Local climate impacts of dipole-like sea surface temperature oscillations in the Southern Hemisphere
Jeseung Oh and Yong Jung

ABSTRACT

Dipole phenomena in ocean-atmospheric variability such as the Indian Ocean Dipole have been recognized as important factors that greatly affect local climates. This study presents evidence of two dipole modes in sea surface temperature anomaly (SSTA) over high latitude Southern Hemisphere (one in South Pacific and one in South Indian Ocean), identified using empirical orthogonal functions and cross-correlation analysis. These dipole modes have interannual periodicity, which is also explored for their seasonal variability and modes. Herein, a dipole mode is defined as a quasi-periodic oscillation between positive and negative phases in the various climate proxies, though predominantly in SST, which is supported by the signal’s synchronized relationship with atmospheric variability (as recorded by pressure and wind records). In addition, the dipole modes have a clear synchronization relationship to local precipitation records, which is described in this paper. For this purpose, an index to represent the time-dependent evolution of each dipole mode and to better define and understand the teleconnections of the dipole modes with other climate variables was defined. The findings described here provide a more precise and unique understanding of the globally distributed SSTA teleconnections and climate’s synchronized dynamics than that has currently been studied.

Key words | climate synchronization, dipole oscillation, ocean–atmosphere teleconnection, SST (sea surface temperature) variation

ABBREVIATIONS

| ACC | Antarctic Circumpolar Current |
| ACW | Antarctic Circumpolar Wave |
| AR | Auto Regression |
| DMI | Dipole Mode Index |
| ENSO | El Nino Southern Oscillation |
| EOF | Empirical Orthogonal Function |
| GISTEMP | GISS Surface Temperature Analysis |
| IOD | Indian Ocean Dipole |
| IOSD | Indian Ocean Subtropical Dipole |
| MSLP | Mean Sea Level Pressure |
| NAO | North Atlantic Oscillation |
| NW | Northwest |
| PDO | Pacific Decadal Oscillation |
| SARI | Southern African Rainfall Index |
| SE | Southeast |
| SH | Southern Hemisphere |
| SI | South Indian |
| SIDO | South Indian Dipole Oscillation |
| SLP | Sea Level Pressure |
| SP | South Pacific |
| SPDO | South Pacific Dipole Oscillation |
| SST | Sea Surface Temperature |
| SSTA | Sea Surface Temperature Anomaly |
| SVD | Singular Value Decomposition |

This is an Open Access article distributed under the terms of the Creative Commons Attribution Licence (CC BY 4.0), which permits copying, adaptation and redistribution, provided the original work is properly cited (http://creativecommons.org/licenses/by/4.0/).

doi: 10.2166/wcc.2020.115
INTRODUCTION

The variability of the Earth’s climate system is intricately tied to the energy transfer between the ocean and atmosphere. In this paper, dipole patterns of this transfer via the analysis of the sea surface temperature (SST), sea level pressure (SLP), and horizontal wind (U-wind) were determined using both the empirical orthogonal function (EOF) and cross-correlation analysis.

The coupled ocean–atmosphere variability and its effects on the climate system have previously been identified and explained by observing the dominant climate indices such as El Niño Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), and North Atlantic Oscillation (Trenberth & Hurrell 1994; Hurrell 1995). While those climate indices characterize the variability of large ocean basins, previously unknown, dipole-like oscillations over higher latitudes in the Southern Hemisphere (SH) have been identified by analyzing ~100 years of SST anomaly (SSTA) in detail. These dipoles take the form of quasi-periodic oscillations of SSTA between positive and negative phases, such that while there is a below the average SST at one pole of the dipole, there is a simultaneous above-average SST at the other pole. This behavior shares many key characteristic behaviors with the synchronization phenomenon of coupled oscillators observed in complex dynamics.

