Sea-surface temperatures at the sub-Antarctic islands Marion and Gough during the past 50 years

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Sea-surface temperatures (SSTs) have been measured at Marion and Gough islands for nearly 50 years. These are some of the longest records of their kind in the sub-Antarctic. We present the trend, the seasonal cycle, and the time-frequency characteristics of the SST for both islands, which rose by 1.4°C at Marion Island and by 0.5°C at Gough Island over the 50-year period. Intermittent temperature oscillations, with periods of between 1 and 5 years, were observed throughout the record. A 5-year periodicity, compatible with an Antarctic Circumpolar Wave signature, dominated after 1990 in both records. We also observed a strong low-frequency component with a period varying from 9.3 to 11.4 years at Marion Island, and a much weaker component with a period varying from 9.9 to 11.8 years at Gough Island.

Sea-surface temperature (SST) has been measured at the two sub-Antarctic islands of Gough, from 1956 to 1998, and Marion, from 1949 to the present. Marion Island is part of the Prince Edward Island group in the Indian sector of the Southern Ocean (46°52′S, 37°51′E), whereas Gough Island (40°20′S, 10°0′W) lies close to the generic border of the Southern Ocean, the Subtropical Convergence,[1] in the Atlantic sector (Fig. 1). Marion Island therefore lies considerably farther poleward and is even intermittently influenced by eddies from the Antarctic sector that are generated at the South-West Indian Ridge.[2] In this paper, we perform some basic statistical analyses on the two ~50-year-long, monthly-averaged SST records at Marion and Gough. We then investigate the time-frequency characteristics of the temperature-anomaly signals with the continuous wavelet transform technique.

The sea-surface temperature records

The SST records consist of monthly averages based on daily observations (Fig. 2). The temperatures at Gough Island have been measured continuously from January 1956 to August 1998, when the coastal bridge, a natural feature from which observations were made, collapsed. Since then it has been considered too dangerous to continue taking measurements with a hand-held bucket at the island and so records ceased. The SSTs at Marion Island are still measured daily. The observations are carried out by scooping up surface water from a jetty in a special bucket with a mercury bulb thermometer attached, which is read while still immersed in the water sample. We believe that by averaging these potentially imprecise observations for a full month, any non-persistent errors would be removed. Comparison between these observations and those derived from satellite remote sensing[3] for the same region gives us confidence in the accuracy of the observations made at Marion. Obvious errors in the form of outliers in the readings arose from November 1998 to November 2000, due to a faulty thermometer. The record analysed here for Marion Island therefore begins in January 1949 and ends in October 1998. There are a few, relatively short, breaks in the record (Fig. 2, top). We have used the GISST version 2.3 data of the Hadley Centre[4] and the reconstructed SST data of Reynolds and Smith,[3] centred at Marion Island's location, to fill these gaps. As mentioned above, where reconstructed satellite data were compared with bucket observations, the fit was relatively good. We used the GISST information when the satellite data were not available and had to adjust them slightly to fill the gaps, but we have confidence that the mixture of these two data types does not interfere unduly with the statistical analyses performed here.

The mean value and standard deviation of the SSTs for each month are plotted in Fig. 3. At Marion Island, the mean temperature for the 49 years of the record varied from 4.3°C in September to 6.4°C in February. For all months, the mean temperature was 5.3°C and the mean standard deviation was 0.61°C. We note that the mean standard deviation of the de-trended SST was 0.49°C (see next section, where the trend is calculated). At Gough Island, the mean temperature for the 42 years of the record varied from 10.5°C in September to 14.1°C in February. For all months, the mean temperature was 12.2°C and the mean standard deviation was 0.69°C. The amplitude of the mean annual temperature cycle at Gough (3.6°C) is about twice that at Marion (2.1°C). There are anecdotal reports that the Subtropical Convergence in the South Atlantic passes Gough and Tristan da Cunha on a seasonal basis, but to date there has not been any observational evidence for this.[1] Such a movement would conceivably increase the steepness of the seasonal temperature trace during the austral spring and autumn. This is not obvious in the smooth seasonal temperature record of Fig. 2.

