Atmospheric and upper ocean environments of Southern Ocean polar mesocyclones in the transition-season months, and associations with teleconnections

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Abstract

Over middle and higher latitudes of the Southern Hemisphere, intense mesoscale cyclonic vortices that develop in cold air outbreaks -cold air mesocyclones- occur frequently during transition season months. In this study, previously-published mesocyclone inventories for March-April and October-November are compared to atmospheric and upper-ocean variables pertinent to mesocyclogenesis, as provided by reanalyses. This procedure allows determination of the large-scale environments favorable to mesocyclone occurrence: low mid-tropospheric temperatures, greater sea ice extent, and large positive differences in the sea surface temperature (SST) minus low-altitude air temperature, the latter coinciding with enhanced low level winds having a southerly component. We then evaluate the associations between polar mesocyclone formation and dominant patterns of low-frequency variability in the atmospheric circulation; the El Niño Southern Oscillation (ENSO), the Southern Annular Mode (SAM), and the Trans-Polar Index (TPI). Our results suggest that in spring, the intra-hemispheric variability in mesocyclogenesis is dominated by ENSO. In autumn, the influence of ENSO, SAM, and TPI on mesocyclone activity are about equal although the response differs regionally. Moreover, teleconnections' effects on mesocyclone activity are somewhat reduced compared to spring. In both seasons, the phase of the Semi-Annual Oscillation (SAO) modulates the associations with mesocyclones by influencing the latitude of the circumpolar trough and amount of cyclonic activity over the Southern Ocean. These associations likely result from the displacement of the storm track between opposite phases of a given teleconnection and its position relative to the sea ice edge.

Keywords: cold-air mesocyclones, teleconnections, ENSO, SAM, TPI, composite analysis

1. Introduction

Over middle and higher latitudes of the Southern Hemisphere (SH) (Figure 1), intense mesoscale cyclonic vortices that develop in cold air outbreaks, or cold-air mesocyclones [*Heinemann and Claud,* 1997], occur not only in the cold season but also during transition season months [e.g., *Carleton and Song*, 1997]. Previous studies even suggest a maximum frequency of systems in the months of March and October [e.g., *Turner and Row*, 1989; *Bromwich* 1991; *Fitch and Carleton*, 1992; *Carleton and Song*, 1997; *Carrasco and Bromwich*, 1996; 1997a and b; *Carrasco et al.*, 2003]. This situation contrasts with the Northern Hemisphere (NH), where mesocyclone maximum frequencies occur in winter [e.g. *Wilhelmsen*, 1985; *Harold et al.*, 1999; *Blechschmidt,* 2008; *Bracegirdle and Gray*, 2008; *Zahn and von Storch*, 2008]. A likely explanation for the inter-hemispheric differences in mesocyclone seasonal activity is that Antarctica is a source of cold air throughout the year, and latitudinal temperature gradients are intensified over the sub-Antarctic in the equinoctial and immediately adjacent months accompanying the Semi-Annual Oscillation (SAO) of pressure/height and zonal winds [e.g., *van Loon*, 1967; *van Loon and Rogers*, 1984].

Case studies of cold air mesocyclones in the SH can be divided into two broad satellite-observed signature types, namely comma cloud and spiraliform vortices [e.g. *Forbes and Lottes*, 1985; *Carleton and Carpenter*, 1989; *Heinemann*, 1990; *Turner et al*., 1993a; *Carleton*, 1995; *McMurdie et al.*, 1997]. The comma cloud vortex type, with a length scale of 500-1000 km, typically represents deep baroclinicity and occurs in cold advection within the larger circulation of frontal cyclones [e.g., *Mansfield*, 1974; Reed, 1979; *Carleton*, 1987; *Businger and Reed,* 1989]. These systems are associated with Positive Vorticity Advection (PVA) at midtropospheric levels. The spiraliform vortex type, generally of smaller size, tends to occur at higher latitudes deep within cold air [i.e., more barotropic conditions: *Rasmussen*, 1979, 1981; *Rasmussen et al*., 1992; *Turner et al*., 1993a]. Moreover, most cold-air mesocyclones develop over the open sea where their intensity is enhanced by vertical fluxes of heat and moisture. This suggests that a wide variety of mechanisms can be important for the development and maintenance of cold air mesocyclones. Indeed, a long-standing controversy existed on whether baroclinic instability [e.g. *Harrold and Browning*, 1969; *Mansfield*, 1974; *Duncan*, 1977; *Nordeng and Rasmussen*, 1992], conditional instability of the second kind (CISK), or wind-induced surface heat exchange (WISHE; e.g. *Emanuel*, [1986]; *Emanuel and Rotunno*, [1989]; *Rasmussen*, [1989]), would better explain such developments. A consensus was finally reached in 1994 : mesocyclones appear in many forms, leading to the concept of a « spectrum » [*Turner et al*., 1993a] extending from purely baroclinic to purely convective systems, and including hybrid systems.

Because mesocyclones often are associated with significant weather (strong winds; heavy precipitation as rain, hail and/or snow; rough seas), and can develop rapidly, they pose a significant forecasting problem for Antarctic coastal areas and maritime areas of southern Australia, New Zealand, South Africa and Chile. In addition, cold air mesocyclones are an important component of the coupled atmosphere-ocean system: regions experiencing high frequencies of mesocyclones show an associated climatic signature in precipitation, wind speed, and sea level pressure [*Lyons*, 1983; *Bromwich,* 1991; *Sinclair and Cong,* 1992; *Turner et al.*, 1993a; *Carrasco and Bromwich*, 1994; *Carrasco et al.*, 2003]. On decadal and longer time scales, mesocyclones may even help maintain the higher-latitude branch of the thermo-haline circulation, as inferred from the close spatial correspondence between mesocyclone maxima in the northern North Atlantic and the downwelling of cold saline water around Greenland and Labrador [e.g. *Harold et al*., 1999; *Bracegirdle and Gray,* 2008]. A similar relationship may exist in the Antarctic, where coastal polynyas generated or enhanced by strong katabatic winds, participate in the formation of Antarctic bottom water. At least some of those polynya-katabatic wind confluence areas have been noted to coincide with high frequencies of cold-air mesocyclones [e.g., *Carleton* 1992, 2003]. Recently, *Condron et al*. [2008] have shown that a better representation of polar mesocyclones in ERA-40 reanalyses [*Simmons and Gibson*, 2000] would increase Greenland Sea deep water formation by up to 20% in one month. Studies such as these point to the real need to accurately represent mesocyclones in oceanic and coupled climate models, so as to capture the high rates of ocean heat loss otherwise omitted for deep water formation regions.

Accordingly, it is highly desirable to better understand and improve the predictability of time periods and locations of cold-air mesocyclogenesis. Because these systems usually develop within favorable large-scale meteorological environments, especially cold-air outbreaks and PVA [e.g., *Harrold and Browning,* 1969; *Mansfield,* 1974; *Rasmussen,* 1979; *Businger and Reed,* 1989; *Hewson et al.,* 2000; *Claud et al.,* 1992a and b, 1993, 2004], a useful first step towards the aforementioned goal has been to determine the typical (e.g., via composite averaging) regional-scale fields of meteorological variables associated with mesocyclones [e.g., *Businger*, 1985, 1987; *Fitch and Carleton,* 1992; *Carleton and Fitch*, 1993; *Turner and Thomas*, 1994; *Carleton and Song*, 1997; *Carrasco et al*., 1997a and b; *Claud et al*., 2007, 2009]. In general, such studies have shown that increased monthly and seasonal frequencies of cold-air mesocyclones coincide with amplified anomalies in 500 hPa height and temperature fields over middle and higher latitudes, either within the anomalous trough or between the trough and the next upstream ridge (i.e., in the region of persistent cold advection) [*Businger*, 1987; *Ese et al.,* 1988; *Fitch and Carleton*, 1992; *Carleton and Fitch*, 1993; *Turner and Thomas,* 1994; *Carleton and Song*, 1997]. The probability of large numbers of mesocyclones increases where and when these conditions coincide with positive anomalies of the sea surface temperature (SST) and near-surface air temperature difference, as well as sea ice extent, such as in the Ross and Bellingshausen/Amundsen seas [e.g., *Carleton and Carpenter*, 1990; *Carleton and Song*, 1997]. These associations suggest the possibility not only of better characterizing areas susceptible to cold air mesocyclogenesis on monthly to seasonal time scales, but also of improving mesocyclone predictability from consideration of the larger-scale circulation teleconnection patterns within which coupled atmosphere-upper ocean anomalies occur.

Manual interpretation of satellite imagery for mesocyclones, and compositing system frequencies and locations on monthly to seasonal time scales, have revealed preliminary associations with the large-scale atmospheric circulation and teleconnection patterns, particularly El Niño Southern Oscillation (ENSO) [*Carleton and Carpenter*, 1990; *Carleton and Song*, 1997, 2000]. Although the ENSO has its strongest manifestation in the tropical Pacific, it significantly impacts higher-latitude areas of the SH, particularly the southeast Pacific [see *Turner*, 2004 for a review]. The most pronounced teleconnection to ENSO occurs as a Rossby wave train having positive (negative) height anomalies over the Amundsen-Bellingshausen Sea during warm (cold) events, and the reverse pattern in the Weddell Sea [*Carleton*, 1988]. Since about 1977, the ENSO has shifted towards a more negative phase of more frequent and stronger El Niño events. However, extra-tropical climate relationships with ENSO seem not to have been stable even since that time [*Carleton*, 1989; *Bromwich et al.*, 2000], and recent studies [e.g. *Fogt and Bromwich,* 2006; *L'Heureux and Thompson*, 2006] have discussed a possible inter-decadal modulation of the ENSO teleconnection in the high latitude South Pacific by the Southern Annular Mode (SAM). The SAM is the leading mode of atmospheric circulation variations in the SH extra-tropics [e.g., *Kidson*, 1999; *Limpasuvan and Hartmann*, 1999; *Thompson and Wallace*, 2000; *Carleton*, 2003]. The zonally symmetric structure of the SAM reflects the fact that it is driven by anomalies in the eddy flux of zonal momentum over middle latitudes. During SAM positive (negative) phases, the anomalous poleward flux of eddy momentum drives westerly (easterly) anomalies at 55-60°S [e.g., *Karoly*, 1990; *Limpasuvan and Hartmann,* 2000]. The positive phase of SAM is associated with a strengthening and poleward shift of the storm track over the Southern Ocean [*Thompson and Wallace*, 2000]. In recent years, especially in austral summer and autumn seasons, the SAM has shifted into a more positive phase [*Marshall*, 2003], denoted by a decrease in surface pressure over Antarctica and a strengthening of the westerlies in the coastal region as pressure has risen over middle latitudes [e.g., *Gong and Wang*, 1999; *Renwick*, 2004]. In addition to the ENSO and SAM, zonally asymmetric teleconnections of essentially extratropical origin show important associations with temperature, meridional wind and precipitation for key sectors of the Southern Ocean, the first 2 variables also being connected to regional anomalies of the Antarctic sea ice [*Harangozo*, 1997]. In particular, the Trans-Polar Index (TPI), typically defined as the Sea Level Pressure (SLP) anomaly difference between Hobart and Stanley [*Pittock*, 1980, 1984; *Rogers and van Loon*, 1982; *Carleton*, 1989, 2003], depicts the eccentricity of wavenumber one, and has been shown to influence sea ice and mesocyclone distributions in the winter season [*Claud et al*., 2009]. In its positive (negative) phase, TPI is associated with an enhanced ridge (trough) in the Australian region and an enhanced trough (ridge) in the South American Sector.

Because the few studies relating SH teleconnections and mesocyclone occurrence were generally for short time periods (typically a couple of years representing opposite phases), and utilized datasets on atmospheric and oceanic variables that were considerably less comprehensive than those now available, we revisit this issue specifically for the transition-season months. In this paper, we undertake the following sets of analyses: i) Compare previously-published inventories of mesocyclones for selected regions to the newly available high quality long term meteorological reanalyses to identify typical synoptic atmospheric and upper-ocean environments favorable to mesocyclogenesis; and ii) Characterize the associations between composite reanalysis meteorological fields associated with mesocyclones and the large-scale circulation patterns of ENSO, SAM and TPI, by deriving maps of enhanced “mesocyclogenesis potential”, as well as low probability of mesocyclogenesis, in relation to the extreme phases of those teleconnections. Moreover, because the Antarctic sea ice extent is close to its maximum (minimum) in October (March), an examination of the transition season months permits a fuller assessment of the climatic role of sea ice conditions in mesocyclogenesis over higher southern latitudes compared to the winter season. To the knowledge of the authors, this study is the first to address these issues at an hemispheric scale and by considering simultaneously the ENSO, SAM, and TPI.

The paper is organized as follows. In the next section we present the data and analysis methods. In Section 3, we determine variables useful for identifying areas having high frequencies of cold-air mesocyclones, based on previously-published inventories of mesocyclones and the reanalysis fields in transition-season months. In Section 4, we describe associations between the mesocyclone-significant variables and large-scale circulation, as revealed by spatial composites of mesocyclone reanalysis variables according to teleconnection phases. From those composite results, we identify the spatial areas likely to see enhanced -and also suppressed- formation of mesocyclones relative to background levels on hemispheric scales (the Mesocyclogenesis Potential), in Section 5. The results and implications of the study are summarized in Section 6.

