Subtropical anticyclone tracking using Principal Component Analysis

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Summary
Using the National Centers for Environmental Prediction (NCEP) reanalysis daily mean sea level pressure data, the climatology of the subtropical Indian Ocean anticyclone was described for the 58-year period of 1951–2008. Principal components analysis was used to identify the attributes and variability of this quasi-permanent feature. We consider the first two principal components which describe 60% of the total variance. The spatial variance structure of the first principal component (PC1) describes that PC1 is related to winter mode in which anticyclones are present over the maximum region of the subtropical Indian Ocean, Western Australia and South-eastern Africa. Time series of the mean annual principal component scores of PC1 indicate that anticyclones system density has been increasing over the Indian Ocean and adjacent land areas. Principal component two (PC2) is related to the late winter and predominant summer pattern, in which anticyclones are present over the central part of the Indian Ocean. The frequency count analysis, tracking and strength of these systems were accomplished using a numerical algorithm technique. The semi-monthly frequency count of anticyclones, dynamics of the anticyclone system and intensity/strength are presented.
Key words:
Anticyclones; High Pressure System; Indian Ocean; Principal Component Analysis

1. Introduction

The subtropical anticyclones exert a dominant role in determining the climate of the mid-latitudes, and play a key role in the global atmospheric circulation. Analyses of these systems dates back to the 19th century, though the systems of the southern hemisphere have been less well studied. The Indian Ocean anticyclone is perhaps the least studied, though its importance in influencing the circulation patterns of the Indian Ocean, the monsoon, Indian Ocean Dipole and the Southern Annular Mode is now appreciated [1]. [2] showed that the influence of these systems it is of importance to monitor and quantify cyclones of southern ocean regions, especially where the changes in sea ice extent over the past few decades have modified the high latitude baroclinicity. [3] reviewed previous work in the southern hemisphere and using data obtained during the International Geophysical Year (IGY) produced the first detailed climatology. This showed a broad band of anticyclonicity over the Indian Ocean, with the centers of the systems lying south of 30°S throughout the year, and little seasonal latitudinal movement in the Indian Ocean sector, though a tendency for the anticyclones to lie more equator ward in winter and pole ward in summer. A similar pattern of seasonal anticyclonicity was identified using charts from 1973-1987 by [4, 5] with the anticyclone tending to lie closer to Australia in summer and to be located in the central southern Indian Ocean in winter. A more detailed anticyclone climatology for the Southern Hemisphere was developed by [6] using the European Centre for Medium-Range Weather Forecasts (ECMWF) twice daily analyses for the period 1980-1989. Blocking was observed to be rare in the Indian Ocean sector, with the anticyclones there also showing the fastest eastward velocities of any of the ocean basins. The use of automated techniques for tracking cyclones and anticyclones has permitted more rapid and objective analysis of the increasing large amount of data [7, 8, and 9].

The modes of atmospheric variability through the southern hemisphere and the temporal and spatial spectra of these [10] which revealed a quasi-biennial fluctuation in 500 hPa wind speed over the Indian Ocean sector. Recent modelling studies have suggested that winter anticyclonicity in the southern Indian Ocean may be sensitive to the percentage of open water in the sea ice around Antarctica [11]. Many studies have contributed to the analysis of the relation between the Indian Ocean high pressure system and rainfall-runoff variability over Southwestern Australia [12, 13]. Climate change in this

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region has also led to substantial impact on the marine ecosystems along the coast [14]. In order to understand these changes is important to better understand the variability that has occurred in the Indian Ocean anticyclone. The aim of this study is to explore the behaviour of 1000 hPa anticyclonicity over the Indian Ocean between 15-120°E and 10-50°S using the NCEP reanalysis data [15] for the period 1951–2008.