Trends in sea-surface temperature

A linear fit was used to estimate the long-term trend in SSTs at Marion and Gough. Since classical least-squares fitting can have undesired sensitivity to outlying points, we used a robust

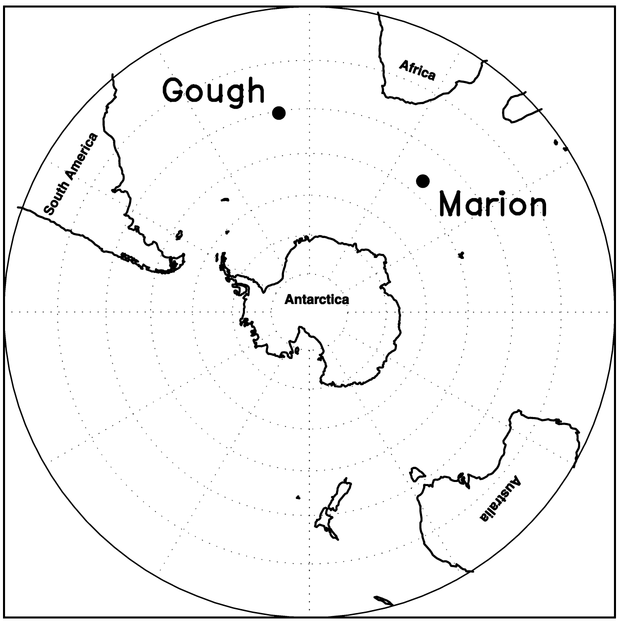

Fig. 1. Locations of Gough and Marion islands in the Southern Ocean.

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technique based on the minimization of the absolute deviation.[5] The trend at Marion Island (Fig. 2, top) was particularly strong, involving an increase in annual mean temperature from 4.5°C in 1949 to 5.9°C in 1998. This corresponds to a rise of 1.4°C in 49 years, or 0.03°C per year, similar to the value extracted from maps of temperature change published in the 2001 IPCC report.[6] This also agrees with the trend found for air temperature measured at the same location.[7] The SST trend at Gough Island (Fig. 2, bottom) was much weaker. Annual mean temperature increased from 11.8°C in 1958 to 12.3°C in 1998, representing a rise of 0.5°C in 41 years, or 0.01°C per year. The weaker trend at Gough Island is consistent with re-constructed SST data[3] for the 40–45°S zone, which indicates that the weakest warming trend between 1950 and 1999 was located in the central South Atlantic, near Gough Island, and the most conspicuous warming lay south-east of Africa near Marion Island. A natural extension of our analysis will be to compare the marked SST increase at Marion with other climate analysis fields, in relation to the global warming observed in the southern hemisphere.

