Rapid climate change in the ocean west of the Antarctic Peninsula during the second half of the 20th century

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[1] The climate of the Western Antarctic Peninsula (WAP) is the most rapidly changing in the Southern Hemisphere, with a rise in atmospheric temperature of nearly 3°C since 1951 and associated cryospheric impacts. We demonstrate here, for the first time, that the adjacent ocean showed profound coincident changes, with surface summer temperatures rising more than 1°C and a strong upper-layer salinification. Initially driven by atmospheric warming and reduced rates of sea ice production, these changes constitute positive feedbacks that will contribute significantly to the continued climate change. Marine species in this region have extreme sensitivities to their environment, with population and species removal predicted in response to very small increases in ocean temperature. The WAP region is an important breeding and nursery ground for Antarctic krill, a key species in the Southern Ocean foodweb with a known dependence on the physical environment. The changes observed thus have significant ecological implications. **Citation:** Meredith, M. P., and J. C. King (2005), Rapid climate change in the ocean west of the Antarctic Peninsula during the second half of the 20th century, *Geophys. Res. Lett.*, *32*, L19604, doi:10.1029/2005GL024042.

1. Introduction

[2] Three regions in the world have shown very rapid atmospheric warming during the second half of the last century [*Vaughan et al.*, 2003]. Of these, only one (the Western Antarctic Peninsula; WAP) is in the Southern Hemisphere. Annual mean atmospheric temperatures here have risen nearly 3°C since 1951, with this warming occurring predominantly during the austral fall and winter (April to September) [*King*, 1994; *King and Harangozo*, 1998; *Turner et al.*, 2005]. The warming has had profound consequences for the Antarctic Peninsula ice sheet, with a recent study showing that the majority of glaciers have retreated during the past 50 years, and that average retreat rates are accelerating [*Cook et al.*, 2005].

[3] Coupled climate models (including those forced with observed increases in greenhouse gases) generally fail to reproduce the WAP warming [*King et al.*, 2004]. Investigations into the cause of the WAP warming have been hampered by the lack of reliable information on atmospheric circulation before the late 1970s. However, recent data have shown a strong correlation between the atmospheric circulation in this region and WAP temperatures. Anomalously cyclonic conditions over the Amundsen-Bellingshausen region are associated with increased warm air advection and thus warmer WAP winters, whilst anomalously anticyclonic conditions are associated with decreased warm air advection and colder WAP winters [*Marshall and King*, 1998]. The trend toward warmer WAP temperatures is thus likely to have been accompanied by a shift toward more cyclonic atmospheric circulation. An increase in precipitation at WAP stations over 1956–1992 [*Turner et al.*, 1997] is consistent with such a shift. Winter temperatures at the WAP have been observed to be strongly dependent on the extent of sea ice in the Bellingshausen Sea (west of the Peninsula), and available evidence indicates that a reduction in sea ice extent coincided with the WAP warming [*King*, 1994; *King and Harangozo*, 1998; *Turner et al.*, 2005; *Vaughan et al.*, 2003].

[4] Given the dramatic changes in atmospheric conditions at the WAP, the potential for changes in the adjacent ocean is clear. This region is an important spawning ground for Antarctic krill, a key species in the Southern Ocean food web that was recently demonstrated to have a significant dependence on changes in the physical environment [*Atkinson et al.*, 2004]. Other marine species sampled in this region have also been shown to have extreme sensitivities to the physical ocean environment, with population and species removal predicted in response to very small increases in temperature [*Peck et al.*, 2004]. In this paper, we examine the climate change in the ocean to the west of the Antarctic Peninsula during the second half of the twentieth century, and its implications.

