Cold air outbreaks enhance Antarctic sea ice growth on monthly timescales

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ABSTRACT

A simple and important mechanism for month-to-month variability in Antarctic sea ice growth and melt is examined: cold air outbreaks. A robust correlation occurs between the frequency of occurrence of cold air outbreaks and the subsequent growth and melt of Antarctic sea ice. Not only does sea ice provide most of the Southern Ocean’s cold air masses, but cold air outbreaks themselves also strongly influence the growth rate of sea ice. Analysis of terms contributing to the sea surface temperature tendency indicates that this relationship is primarily due to heat loss from the ocean to the atmosphere through surface fluxes, with sensible heat fluxes playing a major role. On a timescale of about a month, Ekman dynamics are insufficient to explain the sea ice growth associated with cold air outbreaks.
1. Introduction

Antarctic sea ice variability and trends involve a complex interplay of ocean and atmospheric dynamics. External drivers modulating the Southern Hemisphere sea ice are both natural and human-caused, and include a range of spatial and time scales. Atmospheric drivers include mesoscale and synoptic scale circulations, the Southern Annular Mode, stratospheric ozone loss, and global warming. This paper focuses on short time scale atmospheric circulations’ effect on Antarctic sea ice and considers their relationship to the Southern Annular Mode (SAM).

The positive phase of the SAM, when the Southern Hemisphere jet shifts poleward, is generally associated with increased sea ice (Watterson 2000; Hall and Visbeck 2002; Sen Gupta and England 2006; Ciasto and Thompson 2008; Simpkins et al. 2012) in observations and climate models. Antarctic stratospheric ozone depletion tends to shift the jet poleward into a positive SAM-like state and this appears to have caused the observed positive trend in Antarctic sea ice (Gillett and Thompson 2003; Polvani et al. 2011). The most likely mechanism is Ekman layer dynamics, where increased high-latitude surface westerlies under positive SAM induce northward Ekman transport that cools sea surface temperature (Hall and Visbeck 2002). However, on decadal timescales it is expected that ozone loss and its related circulation changes will deplete Antarctic sea ice due to eventual upwelling of relatively warm water south of the Antarctic circumpolar current (Ferreira et al. 2015).

On even shorter time scales — days to months — Ekman transport alone might not explain the relationship between SAM and sea ice. Sen Gupta and England (2006) found that in the Community Coupled Climate Model, positive SAM resulted in negative sea surface temperature (SST) anomalies the following month. In their simulations, surface fluxes (specifically latent heat fluxes) were the largest contributor to the mixed layer temperature tendency, followed by merid-
ional transport. Watterson (2000) also found that surface latent heat fluxes better explained SST cooling associated with SAM than Ekman transport did, while others argue that Ekman transport and surface fluxes are roughly equal in importance on weekly to monthly timescales (Verdy et al. 2006; Ciasto and Thompson 2008).

In this paper, I focus on high impact synoptic scale events that play an important role in the short term relationship between atmospheric circulation and sea ice: marine cold air outbreaks (MCAOs). The relationship between MCAOs and Antarctic sea ice has not yet been directly examined. In fact, Southern hemisphere (SH) cold air outbreaks have not been studied much at all. Fletcher et al. (2016) recently produced the first climatology of SH MCAOs, comparing their size, strength, seasonality, synoptic development and boundary layer structure, to those in the Northern Hemisphere. They found that MCAOs are rare in summer in both hemispheres, although the annual cycle in both strength and frequency of MCAOs is weaker in the Southern Hemisphere than in the Northern. In both hemispheres MCAOs contain much stronger surface sensible heat fluxes than average, on the order of several hundred W m$^{-2}$.

It is to be expected that sea ice is important for the strength, frequency, severity, and location of Southern Ocean MCAOs. The high elevation of the Antarctic continent means that air masses advected off of Antarctica experience substantial subsidence warming. Katabatic winds in the polar Southern Hemisphere in fact often have a warming effect at the surface (Owens and Zawar-Reza 2015). Back trajectories of MCAOs over the Pacific sector of the Southern Ocean show that most originate over sea ice (Papritz et al. 2015). Fletcher et al. (2016) found, in synoptic composites of cold air outbreaks that Southern Hemisphere cold air outbreak strength tended to be more related to sea ice cover than in the Northern Hemisphere, even in regions where sea ice might be thought to be important, such as the Labrador Sea. Sea ice is a major determinant of the availability of cold air masses. But can MCAOs affect sea ice in return?
I address this question by examining relationships between variability in cold air outbreak frequency and that of sea ice growth and melt using a combination of reanalysis data and observations. I find that months of unusually high (low) cold air outbreak activity are followed by months of unusually high (low) sea ice growth in autumn and winter. I show that this relationship can be explained by SST tendencies associated with large heat fluxes from the ocean to the atmosphere during periods of high MCAO frequency.

