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LETTER

Regional, seasonal, and inter-annual variations of Antarctic and sub-Antarctic temperature anomalies related to the Mansurov effect

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Abstract

We use National Centers for Environmental Prediction/National Center for Atmospheric Research reanalysis data to show that Antarctic surface air temperature anomalies result from differences in the daily-mean duskward component, \( B_y \), of the interplanetary magnetic field (IMF). We find the statistically-significant anomalies have strong geographical, seasonal, and inter-annual variations. For the interval 1999–2002, regional anomalies poleward of 60°S are of diminishing representative peak amplitude from autumn (3.2 °C) to winter (2.4 °C) to spring (1.6 °C) to summer (0.9 °C). Exploiting apparently simplifying properties in the sub-Antarctic region in autumn 1999–2002, we demonstrate that temperature anomalies in this case are due to geostrophic wind anomalies, resulting from the same \( B_y \) changes, moving air across large meridional gradients in zonal mean air temperature between 50 and 70°S over the 7-hour timescale for which a change in \( B_y \) can be expected to persist. Since the tropospheric pressure anomalies causing these winds have been associated with \( B_y \)-driven anomalies in the electric potential of the ionosphere, we conclude that IMF-induced changes to the global atmospheric electric circuit can cause day-to-day changes in regional surface air temperature of up to several degrees Centigrade.

1. Introduction

The effects of solar variability are still major unknowns in our understanding of weather and climate, and hence inadequately represented in atmospheric models (e.g., Gray et al 2010). One hypothesis for how solar variability can affect weather and climate is that solar variability imposed on the interplanetary magnetic field (IMF) modulates the meteorological action of the global atmospheric electric circuit (GEC) in the polar regions. This IMF GEC hypothesis can be broken down into three parts. In summarising these here we emphasise which parts are supported by experimental evidence with a particular focus on Antarctica:

(i) Electric field and current anomaly. It is well established empirically and theoretically that variations in the IMF change the horizontal electric field in the polar ionosphere (e.g., Pettigrew et al 2010). For example, a change in the IMF from ~5 nT duskward to ~5 nT duskward causes the ionospheric electric potential to increase by >20 kV everywhere within a latitudinal radius of ~15° of the southern geomagnetic pole (and similarly decrease the potential around the north geomagnetic pole) (Lam et al 2013). Theoretically, this should cause a corresponding change in the ionosphere-to-ground potential and hence vertical electric field throughout the atmospheric column (Lucas et al 2015). Since all levels of the atmosphere are ionized, by cosmic rays, solar radiation, and surface radioactive sources (Aplin and Harrison 2015), there will also be a corresponding anomaly in the vertical current. Both the vertical electric field and current anomalies have been isolated in measurements on the ground (Burns et al 2006, Panneersevam et al 2007) and in the stratosphere (Byrne et al 1991) in Antarctica.
(ii) Effect on cloud microphysics. Continuity of this vertical current through a stratiform cloud will cause electrical charging at the cloud-air interface because the conductivity in clouds is relatively low due to ion loss by attachment to droplets (Harrison et al 2015). This has been clearly demonstrated in balloon measurements through clouds (Nicoll and Harrison 2016). This study includes observations from Halley, Antarctica.

It is theorised that this charging can change the droplet size distribution within clouds by influencing collisions (e.g., Harrison et al 2015, Tinsley and Zhou 2015). As yet, there is no empirical evidence to support this and consequently this is the most uncertain link in the chain of processes in the GEC hypothesis (Lam et al 2014).

(iii) Meteorological response. If the droplet size distribution is changed in Antarctic clouds by mechanisms (i) and (ii) then this will alter radiative forcing (e.g., Lachlan–Cope 2010), causing large-scale Antarctic surface atmospheric pressure anomalies (e.g., Lubin et al 1998).

A model of the electric field and current anomaly (i) has been developed within an atmospheric GCM framework (Lucas et al 2015) but the meteorological response (iii) has yet to be included because of our understanding of the cloud microphysics (ii) is still to be adequately developed.