2. Data Description

The dataset used in this study is the NCEP reanalysis data obtained from National Center for Environmental Prediction (NCEP) https://www.esrl.noaa.gov/psd/cgibin/db_search/DBSearch.pl?Dataset=NCEP+Reanalysis+Daily+Averages&Variable=Sea+level+pressure&group=0&submit=Search. The data consists of once daily grid point values of mean sea level pressure (MSLP) on a 2.5 by 2.5 latitude-longitude grid for the entire globe. The construction of the data set is described in detail by [16, 17]. It should be mentioned that, after the NCEP reanalysis was performed, a few procedures employed during the assimilation process were identified as incorrect [18]. This resulted in a spurious trend for lower MSLP south of 45°S between 1949 and 1998 with latitudes around 55°S to 80°S most affected. Our analyses focus on 10°-50°S, we were thus satisfied that, for 1000 hPa the anticyclone climatology, the daily reanalysis sea level pressure dataset were reliable enough.

3. Methods

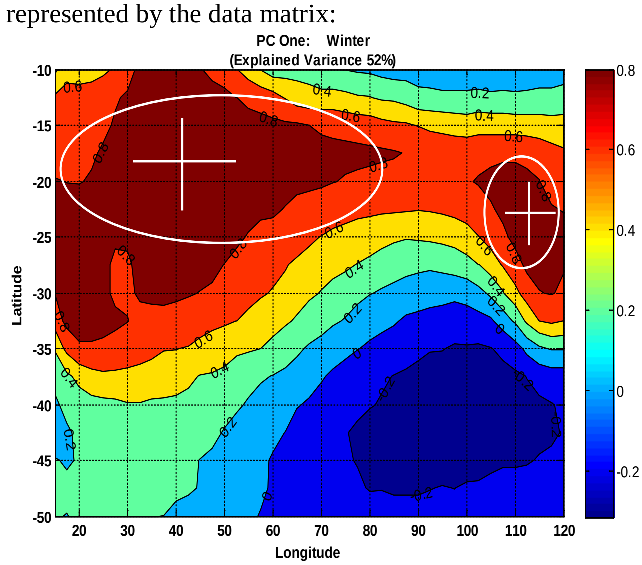
Automated algorithms for the 'finding' and 'tracking' of weather systems have become feasible in recent years with the advancements in computer speed and capacity [7]. [19] showed strong cyclones in terms of absolute thresholds or percentile thresholds of intensity, e.g. the 95th percentile of the Laplacian of MSLP. Consistent with hemispheric results [20], the numbers of identified cyclones in the subantarctic region show large differences between the different tracking methods. We have used the semimonthly anticyclone frequency count scheme developed by [21] in this study. Here an anticyclone is considered to be present at a grid node on a given day when the sea level pressure becomes equal to, or greater than 1020 hPa. This threshold was adopted as values above 1020 hPa invariably isolate regions of anticyclonicity over the subtropical regions of the Indian Ocean and nearby land areas. To describe the theoretical framework of PCA we now present the equations to calculate the eigen values and scores the equations below 1-3.

$$X(t,\mathbf{s}) = \sum_{k=1}^{M} c_k(t) u_k(\mathbf{s}), \qquad (1)$$

$$X = (\mathbf{x}_1, \mathbf{x}_2, \ldots, \mathbf{x}_n)^T = \begin{pmatrix} x_{11} & x_{12} & \ldots & x_{1p} \\ x_{21} & x_{22} & \ldots & x_{2p} \\ \vdots & \vdots & \vdots & \vdots \\ x_{n1} & x_{n2} & \ldots & x_{np} \end{pmatrix} \qquad (2)$$

