”Understanding integrated moisture transport in the monsoon domain”

A Thesis

submitted to
Indian Institute of Science Education and Research Pune
in partial fulfillment of the requirements for the
BS-MS Dual Degree Programme

by

Dilip.V

Indian Institute of Science Education and Research Pune
Dr. Homi Bhabha Road,
Pashan, Pune 411008, INDIA.

April, 2019

Supervisor: Dr.Neena Joseph Mani

Certificate

This is to certify that this dissertation entitled **”Understanding integrated moisture transport in the monsoon domain”** towards the partial fulfilment of the **BS-MS** dual degree programme at the **Indian Institute of Science Education and Research, Pune** represents study/work carried out by Dilip.V at Indian Institute of Science Education and Research under the supervision of **Dr.Neena Joseph Mani**, Assistant Professor, Department of Earth and Climate Science , during the academic year 2018-2019.

Supervisor: Dr.Neena Joseph Mani

Committee:

Name of your Guide: **Dr.Neena Joseph Mani**

Name of your TAC: **Dr.Swapna Panickal**

This thesis is dedicated to my teachers, family and friends.

Declaration

I hereby declare that the matter embodied in the report entitled **"Understanding integrated moisture transport in the monsoon domain"** are the results of the work carried out by me at the **Department of Earth and Climate Science, Indian Institute of Science Education and Research, Pune,** under the supervision of **Dr.Neena Joseph Mani** and the same has not been submitted elsewhere for any other degree.

Dilip

Student: Dilip.V

Supervisor: Dr.Neena Joseph Mani

Acknowledgments

First and foremost, I would like to thank Dr.Neena Joseph Mani for her priceless guidance from the past three years at IISER as a mentor and as a well-wisher. She was always approachable and friendly to discuss anything, be it academics or personal. It was through my sheer luck that she became my mentor and I am glad that she provided me with an opportunity to work in my field of interest at my own pace. There were numerous occasions where she made me realise that I was being an ignorant, overconfident simpleton and advised me to be a better person and work towards staying on course and achieving my goals. I took her advice seriously to improve myself and it has helped me keep a certain discipline in life as well as in academics. I have nothing but gratitude and always will be indebted to her for guiding me.

I would also like to thank Dr.Swapna Panickal for her valuable suggestions during my Mid Year evaluation to help improve my results.

Also, I would like to thank Dr.Suhas Ettamal for his helpful remarks that improved my results.

It would be criminal to not thank my lab members who helped me learn everything that is related to my work and I am always grateful to them for being so.

I would also like to thank the Department of Science and Technology(DST), Ministry of Science and Technology, GoI for providing me with the necessary scholarship to pursue this degree.

Finally, I would like to thank my family and friends who have supported me throughout my life at IISER like always.

Abstract

The identification of intense moisture pathways during the South Asian monsoon has been carried out using an algorithm developed by Yang et al(2018) over the Bay of Bengal and modifying it to identify similar pathways over the Arabian Sea. Using the Integrated Vapour Transport(IVT) fields, the moisture pathways of the low-level jet stream(LLJ) during monsoon that is known to split into two branches namely, the Arabian Sea branch and the Bay of Bengal branch, has been traced and quantified to determine their contributions to the Indian region. The column integrated moisture anomalies were used to understand the buildup of moisture before an active and a break condition over different regions of the monsoon domain.

Contents

Abstract **xi**

List of Figures **1**

1 Introduction **3**

2 Column integrated moisture anomalies over the monsoon domain during active & break conditions **5**

2.1 Data 6

2.2 Identification of active and break condition 6

2.3 Precipitable Water anomalies during Active and Break conditions 8

3 Methodology for detecting atmospheric water vapour transport paths **13**

3.1 Data 13

3.2 Workflow of the algorithm 14

4 Quantifying the moisture contributions of LLJ during monsoon **23**

4.1 Contribution of moisture from both branches of LLJ 23

4.2 Relationship between the DMI and IVT in the two branches of LLJ 26

4.3 Verifying the moisture sources for various regions in the monsoon domain . . 27

5 Conclusions **29**

List of Figures

2.1 The red, yellow and green boxes over Indian subcontinent indicate the Southern Peninsula(9N-22N & 72E-76E), Central(16N-26N & 76E-84E) and Northeastern(21N-26N & 84E-96E) India. The lines across the boxes represent the latitude(24N) and longitude(73.5E) used in flux calculations(refer chapter 3). 6

2.2 10-90 day filtered rainfall anomalies (mm/day) composited for active and break days over (a) South Western India,(b) North Eastern India and (c) Central India. 7

2.3 Left panel 10-90 day filtered precipitable water (shaded, Kgm^{-2}) and 850 hPa wind anomalies (vectors, ms^{-1}) composited for 0, 2, 5, 8, 10 days prior to an active day over South Western India. The right panel shows the evolution of the precipitable water and wind anomalies leading to a break condition over South Western India. 10

2.4 Left panel 10-90 day filtered precipitable water (shaded, Kgm^{-2}) and 850 hPa wind anomalies (vectors, ms^{-1}) composited for 0, 2, 5, 8, 10 days prior to an active day over South Western India. The right panel shows the evolution of the precipitable water and wind anomalies leading to a break condition over Northeast India. 11

2.5 Left panel 10-90 day filtered precipitable water (shaded, Kgm^{-2}) and 850 hPa wind anomalies (vectors, ms^{-1}) composited for 0, 2, 5, 8, 10 days prior to an active day over South Western India. The right panel shows the evolution of the precipitable water and wind anomalies leading to a break condition over Central India. 12

3.1 Workflow of the algorithm used in detection of ARs. [Source: Yang et al(2018)] 14

3.2 Seasonal mean IVT for winter(DJF), spring(MAM), summer(JJA), autumn(SON) and monsoon(JJAS). 16

3.3 The monthly IVT thresholds for various reference latitudes of ARs over Bay of Bengal is shown in (a) and for various reference longitudes of ARs over Arabian Sea(b). 17

3.4 The AR axes for identified ARs on 12 November 2002 over Bay of Bengal(a) and on 21 June 1997 over Arabian Sea(b). 18

3.5 Moisture pathway composites over Bay of Bengal(a) and Arabian Sea(b). The IVT intensity $< 300\ Kgm^{-1}s^{-1}$ are not shown in the raster plot. 19

3.6 Some of the moisture transport paths identified over Bay of Bengal. The IVT is shown as contours and 850hPa wind as vector in ms^{-1}. 20

3.7 Some of the moisture transport paths identified over Arabian Sea. The IVT is shown in contour and 850 hPa wind in vector in ms^{-1}. 21

4.1 Seasonal mean(JJAS) IVT for the Arabian Sea(red) and the Bay of Bengal(blue) branches for the period 1979-2011. 24

4.2 A cartoon representation of Indian Ocean Dipole.[Source: E. Paul Oberlander, Woods Hole Oceanographic Institution] 25

4.3 Seasonal mean(JJAS) DMI index plotted along with normalised IVT anomalies(Thick black line) for both the branches of LLJ. 26

4.4 The correlation between IVT intensity of Arabian Sea branch and Precipitable Water over South Western India(a) and Central India(b), also correlation between IVT intensity of Bay of Bengal branch and Precipitable Water over North East India(c) and Central India(d) for JJAS months of each year from 1979-2011. 27

Chapter 1

Introduction

The South Asian summer Monsoon is a strongly coupled atmosphere-ocean system which represents a strong mode of variability in the global circulation. To study the monsoon as a system, a thorough understanding of the sources and sinks of its moisture supply is necessary. The major source of moisture for the monsoon is the evaporation of surface water from the northern Indian Ocean, the Arabian Sea and the Bay of Bengal, which is picked up and transported by lower level westerly jet(LLJ) stream into the region extending from western India to the north of Bay of Bengal called as monsoon trough. The low-level jet stream comprises of relatively strong winds that blow over the surface mainly restricted to the lower troposphere(winds from 850hPa to surface level) (Goswami(2005)(1)). The objective of this study is to provide a quantitative understanding of the moisture transport during monsoon and determine its relationship with the precipitation along Western Coast, Central India and the North Eastern region of India. It has been observed that the intense LLJ splits into two branches during monsoon, one makes landfall along the Western Coast of India which we refer to as the Arabian Sea Branch and the other making landfall along the Bay of Bengal coast, as the Bay of Bengal Branch and both these branches eventually converge over the monsoon trough. The active and break conditions of the rainfall that occurs during monsoon are driven by the large scale oscillations of the Inter-Tropical Convergence Zone. For predicting the intensity and duration of these events, understanding the nature of the relationship between moisture transport and precipitation is necessary.

While the tropics and the mid-latitudes are known to be under prevailing winds of different direction and the weather systems are driven by different dynamics, intense precipitation events (in the form of rain or snow), in the mid-latitudes, often have their source of moisture in the tropics (David & Villarini(2013a)$^{(3)}$). The regions of long, narrow and intense moisture transport that carry an enormous amount of water vapour from tropics to mid-latitudes are are known as atmospheric rivers(ARs) and has been a major research topic in recent years (Yang et al (2018)$^{(2)}$,Neiman PJ & Ralph FM(2009)$^{(4)}$). The enhanced water vapour transport associated with the ARs are responsible for more than 90and subtropics to the higher latitudes (Zhu & Newell(1998)$^{(6)}$; Ralph & Dettinger(2011)$^{(7)}$). These ARs have typical dimensions with width $<$ 1000 km and length $>$ 2000 km in the mid-latitudes. Algorithms developed for detecting ARs has helped unravel the moisture source for events like heavy snowfall over the Western coast of USA and floods caused by heavy rainfall over Great Britain(Lavers & Villarini(2012)$^{(8)}$, Neiman P J et al(2009)$^{(4)}$). While the ARs are particularly relevant for the mid-latitude weather events, the methodology for detecting moisture source can be useful for understanding tropical rain events as well. Yang et al (2018)$^{(2)}$, used a modified AR detection algorithm for understanding the moisture transport in the tropics, which was used to study the association between extreme rainfall events over Northern India and the moisture transport from the Bay of Bengal. In this study, to understand the nature of moisture transport associated with the two branches of the monsoon, we adopt the methodology followed by Yang et al (2018), with some modifications.