2. Data and Analysis

The transition-season months comprise March, April, October and November (i.e., two adjacent months representing SH autumn and spring, respectively). Individual months rather than two-month averages are considered because conditions can change markedly between adjacent months (for example, sea ice concentration and extent), and our calculations show that the statistical relationships between teleconnections differ on monthly timescales (see section 3a). We do not consider the month of September because, although an equinoctial month like March, it retains characteristics of the SH winter season [*van Loon*, 1966, 1967; *Streten and Troup*, 1973; *Carleton*, 1979] because of the temporal lag between insolation minimum and lowest air temperatures over higher southern latitudes. For example, in most years, the sea ice continues to expand equatorward during September. Accordingly, we included September in our recent study of mesocyclone-circulation teleconnection associations for the winter season [*Claud et al.*, 2009]. The month of May was not considered because there is no mesocyclone inventory available for this month.

a. Mesocyclone inventories

Although there exists a number of long-term climatologies of extra-tropicalcyclone tracks based on reanalyses, they cannot be used for our purpose. For the northern hemisphere, *Condron et al*, 2006 compared satellite-based with reanalysis-based cyclone climatologies, and showed that about 3 out of every 4 systems having a size between 100 and 500 km were not reproduced in ERA-40. It is, therefore, necessary to rely on satellite-based climatologies. Unfortunately, and unlike for the winter season, these satellite-based mesocyclone inventories are few in number for the SH in the transition-season months. However, to help guide our choice of meteorological variables with which to depict cold-air mesocyclone environments, we used the inventories for individual transition-season months given in *Fitch and Carleton* [1992] and *Carleton and Song* [1997] (which include both single-banded mesocyclones evident initially in satellite images as enhanced convection in cold air masses (i.e., “comma cloud”) and multi-banded (“spiraliform”) types). Therefore, in the following analysis, we compare monthly averages of the mapped reanalyses fields with mesocyclone locations derived separately for: i) March, April and October 1988, and centered on the “half-hemisphere” between approximate longitudes 100°E eastward to 50°W [*Fitch and Carleton* 1992; hereafter FC92]; and ii) March-April and October-November 1992 in the Australasian sector (70°E-150°W) [*Carleton and Song*, 1997, hereafter CS97]. The years studied represent large variations in SH atmospheric circulation, including a transition from El Niño to La Niña (1988), and a prolonged El Niño that began in 1991 [*Cullather et al*., 1996; *Trenberth and Hoar*, 1996]. To complement this investigation, we also consider a partial (sample) census of mesocyclones undertaken for March and April 1990 which, unlike the previous inventories, is available for the full SH poleward of 45°S (Figure 1).

In the FC92 study, as for the period March-April 1990, mesocyclones were identified based on visual interpretation of twice-daily medium resolution (5.4 km^2) thermal infrared hard-copy images acquired by the polar-orbiting Defense Meteorological Satellite Program (DMSP). The spatial and temporal resolutions of the DMSP imagery are unlikely to have significantly biased the detection of mesocyclones because shorter-lived systems also tend to be weaker, and most mesocyclones are evident at the 5.4 km^2 resolution used on the half-hemispheric mosaics [e.g., *Carleton*, 1987]. Further details on the DMSP imagery used to derive mesocyclone inventories are given in *Carleton and Carpenter* [1990] and CF93**.**

In the CS97 study, mesocyclones were identified using geosynchronous GMS (Geostationary Meteorological Satellite) images. Although these are less advantageous than the polar-orbiting DMSP owing to the large satellite viewing angles for the higher latitudes, their use was facilitated by rectifying raw images to a polar stereographic format, thereby improving the ability to detect mesocyclones. Also, CS97 noted that most larger mesocyclones over sea ice (for October, November) and ocean areas (all months) were likely to have been captured in the analysis of rectified images.

b. Long-term high resolution reanalyses

Meteorological data are available as reanalyses generated by a numerical forecast model that assimilates available observations. Among those, the ERA-40 data assimilation system [*Simmons and Gibson*, 2000] uses the Integrated Forecasting System (IFS) developed jointly by ECMWF and Météo-France. A three-dimensional variational method assimilates the observations into the model, which has 60 vertical levels and T159 horizontal spectral resolution. Data are available since 1957 for 23 pressure levels with a spatial resolution of approximately 125km (1.125°). A detailed description of the ERA-40 dataset can be obtained at http://www.ecmwf.int/research/era. Since 1979, the reanalysis makes comprehensive use of satellite observations; before then, the atmospheric fields over higher southern latitudes are model-dominated. Hence, to avoid possible discontinuities due to the inclusion of satellite data [e.g. *Bromwich and Fogt*, 2004; *Sterl*, 2004], we study the period 1979-2001.

Despite the availability of monthly ERA-40 SST, we utilize the Extended Reconstructed Sea Surface Temperatures (ERSST), which correspond to a monthly extended reconstruction of global SST based on the Comprehensive Ocean-Atmosphere Data Set and uses sea ice concentrations to improve the high-latitude SST analysis [*Smith and Reynolds*, 2003, 2004]. The ERSSTs have undergone stringent quality control, and are available at the following address: http://lwf.ncdc.noaa.gov/oa/climate/research/sst/sst.html#ersst. Sea ice concentrations retrieved from passive microwave radiances of the NIMBUS-7 SSMR and DMSP SSM/I are obtained from http://nsidc.org/data/seaice_index/ [*Cavalieri et al.*, 1996]. Both the sea ice concentration and SST data have been regridded onto the ERA-40 grid of 1.125° spatial resolution to make all fields compatible.

c. Statistical analysis

To characterize the associations between large-scale teleconnection patterns and mesocyclone environments, we perform temporal linear inter-correlations of teleconnection indices and derive spatial composites of the atmospheric reanalysis fields. The monthly indices for ENSO and TPI were acquired from http://www.cdc.noaa.gov/gcos_wgsp/, and for SAM from http://www.antarctica.ac.uk/met/gjma/sam.html. Because the peak in most ENSO indices typically occurs in the SH summer, we use a seasonal index calculated by averaging the normalized Niño 3.4 SST index [*Trenberth*, 1997] over the broad seasonal period October through February. In addition, we compute correlations and spatial composites for ENSO opposite phases (El Niño, La Niña) both in year0 and the term 12 months earlier (year-1). Previous studies [e.g., *van Loon*, 1984 ; *van Loon and Shea*, 1985 ; *Carleton*, 1988, 2003] have indicated large changes in SLP and other climatic indices (e.g., sea-ice concentration) over SH middle and higher latitudes between ENSO year0 and year-1, particularly for El Niño. For autumn months (March-April), year0 immediately follows the peak in the index while for spring months (October-November), year0 represents the onset year. Thus, in the composites, autumn (year-1) precedes spring (year0) by a half-year, as does spring (year-1) with respect to autumn (year-1).

For each month and teleconnection considered, only the extreme years have been selected for determining the composites. This is a standard procedure in composite analysis as it avoids the noise that can be introduced by including near-neutral years. Depending on the month and teleconnection considered (Table 1), the number of years for producing composites ranges from 3 (November, TPI negative) to 7 (November, SAM negative), with a majority comprising 4 or 5 years.

The statistical significance of the composites is assessed at each gridpoint using a phase-scrambling bootstrap test with 999 samples [*Davison and Hinkley,* 1997], taking into account the autocorrelation characteristics of each time series.

3. Mesocyclone spatial distributions: associated surface and atmospheric fields

In the *Claud et al.* [2009] study for the SH winter-season months, mesocyclone frequencies over the open ocean were found to increase when and where the difference between the SST and the temperature at 925 hPa (SST-T925) increases, in conjunction with south to southwesterly low-level (925hPa) winds (**V**925). These associations suggested strong upward fluxes of heat and moisture, particularly west and south-west of mid-tropospheric troughs and frontal cyclones. Additional favorable conditions for mesocyclones include negative anomalies of temperature at 500 hPa (T500), typically accompanied by greater sea ice extent in those longitudes [e.g. *Yuan et al.*, 1999]. Conversely, unfavorable conditions for mesocyclone development involve negative or only weakly positive SST-T925; low-level winds having northerly components (i.e., a stable lower atmosphere); warm air at 500 hPa; and reduced sea ice extent (i.e., implied downward fluxes of heat typically located east of frontal cyclones and west of high pressure ridges: *Carleton and Carpenter*, 1989]. To determine the extent to which these variables are important for mesocyclogenesis in the transition-season months, we identify their associations with the first satellite observation of each mesocyclone given in the inventories, at the daily level (Table 2). The percentages of mesocyclogenesis associated with a large positive SST-T925 (column 2), low T500 (column 3), or southerly **V**925 (column 4) are stratified by month considered. A threshold of 6K (10K) was used for SST-T925 in the months of March and April (October and November). There is no unique threshold value for T500 because of the latitude dependence**.** The analysis is restricted to latitudes poleward of 45°S (in the 1992 inventory, mesocyclones were reported at latitudes lower than 45^{o}S). Among the three variables, the more robust association is with T500 (Table 2) : mesocyclogenesis is most frequently associated with low T500 (74% of cases, on average). In addition, there is relatively little variation of percentages among the months or periods considered (68-81%). Practically all the remaining cases were first observed in association with large T500 gradients, mostly to the west of troughs. Mesocyclogenesis frequencies of about 60%, on average, are associated with southerly **V**925 and also large SST-T925, although there are large variations from one month/region to another (values range between 49-75.5 % for **V**925, and 45-70% for SST-T925). In addition, for most cases when the meridional component of **V**925 was not from the south, the zonal component of **V**925 was large; that is, cold-air mesocyclones are associated with either southerly winds or strong westerly winds. Specifically for the variable SST-T925, a large number of mesocyclones formed in areas where the horizontal gradient is large.

The results presented in Table 2 confirm those for the winter season [*Claud et al.*, 2009]. Mesocyclones occur preferentially in association with either low temperatures at 500 hPa or proximity to large gradients of T500. Additional favorable conditions for mesocyclones are confirmed to include a large positive difference in SST-T925, coincident with south to southwesterly low-level winds (**V**925). An increase of mesocyclones along the sea ice edge (especially in October; see also *Carleton and Fitch*, [1993], *Carleton*, [1995] and *Carleton and Song*, [2000]), and an association with preferred areas for katabatic winds near the Antarctic coast (the Ross Sea or Adelie Land; March and April 1988) was also noted. Conversely, unfavorable conditions for mesocyclone development (i.e., reduced frequencies of vortices) generally involve negative or only weakly positive SST-T925; low-level winds having northerly components (i.e., a stable lower atmosphere); and warm air at 500 hPa.

4. Composite patterns of reanalysis fields associated with teleconnections

a. Teleconnection statistical inter-relationships

Updated [cf. *Carleton*, 1989] inter-correlations between the teleconnection indices (SAM, ENSO, TPI) for transition-season months (March-April, October-November) are presented in Table 3. A number of studies suggest a change in statistical correlation between the ENSO and Antarctic-region climate variables between the 1980s and 1990s [e.g., for precipitation: *Fogt and Bromwich*, 2006, *Thomas et al*., 2008]. To check whether the inter-correlations are consistent within the recent period, we calculate these separately for 1979-1990 (i.e., first subset of the recent period) and 1991-2000 (second subset). In addition, and for comparison purposes, we calculate correlations for the earlier period 1957-1978.

For the full recent period 1979-2001 (Table 3), TPI and SAM were not significantly correlated at the 90% level, except SAM in March with TPI in October (correlation of 0.33). By contrast, for 1957-1978, correlations between TPI and SAM generally were larger and more significant, especially for the spring. For 1979-2001, SAM and ENSO (year-1) were significantly related only in November at r = 0.33. When considering SAM and ENSO at year0, a positive correlation is obtained in March (0.56) and a negative one during spring (-0.57 in October and -0.4 in November). Changes are evident in the correlations between the two recent sub-periods (1979-90, 1991-2000), with absolute values being generally larger for the latter period. In the 1990s, the increase in the correlations for austral spring is consistent with previous findings [*Fogt and Bromwich*, 2006; *L'Heureux and Thompson*, 2006].

The TPI and ENSO (year-1) in the period 1979-2001 are not significantly correlated. Moreover, the TPI and ENSO at year0 are only significantly negatively correlated in November (-0.37). As was noted with regard to the SAM, these teleconnection inter-correlations generally are not stable on decadal timescales, with even a sign reversal evident between the two sub-periods, particularly in autumn.

For the earlier period 1957-1978, TPI and ENSO were significantly correlated during spring months, at year0 but not at year-1. The SAM and ENSO were significantly positively correlated during spring at year-1, and negatively in April at year0.

The foregoing results confirm the lack of stability in the correlations between teleconnection indices at decadal and multi-decadal scales for transition-season months. Because the period we are considering for the synoptic composites associated with mesocyclones is rather short (1979-2001), caution should be exercised when interpreting results for the months and teleconnections that are significantly correlated (see discussion in Section 5).

b. Composites

The associations between polar mesocyclones and teleconnections are inferred from the composite anomaly fields of SST-T925, the wind at 925 hPa (**V**925), and T(500) (Figs. 3-8). We first discuss the patterns for spring because these precede the peak in ENSO (year0), they pertain to the time around (October) or just after (November) the maximum sea-ice extent, and they follow sequentially the patterns for the winter season (June-September) presented in *Claud et al.* [2009]. Each of the three large-scale teleconnections is discussed successively, emphasizing the months and patterns that show the largest statistically-significant associations. To make more apparent the large-scale associations, we show composite standardized anomalies relative to the 1979-2001 mean fields that are displayed in Figure 2 for each of the four autumn and spring months. Unless specified, only results significant at the 90 % confidence level are discussed. Only a few mapped composites are shown (Figs. 3-8) but they are synthesized in Section 5 with an index of mesocyclogenesis activity, the mesocyclogenesis potential, for October and March.

- spring (October-November)

In the spring of the ENSO onset year (i.e., year 0, Figure 3a, c), a significant signal in SST-T925 and **V**925 is observed, particularly for the anticyclonic circulation anomaly (indicated by **V**925) in the southern Pacific Ocean in October. Because this feature has associated anomalies in SST-T925 and in T500, there are expected to be consequences for mesocyclone formation: conditions are deemed favorable for mesocyclogenesis over the eastern part of the Bellingshausen Sea and to the southeast of New Zealand, but unfavorable over the Amundsen Sea. The results are opposite for La Niña years (Figure 3b, d), which is consistent with the composite circulation changes noted in previous studies [e.g., *van Loon and Shea*, 1985; *Carleton*, 1988]. In November (Figure 3e-h), the El Niño (year 0) has associated positive anomalies of SST-T925, southerly winds, and lower 500 hPa temperatures in the sector 110-150°E, and to the north of the Weddell Sea. Accordingly, these two regions are likely to see increased frequencies of mesocyclones. By contrast, La Niña years likely see more mesocyclone activity equatorward of the sea ice edge at around 65°S, between 150°E and 150°W. Associations between ENSO at year-1 and SST-T925, **V**925 and T500 (not shown) are much weaker compared to year 0, especially in October.

