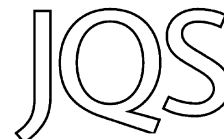


## Rapid Communication

# Potential for Southern Hemisphere climate surprises



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Received 17 April 2015; Revised 25 May 2015; Accepted 1 June 2015

**ABSTRACT:** Climate model results suggest that future climate change in Antarctica will be accompanied by continued strengthening and poleward contraction of the Southern Ocean westerly wind belt. Paleoclimate records suggest past changes in the westerly winds can be abrupt and that healing of the Antarctic ozone hole could lead to poleward contraction of the westerlies and increased meridional atmospheric transport of warm air regionally into Antarctica. An abrupt shift to more meridional circulation could lead to notable changes in moisture availability for extra-Antarctic regions, increased Antarctic ice sheet disintegration and more rapid sea-level rise. Copyright © 2015 The Authors. *Journal of Quaternary Science* Published by John Wiley & Sons, Ltd.

**KEYWORDS:** Antarctica; climate modeling; paleoclimate; Southern Hemisphere climate; westerlies.

This mini review presents the potentially different futures posed by examination of climate models and paleoclimate records. It is a product of AntClim21 (Antarctic Climate in the 21st century), a Scientific Research Programme of the Scientific Committee on Antarctic Research (SCAR). The overarching question for AntClim21 