Research Paper

Annual and Seasonal Variation of Heat Fluxes over the Indian Ocean using OAFlux Data

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ABSTRACT   *The annual and seasonal variations of surface heat fluxes over the northern Indian Ocean is studied utilising OA flux data (1983-2007). The analysis showed much higher amount of net heat gain compared to previous estimates based on other data sets which is consistent with Yu et al. (2007). There is also substantial variations in heat flux with other seasons. The net heat flux is found to be positive in both Arabian Sea and Bay of Bengal during southwest monsoon, whereas previous studies showed net heat loss during this period. The latent heat flux is found to be 15-20% higher in the southern Indian Ocean especially during southwest monsoon compared to earlier estimates. This suggest that the moisture flux from southern hemisphere could be much greater than previously estimated.*

Introduction

Asian monsoon is one of the most amazing climatic phenomena of the world bringing in abundant fresh water to land. The active convective zone developing over India during summer causes the trade wind from south of the equator with its moisture and give precipitation over India and adjacent regions. The surface meteorological variables and resultant heat fluxes in the Indian Ocean is critical to monsoon rainfall.

The Ocean and atmosphere exchange heat at their interface via a number of processes such as solar radiation, sensible heat transfer, long wave radiation and latent heat transfer by evaporation. The heat being exchanged is called heat flux, and its distribution over the ocean is required for all climate studies.(WGASF, 2000; Yu and Weller, 2005). Heat flux parameters are computed from surface meteorological variables using bulk parameterisation. The surface meteorological variables are obtained from various data sets. One of the most widely used data sets is the Comprehensive Ocean Atmospheric Data Set (COADS) which is mostly based on ship observations. The other sources are satellite remote sensing and numerical weather prediction (NWP). However, those data sets suffer from inadequate sampling, incomplete global coverage, relatively short time series, systemic bias and random error (Yu and Weller, 2007)

It has been observed that the COADS based climatology of fluxes have large errors in the Indian ocean particularly in Arabian sea and Bay of Bengal (Yu et al, 2007) and it can induce uncertainties in monsoon forecast. The other sources of heat fluxes such as National Centre for environmental reanalysis 1(NCEP-1) and reanalysis 2 (NCEP-2) and ECMWF forecasts also show large variations among themselves particularly in the Indian ocean region. The study of Shinoda et al (1998) found that the NCEP heat fluxes are underestimated and hence the modelled SST is 30%-40% smaller than actually observed in the western Pacific. The more recent objectively Analysed data synthesising surface meteorology obtained from satellite and atmospheric model reanalysis considerably improved the estimates of global latent heat and sensible heat fluxes (Yu and Weller, 2004)

A comprehensive study of the annual, seasonal and inter-annual variability of heat fluxes of Indian ocean utilising OA Flux, NCEP-1, NCEP-2 and ECMWF data are carried out by Yu et al (2007), for the period 1988-2000.They have found large differences in the estimates of heat fluxes from different data products and the OAflux data is found to be more realistic. The aim of the study is to bring out the annual and seasonal variability of surface heat fluxes of the Indian Ocean based on OAflux data for the period 1958-2010.

2. DATA

Yu et al (2004) attempted to improve the heat flux estimates of the ocean through objectively synthesising satellite and Numerical Weather Prediction (NWP) data. They have also evaluated these heat flux estimates by both statistical comparison and consistency study. It has been found that OAFlux estimates differ from buoy-ship flux measurements by 5% on average (Yu et al, 2007), which is more realistic than flux estimates utilising other datasets. Details about OAflux estimates are discussed by Yu and Weller (2005). In the present paper OAFlux estimates available for the period 1983-2007 in the Indian ocean is utilised to study the annual and seasonal variability.

3. Result and Discussion

The surface meteorological variables such as sea surface temperature, air temperature, wind speed, specific humidity, cloud cover etc are critical for the computation of various heat flux terms. Hence before discussing the surface heat flux climatology, we describe the characteristics of surface meteorological climatology.