2. Methods

[5] We examined oceanographic changes in the region west of the WAP using hydrographic data from two recent compilations of ocean properties spanning the second half of the twentieth century [*Boyer et al.*, 2005; *Levitus et al.*, 2005]. These were originally compiled by the National Oceanographic Data Center, and interpolated onto a 1 degree-square grid at standard depth levels. The Southern Ocean is notoriously data-sparse, particularly during earlier eras; to protect the reliability of our results, we omitted from consideration any (interpolated) gridpoints for which no actual measurements were used when compiling the censuses, and derived decadal means using non-overlapping data fields on the same grid and considering only fields which contained data from within the austral summer. (Strong seasonal bias exists in the timing of data collection, thus data presented here relate solely to the austral summer). Whilst the distribution of times of data collection within the austral summer varied during the sequence of measurements, there was no systematic change in the timings such as could lead to apparent trends in ocean
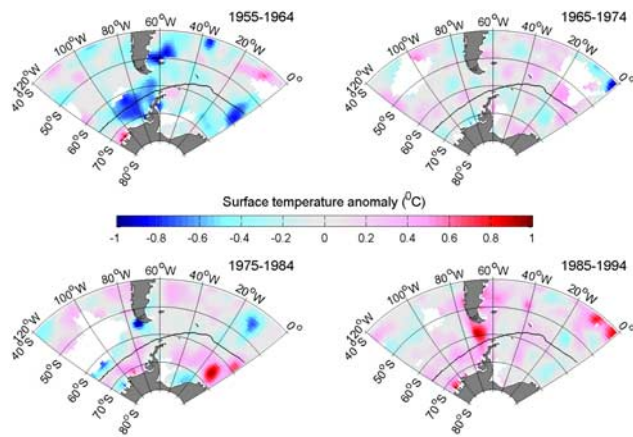
Figure 1. Decadal means of summer surface temperature anomalies for the second half of the twentieth century. Gridcells with no data are left white. Note the significant negative anomalies close to the Antarctic Peninsula during the period 1955–64, a region that becomes progressively warmer during the sequence. The average September ice extent for 1979–2002 is plotted, derived from satellite microwave data as the 15% ice concentration limit using the Bootstrap algorithm [*Comiso*, 1995].

properties. The number of casts used to create each decadal field in the WAP region (here taken as 60–75°S, 60–100°W) are 217 (1955–64), 260 (1965–74), 505 (1975–84) and 425 (1985–94). Further details of the hydrographic data used are available at http://www.nodc.noaa.gov/OC5/WOA01/pr_woa01.html.

[6] A mixed layer model [*Meredith et al.*, 2004; *Price et al.*, 1986] was created to illustrate the key role of sea ice production in determining upper ocean properties. The upper 200 m of an idealized ocean was simulated, using initial ocean conditions from hydrographic data collected at the WAP [*Meredith et al.*, 2004] and surface forcing derived from meteorological data obtained at the WAP. For each timestep, three criteria for vertical stability were applied; these depend on static stability, the bulk Richardson number criterion, and the gradient Richardson number criterion. Following this, vertical advection and vertical turbulent mixing were applied. Vertical advection is permitted in the model, but horizontal advection and mesoscale variability are not. Wind stress is applied as a vector to allow shear at the base of the mixed layer to influence the mixing. The model was run with monthly-mean (seasonally repeating)

values for 4 years. The model was subjected to arbitrary sea ice production in a one-dimensional, unidirectional sense. To illustrate the key role of sea ice production, we ran the model with two configurations: firstly with unaltered forcings, and then with purposefully doubled sea ice production rates.

3. Results

[7] Decadal sea surface temperature anomalies (Figure 1) reveal a large cold anomaly in the Bellingshausen Sea, west of the Peninsula, during 1955–64. This was around 0.8°C colder than average, and extended through Drake Passage toward the South Atlantic. The annual mean air temperature at Faraday Station on the WAP was also anomalously low during this period (−4.9°C (Table 1)), as was the average summer air temperature (−0.1°C (Table 1)). The cold oceanic anomaly during this period was not present subsequently, being replaced by successively warmer waters (Figure 1). The warming was surface-intensified (Figure 2), its magnitude decaying virtually to zero by around 100 m depth. The warming trend is very significant; it greatly exceeds those for the deep Southern Ocean or the global ocean as a whole presented previously [*Gille*, 2002; *Levitus et al.*, 2005], and indicates that the rapid climate change observed in this region is not restricted to the atmosphere.

