CHAPTER - V

SUMMARY AND CONCLUSIONS

An assessment of the role of air-sea interaction on monsoon variability in the Indian Ocean has to begin with an examination of the various energy exchange parameters. Heat budget of the ocean is controlled by the exchange of net radiation, latent heat and sensible heat at the ocean-air interface. Thermal conditions in the upper layers of the Indian Ocean are very much influenced by these energy exchanges and hence influence the oceanic and atmospheric circulations.

Northern Indian Ocean is unique in nature in its seasonally reversing monsoonal winds and surface currents. In order to understand the complex nature of Indian monsoon, study of mixed layer dynamics and heat budget of the northern Indian Ocean is required. This thesis attempts to study the seasonal and daily variations in mixed layer depth (MLD), sea surface temperature (SST), heat content of different layers up to 200m, cyclone heat potential, heat budget and heat advection of the mixed layer and 0-200m layer and the various factors controlling them.

As the mixed layer controls most of the energy exchange processes, an accurate method to estimate MLD is of utmost importance. MLD has been estimated by different methods and compared with that obtained from actual temperature profiles. It has been found that the gradient method followed by Ali et al,
(1987) gives satisfactory results. Hence in this study, MLD is estimated using the gradient method. In order to analyse seasonal variations of MLD and SST, seasonal averages were determined using the temperature profiles during 1977-1986. To match with the Levitus (1982) climatology, MLD has been calculated for the following seasons viz. pre-monsoon (February-April), monsoon (May-July), post-monsoon (August-October) and winter (November-January). Using the temperature climatology of Levitus (1982), climatic variations of MLD and SST have also been studied for comparison with those obtained during 1977-1986. Day to day variations of MLD and SST were also analysed in four polygon areas during May-June 1977 and May-July 1979.

The distribution of heat content in different layers of 50m thickness from surface upto a depth of 200m has been carried out from the temperature profiles during 1977-1986. The variations in heat content have been analysed on a seasonal as well as daily basis during May-July 1977 and 1979. A regression equation to estimate cyclone heat potential (CHP$_{28}$) has been developed using in-situ SST, wind speed and heat content of 28°C isotherm. Using this regression equation, CHP$_{28}$ has been computed utilizing the satellite derived wind speed and SST during 1979. Besides, daily CHP$_{28}$ has also been computed using MONSOON-77 in-situ data. Variations of CHP$_{28}$ during three storm events in the Arabian Sea and Bay of Bengal have been thus analysed in relation to wind speed.
The radiation data and marine meteorological data obtained from NOAA satellite, GOES satellite derived cloud motion winds and ship measured SST, air temperature, dew point temperature and surface pressure were used for the computation of energy exchange parameters (net radiation, latent heat flux and sensible heat flux) during May-July 1979. Net radiation has been estimated from a regression analysis utilizing the planetary absorbed radiation, available radiation at the top of the atmosphere, total water vapour content and cloud cover. Fluxes of latent and sensible heat were evaluated by bulk aerodynamic method using a constant drag coefficient. Heat storage of the mixed layer and 0-200m layer for different seasons and heat advection during monsoon season have been estimated following Hastenrath and Merle (1986).

Variations of MLD have been studied in relation to the change in SST. Shallow mixed layer is observed in the western side of Arabian Sea during pre-monsoon corresponding to the high SST using Levitus (1982) temperature climatology. MLD increases from west to east in the north equatorial Indian Ocean during monsoon season. SST variations during this period show an increasing trend from west to east. During post-monsoon season, high MLD values are seen in the Arabian Sea compared to Bay of Bengal while the reverse is true during winter season. SST exhibits a gradual increasing trend towards east in both Arabian Sea and Bay of Bengal during the post-monsoon season and the trend is similar for Arabian Sea during the winter season also.
In Bay of Bengal, SST increases towards southwest during the winter season.

