Can the equatorial ocean quickly respond to Antarctic sea ice/salinity anomalies?

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[1] El Niño Southern Oscillation (ENSO) plays a critical role in many of the extremes or anomalies of climate, causing floods, droughts and the collapse of fisheries. Recent studies have revealed a statistically–significant link between equatorial processes and sea-ice anomalies in the Southern Ocean. The generally accepted view is that the primary interaction of the equatorial and polar oceans takes place via the atmosphere. Indeed, the lag in these processes is usually of the order of a few months, and is much too quick to be connected with ocean currents. The question is: can climate anomaly signals effectively and rapidly propagate by another oceanic mechanism? It is demonstrated that signals generated by anomalies in the Antarctic sea-ice cover/ salinity distribution can propagate in a wave-like manner in the form of fast-moving barotropic Rossby waves. Such waves propagates from the Drake Passage to the western Pacific in only few days. This signal is reflected at the western boundary of the Pacific and generates an coastally trapped Kelvin wave moving equatorwards. The resulting temperature anomaly propagates northwards along the western coastline to the vicinity of the equator and increases in amplitude in time. The anomaly in the western edge of the equatorial Pacific then begins to move eastward along the equator as a trapped equatorial wave. After about 2–3 months this wave reaches the eastern coast. This process is suggested as one possible direct mechanism by which the extra–tropical ocean can induce anomalies in the equatorial ocean. *INDEX TERMS:* 1635 Global Change: Oceans (4203); 4215 Oceanography: General: Climate and interannual variability (3309); 4255 Oceanography: General: Numerical modeling. **Citation:** Ivchenko, V. O., V. B. Zalesny, and M. R. Drinkwater (2004), Can the equatorial ocean quickly respond to Antarctic sea ice/salinity anomalies?, *Geophys. Res. Lett.*, *31*, L15310, doi:10.1029/2004GL020472.

1. Introduction

[2] In a number of recent studies, the global links between tropical ocean and Antarctic sea ice extent and other parameters have been revealed [*White and Peterson*, 1996; *Yuan et al.*, 1996; *Peterson and White*, 1998; *Yuan and Martinson*, 2000; *Venegas and Drinkwater*, 2001; *Kwok and Comiso*, 2002]. Statistical analyses have shown such links in the form of statistically-significant correlations or "teleconnections" between Antarctic sea-ice anomalies and global climate variability [*Yuan and Martinson*, 2000; *Kwok and Comiso*, 2002]. Such studies identify several similar, compelling teleconnection patterns that implicate a link between sea-ice and tropical ocean variability via the atmosphere. One of these is between the western–central tropical Pacific and the eastern south Pacific and Weddell Sea regions of the Antarctic. In the Amundsen, Bellingshausen and Weddell sectors of polar Southern Ocean a strong correlation exists between the Southern Oscillation and sea ice anomalies [*Yuan and Martinson*, 2000; *Venegas and Drinkwater*, 2001], with a lag that is observed to be dependent on longitude [*Kwok and Comiso*, 2002]. One of the reasons proposed for the interannual and interdecadal variation in the Southern Ocean could be ENSO signals propagating to high latitudes [*White and Peterson*, 1996; *Yuan and Martinson*, 2000]. The correlation between anomalies in Antarctic sea–ice extent and standard indices of ENSO imply that 40% of the variance in the sea–ice extent anomalies is attributable to ENSO [*Yuan et al.*, 1996]. Moreover, recent studies have also shown a strong relationship between these cycles and freshwater volume flux anomalies as a consequence of the supporting role played by sea-ice drift dynamics [*Drinkwater et al.*, 2001]. Usually it is supposed that the signal originates in the tropics and propagates to the high latitudes in the southern hemisphere, rather than vice versa. In these studies there are either few substantive explanations of the physical mechanisms responsible for such a link, or it is proposed that it takes place via the atmosphere. Our aim is to find a possible mechanism responsible for a link between the Antarctic and the tropical ocean via the ocean.

[3] Changes in the tropical sea–surface temperature (SST) can lead to a strong atmospheric response, as a consequence of deep convective boundary layer and the sensitivity of the tropical boundary layer to SST. Even small SST fluctuations can lead to shifts in the location of large–scale convection and result in anomalies in atmospheric heating [*Trenberth et al.*, 1998].

[4] In contrast to the atmosphere, advective processes in the oceans (i.e., if the signal propagates with the ocean current) are rather slow, with time scales of hundreds of years. If the ocean is to play an active role in establishing a connection between the equatorial ocean and the Antarctic, some other much quicker process must be invoked. One of the possible mechanisms is propagating waves, transporting signals very quickly across global ocean basins.