is: How will the Antarctic environment change over the 21st century? To investigate this question AntClim21 invokes in this paper a very broad approach to set the stage for future efforts by the scientific community. In so doing it touches upon ocean–atmosphere–ice–sea-level changes, lessons learned from recent abrupt climate change in the Arctic and some Northern Hemisphere implications, and implications of the foregoing for the Southern Hemisphere.

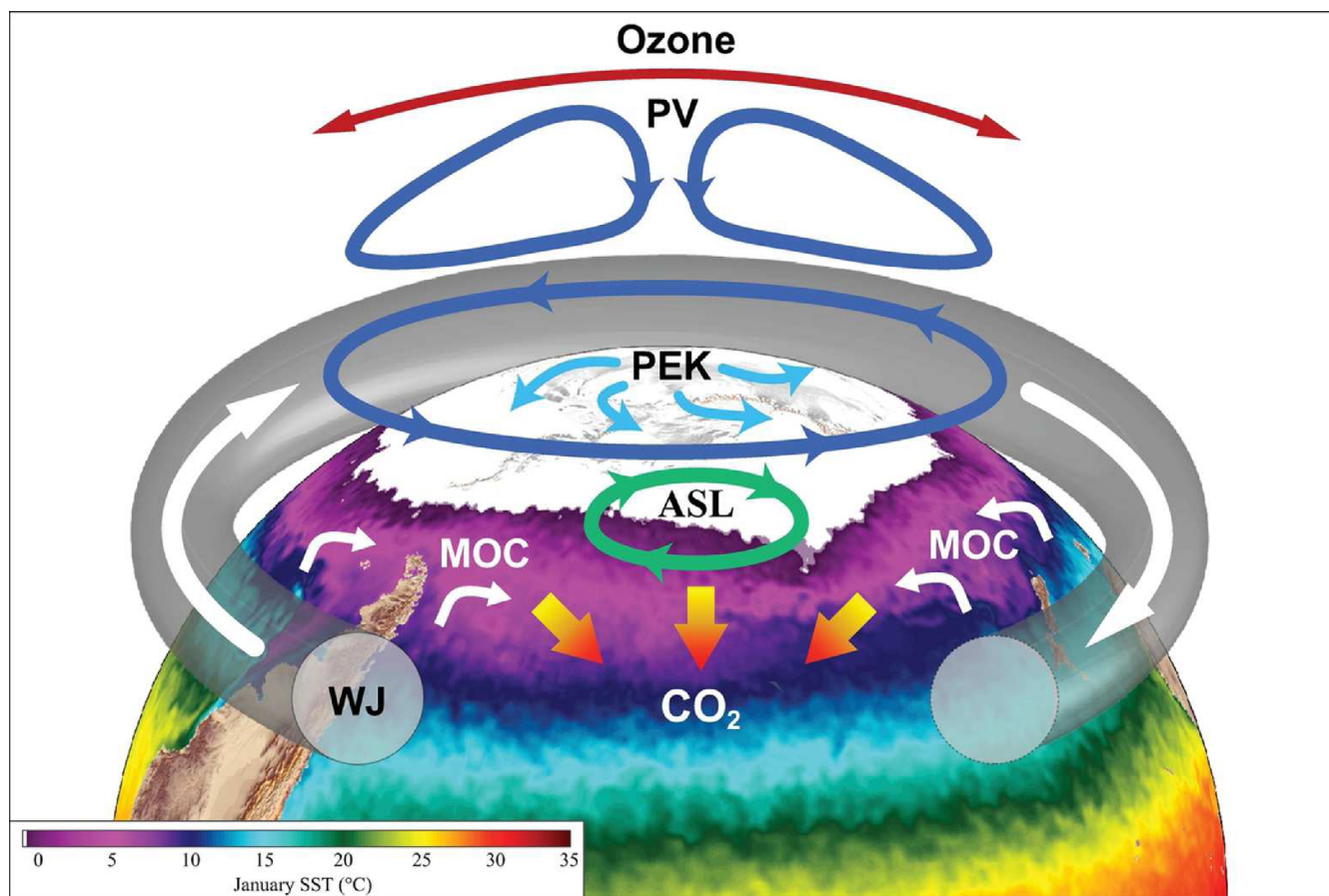
At high southern latitudes the mid-latitude tropospheric jet in westerly winds that encircle Antarctica and influence surface ocean currents, sea ice extent and ocean carbon uptake (Fig. 1) are intensifying in response to greenhouse gas (GHG)-induced warming and depletion of ozone within the stratospheric polar vortex (Thompson *et al.*, 2011). The average displacement of the mid-latitude jet stream and the associated westerlies is poleward (winter  $\sim 3.5^\circ\text{S}$ , summer  $\sim 2.0^\circ\text{S}$ ) and winds have been intensifying (up to 6%) for AD 2001–2010 compared with AD 1981–1990 (Mayewski *et al.*, 2013). Ice core records suggest that relative to the last  $\sim 100\,000$  years this recent poleward migration of the westerlies has led to unprecedented inland penetration of warm air masses and extra-Antarctic source dust, and recently anthropogenic pollutants into West Antarctica (Mayewski *et al.*, 2013).