However, consistent with the above GEC hypothesis, observations have shown that there are correlations between fluctuations in the daily mean of the duskward component, $B_\varphi$, of the IMF and surface air pressure variations (Mansurov et al 1974, Page 1989, Tinsley and Heels 1993, Burns et al 2007, 2008, Lam et al 2013, 2014). This correlation, often referred to as the Mansurov effect, is the clearest and most direct example of a meteorological response to changes in the GEC (Tinsley 2008, Lam and Tinsley 2015). Using data from 11 Antarctic and 7 Arctic stations over the interval 1995–2005, linear regressions of noontime surface air pressure on daily average IMF $B_\varphi$ yielded highly statistically significant correlations in the Antarctic over the entire interval 1995–2005, but in the Arctic over only the interval 1999–2002 (table 1 of Burns et al 2008). Regression coefficients corresponded to a change in pressure of $\sim 1–2$ hPa from a variation in $B_\varphi$ of $\sim 8$ nT. Using reanalysis data, differences in polar noontime surface air pressure of similar amplitude and significance were also found between samples during which daily average IMF $B_\varphi > 3$ nT and $B_\varphi < -3$ nT over the interval 1999–2002 (Lam et al 2013). In both studies the relationship between pressure and $B_\varphi$ is of opposite sign in the Arctic and Antarctic for 1999–2002, as expected from the GEC hypothesis (Burns et al 2008, Lam et al 2013). More recently, a hemispherically asymmetric relationship has also been reported between IMF $B_\varphi$ and zonally-averaged surface pressure above $\sim 70^\circ$ latitude in reanalysis data when averaged over 21 years (1995–2015) and over each of the two separate decades within this (1995–2005 and 2006–2015), which approximately correspond to the last two solar cycles 23 and 24 (Zhou et al 2018).

Extending the Lam et al (2013) analysis from the surface up into the stratosphere, a highly significant (99% field significance level) correlation was also found between IMF $B_\varphi$ and pressure throughout the Antarctic troposphere (Lam et al 2014). The varying time lag with height of the peak correlation provides evidence that the effect originates in the lower troposphere and propagates upwards to the tropopause, consistent with a cloud source.

In addition, there is observational and theoretical evidence that the Mansurov effect in both polar regions modifies the quasi-stationary planetary wave field at mid-latitudes (Lam et al 2013).

Quite recently, a temperature anomaly associated with IMF $B_\varphi$ has been found, of about 0.7 °C averaged over the region poleward of 70 °S and extending up to the 500 hPa atmospheric pressure level (Lam et al 2018). In this paper, we use a similar statistical method (section 2) to identify the sub-Antarctic extension of this temperature anomaly between $\sim 65^\circ$ S and 50 °S at the surface, showing seasonal and inter-annual variations of its geographical structure (section 3.1). By exploiting particularly simple structural properties of the atmosphere existing in this region over the autumns of 1999–2002, we also elucidate some of the physics behind the sub-Antarctic surface temperature anomaly (section 3.2). In this case, we show that the anomaly can be modelled by meridional temperature advection by the geostrophic wind of the Mansurov pressure anomaly and that the amplitude of the temperature anomaly is controlled by the decorrelation time of IMF $B_\varphi$. However, the assumptions used in the model are not expected to generally apply and so the model cannot describe the seasonal and inter-annual variability in the temperature anomaly structure. Overall, we conclude (section 4) that there is both statistical and physical evidence that the surface temperature anomaly is due to the Mansurov effect in which surface air pressure is influenced by IMF $B_\varphi$, consistent with the IMF GEC hypothesis.

2. Data and methodology

We analyze the surface air temperature anomaly with the same method and data sources used to examine the surface air pressure anomaly (Lam et al 2013): We begin with surface air temperature data $T(\lambda, \varphi, y, m, d, h)$...
from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis dataset (Kalnay et al 1996). Geographic location is sampled at 2.5° intervals in latitude $\lambda$ and longitude $\phi$, and four time samples per day are defined here by year $y$, month $m$, day $d$, and hour $h$.

