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On the interannual variability of ocean temperatures around South Georgia, Southern Ocean: forcing by El Niño/Southern Oscillation and the Southern Annular Mode

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Abstract

The ocean around South Georgia, in the southwest Atlantic sector of the Southern Ocean, is highly productive, with large stocks of Antarctic krill supporting extensive colonies of marine and land-based predators. The operation of this ecosystem is strongly influenced by physical forcings, and the role of the El Niño/Southern Oscillation (ENSO) phenomenon has been highlighted previously. Here we examine in detail the transmission of ENSO signals to South Georgia, and investigate other sources of interannual variability.

ENSO variability generates anomalies in sea surface temperature (SST) across the South Pacific via atmospheric teleconnections. These anomalies are advected toward South Georgia within the Antarctic Circumpolar Current (ACC), and previous studies have focussed on long-period advection (order of 2-3 years) from the southwest Pacific. We observe here, however, that the region close to the Antarctic Peninsula in the southeast Pacific is especially susceptible to ENSO forcing via anomalous meridional winds; this induces SST anomalies that are advected to South Georgia on a much more rapid timescale (order 5-6 months). The phasing of these teleconnections is such that anomalies that reach the southeast Pacific from farther west tend to be reinforced here by air-sea-ice interaction.

We also find an important role for the Southern Annular Mode (SAM) in determining SST variability at South Georgia. This is a circumpolar mode of climate variability, and thus can readily influence local SST at South Georgia directly. The SAM is, however, not perfectly zonally symmetric, and (like ENSO) has a particular impact on meridional winds in the southeast

Pacific. The average timescale for SAM influence on South Georgia SST is shorter than that of ENSO, since it includes a stronger component of direct local forcing.

The South Georgia ecosystem is not self-sustaining, with import of krill from breeding and nursery grounds upstream in the ACC being important. We speculate here that these varying meridional winds close to the Antarctic Peninsula play a direct role in promoting/restricting the injection of shelf waters (and the krill therein) into the ACC, following which anomalies in krill density would be advected toward South Georgia. This offers a dynamical mechanism that might contribute to interannual changes in biological communities at South Georgia, in addition to existing theories.

Both SAM and ENSO have shown long-period changes in recent decades, with ENSO exhibiting a higher preponderance of El Niño events compared with La Niña events, and the SAM showing a marked trend toward a higher index state. Such long-period behaviour is likely to induce changes in the South Georgia ecosystem via their impacts on advection and SST, for which an understanding of the physical mechanisms elucidated here will be key to unravelling.

Introduction

The island of South Georgia is situated on the North Scotia Ridge, close to the northeastern limit of the Scotia Sea (Figure 1). It lies within the Antarctic Circumpolar Current (ACC), with the Polar Front (PF) to the north, and the Southern ACC Front (SACCF) looping anticyclonically around the island from the south before retroflecting to the east (Meredith *et al.*, 2003b; Orsi *et al.*, 1995; Thorpe *et al.*, 2002). A comparatively narrow shelf region (around 50-150 km) separates the island from this adjacent deep ocean regime, and whilst shelf and offshelf waters frequently have different hydrographic properties (Brandon *et al.*, 2000; Brandon *et al.*, 1999; Meredith *et al.*, 2005), cross-shelfbreak exchange of waters has been evidenced by drifters and various other means (Meredith *et al.*, 2005; Meredith *et al.*, 2003a).

The waters around South Georgia are characterized by high levels of biological productivity, and play a key role in supporting vast colonies of both marine and land-based predators, including Antarctic fur seals, albatrosses, penguins and whales (see Atkinson *et al.* (2001) for a review). Local availability of Antarctic krill (*Euphausia superba*) is key to the success of the South Georgia predator colonies, since it constitutes a primary food source. The krill population at South Georgia is not self-sustaining however (Everson, 1984), but rather is supplied from breeding grounds farther to the west, with the Antarctic Peninsula, the South Orkney Islands and the Weddell Sea having been highlighted as potential source regions (Murphy *et al.*, 2004b; Murphy *et al.*, 2007). The role of advection by the ACC in supplying krill to the South Georgia ecosystem has been postulated by various workers (e.g. Fach *et al.*, 2002; Hofmann *et al.*, 1998; Murphy *et al.*, 2004a).

Interannual variability in the properties of the waters surrounding South Georgia has been observed by a number of authors. Early observations (1920s and 1930s) showed that extremes in ocean temperature coincided with those in air temperature as recorded at Grytviken (a whaling station on South Georgia, now disused), suggesting a link to large-scale atmospheric conditions (Deacon, 1977). Whitehouse *et al.* (1996) used data from around South Georgia collected between 1926 to 1990 to demonstrate a link between anomalous ocean temperature and the duration of fast-ice in the southern Scotia Sea (South Orkney Islands) the preceding winter. Murphy *et al.* (1995) noted that the fast-ice record appears to reflect circumpolar changes, and observed a regular precessional pattern in sea-ice distribution that is reflected in the South Orkney fast-ice series. These observations again imply the local response at South Georgia to large-scale (basin- or greater) climatic forcing.

Following these works, an analysis of satellite-derived sea surface temperature (SST) recovered immediately adjacent to South Georgia showed significant correlations with interannual variability in the El Niño regions of the tropical/equatorial Pacific (Trathan and Murphy, 2003). A time lag of around 3 years was obtained for positive anomalies in the equatorial Pacific variability to be reflected as positive anomalies at South Georgia; this was attributed to the timescale involved in the advective transfer of ocean anomalies from the Pacific to this region of the Atlantic. Within the southern parts of the ACC, winter temperatures approach or reach the freezing point, hence winter SST anomalies are limited in their range. However, this does not contradict the apparent multi-year persistence of the SST anomalies, since the winter signals are transferred to the sea ice field, which shows anomalies in extent and/or concentration in response to SST anomalies – this is the sea ice "memory" effect (e.g. Gloersen and White, 2001).

More recently, however, an analysis of *in situ* hydrographic data by Meredith *et al.* (2005) has indicated that variability associated with ENSO (the El Niño/Southern Oscillation phenomenon) can impact on South Georgia on a much more rapid timescale than that highlighted by Trathan and Murphy (2003). Meredith *et al.* (2005) noted a response in ocean temperature around South Georgia to the intense 1997/8 El Niño event on a short timescale (order of a few months), and even an instance of direct atmospheric forcing of the ocean surface temperature (i.e. a zero-lag atmospherically-forced response in the South Atlantic to ENSO variability). It was noted that the 1997/8 event was atypical in terms of intensity, so the high-latitude response associated with it may also have been unusual. Nonetheless, Murphy *et al.* (submitted) found that ecosystems parameters at South Georgia could best be represented in a conceptual model when the possibility of direct atmospheric forcing of climate variability was included. It is important to note that all El Niño events are different, and a comprehensive appreciation of the forcings of the physical and ecological system at South Georgia requires that we develop an understanding that encompasses all variability observed.

Kwok and Comiso (2002) used a 17-year series of remotely-sensed SST to investigate the high-latitude signature of ENSO in the Southern Hemisphere. They demonstrated that positive temperature anomalies and ice edge retreat in the Pacific sector were associated with El Niño episodes. They also noted that a negative bias in the Southern Oscillation Index during this period (i.e. a tendency toward more El Niño events than La Niña events), which will have affected the long-term mean SST. A larger-scale view of Figure 3c of Kwok and Comiso (2002) is given here in Figure 2, which shows correlation of southern hemisphere SST with the monthly Bivariate ENSO Time Series (BEST) index (Smith and Sardeshmukh (2000); fuller details of the SST data and BEST ENSO index are given in Section 2 below).

Of particular note in Figure 2 are the alternating bands of positive and negative correlation extending from the equatorial Pacific to the high-latitude Pacific sector of the Southern Ocean. This is a well-known pattern noted previously by many authors (e.g. Trenberth *et al.*, 1998) that is associated with a climatological Rossby wave train (see Turner (2004) for a review). The mechanisms whereby ENSO can generate SST anomalies in the Southern Ocean have been investigated by various authors. For example, Li (2000) used an atmospheric general circulation model coupled to a slab mixed-layer ocean, and found that SST anomalies were generated in the Pacific sector of the Southern Ocean by modifications to the heat flux balance at the air-sea interface associated with changes in cloud cover and radiation. (Our Figure 2 reproduces the main features of Figure 1a of Li (2000)). In particular, it was noted that positive SST anomalies are found in the western part of the South Pacific during the summer months of El Niños.

Also discernible in Figure 2 is a negative anomaly in the southwest Atlantic (around 50°S, 30°W) that coincides with a positive anomaly in the South Pacific. This is a manifestation of what has been termed the Antarctic Dipole (Yuan and Martinson, 2000), a mode of variability that displays an out-of-phase relationship between anomalies (including sea ice cover and air temperature) in the central/eastern Pacific sector of the Southern Ocean and the Atlantic sector. A number of studies have investigated the mechanisms forcing this dipole, including the relative roles of advection by the ACC and coupled air-sea-ice interaction, and its connection to ENSO is now well established (e.g. Holland *et al.*, 2005).

In addition to ENSO, there are other modes of climate variability that have the potential to induce significant interannual variability in the ecosystem at South Georgia. Of particular interest is the Southern Annular Mode (SAM), the leading mode of extratropical climate variability in the Southern Hemisphere (Thompson and Wallace, 2000). Characterised by a large-scale alternation of atmospheric mass between a node centred over Antarctica and an annulus over the lower-latitude Southern Ocean, it is associated with a meridional shift in the position and intensity of the westerly winds (Hartmann and Lo, 1998).

Several authors have noted that impact that the SAM can have on the surface temperature of the Southern Ocean, based on both modeling and observational evidence (e.g. Hall and Visbeck, 2002; Lovenduski and Gruber, 2005; Sengupta and England, 2006). The results of these studies are reprised in Figure 3, which shows the correlation of the SAM index with southern hemisphere SST (note that this Figure is for a 1 month lag between the SAM and SST; this is when correlations are highest, as is demonstrated below. Correlations remain high at marginally longer lags, up to around 4 months). Of particular note is the band of positive correlations along approximately 40°S, which is interrupted in the South Pacific and flanked to the south by a band of negative correlations. This circumpolarity, with a disjoint in the South Pacific, is characteristic of the SAM. The southwest Atlantic sector of the Southern Ocean (including the entire Scotia Sea) shows positive correlations with the SAM. Also apparent in Figure 3 are bands of alternating positive and negative correlations in the South Pacific, similar in form to those shown in Figure 2. This is evidence of some covariability between ENSO and SAM, and the potential dynamical connections between them are already under investigation (e.g. L'Heureux and Thompson, 2006).

Recently, a number of papers have made advances in understanding the response of the South Georgia and South Atlantic ecosystem to interannual changes in local SST (e.g. Leaper *et al.*, 2005; Forcada *et al.*, 2005; Trathan *et al.*, 2006; Murphy *et al.*, submitted; Murphy *et al.*, 2007), emphasizing the importance of understanding the factors that control SST here, their timescales, mechanisms, and how they are likely to change into the future. These papers have concentrated predominantly on links with ENSO at long lags (order of a few years). Other studies have also shown that sub-decadal climate fluctuations can impact on ecosystems at high southern latitudes, with the impact of ENSO on oceanographic and sea ice variation at the western Antarctic Peninsula (WAP) being noted, with consequences for the dynamics of krill and their predators (Fraser and Hofmann, 2003; Quetin and Ross, 2003).

