2015

Not just about sunburn - the ozone hole's profound effect on climate has significant implications for Southern Hemisphere ecosystems

Sharon A. Robinson
University of Wollongong, sharonr@uow.edu.au

David J. Erickson
Oak Ridge National Laboratory

Publication Details

Robinson, S. A. & Erickson, D. J. (2015). Not just about sunburn – the ozone hole's profound effect on climate has significant implications for Southern Hemisphere ecosystems. Global Change Biology, 21 (2), 515-527.

Not just about sunburn - the ozone hole's profound effect on climate has significant implications for Southern Hemisphere ecosystems

Abstract

Climate scientists have concluded that stratospheric ozone depletion has been a major driver of Southern Hemisphere climate processes since about 1980. The implications of these observed and modelled changes in climate are likely to be far more pervasive for both terrestrial and marine ecosystems than the increase in ultraviolet-B radiation due to ozone depletion; however, they have been largely overlooked in the biological literature. Here, we synthesize the current understanding of how ozone depletion has impacted Southern Hemisphere climate and highlight the relatively few documented impacts on terrestrial and marine ecosystems. Reviewing the climate literature, we present examples of how ozone depletion changes atmospheric and oceanic circulation, with an emphasis on how these alterations in the physical climate system affect Southern Hemisphere weather, especially over the summer season (December-February). These potentially include increased incidence of extreme events, resulting in costly floods, drought, wildfires and serious environmental damage. The ecosystem impacts documented so far include changes to growth rates of South American and New Zealand trees, decreased growth of Antarctic mosses and changing biodiversity in Antarctic lakes. The objective of this synthesis was to stimulate the ecological community to look beyond ultraviolet-B radiation when considering the impacts of ozone depletion. Such widespread changes in Southern Hemisphere climate are likely to have had as much or more impact on natural ecosystems and food production over the past few decades, than the increased ultraviolet radiation due to ozone depletion.

Keywords

Antarctica, atmospheric and oceanic circulation, carbon cycle, extreme events, marine and terrestrial ecosystem impacts, ozone hole, precipitation, Southern Annual Mode (SAM), Southern Hemisphere, Southern Ocean, UV radiation

Disciplines

Medicine and Health Sciences | Social and Behavioral Sciences

Publication Details

Robinson, S. A. & Erickson, D. J. (2015). Not just about sunburn – the ozone hole's profound effect on climate has significant implications for Southern Hemisphere ecosystems. Global Change Biology, 21 (2), 515-527.

Not just about sunburn – the ozone hole's profound effect on climate has significant implications for Southern Hemisphere ecosystems.

Running Head: Ozone hole drives Southern Hemisphere climate

Sharon A. Robinson[1] and David J. Erickson III[2]

[1]Institute for Conservation Biology, School of Biological Sciences, The University of Wollongong, New South Wales 2522 Australia.

[2]Computational Earth Sciences Group, Computer Science and Mathematics Division, Oak Ridge National Laboratory P.O. Box 2008, MS 6016 Oak Ridge TN 37831-6016, USA.

Corresponding author: Sharon A. Robinson, **T** +612 42 21 5753; **F** +612 42 21 4135 sharonr@uow.edu.au

Keywords: Southern Annular Mode (SAM); Ozone Hole; atmospheric and oceanic circulation; marine and terrestrial ecosystem impacts; UV radiation; Southern Ocean; Antarctica; precipitation; carbon cycle; extreme events; Southern Hemisphere.

Review Paper

Abbreviations: ACC, Antarctic Circumpolar Current; CFC, chlorofluorocarbons; ODS, ozone depleting substances; greenhouse gases, GHG; SAM, Southern Annular Mode; SH, Southern Hemisphere; ultraviolet UV; ultraviolet-B radiation UV-BR.

Abstract

Climate scientists have concluded that stratospheric ozone depletion has been a major driver of Southern Hemisphere climate processes since about 1980. The implications of these observed and modelled changes in climate are likely to be far more pervasive for both terrestrial and marine ecosystems than the increase in ultraviolet-B radiation due to ozone depletion, however they have been largely overlooked in the biological literature. Here, we synthesise the current understanding of how ozone depletion has impacted Southern Hemisphere climate and highlight the relatively few documented impacts on terrestrial and marine ecosystems. Reviewing the climate literature we present examples of how ozone depletion changes atmospheric and oceanic circulation, with an emphasis on how these alterations in the physical climate system affect Southern Hemisphere weather, especially over the summer season (December-February). These potentially include increased incidence of extreme events, resulting in costly floods, drought, wildfires and serious environmental damage. The ecosystem impacts documented so far include changes to growth rates of South American and New Zealand trees, decreased growth of Antarctic mosses and changing biodiversity in Antarctic lakes. The objective of this synthesis is to stimulate the ecological community to look beyond ultraviolet-B radiation when considering the impacts of ozone depletion. Such widespread changes in Southern Hemisphere climate are likely to have had as much or more impact on natural ecosystems and food production over the past few decades, than the increased ultraviolet radiation due to ozone depletion.

Introduction

Depletion of stratospheric ozone is evident in the ozone hole that appears each austral spring over Antarctica (Figure 1 inset) and occasionally develops over the Arctic (Manney *et al.*, 2011). Ozone depletion is catalysed by chlorofluorocarbons (CFC), and other chemicals that were originally produced as refrigerant and propellant molecules. Ultraviolet (UV) radiation breaks down CFCs and the resultant chlorine radicals catalyse the destruction of stratospheric ozone (Molina & Rowland, 1974). Whilst these reactions can occur across the globe, very low temperatures over the long, Antarctic winter allow the formation of polar stratospheric clouds whose ice particles provide a catalysing surface for ozone depletion, allowing a single chlorine radical to destroy orders of magnitude more ozone molecules, leading to substantial ozone depletion each September/October (NASA, 2014). The difference in ozone dynamics between the Arctic and Antarctic is largely driven by differences in stratospheric temperature, with the Arctic winter being shorter and warmer resulting in less ozone depletion.

These ozone-depleting reactions were identified in the 1970s and the chemicals responsible are now largely regulated under the Montreal Protocol (1987). International action as a result of this highly successful environmental treaty has saved Earth from significantly increased exposure to UV-B radiation (UV-BR; Egorova *et al.*, 2013). By 2065, two thirds of global ozone would have been destroyed (Newman *et al.*, 2009) and by 2100 there would be no ozone layer with severe consequences for all terrestrial and aquatic life on the planet (for details see analysis of the "world avoided" in e.g. Egorova *et al.*, 2013, Newman *et al.*, 2009). Another significant, indirect effect of implementation of this protocol has been the regulation of emissions of ozone depleting substances (ODS) that are potent greenhouse gases (GHG; Velders *et al.*, 2007). Montreal Protocol driven reductions in CFCs and other ODS have successfully reduced the concentration of this suite of GHG in the atmosphere and thus reduced climate-forcing across the globe (Estrada *et al.*, 2013). However, as with other GHG, the long lifetime of these ODS means that the stratosphere over Antarctica is likely to contain significant concentrations of these molecules for several decades and full recovery to 1980s levels is not expected until the middle of this century (Bais *et al.*, 2011). This long lag time illustrates the importance of timely societal and legislative action to alleviate recognised anthropogenic climate impacts.

The stratospheric ozone layer is Earth's primary protection from damaging UV-BR. As a result, in the decades following the Montreal Protocol, concern over ozone depletion stimulated considerable research into its environmental consequences. The impact of UV-BR on terrestrial and aquatic organisms and biogeochemical cycling is regularly synthesised by the United Nation Environment Programme, Environmental Effects Assessment Panel (Ballare *et al.*, 2011, Hader *et al.*, 2011, Norval *et al.*, 2011, Thomas *et al.*, 2012, Zepp *et al.*, 2011). This research has highlighted both negative and positive impacts of increased UV radiation and helped to elucidate the complex role that UV radiation plays in signalling in many organisms (Bornman *et al.*, 2014, Williamson *et al.*, 2014). For example, in humans, exposure to solar UV-BR causes sunburn, photoageing and increasing melanoma rates, but also leads to the production of the essential vitamin D (Thomas *et al.*, 2012, Williamson *et al.*, 2014). If terrestrial plants are exposed to natural solar radiation during growth they generally produce UV-absorbing and antioxidant compounds to reduce any UV damage and have effective DNA damage repair cycles that can mitigate damage if it occurs (Ballare *et al.*, 2011). This ability to photoprotect is not surprising since the evolution of such mechanisms was key to plants' survival on land. In general, organisms that have evolved in regions with high UV-B exposure are better protected than those from historically low UV-BR environments (Robinson *et al.*, 2005, Turnbull *et al.*, 2009, Turnbull & Robinson, 2009), with photoprotection especially well developed in plants from high altitudes and the tropics (Caldwell & Robbercht, 1980, Ziska *et al.*, 1992).

The impact of increased UV-BR due to ozone depletion is often hard to quantify, because it is difficult to separate from increased sun exposure due to changes in human behaviour or to movements of animals or crops from temperate to tropical (low to high UV-BR) locations (Bornman *et al.*, 2014, Williamson *et al.*, 2014). Concurrent GHG induced climate changes and trends in atmospheric aerosol loadings, tropospheric clouds and water vapour impact the ultimate supply of UV-BR to the Earth's surface (Erickson III *et al.*, 2014). In addition, the location of the Antarctic ozone hole over a predominantly ice covered region means that relatively few plants or animals have been exposed to large, ozone related changes in UV-BR. Whilst some Antarctic organisms do appear to be susceptible to this changing UV-BR (Constable *et al.*, 2014, Dunn & Robinson, 2006, Robinson *et al.*, 2005, Snell *et al.*, 2009, Turnbull & Robinson, 2009) overall the declines in terrestrial plant productivity appear relatively modest (estimated at <6%; see Ballare *et al.*, 2011, Newsham & Robinson, 2009). In the ocean, whilst krill are considered susceptible to increasing UV-BR, their ability to acquire compounds that provide protection against UV exposure and their behavioural response to UV-A radiation likely result in reduced exposure to UV-BR and thus less risk of damage (Constable *et al.*, 2014, Newman *et al.*, 2003). However, it is important to recognise that the stress imposed by UV-BR is often concurrent with other stresses, such as temperature or drought stress (Allen *et al.*, 1999, Turnbull & Robinson, 2009) and the cumulative impact of multiple stressors is largely unknown (see Williamson *et al.*, 2014). Relatively subtle changes in UV-BR could also provoke abrupt transformation or 'tipping points' in vulnerable ecological and biogeochemical systems (Clark *et al.*, 2013). The latest UNEP reports have considered the interactions between UV-BR exposure and other climate related changes in detail (e.g. Ballare *et al.*, 2011, Hader *et al.*, 2011, Norval *et al.*, 2011, United Nations Environment Programme, 2012, Zepp *et al.*, 2011).

