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Extreme events as ecosystems drivers: Ecological consequences of anomalous Southern Hemisphere weather patterns during the 2001/2002 austral spring-summer

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Abstract The frequency and severity of extreme events associated with global change are both forecast to increase with a concomitant increase expected in perturbations and disruptions of fundamental processes at ecosystem, community and population scales, with potentially catastrophic consequences. Extreme events should thus be viewed as ecosystem drivers, rather than as short term deviations from a perceived 'norm'. To illustrate this, we examined the impacts associated with the extraordinary weather pattern of the austral spring/summer of 2001/2002, and find that patterns of ocean-atmosphere interactions appear linked to a suite of extreme events in Antarctica and more widely across the Southern Hemisphere. In the Antarctic, the extreme events appear related to particular ecological impacts, including the substantial reduction in breeding success of Adélie penguins at sites in the Antarctic Peninsula as well as for Adélie penguin and snow petrel colonies in East Antarctica, and the creation of new benthic habitats associated with the disintegration of the Larsen B Ice Shelf. Other major impacts occurred in marine and terrestrial ecosystems at temperate and tropical latitudes. The suite of impacts demonstrates that ecological consequences of extreme events are manifested at fundamental levels in ecosystem processes and produce long-term, persistent effects relative to the short-term durations of the events. Changes in the rates of primary productivity, species mortality, community structure and inter-specific interactions, and changes in trophodynamics were observed as a consequence of the conditions during the 2001/2002 summer. Lasting potential consequences include reaching or exceeding tipping points, trophic cascades and regime shifts.

Keywords **Antarctica, atmospheric pressure anomalies, ecosystem processes and drivers, tipping points, trophic cascades, regime shifts**

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1 Introduction

Substantial global focus on current climate change is directed towards identifying environmental and climatic trends and forecasting these and their impacts based on extant data (Pachauri et al., 2014). However, it is becoming apparent that extreme events are also of key importance, and a keen focus on attribution is now developing (Diffenbaugh et al., 2017).

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Analyses by the Intergovernmental Panel on Climate Change (IPCC) of future impacts of climate change associated with extreme weather and climate events predict, for example, that it is virtually certain that the frequency of high temperature extremes will increase, that heat waves will occur with greater frequency and of longer duration, and extreme precipitation events at mid-latitudes and in the wet tropics will very likely become more intense and more frequent (Pachauri et al., 2014). Furthermore, it was recognised that such events and their increased frequencies will amplify existing risks and create new risks for natural and human systems. Difficulty still arises in partitioning the impact of an extreme event from the general rate of change (i.e. the trend line) and from natural variability. Extreme events may also operate under confounding scenarios in surprising and unpredictable ways, despite the general trends present. The lag between physical environmental processes and events, and the resultant biological responses, often hinders the identification of all real linkages present (Jentsch et al., 2007) but this lag is identified in some systems (Gooseff et al., 2017). Extreme or discrete climate events also often demonstrate persistent impacts that are disproportional to their relatively short temporal scales (Altwegg et al., 2017; Gooseff et al., 2017; Vázquez et al., 2015; Barrett et al., 2008; Jentsch et al., 2007; Scheffer and Carpenter, 2003).

The ecological significance of extreme events typically occurs at multiple levels including ecosystems, communities, structure biotypes and direct long-term succession (e.g., Vázquez et al., 2015; Thibault and Brown, 2008; Bortone 2007; Jentsch et al., 2007; Diffenbaugh et al., 2005; White and Jentsch, 2001; Parmesan et al., 2000; Stafford Smith and Morton, 1990). Extreme events can also exceed the physiological thresholds of a species, leading to local population reduction or extirpation, despite the general trend in the environmental parameter occurring within the species-specific operating climatic envelope (Bergstrom et al., 2009; Barrett et al., 2008; Jentsch et al., 2007; Easterling et al., 2000; Parmesan et al., 2000).

Here we explore these issues by analysing the impacts of a suite of extreme events that appears associated with anomalies in atmospheric pressure and sea surface temperature (SST) that occurred across the mid- to high-latitudes of the Southern Hemisphere (SH) during the 2001/2002 austral spring/summer. During this period, a diverse range of regional- and local-scale extreme events were reported in the literature.

We describe the temporal and spatial characteristics of the atmospheric pressure anomalies responsible for these events, then summarise a representative subsample of the reported impacts arising from these anomalies and the extreme events at either regional- or local scales, focusing on the Antarctic region. In particular, we primarily consider here the events that had population- or ecosystem-level impacts. These events provide a rare opportunity to examine hemispheric linkages among climate, extreme events, biological responses and impacts and broad-scale, long-term consequences**.**

2 Methods

During the spring/summer of 2001/2002, signals from a suite of extreme events across the SH emerged. Impacts of these extreme events surfaced in published and unpublished reports over subsequent years. These reports were supplemented for this study with observations from SH field studies, long-term data sets and media reports. Here we synthesise and link these disparate reports and observations in terms of the coupling among physical and biological events and processes.

Anomalies in synoptic patterns during the spring/summer of 2001/2002 were examined and interpreted over the modern historical period of global satellite measurements. Meteorological data for the SH were extracted from the National Centers for Environmental Prediction (NCEP)—Department of Energy (DOE) Reanalysis dataset, hereafter referred to as NCEP-DOE (Kanamitsu et al., 2002). Monthly means were obtained from NCEP-DOE for the geopotential height of the 500 hPa pressure surface (in the mid-troposphere) and the zonal and meridional components of the wind at 1000, 500 and 200 hPa pressure levels (from the near-surface to the upper troposphere); 6-h data was obtained for mean sea level pressure and 950 hPa air temperature. SST data were acquired from the Extended Reconstructed Sea Surface Temperature dataset (ERSST.v5: Xue et al., 2003). Version 8 total column ozone data from the Total Ozone Mapping Spectrometer (TOMS) were also used (Wellemeyer et al., 2004). These analyses allowed examination of hemispheric-scale atmospheric and SST anomalies and their manifestations on local and regional scales.

3 Results and discussion

3.1 Meteorology of the 2001/2002 austral spring and summer

From September 2001 to February 2002, the atmospheric circulation in the SH was dominated by three positive anomalies of atmospheric pressure and geopotential height centred in the southwest Atlantic, central Indian and southwest Pacific sectors of the Southern Ocean (Massom et al., 2006, 2004; Turner et al., 2002). These anomalies (differences from the climatological monthly mean) formed a pronounced zonal (west-east) wave-3 pattern (i.e., having three alternating peaks and troughs as a function of longitude). Zonal wave-3 patterns are a variable though common aspect of the near-surface pressure patterns in the SH (Raphael, 2004) and introduce persistent meridional (north-south) patterns of atmospheric circulation near the three SH mid-latitude continental land masses.

Figure 1 displays the anomaly patterns over the 6-month period for the geopotential height (GPH) of the 500 hPa level (Figure 1a) and the meridional wind at

1000 hPa (Figure 1b). GPH can be considered as a standardisation to the height above mean sea level of pressure surfaces to account for the variation of gravity. The positive GPH anomalies extended from the surface to the upper troposphere. Such a pattern is typically associated with the phenomenon known as blocking in the SH (Raphael, 2004; Trenberth and Mo, 1985). Blocking refers to a circulation pattern involving large anticyclones which form at mid- to high-latitudes (meridional range e.g. 45º–55ºS) and remain quasi-stationary for periods of approximately one week or more. Individual blocking highs (positive GPH anomalies) have the general effect of interrupting the prevailing westerly winds in this latitudinal belt and often lead to significant weather anomalies from

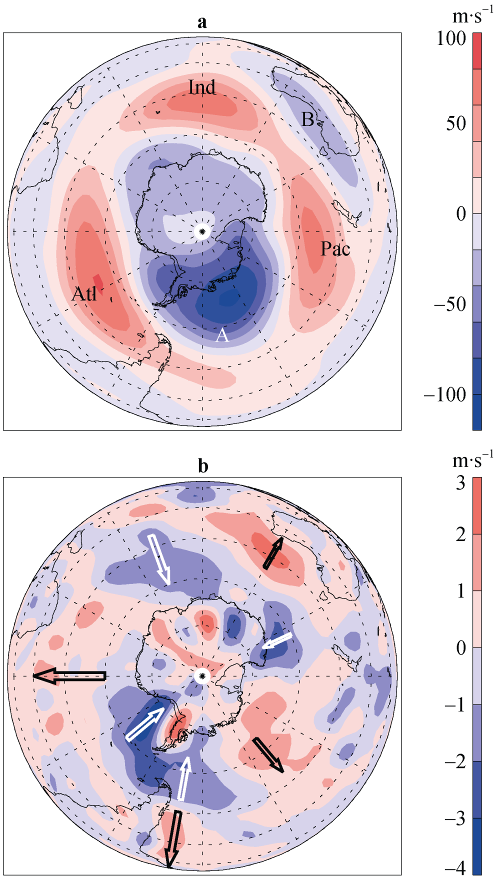

Figure 1 Average Southern Hemisphere deseasonalised atmospheric anomalies (that is, the average difference from the monthly climatological mean) for the period September 2001 to February 2002, derived from NCEP-DOE data, for geopotential height (m) at 500 hPa (**a**) and meridional (south to north) wind (m·s^{-1}) at 1000 hPa (**b**). The base period of the climatology is 1979–2017. Labels in **a** identify the locations of the principal positive geopotential anomalies in the Pacific ('Pac'), Atlantic ('Atl') and Indian ('Ind') sectors of the Southern Ocean, and negative geopotential anomalies in the Amundsen Sea ('A') and southern Australia ('B'). The arrows in **b** indicate the regions of northward (positive; black) and southward (negative; white) wind anomalies. Latitude circles and meridian lines are shown at 15º and 30º intervals, respectively, and the 90ºE meridian is at the top of each plot.

the sub-tropics to Antarctica (Massom et al., 2004; Pook and Gibson, 1999) as they did in the spring/summer of 2001/2002 (Massom et al., 2006, 2004).

