Auto-correlation analysis of ocean surface wind vectors

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The nature of the inherent temporal variability of surface winds is analyzed by comparison of winds obtained through different measurement methods. In this work, an auto-correlation analysis of a time series data of surface winds measured *in situ* by a deep water buoy in the Indian Ocean has been carried out. Hourly time series data available for 240 hours in the month of May, 1999 were subjected to an auto-correlation analysis. The analysis indicates an exponential fall of the auto-correlation in the first few hours with a decorrelation time scale of about 6 hours. For a meaningful comparison between satellite derived products and *in situ* data, satellite data acquired at different time intervals should be used with appropriate 'weights', rather than treating the data as concurrent in time. This paper presents a scheme for temporal weighting using the auto-correlation analysis. These temporal 'weights' can potentially improve the root mean square (rms) deviation between satellite and *in situ* measurements. A case study using the TRMM Microwave Imager (TMI) and Indian Ocean buoy wind speed data resulted in an improvement of about 10%.

1. Introduction

The need for studying temporal variability of oceanic winds has been pointed out by many authors (for example, Ezraty R S 1989). Knowledge of the de-correlation time scale of the parameter is essential when the values of the parameter, measured by different instruments, separated in time (or space) from each other, are inter-compared.

In order to ascertain accuracy of any geophysical parameter, derived by satellites, one has to perform comparison of this parameter with concurrent and co-located *in situ* measurements. In addition to the difference in the nature of measurements, two sets of measurements are seldom precisely co-located and concurrent. As a result a perfect comparison experiment is difficult. However, by making use of the knowledge of temporal/spatial variability of the parameter, a comparison of the measurements separated in time/space can be made more meaningful.

A specific example is comparison of wind speed values as determined by a satellite sensor with the measurements made by ship-borne or buoy-mounted anemometers (considered as 'sea-truth'). Hwang *et al* (1998) reported variation of the correlation coefficient and rms difference between satellite altimeter and buoy measured wind speed in the Gulf of Mexico including the time lag between the measurements as a factor.

The concept of data weight by lags is well known. Studies such as that by Bretherton *et al* (1976) have addressed in detail the problem of spatial objective analysis in 2-dimensions using the technique of optimal interpolation. Weighting of data in time-domain in problems of inter-comparison between satellite and *in situ* data is simpler. Such a problem can be approached by a straightforward application of auto-correlation analysis applied to an accurate time series data set. Such time series data are however very scarce in certain oceanic regions, such as the Indian Ocean. In the given study, such a

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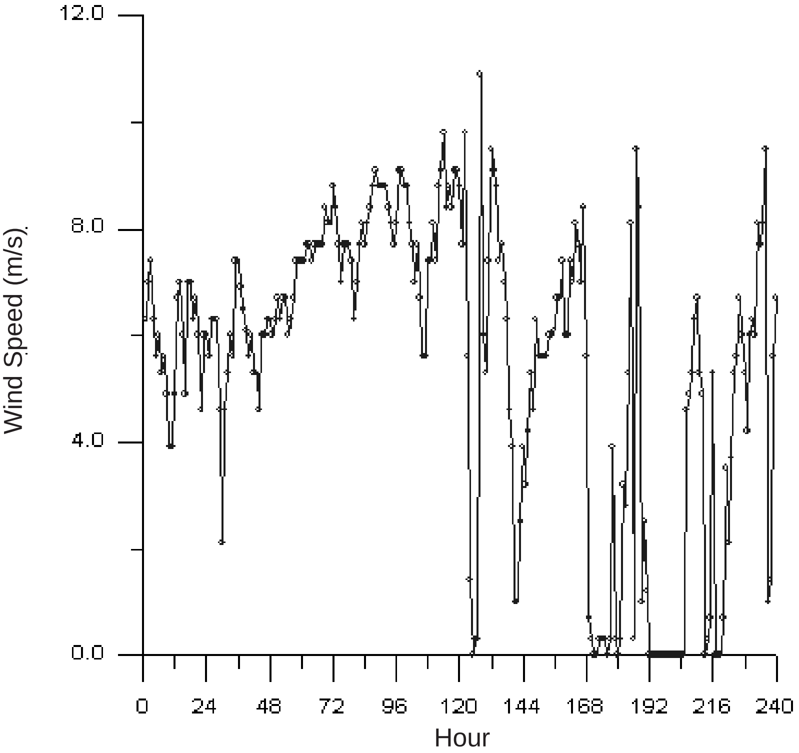

Figure 1. Time series of hourly wind measurements in the Indian Ocean by the data buoy (lat/long: 18.0°/88.1°) during May, 1999.

problem is addressed using time series data of sea surface wind speeds in the north Indian Ocean.

