CHAPTER II
DATA AND METHODOLOGY

The data needed for the present study have been extracted from the unpublished data set of Bunker for the Indian Ocean. It consists of monthly values of surface meteorological parameters like sea surface temperature (SST), air temperature, mixing ratio, air-sea temperature difference, cloud cover, wind speed, sea level pressure, number of observations etc., for the north and south Indian Oceans calculated from the ship/marine weather reports for the period January 1948 to December 1972.

This data set contains data pertaining to 78 Marsden squares (10° X 10° square grids) out of which we have chosen only those squares which lie between latitudes 30°N and 30°S and longitudes 40°E and 100°E. Figure 1a presents the study area with the Marsden square numbers used in the present study. Figure 1b gives the study areas used for computing the evaporation rates over the Arabian Sea (Area A), southern hemisphere (Area B) and Bay of Bengal (Area C).

Figure 2a gives the total number of observations used in the present study for each Marsden Square (MSQ). The numbers are greatest in squares which encompass traditional shipping routes, whereas the numbers are smallest in the southeast part of the study area. Figure 2b gives the number
of months for which data are available for each MSQ out of a possible 300 months; here again the numbers are larger over the northern Indian Ocean than over the south Indian Ocean. Figure 3 gives the mean monthwise data density for the bad (open) and good (circled) composites for the study area over the tropical Indian Ocean.

The quality of the observations have been thoroughly checked in this study using the criteria followed by Joseph (1983) and is as follows:

(a) SST observations in the range 15°C to 35°C were accepted. No check was made of the method of SST observation, whether bucket or engine intake method etc.

(b) For air temperature, the range accepted was from 15°C to 39°C.

(c) For surface pressure, the range accepted was from 981 mb to 1030 mb.

(d) Wind speeds from 0 to 99 knots (i.e., from 0 to 50 ms⁻¹ approximately) was accepted.

The data exceeding the above range limits were very few. Evidently, Bunker, we presume had used some such criteria while preparing the data set.
The rainfall data for the study has been taken from Mooley and Parthasarathy (1984). Average rainfall over the plains for each monsoon season (June through September) is obtained by weighting each station rainfall by the area of the distribution in which the station is located. Data pertaining to about 306 stations evenly distributed over the plains of India were used.

The data pertaining to Southern Oscillation Index (SOI), has been taken from Shukla and Paolino (1983). Here the SOI refers to the difference in pressure between April and January sea level pressure at Darwin. Darwin is located near one of the nodes of the Southern Oscillation (SO), we have also used the pressure tendency rather than the actual pressure in this study following Shukla and Mooley (1987).

The data on the position and location of the 500 mb ridge along 75°E in April for the period 1948 to 1972 has been extracted from Mooley et al., (1986).

The basic parameters needed for computing the air-sea fluxes were then extracted from the Bunker data set. The latent heat flux (L.H.F), sensible heat flux (S.H.F), wind stress (\( \tau \)) have been computed following Bunker (1976) using the bulk aerodynamic formulae. The empirical equations used to compute the above fluxes are the following:
\[ \tau = \rho_\alpha C_D W^2 \]  \hspace{1cm} (1) \\
\[ \text{L.H.F} = \rho_\alpha L C_E (Q_S - Q_a) W \]  \hspace{1cm} (2) \\
\[ \text{S.H.F} = \rho_\alpha C_p C_H (T_S - T_A) W \]  \hspace{1cm} (3)

Where,
\[ \rho_\alpha = \text{air density}. \]
\[ C_D = C_E = C_H = \text{exchange coefficients}. \]
\[ W = \text{wind speed at 10 m above the sea surface (} \text{ms}^{-1} \text{)}. \]
\[ Q_S = \text{specific humidity at} \ T_S \text{. (} \text{gkg}^{-1} \text{)}. \]
\[ Q_A = \text{specific humidity at} \ T_A \text{. (} \text{gkg}^{-1} \text{)}. \]
\[ L = \text{latent heat of vaporisation}. \]
\[ T_S = \text{sea surface temperature (in} \ ^\circ \text{C}). \]
\[ T_A = \text{air temperature at 10 m above the sea surface (in} \ ^\circ \text{C}). \]
\[ C_p = \text{specific heat of air at constant pressure}. \]

A major problem while using the bulk aerodynamic equations for computing the air sea fluxes are the values of various exchange coefficients namely, drag coefficient, \( C_D \), the exchange coefficient for water vapour, \( C_E \) and the exchange coefficient for sensible heat, \( C_H \). Sverdrup (1937), Jacobs (1942), Budyko (1963) and numerous others used the above equations and assumed that the coefficients were
identical, constant and had a value between $1.4 \times 10^{-3}$ to $2.3 \times 10^{-3}$. Many field, laboratory and theoretical experiments have shown that these coefficients are not identical and that they vary with wind speed and atmospheric stability.