SSTs, specifically SSTA, are an important proxy for tracking larger scale climate change due to the strong effects of temperature differences at the ocean–atmosphere boundary on the heat and moisture exchange between ocean and atmosphere, each of which can be visualized as a major climatic oscillator. Small deviations in this surface exchange can have a widespread effect in both the atmospheric circulation and global weather patterns (Ahrens 2010). In addition, SST records are relatively long and accurate climate records, as they predate satellite monitoring, so that when selecting a proxy to judge regional climate, this particular set of proxies is a logical option, though not the only one.

One of the earlier works to use the term dipole in this context (Servain 1991) reported a meridional dipole between the northern and southern hemispheres over the tropical Atlantic Ocean (60 W–15 W, 30N–20S), using the EOF analysis on 27 years of SST data. Deser & Blackmon (1993) showed a dipole-like oscillation in SLP over the North Atlantic Ocean (80W–10E, 70N–15N) for 100 years using SST, SLP, and surface air temperature data. Venegas et al. (1996) made use of 40 years of coupled SST-SLP data and singular value decomposition (SVD) analysis to identify a dipole mode over the South Atlantic Ocean. More recently, Wang (2010) found a subtropical dipole mode in the SH (0S–45S) from the analysis on SST, winds, and heat flux data.

Other dipoles have been identified using an initial dataset before supplementing it with comparable results from model data. The widely studied Indian Ocean Dipole was first found by Saji et al. (1999). They conducted the EOF analysis on SST over the region of 40E–120E and 25N–20S and showed that this dipole mode has a strong effect on the climate variability in all regions surrounding the Indian Ocean. Another dipole pattern in the SSTA over the Southern Indian Ocean was reported in multiple later works, from the analysis of both observed and simulated data by a model (Behera et al. 2000; Behera & Yamagata 2001; Morioka et al. 2012). Yu et al. (2000) identified a zonally oriented dipole over the Northern Subtropical Pacific (130E–70W, 50N–30N) from SSTA data which is a long-term simulation by the University of California at Los Angeles coupled the atmosphere–ocean general circulation model. While the above studies used EOF or SVD analysis to identify the dipole modes, Yuan & Martinson (2000) defined four characteristic correlation patterns between the sea ice extent and global surface temperature, one of which is an Antarctic dipole across the Drake Passage.

Despite extensive studies on ocean-atmospheric dipole mode existence, most have focused on tropical and subtropical ocean basins. In this study, interannual dipole modes in SST over high latitude South Pacific and South Indian Oceans were identified using EOF and cross-correlation analysis and the seasonality of the dipoles were discussed. The synchronized relationship between the ocean dipole modes and atmospheric variability is also discussed, following the definition of synchronization first established by Huygens (Pikovsky et al. 2001) and extended to the climate system by Rial (2012). It is possible to identify stable phase and frequency locking in the two climate dipoles that this paper presents, satisfying the definition of synchronization. In addition, the
dipole oscillators seen in modern climate dynamics may be the result of synchronization that can be suggested.

The rest of this paper is organized as follows: in the section ‘Data and methods’, the dataset and methods used to gain a better understanding of the two identified dipoles were described. The section ‘Results’ details the results; specifically, the proxy analyses surrounding the two synchronized SSTA oscillations are detailed. The section ‘Discussion’ discusses the differences between the newly identified dipole modes and previously published climate phenomena that share certain characteristics with our dipole modes, specifically the Antarctic Circumpolar Wave (ACW), to emphasize the uniqueness of the results presented here. The conclusion will be followed by a summary of the paper’s main findings and suggestions for future avenues of research using the methods introduced here.

DATA AND METHODS

For the SST data in this study, two SST datasets from different organizations were employed; specifically, the extended reconstructed SST V3b by Smith et al. (2008) was adopted, which is available at 2° by 2° latitude-longitude grid resolution from January 1854 to the present (NOAA_ERSST_V3 data is provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado) and GISS Surface Temperature Analysis (GISTEMP) data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their web site at http://www.esrl.noaa.gov/psd/ which is available at 2° by 2° latitude–longitude grid resolution from January 1880 to the present.

