Identifying the roles of the ocean and atmosphere in creating a rapid equatorial response to a Southern Ocean anomaly

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[1] Recent research has identified a rapid ocean response mechanism to salinity anomalies in the Southern Ocean using an idealised ocean model. Here we examine the relative importance of the ocean and atmosphere in creating an equatorial response to a Southern Ocean anomaly. Using a coupled climate model with realistic bottom topography and land relief, two rapid teleconnections are produced from a high latitude anomaly. An equatorial ocean response can be seen after 30 days. The mechanism producing this response is shown to rely on barotropic and baroclinic oceanic wave propagation. A second, atmospheric, response is seen in the Northern Hemisphere (NH) high latitudes, driven by atmospheric Rossby waves. The ocean quickly responds to the atmospheric signal above it, resulting in sea surface temperature anomalies at NH high latitudes.
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1. Introduction

[2] The tropical ocean and atmosphere is a highly active region of the globe. Phenomena such as El Niño [*Philander*, 1990] play an important role in global climate variability. The tropical atmospheric boundary layer is very sensitive to the sea surface temperature (SST). For example, a small SST anomaly in the tropics can lead to shifts in the location of large-scale convection cells and atmospheric heating [*Trenberth et al.*, 1998]. Previous studies suggest atmospheric teleconnections between the strength of the El Niño-Southern Oscillation (ENSO) index and Antarctic sea ice extent [*Karoly*, 1989; *Simmonds and Jacka*, 1995; *Harangozo*, 2000; *Yuan and Martinson*, 2000]. *Peterson and White* [1998] identify a slow ocean teleconnection linking the Antarctic Circumpolar Wave to ENSO.

[3] *Ivchenko et al.* [2004] demonstrate a mechanism by which it is possible for the ocean to rapidly transmit a response, from a high latitude anomaly to the equator, using an ocean only model with an idealised Pacific basin and Southern Ocean domain. *Richardson et al.* [2005] found evidence of this mechanism in HadCM3, the UK Met Office global coupled climate model. Determining the relative importance of the ocean and atmosphere in transmitting this signal to the tropics is important. We examine the initial rapid response of the coupled ocean-atmosphere system to a salinity anomaly in the Weddell Sea, and show that the mechanism is able to propagate in a coupled climate model with realistic topography.

[4] A coupled climate model allows wave propagation to be excited within the ocean. Use of a mixed-layer (ML hereafter) version of the model removes the ocean's dynamic response, preventing wave propagation. Comparison of the full-ocean (FO hereafter) model to the ML version separates the atmospheric and oceanic responses to the anomaly.

[5] Analysis of the kinetic and potential energy of the ocean component of the model reveals a complex barotropic wave response which transmits energy from the source region to the western equatorial Pacific. A second response to the anomaly is seen in the NH high latitudes, transmitted through an atmospheric teleconnection.

2. Data and Method

[6] To identify the ocean and atmosphere components of the teleconnections two versions of the FORTE (Fast Ocean Rapid Troposphere Experiment) coupled climate model were used [*Sinha and Smith*, 2002; *Smith et al.*, 2004]. The ocean component of FORTE has a horizontal resolution of $2^\circ \times 2^\circ$ and 15 z-coordinate layers. Realistic bottom topography and land geometry are used (Figure 1). It has a T42 spectral atmosphere based on primitive equations, with a horizontal resolution of $2.8^\circ \times 2.8^\circ$ and 15 vertical levels. Exchanges between the ocean and atmosphere occur daily. Spinup of the FO model was carried out for 80 years prior to the experiments, starting from rest with the Levitus (temperature, salinity) climatology [*Levitus and Boyer*, 1998; *Levitus et al.*, 1998]. The model is forced solely by incoming solar radiation with no flux adjustments and the climate produced is close to steady state, with an SST drift of 0.3°C/century. Spinup of the ML model was carried out for 20 years, reaching equilibrium much more quickly due to the absence of a dynamic ocean.

[7] A positive salinity anomaly was added to the Weddell Sea (60°W–0°W, 78°S–58°S, Figure 1). The upper 500 m of the region were fixed to a salinity of 36 for 30 days, starting from January, after which the constraint was removed and the model was permitted to evolve freely. The anomaly equates to an average increase in salinity of 1.25 throughout the region. Importantly, the anomaly creates a density gradient which interacts with topography to produce a barotropic wave response through the JEBAR (Joint Effect of Baroclinicity And Relief) effect [*Ivchenko et al.*, 1997]. The presence of topography is essential for the transfer of energy and deep convection caused by the salinity anomaly significantly enhances the effect. Anomalous convection in the Weddell Sea may