$$\overline{x}_{.i} = \frac{1}{n} \sum_{k=1}^{n} x_{ki}. \qquad (3)$$

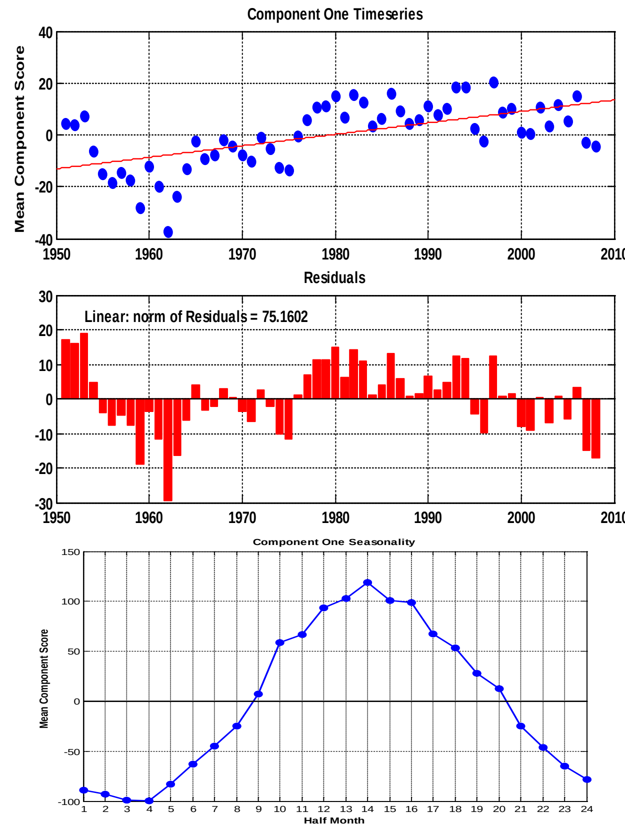
We suppose that we have a gridded data set composed of a space-time field *X(t,* **s***)* representing the value of the field *X*, such as SLP, at time *t* and spatial position **s**. The value of the field at discrete time *ti* and grid point **s***j* is denoted *xij* for *i* = 1,, *n* and *j* = 1, . . . *p*. The observed field is then represented by the data matrix:



We performed data analysis using numerical algorithm as our final dataset consists of frequency counts of high pressure occurrence within 2.5 by 2.5 grid node for 24 half months per year over 58 years. To maintain consistency for the frequency of occurrence in February, for any leap year we used the average respective MSLP values for each grid point of the last two days of month. In the next stage principal component analysis (PCA) is utilized to bifurcate the variance related to the space of anticyclone frequencies. Variables which are defined as columns which are numerous patterns of line nodes over a sub region moving out of eastern South Africa and bisecting Madagascar in the direction of Western Australia, whereas observations (rows) are definition of frequencies for each half month over 58 years.