Associations between the SAM and near-surface climate conditions are stronger in the negative phase than in the positive phase, both in October (Figure 4a-d) and November (Figure 4e-h). In October, during negative SAM, the formation of mesocyclones is expected to be favored along the sea ice edge, especially northeast of the Weddell Sea, yet inhibited over the area 90^o -120°E (Figure 4b, d). In November (negative SAM), mesocyclone development should increase relative to background levels practically everywhere except north of the Ross Sea. As is also observed for March (see below), the SAM positive phase in October shows practically no significant association with SST-T925 and **V**925. Associations are somewhat stronger for **V**925 in November, with significantly increased westerlies over the area 60°-70°S from 10°W **to** 110°W. In November, for positive SAM, negative T500 anomalies prevail over the Antarctic continent and the Ross and Amundsen Seas, while the situation is reversed there for negative SAM.

For the positive TPI in October (not shown), the Bellingshausen Sea and part of the Amundsen Sea should see more mesocyclone activity, given negative T500 anomalies and southerly anomalies of **V**925 in that region. Similarly, over the area between about 150°E and 180^{o}, SST-T925 anomalies are significantly positive, **V**925 southerly anomalies prevail, and T500 anomalies are negative, while at about 180° longitude apart, the opposite results are observed, the latter implying reductions in mesocyclone activity. A positive TPI phase in November (not shown) is likely to be associated with less mesocyclone activity practically everywhere due to significant negative SST-T925 and positive T500 anomalies (the composites in **V**925 are almost never significant). When TPI is negative for both October and November, a large area centered on Drake Passage displays significantly negative SST-T925 anomalies, northerly **V**925 anomalies and positive T500 anomalies, all unfavorable for mesocyclogenesis.

- autumn (March-April)

For ENSO (year0) in March (i.e. a few months after the peak of El Niño, see Table 1), positive SST-T925 anomalies, coincident with southerly wind anomalies occur on both sides of the Antarctic Peninsula (barely significant), and also centered near 150°E (Figure 5). Because these low-level anomalies also co-occur with negative T500 anomalies, mesocyclogenesis is particularly favored. The opposite pattern -and implied suppression of mesocyclogenesis- occurs in the Ross Sea and western Amundsen Sea. This situation contrasts with that for La Niña events, during which the Weddell Sea and the region just west of the Antarctic Peninsula should see fewer mesocyclones because northerly winds blow over negative SST-T925 values, while part of the Ross Sea should see more activity owing to southerly wind anomalies and more positive SST-T925. Associations between ENSO and **V**925 are rather small in April year0 (not shown), with only small regions characterized by significant anomalies of positive SST-T925 and negative T500.

For April in ENSO year-1 (Figure 6), associations with mesocyclone development are stronger than they are in March (not shown). In particular, for Niño years, an anticyclonic circulation anomaly appears in the southern Pacific Ocean between 140-180°W: northerly wind anomalies, a reduced vertical temperature gradient and positive T500 anomalies prevail, all considered unfavorable for mesocyclogenesis. This situation contrasts with that for the area east of 120°W. La Niña events are mostly associated with negative SST-T925 anomalies, coincident with northerly wind anomalies and generally positive T500 anomalies (i.e., unfavorable climatically for mesocyclogenesis) at three locations: between 60 and 100°E, north of the Ross Sea and both sides of the Drake Passage.

For March, the association between a positive SAM phase and mesocyclone activity is observed only for small areas (not shown**)**, however, **t**he association is stronger for the negative phase (not shown) with three areas displaying positive SST-T925 anomalies (at 150°E, 60°E, and 30°W). These areas also correspond to negative T500 anomalies and, in certain locations, southerly **V**925 anomalies, all of which suggest increased mesocyclone activity over the three ocean basins in the SAM negative phase. In April, a SAM negative phase likely sees more mesocyclones in the Drake Passage area, over the region between 10°W and 6°E, and at about 60°S, 180°; all areas having positive SST-T925 anomalies, southerly **V**925 anomalies and negative T500 anomalies. By contrast, a lack of mesocyclones is expected over most of the Amundsen Sea and along the Antarctic coastline for longitudes 90^o -150°E. For the SAM positive phase in April (Figure 8a-d), the anomalies are statistically significant over larger areas compared to March. Because these are mostly negative SST-T925, northerly **V**925 and warmer T500, the expectation is for fewer mesocyclones. One exception is along the Antarctic coastline, between longitudes 60^o -120°E.

For the TPI positive phase in March (Figure **7**), the area between 150°E and 180^{o} is expected to see more mesocyclones given the presence of positive SST-T925, southerly winds, and low T500 anomalies. For three locations (between 50^{o}- 60°S for longitudes 120°W to 150°W; closer to the Antarctic continent, between 90°E and 120°E, and at around 0^{o} longitude), fewer mesocyclones should develop because of negative SST-T925, wind anomalies having a northerly component; and T500 positive anomalies. The latter situation contrasts with that for negative TPI, for which mesocyclone formation is favored away from the continent at around 150°W, 30°W, and to a lesser extent near 120°E. The area between 150°E and 180^{o} should see a dearth of mesocyclones, along with the Bellingshausen and Admundsen seas. Similar alternating patterns are observed for positive TPI in April (Figure 8), even though the association is somewhat less marked. For positive TPI, an increase in mesocyclone activity is expected between 120^{o}-150°W, and for relatively low latitudes, between 30^{o} and 60°E and $120^{\mathbf{o}}$ and 150°E, because of the presence of positive SST-T925, wind anomalies having a northerly component, and negative T500 anomalies. In between those areas, fewer mesocyclones are expected, especially southwest of New Zealand and in the Bellingshausen Sea because unfavorable upper ocean and atmospheric conditions prevail..

5. Mesocyclogenesis Potential for Teleconnection Phases

To depict the spatial areas favorable -and also unfavorable- to mesocyclogenesis for different teleconnections, it is necessary to integrate the important information from each reanalysis composite map. We achieve this objective by applying the “mesocyclogenesis potential” (MCP) method we previously developed for the winter season [*Claud et al.*, 2009], to the spring and autumn months. The MCP denotes the increase in mesocyclone-favorable conditions relative to background activity for a given month, according to four nominal categories of elevated probability: “Increased”, “Moderate”, “High”, and “Maximum”. These categories are determined from the spatial coincidence of overlapping areas for the following mesocyclone-favorable conditions: negative anomalies of T500; positive values of SST-T925; anomalies of **V**925 having a southerly component; and location within 2.5^{o} latitude of the sea-ice edge [*Carleton and Fitch*, 1993] or continental ice margin under off-ice airflow conditions. The four MCP categories are defined as follows: (1) Increased Probability: any one favorable condition present, or two favorable conditions present along with a mesocyclogenesis unfavorable condition (see below); (2) Moderate Probability: any two favorable conditions co-occurring; (3) High Probability: all but one favorable condition present; and (4) Maximum Probability: all four mesocyclone-favorable conditions present present (i.e., southerly winds coinciding with positive SST-T925, location beneath negative T500 anomalies, and proximity to the sea ice or land ice edge).

In determining MCP categories by teleconnection phase, the spatial areas identified for each reanalysis variable (T500, SST-T925, **V**925) are contained within the 90 percent confidence level of the composite, and extend into adjacent areas having large differences of the same sign. The MCP is not determined over the Antarctic continent or ice shelves, or for sea-ice covered areas, because one or more mesocyclone-relevant variables are either absent or have little physical meaning (e.g., SST-T925). This consideration is particularly important in October because of the typically large areal extent of sea ice in that month. The MCP method currently does not weight regional differences in mesocyclone formation factors, such as the important role of katabatic winds in the western Ross Sea or a dominant upper cold pool of air in the Amundsen and Bellingshausen seas [cf. FC92; *Carleton and Fitch*, 1993]. Future refinement of the method to account for such regional differences is desirable. Notwithstanding, the generation of unweighted MCP monthly summary maps (Figures 10-13, discussed below) readily permits intra-hemispheric comparisons of the locations and areal coverage of each category; for opposite phases of the same teleconnection (e.g., El Niño (year0), La Niña (year0)) in a given month, and for similar phases in different months (e.g., El Niño (year0) in March, October).

Those spatial areas that are likely to experience substantially decreased mesocyclogenesis compared to climatology (i.e., -MCP) for SH teleconnection modes, also are determined. These are based upon the overlap of mesocyclone-unfavorable conditions depicted on the reanalysis composites [cf. *Claud et al.*, 2009]. The unfavorable conditions generally are the opposite of those deemed favorable for mesocyclogenesis, as follows: positive anomalies of T500; negative SST-T925; northerly anomalies of **V**925; on-ice airflow. Because we emphasize the mesocyclogenesis potential (i.e., MCP) of teleconnections in this study, we determine only the lowest two probability categories of –MCP: "Not Favorable" (i.e., all but one unfavorable condition present); and "Least Favorable" (all mesocyclone-unfavorable conditions are present). These two low probability categories represent the opposite of the MCP High and Maximum categories, respectively.

The spatial dependencies of the two highest and two lowest probability classes of mesocyclogenesis potential (i.e., MCP, -MCP) are summarized schematically in Figure 9. These idealized relationships are shown with respect to the middle-to-higher latitude storm track, represented by the typical satellite-viewed cloud vortex of a frontal cyclone [*Guymer* 1978]; the associated mid-tropospheric geopotential height and thermal trough/ridge pattern (i.e., assuming equivalent barotropy; *van Loon and Kidson* [1993]); the springtime sea ice extent and concentration; and Antarctic continental ice sheet margin (for early autumn associations). Accordingly, Figure 9 links the meso-scale patterns of mesocyclone-significant upper-ocean and atmosphere variables depicted on the reanalysis composites (Figures 3-8) with the synoptic-scale atmospheric circulation; the latter varying by teleconnection phase. Higher MCP occurs in the cold air advection west and south-west of the storm track, within the trough (i.e., negative T500), because this area typically has strongly positive SST-T925 and enhanced southerly anomalies of **V**925 [e.g., *Yuan et al.*, 1999]. Divergence in the lower-level wind field west of the trough axis resulting from the Coriolis deflection [e.g., *Motoi et al.*, 1998; *Milliff et al.*, 1999] promotes upwelling of colder water on climatic timescales. The maximum values of MCP are located just equatorward of the sea-ice edge under off-ice airflow conditions because of the tendency for enhanced zonal gradients of SST and T925 to develop there [e.g., *Kottmeier and Hartig*, 1990]. These enhanced temperature gradients in the atmospheric boundary layer have been implicated in mesocyclogenesis events near the Antarctic sea ice edge [e.g., *Carleton and Fitch* 1993]. In those longitudes (Figure 9), the sea ice is displaced equatorward of its mean position, with the maximum extent located just west of the thermal/geopotential trough axis. There, wind-induced ice divergence leads to reduced ice concentration, and appreciable ocean-to-atmosphere turbulent heat fluxes. In late summer and early autumn, when sea ice is absent from much of Antarctica, the MCP increases close to the continental ice-sheet margin in areas of off-continent airflow (i.e., southerly winds): "column stretching" of air as it descends the ice sheet is believed to be important in the spin up of many such coastal mesocyclones [e.g., *Turner et al.*, 1993b; *Carrasco and Bromwich*, 1995; *Heinemann*, 1996].

By contrast, east of the storm track -just west of the geopotential/thermal ridge axis-, the probability of mesocyclogenesis is lowest (Figure 9): negative values of SST-T915 over which blow low-level northerly winds, tend to coincide with positive anomalies of T500. Moreover, the associated convergence in the lower-level wind-field promotes downwelling of ocean surface water [e.g., *Motoi et al.*, 1998; *Milliff et al.*, 1999]. In those longitudes also, the sea ice edge is located at higher latitudes as opposed to a location in and just west of the trough, and convergence of the pack increases the ice concentration. Accordingly, ocean-to-atmosphere fluxes of heat are reduced, and may even be reversed, especially under northerly airflow.

The spatial patterns of MCP and –MCP are shown and discussed by teleconnection type and phase (Figures 10-13), for the start months of their respective transition seasons (i.e., October, March). The areas of lowest probability of mesocyclogenesis (i.e., -MCP) occupy unshaded areas on the MCP maps. The two sets of maps (MCP, -MCP) are not necessarily mirror images for a given teleconnection phase: areas of highest and lowest potential can be located in close proximity or some distance removed, depending on the composite reanalysis patterns and their statistical significance (Section 4b). As above, we discuss the patterns for October first, then March. We also comment upon the cross-seasonal persistence of the MCP patterns.

- October

Large differences in the reanalysis-indicated spatial patterns of MCP and -MCP between El Niño (year0) and La Niña (year0) events (Figures 10 and 11) are highly suggestive of a 3-wave pattern. For El Niño (year0), elevated MCP is "predicted" for ocean and adjacent sea-ice areas of the southern Indian Ocean, the south-west Pacific, and south-west Atlantic/Weddell Sea sector, with low probabilities (-MCP) in between. Those areas of low probability in El Niño (year0) become the areas of strong MCP in La Niña (year0) suggesting, as for the winter season [*Claud et al.*, 2009], that the intra-hemispheric-scale variations of MCP are dominated by ENSO. Variations of MCP between ENSO phases (El Niño, La Niña) in year-1 are not quite as large as those for year0, although areal coverage of the High and Maximum probability categories increases particularly south of Australia in El Niño (year-1). In La Niña (year-1), relative to both El Niño (year-1) and La Niña (year0), the biggest increases in MCP occur over middle-to-higher latitudes of the south-west Atlantic and south of New Zealand. Low probability of mesocyclogenesis (-MCP) in La Niña (year-1) is suggested particularly near Antarctica at around 90^{o}E, in contrast to La Niña (year0), when a large area of -MCP is located in the Weddell Sea sector.