[8] Although there are fewer reliable salinity data, it is clear that the upward trend in temperature in the Bellingshausen Sea was accompanied by a trend toward higher summer salinity (Figure 3). This was also strongly surface intensified (Figure 3). The greatest change in surface salinity west of the Peninsula during the second half of the twentieth century was greater than 0.25. The magnitude of this change exceeds even the remarkable change in salinity observed in the Ross Sea during the same period (around 0.1–0.15 [*Jacobs et al.*, 2002]), although notably with the opposite sign and an influence over a shallower depth range.

[9] The trend toward higher surface salinity in the Bellingshausen Sea during summer is consistent with the previous observation of decreasing winter sea ice extent. The key role of sea ice production in explaining these changes is shown in the mixed-layer model runs. During austral winter (the time of highest seasonal salinities), the model run with increased ice production showed marginally higher surface salinities than the run with standard ice production, as a consequence of greater brine rejection (Figure 4, upper panel). This enhanced sea ice formation stores extra freshwater in solid form at the sea surface,

Table 1. Decadal Means of Annual, Winter (June–August) and Summer (December–February) Air Temperatures (°C) at Faraday on the Western Antarctic Peninsula. Also Shown Are Decadal Sea Surface Temperature (SST) and Sea Surface Salinity (SSS) Anomalies at 65°S, 70°W[a]

| | Air Temperature | | | | |
Decade	Annual	Winter	Summer	SST Anomaly	SSS Anomaly
1955–64	−4.9	−10.6	−0.1	−0.7	−0.09
1965–74	−3.5	−7.6	+0.3	0.0	−0.03
1975–84	−4.3	−9.5	+0.3	+0.1	+0.01
1985–94	−3.3	−7.2	+0.8	+0.5	+0.09
1995–04	−2.6	−5.7	+0.8		

[a]Note the period of low atmospheric temperatures during the late 1950s/early 1960s and the progressive warming thereafter, coincident with the warming of the surface ocean west of the Peninsula.
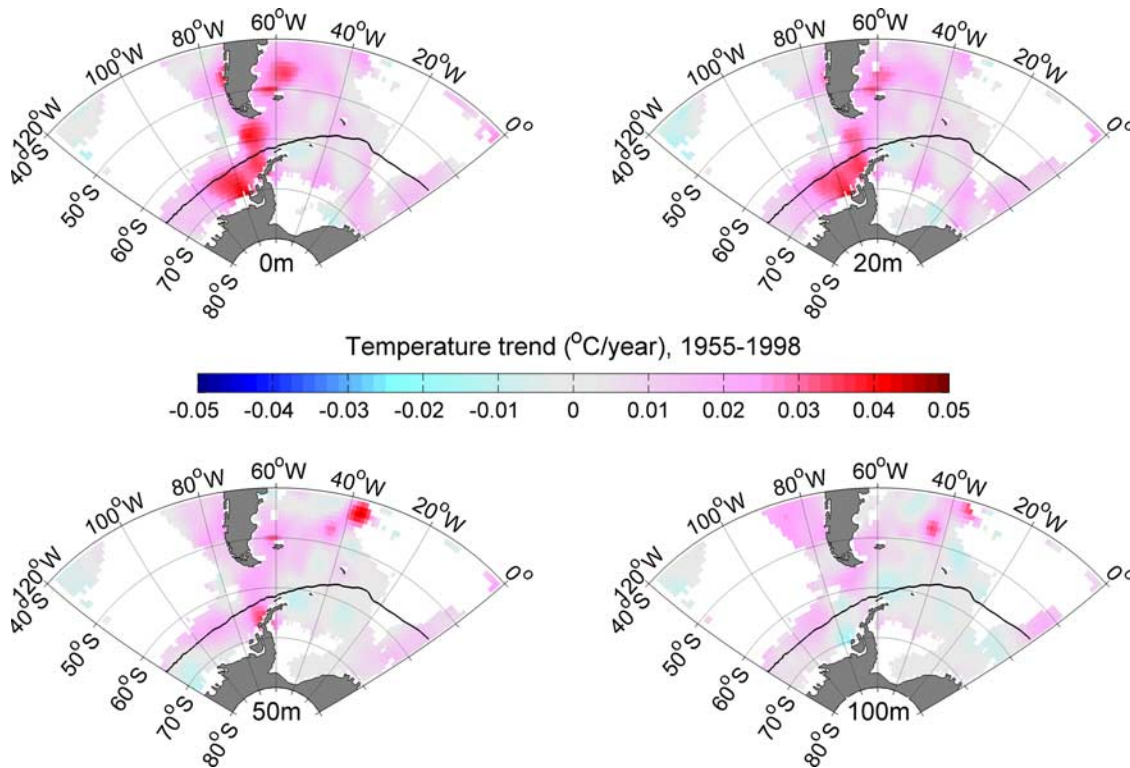
Figure 2. Trends in ocean summer temperature during 1955–1998, for four different depth levels (surface, 20 m, 50 m and 100 m). Gridcells with no data are left white. Note that the significant warming trend observed close to the Antarctic Peninsula is strongly surface-intensified, decaying virtually to zero at 100 m depth.

