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ROLE OF SEAICE IN FORCING THE AUSTRAL SPRING ATMOSPHERIC CIRCULATION IN THE CPTEC AGCM

Christopher A. Cunningham *
Center for Weather Forecast and Climate Studies (CPTEC), São Paulo, Brazil

José Paulo Bonatti
Center for Weather Forecast and Climate Studies (CPTEC), São Paulo, Brazil

1. INTRODUCTION

Sea ice is a very important climate control. Its presence changes the surface properties (e.g., albedo and roughness) and acts as an insulator between the cold atmosphere and the relatively warm ocean. The sea ice changes the nature of interaction between the ocean and the Planetary Boundary Layer (PBL), through substantial suppressing in the sensible and latent heat fluxes in the surface. This strongly isolating property associated to the life time in the order of months or longer suggests that the permanence or absence of extensive layers of sea ice might impact the atmosphere.

Despite this hypothesis, observational studies in general, indicate that sea ice is responsive to the large scale atmospheric circulation, mainly in the interannual time scale (e.g., Carleton, 1988; Simmonds and Jacka, 1995). However, there is substantial evidence that indicates that the sea ice contribution to atmospheric anomalies might be considerable. Simmonds and Budd (1991), for instance, have tested the atmosphere's sensitivity to changes in the fraction water/ice over the sea ice pack in the Southern Hemisphere using a R21 Atmospheric General Circulation Model (AGCM). They found that there is substantial warming near the surface of the sea ice pack when the fraction of open water is increased, due to an increasing in the surface heat fluxes, particularly the sensible heat. In general works dealing with alterations in the sea ice concentration lead to the same conclusion: as the proportion of water increases, the surface fluxes intensify and the temperature near the surface rises.

* *Corresponding author adress:* Christopher A. Cunningham Castro, Center for Weather Prediction and Climate Studies, Dutra km 40, 12630-000, SP; e-mail: christopher.cunningham@cptec.inpe.br

There is another category of experiments involving sea ice as boundary condition: those that consider the sea ice as a continuous layer (100% concentration) and modify its extent, exactly as is the present study. Experiments designed like this aims to examine alterations related to the positioning of the Marginal Ice Zone (MIZ), also called Sea Ice Edge (SIE). The MIZ is the region between the frozen sea and the open sea and it presents a marked discontinuity in the surface radiation budget, surface fluxes of latent and sensible heat, and surface roughness (Weller, 1980). As a result of these contrasts the sea ice domain shows strong cyclogenetic behavior and high cyclone frequency (Simmonds et al., 2006).

Herman and Johnson (1978) were among the first to perform an experiment of sensitivity to sea ice extent. Focusing on the Northern Hemisphere, they executed integrations using the Goddard AGCM with a grid box with 4° of latitude by 5° of longitude, and used an artificial envelope of extreme sea ice conditions (maximum and minimum). They found a significant response to the ice edge difference (maximum-minimum) in SLP, 700-mb temperature, and 300-mb heights over the Arctic and North Atlantic and Pacific Oceans. Their results led to the conclusion that MIZ anomalies are capable of modify local climates in certain regions of the high and mid-latitudes. They noted however that the full atmospheric response, far from local perturbation, could not be explained by local thermodynamics, suggesting that dynamical processes were important for the far-field anomalies.

Recent studies have found evidences that the sea ice distribution might even impact on systems of planetary scale such as the storm track positioning or modes of teleconnection in the atmosphere. Alexander et al. (2004) have tested the sensitivity of the atmosphere to anomalous conditions in the sea ice cover in the Arctic, using the CCM3 (version 3 of the National Center for Atmospheric Research Community Climate Model). The results have shown that anomalies in the sea ice extension in the Sea of Okhotsk generate a wave train that extends downstream over North America. Magnusdottir et al. (2004) performing another experiment with the CCM3 found an atmospheric response to sea ice extension in the North Atlantic region that resembled the North Atlantic Oscillation (NAO).