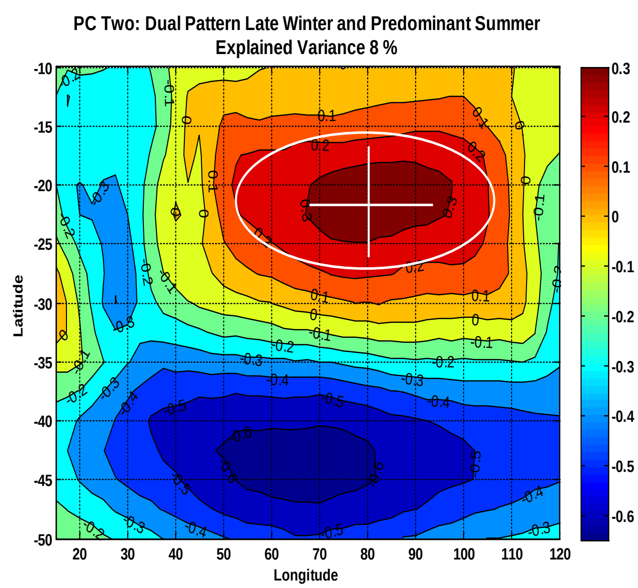
4. Results

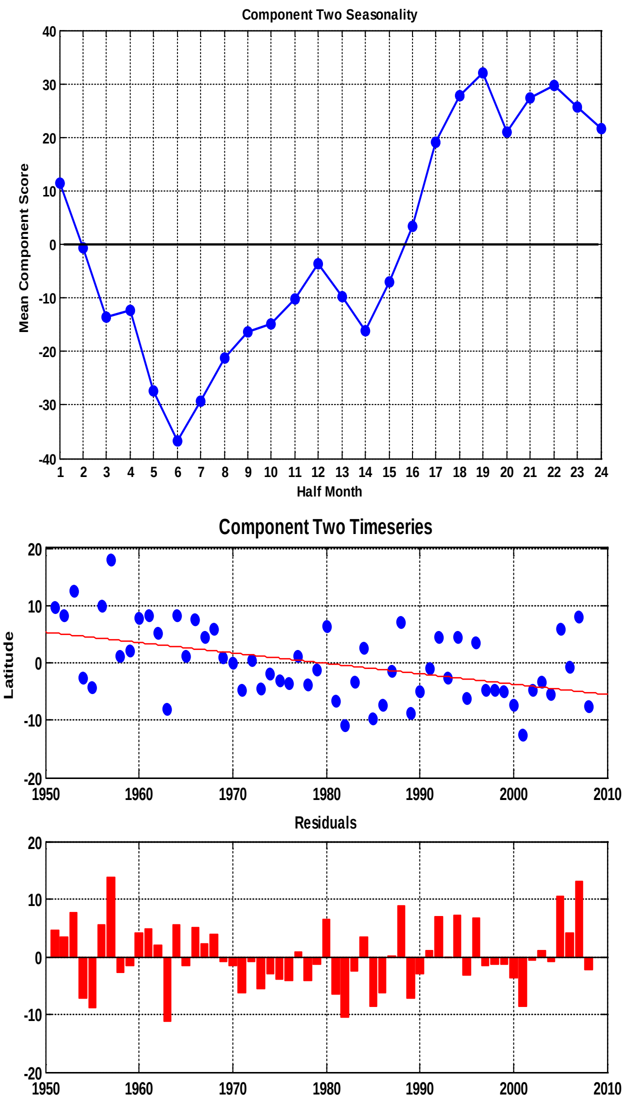
The First Principal Component as presented in (Fig. 1.a) takes on a May-August mode and forms substantial portion of more than half variance of the total change in the complete record. The first PC puts on dual pattern of highest positive loadings taking place over South Africa and Madagascar as well as around Western Australia. Major variation in the frequency of high pressure occurs during the period 1951-2008. Positive scores imply that these dual centers are prone to co-vary, thereby; there is concomitant presence of high pressure over South Africa, Madagascar and Western Australia. Height relative to sea level pressure of the subtropical Central Indian Ocean basis is relatively flat except a few minor positive loadings. When the positive phase of this pattern comes off, uninterrupted streams of anticyclones are present over the subtropical India Ocean Basin. May-October (MJJASO) is of the view that positive mode of this PC (Fig .1.b) takes up major position in winter, and late July posts annual highest score, when dual maximum of winter pattern is dominant. In course of half a month high pressure angles its way from 50 °E to 100 °E and 25 °S to 44 °S for good. In February, negative mode is very rife, when subtropical eastern Indian Ocean basis is taken up by high pressure. Time series of annual component as shown in (Fig 1.c) validates the ubiquitous nature of Principal Component One in the last 30 years. A linear trend applied to the mean annual scores has conspicuous positive inclination in terms of statistics. Albeit, the downward trend is squarely consistent from 1975-2000. Second Principal Component (Fig. 2.a) explaining the multiple patterns which can be labeled as winter and Predominant Summer mode of the subtropical anticyclone and describes at length the 8% of the variance. Positive loadings comes off in the central part of the Indian Ocean centered at 20 °S , 60 °E to 80 °E. Ruling this region, the subtropical India Ocean puts on no changes and continents lying in close proximity exhibits same behavior. In course of half a month with positive loadings, a presence of very potent anticyclone over subtropical Indian Ocean basin is marked by angling its way 15 °S to 30 °S and 50 °E to 100 °E. Second Principal Component with half months negative loadings (Fig. 2.b) are validated by a dearth of high pressure on top of the extra-tropical region of Indian Ocean basin and continents lying in the environs. November and January post highest mean component score (Fig. 2.c), especially when the subtropical high obtains its summer frequency maximum and lowest in March, April. In contrast to component one, rapid fall in anticyclone frequencies in course of the last half century is expressed by the Principal Component Two scores time series. A conspicuous decline is quite clear statistically, implying the late winter and summer mode of subtropical high (Fig. 2.c) has turned into steadily less active in the whole span of the last half century.