however the rejected brine is distributed over the full depth of the winter mixed layer. Consequently, the difference in surface salinity between the two model runs is not very large at this time of year. The following summer, the melting of the extra sea ice formed adds significant extra freshwater at the surface. This stabilises the water column, thus the freshwater anomaly tends to be retained near the surface and the freshening effect at this level is very strong.

Thus, for the surface waters, the summertime freshening caused by enhanced sea ice melt greatly outweighs the salinification caused by the enhanced sea ice formation the previous winter (Figure 4). This process explains the fresher nature of the surface ocean during 1955–64, when ice formation was especially strong in the Bellingshausen Sea
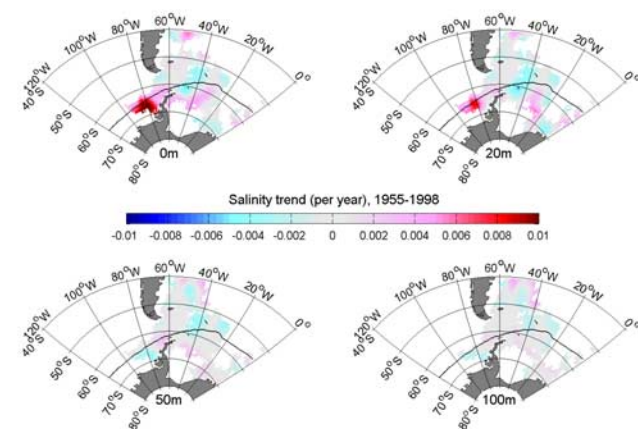

Figure 3. As for Figure 2, but for salinity. Note that the significant trend toward higher salinity west of the Antarctic Peninsula is strongly surface-intensified. Surface salinities in the region of highest trend increased by over 0.25 during the second half of the twentieth century.
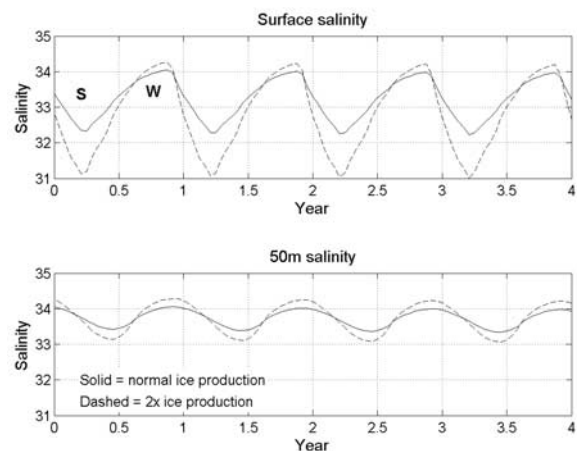

Figure 4. Results from the PWP mixed layer model. Upper panel is surface salinity; lower panel is salinity at 50 m, both as a function of time. Solid line is for model run under standard forcings (the control run); dashed line is same but with arbitrarily doubled sea ice production. Winter (W) and summer (S) conditions are marked. The origin of the horizontal axis is the turn of the year.