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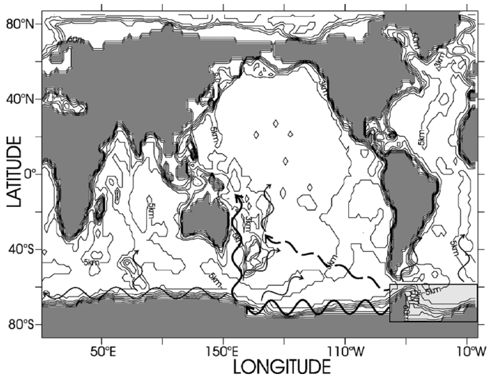

Figure 1. Land mask from the FORTE model, contours show depth in metres. The Weddell Sea anomaly is shaded grey. Arrows indicate the paths of the barotropic waves propagating from the anomaly. The main Kelvin wave (solid) and Rossby wave (dashed) paths discussed in the paper are in bold.

result from Polynya formation [*Gordon and Comiso*, 1988] or changes in sea ice [*Venegas and Drinkwater*, 2001]. Significant salinity anomalies of both signs have been observed in the Weddell Sea area. The anomaly applied to the model is stronger than is realistically possible, but it is only applied for a short period of time. *Ivchenko et al.* [2004] experimented with different magnitudes and durations of anomaly and found that the model responses varied in amplitude but all gave similar results.

[8] The salinity anomaly in the FO model results in strong SST anomalies within the anomaly region. The ML ocean and atmosphere are not capable of responding directly to salinity anomalies so in order to provide the ML atmosphere with a forcing equivalent to that received by the FO model the SST anomaly from the source region is stored daily and imposed onto the ML model ocean in the same location.

[9] A 5 run ensemble was completed for the 360-day control and perturbation runs in both the FO and ML models, with monthly mean output of the diagnostic fields. Two 5 day runs (control and perturbation) of the FO version of the model were also completed with data output every 20 minutes. The high temporal resolution enables the barotropic wave response to be resolved. The first run (BTR-1) covered days 0–5, and the second (BTR-2) covered days 30–35. Anomaly fields are defined as the difference between the perturbation run ensemble mean and the control run ensemble mean.

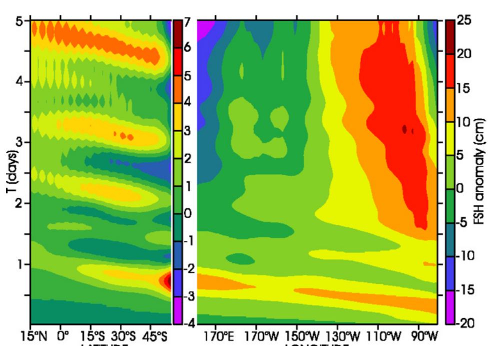

Figure 2. Distance-Time plot of Free Surface Height anomaly (cm) along 60°S and 160°E for initial 5 days of the FO model run (BTR-1).

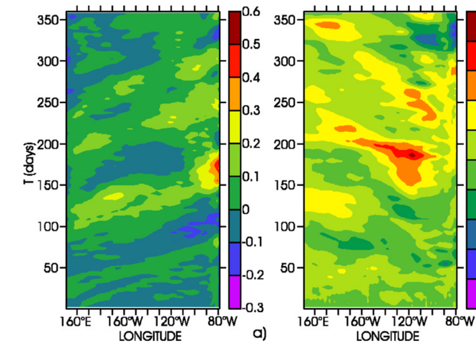

Figure 3. Longitude-Time plot of (a) subsurface temperature anomaly (500 m) and (b) SST anomaly in the equatorial Pacific for 360 days.

3. Results

[10] Use of a high temporal resolution run (BTR-1) allows detailed examination of the initial response over the first 5 days. Deep convection can be seen as an immediate response to the salinity anomaly, because the ocean in this region is weakly stratified. Rapid overturning leads to significant changes of both sign in the source region SST within a day. The free surface height drops rapidly in the Weddell Sea, reaching its minimum after a few days. The perturbation to the free surface excites a rapidly propagating barotropic wave response which propagates across the Pacific in a day (Figure 2), and can be seen to reach all areas of the global ocean within a few days.

[11] Barotropic Rossby waves propagated directly across the Pacific basin to the western boundary in the idealised basin experiment run by *Ivchenko et al.* [2004]. In FORTE topography has a significant effect on the propagation of barotropic Rossby waves. The East Pacific Rise weakens the propagating signal, although barotropic Rossby wave energy can still be seen crossing the Pacific and reaching the western boundary.

