CHAPTER 1
INTRODUCTION

1.1 PREAMBLE

Monsoon Inversion (MI) over Arabian Sea (AS) was first detected more than 50 years ago during the International Indian Ocean Expedition (IIOE) of 1964 from in-situ radiosonde data. It was identified as one of the three objectives for detailed investigation during the major International programme MONsoon EXperiment (MONEX) / First GARP (Global Atmospheric Research Program) Global Experiment (FGGE) in the year 1979. However, subsequently it has received less attention in the last four decades, because of paucity of adequate in-situ or satellite data in this region. After the launch of operational sounder instruments onboard United States of America (USA) and European Space Agency (ESA) operational satellites in 2003 and 2006 respectively, Indian INSAT - 3D in 2014 and improved model reanalysis data sets (ERA - Interim, NCEP etc.) since 2005, it has become possible to investigate this phenomenon observationally in more detail.

Before presenting the important results of the characteristics of monsoon inversion, I have attempted to give an introduction to the subject matter in this Chapter. The important six semi - permanent features of Indian summer monsoon are first described to begin with. The basic differences between monsoon inversion over Arabian Sea vis a vis atmospheric boundary layer in general is then discussed. Earlier efforts on observational aspects of monsoon inversion are summarized. A short discussion on the contribution of satellites (whose data are primarily used in this study) for monsoon research has also been included.

Towards the end of this Chapter, we pose some important scientific questions on Monsoon Inversion. Later three chapters of the thesis address how we have gone about to
investigate them and suggest plausible explanations. A brief description on the organization and contents of each Chapter is also included at the end of this Chapter.

1.2 MONSOON

The word monsoon originates from the Arabic word ‘mawsim’ meaning ‘season’ and word “mausam” refers to “weather” in Hindi and several Indian languages [1, 2]. Thus, Monsoon is a system of alternating winds during the year accompanied by precipitation. It is a seasonal change in atmospheric circulation and precipitation associated with the differential heating of land and ocean. Monsoon winds are largely confined to the tropics between latitudes of 20º N and 20º S on both sides of the equator [1]. These changes are occurring at large spatial and time scales on the globe (Figure 1.1). At small scales, one can observe a similar phenomenon as sea breeze, often observed near coastal stations during late afternoons.

In the present study, we deal with the Indian summer monsoon spread over the months of June to September. Monsoon is the life-line of India. The distribution for rainfall during the four months of monsoon decides the country’s agriculture, economy, water and power requirements. More than 90 % of annual precipitation in central and western India, and more than 50 - 75 % of southern and northern India occur during southwest monsoon season. The area-averaged precipitation over the country is ~ 900 mm during these four months.

The moist air originating from Mascarene island in the southern hemisphere is drawn to the heat low formed over Pakistan and neighbourhood during the northern summer. It originates as southerly winds and after crossing the equator turns southwesterly due to the Coriolis effect and arrives at the Indian peninsula as two stream of currents, one striking the west coast and the other turning around the peninsula as Bay of Bengal branch [1].

India has two kinds of monsoon i.e. South West (SW) monsoon and North East (NE) monsoon. The winds blowing over the Indian continent and its neighbouring oceans
from northeast for six months and from southwest for the rest of the six months constitute these two monsoon systems. The monsoon associated with other continental masses of the earth are not so well marked as the Indian monsoon, but seasonal changes in the wind direction are known to occur over north Australia, western and eastern Africa and southern USA [1].

Figure 1.1. Monsoon regions of the world: (top) June - August (bottom) December - February [3]

Monsoon winds, while passing over the ocean transport a lot of moisture from ocean to land. This undergoes further physical processes like convection, condensation,
precipitation etc. The ocean water gets evaporated and this is stored as latent heat of evaporation. During the reverse phase, condensation occurs at higher altitudes over the land. The stored latent heat energy is released to the environment as latent heat of condensation, during the formation of clouds and rain.

The thermal equator receives the maximum heat energy from the Sun. Mainly, the convection over the thermal equator leads to the formation of a zone of convergence where the trade winds meet, known as the Inter Tropical Convergence Zone (ITCZ). It appears in the satellite imageries as a band of clouds that encircles the globe near equator [4]. The major band of this cloud zone moves northward to ~ 15° N in the northern summer and southward to ~ 15° S in the northern winter. It is responsible for the wet and dry seasons in the tropics. During monsoon, this band moves towards latitudes of Indian land mass, merges with the monsoon trough in this longitude zone and produces copious precipitation.

1.3 SEMI PERMANENT FEATURES OF SOUTH WEST MONSOON

There are six well documented semi - permanent features (depicted in Figure 1.2 with appropriate labels) of the Indian summer monsoon circulation.