The distribution of MLD and SST using the seasonal averages for the period 1977-1986 shows a gradual increase in MLD towards northeast reaching a maximum of 65m around 16° N, 72° E during the pre-monsoon period. In this region more or less low SST prevails. During monsoon season, the minimum MLD observed in the Arabian Sea during the previous season has been replaced by deeper MLD. Bay of Bengal exhibits shallow MLD. Reversal of the zonal slope in MLD is noticed in this season in the north equatorial region in association with the wind reversal. A surface cooling of about 3-4° C is noticed in the western Arabian Sea and it is about 2° C in the Bay of Bengal. Comparatively deep MLD is found during post-monsoon season in the western region which shows a shoaling towards east both in Arabian Sea and Bay of Bengal. The variations in SST are reflected in the corresponding MLD variations. During the winter season, deep MLD is noticed in the northwestern Arabian Sea and in the central Bay of Bengal in association with low SST.

Studies on the daily variations of SST and MLD in various polygon areas show an increase in MLD during 6-20 June and 30 June to 15 July 1977 in the central Arabian Sea. The corresponding variations in SST show a decreasing trend. During 10-22 May 1979, a gradual fall in MLD (about 10m) is noticed to an increase in SST of 0.3° C in the western Arabian Sea.
It is found that mixed layer depth varies with the variations in SST in many cases. During monsoon season, the MLD deepens in the Arabian Sea as a result of increased mixing provided by the rough sea conditions.

Analysis of vertical temperature sections in the equatorial Indian Ocean shows a decreasing trend (about 20m over a 14° longitude) in MLD from west to east before the onset of monsoon and a deepening of 18m over 8° longitude from west to east after the onset of monsoon 1977. The magnitude of decrease from west to east is about 15m over 16° longitude before onset and the increase is about 22m over 17° longitude from west to east after the onset of monsoon during 1979. In the equatorial Indian Ocean, MLD dynamics is not controlled by SST alone but, surface wind stress also plays a major role.

In general, it can be seen that when the SST increase is due to the heating caused by increased insolation, the upper mixed layer gets heated up resulting in a shallow MLD. For example, during pre-monsoon season, shallow MLD is observed in the western Arabian Sea due to high SST. Similarly, when the decrease in SST is due to the heat loss caused by reduced insolation, or increased net loss from the ocean surface, mixed layer deepens. This is true during monsoon season especially in the Arabian Sea. On the other hand, when the increase/decrease in SST is due to an oceanic phenomena, MLD increases/decreases. For example, during upwelling, SST decreases when the cooler water reaches the surface, as can be seen in the vertical section of
the equatorial region between 75° to 77° E during 19-23 July. Similarly, when the MLD increases at the eastern end of the equatorial Indian Ocean as a result of the piling up of warmer surface water, there exists a direct correlation between SST and MLD. Thus depending upon the phenomena SST and MLD are correlated either directly or indirectly.

The variations of heat content in the surface (0-50m) layer show a maximum heat content of $62 \times 10^8$ J/M$^2$ during pre-monsoon season in the Arabian Sea and a minimum of $50 \times 10^8$ J/M$^2$ during monsoon season. This layer shows a heat content of $58 \times 10^8$ J/M$^2$ during post-monsoon and about $53 \times 10^8$ J/M$^2$ during winter season in the central Arabian Sea. In Bay of Bengal, higher heat content is noticed during monsoon season compared to Arabian Sea, and more or less same magnitude during pre-monsoon season and lower heat content during post-monsoon and winter seasons. The zonal variations of heat content in all the lower three layers beyond 50m show similar trend as the surface layer during monsoon and winter seasons, but, the trend is reversed during the other two seasons.

