Response File

This document consists of the:

- Reviewers comments and responses to them indicating the changes made.
- Manuscript

Review 1

GENERAL COMMENTS

The paper of Dar and Ghosh present an interesting "toy-model" of atmospheric transport over the Bay of Bengal between Bangalore and Kolkata. Based on meteorological and stable isotope observations they infer that the Bay of Bengal contributes 77% of the rainfall in June and that this contribution diminishes to 19% in September. This paper was also presented at the 8th EGU Leonardo Conference 2016 in Ourense. I attended this oral presentation and found it really fascinating to see what we can learn from the application of isotopes in hydrology and atmospheric sciences. That being said, I feel that this paper does not do complete justice to the findings of the authors. There is a lot of potentially interesting matter in the research, but it does not always come across well in the paper. I have several suggestions on how to improve the writing style, remove language errors and improve the organization of the manuscript. However, my main point is that the main results of the paper are not well enough presented. I belief that the main findings are articulated on P6,L5-10, but they are not backed up by any figures or tables, nor are these results compared to previous research, and no outlook on the broader implications is given. Below, I list some questions about matters that were not entirely clear in the paper and I list several other suggestions to improve the manuscript. I look forward to see a revised version of this manuscript.

Response:

Thanks. Earlier version is now revised with specific importance given to figures and tables. There is a limited effort towards understanding the hydrological budget in terms of input from continental and oceanic moisture sources. We cited all research papers which we found important in the context

of present work (Krishanamurthy et al 1991, Sengupta et al., 2006, etc). We took specific comments subsequently and addressed them in the specific responses.

SPECIFIC COMMENTS

Comment(R1a)

Nowhere is mentioned how exactly the SW Monsoon period is defined. What does SW stand for? And which months are considered?

"R" is used for precipitation/rainfall and "P" for precipitable water. This may be confusing as "P" is often used for precipitation. I suggest to use "W" for precipitable water instead to avoid confusion.

Response:

We provided description of SW monsoon over Indian region. In our description, we mentioned that the subcontinent receives rainfall during summer time due to reversal of winds which brings moisture from the Arabian Sea to the land and this constitute ~50-90% of the total annual rainfall in the overall region (Gadgil, 2003). The timings for the transport process is also described subsequently where we mentioned that the beginning of June is taken as time for the commencement of SWM while end of September is generally referred to as terminal phase of SWM.

Comment

P1,L2: "generated from a moisture parcel which originates from the Arabian Sea"

I disagree with this choice of words. Generated in my mind implies evaporated from, but it is merely where the HYSPLIT trajectory calculation ends.

Response:

Thanks we rephrased it.

During the SWM, the two principal sources of vapour parcel originating from the Arabian Sea (AS) and the Bay of Bengal (BoB) (Kumar et al. 2010) were

already described. The site at Bangalore (Rahul et al., 2016) receives AS vapour in addition to continental moisture. Based on backward air trajectories and out-going long wave radiation fluxes they confirmed the trajectories of convective activity.

Comment:

P1,L13-L14: Why aren't the sources of Bay of Bengal and India adding up to 100%, but 100-115% instead? Moreover, why isn't Peninsular India mentioned in the main text at all?

Response:

There was a typographical error.

During the period of the SWM 65-75% moisture contribution to precipitation is from the Bay of Bengal and the continental landmass contributes 25%-35%. The vapour generated from the Peninsular India is referred as continental component subsequently in our description. In the revised version we described the importance of peninsular component in the Introduction section.

Comment:

Which TRMM product is used exactly?

Response:

Precipitation (P) data was obtained from the Tropical Rainfall Measurement Mission Project (TRMM) (Huffman et al., 2007) (3B42 V7 derived), Goddard Space Flight Centre Distributed Active Archive Centre (GSFC DAAC) (http://trmm.gsfc.nasa.gov/). This is now mentioned in the text.

Comment:

P3,L19: "calculated for the dew point temperature at 850 mb" This seems to be a major assumption. Is the factor valid for all pressures at which the rainout processes occur? Moreover, what is its value?

Response:

The equilibrium fractionation factor is independent of pressure. However, dew point temperature for moisture saturation varies depending on the location and latitude. We followed our earlier paper and previous work (Rao, 1976) we used dew point temperature at 850 hPa for fractionation factor evaluation. The fractionation factor values range between 1.01210 to 1.01235 in our model study.

Comment:

P3,L30: "δl is the Bay of Bengal surface water isotopic composition" Where is this value taken from, and where can the reader see its value?

Response:

For the surface water isotopic composition of the BoB, the values are extracted from the Global seawater Oxygen-18 Database (V-1.21) (Schmidt et al. 1999) (http://data.giss.nasa.gov/o18data/). An interpolated colour image provided range of values (in the modified Figure 1).

Comment:

P4,L4: "Therefore"
Why "therefore"? As far as I can tell the following Eq. (5) could be written directly after Eq. (2),
It is not entirely clear to me how "F" is defined: is it compared to the original moisture in box 1 or for all boxes separately? It also does not come back in the results later.

Response:

f is defined as the fraction of vapour remaining in each of the boxes after rainout. The fraction of vapour remaining over each box after rainout is calculated separately for each box comparing the moisture in the i^{th} box with that of moisture present in the first box 1. The values for f over each box are given in Table 2.

P4,L14: What are pre-monsoon months? Where do I see results for March?

Response:

Pre-monsoon months are April to May. The calculations have been done only for the SW monsoon period i.e. June, July, August and September.

Comment:

P5,L4-L6: "Isotopic composition of Bay of Bengal surface water and the kinetic enrichment factor based on the ocean conditions of SST, surface relative humidity and wind speed is used to calculate the isotopic composition of the evaporated Bay of Bengal moisture." Please provide a detailed calculation.

Response:

The calculation of the kinetic enrichment factor is based on the formulation given by (Merlivat & Jouzel, 1979). In their study they included both equilibrium and kinetic effect to arrive to the final vapour composition. We provided detail formulation in the schematic layout and presented our results in a tabular format.

Comment:

P6,L5-L6: "The model simulation yields varying monthly contribution of the continental branch of the Arabian sea and Bay of Bengal vapour sources." What does this mean?

Response:

We modified this text. Based on the observation we have shown that the rainwater isotopic signature recorded at Bangalore gets modified due to interplay of processes like continental evaporation and BoB vapour input. The model simulation results yielded a varying % contribution of vapour from continental and the BoB region to match the monthly observation recorded at Kolkata.

Comment:

P6,L8: so the remaining percentages are continental or Arabian Sea?

Response:

The BoB acts as an active source of moisture at the beginning of SWM and the contribution of the total precipitable water varied during summer months. It

was 92±8% in June 73±17% in July 62±17% in August and 47±17% in September. The remaining percentages of vapour were of continental origin.

Comment:

P6,L12: "Previous studies have concluded Bay of Bengal to be the sole contributor of moisture towards precipitation at Kolkata." Which studies?

Response:

We revised this sentence. Both these papers (Sengupta and Sarkar, 2006; and Kumar et al. 2010) showed Bay of Bengal moisture as the only source for Kolkata precipitation.

Comment:

Table 1 needs some more explanation. Why is 2012 data used? I thought the authors were trying to simulate the 2004 monsoon? Are the H-2 and d-excess values relevant? There is also data from GNIP used, so why is this particular dataset relevant anyway?

Response:

The average $\delta^{18}O$ of rainfall over the BoB for the year 2012 collected during the BoB expeditions are only available dataset of rainfall over the BoB region (Table 1). Since our interpretation is based on $\delta^{18}O$ we avoided use of δD and d excess values and removed them from the table.

Comment:

Table 2 contains a lot of information, which is probably better to digest when it would be presented in a figure instead.

Figure 1: The names of Bangalore, Kolkata and Kakinada could also be directly shown in the figure.

Figure 2: d-excess is not used in this manuscript, thus why is this relevant? In which months are the individual points observed? Is this not relevant to indicate?

Response:

Table 2 has been modified. Some observations presented in Table 2 are now presented in Figure 5.