Monsoon inversion over western Arabian Sea, is proposed by the author and coworkers as a new and seventh semi - permanent feature of southwest monsoon. This is the subject matter of this thesis.

The major six semi - permanent features of SW monsoon are described below:

1.3.1 Mascarene high

This is a high pressure area south of the equator; this center of this anticyclone is located near 30° S, 50° E. It is the source region of the east Asian Summer Monsoon which has much influence on the south Asian climate and weather [5]. This is an important feature of the monsoon whose detailed synoptic analysis helps meteorologists and operational forecasters. The intensification of the Mascarene high strengthens the cross - equatorial flow in the form of the east African LLJ and the monsoon current over the
Arabian sea [6]. The intensity is associated with the onset of the monsoon over India as well as well the subsequent fluctuations in its activity [7].

**Semi Permanent Features of SW Monsoon**

1) Mascarene high  2) Pakistan heat low  3) Somali low level Jet (~ 1 km)
4) Tibetan high (~ 5 km)  5) Monsoon Trough  6) Tropical easterly jet (~ 12 km)
7) Western Arabian Sea low level monsoon inversion (~ 1 km)

**Figure 1.2.** Schematic view of the semi-permanent features during South West (SW) monsoon season [8]

1.3.2 Pakistan heat low

During the Northern summer, the temperature over the land is increasing and the air lifts up due to (dry) convection; this forms a large low pressure area over land during the months of March to May over Pakistan. This is a part of the global scale low pressure belt from Sahara up to Myanmar. The centre of the seasonal low has temperature of ~ 45 °C or more. The horizontal steep north south pressure gradient (~ 20 hPa across 1500 km) causes strong surface winds which together with the loose sand produce dust storm. The boundary
layer, consisting of approximately the lowest 1.5 km over these regions experiences a strong temperature inversion [9-11]. The intensity of the heat low has been studied in relation to monsoon activity [12].

1.3.3 Somali Low Level Jet (LLJ) stream

Low Level Jet (LLJ) is also known as Findlater jet or Somali jet, it is a narrow channel of wind with maximum winds near 1.5 km height level off the coast of Somali. It is known to occasionally have speeds of the order of 50 m / s (100 knot) near Madagascar and off the Somali coast [8]. The central axis of the jet oscillates from north-westward in February to East African highlands by June. It stays near the Somali region during the monsoon season with most intense phase. Before reaching the Indian coast, it splits into two branches over the AS. The jet is strongly affected by local factors like topography, friction, and the diurnal cycle of heating. Large scale moisture and momentum transfer is carried by this jet stream.

1.3.4 Tibetan high / anticyclone

There is a large anticyclone (a warm high pressure zone) having its largest amplitude near 200 hPa during the summer monsoon over the Tibetan plateau. This plateau is at a height of ~ 4 km from the mean sea level, with around 2000 km length and 600 km width in the west and 1000 km in the east. The high moves south and southeastward in the September. It is considered to be one of the key factors in the development of monsoon circulation in the region. The atmospheric pressure varies from 700 to 500 hPa on the plateau. The position and movement of the Tibetan high is very much correlated with the western disturbance and monsoon activity over India and the adjoining regions.
1.3.5 Monsoon trough

The monsoon trough is a major semi-permanent feature of the summer monsoon circulation in the lower troposphere and exerts considerable influence on the summer monsoon activity over south Asia [5]. It is an elongated low pressure zone at the surface. The trough line runs from Ganganagar (29.9° N, 73.8° E) to Kolkata (22.6° N, 88.4° E) through Allahabad. This is observed from surface up to an altitude of 500 hPa level (~ 5.5 km) during periods when the monsoon has advanced into the northern parts of India. The monsoon trough shifts from north to south with the activity of monsoon. This is the low-pressure trough at sea level that is a part of the global equatorial trough of the northern summer season extended over lands from west Africa to the east coast of Indo-China [8].

The location of the monsoon trough and axis of heavy monsoon precipitation is generally well poleward of the position of the oceanic ITCZ, within which the majority of tropical oceanic precipitation occurs. The Inter Annual Variability (IAV) and Intra Seasonal Oscillations (ISO), active break spells etc. of monsoon are all connected with the movement and position of ITCZ. Heavy rainfall spells imply deep convection in association with the ITCZ during the active spells or synoptic systems related with weather events. Asnani’s [13] definition of the monsoon was simple: ‘the monsoon is where the ITCZ is’, but it paved the way for what could be called the globalization of the monsoon.

There is also evidence that the monsoon may influence the atmosphere circulation in the extratropics [14, 15].

