Chapter 8

Summary and Conclusions
The thesis "Salient features of the north Indian Ocean associated with the Indian summer monsoon" primarily focuses on certain aspects of the atmosphere and ocean variability in the North Indian Ocean associated with the monsoon. These include the Arabian sea mini warm pool formed in the eastern Arabian Sea during the pre-monsoon season, variability in the ocean response of central and northern Bay of Bengal to atmospheric systems/disturbances during the summer monsoon 99, the marine boundary layer characteristics during the summer monsoon 99 and the variability induced by the atmospheric systems/disturbances, evolution of propagating waves and eddies and their inter-annual variability.

In the Indian Ocean, an active area of recent research is the Indian Ocean warm pool and associated ocean and atmosphere dynamics. However, not much attention is paid to the Arabian Sea mini warm pool, where the onset vortex is formed. In this thesis, the focus is given on the Arabian Sea mini warm pool, which is a part of the Indian Ocean warm pool and formed in the southeastern Arabian Sea prior to the onset of summer monsoon. Utilizing 45 years of data corresponding to the onset date and corresponding rainfall, it was found that an early onset of monsoon over Kerala favoured a good monsoon rainfall and a late onset leads to below normal rainfall. NCEP/NCAR sea surface temperature (SST) data (1960-1998), from ships of opportunities, high resolution TMI SST for typical years were utilized to study the characteristics of the Arabian Sea mini warm pool. As the temperature in the entire Arabian Sea exceeds 29°C during the pre-monsoon, 30°C isotherm was selected to represent the Arabian Sea mini warm pool in this study. The study revealed in the eastern Arabian Sea, maximum temperature occurred approximately two weeks prior to the onset of summer monsoon over Kerala. However, the extent and the core temperature varied depending on the nature of the forthcoming monsoon. One of the notable result was that the dissipation of the mini warm pool started nearly one-two weeks prior to the onset of summer monsoon over Kerala. This was due to the arrival of monsoon winds to the western and central Arabian Sea, which increased vertical mixing processes. This result was confirmed utilizing TMI SST data for 2001, 2002, 2003. It was also found that the warm pool attained its maximum core temperature (30.5°C) and lateral extent (> 30,00000 km²) during wet year compared to normal (30.2°C, > 16,94000 km²) and dry year (< 30°C, in the eastern Arabian sea).
Verification of the results with TMI SST for the years 2001 (below normal), 2002 (dry) and 2003 (above normal) confirmed this conclusion. This suggests that the dissipation of the Arabian Sea mini warm pool, its core temperature and lateral extent can be utilized as a tool to characterize the forthcoming summer monsoon.

The analysis of salinity data indicated the presence of low saline water in the mini warm pool region, with minimum salinity during wet year. Probably, this low saline water might have increased the vertical stratification and thereby causing the occurrence of maximum temperature during wet year. This needs further verification. Two possible sources for the low saline water in the southeastern Arabian Sea have been proposed. One from the Bay of Bengal and other from the western equatorial Indian Ocean.

Information on the marine boundary layer was extremely sparse over the Indian Ocean especially during the monsoon season. The radiosonde data collected during the BOBMEX-99 experimental program onboard the research vessel ORV Sagar Kanya, provided valuable information on the influence of weather systems on the Marine Boundary Layer (MBL) characteristics. The vertical variations of observed parameters such as temperature, humidity, wind speed and direction showed variability with the formation and dissipation of the systems over the Bay of Bengal. Temperature was usually greater than 28°C in the surface layer and decreases with height. Atmosphere was relatively humid (>80%) below 1000 m, throughout the observation period with large variability observed above that till 8000 m. Relative humidity was less than 30% above 11000 m. Wind showed westerlies (1-16 ms⁻¹) below 5000 m and easterlies (>31 ms⁻¹) above 8000 m, with the core around 15000 m. The potential temperature gradient, a measure of the stability of the atmosphere showed negative values indicating unstable situations only in the lower layer below 150 m. The formation of atmospheric systems induced large variations in all these fields. Temperature decreased by the order of 1.5° to 3.5°C below 1000 m, with the maximum gradient below 200 m with the formation of atmospheric systems. No large variation existed above 1000 m. The large variation in humidity values associated with systems were confined in the levels between 1000 and 8000 m. During the formation stage of the systems relative humidity increases to more than 85% in the levels below 7000-8000 m and returned to pre-system values after its dissipation. The
wind speed showed large increase (11-16 ms\(^{-1}\)) during convective systems such as rain with the westerlies below 7500 m. Easterlies are noticed above that with the core of the Easterly Jet stream (>31 ms\(^{-1}\)) between 15000 and 17000 m. This core was confined to nearly 16000 m after the rainfall event thereby reducing the thickness of the core. Potential temperature gradient showed maximum gradient (-0.01°C m\(^{-1}\)) in the lower 50 m, indicating unstable condition associated with the formation of systems.