The climatological temperature variation $T_c$ is then removed to yield an adjusted daily temperature $T_a(\lambda, \phi, y, m, d, h) = T_{12} - T_c$. Here $T_{12} = T(\lambda, \phi, y, m, d, h = 12)$ is the 12 UT surface temperature and $T_c = \langle T_{12} \rangle_y$ is the average of this over the set $Y$ of all available years for each day of year and at each location. The available years for this study were 1948 to 2011. Using a fixed $h = 12$ UT value effectively removes the diurnal variation, and averaging over all years keeping the other variables fixed approximates the seasonal cycle.

For a given set of dates $S$, such as the 1999–2002 time interval used in our original study (Lam et al 2013), we then identify the subset of dates $S^+$ when daily-mean IMF $B_y$ is large and positive ($\geq 3$ nT). To do this we use IMF data from the OMNI dataset (King and Papitashvili 2005) in the geocentric solar magnetospheric (GSM) coordinate system, where positive $B_y$ is aligned from dawn to dusk. For the subset $S^+$, we calculate the mean of the adjusted temperature at each location $T^+ \sim \{T_a(\lambda, \phi, y, m, d, h)\}_{S^+} / S$. Similarly, we also calculate the mean of the adjusted temperature $T^- \sim \{T_a(\lambda, \phi, y, m, d, h)\}_{S^-} / S$ for the subset of dates $S^-$ in $S$ when daily-mean IMF $B_y$ is large and negative ($\leq -3$ nT). We define the difference in these two means as $\Delta T = T^+ - T^-$. The equivalent pressure quantity is $\Delta P = p^+ - p^-$. We will refer to $\Delta T$ and $\Delta P$ as the IMF $B_y$-related air temperature and pressure anomalies.

To test the null hypothesis that there is no difference in the population of adjusted surface temperature values for IMF $B_y \geq 3$ nT compared with that for IMF $B_y \leq -3$ nT (and hence $T^+ = T^-$ and $\Delta T = 0$), we conduct a non-parametric Wilcoxon Rank-Sum test at each location. The test statistic $Z$ is the standardized sum of the ranks of one sample, which is approximately normally distributed. The statistical significance of the result is then the one-tailed probability of obtaining a value of $Z$ or greater by chance from the standard normal distribution. The result of this test is commonly referred to in one of two ways: for a one-tailed probability $P = 0.01$, we can say that the probability of obtaining a value greater than $Z$ by chance is 1%, or we can say (as we do in this paper) that the null hypothesis can be rejected at the 99% confidence level. We also test the field significance of whether the positive and negative $B_y$ samples of $T_a$ are significantly different over a region. Following Wilks (2006), the field significance is well approximated simply by the minimum $P$ value in the region.

In our previous studies (Lam et al 2013, 2014, 2018), the set $S$ comprised all days in the interval 1999–2002. Here, we now separate our analysis into the four austral seasons: summer (December, January and February—DJF), autumn (March, April and May—MAM), winter (June, July and August—JJA), and spring (September, October and November—SON). We also briefly examine how the temperature anomaly evolves over contiguous four-year intervals in the interval 1995–2010. In the context of the IMF GEC hypothesis, this approximately corresponds to solar cycle 23. Shorter intervals are not considered as the sample sizes of the large positive and negative $B_y$ sets $S^+$ and $S^-$ become potentially too small to be statistically reliable, e.g., $\sim 50$ samples for individual years in 1995–1997 and 2004–2010.

In all cases, we analyze the region poleward of 50° S. Within this lies the polar front between the Ferrel and polar cells of atmospheric circulation at ~60° S. The 70° S circle roughly divides the cold and orographically-complicated Antarctic continent from the relatively warm and flat Southern Ocean. Figure 1 shows a map of Antarctica and identifies some key regions that will be referred to below.