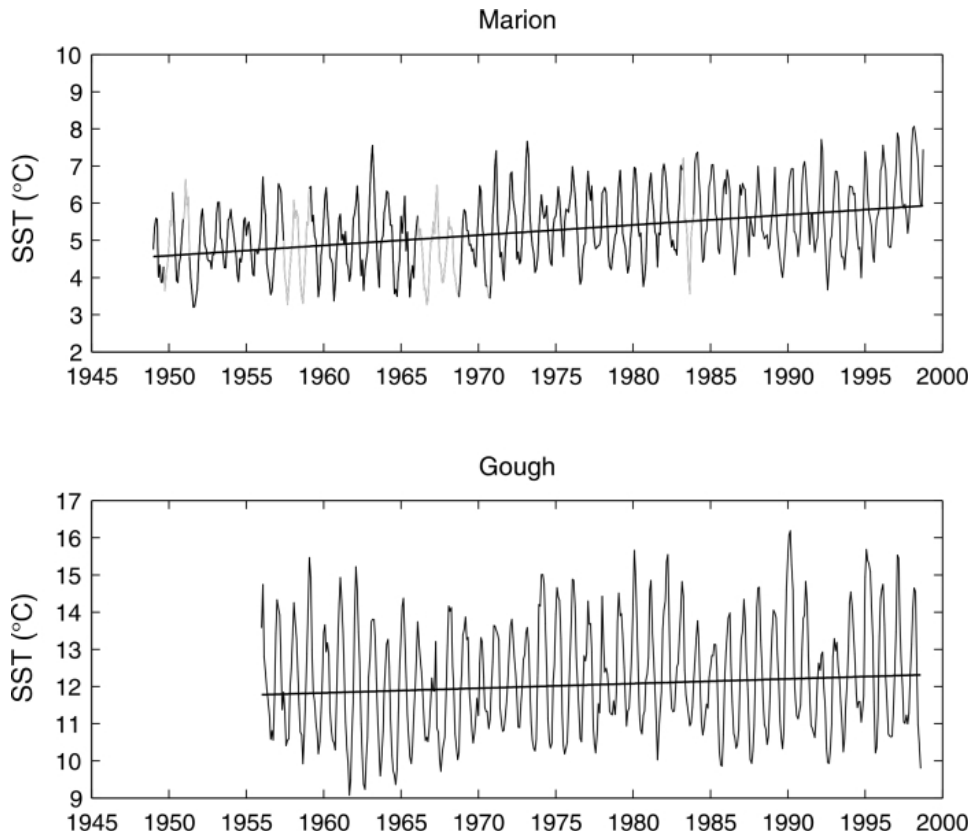

Fig. 2. Monthly means of sea-surface temperature (SST) and their trends at Marion and Gough islands. The breaks in the record which have been re-constructed, are plotted in grey.

Time-frequency characteristics of sea-surface temperature anomalies

To obtain the anomalies, the SST signals at Marion and Gough were de-trended, filtered with a continuous wavelet transform filter to remove the seasonal cycle (see ref. 8 for the method used), smoothed with a 3-month running mean, and finally normalized. We investigated the time-frequency characteristics of the SST anomalies with the continuous wavelet transform (CWT).[9] The CWT expands the SST signal into a two-dimensional parameter space and yields a measure of the relative amplitude of local activity at any time and frequency. The CWT therefore enabled us to estimate the time-frequency characteristics, such as the amplitude and frequency modulations of the different components of the signal. Generally speaking, the CWT is infinitely redundant, the one-dimensional original signal being transformed into a two-dimensional time-frequency image. Nevertheless, the fundamental information can be extracted from the so-called ridges of the CWT. These ridges consist of continuous lines in the time-frequency representation from which the different deterministic components of the signal can be extracted. The wavelet used here was the classical Morlet complex wavelet and we plotted the amplitude (modulus) of the CWT. For each image, the CWT was computed for periods varying from 2 months to 24 years. Beyond 24 years, the amplitudes are negligible and are not displayed. Intermittent oscillations with periods between 1 and 5 years were observed throughout the record. We also observed a strong low-frequency component with a period around 8–12 years for Marion Island (Fig. 4) and a much weaker component with about the same period for Gough Island (Fig. 5). We used the CWT ridge procedure[10] to extract these components with precision. In both CWT images, the low-frequency component can be extracted from one ridge (see the line superimposed on each CWT image), which also provided an estimate of its time-varying period. For Marion, the period of the low-frequency component (Fig. 4) was between 9.3 and 11.4 years, whereas for Gough (Fig. 5) it varied from 9.9 to 11.8 years.

Several analyses of observed and modelled atmospheric and oceanic variables in the mid- to high latitudes of the southern

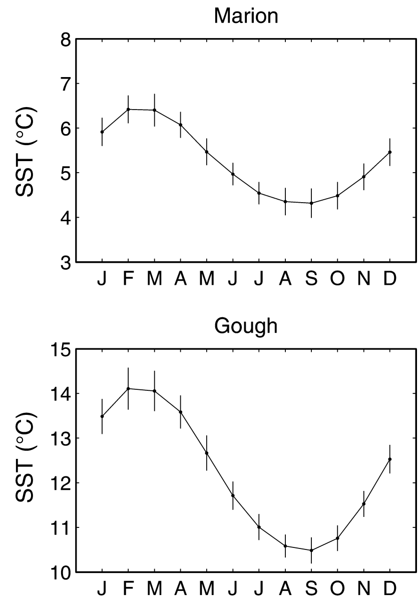

Fig. 3. Mean values and standard deviations (vertical bars) of the sea-surface temperatures (SST) for each calendar month at Marion and Gough islands.