In addition, regional precipitation data from the Global Precipitation Climatology Centre (GPCC, 1901–2010) and University of Delaware precipitation (UDel_AirT_Precip data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their website at http://www.esrl.noaa.gov/psd/, 1901–present) are used to extend the scope of the dipole analysis beyond the oceans. Though new dipoles are not identified in this proxy, it is necessary for demonstrating the widespread effects of the teleconnections elsewhere.

For all of the variables (SST, MSLP, and U-Wind), monthly anomalies are firstly computed as the difference between the monthly value for each year and the climatological value for the month. Then, the anomaly time series are standardized by dividing the monthly time series by the corresponding monthly standard deviation for each grid point. The strong high-frequency components of the monthly time series are removed by calculating 11 months running average (5 months before and after the considered months). A high-pass filter is also applied to remove long-term trends, specifically longer than 8 years. The oscillating period of 2–7 years was focused, which is commensurate with the period of the strongest SST oscillation, ENSO. Prepared data were analyzed by EOF which decomposes the dataset for finding time series and spatial patterns on the data in terms of orthogonal basis functions. Figure 1 summarizes the preprocessing procedure of SST, MSLP, and U-wind for EOF.

RESULTS

Two dipole-like oscillations are identified by the first EOF modes over the South Pacific (South Pacific Dipole...
Oscillation, hereafter SPDO) and South Indian Oceans (South Indian Dipole Oscillation, hereafter SIDO) (Figure 2). The first EOF modes show the existence of the SSTA dipole mode in each basin, which explains 30% (SP: South Pacific) and 20% (SI: South Indian) of the total variance in SSTA, respectively. Both dipole modes have northwest (NW) and southeast (SE) oscillating patterns. To ensure that this finding is not an artifact from the EOF method, pairs of the actual SSTA time series were compared that have maximum negative correlation coefficients between (i) and (ii) in Figure 2 over each basin, as marked with crosses in Figure 3. From Figure 2(c), the SSTA time series and the first EOF mode are commensurate at the scale of interannual oscillations. For further analysis of the teleconnection characteristics of the dipole modes, a dipole mode index (DMI) is defined, as suggested by Saji et al. (1999), Yu et al. (2000), Behera & Yamagata (2001), Muñoz et al. (2010), and Nnamchi et al. (2011). For the DMI calculation in this study, the principal component analysis is applied on nine time series data (one center – marked with crosses in Figure 3 – plus the eight time series from the nearest neighbor grid points surrounding
the dipole center) for each pole. The calculation of the difference of the first principal components is performed between the two poles. The DMIs allow for cross-dipole comparisons as well as comparisons to atmospheric variables by condensing the information from the entire dipole into a single time series.

The various scales and proxies considered here are important to distinguish these newly identified dynamics from the ACW. The specifics of the uniqueness of SPDO and SIDO will be detailed in the ‘Discussion’ section of this paper.

**South Pacific region**

SPDO has been identified as two centers of oscillation over the South Pacific Ocean and ranging from off the SE coast of New Zealand to approximately the edge of the polar front, which is 20° further east. These locations derive from the EOF analysis and are supported by the SSTA comparison between two oscillating centers (Figure 2). Figure 3 shows that the defined DMI well describes the SSTA variation in the interannual time scale over this region. The analysis using the GISTEMP dataset produced the same results (Figure S1, Supplementary Material), which confirms that the dipole mode is not an artifact from the use of one specific dataset. In addition, SPDO is constantly defined in each month from the monthly EOF analysis (Figure 4; note that here, the 11-month running mean SSTA was not used, as is the case in the main text, but rather each month’s data for all years for the analysis of each individual month’s dynamics). Similarly, the refined seasonal analysis indicates that spatial ranges of SPDO’s centers are constant regardless of seasons. Together, this means that this dipole oscillation has been a constant phenomenon in climate variability over this region for at least the last 112 years.