The three regions of positive GPH anomalies were accompanied by an intense negative pressure anomaly which broadly extended from north of the Amundsen Sea in West Antarctica, across the Bellingshausen Sea to the southwestern Weddell Sea (Figure 1a; Massom et al., 2006). Associated with this anomaly were repeated formations of deep low pressure systems. Over the six month period, the negative pressure anomaly in the western Weddell Sea reached more than 10 hPa at sea level, while the sea-level pressure minimum at Halley Station in the southeast Weddell Sea was the lowest recorded within the 50-year record (Turner et al., 2002). At the 500 hPa level, the negative anomaly north of the Amundsen Sea was greater than 100 geopotential metres. These anomalies exceeded 2 standard deviations below the combined mean for spring and summer over years 1979–2008. Persistent negative, although weaker anomalies and subsequent low pressure systems were also observed was just to the north of the Antarctic coast in the central Indian Ocean sector and south of eastern Australia.

Evident from the NCEP-DOE analyses was that during the spring and summer, the prevailing westerly winds were weakened at mid-latitudes and strengthened at high latitudes, particularly in the south-eastern Pacific and in the vicinity of the Antarctic Peninsula (Turner et al., 2002; their Figure 4). Concomitant anomalous southerly wind components were evident to the south of western Australia and off the west coasts of Africa and South America while an anomalously strong northerly component wind was maintained in the eastern Weddell Sea. These anomalies enhanced the prevailing southerly winds near the west coasts of Africa, Australia and South America and contributed to anomalous northerly winds in the vicinity of the Antarctic Peninsula (Massom et al., 2006; Turner et al., 2002) and brought moist northerly winds into the interior of the Antarctic continent (Massom et al., 2004).

In association with the anomalous pressure systems, SST anomalies were observed in various locations throughout the SH oceans (Figure 2). A positive (warm) anomaly developed over tropical east-coastal waters of Australia and a very strong warm anomaly occurred at mid-latitudes between New Zealand and South America. The mid- and high-latitude warm SST anomalies exhibited vertical coupling (i.e., from ocean surface to the air mass above) through to the lower stratosphere, producing anomalies in the circulation of the upper troposphere. In particular, during December 2001, the warm SST anomaly to the east of New Zealand in the pacific sector of the Southern Ocean (Figure 3a; marked '1') had a strong regional influence, which is illustrated through its effect in regionally diluting the stratospheric ozone column (Figure 3b) by raising the height of the tropopause (not shown). This SST feature, together with the other two mid-latitude warm SST anomalies (marked '2' and '3' in Figure 3a) were associated with anomalous anticyclonic circulation through the full depth of the troposphere on their poleward side (as shown by the positive absolute vorticity anomalies apparent in Figures 2c and 2d). Frontal systems tended to be deflected around these anticyclonic features to lie closer to the Antarctic coast and also northward to lower mid-latitudes; this is shown by location of regions of anomalous negative absolute vorticity in Figure 3c and Figure 3d. The warm SST anomaly near New Zealand ('1' in Figure 3a) deepened the geopotential height anomaly in the Amundsen Sea region (marked 'A' in Figure 1a) by steering frontal system into the region and locally strengthening northward winds, leading to stronger cooling of the surface waters and promoting the cool SST anomaly marked 'A' in Figure 3a.

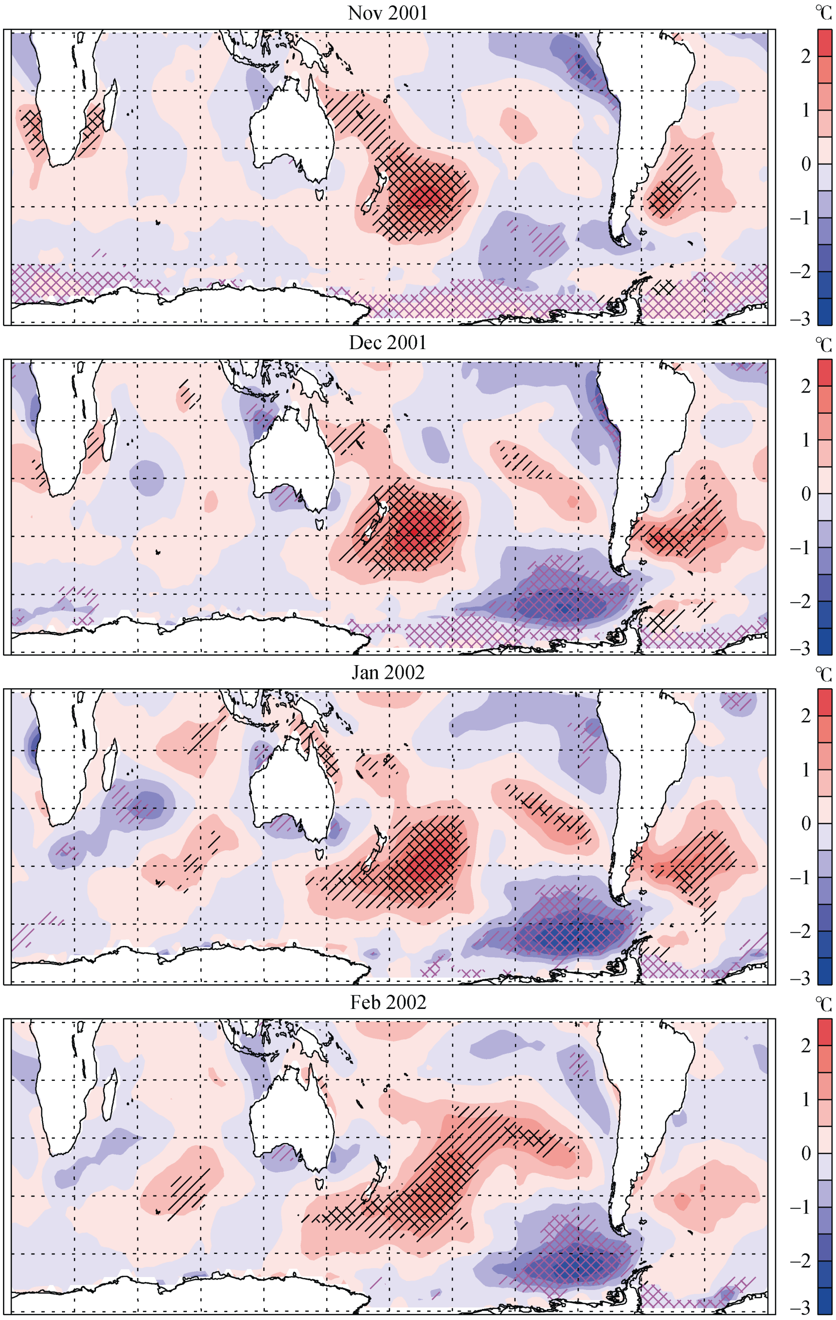

Figure 2 Sea surface temperature anomaly (℃) for the Southern Hemisphere for November 2001 to February 2002 derived from ERSST.v5 (Xue et al., 2003). The anomaly is shown relative to the monthly climatology of the 1979–2017 base period. Single black (magenta) hatching indicates where values are greater than the 5th (less than the 95th) percentile for that location over the base period. Double black (magenta) hatching indicates where values equal the maximum (minimum) value for that location over the base period. Significant warm anomalies can be seen along the Great Barrier Reef near the northeast coast of Australia, the south western Pacific Ocean, the southern Atlantic Ocean and from January in the southern Indian Ocean. Significant cold anomalies can be seen in parts of the Southern Ocean and equatorial eastern Pacific Ocean.