For calculating the amount of moisture that is transported by each branch of the LLJ, we have utilised the integrated vapour transport fields used in the AR detection algorithm to quantify moisture transport during monsoon months and explored its relationship with Indian ocean dipole and precipitable water over monsoon domain. Since, the rainfall intensity over any region is dependent on the availability of moisture in the atmosphere, we tried to understand the influence of availability of moisture on the rainfall during active and break conditions of monsoon by analysing the precipitable water anomalies over the different regions of monsoon domain. Here we have done a comparitive study of the composites of precipitable water(PW) anomalies during the active and break conditions over monsoon domain to understand the accumulation of moisture in the region.

Chapter 2

Column integrated moisture anomalies over the monsoon domain during active & break conditions

The monsoon season is marked by recurring periods of incessant rainfall called active conditions, followed by lull phases of no rainfall activity called break conditions. The active-break cycles of monsoon rainfall are driven by the large-scale oscillations of the oceanic Inter-tropical Convergence Zone (ITCZ) between the equatorial position and the continental position over the monsoon region with a periodicity of 30-60 days. Since the rainfall intensity over any region is dependent on the availability of moisture in the atmosphere, the precipitable water anomalies over the monsoon domain during active and break conditions we analysed. Following the northward movement of the ITCZ and taking into account the differences in precipitation characteristics over different parts of the monsoon domain, evolution of the precipitable water anomalies leading up to active/break conditions over i) Central India(16N-26N,76E-84E), ii) Southern Peninsular region (8N-22N,72E-76E) and iii) Northeastern India(21N-26N,84E-96E) were analysed.

The precipitable water(PW) or column integrated moisture is defined as the total amount of water vapour present in the atmospheric column and calculated as

$$PW = \frac{1}{g}\int_{1000}^{300} q\,dp \tag{2.1}$$

measured in Kgm^{-2} where *'q'* is specific humidity, *'dp'* is difference between the two adjacent pressure levels which is integrated from 1000hPa to 300hPa and *'g'* is the acceleration due to gravity.

2.1 Data

Daily averaged specific humidity and zonal and meridional wind fields at 1.5 spatial resolution for the period 1979-2004 were obtained from the ERA-Interim reanalysis. IMD gridded daily rainfall data at 1 spatial resolution was used for identifying the active/break periods during the June-September monsoon season from 1979-2004.

2.2 Identification of active and break condition

For identifying the active and break days over a particular region, we adopted a method followed by Rajeevan (2010)$^{(5)}$ that defines an active condition as the days which have rainfall anomalies greater than 1 standard deviation for at least three consecutive days and break condition as the days which have rainfall anomalies lesser than 1 standard deviation for at least three consecutive days. The rainfall data were pre-processed by calculating the daily anomalies by removing the climatological mean and a 10-90 day filter was then applied to remove the synoptic scale variability. For each season, the fil-

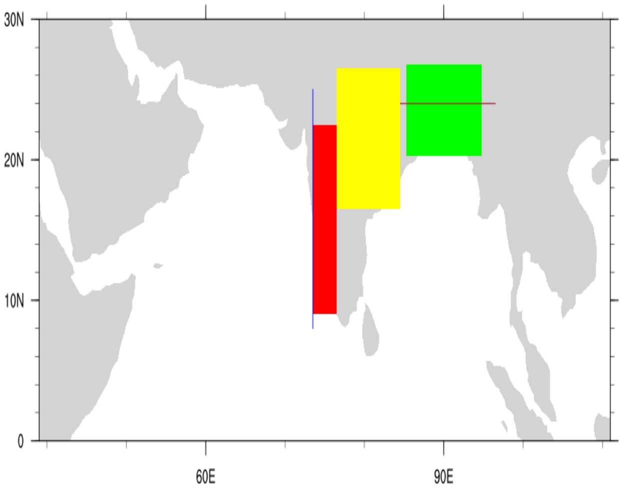
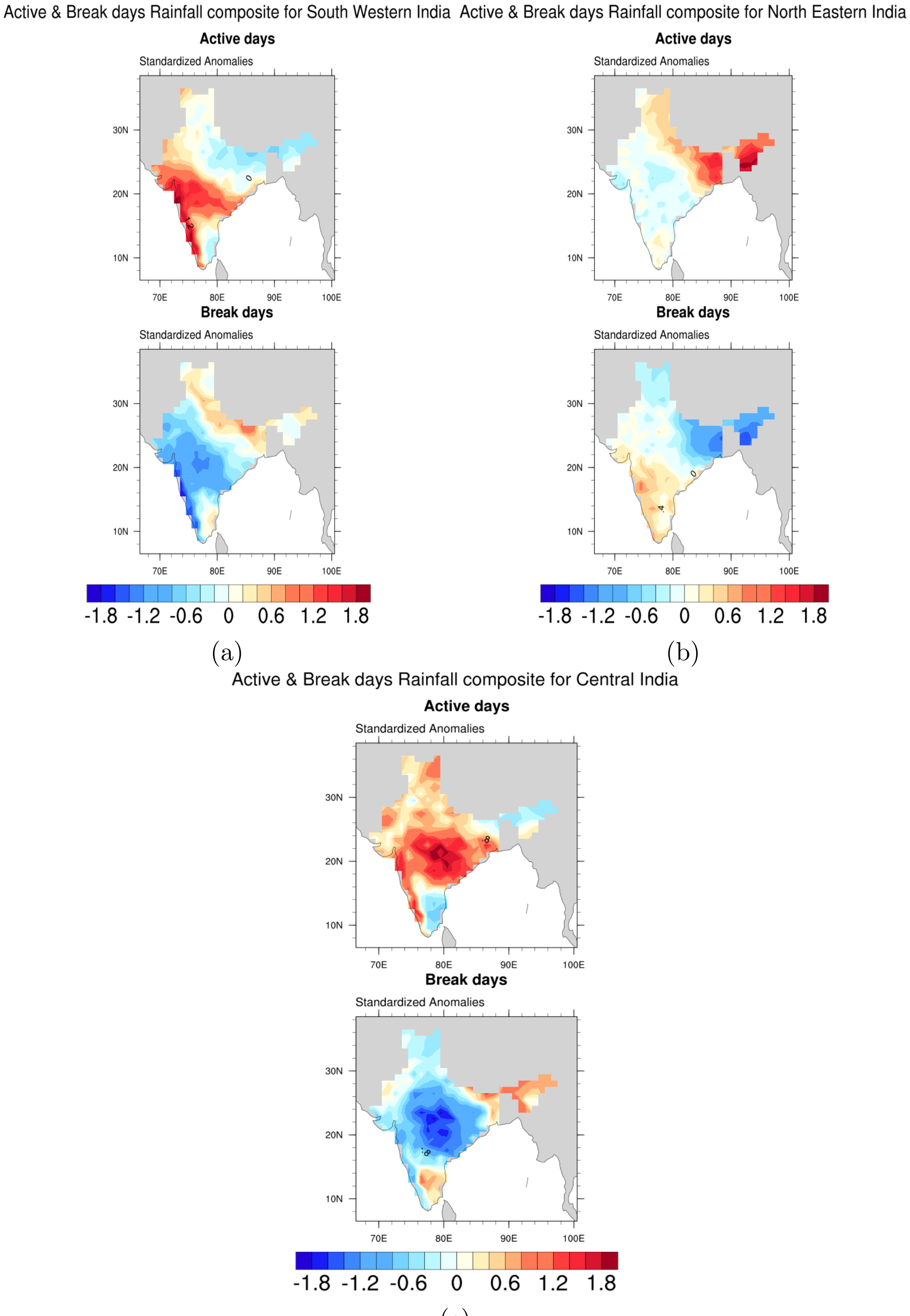


Figure 2.1: The red, yellow and green boxes over Indian subcontinent indicate the Southern Peninsula(9N-22N & 72E-76E), Central(16N-26N & 76E-84E) and Northeastern(21N-26N & 84E-96E) India. The lines across the boxes represent the latitude(24N) and longitude(73.5E) used in flux calculations(refer chapter 3).



(a) (b) (c)

Figure 2.2: 10-90 day filtered rainfall anomalies (mm/day) composited for active and break days over (a) South Western India,(b) North Eastern India and (c) Central India.

tered rainfall anomalies were normalized by dividing through its seasonal standard deviation. The standardized anomalies were then area averaged over the different regions as shown in the **Figure 2.1** Southwestern India(red), Central India(yellow) and Northeastern India(green) to obtain active and break days. The precipitable water anomalies were also pre-processed in the same manner.

If we look at the precipitation during the active and break days for the different study regions, we can clearly see the northward propagation of the ITCZ. **Figure 2.2(a)** shows the composite of rainfall anomaly over South Western India during active and break conditions. In the active composite, we observe positive rainfall anomalies over the Western Ghats and parts of peninsular India and negative rainfall anomalies over the Northern India and South East of the peninsula. In the break composite, we observe negative anomalies over Western, parts of Central and Southwestern India and positive anomalies over foothills of Himalayas. **Figure 2.2(b)** shows the composite of rainfall anomaly over North Eastern India for active and break conditions. For an active day, we observe the entire North East Indian region has a positive anomaly and parts of Central India have a negative anomaly. For a break day, the entire North Eastern region show a negative anomaly and parts of southwestern India show a positive anomaly. Monsoon in these two regions is largely modulated by the orographic effect of the Western Ghats and the Northeast mountain ranges. Monsoon precipitation over Central India, on the other hand, is more homogenous as it is not influenced by orography. During an active condition over the Central Indian region (**Figure 2.2(c)**) negative rainfall anomalies are observed over North Eastern India and South Eastern side of the Indian peninsula and during break days we observe positive anomalies over the same regions.