Figure 1 has been modified to show the names of the stations.

We removed δD and d excess values from the text, table and description.

Comment:

Figure 4: I think this should be split into Bangalore and Kolkata. Is there a big difference in sources during different stages of the monsoon? Can you say something about the relative relevance of each trajectory? I guess the lower level trajectories contain in fact more moisture.

Response:

The trajectories have been split and shown differently for Bangalore and Kolkata. The trajectories captured information on the movements of the air-parcels at different elevations during the South-West monsoon period. 850 hPa corresponds to 1500m is considered the core region of air transport via low level jet stream (Rao, 1976).

Review 2

Specific Comments

Comment:

Abstract: I suggest to re-organize the abstract clarifying mainly theobjectives and method. It is necessary to define the acronym SW monsoon before itsfirst use. Its not clear the period of analysis. Was the study performed for the 2004Monsoon?

Response:

The abstract is now modified. The study was performed based on the observations documented during the South-West monsoon (SWM) months (June, July, August and September) for the year 2004. Availability of coherent data (for the period of 4 months) from three stations along the moisture track was critical for this work.

Comment:

P1L16-17: "Precipitation is the primary source of water on land, brought by the moisture generated due to evaporation of ocean water which gets advected towards the continent." Is the oceanic evaporation the only source of moisture for the land precipitation?

Response:

Precipitation is the primary source of moisture responsible for rain at continental sites while indigenous moisture of continental origin adds up to the original cloud mass.

Comment:

P2L22-25: Please, clarify the aims. Explain the novelty of this work in comparison to the previous studies. In which way do you think your study complement the results Obtained in previous works?

Response:

Previous studies assumed (Sengupta and Sarkar, 2006 and Kumar et al. 2010) the Bay of Bengal (BoB) moisture to be the sole contributor of rain at Kolkata.

In this study we used the precipitation isotope data for two stations over the Indian region namely Bangalore and Kakinada, and the BoB for quantifying the moisture sources responsible for precipitation at Kolkata. Here isotopic data from these stations together with satellite based meteorological observations allowed quantification of moisture contribution from marine BoB and continental landmass for the SWM of 2004.

Comment:

Data and method P2L29-32: Please, define TRMM and include a bibliographic reference for each one of the data sets used.

Response:

The meteorological data used in this study is for the year 2004. Precipitation (*P*) data was obtained from the Tropical Rainfall Measurement Mission Project (TRMM) (Huffman et al., 2007) (3B42 V7 derived), Goddard Space Flight Center Distributed Active Archive Center (GSFC DAAC) *(http://trmm.gsfc.nasa.gov/)*, Total Precipitable Water (*W*) , Air Temperature (*T*), Relative Humidity (*h*), Wind Speed: from Reanalysis 2 (Kanamitsu et al. 2002)*; (http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis2.html).* For the surface water isotopic composition of the BoB values are extracted from the Global seawater Oxygen-18 Database (V-1.21) (Schmidt et al. 1999) *(http://data.giss.nasa.gov/o18data/).* The monthly averaged oxygen isotopic composition ($\delta^{18}O$) for the SWM from the GNIP (*http://www-naweb.iaea.org/napc/ih/IHS_resources_gnip.html*) dataset for Kolkata(2004) and Kakinada(2004). We arrived at monthly averaged $\delta^{18}O$ values for the Bangalore rain during SWM months after considering several years of observations. Although we tried to use 2004 monthly observation for our model study, we had limitation on procuring synchronous data set for every months corresponding to the monsoon time. Important features to operate the model require characterizing the initial isotopic composition at Bangalore for predicting the monthly isotopic values at Kolkata. This was possible after taking into account average monthly observation recorded at Bangalore station for the year 2004. However, lack of observation for the month of August 2004 in the data set was compensated with monthly observations recently

reported in three publications for other years (Rangarajan et al., 2013 and Rahul P. et al., 2016a,b). In both these studies the average monthly values were based to large number of observations and closely matches with the average values presented for the year 2004.The average $\delta^{18}O$ of rainfall over the BoB for the year 2012 collected during the BoB CTCZ expeditions was used as this is the only available dataset of rainfall over the BoB region.

Comment:

P3-L6-12: There is a lack of information concerning the analysis with HYSPLIT. Please
Introduce the hysplit model. How does it work? The input data used? Limitations of the model... Explain your experiments. How have u selected the rainy days during the2004 SW monsoon in each one of these places? Which months have you considered in the analysis? Have you calculated 4-day backward trajectories, haven0t you? Why have you chosen 4-day and not more (or less) days for the BW trajectory analysis? Do the elevations refer to the "initial position" of the particles at Bangalore and Kolkata? Do the colours of the different trajectories shown in the figure 4 identify the elevation of the particle at Bangalore and Kolkata, right? Or do the particles keep in the same elevation during the backward tracks? And why the HYSPLIT results are important for your study?

Response:

Backward air-mass Trajectories for the two stations are shown in Figure 3**. The air-mass was back tracked for -48 hours, -72 hours and -96 hours at 200m, 500m, 1000m, 1500m, 2000m and 2500m elevation above the mean sea level at Bangalore and Kolkata for all rainy days during the year 2004 SWM time. Different colours represent the elevations at which the trajectories reach Bangalore and Kolkata. Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) (Draxler and Hess 1998) analysis from the National Oceanic and Atmospheric Administration (NOAA) Air Research Laboratory (*http://www.arl.noaa.gov/ready/hysplit4.html*) was used to trace the origin of the air-parcel back in time. HYSPLIT is a complete system for computing simple air parcel trajectories as well as complex transport, dispersion, chemical transformation, and deposition simulations (Rolph, 2016 and Stein et**

al. 2015). Back trajectory analysis revealed Arabian Sea and the Northern Indian Ocean as the major contributors for moisture in the air parcels responsible for rain happening during SWM period over the Indian region. (Rahul et al. 2016, Gimeno et al. 2010a, 2011).

The dimensions of the modelling boxes designed along the transport path was based on the HYSPLIT trajectories such that majority of the trajectories pass through them. Level of 850 hPa which corresponds to 1500m was considered as the core of air transport path via low level jet stream (Rao, 1976) in our study.

Comment:

Discussion and results P4L9-13 I miss more discussion concerning the HYSPLIT results. Are you talking about the figure 4? Please, refer to the figures in the text. If I understood it correctly, from figure 4 you can identify only the regions crossed by the air particles tracks, not the moisture uptakes or losses by the particles. How can you affirm that there is "moisture originating from the Arabian Sea" from this figure?

Response:

Rahul et al. (2016) identified Arabian Sea region to be the source of moisture parcel for rain happening at Bangalore. This was based on backward air trajectories and out-going long wave radiation fluxes confirming convective activity. A similar argument was previously suggested to be the origin for the 95% of the moisture particles that reach the Indian region based on global Lagrangian particle dispersion model runs using ECMWF (European Centre for Medium-Range Weather Forecasts) operational analysis for June, July and August (Gimeno et al. 2010a,2011). We cited these references for validation purpose.

Estimates of land and sea moisture contributions to the monsoonal rain over Kolkata deduced based on isotopic analysis of rain water

Shaakir Shabir Dar[1*] and Prosenjit Ghosh[1]

[1]Centre for Earth Sciences, Indian Institute of Science, Bangalore India

shaakirshabir@ceas.iisc.ernet.in,pghoshceas@ceas.iisc.ernet.in

ABSTRACT

Moisture source responsible for rains over Kolkata during summer monsoon can be traced using backward air mass trajectory analysis. A summary of such trajectories between June to September, suggests that these moisture parcels originate from the Arabian Sea, and travel over the dry continental region and then over the Bay of Bengal (BoB) prior to its arrival at Kolkata. We use monthly satellite and ground based observation of the hydro-meteorological variables together with isotopic data of rain water from Bangalore, BoB and Kakinada to quantify the contributions of advected continental and oceanic water vapour in the Kolkata rains. The vapour mass during its transit is modified from its original isotopic value due to addition of evaporated moisture from the BoB and further modification happens due to the process of rain out on the way. The evaporated component is estimated using the Craig and Gordon equation. The rain out process has been simulated using a Rayleigh fractionation model. In this simulation we assume that the initial isotopic composition of vapour originating from the continent is similar to the rainwater composition measured at Bangalore. In order to explain the monthly isotopic composition in southwest monsoon rainwater over Kolkata we invoke 65-75% moisture contribution from the BoB, the remaining moisture comes from the continental landmass.

