The Influence of Southern Hemisphere Sea Ice Extent on the Latitude of the Mid-Latitude Jet Stream

J. Kidston

University of New South Wales, Sydney, NSW, Australia

Taschetto, A. S.

University of New South Wales, Sydney, NSW, Australia

Thompson, D. W. J.

Colorado State University, Fort Collins, Colorado, USA

England, M. H.

University of New South Wales, Sydney, NSW, Australia
An atmospheric general circulation model with prescribed sea-ice and sea-surface temperatures is used to examine the sensitivity of the atmospheric circulation to changes in sea-ice extent in the Southern Hemisphere. Experiments are conducted where the sea-ice edge is expanded or contracted by 7 degrees of latitude compared with its position in a control run. The experiments suggest that the latitude of the sea-ice edge influences the latitude of the Southern Hemisphere mid-latitude jet stream, but that the amplitude of the atmospheric response depends critically on the location and seasonality of the sea-ice anomalies.

During the cold season, the mid-latitude jet shifts significantly poleward when the sea-ice extent is increased, but exhibits very little response when the sea-ice extent is decreased. During the warm season, the jet does not shift significantly regardless of whether the sea-ice edge is extended or contracted. The cause of the asymmetry in the atmospheric response relates to the extent to which the sea-ice anomalies affect meridional temperature gradients in the near-surface baroclinic zone. The results suggest that future decreases in Antarctic sea-ice are unlikely to have a profound effect on the Southern Hemisphere mid-latitude circulation.
1. Introduction

The mid-latitude storm tracks reside in a broad latitudinal zone where the mean-state is baroclinically unstable. In the Southern Hemisphere this is over the Southern Ocean at around 50°S, which is where the largest sea surface temperature (SST) gradients occur (e.g., [Hoskins and Hodges, 2005]). Baroclinic waves are generated near the surface in this region, and then propagate vertically into the free troposphere, where a component of the wave activity propagates meridionally. The meridional propagation is accompanied by a flux of westerly momentum into the latitude of largest wave generation, and the convergence of the momentum flux drives the barotropic component of the extratropical zonal-mean flow (e.g., [Held, 1975; Robinson, 2000].

As such, the region of large meridional gradients in SST over the Southern Ocean is collocated with the mid-latitude jet and its attendant wave growth in the lower troposphere, momentum flux convergence aloft, and “eddy-driven” surface westerlies.

Variability in the SST field is expected to have only a modest effect on the mid-latitude atmospheric circulation. Typical interannual mid-latitude SST anomalies are on the order of 0.5-1 °C, and these yield anomalous surface heat fluxes of 1-5 W m⁻² [Kushnir et al., 2002]. Such small fluxes are not expected to have a significant “direct” thermodynamic effect on the large-scale circulation of the mid-latitude atmosphere, at least on interannual timescales [Kushnir et al., 2002; Sen Gupta and England, 2007]. This is because the typical mid-latitude SST anomaly yields relatively modest changes in the lower tropospheric thickness, and these are readily damped by anomalous meridional temperature advection [e.g. Kushnir et al., 2002]. However, mid-latitude SST anomalies are theorized to have a more notable “indirect” effect on the extratropical circulation via their influence on low level baroclinicity and thus the genera-
tion of baroclinic waves and the location of the mid-latitude jet [Kushnir et al., 2002; Brayshaw et al., 2008]. In modelling experiments, when the surface baroclinicity is perturbed, there is a tendency for the jet to move towards the latitude of the increased baroclinicity and away from latitudes of decreased baroclinicity [Brayshaw et al., 2008; Chen et al., 2010]. In this regard, the eddy fluxes of heat can be thought of as diffusive: the largest meridional eddy heat fluxes (and baroclinic energy conversion) are collocated with the largest meridional temperature gradients, and vice versa. This picture is complicated by non-linear wave-mean flow interaction, where the eddies themselves dictate the mean state of the atmosphere, and consequently the location of the baroclinically unstable zones [e.g. Robinson, 2006].