[5] It is well known that coastally–trapped Kelvin waves propagate along an ocean boundary anticlockwise in the northern hemisphere and clockwise in the southern hemisphere [*Kawase*, 1987; *Johnson and Marshall*, 2002]. If the signal arrives at the equator on the western coast, it propagates along the equator as an equatorial Kelvin wave.

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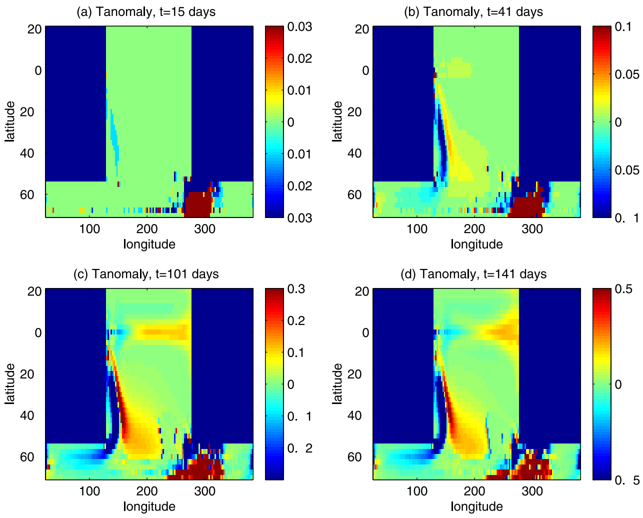

Figure 1. Cartesian representation of the idealised Pacific and Antarctic Circumpolar Current Belt (ACCB) model domain, showing the subsurface temperature anomaly (at the second layer) at four consecutive times (t = 15, 41, 101 and 141 days) in Case 1. The units are in °C.

This scheme is evident for closed basins in the northern hemisphere. However, in the Southern Ocean at the Drake Passage latitudes, there is a periodic, zonally unbounded channel (Antarctic Circumpolar Current Belt (ACCB)) where this scheme is not valid. Consequently, the question posed here is: whether it is possible for a wavelike signal to quickly propagate from a location in the Southern ocean to the equatorial ocean? The answer to this question depends on the opportunity for propagation of the signal in the ACCB. Indeed, as we find below there is an effective and quick response in the tropical ocean to anomalies initiated in the Southern Ocean.

2. Data and Method

[6] To understand the wave–propagation mechanism numerical experiments were carried out with the numerical model INM (Institute of Numerical Mathematics), based on the equations of hydrodynamics [*Zalesny*, 1996]. To improve physical understanding and to allow results to be interpreted more easily, the ocean basin geometry is simplified. The model domain is an area consisting of two connected parts, i.e., a zonal periodic channel and a rectangular basin, representing the Southern Ocean and Pacific, respectively. The external model parameters used here (e.g., wind stress, ocean dimension and depth) are representative of the Pacific and Southern Oceans.

[7] The model is based on the primitive equation system of thermohaline ocean dynamics. The governing equations are written in the bottom following system of coordinates (σ-system). The ocean domain is approximated on a grid 2.5°*2.5°*12 (2.5 degrees latitude and longitude, and 12 σ-levels). The space approximation of the model equations is realized on C grid. The model time step was equal to 12 hours. The numerical algorithm of the model is based on the implicit splitting scheme.

[8] The Southern Ocean bottom topography has a constant depth of 3 km everywhere except for the bump at the model longitude of about 300°, which represents the Scotia Island Arc, the height of which is 1.5 km. In the Pacific the model bottom topography is specified as a linear function of latitude, increasing to the north by 1 km from the depth of the Southern Ocean domain at its northern open boundary. Along the western coastline of the Pacific we constructed a shelf/slope of about 20° east–west extent, and the depth varies by about 800 m between the Western and the Eastern boundaries of the shelf.

[9] The zonally–averaged wind stress was derived from time averaged ECMWF (European Center for Medium range Weather Forecasting) wind fields for the interval 1990–1995 over the Pacific domain. Then a 5-th order polynomial approximation to that field was used. Also, similar polynomial approximations were developed for the zonally averaged surface temperature and salinity over the Pacific from the *Levitus* [1982] climatology.

[10] Numerical experiments were conducted in two stages. In the first stage (integration for 2000 years) the equilibrium solution is calculated starting from constant initial values of temperature and salinity and a motionless ocean. During the second stage (anomaly runs), a local sea surface salinity (SSS) anomaly is applied at the sea surface in the vicinity of the ACC topographic obstacle.

