Wind drives the wave models whether it is for forecasting, hindcasting, or climate simulation. In early days, appropriate wind information were extracted from synoptic weather charts published at regular intervals. Weather charts are normally prepared using mostly ship observations and assuming continuity in the weather pattern over the oceanic regions. Later, with the advent of high speed computers and numerical weather prediction models, regional and hemispheric weather charts have been prepared using objective analysis schemes (Cressman, 1959). These schemes provide winds over a grid mesh using the available information in a given area. While computing winds, the effect of atmospheric stability which is a measure of temperature difference between the sea surface and the overlying air is also considered since it is identified as an important factor influencing the growth of waves (Cardone, 1969).

In addition to wind, wave models also use surface current information if current refraction is to be considered in the prediction. When waves moving through still water encounter a current at an angle with the wave direction, they get refracted and undergo changes in their length, steepness and direction. The effect of a following or opposing uniform current on surface gravity waves was first introduced by Unna (1942). Since 1960, theoretical and experimental aspects of the interaction between gravity waves and currents are receiving increased attention. The problem of waves propagating through a known slowly varying horizontal current is reviewed by Craik (1985). Baddour and Song (1990) have illustrated changes in wave height and length due to the interaction between waves and currents.

III.2 SOURCE OF WIND AND SURFACE CURRENT DATA

The IDWR wind data from 1961 to 1970 was obtained from IMD, New Delhi and utilized in the present study. Fig.2A shows the wind data distribution for the Indian Seas (IMD, 1961-70) over one degree square grids. The mean monthly wind fields of Indian Seas published in the "Climatic atlas of the Indian Ocean, Part-I: Surface climate and atmospheric circulation" by Hastenrath and Lamb (H&L, 1979) are also utilized in this study. The digital wind data used in this atlas was obtained from the Department of
Fig. 2A  Wind data distribution for Indian Seas (IMD, 1961-70).
Atmospheric and Oceanic Sciences, University of Wisconsin, Madison, U.S.A.
The monthly estimates of this atlas over one degree grid resolution were computed based on the observations made by ships for a period of sixty years (H&L, 1911-70). The data distribution is shown in Fig.2B. Surface current data distribution as shown in Fig.2C are mostly based on the ship drift measurements from 1954 to 1994. These data are obtained from the Meteorological Office, Berkshire, U.K. in the form of monthly means for two degree square grids. The size of the thick circle for a given grid indicates the number of observations corresponding to one particular range as indicated on top of the above mentioned figures. It may be noticed that, the wind as well as surface current data are concentrated along shipping lanes. In the case of Fig.2A, the number of data points available along the shipping lanes varies between 5,000 to 10,000 while for the rest of the grids the data density is comparatively less. Same is the case with Fig.2B where the data strength along the shipping lanes mostly exceed 10,000 but for the rest of the grids it is always less than 5,000 excluding a few grids. Compared with the wind data shown in Fig.2A and 2B, surface current data strengths are relatively low. As all the above mentioned data are based on ship measurements, they are mostly biased for the shipping lanes.

III.3 ASSESSMENT OF DATA QUALITY

One of the major difficulties in wave prediction is the non-availability of input winds with desirable accuracy. As already mentioned, the wind as well as surface current data utilized in this study are mostly based on ship reports. The wind data supplied by IMD is similar to the ship reported winds acquired elsewhere. Some ships estimate the winds visually by matching the Beaufort scale and the corresponding sea-state. The ships which are provided by anemometers report the measured winds. However, the height at which the anemometers are installed in different ships vary from 10 to 60m above the sea level (Hamilton, 1986). The observations at different levels from the sea surface are corrected to a common height of 10m which is the reference height for wind measurement at sea recommended by World Meteorological Organization (WMO). Dischel and Pierson (1996) discuss about systematic and random errors in ship-reported winds for use in planning and verifying satellite measurements. Earle and Wilkerson (1986) have concluded that winds measured by ships with anemometers installed are slightly better compared with observed winds of ships without anemometers. The basic data used for the estimation of mean monthly currents used in this study also formed the basis of the atlas by
Fig. 2B
Wind data distribution for Indian Seas (H&L, 1911-70)
Fig. 2C  Surface current data distribution for Indian Seas (1954–94).
Cutler and Swallow (1984). However, the present data set is from 1954 to 1994 whereas Cutler and Swallow used the same data from 1954 to 1984. The data summary is available in their atlas.