2.3 Precipitable Water anomalies during Active and Break conditions

To understand the source and build-up of moisture prior to the development of an active/break day in a region over the monsoon domain, we now look at the evolution of precipitable water and 850 hPa wind anomalies over the region. The following figures shows the composites of precipitable water (plotted as contours) and 850hPa winds (plotted as vectors) during and at 2, 5, 8 and 10 days prior to the development of an active or break condition over South Western India(**Figure 2.3**), North Eastern India(**Figure 2.4**) and

Central India(**Figure 2.5**).

For the active condition over South Western India(Left panel in **Fig 2.3**), we observe the evolution of moisture accumulation with a strong counter-clockwise(positive vorticity) wind anomalies indicating a low-pressure centre around the region originating from the western Bay of Bengal a week before an intense active day. The LLJ westerlies bring in moisture into the region from the Western Indian Ocean and Arabian sea. The easterlies bring in moisture from Northern Bay of Bengal. For the break condition(Right panel in **Fig 2.3**), we observe a strong clockwise(negative vorticity) wind anomalies indicating a high pressure region that originates from the northern part of Arabian Sea around a week before an intense break day that tends to severely deplete the moisture from the region and also the LLJ westerlies have weakened and reversed their direction.

For the active condition over Northeast India(Left panel in Fig 2.4), we observe development of a clockwise(negative vorticity) wind anomalies a few days before an intense active day indicating a high pressure region over Bay of Bengal that intensifies the westerly winds over the Northern Bay of Bengal which accumulates moisture over the region due to obstruction of flow from the Himalayas. The major source of moisture for the region is derived from Northern Bay of Bengal. During break condition(Right panel in Fig 2.4), there is a development of anti-clockwise(positive vorticity) wind anomalies over the Bay of Bengal indicating a low pressure center few days prior to an intense break day that enhances the easterlies over Northern Bay of Bengal which tend to deplete the moisture over the region and enhance over the southern peninsula.

For the active condition over Central India(Left panel in Fig 2.5), we observe two prominent counter-clockwise(positive vorticity) wind anomalies indicating two low pressure centers,one originating over the Arabian Sea and the other over western Bay of Bengal eventually merging to form a single low pressure center over the Central Indian region 2-3 days before an intense active day. During the intense active day, the moisture over Central India is derived from the Arabian Sea, Western Indian Ocean and the Bay of Bengal brought by the strong southwesterly LLJ that reverses during break condition. During break condition(Right panel in Fig 2.5), we observe a clockwise(negative vorticity) wind anomalies that indicate high-pressure region originating over Northern Bay of Bengal and moving inland onto Central India. The northwesterlies over Northern India drives the moisture away from the region and accumulate in Northeastern India.

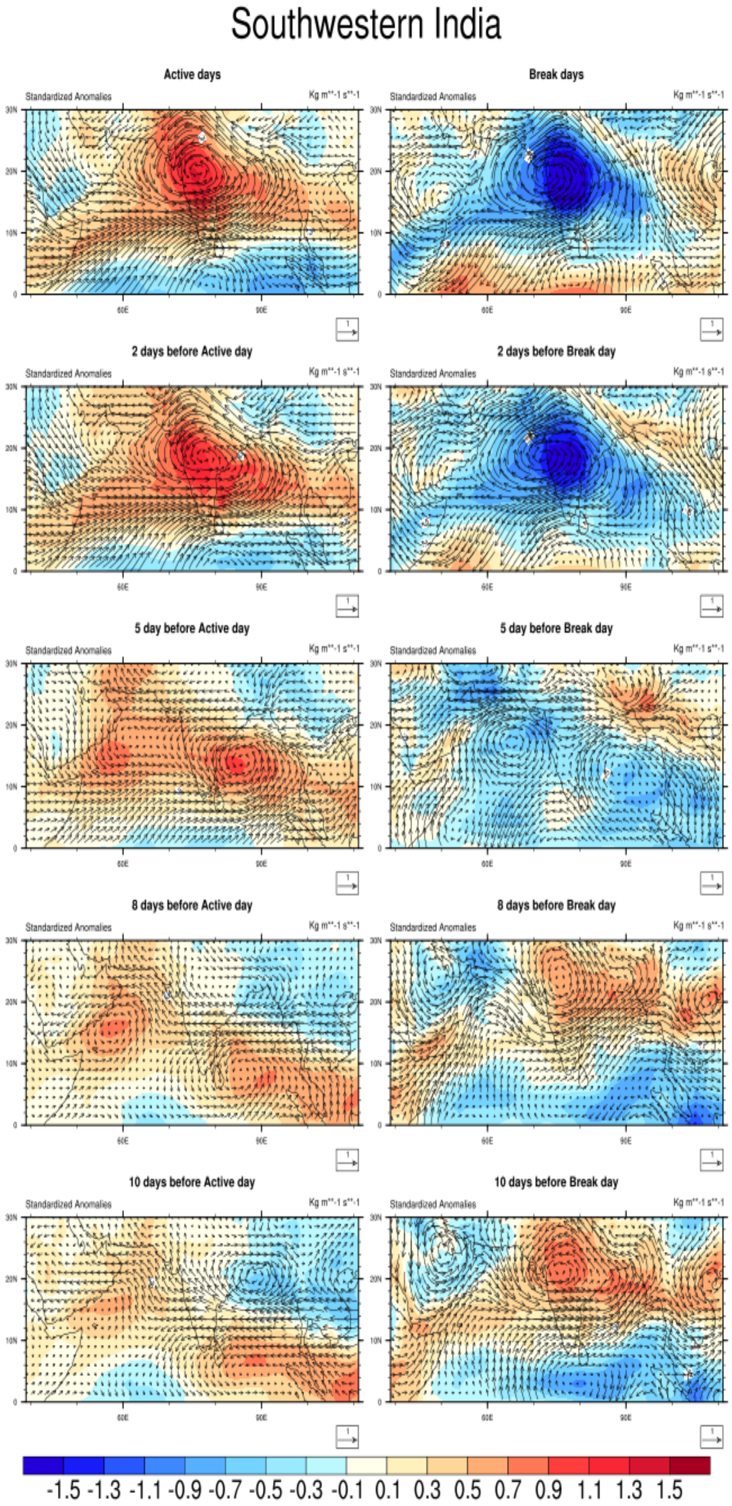


Figure 2.3: Left panel 10-90 day filtered precipitable water (shaded, Kgm^{-2}) and 850 hPa wind anomalies (vectors, ms^{-1}) composited for 0, 2, 5, 8, 10 days prior to an active day over South Western India. The right panel shows the evolution of the precipitable water and wind anomalies leading to a break condition over South Western India.

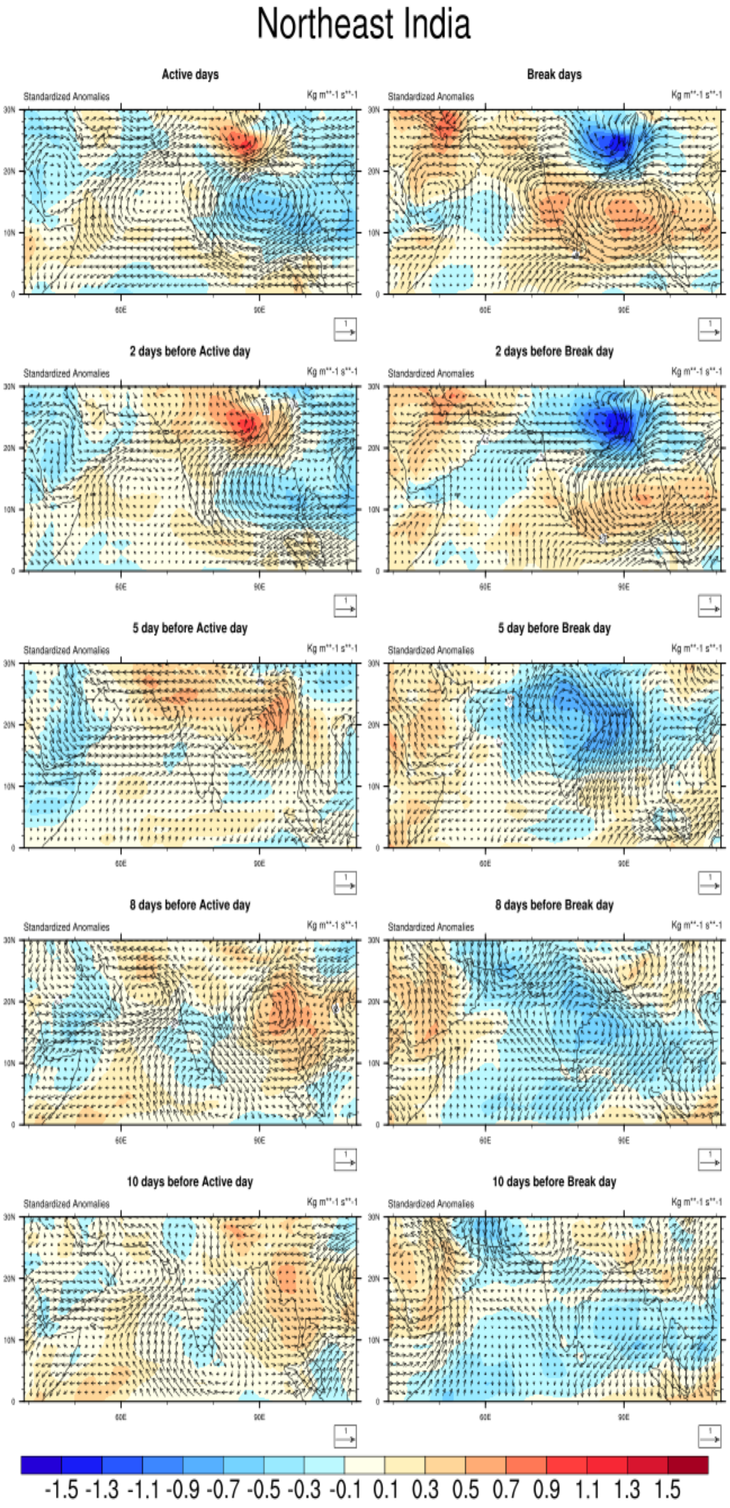


Figure 2.4: Left panel 10-90 day filtered precipitable water (shaded, Kgm^{-2}) and 850 hPa wind anomalies (vectors, ms^{-1}) composited for 0, 2, 5, 8, 10 days prior to an active day over South Western India. The right panel shows the evolution of the precipitable water and wind anomalies leading to a break condition over Northeast India.