The composite October months marked by negative SAM indicate a greater areal coverage of increased MCP compared to the corresponding months of positive SAM, especially over higher-middle latitudes (Figure 10). Interestingly, the area of strongly reduced mesocyclogenesis potential (-MCP) is also larger in October months having negative SAM than in the corresponding months of positive SAM (Figure 11). We compared our results for SAM with those obtained by *Lubin et al.*, [2008] for the region covering the south-east Pacific through south-west Atlantic centered on the Antarctic Peninsula. For the period 1991-94, these authors observed more mesocyclones just west of the Antarctic Peninsula under positive versus negative phases of the SAM, especially during winter, and to a lesser extent in spring. Our results differ, whereby we note an increase in mesocyclone formation potential from about 55^o -62°S for negative SAM, and no clear association over higher latitudes. Reasons for these different results likely include the fact that *Lubin et al.*, [2008] consider September to be a spring month, as well as a possible interference of their results with ENSO. We also note an increased potential for mesocyclone formation in October for El Niño year0 just west of the Antarctic Peninsula.

There is considerably greater areal coverage of MCP in composite October months marked by positive TPI than in corresponding months of negative TPI (Figure 10). While MCP for negative TPI suggests a 3-wave pattern concentrated over middle latitudes, that for positive TPI increases generally for the South Pacific sector and also the south-west Indian Ocean. Areas of strongly decreased -MCP for positive TPI (Figure 11) occur in middle latitudes of the South Atlantic and south-east Indian Ocean, but these are located at somewhat higher latitudes in negative TPI; especially the Bellingshausen Sea through Drake Passage, and just south of New Zealand. Thus, the latitude zone of elevated MCP (decreased -MCP) tends to alternate between extreme phases of TPI: higher (middle) latitudes for positive TPI; middle (higher) latitudes for negative TPI.

- **March**

Similar to the patterns for October, in March there are large variations of MCP and -MCP between El Niño and La Niña (year0), and also between the year0 and year-1 composites for the same phase of ENSO (Figures 12 and 13). For El Niño (year0), broadly similar areas of the SH are predicted to see elevated MCP in composite March months as in October, with the exception of the Indian Ocean area which should see reduced activity. For El Niño year-1, the March composite shows greater differences from the corresponding October composite; notably, decreased activity in longitudes of New Zealand but strongly increased activity in the south-east Atlantic Ocean. Also similar to the October months, the March MCP for El Niño (year0) and La Niña (year0) shows more-or-less opposite geographic patterns: elevated activity for the Weddell Sea and south of New Zealand in El Niño (year0), but greater MCP over the South Pacific Ocean in La Niña (year0). For El Niño (year-1), the MCP pattern similarly contrasts with that for El Niño (year0): elevated MCP occurs in the areas that are predicted to have either near-average values of mesocyclogenesis potential or low probability (i.e., -MCP) in the following year. Generally the same can be said for La Niña (year-1), although strong differences in MCP between year0 and year-1 for the South Pacific sector are restricted to longitudes eastward of about 120^{o}W. Moreover, the area of -MCP extending from the eastern Bellingshausen Sea into the south-west Atlantic in La Niña (year0) did not have elevated potential (MCP) the year before. Finally, it can be said that the MCP maps for El Niño (year-1) and La Niña (year0) show only limited similarity, mostly for the south-central Pacific Ocean and south-east Indian Ocean [cf. *van Loon and Shea*, 1987; *Carleton*, 1988].

The MCP for composite March months marked by extremes of the SAM, shows a contrasting pattern of elevated probability close to Antarctica (over middle and higher latitude ocean areas) in the positive (negative) mode (Figure 12). The pattern of a larger area of strong MCP associated with negative SAM contrasted with positive SAM -and over broadly similar areas of the SH- was also evident for October (Figure 10). However, the pattern of elevated MCP adjacent to Antarctica for positive SAM was not evident in the corresponding MCP map for October, most likely because of the much greater extent of the sea ice in that month and its role in determining the MCP. The low probability areas (-MCP) of each SAM mode occupy broadly the same latitude zone of the opposite mode’s areas of elevated probability (MCP), similar to what was noted for TPI in October. In *Lubin et al*., [2008], focusing on the mesocyclone activity in the region of the south-east Pacific through south-west Atlantic, there was no clear signal during autumn. In agreement with these authors, we also see no clear relationship of SAM with mesocyclogenesis in this region.

For opposite modes of the TPI in March, strongly contrasting spatial patterns of MCP suggest a dominant meridional wave structure (Figure 12). In TPI positive phases, mesocyclogenesis is predicted to increase the most compared to background levels south of Australia and New Zealand, and also in the Amundsen/Bellingshausen seas and western Weddell Sea. Conversely, in negative TPI, elevated MCP is located in middle-to-higher latitudes of the South Pacific, the Atlantic, and the south-east Indian Ocean. Moreover, there is considerable similarity between the low probability (i.e., -MCP) map of either TPI mode (Figure 13) with the high probability (MCP) map of the opposite mode. This raises the possibility of a more-or-less linear relationship between TPI modes in terms of the associated mesocyclogenesis potential, that should be explored in future work.

- Comparisons with Winter Season MCP

We compare the October and March patterns with those derived for the winter season (specifically June) documented in *Claud et al.* [2009] (their Figures 14 and 15). Although the October and March patterns are similar in terms of the area of the SH covered by elevated MCP (i.e., 4 classes of probability), for most teleconnection phases there is a greater area of the hemisphere involved in June. This is especially the case for La Niña (year0, year-1), El Niño (year-1), and Positive SAM. Because the average sea-ice area is greater in October than in June, this increased extent of MCP in the latter month likely results from the phase of the Semi-Annual Oscillation (SAO) and its role in determining the dominant latitude of the circumpolar trough and amount of cyclonic activity over the Southern Ocean. The SAO has similar phase in March and October and an associated higher-latitude displacement of the circumpolar trough in those months, contrasted with June [e.g., *van Loon*, 1967; *van Loon and Rogers*, 1984]. Further, the correlation of ENSO and SAM over the period of interest (in both March and October, 0.56 and -0.57, respectively), and the fact that SAM has been mostly positive during 1979-2001, likely contribute to this result through preventing us from fully disentangling the effect of each teleconnection.

To gain insights into the temporal persistence of the spatial patterns, we inter-compare MCP maps by teleconnection type and phase for March, June, and October. For ENSO, the MCP map for June (year0) should be compared with that of March (year-1), rather than the March (year0) map, because it is for 3 months earlier as opposed to 9 months later. Specifically, for El Niño, areas of elevated MCP occur over the South Atlantic and south-east Indian Ocean in both June (year0) and March (year-1), with the latter month also showing increased potential at high latitudes in the Ross Sea and eastward to the Antarctic Peninsula. This is likely a result of the lack of sea ice in the early autumn. Similarly for La Niña, elevated MCP occupies the three ocean basins in both June (year0) and March (year-1), although these areas are larger in June, as noted above.

The MCP maps for June and October pertain to year0 (i.e., they are 4 months apart), and so may reasonably be compared by teleconnection type and phase. Subjective comparisons of MCP spatial patterns in June and October for ENSO suggest somewhat less similarity than between March (year-1) and June, especially for El Niño. Again, these differences may result from the different SAO phase and its influence on the latitude of the circumpolar trough, in combination with the near-maximum extent of sea-ice in October. A similarly reduced persistence in the spatial patterns of MCP between June and October is evident for SAM positive and negative phases. However, the spatial consistency of MCP in June and October appears considerably higher for TPI, especially the negative phase. The absence of a significant correlation between TPI and the two other teleconnections (Table 3) may help explain this higher spatial consistency, contrasted with those of ENSO and SAM.

Regionally, and in a given year, marked month-to-month variations of mesocyclone activity can occur (e.g., the region south of Australia in October and November 1992, CS97). However, the above composite results raise the issue of the representative nature of the transition-season start month (October, March) and its ability to depict MCP patterns of its respective season (spring, autumn). Examining MCP patterns by teleconnection mode and phase for November and April (not shown), indicates general similarity with the preceding month (October, March) in terms of spatial pattern, although there are differences of detail. These characteristics likely result from the stronger spatial persistence of T500 anomalies between consecutive months, contrasted with SST-T925 or **V**925.

- Potential mechanisms

Although climatic simulations would be necessary to fully assess the mechanisms underlying the features observed in the MCP maps, a few remarks can nevertheless be made:

- For ENSO, Niño years are associated with a storm track shifted equatorward in the South Pacific, but poleward in the Atlantic [*Rind et al*, 2001]. This pattern is accompanied by a high (low) pressure anomaly over the Bellingshausen (Weddell) seas, and corresponding regional circulations that bring warm air to the polar area in the Pacific and cold air out of the Antarctic continent over the southwest Atlantic [*Carleton*, 1988; *Yuan and Martinson*, 2001]. These combined effects explain the reduced frequencies of mesocyclones over the Bellingshausen and Amundsen seas, and the increased frequencies over the Weddell Sea for Niño years (and the opposite for Niña years).

- For SAM, a positive phase implies a poleward shift of the storm track; because many mesocyclones develop in cold air behind frontal cyclones, one would expect more mesoscyclones over higher latitudes. Indeed, this is observed in March with more mesocyclones around the Antarctic coast, but not in October, when the sea ice extent is much greater. However, in October, mesocyclone frequencies increase in the SAM negative phase at around 55°S because of the equatorward shift of the storm track. The area between 100° and 150°W generally displays opposite features to the other longitudes, probably in association with the non annular SST response to SAM [e.g. *Lovenduski and Gruber*, 2005].

- The association of MCP with TPI is linked to the intensity and location of the trough and ridge that express the variations in wavenumber one, and the fact that mesocyclones form preferentially to the west of troughs and east of ridges, due to the combined southerly wind anomalies, cold air advection, upward convective heat fluxes and likely also, strong equatorward advances in the sea ice edge. Thus, the storm track and associated polar-front jet stream is displaced equatorward (poleward) in longitudes of the troughs (ridges).

These observations suggest that the displacement of the storm track plays a major role in the associations between mesocyclones and teleconnections; an additional ingredient is the position of the sea ice border relative to the storm track.

6. Summary

In this study, the climatic environments of SH cold air mesocyclones and their associations with teleconnections were investigated for transition-season months. Several reasons motivated such a study, as follows: (1) The relatively few studies undertaken for the transition season months suggested that they have the highest frequencies of mesocyclones, possibly the result of the Semi-Annual Oscillation that dominates over sub-antarctic latitudes and which reaches its maxima in the spring and autumn seasons. In addition, (2) a clear ENSO response was expected because its climatic « signal » over middle and higher southern latitudes strengthens (weakens), on average, in austral springtime (autumn), thereby providing another point of comparison with the mesocyclone activity. Finally, (3) the Antarctic sea-ice conditions typically change rapidly during the spring and autumn, and the ice is near its maximum (minimum) extent, on average, in October (March). The ultimate objective of our study is to improve climatic (i.e., seasonal/sub-seasonal) predictions of cold-air mesocyclogenesis over the Southern Ocean during these months.

We identified the associated composite atmospheric and upper-oceanic large-scale environments of mesocyclones on monthly time scales. This first step relied on the use of both the long-term high-resolution daily ERA-40 reanalysis and inventories of cold-air mesocyclones based on satellite image interpretation for case-study months of March-April and October-November in 1988 and 1992. Although these inventories were restricted to portions of the SH, we showed that mesocyclones occur preferentially in association with either low temperatures at 500 hPa or proximity to large gradients of T500. Additional favorable conditions for mesocyclones include a large positive difference in SST-T925, coincident with south to southwesterly low-level winds (**V**925) (i.e., implying strong upward fluxes of heat and moisture occurring to the west and south-west of mid-tropospheric troughs and frontal cyclones). An additional mesocyclone-favorable condition in the spring months is proximity to the sea ice. Conversely, unfavorable conditions for mesocyclogenesis include warm air at 500 hPa; negative or only weakly positive SST-T925; northerly low-level winds that blow over these cool waters (i.e., stable lower atmosphere); and reduced sea ice relative to normal (i.e., implying downward fluxes of heat east of frontal cyclones and west of high pressure ridges). It should also be noted that important local factors in mesocyclogenesis, such as katabatic winds, are not explicitly considered here although their influence can be manifest in variables such as greater local sea-ice extent and more strongly positive SST-T925 values offshore. Such an assessment would require specific investigations at smaller scales that are difficult to achieve with the present spatial resolution of the reanalyses and the available satellite-based mesocyclone inventories.

The second objective of the study was to determine spatial associations of reanalysis variables favorable to mesocyclogenesis according to the three large-scale SH teleconnection patterns (ENSO, SAM, TPI). All variables show an association with the three teleconnections, although these are generally weaker than for the winter months: standardized anomalies are of smaller amplitude, the 90% significance level generally covers smaller regions, and the variables more seldom behave congruently. Possibly contributing to this last point is that, contrary to the winter months, the teleconnection indices for some transition-season months are significantly inter-correlated. Notwithstanding, we observed that in spring, the intra-hemispheric variability of mesocyclogenesis is dominated by ENSO. The SAM and TPI remain influential, with the latter teleconnection suggesting a 3-wave pattern within the latitude zone under consideration. This results in more (fewer) mesocyclones over higher (middle) latitudes for positive TPI, and more (fewer) mesocyclones for middle (higher) latitudes for negative TPI. In autumn, ENSO, SAM, and TPI are about equally influential but their response varies regionally. As for spring, large variations between El Niño and La Niña are noted. A positive SAM tends to enhance mesocyclogenesis in regions adjacent to Antarctica, while a dominant meridional wave structure is suggested for TPI. In addition, consideration of the phase of the SAO and its influence on the latitude zone of maximum cyclonic activity over the Southern Ocean, is essential to the interpretation of the results. Modeling work is needed to clearly identify the mechanisms governing these associations, but our results suggest that the displacement of the storm track between opposite phases of a given teleconnection appears to play a major role.

Our results are also relevant to the role of teleconnections in a changing climate; in particular, the positive SAM trend may continue longer term [*Bracegirdle at al.*, 2008], the SAO temporal trend [*van den Broeke* 1998] may either continue or reverse as a result of the strong warming of West Antarctica [*Steig et al.*, 2009], and the recent warming noted for East Antarctica could become statistically significant in the near future. High latitude climate changes such as these almost inevitably will affect the frequencies, and possibly also key longitudes, of cold-air outbreaks and their associated mesocyclone activity [cf. *Kolstad and Bracegirdle*, 2008 for the Arctic]. In turn, these cross-scale atmospheric associations will likely alter the development of Antarctic coastal polynyi and, accordingly, the formation of Antarctic bottom water, resulting in longer-term climate changes.