In the context of 21st century projections, most emission scenarios assume continued increase in GHG concentrations and recovery of stratospheric ozone concentrations above Antarctica by the middle of the century. Most climate models estimate that the response of the tropospheric westerly winds to these two drivers will approximately cancel until the middle of the 21st century, at least in summer, when the effect of the ozone hole at the surface is greatest (Arblaster *et al.*, 2011). However, in scenarios of high GHG emissions, the GHG effect is projected to dominate and lead to an overall increase in strength and maintained southward displacement of the circumpolar westerlies by the year 2100 (Bracegirdle *et al.*, 2013).

The implications of changes in the strength of the westerlies are serious because increased wind-driven incursions of warmed Circumpolar Deep Water onto the adjacent continental margin are suggested as the major driver to melt ice shelves, destabilize grounding lines and ultimately collapse ice sheets (Spencer *et al.*, 2014). The over-deepened, reverse slope bathymetry of Antarctica's continental shelves provides an ideal configuration for a runaway retreat with the potential for abrupt collapse and accelerated sea-level increase (Schofield *et al.*, 2010). This process may already be underway in some regions in West Antarctica where the glacier retreat has been called 'irreversible' (Rignot *et al.*, 2014).

The possibility of a surprise in the rate of ice sheet response and climate change in the Southern Hemisphere is supported by paleoclimate evidence. About 14500 a BP, during Meltwater Pulse 1A, global sea level rose by 20 m with a rate of 4 m per 100 years. Marine sediment reconstructions (Weber *et al.*, 2014) and modeling studies with improved ice sheet resolution and physical representation (Golledge *et al.*, 2014) suggest that this water partially originated from a rapidly

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**Figure 1.** Idealized overview of the Antarctic Ice Sheet and surrounding sea ice, the westerly jet stream [(WJ) grey with white arrow representing the jet core at 250mbar], ozone depletion region [(Ozone) red arrows], the polar vortex [(PV) blue arrows], the polar easterlies and katabatic winds [(PEK) light blue arrows], the Amundsen Sea Low [(ASL) green arrows], Meridional Overturning Circulation [(MOC) white arrows], ocean CO<sub>2</sub> uptake (orange arrows) and January sea-surface temperatures (SST, from The Advanced Very High Resolution Radiometer satellite data). For more specific technical details see ACCE (2009, Chapter 1, The Antarctic Environment and the Global Climate System).

collapsing West Antarctic ice sheet. During the mid-Pliocene, the last time Earth's atmosphere experienced 400 p.p.m. CO<sub>2</sub> concentrations, global sea level rose at least 10m above present to as much as ~20m (Naish and Wilson, 2009), supported by ice sheet/ice shelf modelling (Pollard and DeConto, 2009). Sea-level estimates attributed to CO<sub>2</sub> stabilized at 400–450 p.p.m. support an increase of more than 9 m above present (Foster and Rohling, 2013). Ice sheet model experiments incorporating increased warm water intrusion, surface warming, hydrofracturing and cliff failure provide estimates of sea-level increase and project the loss of the Ross Ice Shelf by 2050 (Pollard *et al.*, 2015) making this event policy relevant.

The paleorecord and current observations highlight the possibility of future rapidly changing westerly wind characteristics. Ice core reconstructions indicate that large, abrupt changes in the position and strength of the westerlies have occurred throughout the Holocene (Mayewski *et al.*, 2013). Proxies for naturally warm and cold past Medieval Climate Anomaly (MCA) and Little Ice Age (LIA) analogues, respectively, reveal significant differences in mid- to high-latitude pressure anomalies, including more La Niña-like and poleward Southern Annular Mode (SAM) AD 1100–1300 patterns during the MCA, and more El Niño-like and equatorward SAM AD 1300–1550, with a return to poleward SAM conditions from AD 1650 to 1800 during the LIA (Goodwin *et al.*, 2013 2014). Coincidentally, recent climate observations reveal trends in Hadley Cell widening (Seidel *et al.*, 2008), poleward migration in mid- to high-latitude storm

tracks and austral westerlies, and associated changes in terrestrial water availability (Arblaster *et al.*, 2011) that exhibit regional characteristics comparable to those in the MCA (Goodwin *et al.*, 2013).

In terms of the mean response to anthropogenic drivers, a key potential for surprise comes from the fact that most climate models simulate the location of the maximum in the tropospheric westerlies as too far equatorward (Bracegirdle *et al.*, 2013). This maximum in westerly winds (the mid-latitude jet) is a major component of the global coupled climate system through its role in modulating heat redistribution and carbon uptake by the Southern Ocean. Although climate models consistently show a poleward shift of the jet position under future warming scenarios, there is a wide range in magnitude and, perhaps tellingly, the models with the smallest biases exhibit the smallest shifts (Kidston and Gerber, 2010). It is therefore possible that in future decades the poleward shift in the tropospheric westerlies will be either smaller or larger than projected by most contemporary climate models.

The rapid recent changes observed over the Arctic and northern mid-latitudes potentially provide lessons relevant to considering potential future rates of Antarctic climate change and related impacts, despite obvious differences in geography between the two regions. From AD 2007 to 2012 mean annual temperatures in portions of the eastern Arctic increased by up to 5 °C (Mayewski *et al.*, 2014) relative to the period AD 1979–2000 and attendant decrease in Arctic sea ice extent dramatically exceeded predicted rates. The greatest increase thus far has been in the eastern Arctic equivalent to