Keywords: *Stable isotope, Monsoon, Vapour Mixing.*

INTRODUCTION:

Indian landmass receives rainfall during summer time due to winds favoring moisture transport from the region of Inter tropical converge zone (ITCZ) located over Indian Ocean region. The process of moisture transport from the oceanic region commences in June and continues till September. This period is generally termed as the Indian Summer Monsoon (ISM) or the South-West Monsoon (SWM). Summer monsoon rain constitutes ~50-90% of the total annual rainfall (Gadgil, 2003) received by the entire country. The air parcel during its northward journey picks up vapour from the surrounding seas; namely Arabian Sea and the Bay of Bengal. Studies have shown that the composition of surface sea water surrounding the Indian landmass can be isotopically distinguishable i.e. heavier values for water in Arabian Sea located in the west and dominated by strong evaporative forcing, whereas the Bay of Bengal (BoB) water in the east is characterized by lighter value due to the influence of rainfall and river runoff [(Gupta & Deshpande, 2003),(Rangarajan, et al., 2013) and (Rahul et al. 2016)]. Isotopic composition measured in the shallow ground water along the transect between Kolkata and New Delhi were used in a simple box model to estimate the percentage of moisture contribution in rain due to the process of evapo-transpiration (ET) (Krishanamurthy & Bhattacharya, 1991). In this study shallow ground water over Indo Gangetic plain was treated as equivalent of rain water due to its short residence time and the estimated value suggests presence of ~40% moisture due to recyling of shallow ground water or rainwater. This was further verified in a recent study where the average monthly (June – September) isotopic composition of rainwater measured at Kolkata and New Delhi were explained by supplementing 20%moisture from the Arabian Sea to a parcel, modified due to Rayleigh based fractionation of original moisture parcel originating from the BoB, beside 45% moisture being included as ET component from recycling of rainwater (Sengupta & Sarkar 2006)(rephrase this statement in pieces) In a more recent observation on vapour isotopic composition from the Northern flood plain station located at the city of Roorkee three moisture sources for vapour were detected; namely BoB, western disturbances and lake water from the nearby region (Krishan, et al., 2014). Satellite based observations and pan evaporation data suggest that the quantity of moisture returned to the atmosphere by the process of evaporation is substantial and plays a significant role in governing the regional water budget. According to global estimates, the hydrological cycle involves an annual rate of evaporation of about half a million cubic kilometers of water, around 86% of which come from the oceans, with the remainder having its origin from the continents (Quante & Matthias, 2006). Using the Eulerian moisture tracking method at a global scale, Ent et al. (2010) showed that about 40% of terrestrial precipitation originates from land evaporation. However, significant variations from this average global value can occur depending on position of station on the continent and net radiation influx, along with influence of factors like land use/land cover (Gimeno et al. 2012).

A quantitative understanding of the hydrological components involving advected and recycled moisture and vapour as a result Evapo-transpiration (ET) is possible using stable isotope tracers (Kendall & McDonnell, 1999). Stable isotopes of oxygen and hydrogen in water provide a method to determine contributions of land and ocean derived moisture due to their distinct isotopic ratios. Isotopic ratios in rainwater and water vapour mirror the isotopic composition of moisture sources modified by the fractionation associated with the mechanism of precipitation during its transport to a continental site [(Dansgard 1964),(Rozanski, 1993),(Gat 2000),(Araguás-Araguás et al. 2000)(Gat, 2005) and (Yoshimura, 2015)]. Attempts have been made for the quantitative determination of the precipitation components using regional analytical models [eg. (Gat & Matsui, 1991), (Krishanamurthy & Bhattacharya, 1991), (Sengupta & Sarkar, 2006),(Froehlich et al. 2008), (Peng et al. 2011),(Pang & Froehlich 2013),(Rahul et al. 2016), etc] and global physics based(?is it physical models?) [eg. (Yoshimura et al. 2003, 2008, 2010), (Jasechko et al. 2013),(Keys et al. 2014), etc] models at different timescales.

Global Network on Isotopes in Precipitation (GNIP) [International Atomic Energy Agency (IAEA)] study over India offer several years of rainwater isotopic values at monthly resolution for different stations along the travel path. This database proves to be extremely useful to delineate the contribution of different moisture sources to the regional precipitation.

In this study we use the rainwater isotopic data from BoB and three stations namely Bangalore, Kakinada and Kolkata. We have used simultaneous satellite based meteorological observations in a two component mixing model to deduce the moisture contribution from continental landmass due to advection (also designated as ET based moisture) and the supply from evaporation of BoB surface water during the year 2004.

DATA AND METHODS:

The easterly winds during the SWM transport moisture that generates over Arabian Sea to continental destinations over Southern India (Rao, 1976). The global Lagrangian particle dispersion model which runs using ECMWF (European Centre for Medium-Range Weather Forecasts) operational analysis for June, July and August suggests that Arabian Sea and the Northern Indian Ocean act as sources of 95% of the moisture responsible for precipitation over the Indian landmass . (Gimeno et al. 2010a,2011). The isotopic composition of rain water at Bangalore during the SWM of 2010 revealed 70% moisture contribution from Arabian Sea while continental rainwater recycling contributed the rest (Rahul et al.,2016) .

The moisture parcels originating from the Arabian Sea move over land under the prevailing easterly winds get modified in terms of composition due to participation of moisture from other sources like recycling of rain or ET of shallow ground water. The measured isotopic composition of rain/vapour at Bangalore, situated equidistant ~ 300 Km inland from the Arabian Sea in the west and BoB in the east serves as an ideal representation of the isotopic signature of continental moisture. Backward air-mass trajectories indicate that the moisture parcel may further travel over land or over BoB before re-entering the Indo-Gangetic plain (Figure 3). The SWM monsoon enter into the Indo Gangetic flood plain through a corridor over eastern coast, near Kolkata.

The air-masses were traced for -48 hours, -72 hours and -96 hours at 200m, 500m, 1000m, 1500m, 2000m and 2500m elevations above the mean sea level at Bangalore and Kolkata for all rainy days during SWM of the year 2004, which experienced a normal rainfall. Indian Meteorological department (IMD) defines a year as a normal monsoon year if the rainfall is half to less than 1½ times the normal (over the land area).Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) (Draxler and Hess 1998) analysis from the National Oceanic and Atmospheric Administration (NOAA) Air Research Laboratory (*http://www.arl.noaa.gov/ready/hysplit4.html*) is used to track the air-parcel back in time. HYSPLIT is a complete system used for computing simple air parcel trajectories as well as complex transport, dispersion, chemical transformation, and deposition simulations (Stein et al. 2015). The back trajectories for Bangalore and Kolkata are displayed in Figure 3

The contribution of continental and BoB moisture to the rain precipitated at Kolkata during SWM is modelled using the isotopic composition of rainwater collected at Bangalore and over the BoB. As the air parcel travels towards Kolkata its isotopic composition gets modified due to interplay of processes like rainout and moisture addition from the BoB . To model the isotopic composition, transect between Bangalore and Kolkata is divided into seven boxes of equal dimensions (Figure 1). It was designed in such a way that the majority of air-mass trajectories passes through it. This size of the boxes is chosen so that the total precipitable water within each box remains fairly uniform. The monthly averaged isotopic $\delta^{18}O$ values for the SWM of different years (2004, 2008, 2010, and 2013) were extracted from IAEA data and other publications. The monthly averaged $\delta^{18}O$ value at Kolkata (2004) is modelled by adopting the isotopic composition of monthly rainwater at Bangalore as an original value (initial condition). While simulating model with two component mixing we assumed near identical (similar to Bangalore) values for moisture originating from the continent. The $\delta^{18}O$ values measured in the rainwater at Kakinada (2004), which is located within the modelling transect is useful to validate our assumption.