Wind shear was generally higher above 15000 m and coincided with the Easterly Jet stream. Nearly zero wind shear was noticed in the level between 10000 and 14000 m, where the effect of both the easterly and low level Westerly Jet Streams are minimum. Associated with the rainfall event when the wind increased, wind shear also increased (0.0118 s\(^{-1}\)) in the levels between 15000 and 20000 m and below 10000 m. The vertical extent of the wind shear zone in the Jet stream region decreased (~3000 m) after the rainfall event.

Coinciding with weak monsoon condition, temperature was above 28°C in the surface layers and low humidity regime (<60%) extended downwards to ~ 5000 m. The wind speed decreased considerably (1-6 ms\(^{-1}\)) during this period and the easterlies also extended downwards to ~5000 m.

The lowering of lifting condensation level below 965-970 mb was also associated with the system formation and the lowest value ~ 997 mb corresponded to the major rain event. A decrease in Boundary Layer Height (BLH) by the order of 1500 m and frictional velocity by the order of more than 0.3 ms\(^{-1}\) was also associated with convective activity.

Understanding of the refractive index conditions of the atmosphere is mostly needed for radar ranging and tracking purposes. The refractive index gradient showed large variations with the changing moisture content and temperature of the atmosphere associated with the systems in the lower layers below 400 m and standard conditions existed above this level. The trapping conditions, which is ideal for tracking existed in the lower layers below 70 m associated with the system formation. The sub-refractive condition in the near surface layers coincided with the rainfall event with standard condition just above this layer and below 30 m. Super-refractive conditions were noticed to exist from 50-400 m during the weak monsoon period.
The physical and oceanographical conditions are different in Northern and central Bay of Bengal. Northern Bay of Bengal is less saline due to large freshwater influx from river discharge. During the summer monsoon, the monsoon trough dips into the northern Bay of Bengal and many systems were also formed over this region. Simultaneous observation at these two station locations, during the BOBMEX experimental programme of summer monsoon 1999 provided an opportunity to study the response of the central and northern Bay of Bengal to the summer monsoon and atmospheric systems that formed over this region. The buoy data available at these locations were also utilized in this work. The central Bay and northern Bay responded differently to the summer monsoon and to the atmospheric systems that formed over this region. The pressure and sea surface temperature values were in general higher over the central Bay. The amplitude of the variations was also comparatively less over the central Bay.

Over the northern Bay, prior to the formation of any atmospheric system, atmospheric pressure is of the order of 1000 mb, air-temperature is of the order of 29°C, wind speed is of the order of 7 ms\(^{-1}\) and SST of the order 28.7°C. With the formation of system, significant decrease is noticed in the atmospheric pressure (998 mb and below), air temperature and SST (< 26°C, < 28°C), while wind speed increased to above 10 ms\(^{-1}\). Winds were southwesterly during weak monsoon condition and west southwesterly during the depression period. However at the central Bay, amplitude of variations was comparatively less. Effect of the systems were noticed here with reduced magnitude. One reason can be due to most of the systems formed in around northern Bay. The atmospheric pressure and SST were generally above 1005 mb and 28.4°C respectively with wind speed around 7 ms\(^{-1}\). Strong winds 10 ms\(^{-1}\) were observed during the active monsoon period. Winds were southwesterly throughout the observation period.

The net heat flux is higher (~400 Wm\(^{-2}\)) over the central Bay. Over the northern Bay net heat gain was less under increased cloud cover and associated systems and increased with weak monsoon condition. The SST-DB, an indication of static stability, increased (>2°C) corresponding to system formation and more pronounced over northern Bay. A notable result was the decrease in specific humidity.
associated with system formation over northern Bay, from more than 0.022 to less than 0.019.