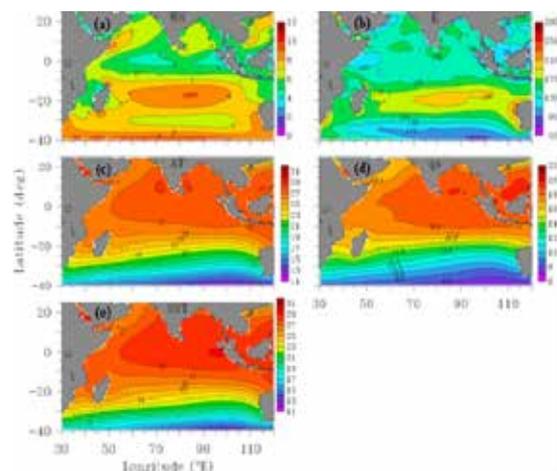### 3.1 Annual climatology of surface meteorological parameters

Fig.1

The annual mean climatology of SST (FIG 1e.) shows temperature in excess of 29°Cin the central and eastern equatorial Indian Ocean north of 10°S ,which is one of the warmest regions

of oceans. In the south Indian Ocean the SST decreases with in-creasing latitude and it drops from about 25° at 20°S to about 15 °C at 40°S. The annual mean air temperature

(Fig. 1c)follows the same pattern except the fact that it is cooler by 1°C-2°C compared to SST.

The winds are strongest (>8m/s)in the south central Indian ocean(Fig.1a) between 15°S-25°S, 60°E-100°E and also south of 35°S. North of the equator the mean winds are strongest off Somalia (>7m/s) and also in central and western bay of Bengal (>6m/s).In general the winds are relatively weak close to the equator especially in the central and eastern equatorial Indian Ocean with wind speed less than 5 m/s. The strong winds in the south central Indian ocean and also Arabian sea and Bay of Bengal are conducive to higher latent heat flux. The annual specific humidity (Fig.1d) shows values below 20 g/kg north of 20°S with a decreasing trend towards south, which also aids higher evaporation(Fig1b) in the In-dian ocean.

3.2 Annual Climatology of Surface Fluxes.
The annual climatology of net heat flux (Fig.2d) suggests net heat gain in the entire Indian ocean north of 20°S with Qnet exceeding 75W/m² in the western equatorial Indian Ocean and >50W/m² west of 70°E . Similarly substantial Qnet is also found in the eastern tropical Indian ocean (>50W/m²) includ-ing East China Sea. Major heat loss is found only between 20°S and 40°S in the western and eastern Indian ocean mainly on account of higher latent heat flux. Yu et al (2007) has reported that the Qnet in the Indian ocean was underestimated in pre-vious estimates based on NCEP-1, NCEP-2 and ECMWF data. The OA Flux climatology of Qnet is broadly in agreement with the climatology of Yu et al(2007)where the dataset was of shorter duration (1988-2000), except the fact that the zone of negative Qnet (net heat loss) is of much larger area in the south Indian ocean.

It is also interesting to note that the net shortwave heat flux (QI) due to solar radiation is also maximum(< 260W/m²) in the western equatorial Indian ocean(Fig.2a).There is also a decreasing trend of shortwave heat flux from west to east in the equatorial Indian ocean with values greater than 200W/m² in the eastern portion. South of 20°S the QI decreases with in-creasing latitude.

The net long wave radiation (QB) is a loss term in the heat bal-ance and it is a function of SST and cloud cover. Values over 60 W/m² is observed in the western Indian ocean, Bay of Bengal and south eastern Indian ocean. Rest of the regions shows QB between 40-60 W/m².

The sensible heat flux mostly depend on air-sea temperature difference and and its contribution is very small compared to other heat flux components. Hence the sensible heat flux is not included in this study.

The net long wave radiation (QB) is a loss term in the heat bal-ance and it is a function of SST and cloud cover. Values over 60 W/m² is observed in the western Indian Ocean, Bay of Bengal and southeastern Indian Ocean (Fig.2b). rest of the regions QB is between 40-60 W/m².