The objective of this study is to examine the potential impact on the atmosphere of the anomalous sea ice coverage conditions observed during 1998, in the Ross and Amundsen sectors around the Antarctic. The reasons that led to choose those regions and this year in particular are given in the section 2. Here we focus on the results in the Pacific and Atlantic sectors during the 1998 year and particularly during August-September-October (ASO), which corresponds to the climatological time of the year with most extensive sea ice coverage.

2. MODEL AND EXPERIMENTAL DESIGN

An experiment with the CPTEC's Atmospheric General Circulation Model (CPTEC AGCM) was performed in order to evaluate the feedback on the atmosphere of the anomalous sea ice layer during 1998. AGCMs proved to be useful laboratory tools in climate research, since they can be used to perform controlled experiments that determine the atmospheric response to variations in one external factor while all other external factors are held fixed.

The record of monthly sea ice area (i.e., the actual area, it does not include areas of open water at sub-pixel resolution) in the Ross Sea during winter and spring was registered in 1998. At the beginning of the year the anomalies were modest, nevertheless during the austral spring, period where extension is maximum, the anomalies increased and remaining very large until the end of that year. Regarding the status of ENSO episodes, 1998 was a transition year between a very strong warm event to a very strong and lingering cold episode.

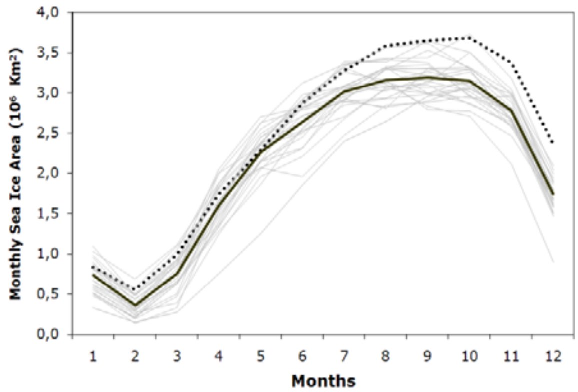

Figure 1 – Annual cycles of sea ice area (areas of open water are not counted up at sub-pixel resolution) in the Ross Sea, spanning the period 1979-2005. The upper dotted curve represents the year with the most (1998) sea ice area during the peak season (ASO). The thick black line is the long term mean (1979-2005).

The CPTEC AGCM is a modified version of the spectral COLA AGCM, which was in turn adapted from the National Centers for Environmental Prediction (NCEP) AGCM. Continuous modifications made by CPTEC's staff generated new versions of CPTEC-COLA, differing along time from COLA versions. The current CPTEC AGCM version is quite different from the COLA GCM in many aspects, for instance, the work done to improve performance in shared and distributed memory architecture computers. More details about achievements in the model developments can be found in Panetta et al. (2007). The sea ice treatment in the CPTEC's model however passed through few modifications. The current formulation is identical to that used in the original COLA AGCM. Detailed information about sea ice treatment the can be found in (Kinter, et al., 1997).

The sea ice information is ingested into the model merged with the Sea Surface Temperature (SST). The distinction is made when the SST is above or below the freezing temperature of sea water (-1.8° C), hence the model assumes that either there is sea ice or there is open ocean at a given grid point. Figure 2 shows the synthesized boundary forcing corresponding to October. Since we decided to use *observed* (during the entire 1998 year) sea ice area anomalies to compose the synthetic boundary condition, there were undesirable regions with less ice than normal, even though our purpose is to study the atmosphere reaction to greater regions covered by sea ice.

One advantage of the current experiment in comparison to previous sea ice AGCM studies is the higher horizontal resolution used in the integrations. While several other studies used T042 (e.g., Magnusdottir et al., 2004), or even coarser resolutions (Hudson and Hewitson, 2001), the current experiment was set as a T062 horizontal resolution with 28 levels in a sigma vertical coordinate system. This horizontal resolution is equivalent to a Gaussian grid with resolution of 1.875° degrees. At the equator this grid equals 210 kilometers, but in the sea ice region (between 60°S e 75°S roughly) it is finer: equivalent to 100 and 50 kilometers respectively.