Another important result was the critical limit for the sea surface temperature. It was noticed that whenever, SST increased beyond 28.7°C over the northern Bay, systems were formed over the Bay of Bengal. The same was true for the convective systems associated with rainfall event also. A lag of 2-3 days was also noticed between the ocean pressure minimum and SST minimum.

The mixed layer depth shoaled/deepened during the period of increased/decreased winds at the central Bay and suggested the role of forcing other than local in controlling the mixed layer variations. A one-dimensional model of Miller (1976) was utilized to simulate the mixed layer characteristics in the northern and central Bay of Bengal. Large disagreement between observation and simulation was noticed at both the stations, suggesting the dominance of remote forcing over local forcing. This can be attributed to rich eddy fields, complex circulation pattern, long period waves and internal waves occurring in this region.

The surface winds over the Indian Ocean are notable for its seasonal reversal. NCEP/NCAR surface winds at 10 m level were utilized to examine the surface wind and wind stress curl for the years 1993-1997 and to study their inter-annual variability. 1994 and 1997 were El Nino years and Indian Ocean Dipole events were also reported during these years. Analysis of surface winds revealed peculiar characteristics during these years. The westerly winds over the equatorial Indian Ocean during the transition period between the monsoons were weak during 1994 and 1997 (<2 ms⁻¹) compared to the other years and even easterlies appeared over the region during this period. The northeasterly winds were stronger and southwesterlies were weaker over the Bay of Bengal during the 1993, 1995 and 1996 winter and summer monsoon respectively. The southeast trade winds over the south Indian Ocean were more prominent during 1994 and 1997, over the eastern Indian Ocean along the Sumatra coast as it extended more northwards over the equatorial region from June to December.

Wind stress curl also reversed seasonally to positive/cyclonic or negative/anticyclonic with the monsoon winds. They are also important as they favour cyclonic/anti-cyclonic circulation over the region. The regions of positive/negative
curl were separately discussed for further use of this information in studying the propagating waves and eddies.

The curl of the wind stress were in general negative/anti-cyclonic during the northeast (winter) monsoon period favouring anti-cyclonic circulation in the ocean over the northwestern Arabian Sea, southern tip of India and offshore regions extending westwards, over Sri Lanka region, the western Bay and over the Somali coast. However, in the offshore regions of the Somalia and extending northwards, the curl was positive or cyclonic. The curl value decreases and changes its sign with the progress of season. During the summer monsoon season, the curl became positive/cyclonic favouring cyclonic circulation over the southern tip of India and west coast of India extending westwards and over western Bay, over the coast of Arabia and western Arabian Sea, over the east coast of India and around Sri Lanka. Along the Somali coast during the summer monsoon, the curl was positive and it was negative to the east, extending to the central regions of the Arabian Sea. The large variability in the winds and its curl can cause corresponding variability in the sea level also.

The positive or negative curl over the study region revealed large inter-annual variability during the years 1993-1997. It was found that the negative curl over the southern tip of India during December/January remained there offshore till March/April for all the years and is shifted more southwards during January 1994 and 1997 compared to other years. The positive curl during the summer monsoon over the west coast of India also showed large variability with similar pattern during 1994 and 1997 as the curl became negative earlier by November itself compared to other years. During other years, this positive curl extended over the west coast upto 15°-20°N and remained over the southern tip during October/November also. Over the northwestern Arabian Sea the curl was negative from November/December onwards till May and turned positive by June. But during 1995 and 1997 curl remained negative during June also. Over the Sri Lankan region, the curl was positive through out the summer monsoon season. In the offshore regions of Somalia, the extension of the negative curl during the summer monsoon showed large inter-annual variability. Similar pattern of negative curl was noticed during 1993 and 1994 June but sign changed comparatively earlier in 1994. During 1996, the extension of the negative curl over this region was
higher compared to 1995 and 1997, but less than 1993 and 1994 June. The extension of the negative curl in August 1997 was higher than all other years.