2. Auto-correlation analysis

This study makes use of wind vector data acquired by the National Institute of Ocean Technology (Department of Ocean Development, India), which has installed several deep ocean buoys in the seas around India. Each wind measurement is a 10-min. average (time of one sample is one second) at once every three hours (Premkumar *et al* 1999). For the present study hourly measurements were acquired by a buoy located in the Bay of Bengal (latitude/longitude 18.0°/88.1°) during a special campaign conducted during the pre-monsoon month of May, 1999. Figure 1 shows this time series of wind speed. It covers a long time span of 10 days (240 hours) of continuous data with a one-hour interval, exhibiting a wide spectrum of variability.

The time-series of sea surface winds were first subjected to an auto-correlation analysis. Assuming stationarity of the time series, one can compute the auto-correlation function of the time series using the formula (Anderson 1971; IMSL 1991):

$$\rho(k) = \sigma(k)/\sigma(0) \tag{1}$$

where, k is the lag and $\sigma(k)$ is the auto-covariance function for lag k, and is given by

$$\sigma(k) = (1/n)\sum_{t=1}^{n-k}(X_t - \mu)(X_{t+k} - \mu) \tag{2}$$

where μ is the mean of the time series.

The auto-correlation values were computed for different spans of time (6 hours up to 240 hours). This is represented in figure 2. The top curve is for auto-correlation values for a 1-hour lag for varying lengths of time series, represented by the number of observations in abscissa. The second curve is an auto-correlation for a 2-hour lag, and the third curve is for a 3-hour lag. All the curves show an approach to convergence after the initial fluctuations with convergence when the number of observations exceeds 200. (An exercise carried out earlier with a limited data set consisting of a time series of 74 hours acquired by the ship-borne anemometer on board ORV Sagar Kanya during the August, 1999 BOBMEX campaign had inadequate data length for convergence and was not useful for the present analysis (Sarkar *et al* 2000).

The exercise was repeated for the zonal and the meridional components of the wind for the same data set. The results indicate (figure 3a) that the trend in convergence of the zonal wind is similar (occurring at around 200 observations) to the

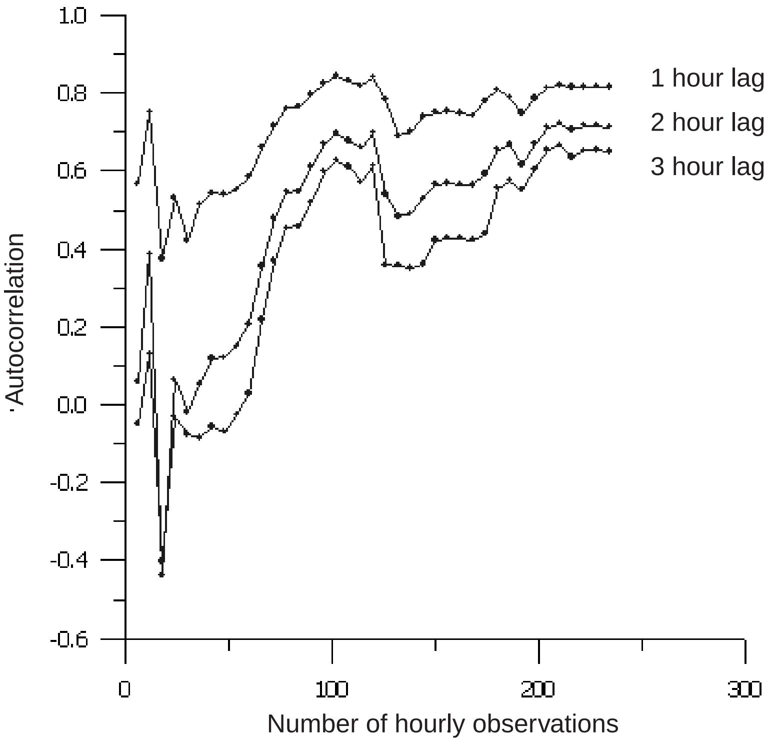

Figure 2. Variation of auto-correlation of wind speed with increasing number of observations for different time lags (1, 2, 3 hours).

case of wind speed magnitude. For the meridional wind (figure 3b), the convergence occurs earlier (at around 150 observations). This exercise ensures that the number of observations (240) is sufficient for a faithful representation of the auto-correlation of the time series.