In contrast to the SST field, variability in sea-ice extent is associated with relatively large surface heat flux anomalies [Magnusdottir et al., 2004], typically as large as 100 W m$^{-2}$ [e.g. Alexander et al., 2004]. Sea-ice anomalies therefore have the potential to exert a more significant influence on the atmospheric circulation than SST anomalies. Model studies focused on the Northern Hemisphere have found that removing ice around Greenland causes the mid-latitude jet to shift equatorward [Magnusdottir et al., 2004; Deser et al., 2004]. In contrast, model studies focused on the Southern Hemisphere have found that removing sea-ice from around Antarctica during austral winter causes the mid-latitude jet to shift poleward [Simmonds and Budd, 1991; Simmonds and Wu, 1993; Menndez et al., 1999]. Menndez et al. [1999] argued that there is very little atmospheric response to the removal of Southern Hemisphere sea-ice during austral summer, since the climatological air-sea heat fluxes are relatively small at that time, such that perturbing the sea-ice field yields relatively small changes in diabatic heating.
Understanding the atmospheric response to sea-ice variability is important, since sea-ice is expected to change in response to future climate change. The influence of future trends in sea-ice concentration on the atmospheric circulation depends on both the areal extent and the latitude of the sea-ice changes. For example, Deser et al. [2010] argue that the negative feedback that North Atlantic sea-ice anomalies exert on the latitude of the mid-latitude jet is likely to be small in practice because the area covered by the projected sea-ice anomalies is relatively small. In contrast Southern Hemisphere sea-ice covers a broader geographical region and protrudes further equatorward than Northern Hemisphere sea-ice, thus there is a greater potential for a large scale atmospheric response to changes in sea-ice over the Southern Ocean. However, future changes in Southern Hemisphere sea-ice extent remain unclear, and observations indicate only small net changes in Southern Hemisphere sea-ice extent over the past few decades [Cavalieri et al., 1997; Cavalieri and Parkinson, 2008; Liu et al., 2004]. Numerical experiments generally project widespread decreases in Southern Hemisphere sea-ice in response to increasing greenhouse gases [Sen Gupta et al., 2009], but some studies indicate increases [Manabe et al., 1992; Zhang, 2007].

The goal of this study is to examine the large-scale response of the Southern Hemisphere atmospheric circulation to anomalies in sea-ice extent. This is accomplished by forcing an atmospheric general circulation model with large increases and decreases in sea-ice extent during both the Southern Hemisphere warm and cold seasons. The application of such large changes in ice extent allows us to derive some general and apparently robust results regarding the role of sea-ice anomalies in the large-scale Southern Hemisphere extratropical circulation. The results suggest that: 1) large decreases in sea-ice extent have no discernible impact on the large-scale
atmospheric circulation during either the warm or cold seasons; 2) large increases in sea-ice extent perturb the large-scale atmospheric circulation during the cold season, but not during the warm season; and 3) the changes in the large-scale atmospheric flow during the cold season are consistent with the effects of the sea-ice boundary on lower level baroclinicity. The implications of the results are that: 1) future reductions in Southern Hemisphere sea-ice extent are expected to exert very little influence on the large-scale atmospheric circulation, at least in the Southern Hemisphere; and 2) year-to-year variability in sea-ice has implications for seasonal prediction mainly during the cold season and only in the case of increases in sea-ice extent.

2. Data and Methods

The atmospheric general circulation model (AGCM) used in this study is the Community Atmosphere Model (CAM3) from the National Center for Atmospheric Research (NCAR). The model was run in T42 horizontal resolution, with 26 vertical levels. The vertical coordinates are a sigma-pressure hybrid system that combines a terrain-following sigma coordinate at the surface with a pressure-level coordinate at the top of the model. A complete description of the CAM3 can be found in Collins et al. [2006].

