

## The influence of Southern Hemisphere sea-ice extent on the latitude of the mid-latitude jet stream

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[1] 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 1) any future decreases in Antarctic sea-ice are unlikely to have a profound effect on the Southern Hemisphere mid-latitude circulation; and 2) the usefulness of sea-ice variability for seasonal prediction is limited to the cold season and to the case of increases in sea-ice extent. **Citation:** Kidston, J., A. S. Taschetto, D. W. J. Thompson, and M. H. England (2011), The influence of Southern Hemisphere sea-ice extent on the latitude of the mid-latitude jet stream, *Geophys. Res. Lett.*, 38, L15804, doi:10.1029/2011GL048056.

### 1. Introduction

[2] 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

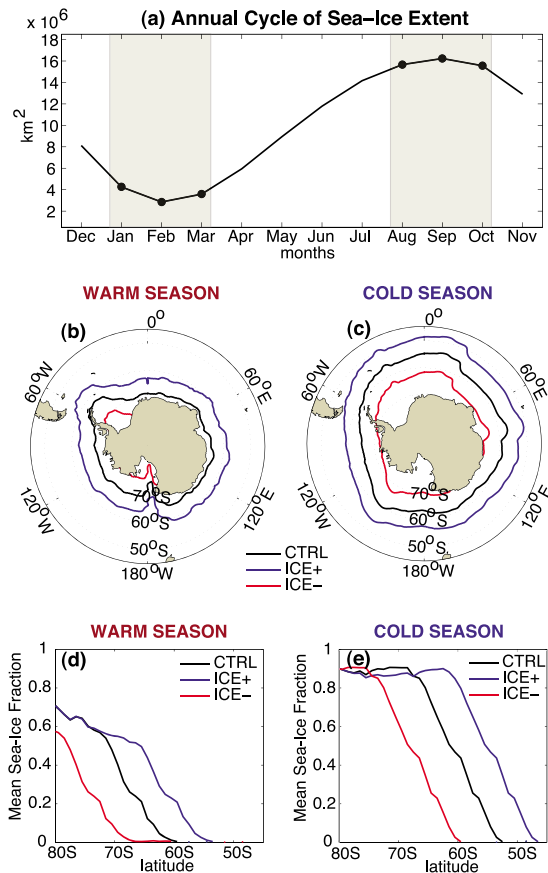
extratropical zonal-mean flow [e.g., *Held*, 1975; *Robinson*, 2000]. As such, the region of large meridional gradients in SST over the Southern Ocean is collocated with the mid-latitude jet and its attendant wave growth in the lower troposphere, momentum flux convergence aloft, and “eddy-driven” surface westerlies.

[3] 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<sup>-2</sup> [*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 generation of baroclinic waves and the location of the mid-latitude jet [*Kushnir et al.*, 2002; *Nakamura et al.*, 2008; *Brayshaw et al.*, 2008]. In modeling 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.

[4] 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<sup>-2</sup> [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; *Menéndez et al.*, 1999]. *Menéndez 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

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**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 ( $ICE^+$ , blue line), and the experiment where the sea-ice extent is decreased ( $ICE^-$ , red line). (c) The same as Figure 1b 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 Figure 1d but for the cold season.

that time, and perturbing the sea-ice field yields relatively small changes in diabatic heating.

[5] 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

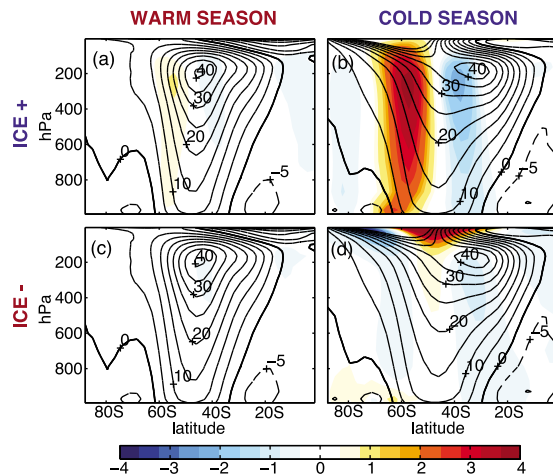
indicate only small net changes in Southern Hemisphere sea-ice extent over the past few decades [*Cavaliere et al.*, 1997; *Cavaliere and Parkinson*, 2008; *Liu et al.*, 2004]. Numerical experiments generally project widespread decreases in Southern Hemisphere sea-ice in response to increasing greenhouse gases [*Sen Gupta et al.*, 2009], but some studies indicate increases [*Zhang*, 2007].