Section 2 describes our MCAO index and data used. Section 3 presents lagged correlations between MCAO frequency and sea ice growth/melt. In Section 4 I present the relationship between MCAOs and the Southern Annular Mode and compare contributions to the SST tendency between surface fluxes and Ekman transport. Section 5 summarizes and discusses the results.

2. Data and definition of MCAO

As in Fletcher et al. (2016), I define MCAOs with a cold air outbreak index based on reanalysis data:

\[ M = \theta_{SKT} - \theta_{800}, \] (1)

where \( \theta_{SKT} \) is the surface skin potential temperature and \( \theta_{800} \) is that at 800 hPa. I define a cold air outbreak as \( M > 0 \), i.e., a fairly deep unstable boundary layer.

The reanalysis used is that provided by the European Centre for Medium Range Weather Forecasting Interim Reanalysis (ERA-Interim, Dee et al. 2011, http://apps.ecmwf.int/datasets/data/interim-full-daily/). To define \( M \) I use twice daily instantaneous skin temperature, 800 hPa temperature, and sea level pressure. From this I calculate monthly mean values of \( M \) and the frequency with which \( M > 0 \). For additional analysis I also use ERA-Interim SST and surface fluxes: sensible, latent, net shortwave, and net longwave. All data are twice daily and instantaneous except for surface fluxes, which are averages over the 12 hours following the instan-
taneous data. The data is on a 1° × 1° grid for 20° S-85° S over the period 1980-2008. I construct monthly mean climatologies and anomalies from monthly means for each variable.

For sea ice, I use the Hadley Centre HadISST dataset (Rayner et al. 2003, http://www.metoffice.gov.uk/hadobs/hadisst/), which provides monthly means of sea ice cover. I use the portion of the dataset covering 1980-2008 and construct similar monthly climatologies and anomalies. A discontinuity in the data occurs at the start of 2009; this is why I use data only through 2008. Because the HadISST grid is offset from the ERA-Interim grid by a half degree, the HadISST data is interpolated to the ERA-Interim grid prior to constructing the climatology.

This study also uses the monthly gridded Southern Ocean mixed layer depth (MLD) climatology from Dong et al. (2008), available as auxiliary material from their publication.

Analysis methods are described in their respective sections. Results are generally presented by season: autumn is March-May (MAM), winter is June-August (JJA), spring is September-November (SON), and summer is December-February (DJF).

3. The correlation between MCAOs and sea ice

I hypothesize that high MCAO frequency leads to increased growth of sea ice in the autumn and winter and reduced melt of sea ice in the spring and summer. This hypothesis is explored first with correlations over various lead/lag relationships: MCAOs leading sea ice growth, MCAOs lagging sea ice growth, and zero lead/lag. MCAO frequency is defined as the relative frequency of occurrence (RFO) of \( M > 0 \). Monthly RFO anomalies are calculated with respect to long term monthly means. Sea ice growth is defined as the one-sided difference in sea ice cover from one month to the next. So, for example, the one-month lagged correlation between MCAOs and sea ice in March is the correlation between anomalous MCAO RFO in that month and the anomalous change in sea ice cover between March and April. However, zero lag correlations are computed
with the centered difference for sea ice cover; in the above example this would be the growth of sea ice between February and April, scaled by a factor of 1/2.

There are *a priori* reasons to not expect a positive correlation between the growth or melt of sea ice and cold air outbreak frequency at a given location, with zero lead or with sea ice leading MCAOs. If a location has unusually high sea ice cover, fewer cold air outbreaks will occur there because the surface skin temperature is low. This was in fact the case, with weak or negative correlations occurring between sea ice and MCAOs with zero or positive lag. Overall correlations for the high latitude Southern Ocean are shown in Table 1.

While the presence of sea ice suppresses MCAOs at the location of the ice, it is likely that it will enhance the frequency of cold air outbreaks over the open ocean downstream from the that location. I tested this by computing the correlation between sea ice growth at one point and MCAO frequency over all points within 1000 km of the sea ice, with zero or one month lag. A few examples of such one point correlation maps are shown in Fig. 1. The correlation is highest in winter and spring with no lag. The negative correlation near the location of the sea ice growth is consistent with Table 1. Positive correlations are to the northeast of the sea ice growth, as expected for the cyclonic flow associated with cold air outbreaks (Fletcher et al. 2016). In these regions, sea ice growth occurs with (or is quickly followed by) enhanced frequency of cold air outbreaks downstream.