Figure 4 shows the variation of auto-correlation with time lag with all 240 hours' observations. The pattern of variation with time lag up to about eight hours is seen to be quite close to an exponential function and the subsequent analyses were restricted to time lags up to eight hours. The computed values of auto-correlation were fitted to the exponential function $f(t)$, given by the following equation

$$f(t) = \exp(-t/t_e). \tag{3}$$

The value of t_e for the wind speed magnitude is found to be 6.32 hours, while for zonal and meridional components it is 5.18 and 4.87 hours respectively. These numbers represent the e-folding values of the auto-correlation of oceanic winds in a time domain (the decorrelation time). The fitted auto-correlation values by the exponential function (3) are found to be correlated to the actual values quite well (r^2 value is as high as 0.99). The exponential fall of auto-correlation for wind speed magnitude, the zonal winds and the meridional winds are depicted in figures 4, 5 (a and b), respectively.

3. Weighting scheme

In order to make use of all *in situ* data with different time lags, a weighting scheme, similar to the one used in meteorological data assimilation (Cressman 1954) can be used. For a meaningful comparison of satellite and buoy data, we suggest that the difference between them be multiplied by the following Cressman weights:

$$\begin{aligned} W(t) &= \frac{\tau^2 - t^2}{\tau^2 + t^2} \qquad && t < \tau, \\ W(t) &= 0 && t \geq \tau. \end{aligned} \tag{4}$$

Here, t is the time interval between the two data sets and τ is a threshold value for time beyond which the function assumes the value of 0. The value of τ in our study was taken as 1.5 hour. This is the lag at which the auto-correlation falls to 0.9. It is appropriate for carrying out comparisons of satellite derived winds with those obtained *in situ* if the difference between them are weighted as a function of time lag by the scheme described above.

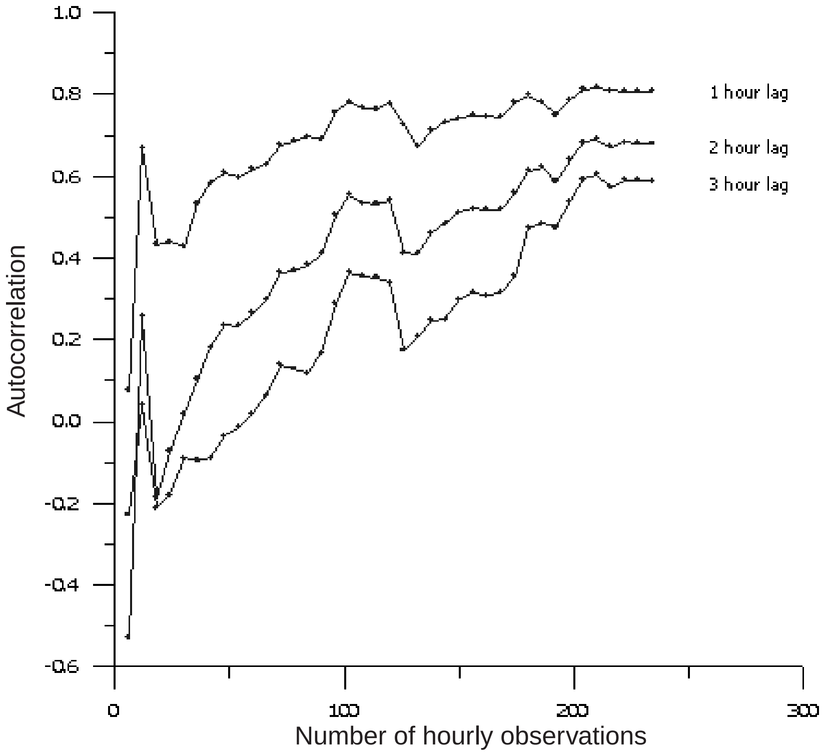

Figure 3(a). Variation of auto-correlation of zonal wind with increasing number of observations for different time lags (1, 2, 3 hours).