[12] Wave energy is channeled along the Southern Ocean in the form of coastally trapped barotropic Kelvin waves, and is removed from the Southern Ocean by a succession of barotropic waves which are seen to propagate along ridge features such as the Mid-Atlantic Ridge and the East Pacific Rise. Barotropic waves follow topographic ridges across the Southern Ocean to Australia and New Zealand and follow the western boundary of the Pacific to the Equator (Figure 2). The clearest barotropic response comes from the start of the perturbation. Successive waves are weaker, but are still clearly visible. Examination of the second high temporal resolution run (BTR-2), not shown, reveals that the same barotropic response persists. The strongest response remains in the Southern Ocean, although wave propagation can clearly be seen in the Pacific, Atlantic and Indian ocean basins. Energy reaches the western boundary of the Pacific in the barotropic mode through both Rossby wave and Kelvin wave propagation.

[13] Data from the lower temporal resolution FO model simulation show baroclinic Kelvin waves propagating east-

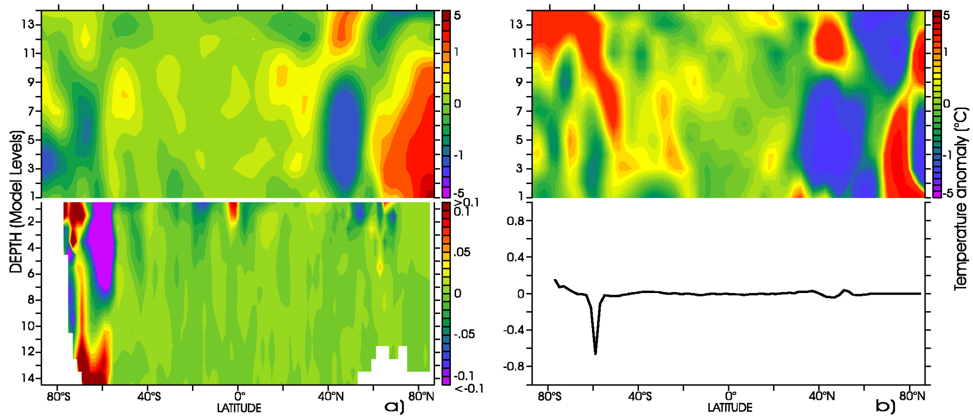

Figure 4. Snapshot of zonally averaged temperature anomalies after 1 month for ocean (lower) and atmosphere (upper) in (a) the FO model and (b) the ML model.

ward along the thermocline at the Equator, crossing the Pacific in 70 days (Figure 3a), which agrees with theory. Propagation begins almost immediately after the start of the run. The waves reflect from the eastern boundary as a series of Rossby waves that are easily visible in the SST (Figure 3b). Propagation of these Rossby waves does not begin until the Kelvin wave first arrives at the eastern boundary. The ML model response displays no evidence of such a disturbance in the SST.

[14] The FO model shows significantly more response in the equatorial and tropical region than the ML model, whilst similar responses in the Southern Ocean and the NH high latitude ocean occur in both models (Figure 4). Equatorial SST anomalies greater than 0.1°C appear after one month in the FO model, similar in magnitude to the anomalies seen in the NH high latitudes. The ML model has no distinguishable temperature anomalies in the equatorial region at this time. The NH response seen in both models also appears one month after the start of the integration. The signal at the equator in the FO model continues to strengthen until the peak SST anomaly occurs after 180 days. No significant signal is seen in the tropical atmosphere until this time.

[15] Equatorial and tropical atmospheric temperature variation in the FO model is very small, compared to anomalies in excess of 1°C seen in the extra-tropics and polar regions. Atmospheric responses to the perturbation are similar in both the FO and ML models throughout the duration of the run. The first remote atmospheric temperature response to the perturbation is seen in the NH high latitudes. This response appears after 30 days in both the ML and FO models, with the NH high latitude atmosphere influencing the SST below it within 2 to 3 days. Following the path of the anomalies in the atmosphere over time it is possible to see a bridge over the tropical latitudes (Figure 4). The first anomaly appears in the source region. It then extends upward and equatorward before descending to produce an anomaly in the high latitude NH surface air temperature, resulting in an SST anomaly shortly after. This bridge can be seen to form before the anomaly has dispersed around the high latitude southern hemisphere, which takes around 50 days. No significant equatorial SST response occurs in the ML model.

[16] Analysis of the kinetic and potential energy of the ocean are used to help clarify the complex process of wave propagation and energy exchanges occurring in the Pacific. Volume averaged values of barotropic and baroclinic kinetic energy, available potential energy and potential energy anomaly are calculated throughout the domain. Near the source of the anomaly all energy values show a strong initial pulse peaking 50 days into the run. After the peak, energy levels decline rapidly over the next 50 days as energy disperses from the source region. Values in the source region continue to reduce over the duration of the run. Barotropic kinetic energy can be seen propagating along the coast of Antarctica toward the western Pacific. Advection of the signal eastward from the source is also visible. For the duration of the run the majority of the energy remains in the Southern Ocean.

