Moisture trajectories during heavy rainfall events using Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model

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Abstract. Heavy rainfall inducing other catastrophic events are frequently experienced globally. Understanding the mechanisms of moisture transport during such events will help in furthering our knowledge about such systems. In the current study, estimation of most likely moisture trajectories is performed using back trajectory analyses. Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model available from National Oceanic and Atmospheric Administration’s (NOAA) Air Resources Laboratory (ARL) is used for the purpose. A preliminary analysis is conducted by calculating the frequencies of back trajectories from two locations in Kerala for three heavy rainfall cases. The analysis indicates that both the locations have similar pattern of moisture trajectories during the cases occurring in south west monsoon and pre monsoon periods. However, a change in the behaviour of the trajectories for the two locations is observed for the case during the north east monsoon period. Since this study involved only individual cases, robust conclusions cannot be made based on this for the dynamics of moisture transport for these locations. More detailed analysis will follow this preliminary study in future for the purpose.

1. INTRODUCTION

Precipitation at a location can arise from two sources namely (i) local-scale evaporation of water, which brings in moisture to the atmosphere and (ii) moisture advected into the region from other locations. Atmospheric circulation results in water vapour being carried over to distant locations. This forms an integral part of global hydrologic cycle. Transport of moisture to a location depends upon the dynamics of atmosphere as well as the availability of sources of moisture. Formation of precipitation depends on this transport as well as the interaction with the topographical features. Moisture advection and resulting precipitation are complex phenomena. Even though the question of origin of rain at a place is very interesting, it is not easy to find out the details of the processes involved.

Modelling of moisture transport can be done in either the Eulerian formulation or the Lagrangian formulation of fluid motion. In the Eulerian model approach of fluid flow, a specific location in space is focussed upon and the particle motion is considered as a continuum. On the other hand, the Lagrangian formulation focusses on individual particles and tracks their evolution in space and time.
[1] explains that since the Eulerian concept doesn’t take care of moisture changes that occur during transport, it is not effective in assessing the sources of moisture accurately. Lagrangian models, however, are able to estimate the trajectories as well as quantify the changes that happen during the transport also.

There are several previous studies which utilised Lagrangian formulation to determine the origin of moisture in a global scale (eg : [2]) and regional scale (eg : [3],[4],[5]). Over India, there are a few studies which utilised the Lagrangian approach to identify the source of moisture during rainfall events. [6] identified the source region for rainfall over Ahmedabad during South West monsoon season during June to September. [7] analysed the influence of continental and marine moisture sources in the daily rainfall characteristics along the foothills of Himalayas.

In the current study, Lagrangian model formulation is utilized to identify the sources of moisture for heavy rainfall events over two locations in Kerala. Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model available from National Oceanic and Atmospheric Administration’s (NOAA) Air Resources Laboratory (ARL) is utilized here for the analysis[8]. The model (available from https://www.ready.noaa.gov/HYSPLIT.php) can either be installed in a PC or be run interactively through the READY website[9].

The seasons in India are divided into 4 as per India Meteorological Department (IMD). (i) winter season (January-February), (ii) Pre-monsoon (March-May), (iii) South West monsoon (June-September) and (iv) Post monsoon season (October-December). Winter season in India usually consists of relatively cooler and drier climatic conditions. Pre monsoon period follows this season. During the pre-monsoon period, the temperatures become higher. Small amounts of rainfall are received during this season, and the pattern shows large variability spatially and temporally. Low pressure systems and cyclones form during this period, which also provides some rainfall to the country. During the South West monsoon period, the winds from the South-West carrying a lot of moisture from the ocean, travel towards the Indian mainland, resulting in rainfall. In contrast, during the post monsoon period, wind from the north Indian land mass, while retreating to the ocean results in rainfall over the southern region of the subcontinent. The rainfall during this season is confined mainly to the southern states of India. This season also witnesses low pressure systems and cyclones in the Bay of Bengal. The underlying dynamics behind the rain events that are experienced during these various seasons are also varied. Understanding the dynamical characteristics of the rainfall events will help towards creating better models and tools for effective monitoring and forecasts. This also helps in mitigating the various natural hazards that result from heavy rainfall events. Early warning of landslides (eg [10],[11]), understanding of flood events (eg [12]) and droughts ([13]) will also benefit from accurate rainfall prediction. This is a complicated problem made more complex due to the changes in rainfall trends observed in recent years (eg [14]) due to the various interactions between the different aspects of the climate system.

