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Ice core and climate reanalysis analogs to predict Antarctic and Southern Hemisphere climate changes

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ABSTRACT

A primary goal of the SCAR (Scientific Committee for Antarctic Research) initiated AntClim21 (Antarctic Climate in the 21st Century) Scientific Research Programme is to develop analogs for understanding past, present and future climates for the Antarctic and Southern Hemisphere. In this contribution to AntClim21 we provide a framework for achieving this goal that includes: a description of basic climate parameters; comparison of existing climate reanalyses; and ice core sodium records as proxies for the frequencies of marine air mass intrusion spanning the past ~2000 years. The resulting analog examples include: natural variability, a continuation of the current trend in Antarctic and Southern Ocean climate characterized by some regions of warming and some cooling at the surface of the Southern Ocean, Antarctic ozone healing, a generally warming climate and separate increases in the meridional and zonal winds. We emphasize changes in atmospheric circulation because the atmosphere rapidly transports heat, moisture, momentum, and pollutants, throughout the middle to high latitudes. In addition, atmospheric circulation interacts with temporal variations (synoptic to monthly scales, inter-annual, decadal, etc.) of sea ice extent and concentration. We also investigate associations between Antarctic atmospheric circulation features, notably the Amundsen Sea Low (ASL), and primary climate teleconnections including the SAM (Southern Annular Mode), ENSO (El Nîno Southern Oscillation), the Pacific Decadal Oscillation (PDO), the AMO (Atlantic Multidecadal Oscillation), and solar irradiance variations.

1. Introduction

Recent changes in Southern Hemisphere (SH) atmospheric circulation, notably the poleward migration and intensification of the westerlies, are a consequence of both human source increases in tropospheric greenhouse gases and decreases in lower stratospheric ozone (Polvani et al., 2011). The implications for future changes in SH atmospheric circulation are highly relevant to the prediction of moisture availability and transport, storminess, marine and terrestrial ecosystem responses, sea ice extent and concentration, ocean circulation and sea level rise (Schofield et al., 2010; Spencer et al., 2014; Mayewski et al., 2015). In addition, recent research suggests East Antarctica has experienced recent rapid ice sheet changes (Greenbaum et al., 2015; Aitken et al., 2016). The Pacific coastal sector of West Antarctica and the Antarctic Peninsula, in particular, are undergoing rapid increases in glacier velocity, mass loss of ice, surface warming, and snowfall

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accumulation (ACCE, 2009; Mayewski et al., 2009; Bromwich et al., 2013; Rignot et al., 2014; Thomas et al., 2015; Pedro et al., 2016). Changes in atmospheric circulation play a key role in these cryospheric rapid increases through the poleward advection of heat and moisture (Nicolas and Bromwich, 2011), and also through the shoreward delivery of ocean heat that drives basal glacier melt (Pritchard et al., 2012). Climate modeling and analog studies of past climates agree that the recently observed poleward displacement of the westerlies will likely continue under future warming and healing of the Antarctic ozone hole (Bracegirdle et al., 2013; Mayewski et al., 2015), but they differ by suggesting either an intensification of primarily westerly winds (i.e., stronger zonal winds and reduced tropospheric wave amplitude), or intensification of primarily meridional winds (weaker westerlies and greater circulation meridionality), respectively (Bracegirdle et al., 2013; Mayewski et al., 2015, respectively).

2. Relationships between atmospheric circulation and precipitation, temperature, and sea ice concentration

Enhanced marine air mass intrusion into Antarctica is associated with increased temperature advection and moisture transport (Nicolas and Bromwich, 2011). The time-averaged (i.e., climatological) low-pressure center over the Bellingshausen-Amundsen Sea (ASL) comprises in excess of 550 singular depressions per year incoming from the Pacific (Fogt et al., 2011). This feature is associated with low temperatures from cold offshore advection and sea ice formation (Bromwich et al., 2013; Criscitiello et al., 2014; Landrum et al., 2012). Interannually, the ASL comprises a "pole of maximum variability" in the MSLP field (Connolley, 1997). When the ASL is strong (i.e., in the long-term mean and also during ENSO "cold"– La Niña– events there is enhanced cold advection and greater sea ice extent westward towards the Ross Sea sector, but warm advection and reduced ice extent occur towards the western side of the Antarctic Peninsula (e.g., Carleton et al., 1998; Turner, 2004). Conversely, when the ASL is weak, and high pressure anomalies dominate the Bellingshausen-Amundsen Sea region (often in ENSO "warm events", or El Niño), temperatures are below normal and sea ice extent is greater to the eastward in the Peninsula region (Carleton, 2003). Thus, interannual variations in Pacific sector sea ice extent and concentration accompany fluctuations in intensity of the ASL connected to the ENSO (Carleton, 1988; Carleton and Fitch, 1993; Yuan and Martinson, 2000; Holland and Kwok, 2012). Moreover, sea ice extent and concentration tend to vary inversely, especially around the time of maximum ice extent in winter and early spring. These variations are such that stronger southerly or westerly winds advect ice equatorward, reducing ice concentration due to divergence of the pack, whereas stronger and/or more persistent northerly winds (warm advection) force the sea ice edge closer to the Antarctic coast yet with greater ice concentration due to compaction of the pack accompanying ice convergence (Carleton, 1988; Yuan et al., 1999).