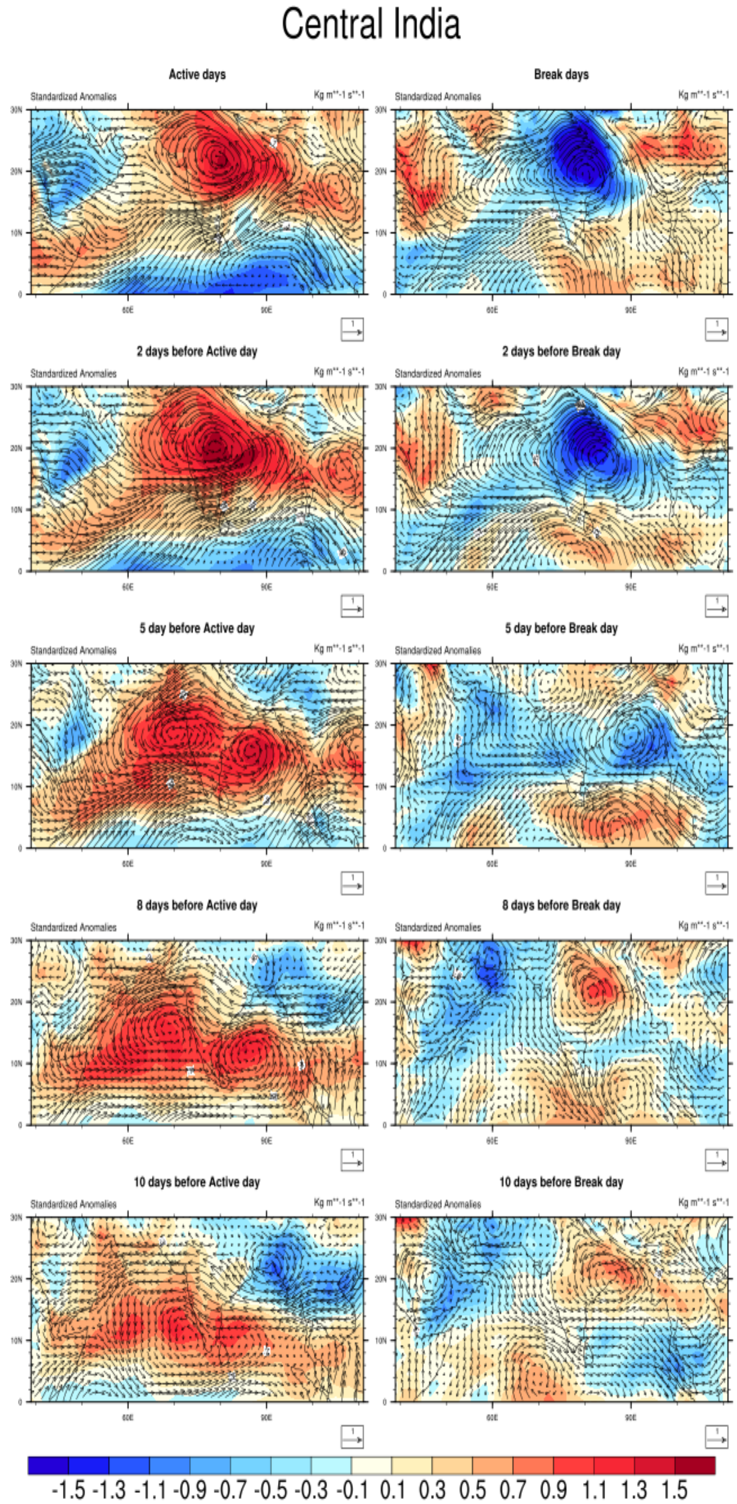


Figure 2.5: Left panel 10-90 day filtered precipitable water (shaded, Kgm^{-2}) and 850 hPa wind anomalies (vectors, ms^{-1}) composited for 0, 2, 5, 8, 10 days prior to an active day over South Western India. The right panel shows the evolution of the precipitable water and wind anomalies leading to a break condition over Central India.

Chapter 3

Methodology for detecting atmospheric water vapour transport paths

For understanding the moisture transport occurring within the South Asian region, we followed Yang et al(2018) methodology and modified it to trace the water vapour transport associated with the two branches of the monsoon flow. The methodology followed by Yang et al (2018) is an extension of the AR detection algorithm developed by Lavers and Villarini(2013*a*)$^{(8)}$. Details of how we adopted the AR detection algorithm to study the moisture transport associated with the monsoon Arabian Sea branch and Bay of Bengal branch is provided in this chapter.

3.1 Data

The main data set used in capturing the moisture transport events is the ECMWF's Era Interim daily dataset with a temporal resolution of 1.5 degrees, from 1979 to 2011. Since we are only studying the moisture transport events during the Indian summer monsoon, data is trimmed for the months May to September. Specific humidity and zonal and meridional wind fields at vertical levels from 1000 hPa to 300hPa levels were used in the modified AR detection algorithm.

3.2 Workflow of the algorithm

The algorithm utilizes the Integrated horizontal Vapour Transport(IVT) field defined by **Equation 3.1**

$$IVT = \frac{1}{g}\sqrt{(\int_{1000}^{300} qudp)^2 + (\int_{1000}^{300} qvdp)^2} \tag{3.1}$$

The IVT measures total horizontal moisture flux passing through an atmospheric column($Kgm^{-1}s^{-1}$) where q is the specific humidity,u and v are the zonal and meridional wind speeds, g is the acceleration due to gravity and dp is difference in pressure between two adjacent pressure levels.

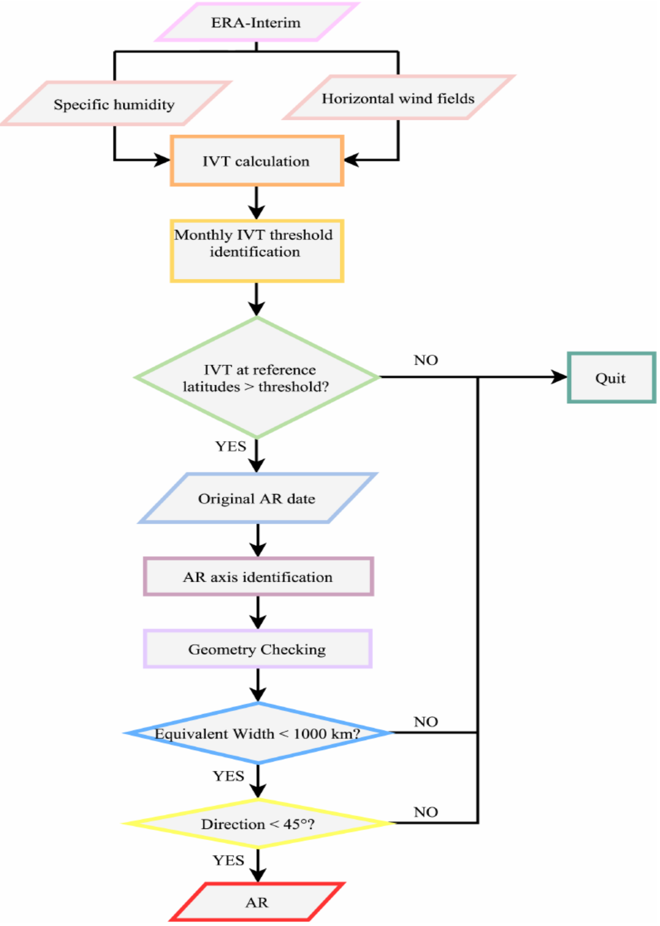


Figure 3.1: Workflow of the algorithm used in detection of ARs. [Source: Yang et al(2018)]

Figure 3.1 shows the workflow of the algorithm used in the detection of ARs (Yang et al 2018). For each month during the monsoon season, the IVT was estimated at every grid point over the monsoon domain (lat&lon) using **Equation 3.1**. Since the AR detection algorithm basically backtraces the water vapour path with respect to a landfall region, a reference latitude/longitude was defined based on the climatological position of a) the Low-level Jet stream crossing the Western Ghats (73.5 E and 75 E) for the Arabian sea branch and b) the latitude of the Head bay of Bengal (24N and 27N) for the Bay of Bengal branch.

The changes in the IVT intensity for different seasons in the South Asian region can be seen in the **Figure 3.2**. The months of autumn(SON) have meridional moisture transport occurring over the Bay of Bengal that brings in more water vapour into the North East India and Bangladesh region. During the monsoon months(JJAS), the moisture transport from the Bay of Bengal is very intense and the direction of transport, for the most part, is eastward(zonal) but a part of this moisture penetrates inland into the Indian subcontinent increasing the water vapour content in the region. The monsoon months(JJAS) have intense transport occurring in both the branches of the LLJ. It is interesting to note that the moisture transport over the Arabian Sea towards the Indian region intensely occurs only during monsoon.

