

Spectral analysis of wind field in the Indian Ocean

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To study the variability in wind fields over the Indian Ocean, we used ERA INTERIM daily winds for the period 1979-2012. In order to analyse the temporal variation of wind field, we partitioned the whole Indian Ocean into 6 zones based on spatial inhomogeneity in the analysed wind fields. Spectral analysis of the time series (extracted at the centre of each zone) was performed using the auto-regression analysis based on the Yule-Walker equations. and it confirms that universality of the spectral shapes. Frequency spectra show distinct annual variations at all zones; semi-annual variations are observed in the Arabian Sea (Z1) and the Bay of Bengal (Z2) due to the seasonal changes and gradually it disappears from equatorial region (Z3) to southern Indian Ocean (Z6). Also, we observe local maxima at the scale of 1 and 0.5 days⁻¹. The characteristic shape of the spectrum was obtained at two different powers of the frequencies. Decay rate and variance at all zones are analysed. The decay rate varies almost linearly as a function of zones Z1 to Z6. Trend of the variance in low frequency range is linear whereas, in high frequency range is exponential. The variance is large in the storm track region. It is found that over the range of frequencies, wind field is independent and is increasing along the zones Z1 to Z6. Latitudinal dependency is clearly observed in both spectral slopes and variances.

[Keywords: Wind spectrum, Auto-regression, Slope, Variance, The Indian Ocean]

Introduction

A stochastic process is used to represent the evolution of random variables over time. Random variables are the variables whose value is subject to variations due to chance (i.e., randomness). As opposed to other mathematical variables, a random variable conceptually does not have a single, fixed value; rather, it can have a possible set of different values, each with an associated probability. The spectral analysis of random variables is defined in terms of the power spectra of the variable versus the frequency. Autoregressive model is a representation of a type of random process. The autoregressive model specifies that the output variable depends linearly on its own previous values. The above procedure describes the unique features in space-time structure of wind and wave field. To our knowledge, such a detailed examination of its statistics in the Indian Ocean is very few.

VanZandt¹ first reported that the spectrum in the free atmosphere has universal shapes. Sato² showed that the vertical wind spectra proportional to the power of $-5/3$ of the frequency in the active periods are likely due to phase modulation of topographically

forced gravity waves in slowly varying background winds. The horizontal wind fluctuation in the troposphere, stratosphere and mesosphere from the middle and upper atmosphere was found to be power of -3 of the wave number^{3,4} analysed the long term wind wave height from the global visual wave data and found that the long-term changes in wind wave height are closely associated with the North Atlantic Oscillation in the Atlantic and with North Pacific Oscillation and El-Nino–Southern Oscillation in the Pacific. Caires and Sterl⁵ estimated the 100 year return values of wind speed and significant wave height from ERA-40 data. Tsuchiya et al.⁶ studied the behaviour of surface meteorology in terms of frequency spectra.

Polnikov et al.⁷ has done the statistical analysis for the average wind and wind energy over the Indian Ocean spatially and temporally, and studied the variability and interaction of wind field on the climate scale. The wind was obtained from the NCEP/NOAA site with $1^\circ \times 1.25^\circ$ resolution with 3 hourly intervals for the period 1998-2008. The analysis was done with portioning the Indian Ocean into 6 zones based on the spatial inhomogeneity of

the analyzed wind field. The analysis includes: i) spatial variation of averaged wind and wind-energy flux over the Indian Ocean and zones, ii) temporal variations of the above fields at fixed points of each zone, iii) construction of the histogram and iv) calculation of first four statistical moments for the wind field. Polnikov *et al.*⁸ studied the wind – wave variability in the Indian Ocean for the period 1998 – 2009. Wind was obtained from the NCEP/NOAA archive and for wave generation, original WAM cycle 4 models with new source function⁹ was used. They have analysed the spatial and temporal variation of wave height and wave energy in the Indian Ocean. Recently, Porgaskii *et al.*¹⁰ studied the joint analysis of the wind and wave field variability and their 12 year trends in the Indian Ocean for the period 1998–2009. They found that the decay law of the spectrum is similar to the law of the decay for isotropic turbulence spectra¹¹.