In this paper, we present a comprehensive analysis of the roles of the two leading modes of high-latitude southern hemisphere climate variability (ENSO and the SAM) in determining interannual changes in SST around the island of South Georgia and in the southwest Atlantic sector of the Southern Ocean. Since these are large (planetary or hemispheric) modes of variability, by necessity the analysis addresses comparable scales. The purpose is to understand the timescales and mechanisms by which the interannual variability is generated, an important precursor to enabling predictions of how the system might change in the future. The understanding we gain, in particular of the processes that transmit the signals to the southwest Atlantic, adds insight into the operation of the regional and local ecosystem.

Data

For this paper, we use the Bivariate ENSO Time Series (BEST) index (Smith and Sardeshmukh, 2000). Traditionally, the Niño 3.4 index has been used as a measure of ENSO strength in the tropical Pacific, however the BEST index offers advantages in the inclusion of some explicit atmospheric processes. (For comparison, the BEST and Niño 3.4 indices show a correlation of 0.81 based on monthly-mean data, and 0.98 for monthly data smoothed with a 2-year filter). Monthly values of the BEST index were obtained from the Climate Diagnostics Center (CDC) of the National Oceanographic and Atmospheric Administration (NOAA) (data available at http://www.cdc.noaa.gov/people/cathy.smith/best/). The SAM index we use was obtained from the Climate Prediction Center of the National Centers for Environmental Prediction (NCEP). Monthly values were used, obtained from http://www.cpc.ncep.noaa.gov/.

The SST data we used are those produced by Reynolds *et al.* (2002), obtained from the NOAA CDC. The data are optimum interpolation SST values, produced on a one-degree grid using *in situ* and satellite SST, plus SST simulated by sea-ice cover. Data are available at http://www.cdc.noaa.gov/cdc/data.noaa.oisst.v2.html covering the period 1981 to 2005. Meredith *et al.* (2005) examined a series of images from this dataset during a period of *in situ* data availability around South Georgia, and found that the spatial and temporal coverage of the remotely-sensed data was useful in explaining the observed *in situ* changes in surface water properties.

Sea ice concentration data were obtained from the National Snow and Ice Data Center, having been derived using Nimbus-7 SMMR and DMSP SSM/I passive microwave data (data available at http://nsidc.org/data/docs/daac/nsidc0051_gsfc_seaice.gd.html). Surface wind stress data used were obtained from the ECMWF ERA40 reanalysis covering the period 1957 to 2002 (Uppala *et al.* (2005); see also http://www.ecmwf.int/research/era/), though here we only use data that overlap temporally with the satellite-derived SST data. Marshall (2003) identified ERA40 as being the reanalysis that currently best represents atmospheric circulation at high southern latitudes during the satellite era.

For the present paper, we derived anomalies of SST, wind stress and ice concentration by removing the mean seasonal cycle from the time series of each gridpoint in the global fields. Sea ice extent was derived by extracting the northernmost occurrence of the 15% sea ice concentration value along a given line of longitude in each monthly sea ice field, and anomalies of these time series were derived by removing the mean seasonal cycle.

Results

From the global gridded SST product, we extracted a time series of SST from 53.5°S, 32.5°W, immediately adjacent to South Georgia and in an area we believe to be suitably representative. (The results obtained are not critically dependent on the exact location chosen). This is used as our baseline series of South Georgia SST, and is shown in Figure 4 alongside (a) the BEST ENSO index, and (b) the SAM index. Several features are apparent, including the very cold conditions around South Georgia in 1998 noted previously by Meredith *et al.* (2005), and connected to the strong 1997/98 El Niño event. These same series are shown in Figure 5, but smoothed with a 2-year filter to illustrate more clearly any relationships between the series on the interannual periods of interest here. The connections between the series are more immediately apparent in the smoothed series, with South Georgia SST showing a near-antiphase relationship with ENSO and a nearly in-phase relationship with the SAM. We note that the ENSO and SAM series show evidence of co-variability; the degree to which this is due to dynamical interaction between these modes (e.g. L'Heureux and Thompson, 2006) as opposed to an artifact of the way the series were calculated is part of an ongoing investigation.

Figure 6 shows simple cross-correlation functions for these same series. The solid curve in this figure denotes correlations based on the monthly anomalies, whereas the dashed line shows the same cross-correlations but with the series initially smoothed with a 2-year filter. The convention we use for this figure, and in other places in this paper, is that we arbitrarily consider the atmosphere to be the forcing function, with positive lags indicating atmosphere leading the ocean. The cross-correlation of South Georgia SST and ENSO show features broadly consistent with those observed already by Trathan and Murphy (2003), most notably positive correlation at around 30 months lag, and a negative correlation at around 5 months lag. The cross-correlation of South Georgia SST with the SAM shows a positive correlation at short lags, peaking around 1-2 months. It also shows correlations at longer periods (around 2-3 years). As a rough guide, the 95% and 99% significance levels for the zero-lag correlations (calculated as per Trenberth

(1984)) are given in the caption of Figure 6. It should be noted, however, that sample cross-correlation functions can be deceptive, as the sample estimate is a function of the convolution of the autocorrelation functions of the individual times series, leading to often severe smearing of the r-values as a function of lag, including smearing of the cross-correlation function into lags for which there is no true correlation, and leading to unreasonably large bias with larger lags. However, they are very useful to help visualize and evaluate the relationship between the series, and are shown here for this purpose.

More rigorous tests of statistical significance and physically-meaningful connections are provided by cross-spectral analyses. These are shown in Figures 7 and 8 for South Georgia SST with ENSO and the SAM respectively. For these, we calculated power spectral densities using Welch's method of averaged periodograms. The signals were divided into overlapping sections, each of which was detrended and windowed with a Hanning window. Coherence functions were then derived as the absolute components of the cross-spectral density squared divided by the product of the power spectral densities. Significance levels were derived using equivalent degrees of freedom that depended on the length of the series used and the width of the window, as per Emery and Thomson (1997).

For the interannual frequencies of interest here, significant coherence is observed between South Georgia SST and ENSO at periods of approximately 18 months and longer. The phase spectrum confirms the near-antiphase relationship between the series, consistent with the significant negative correlation at short-period lag observed in Figure 6. For South Georgia SST and the SAM (Figure 8), significant coherence is observed for periods of around 25 months and longer.

The phase spectrum shows a tendency toward a nearly in-phase relationship, again consistent with the positive correlation at short lags observed in the cross correlation (Figure 6). Note that for both the SAM and ENSO, the short time-lag relationships observed in the cross correlations (order of a few months or less) dominate the cross spectra.

Cross spectra and linear cross correlations can be informative regarding the timescales on which specific processes influence others, and any potential lags. They do not, however, provide spatial information with which to interpret the functions obtained. Spatial maps of correlation can help with this, especially when viewed across a range of lags. Figures 2 and 3 showed the instantaneous (or near-instantaneous) southern hemisphere "footprints" of ENSO and the SAM, and, of particular interest to us, illustrate their high-latitude impacts. Complementary to these, Figure 9a shows the spatial map of correlation of our South Georgia baseline SST time series with hemispheric SST. The correlation is unity, by definition, at the location from which the baseline SST was extracted; the "bullseye" centred on South Georgia shows the spatial extent of the anomaly that our baseline series represents.

Figure 9a, which is for zero lag between South Georgia SST and hemispheric SST, shows the influence of both ENSO and the SAM. Note in particular the alternating bands of positive and negative correlation in the equatorial and South Pacific, indicative of the atmospheric Rossby wave train that carries ENSO signals to high latitudes (c.f. Figure 2). Figure 9a also shows very clearly that positive anomalies in the southwest Atlantic sector of the Southern Ocean (including South Georgia and the Scotia Sea) coincide with negative anomalies in the Pacific sector. This is the characteristic pattern of the Antarctic dipole, at one node of which sits South Georgia. The influence of the SAM is also discernable in Figure 9a (c.f. Figure 3), with a band of positive correlations along 40°S, flanked by negative correlations to the south, and with the negative node of the dipole coinciding spatially with the interruption to the circumpolar SAM signal in the South Pacific. Note that, in Figure 3, the whole Scotia Sea (including South Georgia) was covered by a positive correlation as part of the SAM pattern; this is the same area that is covered by positive correlations in Figure 9a.

Examining maps of lagged spatial correlations is often informative when the system under study involves advection of anomalies. Figure 9(b-f) shows such lagged correlations, for 3, 6, 12, 18 and 24 months respectively. It can be seen in these figures that the anomaly centred on South Georgia in Figure 9a is observed progressively farther westward (i.e. farther "upstream" in the ACC) at longer lags between South Georgia SST and southern hemisphere SST. For 3 months lag, the anomaly extends through Drake Passage, and for 6 months lag it flanks the WAP. At 24 months lag, the anomaly is roughly in the centre of the Pacific sector of the Southern Ocean. Note that at this lag, the whole pattern of anomalies in the South Pacific has reversed, i.e. we see a La Niña-like pattern at zero lag and an El Niño–like pattern at 24 months lag (compare Figure 9a with 9f).

This movement of the anomaly in the ACC has been interpreted previously as the cause of the long-period (2-3 year) connection between ENSO and South Georgia SST, and the results shown here do not contradict this. Note, however, that at 18 months lag, the magnitude of the correlation within the anomaly in the South Pacific (circled in Figure 9e) is actually slightly less than it is at 24 months lag. This is counterintuitive if one presumes that the anomaly is created in the south or southwest Pacific (via processes investigated by e.g. Li (2000)), and is then simply advected in the ACC toward South Georgia, since under this scenario the correlation would increase monotonically with decreasing lag. That this does not occur is evidence that a purely advective process cannot be responsible for transferring and sustaining the anomaly as it progresses across the South Pacific toward South Georgia. Instead, atmospheric processes must also be involved. This is consistent with the observation that ENSO has a strong high-latitude impact in the southeast Pacific sector of the Southern Ocean (e.g. Turner, 2004), and the recognition that ocean anomalies created farther to the west that pass through this region will be modified further by air-sea interaction due to ENSO as they progress.

To address this further, we repeated the correlation analysis shown in Figure 9 but using hemispheric wind data rather than hemispheric SST data. The most significant results are obtained for 5-6 months lag; Figure 10 shows the spatial patterns of correlation with meridional and zonal winds for the latter of these. The most striking feature in this figure is the correlation with the rotating winds in the southeast Pacific, i.e the positive correlation with meridional winds centred on around 140°W and negative correlation centred just west of Drake Passage in Figure 10a, and the positive correlation between 40° and 60°S flanked to the south by negative correlation in Figure 10b. This is the pattern of winds rotating around the anomaly in surface atmospheric pressure that is commonly found in the southeast Pacific during ENSO events (Turner, 2004).

There is good evidence that the meridional winds are of prime importance in sustaining and modifying the SST anomalies in the South Pacific as they transit toward South Georgia. In particular, the meridional winds immediately to the west of Drake Passage (the longitude of the WAP and the Bellingshausen Sea) are held to be key. Recall that the strongest correlation between ENSO and South Georgia SST was at around 5 months lag (Figure 6), and (with reference to Figure 9c), it is clear that anomalies that reach South Georgia pass the vicinity of the WAP and the Bellingshausen Sea around 5-6 months earlier, at which point they experience anomalous meridional winds that reinforce the SST anomaly. (This timescale for advection of anomalies from the WAP to South Georgia is broadly consistent with *in situ* measurements using passive drogued drifters, which make the journey from the South Shetland Islands at the northern end of the WAP to South Georgia in around 110-120 days (Ichii *et al.*, 1998)).

