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To cite this article: Gong Dao-Yi, Gao Yong-Qi, Hu Miao & Guo Dong (2013) Association of Indian Ocean ITCZ Variations with the Arctic Oscillation during Boreal Winter, Atmospheric and Oceanic Science Letters, 6:5, 300-305

To link to this article: http://dx.doi.org/10.3878/j.issn.1674-2834.12.0108

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Published online: 12 Aug 2015.

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Association of Indian Ocean ITCZ Variations with the Arctic Oscillation during Boreal Winter

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Received 18 December 2012; revised 11 January 2013; accepted 14 January 2013; published 16 September 2013

Abstract In this study, the authors analyzed the associations between the Arctic Oscillation (AO) and the tropical Indian Ocean (TIO) intertropical convergence zone (ITCZ) in boreal winter for the period 1979–2009. A statistically significant AO-TIO ITCZ linkage was found. The ITCZ vertical air motion is significantly associated with the AO, with upward (downward) air motion corresponding to the positive (negative) AO phase. The Arabian Sea anticyclone plays a crucial role in linking the AO and the TIO ITCZ. The Arabian Sea vorticity is strongly linked to high-latitude disturbances in conjunction with jet stream waveguide effects of disturbance trapping and energy dispersion. During positive (negative) AO years, the Arabian Sea anticyclone tends to be stronger (weaker). The mean vorticity over the Arabian Sea, averaged from 850 hPa to 200 hPa, has a significant negative correlation with AO (r = −0.63). The anomalous anticyclone over the Arabian Sea brings stronger northeastern winds, which enhance the ITCZ after crossing the equator and result in greater-than-normal precipitation and minimum outgoing long-wave radiation.

Keywords: Arctic Oscillation, tropical Indian Ocean, ITCZ, teleconnection


1 Introduction

The intertropical convergence zone (ITCZ) is the dominant atmospheric circulation system controlling the tropical Indian Ocean (TIO) climates. During January through March, the ITCZ moves to its southernmost location (5°–10°S), and seasonal precipitation along the ITCZ contributes 30%–50% of total annual precipitation across the tropical southern Indian Ocean; this ratio exceeds 60% to the north of Madagascar where the ITCZ is located farther south compared to the eastern TIO (Jury et al., 1994; Schott et al., 2009; Vialard et al., 2011; Gong et al., 2013). In previous studies, the role of thermal forcing in modulating variation in the ITCZ has been intensively analyzed. Temperature anomalies caused by global warming or aerosol pollution-induced cooling can alter thermal gradients, resulting in global ITCZ anomalies that correspond to changes in its South-North mitigation between the two hemispheres. The TIO ITCZ is of particular interest since the Indian monsoons co-vary closely with it. The TIO ITCZ tends to be enhanced along the relatively warmer hemisphere (Broccoli et al., 2006; Kang et al., 2008; Chiang and Friedman, 2012; Frierson and Huang, 2012). McCarthy et al. (2012) simulated the influence of land-cover change, and found that when vegetation dynamics are considered there is a large-scale cooling of the Northern Hemisphere that results in a southward shift of the ITCZ and weakening of the Indian monsoon. Regional air-sea interactions also play an important role in variation of the ITCZ, where feedbacks among surface wind, evaporation, and sea-surface temperature (SST) are keys to sustaining the latitudinal asymmetry of SST gradients (Xie and Philander, 1994; Philander et al., 1996). Sato et al. (2007) reported that surface-wind-relevant SST and upwelling may influence ITCZ precipitation in the northern TIO in autumn. In addition, increasing evidence reports that the northern mid- and high-latitude atmospheric circulation can exert an indirect influence on the TIO climate. With regard to the mid/high-latitude circulation and Indian Ocean climate linkage, the Rossby wave is suggested to play a key role in bridging the teleconnection. For example, Pan and Li (2008) demonstrated that the mid-latitude disturbances propagate southeastward and that signals originated from western Europe can reach the TIO within several days, resulting in intraseasonal oscillation anomalies. Recent studies have found that the Arctic Oscillation (AO)/North Atlantic Oscillation (NAO) is related to tropical intraseasonal time scale variations (Zhou and Miller, 2005; Cassou, 2008; Lin et al., 2009; Yuan et al., 2011). In a simulation study, Lin and Brunet (2011) confirmed that the NAO can trigger wind anomalies over the Indian Ocean within about 10 days. Note that the majority of these AO-TIO climate relationship studies focus on intraseasonal timescales (particularly the Madden-Julian Oscillation). Gong et al. (2013) recently reported an interannual linkage between boreal winter AO and TIO precipitation, revealed by observation and historical climate simulations. The aim of the present study is to explore the possible association between year-to-year variations of the AO and the TIO ITCZ.

