What are Marine Ecological Time Series telling us about the ocean? A status report

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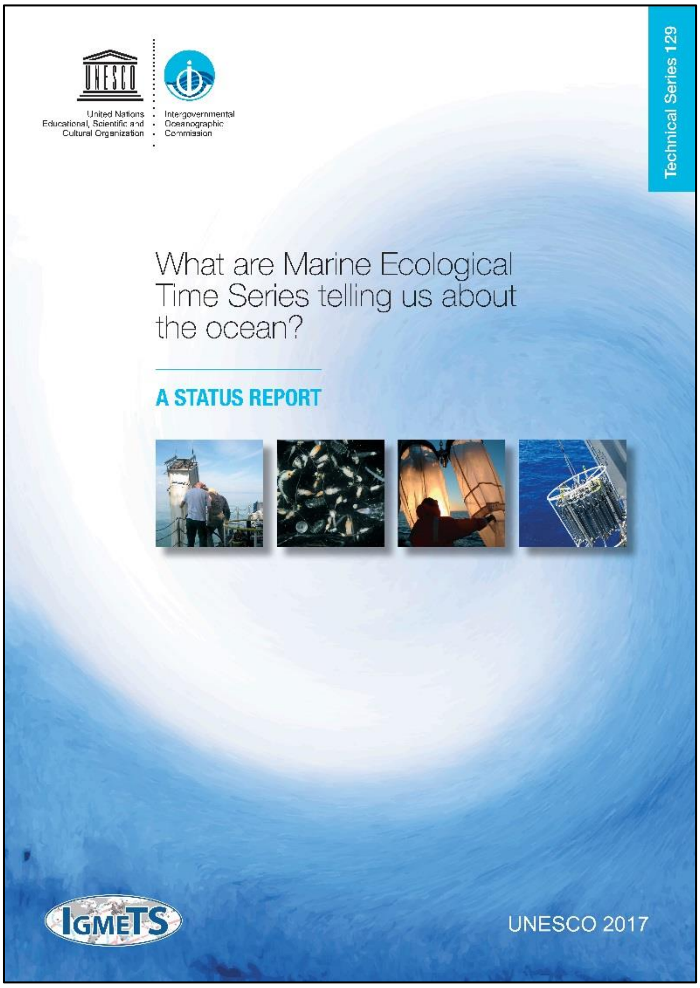

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6 Southern Ocean

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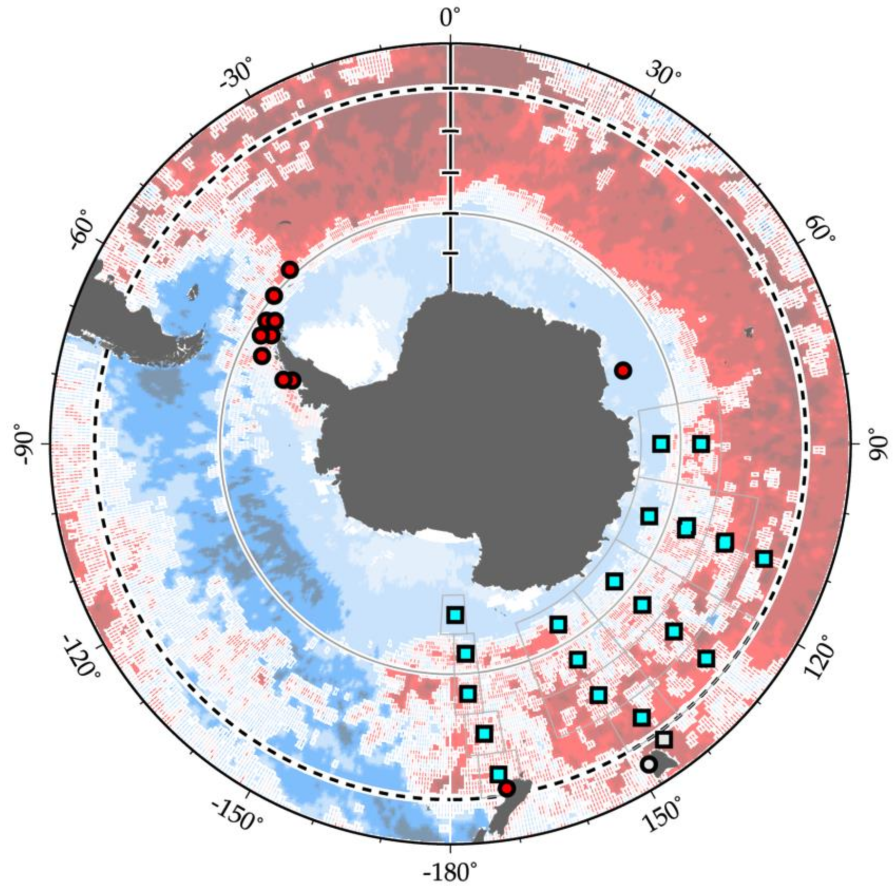

Figure 6.1. Map of IGMETS-participating Southern Ocean time series on a background of a 10-year time-window (2003–2012) sea surface temperature trends (see also Figure 6.3). At the time of this report, the Southern Ocean collection consisted of 32 time series (coloured symbols of any type), of which 21 were from Continuous Plankton Recorder subareas (blue boxes). The dashed line at 45°S indicates the boundary between the IGMETS Southern Ocean region and other IGMETS regions in this report (e.g. South Pacific, South Atlantic, Indian Ocean), while the gray line at 60˚S indicates the Antarctic Treaty boundary. Uncoloured (gray) symbols indicate time series being addressed in a different regional chapter. See Table 6.3 for a listing of this region's participating sites. Additional information on the sites in this study is presented in the Annex.

Participating time-series investigators

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6.1 Introduction

The Southern Ocean is a vast ocean region that surrounds the Antarctic continent. It forms the southern connections to the Atlantic, Pacific, and Indian oceans and, while its northern boundary is not clearly defined ecologically, the northern limit, by treaty, is defined as 60°S (Figure 6.1, gray line). Based on hydrographic regimes, the Southern Ocean extends to the Subtropical Front (Figure 6.2), which can be found north of 40°S in some regions (Orsi *et al*., 1995; Belkin and Gordon, 1996; Moore and Abbott, 2000; Sokolov and Rintoul, 2009a, b; Talley *et al*., 2011).

The cold (< ~5°C) waters associated with the Southern Ocean occupy this ~60 million km^2 region south of the Antarctic Polar Front. This is a mainly deep ocean habitat, especially in the eastern Atlantic, Indian, and Pacific sectors; only 12% of the area south of the Antarctic Polar Front comprises shelf and slope waters shallower than 2000 m (Atkinson *et al*., 2009). Using ETOPO2-v2 bottom topography data (National Geophysical Data Center, 2006), 12.4% of the IGMETS-defined Southern Ocean area was shallower than 2000 m, 9.8% shallower than 1000 m, 6.3% shallower than 500 m, and 4.6% shallower than 250 m. Despite the depth of these shelves (most > 200 m) and their limited spatial extent, they are still important biogeochemically and ecologically due to their effect on hydrography, nutrient supply, carbon drawdown, and the Southern Ocean foodweb. For example, the elevated productivity of the Southwest Atlantic sector relates to its relatively shallow and rugged, complex bathymetry and concomitantly high inputs of iron into the generally low iron environment of the Antarctic Circumpolar Current (Atkinson *et al*., 2008).

The circulation in the Southern Ocean is unique in the world's oceans with the Antarctic Circumpolar Current (ACC), which circulates clockwise around the continent continuously, driven by wind stress and buoyancy forcing, and transports about 100 Sv (1 Sv = 106 m^3 s^{-1}) eastward (Orsi *et al*., 1995) (Figure 6.2a). The ACC has a structured frontal system composed of three major surface fronts: the Subantarctic Front (SAF), the Polar Front (PF) in the middle, and the Southern ACC Front (SF) (Figure 6.2b). The SAF defines the northern boundary of the ACC, marked by a major change in temperature, salinity, sea surface height, and speed and direction of current flow, all which act as a major biogeographic boundary for plankton (McLeod *et al*., 2010; Hosie *et al*., 2014). Farther south of the SF is the southern limit of the ACC (Southern Boundary; Orsi *et al*., 1995). Average sea surface temperature (SST) is > 4°C north of the SAF and < 2°C south of the PF. Closer to the Antarctic continent and on the continental shelf, a westward flowing counter-current flows during some portions of the year (e.g. Moffat *et al*., 2008). Between the SF and the Antarctic continent, SST is about –1.0°C.