In order to further characterize this synchronized dipole, the investigation of SPDO’s ocean–atmosphere dynamics is performed by studying the relationship of this SSTA proxy’s oscillation to SLP and zonal wind (U-wind) data. The results of the correlation coefficient analysis between the DMI of SPDO and the aforementioned proxies are seen in...
Figures 5(a) and 5(b), respectively. These analyses show that during positive phases of the DMI (i.e., when there is a positive anomaly over the NW pole and corresponding negative anomaly over the SE pole), there is a simultaneous positive SLP anomaly (SLPA) directly between the poles, with a negative SLPA over the greater southeastern region of the dipole.

This positive DMI is also directly related to the occurrence of a westerly zonal wind along the boundary of the...
SLPA between the two poles, as is expected given the hemisphere and pressure differences. It is also important to note that while this synchronized, oscillating system is persistent throughout the available proxy records, it is significantly weakened for the period of July–September or during the Austral winter (see Figures 6 and 7).

The regional impacts of and influences on SPDO were also studied via additional proxies, including South American precipitation records and recorded El Niño anomalies. Composition of the precipitation records (outlined in the ‘Data’ section) during the time of strong values of SPDO DMI indicates a strongly linked and potentially synchronized phase relationship (Figure 8(a)). During the positive (negative) DMI phase, it is linked to less (more) precipitation over a large region of southeastern South America (Figures 8(a) and 8(b)). The significance of this relationship is statistically supported by that the averaged precipitation anomalies are about 15 cm, while the standard deviation of the precipitation anomaly over South America is 4.75 cm. However, given that SPDO is located in the Pacific, it is reasonable to assume that some, if not all behaviors here are linked to El Niño and its effects on the dipole modes. To this end, the Niño 3.4 time series and SPDO’s DMI were analyzed for a better understanding of their dynamics. SPDO DMI and Niño 3.4 have a correlation coefficient of ~0.47, which is not necessarily convincing in either direction. However, a simple auto-regression (AR) model indicates that while El Niño has some clear effects, the persistence of the internal oscillations of SPDO is independent of this influence and required other influence than El Niño to recreate the

![Figure 6](http://iwaponline.com/jwcc/article-pdf/12/2/311/866007/jwc0120311.pdf)

Figure 6 | Correlation coefficients between DMI-SP and SLPA in each month over the South Pacific Ocean. Each figure shows each month, and the values in parenthesis represent the maximum correlation coefficients between DMI and SLPA within the presented spatial domain.

![Figure 7](http://iwaponline.com/jwcc/article-pdf/12/2/311/866007/jwc0120311.pdf)

Figure 7 | Correlation coefficients between DMI-SP and U-Wind in each month over the South Pacific Ocean. Each figure shows each month and the values in parenthesis represent the maximum correlation coefficients between DMI and U-wind within the presented spatial domain.
observed oscillations. Details of the model and its results are summarized in the section ‘Discussion’.

**Southern Ocean and Indian Ocean regions**

SIDO is identified from the first EOF mode over the southern Indian Ocean basin and shows that the NW–SE pattern is similar to SPDO (Figure 2(b)). This dipole spans a region from within the south of the Indian Ocean (∼40°S and ∼85°E) to below Australia (∼60°S and ∼115°E). Importantly, the correlation coefficient analysis between SIDO DMI and SSTA (Figure 3) shows that SIDO variability accounts for the majority of variation over the high latitudes of the southern Indian Ocean.

Again, a second SSTA dataset (from GISTEMP) was used to show the robustness of this analysis to the dataset used. However, in this case, the month-by-month analysis shows that the dipole mode remains strong in all individual months, with the exception of December when it seems to die out almost entirely. The complete seasonal variations of this dipole are detailed in Figure 9.