Together with rainwater isotopic data, monthly averaged meteorological data (2004) and isotopic composition of BoB surface water have been used in this study. Precipitation (*P*) data from the Tropical Rainfall Measurement Mission Project (TRMM) (Huffman et al., 2007) (3B42 V7 derived), Goddard Space Flight Center Distributed Active Archive Center (GSFC DAAC) *(http://trmm.gsfc.nasa.gov/)*, Total Precipitable Water (*W*) , Air Temperature (*T*), Relative Humidity (*h*), Wind Speed: from the Reanalysis 2 (Kanamitsu et al. 2002) dataset*; (http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis2.html)* have been used*.* Surface water isotopic composition over BoB was extracted from the Global seawater Oxygen-18 Database (V-1.21) (Schmidt et al. 1999) *(http://data.giss.nasa.gov/o18data/)*. The monthly averaged oxygen isotopic composition ($\delta^{18}O$) for the SWM of the year 2004 was retrieved from the IAEA-GNIP (*http://www-naweb.iaea.org/napc/ih/IHS_resources_gnip.html)* dataset for the stations located at Bangalore, Kolkata and Kakinada. The isotopic composition of rainwater at Bangalore for the year 2008 was obtained from Rangarajan et al. (2013), while for other year (2010 and 2013) was obtained from Rahul P et al. (2016a,b) respectively. Figure 2 depicts the oxygen isotopic composition ($\delta^{18}O$) for Bangalore, Kakinada and Kolkata. Table 1 shows the oxygen isotopic composition ($\delta^{18}O$) of BoB rainfall for the year 2012 collected during the CTCZ-2012 expedition. An average isotopic composition of rainfall recorded over the BoB is used to obtain a representative isotopic value for demonstrating the evaporated moisture on top of BoB using the Craig and Gordon equation.

Designing Rayleigh's model for rainout

Rayleigh's distillation equation was modified to include a vapour mixing process. The isotopic composition of the continental and the BoB vapour mixture has been numerically simulated using the improvised version of Rayleigh distillation model. Figure 4 shows a schematic representation of the numerical expression and procedure. The model is run for the months covering SWM period. The oxygen isotopic composition of rainwater at the continental stations and the BoB, meteorological parameters, BoB surface water isotopic composition and satellite based precipitation data are used as input parameters to actuate the model. The $\delta^{18}O$ of Kolkata rain is predicted after introducing modification in the isotopic composition of residual vapour measured at Bangalore. The procedure involves accounting for the rainout in the Rayleigh's distillation model and a two component mixing formulation where advected vapour and the vapour supplied from the BoB are mixed to generate an integrated vapour.

$\delta^{18}O$ value in vapour over Bangalore region is used as an original isotopic value (initial condition) to start the model run. Isotopic composition of the vapour is calculated from the measured isotopic values of rain water assuming an equilibrium fractionation. As the moisture parcel loses water by the process of rainout the residual vapour isotopic composition is given by:

$$\delta_{Vi} = (\delta_{Vi,0} + 1) f^{\alpha_i - 1} - 1$$

δ_{Vi} is the isotopic composition of the vapour after rainout in the i^{th} box, $\delta_{Vi,0}$ is the initial isotopic composition of vapour, α_i is the fractionation factor (Majoube, 1971) calculated for the dew point temperature at 850hPa. The level is appropriately suited as the core of air transport via low level jet stream adjudged as the major transport pathway for the summer monsoon precipitation (Rao,1976). The fractionation factor is calculated for each box at this level. f_i is the fraction of vapour remaining in the air mass after rainout, given by:

$$f_i = \frac{W_1 - \sum P_i}{Wi}$$

W is the total precipitable water over the box and *P* is rainfall over each boxes the subscript denotes box number.

Upon leaving the continental landmass, the air parcels traverses over the BoB and picks up moisture along the way leading to a modification of the original vapour isotopic value. In order to account for this change, the modified equation to calculate the fraction of vapour remaining in the i^{th} box is:

$$f_i = \frac{W_1 - (P_i - E_{i-1})}{W_i}$$

E is the evaporation contribution from the BoB. Moisture in the air mass is replenished as it travels over the BoB.

The isotopic composition of the evaporation flux over each box is estimated using the Craig and Gordon model (Craig & Gordon, 1965):

$$\delta_{Vi(BOB)} = \frac{\delta_l - h\delta_a - \epsilon^* - \epsilon}{1 - h}$$

Where $\delta_{Vi(BoB)}$ is the isotopic composition of the vapour supplied by the BoB, δ_l is the BoB surface water isotopic composition, *h* is the relative humidity, δ_a is the isotopic composition of the vapour over the BoB calculated assuming an equilibrium relationship between rain and vapour over the BoB, ϵ^* is equilibrium enrichment factor (Majoube, 1971) and ϵ is the kinetic enrichment factor (Merlivat & Jouzel, 1979). $\epsilon^* = (\alpha - 1) \times 10^3$, α is the equilibrium fractionation factor.

The isotopic composition of the resultant vapour formed by mixing of two moisture sources depletes the heavy isotopes with progressive rainout. The depleted vapour moves to the next box and is mixed with the moisture generated by the BoB, the resulting vapour undergoes rainout and so on until final value in Kolkata rainwater is achieved.

DISCUSSION AND RESULTS:

After spawning from the Arabian Sea, as the air mass enters the Indian landmass through the western coast, the constitution of the moisture parcel gets modified due to the process of rainout, addition of continental vapour or the BoB before re-entering the corridor of Indo Gangetic plain through the east coast. The isotopic composition of vapour over Bangalore is taken as the representative of the continental vapour. The air mass isotopic composition is modified as it moves towards Kolkata under the prevailing wind direction during the SWM. The $\delta^{18}O$ value decreases consistently as the SWM period progresses and follows a pattern similar to each other for the sites at Kolkata and Bangalore. The $\delta^{18}O$ of rainfall approaches minima for the month of October for both locations (Figure 2Monthly averaged $\delta^{18}O$ isotopic composition for Bangalore (blue circle) station. The bars represent the standard deviation from monthly mean. Isotopic composition of Kakinada (green square) and Kolkata (red diamond for the year 2004Figure 2). A consistent pattern recorded in the isotopic values during the SWM period at both sites suggests a common source for moisture responsible for rain. This is confirmed from the observation documenting the backward trajectories for both stations. However, there were situations during SWM period where a large difference in the monthly rainwater isotopic data of the two stations is noted. On the other hand, such lack of consistent temporal pattern suggests involvement of different sources. In the time series analysis of rainfall $\delta^{18}O$, a monthly lag in registering the isotopic minima is noticeable corresponding to the timing of rainfall maxima at both the stations. This indirectly implies participation of second moisture source in case of Kolkata precipitation. Such pattern can be consistently explained employing Rayleigh distillation model after taking into account the rainout process and mixing of vapour generated from the BoB region.

The air parcel during SWM period moves towards Kolkata from Bangalore under the prevailing wind where the original isotopic composition is modified due to the interplay of i) rainout which follows Rayleigh type distillation and ii) mixing of the vapour generated over the BoB. For *E=0* i.e. assuming no moisture contribution from the BoB for the whole season, the model derived $\delta^{18}O$ value for rainfall at Kolkata is -8.04±0.96 ‰. This value is lighter than the observed value by 2.3‰.

Table 2 shows fraction of vapour remaining in the air mass (*f*) and the isotopic composition of vapour ($\delta^{18}O_v$) calculated over each modelling boxes for the SWM months. The vapour isotopic composition decreases as the monsoon progresses with most depleted values observed during the month of September. This depletion is indicative of the gradual reduction in contribution of BoB moisture due to saturated nature of incoming air parcel laden with vapour originating from Arabian Sea. Figure 5 shows the *E/P* ratio for each of the boxes (*E=0* for the first box since the BoB contribution at Bangalore is assumed to be zero). The mixing of the advected component and the BoB component led to modification of the vapour isotopic composition. The final isotopic composition of the vapour is governed by the relative contributions of both of these sources.