It is also becoming apparent that, whilst increases in UV-BR have mainly been localised to the polar and sub-polar regions, ozone depletion has had profound effects on many other aspects of the

Southern Hemisphere (SH) climate (Polvani *et al.*, 2011, Thompson & Solomon, 2002, Thompson *et al.*, 2011, Turner *et al.*, 2014). This paper provides a synthesis of the impacts of ozone depletion on SH wind patterns, hydrology and temperatures and illustrates how these might be impacting terrestrial and marine ecosystems and biogeochemical cycles far more dramatically than the coincident increased UV-BR. Our thesis is that whilst these are likely to have had a significant impact over the past few decades they have only recently started to be evaluated by the ecological community. In the coming decades these ozone-climate inter-relations and feedbacks are likely to emerge as major components that contribute to the understanding of Earth system science in the SH.

The ozone hole drives temperature, precipitation and wind energy changes around and across the Antarctic continent during the austral summer

Ozone normally heats the stratosphere as solar radiation is absorbed, so the stratosphere over the South Pole is 6˚C cooler than it was prior to ozone depletion. This cooling of the stratosphere lifts the polar tropopause (Figure 1; Son *et al.*, 2008, Thompson & Solomon, 2002, Thompson *et al.*, 2011). As a result, over the past four decades, atmospheric pressure has declined over the South Pole and risen over the mid-latitudes causing the SH polar jet stream to shift poleward, especially during the austral summer (Figure 1; Gillett & Thompson, 2003, Jones, 2012, Kang *et al.*, 2011, Marshall, 2003, Sexton, 2001, Son *et al.*, 2008, Son *et al.*, 2009). While the loss of stratospheric ozone happens in the austral spring, the greatest impact at the surface is felt during the summer and autumn due to the lag associated with the downward propagation of the signal (Orr *et al.*, 2012). The mode of climate variability that captures differences in atmospheric pressure between the mid- and high-latitudes of the SH is known as the Southern Annular Mode (SAM or Antarctic Oscillation; defined as the zonal mean sea-level pressure difference between the latitudes of 40˚S and 60˚S). The Antarctic ozone hole shifts the polar jet south by 1–2˚ of latitude, consistent with a more positive SAM, in austral summer (Orr *et al.*, 2012, Thompson *et al.*, 2011, Turner *et al.*, 2014 and references therein). Since the late 1970s the strength of the Southern Ocean polar jet has increased by 15–20% (Korhonen, 2010, Turner & Marshall, 2011). Climate models, which can separate, via different model configurations, the contribution due to ozone depletion from GHG forcing, suggest that the bulk of these SAM related changes, in the austral summer, have occurred because of the development of the Antarctic ozone hole with only a small contribution to date from increases in GHG (Gonzalez *et al.*, 2014, Lee & Feldstein, 2013, McLandress *et al.*, 2011, Polvani *et al.*, 2011, Son *et al.*, 2010, Son *et al.*, 2008, Son *et al.*, 2009).

By cooling the polar stratosphere, the Antarctic ozone hole thus increases the thermal gradient between the Pole and the mid-latitudes and helps to seal off the Antarctic continent from lower latitudes by strengthening and tightening the vortex of westerlies that flow around the polar cap (Figure 1). The strong vortex locks very cold air on the high Antarctic land mass, sheltering the coldest region on Earth from the effects of greenhouse warming and explaining the cooling trend observed over much of East Antarctica in the past 30 years (Figures 2 & 3; Convey *et al.*, 2009, Turner *et al.*, 2009, Turner *et al.*, 2014, Wu *et al.*, 2013). Thus loss of stratospheric ozone and the resultant reduced poleward heat flux, is manifest as a slight cooling at stations around the coast of East Antarctica. Effectively, ozone depletion has helped to shield most of Antarctica from the bulk of SH warming with consequences that radiate across the globe. Maintaining frigid temperatures over Antarctica has implications for both the ecosystems of that continent and the rest of the planet in terms of ice melt and consequent sea level rise (Turner *et al.*, 2014). Ozone effects on SAM should become weaker as ozone concentrations recover over the next century reducing Antarctica's buffer against SH warming, but this may well be countered by the effect of increasing GHG on the SAM index (see Figure 1: Abram *et al.*, 2014, Dixon *et al.*, 2012, Perlwitz, 2011).

Whilst East Antarctica has cooled slightly, on the west of the continent this tightening of the vortex draws milder maritime air over the Antarctic Peninsula and onto the Larsen Ice Shelf resulting in parts of this region becoming some of the fastest warming regions on the planet (Orr *et al.*, 2008). Such rapid warming contributes to enhanced melting and break up of ice sheets e.g. the collapse of the Larsen B ice shelf in 2002 (Rignot *et al.*, 2014, Turner *et al.*, 2009, Turner *et al.*, 2014). In addition to causing the poleward shift and strengthening of the westerlies, the change in the SAM has led to a decrease in the annual and seasonal numbers of cyclones south of 40˚ S (Turner *et al.*, 2014). There are now fewer but more intense cyclones in the Antarctic coastal zone between 60 and 70˚ S, except in the Amundsen-Bellingshausen Sea region (Simmonds *et al.*, 2003). The combination of the stronger westerlies around the continent, with the off-pole displacement of Antarctica, has led to a deepening of the Amundsen Sea Low, with consequent effects on temperature and sea ice in the coastal region of West Antarctica. From ice-core records it appears that intensification of the westerlies and the Amundsen Sea Low started over a 100 years ago (Dixon *et al.*, 2012). A recent long-term proxy reconstruction shows that the SAM index is now at its highest level for at least 1000 years (Abram *et al.*, 2014). Their modelling suggests that increasing GHG caused a positive shift in the SAM index in the early 20th century but in recent decades the intensification associated with ozone depletion is more pronounced (Abram *et al.*, 2014, Abram *et al.*, 2013, Dixon *et al.*, 2012). It should be noted that ozone forcing of the SAM index occurs mainly in the austral summer whilst GHG forcing is most evident in other seasons (McLandress *et al.*, 2011, Polvani *et al.*, 2011, Son *et al.*, 2010, Son *et al.*, 2008, Son *et al.*, 2009). This suggests that the impact of any ozone-hole-induced climate change is likely to be more pronounced in summer and in ecosystems where summer is the major growing season.

The ozone-induced shift in the latitudes where the westerlies are strongest, results in very different atmospheric precipitation and temperature environments over much of the SH. These shifts in climate characteristics may play a role in explaining recent occurrences of droughts, floods and associated ecological disturbances. Changes in wind speed and direction have wide reaching effects on hydrology, wildfires and wind transport of organic and inorganic substances (e.g. wind transport, and subsequent deposition, of iron impacting oceanic biogeochemical processes; of propagules leading to colonization and of pollution with its associated human health and ecological impacts), as well as on structural engineering (reviewed in McVicar *et al.*, 2012). Changing wind patterns have important broader implications for marine and terrestrial ecosystems throughout the SH. As the following sections demonstrate, these effects of ozone depletion are likely more widespread and potentially more fundamental than those due to the increase in UV-BR.

The ozone hole affects summer climate across the entire Southern Hemisphere

Depletion of stratospheric ozone affects the entire SH circulation, from the polar region to the subtropics, and from the stratosphere to the surface (Son *et al.*, 2009). Climate scientists now conclude that the formation of the ozone hole has impacts well beyond the mid- and high-latitudes of the SH (Gonzalez *et al.*, 2014). This section details how this has led to shifts in rainfall, aerosols, clouds, water vapour and changing temperature across the SH continents and oceans.

Precipitation

Climate models and observations (1979-2000) show that ozone depletion and the shift of the polar jet are linked to both a poleward expansion of the mid-latitude, subtropical dry-zone (Figure 1 and 2) and increased austral summer, subtropical precipitation (Kang *et al.*, 2011, Polvani *et al.*, 2011, Purich & Son, 2012, Thompson *et al.*, 2011). This has resulted in drying at the southern tip of South America and across Southern Australia, wetter summers over South Africa, SE Australia and New Zealand and increased precipitation and the subsequent freshening of the southern ocean (Kang *et al.*, 2011, Kang *et al.*, 2013, Polvani *et al.*, 2011, Purich & Son, 2012).

The poleward shift of the subtropical dry-zone has brought increased drought to the tip of South America (Figure 2). Tree-rings from the conifer *Austrocedrus chilensis* provide a proxy for soil moisture in the Temperate-Mediterranean transition zone of the Andes (35.5˚ to 39.5˚ S) over the past 657 years (Figure 2; Christie *et al.*, 2011). The increased frequency of extreme droughts observed over the last 100 years correlates with a more positive SAM index in late spring and summer suggesting a link to ozone depletion (Christie *et al.*, 2011). This region of South America is a biodiversity hotspot and generates most of Chile's hydropower, thus climate drying and loss of ecosystem services is of major concern (Christie *et al.*, 2011).