Figures. 1. (a) First principal component loadings, (b) mean half-month component scores for principal component one (c) mean annual component scores for principal component one.

Note: Half month one is the first half of January, half month two the second half of January, etc.





Figures. 2. (a) Second principal component loadings, (b) mean half-month component scores for principal component two (c) mean annual component scores for principal component two.

Note: Half month one is the first half of January, half month two the second half of January, etc.

5. Conclusion

The study in question has put into practice entirely automated techniques to aggregate statistical information for the geographical expanse motion and expounds on the central pressure regions of the southern hemisphere anticyclones and their associated lifecycle traits. Anticyclone presence at a grid node on a given day, is inferred by using the rule "when the sea level pressure measured up as equal and extends beyond 1020 hPa" finding from outer edge map of anticyclone system density, location of formation and spatial expansion have showed that a belt of maximum anticyclone frequency lying in-between at 20 °S to 42 °S throughout the year exempting one or two half during winter season. A broad band of enhanced anticyclone system density, anticyclone formation and dissipation was evident across the Indian Ocean exhibited from Southwest Australia to Southeast Africa in all seasons. Most markedly from May to September anticyclone centers were found to peak around the latitudes 20°S –42°S. This quasi-permanent subtropical anticyclone system over the Indian Ocean has a major impact on the weather and climate of much of Western Australia and South Africa. Conducting scrutiny of frequency of high pressure for brink value of 1020hPa, we have analyzed variation in the severity, size and traits relating to geographical expanse of the Indian Ocean Subtropical anticyclone in both seasonally and inter-annually. The majority of variation in high pressure over the subtropical Indian Ocean and continents lying in close proximity are governed by two patterns: a single late winter and summer maximum over the Central Indian Ocean that attains its peak in November and a dual winter maxima pattern with anticyclone covering land mass of Western Australia and South Africa that marks its extreme in July. In the remaining period of the year, the Indian Ocean high takes up fluctuating patterns, that is, it shifts its operations between two common modes. Not as common in other parts of the year, area of highest anticyclone frequency (and highest central pressure) likely to move its position and covers the area slowly (e.g. May through August). The two initial Principal Components provide reason for more than two thirds of aggregate variance in the data. Looking at the first component and exempting the first, the inter-annual variation dating back to the past century is measureable to the average seasonal variation. An exhaustive account of regional climate variability within the acting forces of Indian Ocean high pressure and how the regional climatic variables targeted by this high pressure system inclusive of precipitation and fluvial flow will be the focus of research and analysis in an upcoming paper.

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References

[1] Schott FA, Xie SP, McCreary Jr JP. Indian Ocean circulation and climate variability. Reviews of Geophysics. 2009, 47(1).

[2] Simmonds I. Comparing and contrasting the behaviour of Arctic and Antarctic sea ice over the 35 year period 1979-2013. Annals of Glaciology. 2015, 56,18-28. DOI:10.3189/2015AoG69A909.

[3] Taljaard JJ. Development, distribution and movement of cyclones and anticyclones in the Southern Hemisphere during the IGY. Journal of Applied Meteorology. 1967, 6, 973-87.

[4] Leighton RM. Monthly anticyclonicity and cyclonicity in the southern hemisphere; Averages for january, april, july, and october. International journal of climatology. 1994, 14, 33-45.