hemisphere have revealed the existence of concurrent anomalies that appear to propagate eastward on interannual time scales. White and Peterson[11] were the first to report that anomalies in the extent of Antarctic sea ice, SST, and pressure and winds at sea level propagate eastward around the Southern Ocean as a bimodal phenomenon called the Antarctic Circumpolar Wave (ACW). The ACW as revealed by their analysis for the period 1982–95 has a periodicity of 4–5 years at any location and takes approximately 8 to 10 years to encircle Antarctica. Marion and Gough islands lie within a region generally considered to be influenced by the ACW (40–60°S). A periodicity around 5 years, compatible with an ACW signature, dominates after 1990 in the Gough CWT image (Fig. 5) and also in that of Marion (Fig. 4), but with a weaker amplitude. The periods of the low-frequency components are close to the typical precession period (8–10 years) of the ACW, but it is improbable that ACW propagation can be observed in the SST signal at one location only. Indeed, one needs at least two geographically separate records to evaluate a longitudinal propagation. We have analysed the passage of the ACW from Gough to Marion and hope to publish the details elsewhere.

The Prince Edward Islands, of which Marion Island forms part, lie in a very special location as far as temporal variability is concerned. They are situated at the equatorward border of an anomalous region of exceptionally high current variability.[2] It has now been demonstrated that this flow variability comes about as the result of eddy formation at the South-West Indian Ridge, upstream of the islands.[2] The individual eddies drift past the islands over periods of a month or two. We believe that their distinguishable temperatures can be observed in the daily SST records at Marion Island. Besides the ACW signature, one can therefore only speculate at this stage on the oscillations with periods between 1 and 5 years that are evident in the SST record at Marion (Fig. 4). It may be that the area of increased mesoscale turbulence, consisting of colder eddies from the south, extends farther equatorward during some years and not so far in others. This might give Marion Island a more sub-Antarctic environment during the former periods and a more Antarctic one during the latter. To date, the record of altimetric observations is too short to make any firm conclusions in this regard.