2 Data and method

Satellite observation of interpolated outgoing longwave...
radiation (OLR) data is used (Liebmann and Smith, 1996). This data set, available from 1979, has a resolution of 2.5° latitude × 2.5° longitude. Atmospheric circulation data employed in the study are obtained from the European Centre for Medium-Range Weather Forecasts Reanalysis (ERA)-Interim datasets with 1.5° spatial resolution and 37 pressure levels in the vertical direction. The monthly mean fields used in the study are available from January 1979 (Dee et al., 2011). The AO index provides the corresponding time coefficients of the first empirical orthogonal function of monthly sea-level pressure North of 20°N (Thompson and Wallace, 1998). Because the AO develops most actively during January-February-March (JFM), we confined our analysis season within boreal winter (JFM). All variables analyzed (including AO, OLR, and atmospheric circulation) are averaged from January through March to yield the seasonal means for the analysis period of 1979-2009. The seasonal mean OLR for JFM would filter out the synoptic-intraseasonal scale variations; in particular, variations in the Madden-Julian Oscillation would largely be smoothed out.

Annual variation in the TIO climate is largely impacted by El Niño/Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD). We attempted to linearly remove ENSO and IOD signals in all variables using multi-regression analysis, and found that the anomalies in OLR and atmospheric circulation corresponding to AO were similar (figures not shown), suggesting the AO-ITCZ link is very likely to be independent of ENSO and IOD (Fig. 1). Therefore, our analysis as demonstrated below is based on the original time-series.

3 Results and discussions

The convergence of airflow along the ITCZ brings abundant convective precipitation, which can be measured by the outgoing longwave radiation minimums. Here we examined the possible connection between the AO and ITCZ by computing AO index-OLR correlations. To get an idea of their quantitative values, the regression coefficients are also estimated using an ordinary least-squares approach, where OLR is the predictand variable and AO index is the independent variable. The regression coefficients are plotted in Fig. 1. The outstanding feature is that the negative OLR anomalies appear in the southern TIO with a large-scale, east-west-oriented structure. The anomalous OLR center appears in the central TIO where the negative departures are lower than −3 W m⁻². Miller et al. (2003) analyzed the composites of OLR using more positive and negative AO cases and found that the negative anomalies in OLR data is used (Liebmann and Smith, 1996). This data set, available from 1979, has a resolution of 2.5° latitude × 2.5° longitude. Atmospheric circulation data employed in the study are obtained from the European Centre for Medium-Range Weather Forecasts Reanalysis (ERA)-Interim datasets with 1.5° spatial resolution and 37 pressure levels in the vertical direction. The monthly mean fields used in the study are available from January 1979 (Dee et al., 2011). The AO index provides the corresponding time coefficients of the first empirical orthogonal function of monthly sea-level pressure North of 20°N (Thompson and Wallace, 1998). Because the AO develops most actively during January-February-March (JFM), we confined our analysis season within boreal winter (JFM). All variables analyzed (including AO, OLR, and atmospheric circulation) are averaged from January through March to yield the seasonal means for the analysis period of 1979-2009. The seasonal mean OLR for JFM would filter out the synoptic-intraseasonal scale variations; in particular, variations in the Madden-Julian Oscillation would largely be smoothed out.

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3 Results and discussions

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Figure 1 (a) Regressions of original OLR against the JFM AO index; (b) Same as (a) but the IOD and ENSO signals have been removed from the OLR. Positive contours are shown in red, and the negative contours are shown in blue. Gray shading in (a) and (b) denote the 90% confidence level. (c) Regression of the 850-hPa horizontal wind (V, vectors) against the JFM AO index. Only vectors at the 90% confidence level are shown; (d) The climate mean of 850-hPa horizontal winds. AH denotes the Arabian High.
OLR anomalies show a basin-wide scale in the east-west direction, and that the OLR minimums below −10 W m\(^{-2}\) are located along approximately 0–10\(^\circ\)S spanning from the eastern TIO to the west (see Miller et al., 2003, Fig. 6). This is generally consistent with the results of our regression analysis.

