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Seasonal Wind Pattern Model Development for Coral Reef Monitoring

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Abstract:
Wind pattern model development is vital for coral reef monitoring due to its dependency on sea surface wind. Wind in Malaysia is influenced primarily by four monsoon season; Northeast and Southwest monsoon with two transition period; April and October inter monsoon and categorized as low wind with annual mean speed of 3-5 m/s. Current wind study utilized limited wind data hence neglects the seasonal characteristics of wind behaviour in wind pattern model simulation. In this study, the Mixed-Layer Conveyor (MLC) model was adopted to simulate wind parameters such as wind speed distribution, direction, days in distinct monsoon to derive cumulative wind of distinct season. This can be used to describe wind behaviour of distinct monsoon season on coral reef growth. Result shows that the derived cumulative wind fit with an actual wind data (0.89). The model developed has an ability to derive seasonal wind cumulative productivity data to be used in estimation of the highest wind and lowest wind production.

Keywords: *Coral reef, Ekman transport, Mixed-layer Conveyor model, Northeast monsoon, wind pattern*

I. Introduction

Coral reefs are important because they provide habitat for at least quarter of all marine species, with structures in an abundance and calcifying activities of simple metazoan animals called corals and other organisms. Coral reefs biodiversity had been threatened by local and global stressors. Studies conducted by [1] and [2] shows that the copepod community varies with monsoon season and related with seasonal environmental changes in coral reef in South East Asia. Coral reef ecosystem is highly sensitive to any changes either chemically

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or physically. One of the major factor that influenced the growth of coral reefs is the wind pattern. Study done by [3] concluded that the wind patterns had a great influence on reef's larval dispersal trajectories and assume wind as a principal driver of currents in shallow waters. This is due to wind reaction on sea surface current that created wind streak; wind-roughened sea surface current or wave [4]. This was discussed by previous researcher in the theory of Bragg's scattering that established the relationship of wind speed and direction to sea surface current and how they influence each other. Meteorologically, wind is an important measure to observe daily weather, rainfall distribution and develop the warning system of any natural hazard such as hurricane, flood or tsunami.

Malaysia being enclosed by Andaman Sea and Straits of Malaccaat the west side, and South China Sea, Sulu Sea and Celebes Sea to the east side experienced seasonal monsoon season each year. This is due to the large-scale difference in land-sea heating in the Asia continent. As part of the Maritime continent, Malaysia experiences wet monsoon during boreal winter and this season is called Northeast monsoon (NEM). On the other hand, during Boreal summer, Malaysia goes through dry season also known as Southwest monsoon (SWM) [5].

These all year monsoon seasons and its transition period highly influenced wind speed and its direction in Malaysia [6]. SWM that occurs in April to September each year carries wind from Indian Ocean from Southwest to North-eastward. SWM, also called as summer monsoon conveys drier wind. WhereasNEM that occurs in November to March each year carries wind from Northeast to South-westward. NEM carries humid wind with high rainfall density along this period. The transitional period between these two monsoon seasons is called inter-monsoon which occurs in April to May (April intermonsoon, AIM) and September to October (October intermonsoon, OIM) each year. This period experiences fluctuation in wind direction, and relatively low wind speed [7]. In addition, Malaysia faces humid air and a rise in temperature especially in the afternoon.

These monsoon seasons occurred due to an effect of uneven cooling and heating of Earth's surface. Earth's surface cooling and heating derived a driving force of horizontal wind motion [8]. Monsoon season highly affect Southern Asia as a large landmass which cools quickly than its surrounding oceans. Hence, the continent develop a strong centre of high pressure that will cause outflow of air as wind along winter. In contrary, during summer, Asia continent heats quickly, in contrast to winter season, where it develops large air pressure centre. Thus, warm and moist tropical air from ocean attracts into the low pressure centre [9]. This contrast of summer and winter phenomena creates apparent different of wind speed, direction and its distribution. Besides that, spatial location and topography also influence wind.

In Malaysia for instance low wind has an average speed of 3 to 5 meter per second (m/s). However, there is a challenge in understanding the seasonal low wind that varies according to the monsoon season. For example, [10] performed time series analysis which incorporated an Auto-regressive and Moving Average (ARMA) model while [11] and [12] applied Kalman filters method to forecast temporal wind pattern. However, it has a limitation in long-term temporal wind with its spatial characteristics.