The model was run with a seasonally varying climatology prescribed for the land, ocean, and sea-ice components. For the control run (CTRL), the SST and the fractional area of sea-ice coverage (F) were taken from the Hadley Centre global analyses between December 1979 and November 2008 (HadISST1, Rayner et al. [2003]). This data is available at 1°x1° resolution, and was interpolated to the same horizontal resolution as the AGCM. The Community Sea Ice Model (CSIM5; Briegleb et al. [2004]) was used to calculate energy fluxes between the ice and the atmosphere.
In addition to *CTRL*, an experiment named *ICE*+ was conducted in which the extent of the sea-ice was increased by 7° of latitude over its climatological position in the Southern Hemisphere. At each longitude, the value of F in the gridbox closest to the continent remains unchanged. Equatorward of this, all values of F were shifted 7° towards the equator. The resulting “gap” in sea-ice was then filled by a linear interpolation between the two values of F that were previously contiguous. A third experiment (*ICE*−) was conducted where the extent of the sea-ice was reduced by 7° relative to the climatological coverage over the Southern Hemisphere. Here the values of F for the gridboxes within 7° of the continent were removed, and all remaining values were shifted 7° towards the pole.

All numerical experiments were integrated for 50 years, and thus the seasonally-varying control climatology, the response to *ICE*+, and the response to *ICE*− are for all practical purposes derived from 50 independent samples.

### 3. Results

The seasonal cycle of sea-ice extent integrated over the entire Southern Hemisphere is shown in Figure 1 (a). The results are given in units of square kilometres, and were found by 1) multiplying the prescribed sea-ice extent and fractional sea-ice coverage at all gridboxes and 2) summing the resulting products over the entire Southern Hemisphere. There is a strong seasonal cycle in Southern Hemisphere sea-ice extent which clearly lags the seasonal cycle of insolation by 2-3 months: sea-ice extent peaks in September and has its lowest areal extent in February. The shaded regions in Figure 1 (a) denote the times of maximum and minimum Southern Hemisphere sea-ice extent, and will be referred to hereafter as the warm (Jan-Mar), and cold (Aug-Oct) seasons.
The location of the sea-ice edge (defined as \( F = 0.15 \)) is shown for all three experiments in Figures 1 (b) and (c) for the warm and cold seasons, respectively, with the associated zonal means shown in panels (d) and (e). In the \( ICE^+ \) experiment, the sea-ice edge is extended uniformly at all longitudes. In the \( ICE^- \) experiment, the sea-ice edge is decreased uniformly at all longitudes during the cold season, but is withdrawn by either 7 degrees latitude or up to the continental boundary during the warm season. Nevertheless, sea-ice extent is clearly reduced in \( ICE^- \) during the warm season, particularly around the Peninsula and western Antarctica (Figure 1b).

The response of the zonal-mean flow to the different sea-ice extent configurations is presented in Figure 2, shown as the difference between the 50-year average of the perturbed sea-ice experiments (\( ICE^+ \) and \( ICE^- \)) and \( CTRL \), for both the cold and the warm seasons. The shading corresponds to the amplitudes of the differences, and differences are only shaded where the associated t-statistic is significant at the 95% level based on a 2-tailed test assuming 50 independent samples. The most striking aspects of the results in Figure 2 are that: 1) the response of the zonal-mean zonal flow is robust for the experiment \( ICE^+ \) during the cold season (Figure 2b); but 2) the response is extremely weak for both experiments during the warm season (Figures 2a, 2c), and for the \( ICE^- \) experiment during the cold season (Figure 2d). The equivalent-barotropic nature of the cold season response to \( ICE^+ \) is indicative of a poleward shift in the mid-latitude jet, and can be described as a shift towards the high index polarity of the Southern Annular Mode (SAM). The cold season response to \( ICE^- \) is accompanied by marked increases in the eddy fluxes of heat in the lower troposphere near 60°S and in the eddy fluxes of momentum at the tropopause level near 50°S (results not shown).
The results in Figure 2 can be interpreted in the context of the corresponding changes in surface air temperature \( T_s \). During the cold season, increasing the sea-ice extent results in a band of anomalously cold \( T_s \) at the latitudes of increased sea-ice extent (Figure 3b). The cold anomalies in \( T_s \) are consistent with the insulating effects of the sea-ice anomalies, i.e., the sea-ice anomalies insulate the atmosphere from the much warmer ocean and thus reduce the sea-air heat flux. The anomalous cooling results in a sharp increase in the meridional temperature gradient \( T_y \) near about 55 S (Figure 4b). Since the generation of baroclinic waves in the lower troposphere (and thus the eddy heat flux and the mid-latitude jet) tend to follow the changes in lower tropospheric baroclinicity, increasing \( T_y \) on the poleward flank of the mid-latitude jet yields a poleward shift in the latitude of the jet [Brayshaw et al., 2008; Chen et al., 2010].