[King and Harangozo, 1998], and the subsequent trend toward higher salinities as ice formation decreased. The lower panel of Figure 4 shows that the effect of this process decreases significantly with depth, in accord with the observations.

4. Discussion

[10] The explanations we have presented for the observed changes are essentially one-dimensional, and do not invoke changing circulation of either ocean or ice to explain the observations. Clearly changes in circulation can occur, but they are apparently not the critical factor in explaining the observed trends. For example, sea ice drift in the Bellingshausen Sea is less persistent than in the strong gyres of the Weddell and Ross Seas [Stammerjohn et al., 2003]. Once formed, advection will act to move oceanic anomalies out of the WAP region. However, the forcings for the ocean trends (from the atmosphere and cryosphere) remain in the area of the WAP, thus the ocean anomalies will always be strongest here. Air/sea/ice interaction will progressively erode these anomalies as they advect away from the region.

[11] Note that we explain the observed oceanographic trends as surface-induced responses to atmospheric and cryospheric changes. Other possible theories, such as enhanced upwelling of underlying warmer waters, do not explain the observations, in particular the surface intensification of the trends. The pattern of response is consistent with a trend toward increasingly cyclonic atmospheric conditions in the region, as inferred previously [Marshall and King, 1998].

[12] Significant feedbacks will be induced from the oceanic trends. Both the temperature and salinity trends are in a direction that will act to reduce future sea ice production. Since a reduction in ice cover was important in the instigation of these trends, they thus constitute positive feedbacks acting to promote further warming and salinification of the summer ocean surface. The magnitudes of these feedbacks are very significant: a $1°C$ warming of the upper 25 m of the water column is equivalent to the energy required to form about 0.3 m of sea ice. This is a large fraction of the winter ice thickness in the Bellingshausen Sea (typically $0.5-1.0$ m [Timmermann et al., 2004]). Consequently, the observed warming of the ocean in summer will have contributed very significantly to a reduction in winter sea ice extent, and, in turn, to the rapid atmospheric warming that has been observed in this region during winter.

[13] There are other significant cryospheric impacts of these findings. For example, it was shown recently that the majority of glaciers on the Antarctic Peninsula are retreating, and that the retreat rates are accelerating [Cook et al., 2005]. Other works have shown that the melt rates of glaciers depend critically on the temperature of the ocean that they are in contact with [Shepherd et al., 2004]. Consequently, our findings of very strong surface warming and positive ocean feedbacks have significant implications for the future of the ice sheet in this region.

[14] Antarctic krill populations in the Southern Ocean have declined since the 1970s, and it was argued recently that changes in sea ice formation and distribution were important for this [Atkinson et al., 2004]. Krill are believed to favour cold water, however the possible influences of changes in ocean temperature were not considered. Our results suggest that, for the depth range of relevance to krill, major oceanographic changes have occurred in one of their key spawning and nursery areas during the second half of the twentieth century. If ocean temperatures continue to rise, and sea ice formation decreases further, it is very possible that the krill population will see significant further declines. This has broader implications for the regional-scale ecosystem, for which krill is a key species. From analysis of samples collected between 8 and 15 m depth at the WAP, it is known that other species in this region are very sensitive to changes in ocean temperature, due to a loss of aerobic capacity as warming occurs [Peck et al., 2004]. It was suggested that the majority of Antarctica's benthic species would be at risk of at least population level losses from only a $1-2°C$ increase in local summer ocean temperatures [Peck et al., 2004].

[15] Our work has shown that changes of a magnitude significant to the operation of the ecosystem are conceivable at the WAP over just a few decades, and are already underway. Further, we have shown that the changes in ocean properties, with higher temperatures and higher salinities, both act as positive feedbacks. Consequently, we conclude that the ocean is acting to sustain and amplify the atmospheric and cryospheric changes, making serious impacts on the marine ecosystem even more likely.

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