When these one-point correlation maps were all averaged together for a given season, a weakly positive correlation still exists to the northeast of the sea ice, but the maximum correlation is rarely larger than 0.3 and is not statistically significant (not shown). It’s likely that there is too much variability in the location of “downstream” to produce a robust correlation.

A significant positive correlation does exist with MCAOs leading sea ice growth, as shown in Figure 2. This is most true in autumn and winter. In Fig. 2, a positive correlation can occur
for a number of reasons. 1) In autumn and winter, anomalously high (low) MCAO frequency is followed by anomalously high (low) sea ice growth the following month. 2) In spring and summer, anomalously high (low) MCAO frequency is followed by anomalously low (high) sea ice melt the following month. For simplicity sake, I will generally refer only to the first reason, for high MCAO frequency, for the rest of this paper. Overall correlations for the high latitude Southern Ocean (50-70°S) are statistically significant in autumn and winter and have values around 0.2-0.3 (Table 1). Locally, especially in the Ross and Weddell Seas, it is as high as 0.8.

4. Attributing SST tendency to MCAOs: Ekman transport vs surface fluxes

a. MCAOs and the Southern Annular Mode

There are several explanations for the lag correlation between MCAOs and growth of sea ice. These explanations are not mutually exclusive.

The first explanation is that the anomalous sea ice growth that follows MCAOs is not caused by MCAOs, but rather by a third phenomenon that is correlated with cold air outbreaks and sea ice. The most obvious candidate for this is the Southern Annular Mode.

Figure 3 shows that positive SAM is generally associated with increased frequency of occurrence of MCAOs at high latitudes. This is unsurprising: the poleward shift of the jet during the positive phase of SAM should be conducive to cold air outbreaks, which tend to be embedded in extratropical cyclones (Papritz et al. 2015; Fletcher et al. 2016). Bracegirdle and Kolstad (2010) found a qualitatively similar relationship between SAM and the 90th percentile value of MCAOs. This means that the relationship between SAM and MCAOs holds for both MCAO strength and frequency of occurrence. Average RFO is around 0.05-0.2 in the high latitude Southern Ocean
during winter (Fletcher et al. 2016), so in the blue regions of Fig. 3a-b, MCAOs occur around 10-50% more frequently in association with positive SAM than on average.

As discussed in Section 1 positive SAM is associated with anomalously high sea ice cover (Watterson 2000; Hall and Visbeck 2002; Sen Gupta and England 2006; Ciasto and Thompson 2008; Simpkins et al. 2012). It has been argued that the anomalous Ekman transport associated with increased westerlies under positive SAM is the source of SST cooling and enhanced sea ice (Hall and Visbeck 2002). The pattern shown in Figure 2 is very similar to the relationship between SAM and sea ice cover found by Simpkins et al. (2012). Figure 4 shows that zonal wind stress anomalies in the ballpark of 0.01-0.02 N m$^{-2}$ occur when MCAO frequency increases by 20%. It is therefore possible that months of high MCAO frequency are disproportionately positive SAM months and that the enhanced sea ice growth following MCAOs occurs because of enhanced Ekman transport associated with SAM.

b. Terms in the SST tendency associated with MCAOs

If, on the other hand, MCAOs are directly contributing to enhanced sea ice growth, then the mechanism would be enhanced surface fluxes, especially the sensible heat fluxes that are much higher than average in SH MCAOs (Fletcher et al. 2016). The increased heat loss from the ocean to the atmosphere during MCAOs cools the SST and could lead to earlier freezing. This is the second possible explanation I consider.

To compare the two explanations, I first examine the terms in the SST tendency equation for short timescales (Ferreira et al. 2015),

$$\frac{\partial T}{\partial t}_{\text{MCAO}} = -v_{\text{MCAO}} \frac{\partial \tilde{T}}{\partial y} + F_{\text{MCAO}}, \quad (2)$$
where $T$ is the SST; $v$, $y$, and $t$ have their usual meanings; and $\bar{T}$ is the monthly climatological mean SST. $\phi_{MCAO}$ refers to the average of anomalies sampled only during months with MCAO RFO greater than 20% above average. I chose 20% frequency anomalies because this is in the ballpark of the increase in frequency associated with one standard deviation of the SAM index in winter (Fig. 3). Results are insensitive to this choice between 15-25%, but choosing a higher RFO anomaly threshold results in too little data to draw conclusions. Months with RFO anomalies exceeding this threshold will be referred to as ”months of frequent MCAOs” or similar for the rest of this paper.