The lack of a robust response to sea-ice anomalies of either sign during the warm season is also consistent with the changes in \( T_s \). During the warm season, the magnitude of the \( T_s \) anomaly is much smaller than it is during the cold season (compare the left and right columns of Figure 3). The modest warm season response in \( T_s \) is consistent with the relatively weak climatological air-sea heat flux during the warm season. Put simply the sea-ice is less effective at altering the total air-sea heat flux because the atmosphere and ocean are near the same temperature (see also [Menndez et al., 1999]). Since the corresponding changes in lower tropospheric baroclinicity are very small during the warm season (Figures 4a and 4b), it follows that the response of the mid-latitude jet \( \bar{u} \) is weak.

Why is there no atmospheric response to decreasing sea-ice during the cold season? Unlike the warm season, the reduction of sea-ice in the cold season leads to large changes in \( T_s \) (Figure 3d). However, despite this significant change in \( T_s \), there is no pronounced change in
the atmospheric flow. There are two possible explanations for the apparent non-linearity of the cold season response. The first is that the changes in total $T_y$ between $ICE^+$ and $ICE^-$ have very different projections onto the latitude of the climatological mean mid-latitude jet. For example, the cooling in $ICE^+$ is equatorward of the climatological ice-edge, whereas the warming in $ICE^-$ is poleward of the climatological ice edge. Thus the changes in $T_y$ in experiment $ICE^+$ lie just poleward of the climatological mean jet and its associated baroclinic zone, whereas the changes in $T_y$ in experiment $ICE^-$ lie far poleward of the jet. As such, increases in sea-ice extent are presumably more effective at influencing developing baroclinic waves and the latitude of the jet than decreases in sea-ice extent. Tentative support for this idea can be found in the results of Chen et al. [2010], where changes in $T_y$ have a larger impact when they are located close to the climatological maximum $T_y$.

A second explanation may lie in the sign (i.e., not the location) of the changes in $T_y$. An increase in $T_y$ has the potential to change the latitude of maximum $T_y$, which presumably determines the latitude of largest baroclinic wave generation (Kushnir and Held 1998). In contrast, a decrease in $T_y$ does not alter the latitude of maximum $T_y$, assuming the decrease is away from the latitude of the climatological maximum. To the extent that growing eddies “feel” the total (not anomalous) $T_y$, it follows that the changes in $T_y$ incurred during the $ICE^+$ experiment are more effective at shifting the latitude of the jet (Figure 4 red line) than those incurred during the $ICE^-$ experiment (Figure 4 blue line).

4. Discussion and Conclusions

The results of this study reveal that the latitude of the sea-ice edge has a notable influence on the latitude of the mid-latitude jet, but that the amplitude of the atmospheric response depends
critically on the location and seasonality of the sea-ice anomalies. The results suggest that, in
general, sea-ice anomalies have a demonstrable effect on the extratropical circulation only if
they project onto the climatological-mean near-surface baroclinicity. In the experiments exam-
ined here, the extratropical circulation is only sensitive to increasing sea-ice extent during the
cold season.

