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[1] Sea surface temperatures have been measured at the islands of Marion (47°S, 38°E) from 1949 to 1998 and Gough (40°S, 10°W) from 1956 to 1998. These are some of the longest records of their kind in the sub-Antarctic. Evidence for the passage of the Antarctic circumpolar wave is apparent at each island, presenting one of the most extended documentation of this phenomenon to date. The highest, negative correlation between the anomalies in each island's sea surface temperature record and the sea ice extent anomalies is observed directly south of each individual island. The sea surface temperature anomalies at Gough lead those at Marion by about one year in average, with mean precession periods of 8.6, 8.9, and 10.4 years in the 60s, 80s and 90s, respectively. These precession periods can be compared to those observed in the sea ice extent anomalies. **Citation:** Mélice, J.-L., J. R. E. Lutjeharms, H. Goosse, T. Fichefet, and C. J. C. Reason (2005), Evidence for the Antarctic circumpolar wave in the sub-Antarctic during the past 50 years, *Geophys. Res. Lett.*, *32*, L14614, doi:10.1029/2005GL023361.

1. Introduction

[2] In recent years, several analyses of observed and modeled atmospheric and oceanic variables in the mid- to high latitudes of the Southern Hemisphere have revealed the existence of concurrent anomalies that appear to propagate eastward on interannual timescales. *White and Peterson* [1996] (hereinafter WP96) were the first to report that anomalies in the Antarctic SIE, SST, sea level pressure and winds propagate eastward around the Southern Ocean as a wave called the Antarctic circumpolar wave (ACW). The ACW as revealed by their analysis for the period 1982–1994, has a periodicity of 4–5 years at any location and takes approximately 8 to 10 years to encircle Antarctica. Some papers [*Carril and Navarra*, 2001; *Connolley*, 2003; *Simmonds*, 2003; *Venegas*, 2003] have shown that the ACW is modulated by interdecadal variability and that its character in terms of speed, spatial structure and mechanism of variability etc. is very dependant of the period analyzed, with even sometimes no clear sign of precession.

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[3] To study the variation of the ACW, it is desirable to use long-term record; unfortunately, the earliest NCEP-NCAR analyses are unreliable in this region, and it is only in the satellite era after 1979 that their quality becomes good [*Fichefet et al.*, 2003]. However, there are a few long-term records from individual stations that can be examined for longer-term variations [*Connolley*, 2003]. Marion and Gough Islands are within the region generally considered to be influenced by the ACW (40°–60°S) and are sufficiently close to evaluate its longitudinal propagation. The original SST records at the two islands, together with the simulated SIE which will be described afterwards, provide therefore an opportunity to check for the existence, and to explore the characteristic of the ACW in the sub-Antarctic region for the last ~50 years. The reason why we will compare the SIE to the SST at the two islands is that there is a consistent ACW signal in the SIE [e.g., *Gloersen and White*, 2001; *Simmonds*, 2003]. Moreover, there is a recent paper based on numerical simulations [*Carril et al.*, 2004] in which the relevance of the SIE as an active component of the ACW is highlight. This last paper stresses clearly the importance of the sea-ice variability as a component of the ACW.

[4] Sea surface temperature (SST) has been measured at the two sub-Antarctic islands (Figure 1) of Gough from 1956 to 1998 and Marion from 1949 to 1998 [*Mélice et al.*, 2003]. Marion Island is part of the Prince Edward Island group in the Indian sector of the Southern Ocean, whereas Gough Island lies close to the generic border of the Southern Ocean, the Subtropical Convergence [*Lutjeharms et al.*, 1993], in the Atlantic sector. Marion Island therefore lies considerably farther poleward and is intermittently influenced by eddies from the Antarctic sector that are generated at the South-West Indian Ridge [*Ansorge and Lutjeharms*, 2003]. In this paper, we explore the relationships of the anomalies of the two ~50 years monthly averaged records with the Antarctic sea ice extent (SIE) over the period 1958–1998.

[5] The SIE data used here consist of 240 time series (monthly values from 1958 to 1999) with 1.5° of resolution in longitude. They are the output of the *Fichefet et al.* [2003] hindcast simulation carried out with a global ice-ocean model driven by the NCEP-NCAR reanalysis daily surface air temperatures and winds. We have used these simulated SIE data instead of the observed SIE records because: (1) there are very few SIE observations before 1979 and the simulated data cover a period much longer than the observed series available, (2) the variability of the SIE is well reproduced by the hindcast simulation over the 1979–1998 period when satellite observations are available to verify it, (3) they can be used for exploring the associations between SIE and SST at Marion and Gough contin-

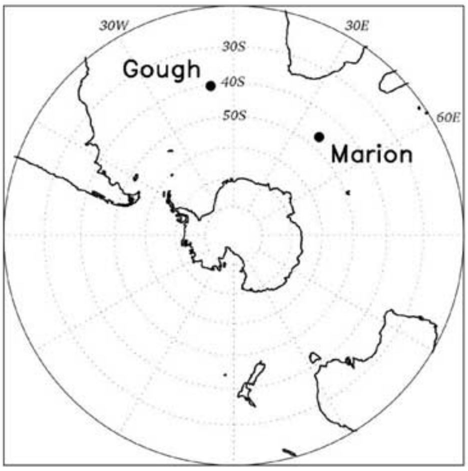

Figure 1. Locations of Gough (40°20′S, 10°0′W) and Marion (46°52′S, 37°51′E) islands.

uously from 1958 to 1998. We emphasis that there is a lack of data over the Southern Ocean during the early years of NCEP. For this reason, we will be careful to perform our analyses before and after the satellite period.