Closer to the equator, Southeastern South America shows an exceptional increase in rainfall (as much as 50 mm month^{-1} from 1960-1999). The bulk of this rainfall occurs in the summer season (December to February) so Gonzalez and coworkers (2014) compared climate models with and without ozone depletion in order to separate the contributions from ozone and GHG forcings. All six models clearly show that the increased precipitation over the region responds to ozone depletion and suggest that the response to ozone depletion is larger than that due to GHG. The link with ozone depletion also explains why the increase in precipitation has been seen in summer and not winter (June to August, Figure 2; Gonzalez *et al.*, 2014). Since this increased summer precipitation has led to an expansion of agriculture with significant economic consequences, understanding how rainfall will change with recovery of the ozone layer is of considerable interest.

The high SAM index resulting from ozone depletion is similarly associated with changing subtropical (~35–50° S) wind patterns which enhance moisture transport from the ocean to Eastern Australia and New Zealand leading to increased summertime precipitation on the eastern slopes of the Southern Alps of New Zealand and the Great Dividing Range of Southeastern Australia (Figure 2; see Thompson *et al.*, 2011 and refs therein). Corresponding decreases in precipitation (Figure 2) are observed on the western slopes of the New Zealand Southern Alps, the western half of Tasmania (Hendon *et al.*, 2007) and over much of Southern and especially South Western Australia (Purich & Son, 2012, Thompson *et al.*, 2011).

Recent modelling studies suggest that stratospheric ozone loss since the late 1970s has increased the frequency and intensity of extreme precipitation in the austral summer (Böning *et al.*, 2008, Purich & Son, 2012). Whilst gradual and consistent increases in mean precipitation are likely to be beneficial (as described above for Southeastern South American agriculture), changes in the frequency and intensity of very heavy precipitation can have direct and immediate negative impacts on society (Rojas *et al.*, 2013, Vörösmarty *et al.*, 2013). Modelling studies by Kang *et al*. (2013) suggest that ozone depletion drives distinct geographical patterns of more extreme daily precipitation events across zones that are getting wetter (high and subtropical latitudes) versus lighter precipitation where mean drying is occurring (e.g. over mid-latitudes including the tip of South America). Increased extreme precipitation in wetter areas is likely to increase flooding events whilst conversely in the drier areas droughts become more frequent. Such extremes of precipitation (droughts and floods) can be economically and socially devastating (Kendon *et al.*, 2014, Keogh *et al.*, 2011). Given the importance of water availability for all life on Earth, its vital role in human and ecosystem health, and its importance for food security, this finding suggests ozone depletion has had far greater ecosystem impacts than previously anticipated.

Temperature

Changes to circulation processes due to ozone depletion and a positive phase of the SAM have also been linked with temperature changes across the SH. In addition to the slight summer cooling of East Antarctica and the higher than normal temperatures over Patagonia and the Antarctic Peninsula, the populated continents to the north also appear to have been affected. Ozone depletion has been linked to higher than normal summertime temperatures throughout much of New Zealand and lower than normal summertime temperatures over central and eastern subtropical Australia (see Thompson *et al.*, 2011 and references therein). In addition, recent work suggests that the shift to warmer summers in Southern Africa strongly correlates with the large ozone hole era (1993-2010; Manatsa *et al.*, 2013). Re-analysis of satellite data focusing on October to December was used to separate ozone hole impacts from those associated with GHG forcing (Manatsa *et al.*, 2013). Whilst this paper does not specifically link to biological consequences it illustrates the potential impacts of ozone depletion for Southern Africans, in terms of their personal, agricultural and ecosystem health, and the importance of further investigating these ozone-hole-induced climate changes on ecological systems and processes. Improved understanding of the linkages between ozone and SH climate could also improve seasonal forecasting which in turn has adaptive and economic benefits.

Climate-related effects of the ozone hole on Southern hemisphere terrestrial and marine ecosystems

This section highlights some of the ways ozone depletion has impacted terrestrial and marine ecosystems through climatic change other than UV radiation. Whilst such changes are likely to have had a significant impact over the past few decades, the link to ozone depletion has only recently started to be considered. In this section we document those studies that have directly linked biological or ecological change to ozone depletion and/or positive summer SAM-related climate changes (see Figure 2).

Southern Hemisphere terrestrial and aquatic ecosystems

The strengthening and poleward shift of the westerlies around Antarctica has been linked to increased growth of trees in New Zealand (Villalba *et al.*, 2012), decreased growth of South American trees and Antarctic mosses (Clarke *et al.*, 2012, Villalba *et al.*, 2012), biodiversity changes in Antarctic lakes (Hodgson *et al.*, 2006) and changes to dust deposition in West Antarctica and the Southern Ocean (Cataldo *et al.*, 2013, McConnell *et al.*, 2007).

The ozone-hole/SAM changes to SH precipitation and temperature described above have been linked to significant changes in temperate tree growth over the past 50 years that are unprecedented over the last 600 years (Villalba *et al.*, 2012). The trends in radial growth of temperate forest trees since the

1950s reflect the drying and warming patterns observed over mid-latitudes in the SH, induced by stratospheric ozone depletion, and are consistent with the positive trend in the SAM. Up to 50% of the decline in growth rates of three Patagonian tree species (*Austrocedrus chilensis, Araucaria aracana* and *Nothofagus betuloides)* since the 1950s is associated with SAM-induced decreased precipitation in the Andes much of which is linked to ozone depletion. The same circulation patterns have increased precipitation and warmed subalpine areas of New Zealand, resulting in higher than average growth rates in *Halocarpus biformis* trees (in this case SAM explains a third of the growth increase; Villalba *et al.*, 2012).

The Antarctic continent is a vast desert with most of the water locked up as ice. Water is therefore a key limiting factor for all Antarctic life (Convey *et al.*, 2014, Robinson *et al.*, 2003, Wasley *et al.*, 2006). In the short austral summer melting snow and ice provide water for growth but increasing wind speeds appear to be reducing the biologically available water. Decreased growth rates of Antarctic mosses and increased salinity of Antarctic lakes are both associated with declining water availability in East Antarctic coastal sites and correlate with locally increasing wind speeds. The availability of liquid water to organisms broadly depends on the balance between annual precipitation and losses by evaporation, sublimation, and freezing (Convey *et al.*, 2014). Increased wind causes evaporation and in polar and alpine environments sublimation and scouring of snow. Growth rates of the Antarctic moss species, *Ceratodon purpureus*, have declined three fold at two sites in the Windmill Islands, East Antarctica since the 1980s. These declines in growth rate were linked to decreasing water availability within the moss beds and growth rates were strongly negatively correlated with wind speeds over the summer season ($r^2 = 0.78$; Clarke *et al*., 2012). The increased wind speeds result in alterations to the surface water and energy exchanges, budgets and balances that dry the moss beds. Lake sediments from three lakes in the same region also show a remarkably rapid increase in salinity in the top 5-10 mm of sediment, representing the last few decades of the 20th Century (Hodgson *et al.*, 2006). Changes in salinity were inferred from changes in the diatom assemblage deposited in sediments. In general, throughout the Holocene the lakes became fresher, consistent with a long-term positive moisture balance, however the increasing salinity in recent decades is apparent in all three lakes and is consistent with increasing wind speeds (Hodgson pers. comm.). Both these studies point to increased desertification of the Windmill Islands of East Antarctica due to the increasing wind speeds that result from ozone depletion. It is important to keep in mind however, that there is large natural variability in polar regions and extracting a signal related to a specific process is very difficult (Thomas *et al.*, 2013).

Unlike East Antarctica which has experienced slight cooling and a drying trend in summer linked to ozone depletion, the Antarctic Peninsula region is warmer and wetter, due to both increased precipitation and melt (Figure 2; but note large variability described above). On Alexander Island growth rates of the moss species *Polytrichum strictum* increased rapidly from 1950 to the late 1970s but have decreased since then. Concurrent with this, populations of testate amoeba have increased rapidly over the last 50 years (Royles *et al.*, 2013). The microbial activity (testate amoeba) has been linked to warming, which also accounts for the initial increased moss growth, whilst the recent declining growth is most likely due to the increased water levels eventually making it too wet for optimum moss productivity. On Signy Island, another moss species, *Chorisodontium aciphyllum,* has shown growth rates since the 1970s that are almost 4 times the mean rate over the previous 200 years (3.9 versus 1 mm yr^{-1} Royles *et al.,* 2012). In lakes on this same island, phytoplankton populations (measured as chlorophyll a content) more than doubled between 1980 and 1995 (Quayle *et al.*, 2002). Like Alexander Island, Signy Island is also getting warmer and wetter and summer changes are likely linked to ozone depletion and the southerly shift in the polar jet. It would be useful to determine if these moss growth rates and changes in microbial ecosystems correlate with the summer SAM index and thus provide additional evidence of ozone-hole, climate-related change.

Winds also transport inorganic and organic components of dust (including nutrients and propagules) from lower latitudes into the Southern Ocean and Antarctica. Changes to the location or strength of winds can affect the sources of dust and the quantities transported. Changes in the westerly wind patterns are reported to have caused a doubling of dust particles in ice cores in West Antarctica over the 20th Century (Cataldo *et al.*, 2013, McConnell *et al.*, 2007). The size of the dust particles transported is strongly proportional to the strength of both the summer westerlies and the summer cyclone depth which is consistent with a link to ozone-depletion/positive SAM (Cataldo *et al.*, 2013). Northerly air mass incursions into central and western West Antarctica have increased significantly in recent decades bringing dust and anthropogenic pollutants into Antarctica from other continents (Mayewski *et al.*, 2013). This rise is unprecedented for at least the past 200 years and is coincident with intensification of the polar westerlies. Increased drought in the southern tip of South America increases the likelihood that dust will be picked up by the stronger winds and thus exposes the previously isolated Antarctic continent to both increased pollution and increased likelihood of colonization by species, through fungal or bacterial spores or plant propagules being transported from the north (Frenot *et al.*, 2005).