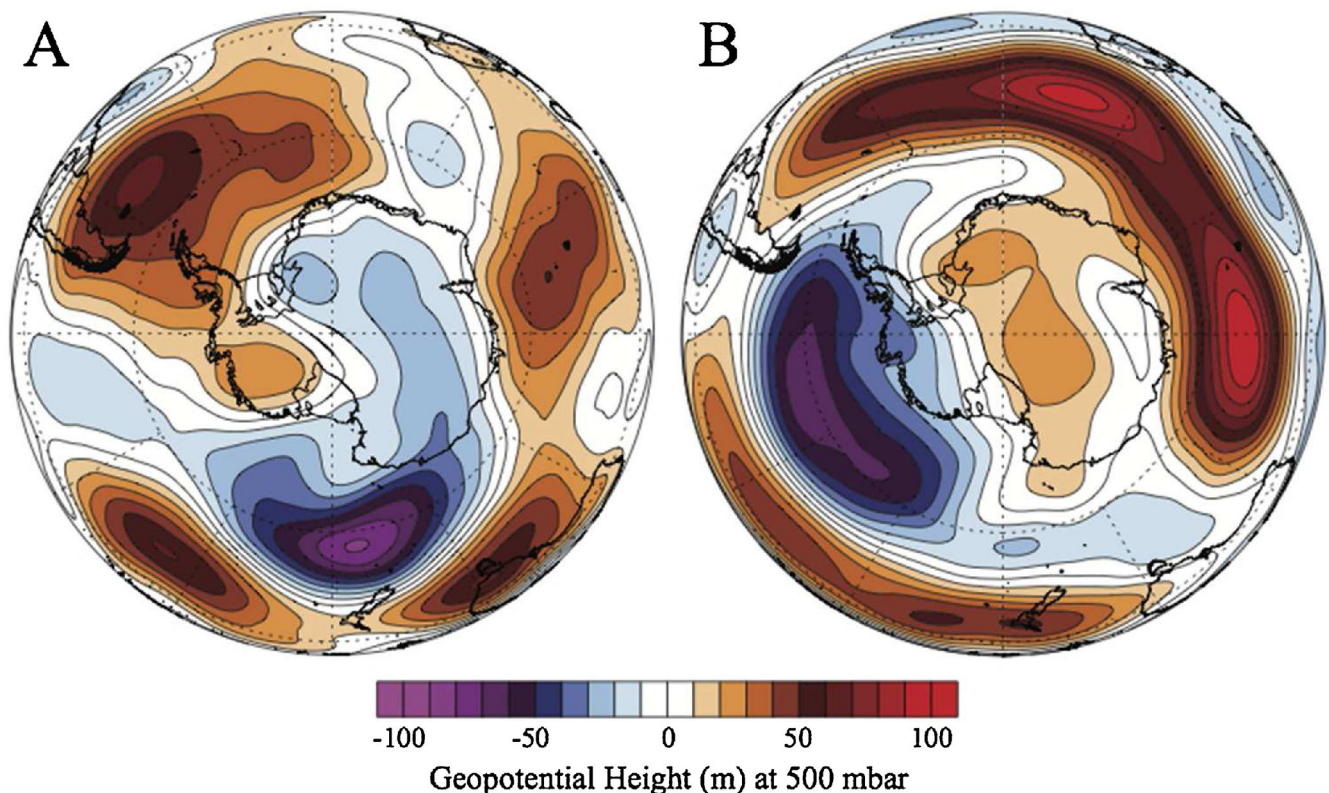
a doubling in the number of annual melting degree-days for this region (Mayewski *et al.*, 2014). It has been suggested that Arctic warming has led to larger-amplitude planetary waves in the Northern Hemisphere and attendant increases in extreme events at mid- to high northern latitudes (Screen and Simmonds, 2014; Francis and Vavrus, 2015). In addition, the effects of tropical variability appear to have propagated poleward to influence the Arctic and the mid-latitudes (Ding *et al.*, 2014; Trenberth *et al.*, 2014). Although there is still only emerging evidence for historical trends in the amplitude of planetary waves (Barnes, 2013) their variability is a contributor to the presence of regionally distributed atmospheric circulation changes such as the weakening of zonal winds over central Asia coincident with Northern Hemisphere warming (Grigholm *et al.*, 2015).