The present paper deals with the detailed stochastic process of spectral analysis for the wind field in the Indian Ocean for the period 1979 - 2012. ECMWF INTERIM winds with the resolution of 1.5°x 1.5° with 6 h interval¹² are used for the study. The time and space coverage of this data set makes it ideal for the study of wind and wave phenomena over the whole globe.

Materials and Methods

The study area covers the whole Indian Ocean with the domain 10.5°E – 144°E longitude and 69°S – 30°N latitude as shown in Fig.1. In order to study the wind field, ECMWF INTERIM winds available

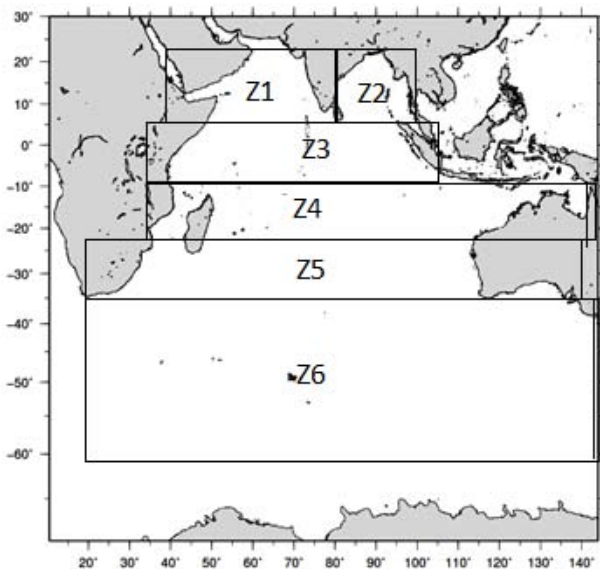


Fig. 1—Study. Indian Ocean

Table 1—The central point coordinates for the zones in the Indian Ocean

Zone	Latitude (°)	Longitude (°)
1	14N	62.5E
2	15N	88.75E
3	0N	80E
4	17S	80E
5	29S	80E
6	49S	80E

in 1.5°x1.5° with 6 h interval for the period 1979–2012 were utilized.

Further, the whole Indian Ocean is divided into 6 zones (as shown in Fig. 1) based on the wind variability in the Indian Ocean⁸. Taking the presence of local extrema in the wind field as a basis for zoning, the following areas could be distinguished as: Arabian Sea (Z1), Bay of Bengal (Z2), equatorial part of IO (Z3) southern part of the trade wind in IO (Z4), southern subtropical part of IO (Z5) and southern IO (Z6). The time series of wind and wave fields are extracted at each central point of the zones. The coordinates of central point of 6 zones are given in the Table 1.

Spectral analysis of the time series was performed using the method of auto-regression analysis based on the Yule-Walker equations. The auto-regressive model specifies that the output variable depends linearly on its own previous values. The Yule-Walker equation is as follows:

$$\gamma_m = \sum_{k=1}^p \phi_k \gamma_{m-k} + \sigma_\epsilon^2 \delta_{m,0} \quad \dots (1)$$

Where, $m = 0, p$, yielding $p+1$ equations. Here γ_m is the auto covariance function of X_t , σ_ϵ is the standard deviation of the input noise process, and $\delta_{m,0}$ is the kronecker delta function.

Yule-Walker method estimates the power spectral density (PSD) of the input using the Yule-Walker auto-regressive method with the confidence intervals of 20% in the logarithmic scale. This method, also called the autocorrelation method, fits an autoregressive (AR) model to the windowed input data. The detailed description of this method is given in¹³. The characteristic shape of the spectrum at each zone has been studied.

Results and Discussion

Statistical characteristics of wind and wave fields are examined in terms of frequency spectra. The

frequency spectra have a characteristic shape proportional to two different powers of the frequency in the lower frequency ranges $(100 - 10 \text{ days})^{-1}$ and higher $(9 \text{ days} - 12 \text{ h})^{-1}$ than the transition frequency of $(\text{several days})^{-1}$. The shape of the spectrum is given by

$$S(\omega) = \alpha \omega^{-\beta_k} \dots (2)$$

The eqn. 2 is estimated by the least square fitting method. Where ω , α and β_k are the frequency, the constant and the spectral slope respectively. Where $k=L$ ($k=H$) indicates the lower (higher) frequency range. Transition frequency ranges between 20 and 6 days. The mean transition frequency is set for 10 day^{-1} . The spectrum shows the long and short scale variability with pronounced peaks. The spectral analysis for all the physical parameters is as follows.