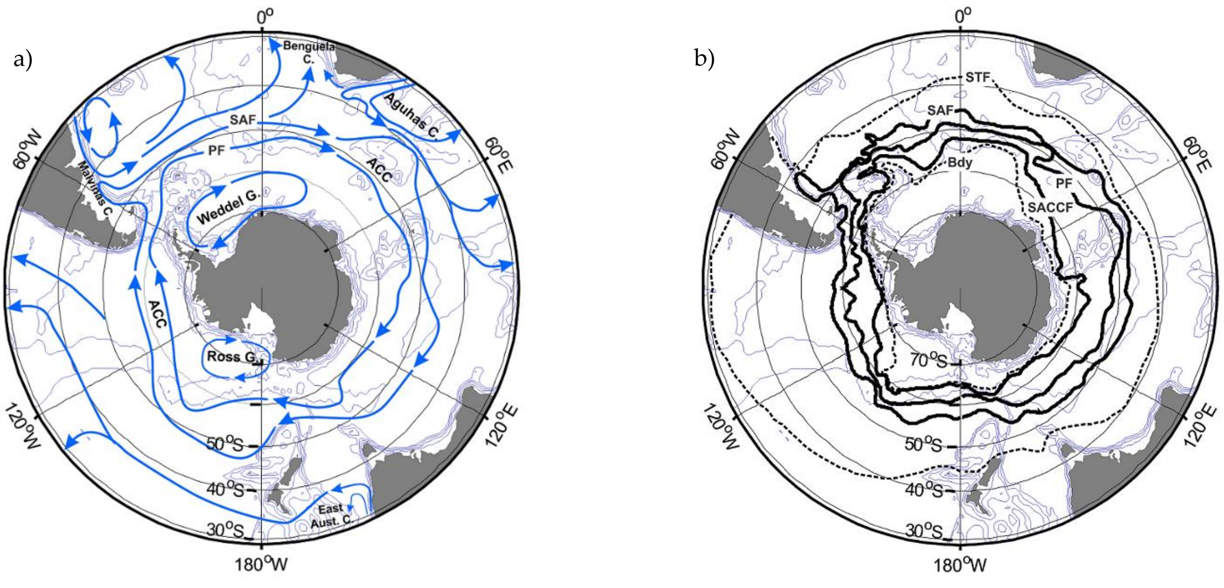

Figure 6.2. a) Major Southern Ocean currents (redrawn from/retrieved from the Encyclopedia of Earth, http://www.eoearth.org). b) Southern Ocean frontal features: ACC - Antarctic Circumpolar Current, STF - Subtropical Front; SAF – Subantarctic Front; PF – Polar Front; SACCF – Southern ACC Front; Bdy – Southern boundary of the ACC (Fronts data from Orsi and Harris, 2001).

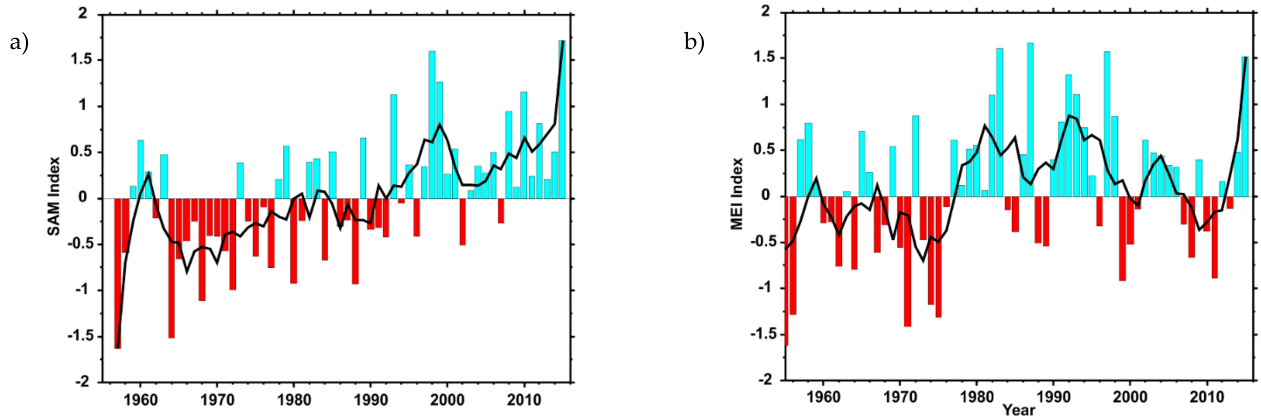

Figure 6.3. a) The Southern Annular Mode (SAM) index changes since 1957 (data: https://legacy.bas.ac.uk/met/gjma/sam.html); b) The Multivariate ENSO Index (MEI) changes since 1957 (data: http://www.esrl.noaa.gov/psd/enso/mei/).

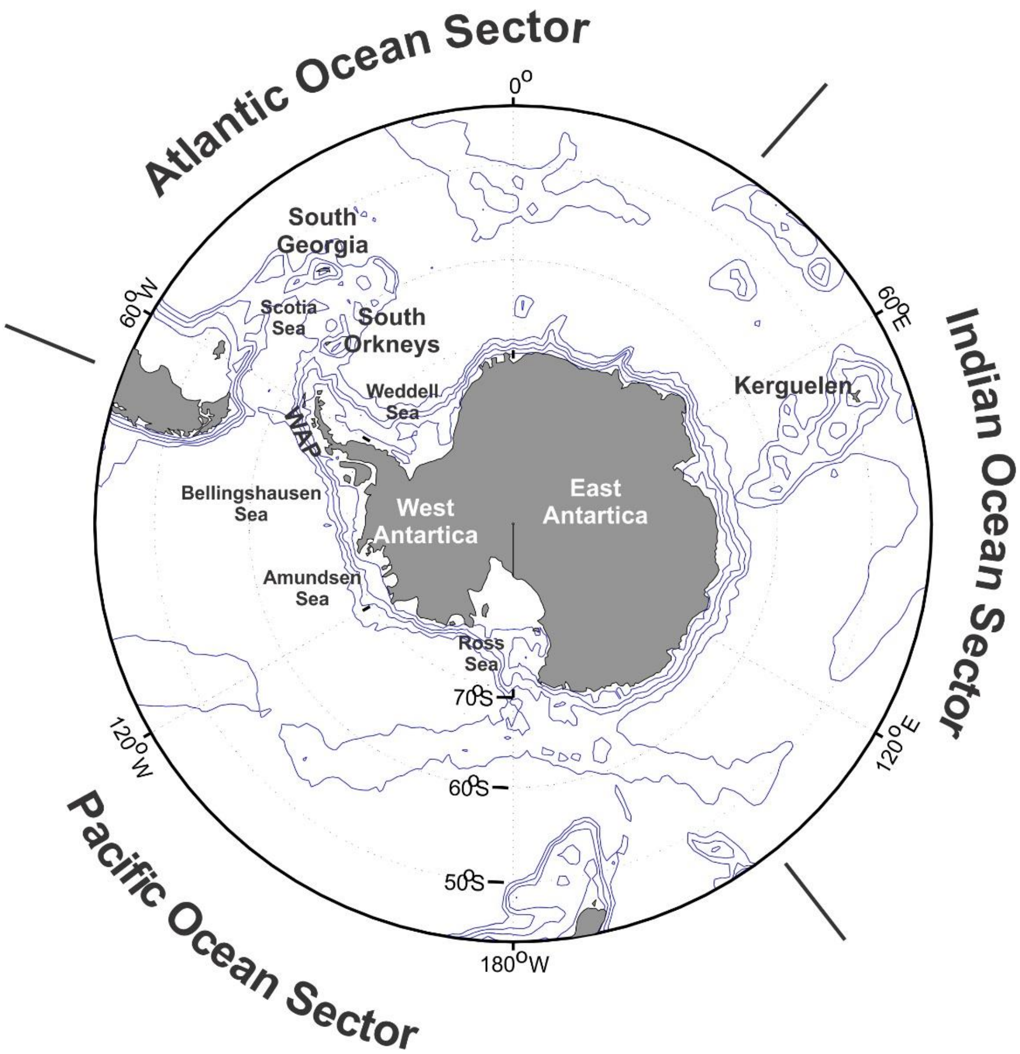

Figure 6.4. Map indicating regions of importance with the Southern Ocean and Antarctica landmass.