The present study is a first step towards understanding the mechanisms behind heavy rainfall events during various seasons, over Kerala. Here, the back trajectories of air parcels are simulated using the HYSPLIT model to understand the possible source of moisture during different seasons in two locations namely Kochi and Thiruvananthapuram in Kerala. More detailed analysis involving satellite observations (eg [15]) and other parameters are not undertaken within this study. The paper is arranged as follows: the HYSPLIT model description is provided, followed by the cases that are analysed in the study. The details of trajectory analysis methodology are explained. Results are discussed and the future research possibilities are also touched upon.
2. HYSPLIT MODEL DESCRIPTION

HYSPLIT model is one of the popularly used models which is useful to calculate trajectories of air parcels, dispersion, transport, transformation and deposition of pollutants. It uses a Lagrangian formulation in the calculation of advection and diffusion. This approach involves a frame of reference which moves along with the particle motion. On the other hand, concentrations of pollutants in the air are calculated using the Eulerian approach which involves a fixed frame of reference. Therefore, the model calculation involves a hybrid approach. The model is utilized both in research as well as for emergency response in the event of dispersion of harmful pollutants.

The HYSPLIT model calculates the advection of a particle or a puff. A puff is a 3-dimensional cylinder which involves growth of distribution of concentration in horizontal and vertical directions. If it overgrows a grid, the puff may split up. A particle is a point mass. If a 2D object has a puff distribution in the horizontal and a particle behaviour in the vertical, it is termed as a hybrid. The puff-particle hybrid approach is useful. In the horizontal dimension, fewer puffs are required as compared with the number of particles. In the vertical, particles approach can better capture wind shear.

The model takes in parameters such as wind speed, direction, temperature, moisture etc. in a regular spatial grid at different levels in the atmosphere. Suppose the initial position of the particle is \( P(t) \). Assume that the three-dimensional velocity vector at the initial position is given by \( v(P, t) \). The first guess position, \( P'(t + \Delta t) \) is given by

\[
P'(t + \Delta t) = P(t) + v(P, t)\Delta t
\] (1)

The final position is calculated using

\[
P(t + \Delta t) = P(t) + 0.5[v(P, t) + v(P', t + \Delta t)]\Delta t
\] (2)

The time step of integration, \( \Delta t \), may vary during the simulation. The value of time step is calculated based on the requirement that the grid spacing should be more than the advection distance in each time step. Using the maximum transport speed in the previous hour, the maximum value of transport velocity is estimated. The time step is calculated using

\[
U_{\text{max}}\Delta t < 0.75
\] (3)

Time steps may vary from a minimum of 1 minute to a maximum of 1 hour.

Greater precision is not achieved even if higher order integration methods are used as observations are interpolated linearly to the integration point from the grid.

3. CASES ANALYSED

Three cases of heavy rainfall events over Kerala are selected for the study. These events are selected from newspaper reports. The events are selected in such a way that they span the three seasons where rainfall is received over Kerala.

Case 1: Heavy rainfall on 21st October 2019 – Several regions of Kerala experienced heavy rainfall spells on the 21st of October 2019. This rainfall was due to the strengthening of the north east monsoon circulation.
Case 2: Heavy rainfall on 8\textsuperscript{th} August 2020 – This event occurred during the South West monsoon 2020. During this period, the atmospheric conditions were favourable for rainfall occurrence.

Case 3: Heavy rainfall on 15\textsuperscript{th} May 2021 – Cyclone Tautke was a powerful tropical cyclone which formed in the Arabian sea. Several places in Kerala experienced heavy rainfall due to the influence of the cyclone.

4. INPUT DATA

The model utilises meteorological data in a specific format, available over a latitude-longitude grid, at various heights and time periods during the simulation interval. The data in the required format is available from various sources. The present study utilises data from global data assimilation system (GDAS) from the National Center for Environmental Prediction (NCEP) \cite{16}. The dataset contains observations of atmospheric parameters from weather stations, weather RADARs, satellites, balloons, aircraft reports etc combined into a 3 dimensional model grid. The dataset is available in various resolutions. The present study utilises data in a 1° x 1° horizontal resolution. The data is available mainly in binary format.