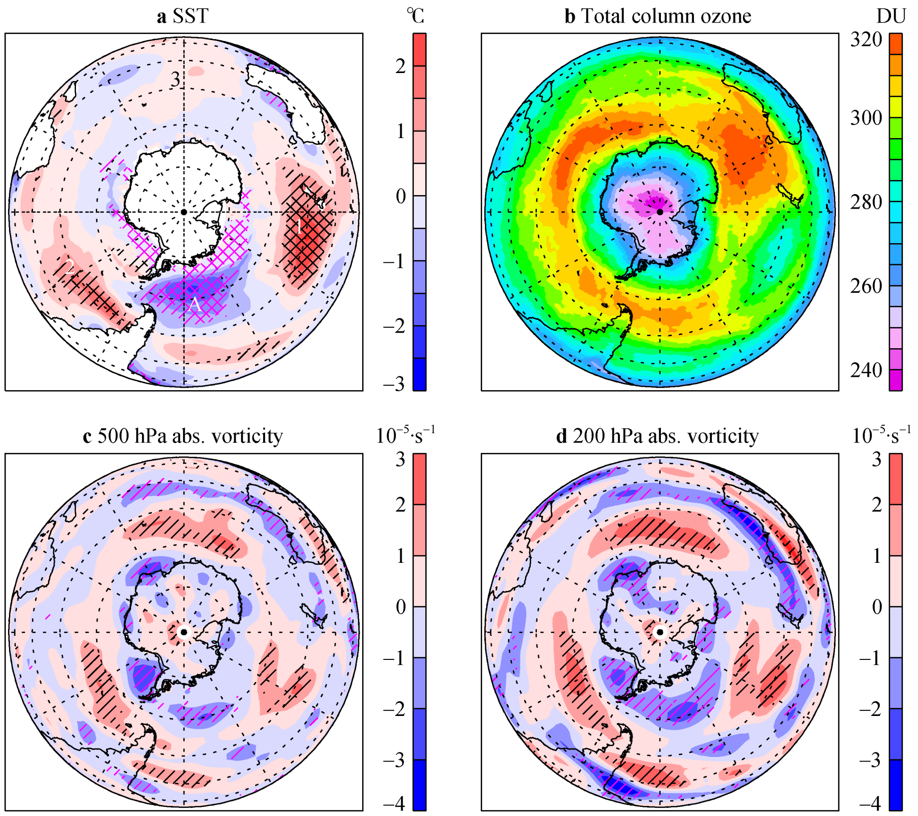

Figure 3 December 2001 average distributions for latitudes south of 20ºS of: **a**, Sea surface temperature (SST) anomaly (from ERSST.v5; units ºC); **b**, TOMS total column ozone (units: Dobson Units); **c** and **d**, Absolute vorticity anomaly at 500 hPa and 200 hPa, respectively (units 10^{-5}·s^{-1}). Absolute vorticity is derived from the NCEP-DOE zonal and meridional winds. Anomalies for SST (vorticity) are evaluated with respect to the 1979–2017 (1979–2014) December climatology. In **a**, **c** and **d**, single black (magenta) hatching indicates where values are greater than the 5th (less than the 95th) percentile for that location over the base period. In **a**, double black (magenta) hatching indicates where values equal the maximum (minimum) value for that location over the base period. In **a**, the features marked with numerals (at 45ºS latitude, and longitudes of 170ºW (‘1’), 30ºW (‘2’) and 90ºE (‘3’)) are locations in the approximate wave-3 pattern centres (corresponding to ‘Pac’, ‘Atl’ and ‘Ind’ in Figure 1); ‘A’ marks the general region of the Amundsen Sea. Latitude circles are shown at 15º intervals, and the 90ºE meridian is at the top of each plot.

More widely across the SH in the 2001/2002 spring/summer, the El Niño Southern Oscillation (ENSO) was in a neutral phase, following a weak La Niña event that took place in early to mid-2000, and preceding a moderate El Niño event which began in late 2002 (Waple and Lawrimore, 2003, 2002). The phase of the Indian Ocean Dipole (IOD) was also neutral. The observed geopotential height anomalies and associated strengthening of the zonal winds near 60°S latitude shown in Figure 1 were consistent with the generally positive phase of the Southern Annular Mode (SAM; Marshall, 2018) during this extended period.

As we discuss below, the weather associated with the anomalous patterns of atmospheric circulation during the 2001/2002 spring and summer appears linked to a number of connected extreme events across the SH. Impacts of the extreme events were numerous, extending from the South Pole to the mid-latitudes of the southern continents and affected not only physical systems such as sea ice and the Antarctic ice sheet, but also ecosystems and human activities (Table 1). In the remainder of this section, we document and describe selected extreme events in the SH during the 2001/2002 summer, focussing primarily on Antarctica, including representative examples for which persistent effects have been now published.

3.2 Effects in the Antarctic Peninsula

In the West Antarctic Peninsula region, the unusual persistence of strong, moist and relatively warm north-north-westerly winds had a major impact on regional sea ice and ocean conditions over the spring-summer of 2001/2002 (Massom et al., 2006). Initially, this led to extreme wind-driven sea ice convergence against the western Antarctic Peninsula and islands to create a highly compact and thick ice cover (to 20 m thick). This in turn resulted in a negative ice-extent anomaly in spring that was large compared to the long-term (1979–2000) mean in the Bellingshausen Sea (Massom et al., 2006) — a region that has experienced major sea ice loss in the past few decades coincident with a sustained warming of ~0.5℃ per decade (Stammerjohn et al., 2008). The moist northerly airstream

Table 1 Localities of extreme climate and climate driven events and reported biological responses in 2001/2002 austral spring and summer

Locality and dates	Extreme event(s)	Biological impacts/response(s)
Andean Foothills, Chile, Feb. 2002.	Intense fires destroy approximately 2×10^8–5.3×10^8 m^2 (Page et al., 2008; National Oceanic and Atmospheric Administration, 2002).	Destruction of native forests.
Palmer Station, Antarctic Peninsula, Oct. 2001–Feb. 2002.	Persistent heavy pack ice and blizzards (Massom et al., 2006).	Return to colonies of breeding Adélie penguins hindered, breeding population more than halved for season (Massom et al., 2006).
North-eastern tip, Antarctic Peninsula, Mar. 2002.	Collapse of 3275 km^2 Larsen B ice Shelf, 720 billion tonnes disintegrated in less than a month (Scambos et al., 2003).	Colonization by pioneer species of new benthic habitat created by collapse of ice shelf observed in 2007 (Gutt, 2008).
SE Weddell Sea, Antarctic, Dec. 2001–Feb. 2002.	Persistent and extensive pack ice, research vessel unable to resupply research station (Turner et al., 2002).	
Marion I, Indian Ocean, Apr. 2002.	Highest number ("dozens") of icebergs observed off island since 1948 (S. Chown pers. comm., 2012).	
Iles Kerguelen, Indian Ocean, Jan. 2002.	Drought: rainfall 10% of 50-year monthly mean (5.6 mm vs 54.8 mm; Y. Frenot, pers. comm., 2012).	
Mawson Station, East Antarctica, Dec. 2001.	Three-fold increase in blizzard days. Rare northerly winds.	Vagrant duck blown in on strong northerly winds from Iles Kerguelen (2100 km to N)(Johnstone and Irvine, 2004).
Prydz Bay, East Antarctica, Dec. 2001–Jan. 2002.	Sea ice extent and concentration highest for 1979–2006 (B. Raymond unpubl. data; Heil 2006), persistent and extensive pack ice, resupply vessel beset for ~4 weeks.	
Davis Station, East Antarctica, Jan. 2002.	Increased frequency of gales and blizzards (Heil, 2006).	Near-complete breeding failure of snow petrels (S. Ward and R. Delaney pers. comm.).
Casey Station, East Antarctica, Nov. 2001–Mar. 2002.	Decreased frequency of summer gales.	Low breeding success of snow petrels (Olivier et al., 2005).
Dome C, East Antarctica	Moist air transferred across Antarctic continent and deposited as rare snow event (Massom et al., 2004).	
Dumont d'Urville Station, East Antarctica, Jan. 2002.	Rainfall (rather than snow) associated with moist air (Massom et al., 2004) on seven days (Y. Frenot, pers. comm., 2012).	Additional free water available for terrestrial ecosystems.
Cape Denison, Commonwealth Bay, East Antarctica, Jan. 2002.	Heatwave–ice and snow melt, resultant floods exposing artefacts from Mawson's 1911–1913 research expedition (D. McIntyre, unpubl. data).	
Ross Sea region, Antarctica, Dec. 2001–Jan. 2002.	Heatwave spanning 5° latitude, record air temperatures to +10℃, flash floods in Dry Valleys (Barrett et al., 2008; Doran et al., 2008).	Additional free water available for terrestrial ecosystems (Doran et al., 2008).
South Pole, Jan. 2002.	Heatwave, five daily maximum temperature records set. Air temperature reached –18.1℃ on 11 Jan. 2002 (Massom et al., 2006).	
Vostok, Antarctica, Nov. 2001–Jan. 2002.	Air temperatures reached 3.2℃ (1.5 standard deviations) above long-term means (Turner, 2003; Turner et al., 2002).	
Tasmania, Australia, Sep. 2001 –Feb. 2002.	Unseasonable cool, wet spring and summer (Bureau of Meteorology, 2002a, 2001).	Wine and honey crops decreased by 30% due to reduced flower and nectar production (Department Of Primary Industries And Water, 2008).
Victoria, Australia, Dec. 2001.	Unseasonable, summer snowfalls (Bureau of Meteorology, 2002b).	
New South Wales, Australia, Dec. 2001–Jan. 2002.	Firestorms and heatwave; 660000 ha destroyed by fire (Bureau of Meteorology, 2003, 2002c, 2002d, 2002f). Fruit bat colonies affected by extreme air temperatures.	Large scale destruction of remnant vegetation. Longest recorded fire-fighting campaign in 200 years (Halperin, 2002; Whelan, 2002). Mortality in nine fruit bat colonies (Welbergen et al., 2008).