The experiment consists of the integration of two large ensembles of the CPTEC AGCM. Those were forced under conditions that are identical apart from the sea ice layer distribution in the Ross and Amundsen Seas sector. The Ross Sea is a deep bay of the Southern Ocean in Antarctica between Victoria Land and Marie Byrd Land, delimited roughly eastward between 150°E to 150°W. The Amundsen Sea is the ocean adjacent to the east, extending up to the Thurston Island (99°W).

We hypothesize that the Ross and Amundsen sectors of the sea ice pack around Antarctic might be a key region regarding the feedback of sea ice onto creation and/or propagation of atmospheric disturbances. There are observational and experimental evidences that support this hypothesis. Ambrizzi et al. (1995), for instance, found a key point inside this region (60°S, 175°W) associated with a wave pattern 3 of zonal wavenumber 3 that was able to evolve and propagate from the Southern Pacific into the tropical eastern Pacific and Atlantic. Another characteristic that might be favorable to the interaction between sea ice and atmospheric perturbations is the climatological positioning of the polar jet exit region into this region. The jet streams represent longitudinal non-uniformities in the mean zonal flow that can feed low frequency atmospheric perturbations (Simmons et al., 1983).

The first ensemble consists of 40 members integrated for 2 years each and forced with climatological sea ice and SST as lower boundary condition. The first year allows the model to stabilize while the second year was used as a stable reference state of the atmosphere. A Principal Component Analysis of the 500 hPa geopotential height anomalies of some earlier members (analyzed while the integration was still being performed) showed that the model's circulation takes approximately 25 pentads to reach a state of equilibrium. Hence, an entire year is a satisfactory margin to let the model´s atmosphere reach its equilibrium state. This first ensemble will be hereafter called CTRL.

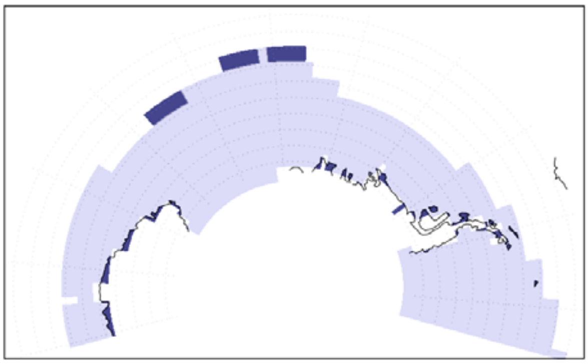

Figure 2 – Illustration of sea ice boundary condition used to force the experiment. The light blue color indicates the grid points with climatological area cover. The dark blue grid cells correspond to the observed monthly mean sea ice extension (delimited by the 15% concentration isoline) in October 1998.

In the second ensemble the sea ice layer was altered only in the Ross and Amundsen Seas, assuming the monthly mean observed values during 1998 (Figure 2). Outside Ross and Amundsen Seas sector the sea ice extension was maintained following the climatological annual cycle (1971-200) aiming to isolate the source of forcing. This synthetic lower boundary condition made use of actual observed sea ice anomalies in order to give a more realistic response.

The SST field was maintained following the climatological cycle everywhere in the globe (i.e., Southern and Northern Hemispheres) in an attempt to reduce or even eliminate the extratropical response associated to variations in the tropical SST patterns, i.e., the El Niño-Southern Oscillation (ENSO) variability.

The anomalous atmospheric response is defined as the ensemble average of the perturbed simulation minus the ensemble average from the CTRL. The initial conditions for all the experiments were taken from the ERA-40 ECMWF Reanalysis (Uppala, et al., 2005) with resolution of 1.125º degree of lat/lon. The MCGA was configured to output daily results that were grouped into pentad data subsequently, for the sake of data compress. This implies that the resulting data set minimizes or does not contain the high frequency variability associated to the baroclinic development of synoptic systems.