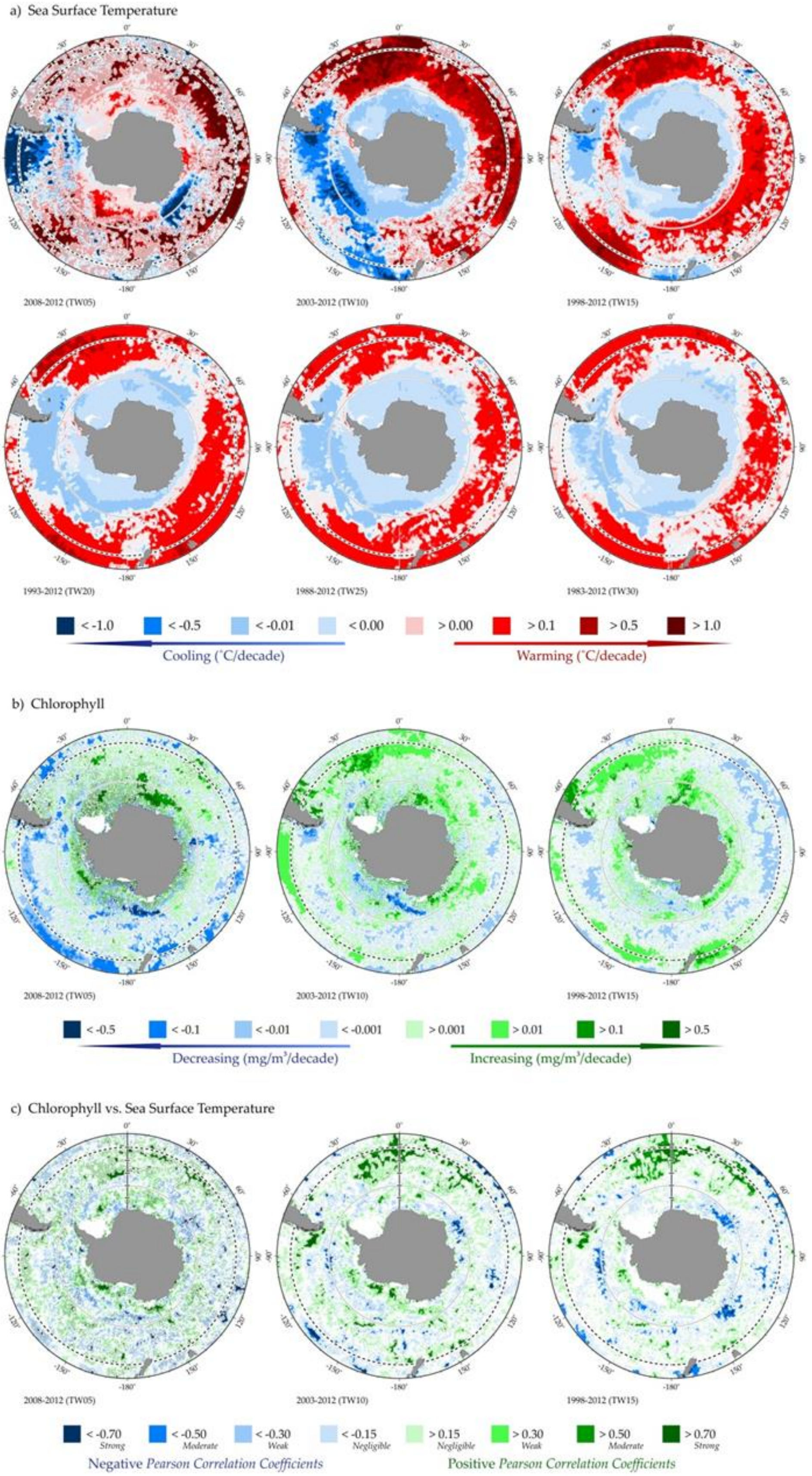

Figure 6.5. Annual trends in Southern Ocean sea surface temperature (SST) (a) and sea surface chlorophyll (CHL) (b), and correlations between chlorophyll and sea surface temperature for each of the standard IGMETS time-windows (c). See "Methods" chapter for a complete description and methodology used.

Over the past 50+ years, environmental conditions in portions of the Southern Ocean have been changing rapidly, while in other portions, the change has been moderate, but still substantial (Turner *et al*., 2005; Gille, 2008; Whitehouse *et al*., 2008; Constable *et al*., 2014; Gutt *et al*., 2014). The changes may be related to the Southern Hemisphere Annular Mode (SAM), also known as the Antarctic Oscillation (AAO), which describes the north–south movement of the westerly winds that circle Antarctica between the mid-high latitudes (poleward of 40°S; Ho *et al*., 2012). A high positive SAM has dominated for nearly two decades (Abram *et al*., 2014; Figure 6.3). A positive SAM is associated with significant decreases in mean sea level pressure (MSLP) and a contraction of the westerly wind belt towards Antarctica. The increased wind speeds may drive the Polar Front of the ACC poleward.

6.2 General patterns of temperature and phytoplankton biomass

IGMETS' time series of satellite-derived surface temperatures show that, over the past 30 years (1983–2012), around half (55.9%, 44% at $p < 0.05$) of the Antarctic Ocean has cooled (Figure 6.5; Table 6.1). Most of this cooling was observed in the areas closer to the Antarctic continent. This cooling trend was sustained over shorter time-windows (e.g. 15 and 10 years) until the 5-year time-window; in the latter, there was warming throughout much of the entire Antarctic Ocean (66.8% warmed, 26.1% at $p < 0.05$; Figure 6.5; Table 6.1). These results may seem contradictory to numerous studies which have reported warming in the Antarctic Ocean (Aoki *et al*., 2003; Fyfe, 2006; Ducklow *et al*., 2007, Böning *et al*., 2008; Gille, 2008; Dinniman *et al*., 2012; Constable *et al*., 2014). The differences lay in the time-windows selected and the spatial areas used for the calculations. Overall, an average of temperature changes across the entire Antarctic Ocean region over the past 30 years yields an overall warning trend.

It is important to remember that satellite-derived temperature only captures surface waters. Since the 1930s, the Southern Ocean has warmed progressively from the subsurface to > 700 m depth (Gille, 2008). The strength of this long-term warming trend appears to be highly variable, and depends on the time-window and location of the study. Around South Georgia in the Southwest Atlantic sector, where records were compared over an 81-year period, the warming extended to > 700 m and occurred at a faster rate than the overall average noted by Gille (2008), with a 2.3°C increase in near-surface waters in austral winter and a 0.9°C increase in summer. On the Antarctic continent, the central West Antarctic is one of the fastest warming regions globally (Bromwich *et al*., 2012). The nearby West Antarctic Peninsula (WAP) is also a region with rapid change, and average air temperatures have risen about 2.9°C from 1951 to 2005 (Vaughan *et al*., 2003; Meredith and King, 2005; Stammerjohn *et al*., 2008). In this region, substantial increases in water heat content and SST have also been reported (Martinson *et al*., 2008; Steinberg *et al*., 2015). The north/south orientation of the WAP results in a latitudinal climate gradient, with warmer temperatures and much less sea ice in the north and colder and higher ice conditions in the south (Ducklow *et al*., 2013; Steinberg *et al*., 2015).

Changes in ocean temperature are also concomitant with trends in sea ice. Sea ice is a major ecological habitat for many marine species, and the timing of sea ice advance and retreat, as well as its seasonal duration, affects the ecology of the region. While observational data suggest that sea ice has decreased since the 1950s (Clarke and Harris, 2003; Curran *et al*., 2003; de la Mare, 1997, 2009), the most recent 30 years of satellite data suggest an increase in maximum sea ice extent for the Southern Ocean as a whole (Gagné *et al*., 2015). However, there is vast heterogeneity in sea ice extent (Stammerjohn *et al*., 2012). For example, in the area west of the WAP, including the Bellingshausen Sea, sea ice duration has been significantly shortened due to earlier spring retreat and later autumn advance. The summer ice-free season is now three months longer than it was in 1979/80. An opposite pattern has been observed in the western Ross Sea region, where the summer ice-free water period has been shortened by 2.5 months (Stammerjohn *et al*., 2012). For much of the rest of the Southern Ocean, the pattern of sea ice seasonal change has been modest.

Trends in satellite-derived chlorophyll have been variable, with different regions showing significant positive or negative trends over the past 15 years (Figure 6.5; Table 6.2). Over the entire Southern Ocean, the spatial distribution of trends has been quite evenly balanced. For example, during 1998–2012, 53.3% (20.4% at $p < 0.05$) of the Antarctic Ocean exhibited an increase in chlorophyll, while 46.7% (17.7% at $p < 0.05$) showed a decrease. One area of increased concentration was close to the

Antarctic continent, consistent with regions of cooling temperature (Figure 6.5). Near the Antarctic continent, the spring bloom is occurring earlier and persisting longer due to a shallowing of the surface mixed layer and increasing solar radiation (Sokolov, 2008; Johnston and Gabric, 2011). The Southern Ocean is largely a high-nutrient, low-chlorophyll (HNLC) region (Banse, 1996; Moore and Abbott, 2000). In northern portions of the Southern Ocean that are in the "Permanently Open Ocean Zone" (POOZ; Moore and Abbott, 2000) and away from land areas and fronts, chlorophyll levels remain low year-round, largely because of iron limitation (Meskhidze *et al*., 2007), light limitation (van Oijen *et al*., 2004), and a result of grazing by zooplankton (Banse, 1996). Increasing chlorophyll and strong phytoplankton blooms occur in areas in the vicinity of land masses, such as the southern tips of South America, Africa, Australia, New Zealand, and downstream of islands such as Kerguelen, where iron inputs are greater (von der Heyden *et al*., 2012). There were 10- and 15-year trends of strongly increasing chlorophyll along the STF, particularly through the South Atlantic sectors (Figure 6.5). When a positive SAM aligns with a positive ENSO (MEI, see Figure 6.3) event, eddy kinetic energy increases significantly along the STF (Langlais *et al*., 2015), potentially stimulating blooms of coccolithophores (Balch *et al*., 2011) during austral summer (December–January).