Continued

Locality and dates	Extreme event(s)	Biological impacts/response(s)
Queensland, Australia, Dec. 2001–Feb. 2002.	Heatwave, hottest period since 1903 (Bureau of Meteorology, 2002d). Great Barrier Reef sea surface temperatures exceed 30℃ (Berkelmans et al., 2004; Wilkinson, 2002). Wet season fails along tropical coast, typically 30%–50% of mean rainfall. Bundaberg Dec.–Mar. rainfall lowest since records began in 1887: 168 mm vs mean 552 mm (Bureau of Meteorology, 2002e).	Severe coral bleaching on Great Barrier Reef (Bureau of Meteorology 2003; Wilkinson, 2002).
Macquarie Island, Southern Ocean, Sep.–Nov. 2001.	Drought conditions spring and summer (D. M. Bergstrom, unpubl. data).	Identified as possible minor driver in feral rabbit population explosion (Bergstrom et al., 2009).
New Zealand, Nov. 2001–Dec. 2001.	Floods (National Institute of Water and Atmospheric Research, 2002; McGavin, 2002, 2001).	Honey crop reduced by 53% due to reduced nectar production (Ministry of Agriculture and Fisheries, 2002).

also led to high snowfall under blizzard conditions, resulting in a snow cover over the sea ice zone that was significantly thicker than the climatological mean (Massom et al., 2006). This combined with the extreme wind-driven sea ice compaction and thickness to create an ice cover that persisted through summer along areas of the West Antarctic coast where it normally melts back, i.e., the spring-time negative ice-extent anomaly switched to a positive anomaly in the subsequent summer (Massom et al., 2006).

The extreme sea ice and snow cover conditions that persisted from October 2001 to February 2002 had major (both positive and negative) impacts on biological/ecological processes in the region (Massom et al., 2006). An intense and extensive phytoplankton bloom developed within the highly-compact marginal ice zone. Subsequently, this intra-ice bloom was followed by an anomalously intense late spring/early summer phytoplankton bloom in the open ocean. While the West Antarctic Peninsula region is known as an area of relatively high levels of sea-ice algal production compared to other Antarctic sectors (Smith and Comiso, 2008), the intense algal bloom in 2001 occurred relatively far to the south. Furthermore, the bloom contributed to the food chain unusually early in the season (mid-October).

Moving into summer, the anomalous persistence of compact thick and highly deformed coastal sea ice disrupted penguin breeding activities at a number of localities by delaying the return of birds to their colonies. Some coastal areas of the Antarctic were also subjected to unseasonable blizzards and record gales. At Anvers Island on the central west coast of the Antarctic Peninsula (~64.04ºS, 64.46ºW), the persistent heavy ice conditions combined with unusually heavy snowfall to cause a disastrous breeding season of Adélie penguins (*Pygoscelis adeliae*) in 2001/2002, i.e., the largest between-year population decrease (40%) in the 28-year record up to that point and the lowest breeding success (mean of 0.78 chicks crèched per pair compared to a long-term average of 1.35; Massom et al., 2006).

The breeding population size represented a low point up to that time in the progressive decrease of this colony of between 1975/1976 and 2000/2001 of approximately 50% (Smith et al., 2003; Fraser and Patterson, 1997) and was largely due to adult birds deferring breeding due to the extreme environmental conditions (e.g., the persistence of a compact zone of thick sea ice along the coast through the spring-summer and thick snow), although some adult mortality has also been implicated in this decrease. Key breeding-season events for the penguins were delayed by approximately one week, i.e., the timing of peak egg-laying and peak fledging of the surviving chicks (Massom et al., 2006). Furthermore chick fledging mass exhibited a substantial decline during this season compared with other years (1987–2011; Cimino et al., 2014).

In concert and within the context of a "habitat optimum" model (Fraser and Trivelpiece, 1996), these results were interpreted by Massom et al. (2006) as supporting the premise that when adverse environmental conditions (e.g. extensive sea ice and deep onshore snow accumulation) breach life-history thresholds, the affected populations are unable to recover on inter-annual timescales. The population decrease was compounded by the low breeding success, which was primarily due to nest flooding and drowning of eggs and small chicks due to the melt of the deep spring snow accumulation (Ducklow et al., 2007; Massom et al., 2006).

On the other (eastern) side of the Peninsula, the exceptional persistence of strong and relatively warm north-westerly winds (van den Broeke, 2005; Turner et al., 2002) associated with the South Atlantic blocking high combined with the deep low-pressure anomalies to the south led to major regional sea ice redistribution away from the western Weddell Sea. This created the most severe summer sea ice conditions in the south eastern sector of the Weddell Sea in at least 50 years, and delayed the British Antarctic Survey ship from resupplying Halley Base by two months (British Antarctic Survey, 2007; Turner et al., 2002).

The warm air caused extensive surface melting on the Larsen B Ice Shelf (Scambos et al., 2003) from December

2001 to February 2002 inclusive, and, at a rate three times greater than the mean of the previous five summers. Surface temperatures at Esperanza Station near the tip of the Antarctic Peninsula (63.4°S, 57.0°W) experienced near-record values at this time (for the period 1945–present). It is believed that hydrodynamic forcing by surface meltwater percolating downwards through crevasses during this exceptional melt event contributed to the cataclysmic disintegration of ~3300 km^2 of the Larson B Ice Shelf in late-January to early March 2002, following weakening of the shelf by successive years of surface melt (Scambos et al., 2003) and thinning (Shepherd et al., 2003). This extraordinary event, which appears to have been inevitable but potentially hastened by the anomalous weather conditions from late 2001, involved the wholesale collapse, in a matter of weeks, of a feature that took millennia to form and indeed had remained largely intact since the Last Glacial Maximum, i.e., since ~12000 BP (Gilbert and Domack, 2003). The collapse released thousands of icebergs into the Southern Ocean. Moreover, the sudden removal of the ice-shelf "buttress" resulted in an observed acceleration in ice discharge from outlet glaciers draining into the region, to directly contribute to sea level rise (Scambos et al., 2003). The Larsen B Ice Shelf collapse resulted in the creation of new benthic habitat, which within five years showed substantial evidence of recolonization, particularly by pioneer species including fast growing sea squirts, various echinoids, sponges and other benthic organisms (Gutt et al., 2011; Gutt, 2008; Janussen, 2008; Montiel et al., 2008).

3.3 Effects over the Antarctic continent

The circumpolar atmospheric anomaly pattern also resulted in unusual meridional intrusions of relatively warm and moist air across the sea ice and Antarctic coastline and onto far-inland regions of the ice sheet (Massom et al., 2004; Turner et al., 2002). This air originated from as far north as 35º–40ºS (Figure 1b). On the periphery of the Antarctic continent, rainfall (as opposed to snowfall) was recorded over a period of nine days at Casey in Wilkes Land and at Dumont d'Urville in Adélie Land (both in East Antarctica) in mid-January 2002. Farther south, significant snowfall occurred at Dome C on the East Antarctic Ice Sheet (74.5ºS, 123.0ºE, elevation 3280 m) in late-December 2001 to early January 2002 (Massom et al., 2004)—a rare event for this very dry region of the high interior ice sheet plateau.

These incursion episodes also affected ice-sheet surface and near-surface properties by causing abrupt increases in surface wind speed and air temperature in an environment normally characterized by prevailing low temperatures and calm conditions (Massom et al., 2004). Relative "heatwaves" were recorded at this time at a number of locations in Antarctica. McMurdo Station (77.8ºS, 166.7ºE) in the Ross Sea sector experienced a record high air temperature of 10.5℃ on 30 December 2001, 1.1℃ higher than the previous record set in the mid 1970s and approximately 11 standard deviations above the monthly mean (−3.2±1.48℃; Doran et al., 2002). Relatively high temperatures in the usually aptly-named Dry Valleys resulted in flash flooding from melted glacial ice (Doran et al., 2008). Unusually warm conditions were also recorded at the South Pole i.e. −14.8℃ (almost eight standard deviations above the monthly mean December temperature of −28℃), while Vostok (78.5ºS, 106.9ºE, elevation 3488 m) experienced a temperature of −16.5℃ on 11 January 2002, close to the record high of −13.3℃ (on 6 January 1974) (Turner et al., 2002).

The anomalously high temperatures in the Dry Valleys in continental Antarctica were linked to the low pressure atmospheric anomalies over the Ross Sea region and associated strong down-valley winds. Temperatures there were the highest recorded since 1985 (Gooseff et al., 2017; Barrett et al., 2008). Compared to the relatively cool summer season of 2000/2001 (Doran et al., 2008), the mean number of days when air temperatures were above freezing at 12 lakes in 2001/2002 ranged between 2.3 to 143.1 d (grand mean 56.8 d) in contrast to the annual range of 0.0 to 25.6 d (grand mean 5.4 d). Air temperatures on some days exceeded 10℃, and the resultant physical effects comprised significant loss of glacial mass, a 3- to nearly 6000-fold increase in annual stream flows, melting of sub-surface ice and an increase in lake water levels that reversed, in just three months, the results of regional cooling that had extended over the 14 previous years (Barrett et al., 2008; Doran et al., 2008, 2002). Ecosystem properties were altered both in terrestrial and limnetic realms as a result. The pulse of melt-water persisted for several years following the 2001/2002 summer. Nutrient inputs into lakes were enhanced and primary production was stimulated, as were the populations of a subordinate soil nematode species (Barrett et al., 2008; Foreman et al., 2004). Thus, this extreme warming event had direct effect on short-term ecosystem biodiversity and processes in the region (Gooseff et al., 2017).