During the warm season months, the sea-ice edge lies too far south of the Southern Hemi-
sphere baroclinic zone to have an impact on the mid-latitude jet. In contrast, during the cold
season months, the sea-ice edge lies just to the south of the Southern Hemisphere baroclinic
zone. During this season, increasing sea-ice extent can have a pronounced influence on $T_y$ in
the vicinity of the near-surface baroclinic zone, acting to draw the jet poleward. Interestingly,
decreasing sea-ice extent during the cold season has little effect on the latitude of the eddy-
driven jet, despite the fact that $T_y$ is noticeably reduced at high-latitudes in this scenario. We
have speculated that the non-linearity of the cold-season response is due to the facts that: 1) the
changes in $T_y$ associated with a decrease in sea-ice are located much further poleward (and thus
farther from the mean baroclinic zone) than those associated with an increase in sea-ice; and 2)
the changes in $T_y$ associated with a decrease in sea-ice are less effective at altering the latitude
of maximum $T_y$ (i.e., the latitude of the baroclinic zone) than those associated with an increase
in sea-ice extent.

These results have two important implications for large-scale Southern Hemisphere climate
variability. First, they suggest that future decreases in Southern Hemisphere sea-ice extent
are unlikely to have a pronounced effect on the large-scale atmospheric circulation during any
season. Second, they suggest that seasonal prediction of Southern Hemisphere climate due to
sea-ice anomalies is limited to cases of increased sea-ice extent during the cold season months.

This study also has potential implications for past climate states, particularly for cold epochs, when enhanced Antarctic sea-ice may have significantly altered the location and intensity of the Southern Hemisphere jet stream.

**Acknowledgments.** M. H. England and A. S. Taschetto were supported by the Australian Research Council. The use of NCAR CAM3 model is gratefully acknowledged. This research was undertaken on the NCI National Facility in Canberra, Australia, which is supported by the Australian Commonwealth Government.

**References**


Figure 1: (a) The annual cycle of Southern Hemisphere surface area covered by sea-ice. The shading indicates the months with the minimum and maximum sea-ice extent, which are taken as the warm and cold season respectively. (b) The latitude of the edge of the sea-ice (where the fraction of surface coverage, $F$, equals 0.15) for the control experiment ($CTRL$, black line), the experiment where the sea-ice extent is increased ($ICE^+$, red line), and the experiment where the sea-ice extent is decreased ($ICE^-$, blue line). (c) The same as (b) but for the cold season. (d) The zonal-mean $F$ during the warm season as a function of latitude, for $CTRL$ (black line), $ICE^+$ (red line), and $ICE^-$ (blue line). (e) The same as (d) but for the cold season.

Figure 2: The difference between the zonal-mean zonal wind ($\bar{u}$, in $ms^{-1}$) in the perturbed ice experiments and the value in $CTRL$. (a) warm season, $ICE^+$; (b) cold season, $ICE^+$; (c) warm season, $ICE^-$ and (d) cold season, $ICE^-$. Shading corresponds to the amplitudes of the differences. Differences are only shaded where the associated t-statistic is significant at the 95% level based on a 2-tailed test of the t-statistic assuming 50 independent samples.

Figure 3: The difference between the surface temperature ($T_s$) in the perturbed ice experiments and the value in $CTRL$. (a) warm season, $ICE^+$; (b) cold season, $ICE^+$; (c) warm season, $ICE^-$ and (d) cold season, $ICE^-$. The shading shows only statistically significant differences.

Figure 4: (a) The meridional temperature gradient at 850 hPa during the cold season for $CTRL$ (black line), $ICE^+$ (red line), and $ICE^-$ (blue line). (b) The same as (a) but during the warm season.