Areas of positive covariation between temperature and chlorophyll were strongest along the STF in the Atlantic sector, reflecting the close connection between phytoplankton and physics in this environment (Carranza and Gille, 2015).

Table 6.1. Relative spatial areas (% of the total region) and rates of change within within the Southern Ocean region that are showing increasing or decreasing trends in sea surface temperature (SST) for each of the standard IGMETS time-windows. Numbers in brackets indicate the % area with significant ($p < 0.05$) trends. See "Methods" Chapter for a complete description and methodology used.

Latitude-adjusted SST data field surface area = 59.4 million km²	**5-year** (2008–2012)	**10-year** (2003–2012)	**15-year** (1998–2012)	**20-year** (1993–2012)	**25-year** (1988–2012)	**30-year** (1983–2012)
Area (%) w/ increasing SST trends ($p < 0.05$)	**66.8%** (*26.1%*)	45.8% (*31.5%*)	**57.5%** (*40.0%*)	45.7% (*33.4%*)	46.7% (*34.4%*)	44.1% (*31.8%*)
Area (%) w/ decreasing SST trends ($p < 0.05$)	33.2% (*11.9%*)	**54.2%** (*41.6%*)	42.5% (*29.8%*)	**54.3%** (*42.9%*)	**53.3%** (*45.2%*)	**55.9%** (*44.0%*)
> 1.0°C decade⁻¹ warming ($p < 0.05$)	15.7% (*12.8%*)	4.6% (*4.6%*)	0.1% (*0.1%*)	0.0% (*0.0%*)	0.0% (*0.0%*)	0.0% (*0.0%*)
0.5 to 1.0°C decade⁻¹ warming ($p < 0.05$)	15.3% (*6.9%*)	16.2% (*16.0%*)	9.8% (*9.8%*)	0.8% (*0.8%*)	0.0% (*0.0%*)	0.0% (*0.0%*)
0.1 to 0.5°C decade⁻¹ warming ($p < 0.05$)	20.9% (*4.6%*)	18.9% (*10.7%*)	35.6% (*29.1%*)	31.9% (*30.2%*)	27.8% (*27.2%*)	20.0% (*19.9%*)
0.0 to 0.1°C decade⁻¹ warming ($p < 0.05$)	14.9% (*1.7%*)	6.1% (*0.2%*)	12.1% (*1.1%*)	13.0% (*2.4%*)	18.9% (*7.2%*)	24.1% (*11.9%*)
0.0 to –0.1°C decade⁻¹ cooling ($p < 0.05$)	6.7% (*0.4%*)	12.2% (*6.2%*)	24.5% (*15.4%*)	31.1% (*21.2%*)	36.6% (*28.7%*)	43.6% (*31.7%*)
–0.1 to –0.5°C decade⁻¹ cooling ($p < 0.05$)	12.4% (*2.2%*)	29.0% (*22.5%*)	17.2% (*13.7%*)	23.1% (*21.7%*)	16.7% (*16.5%*)	12.4% (*12.3%*)
–0.5 to –1.0°C decade⁻¹ cooling ($p < 0.05$)	8.4% (*4.4%*)	10.9% (*10.8%*)	0.7% (*0.7%*)	0.1% (*0.1%*)	0.0% (*0.0%*)	0.0% (*0.0%*)
> –1.0°C decade⁻¹ cooling ($p < 0.05$)	5.7% (*4.9%*)	2.1% (*2.1%*)	0.0% (*0.0%*)	0.0% (*0.0%*)	0.0% (*0.0%*)	0.0% (*0.0%*)

Table 6.2 Relative spatial areas (% of the total region) and rates of change within the South Ocean region that are showing increasing or decreasing trends in phytoplankton biomass (CHL) for each of the standard IGMETS time-windows. Numbers in brackets indicate the % area with significant ($p < 0.05$) trends. See "Methods" chapter for a complete description and methodology used.

Latitude.-adjusted CHL data field surface area = 59.6 million km²	**5-year** (2008–2012)	**10-year** (2003–2012)	**15-year** (1998–2012)
Area (%) w/ increasing CHL trends ($p < 0.05$)	45.8% (*9.9%*)	**60.8%** (*21.8%*)	**53.3%** (*20.4%*)
Area (%) w/ decreasing CHL trends ($p < 0.05$)	**54.2%** (*19.5%*)	39.2% (*10.8%*)	46.7% (*17.7%*)
> 0.50 mg m^{-3} decade^{-1} increasing ($p < 0.05$)	5.3% (*2.5%*)	0.7% (*0.4%*)	0.3% (*0.2%*)
0.10 to 0.50 mg m^{-3} decade^{-1} increasing ($p < 0.05$)	15.4% (*5.1%*)	7.6% (*4.8%*)	3.8% (*2.7%*)
0.01 to 0.10 mg m^{-3} decade^{-1} increasing ($p < 0.05$)	20.6% (*2.2%*)	41.2% (*16.3%*)	34.4% (*16.9%*)
0.00 to 0.01 mg m^{-3} decade^{-1} increasing ($p < 0.05$)	4.4% (*0.1%*)	11.3% (*0.3%*)	14.9% (*0.6%*)
0.00 to –0.01 mg m^{-3} decade^{-1} decreasing ($p < 0.05$)	4.2% (*0.0%*)	10.3% (*0.5%*)	16.5% (*2.1%*)
–0.01 to –0.10 mg m^{-3} decade^{-1} decreasing ($p < 0.05$)	35.3% (*11.8%*)	24.7% (*8.2%*)	28.7% (*15.0%*)
–0.10 to –0.50 mg m^{-3} decade^{-1} (decreasing) ($p < 0.05$)	11.8% (*6.2%*)	3.9% (*1.9%*)	1.4% (*0.5%*)
> –0.50 mg m^{-3} decade^{-1} (decreasing) ($p < 0.05$)	2.8% (*1.5%*)	0.3% (*0.2%*)	0.1% (*0.1%*)

6.3 Trends from *in situ* time series

At the time of this report, the IGMETS Southern Ocean region had 32 participating *in situ* time series (Figure 6.1; Table 6.3). The largest collection of time series came from the SCAR Southern Ocean Continuous Plankton Recorder (SO-CPR) survey (Hosie *et al*., 2003; McLeod *et al*., 2010), followed by time series from KRILLBASE, the US-AMLR programme, and the Palmer-LTER. While few in number, many of these time series were 10+ years in length. Examples of trends for selected variables over the 10-year (2003–2012) time-window are shown in Figure 6.6. The full suite of time-windows and available variables can be viewed in the IGMETS Explorer (http://igmets.net/explorer).

Based on the limited data available, *in situ* temperature trends were mixed (Figure 6.6, top left panel). There was some agreement between satellite and *in situ* SST, but the level of agreement varied over different time-windows and over different subregions. This was likely due to spatial and temporal variability of the *in situ* and satellite data. For example, there was general agreement between *in situ* and satellite data in the area of the WAP. However, in the ACC, the level of correspondence between the CPR time series and satellite data varied, depending on the time-window. The CPR boxes each represent a large spatial area, compared to a transect line or single station, which could have contained subareas both warming and cooling. The overall trend shown is an average of all those trends. In addition, the CPR transect was a single cruise within that month, while the satellite data is a monthly average. It has also been suggested that there is distinct seasonality to the temperature trends observed in Antarctica (Schneider *et al.*, 2012); it is possible that this also played a role in the difference observed between the satellite-derived and *in situ* temperature trends. Munida, off the southeast of New Zealand (see Table 6.3), was one of the stations that showed consistent cooling in all time-windows (15, 10, and 5 years). Munida is poleward of the STF and in Subantarctic surface waters (SASW) in the Subantarctic zone (SAZ), in a region strongly influenced by these mixing