3. Results

3.1. Statistical identification of the IMF $B_y$-related surface air temperature anomaly and its inter-annual and seasonal variation

The IMF $B_y$-related surface air temperature anomaly field $\Delta T$ has considerable inter-annual variability over the interval 1995–2010. In figure 2, we show $\Delta T$ poleward of 50° S averaged over successive 4-year intervals: (a) 1995–1998, which includes the solar minimum of solar cycle 22/23 and rising phase of the solar cycle 23, (b) 1999–2002, around solar maximum and early declining phase, (c) 2003–2006, late declining phase, and (d) 2007–2010, the prolonged solar minimum of solar cycle 23/24 (Hathaway 2015). In each interval, there is considerable spatial variation of $\Delta T$ with both negative and positive anomalies. The range of $\Delta T$ is of a similar size in all intervals but broadly highest in 2007–2010 (figure 2(d)) and lowest in 2003–2006 (figure 2(c)). There is little similarity in the spatial structure of $\Delta T$ between intervals, suggesting considerable inter-annual variability to complicate our understanding of the temperature anomaly. The only stable feature we can identify is the sub-Antarctic region equatorward of ~65° S in intervals 1995–1998 and 1999–2002 (figures 2(a), (b)). Here areas of clearly positive $\Delta T$ (i.e., reddish) in one interval are typically also positive in that area in the other interval (or at least not clearly of the opposite sign, i.e., bluish). And conversely, for areas of clearly negative $\Delta T$. Thus, we shall henceforth focus on the interval 1999–2002, which should minimize complications from inter-annual
variability and take advantage of knowledge gained from our previous studies of this period (Lam et al 2013, 2014, 2018), as well as by Burns et al (2008).

The IMF $B_y$-related surface air temperature anomaly field $\Delta T$ over the interval 1999–2002 has a strong seasonal dependence (figure 3). To characterize this, we calculate a representative peak amplitude (RPA) of $\Delta T$ for each season over the region poleward of 60 °S where the largest anomalies lie. The RPA is defined as half the range between the 5th percentile of the $\Delta T$ distribution (which is always below 0 °C) and the 95th percentile (always above 0 °C). The $\Delta T$ values at 5th and 95th percentiles are chosen rather than the peaks because they are more statistically stable. The largest RPA (3.2 °C) occurs in autumn (figure 3(b)), the next largest (2.4 °C) occurs in winter (figure 3(c)), with a slightly lower value in spring (figure 3(d)) of about 1.6 °C. The lowest RPA (0.9 °C) is in summer (figure 3(a)) when $|\Delta T|$ itself does not exceed 2 °C anywhere in the Antarctic region.

It is thus evident that the mean $\Delta T \approx 0.7$ °C over Antarctica and over all seasons in 1999–2002 found by Lam et al (2018) belies considerable complexity in the spatial structure of $\Delta T$ and its variability. To understand some of the physics behind this, we will now focus on the autumn season in 1999–2002 (figure 3(b)), which has the largest amplitudes and levels of statistical significance for $\Delta T$ and, as we shall see later, is amenable to some theoretical analysis.