3. RESULTS

Figure 3 shows the surface fluxes averaged over the ASO season. Latent and sensible heat fluxes from the surface of the world to the atmosphere are important energy sources for the atmosphere. In the CPTEC MCGA these are parameterized according to bulk aerodynamic schemes in which the flux is assumed to be proportional to the surface wind speed and the potential (moisture or temperature difference between the surface and air near the surface).

As expected, the model responds with attenuated fluxes of latent and sensible heat when the sea ice layer is in excess, resulting in large negative anomalies of net upward surface fluxes. The contrary is true when the sea ice layer is retreated: positive net upward surface fluxes can be seen right above the ice retreatment, due to heat releasing by the ocean.

The seasonal mean simulated values of sensible heat during the spring (ASO) showed magnitudes as large as 120 $W.m^{-2}$. The anomalies during this trimester presented the highest magnitudes compared to the other seasons within the simulated annual cycle in 1998. The sensible heat flux anomalies are larger than the latent heat anomalies, a result that is consistent with findings in other works dealing with similar experiments (e.g., Simmonds and Budd, 1991). However, the proportion between this two quantities is considerable different. Simmonds and Budd (1991) found that in general the latent heat surface fluxes were one third from their counterparts sensible heat fluxes. Alexander, et al. (2004) found that the sensible heat fluxes were about twice the latent anomalies. Here it can be seen (Figure 3) that the sensible heat fluxes are larger in magnitude that the latent heat fluxes in a proportion that is about 1.5 for negative anomalies and approximately 2.5 in the positive anomalies case.

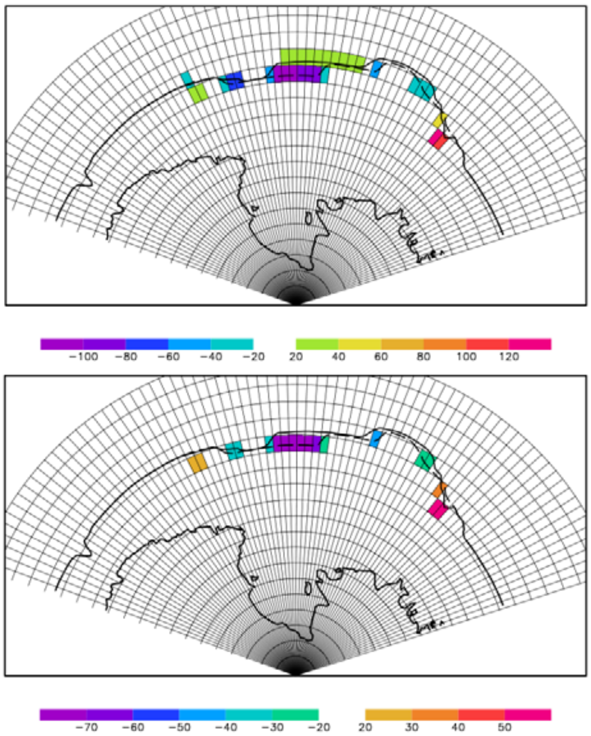

Figure 3 – August to October (ASO) averaged surface sensible and latent heat fluxes anomalies. Dashed curve indicates the LTM sea ice edge. The continuous line indicates the altered (Ross and Amundsen seas) sea ice edge.

The pattern of 2-m temperature anomalies indicates that there is an associated anomalous cooling of the air due to the excessive sea ice coverage. Co-located with the most intense anomalies in the upward fluxes are the lowest temperature anomalies, in the central-eastern sector of the sea ice edge in the Ross Sea. The temperature falling was substantial near the surface (2-meter temperature), presenting negatives anomalies as high as 5.0 K, but decreased rapidly with height registering -0.7 K at 850 hPa (not shown). It can be noticed that the area with negatives anomalies of 2-m temperature extends into locations inside the sea ice pack, where there are no modifications in the surface fluxes. Apparently this is due to advection by the predominant low level winds, as suggested by Figure 4 that shows the climatological simulated (CTRL) flow at 925 hPa.