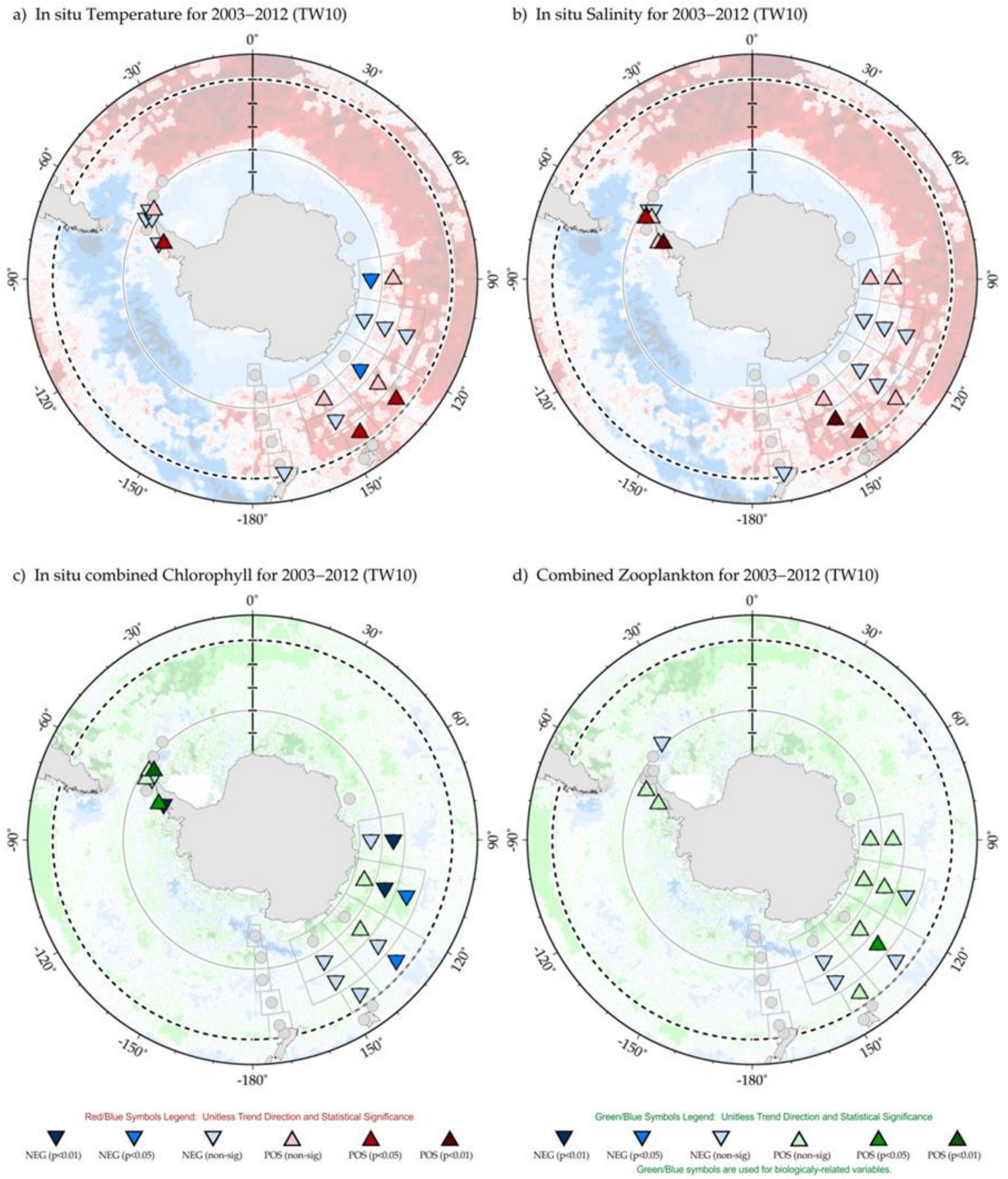

Figure 6.6. Map of Southern Ocean region time-series locations and trends for select variables and IGMETS time-windows. Upward-pointing triangles indicate positive trends; downward triangles indicate negative trends. Gray circles indicate time-series site that fell outside of the current study region or time-window. Additional variables and time-windows are available through the IGMETS Explorer (http://IGMETS.net/explorer). See "Methods" chapter for a complete description and methodology used.

and current regimes (Currie and Wowk, 2009). Although there is considerable small-scale spatial and temporal variability in SST trends in this region off southeast New Zealand, the SASW has been cooling for the last 30 years (Figure 6.3), possibly induced by the positive SAM. During a positive SAM, the southern hemisphere westerly winds tend to move farther southwards and increase in intensity (Thompson *et al*., 2000), resulting in stronger cold water upwelling in the SAZ and declining SST (Hall and Visbeck, 2002; Oke and England, 2004). Munida also showed decreasing salinity trends over the 10- and 15-year time-windows (1998–2012 and 2003–2012, respectively), possibly indicating more SASW. Salinity trends from the SO-CPR time series showed a mixture of trends, possibly reflecting variations in the circulation patterns.

Over the 15- and 10-year time-windows, most of the chlorophyll trends around the Antarctic Peninsula (the left-most arm of Antarctic pointing towards South America) were positive (increasing) (Figure 6.6, bottom left panel), while most of the chlorophyll trends from the SO-CPR areas were decreasing (many at $p < 0.05$). Over this time-period, the Antarctic Peninsula area was a region of general SST cooling and increasing chlorophyll. A notable exception was the WAP. In spite of changes at the surface, the ocean heat content over the WAP shelf showed an increasing trend due predominantly to enhanced upwelling of warm upper circumpolar deep water (UCDW) onto the shelf (Martinson *et al*., 2008; Steinburg *et al*., 2012; Ducklow *et al*., 2013). The SO-CPR areas were mostly located over the warming ACC and thus yielded decreasing chlorphyll trends. However, in two locations over the 10-year time-window, the trends were positive. These positive chlorophyll trends are potentially associated with variability in wind stress throughout summer (Carranza and Gille, 2015). The negative chlorophyll trend at Munida is possibly related to dynamics of the SAZ (Matear *et al*., 2013). In the SAZ, phytoplankton might be seasonally limited by iron (Boyd *et al*., 2001) or grazing (Banse, 1996), but they are undoubtedly limited by irradiance for most of the year (van Oijen *et al*., 2004). Thus, they are unlikely to respond positively to the greater vertical mixing implied by declining SST.

Between 2003 and 2012 (and also over the 15-year time-window), nitrate and phosphate concentrations increased significantly at Munida; an increase in surface phosphate concentrations was also reported by Currie and Wowk (2009). These observations support the model prediction of a more vigorous upwelling in the SAZ resulting from the positive phase of the SAM (Matear and Lenton, 2008). In contrast, surface macronutrient concentrations (silicate, phosphate, and nitrate) showed a consistent decrease over the 10- and 5-year time-windows at the PALMER station. It has been suggested that UCDW represents one of the major sources of nutrients to the WAP region (Prézelin *et al*., 2000) and that nutrient concentrations track temperature in the UCDW; thus, nutrient concentrations are expected to increase with increasing temperature (Ducklow *et al*., 2012). It is possible that the declining trends observed in macronutrients are a reflection of increased phytoplankton populations measured in the area. It has been noted that seasonal nutrient depletions reflect abundance and type of phytoplankton (Ducklow *et al*., 2012).

Time-window-qualifying diatom and dinoflagellate data were not available from any of the time-series sites at the time of this report. Montes-Hugo *et al*. (2009) found that, in the northern WAP during 1998–2012, there was a shift from diatoms to dinoflagellates due to increased winds and deeper mixed layers. Near the Antarctic continent, the seasonal cycle of phytoplankton production in the Southern Ocean is strongly tied to solar radiation, cloud cover, the ebb and flow of sea ice, and mixed-layer dynamics. In the ice-covered regions of the Southern Ocean during winter, under-ice algae and other microorganisms provide a source of food for larger zooplankton, including krill (Arrigo and Thomas, 2004). During spring, nutrients are released by the melting sea ice and stimulate the bloom of algae in the vicinity of the retreating ice edge. Although there is evidence of data collection by researchers (Cassar *et al*., 2015), the lack of available information on phytoplankton species in most areas of the Southern Ocean precludes any conclusions regarding regional community changes over time.

Extensive datasets on meso- and macrozooplankton from various nations span the last 100 years; combining these is still a work in progress. In the Atlantic sector, the greatest abundance of macrozooplankton generally occurred in the vicinity of the STF, while abundance was lower in the more southern regions (Mackey *et al*., 2012, a trend also seen in the mesozooplankton (Ward *et al*., 2014). A warming of the Antarctic Circumpolar Current and the shift of the currents poleward has been predicted to cause decreases in the cold-water species, especially those living closest to the Antarctic continent, and increases in the warm-water species (Mackey *et al*., 2012).

Krill (principally *Euphausia superba*) and salps (especially *Salpa thompsoni*) play key roles in the Antarctic ecosystem, and their distribution and abundance has been studied by a number of investigators (Foxton, 1966; Loeb *et al*., 1997; Atkinson *et al*., 2004, 2008, 2009; Pakhomov *et al*., 2006; Lee *et al*., 2010; Loeb and Santora, 2012). *E. superba* is a cold-water species that predominately lives in ACC waters south of the PF to the ice shelves to the south. As adolescents and adults, *E. superba* aggregates in swarms and schools and is known for avoidance of capture by traditional net sampling. It occurs in highest abundance in the southwestern Atlantic sector of the Southern Ocean (Atkinson *et al*., 2008). In contrast, *S.*

thompsoni is found in warmer, less-productive waters than krill, and while its abundance fluctuates greatly between years in a similar manner to krill, its overall circumpolar distribution is more even (Pakhomov *et al*., 2002; Lee *et al*., 2010).