1.3.6 Tropical Easterly Jet (TEJ)

The Tropical Easterly Jet (TEJ) is an upper level (~ 150 hPa) easterly wind that starts in late June and continues until late September. It is an important semi-permanent upper tropospheric feature of the of summer monsoon circulation over the South Asian region. The north-south movement as well as the structure of the TEJ is observed to be closely linked to the monsoon activity [5]. It is a strong jet flowing from south-Asia to
Africa at an altitude of ~ 15 km above the surface of earth centered around 15º N, 50 - 80º E with a speed of roughly 40 - 50 m / s.

### 1.3.7 Other aspects related to South West monsoon

Another synoptic feature of onset and good monsoon is the weakening of the upper tropospheric westerly jet over northern Pakistan and adjoining India and the ultimate northward shifting of westerly Sub - Tropical Jet (STJ) to north of Himalayas. This provides help to penetration and advancement of monsoon towards higher latitudes.

Quasi - Biennial Oscillation (QBO) in the tropical stratospheric winds is defined as a reversal of the zonal wind direction above about 17 km altitude over the tropics from strong easterlies to strong westerlies and back approximately every other year. At their strongest, the easterly winds have about twice the speed of the westerly winds. The period of QBO is 26 - 27 months, and a range of 23 to 30 months [16, 17]. The relationship of the QBO with Monsoon is shown by many authors like Sathiyamoorthy, Hastenrath etc [16, 18, 19].

ENSO (El Nino /Southern Oscillation) is another aspect and predictor of Monsoon. El Nino refers to much bigger semi periodic occurrence identified in full as ENSO. The Southern Oscillation is a movement in the relative sea surface temperature values between eastern and western tropical southern pacific. An El Nino occurs while the easterly trade winds in the tropical Pacific decline or reverses path. During the El Nino periods, the surface pressure in the western Pacific is less than the eastern pacific. The wind blows from east to west, allowing cooler water to upwell in the east and resulting in higher sea surface levels in the Western Pacific than in the Eastern Pacific. The opposite is La Nina, and is characterized by a cooling event in the tropical eastern Pacific. This results in the return of powerful easterly trade winds that flows from the region of the high to low pressure. Warm and cold ENSO events reveal that a majority of the warm episodes are accompanied by below-normal summer rainfall in India and northern Australia, and above-normal winter rainfall in southeast Asia during cold ENSO events [20].
The Indian Ocean Dipole (IOD) is defined by the difference in sea surface temperature (SST) between two areas (or poles, hence a dipole) - a western pole in the AS (Western Indian Ocean) and an eastern pole in the eastern Indian Ocean, south of Indonesia [4, 5]. The IOD affects the climate of Australia and other countries that surround the Indian Ocean basin, and is a significant contributor to rainfall variability in this region. The IOD involves an aperiodic oscillation of sea surface temperatures, between "positive", "neutral" and "negative" phases [5].

1.4 ATMOSPHERIC BOUNDARY LAYER (ABL)

Stull [21] defines the ABL as ‘the part of the troposphere that is directly influenced by the presence of Earth’s surface, and responds to surface forcing with a time scale of about an hour or less’.

Within the ABL, there are rapid fluctuations and strong vertical mixing in the temperature, moisture, heat fluxes, flow velocity momentum fluxes etc. Above the boundary layer is the free atmosphere where the wind is approximately geostrophic and the drag (friction) is negligible [22], while within ABL the wind is affected by surface drag. The Figure 1.3 is depicting the structure and evolution of ABL. This is characterized by surface layer, convective mixed layer and an entrainment zone during the day time and stable layer, residual layer and capping inversion during the night time [21].
The ABL represents the lowest 1 - 3 km of the atmosphere and typically contains the majority of water vapor within the column and also the air in ABL is influenced by the earth’s surface and responds to surface forcing such as frictional drag, evapotranspiration, heat transfer, pollutant emission, and topography [23]. The surface layer is the lowest layer of the atmosphere in contact with the earth’s surface and has mechanical turbulence by strong winds. Above this convective mixed layer is characterized by turbulence created from forced or free convection that actively mixes such quantities as aerosols, potential temperature and wind speed [21]. During the night time, thermals cease, allowing turbulence to decay in the formerly well mixed layer of air is called residual layer (the former air is now called the residual layer because it contains moisture and heat ) [24].

During the night time, absence of heating from sun suppresses the turbulence by a layer known as stable boundary layer above the surface layer. The stable layer or temperature inversion is capping the ABL. Turbulent mixing in the bottom of the statically stable troposphere creates this cap, and in turn this cap traps turbulence below it. There are
intermittent turbulences present in the entrainment zone. During night, turbulence in the
entrainment zone ceases, leaving a non turbulent separation layer called capping inversion,
which is still strongly statically stable.