The Antarctic climate system exhibits the largest natural variability in atmospheric pressure in the Southern Hemisphere, particularly regionally over West Antarctica and the Antarctic Peninsula (Connolley, 1997). This variability is driven significantly by natural variability in the tropics, which can both enhance and subdue ozone- or GHG-related trends on decadal timescales (Schneider and Steig, 2008; Ding *et al.*, 2011). In the future it is possible that such natural variability will produce changes that appear surprising in the context of longer-term background trends, potentially because the mechanisms by which natural variability operates may be impacted by anthropogenic activity. As an example, modes of variability such as El Niño Southern Oscillation (ENSO) (Cai *et al.*, 2015) and the SAM (Thompson *et al.*, 2011) are both projected to change significantly due to anthropogenic forcing. While future changes to tropical phenomena such as ENSO are not well constrained among models, recent work suggests that by warming and expanding the tropics and pushing the tropospheric westerly jet poleward, GHG increases will

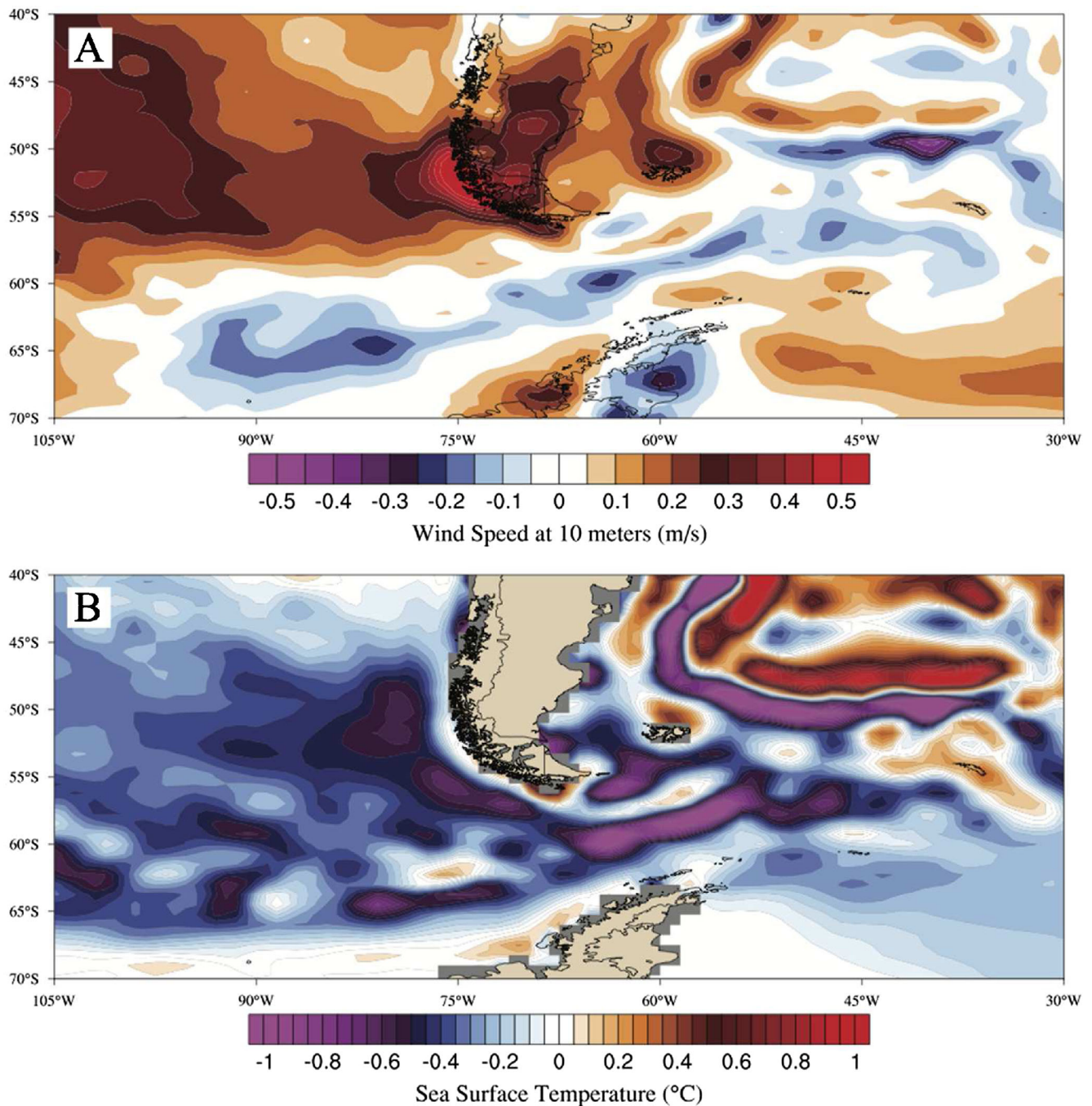
probably influence southern high-latitude circulation (Lu *et al.*, 2008; Grise and Polvani, 2014).