Following the precedent set in analyzing the previous dipole mode, the DMI time series was compared to SLP and U-wind for a better understanding of the set of mechanisms responsible for its dynamics. Once again, a strong connection is seen with both (Figures 10(a) and 10(b)). When a positive dipole mode is seen in the DMI (warming over the NW and cooling over the SE), a high-pressure
Figure 9 | EOF analysis of SST anomaly over the South Indian Ocean for each month.

Figure 10 | (a) Correlation coefficients between DMI-SI and SLPA in the interannual time scale. Black crosses are marked to show the dipole centers. The values in parenthesis represent the maximum correlation coefficients between the DMI and SLPA within the presented spatial domain. (b) Same with (a) but correlation coefficients between DMI-SI and U-Wind.
(positive) SLPA forms between the two centers of the dipole, while a negative anomaly is formed near Antarctica. This pressure system correlates with the westerly wind seen along the 60°S over the SE pole. Due to the nature of vortex behavior and the presence of high SLP, this corresponds to easterly winds over the NW pole of the oscillator. These ocean–atmospheric relationships are relatively weakened in August–October (Figures 11 and 12), and this might be caused by smaller heat exchange during the Austral winter.

Further, the SIDO DMI dynamics are strongly teleconnected with precipitation over NW Australia, especially during positive anomaly periods. This is seen in the precipitation composition during the time of strong dipole occurrence (Figures 8(c) and 8(d)). This suggests the ability to predict some aspects of Australian rainfall through the knowledge of the DMI dynamics, especially with other knowledge about monsoon behavior in the Indian Ocean, but does not necessarily support the idea of causality between the two systems. However, it is likely that the two systems are teleconnected.

It is also worthwhile to consider SIDO’s relationship to SPDO, especially given the earlier suggestion that the two might simply be part of the ACW. The comparison of the two DMIs shows that this is highly unlikely, as they are not correlated at all. This implies that the two dipoles do not share most dynamic behaviors or periods, though they do have similar superficial structures with their NW–SE patterns.

![Figure 11](image1.png)  
**Figure 11** | Correlation coefficients between SIDO and SLPA in each month over the South Indian Ocean. Each figure shows each month and the values in parenthesis represent the maximum correlation coefficients between DMI and SLPA within the presented spatial domain.

![Figure 12](image2.png)  
**Figure 12** | Correlation coefficients between SIDO and U-wind in each month over the South Indian Ocean. Each figure shows each month and the values in parenthesis represent the maximum correlation coefficients between DMI and U-wind within the presented spatial domain.
DISCUSSION

Although the results above suggest the independence of the two identified dipoles, their interannual periods of oscillation do naturally suggest a connection to the ACW, as the ACW is the largest, consistently identified, oscillating phenomenon encompassing the entirety of the region studied in this paper, as well as possibly relating them to other oscillations in the area, including the ENSO. However, by using the AR1 model method and extensions, which has been used to establish the incidence of the Southern PDO from the PDO (Shakun & Shaman 2009) as well as clearly understanding previously published oscillation dynamics for the region, we find that SPDO and SIDO are not subsumed by the ACW or any other previously published climate oscillation, although they often do appear to interact.

Of the numerous papers published on the subject of the ACW, it is important to note several key works that clearly discuss the physical characteristics of the oscillation so as to best differentiate SPDO and SIDO. The ACW was first identified and defined by White & Peterson (1996) as anomalies in SLP, wind stress, SST, and sea ice extent around Antarctica which were caused by SSTAs in the western, subtropical, South Pacific spreading south and east in the ocean on an interannual scale. Qiu & Jin (1997) disputed this characterization and showed that ACW oscillations are not directly forced by the tropical ENSO activity, but rather that they are the result of instability in the Antarctic Circumpolar Current (ACC) and its corresponding atmospheric behavior. White et al. (1998) later published an article describing the covariance of SST and SLPAs in the Antarctic region, which created a spiral pattern in the Southern Ocean. This structure aligns with our dipoles in that one oscillating center is found in the positive anomaly area identified in this paper, while the other is found in the negative, for both of the dipoles in the region. This may suggest a pumping structure either driving the wave or resulting from the wave, but does demonstrate that the two teleconnection structures may both be active, with the dipoles providing a potential underlying structure for the wave. However, it is reassuring that the dipole behavior previously mentioned is not a simple wave powered by the ACC due to the dynamics noted in Figure 13. The anomalies noted as dipoles in this paper are not smoothly transitioning around the ACC, but rather clearly oscillating at two distinct positions without a direct connection, requiring that they are synchronized through more intermediate systems, potentially including pressure and wind. This indirect atmospheric connection is far more in line with the results discussed above than a direct oceanic signal.