3.3.1 Australia and New Zealand

The persistent low pressure anomaly over southern Australia and the Tasman Sea (marked 'B' in Figure 1a) caused much of southern New Zealand and areas of southern Australia to experience persistent cold, wet conditions during spring-summer 2001/2002, with record rains and/or floods and anomalous December snowfalls in alpine areas of Australia (Bureau of Meteorology, 2002a). Figure 4 illustrates a typical synoptic outcome for Australia as a consequence of the aforementioned low pressure anomaly, with hot north to north-westerly winds bringing heatwaves and fanning fires on the subtropical and temperate eastern seaboard and cold moist southerly winds bringing snow to highland areas in the south-eastern region. In Tasmania, low flower production resulted in a 44% reduction in wine grape yields ($3.51\ t{\cdot}10^{-4}{\cdot}m^{-2}$) compared to a mean for 1999–2008 of $6.18\pm1.37\ t{\cdot}10^{-4}{\cdot}m^{-2}$, and a subsequent reduction in wine production volume (Department of Primary Industries and Water, 2008). Additionally, low flower and nectar production within forest and pasture ecosystems resulted in a 50% decrease in the quantity of commercially harvested honey. In New Zealand, honey production (a measure of plant reproductive success) in 2002 was just 53% of the mean of production for 1997 to 2001, one of the lowest crops on record (Ministry of Agriculture and Fisheries, 2002).

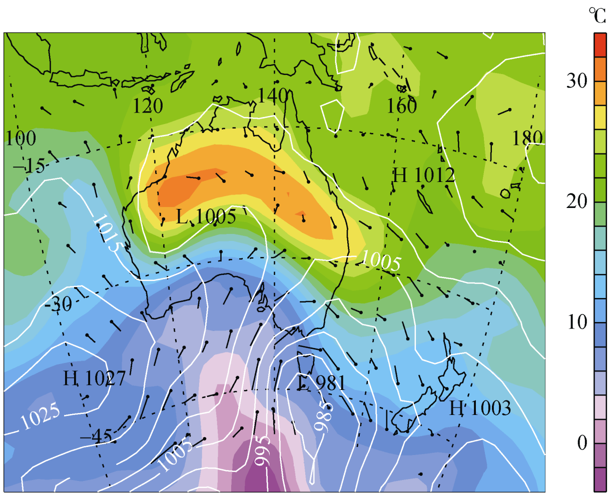

Figure 4 Synoptic pattern for the Australian region from the NCEP-DOE reanalysis for 00 h UT, 25 Dec. 2001. Shown are temperatures (coloured contours) on the 950 hPa pressure surface (at a height approximately 1 km above mean sea level), the mean sea level pressure (white contour, with values in hPa), locations of high (H) and low (L) pressure centres, and wind vectors (lines with arrow heads showing estimated horizontal air movement in 6 h of time). Shown are very southerly high pressure systems to the west and east of Australia and a deep low pressure system between Tasmanian and New Zealand.

Coincident with lower temperatures in south-eastern Australia, the east coast of Australia experienced heat waves, drought and firestorms (World Meteorological Organization, 2003) from late in the austral spring until the middle of January 2002. The combination of a blocking high to the southwest of Australia and a deep and persistent trough over central and eastern Australia resulted in cold, dry air moving northwards over the continent before being steered around the trough. As this extremely dry air moved to the northern side of the trough it was heated by the underlying surface and then steered towards the east as a strong north-westerly airstream which continued to warm as it descended on the coastal side of the Great Dividing Range.

Extreme temperatures (exceeding 42℃) resulting from the descending air, killed over 3500 fruit bats (*Pteropus spp.*) from nine mixed-species colonies in New South Wales (NSW). Mortality was greatest in the Black Flying Fox (*P. alecto*) with up to 13% of total colony populations affected, and mortalities to 49% of juveniles (Welbergen et al., 2008). Such major changes in population structures of sympatric species may alter colony demographics, and in the long term, affect species survival and impact on ecosystem services (Welbergen et al., 2008). Fruit bats are known to play major ecosystem roles, including pollination of wild and cultivated crops and seed dispersal (Fuijita and Tuttle, 1991).

Strong hot north-westerly winds which originated in the west of the continent (Figures 1b and 3) fanned fire-storms. On Australia's east coast in NSW, the Black Christmas fire emergency event lasted a record 22 d, with over 900 fires destroying a total of 7.53×10^9 m^2 across national parks, urban and agricultural areas (Emergency Management Australia, 2002; Halperin, 2002). The fires burnt coastal heath, dry open sclerophyll, woody-leaved, shrublands, tall forests and some small pockets of rainforest (Halperin, 2002). South of Sydney, the Royal National Park was subjected to high-temperature fires that destroyed 70% of the Park, including recovery-phase vegetation returning after extreme fires in 1994 (Whelan, 2002). The 2001/2002 fire event was the third in 13 years; such high fire frequency is considered to provide insufficient time for the plant's regeneration capacity to be rebuilt, and adverse changes such as decreases in dominant plant species are anticipated (Bradstock in the reference Halperin, 2002), as consecutive fire intervals of six and seven years are too short for many plants species to recover (Whelan, 2002).

In subtropical northern NSW, an intense wildfire burnt through approximately two-thirds of Bundjalung National Park, including its extensive coastal dune system (Thomas et al., 2006). The fire occurred under extreme fire weather conditions (>40℃ air temperatures, <10% relative humidity and strong north-westerly winds). The fire was so intense that it destroyed the seaward fore-dune vegetation and the margins of rainforest patches. The Park contained an extensive infestation of the invasive alien plant bitou bush (*Chrysanthemoides monilifera* ssp. *rotundata*). A consequence of the wildfire was extensive post-fire weed seedling regeneration (12□1, bitou bush □ native seedling population ratio) which required management intervention to prevent a long term ecosystem impact (Thomas et al., 2006). A total of 230000 people were affected by the east coast fires in 2001/2002, 7000 stock animals were killed and tourism, agriculture and forestry industries suffered multi-million dollar losses. The NSW Government spent over AUD 200 million fighting the fires, and a further AUD 80 million was spent in insurance payouts (Emergency Management Australia, 2002).

Substantial impacts were observed within and around the Sydney Sandstone Basin region. Within this catchment, pockets of the fire reached extreme intensities, producing heat energy levels exceeding 70000 $kW\cdot m^{-1}$ (Chafer et al., 2004) and physical impacts recorded across the burnt catchments included widespread erosion, and colluvial and alluvial deposition of topsoil in footslope locations and in river systems (Shakesby et al., 2003). Water repellence by the soil due to exposure to fire persisted for two years after the fires in studied locations (Doerr et al., 2004).

Evidence for the impact of a subsequent effect of the extreme event at the population level was noted for the small eyed snake *Cryptophis nigrescens*. In Morton National (160 km south of Sydney) and eight months after the wildfire, populations were down by 48%, suggesting that either the Black Christmas fires killed many snakes or they emigrated from fire-affected localities. Furthermore, the impact of the fires on the snakes persisted for up to five years with up to a 37% reduction in annual survivorship compared with pre-fire years (based on data spanning 16 years from a capture-mark recapture program, Webb and Shine 2008). No significant change in survival was observed in sympatric species (e.g., the broad-headed snake, *Hoplocephalus bungaroides*).

Unusually hot and still weather during the 2001/2002 summer also resulted in increased sea temperatures at the Great Barrier Reef (Berkelmans et al., 2004). A mass bleaching event followed in the Great Barrier Reef Marine Park, affecting a much larger area (almost 60% of the total reef area; Wilkinson, 2002) than an earlier event in 1998 when 16% of the world's corals died (Walther et al., 2002). Although inshore reefs were the most severely affected in both 2002 and 1998, many more offshore reefs were affected in 2001/2002. There was extensive mortality on a few inshore reefs, with up to 90% of corals dying at the worst affected sites. The overall pattern was complex and highly variable (from negligible to severe). Bleaching was generally most severe in shallow water and strong patterns of species susceptibility were seen at all sites. The 2001/2002 bleaching spanned most of the 2000 km length and 300 km width of the reef, and was the worst bleaching event recorded for the reef (Wilkinson, 2002). This considerable bleaching event was due to a <1℃ increase in sea surface temperatures (Berkelmans et al., 2004). Coral reefs are known to be profoundly sensitive to even minimal increases in water temperatures. Further research has suggested that thermally-sensitive taxa die at <1℃ above their bleaching threshold, and many at <0.5℃, highlighting the fact that a very fine line exists between recovery and death of thermally-sensitive corals following bleaching (Berkelmans et al., 2004).

3.3.2 South America and Southern Africa

The anomalous meridional winds in the vicinity of South America (Figure 1b) produced significant effects in the southern portion of the continent during the 2001/2002 summer. Catastrophic bushfires burned nearly 2×10^8 m^2 of temperate forests in the Andean Araucarian region of Chile (Page et al., 2008). Private forests, three National Parks and four National Reserves were affected. Tolhuaca National Park and Malleco National Reserve each lost more than 50% of their forested area. The fires were characterised by their extent and extreme severity (Gonzalez et al., 2005). Simultaneously, three consecutive months of above-average precipitation in Argentina and adjacent areas of Uruguay from August to October 2001 led to flooding in the Pampas region, inundating more than 3.2×10^{10} m^2 of agricultural land. Buenos Aires reported almost 250 mm of rainfall in October, more than twice the normal amount (World Meteorological Organization, 2002), while south-eastern Brazil experienced anomalous high rainfalls (Muza et al., 2009; National Oceanic and Atmospheric Administration, 2002). Lima, Peru also experienced extreme flash flooding (National Oceanic and Atmospheric Administration, 2002).