The distributions and abundance of these two species of krill and salps are related to a range of factors including sea surface temperature, water depth, productivity, and the extent of seasonal sea ice cover (Stammerjohn *et al*., 2008; Lee *et al*., 2010). Over the past several decades, an inverse relationship between these two species has been observed (Lee *et al*., 2010; Loeb and Santora, 2012). In spite of strong 3–5-year oscillations, the longer-term (ca. 30-year) data compilations provided by KRILLBASE suggest that krill populations have been decreasing and salps increasing over parts of their ranges (Atkinson *et al*., 2004). The population trends and oscillations of both species have now been linked to a variety of factors including winter sea ice (Loeb *et al*., 1997; Atkinson *et al*., 2004), the Southern Annular Mode (Saba *et al*., 2014; Steinberg *et al*., 2015), ENSO (Loeb and Santora, 2012), and the Antarctic Circumpolar Wave (Lee *et al*., 2010), as well as to changing top–down controls (Ainley *et al*., 2007). Researchers agree that the duration and the location of the time series are critical factors that will determine which forcing function is found to dominate species dynamics (Loeb and Santora, 2012). In addition, a better mechanistic understanding is still needed to make informed projections on how these key species will respond with future climatic variations (Alcaraz *et al*., 2014).

The IGMETS zooplankton trends (e.g. Figure 6.6, bottom right panel) only looked at the state of the entire zooplankton community, while the literature studies mentioned in the above paragraphs discussed changes in dominant species or groups. It is possible that the trends seen in the IGMETS zooplankton reflect this shift in species dominance. However, without looking deeper into species assemblages, coupled with additional physical and chemical variables, it is difficult to draw any conclusions at this point. It is also important to note that, superimposed on the long-term trends, 4–6-year abundance oscillations have been identified for certain zooplankton species and have been linked to both the SAM and the ENSO climate indices (Steinberg *et al*., 2015), adding further complexity to the picture.

6.4 Conclusions

Both long-term trends and subdecadal cycles are evident in the Southern Ocean on multiple trophic levels and are strongly related in complex ways to climate forcings and their effects on the physical oceanographic system. Antarctic marine ecosystems have changed over the past 30 years in response to changing ocean conditions and the extent and seasonality of sea ice. These changes have been spatially heterogeneous, which suggests ecological responses depend on the magnitude and direction of the changes and their interactions with other factors. In the Southern Ocean, there are few *in situ* time series that measure a comprehensive suite of biological, ecological, and hydrographic measurements; this handicap precludes a deeper understanding of changing conditions in the region. With predictions of an overall strengthening of westerly winds in response to the positive SAM index, it is expected that higher phytoplankton concentrations will be found southward (Constable *et al*., 2014). The response of zooplankton may be more regionally specific, depending on sea ice, primary production, and seasonal dynamics of the physical forcings.

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Table 6.3. Time-series sites located in the IGMETS Southern Ocean region. Participating countries: New Zealand (nz), United Kingdom, (uk), United States (us), and multiple-country efforts (zz). Year-spans in red text indicate time series of unknown or discontinued status.

No.	IGMETS-ID	Site or programme name	Year-span	T	S	Oxy	Ntr	Chl	Mic	Phy	Zoo
1	nz-10101	Munida Time Series (*Western South Pacific*)	1998–present	X	X	-	X	X	-	-	-
2	uk-30401	KRILLBASE: Atkinson Krill Study (*Southern Ocean*)	1976–2003 (?)	-	-	-	-	-	-	-	X
3	uk-30402	KRILLBASE: Antarctic Peninsula and western Scotia Sea (*Southern Ocean*)	1975–present	-	-	-	-	-	-	-	X
4	uk-30403	KRILLBASE: Eastern Scotia Sea and South Georgia (*Southern Ocean*)	1975–present	-	-	-	-	-	-	-	X
5	uk-30404	KRILLBASE: Indian Ocean Sector (*Southern Ocean*)	1981–2006 (?)	-	-	-	-	-	-	-	X
6	uk-30501	Rothera Time Series (RaTS) (*Southern Ocean*)	1998–present	X	X	-	-	X	-	-	-
7	us-30501	Palmer Station Antarctica LTER (*Antarctic*)	1989–present	X	X	X	X	X	-	-	X
8	us-50701	AMLR Elephant Island – EI (*Southern Ocean*)	1995–present	X	X	-	-	X	-	-	-
9	us-50702	AMLR South – SA (*Southern Ocean*)	1995–present	X	X	-	-	X	-	-	-
10	us-50703	AMLR West – WA (*Southern Ocean*)	1995–present	X	X	-	-	X	-	-	-
11	us-50704	AMLR Joinville Island – JI (*Southern Ocean*)	1997–present	X	X	-	-	X	-	-	-
12	zz-40101	SCAR SO-CPR Aurora 080-100-B5560 (*Southern Ocean*)	1991–present	X	X	-	-	X	-	-	X
13	zz-40102	SCAR SO-CPR Aurora 080-100-B6065 (*Southern Ocean*)	1991–present	X	X	-	-	X	-	-	X
14	zz-40103	SCAR SO-CPR Aurora 100-120-B5055 (*Southern Ocean*)	1998–present	X	X	-	-	X	-	-	X
15	zz-40104	SCAR SO-CPR Aurora 100-120-B5560 (*Southern Ocean*)	1991–present	X	X	-	-	X	-	-	X
16	zz-40105	SCAR SO-CPR Aurora 100-120-B6065 (*Southern Ocean*)	1997–present	X	X	-	-	X	-	-	X
17	zz-40106	SCAR SO-CPR Aurora 120-140-B4550 (*Southern Ocean*)	1998–present	X	X	-	-	X	-	-	X
18	zz-40107	SCAR SO-CPR Aurora 120-140-B5055 (*Southern Ocean*)	1997–present	X	X	-	-	X	-	-	X
19	zz-40108	SCAR SO-CPR Aurora 120-140-B5560 (*Southern Ocean*)	1995–present	X	X	-	-	X	-	-	X

No.	IGMETS-ID	Site or programme name	Year-span	T	S	Oxy	Ntr	Chl	Mic	Phy	Zoo
20	zz-40109	SCAR SO-CPR Aurora 120-140-B6065 (*Southern Ocean*)	1995–present	X	X	-	-	X	-	-	X
21	zz-40110	SCAR SO-CPR Aurora 140-160-B4550 (*Southern Ocean*)	1999–present	X	X	-	-	X	-	-	X
22	zz-40111	SCAR SO-CPR Aurora 140-160-B5055 (*Southern Ocean*)	1995–present	X	X	-	-	X	-	-	X
23	zz-40112	SCAR SO-CPR Aurora 140-160-B5560 (*Southern Ocean*)	1995–present	X	X	-	-	X	-	-	X
24	zz-40113	SCAR SO-CPR Aurora 140-160-B6065 (*Southern Ocean*)	1997–present	X	X	-	-	X	-	-	X
25	zz-40131	SCAR SO-CPR Shirase E108111-S4550 (*Southern Ocean*)	2000–present	X	X	-	-	X	-	-	X
26	zz-40132	SCAR SO-CPR Shirase E108111-S5055 (*Southern Ocean*)	1999–present	X	X	-	-	X	-	-	X
27	zz-40133	SCAR SO-CPR Shirase E108111-S5560 (*Southern Ocean*)	1999–present	X	X	-	-	X	-	-	X
28	zz-40151	SCAR SO-CPR Aotea B4550 (*Southern Ocean*)	2008–present	-	-	-	-	-	-	-	X
29	zz-40152	SCAR SO-CPR Aotea B5055 (*Southern Ocean*)	2008–present	-	-	-	-	-	-	-	X
30	zz-40153	SCAR SO-CPR Aotea B5560 (*Southern Ocean*)	2008–present	-	-	-	-	-	-	-	X
31	zz-40154	SCAR SO-CPR Aotea B6065 (*Southern Ocean*)	2008–present	-	-	-	-	-	-	-	X
32	zz-40155	SCAR SO-CPR Aotea B6570 (*Southern Ocean*)	2008–present	-	-	-	-	-	-	-	X

6.6 References

Abram, N. J., Mulvaney, R., Vimeux, F., Phipps, S. J., Turner, J., and England, M. H. 2014. Evolution of the Southern Annular Mode during the past millennium. Nature Climate Change, 4(7): 564–569, doi:10.1038/nclimate2235.

Ainley, D. G., Ballard, G., Ackley, S., Blight, L. K., Eastman, J. T., Emslie, S. D., Lescroël, A., *et al*. 2007. Paradigm lost, or is top-down forcing no longer significant in the Antarctic marine ecosystem? Antarctic Science, 19: 283–290.

Alcaraz, M., Almeda, R., Duarte, C. M., Horstkotte, B., Lasternas, S., and Agustí, S. 2014. Changes in the C, N, and P cycles by the predicted salps-krill shift in the Southern Ocean. Frontiers in Marine Science, 1: 45, doi:10.3389/fmars.2014.00045.

Aoki, S., Yoritaka, M., and Masuyama, A. 2003. Multidecadal warming of subsurface temperature in the Indian sector of the Southern Ocean, Journal of Geophysical Research, 108: 8081, doi:10.1029/2000JC000307.