3. Results

[11] The results obtained are based on a number of experiments with different positions of the initial SSS disturbance, its amplitude and ocean bottom topography. Generally speaking all experiments are produced qualitatively similar results. In this study we concentrate only on two experiments. The experiment in Case 1 has the largest amplitude of initial SSS disturbance, with a positive anomaly of 2 psu applied for a duration of 2 month. The experiment performed in Case 2 is a smaller amplitude disturbance of 0.25 psu applied for a longer duration of 1 year.

[12] Model experiments have allowed us to carefully trace the chain of anomaly transfer. Density anomalies, caused by induced SSS anomalies above the variable bottom topography around Antarctica can excite barotropic Rossby waves that propagate quickly to the western Pacific (Figure 1a). Interaction of the barotropic Rossby wave with a western ocean basin coastline generates a Kelvin wave–like boundary mode (Figure 1b). Due to this process a density/temperature anomaly appears along the western Pacific boundary and moves sequentially equatorward. This temperature anomaly propagates eastwards along the equator to the eastern Pacific coast as a trapped equatorial Kelvin wave. (Figures 1c–1d). When the anomaly reaches the eastern coast, it generates poleward coastal Kelvin waves (Figures 1c–1d).

[13] As a consequence of the chain of events above, positive/negative temperature anomalies are formed near the eastern coast of the tropical Pacific. This chain of events may invigorate, reinforce or suppress ENSO cycles. In our experiments the formation of the positive/negative anomalies depends on several factors, such as initial position of the SSS anomaly relative to a topographic obstacle, and the configuration of the bottom topography of the western Pacific (existence of the western slope and continental shelf). At the western continental shelf there is

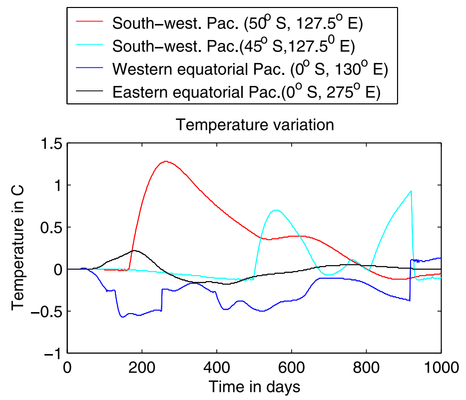

Figure 2. The time variation of the subsurface (level 2) temperature anomaly for four locations (Case 1).

an acceleration in anomaly formation along the western coast. The amplitude of this response is stronger if the duration of the initial disturbance is longer (in our experiments a decrease in the initial SSS anomaly does not necessarily lead to a decrease in temperature response on the equator if the initial disturbance has a longer duration). Similarly, the amplitude of response is also stronger if the ACC transport is higher (note that the ACC transport in our experiments is at least three times smaller than it is in reality [*Ivchenko et al.*, 1996], because of the domain/topography configuration). External parameters, such as topography and model space resolution, would also affect the amplitude of the equatorial response. The strong temperature anomaly appears in the south–western Pacific and western equatorial Pacific after a few months in Case 1 (see Figure 2).

[14] In the experiment with the smallest initial disturbance of 0.25 psu (Case 2) the local temperature anomalies reached −0.56°C and +0.51°C in the south–western Pacific, with value in the western equatorial Pacific between −0.40°C and +0.53°C (see Figures 3–4). The greatest positive and negative anomalies occurring along the equator in the central and eastern Pacific usually happen after 3–7 months, i.e., earlier than after two years (the time corresponding to the Figures 3–4).

[15] Importantly, the initial SSS disturbance has to happen in the vicinity of steep topography to generate barotropic Rossby waves. The wave–generating response is enhanced if deep convection also takes place. The fastest signal moving along the equatorial Pacific is propagated by the means of the first mode of the equatorial trapped wave. The signs of incoming temperature anomalies to the eastern part of equatorial basin is defined by the projection of the actual disturbed temperature field near the eastern part of equatorial Pacific into the series of vertical modes. The structure of the actual disturbed temperature field in the western equatorial Pacific is dependent on the incoming barotropic signal and on the resulting generated baroclinic response. The temperature disturbance is enhanced by mixing in the western Pacific upper ocean.