[5] Jones DA, Simmonds I. A climatology of Southern Hemisphere anticyclones. Climate Dynamics. 1994, 10, 333-48.

[6] Sinclair MR. A climatology of anticyclones and blocking for the Southern Hemisphere. Monthly Weather Review. 1996, 124, 245-64.

[7] Keable M, Simmonds I, Keay K. Distribution and temporal variability of 500 hPa cyclone characteristics in the Southern Hemisphere. International Journal of Climatology. 2002, 22, 131-50.

[8] Pezza AB, Ambrizzi T. Variability of Southern Hemisphere cyclone and anticyclone behavior: Further analysis. Journal of Climate. 2003, 16, 75-83.

[9] Pezza AB, Simmonds I, Renwick JA. Southern Hemisphere cyclones and anticyclones: Recent trends and links with decadal variability in the Pacific Ocean. International Journal of Climatology. 2007, 27, 1403-19.

[10] Swanson GS, Trenberth KE. Interannual variability in the Southern Hemisphere troposphere. Monthly Weather Review. 1981, 109, 1890-7.

[11] Simmondsxs I, Budd WF. Sensitivity of the Southern Hemisphere circulation to leads in the Antarctic pack ice. Quarterly Journal of the Royal Meteorological Society. 1991 , 17,1003-24.

[12] Hameed S, Iqbal MJ, Collins D. Impact of the Indian Ocean high pressure system on winter precipitation over western and southwestern Australia. Australian Meteorological and Oceanographic Journal. 2011, 61, 159.

[13] Rehman SU. Influence of Indian Ocean high pressure on streamflow variability over southwestern Australia. Annals of Geophysics. 2014, 57, 2-12.

[14] Wernberg, T., Bennett, S., Babcock, R.C., de Bettignies, T., Cure, K., Depczynski, M., Dufois, F., Fromont, J., Fulton, C.J., Hovey, R.K., Harvey, E.S., Holmes, T.H., Kendrick, G.A., Radford, B., Santana-Garcon, J., Saunders, B.J., Smale, D A., Thomsen, M.S., Tuckett, C.A., Tuya, F., Vanderklift, M.A. and Wilson, S. Climate-driven regime shift of a temperate marine ecosystem. Science, 2016 353, 169-172.

[15] Kalnay E, Kanamitsu M, Kistler R, Collins W, Deaven D, Gandin L, Iredell M, Saha S, White G, Woollen J, Zhu Y. The NCEP/NCAR 40-year reanalysis project. Bulletin of the American meteorological Society. 1996, 77, 437-72.

[16] Kistler R, Kalnay E, Collins W, Saha S, White G, Woollen J, Chelliah M, Ebisuzaki W, Kanamitsu M, Kousky V, van den Dool H. The NCEP–NCAR 50-year reanalysis: monthly means CD-ROM and documentation. Bulletin of the American Meteorological society. 2001, 82, 247-68.

[17] Hines KM, Bromwich DH, Marshall GJ. Artificial surface pressure trends in the NCEP–NCAR reanalysis over the Southern Ocean and Antarctica. Journal of Climate. 2000, 13, 3940-52.

[18] Grieger J, Leckebusch GC, Donat MG, Schuster M, Ulbrich U. Southern Hemisphere winter cyclone activity under recent and future climate conditions in multi-model AOGCM simulations. International Journal of Climatology. 2014, 34, 3400-16.

[19] Neu U, Akperov MG, Bellenbaum N, Benestad R, Blender R, Caballero R, Cocozza A, Dacre HF, Feng Y, Fraedrich K, Grieger J. IMILAST: A community effort to intercompare extratropical cyclone detection and tracking algorithms. Bulletin of the American Meteorological Society. 2013, 94, 529-47.

[20] Davis RE, Hayden BP, Gay DA, Phillips WL, Jones GV. The north atlantic subtropical anticyclone. Journal of Climate. 1997, 10, 728-44.

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