1.5 TYPES OF INVERSION LAYERS

Basic types of inversion are proposed by many researchers (Yasmeen (2010),
Radiation and subsidence are two basic types of low - level inversions [26].

1.5.1 Radiation inversion

Radiation inversion forms when the earth’s surface cools rapidly. It is a common
form of the inversion. As the earth’s surface cools, so does the air layer close to the
surface. On clear nights, land and the air next to it will cool more rapidly than air aloft due
to radiation cooling [27]. If this layer cools to a temperature below the air above, we have a
very stable kind of situation. This impedes the vertical motion of the air. This inversion is
usually occurring in late evening and early morning under clear sky conditions. The same
conditions are conducive to nocturnal inversion for day time instability. There is common
diurnal cycle for both nocturnal inversion as well as day time instability. So the effect of
the radiation inversion is short lived. Sometimes during the day time warming may not be
strong enough to finish the inversion layer e.g. during thick fog conditions may reduce the
effect of sunlight. Under these conditions, several days of radiation inversion may result.
The condition over AS near to the cold SST region is this kind of inversions. During the
monsoon time there are low levels clouds over the AS, which make this kind of inversion
more prominent.

1.5.2 Subsidence inversion

Subsidence inversion is almost always associated with anticyclones (high pressure
systems). As the air descends, the higher pressure at lower altitudes compresses and warms
it at the dry adiabatic lapse rate. Normally this warming occurs at a rate faster than the environmental lapse rate. The inversion layer thus formed is often elevated several hundred meters above the surface during the day. At night, due to surface cooling, the base of a subsidence inversion often descends, perhaps to the ground. The subsidence of warm air at upper level (~ 700 hPa) produces the inversion at lower level (~ 900 or 850 hPa) [28, 29]. Thus, at the same time there is surface radiation inversion during the night time and elevated inversion during day time. The mixing layer is very narrow in these regions, so it will never become deep. Over the AS, the descending branch of Walker circulation is producing this kind of permanent inversion during the monsoon time [30]. The trade wind inversion also falls in this class.

1.5.3 Frontal inversion

Frontal inversion is mainly due to the frontal trapping. At the leading edge of either front, the warm air overrides the cold, so that little vertical motion occurs in the cold air layer closest to the surface. The strength of the inversion depends on temperature difference between the two air masses. As the fronts are moving horizontally, the effects of the inversion are usually short-lived, and wind flow compensates the vertical motion.

1.5.4 Advection inversion

Advection inversion is related to the horizontal flow of the warm air. When warm air moves over a cold surface, conduction and convection cools the air closest to the surface, causing surface-based inversion. This inversion is most likely to occur in winter when warm air passes over snow cover or extremely cold land.

1.6 MONSOON LOW LEVEL INVERSION

Low level monsoon inversion can be looked upon as the monsoon ABL over the western Arabian Sea. The major suggested cause of this MI is Walker circulation. The deep subsidence over the AS is provided by the downward branch of Walker circulation and
Hadley circulation [31, 32]. This oceanic sinking branch of the Walker cell is important feature to see the establishment of MI. MI is associated with the advection over the AS from Arabia also. Both factors are governing this phenomenon and have their effect over the Indian summer monsoon. Some of the major characteristics of MI are: inversion height, inversion frequency and inversion strength. The frequency of MI is also linked with the activity of monsoon.

MI is the temperature inversion above the ground below ~ 2 - 3 km. Monsoon inversion is a phenomenon which is seen over the west coast of Arabian Sea from pre monsoon (around mid of May) through entire monsoon to post monsoon (around mid October) months covering the most part of the AS. Sometimes the MI arrives up to Madhya Pradesh (India) as reported by Sikka et al [6]. The variation of MI is seen associated with intra - seasonal oscillation. During the break spell, it is covering whole of AS. Normally during the Monsoon season it is confined to west of 65° E.

Colon (1964) and Desai (1968) reported the findings of their works on the interaction of summer monsoon current and the sea surface over the Arabian Sea [33, 34]. The southwesterly winds are usually quite strong in the lower levels over the south/central Arabian Sea and adjoining peninsula with the maximum at the 850 hPa level, which is the reason for the inversion over the western coast of India and central Arabian Sea [5]. The dust content in the atmosphere at sometimes extends vertically almost a height of 10 km [35]. The radiational effect of the dust content is such that it induces cooling in the upper layers which results in large - scale sinking [10], thus enhance the conditions for a drier climate and a layer of inversion around 700 to 600 hPa levels. The inversion suppresses the convective activity and ascent of the moist air, thereby suppressing the cloudiness and precipitation.