2. Evidence for the Antarctic Circumpolar Wave in the Sea Surface Temperatures Anomalies at Marion and Gough Islands

[6] To obtain the anomalies, the SST series at Marion and Gough and the simulated SIE series are first de-trended. Since least-square fitting can have undesired sensitivity to outlying points, we used a robust technique based on the minimization of the absolute deviation [*Press et al.*, 1992]. The de-trended series are then filtered with a continuous wavelet transform filter to remove the seasonal cycle (see *Jury et al.* [2002] for the method used), smoothed with a 3-month running mean, and finally normalized. The SST anomalies series at Marion and Gough are displayed by *Mélice et al.* [2003]. We explore the relationship between the SST anomalies at Marion and Gough and the SIE anomalies by computing their cross-correlation coefficient for the 1958–1998 period. To test the significance of the correlation coefficient, we take into account the presence of auto-correlation in the data by estimating the effective numbers of freedom, calculated from the autocorrelation coefficient of the two records [*Yuan and Martinson*, 2000], for the largest period found in the wavelet spectra of the series [*Mélice et al.*, 2003].

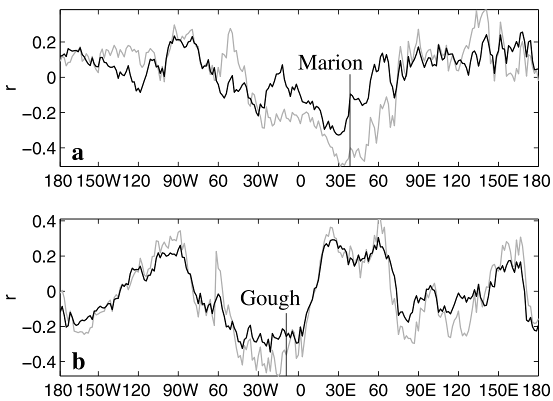

Figure 2. (a) Correlation coefficient between the SST anomalies at Marion and the simulated Antarctic sea ice extent (SIE) anomalies for 1958–98 (black), and 1979–1998 (gray). Marion's longitude is indicated. (b) same as (a), but for Gough.

[7] The highest correlation coefficient between Marion SST and the SIE ($r = -0.33$, significant at the 0.01 level) is observed for the SIE signal at 32°E (Figure 2a), thus relatively close to Marion's longitude (38°E). A positive anomaly at Marion SST corresponds to a SIE anomaly decrease south of Marion. The same holds for Gough, where the highest correlation coefficient between Gough SST and the SIE ($r = -0.35$, 0.01 level) is observed for the SIE signal at 22°W (Figure 2b), close to Gough's longitude (10°W).

[8] We do not have too much confidence in the simulated SIE before 1979 because the reliability of the NCEP-NCAR reanalysis data used for the hindcast simulation is questionable before that date. For this reason, the same correlation analyses are also performed for period 1979–1998 when the variability of the simulated SIE was verified by satellites observations. For 1979–1998, the highest (negative) correlation of the SST with the SIE is at 31°E ($r = -0.48$, 0.05 level) for Marion (Figure 2a) and 15°W ($r = -0.47$, 0.05 level) for Gough (Figure 2b). These results indicate that, as for 1958–1998, the highest correlation is observed south of each island. Interestingly, this is also true when using the first half of the period: for 1958–1978, the highest (negative) correlation is at 23°E ($r = -0.38$, 0.05 level) for Marion and at 7°W ($r = -0.40$, 0.05 level) for Gough.

[9] Figure 3 shows the Hovmöller plot of the 1958–1999 SIE anomalies defined as above, and filtered to exclude periods lower than 1.5 years. The dashed lines correspond

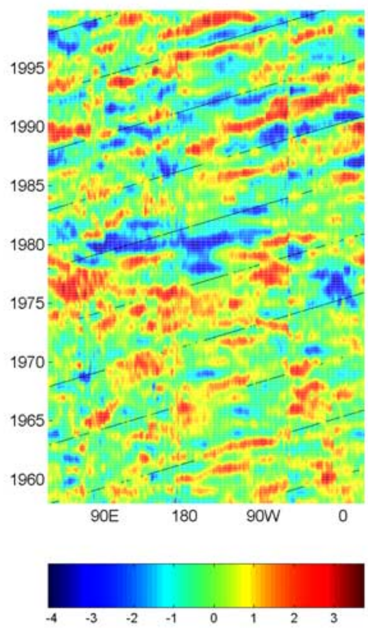

Figure 3. Hovmöller diagram of the simulated Antarctic sea ice extent anomalies for 1958–1999.