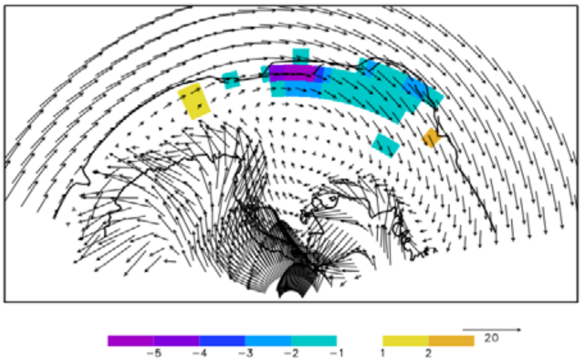

Figure 4 – August to October (ASO) averaged anomalous 2 meters temperature (shaded) and flow at 925 hPa in the CTRL simulation. The dashed curve indicates the LTM sea ice edge. The continuous line indicates the altered (Ross and Amundsen seas) sea ice edge.

It is important to be aware of the inherent variability of the atmosphere. The atmospheric circulation simulated by the AGCM is turbulent as is that of the real atmosphere. Therefore the true signal, excited by the prescribed change in boundary conditions, is masked by random variations (arising as a result of the scale interaction) in a manner that even when the modifications in the experimental run have no effect on the simulated climate, the difference field will be nonzero and will show structure reflecting the random variations in the control and experimental runs. Therefore, it is absolute necessary to apply a statistical test to verify the statistical significance of the detected signal. Recognizing this we applied a Student's t test do identify the significant shift, if any, in the ensemble means (Sardeshmukh, et al., 2000).

Figure 5 shows the patterns of anomalies in the surface pressure associated to the perturbed sea ice condition. Since the sea ice forms at the sea level the surface pressure and the mean sea level pressure are equivalent. The unmasked values indicate the grid points where the differences (i.e., the anomalies) in the means of two populations (i.e., the ensembles) can be considered significant at a 5% significance level. These results show that the cooling near surface is able to induce an anomalous high surface pressure accompanied by an anticyclone circulation at 925 hPa right above the most intense cooling at surface.

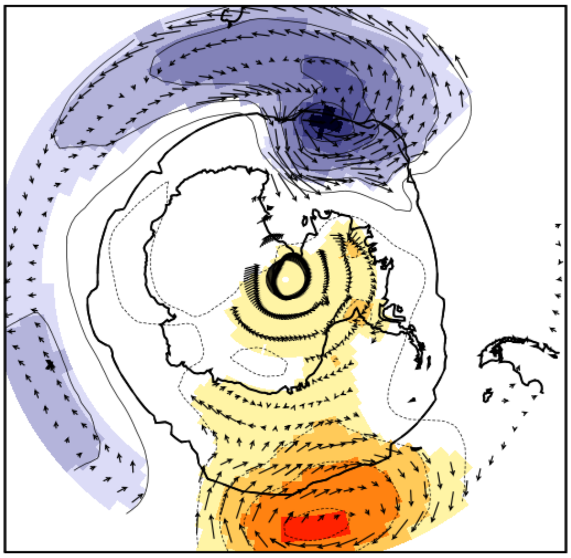

Figure 5 – Simulated anomalous surface pressure averaged during August to October 1998. The unmasked values are statistically significant at 5% level. The contour levels are -1.2 -.9 -.6 -.3 for the reddish tones and 3 6 9 1.2 1.5 and 1.8 for the blue tones. The wind vectors are scaled such that and arrow 1 inch length equals 2 $m.s^{-1}$.