Studies by several authors (Shea (1972); Wu (1968); Deacon and Webb (1962); Wilson (1960) etc., ) both in field and laboratory experiments indicate that the drag coefficients increase with the wind speed. The general variation is from $1 \times 10^{-3}$ for the low wind speeds to $4 \times 10^{-3}$ for hurricane winds. Values at very high wind speeds are less certain since there are only few estimates.

Studies of Budyko (1963); Bunker (1952,1972); Holland (1972); Kondo (1973); Riehl and Malkus (1961) have shown that the $C_E$ value increases with speed upto $30 \text{ ms}^{-1}$ with a possible decrease above that value. The stability of the air reduces both the $C_D$ and $C_E$, while the instability enhances the values.

There is evidence from various studies that the heat transfer coefficients may be larger than the water vapour coefficient. Dunckel et al., (1974) established that average $C_H$ value was $1.78 \times 10^{-3}$ by two methods. Smith and Banke (1975) found that $C_H = 1.5 \times 10^{-3}$, while Muller-Glewe and Hinzpeter (1974) determined that $C_H = 1 \times 10^{-3}$ over the
Baltic Sea. Frieche and Schmitt (1975) have studied the measurements by eight authors, including themselves. They found a strong dependency on stability but did not investigate the dependency on wind speed. They concluded that $C_H$ equals $1.46 \times 10^{-3}$ for very unstable conditions, $0.97 \times 10^{-3}$ for moderate winds and instabilities and $0.86 \times 10^{-3}$ for stable conditions.

In the present study we use the exchange coefficients used by Bunker (1976) and given in tables 1 and 2 for various wind speeds and atmospheric stability conditions. The fluxes have been computed from each individual ship observation and later averaged for different MSQ's for different months.

The fluxes of solar radiation and infrared radiation have been computed (Bunker, 1976) and is as follows:

\[
\text{SW} = Q_0 (1-x) (1-an-bn^2) \quad (4)
\]

\[
\text{LW} = \varepsilon \sigma (11.7-0.0023 \sqrt{e_a}) (1-cn) (1-cn) + 4 \varepsilon \sigma \sigma_a^3 \left( \sigma_s - \sigma_a \right) \quad (5)
\]

where,

\[
\text{SW} = \text{incoming solar radiation absorbed by the ocean (Wm}^{-2}).
\]
\( \text{LW} \) = outgoing longwave radiation \((\text{Wm}^{-2})\).

\( Q_0 \) = shortwave radiation incident on the earth's surface on a cloudless day (from a table given in Kondratyev (1969)).

\( \alpha \) = albedo of the sea surface (from Payne (1972)).

\( N \) = observed mean monthly cloudiness.

\( a = b \) = empirical constants = 0.38 (following Bunker (1976)).

\( \varepsilon \) = emissivity = 0.96

\( \sigma \) = stefan Boltzmann's constant.

\( \theta_a \) = average absolute temperature of air \((\text{oK})\).

\( \theta_s \) = average absolute temperature of sea \((\text{oK})\).

\( e_a \) = vapour pressure pressure of the air at 10 m above the sea surface \((\text{mb})\).

\( c \) = variable cloud cover coefficient.

The net radiation at the sea surface is the incoming solar radiation absorbed by the ocean less the outgoing radiation and is given by:

\[
R = SW - \text{LW} \quad \text{--- (6)}
\]

The net heat gain by the ocean \((\text{H.G.O})\) is given by the net radiation absorbed minus the sensible and latent heat fluxes at the surface, and is given by:
\[ H.G.O = R - (L.H.F + S.H.F) \quad ---- (7) \]

The meridional heat transport can be estimated in three different ways, (a) Residual method (b) Direct estimates and (c) The surface energy balance method.