The ocean loses substantial heat by way of latent heat flux (QE). The latent heat flux depends on wind speed, air-sea temperature difference and also relative humidity. The evapo-rative latent heat flux is also a loss to the ocean. The annual latent heat flux (Fig.2c) is found to be maximum in the south Indian ocean between 15°S-25°S with values exceeding 140W/m². The latent heat flux exceeds 120W/m² in the rest of the tropical Indian ocean except western and eastern equato-rial Indian ocean. The result of Tomita and Kubota (2004) also showed similar pattern using COADS data in latent heat flux, but their estimates are about 15%-20% lower than with pre-sent estimates. South of 30°S, latent heat flux decreases with increasing latitude and drops below 80 W/m² near 40°S in the eastern Indian ocean.
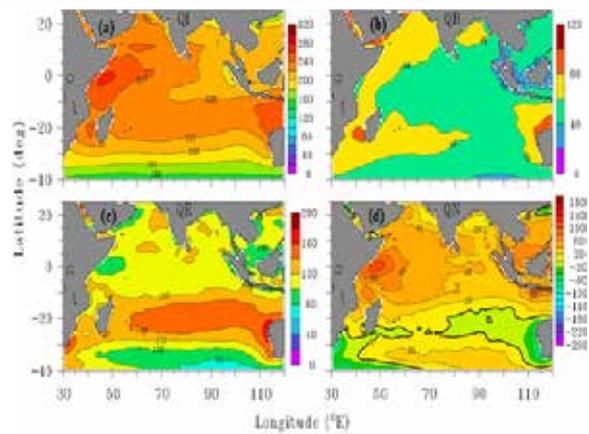

Fig.2

4. Seasonal Climatology
The surface meteorological parameters and resultant heat fluxes vary considerably in the annual cycle. To understand the seasonal variability, the meteorological parameters are averaged over four specific periods such as Dec-Mar (winter), April-may (pre monsoon), June-Sept (south west monsoon) and Oct-Nov(post Monsoon). It should be noted that the winter pe-riod considered is boreal winter, which is also summer (austral summer) in the southern hemisphere.

4.1 Seasonal Climatology of surface meteorological param-eters
The seasonal climatology of all surface meteorological param-eters shows very large variability. The SST (Fig.3) shows sub-stantial westward extend(up to 45°E) of warm waters (>30°C)in the equatorial ocean which cools and the 28°C isotherm waters are seen along east of 60°E during monsoon and post monsoon, whereas warm waters extend (>28°C)up to south western In-dian ocean during winter. Waters south of 20°S are much cooler during monsoon and post monsoon on account of austral winter and high latent heat flux, which is also reflected in air tempera-ture (Fig.4). As in the case of annual mean the air temperature is lower by1°C-2°C to SST.
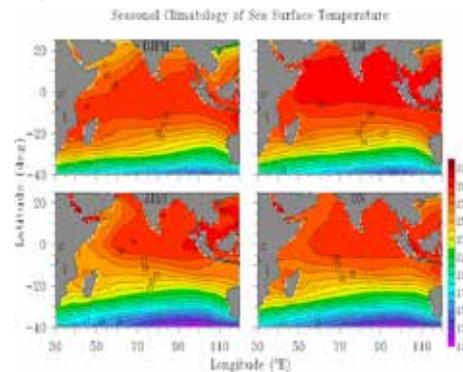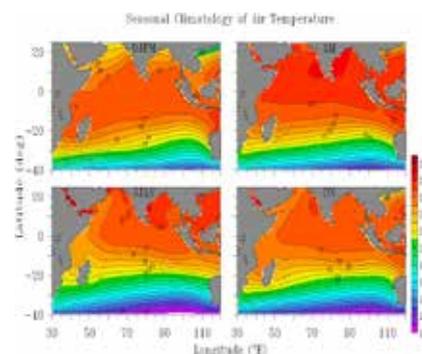

Fig. 3

Fig.4

Substantial seasonal variations are observed in the wind speed also. (Fig.5). During pre monsoon the winds are very weak in most regions north of 10°S with speed less than 4m/s with the exception of northern Arabian sea and western Bay of Bengal. Wind speed is higher (>8m/s) in the belt 65°E- 100°E centred around 20°Swhich decreases to ~ 5 m/s southward and again increasing near 40°S.On the other hand very strong winds occurs during summer monsoon with peak values in the western Arabian Sea(>11m/s), central Bay of Bengal (>9m/s) and south of 10°S-25°S(>9m/s) and also south of 35°S.