The decrease in heat content between the first and second layers is about $9 \times 10^8$ J/M$^2$ in the eastern Arabian Sea which shows a regular fall towards west during pre-monsoon season. During monsoon season, it is about $16 \times 10^8$ J/M$^2$ on the eastern side and about $2 \times 10^8$ J/M$^2$ on western side of the Arabian Sea, whereas in Bay of Bengal, this type of conspicuous zonal variations are not
present. This heat content variations are mostly controlled by the variations in SST, mixed layer cooling and vertical advective processes in the upper thermocline. During post-monsoon season, the lowering is less on the western side than the eastern section both in Arabian Sea and Bay of Bengal. This is because of the cooling and deepening of mixed layer on the western and shallow MLD on the eastern side.

Beyond 100m, the successive layers show larger heat loss on the eastern Arabian Sea during monsoon and winter seasons, but, this trend is reversed during pre and post-monsoon seasons in Arabian Sea and Bay of Bengal. This difference in heat content is mostly associated with the temperature gradient in the thermocline.

Day to day variations of heat content of the surface layer mostly follow the variations in SST. The lower three layers show more or less opposite trend in heat content variations as compared to the surface layer. The heat loss between successive 50m layers increases downwards during 30th June to 15th July 1979, because of the decrease in downward advective transfer of heat from the surface to lower layers. During 6-20th June 1977, the heat loss between the second and third layer is less compared to the layers above and below. The heat loss in each 50m layer exhibits almost similar magnitudes during 16-23rd May 1979. In June 1979, the reduction in heat between second and third layers appears to be higher than the layers above and below. This is due
to sharp temperature gradient in the thermocline up to 150m. In Bay of Bengal, during July, the surface layer shows minor fluctuations in heat content, but, the lower three layers exhibit large variations. This may be due to the vertical oscillations of thermocline.

Analysis of CHP28 during three storm events reveals that increase in heat potential is accompanied by high SST and low MLD before the formation of storm and decreased heat content, low SST and deep MLD after the storm events. This implies that heat has been taken away by the storm in the form of latent heat along its track.

Spatial distributions of heat budget components in the northern Indian Ocean show dramatic changes during different phases of southwest monsoon. Maximum variations in net radiation are noticed in the southwestern Arabian Sea associated with the intensification of convective clouds just before the onset. Latent and sensible heat show comparatively lower values than those during the onset period. Ocean gain a maximum heat of 120W/M² in the western Arabian Sea due to increased net radiation and low latent heat release. A minimum gain of 50W/M² is noticed in the Bay of Bengal.

Considerable reduction in net radiation is noticed during the onset period due to the intensification and migration of convective clouds. Eastern Arabian Sea registered maximum latent heat of 200W/M² where the cloud cover shows maximum variations.
This is due to maximum condensation as a result of more latent heat release. Sensible heat flux increases by 10W/M² both in Arabian Sea and Bay of Bengal. During onset period, ocean loses a maximum heat of 60W/M² near the southwest coast of India. In most parts of Bay of Bengal also recorded heat loss of about 30W/M² in association with low net radiation and high latent heat.

Net radiation recovers its maximum during break period. Latent heat, sensible heat and cloud cover show low values compared to the onset period. Ocean gains heat during this period throughout the study area except in a limited area in the northern Arabian Sea where a loss of 5W/M² is noticed. In the daily variations also, heat exchange components exhibit similar variations. The oceanic heat gain is, in general, mainly controlled by variations in net radiation and latent heat flux. Heat loss during monsoon season produces a positive feedback for the development and intensification of convective clouds.

Variations in heat storage of mixed layer and 0-200m layer indicate an overall positive heat storage during pre-monsoon and heat depletion during monsoon season. Heat storage minus surface heat gain gives the degree of heat advection indicating heat export during monsoon season in the north Indian Ocean. On an average, heat export from both the mixed layer and 0-200m layer is found to be more than twice the surface heat gain during this season.
The present investigations have brought out the role played by the various air-sea interaction parameters during the different phases of Indian monsoon. The advective transfer of heat in different latitude belts in the north Indian Ocean has been established and quantified. The studies also enable us to highlight the influence of oceanic heat content in the genesis of cyclonic storms in the Indian Ocean.