Finally, this study points to the need for long-term hemisphere-wide satellite-based mesocyclone climatologies developed explicitly for transition-season months, thereby spanning a range of teleconnection phases, and against which the MCP and -MCP maps may be corroborated.

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Figure captions

Figure 1. Map of Antarctica, indicating geographic features mentioned in the text.

Figure 2. Wind vector at 925 hPa (**V**925, m/s) and difference between SST and temperature at 925 hPa (T925, K) climatology for the period 1979-2001 for a) March, b) April, c) October, d) November. Corresponding temperatures at 500 hPa (T500, K) for e) March, f) April, g) October, h) November.

Figure 3**.** Composite standardized anomalies of the difference SST-T925 and **V**925 with respect to El Niño and La Niña events, and T500 for October of year0 (4 panels above, a-d) and November of year0 (4 panels below, e-h).

Only anomalies of **V**925 corresponding to a 90% confidence level following a phase-scrambling procedure with 999 samples are plotted (See text for more details). For (SST-T925) and T500 anomalies, the 90% confidence level is superimposed (dashed line). Grey areas correspond to grid points where at least one SST monthly value used to construct the composites was set to "undefined" because of land or sea ice.

Figure 4. Similar to Figure 3, but for SAM.

Figure 5. Similar to Figure 3, but for March.

Figure 6. Similar to Figure 5, but for April, and year-1.

Figure 7. Similar to Figure 5, but for March and TPI.

Figure 8. Similar to Figure 7, but for April and for SAM (4 panels above) and TPI (4 panels below).

Figure 9. Spatial dependence of MCP categories High Potential (area A) and Maximum Potential (area B), and –MCP categories of Lowest Potential (area C) and Low Potential (area D), for coupled atmosphere and upper-ocean anomalies in middle and higher southern latitudes associated with an anomalous trough-ridge pattern. The time-averaged "storm track" - oriented north-west to south-east - is denoted by the satellite-viewed frontal cloud vortex (the larger shaded signature); a smaller "Positive Vorticity Advection (PVA) maximum" (i.e., comma-cloud mesocyclone) is located just west of the frontal cyclone/storm track (both from Guymer 1978). Divergence: DIV (convergence: CON) of the pack ice, and associated reduced (increased) ice concentration, is shown by the dashed (full) line demarcating the ice-ocean margin. The single line denoted T500 is a representative isotherm at the 500 hPa level, and can also be considered a geopotential height contour at 500 hPa, owing to equivalent barotropy of the Southern Hemisphere extratropical atmosphere ; a negative v925 (meridional component of V925) corresponds to a southerly wind.

Figure 10. Maps of enhanced mesocyclogenesis potential, MCP (refer text) in October associated with large-scale teleconnections (4 classes).

Figure 11. Maps of suppressed mesocyclogenesis potential, -MCP (refer text) in October associated with large-scale teleconnections (2 end probability classes).

Figure 12. Similar to Figure 10, but for March.

Figure 13. Similar to Figure 11, but for March.

	Niño Year$_0$	Niña Year$_0$	TPI +	TPI -	SAM +	SAM -
March	1983, 1987, 1992, 1995, 1998	1985, 1989, 1996, 1999, 2000	1985, 1988, 1993, 1994	1979, 1984, 1997, 1999	1979, 1982, 1994, 1996, 1997	1980, 1981, 1986, 1988, 1999
April			1985, 1987, 1988, 1989, 2001	1979, 1981, 1995, 1998	1982, 1988, 1998, 1999, 2001	1980, 1981, 1990, 1991
October	1982, 1986, 1991, 1994, 1997	1984, 1988, 1995, 1998, 1999	1982, 1984, 1990, 1992	1986, 1988, 1989, 2001	1983, 1991, 1996, 1999, 2001	1982, 1988, 1995, 1997
November			1986, 1988, 1989 1990, 2000	1987, 1991, 1994	1981, 1983, 1985, 1998, 1999, 2001	1979, 1980, 1982, 1994, 1996, 1997, 2000

Table 1. List of years considered for producing the composites.

months	Large SST-T925	Low T500	**V**925 with a southerly component
March 1988 (37)	70	81	49
April 1988 (53)	70	68	75.5
October 1988 (50)	56	74	60
March 1992 (47)	62	74.5	51
April 1992 (51)	68.5	72.5	61
October 1992 (59)	64.5	81	60
November 1992 (51)	45	67	56
March 1990 (14)	50	71	50
April 1990 (16)	62.5	75	56

Table 2. Percentages of mesocyclones associated with ERA-40 daily fields of large SST-T925 (column2), low T500 (column 3), and a southerly **V**925 component (column 4), for each transition-season month considered. The total number of mesocyclones in each month is given in parentheses beneath each month/year label.

SAM TPI	March	April	October	November
March	0,09 0,16	0,04 **0,34**	-0,20 -0,14	0,12 -0,22
April	-0,03 0,14	0,10 0,19	-0,04 **0,36**	0,06 **0,53**
October	**0,33** -0,04	-0,29 **-0,36**	0,17 **0,37**	-0,16 **0,38**
November	-0,30 0,04	0,08 -0,11	-0,10 **0,60**	0,28 **0,79**

79-01
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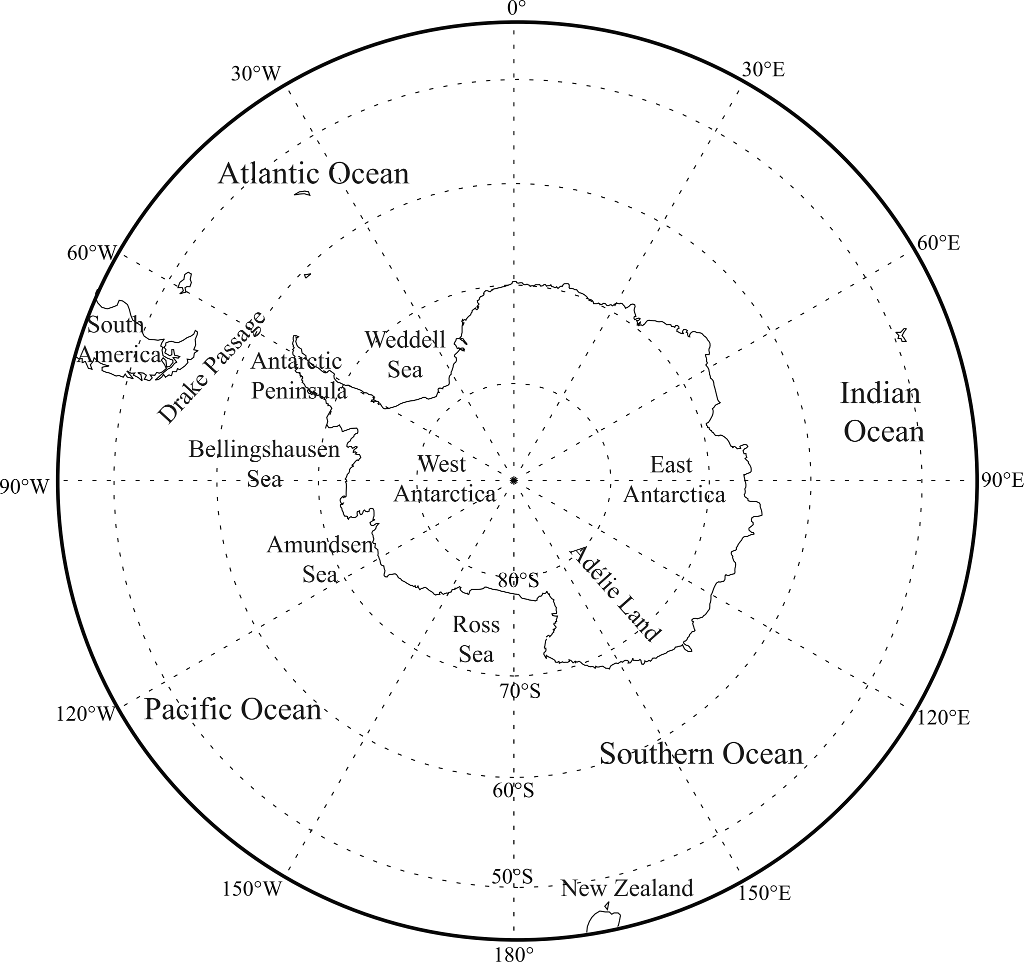
Niño, Year 0

	1956-1977	1978-2000	1979-1990	1991-2000
SAM March	-0,17	**0,56**	**0,58**	**0,64**
April	**-0,49**	-0,24	0,06	**-0,71**
October	-0,24	**-0,57**	0,17	-0,48
November	0,02	**-0,40**	**-0,50**	**-0,66**
TPI March	-0,11	0,00	-0,03	0,03
April	-0,23	0,07	-0,37	**0,59**
October	**0,36**	0,11	0,12	0,10
November	**-0,36**	**-0,37**	-0,18	**-0,60**

Niño, Year -1

	1956-1977	1978-2000	1979-1990	1991-2000
SAM March	0,30	-0,21	-0,11	**-0,47**
April	0,09	0,30	0,28	0,28
October	**0,37**	-0,22	-0,04	**-0,51**
November	**0,33**	**0,33**	0,31	0,37
TPI March	0,16	-0,33	**-0,56**	-0,03
April	0,15	0,01	-0,03	0,10
October	0,12	0,25	0,05	**0,50**
November	0,13	-0,30	-0,31	-0,29