[17] Heat storage in the ML model is far smaller than in the FO model, resulting in anomalously large SSTs which can produce a positive feedback with the overlying atmosphere. This results in the ML model having higher amplitude SST variance compared to the FO model, which is able to advect and diffuse heat into a far greater volume of water, preventing excessive SSTs from occurring. The high temperature variance in the ML model dominates the mid-latitudes (Figure 5). The greater response of the FO model to the anomaly in the Southern Ocean is clear. It is also seen to dominate the equatorial region, as well as some locations in NH high latitude Pacific and Atlantic. Topographic

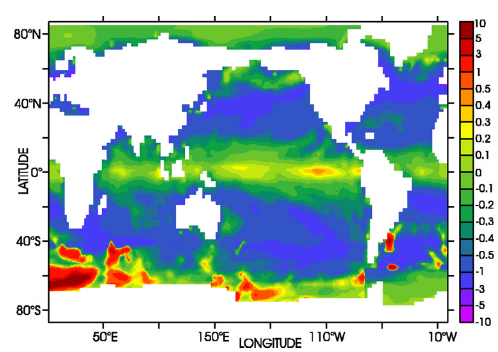

Figure 5. Time and ensemble averaged values of anomaly of T^2 (T^2(FO) − T^2(ML)), with a non-linear scale. Positive(negative) values indicate larger FO(ML) anomalies.

features which extend equatorward from the Southern Ocean, such as the Mid Atlantic Ridge and the Kerguelen Archipelago, also show high levels of energy.

4. Summary and Discussion

[18] The results demonstrate two distinct responses from the salinity anomaly and the contrasting roles of the ocean and atmosphere are made clear.

[19] The ocean mechanism identified is similar to that described in the idealised experiments carried out by *Ivchenko et al.* [2004]. The energy from the anomaly in the Weddell Sea arrives at the western Pacific boundary via two ocean wave mechanisms. Barotropic Rossby waves transmit the signal directly across the Pacific Ocean. Barotropic Kelvin waves follow the Antarctic coastline and form waves which propagate along the ridge systems that extend away from the Southern Ocean. The Kelvin and topographic wave response may not have appeared in the idealised model basin used by *Ivchenko et al.* [2004] due to the absence of topographic ridges. Waves propagate along these ridges which provide a connection between Antarctica and the land masses in the southern hemisphere.

[20] Analysis of the energy budget has clarified the mechanism. The increase in salinity caused by the anomaly drives deep convective overturning in the Weddell Sea and Drake Passage. Interaction between the convection and the bottom topography allows energy exchange between the baroclinic and barotropic modes of propagation, which excites a barotropic wave response that propagates to the western Pacific. Upon reaching the western Pacific, interaction of the barotropic signal with the boundary and topography transfers energy to the baroclinic modes, generating an equatorward baroclinic Kelvin wave response. At the Equator the signal then propagates eastward across the Pacific. Poleward propagating Kelvin waves are formed at the eastern boundary, which in turn form westward propagating Rossby waves which carry energy westward into the basin interior. The equatorial response is very rapid (order of days) due to the involvement of the barotropic mode. Initially the amplitude of the response is weak, but the cumulative effect of a succession of barotropic waves bringing energy to the western boundary results in strong changes in SST. Kelvin waves can be seen propagating in other locations, but these have not been examined in detail here. The strongest SST anomaly in the equatorial Pacific occurs 6 months into the model run, with an amplitude of 2°C. Such a strong equatorial response suggests that this mechanism has good potential for triggering El Niño events, and future work will examine this.

[21] The atmospheric response is shown to affect the NH. Strong SST anomalies formed in the source region perturb the atmosphere and excite an atmospheric Rossby wave response. Rossby waves in the upper troposphere transmit the energy across the equator and into the NH high latitudes [*Tomas and Webster*, 1994]. After 30 days SST anomalies in the NH high latitudes are seen.

[22] The absence of an equatorial SST response in the ML model shows clearly that the presence of a dynamic ocean is necessary for this teleconnection between the Southern Ocean and the tropics to occur. Both the FO and ML models demonstrate significant responses in the NH high latitudes, implying that the mechanism responsible for this response is predominantly atmospheric.

[23] The anomaly applied to this model is larger than would be realistically expected, but is of very short duration. In reality significant changes in the sea ice occur on seasonal or longer timescales, resulting in weaker but more persistent anomalies. The response to the anomaly applied in these experiments is large, with equatorial SST anomalies of 2°C, however *Ivchenko et al.* [2004] have shown that smaller anomalies applied for longer time periods produce similar results.

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