In this study the characteristic features of MI during the summer monsoon mainly over the AS, Indian sub - continent and the adjoining Indian seas, are described. Table 1.1 compares the basic difference between MI and ABL.
Table 1.1. Comparison of Monsoon Inversion and Atmospheric Boundary Layer

<table>
<thead>
<tr>
<th>Property</th>
<th>Monsoon Inversion</th>
<th>Atmospheric Boundary Layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height</td>
<td>Less diurnal and daily variation.</td>
<td>Large diurnal and seasonal variation.</td>
</tr>
<tr>
<td>Strength and depth</td>
<td>Higher strength (2 - 6 K) and thickness (~1 - 1.5 km)</td>
<td>Less strength (1 - 2 K) and thickness (~100 m - 1 km)</td>
</tr>
<tr>
<td>Timing</td>
<td>Late pre - monsoon, monsoon, starting of post monsoon season</td>
<td>Throughout the year</td>
</tr>
</tbody>
</table>

1.7 ATMOSPHERIC STABILITY

The buoyancy of an air parcel depends upon the atmospheric pressure and temperature of the environmental lapse rate. When it is displaced vertically, its movement is a function of atmospheric stability. A stable atmosphere resists the vertical motion of the parcel means the parcel will come to its original position after vertical displacement.

The vertical movement of the air is characterized by four basic conditions that describe the general stability of the atmosphere viz. stable, unstable, neutral and inversion. In stable conditions, this vertical movement is discouraged, whereas in unstable conditions the air parcel tends to continue to move in the direction of displacement [36]. When conditions neither encourage nor discourage air movement beyond the rate of adiabatic heating or cooling, they are considered neutral. When conditions are extremely stable, cooler air near the surface is trapped by a layer of warmer air above it. This condition, called an inversion, allows virtually no vertical air motion. These conditions are directly related to pollutant concentrations in the ambient air [37, 38].
1.8 ATMOSPHERIC STABILITY INDICES

The stability of atmosphere is indicated with appropriate indices, Lifted Index (LI), K - index, Total - Totals index, Convective Available Potential Energy (CAPE) etc. There are many other indices, which are used by meteorologists to deal with the atmospheric processes. The following indices are related to the lower atmosphere explaining the state of the atmosphere.

1.8.1 Lapse rate

The lapse rate is defined as the rate at which air temperature changes with height in the atmosphere it is approximately 6 to 7 K / km (in troposphere). If these values become very low or negative (inversion) this becomes a case of stable atmosphere.

1.8.2 Lifted Index

Lifted Index (LI) is the temperature difference between an air parcel lifted adiabatically and the temperature of the environment. An air parcel is lifted from the surface with temperature and mixing ratios representative of the mean values of the lowest 100 hPa of the atmosphere. This is done in order to capture low level boundary layer temperature and moisture conditions while reducing diurnal effects [39].

\[
LI = T_{500} - T_{pd\ 500}
\]  --- (1.1)

where \( T_{500} \) is the temperature at 500 hPa, \( T_{pd\ 500} \) is the temperature of a parcel lifted dry adiabatically from 850 hPa to its condensation level and moist adiabatically to 500 hPa.

LI accounts for low level moisture implicitly when lifted parcel reaches saturation. The positive values represent stable and negative values unstable atmosphere.
1.8.3 K - index

The K - index arithmetically combines the 850 - 500 hPa temperature difference, the 850 hPa dew point (a direct measure of low - level moisture content), and the 700 hPa dew point depression (an indirect measure of the vertical extent of the moist layer) to help forecast continental summertime air mass thunderstorm potential [40].

\[
K = \text{Vertical Totals + lower tropospheric moisture characteristics}
\]

\[
K = (T_{850} - T_{500}) + (T_{d,850} - T_{dd,700})
\]

--- (1.2)

where \( T_{850} \) is the temperature at 850 hPa, \( T_{500} \) is the temperature at 500 hPa, \( T_{d,850} \) is 850 hPa dew point value and \( T_{dd,700} \) is 700 hPa dew point depression,

\[
T_{dd,700} = (T_{700} - T_{d,700})
\]

1.8.4 Convective Inhibition

Convective INHibition (CINH) is known as measure of the amount of energy needed in order to initiate convection [41]. CINH is the area of the sounding between parcel’s starting level and to the level at which CAPE behind to be positive [42, 43].

\[
\text{CIN} = \int_{Z_{\text{bottom}}}^{Z_{\text{top}}} \left( \frac{T_{v,\text{Parcel}} - T_{v,\text{env}}}{T_{v,\text{env}}} \right) g \, dz
\]

--- (1.3)

where \( T_{v,\text{Parcel}} \) is virtual temperature of the air parcel, \( T_{v,\text{env}} \) is virtual temperature of the environment, \( g \) is gravity.