The winds during the transition period between monsoons drive the equatorial Jet, and force the eastward propagating Kelvin waves. On reaching the eastern boundary, a part of it reflects back as Rossby waves and other part propagates northward and southward as coastally trapped Kelvin waves. The TOPEX/Poseidon Sea Surface Height (SSH) anomaly data were utilized to study the propagating waves along typical sections viz. equator (0°), central Arabian sea, Bay of Bengal along (15°N) and in the south Indian Ocean (along 15°S & 20°S). Wavelet analysis technique was also utilized to determine the prominent harmonics embedded in the time-series of SSH field at selected locations. Along the equator, positive SSH, representing downwelling Kelvin wave propagated from the western Indian Ocean during March/April and September/October and reached the eastern Indian Ocean within a gap of one month thus indicating the semi-annual periodicity of these waves. This was supported using wavelet analysis also. The speed of this downwelling Kelvin wave was computed to be ~ 250 cms\(^{-1}\). These SSH anomalies indicating Kelvin wave propagation revealed large inter-annual variability. Another notable result was that corresponding to the weak equatorial westerlies during the transition period of 1994 and 1997, downwelling equatorial Kelvin waves were also weak. In these years, the upwelling signals were more prominent in the eastern equatorial Indian Ocean. During other years, when the equatorial westerlies were strong, equatorial downwelling Kelvin waves were also prominent.

The westward propagation of positive SSH anomalies from the eastern Arabian Sea (along 15°N) during December/January, denoted Rossby waves propagation from their speed (between 8-10 cms\(^{-1}\)) and direction of propagation. Wavelet analysis revealed annual harmonic to be significant in this region. This also supported the result, as annual periodicity, westward propagation and its speed coincide with that of the annual Rossby waves propagation in the eastern Arabian Sea along this latitude. It was also interesting to notice these signals to be more prominent during 1994 and 1997, inspite of weak equatorial westerlies, and when El Nino and Indian Ocean Dipole (IOD) events were also reported to have occurred. The prominent wave during 1994 and 1997 can be associated with the previous years
downwelling Kelvin wave i.e. of 1993 and 1996 respectively, which reached there during this period. This analysis also supported the role of equatorial wind (as downwelling Kelvin wave) in causing inter-annual variability in the propagation of waves in the eastern Arabian Sea.

Another interesting feature noticed was the formation of a high of non-propagating nature in the western Arabian Sea, from November to May/June, but extending to the central regions. This was found to be associated with the persisting anti-cyclonic circulation over the northwestern Arabian Sea during this period. This high limited the westward extension of the positive SSH formed in the eastern Arabian Sea. When the Rossby wave propagation from the eastern Arabian Sea was weak especially during 1995, this high extended more eastward.

In the central Bay of Bengal (15°N) also, westward propagating positive signals were noticed from the eastern Bay, during May/June and November/December, but prominent only in certain years. This was also associated with the downwelling Kelvin waves from the equatorial Indian Ocean. The signals were less prominent during 1994 and 1997 when the equatorial downwelling Kelvin wave was weak. The speed of westward propagation of this high ~12 cms⁻¹ also corresponds to the Rossby wave speed along this latitude. In 1994 and 1997, when weak northeasterlies occurred over the Bay region, the high anomalies from the eastern Bay also appeared weak, suggesting the role of equatorial as well as Bay winds in causing inter-annual variability in the wave propagation. In the south Indian Ocean (along 15°S & 20°S), the Rossby wave propagation was clearly identified from the eastern Ocean, which took almost two years to reach the western Indian Ocean suggesting a speed of 12.6 cms⁻¹. Large inter-annual variability was noticed in the SSH anomalies in the south Indian Ocean and the southeast trade winds were also noticed to play a major role in the formation and propagation of these SSH anomalies. A major conclusion emerged from this study is the influence of surface winds on wave propagation and its inter-annual variability. Thus the winds form an integral part in controlling the ocean dynamics.

The Daubechies wavelet was utilized to decompose the prominent harmonics embedded in the SSH signals and their confidence level was tested using significance test. In the equatorial region prominent harmonics were in the bands of ISO (intra-
seasonal), 3-4 month, semi-annual, annual and above annual. In the equatorial region prominent harmonics were in the semi-annual band at the western and eastern equatorial Indian Ocean and attributed to semi-annual reversal of winds and associated semi-annual Kelvin waves. In the central Arabian Sea annual periodicity corresponding to annual Rossby waves dominated and in the Bay of Bengal (near the coast), prominent harmonic was in 3-4 month band. In the south Indian Ocean low frequency signal was noticed to be prominent i.e. annual and biennial. Large spatial as well as temporal variability was noticed in all the harmonics.