The first term on the RHS is the Ekman transport calculated from the anomalous surface wind stress during months of frequent MCAOs. If this term is large it is likely due to SAM rather than MCAOs directly. $F_{MCAO}$ represents the net surface heat fluxes into the ocean: sensible, latent, shortwave, and longwave. It represents a direct effect of MCAOs on SST, particularly the sensible heat flux term. Obtaining an SST tendency from these RHS terms also requires an assumption about the mixed layer depth, and for this I used the monthly gridded Southern Ocean MLD climatology from Dong et al. (2008). Thus the surface flux term can be written

$$F_{MCAO} = \frac{1}{\rho_w C_w h_{ML}} (SHF_{MCAO} + LHF_{MCAO} + SW_{MCAO} + LW_{MCAO}),$$  \hspace{1cm} (3)

where SHF, LHF, SW, and LW refer to sensible, latent, net shortwave, and net longwave surface fluxes, respectively, in units of W m$^{-2}$. $\rho_w$, $C_w$, and $h_{ML}$ are the density of seawater, the heat capacity of sea water, and the mixed layer depth, respectively. The Ekman transport term can be written

$$-v_{MCAO} \frac{\partial \bar{T}}{\partial y} = \frac{\tau_{MCAO}}{\rho_w f \delta_{ek}} \frac{\partial \bar{T}}{\partial y},$$  \hspace{1cm} (4)
where $f$ is the Coriolis parameter, $\delta_{ek}$ is the Ekman layer depth, assumed to be 100 m following Rintoul and England (2002), and $\tau^{MCAO}$ is the zonal wind stress anomaly during months with MCAOs occurring 20% more often than the climatological mean (shown in Fig. 4).

Figure 5 shows these terms during the time of greatest SST cooling, March-June. The top panel shows the climatological mean SST tendency during this period. Typical SST cooling rates are 0.4-1.0 °C per month.

Figure 5b shows the anomalous SST cooling when MCAOs occur 20% more often than usual for those months. In some locations higher frequency MCAOs are associated with reduced SST cooling, but in most places, especially the Ross, Amundsen, and Bellingshausen Seas and east of Argentina, there is an increased rate of cooling by up to 0.4 °C per month. Assuming that SSTs start around 2 °C in March and freeze at -2 °C, freezing could occur a month or more earlier in a location with this cooling anomaly.

Figure 5c shows $F_{MCAO}$ (Eqn. 3) during the same months, while Fig. 5d shows the Ekman term (Eqn. 4). The flux term is of similar magnitude to the overall anomalous cooling associated with high MCAO activity. The Ekman term is considerably smaller, suggesting that the MCAO-sea ice relationship shown in Fig 2 cannot simply explained by Ekman transport-related cooling of SSTs caused by SAM.

Figure 5e shows the tendency in sea ice cover associated with Ekman surface currents associated with the zonal wind stress anomalies that occur when MCAOs are 20% more frequent, i.e., the advective tendency in sea ice that might be attributed to the relationship between MCAO frequency and SAM. The effect is very small (less than 1% per month) or of the wrong sign to explain the correlation in Fig. 2.

Figure 6 further illustrates the difference between the flux and Ekman terms in explaining the SST tendency associated with MCAOs. Here the data is shown for individual months and grid-
points. In early-mid autumn (March and April), there is a strong anomalous SST cooling associated with MCAOs that cannot be explained by surface fluxes or Ekman transport. This either reflects a process we have not considered, such as entrainment of water below the mixed layer, or an overestimate of the mixed layer depth (or both). Given that increased MCAO frequency is associated with increased storminess, the former is more likely than the latter. Conversely, in late autumn and early winter the surface flux cooling associated with MCAOs is stronger than the overall cooling. In this case the high MCAO frequency may create a MLD that is deeper than the climatological mean, leading to an overestimate of the SST tendency from surface fluxes.

Previous researchers (Verdy et al. 2006; Ciasto and Thompson 2008) have found that SAM influences SSTs roughly equally through Ekman transport and surface fluxes, mainly latent heat fluxes. Hall and Visbeck (2002) focused primarily on the Ekman transport mechanism. But studies that look primarily on the weeks-to-months timescale we consider here find surface latent heat fluxes to dominate (Watterson 2000; Sen Gupta and England 2006). Here, we find that the influence of MCAOs on SST acts not only primarily through surface fluxes, but that sensible heat fluxes are even greater than latent heat fluxes in their contribution to SST cooling. This is shown in Figure 7. Sensible heat fluxes dominate poleward of 60S and latent heat fluxes dominate equatorward of about 55S. Between these latitudes the contributions are equal.