Table 3. Correlation coefficients of teleconnection indices for transition-season months (March-April and October-November), and over different time periods. Values in bold are significant at the 90% confidence level.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East Antarctica
90°W
90°E
Amundsen Sea
Adélie Land
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120°W
Pacific Ocean
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Southern Ocean
60°S
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New Zealand
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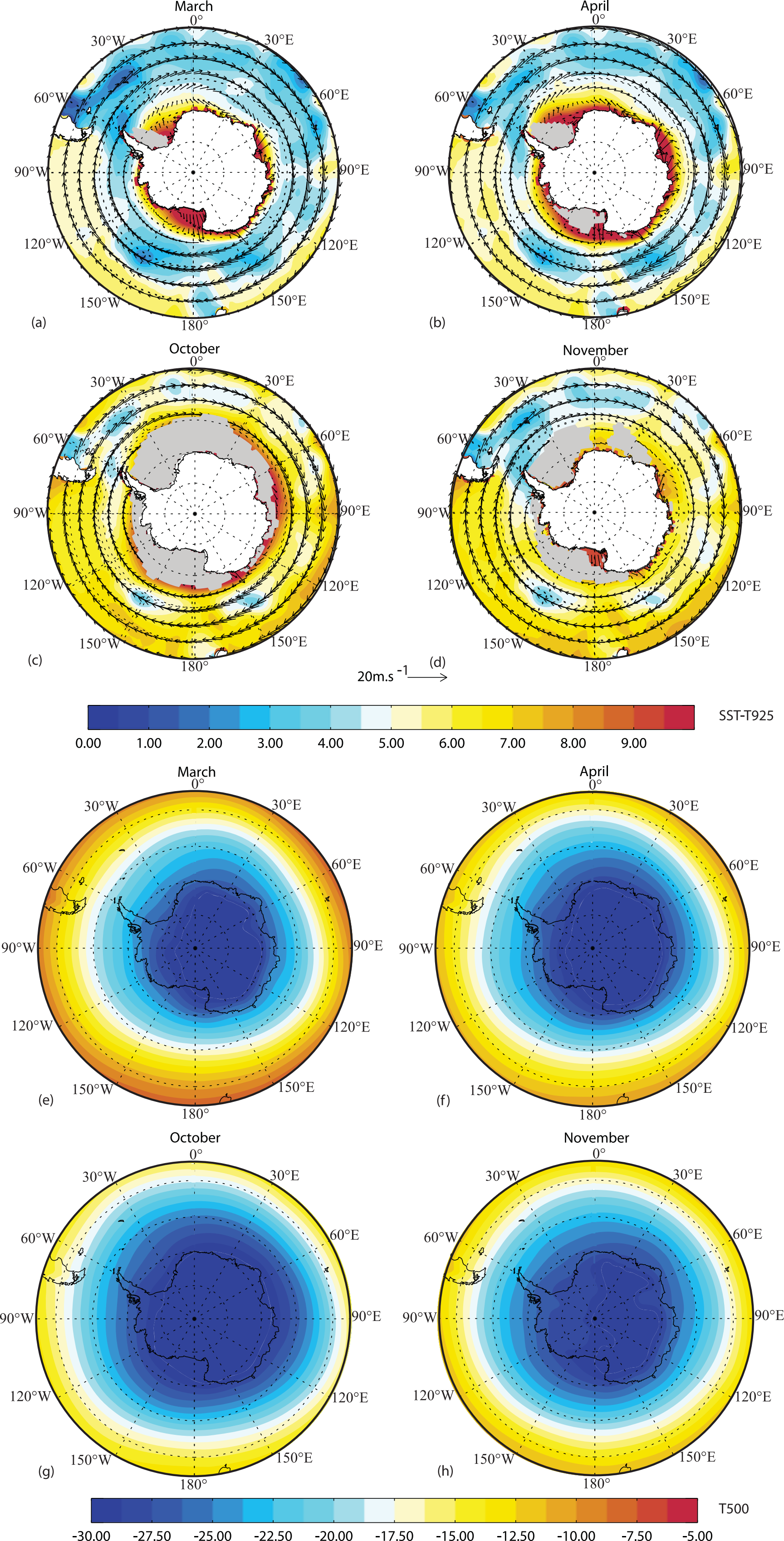
150°E
180°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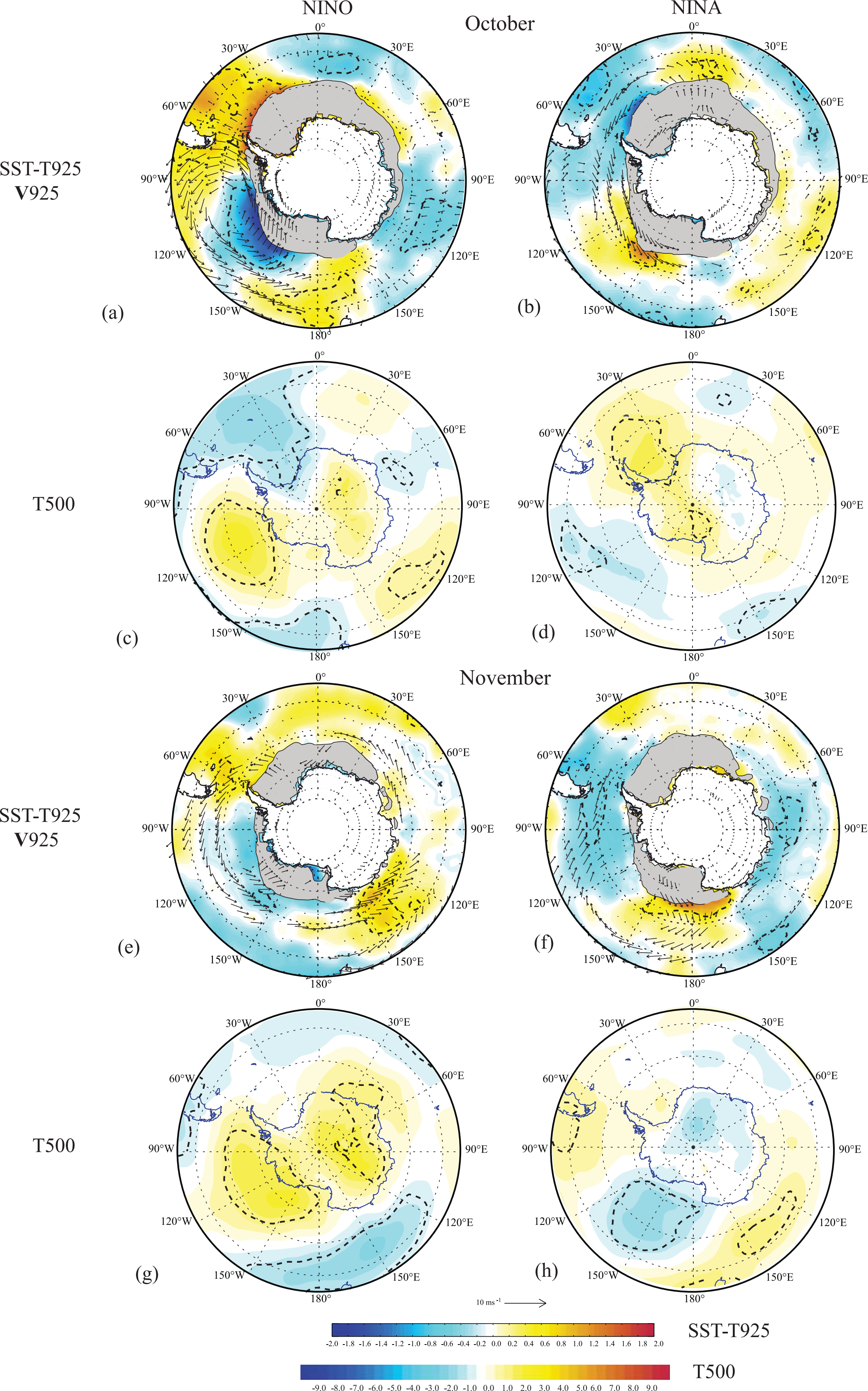
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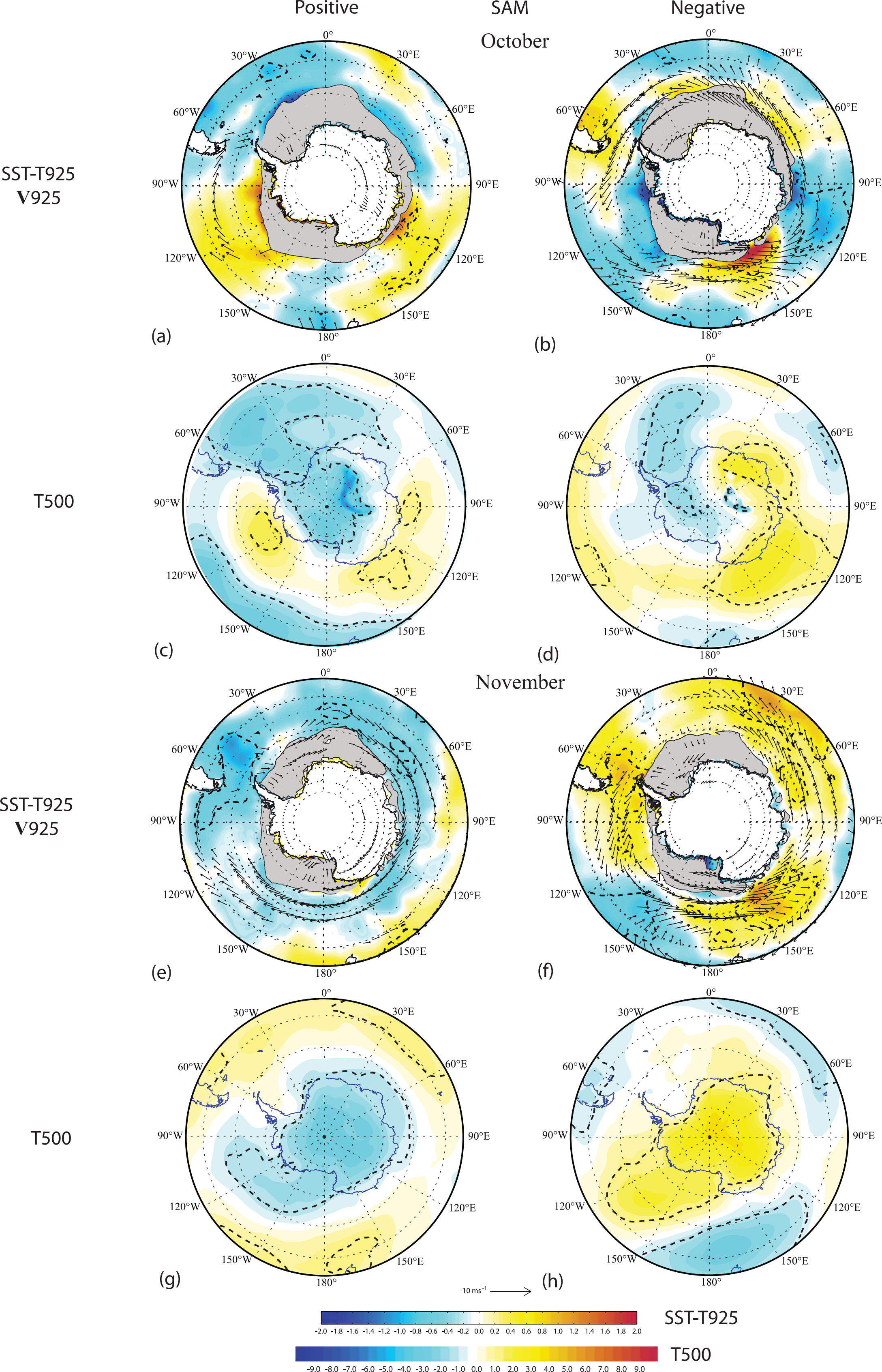
T500
-9.0 -8.0 -7.0 -6.0 -5.0 -4.0 -3.0 -2.0 -1.0 0.0 1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0 9.0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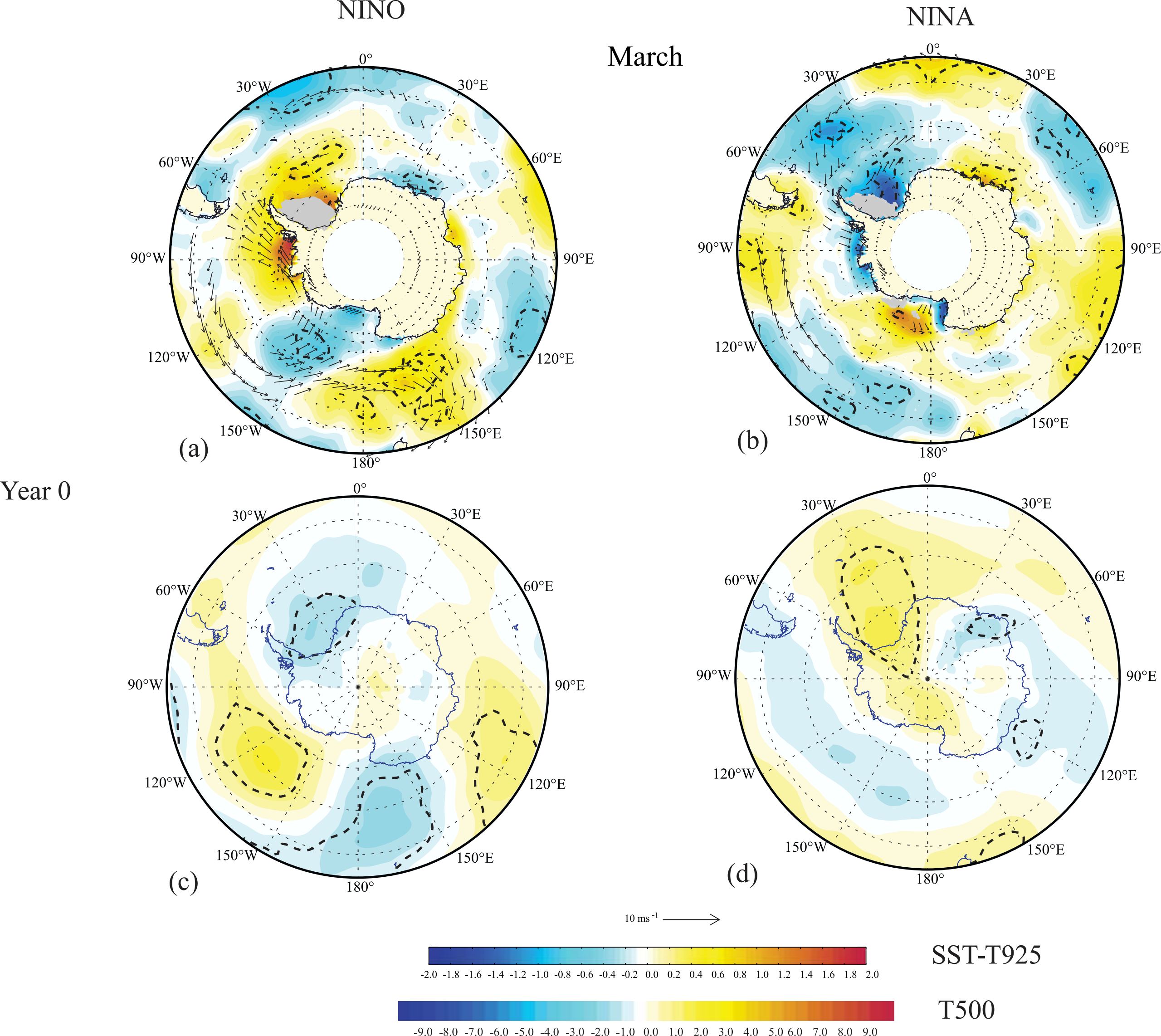
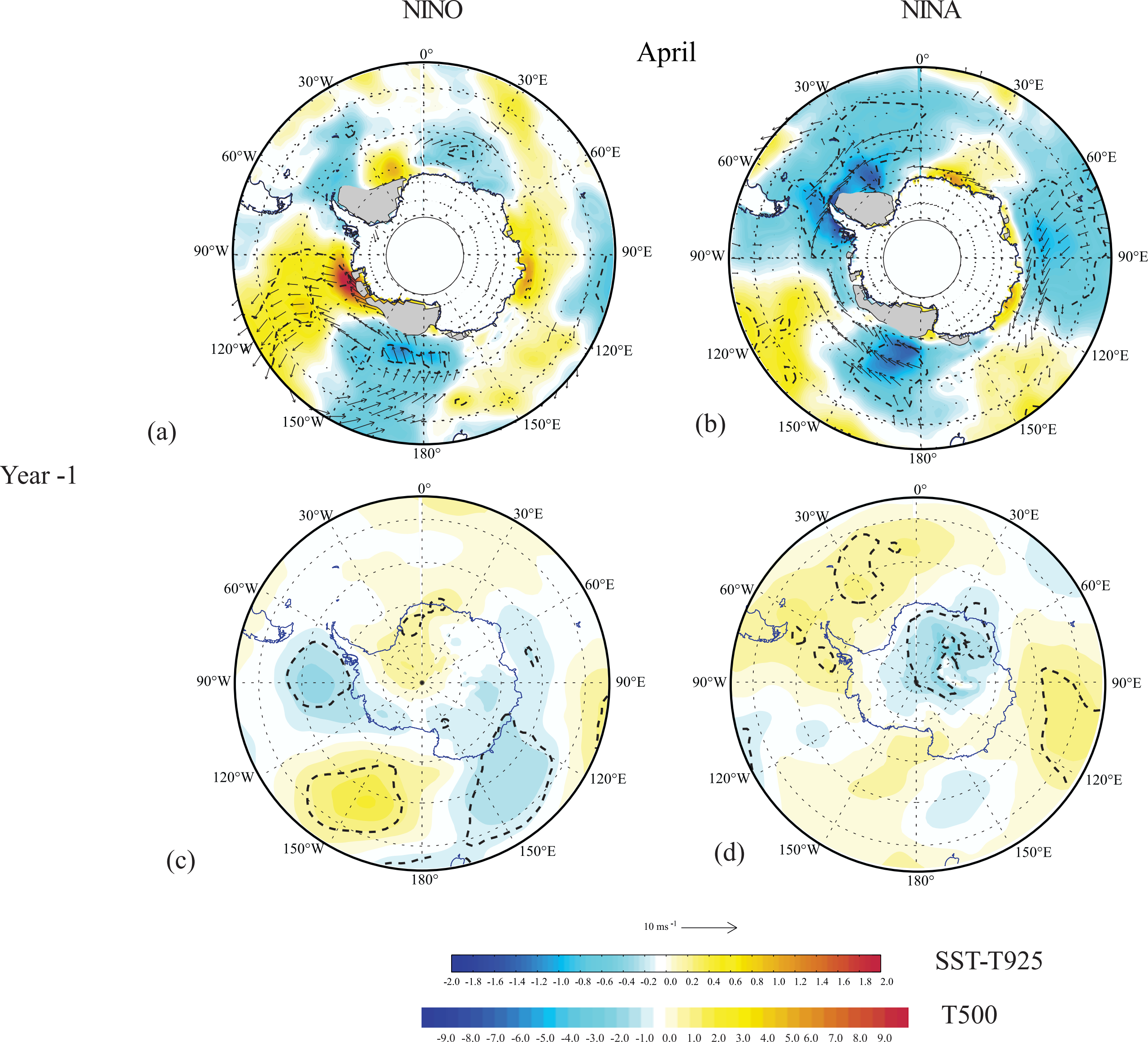
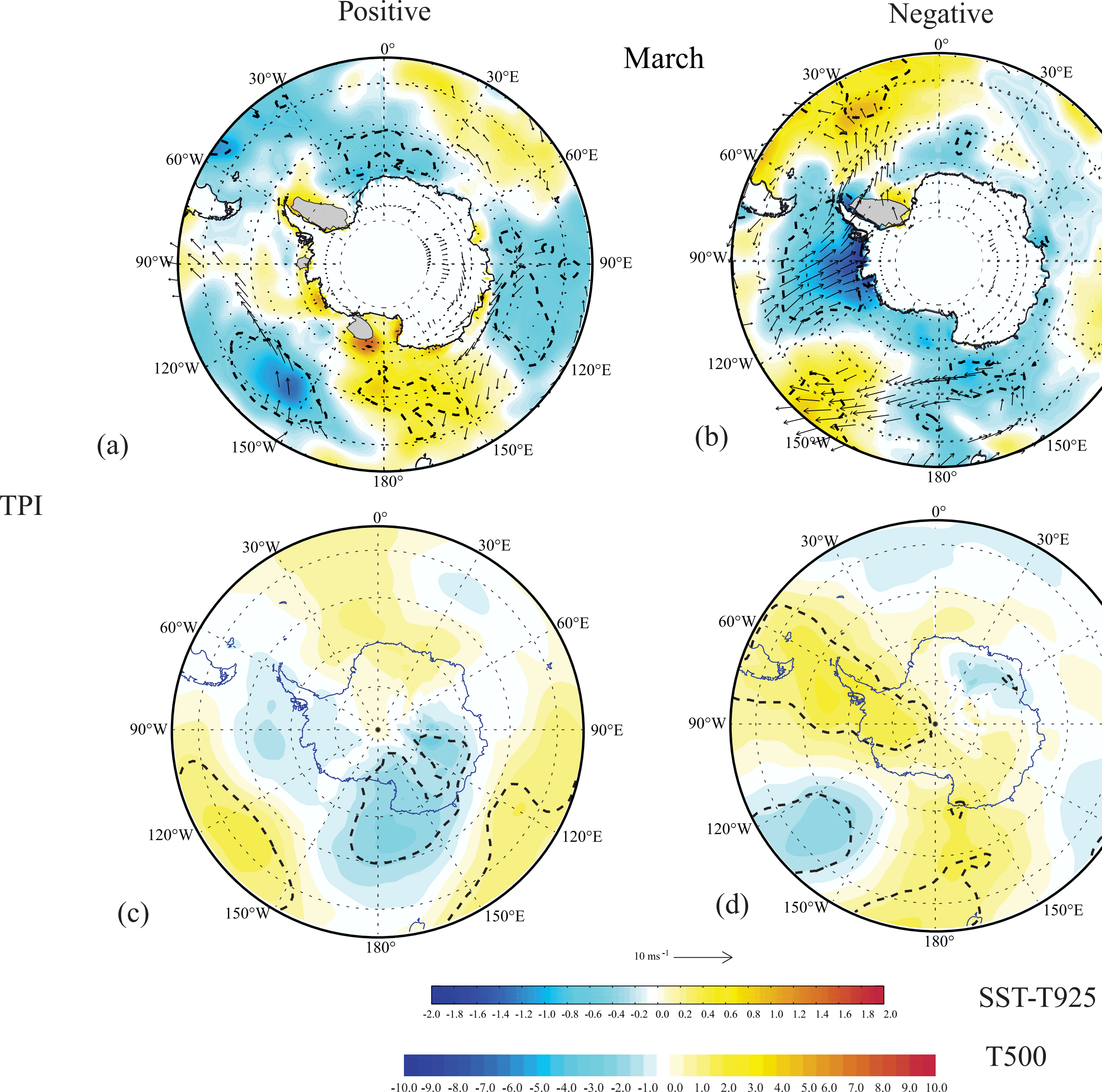
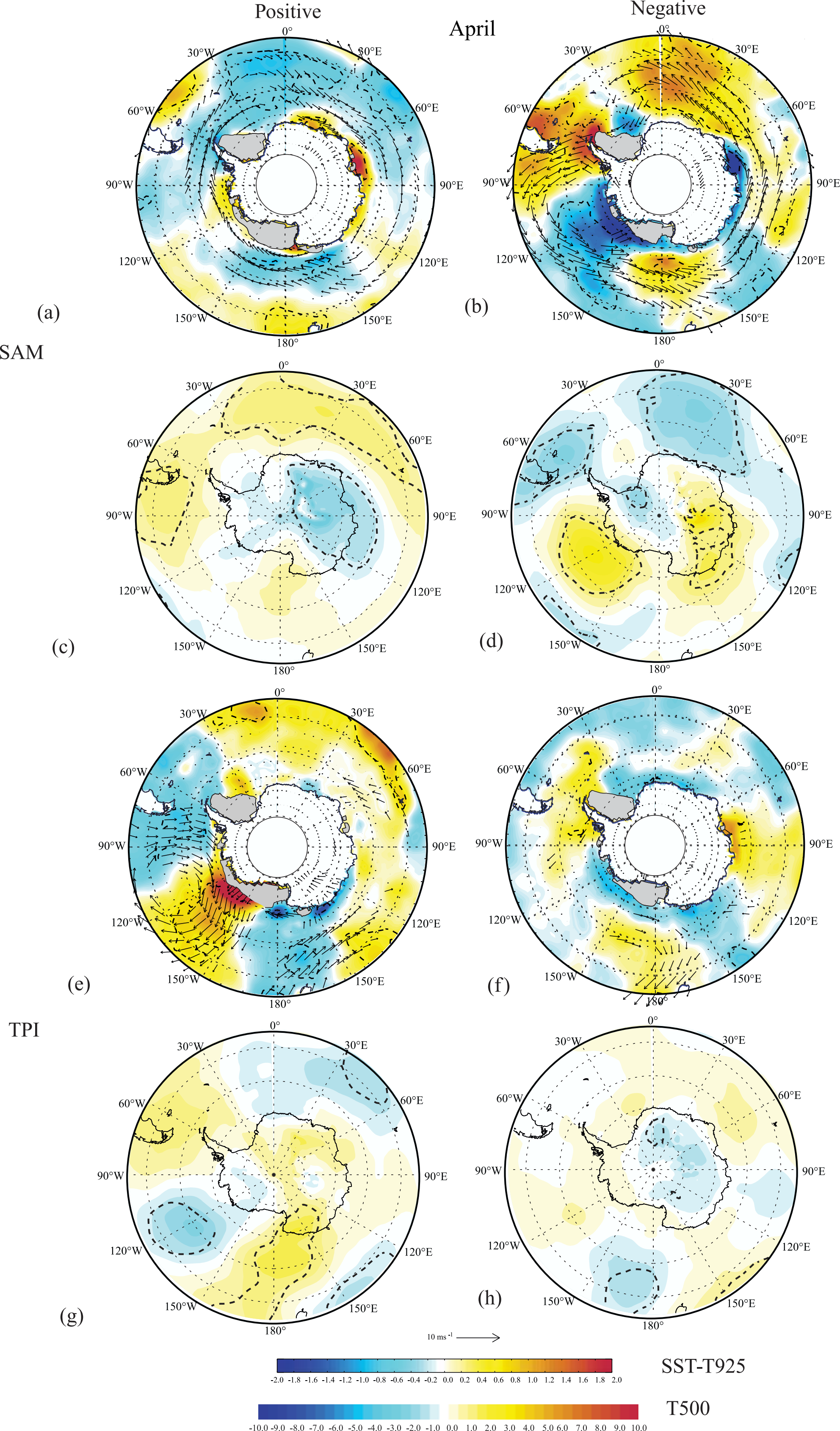
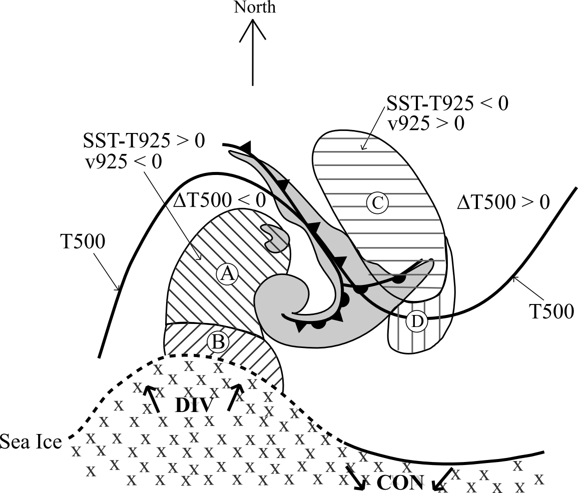
10 ms⁻¹
SST-T925
-2.0 -1.8 -1.6 -1.4 -1.2 -1.0 -0.8 -0.6 -0.4 -0.2 0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0
T500
-9.0 -8.0 -7.0 -6.0 -5.0 -4.0 -3.0 -2.0 -1.0 0.0 1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0 9.0