If these studies are representative, the climate-related effects of ozone depletion on SH terrestrial ecosystems are likely far larger than the UV-BR effects reported to date. Since the ozone hole is located over Antarctica, it impinges on a relatively small area of ice-free land. Through its effects on SAM and thus on summer temperatures, circulation and precipitation across all the SH continents, ozone depletion is likely affecting many other terrestrial ecosystems. The most impacted are likely to be those where summer weather patterns have changed due to ozone depletion (see Figure 2) and especially those where summer is a major growing season.

Southern Hemisphere marine ecosystems

Through its impacts on SAM the ozone hole has significant and far-ranging impacts on oceanic circulation, ecosystems and chemistry throughout the austral summer. The SAM contributes a large proportion (ca. 35%) of the SH climate variability on timescales ranging from daily to decadal (see Turner & Overland, 2009 and refs therein). The ozone linked strengthening of the polar jet over the Southern Ocean and its shift southwards has a major impact on the marine environment (Figure 3; Toggweiler & Russell, 2008). Changes in the upper ocean as a result of these increased winds include upwelling and outgassing of CO_2 (Dufour *et al.*, 2013, Ito *et al.*, 2010, Le Quéré *et al.*, 2007, Lovenduski *et al.*, 2007) and changes to the vertical supply of nutrients from deep waters to the surface with flow on impacts for phytoplankton. Above the surface, changing atmospheric circulation, precipitation and consequent soil moisture trends affect the timing and magnitude of iron and dust delivery to various oceanic regions. For example, increasing dust transport from Patagonia brings more iron into the ocean resulting in increased phytoplankton blooms (e.g. around James Ross Island; Erickson III *et al.*, 2003).

The stronger polar westerlies induced by the ozone hole stir the Southern Ocean significantly more than they did prior to ozone depletion (Figure 3). This accelerated ocean overturning moves CO_2 rich waters from depth resulting in increased surface ocean pCO_2 which could decrease the capacity of the Southern Ocean to absorb atmospheric CO_2 (Le Quéré *et al.*, 2007). Waugh and coworkers (2013) compared CFCs in seawater in the 1990s versus mid to late 2000s to trace the impact of the polar jet on ocean upwelling and mixing. They showed that strengthened westerlies have accelerated an existing wind-driven circulation that draws deep water to the ocean surface at 60° S and carries it to the northward edge of the jet stream where it sinks (Figure 3). This faster overturning is likely reducing net uptake of CO_2 by the Southern Ocean, slowing the ocean's uptake of carbon dioxide and therefore accelerating greenhouse warming (Lenton *et al.*, 2009, Tanhua *et al.*, 2013, Waugh *et al.*, 2013).

The Antarctic Circumpolar Current (ACC) has warmed more rapidly than the global ocean as a whole, increasing by 0.06˚C per decade down to depths of 1 km over the 1960s to 2000s, and by 0.09˚C per decade since the 1980s (Turner *et al.*, 2014). The warming is more intense on the southern side of the ACC than north of it, with a maximum increase of 0.17˚C per decade at depths up to 0.5 km, south of the Polar Front (Böning *et al.*, 2008, Gille, 2002). Climate modeling studies suggest that the ACC has moved southwards in response to the change in the position of the atmospheric polar jet, but this is still a matter of debate amongst climate scientists (Graham *et al.*, 2012, Turner *et al.*, 2014). North of the ACC, a significant freshening has also been observed since the 1980s (Böning *et al.*, 2008). This warming and freshening of the Southern Ocean has been linked to GHG forcing and ozone related SAM trends (Böning *et al.*, 2008, Son *et al.*, 2009). The stronger atmospheric polar jet appears to have caused an increase in the intensity of Southern Ocean eddies which push more ocean heat southward towards the ice sheets of Antarctica (Lenton *et al.*, 2009, Waugh *et al.*, 2013). Increased transport of warm, circumpolar deep water underneath floating ice sheets results in elevated melt rates and thinning of marine ice sheets such as the Thwaites Glacier, resulting in retreats of up to 1.8 km yr^{-1} (Jacobs *et al.*, 2011, Joughin *et al.*, 2014, Rignot *et al.*, 2014). These studies suggest that this process is now irreversible and could lead to collapse of these ice sheets and therefore >1 m of sea level rise over the next 200-900 years (Joughin *et al.*, 2014, Rignot *et al.*, 2014). Through their combined ability to induce a more positive phase of the SAM, increasing GHG and ozone depletion are enhancing an ocean circulation pattern of subsurface warm waters that melt glaciers beyond their grounding lines, whilst pushing cooler surface waters northward (Figure 3; Rignot *et al.*, 2014).

Changes to wind speeds, water temperatures and ocean overturning likely have impacts on ocean ecosystems. Years with stronger westerly winds showed better recruitment of both 1- and 2-year-old krill and higher chlorophyll density (1982-1998; Naganobu *et al.*, 1999). If such correlations can be substantiated as causal relationships it could mean that ozone effects on wind patterns are as important to marine food webs as the UV-BR impacts.

Sea ice is a critical component of marine polar ecosystems serving as a habitat, a resting and breeding platform and as a protective barrier (Constable *et al.*, 2014). Whilst sea ice decline in the Arctic since 1979 is one of the most dramatic illustrations of climate change, by contrast overall Antarctic sea ice has increased slightly (Turner *et al.*, 2009, Turner *et al.*, 2014). Patterns of sea ice changes (both losses and gains) seen around West Antarctica and sea ice seasonality around East Antarctica are complex (Constable *et al.*, 2014, Holland & Kwok, 2012, Massom *et al.*, 2013, Turner *et al.*, 2009, Turner *et al.*, 2014). Models suggest that springtime ozone depletion should have resulted in decreased sea ice around Antarctica but this is not apparent, presumably because GHG forcing plays a dominant role (Sigmond & Fyfe, 2014). During positive SAM phases the intensification of the colder westerly winds causes Ekman drift to strengthen northward extending sea-ice seasonality and area (Holland & Kwok, 2012, Maksym *et al.*, 2012, van den Hoff *et al.*, 2014).

Changes to circulation patterns (both atmospheric and ocean currents) and precipitation over the southern ocean obviously have major implications for southern ocean biota, but also for future ocean storage of carbon dioxide. If these circulation patterns are impacting on sea ice and ice shelves, as has been proposed, then there will be major biological impacts and potential tipping points (see Clark *et al.*, 2013, Constable *et al.*, 2014). Changes to sea ice will affect photoautotrophs at the base of the food web, invertebrates within the ocean as well as the reproductive success of ice obligate penguins and southern elephant seals (Constable *et al.*, 2014, van den Hoff *et al.*, 2014).

Ecological tipping points, the ozone hole and future Southern Hemisphere climate

Tipping points in Antarctic marine and terrestrial ecosystems (Brook *et al.*, 2013, Lenton & Williams, 2013) maybe influenced by the biogeochemical interactions of these ozone depletion and GHG related changes in climate. Areas in the polar regions where summer maximum temperatures are close to 0˚C require only modest increases in temperature to unleash widespread melt (Abram *et al.*, 2013) with widespread ecological consequences (Convey *et al.*, 2014, Robinson *et al.*, 2003). It appears that Earth has already reached some such tipping points, as evidenced by the melting of the West Antarctic ice sheet (Joughin *et al.*, 2014, Rignot *et al.*, 2014). The impact of light-driven tipping points in polar ecosystems has been demonstrated (Clark *et al.*, 2013). Earlier sea ice melt that brings the date of ice-loss closer to midsummer causes an exponential increase in both photosynthetically active and UV radiation (Clark *et al.*, 2013). This is likely to drive ecological tipping points in which UV tolerant primary producers (plants and algae) flourish and out-compete dark-adapted communities (Clark *et al.*, 2013, Erickson III *et al.*, 2014). Tipping points could also be triggered by the combination of positive SAM related climate factors with ozone related changes to UV radiation flux (Erickson III *et al.*, 2014). The trends and potential abrupt changes in UV radiation due to drought induced aerosol distributions, anthropogenic pollution, and column ozone depletion over specific areas can act in concert to induce rapid ecological changes (Bernhard *et al.*, 2013).

The SAM is an important modulator of SH climate and ecological health and a diverse array of ecosystem services. The close coupling of SH ecological systems to attributes of the SAM, such as precipitation and temperature, is thus indirectly related to the ozone hole as well as GHG forcing (Abram *et al.*, 2014). During austral summer over the next ~50 years, the effects of ozone recovery on the SAM are expected to be roughly equal but opposite to those due to increasing GHG (see Figure 1). During other seasons however, increasing GHG are expected to continue to drive the SAM towards its high index polarity unopposed by ozone recovery. The SAM is thus expected to continue to have a marked effect on future SH climate change (Abram *et al.*, 2014). Recent studies suggest that SAM and the El Niño-Southern Oscillation (ENSO) climate modes can also interact, with El Niño usually associated with negative and La Niña with positive SAM states (Fogt *et al.*, 2011, Raut *et al.*, 2014, Wang & Cai, 2013). Whilst recovery of the ozone hole will likely have widespread and complex effects on SH climate processes, predicting these accurately requires a better understanding of how SAM and ENSO interact and will respond to ozone recovery and increasing GHG (Abram *et al.*, 2014, Raut *et al.*, 2014). Although only a few studies have sought to relate biological changes to the ozone related climate change in the SH, those that do, report unprecedented changes in the second half of the 20th Century compared to historic records (Hodgson *et al.*, 2006, McConnell *et al.*, 2007, Villalba *et al.*, 2012). A better understanding of how the SAM will respond to recovery of the ozone hole and increasing GHG concentrations is thus vital to determine how SH ecosystems and ecosystem services will fare over the coming century.

