Variability of wind stress curl over the Indian Ocean during years 1970-1995

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Received 13 July 2001, revised 28 February 2002

Climatological and interannual variability aspects of monthly mean pseudo-stress curl over the Indian Ocean for the period 1970-1995 are explored. A harmonic analysis of the curl fields finds most of the variance of the northern basins dominated by semi-annual variability. In particular the coastal areas of Somalia and south/southwestern India have large contributions from this harmonic. In the southern basin, interannual harmonics are the primary ones of curl variance. Biennial oscillatory behaviour is only sporadically evident in various harmonics between 20 and 30 months, and was absent north of 10°S. An EOF analysis confirms that the summer monsoon is the dominant feature compared to the winter monsoon. The mean positive curl in the eastern Arabian Sea indicated positive Ekman velocities (upwards) enhancing coastal upwelling in this region. More exceptional and not previously noted factor is an opposite and somewhat dramatic reduction of curl magnitude since 1988/89. The rate of decline is much larger than the (positive) trend in the early 1980’s and was most notable in the early part of the summer monsoon. It is also evident in the winter monsoon periods, but not so for other months of the year. Additional evidence supports this change in variability patterns.

[ Key words. Interannual variability, Indian Ocean, surface curl, EOF analysis, harmonic analysis ]

One of the characteristic features over the Indian Ocean is the seasonal reversal of winds, dominated by monsoons in the Northern Hemisphere. Several studies have been made on the variability of turbulent fluxes over the Indian Ocean1-4. The pseudo stress (pseudo stress is the wind speed times its component values) was analysed using the method of EOF analysis1 for the period 1977-1985. It is found that there is little interannual variability in the northern Indian Ocean compared to the southern Indian Ocean. However, some of the results reported in the work (ref. 1) may be verified with a longer time series data. The variability of surface meteorological fields using COADS data from 1960-1989 was studied2. A positive correlation was found between wind fields and latent heat flux in the Arabian Sea and Southern Hemisphere trade wind regions.

A comprehensive study was carried out using a numerical model of wind-driven Indian Ocean circulation3. They found that most intense (high amplitude) period was 1983-1986 and related this increase in the winds with the perturbations in the model generated layer thickness in the region of the East African Coastal Current (EACC) and Somali Current as the model circulation is completely wind-driven. Recently, seasonal variability in the upper layers has been studied4 using the climatological temperature data of Levitus5. Their study revealed that annual cycle of the wind stress was strong compared to semi-annual amplitudes and its maximum was found in the central Arabian Sea.

Variability of all the processes is likely on all time scales; forcing at one latitude is eventually felt at another. This variability might modulate the monsoons and so is of potentially great interest. Any feedback by the ocean to the atmosphere would tend to enhance the robustness of the variability and enhances its predictability. It is therefore crucial to know how the ocean feeds back on the atmosphere. One important aspect about the large mid-ocean gyres is that their transport is determined not simply by the wind stress but by the latitudinal variation of the east-west winds (the curl of the wind stress). A brief review of the surface circulation in the Indian Ocean is presented below.

During the boreal summer, a two-gyre system was often observed6-8 in the boundary current which flows toward the north and northeast from the coast of Mozambique (11°S) to the island of Socotra at 12°N. In the southern hemisphere, westward flowing South Equatorial Current (SEC) makes up the northern boundary of the counter clockwise subtropical gyre closed at 40°S. The northward flowing branch has two distinct features in both monsoon seasons. During the
southwest monsoon (June to September), it rounds Madagascar and then feeds into the northward flowing Somali Current. During the northeast monsoon (November to February), it also continues over from north Madagascar to the east African coast and then meets the southward flowing current at 3°S. The eastern boundary current in the southern Indian Ocean is unique. The west Australian Current is displaced offshore by a southward flowing called the Leeuwin Current. The current produces a mild climate in southern Australia. This current weakens during ENSO events and contributes to Australian drought conditions associated with these events.

There is not much in the literature describing variability of the wind stress curl (or pseudo stress curl) in the Indian Ocean though it is regarded as an essential forcing for ocean circulation; in particular, it has been related to vertical (upward) motion at the bottom of the oceanic mixed layer. The wind stress curl is considered to be very important as it primarily drives large-scale surface-ocean gyres or large circulating surface current systems and it has large seasonal variability. In the present work, many years of monthly mean surface wind curl is analysed to study the interannual variability. The EOF analysis technique is used to provide physical interpretations of the significant eigenvectors.