1.8.5 Convective Available Potential Energy

Convective Available Potential Energy (CAPE) is the positive area on a sounding (the area between the parcel and environmental temperature throughout the entire sounding) [44].

\[
\text{CAPE} = \int_{Z_{f}}^{Z_{n}} g \left( \frac{T_{v,\text{Parcel}} - T_{v,\text{env}}}{T_{v,\text{env}}} \right) \, dz
\]

--- (1.4)

where \( z_{n} \) is the height of the equilibrium, \( z_{f} \) is the level of free convection.
1.8.6 Showalter Index

Showalter Index (SI) [45] is defined in terms of temperature difference:

\[ \text{SI} = T_{500} - T_{P500} \]  --- (1.5)

where \( T_{P500} \) is the 500 hPa temperature which a parcel will achieve if it is lifted dry-adiabatically from 850 hPa to its condensation level and then moist-adiabatically to 500 hPa.

This index is a function only of 850 and 500 hPa levels. It also provides an estimate of the latent instability of the layer, in that a negative value reveals the existence of positive buoyant energy above the level of free convection (LFC) and the possibility of subsequent free convection.

1.8.7 Modified K-index

The Modified K-index is similar to that of the K-Index except that instead of the \( T \) and \( T_d \) at 850 hPa, the average temperature and dew point between 850 hPa and the surface are used.

\[ \text{Modified K-index} = (T - T_{500}) + T_d + (T_{700} - T_{d700}) \]  --- (1.6)

where, \( T = (T_{sfc} + T_{850})/2 \) and \( T_d = (T_{d_{sfc}} + T_{d_{850}})/2 \)

In this index the surface values are also considered into account, so this index stand alone may be used to predict thunderstorm [46].

1.8.8 Total - Totals index

Total - Totals (TT) index is defined as

\[ \text{TT} = \text{Vertical Totals} + \text{Cross Totals Indices} \]

\[ \text{TT} = (T_{850} - T_{500}) + (T_{d850} - T_{500}) \]  --- (1.7)

It combines lower tropospheric lapse rate (doubled) + amount of moisture at low levels. It does not account for low level moisture above or below 850 hPa.
1.8.9 Mid - Tropospheric moisture Index

A new index is proposed by us in this study and named Mid - Tropospheric moisture Index (MTI). It is the ratio of total precipitable water vapour content from surface to top of the atmosphere to mid tropospheric (700 - 500 hPa) water vapour content.

\[
MTI = \frac{\text{Total Column WV Content}}{\text{Mid Tropospheric WV Content (700 - 500 hPa)}}
\]  --- (1.8)

Troposphere’s state of static stability is a steady property of the atmospheric system such that vertical displacements or disturbances introduced into the steady state will be damped, enhanced, or persist unchanged. There is no index for the low level monsoon inversion which can work over AS. In this study a ratio index based on moisture content is studied using one year data.

1.9 SATELLITE METEOROLOGY

Meteorological satellites are today the backbone of global weather observations and forecast. The first operational meteorological satellite, Television Infrared Observational Satellite - 1 (TIROS - 1), was launched by USA on 01 April, 1960 with a simple TV camera. Since then many improvements in the instruments have taken place - both by way of resolution and accuracy.

The satellites observe the surface and the atmosphere of the earth in various wavelength bands – Ultra Violet (UV), visible, infrared, microwaves etc. Most of the satellites are with passive instruments. However, in the past two decades, RADARs (RAdio Detection And Ranging) and LIDARs (LIght Detection And Ranging) have also been placed onboard. The satellites basically measure the reflected, scattered or emitted radiation from earth - atmosphere system which get modified by the atmospheric constituents. By using appropriate radiative transfer algorithms, the meteorological / oceanic parameters of relevance to weather and climate are obtained. atmospheric temperature, humidity profiles, winds, cloud cover, outgoing longwave radiation (OLR),
rainfall, sea and land surface temperatures, vegetation and snow cover, etc. are some of the operational parameters routinely available to the global community from the satellites.

There are two classes of meteorological satellites - geostationary (monitoring a particular zone, e.g. INSAT - 3D) and orbiting (which make global observations every 12 hours e.g. MetOp, NOAA, GPM etc.). Figure 1.4 shows the constellation of satellites available presently, providing a wealth of data, which are also useful for climate change studies.