Arrigo, K. R., and Thomas, D. N. 2004. Large scale importance of sea ice biology in the Southern Ocean. Antarctic Science, 16(04): 471–486.

Atkinson, A., Siegel, V., Pakhomov, E. A., Jessopp, M. J., and Loeb, V. 2009. A re-appraisal of the total biomass and annual production of Antarctic krill. Deep-Sea Research I, 56: 727–740.

Atkinson, A., Siegel, V., Pakhomov, E., and Rothery, P. 2004. Long-term decline in krill stock and increase in salps within the Southern Ocean. Nature, 432: 100–103.

Atkinson, A., Siegel, V., Pakhomov, E. A., Rothery, P., Loeb, V., Ross, R. M., Quetin, L. B., *et al.* 2008. Oceanic circumpolar habitats of Antarctic krill. Marine Ecology Progress Series, 362: 1–23.

Balch, W. M., Drapeau, D. T., Bowler, B. C., Lyczskowski, E., Booth, E. S., and Alley, D. 2011. The contribution of coccolithophores to the optical and inorganic carbon budgets during the Southern Ocean Gas Exchange Experiment: New evidence in support of the "Great Calcite Belt" hypothesis. Journal of Geophysical Research: Oceans, 116(C4): doi:10.1029/2011JC006941.

Banse, K. 1996. Low seasonality of low concentrations of surface chlorophyll in the Subantarctic water ring: underwater irradiance, iron, or grazing? Progress in Oceanography, 37(3): 241–291.

Belkin, I. M., and Gordon, A. L. 1996. Southern Ocean fronts from the Greenwich meridian to Tasmania, Journal of Geophysical Research, 101: 3675–3696.

Böning, C. W., Dispert, A., Visbeck, M., Rintoul, S. R., and Schwarzkopf, F. U. 2008. The response of the Antarctic Circumpolar Current to recent climate change. Nature Geoscience, 1: 864–869.

Boyd, P. W., Crossley, A. C., DiTullio, G. R., Griffiths, F. B., Hutchins, D. A., Queguiner, B., Sedwick, P. N., *et al*. 2001. Control of phytoplankton growth by iron supply and irradiance in the subantarctic Southern Ocean: Experimental results from the SAZ Project. Journal of Geophysical Research: Oceans, 106(C12): 31573–31583.

Bromwich, D. H., Nicolas, J. P., Hines, K. M., Kay, J. E., Key, E. L., Lazzara, M. L., Lubin, D., *et al*. 2012. Tropospheric clouds in Antarctica. Reviews of Geophysics, 50: RG1004, doi:10.1029/2011RG000363.

Carranza, M. M., and Gille, S. T. 2015. Southern Ocean wind-driven entrainment enhances satellite chlorophyll-*a* through the summer. Journal of Geophysical Research: Oceans, 120: 304–323, doi:10.1002/2014JC010203.

Cassar, N., Wright, S. W., Thomson, P. G., Trull, T. W., Westwood, K. J., de Salas, M., Davidson, A., *et al*. 2015. The relation of mixed-layer net community production to phytoplankton community composition in the Southern Ocean, Global Biogeochemical Cycles, 29: 446–462, doi:10.1002/2014GB004936.

Clarke, A., and Harris, C. M. 2003. Polar marine ecosystems: major threats and future change. Environmental Conservation, 30: 1–25.

Constable, A. J., Melbourne-Thomas, J., Corney, S. P., Arrigo, K. R., Barbraud, C., Barnes, D. K. A., Bindoff, N. L., *et al*. 2014. Climate change and Southern Ocean ecosystems I: How changes in physical habitats directly affect marine biota. Global Change Biology, 20: 3004–3025, doi:10.1111/gcb.12623.

Curran, M. A. J., van Ommen, T. D., Morgan, V. I., Phillips K. L., and Palmer, A. S. 2003. Ice core evidence for Antarctic sea ice decline since the 1950s. Science, 302: 1203–1206.

Currie, D. E., and Wowk, K. 2009. Climate change and CO_2 in the oceans and global oceans governance. Carbon & Climate Law Review, 3(4): 18.

de la Mare, W. K. 1997. Abrupt mid-twentieth-century decline in Antarctic sea ice from whaling records. Nature, 389: 57–60.

de la Mare, W. K. 2009. Changes in Antarctic sea-ice extent from direct historical observations and whaling records. Climatic Change, 92(3–4): 461–493, doi:10.1007/s10584-008-9473-2.

Dinniman, M. S., Klinck, J. M., and Hofmann, E. E. 2012. Sensitivity of circumpolar deep water transport and ice shelf basal melt along the West Antarctic Peninsula to changes in the winds. Journal of Climate, 25(14): 4799–4816. doi:10.1175/jcli-d-11-00307.1.

Ducklow, H. W., Baker, K., Martinson, D. G., Quetin, L. B., Ross, R. M., Smith, R. C., Stammerjohn, S. E., *et al*. 2007. Marine pelagic ecosystems: the West Antarctic Peninsula. Philosophical Transactions of the Royal Society of London B, 362: 67–94.

Ducklow, H., Clarke, A., Dickhut, R., Doney, S. C., Geisz, H., Huang, K., Martinson, D. G., *et al*. 2012. The marine system of the Western Antarctic Peninsula. *In* Antarctic Ecosystems: An Extreme Environment in a Changing World, pp. 121–159. Ed. by A. Rogers, N. Johnston, E. Murphy, and A. Clarke. Blackwell, London. 564 pp.

Ducklow, H. W., Fraser, W. R., Meredith, M. P., Stammerjohn, S. E., Doney, S. C., Martinson, D. G., Sailley, S. F., *et al*. 2013. West Antarctic Peninsula: an ice-dependent coastal marine ecosystem in transition. Oceanography, 26(3): 190–203.

Foxton P. 1966. The distribution and life history of *Salpa thompsoni* Foxton with observations on a related species *S. gerlachei* Foxton. Discovery Reports, 34: 1–116.

Fyfe, J. C. 2006. Southern Ocean warming due to human influence, Geophysical Research Letters, 33: L19701, doi:10.1029/2006GL027247.

Gagné, M-È., Gillett, N. P., and Fyfe, J. C. 2015. Observed and simulated changes in Antarctic sea ice extent over the past 50 years, Geophysical Research Letters, 42: 90–95, doi:10.1002/2014GL062231.

Gille, S. T. 2008. Decadal-scale temperature trends in the Southern Hemisphere Ocean. Journal of Climate, 21(18): 4749–4765.

Gutt, J., Bertler, N., Bracegirdle, T. J., Buschmann, A., Comiso, J., Hosie, G., Isla, E., *et al*. 2014. The Southern Ocean ecosystem under multiple climate change stresses – an integrated circumpolar assessment. Global Change Biology, 21: 1434-1453, doi:10.1111/gcb.12794.

Hall, A., and Visbeck, M. 2002. Synchronous variability in the Southern Hemisphere atmosphere, sea ice, and ocean resulting from the annular mode. Journal of Climate, 15(21): 3043–3057.

Ho, M., Kiem, A. S., and Verdon-Kidd, D. C. 2012. The Southern Annular Mode: a comparison of indices. Hydrology and Earth System Sciences, 16: 967–982.

Hosie, G. W., Fukuchi, M., and Kawaguchi, S. 2003. Development of the Southern Ocean Continuous Plankton Recorder Survey. Progress in Oceanography, 58(2–4): 263–283.

Hosie, G., Mormede, S., Kitchener, J., Takahashi, K., and Raymond, B. 2014. Near surface zooplankton communities. *In* The CAML/SCAR-MarBIN Biogeographic Atlas of the Southern Ocean, pp. 422–430. Ed. by C. De Broyer, P. Koubbi, H. Griffiths, B. Danis, B. David, S. Grant, J. Gutt, *et al*. Scientific Committee on Antarctic Research, Cambridge, UK. 498 pp.

Johnston, B. M, and Gabric, A. J. 2011. Interannual variability in estimated biological productivity in the Australian sector of the Southern Ocean in 1997–2007. Tellus, 63B: 266–286.

Langlais, C. E., Rintoul, S. R., and Zika, J. D. 2015. Sensitivity of Antarctic Circumpolar Current transport and eddy activity to wind patterns in the Southern Ocean. Journal of Physical Oceanography, 45: 1051–1067, doi:10.1175/JPO-D-14-0053.1.

Lee, C. I., Pakhomov, E., Atkinson, A., and Siegel, V. 2010. Long-term relationships between the marine environment, krill and salps in the Southern Ocean. Journal of Marine Biology, 2010: 1–18, doi:10.1155/2010/410129.

Loeb, V. J., and Santora, J. A. 2012. Population dynamics of *Salpa thompsoni* near the Antarctic Peninsula: growth rates and interannual variations in reproductive activity (1993–2009). Progress in Oceanography, 96: 93–107.

Loeb, V., Siegel, V., Holm-Hansen, O., Hewitt, R., Fraser, W., Trivelpiece, W., and Trivelpiece, S. 1997. Effects of sea-ice extent and krill or salp dominance on the Antarctic food web. Nature, 387: 897–900.