The role of meridional winds in controlling conditions at the WAP was investigated previously by Harangozo (2006), who found a remarkably strong relationship between meridional winds and ice extent here. He noted that a local relationship of this strength was unique in both polar regions, and was a consequence of wind-induced ice drift being the dominant process controlling ice extent, whereas in other regions ice growth and ocean currents can be more important. He noted also that the north-south alignment of the WAP coast was crucial to explaining the strong relationship, because it prevented eastward ice drift in response to the prevailing westerly winds. Many of the arguments advanced by Harangozo (2006) are equally applicable to SST as to sea ice extent. SST anomalies and sea ice extent anomalies are strongly coupled on interannual timescales in the Southern Ocean (e.g. Gloersen and White, 2001); this is true even for an unusual area such as the ocean west of the WAP. As a reflection of this, Figure 11 shows ice extent at 70°W (smoothed with a 2-year filter) alongside (a) ENSO, (b) the SAM, and (c) South Georgia SST. The in phase relationship between ENSO and ice extent is clear, as is the antiphase relationship between ice extent and the SAM (commented on below). Most significantly, there is a clear relationship between 70°W ice extent and South Georgia SST, which is almost antiphase but for a lag of just a few months (cross-correlations and –spectra confirm this; not shown). This agrees with the above hypothesis of meridional winds at the western Peninsula influencing strongly both the sea ice and SST fields, with the SST anomalies created then being advected to South Georgia in the ACC over the course of 5-6 months.

The above concept of meridional winds at the WAP influencing both sea ice and SST is in agreement with the observational study of Meredith *et al.* (2004a), who used a long time series of hydrographic data from the WAP shelf to investigate anomalous ocean conditions observed there during 1998. They noted that the anomalous ocean conditions (which included a deepened mixed layer, as well as surface anomalies) were primarily forced by a change in the rate of sea ice production, in response to a change in meridional winds associated with the 1997/98 El Niño. Although the data used were from a coastal site, they argued for the broader-scale representativeness of their data set.

We have thus seen that a significant part of the ENSO signal that influences SST at South Georgia is imprinted on the ocean just upstream of Drake Passage, i.e. in the Bellingshausen Sea close to the WAP. This does not negate the existence of anomalies that propagate toward South Georgia from much further west across the Pacific (indeed this process is apparent in Figure 9), but it does imply that a very significant proportion (possibly the bulk) of the ENSO-related variability in SST that is observed at South Georgia is imprinted on the ocean surface much closer to Drake Passage.

Of particular interest is the phasing of the ENSO-related anomalies generated close to the WAP with respect to those generated in the western part of the South Pacific. In general, the phasing is such that the anomalies coincide in the southeast Pacific with the same sign and hence reinforce, strengthening and sustaining the anomalies as they are advected across the South Pacific. However, depending on the periodicity of ENSO variability in the equatorial/tropical Pacific in relation to variability in the advective timescale across the South Pacific, this need not always be the case. Antiphase variability generated locally and remotely in the southeast Pacific would tend to dampen anomalies as they are advected toward the South Atlantic.

This is potentially of significance with relation to long-period behaviour of the Antarctic Circumpolar Wave (ACW; e.g. White and Peterson, 1996), a mode of climate variability with two opposing sets of anomalies that propagate around the Southern Ocean. Although the link between the ACW and ENSO has been established (e.g. Peterson and White, 1998), it has also been noted that the ACW exists only during certain time periods, and is distorted or absent during others (Connolley, 2002). Two views tend to prevail when considering the ACW, firstly that it is a genuine coupled phenomenon, sustained by local air-sea interaction, and secondly that it is more the passive advection of anomalies by the ACC. Our findings suggest that, for the South Pacific and southwest Atlantic sectors of the Southern Ocean, a "resonance" phenomenon may better explain the ACW behaviour (especially at longer periods), with the phasing of advective anomalies with relation to local air-sea-ice interaction controlling their strengthening or damping.

Unlike ENSO, which has its strongest footprint in the South Pacific, the SAM is a circumpolar mode of climate variability and thus has the ability to influence South Georgia SST more directly through local air-sea interaction processes. Note that our finding of most significant correlation at approximately 1 month lag between the SAM and South Georgia SST is supported by Sengupta and England (2006), who also observe a lag of this magnitude, which they ascribe to the large thermal capacity of the ocean mixed layer. They argue that the SST response is driven primarily by two factors, namely the action of meridional currents and the response of air-sea heat fluxes. They note specifically that all of the sensible, latent and net radiation fluxes work in unison to given a positive SST response to increasing SAM in a band stretching from Drake Passage eastward to Australia (the peak response they found is very close to Drake Passage, i.e. immediately upstream from South Georgia in the ACC).

Although we have stressed that the SAM is a circumpolar mode, and so has the potential to influence South Georgia SST locally via its footprint in the southwest Atlantic, it should be noted that it is not perfectly zonally symmetric. This is readily seen in Figure 12, which shows the spatial pattern of correlation of meridional and zonal winds with the SAM index. As expected for the SAM, zonal winds show a strong positive correlation for the band of westerlies that overlie the ACC (Figure 12b). However, the non-zonal aspects of the SAM are clearly seen in Figure 12a, where SAM-related meridional wind anomalies can be seen over the Southern Ocean, most notably in the Pacific sector. The most significant of these are centred in the Bellingshausen Sea, adjacent to the WAP. (For comparison, Figure 13 shows the correlation of the same meridional and zonal winds, but with ENSO rather than the SAM. Note that the pattern of correlation with meridional winds in the south and southeast Pacific is the same as that seen for the correlation of winds with South Georgia SST (Figure 10a), just with the signs reversed).

These SAM-related meridional wind anomalies in the Bellingshausen Sea mean that, in a manner similar to ENSO influencing sea ice extent and SST close to the WAP, the SAM can also induce such anomalies that then advect to South Georgia. (This is seen also in Figure 11b, where an anti-phase relationship between the SAM and ice extent at 70°W can be seen). Note that the lag between the SAM and SST anomalies at South Georgia induced via this process will be longer than for anomalies induced locally by forcing by the SAM, since the advective transfer timescale is of order 5-6 months. Combined, these local and remote processes would give an average lag larger than zero but shorter than that for ENSO, as is seen in the observations (Figure 6b, c.f. Figure 6a).

Concluding remarks

We have seen that SST at South Georgia (and more generally in the southwest Atlantic) is subject to both local and remote forcing by at least two large-scale coupled modes of climate variability in the Southern Hemisphere (SAM and ENSO), with strong implications for physical forcing of the marine ecosystem here. The mechanisms whereby these modes influence SST across the South Pacific and into the southwest Atlantic are shown schematically in Figure 14. (Although by necessity a simplification, this schematic captures the main elements of the system). Taking a starting point of an El Niño event (Year 0 in Figure 14a), the sequence progresses as follows: (a) ENSO and SAM create SST anomalies in the southwest Pacific through remote teleconnections and local processes respectively. At this time, a previously-formed anomaly of opposite sign generally occupies the southwest Atlantic. (b) During the next ~2 years, the SST anomaly is advected by the ACC to the southeast Pacific adjacent to the WAP, where meridional winds associated with both ENSO and the SAM modify the anomaly through air-sea-ice interaction. (Note the phase of ENSO has typically reversed during this ~2 year period, hence the modification is generally a reinforcement rather than a dampening). Much of the SST variability observed in the southwest Atlantic is associated with these interactions in the southeast Pacific. (c) Around 6 months later, the anomaly reaches South Georgia and environs, still being subjected to air-sea interaction from both ENSO and the SAM. Note that Figure 14 depicts conditions relative to an El Niño in Year 0 (Figure 14a); conditions following a La Niña event in Year 0 would show the same patterns but with reversed signs.

The time period of our study is, by necessity, the satellite era. During this period, ENSO had a marked preponderance of El Niño events compared with La Niña events, due to the large El Niños in 1983, 1987, 1992 and 1998. This has given ENSO indices a pronounced bias during this period, and the sign of the correlation between South Georgia SST and ENSO suggests that this might have induced a cold bias in South Georgia SST for this period. Long-period behaviour is also apparent in the SAM, which has shown a marked trend toward a higher-index state (i.e. stronger circumpolar winds) during recent decades (e.g. Thompson *et al.*, 2000). The in phase relationship we have observed between SAM and South Georgia SST suggests this might be reflected as an increase in South Georgia SST for this period, were this the only forcing. However, over the time period of our study, the South Georgia SST actually showed a small negative trend, equivalent to a cooling of 0.14°C over the total period (note though that this is a small fraction of the standard deviation of the series of 0.45°C). Thus, whilst we have seen that the SAM can influence South Georgia SST at interannual timescales, and it certainly has the potential to do so on longer (decadal) timescales, it was apparently not the prime driver of the direction of SST change here during the 1980s and 1990s, in that the change in SST that one would predict based on the SAM changes is of the opposite sign to that observed. Instead, it is more likely that the variability in ENSO and other climate-scale processes dominated the direction of SST change here during this period. Nonetheless, if the SAM continues to show an upward trend, changes in SST around South Georgia must be expected in response, with potential consequences for the marine ecosystem. It is worth noting that the trend in the SAM has been ascribed to anthropogenic effects, at least partially, with both greenhouse gas emissions and ozone depletion being implicated (Marshall *et al.*, 2004; Thompson and Solomon, 2002). Thus long-period changes in the South Georgia ecosystem that are ultimately ascribed to the trend in the SAM should also be considered as originating at least partially from anthropogenic causes.

With regard to ENSO, we note that the results we obtain here are derived from moderately long series that include a number of El Niño events. As such, the correlational and spectral analyses we performed are best considered to be representative of "canonical" ENSO events. However, individual events can vary greatly, and can have dramatically different impacts on high latitude ocean properties (Lachlan-Cope and Connolley, 2006). Understanding the generic high-latitude response to ENSO (also to SAM) is the first step toward maintaining a sustained high level of skill in prediction; however, understanding the causes of individuality in each event is also required, and further work is needed to develop this.

In this paper, we have viewed the ocean largely as a simple receptor and advector of atmospherically-induced SST anomalies, and the results we have seen support this being a reasonable zero-order depiction. This is also consistent with the results of Verdy *et al.* (2006), who also observed that a reasonable approximation of SST anomalies in the ACC could be obtained by considering SAM and ENSO forcing of the ocean mixed layer combined with a simple model that advects anomalies. Verdy *et al.* (2006) state that they find no compelling evidence for ocean-atmosphere coupling in maintaining or transferring SST anomalies. However, recent evidence has suggested that there is feedback from SST anomalies to the atmosphere that can influence the magnitude of the SAM (Marshall and Connolley, 2006; Sengupta and England, 2006); this is potentially significant when attempting to predict the response of South Georgia SST to potential long-period changes in SAM forcing.

We note that a number of the relationships we have described here are similar in nature to those outlined previously in terms of an Antarctic Dipole. This is perhaps not surprising for the ENSO connections, since the link between ENSO and the Antarctic Dipole is well established (e.g. Yuan, 2004). It is hoped that the mechanisms we have outlined (including the important roles of oceanic advection and the SAM) will enable progress in better understanding the dynamical nature of this phenomenon also.

With respect to the rate of advection of anomalies by the ACC, it is known that this will vary in response to changes in the SAM (Meredith *et al.*, 2004b), although the changes in transport rate are small. However, potentially of much more significance is the observation that eddy activity in the Southern Ocean responds circumpolarly to a change in the SAM (Meredith and Hogg, 2006).