Since we observe from **Figure 3.2** that there is an intra-annual variability in the IVT-intensity, monthly IVT strength thresholds were to be determined. They were calculated by taking the maximum value of daily IVT values at reference latitudes 24N & 27N(longitudes 73.5E & 75E) and regrouping them by month. Then the 85^{th} percentiles of each group is determined as the monthly thresholds. Apart from determining the thresholds, the reference latitudes(longitudes) were used to locate the endpoints of the AR axis. The chosen reference latitudes(longitudes) were sufficient enough to cover all the ARs present in the study region.

The **Figure 3.3 (a)** & **(b)** represents the variation of IVT intensity threshold for ARs over Bay of Bengal and Arabian Sea respectively. In **Figure 3.3(a)**, the distribution of monthly IVT thresholds is strongly influenced by monsoon as we can see the intensity is highest during monsoon months of JJAS and lowest during the autumn(SON) and winter(DJF) months. The seasonality in IVT threshold is apparent with annual peak in July for all reference latitudes over northern India reaching greater than 600 $Kgm^{-1}s^{-1}$.

In **Figure 3.3(b)**, the distribution of monthly IVT thresholds is also strongly influenced by monsoon as the moisture flux reaches a maximum during the months of JJAS and reaches a minimum during winter(DJF) and early spring(March & April). The slight increase in the intensity during November over inland can be attributed to the retreating monsoon winds that bring moisture from the Bay of Bengal into the southern peninsular region. As the winter progresses, the northeasterly winds weaken and moisture present in the south peninsular

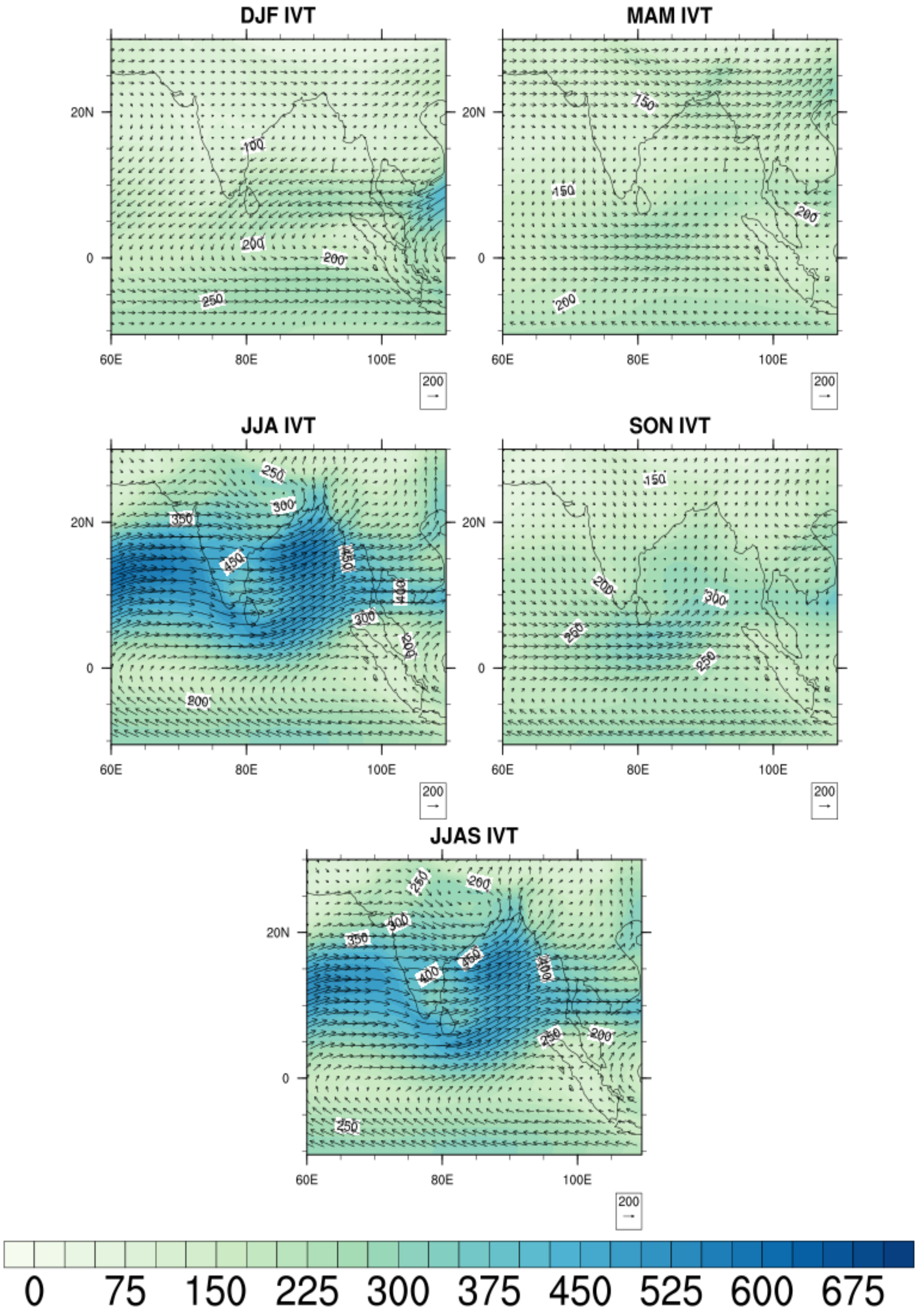
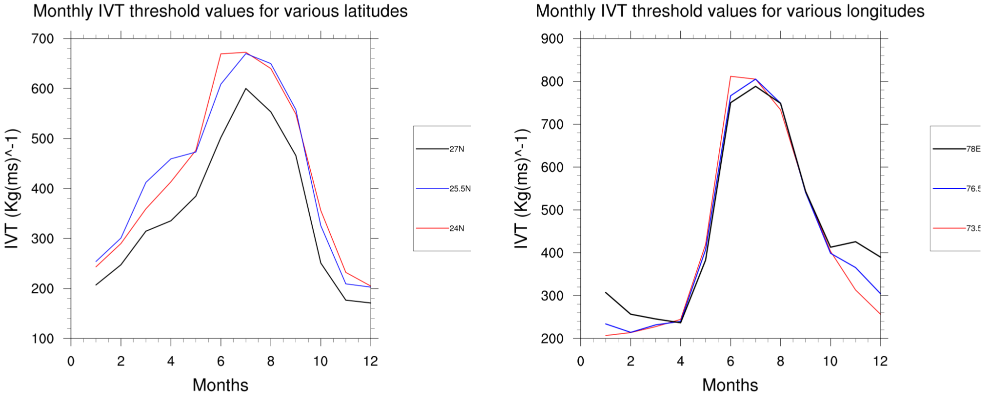


Figure 3.2: Seasonal mean IVT for winter(DJF), spring(MAM), summer(JJA), autumn(SON) and monsoon(JJAS).



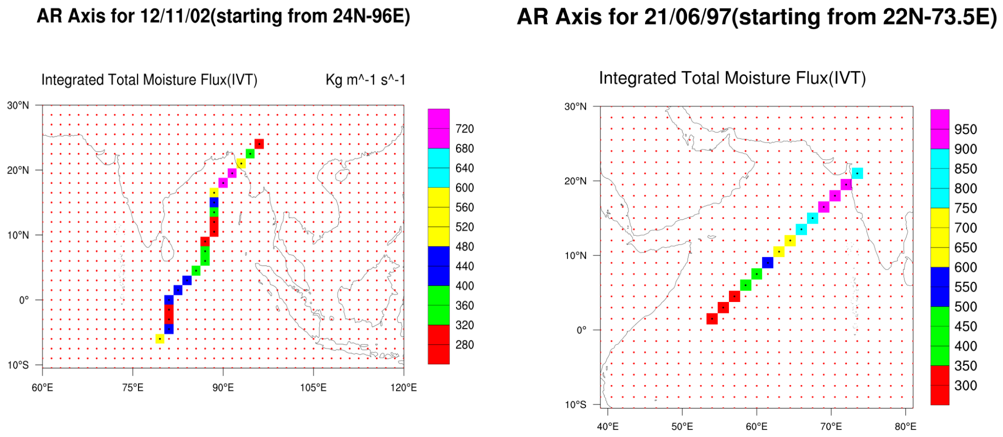
(a) (b)

Figure 3.3: The monthly IVT thresholds for various reference latitudes of ARs over Bay of Bengal is shown in (a) and for various reference longitudes of ARs over Arabian Sea(b).

region decreases due to evaporation and reaches a minimum during early spring(March & April). In the late spring(May), the southwesterly trade winds bring back moisture into the region from the Arabian Sea and thereby increasing the IVT intensity. The IVT intensity during its peak is greater than 800 $Kgm^{-1}s^{-1}$ and the minimum is around 200 $Kgm^{-1}s^{-1}$. Comparing to the Bay of Bengal counterpart, the Arabian Sea ARs have higher IVT thresholds due to strong westerly winds during the monsoon. We see an increasing trend in the moisture flux as we go deeper into inland($78E > 76.5E > 73E$) which might be because of higher evaporation in the region.

The next step mentioned in the algorithm determines the axis of the AR(the central line of the AR) that helps in the process of filtering out monsoon circulation and cyclones over the region. As ARs are referred to a strong poleward transport of water vapour, the moisture transport that does not follow such directionality will be excluded. Since we were interested in tracing the path of moisture transport during monsoon, we used the same process to identify monsoon circulation instead of Atmospheric Rivers in our study.