While the foregoing clearly distinguishes the SPDO and SIDO dipoles from the ACW, other studies identified alternative dipole behaviors in the Southern Pacific and Indian Oceans. These include the work by Garreaud & Battisti (1999) on the variability of the SH tropospheric circulation and its connection to the interannual variability in the South Pacific basin around 30°S. Their analysis was confined to latitudes lower than 40°S, and thus does not include the full region of our study or our dipoles. Behera & Yamagata (2001) did identify a subtropical SST dipole in the southern Indian Ocean known as the Indian Ocean Subtropical Dipole, which is visible in the first PC of our EOF analysis, most clearly in February. However, stable dipole-like oscillation is not seen for this system if the spatial range of the data is extended, and remains relatively weak when compared to SIDO. Wang (2010) and Morioka et al. (2012) both published on links between SSTAs within the southern ocean region of this study and average rainfall events in Africa, though neither made clear use of defined dipole behavior in their investigations. Wang (2010) chose to unify SST dipoles to represent a global climate mode throughout the southern, subtropical oceans, using latitudes below 45°S only. Meanwhile, Morioka et al. (2012) confined their regional consideration to the southern Indian and southern Atlantic Oceans in direct comparison to the Southern African Rainfall Index which averages rainfall anomalies south of 10°S from 1960 to 2008. Our study analyzes a much wider range of latitudes in both datasets, and clearly notes the dynamics of SSTAs oscillations which provide a better understanding of the larger interactions of the connections with the global climate system and previously studied systems.

Specifically, we follow the work of Shakun & Shaman (2009) in their methodology for establishing the independence of the SPDO and PDO indices. While their work focused on the decadal variations of the Southern Pacific, our work confined the range of frequencies studied to

Downloaded from http://iwaponline.com/jwcc/article-pdf/12/2/311/866007/jwcc0120311.pdf by guest
The AR1 model was modified, which took into account direct forcing from ENSO but no forcing from the PDO, in order to introduce a lag in connection with ENSO. The modified model is as follows:

\[ Y_i = a Y_{i-1} + b \text{Nino3.4} + \xi \]

wherein \( Y \) is the SPDO DMI, \( i \) represents the time step, \( a \) and \( b \) are forcing amplitude parameters which will be iterated over to find the best fit between the model and the data, and \( \xi \) is the random noise variable. Then, correlation coefficients were calculated between observed DISP DMI and DMI generated from the model to inspect the impacts of El Niño on the SPDO. Figure S3 shows that while some correlation between model and data can be achieved with a minimal influence from the internal oscillation dynamics of the system or ENSO 3.4, in order to best fit the data or even create a significant correlation coefficient, the two forcing parameters are required to be near one. This shows a definite interaction between SPDO and ENSO, but also clearly demonstrates the independence of the internal oscillations of the SPDO system.
The influence of the internal dynamics of SPDO in this model is another indication of the synchronized nature of this oscillator system. The two poles of the dipole are physically separate without a clear direct connection between them, leading to only weakly interacting signals being transferred between them. However, the two poles oscillate in a stable, anti-phase manner over the duration of the record, demonstrating their constant phase and frequency lock, which, as mentioned earlier, is the definition of a synchronized system. SIDO also demonstrates this behavior, supporting the supposition that both oscillating systems are the result of the synchronization of weakly interacting, nonlinear, climate oscillators that have self-organized from some unknown initial state. Given that this stable phase relationship is often used to identify teleconnections, it is possible that some, if not all, previously identified, linked climate oscillators may be the result of this phenomenon.