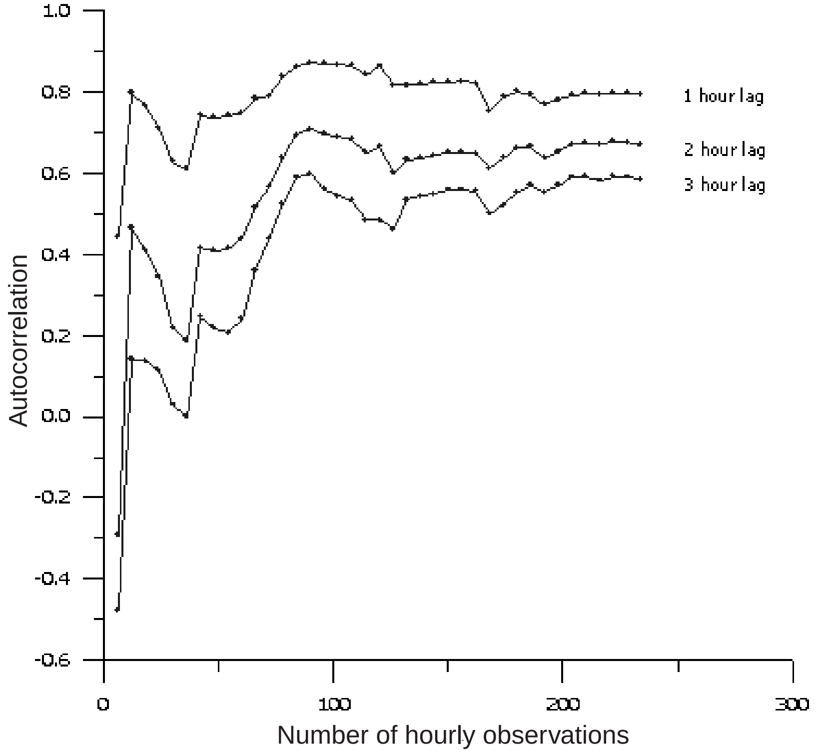

Figure 3(b). Variation of auto-correlation of meridional wind with increasing number of observations for different time lags (1, 2, 3 hours).

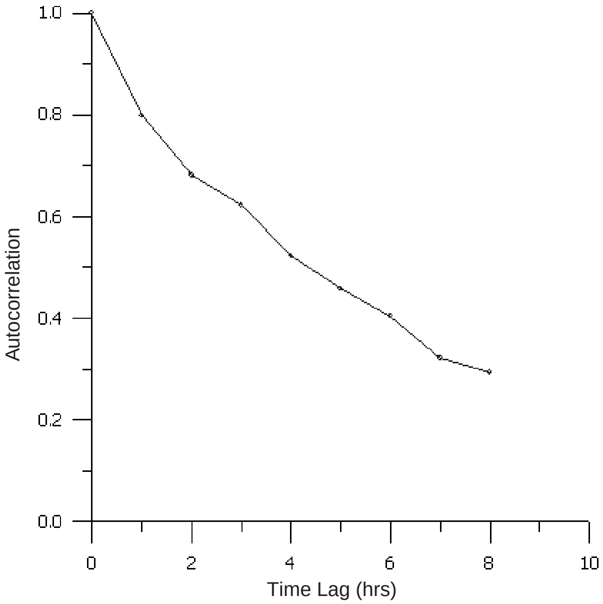

Figure 4. Variation of auto-correlation of wind speed with time lag for 240-hour-long time series.

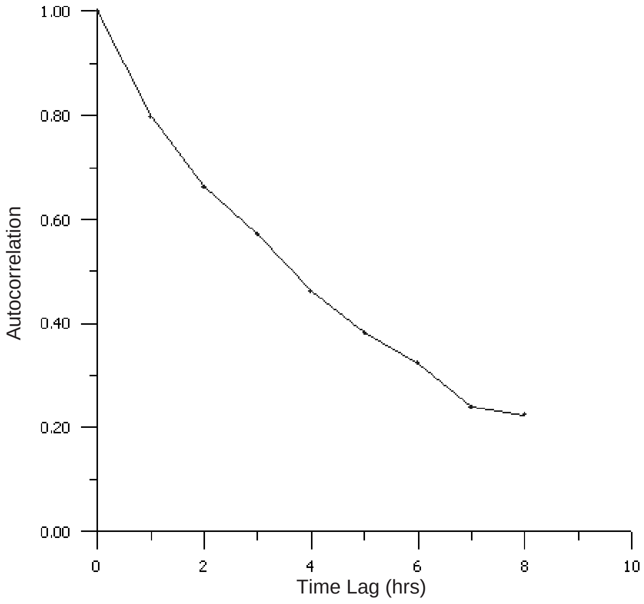

Figure 5(a). Variation of auto-correlation of zonal wind with time lag for 240-hour-long time series.

4. A case study with satellite winds

In order to assess the impact of the temporal weightage, a case study of comparison experiment of wind speed derived from the space-borne TRMM Microwave Imager (TMI) with those by spatially co-located ocean buoy data was carried out using temporal 'weights' derived using the scheme discussed above.