Sengupta & Sarkar, 2006 held the cyclonic disturbances originating from the BoB responsible for the maximum drop in isotopic values during early phase of the SWM. There is a tendency of low pressure zones to develop and remain confined to ~20^0N in the BoB during onset time. The position of such low pressure zones shifts southward to ~15^0N during the later phase of the SWM. This explains the isotopic variability recorded in the Kolkata rainfall (Sengupta & Sarkar 2006) during SWM period. It is noteworthy that the significant differences in the evaporation contribution arise from box number 5,6 and 7. The contribution from evaporation for the first four boxes remains somewhat the same for the whole period of the SWM. For the month of September, the contribution from box 5,6 and 7 is smaller than the boxes 1-4. This can be attributed to the decreasing strength of the monsoonal wind and more contribution of moisture originating from the continent. Rayleigh's distillation model is used to track further changes in the isotopic composition of the vapour ($\delta^{18}O_v$), as the vapour loses water progressively during condensation. The Figure 6 depicts the model results at monthly and the seasonal time scales. The isotopic composition of vapour is calculated from the rainfall isotopic composition calculated assuming equilibrium between vapour and the liquid phase. The model has used three values as initial conditions ($\delta^{18}O_v$ [($\delta^{18}O_{mean}+\delta^{18}O_{SD}$), $\delta^{18}O_{mean}$ and ($\delta^{18}O_{mean}-\delta^{18}O_{SD}$)), capturing the uncertainty or spread in the continental vapour isotopic value measured at Bangalore. This includes monthly uncertainty in rainwater isotope values based on number of samples collected during a month. The model performance is fair, within the uncertainty limits at a monthly time scale. However, the model performance improves significantly when the same simulation is run with average $\delta^{18}O$ for the entire SWM period, the modeled value is -6.05(±0.69) ‰ and the actual observed value is 5.76(±1.99) ‰.

Model Validation:

The Figure 6 depicts the mean modeled isotopic composition for rain water at each box with error bars representing the standard deviation from the mean values of isotopes obtained from ($\delta^{18}O_v$ [($\delta^{18}O_{mean}$+$\delta^{18}O_{SD}$), $\delta^{18}O_{mean}$ and ($\delta^{18}O_{mean}$-$\delta^{18}O_{SD}$)] uncertainty in the initial vapour isotopic values. To validate our model predicted results, the values are compared with the isotopic composition of rain at Kakinada, which lies in the transport pathway. The station lies in the Box 4 of the transect (Figure 1) and the $\delta^{18}O$ of rain observed at Kakinada during the SWM is -3.8(±2.23) ‰. The observed value is very close to the model predicted value of - 4.16(±1.27) ‰.

The model simulation yields a varying monthly contribution of vapour from land and oceanic sources. The BoB acts as an active source of moisture at the beginning of SWM and its contribution to vapour as simulated by the model over Kolkata (Box7) given as a percentage of the total precipitable water is 92±8% in June 73±16% in July 62±17% in August and 47±17% in September. The BoB vapour supply diminishes as the monsoon gradually becomes weaker and wind patterns reverses upon onset of north easterlies.

CONCLUSIONS:

In this study we have quantified the source of moisture precipitating as rain at Kolkata. Here we identify two source using HYSPLIT back trajectories targeting continent and BoB. The BoB is the major moisture contributor to precipitation at Kolkata supplying overall 65-75% of the total precipitation during the entire SWM and the continental contribution varies from 25-35%. The contribution of the BoB as the source of moisture at Kolkata attained maxima at the commencement of SWM during June but as strength of the monsoon decreases, the moisture contribution from BoB diminishes while the role of continent contributing vapour due to recycling of rainwater or shallow ground water become important. The performance of the model is limited at a monthly time scale but performs well for the whole period of the SWM within the limit of uncertainty. The limitations at a monthly scale may arise due to the model assumption where the isotopic composition of the BoB surface water and the isotopic composition of rain over the BoB were held constant over the entire duration of SWM. This assumption is made due to the unavailability of high resolution datasets over the BoB. The performance of the model can be improved taking into consideration the monthly variation in the vapour and surface water isotopic composition of rainfall over the BoB. This is the first estimates of such kind where variable contribution of continental moisture in rain over Kolkata is invoked to explain the observation in the $\delta^{18}O$ of rainwater measured at the same site. The findings have major implications to the regional water vapour budget in the context of past and future climatic scenarios. The role of phenomena like El Nino Southern Oscillation (ENSO) or Indian Ocean Dipole (IOD) on the relative contributions of continental and oceanic sources during the SWM can be investigated with simultaneous observation.

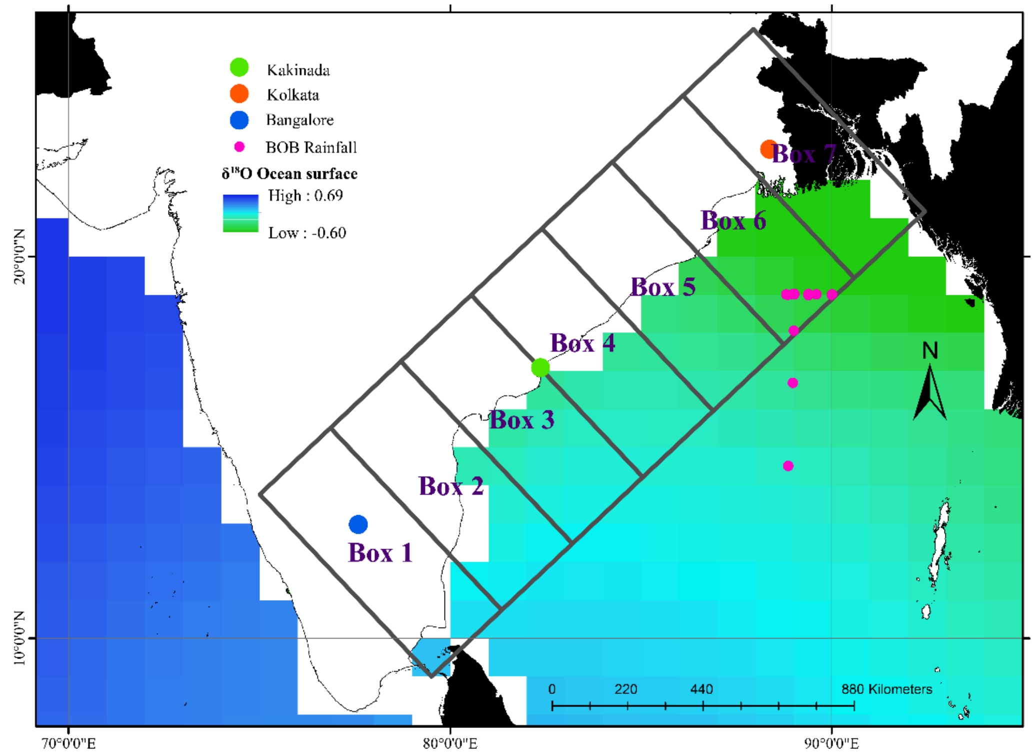

Figure 1 Study area and modelling transect divided into boxes of equal dimensions. The modelling transect was chosen such that majority of the HYSPLIT trajectories pass through it. Orange, green and blue circles represent the location of Kolkata, Kakinada and Bangalore stations respectively. The ocean layer represents the $\delta^{18}O$ surface water isotopic composition (Schmidt et al. 1999). The isotopic composition remains fairly constant over the BoB with slightly depleted values near the Ganges delta (Box 7) due to the freshwater mixing. Solid pink circles represent the locations of rainfall collected for isotopic measurements over the BoB.