These Strong winds are conducive for large latent heat flux which feeds the monsoon winds. The equatorial winds are relatively weak which decreases from about 7m/s in the western Indian ocean to about 4m/s in the eastern side. During post monsoon, strongest winds occur in the southern hemisphere centred about 20°S in the south central Indian ocean (> 9m/s). Relatively stronger winds occur off Somalia and south western Arabian Sea (5-6m/s) compared to equatorial Indian ocean where the winds are rather weak(3-4m/s). More or less same pattern follows during winter except the fact that there is a reduction in wind speed maximum in the southern hemisphere (~7m/s) whereas the wind strengthened in East China sea(>8m/s). It is important to note that strongest winds occur in the south central Indian ocean centred around 20°S except during southwest monsoon where the wind speeds are comparable in the western Arabian Sea and Bay of Bengal.
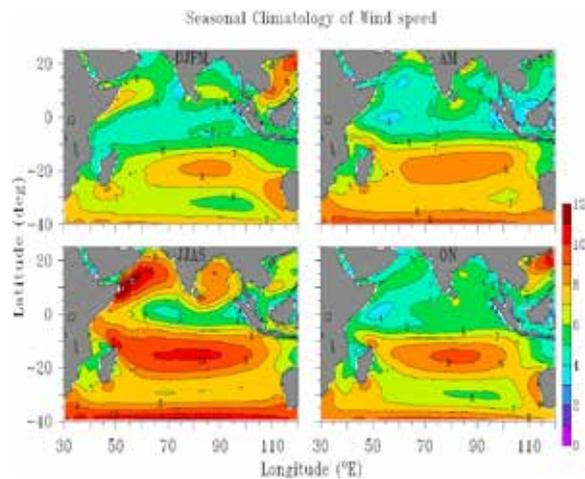

Fig.5

The seasonal variation of Specific humidity (Fig.6) show substantial variation in the northern Indian ocean only during monsoon and winter. During monsoon, specific humidity above 20 g/kg is observed in the northern Arabian Sea, Bay of Bengal and South China Sea. Low specific humidity is generally prevail (<15g/kg) south of 20°Sduring all seasons except winter (Austral Summer) where similar values are observed south of 30°S in south western Indian ocean and south of 20°S in the south eastern Indian ocean.
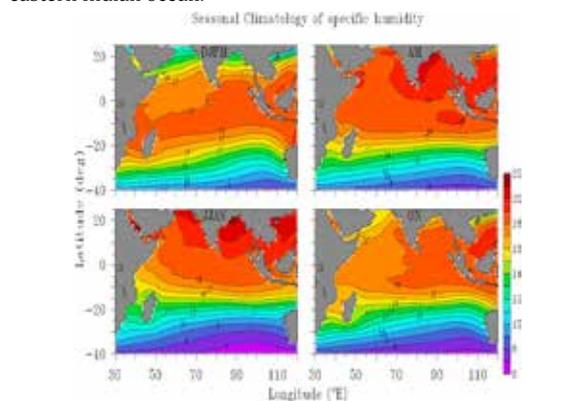

FIG .6

4.2 Seasonal climatology of heat fluxes

The seasonal variation of surface heat fluxes is an important aspect, which in not adequately addressed for the Indian ocean region. Using COADS climatology Mohanty et al. (1996) tried to relate the variability of surface heat fluxes to monsoon rainfall. For the following discussion the surface fluxes are mapped for pre-monsoon (April-May), monsoon (June-Sept), post monsoon (Oct-Nov) and winter (Dec-March).
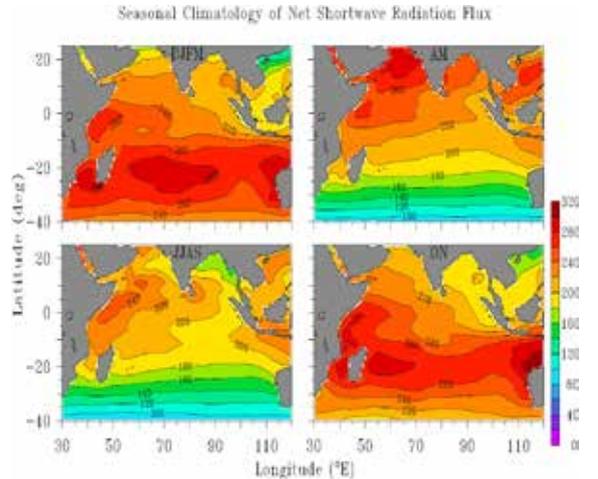