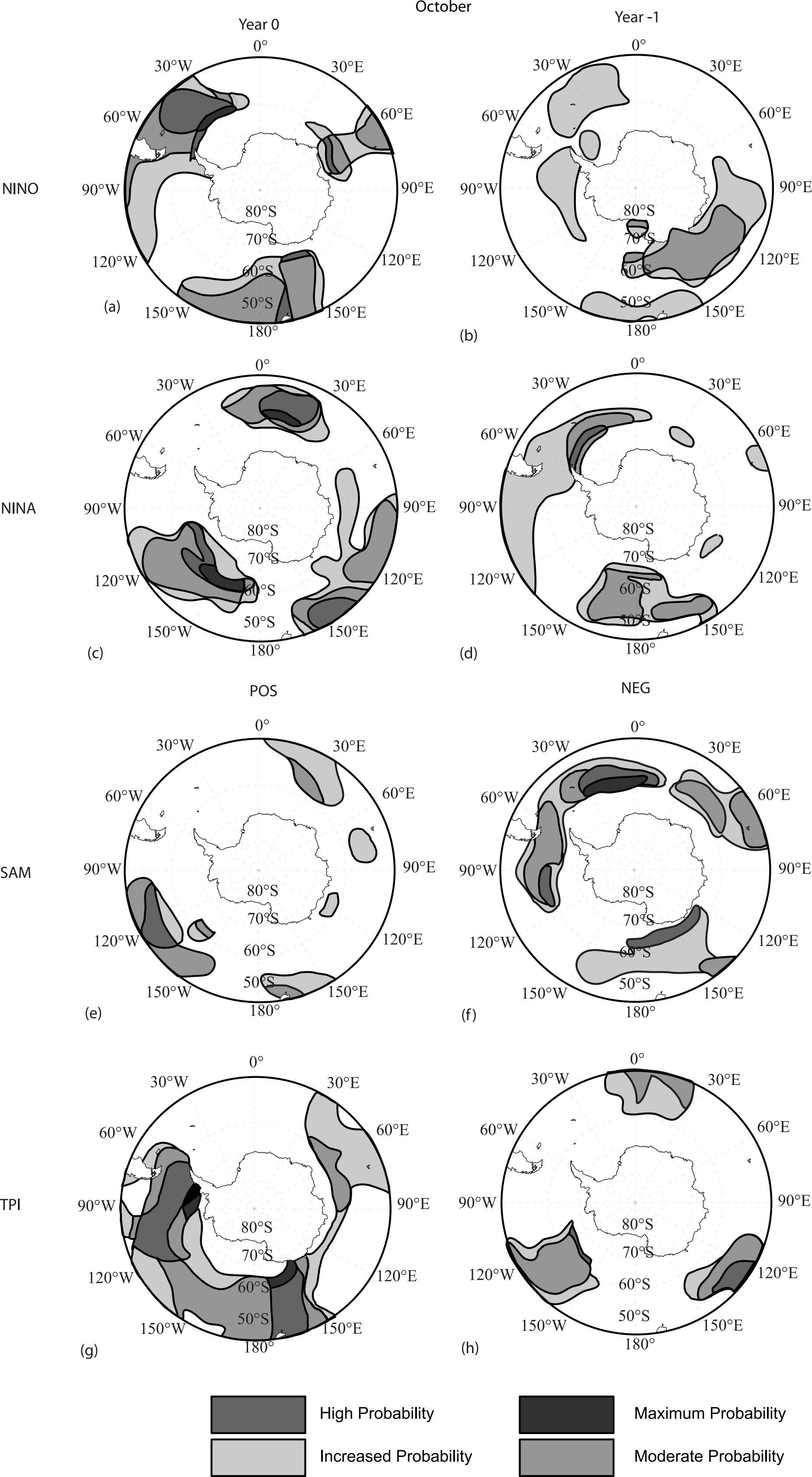

NINO
NINA
March
Year 0
0°
30°E
60°E
90°E
120°E
150°E
180°
150°W
120°W
90°W
60°W
30°W
(a)
(b)
(c)
(d)
10 ms -1
SST-T925
-2.0 -1.8 -1.6 -1.4 -1.2 -1.0 -0.8 -0.6 -0.4 -0.2 0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0
T500
-9.0 -8.0 -7.0 -6.0 -5.0 -4.0 -3.0 -2.0 -1.0 0.0 1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0 9.0