Remotely sensed wind study involves the modelling of a high spatial resolution wind speed retrieval algorithm from remote sensing image data. In remote sensing, Radar has been successfully used in wind study as can be seen in ERS-2 SAR [10]

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and [11], RADARSAT-1 SAR [13] and [14], ENVISAT ASAR [15], TerraSAR-X [16], and Pi-SAR [17]. Wind study that utilized Synthetic Aperture Radar (SAR) images also includes an extraction of wind direction done by [18] using wavelet transform (WT) technique. However, this technique only applicable on SAR images acquired at high wind speed profile of at least 7 m/s.A number of wind pattern model were developed by researchers using different approaches and methods. This included wind pattern forecast model [19] and wind pattern on coastal upwelling model [20].

This study aims to model seasonal pattern of low wind by using the combination of satellite image and statistical data. Wind model that is used in this work is known as Mixed-Layer Conveyor (MLC) model and was developed to derive biological production in shelf ecosystems driven by coastal upwelling. It was developed based on Ekman transport and surface water theory. Surface water was set in motion by winds that deflected the cum sole relative to the wind direction by Coriolis Effect. Then, wind energy was transferred down into the water column from each water layer to the layer underneath. Consistent blow of wind over deep water develops Ekman spiral, i.e. the situation where the surface current is deflected at 45° and current speed decreases with the increase of depth. Mean water transport that is also known as Ekman transport is where the Ekman spiral develops at 90° to the wind.

This theory is similar to the production of wind-streak on sea surface. Wind-to-water interaction produce upwelling of nutrient such as phytoplankton and zooplankton [21] from ocean to sea surface. Thus, wind pattern forecast model development was done using MLC theory that been modified to meets the criteria of monsoonal wind that characterized wind in regional study area.

The effect of high offshore wind is the conventional volume upwelled that can be considered as the predictor of shelf productivity. By neglecting the wind trend in nutrient production estimation, an annual production at constant wind was estimated and it was found that the total prediction of volume upwelled differed from the productivity calculation derived using above model. The increase of wind speed results in the decrease of the production due to slower plankton response. This scenario explains the influence of wind on ocean currents and the drift of the nutrient produced across the sea surface. The relationship of wind to wave is not limited as the medium to transport the sea surface particle only, but also include wave intensity [22], height [23], speed and direction [24]. In regions that experience monsoon season, especially, the variation of wind is vital to be considered in order to achieve optimal model of wind pattern.

II. Data Acquisition

The study site is in Kuala Terengganu, at the East Coast of Peninsular Malaysia. This site was chosen due to the monsoonal wind properties and the historical wind speed data availability. Wind speed in Kuala Terengganu were found torange between 2-5 m/s. Daily ground measurement of the wind speed were recorded using an anemometer in meter per second (m/s). The data was provided by Malaysian Meteorological Department (MMD) from their tower station installation at the area of interest. Table I summarizes the daily wind speed data that was recorded using an anemometer in the chosen site.

Table I

Daily Wind Speed Data Recorded by Anemometer in Study Site

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Location	Data Period	Station	Tower Heights
Kuala Terengganu	November 2004 – March 2005	Kuala Terengganu Airport	10 meter: 5.2m MSL

Kuala Terengganu wind speed data that was used is the daily data recorded during 2005 Northeast monsoon season (1st November 2004 – 31st March 2005) in meter per second by an anemometer installed at (5° 23’ N latitudes and 103° 06’ E longitudes) Kuala Terengganu, Airport station at 5.2 meter above Mean Sea Level (MSL).

Fig. 1 below shows the image of Wide-3 RADARSAT-1 SAR data that was used in this study to extract high resolution of wind direction. Wide-3 RADARSAT-1 SAR image that was acquired on 20 March 2005 captured an image over Kuala Terengganu, Malaysia.