Conclusions

Until very recently, research into the impact of ozone depletion was largely focused on the direct impacts of increased UV radiation as summarized in the quadrennial UNEP EEAP reports. The realisation that stratospheric ozone depletion has been a major driver of SH climate processes over the late 20th Century has significant implications for all SH ecosystems. Through its influence on atmospheric circulation, ozone depletion has helped to shield the Antarctic continent from much of the effect of global warming over the past half century (Abram *et al.*, 2014, Convey *et al.*, 2009, Turner *et al.*, 2009, Turner *et al.*, 2014, Wu *et al.*, 2013). This effect is not likely to continue. Over the next century ozone concentrations above the Antarctic should recover but atmospheric concentrations of GHGs will continue to increase, as a result temperatures across Antarctica are projected to increase by several degrees and sea ice will be reduced (Sigmond & Fyfe, 2014, Turner *et al.*, 2014). This has major implications for the loss of ice sheets and for global sea level rise

(Jacobs *et al.*, 2011, Joughin *et al.*, 2014, Rignot *et al.*, 2014) with consequentially profound effects for life on Earth.

To date the implications of these ozone related climate changes for both terrestrial and marine SH ecosystems have been largely overlooked in the biological literature. If the biological impacts of elevated UV-BR due to ozone have been less severe than first predicted, recent climate science shows us that the impact of ozone depletion on SH climate processes generally, deserves consideration. In this review, we have highlighted some of the ways ozone depletion has impacted terrestrial, marine and aquatic ecosystems. These include changes to wind patterns which have induced drying in East Antarctica leading to decreased moss growth and biodiversity changes in lakes (Clarke *et al.*, 2012, Hodgson *et al.*, 2006) and changes in precipitation in New Zealand and Patagonia which have significantly affected tree growth (Villalba *et al.*, 2012). If these studies are representative, the climate-related effects of ozone depletion on ecosystems are likely far larger than the UV-BR effects reported to date. Ozone depletion has been implicated in keeping East Antarctica cold, warming the Antarctic peninsula and changing wind patterns and precipitation across the SH. In light of these observed climate events it is virtually certain that many SH terrestrial and marine ecosystems have changed.

Whilst the altered patterns of temperature, circulation and precipitation described above are likely to have already produced marked effects on natural ecosystems, forestry and agricultural productivity across the SH, it is difficult to document the contribution of ozone depletion, since so few studies have sought to correlate ecosystem changes to ozone depth except in relation to increased UV-BR. Unlike the ozone hole effects on UV-BR, which are likely to be most dramatic in the austral spring (September to November), most of these other climate impacts will be strongest during austral summer (December to February). This means they could easily be missed due to the lag between the ozone depletion event and the consequent feedbacks through to climate. In the same way that elucidation of the role that ozone depletion plays in SH climate has occurred through re-analysis of summer trends in climate, similar re-analysis of ecological data would determine the role that ozone depletion has played in shaping ecosystem processes through climate change. Hopefully by synthesizing the state of the climate science, this paper will facilitate discussion and consideration of the ozone hole as a driver for austral summer SH ecosystem impacts more broadly and stimulate such re-analysis.

Acknowledgements. SAR acknowledges receipt of Australian Research Council Grant (DP110101714) and Australian Antarctic Science Grants 3129 and 4046. DJE acknowledges the support of Oak Ridge National Laboratory, which is supported by the Office of Science of the U.S. Department of Energy under Contract Number DE-AC05-00OR22725. We thank Andrew Netherwood for production of all figures and Stephen Wilson, members of the Robinson Research Group and two anonymous reviewers for feedback on drafts of the manuscript.

Dedication: This paper is dedicated to the memory of Warwick Hillier (1967 – 2014). Warwick's scientific passion was to understand the mechanism for light-driven water oxidation in photosynthesis, which ultimately produces Earth's oxygen-rich atmosphere and leads to the formation of the ozone layer. Warwick and Sharon had many discussions about the topics in this paper. As his 6-year old daughter Stella said, the ozone layer is a place where lots of Oxygen hangs out!

References

Abram NJ, Mulvaney R, Vimeux F, Phipps SJ, Turner J, England MH (2014) Evolution of the Southern Annular Mode during the past millennium. *Nature Climate Change*, **4**, 564–569.

Abram NJ, Mulvaney R, Wolff EW, Triest J (2013) Acceleration of snow melt in an Antarctic Peninsula ice core during the twentieth century. *Nature Geoscience,* **6**, 404-410.

Allen DJ, Nogues S, Morison JIL, Greenslade PD, Mcleod AR, Baker NR (1999) A thirty percent increase in UV-B has no impact on photosynthesis in well-watered and droughted pea plants in the field. *Global Change Biology,* **5**, 235-244.

Bais AF, Tourpali K, Kazantzidis A *et al.* (2011) Projections of UV radiation changes in the 21st century: Impact of ozone recovery and cloud effects. *Atmospheric Chemistry and Physics,* **11**, 7533-7545.

Ballare CL, Caldwell MM, Flint SD, Robinson SA, Bornman JF (2011) Effects of solar ultraviolet radiation on terrestrial ecosystems. Patterns, mechanisms, and interactions with climate change. *Photochemical & Photobiological Sciences,* **10**, 226-241.

Bernhard G, Dahlback A, Fioletov V *et al.* (2013) High levels of ultraviolet radiation observed by ground-based instruments below the 2011 Arctic ozone hole. *Atmospheric Chemistry and Physics,* **13**, 10573-10590.

Böning CW, Dispert A, Visbeck M, Rintoul SR, Schwarzkopf FU (2008) The response of the Antarctic Circumpolar Current to recent climate change *Nature Geoscience,* **1**, 864-869.

Bornman JF, Barnes P, Robinson SA, Ballaré CL, Flint SD, Caldwell MM (2014) Solar ultraviolet radiation and ozone depletion-driven climate change: impacts on terrestrial ecosystem. *Photochemical & Photobiological Sciences, in revision.*

Brook BW, Ellis EC, Perring MP, Mackay AW, Blomqvist L (2013) Does the terrestrial biosphere have planetary tipping points? *Trends in Ecology & Evolution,* **28**, 396-401.

Caldwell MM, Robbercht R (1980) A steep gradient of solar ultraviolet-B radiation in the Arctic-Alpine zone. *Ecology,* **61**, 600-611.

Cataldo M, Evangelista H, Simoes JC *et al.* (2013) Mineral dust variability in central West Antarctica associated with ozone depletion. *Atmospheric Chemistry and Physics,* **13**, 2165-2175.

Christie DA, Boninsegna JA, Cleaveland MK, Lara A (2011) Aridity changes in the Temperate-Mediterranean transition of the Andes since AD 1346 reconstructed from tree-rings. *Climate Dynamics,* **36**, 1505-1521.

Clark GF, Stark JS, Johnston EL, Runcie JW, Goldsworthy PM, Raymond B, Riddle MJ (2013) Light-driven tipping points in polar ecosystems. *Global Change Biology,* **19**, 3749–3761.

Clarke LJ, Robinson SA, Hua Q, Ayre DJ, Fink D (2012) Radiocarbon bomb spike reveals biological effects of Antarctic climate change. *Global Change Biology,* **18**, 301-310.

Constable AJ, Melbourne-Thomas J, Corney SP *et al.* (2014) Climate change and Southern Ocean ecosystems I: How changes in physical habitats directly affect marine biota. *Global Change Biology*, DOI 10.1111/gcb.12623.

Convey P, Bindschadler R, Di Prisco G *et al.* (2009) Antarctic climate change and the environment. *Antarctic Science,* **21**, 541-563.

Convey P, Chown SL, Clarke A *et al.* (2014) The spatial structure of Antarctic biodiversity. *Ecological Monographs,* **84**, 203-244.

Dixon DA, Mayewski PA, Goodwin ID, Marshall GJ, Freeman R, Maasch KA, Sneed SB (2012) An ice-core proxy for northerly air mass incursions into West Antarctica. *International Journal of Climatology,* **32**, 1455-1465.

Dufour CO, Sommer JL, Gehlen M, Orr JC, Molines J-M, Simeon J, Barnier B (2013) Eddy compensation and controls of the enhanced sea-to-air CO_2 flux during positive phases of the Southern Annular Mode. *Global Biogeochemical Cycles,* **27**, 950-961.

Dunn JL, Robinson SA (2006) Ultraviolet B screening potential is higher in two cosmopolitan moss species than in a co-occurring Antarctic endemic moss: Implications of continuing ozone depletion. *Global Change Biology,* **12**, 2282-2296.

Egorova T, Rozanov E, Gröbner J, Hauser M, Schmutz W (2013) Montreal Protocol Benefits simulated with CCM SOCOL. *Atmospheric Chemistry and Physics,* **13**, 3811-3823.

Erickson III DJ, Hernandez J, Ginoux P, Gregg W, Mcclain C, Christian J (2003) Atmospheric iron delivery and surface ocean biological activity in the Southern Ocean and Patagonian region. *Geophysical Research Letters,* **30**, 1609.

Erickson III DJ, Sulzberger B, Zepp RG, Austin AT (2014) Effects of solar UV radiation and climate change on biogeochemical cycling: Interactions and feedbacks. *Photochemical & Photobiological Sciences, in revision*.

Estrada F, Perron P, Martínez-López B (2013) Statistically derived contributions of diverse human influences to twentieth-century temperature changes. *Nature Geoscience,* **6**, 1-6.

Fogt RL, Bromwich DH, Hines KM (2011) Understanding the SAM influence on the South Pacific ENSO teleconnection. *Climate Dynamics,* **36**, 1555-1576.

Frenot Y, Chown SL, Whinam J, Selkirk PM, Convey P, Skotnicki M, Bergstrom DM (2005) Biological invasions in the Antarctic: extent, impacts and implications. *Biological Reviews,* **80**, 45-72

Gille ST (2002) Warming of the Southern Ocean since the 1950s. *Science,* **295**, 1275-1277.

Gillett NP, Thompson DWJ (2003) Simulation of recent Southern Hemisphere climate change. *Science,* **302**, 273–275.