In this case, the spatial structure of $\Delta T$ can be characterized as follows: The largest positive values of $\Delta T$ are located in a region to the east of the Antarctic Peninsula—in the Weddell Sea and on the Ronne Ice Shelf (cf figure 1). Here there is a cluster of 20 grid points centered at 75.25°S, 314.25°E with each point value of $\Delta T \geq 5$ °C and above the 99.9% confidence level. Thus, the field significance of this region also exceeds the 99.9% confidence interval (Wilks 2006). The largest negative values occur in the Ross Sea and on the Ross Ice Shelf ($\Delta T \leq -6$ °C and above the 99.9% confidence level for a group of 31 grid points centered at 80°S, 195.65° E). Another significant area of positive $\Delta T$ occurs over and offshore of Wilkes Land ($\Delta T \geq 2$ °C and above the 99% confidence level for 25 grid points centered at 67.80°S, 114.20°E). More generally, equatorward of about the 70 °S circle that roughly defines the Antarctic coastline, the large-scale anomaly structure divides into three alternating positive and negative anomaly regions, each above the 90% confidence interval and with peaks above the 99% confidence interval. The three positive anomaly regions are in the Weddell and Ross sea sectors, and in the sector between Wilkes Land and Kemp Land. The three negative anomaly regions lie between these, in the Bellinghausen-Amundsen Sea, Coats Land, and Dronning-Maud Land sectors. Thus this suggests an $m \approx 3$ azimuthal wave structure over this entire 50–70 °S sub-Antarctic region with a field significance given by the lowest $P$ value within the region (Wilks 2006), i.e., exceeding the 99% confidence interval.

3.2. Physical analysis of the surface air temperature anomaly

To investigate the physical origin of this spatial structure, figure 4(b) compares $\Delta T$ from figure 3(b) with the IMF $B_y$-related surface air pressure anomaly field $\Delta p$ identified in our original study (Lam et al 2013). The zonal

![Figure 1. A map of Antarctica.](image)
structure of $\Delta T$ equatorward of 70°S also resembles an $m \approx 3$ wave with anomaly lows (grey contours) centered near 40°E, 175°E, and 290°E at 50°S (the outer boundary of the figure). This $m \approx 3$ wave was first identified in the study of Lam et al. (2013), but was not analyzed then according to season.

In the geostrophic approximation, where the forces due to friction and flow curvature are neglected such that the Coriolis and pressure gradient forces are balanced, air flows along isobars: clockwise around low pressure centres in the southern hemisphere. Thus the sub-Antarctic $m \approx 3$ wave in the surface air pressure anomaly creates a meridional wind anomaly such that air is perturbed poleward to the east of each of the three lows, and equatorward to the west of them. Now comparing also the $\Delta p$ anomaly to the seasonal mean of the zonally-averaged surface air temperature $T_z$ (figure 4(a)), there is a strong equatorward gradient in $T_z$ such that a poleward wind anomaly can be expected to transport warm air towards Antarctica and an equatorward wind anomaly will transport cold air off Antarctica.

This then appears to explain the structure of $\Delta T$ in figure 4(b) in that the poleward wind anomalies (red boxes) carry warm air poleward to create positive $\Delta T$ anomalies and the equatorward wind anomalies (blue boxes) carry cold air equatorward to create negative $\Delta T$ anomalies. For example, in the Weddell Sea (~310°E), highly-meridional IMF $B_y$-related winds are, on average, drawing relatively warm air onto the Antarctic continent creating the $\Delta T \geq 5$ °C region remarked on earlier. On the other side of the Antarctic Peninsula, the IMF $B_y$-related wind draws air equatorward, off the continent, into the Bellingshausen and Amundsen Seas (~260°E) to create the $\Delta T \leq -2$ °C region. Elsewhere off the continent, the relationship between $\Delta T$, meridional wind flow, and meridional gradient in zonal mean temperature also seems to hold. The only exception to the relationship is the area of negative $\Delta T$ centred at the coastal edge of the Ross Ice Shelf where our simple geostrophic analysis likely breaks down because the isobars of $\Delta p$ are of high curvature.
To substantiate this, let us assume a model where the onset of a geostrophic wind anomaly due to an enhancement of IMF $B_y$ at time $t = 0$ perturbs the motion of a parcel of air to advect it from some origin A to another location B, retaining the unperturbed (i.e., seasonal-average) temperature of its origin. If the seasonal-average temperature $\langle T \rangle$ is longitudinally invariant (as it approximately is—not shown) then the change in temperature at location B is given by the time integral of the meridional advective derivative of the unperturbed temperature due to the action of the perturbed flow $\Delta u$ over the time $\tau$ taken to move from A to B:

$$
\Delta T = \int_{0}^{\tau} \frac{\Delta u_\theta}{r} \frac{\partial \langle T \rangle}{\partial \theta} \, dt \approx -\frac{\Delta u_\theta}{r} \frac{\partial \langle T \rangle}{\partial \theta} \tau \\
\approx \frac{\tau}{\langle \rho \rangle \Omega r^2 \sin 2\theta} \frac{\partial \Delta p}{\partial \varphi} \frac{\partial \langle T \rangle}{\partial \theta}
$$