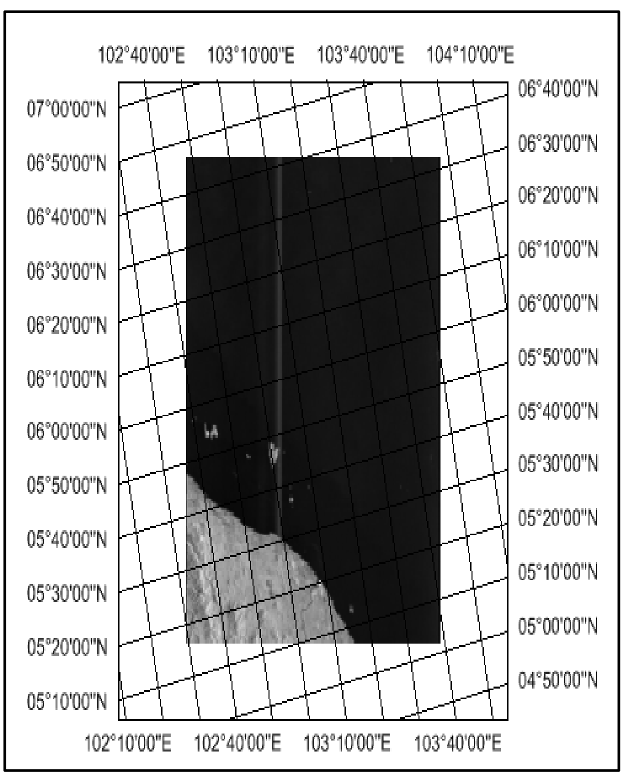

Fig. 1Wide-3 RADARSAT-1 SAR data acquired at Kuala Terengganu, Malaysia during 2005 NEM

Wide-3 RADARSAT-1 SAR data that was used in this study was acquired in 20 March 2005 at 2246 hours at the range of 39°-45° incidence angle with swath width of 150km.

III. METHODOLOGY

Seasonal wind pattern model for coral reef monitoring that was developed in this study involved parameters discussed above; seasonal wind speed, wind distribution and wind direction in the model that was adapted from Mixed-Layer Conveyor (MLC) model. This model simulates the rate of production from the wind pattern that used ocean wind profile and the distribution model to estimate the cumulative capacity of production.

The general algorithm adopted is as Eq. 1 where f is the frequency of I that denotes the irradiance dependence of phytoplankton, and$P$ productivity. The cumulative nutrients uptake by phytoplankton and cumulative consumption of phytoplankton by zooplankton to the time the water parcel leaves the shelves was described in the following Eq. 2.

$$F_p(T) = \int_0^T \frac{V_m N}{K_s + N} f(I) P dt \quad (1)$$

$$F_z(T) = \int_0^T \gamma R_m (1 - e^{\Lambda P}) Z dt \quad (2)$$

Eq. 1 and 2 showed that both model depend on the initial nutrient concentration and light level. Then, cross-shelf transport was determined by assessing the rate of Ekman transport cross-shelf and the mixed layer depth. The shelf production rate for phytoplankton and zooplankton is the product when the water parcels were brought to the surface and

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spread offshore. The rate of production that is taken as cumulative wind production in this study at time t is represented as Eq. 3 below.

$$B(t) = v(t)F[T(t)] \quad (3)$$

$B(t)$ is the rate of nutrient production as the product of the wind reaction on water surface that caused the water parcels to be forced up to the surface. The velocity of the cross-shelf was denoted by $v(t)$, F is the cumulative production and T is the shelf transit time for particle upwelled at t time. The cross-shelf velocity was determined by the wind speed by considering the Ekman transport theory in wind-upwelling system relationships.

The total nutrient production in time interval ranged between $0 \leq t \leq \tau$is determined by several factors; wind velocity, the cumulative production and the time of the shelf to transit during the upwelling events that leads to the formation of Eq. 4.

$$\alpha(\tau) = \int_0^{V(\tau)} \left(V^{-1}(x+W) - V^{-1}(x)\right) g(x)dx \quad (4)$$

This equation derives the total production of wind at τ time and W is the ratio of the local shelf width.The seasonal grouped based on two monsoons and two inter monsoons season of forecasted wind speed, the statistical measure of wind speed such as mean and standard deviation were then inserted into the derived wind pattern forecast model.

$$\gamma(T) = \theta_T \int_0^T s.\frac{1}{2}\left[1 + erf\left(\frac{\ln x - \mu}{\sigma\sqrt{2}}\right)\right] dt \quad (5)$$

Wind pattern model, $\gamma(T)$was used to derive the cumulative wind production in each monsoon season by using mean wind speed, μ, its standard deviation of distinct monsoon, σ, the total time of monsoon season in a unit of day, t, and s is the time period in one specific monsoon season where the wind speed and distribution measurement were taken. For the whole season wind pattern, s is equal to t, and for the estimation of 10 days' wind, s is equal to 10.