Gonzalez PLM, Polvani LM, Seager R, Correa GJP (2014) Stratospheric ozone depletion: a key driver of recent precipitation trends in South Eastern South America. *Climate Dynamics,* **42**, 1775-1792.

Graham RM, Boer AM, Heywood KJ, Stevens DP (2012) Southern Ocean fronts: Controlled by wind or topography? *Journal of Geophysical Research,* **117**, C08018.

Hader DP, Helbling EW, Williamson CE, Worrest RC (2011) Effects of UV radiation on aquatic ecosystems and interactions with climate change. *Photochemical & Photobiological Sciences,* **10**, 242-260.

Hendon HH, Thompson DWJ, Wheeler MC (2007) Australian rainfall and surface temperature variations associated with the Southern Hemisphere Annular Mode. *Journal of Climate,* **20**, 2452–2467.

Hodgson DA, Roberts D, Mcminn A, Verleyen E, Terry B, Corbett C, Vyverman W (2006) Recent rapid salinity rise in three East Antarctic lakes. *Journal of Paleolimnology,* **36**, 385-406.

Holland PR, Kwok R (2012) Wind-driven trends in Antarctic sea-ice drift. *Nature Geoscience,* **5**, 872-875.

Ito T, Woloszyn M, Mazloff M (2010) Anthropogenic carbon dioxide transport in the Southern Ocean driven by Ekman flow. *Nature,* **463**, 80-83.

Jacobs SS, Jenkins A, Giulivi CF, Dutrieux P (2011) Stronger ocean circulation and increased melting under Pine Island Glacier ice shelf. *Nature Geoscience,* **4**, 519-523.

Jones J (2012) Tree rings and storm tracks. *Nature Geoscience,* **5**, 764-765.

Joughin I, Smith BE, Medley B (2014) Marine ice sheet collapse potentially underway for the Thwaites Glacier Basin, West Antarctica. *Science,* **344**, 735-738.

Kang SM, Polvani LM, Fyfe JC, Sigmond M (2011) Impact of polar ozone depletion on subtropical precipitation. *Nature Geoscience,* **332**, 951-954.

Kang SM, Polvani LM, Fyfe JC, Son SW, Sigmond M, Correa GJP (2013) Modeling evidence that ozone depletion has impacted extreme precipitation in the austral summer. *Geophysical Research Letters,* **40**, 4054-4059.

Kendon EJ, Roberts NM, Fowler HJ, Roberts MJ, Chan SC, Senior CA (2014) Heavier summer downpours with climate change revealed by weather forecast resolution model. *Nature Climate Change*, **4**, 570–576.

Keogh DU, Apan A, Mushtaq S, King D, Thomas M (2011) Resilience, vulnerability and adaptive capacity of an inland rural town prone to flooding: A climate change adaptation case study of Charleville, Queensland, Australia. *Natural Hazards,* **59**, 699-723.

Korhonen H, K. S. Carslaw, P. M. Forster, S. Mikkonen, N. D. Gordon, and H. Kokkola. (2010) Aerosol climate feedback due to decadal increases in Southern Hemisphere wind speeds. *Geophysical Research Letters,* **37**, DOI:10.1029/2009GL041320.

Le Quéré C, Rodenbeck C, Buitenhuis ET, Conway TJ (2007) Saturation of the Southern Ocean CO_2 sink due to recent climate change. *Science,* **316**, 1735-1738.

Lee S, Feldstein SB (2013) Detecting ozone- and greenhouse gas-driven wind trends with observational data. *Nature Geoscience,* **339**, 563-567.

Lenton A, Codron F, Bopp L, Metzl N, Cadule P, Tagliabue A, Le Sommer J (2009) Stratospheric ozone depletion reduces ocean carbon uptake and enhances ocean acidification. *Geophysical Research Letters,* **36**, 10.1029/2009gl038227.

Lenton TM, Williams HTP (2013) On the origin of planetary-scale tipping points. *Trends in Ecology & Evolution,* **28**, 380-382.

Lovenduski NS, Gruber N, Doney SC, Lima ID (2007) Enhanced CO_2 outgassing in the Southern Ocean from a positive phase of the Southern Annular Mode. *Global Biogeochemical Cycles,* **21**, GB2026, doi:2010.1029/2006GB002900.

Maksym T, Stammerjohn SE, Ackley S, Massom R (2012) Antarctic sea ice—A polar opposite? *Oceanography,* **25**, 140-151.

Manatsa D, Morioka Y, Behera SK, Yamagata T, Matarira CH (2013) Link between Antarctic ozone depletion and summer warming over southern Africa. *Nature Geoscience,* **6**, 934-939.

Manney GL, Santee ML, Rex M *et al.* (2011) Unprecedented Arctic ozone loss in 2011. *Nature,* **478**, 467-475.

Marshall GJ (2003) Trends in the southern annular mode from observations and reanalyses. *Journal of Climate,* **16**, 4134-4143.

Massom R, Reid P, Stammerjohn S, Raymond B, Fraser A, Ushio S (2013) Change and variability in East Antarctic sea ice seasonality, 1979/80–2009/10. *PLoS ONE,* **8**, e64756.

Mayewski PA, Maasch KA, Dixon D (2013) West Antarctica's sensitivity to natural and human‐forced climate change over the Holocene. *Journal of Quaternary Science,* **28**, 40-48.

McConnell JR, Aristarain AJ, Banta JR, Edwards PR, Simões JC (2007) 20th-Century doubling in dust archived in an Antarctic Peninsula ice core parallels climate change and desertification in South America. *Proceedings of the National Academy of Sciences of the United States of America,* **104**, 5743-5748.

McLandress C, Shepherd TG, Scinocca JF, Plummer DA, Sigmond M, Jonsson AI, Reader MC (2011) Separating the Dynamical Effects of Climate Change and Ozone Depletion. Part II: Southern Hemisphere Troposphere. *Journal of Climate,* **24**, 1850-1868.

McVicar TR, Roderick ML, Donohue RJ *et al.* (2012) Global review and synthesis of trends in observed terrestrial near-surface wind speeds: Implications for evaporation. *Journal of Hydrology,* **416-417**, 182-205.

Molina M, Rowland F (1974) Stratospheric sink for chlorofluoromethanes: chlorine atomic-catalysed destruction of ozone. *Nature,* **249**, 810-812.

Naganobu M, Kutsuwada K, Sasai Y, Taguchi S, Siegel V (1999) Relationships between Antarctic krill (*Euphausia superba*) variability and westerly fluctuations and ozone depletion in the Antarctic Peninsula area. *Journal of Geophysical Research-Oceana,* **104**, 1-15.

NASA (2014) Ozone Hole Watch. National Aeronautics and Space Administration. Goddard Space Flight Center. http://ozonewatch.gsfc.nasa.gov/

Newman PA, Oman LD, Douglass AR *et al.* (2009) What would have happened to the ozone layer if chlorofluorocarbons (CFCs) had not been regulated? *Atmospheric Chemistry and Physics,* **9**, 2113-2128.

Newman SJ, Ritz D, Nicol SC (2003) Behavioural reactions of Antarctic krill (*Euphausia superba* Dana) to ultraviolet and photosynthetically active radiation. *Journal of Experimental Marine Biology and Ecology,* **297**, 203-217.

Newsham KK, Robinson SA (2009) Responses of plants in polar regions to UV-B exposure: a meta-analysis. *Global Change Biology,* **15**, 2574-2589.

Norval M, Lucas RM, Cullen AP, De Gruijl FR, Longstreth J, Takizawa Y, Van Der Leun JC (2011) The human health effects of ozone depletion and interactions with climate change. *Photochemical & Photobiological Sciences,* **10**, 199-225.

Orr A, Bracegirdle TJ, Hosking JS (2012) Possible dynamical mechanisms for Southern Hemisphere climate change due to the ozone hole. *Journal of the Atmospheric Sciences,* **69**, 2917-2932.

Orr A, Marshall GJ, Hunt JCR *et al.* (2008) Characteristics of summer airflow over the Antarctic Peninsula in response to recent strengthening of westerly circumpolar winds. *Journal of the Atmospheric Sciences,* **65**, 1396-1413.

Perlwitz J (2011) Tug of war on the jet stream. *Nature Climate Change,* **1**, 29-31.

Polvani LM, Waugh DW, Correa GJP, Son S-W (2011) Stratospheric Ozone Depletion: The Main Driver of Twentieth-Century Atmospheric Circulation Changes in the Southern Hemisphere. *Journal of Climate,* **24**, 795-812.

Purich A, Son S-W (2012) Impact of Antarctic ozone depletion and recovery on Southern Hemisphere precipitation, evaporation, and extreme changes. *Journal of Climate,* **25**, 3145-3154.

Quayle WC, Peck LS, Peat H, Ellis-Evans JC (2002) Extreme responses to climate change in Antarctic lakes. *Science,* **295**, 645.

Raut BA, Jakob C, Reeder MJ (2014) Rainfall changes over Southwestern Australia and their relationship to the Southern Annular Mode and ENSO. *Journal of Climate,* **27**, 5801-5814.

Rignot E, Mouginot J, Morlighem M, Seroussi H, Scheuchl B (2014) Widespread, rapid grounding line retreat of Pine Island, Thwaites, Smith and Kohler glaciers, West Antarctica from 1992 to 2011. *Geophysical Research Letters*, **41**, 3502–3509.

Robinson SA, Turnbull JD, Lovelock CE (2005) Impact of changes in natural ultraviolet radiation on pigment composition, physiological and morphological characteristics of the Antarctic moss, *Grimmia antarctici*. *Global Change Biology,* **11**, 476-489.

Robinson SA, Wasley J, Tobin AK (2003) Living on the edge - Plants and global change in continental and maritime Antarctica. *Global Change Biology,* **9**, 1681-1717.

Rojas R, Feyen L, Watkiss P (2013) Climate change and river floods in the European Union: Socio-economic consequences and the costs and benefits of adaptation. *Global Environmental Change,* **23**, 1737-1751.