These authors observed a time lag between SAM forcing and ocean eddy response (around 2-3 years), and they argued that the poleward eddy heat flux (and hence ocean temperature) could also show a response on this timescale. This implies a level of complexity in the ocean/atmosphere system that is not included in our results above, and is not captured by the current generation of coarse-resolution climate models. It will, however, need careful consideration if the long-term changes in ocean properties and ecosystems are to be reliably predicted.

The ecosystem at South Georgia is known to be heavily reliant on a supply of Antarctic krill to sustain the large colonies of predators. This krill is believed to be sourced, at least in part, from key breeding and nursery grounds at the WAP, with advection by the ACC to South Georgia an important process in maintaining the supply of krill to this location (Murphy *et al.*, 2007). A range of studies has shown this process to be in operation, and it is also believed that numerous factors (including the presence of extensive sea ice in the Scotia Sea) are critical in sustaining the krill as they are advected toward South Georgia (see Fach *et al.* (2006), Fach and Klinck (2006) and Murphy *et al.* (2007) for recent comprehensive studies).

It has been shown in modelling studies that relatively small movements of the SACCF adjacent to the WAP can greatly reduce the possibility for transport of krill from this region to South Georgia (Fach and Klinck, 2006). We extend this finding to suggest here that the direction and strength of meridional wind anomalies at the WAP can be instrumental in promoting the retention of surface and near-surface waters south of the southern edge of the ACC, or conversely enhancing the injection of such waters from this location into the ACC (this is the process by which SST and sea ice anomalies are generated; see above). Anomalies in krill density in the southern ACC would then be created, with the potential to be reflected ultimately as anomalies in krill density around South Georgia. Although this requires further study for proof (ideally with high-resolution physical/biological ocean modelling), this represents a direct physical mechanism that can generate interannual variability in the Scotia Sea and South Georgia ecosystems. ENSO-related interannual variability has already been observed in various ecosystems indicators at South Georgia and in the South Atlantic, thus we suggest that this mechanism should be investigated further as a matter of priority to better understand the causes of this relationship.

To summarise, we have developed a conceptual framework whereby SST at South Georgia is forced by a combination of local and remote processes, with interannual variability induced through a combination of ENSO and the SAM. We have observed the previously-highlighted long-period advection of anomalies to South Georgia (advective periods of a few years); we stress here however that modification of these anomalies and shorter-period advection within the ACC from immediately upstream in the southeast Pacific are key processes, as is direct atmospheric forcing at the ocean surface. Combined, these imply a more direct connection between atmospheric modes of climate variability and ocean properties in the southwest Atlantic. These processes all require consideration when assessing the physical forcing of the South Georgia marine ecosystem, its connectivity with regions upstream in the ACC, and how the system is likely to change into the future.

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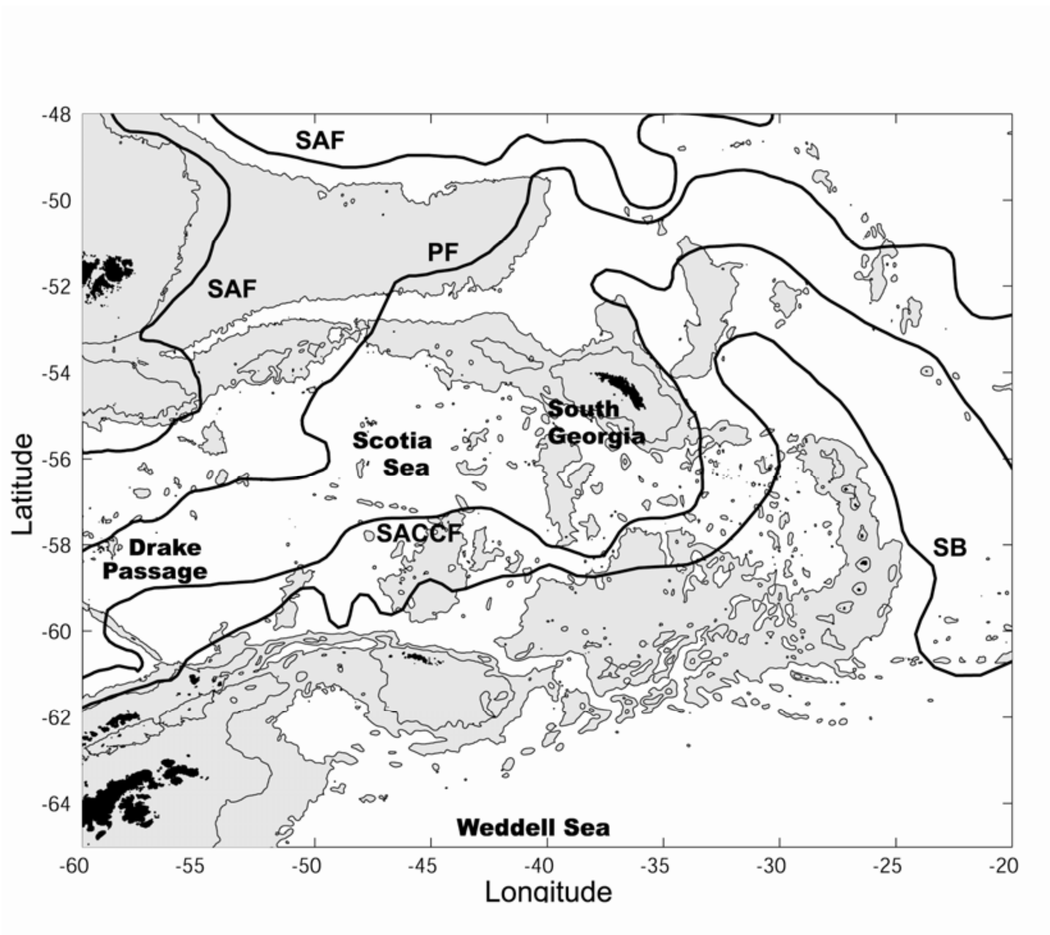

Figure 1. Bathymetry surrounding South Georgia. The 1000 and 3000m isobaths are marked; depths shallower than 3000m are shaded. The positions of the ACC fronts are marked schematically, based on Orsi *et al.* (1995) and updated following Meredith *et al.* (2003b) and more recent information. SAF = Subantarctic Front; PF = Polar Front; SACCF = Southern ACC Front; SB = Southern Boundary of the ACC.

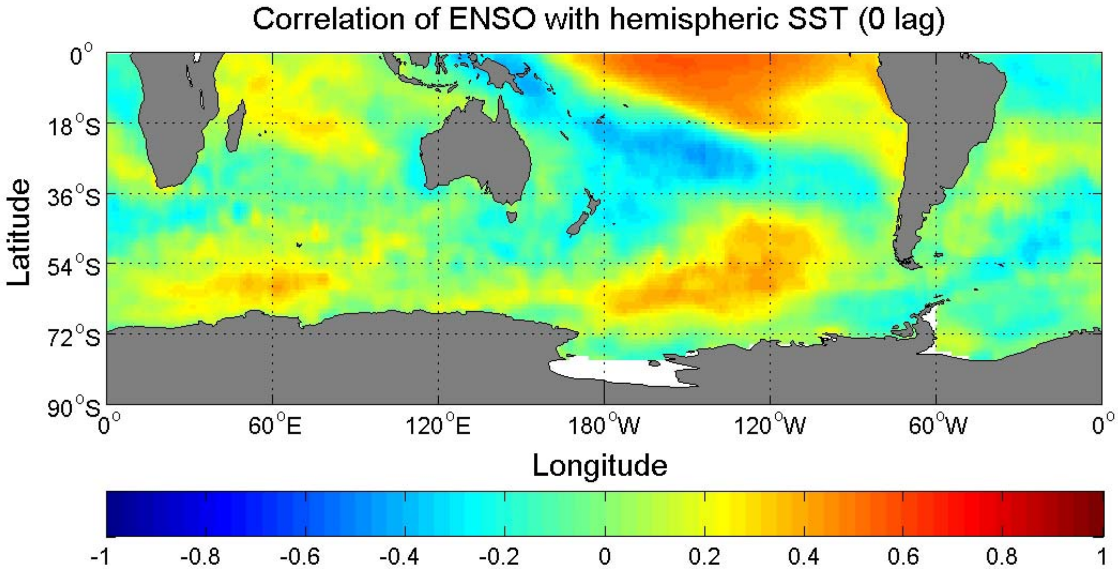

Figure 2. Spatial pattern of correlation of monthly-mean Sea Surface Temperature (SST) with the Bivariate ENSO Time Series (BEST) index. Note in particular the alternating bands of positive and negative correlation in the equatorial/South Pacific.

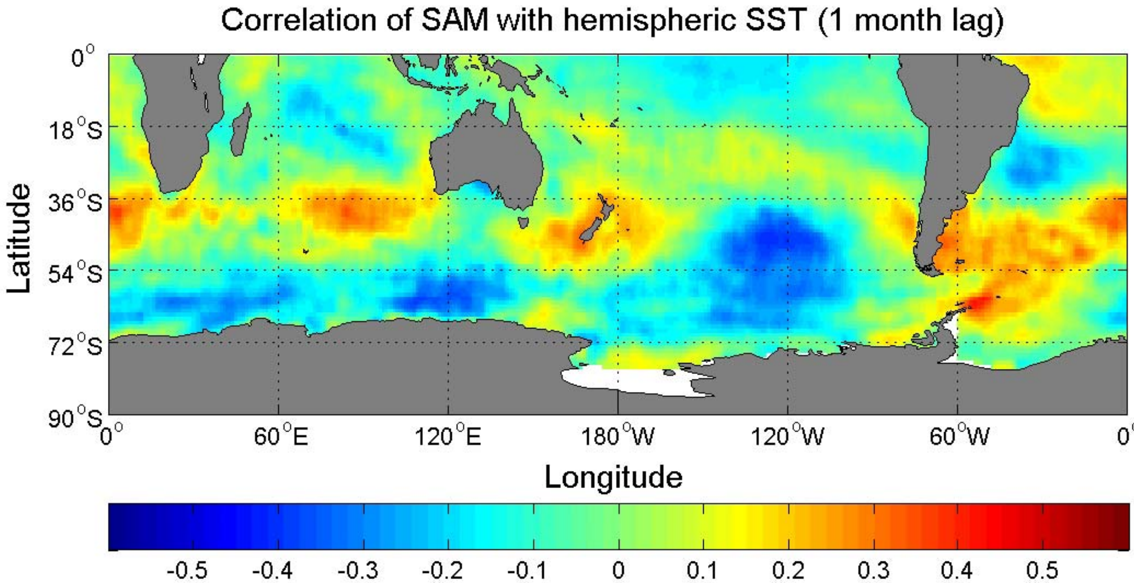

Figure 3. Spatial pattern of correlation of the Southern Annular Mode (SAM) index with global monthly-mean Sea Surface Temperature (SST), for 1 month lag. Note in particular the band of positive correlation along approximately 40°S, flanked to the south by a band of negative correlation, and interrupted in the South Pacific. Note also that the Scotia Sea (Figure 1), including the area surrounding South Georgia, is marked by pronounced positive correlation. (Colour scale differs from that used in Figure 2).