[6] 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 large changes in ice extent allows us to derive some general 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 very little 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; 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

[7] 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 work by *Collins et al.* [2006]. The model simulates the large-scale features of Earth's climate reasonably well, although one notable exception is that the Southern Hemisphere westerlies [*Hurrell et al.*, 2006] are rather strong. It is possible that this would impact the sensitivity of the latitude of the westerlies to boundary forcings, but it should not qualitatively affect the results of this study.

[8] 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]). The Community Sea Ice Model (CSIM5) was used to calculate energy fluxes between the ice and the atmosphere. Sea-ice thickness affects the surface energy exchange in the model through albedo, and the ice albedo is constant when the thickness is above 0.5 m. Thus changing thickness is analogous to changing  $F$ , but thickness variations only exert a relatively small influence, near the sea-ice edge where it becomes thin. To force the atmosphere with large variations



**Figure 2.** The difference between the zonal-mean zonal wind ( $\bar{u}$ , in  $\text{m s}^{-1}$  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. The contours show the value of  $\bar{u}$  in *CTRL*.

in surface albedo due to changes in sea-ice, only  $F$  is altered, with the sea-ice thickness set to 1 m (2 m) in the Southern (Northern) Hemisphere.

[9] In addition to *CTRL*, an experiment named  $ICE^+$  was conducted in which the extent of the sea-ice was increased by  $7^\circ$  of latitude over its climatological position in the Southern Hemisphere. At each longitude, the value of  $F$  in the grid box closest to the continent remains unchanged. Equatorward of this, all values of  $F$  were shifted  $7^\circ$  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  $7^\circ$  relative to the climatological coverage over the Southern Hemisphere. Here the values of  $F$  for the grid boxes within  $7^\circ$  of the continent were removed, and all remaining values were shifted  $7^\circ$  towards the pole.

[10] 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.

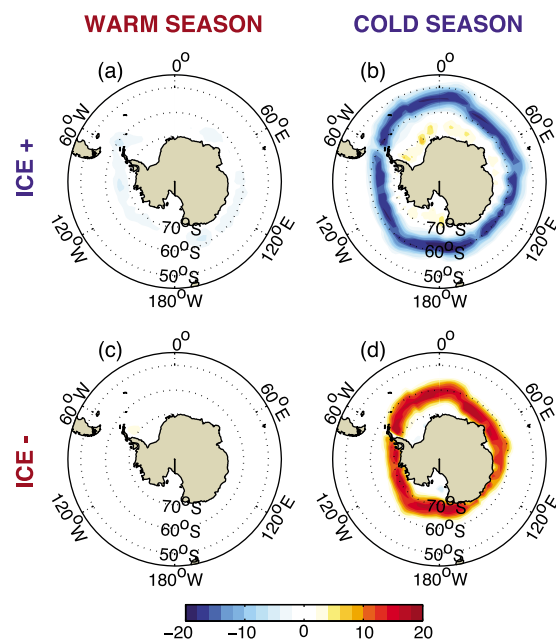
### 3. Results

[11] The seasonal cycle of sea-ice extent integrated over the entire Southern Hemisphere is shown in Figure 1a. 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 grid boxes and 2) summing the resulting products over the entire Southern Hemisphere. Sea-ice extent peaks in September and has its lowest areal extent in February. The shaded regions in Figure 1a 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.

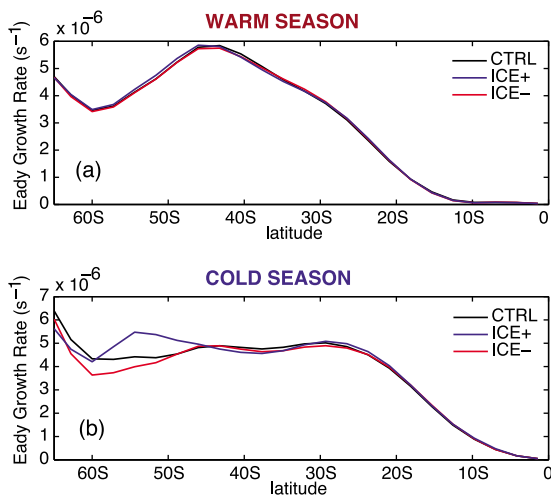
[12] The location of the sea-ice edge (defined as  $F = 0.15$ ) is shown for all three experiments in Figures 1b and 1c for the warm and cold seasons with the associated zonal means shown in Figure 1d and 1e. In the  $ICE^+$  experiment, the sea-ice edge is extended uniformly at all longitudes. In the  $ICE^-$  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).

[13] 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 and 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. The cold season response to  $ICE^+$  is accompanied by marked increases in the eddy fluxes of heat in the lower troposphere near  $60^\circ\text{S}$  and in the eddy fluxes of momentum at the tropopause level near  $50^\circ\text{S}$  (results not shown).