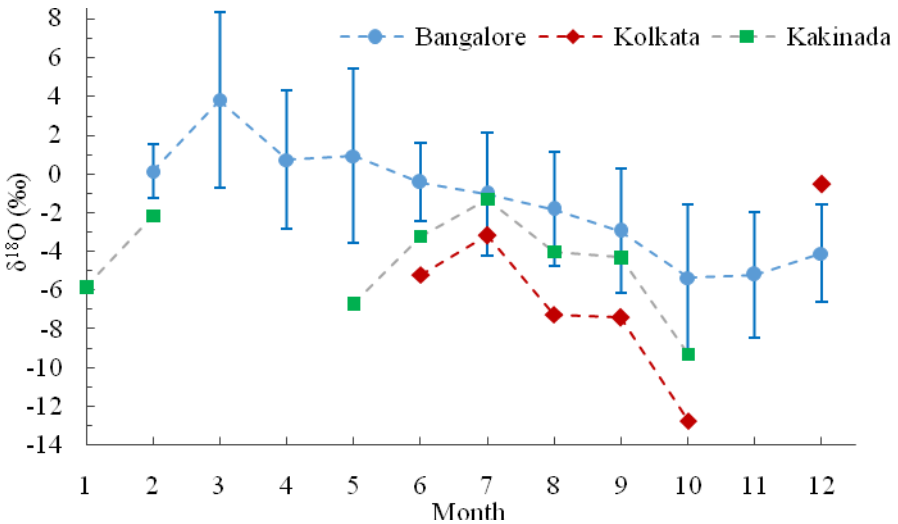

Figure 2Monthly averaged $\delta^{18}O$ isotopic composition for Bangalore (blue circle) station. The bars represent the standard deviation from monthly mean. Isotopic composition of Kakinada (green square) and Kolkata (red diamond for the year 2004.

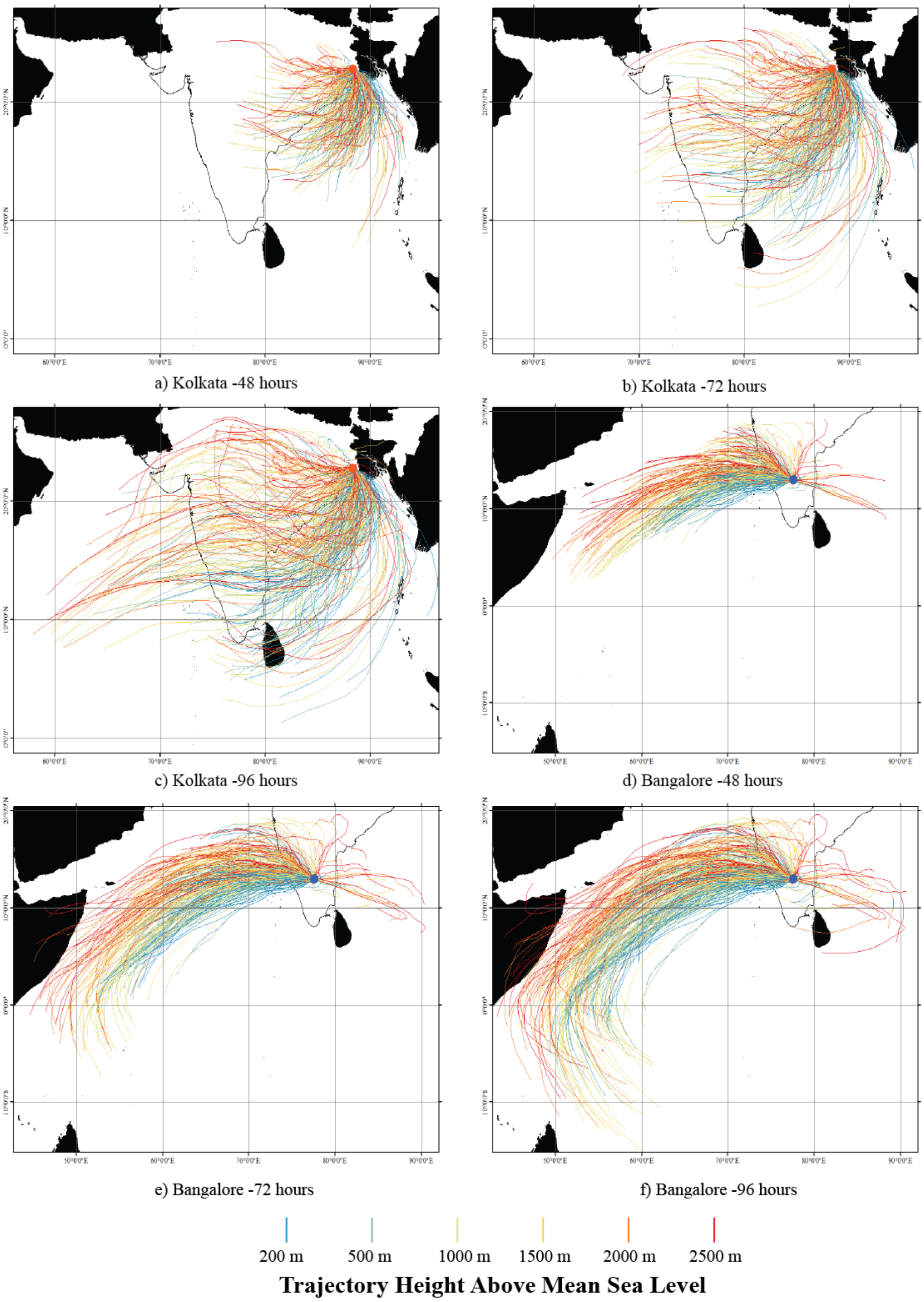

Figure 3Backward air-mass Trajectories (-48 hours, -72 Hours and -96 hours prior to a rainy day at 200m, 500m, 1000m, 1500m, 2000m and 2500m above MSL for a single year (2004) at Bangalore and Kolkata during all rainy days of the SWM. The modelling transect is chosen such that majority of the trajectories pass through it.

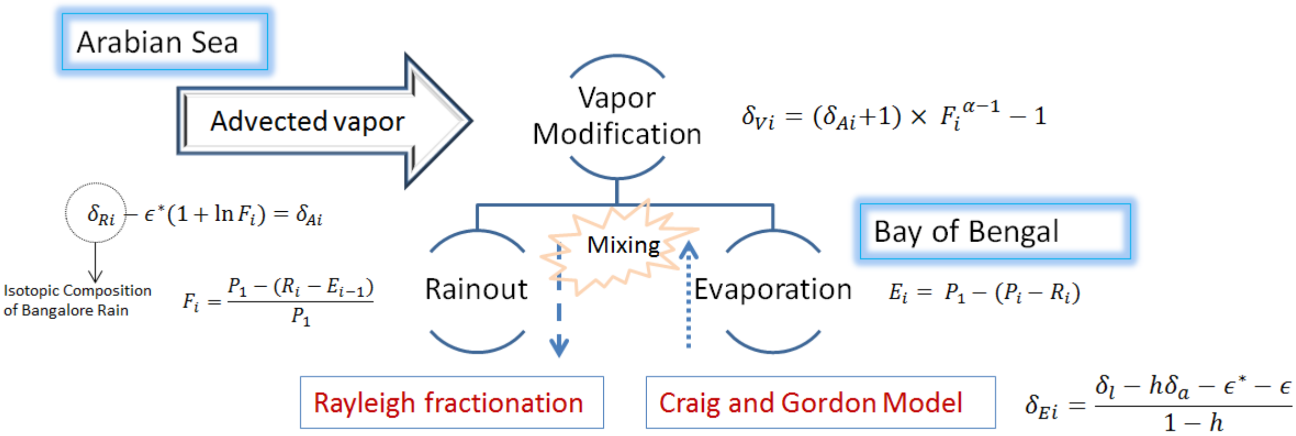

Figure 4 Schematic of the modelling procedure involved.