The simultaneous atmospheric circulations at the lower troposphere (850 hPa) are also examined and plotted in Fig. 1. The outstanding feature is the anomalous westerlies along approximately 10\(^\circ\)S, spanning from approximately 50–90\(^\circ\)E. Accompanying the enhanced western winds, there are significant northeastern winds from 50\(^\circ\)E to 70\(^\circ\)E and from 80\(^\circ\)E to 90\(^\circ\)E in the northern Indian Ocean, which flow across the equator and then move southeastward. The anomalous northeastern winds clearly originate from an anticyclone that appears over a large-scale region spanning from the eastern Arabian Peninsula across the Arabian Sea to eastern India. We note that there is a high-pressure system, the Arabian High, in the seasonal mean climatological circulation field near the surface (see Fig. 1d). The anomalous low-level circulation suggests that during the positive (negative) AO years the enhanced (weakened) Arabian High causes anomalous cross-equator airflow, which tends to strengthen (weaken) the ITCZ and results in more (less) precipitation and low (high) OLR. In the middle and upper troposphere (500 hPa and 200 hPa respectively), the anomalous atmospheric circulations are dominated by a huge anticyclone that resides over the Arabian Sea and neighboring regions. In association with the anticyclone, an anomalous zonal wind appears in a broad belt spanning from northern Africa across the Arabian Peninsula to northern India between about 20–25\(^\circ\)N. There are anomalous easterlies to the southern branch of the anomalous anticyclone, between about 0–10\(^\circ\)N. The anomalous anticyclone over the Arabian Sea is nearly barotropic, appearing through the troposphere (see also Gong et al., 2013, Fig. 4).

We examined the three-dimensional air motion in association with the AO by computing the latitude-vertical structure of the atmospheric circulation along 50–90\(^\circ\)E. These longitudes are chosen because significant western winds and anomalous OLR are located in the TIO (Fig. 1). The zonal (\(u\)), meridional (\(v\)), and vertical (\(w\)) winds, and specific humidity (\(q\)) are plotted together in Fig. 2, all shown as the regression coefficients upon the AO index. The strongest westerly belt appears in 20–30\(^\circ\)N (i.e., to the north of the anomalous anticyclone) and extends from approximately 700 hPa to 150 hPa with maximum anomalies (>1.6 m s\(^{-1}\)) within 400–200 hPa. Over the tropics, there are anomalous eastern winds between 20\(^\circ\)S and 20\(^\circ\)N. The easterly anomalies between 700 hPa and 300 hPa are about −0.4 to −1.2 m s\(^{-1}\), while above 300 hPa the values are lower than −1.2 m s\(^{-1}\). At the same time, southward and downward air motions dominate in the northern section of the Indian Ocean. Most interestingly, a strong ascending motion appears aloft the lower convergence zone between 5–10\(^\circ\)S, extending from the surface to 150 hPa. Accompanying the remarkable ascending, positive specific humidity anomalies extend from 850 hPa to 300 hPa with a maximum between 700 hPa and 500 hPa.

In order to examine the temporal variations of the ITCZ, we computed the regional mean vertical velocity over 6–10.5\(^\circ\)S and 50–90\(^\circ\)E, from 850 hPa to 300 hPa. Significant negative ITCZ vertical motion with AO was clear, with upward (downward) air motion corresponding well to the positive (negative) AO phases. To confirm the temporal covariation between the ITCZ and AO, we explored annual fluctuations of the ITCZ by examining the regional mean vertical air-motion velocity over 6–10.5\(^\circ\)S and 50–90\(^\circ\)E from 850 hPa to 300 hPa. Their out-of-phase
co-variation was evident, with maxima of omega in years 1985, 1999, and 2004 corresponding to negative AO indices; and minima in 1989, 2002, and 2008 corresponding to positive AO indices (Fig. 3a). Two time series yield a significant correlation of $r = -0.34$. In addition, we examined the Arabian anticyclonic variations. To highlight the barotropic feature, we computed the regional vorticity over the anticyclone center through the troposphere (i.e., averaging over 15–25°N and 50–70°E from 850 hPa to 200 hPa). As shown in Fig. 3b, the vorticity has a significantly negative correlation with AO ($r = -0.63$). These analyses imply that during positive (negative) AO years

Figure 4  Regression coefficients of the meridional winds at 300 hPa against: (a) AO, (b) tropical vertical air motion ($\omega$), and (c) the Arabian Sea vorticity. To facilitate comparison, the vertical motion in (b) has been multiplied by $-1$ to correspond to ITCZ ascending air motion. Units: m s$^{-1}$. Gray shading represents values above the 90% confidence level.
the anticyclonic circulation would be enhanced (weakened), accompanied by a stronger (weaker) ITCZ ascending in the TIO.