[14] 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 lati-



**Figure 3.** The difference between the surface temperature ( $T_s$ ) in the perturbed ice experiments and the value in *CTRL* (in  $^\circ\text{C}$ ). (a) Warm season,  $ICE^+$ ; (b) cold season,  $ICE^+$ ; (c) warm season,  $ICE^-$  and (d) cold season,  $ICE^-$ .



**Figure 4.** (a) The Eady growth rate at 850 hPa during the warm season for *CTRL* (black line), *ICE*<sup>+</sup> (blue line), and *ICE*<sup>-</sup> (red line). (b) The same as Figure 4a but during the cold season.

tudes 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 ( $\partial_y T$ ) near about 55 S. The common metric that relates changes in  $\partial_y T$  to baroclinic instability and eddy generation is the Eady growth rate, and it can be seen that this increases in *ICE*<sup>+</sup> at latitudes on the poleward flank of the baroclinic zone in *CTRL* (Figure 4b). The generation of baroclinic waves in the lower troposphere (and thus the eddy heat flux and the mid-latitude jet) tend to follow the increases in lower tropospheric baroclinicity [Brayshaw *et al.*, 2008; Chen *et al.*, 2010], and so increasing the Eady growth rate on the poleward flank of the mid-latitude jet yields a poleward shift in the latitude of the jet.

[15] 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 Menéndez *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. Raphael *et al.* [2011] forced a similar model with realistic sea-ice anomalies and also found very little time-mean response during the warm season.

[16] Why is there relatively little 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. The obvious difference that may explain the apparent non-linearity of the cold season response is the

location of the changes in  $\partial_y T$ . The cooling in *ICE*<sup>+</sup> is equatorward of the climatological ice-edge, whereas the warming in *ICE*<sup>-</sup> is poleward of the climatological ice edge. There is an anomalous increase in  $\partial_y T$  on the equatorward edge of the extra ice in *ICE*<sup>+</sup>, and this increased  $\partial_y T$  lies immediately poleward of the climatological storm track and its associated baroclinic zone. Conversely the changes in  $\partial_y T$  in experiment *ICE*<sup>-</sup> lie farther poleward of the climatological jet. This can be seen in Figure 4b, where the increase in the Eady growth rate in *ICE*<sup>+</sup> is around 5 degrees equatorward of the corresponding decrease in *ICE*<sup>-</sup>. 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] and Brayshaw *et al.* [2008], where changes in  $\partial_y T$  have a larger impact when they are located close to the climatological maximum  $\partial_y T$ .

#### 4. Discussion and Conclusions

[17] The results of this study reveal that the latitude of the sea-ice edge has a notable influence on the latitude of the Southern Hemisphere 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 impact the climatological-mean near-surface baroclinicity. In the experiments examined here, the extratropical circulation is only sensitive to increasing sea-ice extent during the cold season.

[18] In contrast to the warm season, during the cold season sea-ice has a large impact on the near-surface air temperature. Furthermore, the sea-ice edge lies just to the south of the Southern Hemisphere baroclinic zone. This means that increasing sea-ice extent can have a pronounced influence on  $\partial_y T$  in the vicinity of the near-surface baroclinic zone during the cold season, and acts to draw the mid-latitude jet poleward. Interestingly, decreasing sea-ice extent during the cold season has little effect on the location of the jet, despite the fact that  $\partial_y T$  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 the changes in  $\partial_y T$  associated with a decrease in sea-ice are located further poleward (and thus farther from the mean baroclinic zone) than those associated with an increase in sea-ice.

[19] These results may have important implications for large-scale Southern Hemisphere climate variability. First, they suggest that any future decreases in Southern Hemisphere sea-ice extent are unlikely to have a pronounced effect on the large-scale atmospheric circulation during any season (assuming that any indirect impact on ocean circulation is likely to be small). 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. 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.