**Figure 1.4.** Global operational satellites in geostationary and low earth orbits[3]
1.10 PAST EFFORTS TO UNDERSTAND MONSOON INVERSION

Some important experiments have been conducted from time to time by the scientific community to understand specific aspects of monsoon and its linkages with global circulation. Some of these International field experiments conducted of relevance to Arabian Sea aspects are: International Geophysical Year (IGY) during 1957 - 58, International Indian Ocean Expedition (IIOE) during 1963 - 66, Indo - Soviet Monsoon Experiment (ISMEX) during 1973, Monsoon - 77, Global Atmospheric Research Program (GARP) / Summer MONsoon EXperiment (MONEX) - 1979, Tropical Oceans Global Atmosphere (TOGA) during 1985 - 95 etc. Besides these International programmes, there have also been national field campaigns - Monsoon Trough Boundary Layer EXperiment (MONTBLEX) during 1989 - 90, Land Surface Process Experiment (LASPEX) during 1995 - 96, Bay of Bengal and Monsoon EXperiment (BOBMEX) during 1998 - 1999, and ARabian sea Monsoon EXperiment (ARMEX) during 2003 - 2005.

1.10.1 Experiments conducted over India and adjoining Indian Ocean

The International Indian Ocean Experiment (IIOE) during 1963 - 65 was the first field experiment to yield the large boundary layer data over the Indian region. During IIOE, observations were taken from surface and upper air observatories, ships, aircrafts, buoys. The observations from the experiment established the existence of low level atmospheric inversion over the west and central Arabian Sea that disappeared as the monsoon current approached the west coast of India [34, 47]. The boundary layer measurements were made by Bunker (1965) [48] and provided some insight into the temperature and moisture stratification and transport of moisture and sensible heat in the region, particularly north of 10° N in Arabian Sea.

In the year 1973, the Indo - Soviet Monsoon Experiment (ISMEX) was conducted over west Indian Ocean by four Russian research vessels from 19 May to 8 July. Radiosonde and RADAR data were taken onboard ships at 6 to 12 hourly intervals. Very few observations are taken below 100 m height. The ISMEX data provides vertical
thermodynamic and kinematic structure of the boundary layer in the west Indian Ocean during Indian summer monsoon.

GATE (GARP (Global Atmospheric Research Program) Atlantic Tropical Experiment) was the first large scale international field experiment of GARP conducted during 1974 to study the energetic and dynamics of cloud clusters that drift from the African continent over the Atlantic Ocean to cause the ITCZ convection. The experiment was organized by the World Meteorological Organization (WMO) and conducted by various nations.

MONEX (MONsoon EXperiment) was designed as part of the First GARP Global Experiment (FGGE) from 1 December 1978 to 30 November 1979 to cover the Arabian Sea, Bay of Bengal, Indian Ocean and southeast Asia. Its two main component programs are a) the summer MONEX programme to study the summer monsoon over India and neighbourhood during 1 May to 31 July 1979 and b) the winter MONEX programme to study the winter monsoon over Indonesia - Malaysia region during 1 December 1978 to 5 March 1979. One of the geostationary GOES satellites of US was shifted over the Indian Ocean for a year during FGGE / MONEX. Study of the interactions between the SW monsoon and the ABL was the one of topics of research since the IIOE. One of the three major objectives of MONEX was understanding the monsoon inversion over the Arabian Sea. During the IIOE, MI was studied over the AS by placing an instrumented buoy. MONEX - 1979 campaign was also conducted over the whole AS using special techniques and instruments. Over the AS near surface winds are strong and the surface is rough that both the sea surface and the lower troposphere monsoon are exchanging fluxes of momentum, latent heat and sensible heat in more energetic manners [5]. The summer MONEX was conducted in two phases. The first phase covered the Arabian Sea and the second phase covered the Bay of Bengal. The experiment provided a better data set than that had ever been collected before in the Indian Monsoon region. The boundary layer over the Arabian Sea was further investigated by Pant [49, 50] and Ramanthan [51] using the Indo - Soviet Monsoon Experiment ISMEX - 78. Monsoon - 77, MONEX - 79 and Monsoon - 88 gave further insight into the AS marine boundary layer. The boundary layer in the large - scale monsoon air stream encounters strong interactions across the highly
complex surfaces of the ocean and solid landmass over which it flows. The earlier experiments focused on the marine ABL.

To study the ABL over the Indian monsoon trough region wherein for four months from June to September every year organised moist convection prevails over the sub continental scale, a large - scale field experiment was conducted. The experiment was called Monsoon Trough Boundary Layer Experiment (MONTBLEX) and was conducted from 1987 to 1990. It was conducted to understand the variability of the atmospheric as well as marine boundary layer in relation to monsoon trough over the land and northern Bay of Bengal. A pilot experiment was carried out at Kharagpur during 1 - 7 July 1989. Slow and fast response tower instruments, minisonde and humidity instruments were used in the experiment. The full field experiment began from March 1990 and made use of four towers at Varanasi, Delhi, Jodhpur and Calcutta, Doppler sodar and monostatic sodar, tethered balloons, minisonde, surface and upper air observations, Aircraft flights, special cruise of Ocean Research Vessel (ORV) Sagarkanya during August - September 1990 over North Bay of Bengal, INSAT pictures and weather radar observations in the India Meteorological Department (IMD) network. Observations were taken during all types of weather situations. The experiment collected vast amount of data over a vast region, which will continue to be analysed for a long time revealing various features of the Indian monsoon.