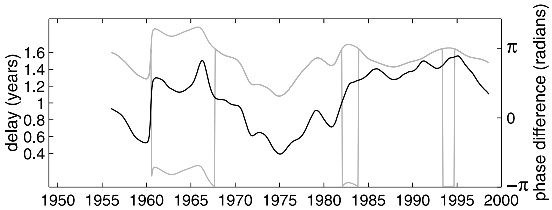

Figure 4. Phase difference, unwrapped phase difference (gray), and delay (black) between the SST anomalies at Marion and Gough (positive when Gough leads).

to a precession speed of 45° per year. The ACW identified by WP96 is clearly seen from ~1980 to 1999. It can also be observed, but less clearly, from ~1958 to ~1970. From ~1970 to ~1980 there is no clear sign of ACW, and a pattern in the form of standing, or even westward propagating waves is sometimes observed. The significant inverse correlation between the SST series and the SIE south of the islands implies that the presence of the ACW in the simulated SIE is an indication of the potential existence of the ACW at Gough and Marion.

[10] The presence of the ACW at Gough and Marion may be observed in Figure 2a and more clearly in Figure 2b (gray curve) where the two highest correlation coefficients between Gough SST and SIE for 1979–1999, are at 89°W (r = 0.36, 0.1 level) and 59°E (r = 0.42, 0.1 level). The mean period, evaluated by the continuous wavelet transform, of the 1979–1998 Gough SST anomalies and the SIE anomalies at these two longitudes, varies from 2.8 to 4.9 years [*Mélice et al.*, 2003]. With the 148° difference between the two successive correlation highest values, this corresponds to an eastward propagating wave taking 2.8 to 4.9 years/148° × 360° = 6.8 to 11.9 years to encircle Antarctica. These values cover the typical 8–10 years precession period of the ACW observed in WP96. One possible speculation about the relatively weak signal of the ACW in Marion could be related to the fact that the ACW is particularly strong in the south Pacific and south Atlantic oceans, but it is weaker in the Indian sector.

[11] The lags and leads between the SST anomalies at Gough and those at Marion are then estimated with the lagged correlation method, with lags varying from –24 to 24 months. A positive lag means that the SST anomalies at Gough lead those at Marion. Correlations are always small ($|r| < 0.1$) for negative lags. The highest correlation coefficient (r = 0.34, 0.01 level) is obtained with the SST anomalies at Gough leading those at Marion by 10 months. For lags varying from +9 to +13 months the correlation coefficient is always larger than 0.355, thus close to the highest value (r = 0.34). This is an indication that the lags vary with time.

[12] We investigate with more precision the eastward propagation of the SST anomalies from Gough to Marion by estimating the time-varying phase difference and delay (Figure 4) between the two SST anomalies series with the continuous cross-wavelet transform technique. The method is described in the appendix of *Jury et al.* [2002] and of *Mélice and Servain* [2003]. The phase difference and delay are computed in the 1 to 8 years interval, where all the spectral power is concentrated [*Mélice et al.*, 2003]. The mean delay for the 1956–1998 is 1.05 years. This corresponds to an eastward propagation taking 7.9 years to encircle Antarctica. The precession period varies strongly with time. The mean precession periods for the 50s, 60s, 70s, 80s, and 90s are 5.5, 8.6, 5.0, 8.9, and 10.4 years, respectively. The two last periods agree well with the 8–10 years of the ACW precession period described by WP96. They are also in agreement with *Carril and Navarra* [2001] and *Simmonds* [2003] who found that the ACW was fast in the 80s and slower in the 90s. The low periods found in the 70s could be the result of interaction between two interannual signals with different frequency and structure as discussed by *Venegas* [2003], and are consistent with the lack of ACW seen prior to 1982 [*Connolley*, 2003]. In the 60s, the 8.6 years period indicates a return to WP96 ACW-like conditions, as observed by *White and Cayan* [2000, Figure 6]. Finally, these different precession periods can be compared to those observed in the Hovmöller diagram of the simulated SIE anomalies (Figure 3).

3. Conclusions

[13] In the sub-Antarctic region, there are very few long-term records from individual stations that can be examined for long-term variations. The ~50 year long SST records at Marion and Gough islands are some of the longest of their kind in the sub-Antarctic and therefore provide a very important data set for investigating the climate variability of a large region of the mid-latitude Southern Hemisphere. Our analyses suggest the presence of the ACW in the SST anomalies at Gough and Marion, with mean precession periods of 8.6, 8.9 and 10.4 years in the 60s, 80s and 90s, respectively. We also observed that the highest, negative correlation between the anomalies in each island's SST record and the *Fichefet et al.* [2003] simulated SIE anomalies is observed directly south of each individual island. This correlation suggests that there may be a relationship between the SST anomalies in the sub-Antarctic and the sea ice extent anomalies, since both have the same ACW characteristics in terms of time-varying precession period. Our objective in the future is to use models to further study the physical basis of such correlations by investigating the impact of Southern Hemisphere climate modes on the Antarctic sea-ice ocean system and on the SST variability at Marion and Gough Islands.

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