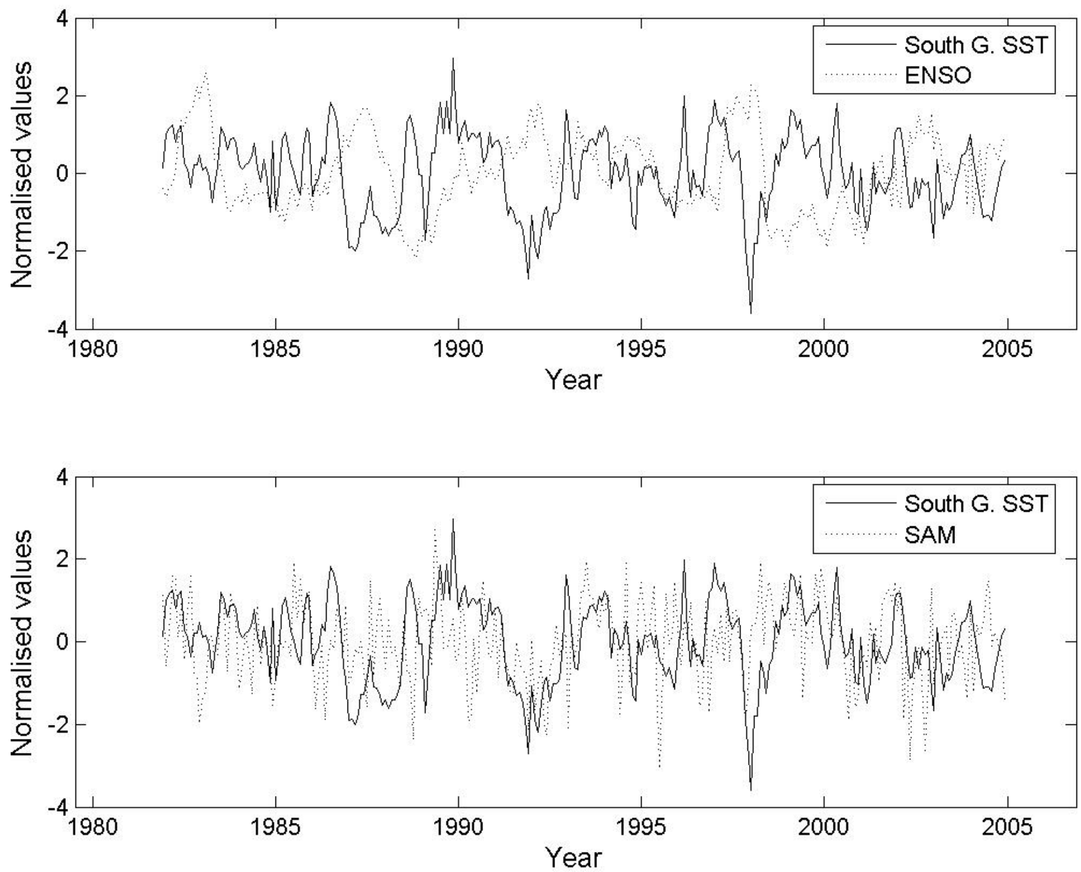

Figure 4. (a) Time series of SST at South Georgia (solid) and the ENSO BEST index (dashed). (b) SST at South Georgia (solid; as per (a)) and the SAM index. Normalisation was performed by subtracting the mean from each series, and dividing by their standard deviations.

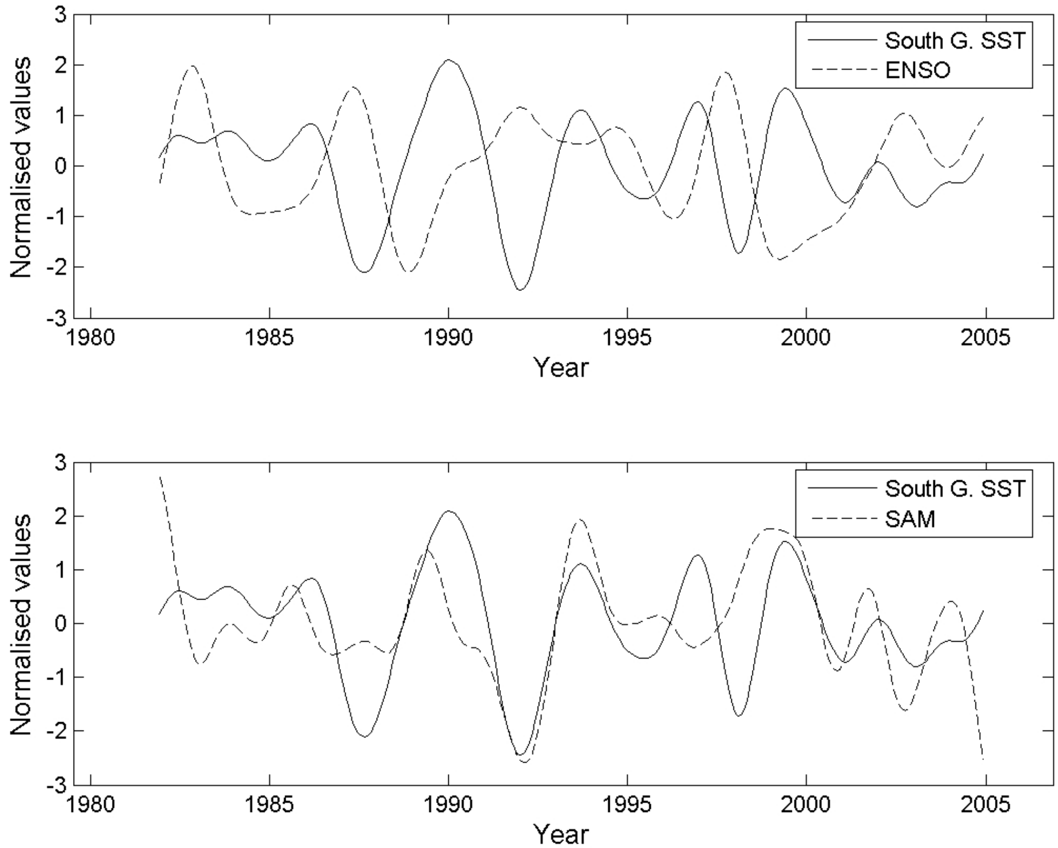

Figure 5. As for Figure 4, but for series smoothed with a 2 year filter to highlight interannual variability.

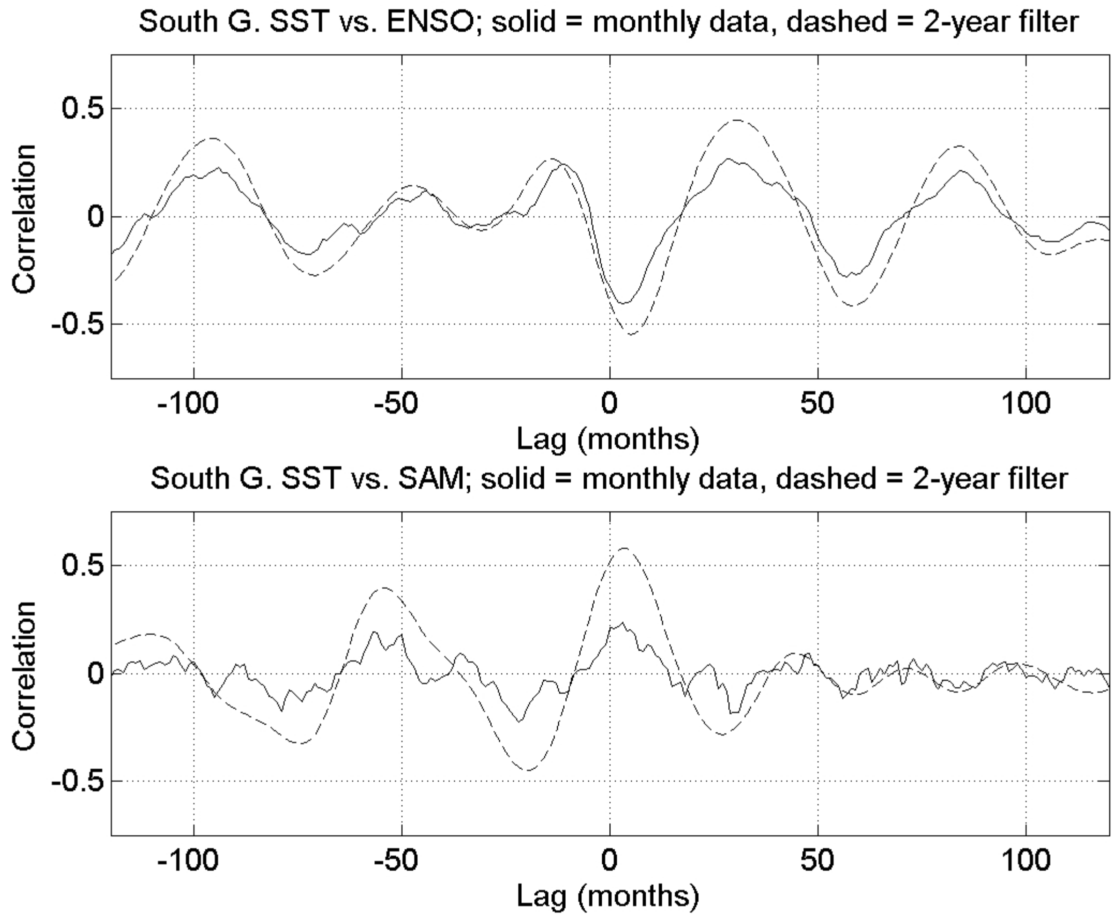

Figure 6. Lagged cross-correlation functions for (a) South Georgia SST and ENSO, and (b) South Georgia SST and the SAM. Solid curves denote correlations based on monthly anomalies; dashed curves denote correlations based on series smoothed with a 2 year filter. For the upper panel (a), the 95 and 99% significance levels at zero lag (derived accounting for autocorrelation in the series as per Trenberth (1984)) are 0.29 and 0.38 for the monthly data respectively, and 0.51 and 0.62 for the 2-year filtered data respectively. For the lower panel (b), the corresponding 95 and 99% significance levels are 0.15 and 0.20 for the monthly data respectively, and 0.42 and 0.56 for the 2-year filtered data respectively.