The intensity of annual and half year variability is high and clearly distinguished at Z1 (Fig. 2). Further, the spectrum falls smoothly from the period of 100 days, and no white noise is observed. On the higher frequency side, well-marked maxima at the scales of 1 and 0.5 days are observed. The decay rate in the low frequency part (β_L) is found to be -1.105 and in the high frequency part (β_H) -1.403.

Two distinct peaks are observed at the scale of 1 and 0.5 year at Z2 (Fig. 2) and followed by shelf (white noise). The spectral slope is found to be $\beta_L = -0.816$ and $\beta_H = -1.372$. Two high intensity local maxima are observed at the scale of 1 and 0.5 days.

The intensity of the annual variability has decreased in the equatorial part of the IO (Z3) with

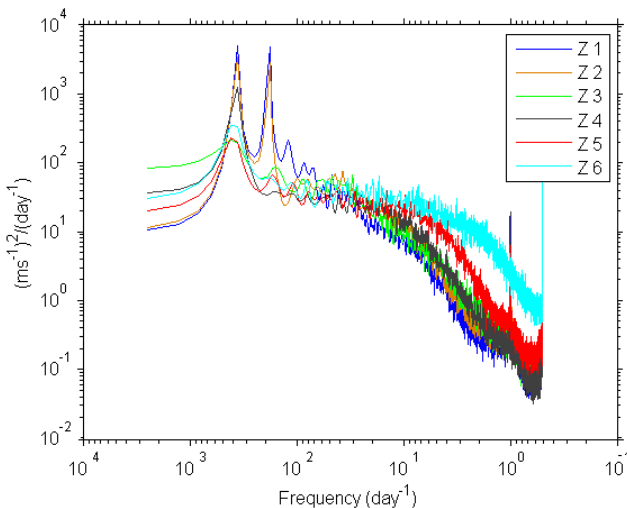


Fig. 2—Frequency spectra of wind speed at all central point of zones in Indian Ocean

the spectrum falls steeply from the period of 40 days. Later, two local maxima are observed at the scale of 1 and 0.5 days (Fig. 2). The decay rate is found to be $\beta_L = -0.945$ and $\beta_H = -1.575$.

Sudden increase in the intensity of the annual maximum and the disappearance of half yearly maximum are observed at Z4 (Fig. 2) followed by white noise (from 200 to 10 days). The spectrum slope is observed to be $\beta_L = -0.363$ and $\beta_H = -1.853$ and two local distinct peaks were at the scale of 1 and 0.5 days.

The intensity of the annual maximum is decreased from the zone Z4 to Z5 (Fig. 2) followed by white noise from 100 to 10 days. Two distinct peaks are observed at the scale of 1 and 0.5 days and the decay rate is $\beta_L = -0.198$ and $\beta_H = -1.964$.

Annual maximum is observed with the following white noise from the period of 100 days to 10 days at Z6 (Fig. 2). Only one distinct local maximum is observed at the scale of 0.5 day. The spectrum decay rate is found to be $\beta_L = -0.161$ and $\beta_H = -1.549$.

The spectral slopes and variance for wind field in the lower and higher frequency ranges as a function of zone are shown in Fig. 3 and Fig. 4 respectively.