The T/P SSH data was further utilized to identify the major eddies in the north Indian Ocean and their inter-annual variability. The major eddies in the north Indian Ocean identified were the Lakshadweep High (LH) and Lakshadweep Low (LL), the Arabian Anti-cyclonic high, Somali eddies and the eddies in the Bay of Bengal.

The LH started forming in the Lakshadweep region with the arrival of equatorial downwelling Kelvin wave (as coastally trapped) of April at the southwest coast of India by November. These coastal Kelvin waves radiate Rossby waves westward. The LH propagated westward, coinciding with the speed of Rossby wave propagation. Thus the Rossby waves were noticed to play a major role in the formation of this LH. The wind stress curl over this region was also negative favouring the formation of high in SSH. A noticeable result from the study was the large inter-annual variability in the dimension, speed, and number of multiple eddies of this LH. The least dimension of the LH was noticed during 1994-1995 (<200 km). This can be associated with the weak equatorial downwelling Kelvin wave of April/May 1994. In all other years, the dimension of this eddy was greater than 500 km. The LH dissipated by May.

The LL, formed off the southwest coast of India, from May onwards and correspondingly wind stress curl was positive/cyclonic favouring the development of low SSH during this period. This also propagated westward at the Rossby wave speed of propagation. The low extended all over the Arabian Sea basin by November/December and started dissipating from the west coast with the formation of LH in November.

The LL also showed large inter-annual variability. The extent of this low was noticed to be least in the Arabian Sea during 1994 and 1997. Corresponding cyclonic
wind stress curl changed to negative/anti-cycloonic earlier in November itself during these years. In addition, in these to two years, El Nino and IOD vents were reported causing considerable warming in these regions, which also might have limited the westward extension of the LL.

The Somali anti-cycloonic eddies formed off the Somali coast during summer monsoon from June/July onwards and corresponding wind stress curl was also found to be anti-cycloonic in the offshore regions, favouring the development of high in SSH. Large inter-annual variability was noticed in the dimension of these eddies in all the years. These eddies merged together in some years and dissipated by October. The dimension of this eddy was the least during the initial phases of the 1994 and increased later in September only. In all other years, dimension of this eddies became greater than 200-500 km during June/July itself.

In the western Bay of Bengal, anti-cycloonic eddies were noticed during January-June period, off Sri Lanka and off northwestern Bay of Bengal. The wind stress curl was negative/anti-cycloonic over this region favouring the formation this high. A cycloonic eddy was also noticed in between these two anti-cycloonic eddies. Both these eddies changed their dimension and position with the progress of time. By April/May, a single eddy probably by the merging of these anti-cycloonic eddies were noticed in the western Bay. The dissipation started from May/June onwards. These eddies showed inter-annual variability in their dimension and center of location. During 1993, 1994, 1996 and 1997, the dimension of these anti-cycloonic eddies of Sri Lanka and northern Bay was higher (200km to 500 km), while in 1995 it was less (~100 km). The winds along with wind stress curl over the region and coastal Kelvin wave from the equatorial region were noticed to play a major role in the development of these eddies. The Sri Lanka dome, a region of low sea level formed east of Sri Lanka during the summer monsoon period. The corresponding wind stress curl was positive/cycloonic favouring the development of negative SSH in the ocean. The dissipation of this dome is associated with the weakening of positive curl in this region.

Scope for future work

In this thesis, attempts were made to understand various aspects of time-scale variability of major features occurring in the Indian Ocean associated with Indian
The results from the thesis can be utilized as an input for model studies for prediction of monsoon, understanding the ocean dynamics, for radar tracking and ranging etc. Arabian Sea mini warm pool has been studied utilizing limited data sets. The results presented in this thesis can be confirmed by extending the analysis for long period to bring out characteristic features during different types of monsoon. Numerical model studies suggested the importance of remote forcing at northern and central Bay. Hence inclusion of remote forcing can give a better simulation of the major ocean dynamics. The response of the atmospheric systems formed over Bay of Bengal to the characteristics of marine atmospheric boundary layer and upper layer was studied here as a case study. An extension of this work for more years could be used to confirm the results. It has been found that the eddies and propagating waves influence the major ocean dynamics of the Indian Ocean. So, a detailed study in this direction will help for a better understanding of these features and hence the climate over this region.