The residual method calculates the oceanic flux \( F_o \) as the difference between the net radiation \( R_{\text{net}} \) received at the top of the atmosphere and the divergence of the atmospheric flux \( F_a \), and is given by:

\[ F_o = R_{\text{net}} - \text{div} \ F_a \quad ---- (8) \]

The direct estimates are made by vertically integrating the fields of the products of meridional velocity and temperature. The surface energy balance method uses the balance at the ocean-atmosphere interface. The balance at the surface of the ocean can be written as

\[ H.G.O = S_o + \text{div} \ F_o = SW - LW - (L.H.F + S.H.F) \]

where,

- \( H.G.O \) = heat gain at the ocean surface \((\text{Wm}^{-2})\).
- \( \text{div} \ F_o \) = oceanic flux divergence \((\text{Wm}^{-2})\).
- \( S_o \) = heat storage \((\text{Wm}^{-2})\).
- \( SW \) = incoming shortwave solar radiation absorbed by the ocean \((\text{Wm}^{-2})\).
\[ LW = \text{outgoing longwave radiation (Wm}^{-2}) \]
\[ \text{L.H.F} = \text{latent heat flux (Wm}^{-2}) \]
\[ \text{S.H.F} = \text{sensible heat flux (Wm}^{-2}) \]

Again in the long term mean, the term \( S_0 \) vanishes as it can be safely assumed that there are no long term temperature changes. The above equation then reduces to:

\[ H.G.O = \text{div} F_0 \]

The above equation indicates that the heat gain at the oceanic surface can be used as an estimate of oceanic flux divergence. The meridional heat transport then can be calculated by using the Green's theorem by integrating the energy flux divergence with respect to area using appropriate boundary conditions. The most common assumption (and probably the best) is that the flux vanishes at the northern or southern boundary of the ocean basin. The transport for the Indian Ocean has been computed assuming zero net flux at 30\(^\circ\)N. Transport values were then computed for each ten degree latitude belts.

The zonal anomaly of the sea surface temperature were computed as follows: The SST values for every two degree latitude-longitude grid points were estimated by visual interpolation (for both global operational SST computation (GOSSTCOMP) as well as climatological charts).
The zonal anomalies ($T_z$) were then calculated as follows:

$$T_z = T - \overline{T},$$

where $T$ and $\overline{T}$ are the observed grid point and zonal mean SST's respectively.

**ERRORS**

The errors involved in the study can be broadly categorized as systematic and random errors. The main source of systematic errors are: a) uncertainty of bulk aerodynamic formulae in the computation of accurate fluxes b) bias from inadequate data sampling in both time and space and c) instrumental, observational and reporting errors.

Blanc (1987) has shown that the average accuracies of the bulk method ranges from 35% to 105% for stress magnitudes of $0.025 - 1.0 \text{ Nm}^{-2}$, 35%-220% for sensible heat flux magnitudes of 5-150 Wm$^{-2}$ and 40%-215% for latent heat flux magnitudes of 10-300 Wm$^{-2}$.

It should be noted here that these large inaccuracies arise because of the utilization of extreme values in different ranges as can be seen from Table 1. For example, the value of $C_D$ for 5 ms$^{-1}$ is given as $0.06 \times 10^{-3}$ whereas it has a value of $0.77 \times 10^{-3}$ (a factor of 13) for a
value of 5.01 ms$^{-1}$, for the same air-sea temperature difference. We realise this and presume that the data set pertains to the zones of values where the coefficients change gradually.

Weare and Strub (1981) have shown that the errors can occur due to inadequate sampling in both space and time. This can be mainly due to the uneven sampling within the specified time and also uneven data distribution within the grid. For example, in the case of grid along which a major shipping lane exists there will be large errors in the fluxes computed because the data density of other regions will be meagre and hence a true representation of the fluxes for the grid will not be possible. The same holds good for regions where the tropical cyclones and monsoon depressions exist.

Recent study of Vinayachandran et al., (1989) have shown that there exists bias from observation techniques and instrumentation. By comparing the data obtained from the research vessel ORV Sagar Kanya and the published marine weather reports from Indian Daily Weather Report (IDWR), they have found that the latent heat flux was less by about 35% in the case of IDWR. In addition, the inaccurate positioning of the anemometer and various meteorological equipments also result in large errors.
The main source for random errors is the non-uniform techniques and reporting and archiving methods (Hsiung, 1984). This is most evident in the case of the radiative and latent heat fluxes. An inaccurate observation of cloud cover can result in large errors in the radiative flux term, since this parameter unlike the other observations is largely observer dependent. In the case of latent heat flux, since the flux is a function of both the transfer coefficient and wind speed, and the transfer coefficient again being a function of wind speed, an error in the wind speed can result in large error in latent heat flux.

These types of errors in general decrease with increasing number of observations and by the methods of averaging both in space and time. In the present study, the errors are likely to be at their minimum since we have analysed for ten degree square grids (MSQ's) and there are sufficient number of observations for the study period and the data is more or less uniformly distributed (Figure 2a and 2b) and we are examining only the longterm annual and seasonal means. The errors are also expected to be uniformly distributed and do not alter the conclusions.
TABLE 1

Drag coefficients $C_D \times 10^3$

(Reproduced from Bunker (1976)).