Southern Africa was largely unaffected by climate extremes during the period, likely because of the absence of strong circulation anomalies in the region. Most of southern Africa received generally below average rainfalls during the 2001/2002 summer, although some regions experienced intense rainfall during January 2002 from an isolated weather event (Snyman, 2005; Waple and Lawrimore, 2002).

4 Synthesis and conclusions

Using published literature, we have drawn links between a suite of individual extreme events during the 2001/2002 austral spring-summer seasons and anomalous and persistent SH-wide circulation patterns. While it is likely that comparable events over similar temporal and spatial scales have occurred in the past, new tools such as meteorological reanalyses, remote sensing and meta-data analyses now allow us to explore global climate teleconnections more rapidly and with greater powers of integration. Integrating this suite of extreme events over the SH clearly demonstrates the merits of holistic, broadscale interdisciplinary approaches to explore for connections, and contributes to our increased understanding of biological responses to changes in the physical environment.

Extreme events can be categorised into two types: those that exceed a single threshold and those that present a sequence of events repeatedly exceeding a threshold (Katz and Brown, 1992). Because the broad-scale atmospheric circulation anomalies persisted for up to six months, the case studies that we have presented in general exhibit complex forms of extreme events in which the duration of the excursion above a threshold persisted for many days, thereby enhancing their impact. For example, air temperatures in the Dry Valleys region of Antarctica exceeded 10℃ for five consecutive days allowing glacier melt, and minimum nocturnal air temperatures on the east coast of Australia remained high for much of the 22 d fire emergency to greatly contribute to the persistence of the Australian fire storms in 2001/2002. In terms of global change, the distribution, magnitude or frequency of extreme events can vary either with a change in variability (variance of distribution) or with changes in the mean of a significant climate parameter, as either will alter the tail of the associated probability distribution function (PDF) (see Katz and Brown, 1992).

Strong regional warmings in the Pacific Ocean during El Niño conditions have been shown to produce widespread climate anomalies on seasonal time-scales, including in the Pacific sector of the Southern Ocean and Antarctica (e.g., Lee et al., 2010). The IOD has been shown to have teleconnections to the Indian and Pacific sectors of the Southern Ocean which influences circulation patterns and Antarctic sea ice conditions in these sectors (Nuncio and Yuan, 2015). The 2001/2002 spring-summer could not be identified as an outlier, or even as being exceptional, in terms of the processes that are currently considered to be the major climate drivers. The SAM was generally in a positive phase during the time period, although not extremely so despite some months with strong positive SAM values (Marshall, 2018), and the IOD and ENSO were both neutral (National Oceanic and Atmospheric Administration, 2018a, 2018b). Despite the lack of strong signals in these indices, sea surface temperatures in the southern Pacific Ocean were anomalous as was the enhanced zonal wave-3 hemispheric pattern. Reinforcing the significance of this anomalous pattern was the generation of blocking highs in the Indian Ocean over a period of six months, in an area where they rarely establish (Pook and Gibson, 1999).

While we have focussed this study on documenting the biological responses of the extreme events that occurred during the 2001/2002 spring and summer, it is clear that we are not as advanced in our understanding of the controlling factors in the variability in climate as we need to be. We know the ‘how’ behind the 2001/2002 anomalous austral climate event (i.e., the regional atmospheric circulation and SST anomalies), but we still do not understand fully why these specific features developed. Further work is needed to more fully quantify the certainty of the linkages we have noted here. One possible way forward in this regard is to investigate how specific ecosystems (e.g., regional Antarctic bird populations) respond to specific weather regimes, identify the main controlling factors on these regimes (such as large-scale influences from the dominant modes of climate variability such as ENSO and the SAM, or more local and transient influences such as cold or warm outbreaks), and then evaluate the likelihood of these factors using meteorological reanalyses and climate simulations.

As the tail of the PDF is more sensitive to changes in variability than changes in the mean (Katz and Brown, 1992), small variations in significant parameters lead to cumulative anomalous effects at regional scales. In examining the impact of extreme events in Europe, Schaeffer et al. (2005) identified two large-scale mechanisms that could change the shape (and therefore the tail) of PDFs: large-scale circulation changes that alter the frequency and/or wind speed from a particular direction, and temperature gradient effects where the temperature of air masses might change upstream of a certain region. In the 2001/2002 anomalous austral spring-summer, both of these processes were evident. The blocking highs and accompanying quasi-stationary lows contributed to increased meridional winds blowing on to the Antarctic continent in places, to cause heavy sea ice compaction, the passage of anomalously warm and moist winds across ice shelves, and increased precipitation in various locations (both coastal and deep inland on the ice sheet desert). The meridional winds also contributed to temperature anomalies and indeed relative “heatwaves” in the Dry Valleys and at the South Pole. Furthermore, air streams moving across central Australia from the south were heated as they were steered around a semi-stationary trough to become hot, dry north-westerly winds that produced extreme temperatures along the east coast of Australia and contributed to the outbreak of wild fires.

Thus despite complex and somewhat currently opaque drivers for the extreme events, there is a common thread that links them; the direct cause can most likely be attributed to persistent large-scale changes in atmospheric circulation near the surface that are promoted by interactions with the oceans or land masses.

An emerging pattern from the literature on the impacts of extreme events is that these events result in long term, persistent effects relative to their short durations (e.g., Gooseff et al., 2017; Barrett et al., 2008; Jentsch et al., 2007; Scheffer and Carpenter, 2003; Holmgren and Scheffer, 2001; Stafford Smith and Morton, 1990). The suite of events described here associated with the anomalous 2001/2002 spring-summer demonstrates the breadth and capacity of this persistence, with the consequences of extreme events occurring in marine, terrestrial, temperate and polar environments. In our case studies, short-term (annual to sub-decadal) biological effects have now been described and linked with their causal mechanisms.

Yet to emerge from these case studies is an indication as to whether the extreme events exceeded biological thresholds for the species involved. However, through the examination of the biological responses to the suite of extreme events associated with the 2001/2002 austral spring-summer (Table 2), it can be seen that the ecological consequences of the extreme events are manifested at fundamental levels in ecosystem processes. Changes in the rates of primary productivity, species mortality, community structure and inter-specific interactions, and changes in trophodynamics were common and extensive consequences. These field observations are consistent with experimental findings from 46 studies that observed changes in above- and below-ground productivity, altered species behaviour and phenology, and reduced reproductive success (Jentsch et al., 2007). Additional potential consequences of the 2001/2002 austral summer comprised reaching or exceeding species’ tipping points, trophic cascades and regime shifts. Isaac (2009) has argued that while long term changes in climate will clearly affect life history and extinction risk, in the short term it will be extreme events that will likely have the most impact on populations. With predicted increases in the frequency and severity of extreme events associated with global climate change (Pachauri et al., 2014), we can predict a concomitant increase in major perturbations and disruptions of core processes at ecosystem, community and population scales with potentially catastrophic consequences for affected ecosystems. Two of the systems mentioned here have since experienced repeat extreme events with pulse flooding in the Dry Valleys in Antarctica in 2009 (Nielsen et al., 2012) and two coral bleaching events on the Great Barrier Reef (Darling and Côté, 2018). Both from observed and experimental findings, our work further emphasises that extreme events should be viewed as potential ecosystem drivers rather than short term deviations from the norm.

Table 2 Ecological consequences of biological responses to extreme events

Observed biological response to extreme event (drivers)	Actual or potential ecological consequence/s
Western Antarctic Peninsula—early atypical spring phytoplankton bloom, temporally mismatched with annual pattern.	Altered primary productive regime. Increased temporal unpredictability within food chain.
Western Antarctic Peninsula—significant decrease in penguin breeding population size. Either increased mortality in breeding population or increased proportion of deferred breeding.	Increased annual mortality potentially reaching a tipping point for top order predators.
Western Antarctic Peninsula—one week offset in penguin breeding time. Delay in breeding phenology.	Change in the manifestation of life history strategy at the individual level. Potential temporal mismatch in predator/prey relationship and subsequent tropic cascade. Altered trophodynamics.
Dry Valleys, Antarctica—changes in nematode populations and phytoplankton bloom.	Altered primary productive regime. Changes in species composition and changes in trophodynamics of terrestrial and limnetic ecosystems.
Eastern Australia—repeated burning of plant communities, reduced population size post fires in a snake species.	Increased population mortality. Potential regime shift due to shift in plant community composition. Changes in species composition and changes in trophodynamics. Altered equilibrium in sympatric species.
Eastern Australia—extreme air temperatures affecting nine mixed—species fruit bat colonies	Increased population mortality. Changes in species composition of colonies. Potential tipping point of species and altered ecosystem services.
Great Barrier Reef, Australia—repeated coral bleaching events.	Increased population mortality. Altered primary productive regime. Changes in species composition and changes in trophodynamics. Potential regime shift due to shift in coral community composition.

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References

Altwegg R, Visser V, Bailey L D, et al. 2017. Learning from single extreme events. Philos T R Soc B, 372: 20160141, doi: 10.1098/rstb.2016.0141.

Barrett J E, Virginia R A, Wall D H, et al. 2008. Persistent effects of a discrete warming event on a polar desert ecosystem. Global Change Biol, 14(10): 2249-2261.

Bates B C, Kundzewicz Z W, Wu S, et al. 2008. Climate Change and Water. Technical Paper of the Intergovernmental Panel on Climate Change. Geneva: IPCC Secretariat. 210.