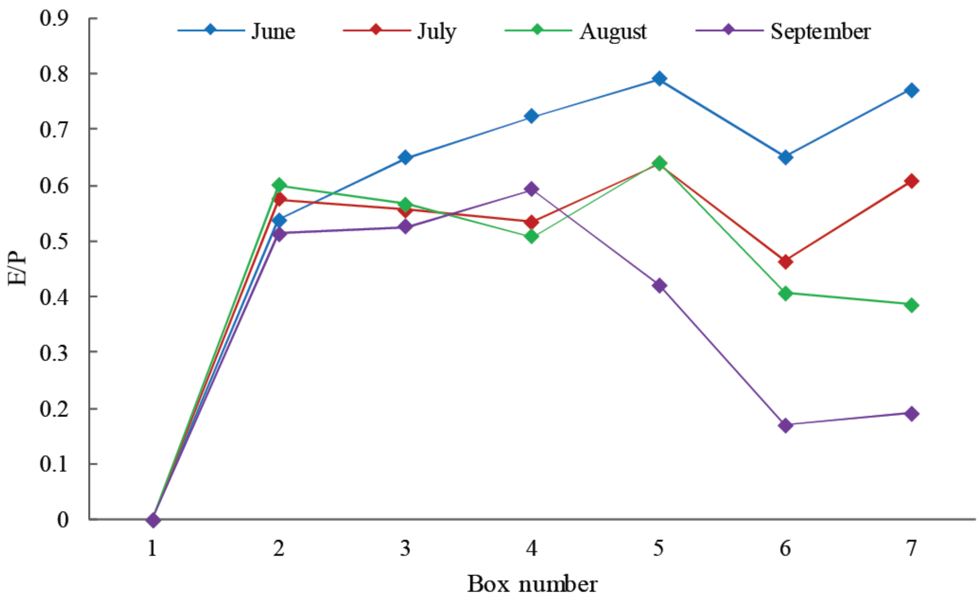

Figure 5E/P ratio for each box of the modelling transect for the SWM months of 2004..

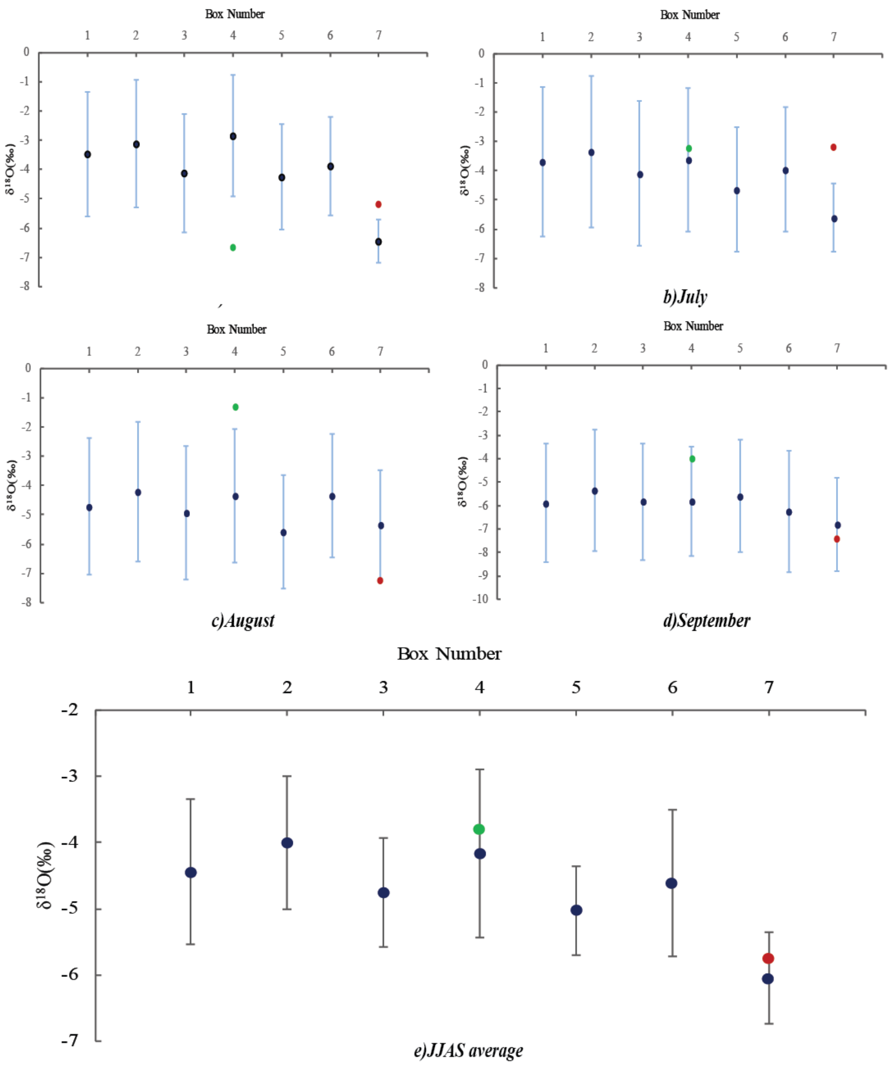

Figure 6Dark blue represents the mean modelled δ^{18}O (‰) isotopic composition of rain over each box as calculated from Rayleigh's distillation equation(5a-5d for the individual SWM months and 5e for the whole period of the SWM). The bars represent the standard deviation. Green and red solid circles represent the mean observed isotopic composition of rain at Kakinada and Kolkata respectively.

Table 1Rainwater isotopic composition and collection locations over BoB collected during 2012 Expedition.

S no.	Latitude (Decimal Degrees)	Longitude (Decimal Degrees)	*δ^{18}O(‰)*
1	18.99	89.39	-1.74
2	18.99	89.39	-1.55
3	18.99	89.39	-1.53
4	19.02	89.39	-1.31
5	19.00	89.60	-4.26
7	19.00	90.00	-4.80
8	19.00	88.84	-3.71
9	19.00	88.84	-3.58
10	19.00	88.84	-3.55
11	19.01	88.80	-2.60
12	19.01	89.00	-3.18
13	19.01	89.00	-0.06
14	19.01	89.01	-2.04
15	19.01	89.01	-2.14
17	19.01	89.01	-1.42
18	19.00	89.01	-1.54

19	19.02	89.01	-1.32
20	19.02	89.01	-0.06
21	19.02	89.02	-0.04
22	19.02	89.02	-3.55
23	19.00	89.02	-2.98
24	19.00	89.00	-2.68
25	19.01	89.00	-2.84
26	19.01	89.01	-0.71
27	19.01	89.01	-0.78
28	19.01	89.00	-0.88
29	19.01	89.00	-0.97
30	19.01	89.01	-0.81
31	19.01	89.01	-0.14
32	18.06	89.01	-0.57
33	16.69	88.98	-1.98
34	14.51	88.86	-0.36

Table 2 Fraction of vapour remaining over each box and the modelled isotopic composition of vapour over each box for the year 2004. The values in brackets are the standard deviation from the calculated man values.

Box	**1**	**2**	**3**	**4**	**5**	**6**	**7**	
f	0.9354	0.9676	0.8748	0.9903	0.8588	0.8872	0.6804	**June**
$\delta^{18}O_v$(‰)	-13.11 (±2.57)	-13.10 (±2.58)	-13.08 (±2.50)	-13.08 (±2.52)	-13.06 (±2.39)	-13.03 (±2.33)	-12.98 (±1.96)	
f	0.9262	0.9586	0.8895	0.9295	0.8369	0.7504	0.9125	**July**
$\delta^{18}O_v$(‰)	-13.24 (±2.75)	-13.23 (±2.74)	-13.22 (±2.75)	-13.20 (±2.74)	-13.18 (±2.73)	-13.16 (±2.73)	-13.12 (±2.72)	
f	0.9135	0.9591	0.888	0.9407	0.8192	0.9286	0.8327	**August**
$\delta^{18}O_v$(‰)	-14.19 (±2.95)	-14.18 (±2.96)	-14.16 (±2.95)	-14.15 (±2.94)	-14.12 (±2.94)	-14.11 (±2.93)	-14.08 (±2.93)	
f	0.8987	0.9511	0.8986	0.8859	0.9103	0.8673	0.7761	**September**
$\delta^{18}O_v$(‰)	-15.32 (±3.21)	-15.31 (±3.21)	-15.29 (±3.20)	-15.27 (±3.20)	-15.25 (±3.20)	-15.23 (±3.19)	-15.19 (±3.18)	

References

Araguás-Araguás, L., Froehlich, K., and Rozanski, K.: Deuterium and oxygen-18 isotope composition of precipitation and atmospheric moisture, Hydrological Processes, 14, 1341–1355, 2000.