In this study, monthly variations of wind in space and time are established based on the above mentioned data sets covering 10 to 60 years. Although there are limitations for ship reported data as discussed above and durations of wind and surface currents differ from one another, they can be safely used for the analysis of climatic mean conditions. The data which exceed a decade and more, can be considered as long enough for such studies (Hastenrath and Greischar, 1991). Moreover, errors involved in the individual estimates should not be critical for analysis of long-term mean monthly variations.

A detailed account of the wind (IMD) and surface current data for the individual months is given in Table 3. It may be seen that the wind data for the ten year period (1961-70) varies from about 50,600 to 58,000 observations per month. However, the surface current data (1954-94) is about four times the period of wind data of IMD and the number of observations per month varies from nearly 28,000 to 38,000. The amount of raw data processed by Hastenrath and Lamb (1979) for the estimation of mean monthly fields of wind (H&L, 1911-70) and surface current are 17,13,450 (approx.) and 3,73,264 respectively. Excluding the mean monthly fields of H&L, the total number of IMD wind observations used in this study are 6,47,136 after discarding observations which do not appear to be realistic. For example, wind speeds greater than 40 m/s were rejected. Secondly, observations which contain both the wind speed and wind direction were only considered for analysis as the mean wind fields are computed through vector averaging.
Table 3. Number of data points used for the analysis of wave model input data

<table>
<thead>
<tr>
<th>Month</th>
<th>Wind (1961-70)</th>
<th>Surface current (1954-94)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 January</td>
<td>51,587</td>
<td>36,149</td>
</tr>
<tr>
<td>2 February</td>
<td>53,466</td>
<td>27,969</td>
</tr>
<tr>
<td>3 March</td>
<td>57,974</td>
<td>37,898</td>
</tr>
<tr>
<td>4 April</td>
<td>54,424</td>
<td>28,556</td>
</tr>
<tr>
<td>5 May</td>
<td>56,726</td>
<td>32,664</td>
</tr>
<tr>
<td>6 June</td>
<td>54,394</td>
<td>30,260</td>
</tr>
<tr>
<td>7 July</td>
<td>55,162</td>
<td>29,794</td>
</tr>
<tr>
<td>8 August</td>
<td>56,679</td>
<td>30,236</td>
</tr>
<tr>
<td>9 September</td>
<td>50,603</td>
<td>32,149</td>
</tr>
<tr>
<td>10 October</td>
<td>53,093</td>
<td>28,671</td>
</tr>
<tr>
<td>11 November</td>
<td>51,343</td>
<td>28,883</td>
</tr>
<tr>
<td>12 December</td>
<td>51,683</td>
<td>30,035</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>6,47,136</strong></td>
<td><strong>3,73,264</strong></td>
</tr>
</tbody>
</table>

III.4 ESTIMATION OF MEAN MONTHLY WIND FIELDS

As the IMD wind data (1961-70) density is much higher compared to that of H&L (1911-70), both the data sets are suitably combined to estimate the resultant wind fields. The mean winds using IMD data is computed as given below.

\[
X_{10} = \frac{\sum_{i=1961}^{1970} N_i X_i}{\sum_{i=1961}^{1970} N_i} \quad \ldots \quad 3.1
\]

where \( I \) denotes the year, \( X \) denotes individual monthly mean value of a given parameter, \( N \) denotes the number of observations from which individual monthly means are computed and \( \bar{X}_{10} \) is the calculated ten-year average of the parameter considered (in this case, \( u \) or \( v \) component of wind).
The u and v components are computed using the ship reported wind speed (U in m/s) and direction (θ in degrees) using the following equation

\[ u = U \cos \theta \text{ and } v = U \sin \theta \] .... 3.2

While computing the above mentioned individual mean monthly wind components for different years, a simple two way interpolation scheme (Mathews, 1987) is adopted for the grids without any observation. Finally, the ten-year mean components over one degree resolution are smoothed using Laplacian method (Carnahan et al., 1969).

It is ascertained that only a part of the IMD wind data (less than 30%) has formed the basis of the sixty-year mean wind fields of H&L. Therefore, the ten-year average of IMD data and the sixty-year average of H&L (\( \bar{X}_{60} \)) are combined as follows:

\[ \bar{X}_{60} = \frac{6 \times \bar{X}_{60} + 0.7 \times \bar{X}_{10}}{6 + 0.7} \] .... 3.3

where \( \bar{X}_{60} \) denotes sixty-year monthly average of the wind component and \( \bar{X}_{60} \) is the combined wind component.