Royles J, Amesbury MJ, Convey P, Griffiths H, Hodgson DA, Leng MJ, Charman DJ (2013) Plants and soil microbes respond to recent warming on the Antarctic Peninsula. *Current Biology,* **23**, 1702-1706.

Royles J, Ogée J, Wingate L, Hodgson DA, Convey P, Griffiths H (2012) Carbon isotope evidence for recent climate-related enhancement of CO_2 assimilation and peat accumulation rates in Antarctica. *Global Change Biology,* **18**, 3112-3124.

Sexton DMH (2001) The effect of stratospheric ozone depletion on the phase of the Antarctic Oscillation. *Geophysical Research Letters,* **28**.

Sigmond M, Fyfe JC (2014) The Antarctic Sea Ice Response to the Ozone Hole in Climate Models. *Journal of Climate,* **27**, 1336-1342.

Simmonds I, Keay K, Lim EP (2003) Synoptic activity in the seas around Antarctica. *Monthly Weather Review,* **131**, 272-288

Snell KRS, Kokubun T, Griffiths H, Convey P, Hodgson DA, Newsham KK (2009) Quantifying the metabolic cost to an Antarctic liverwort of responding to an abrupt increase in UVB radiation exposure. *Global Change Biology,* **15**, 2563-2573.

Son SW, Gerber EP, Perlwitz J *et al.* (2010) Impact of stratospheric ozone on Southern Hemisphere circulation change: A multimodel assessment. *Journal of Geophysical Research-Atmospheres,* **115**, 10.1029/2010jd014271.

Son SW, Polvani LM, Waugh DW *et al.* (2008) The impact of stratospheric ozone recovery on the Southern Hemisphere westerly jet. *Nature Geoscience,* **320**, 1486-1489.

Son SW, Tandon NF, Polvani LM, Waugh DW (2009) Ozone hole and Southern Hemisphere climate change. *Geophysical Research Letters,* **36**, 10.1029/2009GL038671.

Tanhua T, Bates NR, Körtzinger A (2013) The marine carbon cycle and ocean carbon inventories. In: *Ocean Circulation and Climate.* pp 787-815. Elsevier Ltd.

Thomas ER, Bracegirdle TJ, Turner J, Wolff EW (2013) A 308 year record of climate variability in West Antarctica. *Geophysical Research Letters,* **40**, 5492-5496.

Thomas P, Swaminathan A, Lucas RM (2012) Climate change and health with an emphasis on interactions with ultraviolet radiation: A review. *Global Change Biology,* **18**, 2392-2405.

Thompson DWJ, Solomon S (2002) Interpretation of recent Southern Hemisphere climate change. *Science,* **296**, 895-899.

Thompson DWJ, Solomon S, Kushner PJ, England MH, Grise KM, Karoly DJ (2011) Signatures of the Antarctic ozone hole in Southern Hemisphere surface climate change. *Nature Geoscience,* **4**, 741-749.

Toggweiler JR, Russell J (2008) Ocean circulation in a warming climate. *Nature,* **451**, 286-288.

Turnbull JD, Leslie SJ, Robinson SA (2009) Desiccation protects two Antarctic mosses from ultraviolet-B induced DNA damage. *Functional Plant Biology,* **36**, 214-221.

Turnbull JD, Robinson SA (2009) Accumulation of DNA damage in Antarctic mosses: Correlations with ultraviolet-B radiation, temperature and turf water content vary among species. *Global Change Biology,* **15**, 319-329.

Turner J, Adams BJ, Arthern R *et al.* (2009) The Instrumental Period. In: *Antarctic Climate Change and the Environment.* (eds Turner J, Bindschadler R, Convey P, Prisco GD, Fahrbach E, Gutt J, Hodgson D, Mayewski P, Summerhayes C) pp 183-298. Cambridge, UK, Scientific Committee on Antarctic Research.

Turner J, Barrand NE, Bracegirdle TJ *et al.* (2014) Antarctic climate change and the environment: An update. *Polar Record,* **50**, 237-259.

Turner J, Marshall GJ (2011) *Climate Change in the Polar Regions,* Cambridge, Cambridge University Press.

Turner J, Overland J (2009) Contrasting climate change in the two polar regions. *Polar Research,* **28**, 146-164.

United Nations Environment Programme EEAP (2012) Environmental effects of ozone depletion and its interactions with climate change: progress report, 2011. *Photochemical & Photobiological Sciences,* **11**, 13-27.

van den Hoff J, McMahon CR, Simpkins GR, Hindell MA, Alderman R, Burton HR (2014) Bottom-up regulation of a pole-ward migratory predator population. *Proceedings of the Royal Society B: Biological Sciences,* **281**, 20132842-20132842.

Velders GJM, Andersen SO, Daniel JS, Fahey DW, McFarland M (2007) The importance of the Montreal Protocol in protecting climate. *Proceedings of the National Academy of Sciences of the United States of America,* **104**, 4814-4819.

Villalba R, Lara A, Masiokas MH *et al.* (2012) Unusual Southern Hemisphere tree growth patterns induced by changes in the Southern Annular Mode. *Nature Geoscience,* **5**, 793-798.

Vörösmarty CJ, De Guenni LB, Wollheim WM *et al.* (2013) Extreme rainfall, vulnerability and risk: A continental-scale assessment for South America. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences,* **371**, 20120408.

Wang G, Cai W (2013) Climate-change impact on the 20th-century relationship between the Southern Annular Mode and global mean temperature. *Scientific Reports,* **3**, 2039.

Wasley J, Robinson SA, Lovelock CE, Popp M (2006) Some like it wet - Biological characteristics underpinning tolerance of extreme water stress events in Antarctic bryophytes. *Functional Plant Biology,* **33**, 443-455.

Waugh DW, Primeau F, Devries T, Holzer M (2013) Recent changes in the ventilation of the Southern Oceans. *Nature Geoscience,* **339**, 568-570.

Williamson CE, Zepp RG, Lucas RM *et al.* (2014) Solar ultraviolet radiation in a changing climate. *Nature Climate Change,* **4**, 434-441.

Wu Y, Polvani LM, Seager R (2013) The importance of the Montreal Protocol in protecting Earth's hydroclimate. *Journal of Climate,* **26**, 4049-4068.

Zepp RG, Erickson Iii DJ, Paul ND, Sulzberger B (2011) Effects of solar UV radiation and climate change on biogeochemical cycling: interactions and feedbacks. *Photochemical & Photobiological Sciences,* **10**, 261-279.

Ziska LH, Teramura AH, Sulivan JH (1992) Physiological sensitivity of plants along an elevational gradient to UV-B radiation. *American Journal of Botany,* **79**, 863-871.

Figure Legends

Figure 1. The Antarctic ozone hole (inset) and its impact on Southern Hemisphere atmospheric circulation. Stratospheric ozone depletion and resultant cooling over Antarctica has caused the tropopause to lift, allowing the Hadley Cell and the polar jet stream to shift towards the South. The speed of the jet has also increased as most of Antarctic cools slightly while the rest of the world warms (see text for details). The polar shift in the jet and its increased strength has changed atmospheric and oceanic circulation throughout the Southern Hemisphere consistent with a more positive phase of the Southern Annular Mode (SAM). Over the past century, increasing greenhouse gases and then ozone depletion over Antarctica have both pushed the SAM towards a more positive phase (black arrows) and the SAM index is now at its highest level for at least 1000 years (Abram *et al.*, 2014). As a result, high latitude precipitation has increased and the mid-latitude dry zone has moved south as shown. The resultant changes to precipitation and temperature and some of their ecosystem impacts are shown in Figures 2 and 3. As the ozone hole recovers, increased greenhouse gas forcing will likely take over and the position of the jet is thus predicted to remain in this more southerly location. Main figure redrawn from (Perlwitz, 2011) with the ozone hole over Antarctica 17th September 2006 reproduced from NASA Ozone Watch (NASA, 2014).

Figure 2. The Southern Hemisphere showing impacts of the positive phase of the Southern Annular Mode (SAM) on atmospheric circulation, wind patterns and precipitation, as well as oceanic currents and temperatures. Associated biological impacts are shown where available. During the summer months the positive phase of the SAM is associated with ozone depletion over Antarctica although greenhouse gas forcing is also important throughout the rest of the year. NZ = New Zealand. Data sources in text.

Figure 3. Cross section schematic of the Southern Ocean showing the main responses to the ozone hole induced positive phase of the Southern Annular Mode (SAM). The poleward shift and strengthening of polar jet enhances the Antarctic Circumpolar Current and drives increased upwelling of deep carbon-rich water and the associated overturning circulation in the ocean (large blue arrows). Upwelling of warmer deep water also melts the bottom of marine ice sheets leading to instability. South of the polar jet stream, temperatures have decreased (blue) while to the North temperatures have increased (red). Clouds indicate areas with increased precipitation (over the equator and at the pole) with the reduced subsistence zone between (c.f. Figure 1). MLD = mixed layer depth.