Mackey, A., Atkinson, A., Hill, S., Ward, P., Cunningham, N. J., Johnson, N., and Murphy, E. J. 2012. Antarctic macrozooplankton of the southwest Atlantic sector and Bellingshausen Sea: baseline historical (Discovery Investigations, 1928–1935) distributions related to temperature and food, with projections for subsequent ocean warming. Deep-Sea Research II, 59–60: 130–146.

Martinson, D. G., Stammerjohn, S. E., Iannuzzi, R. A., Smith, R. C., and Vernet, M. 2008. Western Antarctic Peninsula physical oceanography and spatio-temporal variability. Deep-Sea Research II, 55(18–19): 1964–1987.

Matear, R. J., Chamberlain, M. A., Sun, C., and Feng, M. 2013. Climate change projection of the Tasman Sea from an Eddy-resolving Ocean Model. Journal of Geophysical Research: Oceans, 118(6): 2961–2976.

Matear, R. J., and Lenton, A. 2008. Impact of historical climate change on the Southern Ocean carbon cycle. Journal of Climate, 21(22): 5820–5834.

McLeod, D. J, Hosie, G. W., Kitchener, J. A., Takahashi, K. T., and Hunt, B. P. V. 2010. Zooplankton atlas of the Southern Ocean: The Southern Ocean Continuous Plankton Recorder Survey (1991-2008). Polar Science, 4(2): 353–385, doi:10.1016/j.polar.2010.03.004.

Meredith, M. P., and King, J. C. 2005. Rapid climate change in the ocean west of the Antarctic Peninsula during the second half of the 20th century. Geophysical Research Letters, 32(19): L19604, doi:10.1029/2005GL024042.

Meskhidze, N., Nenes, A., Chameides, W. L., Luo, C., and Mahowald, N. 2007. Atlantic Southern Ocean productivity: Fertilization from above or below? Global Biogeochemical Cycles, 21: GB2006, doi:10.1029/2006GB002711.

Moffat, C., Beardsley, R. C., Owens, B., and van Lipzig, N. 2008. A first description of the Antarctic Peninsula Coastal Current. Deep-Sea Research II, 55: 277–293.

Montes-Hugo, M., Doney, S. C., Ducklow, H. W., Fraser, W., Martinson, D., Stammerjohn, S. E., and Schofield, O. 2009. Recent changes in phytoplankton communities associated with rapid regional climate change along the Western Antarctic Peninsula. Science, 323: 470–1473.

Moore, J. K., and Abbott, M. R. 2000. Phytoplankton chlorophyll distributions and primary production in the Southern Ocean, Journal of Geophysical Research: Oceans, 105: 28709–28722.

National Geophysical Data Center. 2006. 2-minute Gridded Global Relief Data (ETOPO2) v2. National Geophysical Data Center, NOAA. doi:10.7289/V5J1012Q.

Oke, P. R., and England, M. H. 2004. Oceanic response to changes in the latitude of the Southern Hemisphere subpolar westerly winds. Journal of Climate, 17(5): 1040–1054.

Orsi, A. H. and Harris, U. 2001(updated 2015). Locations of the various fronts in the Southern Ocean. Australian Antarctic Data Centre-CAASM Metadata (http://data.aad.gov.au/aadc/metadata/metadata_redirect.cfm?md=/AMD/AU/southern_ocean_fronts).

Orsi, A. H., Whitworth III, T., and Nowlin Jr., W. D. 1995. On the meridional extent and fronts of the Antarctic Circumpolar Current. Deep-Sea Research I, 42(5): 641–673.

Pakhomov, E. A., Atkinson, A., Meyer, B., Oettl, B., and Bathmann, U. 2004. Daily rations and growth of larval krill *Euphausia superb* in the Eastern Bellingshausen Sea during austral autumn. Deep-Sea Research II, 51: 2185–2198.

Pakhomov, E. A., Dubischar, C. D., Strass, V., Brichta, M., and Bathmann, U. V. 2006. The tunicate *Salpa thompsonia* ecology in the Southern Ocean. I. Distribution, biomass, demography and feeding ecophysiology. Marine Biology, 149: 609–623.

Prézelin, B. B., Hofmann, E. E., Mengelt, C., and Klinck, J. M. 2000. The linkage between upper circumpolar deep water (UCDW) and phytoplankton assemblages on the west Antarctic Peninsula Continental Shelf. Journal of Marine Research, 58: 165–202.

Saba, G. K., Fraser, W. R., Saba, V. S., Iannuzzi, R. A., Coleman, K. E, Doney, S. C., Ducklow, H. W., *et al*. 2014. Winter and spring controls on the summer food web of the coastal West Antarctic Peninsula. Nature Communications, 5: 4318, doi:10.1038/ncomms5318.

Schneider, D. P., Deser, C., and Okumura, Y. 2012. An assessment and interpretation of the observed warming of West Antarctica in the austral spring. Climate Dynamics, 38(1–2): 323–347.

Sokolov, S. 2008. Chlorophyll blooms in the Antarctic Zone south of Australia and New Zealand in reference to the Antarctic Circumpolar Current fronts and sea ice forcing, Journal of Geophysical Research, 113: C03022, doi:10.1029/2007JC004329.

Sokolov, S., and Rintoul, S. R. 2009a. Circumpolar structure and distribution of the Antarctic Circumpolar Current fronts: 1. Mean circumpolar paths. Journal of Geophysical Research, 114: C11018, doi:10.1029/2008JC005108.

Sokolov, S., and Rintoul, S. R. 2009b. Circumpolar structure and distribution of the Antarctic Circumpolar Current fronts: 2. Variability and relationship to sea surface height. Journal of Geophysical Research, 114: C11019, doi:10.1029/2008JC005248.

Stammerjohn, S. E., Martinson, D. G., Smith, R. C., Yuan, X., and Rind, D. 2008. Trends in Antarctic annual sea ice retreat and advance and their relation to ENSO and Southern Annular Mode variability, Journal of Geophysical Research, 113: C03S90, doi:10.1029/2007JC004269.

Stammerjohn, S., Massom, R., Rind, D., and Martinson, D. 2012. Regions of rapid sea ice change: an interhemispheric seasonal comparison. Geophysical Research Letter, 39(6): L06501, doi:10.1029/2012GL050874.

Steinberg, D. K., Martinson, D. G., and Costa, D. P. 2012. Two decades of pelagic ecology of the Western Antarctic Peninsula. Oceanography, 25(3): 56–67, http://dx.doi.org/10.5670/oceanog.2012.75.

Steinberg, D. K., Ruck, K. E., Gleiber, M. R., Garzio, L. M., Cope, J. S., Bernard, K. S., Stammerjohn, S. E., *et al*. 2015. Long-term (1993–2013) changes in macrozooplankton off the Western Antarctic Peninsula. Deep-Sea Research I, 101: 54–70.

Talley L. D., Pickard G. L., Emery W. J., and Swift J. H., 2011. Descriptive Physical Oceanography: An Introduction (Sixth edn), Elsevier, Boston. 560 pp.

Thompson, D. W., Wallace, J. M., and Hegerl, G. C. 2000. Annular modes in the extratropical circulation. Part II: Trends. Journal of Climate, 13(5): 1018–1036.

Turner, J., Colwell, S. R., Marshall, G. J., Lachlan-Cope, T. A., Carleton, A. M., Jones, P. D., Lagun, V., *et al*. 2005. Antarctic climate change during the last 50 years. International Journal of Climatology, 25(3): 279–294.

Vaughan, D. G., Marshall, G. J., Connolley, W. M., Parkinson, C., Mulvaney, R., Hodgson, D. A., King, J. C., *et al*. 2003. Recent rapid regional climate warming on the Antarctic Peninsula. Climatic Change, 60: 243–274.

van Oijen, T., van Leeuwe, M. A., Granum, E., Weissing, F. J., Bellerby, R. G. J., Gieske, W. W. C., and de Baar, H. J. W. 2004. Light rather than iron controls photosynthate production and allocation in Southern Ocean phytoplankton populations during austral autumn. Journal of Plankton Research, 26: 885–890.

von der Heyden, B. P., Roychoundhury, A. N., Mtshali, T. N., Tyliszczak, T., and Myneni, S. C. B. 2012. Chemically and geographically distinct solid-phase iron pools in the Southern Ocean. Science, 338: 1199.

Ward, P., Tarling, G, A., and Thorpe, S. E. 2014. Mesozooplankton in the Southern Ocean: Spatial and temporal patterns from Discovery Investigations. Progress in Oceanography, 120: 305–319.

Whitehouse, M. J., Meredith, M. P. Rothery, P., Atkinson, A., Ward, P., and Korb, R. E. 2008. Rapid warming of the ocean around South Georgia, Southern Ocean, during the 20th century: forcings, characteristics and implications for lower trophic levels. Deep-Sea Research I, 55: 1218–1228.