4. Summary and Discussion

[16] We have demonstrated that there is an effective and quick response in the tropical ocean to the SSS anomalies initiated in the Southern Ocean. It is proposed that these initial SSS anomalies can be stimulated as a consequence of enhanced ice growth coupled with positive sea–ice extent anomalies. To understand the mechanism, a number of numerical experiments were carried out for a simple geometry ocean basin with a primitive equation model INM. Experiments have allowed us to find a potential missing link in the chain of anomaly transfer. We represent the whole scheme as follows:

[17] • (the missed link) density anomalies, caused by sea ice induced SSS anomalies above the variable bottom topography around Antarctica generate barotropic Rossby waves that quickly propagate to the western Pacific.

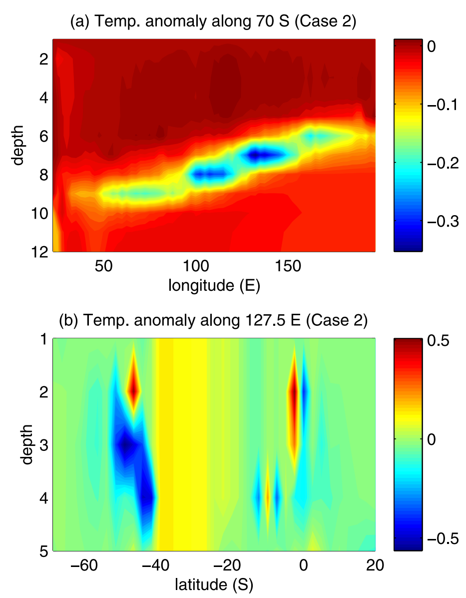

Figure 3. (a) The temperature anomaly on the zonal section along 70°S in Case 2 after 2 years. (b) The temperature anomaly on the meridional section along 127.5°E in Case 2 after 2 years. The units are in °C.

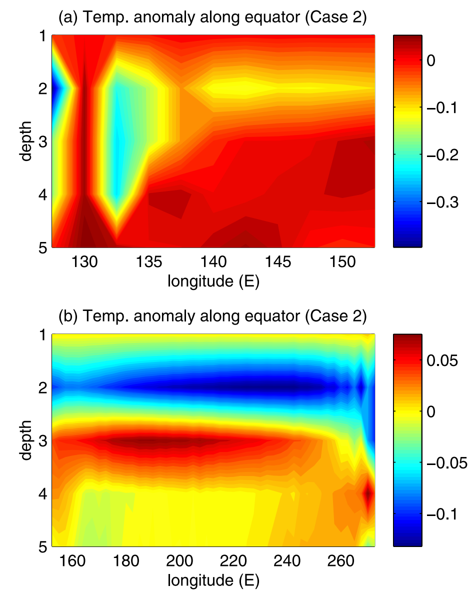

Figure 4. (a, b) The temperature anomaly on the zonal section along equator in Case 2 after 2 years. The units are in °C.

[18] • interaction of the barotropic Rossby wave with a western ocean basin coastline generates a Kelvin wave–like boundary mode.

[19] • due to this process a density/temperature anomaly appears along the western Pacific boundary and moves equatorward.

[20] • this temperature anomaly propagates eastwards along the equator to the eastern Pacific coast as a trapped equatorial Kelvin wave.

[21] • when the anomaly reaches the eastern coast, it generates poleward coastal Kelvin waves.

[22] As a consequence of the above chain of events, positive/negative temperature anomalies are formed near the eastern coast of the tropical Pacific. These events may reinforce or suppress ENSO cycles.

[23] Our main efforts have been applied to study the mechanisms of the quick response of the western and equatorial Pacific to an initial anomaly first generated at a specific, distant position in the Antarctic Circumpolar Current area (like Drake Passage or Weddell Sea). For this purpose a typical range of average values of anomaly were introduced. So, even in the experiment with the smallest initial disturbance (0.25 psu) the local temperature anomalies reached $-0.56°C$ and $+0.51°C$ in the south–west Pacific, with value in the western equatorial Pacific between $-0.40°C$ and $+0.53°C$. Note, that the largest magnitude positive and negative anomalies usually occur after 3–7 months along the equator in the central and eastern Pacific. This is significantly earlier than the situation after a 2 year interval corresponding to Figures 3–4.

[24] The proposed mechanism allows us to estimate the time of equatorial response to major rapid changes in the high latitudes. This mechanism could, under the right circumstances, have significance with respect to rapid extra-tropical tropical oceanic links. Furthermore it may provide a missing link with respect to two–way interactions and teleconnections between Antarctic sea ice conditions and El Niño Southern Oscillation.

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