The endpoint of the AR axis is defined as the location of maximum daily IVT value along the reference latitudes(longitudes). Then the back trajectory algorithm is used to identify the AR axis by searching for the highest IVT values in the adjacent grids to the south, southeast and southwest of the end point of the AR axis. Such a procedure is iterated until



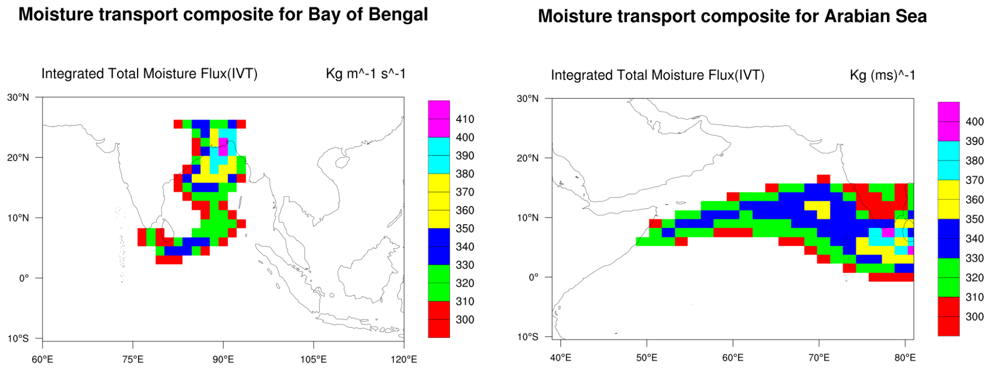
(a) (b)

Figure 3.4: The AR axes for identified ARs on 12 November 2002 over Bay of Bengal(a) and on 21 June 1997 over Arabian Sea(b).

it reaches the end point for successive grids to obtain the AR axis. Some of the axes of ARs identified over the Bay of Bengal and the Arabian Sea are shown in the **Figure 3.4**. The location of the maximum IVT on the reference latitude(24N) and longitude(73.5E) is used as the starting point.

To identify the mean flow of moisture pathway during monsoon, we plotted the composites of all the identified AR dates. The **Figure 3.5(a)** shows the moisture transport composite over the Bay of Bengal and **Figure 3.5(b)** over the Arabian Sea for all the identified AR dates. Only the region of intense IVTs($> 300\ Kgm^{-1}s^{-1}$) are shown in the raster plot. The rastered region identified over the Bay of Bengal and the Arabian Sea gives a pretty good idea about the mean occurrence of the moisture pathway. For Arabian Sea composite, the axis of the pathway is more tilted to align along East-West extending from 5N to 15N, since the zonal component of the wind dominates during monsoon. Whereas for Bay of Bengal pathway, the alignment is mostly meridional extending from the equator to the mid-latitudes.

The direction and width thresholds are then applied to identify ARs from typical monsoon and cyclones. If IVT strength and length of the axis of ARs are only considered in the study of moisture transport during monsoon, the moisture convergence in the low-pressure region and intense surface winds during the monsoon can also be falsely identified as ARs. The



(a) (b)

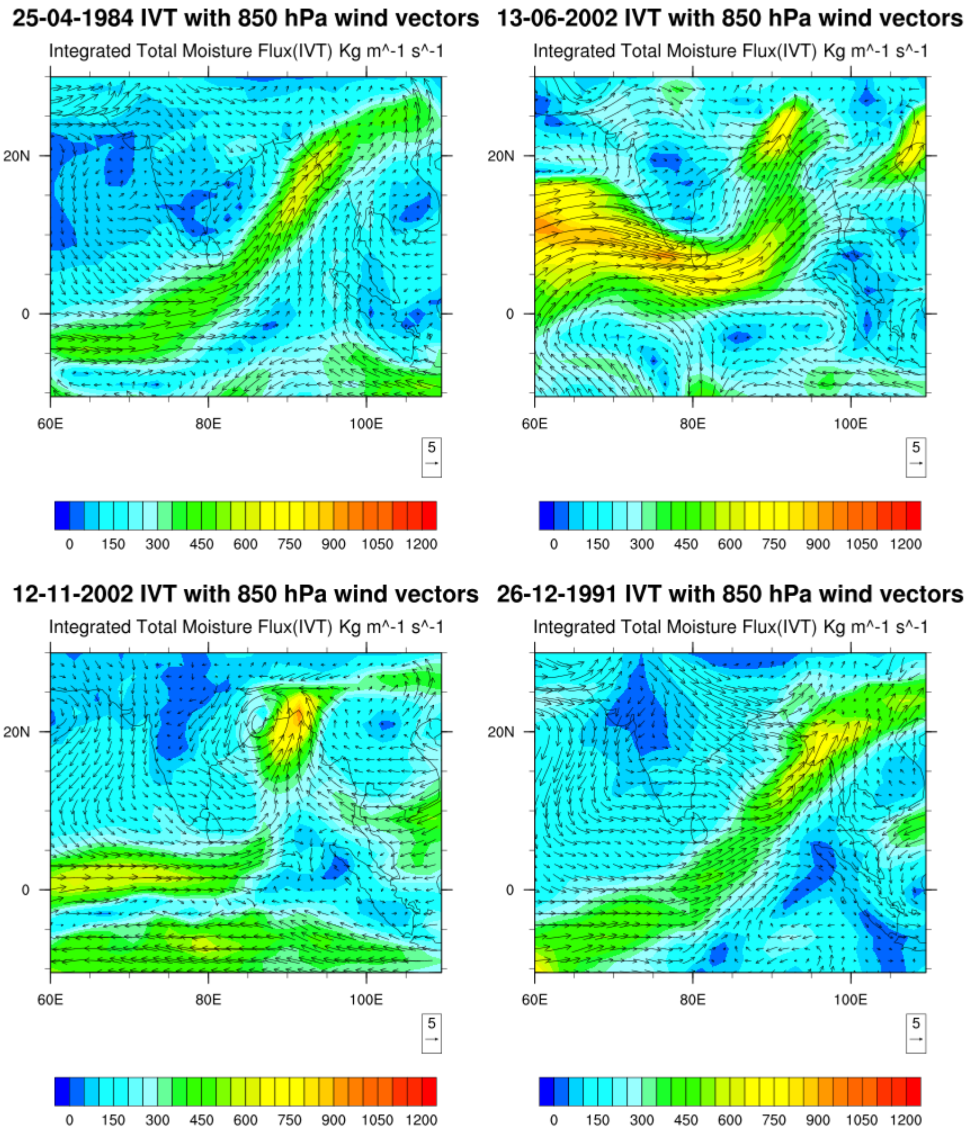
Figure 3.5: Moisture pathway composites over Bay of Bengal(a) and Arabian Sea(b). The IVT intensity $< 300\ Kgm^{-1}s^{-1}$ are not shown in the raster plot.

included angle between the mean moisture transport direction of grids along the axis and the AR axis should not exceed 45°. The equivalent width(EW) given by the **Equation 3.2**

$$EquivalentWidth = \frac{area}{length} \tag{3.2}$$

where area refers to the total number of grids with IVT threshold greater than the monthly threshold in the axis coverage region and length refers to the number of contiguous grids is used to represent the width of an AR that should be < 1000 km(about 7 grids). Since our work is focused on the tracing of the moisture paths during monsoon, the equivalent width criteria can be ignored.

By following the algorithm we were able to identify and trace the moisture paths over the Bay of Bengal and the Arabian Sea during monsoon. We identified about 1691 AR dates at 24N reference latitude and 1615 AR dates at 73.5E reference longitude for the time spanning 1979-2011. Due to time constraints, we were able to trace the moisture transport for only a few days out of all the identified AR dates. Some of the moisture transport paths identified for the AR dates over Bay of Bengal region can be seen in **Figure 3.6**. The top left and bottom right figures show a clear AR structure(marked in green and yellow contours) that extends diagonally from 10S to 25N over the Bay of Bengal. The result shown in the top right shows the monsoon flow over the Bay of Bengal. The left bottom figure shows moisture