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## References

- Alexander, M. A., U. S. Bhatt, J. E. Walsh, M. S. Timlin, J. S. Miller, and J. D. Scott (2004), The atmospheric response to realistic Arctic sea ice anomalies in an AGCM during winter, *J. Clim.*, *17*(5), 890–905.
- Brayshaw, D. J., B. Hoskins, and M. Blackburn (2008), The storm-track response to idealized SST perturbations in an aquaplanet GCM, *J. Atmos. Sci.*, *65*(9), 2842–2860.
- Cavaliere, D. J., and C. L. Parkinson (2008), Antarctic sea ice variability and trends, 1979–2006, *J. Geophys. Res.*, *113*, C07003, doi:10.1029/2007JC004558.
- Cavaliere, D. J., P. Gloersen, C. L. Parkinson, J. C. Comiso, and H. J. Zwally (1997), Observed hemispheric asymmetry in global sea ice changes, *Science*, *278*(5340), 1104–1106.
- Chen, G., R. A. Plumb, and J. Lu (2010), Sensitivities of zonal mean atmospheric circulation to SST warming in an aqua-planet model, *Geophys. Res. Lett.*, *37*, L12701, doi:10.1029/2010GL043473.
- Collins, W. D., et al. (2006), The formulation and atmospheric simulation of the community atmosphere model version 3 (CAM3), *J. Clim.*, *19*(11), 2144–2161, doi:10.1175/JCLI3760.1.
- Deser, C., G. Magnusdottir, R. Saravanan, and A. Phillips (2004), The effects of North Atlantic SST and sea ice anomalies on the winter circulation in CCM3. Part II: Direct and indirect components of the response, *J. Clim.*, *17*(5), 877–889.
- Deser, C., R. Tomas, M. Alexander, and D. Lawrence (2010), The seasonal atmospheric response to projected Arctic sea ice loss in the late twenty-first century, *J. Clim.*, *23*(2), 333–351.
- Held, I. M. (1975), Momentum transport by quasi-geostrophic eddies, *J. Atmos. Sci.*, *32*(7), 1494–1497.
- Hoskins, B. J., and K. I. Hodges (2005), A new perspective on Southern Hemisphere storm tracks, *J. Clim.*, *18*(20), 4108–4129.
- Hurrell, J. W., J. J. Hack, A. S. Phillips, J. Caron, and J. Yin (2006), The dynamical simulation of the Community Atmosphere Model version 3 (CAM3), *J. Clim.*, *19*(11), 2162–2183.
- Kushnir, Y., W. A. Robinson, I. Blade, N. M. J. Hall, S. Peng, and R. Sutton (2002), Atmospheric GCM response to extratropical SST anomalies: Synthesis and evaluation, *J. Clim.*, *15*(16), 2233–2256.
- Liu, J., J. Curry, and D. Martinson (2004), Interpretation of recent Antarctic sea ice variability, *Geophys. Res. Lett.*, *31*, L02205, doi:10.1029/2003GL018732.
- Magnusdottir, G., C. Deser, and R. Saravanan (2004), The effects of North Atlantic SST and sea ice anomalies on the winter circulation in CCM3. Part I: Main features and storm track characteristics of the response, *J. Clim.*, *17*(5), 857–876.
- Menéndez, C. G., V. Serafini, and H. Le Treut (1999), The effect of sea-ice on the transient atmospheric eddies of the Southern Hemisphere, *Clim. Dyn.*, *15*, 659–671.
- Nakamura, H., T. Sampe, A. Goto, W. Ohfuchi, and S.-P. Xie (2008), On the importance of midlatitude oceanic frontal zones for the mean state and dominant variability in the tropospheric circulation, *Geophys. Res. Lett.*, *35*, L15709, doi:10.1029/2008GL034010.
- Raphael, M., W. Hobbs, and I. Wainer (2011), The effect of Antarctic sea ice on the Southern Hemisphere atmosphere during the southern summer, *Clim. Dyn.*, *36*, 1403–1417.
- Rayner, N. A., D. E. Parker, E. B. Horton, C. K. Folland, L. V. Alexander, D. P. Rowell, E. C. Kent, and A. Kaplan (2003), Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century, *J. Geophys. Res.*, *108*(D14), 4407, doi:10.1029/2002JD002670.
- Robinson, W. A. (2000), A baroclinic mechanism for the eddy feedback on the zonal index, *J. Atmos. Sci.*, *57*(3), 415–422.
- Sen Gupta, A., and M. H. England (2007), Coupled ocean, atmosphere feedback in the Southern Annular Mode, *J. Clim.*, *20*(14), 3677–3692.
- Sen Gupta, A., A. Santoso, A. S. Taschetto, C. C. Ummenhofer, J. Trevena, and M. H. England (2009), Projected changes to the Southern Hemisphere ocean and sea ice in the IPCC AR4 climate models, *J. Clim.*, *22*(11), 3047–3078.
- Simmonds, I., and W. F. Budd (1991), Sensitivity of the Southern Hemisphere circulation to leads in the Antarctic pack ice, *Q. J. R. Meteorol. Soc.*, *117*, 1003–1024.
- Simmonds, I., and X. Wu (1993), Cyclone behaviour response to changes in winter Southern Hemisphere sea-ice concentration, *Q. J. R. Meteorol. Soc.*, *119*, 1121–1148.
- Zhang, J. (2007), Increasing Antarctic sea ice under warming atmospheric and oceanic conditions, *J. Clim.*, *20*(11), 2515–2529.

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