Finally, the resultant wind speed and direction for the individual months over a one degree grid is estimated as follows:

Wind speed = \( \sqrt{u^2 + v^2} \) and

Wind direction = \( \tan^{-1}\left(\frac{u}{v}\right) \) ... 3.4

Following equations 3.1 to 3.4, the monthly wind fields for the Indian Seas from January to December averaged over one degree squares are estimated and shown in Fig.3A to 3C. The contours represent wind speed in meters/second and the arrows represent wind direction from true north.
III.5 DISCUSSION ON THE INDIAN MONSOON AND SURFACE CIRCULATION

Seasonal reversal of the surface wind field over the tropical Indian Ocean, known as the Indian monsoon, has profound effects on upper hydrospheric structure and surface current systems. The wind system completely reverses between the boreal winter (November to April) and the boreal summer (May to October) so that a substantial seasonal departure from geostrophic balance is expected for the surface currents (Hastenrath and Greischar, 1991). The following sections summarize characteristic features of the winter and summer monsoon winds and the associated surface circulation in the Indian Seas.

III.5.1 Summer and winter monsoon winds

As already indicated, the wind fields shown in Fig.3A-C are largely characterized by season to season variations. A comprehensive analysis of the same is presented here. Although mean monthly winds are shown in Fig.3A-C, it may be difficult to make a proper analysis based on these figures if one tries to sum up overall basin scale variabilities. Therefore, the observed joint probability density for u and v components of wind at 1 m/s interval is computed (Jenkins and Watts, 1968) for both the Arabian Sea and Bay of Bengal based on the IMD data. Contour diagrams for the joint probability distributions from January to December are shown in Fig.4A-D. The outermost contour has the lowest probability value of 0.002 and the contour interval is also 0.002. Thus, the innermost contour has the maximum probability value which may vary from month to month. Probability density values for the respective u and v components indicate their duration of occurrence in a given month (total probability = 1.0). For example, during the month of April (Fig.4B), the lower wind speed values have the maximum probability. The probability distribution reveal that the winds during April are highly variable in the Arabian Sea as well as the Bay of Bengal. The reverse is the case during July as the maximum probability is associated with higher winds though there is some variation in the wind pattern between the Arabian Sea and Bay of Bengal. Seasonal variations in the winds based on both the mean monthly wind fields (Fig.3A-C) and the monthly joint probability distributions (Fig.4A-D) are discussed below.

During the winter monsoon (November through February), the north-east trade winds blow outwards from the Asiatic high pressure region to the
Fig. 3B  Mean surface wind fields for Indian Seas
(Contour interval 1 m/s).
Fig. 3C  Mean surface wind fields for Indian Seas  
(Contour interval 1 m/s).
Fig. 4A Observed joint probability distribution for u & v components of winds. [a] Arabian Sea, [b] Bay of Bengal. The value of lowest contour (outermost) and contour interval are 0.002.
Fig. 4B  Observed joint probability distribution for $u$ & $v$ components of winds. [a] Arabian Sea, [b] Bay of Bengal. The value of lowest contour (outermost) and contour interval are 0.002.
Fig.4C  Observed joint probability distribution for u & v components of winds. [a] Arabian Sea, [b] Bay of Bengal. The value of lowest contour (outermost) and contour interval are 0.002.
Fig. 4D Observed joint probability distribution for $u$ & $v$ components of winds. [a] Arabian Sea, [b] Bay of Bengal. The value of lowest contour (outermost) and contour interval are 0.002.
Arabian Sea and Bay of Bengal (Hastenrath and Lamb, 1979). This is clearly seen from the spatial as well as joint probability distributions (Fig. 3C & 3A; Fig. 4D & 4A). The southward shifting of wind speed maxima is very prominent in the Arabian Sea compared to that in the Bay of Bengal (Fig. 3C & A). The average wind speed over the whole of the Arabian Sea and Bay of Bengal remains higher (about 5.5 m/s) during December and January compared to the rest of the winter monsoon months. Fig. 4D & 4A reveal that the overall wind pattern during December to February remains the same for the Arabian Sea and Bay of Bengal. However, during November the northeast component remains stronger in the Arabian Sea compared to the Bay of Bengal. During March and April, the winter monsoon wind patterns gradually weaken and evolve into the characteristic summer monsoon winds. Anticyclonic vortices develop over both the Arabian Sea and Bay of Bengal during April (Fig. 3A). The resultant winds over the central Bay of Bengal are of low magnitude as the wind directions show maximum variability.