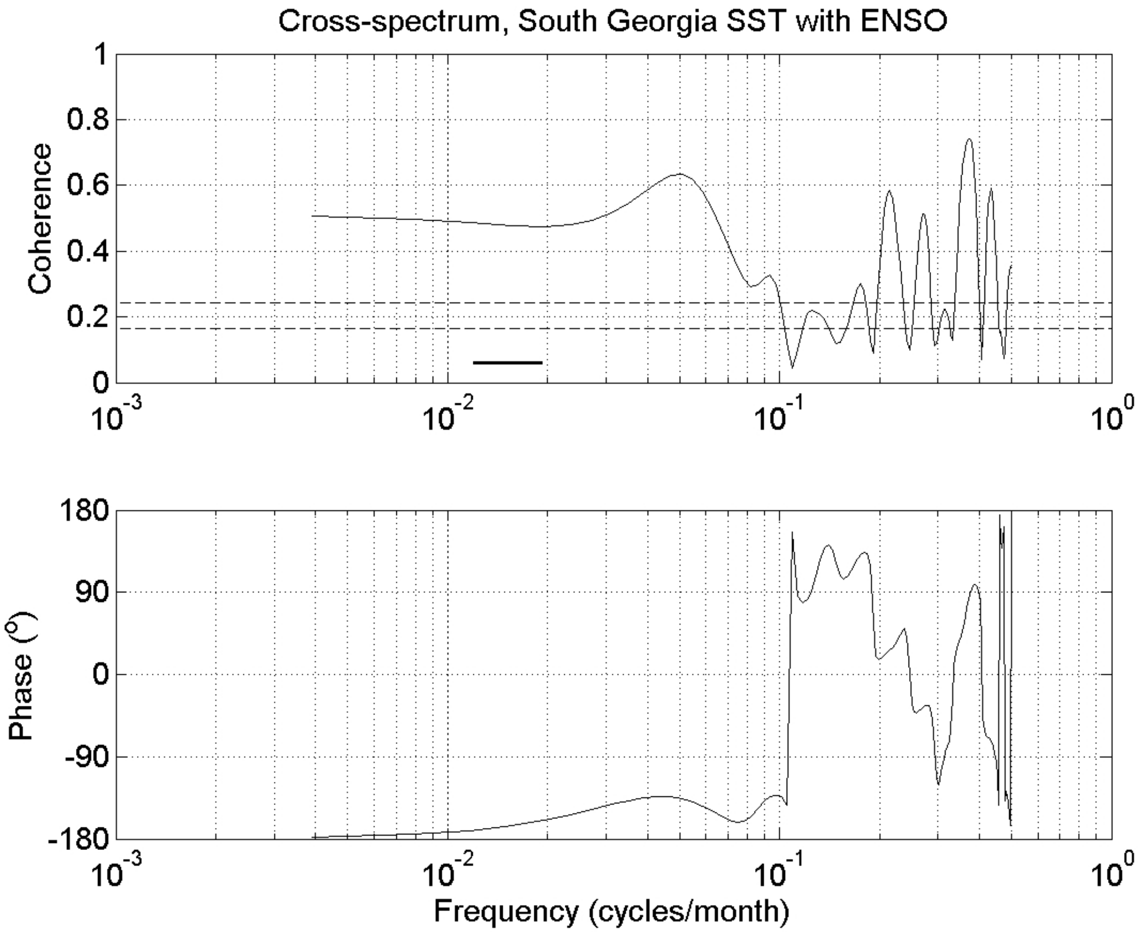

Figure 7. Cross spectrum between South Georgia SST and ENSO. The horizontal dashed lines in the coherence spectrum denotes the 95% and 99% significance levels. The horizontal bar in the coherence spectrum denotes bandwidth, calculated as per Harris (1978). (Note that the logarithmic horizontal axis would reduce the apparent length of this bar at higher frequencies).

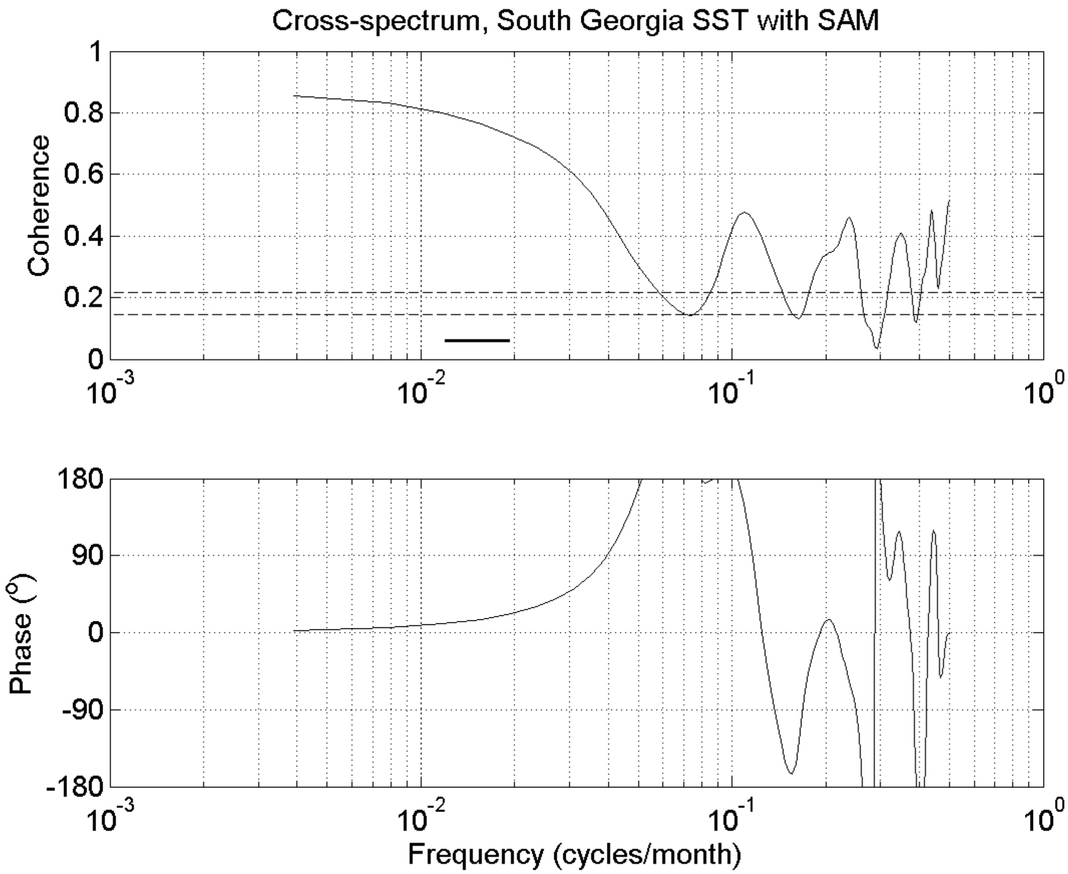

Figure 8. As for Figure 7, but for the cross-spectrum between South Georgia SST and the SAM.

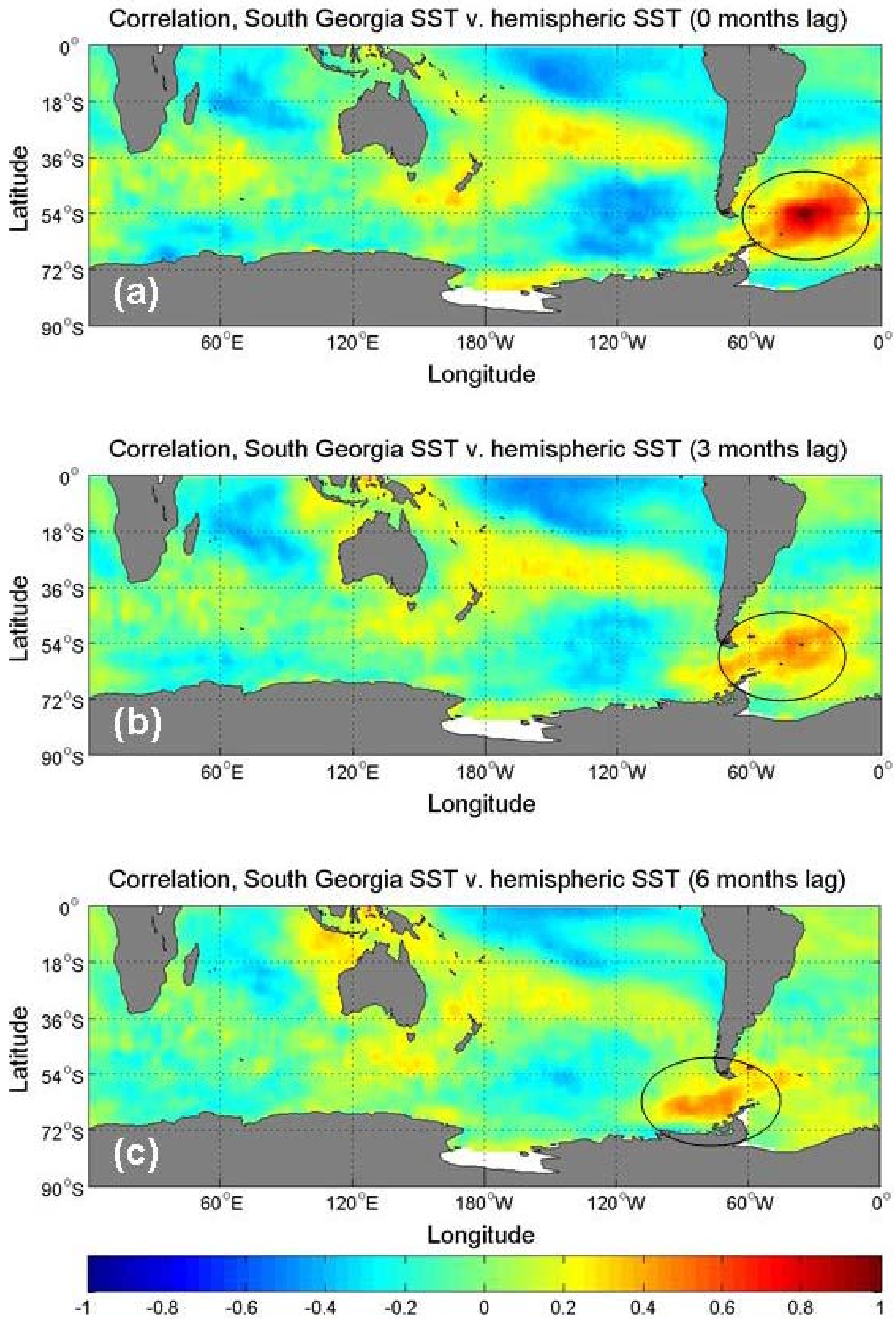

Figure 9(a-c). Spatial patterns of correlation between monthly-mean South Georgia SST and Southern Hemisphere SST, for (a) 0 month lag, (b) 3 months lag and (c) 6 months lag. Note that the anomaly around South Georgia at 0 months lag (circled in 9a) is seen progressively further upstream in the ACC at longer lags.