Bergstrom D M, Lucieer A, Kiefer K, et al. 2009. Indirect effects of invasive species removal devastate World Heritage Island. J Appl Ecol, 46(1): 73-81.

Berkelmans R, De'Ath G, Kininmonth S, et al. 2004. A comparison of the 1998 and 2002 coral bleaching events on the Great Barrier Reef: spatial correlation, patterns, and predictions. Coral Reefs, 23(1): 74-83.

Bortone S A. 2007. Establishing an environmental bioindicator network to evaluate the impact of extreme events. Environ Bioindicators, 2(2): 57-59.

British Antarctic Survey. 2007. Proposed construction and operation of Halley VI research station, and demolition and removal of Halley V research station, Brunt Ice Shelf, Antarctica. Final Comprehensive Environmental Evaluation. 101.

Bureau of Meteorology. 2001. Weather variety the spice of Tasmanian life in 2001. Media Release – Tasmanian Regional Office 28 December 2001. [2018-04-30]. http://www.bom.gov.au/announcements/ media_releases/ tas/20011228.shtml.

Bureau of Meteorology. 2002a. Summer 2001-02 a cool one in Tasmania. Media Release – Tasmanian Regional Office 28 February 2002. [2018-04-30]. http://www.bom.gov.au/announcements/media_releases/tas/ 20020228.shtml.

Bureau of Meteorology. 2002b. Cool summer for Victoria. Monthly Climate Summary – Victorian Regional Office 1 March 2002. [2018-04-30]. http://www.bom.gov.au/announcements/media_releases/vic/20020301.shtml.

Bureau of Meteorology. 2002c. Summer 2001-2002 (December to February). Media Release – NSW Regional Office 1 March 2002. [2018-04-30]. http://www.bom.gov.au/announcements/media_releases/nsw/20020301.shtml.

Bureau of Meteorology. 2002d. No holiday as Queensland hit by a record Christmas hot spell. Media Release – Queensland Regional Office 11 January 2002. [2018-04-30]. http://www.bom.gov.au/announcements/media_releases/qld/20020111.shtml.

Bureau of Meteorology. 2002e. Queensland wet season fails again. Media Release – Queensland Regional Office 4 April 2002. [2018-04-30]. http://www.bom.gov.au/announcements/media_releases/qld/20020404.shtml.

Bureau of Meteorology. 2002f. Bureau of Meteorology Annual Climate Summary 2001. [2018-04-30]. http://www.bom.gov.au/climate/annual_sum/2001/AnClimSum01.pdf.

Bureau of Meteorology. 2003. Annual Climate Summary 2002. [2018-04-30]. http://www.bom.gov.au/climate/annual_sum/2002/AnClimSum02.pdf.

Chafer C J, Noonan M, Macnaught E. 2004. The post-fire measurement of fire severity and intensity in the Christmas 2001 Sydney wildfires. Int J Wildland Fire, 13(2): 227-240.

Cimino M A, Fraser W R, Patterson-Fraser D L, et al. 2014. Large-scale climate and local weather drive interannual variability in Adélie penguin chick fledging mass. Mar Ecol Prog Ser, 513: 253-268.

Darling E S, Côté I M. 2018. Seeking resilience in marine ecosytems. Science, 359(6379): 986-987.

Department of Primary Industry and Water. 2008a. Wine industry Fact sheets 2001 to 2009. [2010-5-21]. http://www.dpiw.tas.gov.au/inter.nsf/Topics/EGIL-57V8ES?open.

Department of Primary Industries and Water. 2008b. Wine Industry Fact Sheet 2008. [2009-5-21]. http://www.dpiw.tas.gov.au/inter.nsf/WebPages/CART-7JS3HD?open.

Diffenbaugh N S, Pal J S, Trapp R J, et al. 2005. Fine-scale processes regulate the response of extreme events to global climate change. P Natl Acad Sci USA, 102(44): 15774-15778.

Diffenbaugh N S, Sing D, Mankin J S, et al. 2017. Quantifying the influence of global warming on unprecedented extreme climate events. P Natl Acad Sci USA, 114(19): 4881- 4886.

Doerr S H, Blake W H, Shakesby R A, et al. 2004. Heating effects on water repellency in Australian eucalypt forest soils and their value in estimating wildfire soil temperatures. Int J Wildland Fire, 13(2): 157-163.

Doran P T, Mckay C P, Fountain A G, et al. 2008. Hydrologic response to extreme warm and cold summers in the McMurdo Dry Valleys, East Antarctica. Antarct Sci, 20(5): 499-509.

Doran P T, Priscu J C, Lyons W B, et al. 2002. Antarctic climate cooling and terrestrial ecosystem response. Nature, 415: 517-520.

Ducklow H W, Baker K, Martinson D G, et al. 2007. Marine pelagic ecosystems: the West Antarctic Peninsula. Philos T R Soc B, 362(1477): 67-94.

Easterling D R, Meehl G A, Parmesan C, et al. 2000. Climate extremes: observations, modelling, and impacts. Science, 289(5487): 2068-2074.

Emergency Management Australia. 2002. EMA disasters database. [2009-5-28]. http://www.ema.gov.au/ema/emadisasters.nsf/54273a46-a9c753b3ca256d0900180220/b976c92612364519ca256d330005af22?OpenDocument.

Foreman C M, Wolf C R, Priscu J C. 2004. Impact of episodic warming events on the physical, chemical and biological relationships of lakes in the McMurdo Dry Valleys, Antarctica. Aquat Geochem, 10: 239-268.

Fraser W R, Patterson D L. 1997. Human disturbance and long-term changes in Adélie penguin populations: A natural experiment at Palmer Station, Antarctic Peninsula//BATTAGLIA B, VALENCIA J, WALTON D W H. Antarctic communities: Species, structure and survival. Cambridge University Press, 445-452.

Fraser W R, Trivelpiece W Z. 1996. Factors controlling the distribution of seabirds: winter-summer heterogeneity in the distribution of Adélie penguin populations//ROSS R M, HOFMANN E, QUETIN L B. Foundations for ecological research west of the Antarctic Peninsula. American Geophysical Union, 257-272.

Fujita M S, Tuttle M D. 1991. Flying-foxes (Chiroptera: Pteropodidae): threatened animals of key ecological and economic importance. Conserv Biol, 5(4): 455-463, doi: 10. 1111/j.1523-1739.1991.tb00352.x.

Gilbert R, Domack E W. 2003. Sedimentary record of disintegrating ice shelves in a warming climate, Antarctic Peninsula. Geochem Geophy Geosy, 4(4): 1038, doi: 10.1029/2002GC00044.

Gooseff M N, Barrett J E, Adams B J, et al. 2017. Decadal ecosystem response to an anomalous melt season in a polar desert in Antarctica. Nat Ecol Evol, 1: 1334-1338, doi: 10.1038/s41559-017- 0253-0.

González M E, Veblen T T, Sibold J S. 2005. Fire history of *Araucaria-Nothofagus* forests in Villarrica national Park, Chile. J Biogeogr, 32(7): 1187-1201.

Gutt J. 2008. Itinerary and summary//GUTT J. The expedition ANT-XXIII/8 of the research vessel "*Polarstern*" to the Antarctic in 2006/2007. Bremerhaven: Alfred Wegener Institute for Polar and Marine Research, 13-15.

Gutt J, Barratt I, Domack E, et al. 2011. Biodiversity change after climate-induced ice-shelf collapse in the Antarctic. Deep-Sea Res PT II, 58: 74-83.

Halperin D. 2002. Black Christmas: in Australia, they're still counting the damage from the devastating wildfires in 2001. Am Forests, 108: 34-40.

Heil P. 2006. Atmospheric conditions and fast ice at Davis, East Antarctica: A case study. J Geophysic Res, 111(C5): C05009, doi: 10.1029/2005JC002904.

Holmgren M, Scheffer M. 2001. El Niño as a window of opportunity for the restoration of degraded arid ecosystems. Ecosystems, 4: 151-159, doi: 10.1007/s100210000065.

Isaac J L. 2009. Effects of climate change on life history: implications for extinction risk in mammals. Endanger Species Res, 7: 115-123.

Janussen D. 2008. Diversity of sponges west and east of the Antarctic Peninsula//GUTT J. The expedition ANT-XXIII/8 of the research vessel "*Polarstern*" to the Antarctic in 2006/2007. Bremerhaven: Alfred Wegener Institute for Polar and Marine Research, 41-47.

Jentsch A, Kreyling J, Beierkuhnlein C. 2007. A new generation of climate change experiments: events, not trends. Front Ecol Environ, 5(7):

365-374.

Johnstone R E, Irvine L G. 2004. Description of an immature male Kerguelen Pintail Anas eatoni collected at Mawson Station, East Antarctica. Western Australian Naturalist, 24: 164-168.

Kanamitsu M, Ebisuzaki W, Woollen J, et al. 2002. NCEP-DEO AMIP-II Reanalysis (R-2). Bull Am Meteorol Soc, 83(11): 1631-1643.

Katz R W, Brown B G. 1992. Extreme events in a changing climate: Variability is more important than averages. Climatic Change, 21(3): 289-302. http://dx.doi.org/10.1007/BF00139728.