With regard to southern high latitudes, the precise implications of variability in mid-latitude planetary wave amplitude for extremes have not been fully quantified. Examination of extremes in climate re-analysis may provide clues to the future of climate change over the Southern Hemisphere. While variability in geopotential height exists throughout the 1979–2013 re-analysis record, at least one early-stage year of the Antarctic ozone depletion period reveals more meridional structure than the example from more recent years (Fig. 2). While one year does not offer a definitive analog, there are no pre-anthropogenic era climate re-analyses from which to test the tendency towards increased meridional structure. A possible implication for future change during a period of ozone recovery is therefore that regional extremes and Antarctic climate may not follow the zonal pattern of continued poleward migration of the austral westerlies, because with poleward migration of the westerlies the Amundsen Sea Low will also move poleward, creating an even more prominent focal point for the development of waves in the zonal wind field.

The variability and change in westerly jet structure have the potential to cause surprises on the regional scale that can have a significant impact in terms of weather extremes, ocean circulation, carbon uptake, sea ice extent and sea-level rise. Storms originating in the westerlies are a major source of winter precipitation over southernmost Africa, Australia, New Zealand and South America, and poleward migration of the northern margin of the westerlies would tend to decrease rainfall in these regions (Shulmeister *et al.*, 2004; Reason and Rouault, 2005; Lamy *et al.*, 2010; Van Ommen and Morgan, 2010; Stager *et al.*, 2012). Similarly, extremes in drought/wetness, sea surface temperature, air temperature and storminess in these regions will have significant implications for



**Figure 2.** DJF (December, January, February) 1979 (A) and DJF 2011 (B) 500-mbar geopotential height anomalies developed from European Center for Medium range Weather Forecasting ERA-Interim re-analysis plotted using Climate Reanalyzer™ to demonstrate examples of meridional-like and zonal-like, respectively, atmospheric circulation patterns.



**Figure 3.** Comparison between the change in wind speed at 10 m above the surface (A) and sea surface temperature (B) over the south-eastern Pacific and south-western Atlantic for the period 2003–2013 minus the period 1979–2002, revealing potential upwelling of cold water associated with increased wind speed. European Center for Medium range Weather Forecasting ERA-Interim re-analysis surface wind speed and sea surface temperature were plotted using Climate Reanalyzer™.

marine and terrestrial ecosystems (Robinson and Erickson, 2015). For example, changes in sea surface temperature, because of upwelling of cold ocean water, are coincident with changes in the strength and latitudinal position of the tropospheric westerlies (Fig. 3).

More research into the understanding of regional circulation change and its impacts on Antarctic climate, with implications for sea ice extent, ocean circulation, carbon uptake and global climate change and sea-level rise, is required to gain a better understanding of plausible future trajectories of regional climate. The increase in ice shelf melt and land ice loss in the Amundsen Sea has been related to the enhanced advection of warm, circumpolar water on the continental shelf associated with the progressive increase in the westerlies possibly originating from the 1980s (Abram

*et al.*, 2014). The consequence of this is a rapid drawdown of the glaciers, contribution to sea-level rise and probably the ongoing destabilization of the entire West Antarctic Ice Sheet. In the Antarctic Peninsula, ice shelf area has declined dramatically along the west coast in response to increased advection of warm waters.

*Acknowledgments.* Support for the preparation of this report came from SCAR and US NSF (1042883).

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