(1)

Here we use geographic spherical polar coordinates, where $r = 6371$ km is the Earth’s radius, $\theta$ is co-latitude, and $\varphi$ is longitude. The first approximation assumes that $\Delta u_\theta \tau$ is small compared to the length scale of variations in $\langle T \rangle$ and the second approximation is the geostrophic approximation, in which $\langle \rho \rangle$ is the atmospheric density and $\Omega = 7.29 \times 10^{-5}$ rad s$^{-1}$ is the angular frequency of the Earth’s rotation.

In figure 4(c) we show the model result $\Delta T$ using the timescale $\tau = 7$ h, seasonal averages $\langle \rho \rangle$ and $\langle T \rangle$ from the reanalysis dataset, and the pressure anomaly $\Delta p$ calculated earlier and reproduced in figure 4(c). Comparing figures 4(c) to (b), it is clear that the model temperature anomaly is similar to the actual reanalysis temperature anomaly, suggesting the model is appropriate. (Note that for $\tau = 7$ h we find that $\Delta u_\theta \tau \sim 40$ km is indeed small, less than the 2.5° latitude resolution of the reanalysis dataset.)

Figure 3. The IMF-$B_y$-related surface air temperature anomaly $\Delta T$ poleward of 50°S in different seasons: (a) austral summer (DJF); (b) autumn (MAM); (c) winter (JJA); (d) spring (SON). Dotted black circles mark 60, 70, and 80°S. The red contours bound Antarctica and other land masses. Black and grey contours show statistical significance at the 99% and 90% levels, respectively.
A possible interpretation of the timescale $\tau$ is that it is the time over which the anomalous geostrophic wind field persists. That is, according to our model, the temperature perturbation at location B will be the temperature of an isothermal parcel of air following a back-trajectory in a given perturbed geostrophic flow field. Assuming the IMF GEC hypothesis (see section 1), then that perturbed geostrophic flow field will be essentially fixed, as assumed in equation (1), for as long as IMF $B_y$ remains in a given state, e.g., $B_y \gg 3$ nT. Longer than this, $B_y$ will be different and hence the geostrophic flow field will be different. By this argument, we expect $\tau$ to be the decorrelation time of IMF $B_y$, i.e., the time for which $B_y$ retains some memory of its previous state. Referring to figure 5, we find that the variation of $B_y$ on short time scales (lag $L < 1$ day) can be approximated by an AR(1)

![Figure 4](image-url)
process with a decorrelation time $t = 7$ h, exactly matching that used in equation (1) to produce the model temperature anomaly (figure 4(c)) that reproduces the empirical anomaly (figure 4(b)).

In summary, by close examination of the sub-Antarctic region in 1999–2002 austral autumn we deduce that the statistically-significant temperature anomaly $\Delta T$ associated with IMF $B_t$ (figure 4(b)) is consistent with a model (figure 4(c)) in which the Mansurov surface pressure anomaly $\Delta p$ associated with IMF $B_t$ (figures 4(b), (c)) creates a geostrophic flow anomaly that isothermally transports the unperturbed air (figure 4(a)) for the time $t = 7$ h over which $B_t$ persists in the state consistent with $\Delta p$ (figure 5). Thus, our detailed analysis of this season provides some physical evidence in support of the IMF GEC hypothesis beyond relying on the statistical significance of the identified anomalies.