25-04-1984 IVT with 850 hPa wind vectors

13-06-2002 IVT with 850 hPa wind vectors

12-11-2002 IVT with 850 hPa wind vectors

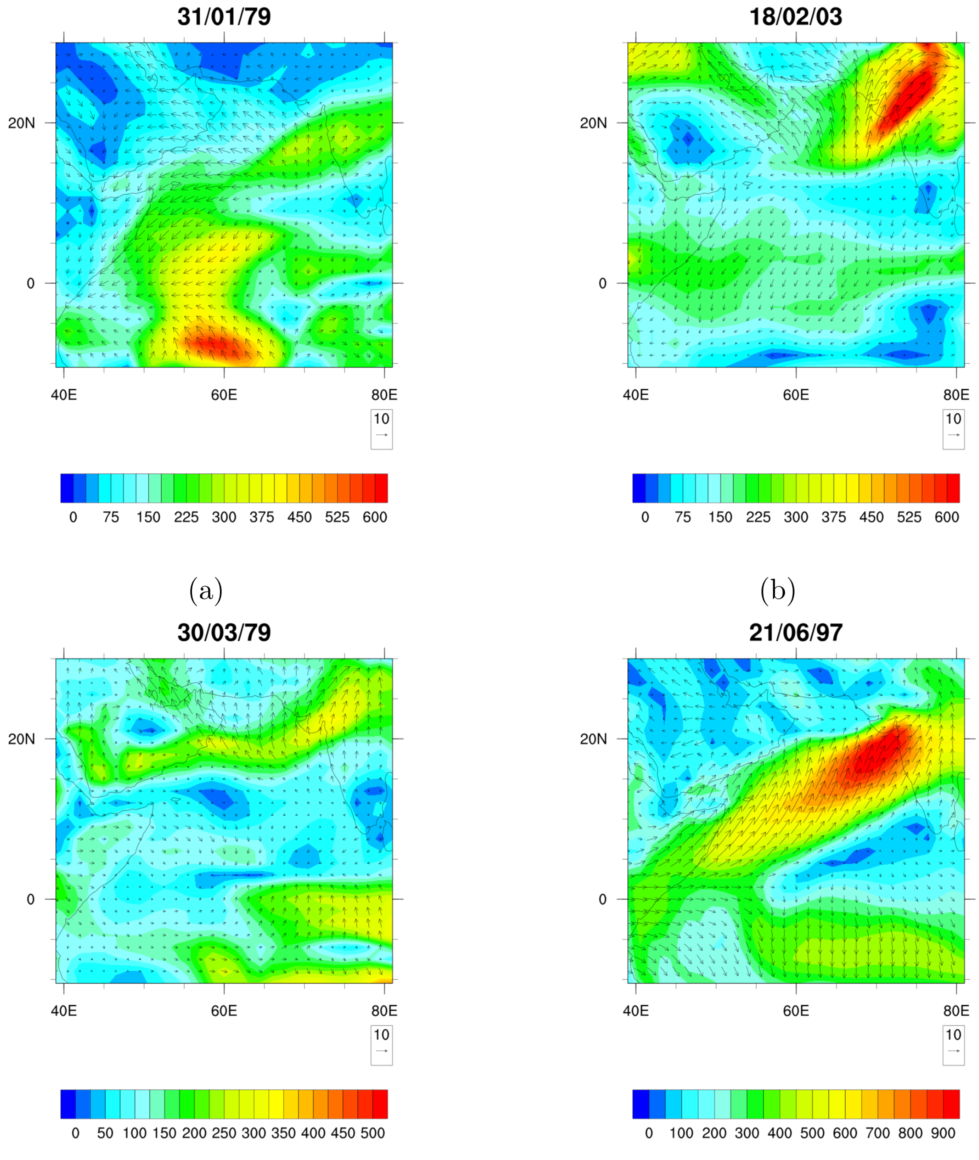
26-12-1991 IVT with 850 hPa wind vectors

Figure 3.6: Some of the moisture transport paths identified over Bay of Bengal. The IVT is shown as contours and 850hPa wind as vector in ms^{-1}.

path during a tropical cyclone over Northern Bay of Bengal during the year 2002.

Some of the moisture transport paths identified for AR dates over the Arabian Sea can be seen in the **Figure 3.7**. In the **Figure 3.7(a)**, the path of the moisture is seen entering Indian peninsula extending from 60E to 80E and 10N to 24N. Since the monthly threshold for January and February is quite low(200 $Kgm^{-1}s^{-1}$) the moisture transport path found is of very less intensity (**Figure 3.7(b) & (c)**). The moisture path during monsoon months of

JJAS(**Figure 3.7(d)**) has a strong influence of low-level jet south westerlies that transport enormous amounts of water vapour into the Indian subcontinent.



(a) (b) (c) (d)

Figure 3.7: Some of the moisture transport paths identified over Arabian Sea. The IVT is shown in contour and 850 hPa wind in vector in ms^{-1}.

Chapter 4

Quantifying the moisture contributions of LLJ during monsoon

In this Chapter, we try to quantify the moisture flux arriving over the monsoon domain, through the two branches of the low-level circulation-viz- the Arabian Sea and Bay of Bengal branch and also look at the interannual variation of the moisture fluxes. Since then the Indian Ocean is a major source of moisture for the monsoon circulation, we also explore whether there is a linkage between the interannual variability of moisture fluxes and the Indian Ocean dipole state. We also explore the relative contribution of the two branches of LLJ in accumulating moisture in the three monsoon regions- Southwest India, Northeast India and Central India, by examining the correlation between the daily IVT and the PW variations during a season.

4.1 Contribution of moisture from both branches of LLJ

To understand the variations in the moisture flux entering the Indian monsoon region from Arabian Sea and Bay of Bengal, through the two branches of LLJ, we examine the variability of the seasonal mean (JJAS) IVT fields. For the Arabian Sea branch, the seasonal mean IVT across the 73.5E longitude (meridionally averaged from 9N-22.5N) was calculated for each year (1979-2011) and for the Bay of Bengal branch, the seasonal mean IVT across the 24N latitude (zonally averaged from 84E-96E) was calculated for each year. The latitude(24N) and longitude(73.5E) were chosen as representative for the incoming flux from respective branches based on the climatological winds over the region during monsoon.

The contribution from both Arabian Sea branch and Bay of Bengal branch of LLJ during monsoon for the years 1979-2011 can be seen in the **Figure 4.1**. In the figure, the red line (blue line) indicates the seasonal mean IVT from Arabian Sea branch(Bay of Bengal branch) respectively. The interannual variations in the seasonal mean IVT for both the branches are quite evident. Compared to the Arabian Sea branch, the Bay of Bengal branch seems to have lesser magnitude possibly due to the stronger winds associated with the Arabian Sea branch. There may be numerous factors that can influence the IVT strength during monsoon ranging from mesoscale to planetary scale, which can modulate the moisture flux at different timescale. Since we are interested in the interannual variability of the moisture flux, we explore the relationship between the interannual variations of the IVT and the major mode of interannual variation in SST and winds over the Indian Ocean, namely the Indian Ocean Dipole (IOD) (Saji et al(1999)$^{(9)}$). The SST pattern in the Indian Ocean is characterized by

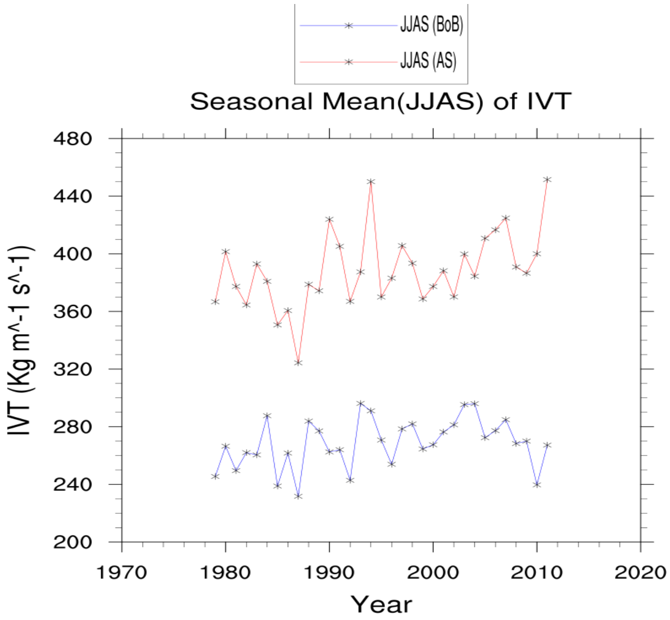


Figure 4.1: Seasonal mean(JJAS) IVT for the Arabian Sea(red) and the Bay of Bengal(blue) branches for the period 1979-2011.

a dipole structure with anomalously higher sea surface temperatures in the eastern equatorial Indian Ocean and cooler SST over the western equatorial Indian Ocean. This pattern and associated winds reverse on an interannual timescale, causing very high rainfall over East Africa and drought over Indonesia(refer **Figure 4.2**). This positive phase of IOD can also produce an increase in summer rainfall over Indian subcontinent even when there is an El Nino (Saji et al (1999)$^{(9)}$). A Dipole Mode Index (DMI) defined as the difference between the area averaged SST anomalies over the Western equatorial Indian Ocean (50E-70E, 10S-10N) and Eastern equatorial Indian Ocean (90E-110E, 10S-Equator) is used to characterize the phases of the IOD. Hence, we examined the extent of IODs influence on the moisture transport during the monsoon in both the branches of LLJ by correlating the DMI with the IVT anomalies in each branch. The monthly Indian Ocean Dipole Mode Index was obtained from HadI-SST dataset for the period 1979-2010.

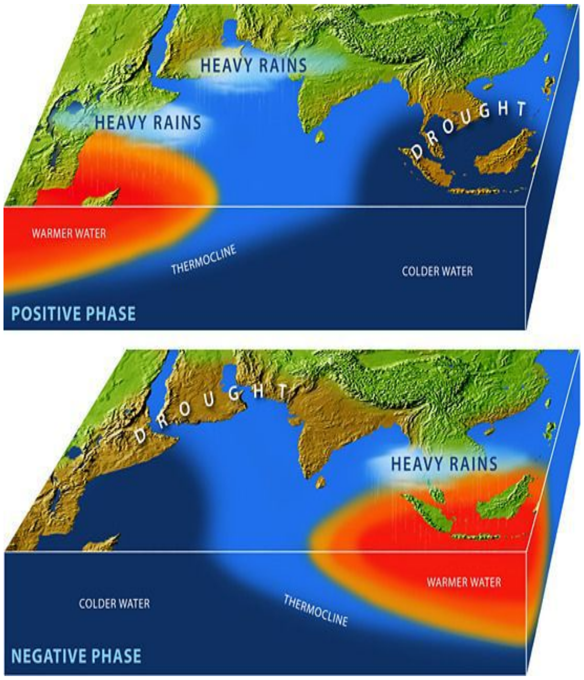
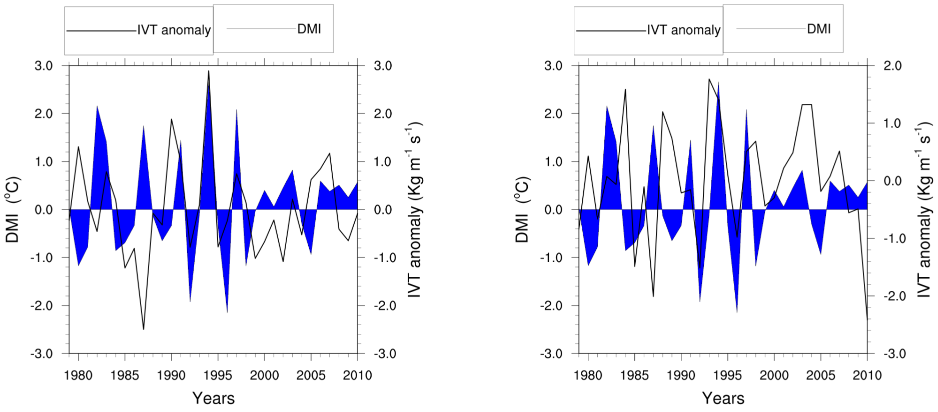