Materials and Methods

A variational method was used to obtain a best guess of the Indian Ocean pseudo-stress field (wind magnitude times the component values) on a 1°×1° grid from 1970-1995. An initial guess field was derived from screening and binning available merchant ship wind reports into 1° boxes and interpolating to fill in data voids. A cost functional having five terms (i.e., constraints) was used to calculate objectively derived monthly maps of pseudo-stress. The five terms include approximation to initial guess; approximation to climatology; a smoothness parameter; and two kinematic terms, approximation of the divergence and curl of the climatology. Each term has a weight associated with it. Using the efficient conjugate-gradient technique, the functional is minimized. The final choice of weights was reflected in the scales resolved in the objective analysis. The final weights were selected based on comparing the results with results of an independent analysis of the same data qualitatively and quantitatively. From these fields of pseudo-stress, curl fields were calculated using finite difference technique in spherical coordinates. Using these 312 monthly fields of pseudo-curl, amplitude and phase of several Fourier harmonics were estimated and an empirical orthogonal function (EOF) technique was applied.

Results

A harmonic analysis technique has been applied to pseudo-curl and calculated proportions of variance for different harmonics. The semi-annual variance is not significant compared to annual variance over much of the Indian Ocean (Fig. 1A,B). However, the semi-annual harmonic is important, south of the southern tip of Indian peninsula due to negative curl associated with NE monsoon and the general negative curl in the Arabian Sea during the southwest monsoon, and the positive curl seen in May and October/November. The annual harmonic was dominant between 5°S to 8°N and near Malaysia due to positive curl patterns associated with NE and SW monsoons. There are two zones in the southern Indian Ocean (15°S-25°S) where a significant proportion of variance (~40%) falls in band for ENSO (3-7 years; Fig. 1C). Similar plots for biennial periods (20-30 months) indicated relatively low values, i.e., < 10 % proportion of variance south of 10° S, and nearly 0 % north of 10° S.

The first three eigenvectors collectively account for 57 % of the total variability in pseudo-curl. The first eigenvector (Fig. 2A), which accounts for 37.7 % of the total variance reveals the expected variability of summer monsoon. The largest positive regions of the curl and negative values of the curl are separated around 16° S which depict that strong winds over the southern hemisphere subtropical gyre. It is also noted that strong positive curl near northeast of Madagascar exists due to the effect of SE jet. In summer monsoon, the positive curl along the coasts of eastern India, Arabia, Somalia, northeast of Madagascar and south China favours upwelling. The time series, which corresponds to the eigenvector (Fig. 2B), showed a steady increase in the positive (summer) amplitude of the curl during 1970-88/89 and a decrease/shift thereafter. (There is no clear correlation to El Nino events). This trend is evident especially in the year-to-year variations of the time series values for EOF 1 (Fig. 2C). Note the distinctive trend (in July/August) toward stronger SW monsoons during the 70’s and 80’s. After 1988/89 there was a very dramatic drop in magnitude, particularly for the early part of the SW monsoon, i.e., June and July. This reduction has not been noted previously. The magnitude for July
decreased by nearly 25%. Premonsoon months May and June exhibit also some decrease of curl magnitudes in the 1990-'95 time period. The recent (post 1988/89) reduction in July curl magnitudes implies a reduction in strong winds responsible for the pattern of EOF 1 (Fig. 2A).

The second EOF accounts for 14.7 % of the variance, (Fig. 3). It depicts primarily the variance during the winter monsoon (peak in January). A distinct band of negative curl exists between 5° S and 16° S which bifurcates regions of positive curl on either side the band. These positive curl regions are responsible for strong positive (upward) movement of mixed layer. In the Arabian Sea, a narrow band of wintertime negative curl exists along the Arabian Peninsula. Likewise the northern half of the Bay of Bengal and South China Sea are also characterized by wintertime negative curl, indicating deepening of the mixed layer. In contrast, the summer pattern (positive curl) covers a much smaller area of the Arabian Sea. The winters of 1975 and 1987 were characterized by weak NE monsoon winds. The 12-month running mean (Fig. 2B), shows the amplitude (negative) is large during 1981-89. The interannual variations of the time series (Fig. 3C) showed a strengthening of winter and spring
(November-March) curl. Note that this strengthening coincides with that indicated in for the SW monsoon, i.e., increased curl magnitude until 1988/89, then weakening to values near to those of the early 1970’s. This increase/decrease is about 33% in January, and less for the November, January, February and March. This decadal variability of the negative curl associated with the NW monsoons as well as the negative curl in the region between the southern trades and the Equator could be explained by a general weakening of the winter/spring winds.