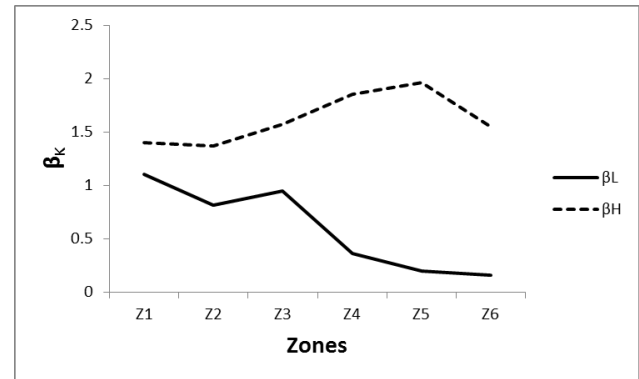


Fig. 3—Spectral slopes of wind field at all central point of zones in the lower and higher frequency ranges of the Indian Ocean

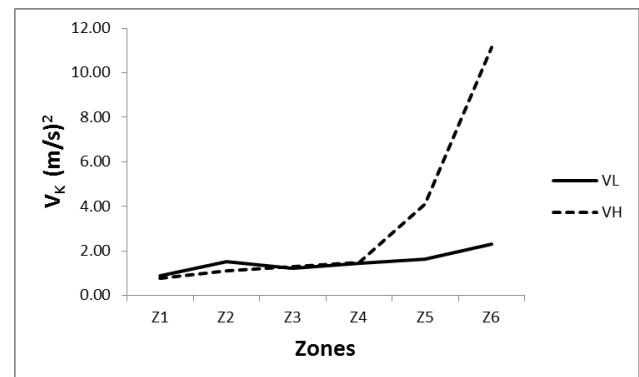


Fig. 4—Variance of wind field at all central point of zones in the lower and higher frequency ranges of the Indian Ocean

The decay rate is almost linear as a function of zones. The spectral slope of low frequency ranges from 0.1 to 1.1 and high frequency from 1.3 to 2.0 (Fig. 3). In the low frequency range, the spectrum decays very steeply (Fig. 2) at zone Z1 (Arabian Sea), whereas due to white noise at Z2 (Bay of Bengal) the spectrum slope decreases. Again at Z3 (Equatorial part of the Indian Ocean) the steepness of the slope has increased. Further, the white noise spectrum is increasing linearly from Z4 (southern part of the trade wind in Indian Ocean) to Z6 (southern Indian Ocean), so the decay rate has decreased. It is found that the decay rate is decreasing in the low frequency range; it means that the shelf life (white noise spectrum) is increasing, whereas, the decay rate in the high frequency range is increasing along the zones from Z1 (Arabian Sea) to Z5 (southern subtropical part of Indian Ocean). At zone Z6 (southern Indian Ocean) slope of the spectrum is decreasing in the high frequency range, this is due to the increase of white noise spectrum (Fig. 2).

In the Bay of Bengal (Z2) the variance is higher compared to that of Arabian Sea (Z1) in the low frequency range, which is due to the presence of white noise spectrum. However, the variance has decreased in the Equatorial Indian Ocean (Z3) as the white noise spectrum has decreased. Further, there is an increase in the variance from zone Z4 (southern part of the trade wind in Indian Ocean) to Z6 (southern Indian Ocean), due to the increase of white noise spectrum. In the high frequency range, there is rapid increase in the variance at Z6 (southern Indian Ocean), due to the increase of white noise spectrum. It means that the wind speed is independent and has the uniform probability distribution over the range of frequencies. From zone Z1 to Z6, the spectral variance in the low frequency range increases linearly, whereas, in the high frequency range, it increases exponentially.

The statistical processing of short term frequencies for measured buoy wind data located in the Arabian Sea and Bay of Bengal has been analyzed by¹⁰. The measured wind spectra were heavily distorted by the noise, at scale less than 1 day. The scales of variability of short term frequencies for measured wind in the Arabian Sea and Bay of Bengal are as follows: 1 year, 40 days, 1 day, ½ day and 1/3 day. However, the half yearly peak, which is observed in the modelled data, is not captured in the buoy data.