Lee T, Hobbs W R, Willis J K, et al. 2010. Record warming in the South Pacific and western Antarctica associated with the strong central-Pacific El Niño in 2009–10. Geophys Res Lett, 37(19): 1-6, doi: 10.1029/2010GL044865.

Marshall G J. 2018. An observation-based Southern Hemisphere Annular Mode Index. [2018-4-30]. http://www.nerc-bas.ac.uk/icd/gjma/sam.html.

Massom R A, Pook M J, Comiso J C, et al. 2004. Precipitation events over the interior East Antarctic Ice Sheet related to mid-latitude blocking high activity. J Climate, 17(10): 1914-1928.

Massom R A, Stammerjohn S E, Smith R C, et al. 2006. Extreme anomalous atmospheric circulation in the West Antarctic Peninsula region in Austral spring and summer 2001/02, and its profound impact on sea ice and biota. J Climate, 19(15): 3544-3571.

Mcgavin T. 2001. Notable weather: Spring 2001. [2009-5-21]. http://vaac.metservice.com/default/index.php?alias=2001spring0192999.

Mcgavin T. 2002. Notable weather: Summer 2001/2002. [2009-5-21]. http://vaac.metservice.com/default/index.php?alias=2001summer0194266.

Ministry of Agriculture and Fisheries. 2002. Horticultural Monitoring. [2009-5-7]. http://www.maf.govt.nz/mafnet/rural-nz/statistics-and-forecasts/farm-monitoring/2002/horticulture/horticulture-14.htm#P4971_208611.

Monteil A, Alonso-Sáez, Bohlmann H, et al. 2008. Macrobenthic communities - asteroid and polychaete diversity//GUTT J. The expedition ANT-XXIII/8 of the research vessel "*Polarstern*" to the Antarctic in 2006/2007. Bremerhaven: Alfred Wegener Institute for Polar and Marine Research, 30-34.

Muza M N, Carvalho L M V, Jones C, et al. 2009. Intraseasonal and interannual variability of extreme dry and wet events over southeastern South America and the subtropical Atlantic during Austral Summer. J Climate, 22(7): 1682-1699.

National Institute of Water and Atmospheric Research. 2002. Climate Summary for Summer 2001-02. [2008-11-20]. http://www.niwa.cri.nz/ncc/cs/seasonal/ma/sclimsum_02_1_summer.

National Oceanic and Atmospheric Administration. 2002. National Centers for Environmental Information, State of the Climate: Global Climate Report for February 2002. [2002-2-30]. https://www.ncdc.noaa.gov/sotc/global/200202.

National Oceanic and Atmospheric Administration. 2018a. Dipole Mode Index. [2018-4-30]. https://stateoftheocean.osmc.noaa.gov/sur/ind/dmi.php.

National Oceanic and Atmospheric Administration. 2018b. Southern Oscillation Index. [2018-4-30]. http://www.cpc.ncep.noaa.gov/data/indices/.

Nielsen U N, Wall D H, Adams B J, et al. 2012. The ecology of pulse events: insights from an extreme climatic event in a polar desert ecosystem. Ecosphere, 3: 1-15.

Nuncio M, Yuan X. 2015. The influence of the Indian Ocean Dipole on Antarctic sea ice. J Climate, 28(7): 2682-2690. https://doi.org/10.1175/JCLI-D-14-00390.1.

Olivier F, Van Franeker J A, Creuwels J C S, et al. 2005. Variations of snow petrel breeding success in relation to sea-ice extent: detecting local responses to large-scale processes? Polar Biol, 28: 687-699.

Parmesan C, Root T L, Willig M R. 2000. Impacts of extreme weather and climate on terrestrial biota. B Am Meteorol Soc, 81: 443-450.

Pachauri R K, Allen M R, Barros V R, et al. 2014. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Switzerland: Alfred-Wegener-Inst.

Pook M J, Gibson T. 1999. Atmospheric blocking and storm tracks during SOP-1 of the FROST Project. Aust Meteorol Mag, 48(2): 51-60.

Raphael M N. 2004. A zonal wave 3 index for the Southern Hemisphere. Geophys Res Lett, 31(23): L23212, doi:10.1029/2004GL020365.

Scambos T, Hulbe C, Fahnestock M. 2003. Climate-induced ice shelf disintegration in the Antarctic Peninsula//DOMACK E, LEVENTER A, BURNETT A, et al. Antarctic Peninsula climate variability: historical and paleoenvironmental perspective. AGU Antarctic Research Series, 335-347.

Scambos T A, Bohlander J A, Shuman C A, et al. 2004. Glacier acceleration and thinning after ice shelf collapse in the Larsen B embayment, Antarctica. Geophys Res Lett, 31: L18402, doi:10.1029/2004GL020670.

Scheffer M, Carpenter S R. 2003. Catastrophic regime shifts in ecosystems: linking theory to observation. Trends Ecol Evol, 18: 648-656.

Shakesby R A, Chafer C J, Doerr S H, et al. 2003. Fire severity, water repellency characteristics and hydrogeomorphological changes following the Christmas 2001 Sydney forest fires. Aust Geographer, 34: 147-175.

Shepherd A, Wingham D, Payne T, et al. 2003. Larsen ice shelf has progressively thinned. Science, 302(5646): 856-859.

Smith R C, Fraser W R, Stammerjohn S E. 2003. Climate variability and ecological response of the marine ecosystem in the western Antarctic Peninsula (WAP) region//GREENLAND D, GOODIN D G, SMITH R C. Climate variability and ecosystem response at long-term ecological research (LTER) sites. Oxford University Press, 158-173.

Smith W O Jr, Comiso J C. 2008. Influence of sea ice on primary production in the Southern Ocean: A satellite perspective. J Geophys Res, 113(C5): C05S93, doi:10.1029/2007JC004251.

Snyman H A. 2005. Rangeland degradation in a semi-arid South Africa – I: influence on seasonal root distribution, root/shoot ratios and water-use efficiency. J Arid Environ, 60(3): 457-481.

Stafford Smith D M, Morton S R. 1990. A framework for the ecology of arid Australia. J Arid Environ, 18(3): 255-278.

Stammerjohn S E, Martinson D G, Smith R C, et al. 2008. Sea ice in the western Antarctic Peninsula region: Spatio-temporal variability from ecological and climate change perspectives. Deep-Sea Res PT II, 55(18-19): 2041-2058.

Thibault K M, Brown J H. 2008. Impact of an extreme climatic event on community assembly. P Natl Acad Sci USA, 105: 3410-3415.

Thomas J, Hofmeyer D, Benwell A S. 2006. Bitou bush control (after fire) in Bundjalong National Park on the New South Wales coast. Ecol Manag Restor, 7: 79-92.

Trenberth K E, Mo K C. 1985. Blocking in the Southern Hemisphere. Mon Weather Rev, 113(1): 3-21.

Turner J. 2003. The meteorology and climatology of the Antarctic Plateau. Memorie della Societa Astronomica Italiana Supplementi, 2: 26-31.

Turner J, Harangozo S A, Marshall G J, et al. 2002. Anomalous atmospheric circulation over the Weddell Sea, Antarctica during the Austral summer of 2001/2002 resulting in extreme sea ice conditions. Geophys Res Lett, 29(24): 2160.

Vázquez D P, Gianoli E, Morris W F, et al. 2015. Ecological and evolutionary impacts of changing climatic variability. Biol Rev, 92(1): 22. https://doi.org/10.1111/brv.12216.

Van Den Broeke M R. 2005. Strong surface melting preceded collapse of Antarctic Peninsula ice shelf. Geophys Res Lett, 32(12): L12815.

Walther G R, Post E, Convey P, et al. 2002. Ecological response to recent climate change. Nature, 416: 389-395.

Waple A M, Lawrimore J H. 2002, State of the climate in 2001. B Am Meteorol Soc, 83(6): S1-S62. https://doi.org/10.1175/1520-0477-83.6.S1

Waple A M, Lawrimore J H. 2003. State of the climate in 2002. B Am Meteorol Soc, 84(6): S1-S68. https://doi.org/10.1175/1520-0477-84.6s.S1.

Webb J K, Shine R. 2008. Differential effects of an intense wildfire on survival of sympatric snakes. J Wildlife Manage, 72(6): 1394-1398.

Welbergen J A, Klose S M, Markus N, et al. 2008. Climate change and the effects of temperature extremes on Australian flying-foxes. P Roy Soc B-Biol Sci, 275: 419-425.

Wellemeyer C G, Bhartia P K, Taylor S L, et al. 2004. Version 8 Total Ozone Mapping Spectrometer (TOMS) algorithm. Proceedings Quadrennial Ozone Symposium, 635-636.

Whelan R. 2002. Don’t fight with fire. Nature, 416(6876): 15.

White P S, Jentsch A. 2001. The search for generality in studies of disturbance and ecosystem dynamics. Prog Bot, 62: 399-450.

Wilkinson C. 2002. Coral bleaching and mortality – the 1998 event 4 years later and bleaching to 2002//Wilkinson C. Status of coral reefs of the world: 2002. Townsville: Australian Institute of Marine Science, 33-44.

World Meteorological Organization. 2002. WMO Statement on the status of the global climate in 2001. WMO-No 940: 12.

World Meteorological Organization. 2003. WMO Statement on the status of the global climate in 2002. WMO-No 949: 12.

Xue Y, Smith T M, Reynolds R W. 2003. Interdecadal changes of 30-yr SST normals during 1871–2000. J Climate, 16(10): 1601-1612.