Climatologically, the mean sea level pressure (MSLP) field indicates a "glacial anticyclone" over the highest elevations of the Antarctic ice sheet and a low-amplitude 3-wave pattern (i.e., 3 troughs and 3 ridges) over middle and high latitudes of the Southern Hemisphere in all seasons (Fig. 1). We present MSLP rather than surface pressure (eg.,

Fogt and Stammerjohn, 2015; cf. their Figs. 6.3, 6.6) to be consistent with our correlation analyses (see below) and to better depict the teleconnection "centers of action", especially the Southern Annular Mode (SAM). Maps of geopotential height (e.g., 500 mbar) would show a broadly similar pattern to Fig. 1 for the Southern Ocean and associated sea ice areas. A poleward contraction of the circumpolar vortex in autumn and spring (MAM, SON, Fig. 1) versus an equatorward expansion in winter and summer (JJA, DJF, Fig. 1), expresses the dominant semi-annual oscillation (SAO) of the extratropical atmosphere on the SH (e.g., Van Loon, 1967; Van Loon and Rogers, 1984). In turn, the SAO interacts with the seasonal patterns of sea ice growth and decay via its influence on the surface wind stress and ocean currents (Large and van Loon, 1989; Enomoto and Ohmura, 1990). These interactions produce a highly asymmetrical temporal pattern of sea ice on the Southern Ocean; a protracted advance in the autumn and winter contrasting with a rapid decay in the spring and summer.

Because there are several climate reanalysis datasets available for investigating climatological behavior, notably atmospheric circulation, we inter-compare our results between the most commonly used climate reanalysis for the SH – ERA-Interim (ERAI) – and an ensemble average of the four leading third-generation reanalyses models (Gen 3) (Auger et al., in review). The models within Gen 3 are CFSR (Climate Forecast System Reanalysis), MERRA (Modern Era Retrospective Reanalysis for Research and Applications), JRA55 (Japanese 55-year Reanalysis), and ERAI. The MSLP behavior is captured equally well in both ERAI and Gen 3 ensemble representations (Fig. 2). Low pressure centers adjacent to East Antarctica comprise the Antarctic Circumpolar Trough (ACT) which is stable in position in DJF and JJA, but contracts slightly poleward with the SAO in the transition seasons. Therefore, the dominant MSLP system comprising the ACT is the ASL. Notably it migrates eastward from winter to summer (Fig. 1).

To investigate the potential role played by atmospheric circulation features (e.g., ASL) in precipitation, temperature and sea ice concentration anomalies around Antarctica we inter-compare these climate parameters statistically using linear correlation with the ERAI fields. We emphasize summer and winter because of the relatively strong shift in ASL longitude position between the extreme seasons.

The correlation of ERAI MSLP and precipitation (PRCP) is moderately strong (~0.5), especially in winter and in West Antarctica and near-coastal Northern Victoria Land (Fig. 3). The association is inverse over the Filchner Ronne Ice Shelf region (i.e., deeper low, more PRCP) in JJA, direct over the Bellingshausen and Amundsen Sea region (deeper low, less PRCP) in JJA, and direct over near-coastal Victoria Land (deeper low, less PRCP) in DJF. These associations also appear in the Gen 3 reanalysis ensemble (CFSR-MERRA-JRA55-ERAI) (not shown).

The correlation of ERAI MSLP and temperature at 2 m above the surface (T2) reveals moderately strong values (~0.5), mostly positive in middle to higher latitudes of the SH and negative in lower latitudes (Fig. 4). Over East Antarctica MSLP and T2 decrease together during both JJA and DJF (i.e., lower pressure with lower temperature, and vice versa). As MSLP decreases over the Filchner-Ronne region T2 rises in JJA, and albeit more weakly and over a smaller area in DJF. When MSLP decreases over the Bellingshausen-Amundsen region of West Antarctica, T2 decreases in both JJA and DJF, only over a more limited region in the summer. These extreme-season correlation patterns are similar to those generated using the Gen 3 ensemble (not shown).

The ERAI reveals areas of moderately strong (~0.5) correlation of winter sea ice concentration (SEAICE) with MSLP and both zonal and meridional winds at 10 m above the surface (U10 and V10, respectively) (Fig. 5). When MSLP is lower in the Amundsen and Ross Seas and offshore from Enderby Land in East Antarctica, SEAICE is increased. The inverse association (i.e., lower MSLP, reduced SEAICE) exists for the Antarctic Peninsula and off Queen Maud and Oates Lands in East Antarctica. With increased westerly airflow SEAICE increases in the Amundsen/Ross Seas and the Indian Ocean sector of East Antarctica, but decreases off near-coastal Northern Victoria Land and the northern tip of the Antarctic