The above analysis suggests that the TIO ITCZ can be enhanced by AO-related anticyclonic circulation over the Arabian Sea. Naturally, the question arises as to why or how the AO exerts influence on the anticyclone. Previous studies have demonstrated that, in association with boreal winter AO/NAO, a Rossby wave train emanates from the North Atlantic, propagates southeastward, and reaches the Asian subtropical jet stream (e.g., Watanabe, 2004). The importance of the subtropical jet stream in trapping and dispersing energy of AO-related disturbances in the conjunction with AO-Asia climate links is emphasized (Li et al., 2008; Mao et al., 2011; Yang et al., 2012). To examine the Rossby wave activities, we computed the meridional wind anomalies at 300 hPa in association with the JFM AO index. As shown in Fig. 4, there are two wave trains. One is located along about 60°N, spanning from the north Atlantic across continental Eurasia. The other wave train is located at about 15°–30°N. Of note, the evident positive v-wind over the Arabian Peninsula and the negative anomalies over India correspond well to the anticyclone over the Arabian Sea. We also examined the wave trains in association with vertical motion of the ITCZ. The pattern remarkably resembles the AO-related spatial feature. Particularly, the wave trains along 15°–30°N can be traced back to the northern Atlantic, and reach East Asia and the northern Pacific along the subtropical jet stream (Fig. 4). Note that Branstator (2002) analyzed the leading mode of the anomalous 300-hPa streamfunction over the northern hemisphere in winter and found that one of the anomalous centers resides over the Arabian Sea. This anomalous center, embedded in a circumglobal teleconnection train, is strongly involved in the south Asian jet stream waveguide effects of disturbance-trapping and energy dispersion. This is supported by the vorticity-related v-wind anomalies. As shown in Fig. 4c, there are two wave trains in association with the Arabian Sea vorticity that are almost identical to the AO-related features. Therefore, we would expect, by inference, that during the positive (negative) AO years the AO-related wave activities would tend to weaken (enhance) the vorticity over the Arabian Sea, resulting in an anomalous anticyclone (cyclone) circulation through the troposphere.

One issue should be clarified regarding the analysis discussed above. The anomalous ITCZ precipitation release latent heat, which feeds back to the atmosphere. For example, Pan and Li (2008) demonstrated that tropical diabatic heating may generate anomalous stream functions over the Arabian Sea. The typical tropical atmospheric feedback is of Gill-type, characterized by an anticyclone to the west of the heating center in the upper troposphere and a cyclone in the lower troposphere. Note that the AO-related atmospheric circulation is dominated by an anticyclone throughout the troposphere over the Arabian Sea. There is no anomalous cyclone in the lower level, nor any southern counterpart of the upper anticyclone. We have tried to remove the AO signals from the 850-hPa circulation, and then regressed the AO-free winds against the TIO precipitation (which is taken as a proxy for latent heating), and found large-scale cyclonic anomalies (figure not shown). Therefore, we may conclude that the AO-related circulation might overwhelm the heating feedback.

4 Summary

In summary, in the present study the possible year-to-year co-variations between the AO and the Indian Ocean ITCZ are examined. The ITCZ vertical air motion is significantly associated with the AO, with upward (downward) air motion corresponding to the positive (negative) AO phase; the correlation has a value of \( r = -0.34 \). The Arabian Sea anticyclone plays a crucial role in bridging the AO and TIO ITCZ. The anomalous anticyclone over the Arabian Sea modulates the TIO ITCZ by enhancing the cross-equator airflow, while the Arabian Sea vorticity is strongly linked to high-latitude disturbances in conjunction with jet stream waveguide effects of disturbance trapping and energy dispersion. The averaged vorticity over the Arabian Sea has a significant negative correlation with the AO (\( r = -0.63 \)). The robust AO-TIO ITCZ links are very likely independent of ENSO and IOD.

Acknowledgements. ERA-Interim reanalysis data used in this study were obtained from European Centre for Medium-Range Weather Forecasts at http://www.ecmwf.int. The interpolated OLR data were provided by the Physical Sciences Division of Earth System Research Laboratory, National Oceanic & Atmospheric Administration, Boulder, Colorado, USA, from their website at http://www.esrl.noaa.gov/psd. This study was supported by Global Change, Environmental Risk and Its Adaptation Paradigms (2012CB955401) and the Chinese Academy of Sciences Strategic Priority Research Program (XDA05110203). GONG Daoyi was supported by the National Natural Science Foundation of China (41375071).

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