IV. Results and Discussion

Wind speed and its distribution model; Lognormal distribution model [25] represent seasonal variation of wind, and wind direction that was extracted from RADARSAT-1 SAR data by using improved wavelet transform technique [23] were used to simulate the seasonal wind pattern model. [24] characterize the dependency of biological production on constant wind magnitude and then describe the influence of time-varying production to wind variations.

The cumulative wind production in each monsoon season from wind speed data was measured and presented in Table II.

TABLE II

WIND PARAMETER DERIVED FROM WIND PATTERN MODEL

Monsoon	**Mean, μ (m/s)**	**S. Deviation, σ**	**t (day)**	**Cumulative wind (m/s)**
NEM	2.458	0.348	755	9070.028
AIM	1.514	0.316	150	1673.145
SWM	1.667	0.317	765	11.923.645
OIM	1.938	0.316	155	1544.162

Table II showed the total wind production in each monsoon season from wind speed data collected. The Southwest monsoon produce the highest cumulative wind at smaller mean wind speed probably due to higher days' count compared to

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Northeast monsoon that have higher mean wind speed. The forecast of cumulative wind in each monsoon season reflect the future atmospheric condition.

A. *Model Validation*

The dependency of derived seasonal wind pattern forecast model was examined using Terengganu wind data from 2005 during the Northeast monsoon season. Wind speed data from 2005 Northeast monsoon starting from November 2004 to end of March 2005 was inserted into the model. 2005 Northeast monsoon has a mean of 7.893 m/s with the standard deviation of 1.76. The minimum wind speed derived occurred at day 25 of the Northeast monsoon with speed of 5.048 m/s while the maximum reached 12.728 m/s in day 39. Most frequent wind speed that blew in year 2005 during Northeast monsoon was ranged between 6-7 m/s that occurred nearly 30 days during the Northeast monsoon season.

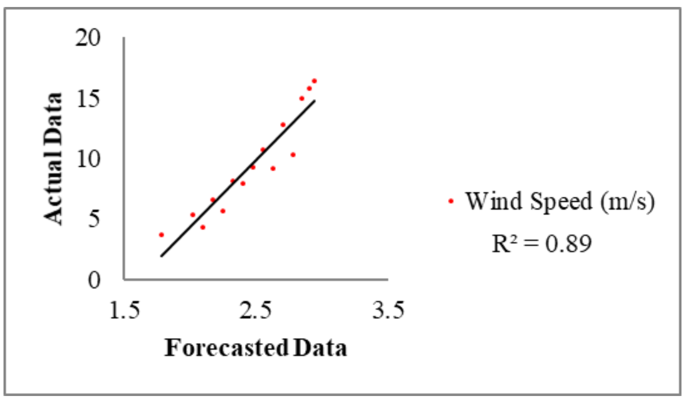

Fig. 2 R-squared value of forecasted wind speed from developed model against actual wind speed data for 2005 NEM

Model validation results shows that the wind speed derived from the model has a fit with an actual data. High coefficient of determination value indicates the ability of the model in indicating all variability of seasonal wind in Northeast monsoon. The probability analysis showed that the most frequent wind speed blew at 6- 9 m/s where the probability of occurrence ranged between 0.05 and 0.75. Wind speed of 9-12 m/s occurred at a probability of 0.75 to 0.95 and happened more than once but not too frequent. Finally, the 0.95 to 0.995 probability of higher wind speed (12-13 m/s) occurred infrequently. The cumulative wind speed estimated from wind speed frequency and probability distribution is 1191.91 m/s. The rate of wind production was derived by using wind pattern forecast model developed. The equation of cumulative wind production for 2005 Northeast monsoon had *t* as 151 days; mean wind speed forecasted as 8.297 m/s with a standard deviation of 2.32 m/s.