Conclusions

The statistical analysis of wind field has been studied over the Indian Ocean for the period 1979 – 2012. The annual variability is distinctly observed at all zones. The half yearly peak is observed only at the zones Z1 (Arabian Sea), Z2 (Bay of Bengal) and Z3 (equatorial Indian Ocean) with decreasing intensity and later the peak disappears at the zones Z4 (southern part of the trade wind in Indian Ocean), Z5 (southern subtropical part of Indian Ocean) and Z6 (southern Indian Ocean). Wind field shows the local maxima at the scale of 1 and 0.5 days⁻¹. The shape of the spectrum at each central point of the zone is analysed. The transition frequency is obtained at 10 days⁻¹. The decay rate and variance are estimated for low and high frequency ranges. The decay rate in the low frequency ranges from 0.1 to 1.1 and for high frequency ranges from 1.3 to 2.0. The decay rate varies almost linearly as a function of zones from Z1 to Z6. The decay rate is decreasing in the low frequency range and increasing in the high frequency range as a function of zone from Z1 to Z6. The spectral slope at zone Z6 (southern Indian Ocean) in the high frequency range is decreasing due to the increase of white noise spectrum. From zone Z1 to Z6, the spectral variance in the low frequency range increases linearly, whereas, in the high frequency range, it increases exponentially. In the southern Indian Ocean the variance in the high frequency range increases rapidly due to the increase of white noise spectrum. This shows that the wind speed is independent with uniform probability distribution over the range of frequencies and is increasing along the zones from Z1 to Z6.

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References

- 1 Vanzandt T, A Universal Spectrum Of Buoyancy Waves In The Atmosphere. *Geophysical Research Letters*, 1982. 9(5):575-578.
- 2 Sato K, Vertical Wind Disturbances In The Troposphere And Lower Stratosphere Observed By The Mu Radar. *Journal Of The Atmospheric Sciences*, 1990. 47(23): 2803-2817.
- 3 Tsuda T, Inoue T, Kato S, Fritts D, And Vanzandt T, Mst

- Radar Observations Of A Saturated Gravity Wave Spectrum. *Journal Of The Atmospheric Sciences*, 1989. 46(15):2440-2447.
- 4 Gulev S K And Grigorieva V, Last Century Changes In Ocean Wind Wave Height From Global Visual Wave Data. *Geophysical Research Letters*, 2004. 31(24):L24302.
 - 5 Caires S And Sterl A, 100-Year Return Value Estimates For Ocean Wind Speed And Significant Wave Height From The Era-40 Data. *Journal Of Climate*, 2005. 18(7):1032-1048.
 - 6 Tsuchiya C, Sato K, Nasuno T, Noda A T, And Satoh M, Universal Frequency Spectra Of Surface Meteorological Fluctuations. *Journal Of Climate*, 2011. 24(17):4718-4732.
 - 7 Pogarskii F, Polnikov V, And Sannasiraj S A, Joint Analysis Of The Wind And Wave-Field Variability In The Indian Ocean Area For 1998–2009. *Izvestiya, Atmospheric And Oceanic Physics*, 2011a 48(6):639-656.
 - 8 Polnikov V, Pogarskii F, Sannasiraj S, And Sundar V, Modeling And Analysis Of The Wind-Waves Field Variability In The Indian Ocean During 1998-2009 Years. *Arxiv Preprint Arxiv:1109.6542*, 2011b.
 - 9 Polnikov V, Wind-Wave Model With An Optimized Source Function. *Izv., Atmos. Ocean. Phys.*, 2005. 41(5):594–610.
 - 10 Pogarskii F, Polnikov V, And Sannasiraj S, Joint Analysis Of The Wind And Wave-Field Variability In The Indian Ocean Area For 1998–2009. *Izvestiya, Atmospheric And Oceanic Physics*, 2012. 48(6):639-656.
 - 11 onin nd lom , *Statistical Hydromechanics*. 1967: Us Department Of Commerce, Clearinghouse For Federal Scientific And Technical Information, Joint Publications Research Service.
 - 12 Berrisford P, Dee D, Poli P, Brugge R, Fielding K, Fuentes M, Kallberg P, Kobayashi S, Uppala S, And, And Simmons A, *The Era-Interim Archive*, In *Technical Report*. 2011.1-23.
 - 13 Polnikov V G, Features Of The Adaptive Spectral Analysis For Hydrodynamic Processes, In *Proceedings Of The 5th All Ussr Meeting For Statistical Meteorology*. 1985: Kazan.146-151.