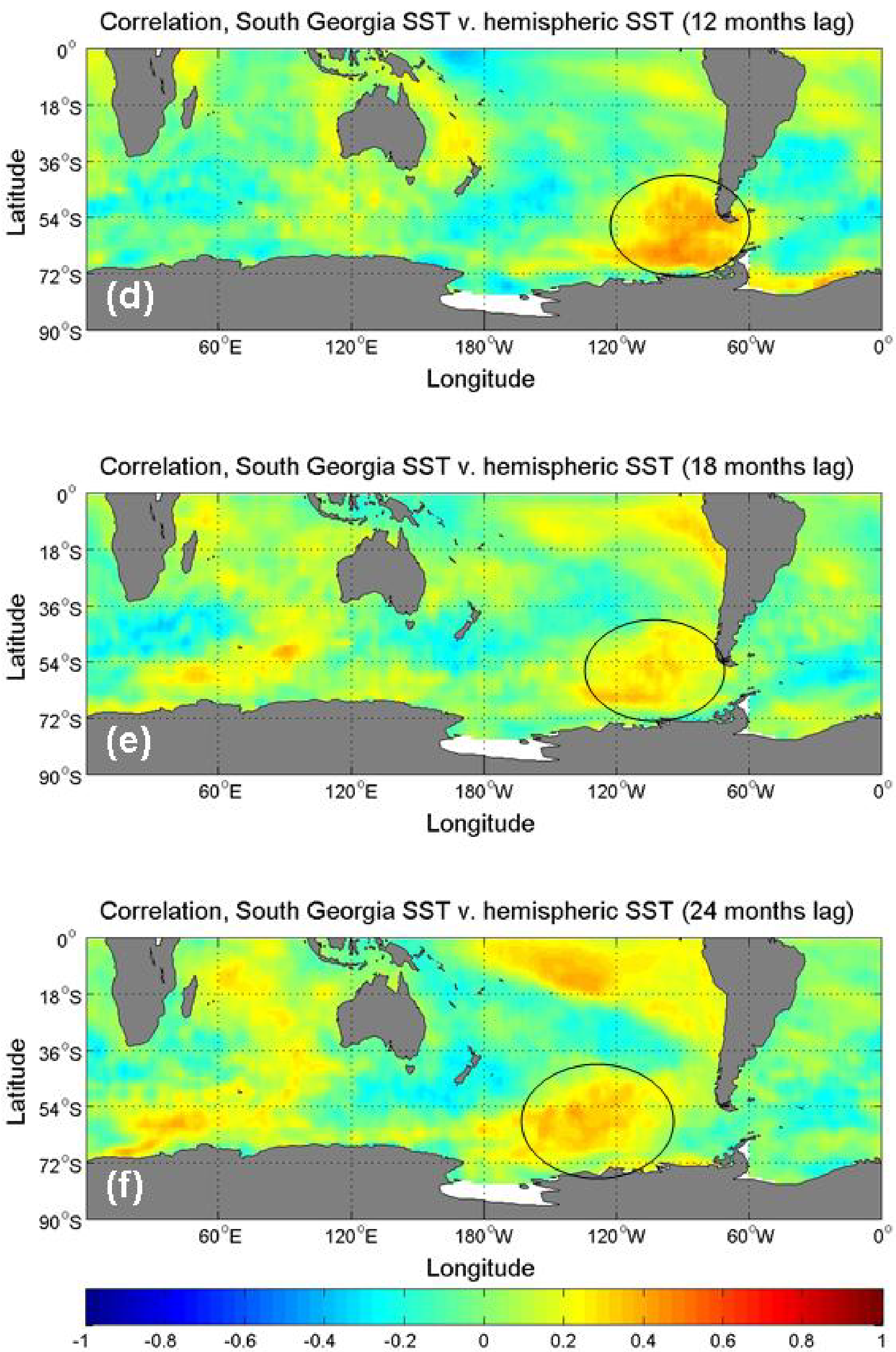

Figure 9(d-f). Spatial patterns of correlation between monthly-mean South Georgia SST and Southern Hemisphere SST, for (d) 12 months lag, (e) 18 months lag and (f) 24 months lag. Note that the anomaly around South Georgia at 0 months lag (circled in 9a) is seen progressively further upstream in the ACC at longer lags.

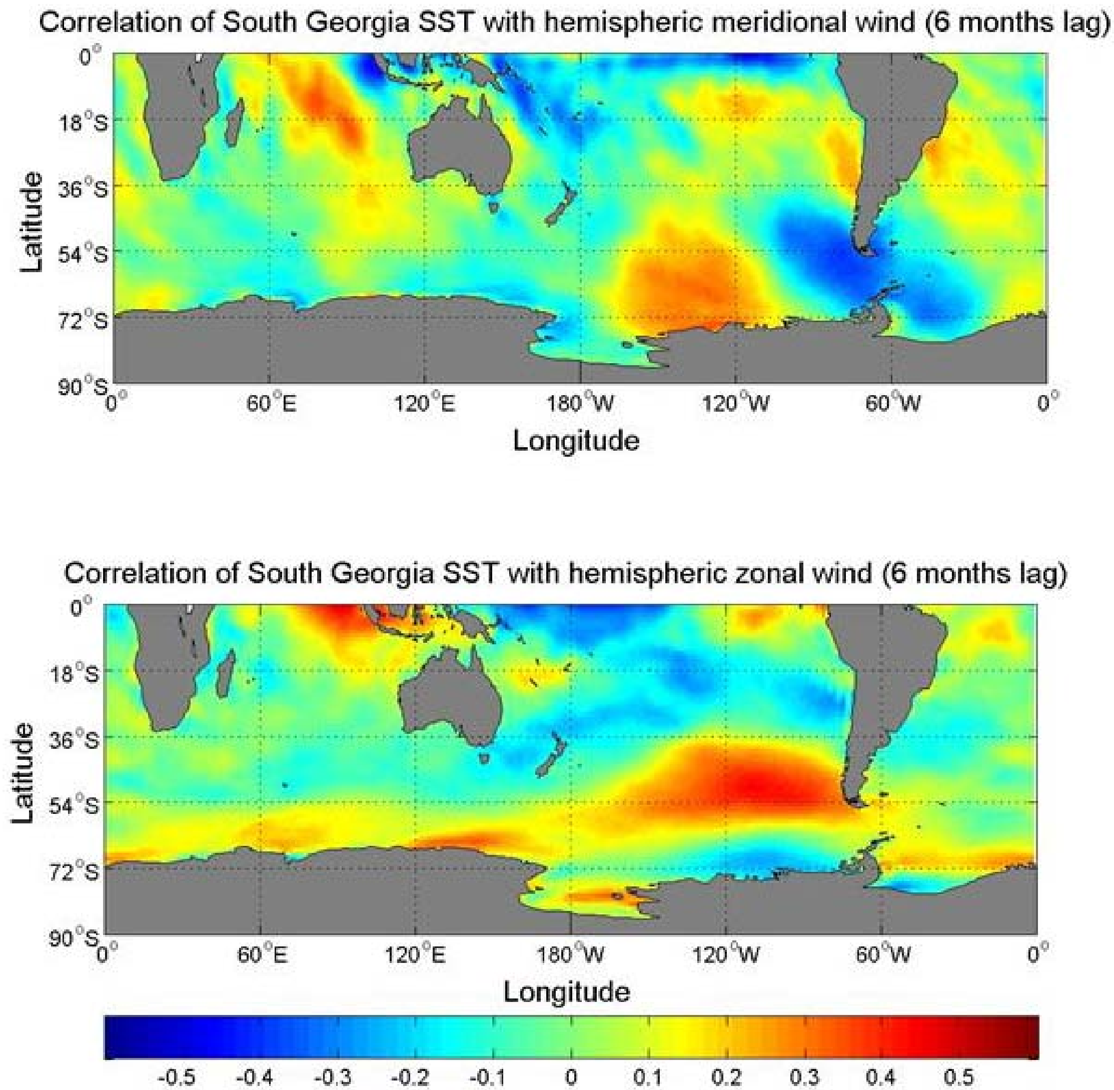

Figure 10. (a) Correlation of monthly-mean South Georgia SST with Southern Hemisphere meridional winds from the ECMWF ERA40 reanalysis. (b) as for (a), but for zonal winds. Note in particular the correlation with rotating winds in the southeast Pacific, immediately west of Drake Passage.

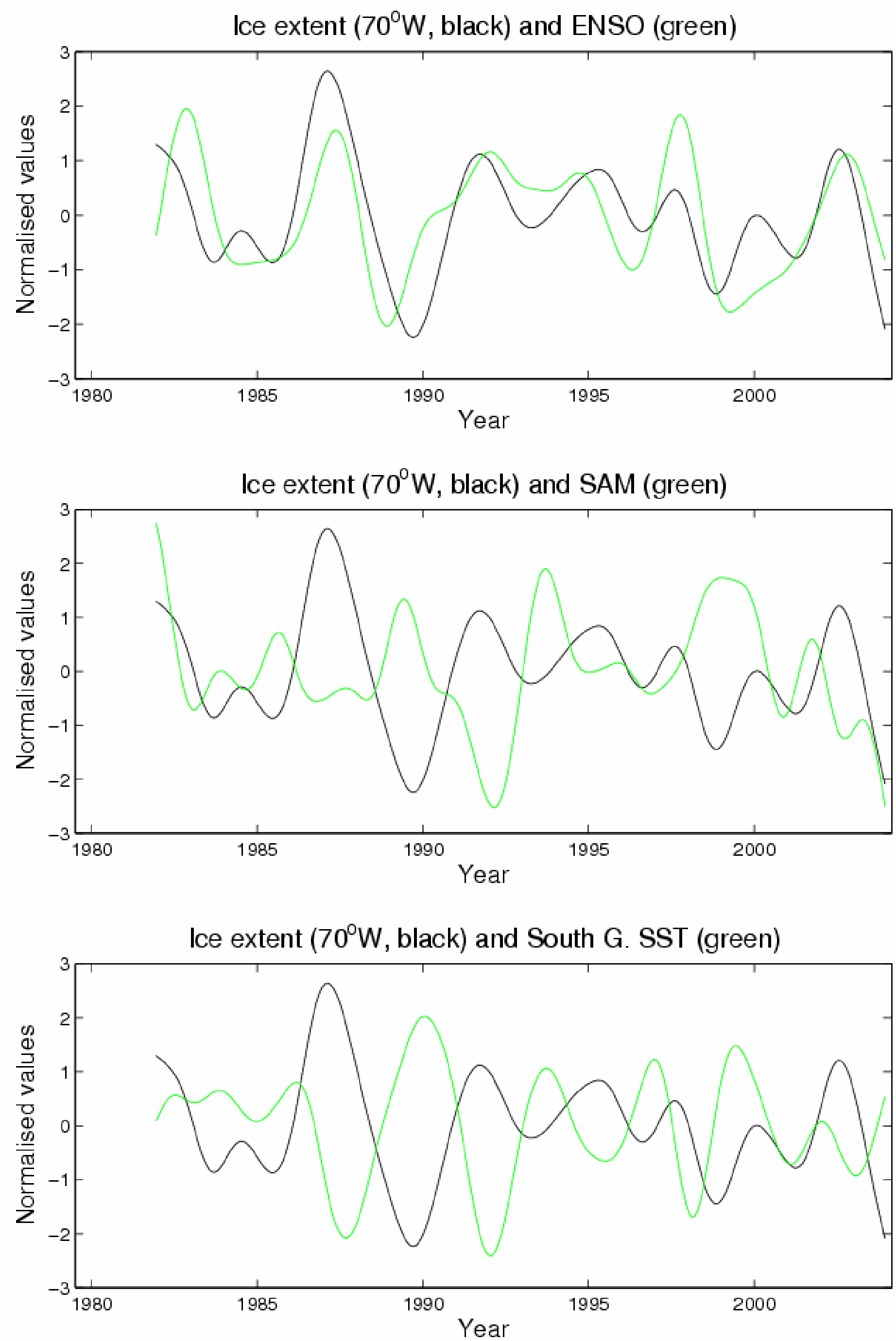

Figure 11. Time series of ice extent at 70°W (longitude of the West Antarctic Peninsula) plotted alongside (a) ENSO BEST index, (b) the SAM index, and (c) South Georgia SST. All series are smoothed with a 2-year filter.