Overall, while there are clear connections to previously identified climate oscillations, SPDO and SIDO are demonstrably independent of these behaviors and are worth further study for a better understanding of their internal dynamics.

CONCLUSIONS

This paper has clearly identified new, synchronized systems of connected SST variations through the use of EOF analysis, correlation coefficients, and the corresponding DMIs of each new dipole. While these results may not be entirely unrelated to previously discovered teleconnection patterns, they are also not replications of these patterns. This work demonstrates a method of the teleconnection analysis that is independent of spatial dataset restrictions and that is capable of providing insight into teleconnection patterns based on proxy networks. Though this paper shows only one pair of SST dipoles with their corresponding ranges of proxy and time interdependencies, other potential dipoles were investigated in an effort to characterize the larger dynamics leading to these stable, interannual teleconnections. Finding patterns here may provide insight into the combined role that the physical and temporal factors play in forming and sustaining these synchronized oscillations. For a complete picture of the dynamics, it will be important to perform the comparable analysis on as many climate proxies as possible as well as on as many identifiable dipoles as possible, in the hope of defining what set of conditions must be true in order to create a sustained synchronization of the climate on the sub-decadal scale.

ACKNOWLEDGEMENT

This paper was supported by Wonkwang University in 2020.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this paper is available at https://dx.doi.org/10.2166/wcc.2020.113.

REFERENCES

Ahrens, C. D. 2010 Essentials of Meteorology: An Invitation to the Atmosphere, 6th edn. Cengage Learning, California, USA, p. 506.

Behera, S. K. & Yamagata, T. 2001 Subtropical SST dipole events in the southern Indian Ocean. Geophys. Res. Lett. 28, 327–330. doi:10.1029/2000GL011451.

Behera, S. K., Salvekar, P. S. & Yamagata, T. 2000 Simulation of interannual SST variability in the tropical Indian Ocean. J. Clim. 13, 3487–3499. doi:10.1175/1520-0442(2000)013<3487:SOISVI>2.0.CO;2.

Compo, G. P., Whitaker, J. S., Sardeshmukh, P. D., Matsui, N., Allan, R. J., Yin, X., Gleason, B. E., Vose, R. S., Rutledge, G., Bessemoulins, P., Brönnimann, S., Brunet, M., Crouthamel, R. I., Grant, A. N., Groisman, P. Y., Jones, P. D., Kruk, M., Kruger, A. C., Marshall, G. J., Maugeri, M., Mok, O., Nordli, H. Y., Ross, T. F., Trigo, R. M., Wang, X. L., Woodruff, S. D. & Worley, S. J. 2011 The twentieth century reanalysis project. Q. J. R. Meteorol. Soc. 137, 1–28. doi:10.1002/qj.776.

Deser, C. & Blackmon, M. L. 1995 Surface climate variations over the North Atlantic Ocean during winter: 1900–1989. J. Clim. 6, 1743–1753. doi:10.1175/1520-0442(1993)006<1743:SCVOTN>2.0.CO;2.

Garreaud, R. & Battisti, D. S. 1999 Interannual (ENSO) and interdecadal (ENSO-like) variability in the southern hemisphere tropospheric circulation. J. Clim. 12, 2113–2123. doi:10.1175/1520-0442(1999)012<2113:IEAEIL>2.0.CO;2.

Hurrell, J. W. 1995 Decadal trends in the North Atlantic Oscillation and relationship to regional temperature and
Kayano, M. T., Andreoli, R. V. & Ferreira de Souza, R. A. 2013 Relations between ENSO and the South Atlantic SST modes and their effects on the South American rainfall. Int. J. Climatol. 33, 2008–2023. doi:10.1002/joc.3569.