Craig, H. and Gordon, L. I.: Deuterium and oxygen 18 variations in the ocean and the marine atmosphere, 1965.

Dansgaard, W.: Stable isotopes in precipitation, Tellus, 16, 436–468, 1964.

Draxler, R. R. and Hess, G.: An overview of the HYSPLIT_4 modelling system for trajectories, Australian meteorological magazine, 47, 295–308, 1998.

Froehlich, K., Kralik, M., Papesch, W., Rank, D., Scheifinger, H., and Stichler, W.: Deuterium excess in precipitation of Alpine regions–moisture recycling, Isotopes in Environmental and Health Studies, 44, 61–70, 2008.

Gadgil, S.: The Indian monsoon and its variability, Annual Review of Earth and Planetary Sciences, 31, 429–467, 2003.

Gat, J.: Some classical concepts of isotope hydrology, in: Isotopes in the Water Cycle, pp. 127–137, Springer, 2005.

Gat, J. and Matsui, E.: Atmospheric water balance in the Amazon Basin: an isotopic evapotranspiration model, Journal of Geophysical Research: Atmospheres, 96, 13 179–13 188, 1991.

Gat, J. R.: Atmospheric water balance—the isotopic perspective, Hydrological processes, 14, 1357–1369, 2000.

Gimeno, L., Drumond, A., Nieto, R., Trigo, R. M., and Stohl, A.: On the origin of continental precipitation, Geophysical Research Letters,37, 2010.

Gimeno, L., Nieto, R., Drumond, A., Durán-Quesada, A. M., Stohl, A., Sodemann, H., and Trigo, R. M.: A close look at oceanic sources of continental precipitation, Eos, Transactions American Geophysical Union, 92, 193–194, 2011.

Gimeno, L., Stohl, A., Trigo, R. M., Dominguez, F., Yoshimura, K., Yu, L., Drumond, A., Durán-Quesada, A. M., and Nieto, R.: Oceanic and terrestrial sources of continental precipitation, Reviews of Geophysics, 50, 2012.

Gupta, S. and Deshpande, R.: Synoptic hydrology of India from the data of isotopes in precipitation, CURRENT SCIENCE-BANGALORE-,85, 1591–1595, 2003.

Huffman, G. J., Adler, R. F., Bolvin, D. T., and Nelkin, E. J.: The TRMM multi-satellite precipitation analysis (TMPA), in: Satellite rainfall applications for surface hydrology, pp. 3–22, Springer, 2010.

Jasechko, S., Sharp, Z. D., Gibson, J. J., Birks, S. J., Yi, Y., and Fawcett, P. J.: Terrestrial water fluxes dominated by transpiration, Nature,496, 347–350, 2013.

Kanamitsu, M., Ebisuzaki, W., Woollen, J., Yang, S.-K., Hnilo, J., Fiorino, M., and Potter, G.: Ncep–doe amip-ii reanalysis (r-2), Bulletin of the American Meteorological Society, 83, 1631–1643, 2002.

Kendall, C. and McDonnell, J. J.: Isotope tracers in catchment hydrology, Elsevier, 2012.

Keys, P. W., Barnes, E., Van der Ent, R., and Gordon, L. J.: Variability of moisture recycling using a precipitationshed framework, Hydrology and Earth System Sciences, 18, 3937, 2014.

Krishan, G., Rao, M., Kumar, B., Kumar, C., Kumar, S., Jaiswal, R., Rao, Y., Tripathi, S., Kumar, M., Garg, P., et al.: Monitoring of Southwest Monsoon using isotope analysis of ground level vapour (Glv) in Indian Sub-Continent, Journal of Earth Science and Climate Change, 5,2014.

Krishnamurthy, R. and Bhattacharya, S.: Stable oxygen and hydrogen isotope ratios in shallow ground waters from India and a study of the role of evapotranspiration in the Indian monsoon, in: Stable Isotope Geochemistry: A Tribute to Samuel Epstein, vol. 3, pp. 187–193,Geochemical Society Special Publications, 1991.

Majoube, M.: Fractionnement en oxygene-18 et en deuterium entre l'eau et sa vapeur, J. Chim. phys, 68, 1423–1436, 1971.

Merlivat, L. and Jouzel, J.: Global climatic interpretation of the deuterium-oxygen 18 relationship for precipitation, Journal of Geophysical Research: Oceans, 84, 5029–5033, 1979.

Peng, T.-R., Liu, K.-K., Wang, C.-H., and Chuang, K.-H.: A water isotope approach to assessing moisture recycling in the island-based precipitation of Taiwan: A case study in the western Pacific, Water Resources Research, 47, 2011.

Quante, M. and Matthias, V.: Water in the Earth's atmosphere, in: Journal de Physique IV (Proceedings), vol. 139, pp. 37–61, EDP sciences, 2006.

Rahul, P., Ghosh, P., and Bhattacharya, S.: Rainouts over the Arabian Sea and Western Ghats during moisture advection and recycling explain the isotopic composition of Bangalore summer rains, Journal of Geophysical Research: Atmospheres, 121, 6148–6163, 2016a.

Rahul, P., Ghosh, P., Bhattacharya, S., and Yoshimura, K.: Controlling factors of rainwater and water vapour isotopes at Bangalore, India:Constraints from observations in 2013 Indian monsoon, Journal of Geophysical Research: Atmospheres, 121, 2016b.

Rangarajan, R., Ghosh, P., and Naggs, F.: Seasonal variability of rainfall recorded in growth bands of the Giant African Land Snail Lis-sachatina fulica (Bowdich) from India, Chemical Geology, 357, 223–230, 2013.

Rao, Y.: Southwest monsoon, vol. 1, India Meteorological Department, 1976.

Rozanski, K., Araguás-Araguás, L., and Gonfiantini, R.: Isotopic patterns in modern global precipitation, Climate change in continentalisotopic records, pp. 1–36, 1993.

Schmidt, G., Bigg, G., and Rohling, E.: Global seawater oxygen-18 database–v1. 21, Online at http://data. giss. nasa. gov/o18data, online at http://data. giss. nasa. gov/o18data, 1999.

Sengupta, S. and Sarkar, A.: Stable isotope evidence of dual (Arabian Sea and Bay of Bengal) vapour sources in monsoonal precipitation over north India, Earth and Planetary Science Letters, 250, 511–521, 2006.

Stein, A., Draxler, R., Rolph, G., Stunder, B., Cohen, M., and Ngan, F.: NOAA's HYSPLIT atmospheric transport and dispersion modeling system, Bulletin of the American Meteorological Society, 96, 2059–2077, 2015.

Van der Ent, R. J., Savenije, H. H., Schaefli, B., and Steele-Dunne, S. C.: Origin and fate of atmospheric moisture over continents, Water Resources Research, 46, 2010.

Yoshimura, K.: Stable water isotopes in climatology, meteorology, and hydrology: A review, Journal of the Meteorological Society of Japan.Ser. II, 93, 513–533, 2015.

Yoshimura, K., Oki, T., Ohte, N., and Kanae, S.: A quantitative analysis of short-term 18O variability with a Rayleigh-type isotope circulation model, Journal of Geophysical Research: Atmospheres, 108, 2003.

Yoshimura, K., Kanamitsu, M., Noone, D., and Oki, T.: Historical isotope simulation using reanalysis atmospheric data, Journal of Geophys-ical Research: Atmospheres, 113, 2008.

Yoshimura, K., Kanamitsu, M., and Dettinger, M.: Regional downscaling for stable water isotopes: A case study of an atmospheric river event, Journal of Geophysical Research: Atmospheres, 115, 2010.