It can be seen that there is a signal in middle to high levels in the atmosphere of the surface perturbation (Figure 6). The center of the anomalous high pressure system at 500 hPa however is displaced northward and westward compared to the center at the surface, suggesting that the surface forcing is not the only factor associated to this anomaly. There is also a significant negative center situated in the eastern hemisphere where there is no intentional surface forcing.

When viewed together those anomalies resemble the teleconnection pattern known as Trans Polar (Pittock, 1980). The Trans Polar pattern arises as result of variations in the wave number 1 that in turns manifest a displacement toward either the Australia/New Zealand or the South America sectors of the circumpolar belt of westerlies, resulting in climate anomalies that are out of phase between those two regions.

Lastly, it is worthwhile to notice that the positive anomaly is largely positioned in a region where the upper westerlies (200 hPa) are decelerating, likely the polar jet exit region. This suggests that the upper level jet stream might be playing an important role feeding the perturbation originated at the surface. Certainly, this hypothesis deserves further investigations.

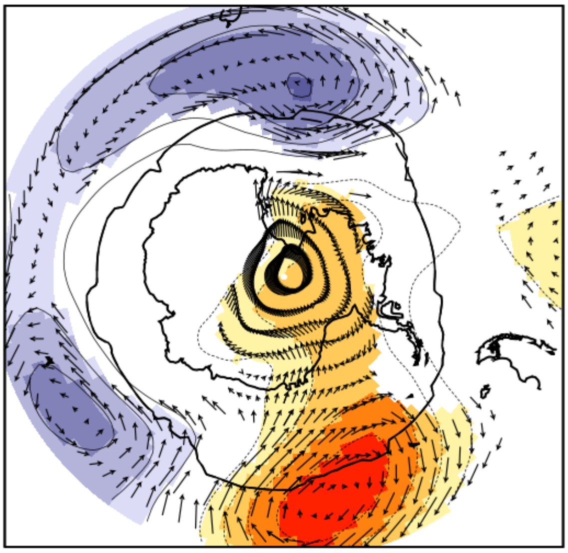

Figure 6 – Simulated anomalous geopotential height at 500 hPa averaged over the trimester ASO 1998. The unmasked values are statistically significant at 5% level according to an ordinary Student's t test to detect differences in the means of two populations. The contour levels are -12 -9 -6 -3 for the reddish tones and 3 6 9 and 12 for the blue tones. The wind vectors are scaled such that and arrow 1 inch length equals 2 $m.s^{-1}$.

4. SUMMARY AND CONCLUDING REMARKS

We have performed an experiment with the CPTEC AGCM in order to assess the role of the sea ice extension in forcing the atmospheric circulation during spring. The experiment was carried out with large ensemble size (60 members) to achieve a satisfactory recognition of signal. The synthetic lower boundary condition was assembled as follows: observed sea ice extension in the Ross and Amundsen sectors of the sea ice pack, climatological sea ice extension in the rest of the sea pack around Antarctic. Global SST followed the climatological annual cycle ever, as well the sea ice pack in the Northern Hemisphere.

The results show that where the sea ice layer was in excess (deficiency) the surface fluxes of latent and sensible heat by the underneath ocean are attenuated (enhanced), leading to large negative (positive) anomalies of net upward surface fluxes. The magnitude of the anomalies was substantial, reaching magnitudes of the order of 100 $W.m^{-2}$ in a seasonal average. In general, the sensible heat flux anomalies presented values larger than the latent heat flux anomalies.

During ASO season, anomalous cooling fluxes in the central-eastern sector of the sea ice edge in the Ross Sea led to a decrease of the near surface temperature. The temperature falling was considerable (>5.0 deg) near the surface but decreased rapidly with height (-0.7 deg at 850 hPa). Associated to the response cooling at the surface there is an anomalously high geopotential pattern at 500 hPa which is statistically significant (Student's t test) at 5% level. This pattern appears to be resultant from both the large scale circulation and the flux induced temperatures anomalies.

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