Morioka, Y., Tozuka, T., Masson, S., Terray, P., Luo, J. & Yamagata, T. 2012 Subtropical dipole modes simulated in a coupled general circulation model. J. Clim. 25, 4029–4047. doi:10.1175/JCLI-D-11-00396.1.

Muñoz, E., Wang, C. & Enfield, D. 2013 The Intra-Americas springtime sea surface temperature anomaly dipole as fingerprint of remote influences. J. Clim. 23, 43–56. doi:10.1175/2009JCLI3006.1.

Nnamchi, H. C., Li, J. & Anyadike, R. N. C. 2014 Does a dipole mode really exist in the South Atlantic Ocean? J. Geophys. Res. 116, D15104. doi:10.1029/2010JD015579.

Pikovsky, A., Rosenblum, M. & Kurths, J. 2001 Synchronization: A Universal Concept in Nonlinear Sciences. Cambridge University Press, New York, USA.

Qiu, B. & Jin, F. F. 1997 Antarctic circumpolar waves: an indication of ocean-atmosphere coupling in the extratropics. Geophys. Res. Lett. 24, 2585–2588. doi:10.1029/97GL02694.

Rial, J. A. 2002 Synchronization of polar climate variability over the last ice age: in search of simple rules at the heart of climate’s complexity. Am. J. Sci. 312 (4), 417–448. doi:10.2475/04.2012.02.

Saji, N. H., Goswami, B. N., Vinayachandran, P. N. & Yamagata, T. 1999 A dipole mode in the tropical Indian Ocean. Nature 401, 360–363. doi:10.1038/43854.

Servain, J. 1991 Simple climatic indices for the tropical Atlantic Ocean and some applications. J. Geophys. Res. 96 (C8), 15137–15146. doi:10.1029/91JC01046.

Shakun, J. D. & Shaman, J. 2009 Tropical origins of North and South Pacific decadal variability. Geophys. Res. Lett. 36, L19711. doi:10.1029/2009GL040313.

Smith, T. M., Reynolds, R. W., Peterson, T. C. & Lawrimore, J. 2008 Improvements to NOAA’s historical merged land-ocean surface temperature analysis (1880–2006). J. Clim. 21, 2283–2296. doi:10.1175/2007JCLI2100.1.

Trenberth, K. E. & Hurrell, J. W. 1994 Decadal atmosphere-ocean variations in the Pacific. Clim. Dyn. 9, 303–319. doi:10.1007/BF00204745.

Venegas, S., Mysak, L. & Straub, D. 1996 Evidence for interannual and interdecadal climate variability in the South Atlantic. Geophys. Res. Lett. 23, 2673–2676. doi:10.1029/96GL02573.

Wang, F. 2010 Subtropical dipole mode in the southern hemisphere: a global view. Geophys. Res. Lett. 37, L10702. doi:10.1029/2010GL042750.

White, W. B. & Peterson, R. G. 1996 An Antarctic circumpolar wave in surface pressure, wind, temperature, and sea-ice extent. Nature 380, 699–702. doi:10.1038/380699a0.

White, W. B., Chen, S. & Peterson, R. G. 1998 The Antarctic circumpolar wave: a beta effect in ocean-atmosphere coupling over the Southern Ocean. J. Phys. Oceanoogr. 28, 2345–2361. doi:10.1175/1520-0485(1998)028<2345:TACWAB>2.0.CO;2.

Yu, J., Liu, T. & Mechoso, C. R. 2000 An SST anomaly dipole in the northern subtropical pacific and its relationships with ENSO. Geophys. Res. Lett. 27 (13), 1931–1934. doi:10.1029/1999GL011340.

Yuan, X. & Martinson, D. G. 2000 Antarctic sea ice extent variability and its global connectivity. J. Clim. 13, 1697–1717. doi:10.1175/1520-0442(2000)013<1697:ASIEVA>2.0.CO;2.

First received 11 June 2019; accepted in revised form 9 January 2020. Available online 11 February 2020.