5. BACK TRAJECTORY ANALYSIS

In back trajectory analysis, a parcel of air is followed backward for a specified time so that the most likely region which provided air to a receiving region is estimated. This can be useful if we want to find out the source of particles which results in polluting a region as well as to track the source of moisture for a region. The HYSPLIT model includes different ways for calculating trajectories. There are options to estimate (1) normal trajectory – a single trajectory for the motion of an air parcel is calculated, (2) trajectory matrix–this option provides a grid of trajectories within two locations, (3) trajectory ensemble – multiple trajectories are estimated from a single location and (4) trajectory frequency – from one location and one height, a trajectory is started every 6 hours. The frequency of passing of trajectories over a grid cell is then estimated. This is normalised by the total number of trajectories or that of end points. The trajectory frequency calculation used in this study is as follows:

\[
\text{Frequency} = 100 \times \frac{\text{number of trajectories passing through each grid square}}{\text{number of trajectories}}
\]

6. RESULTS AND DISCUSSION

Back trajectory calculations are performed for two locations in Kerala (1) Kochi and (2) Thiruvananthapuram. These locations are chosen considering that these are two important cities in Kerala, on the West coast of India. Urban floods are catastrophic phenomena experienced globally. The risks from such events are increasing due to the climate change induced effects as well as due to the rapid urbanisation happening. Hence it is very critical that we understand the Physics behind the urban flooding caused by heavy rainfall events. Identifying the probable sources of moisture which results in such events is therefore important.

Here, trajectory frequencies are estimated using the HYSPLIT model for the aforementioned three cases for the two urban locations.
Back trajectories frequencies estimated for 21st October 2019 for Kochi and Thiruvananthapuram are given in figure 1(a) and figure 1(b) respectively. The star indicates the start location for the model estimation. It is seen that the frequency patterns for both locations are different. Majority of trajectories for Kochi seems to be from local sources, indicating that localised convection might be the major factor which resulted in the rainfall. On the other hand, the trajectories for Thiruvananthapuram indicates that a good number of trajectories have origins elsewhere, in a region North East of the starred location. This is a possible indication of influence of both localised convection as well as moisture advection in the rainfall received over Thiruvananthapuram during the event which occurred during North East monsoon season.

South West monsoon season brings in copious amounts of rainfall over India, when the moisture-laden winds blow from the West of the coast, from the Arabian sea. The back trajectories calculated for both Kochi and Thiruvananthapuram shows similar pattern as well as the oceanic origin of moisture quite clearly. This indicates the nearly uniform way in which moisture advection occurs over Kerala during peak monsoon season.
Cyclone Tautke is a very severe cyclonic storm which originated in the Arabian sea during May 2021. This system brought heavy rainfall over the west coast of India. All the districts of Kerala were affected by the cyclone. Figure 3 shows the back trajectory analysis for the heavy rainfall event which occurred due to the effect of the cyclone Tautke in May 2021. Both Kochi and Thiruvananthapuram have moisture sources in the Arabian sea during this event, which is to be expected. The moisture advection resulting in the rainfall event is evident from the figure 3.

7. CONCLUSIONS AND FUTURE DIRECTIONS

HYSPLIT model is used to analyse the moisture sources for three heavy rainfall events during three seasons over two locations in Kerala. The preliminary analysis conducted using back trajectory frequency analysis indicates the most likely sources of origin of air parcels which resulted in rainfall over Kochi and Thiruvananthapuram. The events during pre-monsoon as well as south west monsoon seasons indicate that both the locations experience heavy rainfall due to moisture advection from the Arabian sea region. However, the event during North East monsoon shows that the source of rainfall for Thiruvananthapuram has likely originated from the East coast region of India, while the same is not true for Kochi. This interesting feature will be analysed further in future studies. Other atmospheric parameters also will be analysed in order to understand the moisture advection during North East monsoon period. The current study is also limited in the number of case studies taken in each of the seasons. More numerical experiments are necessary to arrive at robust conclusions about moisture transport in the region resulting in heavy rainfall events.

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