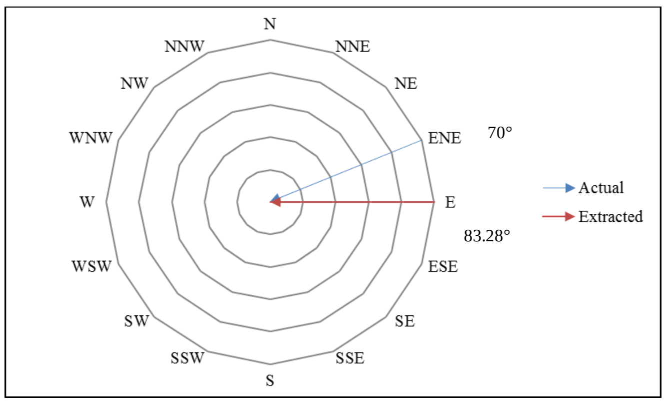

Fig. 3 R-squared value of forecasted wind speed from developed model against actual wind speed data for 2005 NEM

Fig. 3 shows the wind direction extracted from RADARSAT-1 SAR images was 83.28° and actual wind that was measured using wind vane was 70°. The extracted wind direction was used to estimate the cumulative wind during the whole period of 2005 Northeast monsoon season.

$$\gamma(NEM) =$$

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$83.28°_{NEM} \int_0^{NEM=151} 151.\frac{1}{2}\Big[1 +$
$erf \ln 151-8.2972.322 dt$(6)

$$\gamma(NEM) = 83.28°_{NEM};\ 42{,}377.848\ m/s (7)$$

The wind pattern model derived showed that the cumulative wind in 2005 Northeast monsoon is 42,377.848 m/s for 151 days, directed towards 83.28°. The cumulative wind speed is significantly high due to high mean wind speed forecasted for wind data in Terengganu. Terengganu as recorded by Malaysian Meteorological Department (MMD) possess highest mean wind speed in Malaysia throughout the year especially in Northeast monsoon that is also known as 'wet monsoon' due to the high rainfall distribution during monsoon occurred.

Wind pattern model was derived by the combination of wind speed forecast model developed, wind speed distribution and wind direction extracted from RADARSAT-1 SAR data to give high spatial resolution information of wind. These parameters act as an important parameter to successfully project future wind scenario. The results of the analysis showed that wind data in Terengganu agreed to the wind speed data inserted in the model developed. The model that was used by [25] was developed through the understanding of wind variability and biological productivity of sea surface from Ekman transport theory. However, the critical part in determine the relationship of wind behavior with sea surface is to assess the temporal pattern that may leads to highest wind that influence the pattern of sea surface current and wind-wave spectra.

This study introduced the day in each Monsoon season as a time, *t* unit. Each monsoon has their own unique wind speed criteria [26]. The forecasted wind speed of each monsoon season brings distinct criteria of wind in each monsoon and projects the uniqueness in wind speed value forecasted. Then, the statistical analysis of the monsoonal wind speed will then be inferred into the seasonal wind speed distribution model; Log-normal distribution. Specifically, the wind speed information used in Log-normal distribution model is the mean wind speed and standard deviation value of daily and seasonal wind. These statistical parameters were inserted into the developed wind pattern forecast model in order to estimate the cumulative wind in one specific monsoon. Wind direction in this model was derived from the RADARSAT-1 SAR model to incorporate high resolution wind direction information of the study area by using enhanced wavelet transform technique applied on images that were acquired on low wind speed area [27]. This model is able to project the future growth of coral reef in a distinct monsoon that varies from other different monsoon season. This was supported by [32] that concluded the community structure of coral reef is characterize by monsoonal variables such as wind speed, wind direction and water temperature. Extremely high wind speed can destroy the community of coral reefs in shallow water areas and harmful turbulence in the deeper water area.

V. Conclusions

As a conclusion, the wind model has an ability to derive important wind information such as wind speed, wind cumulative productivity to be used in estimation of the highest and lowest wind production and finally the high-resolution wind direction. This model can be used to monitor coral reef community, classify the coral reef for future planning of marine ecosystem and monitor the coral reef hazard. Future work will look into studying the effects of winds on coral reef over a period of time using satellite images.

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