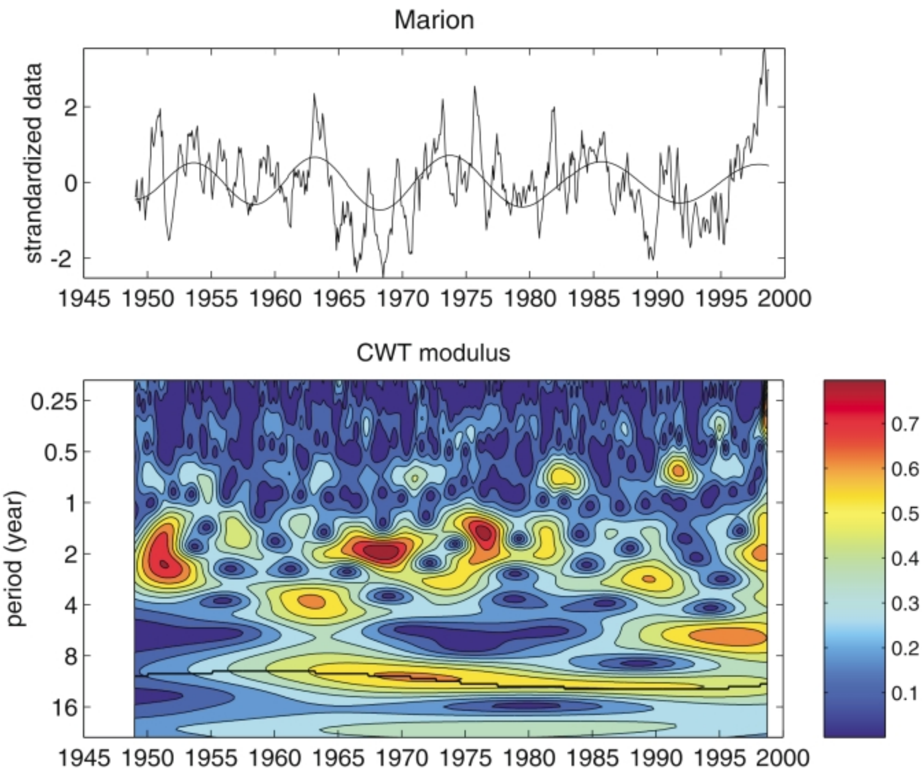

Fig. 4. Top: Marion Island sea-surface temperature anomalies with the low-frequency component superimposed. Bottom: continuous wavelet transform modulus (amplitude) of the anomalies signal for the same temperature record. The thick line is the low-frequency ridge from which the low-frequency component was extracted.

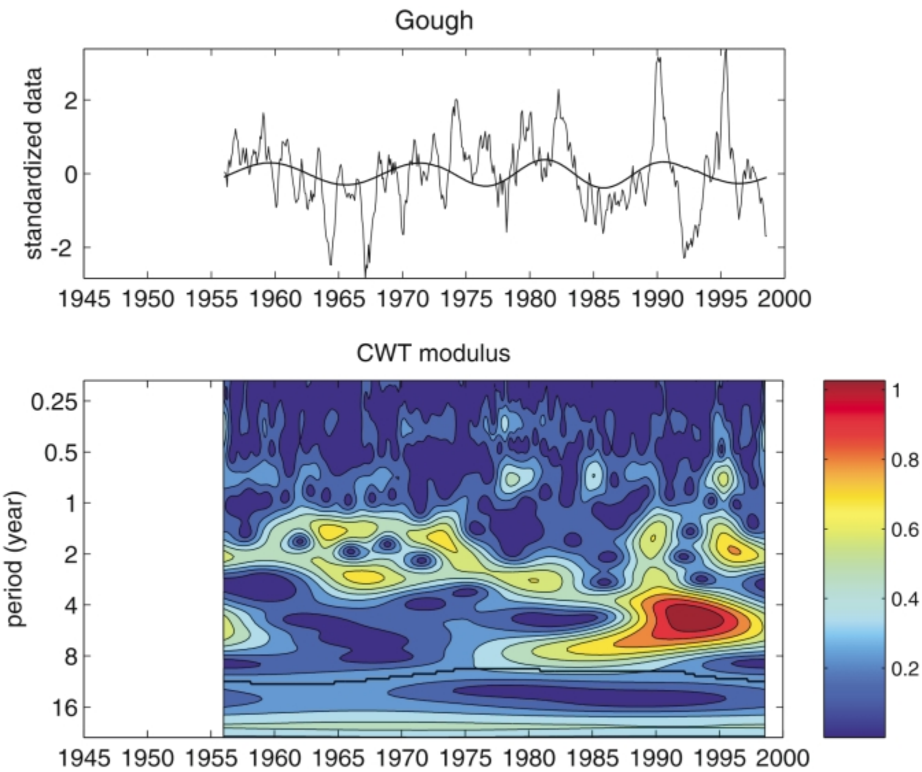

Fig. 5. Top: Gough Island sea-surface temperature anomalies with the low-frequency component superimposed. Bottom: continuous wavelet transform modulus (amplitude) of the anomalies signal for the same temperature record. The thick line is the low-frequency ridge from which the low-frequency component was extracted.

Conclusion

We have explored the SSTs at the sub-Antarctic islands of Gough and Marion. For the last ~50 years, a rise of 1.4°C in sea temperature at Marion and a weaker increase of 0.5°C at Gough were observed. Intermittent oscillations with periods of between 1 and 5 years are evident throughout the records of SST anomalies at both islands. A 5-year periodicity, compatible with an ACW signature, dominated after 1990. A low-frequency component with a period varying from around nine to 12 years was also observed in both records.

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