Fig. 7

In the northern Indian ocean maximum incoming solar radiation occur in pre-monsoon (Fig.7) with peak values over 260 w/m^2 in the Arabian sea and western equatorial Indian ocean, which reduced by about 40-60 w/m^2 during monsoon mainly on account of increased cloud cover. The lower values of insolation in the southern hemisphere with increasing latitude in mostly an account of austral winter. During post–monsoon and winter (boreal winter) the zone of highest insolation shifts to southern hemisphere cantered around 20^{0}S owing to austral summer. Compared to monsoon period there is a marginal increase in insolation (by 10 – 20 w/m^2) in the northern Indian ocean during post monsoon which again decreases in winter. Significantly the present findings are about 10-15% higher than that reported by Mohanty et al (1996) particularly in all season except during monsoon The maximum differences are observed in Arabian Sea, and South Indian Ocean. This is consistent with the findings of Yu et al (2007)

The back radiation (Fig .8) and sensible heat flux are relatively minor terms in heat flux. However due to spatial and time differences in SST and cloud cover, there are relatively significant variations in back radiation. Relatively higher values of back radiation is observed in northern Indian ocean during pre monsoons and winter. (>80 w/m^2) which reduces to about 20-40w/m^2 during monsoon. In the south Indian ocean back radiation is approximately 60w/m^2 which slightly increases during pre-monsoon and monsoon.
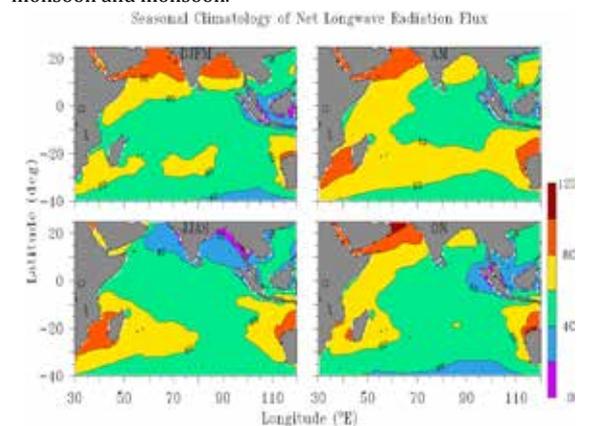

Fig. 8

The seasonal variation of latent heat flux is one of the most important parameter, since it can directly influence rain fall variability over different regions. As in the case of annual mean latent heat flux, the zone of maximum latent heat flux is in the south Indian ocean (between 10-25⁰S), but with large seasonal differences. During pre- monsoon maximum latent heat flux (>160W/m²) occur in the south western Indian ocean while it exceeds 180-200w/m² during monsoon and the zone extends the entire the width of Indian ocean (Fig .9). The zone of maximum latent heat flux shifts southeast ward in the southern hemisphere during post monsoon and winter (austral summer) with values exceeding 140w/m². During post monsoon and winter latent heat flux exceeds, 140 w/m² in northern Arabian Sea and Bay of Bengal. Interestingly the present study indicate only moderate values of LH flux (~ 140 w/m²) in the southern Arabian Sea and Bay of Bengal which in contrary to the findings of Mohanty et al (1996). It should be noted that Mohanty et al (1996) utilized COADS data for the period (1960-1979) for their analysis and Yu et al (2007) has reported the OA flux data (used in the study) is much more accurate than other data sets. The present study has shown that the latent heat from northern Indian ocean is significantly less than earlier estimates while the LH from southern Indian ocean is 10-15% more than reported earlier for southwest monsoon season.