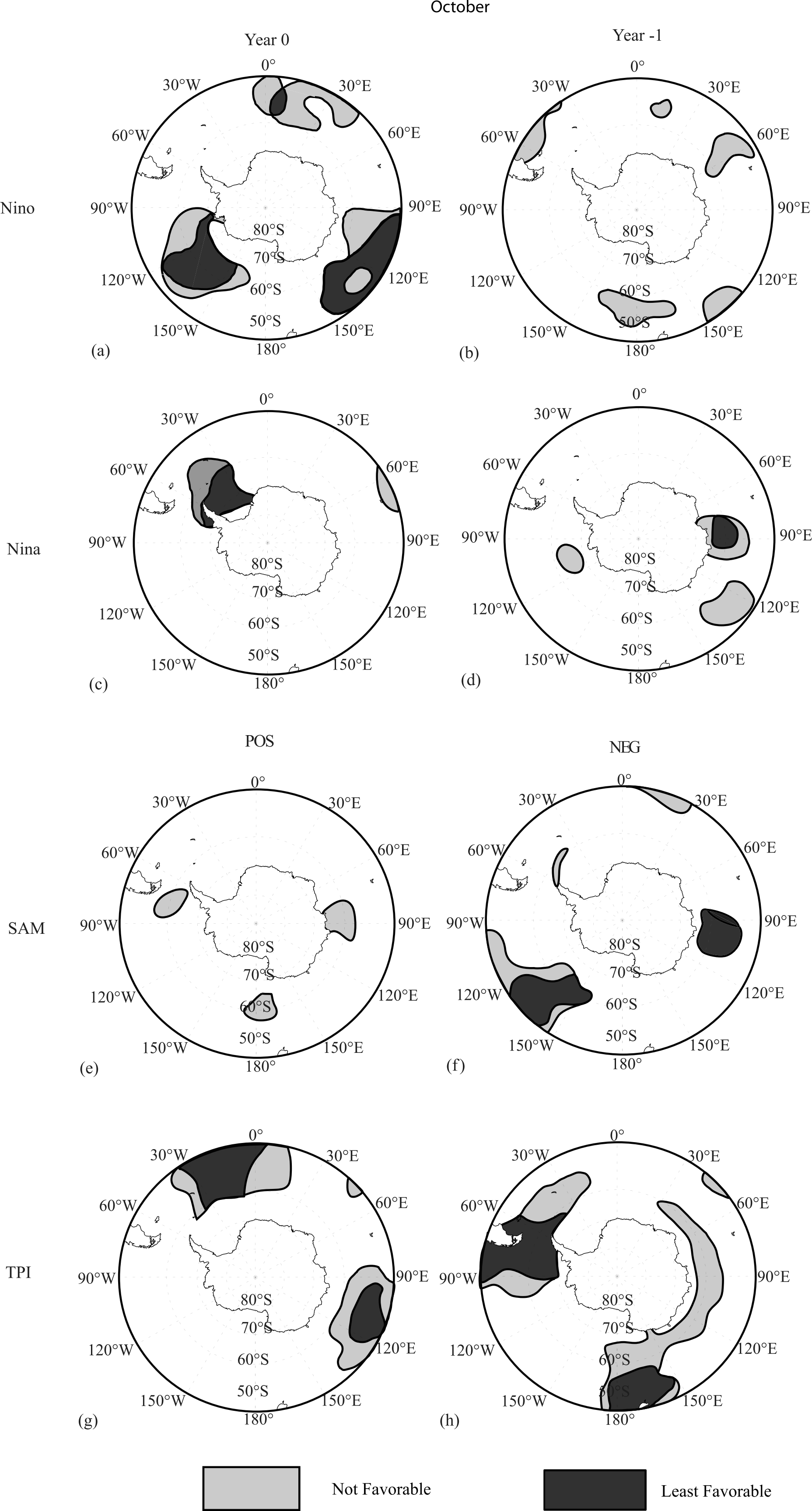

NINO
NINA
April
Year -1
(a)
(b)
(c)
(d)
0°
30°E
60°E
90°E
120°E
150°E
180°
150°W
120°W
90°W
60°W
30°W
10 ms -1
SST-T925
-2.0 -1.8 -1.6 -1.4 -1.2 -1.0 -0.8 -0.6 -0.4 -0.2 0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0
T500
-9.0 -8.0 -7.0 -6.0 -5.0 -4.0 -3.0 -2.0 -1.0 0.0 1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0 9.0

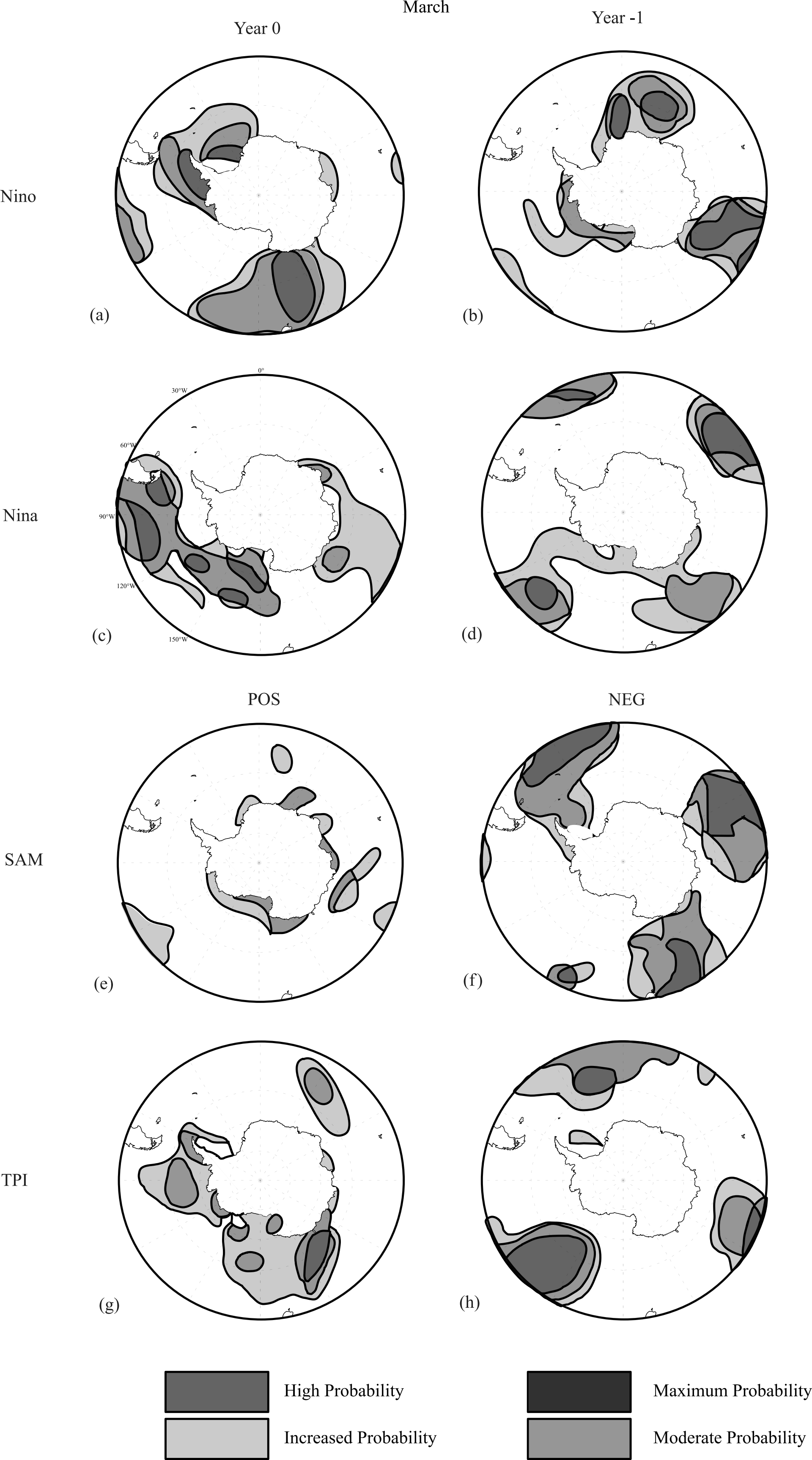

Positive
Negative
March
TPI
0°
30°E
60°E
90°E
120°E
150°E
180°
150°W
120°W
90°W
60°W
30°W
(a)
(b)
(c)
(d)
10 ms⁻¹
SST-T925
-2.0 -1.8 -1.6 -1.4 -1.2 -1.0 -0.8 -0.6 -0.4 -0.2 0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0
T500
-10.0 -9.0 -8.0 -7.0 -6.0 -5.0 -4.0 -3.0 -2.0 -1.0 0.0 1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0 9.0 10.0

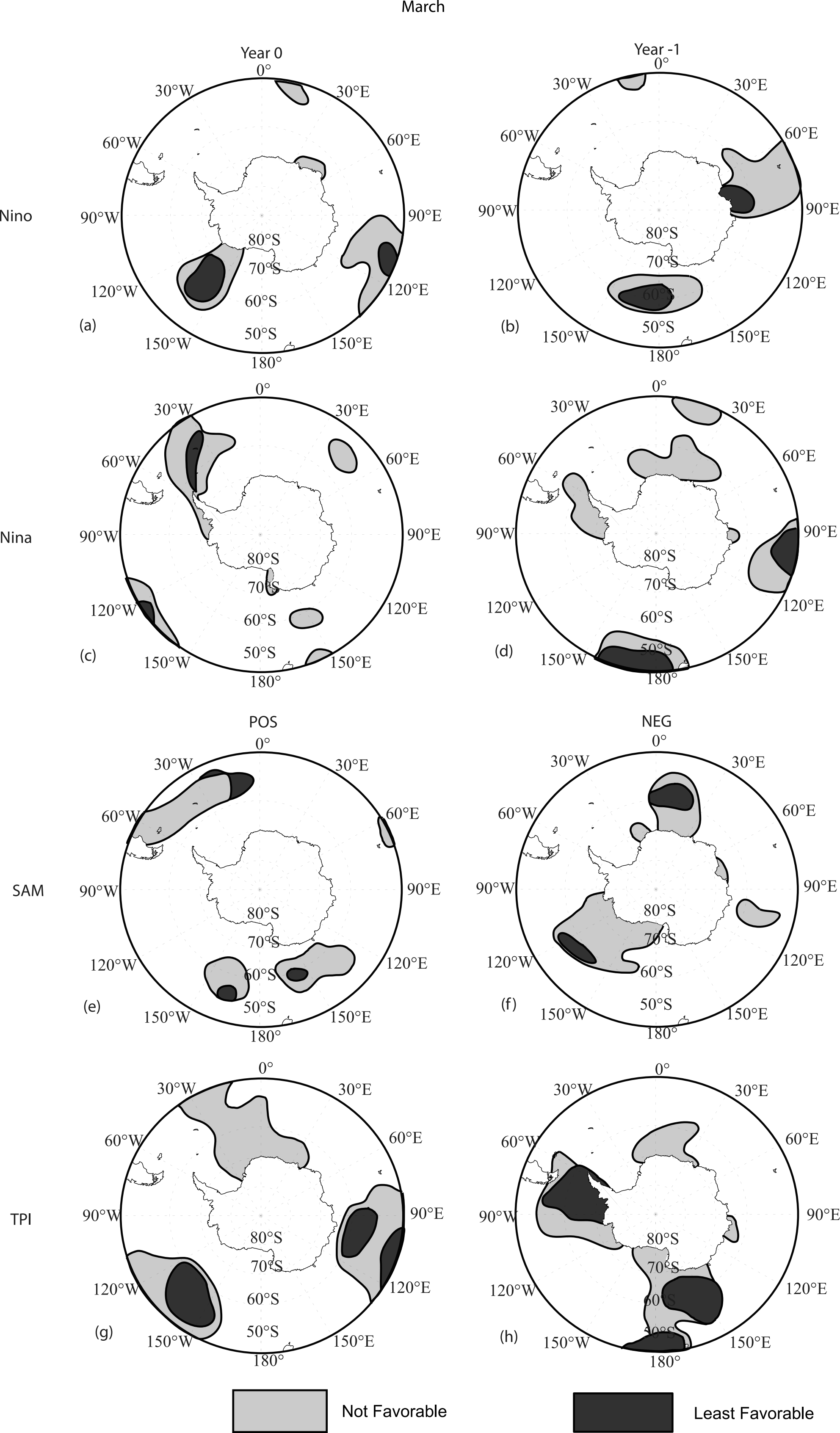

Positive
April
Negative
SAM
TPI
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
0°
30°E
60°E
90°E
120°E
150°E
180°
150°W
120°W
90°W
60°W
30°W
10 ms⁻¹
SST-T925
-2.0 -1.8 -1.6 -1.4 -1.2 -1.0 -0.8 -0.6 -0.4 -0.2 0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0
T500
-10.0 -9.0 -8.0 -7.0 -6.0 -5.0 -4.0 -3.0 -2.0 -1.0 0.0 1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0 9.0 10.0


North
SST-T925 < 0
v925 > 0
SST-T925 > 0
v925 < 0
ΔT500 < 0
ΔT500 > 0
T500
C
A
D
T500
B
DIV
Sea Ice
CON


October
Year 0
Year -1
NINO
NINA
POS
NEG
SAM
TPI
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
0°
30°E
60°E
90°E
120°E
150°E
180°
150°W
120°W
90°W
60°W
30°W
80°S
70°S
60°S
50°S
High Probability
Maximum Probability
Increased Probability
Moderate Probability


October
Year 0
Year -1
Nino
Nina
POS
NEG
SAM
TPI
0°
30°E
60°E
90°E
120°E
150°E
180°
150°W
120°W
90°W
60°W
30°W
80°S
70°S
60°S
50°S
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
Not Favorable
Least Favorable


March
Year 0
Year -1
Nino
(a)
(b)
0°
30°W
60°W
90°W
120°W
150°W
Nina
(c)
(d)
POS
NEG
SAM
(e)
(f)
TPI
(g)
(h)
High Probability
Maximum Probability
Increased Probability
Moderate Probability


March
Year 0
Year -1
Nino
Nina
POS
NEG
SAM
TPI
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
0°
30°E
60°E
90°E
120°E
150°E
180°
150°W
120°W
90°W
60°W
30°W
80°S
70°S
60°S
50°S
Not Favorable
Least Favorable