TMI is a nine-channel linearly polarized passive microwave radiometer based upon the special sensor SSM/I. It has been flying aboard the US Defense Meteorological Satellite Program (DMSP) satellite since 1987. The TMI measures the radiation intensity at five microwave frequencies 10.7, 19.4, 21.3, 37 and 85.5 GHz. The TMI derived sea surface wind speed data used in the study were generated with an algorithm developed by Wentz (1997) as an extension of the SSM/I ocean algorithm. The specific buoys of relevance for the present study were DS3 and DS4 located in the north Indian Ocean at latitude/longitude of 12.17°/90.75°, and 18.48°/87.54°.

All the satellite data that were located within twenty-five kilometers of buoy locations were considered for comparison. About 71 data points for

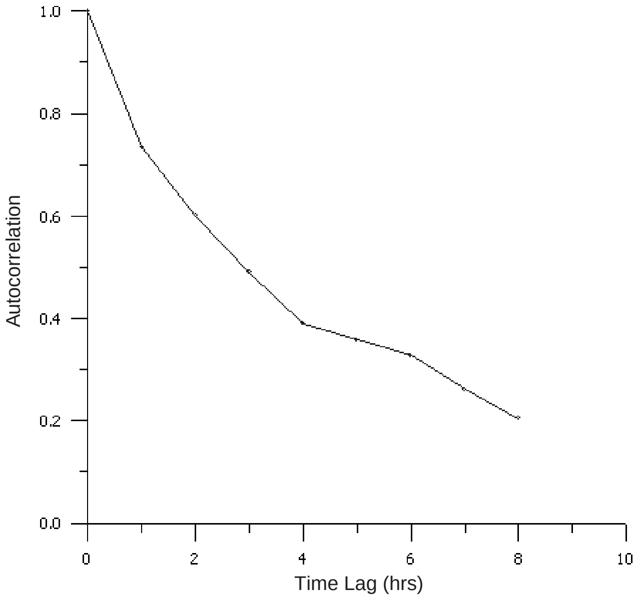

Figure 5(b). Variation of auto-correlation of meridional wind with time lag for 240-hour-long time series.

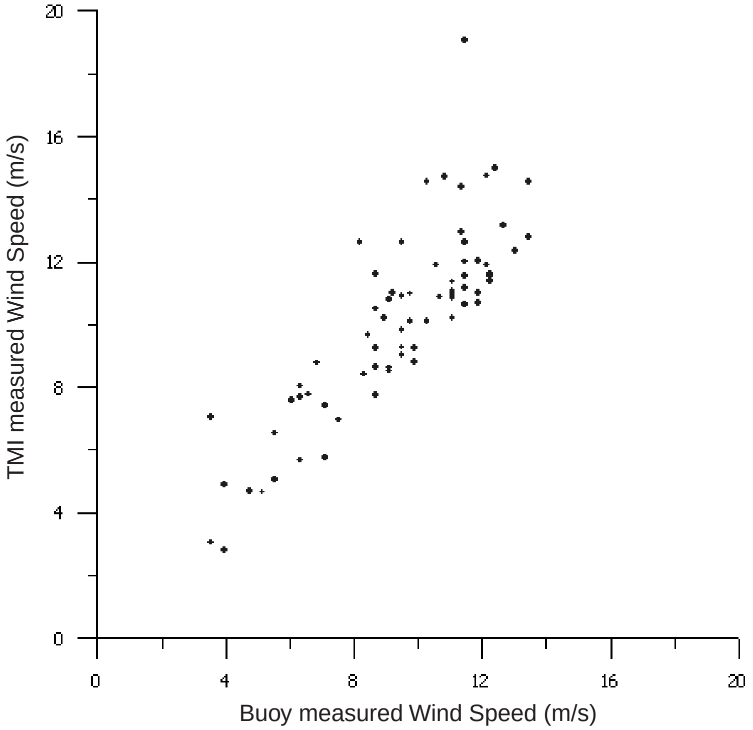

Figure 6. Scatter plot between TMI and buoy measured wind speed during the period June – September, 2000.

the period of June to September, 2000 qualified for the experiment. The match-up satellite-buoy data points are represented as a scatter plot (figure 6).

To evaluate the performance of the proposed weighting scheme, the rms difference between the satellite and *in situ* wind measurements was used as a statistical indicator. The weightage in each case was computed from the time lag (between satellite observation and buoy measurement time) using equation (4). Two values were calculated – one with the temporal weightage and the other without it. The rms difference is found to be 1.59 m/s with weighting compared to 1.74 m/s without. Thus, an improvement of about 10% is seen through weighting.

Acknowledgements

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