Bay Of Bengal and Monsoon EXperiment (BOBMEX) was conducted under the Indian Climate Research Program (ICRP) in the Bay of Bengal in 1999. The aim was to study the air - sea interactions and intraseasonal oscillations in the Bay of Bengal during the summer monsoon using new types of measurements from ships and met - ocean buoys. This was a national program and used several advanced sensors and instruments onboard ship. The pilot experiment was carried out on board ORV Sagarkanya. The experiment arrangement consisted of sensors mounted on a micrometeorological tower fixed on a boom, rain gauge placed on the upper deck of the ship, a GPS receiver, minisonde system signal conditioners, data logger and Pentium based data acquisition and processing system.
ARMEX was latest experiment conducted Eastern Arabian Sea (EAS) during summer monsoon 2002 - 2005. Important results came out as suggested by Bhat [52] that Normally, SST is warmer than that of the air above over the tropical ocean, and transfer of heat is from sea to atmosphere. During the ARMEX period, measurement shows even under strong monsoonal winds, air temperature can remain warmer than that of the surface below.

Thus from the 1980s scientific community is working for understanding the linkages between Monsoon process and MI. This is well known fact that during increased instability in the ABL during weak/break monsoon influenced under suppressed condition and decreased instability under active monsoon and organized convective conditions. Thus the stability plays a major role in the formation of the MI and this MI is affecting the monsoon over the country. Very few experiments are carried out to study the structure and characteristics of the boundary layer over the land locked tropics especially the monsoon boundary layer over the Indian monsoon region. The monsoon flow in its course over India passes over areas of torrential rain and over mountain complexes where its properties are modified due to planetary, regional and local weather systems and the varying topographical features.

1.11 RATIONALE FOR RESEARCH IN MONSOON INVERSION

One of the fundamental reasons for investigating low level inversion over Arabian Sea is that the region represents a notable gap in the understanding of Indian summer monsoon. Arabian Sea inversion has seen relatively less investigated compared to other aspects of Indian summer monsoon. Only during MONEX - 1979, nearly four decades ago, a wealth of in situ observations over the whole of Arabian sea was collected.

With the availability of satellites with better horizontal, vertical and spectral resolutions and with a vast improvement in data assimilation methods providing better reanalysed data sets in the last decade, it has become possible now to study this phenomena in more detail including its interannual / intraseasonal variabilities.
1.12 RESEARCH QUESTIONS

We have set about the task by asking a few basic questions on monsoon inversion.

**How to detect the Monsoon Inversion from satellite data?**

Satellite instruments have a limitation to detect temperature variations over short vertical intervals vis a vis radiosonde observations, to document the monsoon inversion in detail, the primary objective was to delineate them from the operational satellite data and validate with in situ observations.

**What are the characteristics of Monsoon Inversion over the Arabian Sea?**

The next important step is to understand when and where they form, how long they last and know their temporal and spatial variations.

**What are the mechanisms responsible for inversion formation and maintenance?**

There are several causes of inversion formation. The understanding to date indicate that both subsidence and advection have an important role in MI formation and maintenance. Our main objective in this work is to clearly distinguish their respective roles. The above objectives have been addressed in this work in three chapters dealing with the results of analysis of satellite and Reanalysis data.

1.13 Thesis Structure

- **Chapter 2** - Sources of Data: An explanation of the various data sets used and instruments / Model Analysis providing them.

- **Chapter 3** - Observation of Thermal Inversion from radiosonde and IASI: detection, classification and validation of inversion from IASI data is carried out with in - situ radiosonde data.

- **Chapter 4** - Characteristics of Monsoon Inversion over Arabian Sea: A detailed investigation of the low level inversion over the AS for all datasets used is carried
out. A composite analysis for the inversion is done in this chapter like climatology of strength, height and percentage of occurrence. Inversion strength in relation to overall monsoon performance is also studied.

- **Chapter 5** - Mechanism of formation and maintenance of Monsoon Inversion: Diagnostics from ERA - Interim is carried out. Subsidence and advection influences have been quantified.

- **Chapter 6** - Summary and Conclusions: The highlights of the investigation on MI from our study are summarized. The main conclusions are listed with a brief description of scope for future work in this area.