Applying the model given by equation (1) to the empirical sub-Antarctic temperature anomaly in the other seasons in the 1999–2002 interval (figure 3), we find (not shown) that the anomaly magnitude is reasonably well reproduced, broadly consistent with the changing latitudinal gradient of the seasonal-average temperature. However, its spatial structure is less well explained. This is not really surprising given the assumptions used to derive equation (1), which are unlikely to be generally satisfied from season to season, as well as from year to year (figure 2). For example, the simple $m \approx 3$ structure of $\Delta p$ appears to break down in other seasons (not shown) which may weaken the geostrophic approximation, and the isothermal approximation is generally unexpected. This emphasises the need to improve our understanding of postulated interaction of the GEC with clouds such that the IMF GEC hypothesis may be implemented and tested in a general circulation model (see section 1) and its wider meteorological impacts explored.

Figure 5. Autocorrelation function (ACF) of IMF $B_t$. Top panel: The black curve shows the ACF of 1-hour averaged IMF $B_t$ from 1999–2002 for lags $-40 \leq L \leq 40$ days. The red dotted curve shows a replica of the ACF for lags $13 \leq L \leq 40$ days shifted by $-27$ and $-54$ days in order to demonstrate the periodic structure at the $\tau_a = 27$ day solar rotation period. The orange dashed curve shows the ACF of a model of IMF $B_t$ given by $B_t(t) = \text{sgn}(2\pi / \tau_a) + a \text{sgn}(2\pi / \tau_a) + bB_t(t - \delta) + \varepsilon$ where $a = 0.4$, $b = 0.87$, $\delta = 1$ h, and $\varepsilon$ is a normally-distributed random variable with zero mean and standard deviation $\sigma = 0.8$. Bottom panel: An expanded version of the top panel for lags $0 \leq L \leq 4$ days.
Assuming our interpretation is correct, it is perhaps remarkable that the relatively feeble electromagnetic power input to the Earth system associated with the IMF ($10^{13}$ W at most [Koskinen et al 2002]) compared to the $10^{17}$ W of incoming solar radiation) is able to cause such large regional temperature anomalies. Clearly, the temperature response is highly non-linear. The effect of the IMF on atmospheric pressure is fairly weak. As can be seen in figure 4, the pressure perturbation is predominantly an $m \approx 3$ wave with an amplitude of about 4 hPa around the 60 °S latitude circle. This corresponds to a geostrophic wind perturbation of about 1.6 m s⁻¹, corresponding to a light breeze on the Beaufort scale. However, its effect on temperature is greatly amplified by the wind carrying air across the strong background latitudinal temperature gradient, particularly in the autumn season studied in detail here. It is this role of the IMF GEC in regulating heat transport that appears to be main source of the observed non-linear response.

4. Conclusions

We have analyzed seasonal and geographical dependences of surface air temperature anomalies in the Antarctic region due to differences in the IMF $B_y$ component of the interplanetary magnetic field. Regional anomalies up to $\sim 5$ °C are found in 4-year averages between 1995 and 2010 (approximately solar cycle 23) and in seasonal averages during 1999–2002. For the 1999–2002 interval, anomalies poleward of 60 °S have representative peak amplitudes in autumn, winter, spring and summer of 3.2 °C, 2.4 °C, 1.6 °C and 0.9 °C, respectively. In 1999–2002 autumn, the localized temperature anomalies to the east and the west of the Antarctic Peninsula were found to be $5$ °C in the Weddell Sea and $-2$ °C in the Amundsen Sea and have a $m \approx 3$ wave structure in the sub-Antarctic region. We have demonstrated that the sub-Antarctic autumn temperature anomalies result from IMF $B_y$-driven changes to surface atmospheric pressure attributed to the global atmospheric electric circuit (Lam et al 2013, 2014) that drive air across the large meridional gradients in air temperature between 50 and 70 °S, i.e., in the Southern Ocean outside Antarctica. Given the size of the temperature anomalies, we conclude that it is important to understand the mechanisms behind these global atmospheric electric circuit-related influences on meteorology, and to implement and test them in numerical models.

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