5. Summary and conclusion

In this paper I have shown that a strong lag correlation exists between the frequency of marine cold air outbreaks and the growth of sea ice over the high latitude Southern Ocean. This correlation is strongest in autumn and winter in the Ross and Weddell Seas, where $R$ is as high as 0.8. Although there is a strong relationship between MCAO frequency and the Southern Annular Mode, a cross correlation with SAM is not the only mechanism explaining the correlation. MCAOs contain
sensible heat fluxes much greater than average, and these sensible heat fluxes contribute strongly to anomalous sea surface cooling. The surface sensible heat flux signature of MCAOs is stronger than that associated with SAM in Sen Gupta and England (2006, their Fig. 13). Unlike the studies of Watterson (2000); Verdy et al. (2006); Ciasto and Thompson (2008), the sensible heat flux is the largest contributor to the SST cooling, with greater amplitude than the latent or radiative fluxes as well as the Ekman transport.

It is furthermore found that enhanced sea ice growth increases the frequency of occurrence of MCAOs downstream of the sea ice (to the northeast for the cold air sector of a Southern Hemisphere extratropical cyclone). A feedback may exist in which increased frequency of cold air outbreaks (caused, for example by positive SAM) enhances sea ice growth. This then increases MCAO frequency further downstream of the new sea ice. By this mechanism anomalies in both sea ice and MCAO frequency may be maintained and increased.

It is also possible that MCAOs are an important mechanism through which SAM influences SST and sea ice variability, especially at smaller spatial and time scales. The increased frequency and strength of cold air outbreaks during the positive phase of SAM leads to sensible heat loss from the ocean to the atmosphere. The enhanced high-latitude westerlies associated with positive SAM (and not necessarily directly related to MCAOs) contributes by enhancing surface fluxes outside of cold air outbreaks and through Ekman transport. Ekman transport is the primary mechanism on the months-to-years time scale, but it is not fast enough to cause major SST cooling on shorter time scales. Because the SAM does vary on these shorter time scales, synoptic scale circulations, including cold air outbreaks, play an important role in modulating the SAM-sea ice relationship.
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References


Fletcher, J. K., S. L. Mason, and C. Jakob, 2016: The climatology, meteorology, and boundary layer structure of marine cold air outbreaks in both hemispheres. *J. Climate*, in press.


Table 1. Lead/lag correlations between sea ice growth and MCAO event frequency, all oceanic longitudes 55-70 S. Bold numbers are statistically significant at 95% confidence level.
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<table>
<thead>
<tr>
<th>Season</th>
<th>Ice leads MCAOs</th>
<th>No lead/lag</th>
<th>Ice lags MCAOs</th>
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<tbody>
<tr>
<td>Winter (JJA)</td>
<td>-0.08</td>
<td><strong>0.09</strong></td>
<td><strong>0.20</strong></td>
</tr>
<tr>
<td>Spring (SON)</td>
<td>-0.05</td>
<td>0.08</td>
<td><strong>0.13</strong></td>
</tr>
<tr>
<td>Summer (DJF)</td>
<td>-0.03</td>
<td>0.02</td>
<td>0.07</td>
</tr>
<tr>
<td>Autumn (MAM)</td>
<td>-0.08</td>
<td><strong>0.20</strong></td>
<td><strong>0.30</strong></td>
</tr>
</tbody>
</table>
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Fig. 2. Correlation between monthly MCAO frequency of occurrence anomalies and anomalous sea ice growth during the subsequent month. Only areas that are statistically significant at the 95th% confidence level are shown.

Fig. 3. Monthly MCAO frequency of occurrence regressed onto the Southern Annular Mode index for each season.

Fig. 4. Zonal wind stress anomalies associated with a 20% increase in MCAO frequency of occurrence.

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Fig. 6. Scatterplot of anomalous SST tendency associated with MCAO frequency greater than 20% above average (vertical axis) vs SST tendency attributable to surface fluxes (left) and Ekman transport (right) when MCAO frequency is greater than 20% above average.

Fig. 7. Zonal mean contributions of sensible, latent, shortwave, and longwave fluxes to the anomalous SST tendency associated with surface fluxes in MCAOs shown in Fig. 5c. Average is for March-June.
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