During the summer monsoon period, southwesterly and westerly winds sweep the Arabian Sea and Bay of Bengal. July is considered as the peak of the southwest monsoon during which mean wind speed reaches up to 16 m/s in the Arabian Sea (Fig. 3B). The Bay of Bengal also experiences higher winds compared to the rest of the summer monsoon months. The wind direction during the summer monsoon (May through September) does not show much variations in the Bay of Bengal (predominantly southwesterly). Fig. 4B & C show that the Arabian Sea winds gradually change their direction from May to September. The winds approach towards the Indian continent from west and north of northwest. The major reversal to Asian winter monsoon conditions occurs from September to October. The resultant winds in the Bay of Bengal become weak and variable while the Arabian Sea experiences wind blowing with a marked northerly component (Fig. 3C). The wind speed minima are again characterized with variable wind directions with the reappearance of strong northeast winds over the Arabian Sea and the western Bay of Bengal by the month of November.

III.5.2 Monsoonal surface circulation

The mean monthly fields of surface currents obtained from the British Meteorological Office over two degree grids are shown in Fig. 5A-C for January to December in a way similar to the mean monthly wind fields (Fig. 3A-C). A brief outline of the monsoonal surface circulation is presented below.
Fig. 5A  Mean surface current fields for Indian Seas
(Contour interval •1 m/s).
Fig. 5B Mean surface current fields for Indian Seas (Contour interval 1 m/s).
Fig. 5C  Mean surface current fields for Indian Seas (Contour interval \(1 \text{ m/s}\)).
The monthly mean current fields shown in Fig. 5A-C reveal that the observed surface circulation of the tropical Indian Ocean undergoes dramatic reversals with the monsoonal reversal of winds. During the northeast monsoon, a westward directed current known as the Northeast Monsoon Current appear to the south of the Indian subcontinent, currents with westward component are confined to the northern part of the Arabian Sea and Bay of Bengal during November and December. The flow is southwestward along the east coast and northwestward along the west coast of India. Eastward flow covers lower latitudes. In March and April, anticyclonic gyres develop in the Arabian Sea and Bay of Bengal in response to the anticyclonic vortices in the surface wind field (Hastenrath and Greischar, 1989). With the onset of the southwest monsoon (May to September), a clockwise gyral circulation dominates the open Arabian Sea. During this period, an eastward surface flow known as the Southwest Monsoon Current appears in the southeastern part of the Arabian Sea. This current is opposite in direction to the Northeast Monsoon Current. An intense surface current known as the Somali Current flows northeastward along the coast of eastern Africa (Hastenrath and Greischar, 1991). From June to September, the Somali current extends eastward and occupies most of the northern parts of the Arabian Sea and hugs the west coast of India with southeastward flow direction.

III.6 INPUT DATA SPECIFICATION FOR THE PRESENT STUDY

Ideally, the input data specification to a wave model must allow for the important physical processes of wave generation, growth, and dissipation to be appropriately represented in the wave model. Keeping this in view, a mean climatic year of wind is derived for wave climate simulation using statistical and probabilistic approaches as described below.

It was mentioned in Chapter-I that a mean climatic year of wind can be established by averaging historical data for the corresponding hours of wind observation or at least for each day of the year. However, this is not possible in the present study since the available data strength is insufficient. Therefore, based on the data obtained from IMD, monthly joint probability distributions (Jenkins and Watts, 1968) for u and v components of the wind are computed to establish wind variations for all the required grids. It is considered that each grid should have a minimum of 600 data
points for computing the monthly probability distribution as the data covers a period of ten years (1961-70) and there should be two observations available in a day (i.e. 10x30x2). However, the number of observations could reach close to 600 only for a few grids during some months. Hence the data from neighboring grids were considered to attain the required number of observations. The schematic diagram below shows the search radius for

The above schematic diagram shows the search radius (in degrees) for Indian Seas where each digit represents one particular sea grid (1x1 degree) and star represents land grids.

The grids which do not satisfy the above condition for the month of January. As an example, if the search radius is 1, equal number of observations from each of the adjacent grids distributed over ten years period (by selecting a suitable time window) are used to cater for the observations in short of 600. The total number of grids considered in this
case is nine (3x3). For a search radius of 2, data from 25 grids including
the representative grid are considered and so on. Search radii for the
other months were also estimated.

Fig. 6 shows the observed joint probability distribution for two
representative grids, one in the Arabian Sea (67.5°E, 12.5°N) and the other
in the Bay of Bengal (87.5°E, 12.5°N) during the month of July. The figure
indicates that the winds are slightly west of southwesterly in the Arabian
Sea grid and exactly southwesterly in the Bay of Bengal grid. It also
reveals that the winds are relatively steady in the latter case. Such
distributions also give an idea about the period of occurrence for a given
u and v component of wind in a month which will be utilized to derive
probable wind variations.