<table>
<thead>
<tr>
<th>Air minus sea surface temperature class (K)</th>
<th>4.9</th>
<th>0.9</th>
<th>0.1</th>
<th>-0.3</th>
<th>1.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind speed (ms$^{-1}$) &gt; 5.0 to 0.01-5.0</td>
<td>1.0</td>
<td>0.2</td>
<td>-0.2</td>
<td>-1.0</td>
<td>-4.9</td>
</tr>
<tr>
<td>0.01-5.0</td>
<td>0.06</td>
<td>0.60</td>
<td>0.98</td>
<td>1.20</td>
<td>1.32</td>
</tr>
<tr>
<td>5.01-10.0</td>
<td>0.77</td>
<td>1.30</td>
<td>1.43</td>
<td>1.54</td>
<td>1.60</td>
</tr>
<tr>
<td>10.01-15.0</td>
<td>1.47</td>
<td>1.72</td>
<td>1.80</td>
<td>1.87</td>
<td>1.90</td>
</tr>
<tr>
<td>15.01-20.0</td>
<td>1.95</td>
<td>2.04</td>
<td>2.10</td>
<td>2.16</td>
<td>2.22</td>
</tr>
<tr>
<td>20.01-25.0</td>
<td>2.26</td>
<td>2.30</td>
<td>2.35</td>
<td>2.40</td>
<td>2.42</td>
</tr>
<tr>
<td>25.01-30.0</td>
<td>2.52</td>
<td>2.54</td>
<td>2.57</td>
<td>2.60</td>
<td>2.62</td>
</tr>
<tr>
<td>30.01-35.0</td>
<td>2.78</td>
<td>2.79</td>
<td>2.80</td>
<td>2.80</td>
<td>2.80</td>
</tr>
<tr>
<td>35.01-40.0</td>
<td>3.00</td>
<td>3.00</td>
<td>3.00</td>
<td>3.00</td>
<td>3.00</td>
</tr>
<tr>
<td>40.01-50.0</td>
<td>3.20</td>
<td>3.20</td>
<td>3.20</td>
<td>3.20</td>
<td>3.20</td>
</tr>
<tr>
<td>&gt;50.0</td>
<td>3.40</td>
<td>3.40</td>
<td>3.40</td>
<td>3.40</td>
<td>3.40</td>
</tr>
<tr>
<td>Wind speed (ms⁻¹)</td>
<td>0.0-3.0</td>
<td>3.0-6.0</td>
<td>6.0-9.0</td>
<td>9.0-12.0</td>
<td>12.0-15.0</td>
</tr>
<tr>
<td>------------------</td>
<td>---------</td>
<td>---------</td>
<td>---------</td>
<td>---------</td>
<td>---------</td>
</tr>
<tr>
<td></td>
<td>0.07</td>
<td>0.22</td>
<td>0.69</td>
<td>1.06</td>
<td>1.39</td>
</tr>
<tr>
<td></td>
<td>0.30</td>
<td>0.67</td>
<td>1.17</td>
<td>1.36</td>
<td>1.58</td>
</tr>
<tr>
<td></td>
<td>0.72</td>
<td>1.12</td>
<td>1.48</td>
<td>1.48</td>
<td>1.61</td>
</tr>
<tr>
<td></td>
<td>1.32</td>
<td>1.34</td>
<td>1.53</td>
<td>1.53</td>
<td>1.64</td>
</tr>
<tr>
<td></td>
<td>1.65</td>
<td>1.45</td>
<td>1.58</td>
<td>1.58</td>
<td>1.68</td>
</tr>
<tr>
<td></td>
<td>2.05</td>
<td>1.68</td>
<td>1.79</td>
<td>1.79</td>
<td>1.74</td>
</tr>
<tr>
<td></td>
<td>2.52</td>
<td>2.01</td>
<td>1.79</td>
<td>1.79</td>
<td>1.84</td>
</tr>
</tbody>
</table>

Exchange coefficients $C_E \times 10^3$

(Reproduced from Bunker (1976)).
Fig. 1

a Marsden square numbers used in the present study.

b Study areas used to compute mean evaporation over Arabian sea (A), Southern hemisphere (B), and Bay of Bengal (C)
Total number of observations ($\times 10^3$) used in the present study.

Number of months out of a possible 300 months.

Fig. 2
Fig. 3

Mean monthwise distribution of data density for bad (open) and good monsoon (circled) composites.