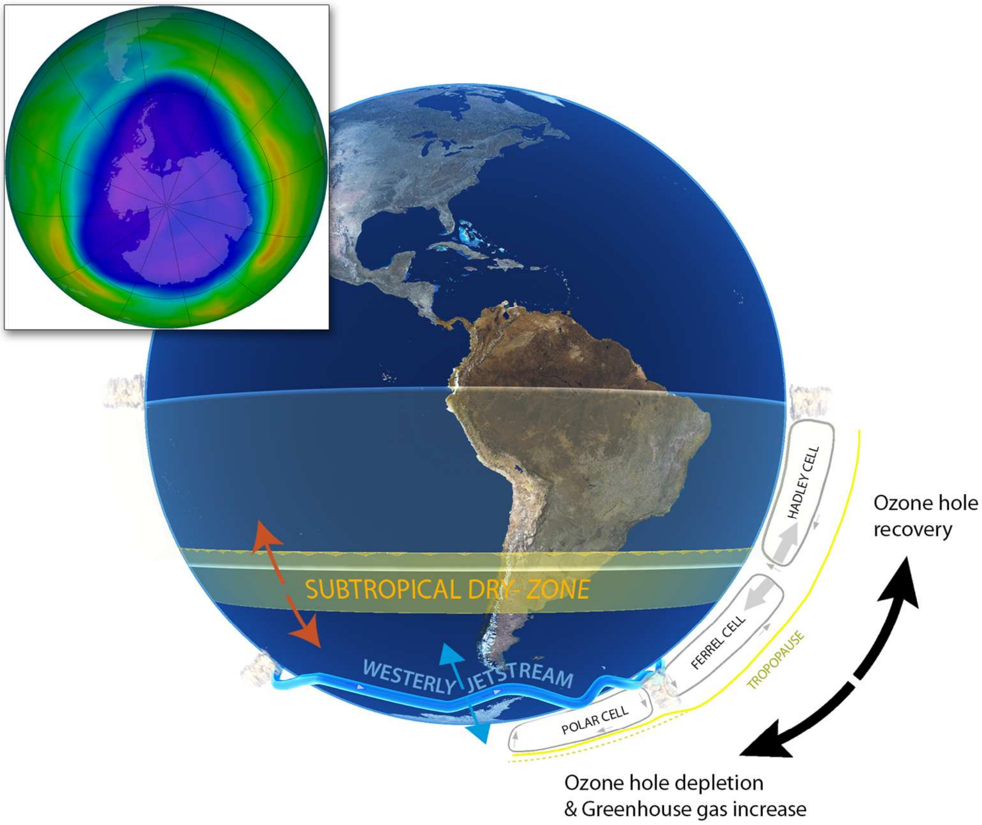

Figure 1. The Antarctic ozone hole (inset) and its impact on Southern Hemisphere atmospheric circulation. Stratospheric ozone depletion and resultant cooling over Antarctica has caused the tropopause to lift, allowing the Hadley Cell and the polar jet stream to shift towards the South. The speed of the jet has also increased as most of Antarctic cools slightly while the rest of the world warms (see text for details). The polar shift in the jet and its increased strength has changed atmospheric and oceanic circulation throughout the Southern Hemisphere consistent with a more positive phase of the Southern Annular Mode (SAM). Over the past century, increasing greenhouse gases and then ozone depletion over Antarctica have both pushed the SAM towards a more positive phase (black arrows) and the SAM index is now at its highest level for at least 1000 years (Abram et al., 2014). As a result, high latitude precipitation has increased and the mid-latitude dry zone has moved south as shown. The resultant changes to precipitation and temperature and some of their ecosystem impacts are shown in Figures 2 and 3. As the ozone hole recovers, increased greenhouse gas forcing will likely take over and the position of the jet is thus predicted to remain in this more southerly location. Main figure redrawn from (Perlwitz, 2011) with the ozone hole over Antarctica 17th September 2006 reproduced from NASA Ozone Watch (NASA, 2014).
140x117mm (300 x 300 DPI)

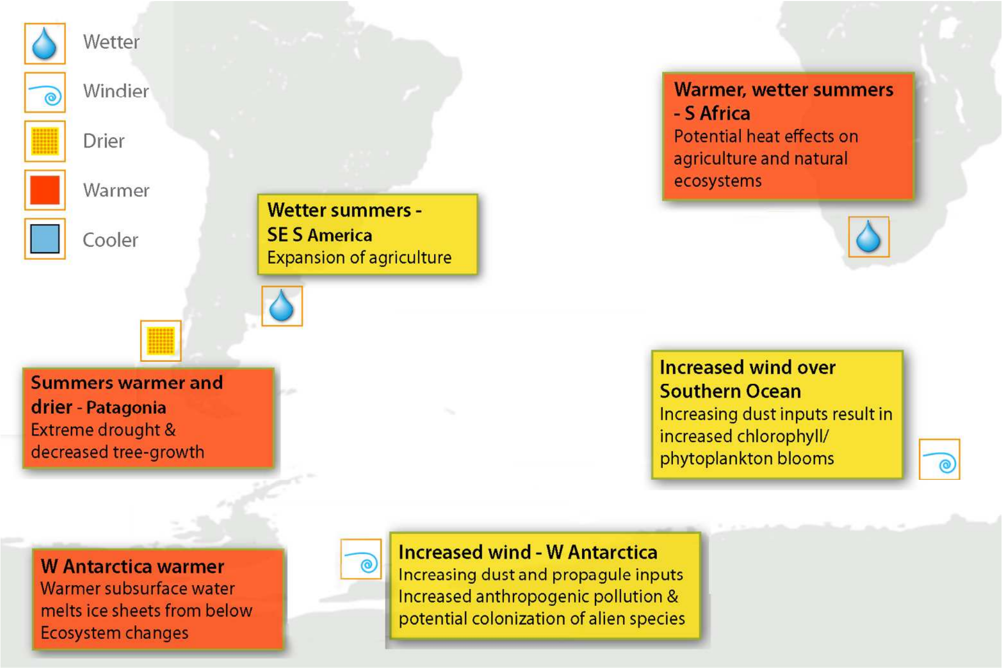

Figure 2. The Southern Hemisphere showing impacts of the positive phase of the Southern Annular Mode (SAM) on atmospheric circulation, wind patterns and precipitation, as well as oceanic currents and temperatures. Associated biological impacts are shown where available. During the summer months the positive phase of the SAM is associated with ozone depletion over Antarctica although greenhouse gas forcing is also important throughout the rest of the year. NZ = New Zealand. Data sources in text.
173x116mm (300 x 300 DPI)

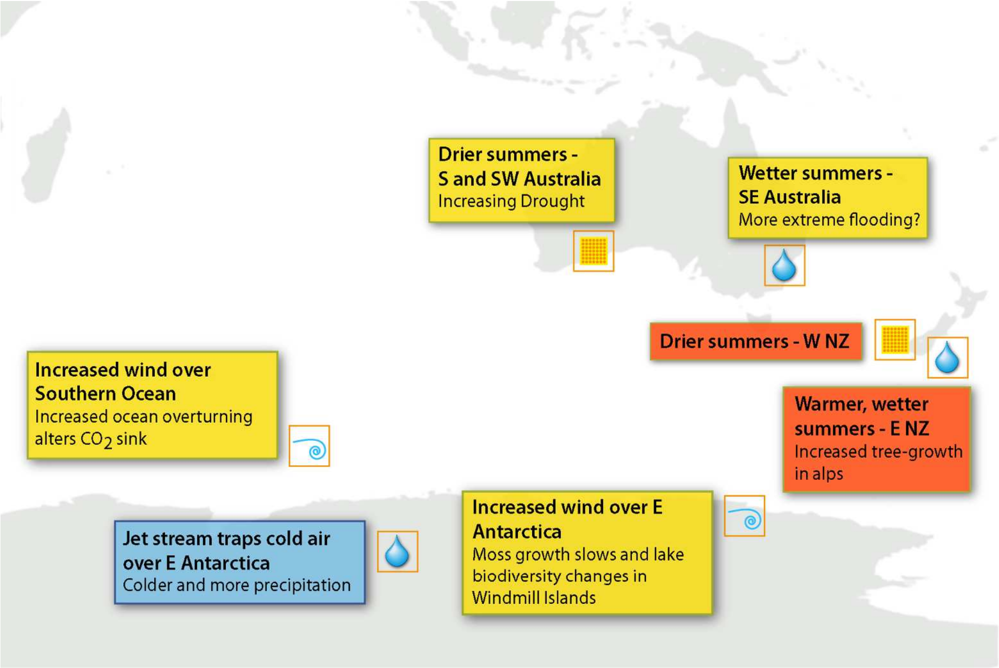

Figure 2 continued
173x116mm (300 x 300 DPI)

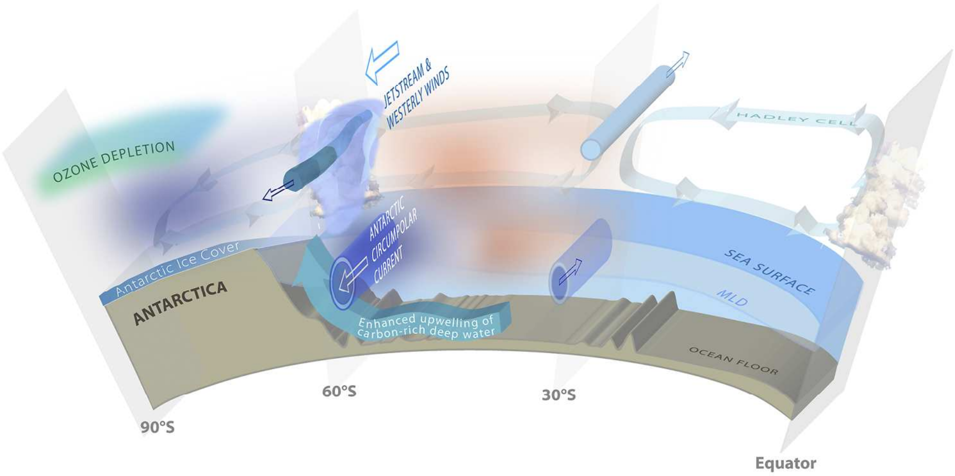

Figure 3. Cross section schematic of the Southern Ocean showing the main responses to the ozone hole induced positive phase of the Southern Annular Mode (SAM). The poleward shift and strengthening of polar jet enhances the Antarctic Circumpolar Current and drives increased upwelling of deep carbon-rich water and the associated overturning circulation in the ocean (large blue arrows). Upwelling of warmer deep water also melts the bottom of marine ice sheets leading to instability. South of the polar jet stream, temperatures have decreased (blue) while to the North temperatures have increased (red). Clouds indicate areas with increased precipitation (over the equator and at the pole) with the reduced subsistence zone between (c.f. Figure 1). MLD = mixed layer depth.
170x87mm (300 x 300 DPI)