In a given month, for any particular region in the Arabian Sea or the
Bay of Bengal, wind variations can take place in a variety of ways and it
is very difficult to determine the winds during extreme weather conditions
such as cyclones and hurricanes. However, if one excludes extreme weather
conditions, there are few simple rules which may apply for the weather
variations in a given area. It is very likely that strong winds blow
southwesterly over long distances in the open Arabian Sea during the month
of July. Irrespective of the month and region, winds of low magnitudes vary
more in direction compared with winds of high magnitudes. It means that
steadiness increases with increase in wind speed. Variations in wind speed
can be associated with changes in direction, which can be either clockwise
or anticlockwise. If the wind speed goes on increasing, it should start
decreasing after it reaches a maximum. Likewise there are a number of thumb
rules which can be easily adopted. The present study adopts the most simple
pattern of wind variation discussed below. This should fairly represent the
mean climatic year of wind for the respective grid areas.

The observed joint probability distributions of wind anywhere in the
Indian Seas reveal that the winds more or less vary in speed as well as
direction throughout the year although the magnitude may be different from
month to month. A simple schematic representation for estimation of winds
based on the observed joint probability distribution of u and v components
is shown in Fig. 7. In this study, the observed wind variations during a
month are divided into four phases to take care of the growth and decay of
waves. In PHASE-I, it is assumed that wind speed gradually increases from
its minimum to the maximum value following the observed probability
Fig. 6 Observed joint probability density for u and v components of wind during July.
Fig. 7  Schematic representation for wind estimation from observed joint probability distribution of $u$ and $v$ components (Arrows indicate the mode of wind shift).
distribution and the change in wind direction is clockwise. The arrows indicate the mode of wind shift which starts with $u=0.5 \text{ m/s}$ and $v=0.5 \text{ m/s}$. Once the wind reaches its maximum, its magnitude starts decreasing in the opposite direction as shown by the arrows in PHASE-II. PHASE-III and PHASE-IV also follow a similar pattern of wind shift as in the cases of PHASE-I and PHASE-II, with the change in wind direction in PHASE-I being anticlockwise.

In a given month, particular $u$ and $v$ components of wind persist for a duration which is directly proportional to the probability density. Hence, following Fig.7 and walking in the direction of the arrows, winds are estimated for all the required grids based on the probability distributions for January through December. As the probability distributions were computed based on the ten years data from IMD, the estimated winds for establishment of mean climatic year are corrected using the sixty-year mean wind fields shown in Fig.3A-D. The correction is made by multiplying the $u$ and $v$ components of wind uniformly by a factor (C.F.) indicated below:

$$\text{C.F.} = \frac{\bar{X}_{80}}{\bar{X}_{umcy}}$$

$\bar{X}_{umcy}$ is the mean of the uncorrected winds. The corrected winds for the mean climatic year is shown in Fig.8A & B for two selected grids. Each of these figures consists of twelve stick plots representing the gross specification of the temporal wind variation from January to December. Plot for each month contains 144 representative wind sticks that are equally spaced in time. Fig.8A & B give an idea on the general wind pattern for all the months in a year for the two selected grids. As the winds are estimated for all the grids, there are 144 representative wind fields available for a given month. These winds are used as input to drive the wave model. Based on the wind input time step, the number of wind fields can vary accordingly. In the present study, the wind input is provided to the model for 72 hours period representing a month at half an hour interval. Further discussion on this is done in Chapter-IV. However, there is no restriction that only 144 wind fields are to be used as input. The present study restricts the surface current input to representative monthly mean values.
Fig. 8A The mean climatic year of winds (January: bottom & December: top).
Fig. 8B The mean climatic year of winds (January: bottom & December: top).
The input wind specifications to the wave model (e.g., Fig. 8A & B) clearly demonstrate the most general pattern of wind variations during different months of the climatic year of winds. They reflect the seasonal reversal of winds between the boreal winter and the boreal summer. Fig. 8B show that, the winds are strong and steady during May to September but variable during March. Normally, deep depressions and cyclones occur in the Bay of Bengal during October and November. Thus abnormally strong winds lasting for about a week or more may be noticed during October (Fig. 8B). By and large, these winds estimated using the statistical and probabilistic approaches follow the general patterns of wind variation during a year and the same will be utilized for the present simulation experiment.