The third EOF shows also significant interannual variability (Fig. 4). However, it accounts only for 4.4% of the total variance. These patterns describe the fall/winter seasonal variation (i.e. October, November, and February). It is noted that maxima curl (positive in fall, negative in winter) was located just northeast Madagascar. This is the result of the weakening of the southern trades during January and February. In the following months, the trades increase and consequently negative curl dominates in this region. The band between the equator and 10°S reflects the winter (maximum in February) positive curl associated with the seasonal westerlies.

This EOF also indicates positive values off the Somali coast during October and November, which is similar to that in July. Along the SW coast of India, the positive curl in September/October reflects the
westerly wind jet between the equator and 10°N. This contradicts previous analyses of curl fields\textsuperscript{11,12} which indicate downwelling (i.e., downward or negative Ekman vertical velocities) is to be expected during these months. Additionally, in examining closely the wind fields, it is clear there is considerable positive curl (and hence positive, upward vertical Ekman vertical velocities) in this region, with maximum values in September/October. The eastern Arabian Sea is a region of relatively having large SST and subsurface temperature variability on interannual scales\textsuperscript{13,14}. Our results suggest that the wind curls have relatively high variance in this region, and during the months of September/October the (positive) Ekman vertical velocities will enhance coastal upwelling in these regions. Interannual variability for this EOF likewise indicates general increase of curl magnitudes in February and October/November during the late 70’s to late 80’s. An increase in the October/November amplitudes of the curl was noticed in late 1990-'92 than the summer and winter trends. However, the peaks in February were found during in 1980-'90. It was also noted that the relatively larger variability of curl in February compared to October/November. This pattern also does not reflect generally the reduction in curl magnitudes noted previously to occur after 1988/89.

Discussion

Monthly mean 1° grided pseudo-stress curl fields for 1970-1995 showed that most of the variance of the northern basins was due to semi-annual and annual variations (primarily due to wind-jetlike features). In particular the coastal areas of Somalia and south/southwestern India have unexpected large contributions from these harmonics. In the southern basin, interannual harmonics were the primary drivers of curl variance. It is interesting to note that biennial oscillatory behaviour, while evident in some of the EOF patterns, was only sporadically evident in various harmonics between 20 and 30 months, and was absent north of 10° S.

An EOF analysis of the monthly curl fields reflects the highly seasonal nature of the Indian Ocean winds (and hence curl). This analysis partitioned the features of summer, winter, and spring/fall into separate patterns. As expected, the patterns reflected large-scale features, but more notably they highlighted regional variability patterns such as the South-easterly jet north of Madagascar and tight curl gradients and values in several coastal regions (e.g., Somalia, and Indian subcontinent). In contrast to recent findings, we noted the mean positive curl in the eastern Arabian Sea, indicating positive Ekman velocities (upwards) enhancing the coastal upwelling in this region. Additionally, interannual variability of curl for this region was detected (in a single EOF mode). The substantial SST variability noted in this region was still subject to much speculation.

Finally, we noted a general increase through the 1980’s and then a more rapid decrease of curl magnitudes, particularly during SW and NE monsoons. The increase may be due to changes in the wind observing system\textsuperscript{14}, however this relatively rapid decline in curl magnitudes is not readily explained by such arguments. Indeed further evidence of climatic changes near 1988/89 was evident in EOF analysis of (independent) monthly SST anomalies over the same region (not shown). In this analysis, the period 1990-95 was notably changed from previous years. Post 1990 was characterized by reduced SST anomalies in western Indian Ocean basin, but larger amplitude SST anomalies were observed in the area of the southern trades and in the area southwest of Sumatra/Java. The impact of these trends in the curl on ocean circulation is not known. However, it was shown\textsuperscript{3} that the increase of trade winds and equatorial westerlies (e.g. during 1983-'85) generates perturbations in the East African Coastal Current (EACC) and Somalia current. Consequently the Indonesian throughflow was reduced through equatorial waves and hence potentially impacting SST. Similar exploration of the recent 1990-present period may lead to further insight on interannual variability of the Indian Ocean.

References

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