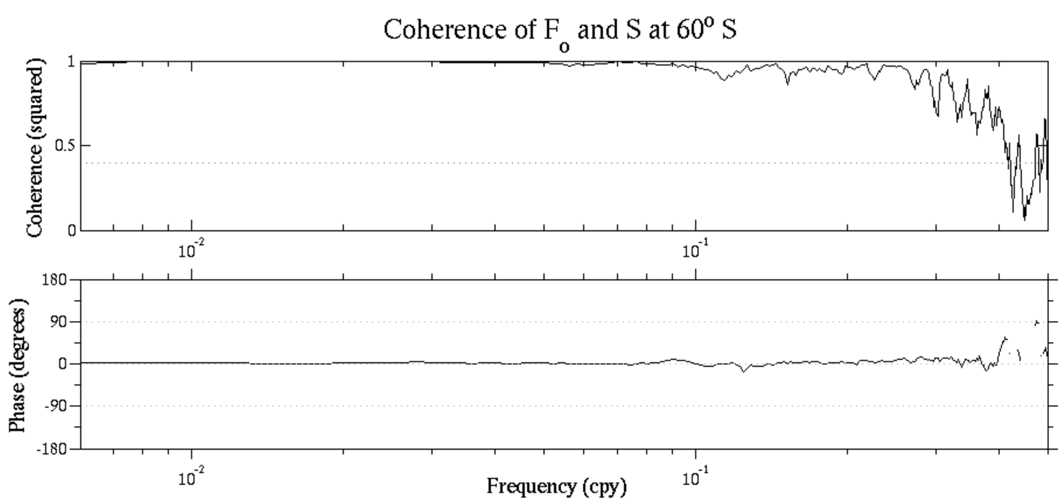

Figure 5: Coherence between oceanic heat transport (F_o) and oceanic heat storage (S) at 60^{o}S.

To further prove that this heat storage term does have a large influence at these latitudes and timescales, a spectral analysis was performed at 60° S and can be seen in Figure 6. Included in this figure are the S, $F_o + S_{oa}$, F_o, and S_{oa}. All three of these terms have a similarly prominent signal on timescales from one hundred years down to about three years, which is a good indication of the importance of S in this problem. This is an important result because, as stated above, the Bjerknes Compensation is only able to hold when changes in the heat storage of the ocean are trivial compared to the heat transport of the entire ocean; clearly this is not the case at this latitude.

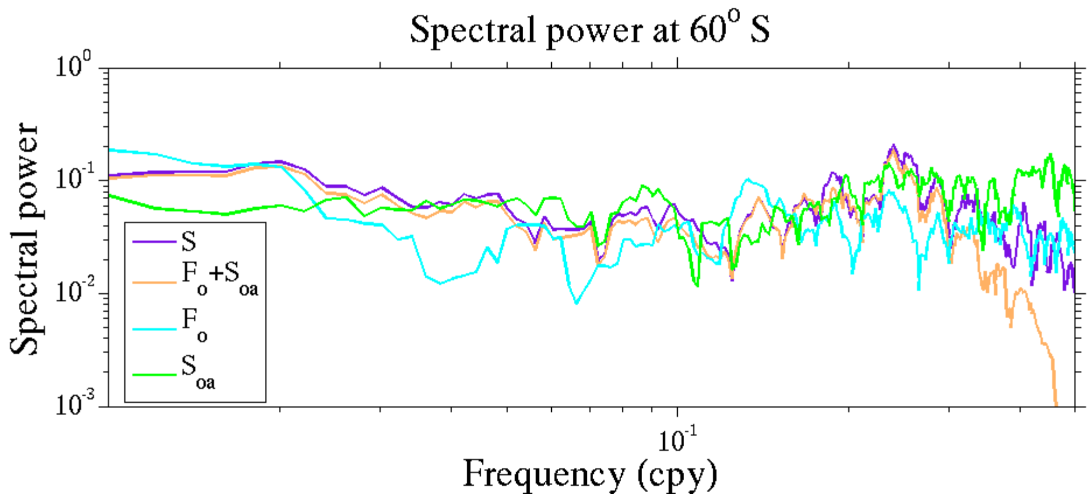

Figure 6: Power spectrum at 60° S of S (purple), $F_o + S_{oa}$ (orange), F_o (cyan), and S_{oa} (green).

IV. CONCLUSIONS

After performing various tests using statistical methods on the time series datasets provided from CCSM4, it is clear that a Bjerknes Compensation could not be found in the region of the Southern Ocean (south of 50° S). The variability between the oceanic heat transport and atmospheric heat transport did not compensate one another as would be expected in such a balance, and this was found to be due to a larger than anticipated effect of the oceanic heat storage term on these multidecadal timescales.

Further study investigating the oceanic heat storage term in the Northern Hemisphere, where Bjerknes Compensation was previously found to hold, would be quite interesting. It would be intriguing to see how this storage term affects the Compensation at these Northern latitudes as well as on which timescales; perhaps it is simply the unique climate of the Southern Ocean region which precludes the Compensation in this region.

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