Figure 4.2: A cartoon representation of Indian Ocean Dipole.[Source: E. Paul Oberlander, Woods Hole Oceanographic Institution]



(a) Arabian Sea branch

(b) Bay of Bengal branch

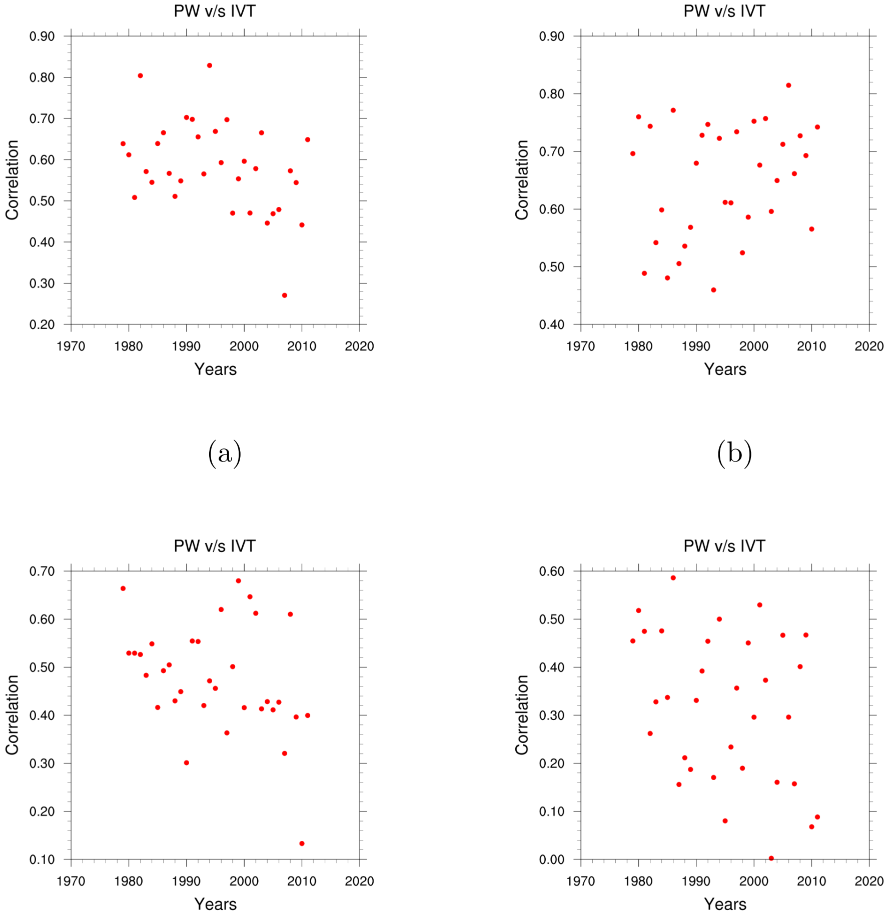
Figure 4.3: Seasonal mean(JJAS) DMI index plotted along with normalised IVT anomalies(Thick black line) for both the branches of LLJ.

4.2 Relationship between the DMI and IVT in the two branches of LLJ

We used the standardized anomalies of IVT from both the branches to compare with the DMI, which represents the positive and negative phases of Indian Ocean Dipole. **Figure 4.3** shows the seasonal mean (JJAS) DMI index (shaded in blue), along with the seasonal mean (JJAS) normalised IVT anomalies for both Arabian Sea branch and Bay of Bengal branch (thick black line). Though some antiphase relationship is visible between the DMI and the Arabian Sea IVT variability, the overall correlation is only 0.2. On the other hand, the correlation between the seasonal mean DMI and the Bay of Bengal branch with seasonal mean IVT anomalies is only about 0.1. A more detailed analysis of the lead-lag variations of the IOD state and the IVT anomalies need to be carried out to make sense of the influence of the IOD on moisture transport.

4.3 Verifying the moisture sources for various regions in the monsoon domain

The IVT indicates the moisture transported into a monsoon region by the low-level winds. We now explore the relationship between the IVT and the total precipitable water (PW) over different parts of the monsoon domain. A strong correlation in the variability of IVT and



(a) (b)

(c) (d)

Figure 4.4: The correlation between IVT intensity of Arabian Sea branch and Precipitable Water over South Western India(a) and Central India(b), also correlation between IVT intensity of Bay of Bengal branch and Precipitable Water over North East India(c) and Central India(d) for JJAS months of each year from 1979-2011.

that in the PW over a region would possibly indicate the path of the moisture transport and the contribution coming from advection of moisture by winds versus local evapotranspiration. The South Western region of the Indian peninsula is presumed to get its moisture largely from the Arabian Sea branch and the North Eastern Indian region mostly gets its moisture from the Bay of Bengal branch of LLJ during monsoon. Since the moisture from the Arabian Sea and Bay of Bengal converge in the monsoon trough over central India during monsoon, the central Indian region or the core monsoon region is assumed to get its moisture supply from both the branches of LLJ.

Now to see how these contributions reflect in the total PW over a monsoon region and its variability, during a season, the daily IVT intensity was correlated with the daily values of PW during the JJAS months separately for Southwest India, North East India and Central India and for the two branches of LLJ. **Figure 4.4** shows how this correlation has varied over the different monsoon seasons during 1979-2011. The correlation between IVT of the Arabian Sea branch and PW over South Western India (**Fig 4.4(a)**) show significantly high correlation, with the correlation exceeding 0.5 for most of the years. Since the correlation is strong, we can safely assume that the moisture brought inland by the Arabian Sea branch is one of the major moisture sources for South Western India possibly explaining 25% of the PW variance. A similarly strong relationship can be seen between the PW over Central India and the IVT associated with the Arabian Sea branch (**Fig 4.4(b)**), with the correlations exceeding 0.4 for most of the years. The correlation between IVT of the Bay of Bengal and PW over North East India(**Fig 4.4(c)**) varies between 0.35 & 0.65, for most of the years indicating that the major moisture source for the region is the Bay of Bengal branch. On the other hand the correlation between PW over Central India and IVT by the Bay of Bengal branch show a relatively weak correlation (**Fig 4.4(d)**) between 0.15 & 0.35, and large year to year variability indicating that possibly the moisture supply to the Central India region is through the Arabian sea branch transport and local evapotranspiration and there could be large year to year variation in the contribution from each component.

Chapter 5

Conclusions

We have tried a new approach to studying moisture transport in the South Asian region by following the methodology adopted by Yang et al(2018) and modifying it accordingly to study the nature of moisture transport during monsoon. We found that this methodology is very useful in identifying and tracing the moisture transport pathways of the two branches of LLJ.

By using IVT fields, we were able to capture the moisture contributions by the two branches of LLJ during monsoon over the Indian region. The Arabian Sea branch contributes more moisture than the Bay of Bengal branch to the Indian region. The influence of the Indian Ocean dipole on the moisture transport by both the branches of LLJ during monsoon is not clear due to low correlation.

The evolution of moisture accumulation and depletion during the active and break conditions over various regions in the monsoon domain gave an insight into the sources of moisture during monsoon. The major moisture source for Southwestern India and Central India during active conditions are the Arabian Sea, Bay of Bengal and Northern Indian ocean. Whereas for the Northeastern region, the major moisture source during an active period is the Bay of Bengal. The positive vorticity in wind anomaly fields were observed during an active condition and negative vorticity during breaks over the monsoon domain.

Bibliography

[1] Goswami, B. N.,South Asian monsoon, Intraseasonal Variability in the Atmosphere-Ocean Climate System, 2005, Springer Berlin Heidelberg, 19-61.

[2] Yang, Y. , Zhao, T. , Ni, G. and Sun, T., 2018, Atmospheric rivers over the Bay of Bengal lead to northern Indian extreme rainfall., *Int. J. Climatol*, 38.

[3] Lavers, D. A., Villarini, G., Allan, R. P., Wood, E. F., and Wade, A. J., 2012, The detection of atmospheric rivers in atmospheric reanalyses and their links to British winter floods and the largescale climatic circulation, *J. Geophys. Res.*

[4] Neiman P. J., White A. B., Ralph F. M., Gottas D.J., Gutman S. I., 2009, A Water Vapour Flux Tool for Precipitation Forecasting, *Proceedings of the ICE-Water Management*

[5] Rajeevan, M., Gadgil, S. & Bhate, J., 2010, Active and break spells of the Indian summer monsoon, *J Earth Syst Sci*

[6] Zhu, Y., and Newell, R., 1998, A proposed algorithm for moisture fluxes from atmospheric rivers., *Mon. Wea. Rev.*

[7] Ralph, F. M., and Dettinger, M. D., 2011, Storms, floods, and the science of atmospheric rivers, *Eos.*

[8] Lavers, D. A., Villarini, G., 2013a, Atmospheric riversand flooding over the Central United States, *J. Clim.*

[9] Hameed, Saji and Goswami, B. N. and Vinayachandran, Pn and Yamagata, Toshio, 1999, A dipole mode in the Tropical Indian Ocean, *Nature*, 360-3.