south of 10⁰S. These estimates are (heat loss) much larger than those of Mohanty et al (1996). Previous estimates (Hasternrath and Lamb 1979; Mohanty et al 1996) showed substantial net heat loss (>75w/m²) in the central Arabian sea and western Bay of Bengal (>25 w/m²). However the present study shows either marginal net heat gain/loss in major parts of these regions. The present study also shows substantial net heat gain (50-100 w/m²) in the western equatorial Indian ocean and western Arabian sea while the study of Mohanty et al (1996) showed only marginal net heat gain in these regions (~ 25 w/m²). This also confirms the fact that the heat fluxes from southern Indian ocean plays a very significant role during monsoon. During post monsoon the net heat flux is maximum (over 100 w/m²) in the southwestern Indian ocean and most of the Indian ocean except southeastern Indian ocean

gains heat. However the net heat gain is about 10-15% higher than those of Mohanty et al (1996). During winter, the entire south Indian ocean gains heat mainly due to higher solar radioactive flux owing to southern summer. However, there is negative heat flux particularly in northern Arabian sea and Bay of Bengal (-25to-50 w/m2) owing to reduction in solar radiation and large evaporation.
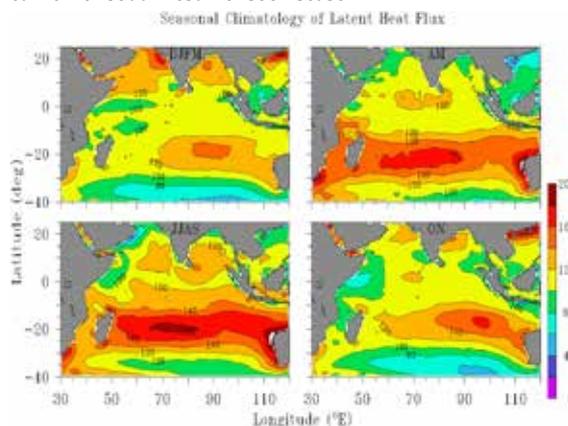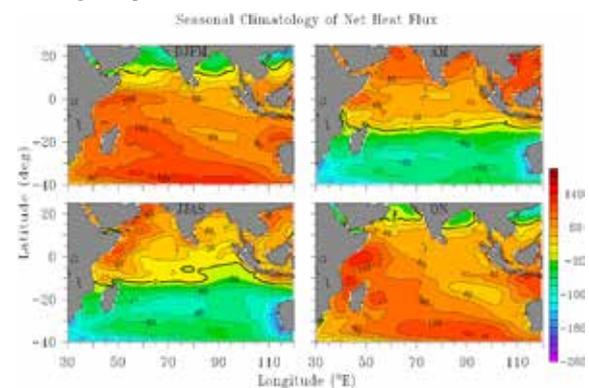

Fig. 9

The seasonal variation of net heat flux from the present study shows (Fig.10) shows very interesting patterns. Net heat flux is largely positive with values over 100w/m² is observed in South China sea, major parts of Arabian sea and Bay of Bengal and western equatorial India ocean during pre-monsoon. Thus the whole of north Indian ocean gains substantial amount of heat during pre monsoon. South of 10⁰ S there is net heat loss during this period mainly on account of large latent heat flux. During monsoon the entire region south of 10⁰S loses substantial amount of net heat flux owing to high amount of latent heat flux and reduction in solar radiative flux owing to southern hemisphere winter. The net heat flux >-150 w/m² in the southwestern and southeastern Indian ocean and exceeds -100 w/m²

Fig.10

Summary and Conclusions
The annual and seasonal variations of surface meteorological variables and heat fluxes utilising more reliable OA flux data show many significant results. The short wave radiation and latent heat flux are the dominating contributors in the net heat flux, and both are found to be larger than estimated using other data sets. The net heat flux in both Arabian Sea and Bay of Bengal is found to be positive during southwest monsoon contrary to previous estimates on account of higher insolation and marginally lower latent heat flux compared to previous estimates. On the other hand the latent heat flux from southern hemisphere is much larger than previous estimates especially during pre-monsoon and southwest monsoon. This suggests that the moisture flux from southern hemisphere during these periods could be of much greater importance in monsoon activity.

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