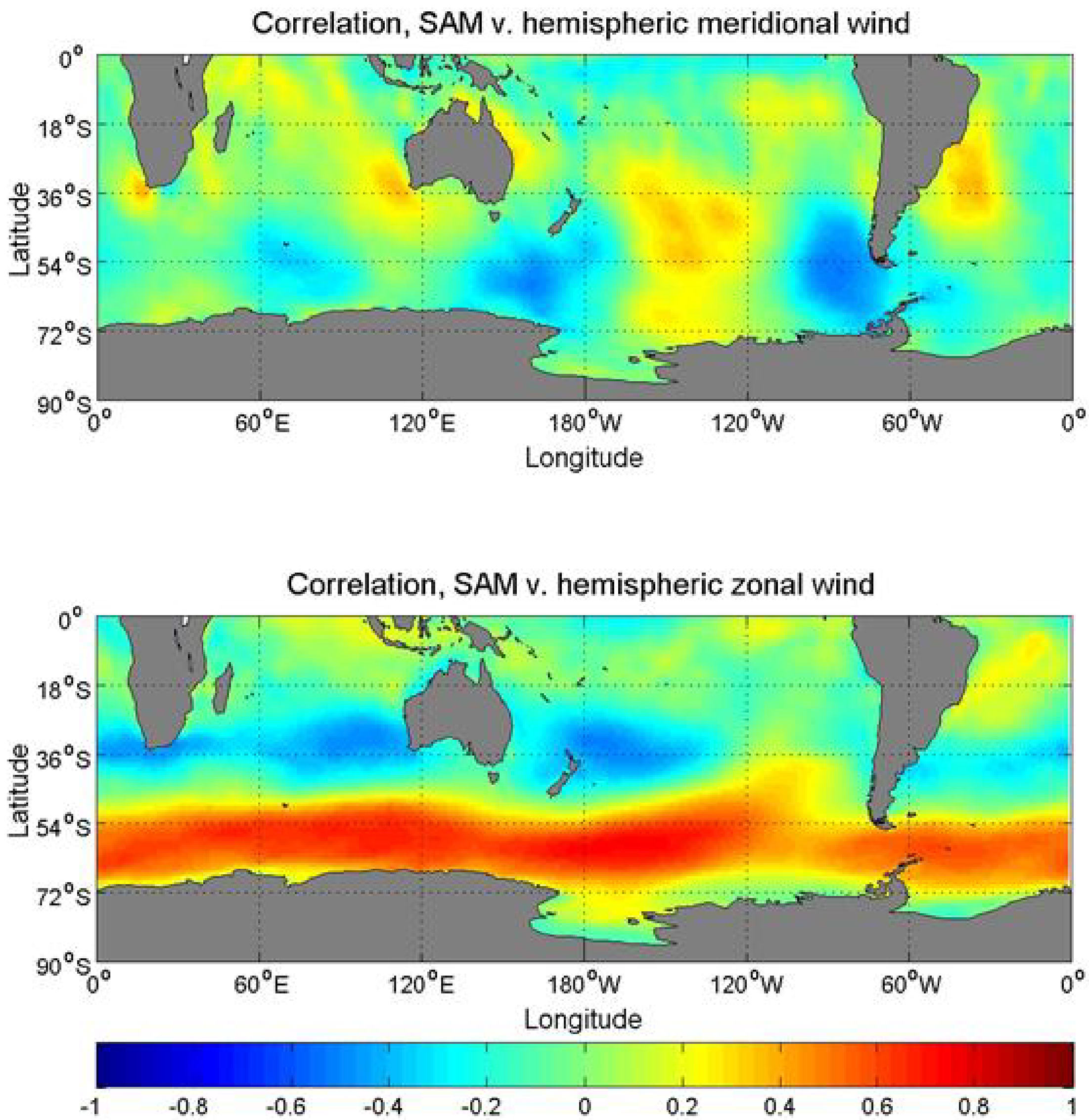

Figure 12. Spatial pattern of correlation of the SAM index with (a) Southern Hemisphere meridional winds, and (b) Southern Hemisphere zonal winds. Note in particular that the SAM induces strong meridional wind anomalies close to 70°W.

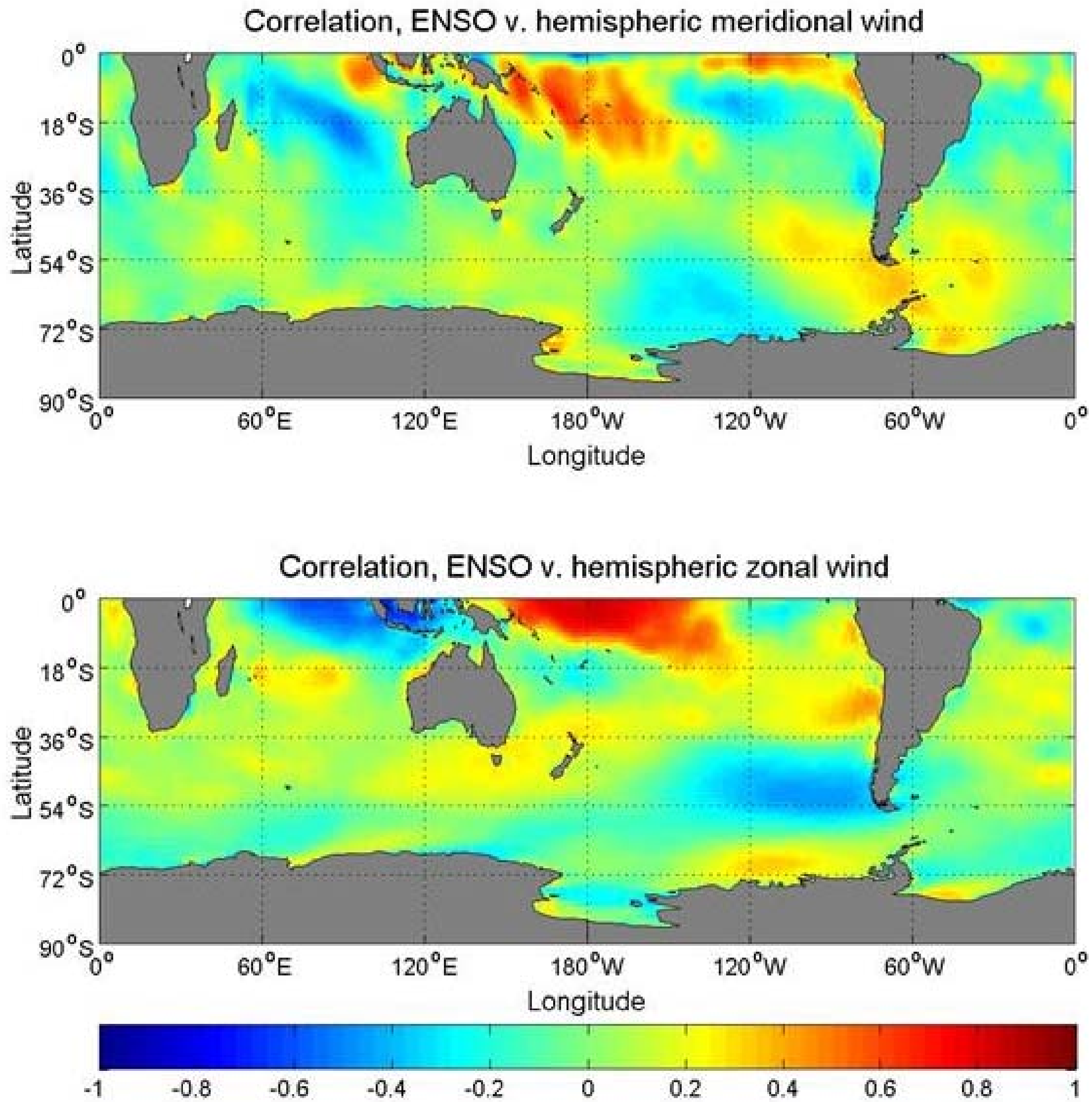

Figure 13. As for Figure 12, but for ENSO rather than the SAM.

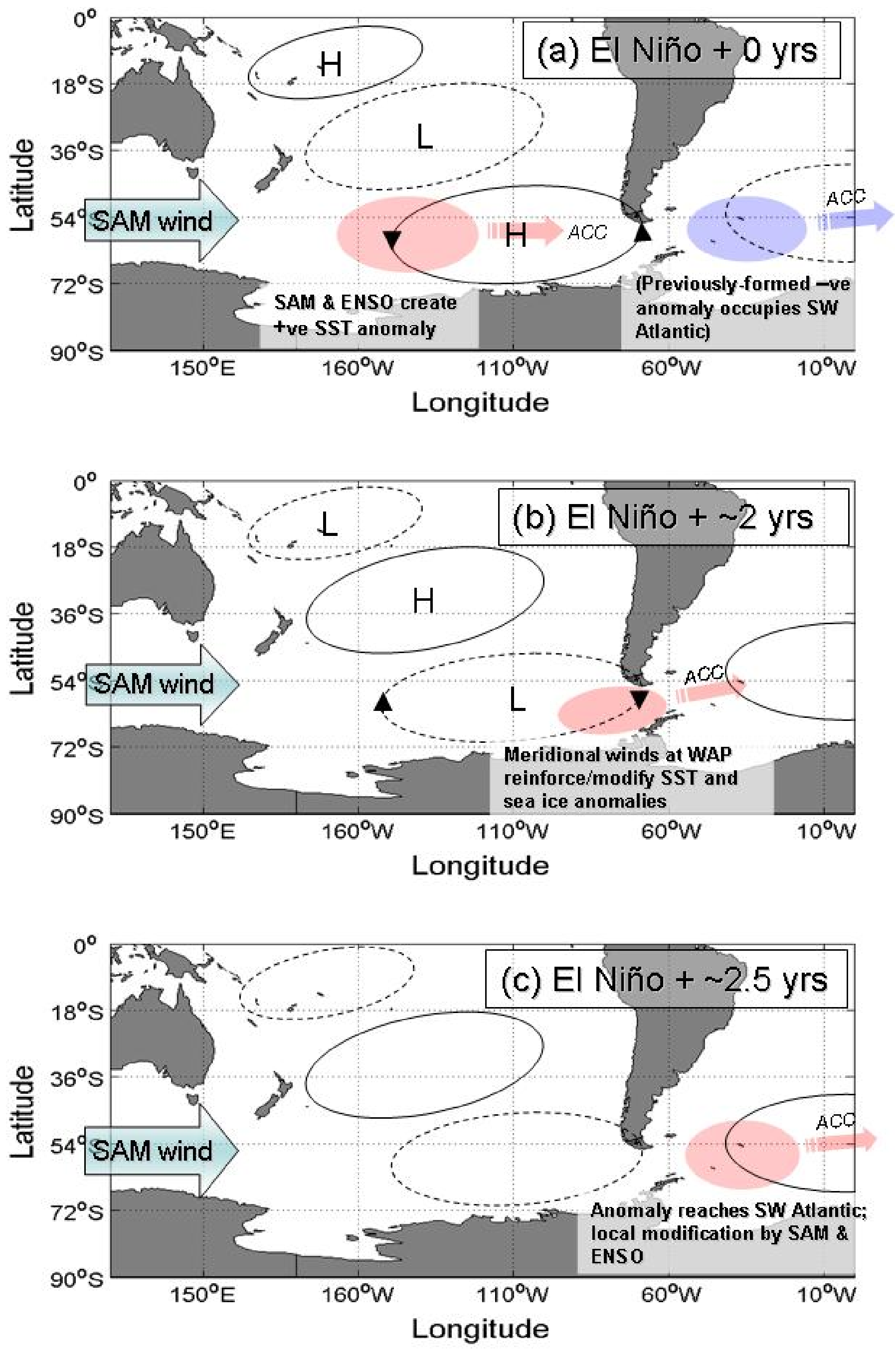

Figure 14. Schematic of the processes whereby ENSO and the SAM induce interannual variability in SST across the South Pacific and into the southwest Atlantic. SST anomalies are depicted as warm (pink) and cool (blue) patches. Open ellipses (solid and dashed) denote ENSO-related surface atmospheric pressure anomalies of opposite sign, flanked by rotating winds of opposite directions (arrows). Note that this figure depicts conditions relative to an El Niño in Year 0 (Figure 14a); conditions following a La Niña event in Year 0 would show the same patterns but with reversed signs. See main text for discussion of mechanisms.