Earth Syst. Dynam. Discuss., doi:10.5194/esd-2016-63, 2016
Manuscript under review for journal Earth Syst. Dynam.
Published: 14 December 2016

Earth System Dynamics
Discussions
Open Access

Presence of continental and Bay of Bengal moisture in rainfall at Kolkata, revealed through simultaneous observation from land and sea during South-West monsoon of 2004

Shaakir Shabir Dar[a] and Prosenjit Ghosh[a]

[a]Centre for Earth Sciences, Indian Institute of Science, Bangalore, India 560012

Correspondence to: Prosenjit Ghosh (pghosh@ceas.iisc.ernet.in)

Abstract. The backward air mass trajectory analysis (HYSPLIT) during the summer monsoon suggests that the rain which precipitates at Kolkata is generated from a moisture parcel which originates from the Arabian Sea and moves inland over the dry Indian subcontinent or over the Bay of Bengal. We used monthly satellite and ground based measurements of the hydro-meteorological variables together with isotope data from Bangalore, Bay of Bengal and Kolkata and other locations to quantify the contribution of different moisture sources during the SW Monsoon. The vapor mass as it moves under the prevailing wind direction was subjected to isotopic modification due to addition of evaporated moisture from Bay of Bengal and rainout process. This was simulated using Craig and Gordon model and Rayleigh fractionation model respectively. The moisture generated during the process of evaporation from Bay of Bengal surface ocean gets advected towards the continent and precipitates as rainfall or snowfall over the Indo-Gangetic plain. We assumed based on our observation that the initial isotopic composition of vapor originating from the peninsular continental source is similar to our observation recorded at Bangalore station. It is found that the isotopic signature of Bangalore is completely lost albeit the significant contribution of the moisture from Bay of Bengal. To explain the isotopic composition of precipitation at Kolkata during the SW-Monsoon, it was necessary to invoke 75-80% moisture contribution from the Bay of Bengal whereas the evaporated moisture parcel from the Peninsular India contribute 25%-35%.

1 Introduction

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. Precipitation falling over the continents follows labyrinthine paths with the origin mostly restricted to oceanic setting. During its journey to the continental region the process like rainout, evaporation of rain water and additional moisture input from evapotranspiration of continental water bodies and surrounding vegetation further modify the water vapour content in the air parcel. The quantitative understanding of all these components; advected moisture, recycled moisture and vapor due to process of Evapotranspiration (ET) is possible using stable isotopic tracers Kendall and McDonnell (2012). Satellite based observation and pan evaporation data suggested 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 balance. Globally 40% of terrestrial precipitation originates from land evaporation alone van der Ent et al. (2010). However, on a regional scale significant variations from this global value are observed depending on the position of the continent and net radiation influx, beside factors like land use/land cover etc. Stable isotopes of oxygen and hydrogen in water provide alternate method to trace contribution of land derived moisture due its distinct isotopic ratios. The usefulness of this natural tracer in understanding the hydrological cycle and atmospheric circulation pattern is well documented. Isotopic ratios in rainwater and vapour mirror the isotopic composition of moisture source and reflect the fractionation associated with the mechanism of precipitation during it journey to a continental site Dansgaard (1964), Rozanski et al. (1993) and Gat (1996).

Indian region receives rainfall during summer time due to monsoonal winds which brings moisture packet from the Arabian Sea region and rain across the country. GNIP observatory network over India contain monthly data set covering several years of observations. Results are useful to understand the participation of different moisture source in a regional precipitation. Studies have shown influence of factors like isotopic composition of surface sea water surrounding the Indian landmass; with Arabian Sea (AS) being evaporation dominated and Bay of Bengal (BoB) precipitation and runoff dominated Gupta and Deshpande (2003), Rangarajan et al. (2013), Rahul et al. (2016). Based on isotopic analysis of air moisture at Roorkee India, Krishan et al. (2012) three water reservoirs for the origin of moisture was identified namely Bay of Bengal (BoB), Western Disturbances (WD) and enriched lake water. In a study conducted on shallow ground water isotopes across the intersect between Kolkata and New Delhi, the percentage of recycled moisture in the precipitation was quantified employing a simple box model Krishnamurthy and Bhattacharya (1991). The study predicted that 40% of rainwater that has precipitated has to be put back into the vapour system to explain the observation documented at New Delhi. This was further refined in a recent study where the average isotopic composition of rainfall at Kolkata and New Delhi was explained adopting $\approx 20\%$ mixing of Arabian Sea (AS) moisture with the vapour generated over Bay of Bengal (BOB) along with $\approx 45\%$ moisture been recycled due to Evapotranspiration Sengupta and Sarkar (2006). There have been repeated attempts to quantify the exact moisture recycling using the isotopic composition of precipitation.

The aim of the present study is quantification of moisture contribution from Bay of Bengal and continental vapour in the rain happening at Kolkata during the SW Monsoon period. This was possible based on simultaneous observations on monthly rainwater isotope ratio at Bangalore, Kolkata and rainwater samples collected across Bay of Bengal region during the time of the southwest monsoon.

2 Data and Methods

Transect between Bangalore and Kolkata is divided into boxes of equal dimensions depicted in Figure 1. The hydrometeorological remote sensing data is incorporated into a GIS framework and the meteorological parameters are derived for the study area. The data used for the study is: Precipitation (R) : TRMM ; .25 degree spatial resolution ($http://trmm.gsfc.nasa.gov/$), total precipitable water (P) , air temperature (T), relative humidity (h), wind speed: NCEP-DOE Reanalysis 2; 2.5 degree spatial resolution ($http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis2.html$), Global Sea Water Oxygen-18 Database ($http://data.giss.nasa.gov/o18data/$) and oxygen and hydrogen isotopic compositions of precipitation from International Atomic Energy Agency's Global Network in Precipitation (IAEA-GNIP) data for Kolkata and Bangalore $(http://www.naweb.iaea.org/napc/ih/IHS\_resources\_gnip.html)$ (Figure 2 and Figure 3).

The value of a meteorological parameter for each of the boxes is taken as an average of the 2.5 degree resolution pixels present within each of the boxes. TRMM data which is available at 0.25 degree spatial resolution is aggregated to 2.5 spatial resolution which is same as the spatial resolution of Reanalysis 2 data.

Backward Airmass Trajectories for the two stations is shown in (Figure 4). The airmass 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 of 2004 Southwest Monsoon. Back trajectory analysis reveals the origin of moisture parcel responsible for rain happening at Kolkata and Bangalore. While most of the air mass trajectories at Bangalore originate from the Arabian Sea, the majority of trajectories reaching Kolkata originate either from the continental region or Bay of Bengal. Statistical analysis of HYSPLIT data confirmed that the 85% of the trajectories originate or pass over Bay of Bengal suggesting a substantial contribution of Bay of Bengal vapour in rain at Kolkata.

The $\delta^{18}O$ of Kolkata rain is predicted accommodating the rain isotope values measured at Bangalore and employing the rainout process in the Rayleigh's distillation model. The $\delta^{18}O$ of vapor over Bangalore is adopted as initial composition to start the model run. The isotopic composition of vapor is calculated from the isotopic composition of rain assuming equilibrium. As the moisture packet loses water by condensation the isotopic composition of the vapor remaining after rainout is given by:

$$\delta V_i = (\delta V_{i_0} + 1) \times f_i^{\alpha_i - 1} - 1 \tag{1}$$

where δV_i is the isotopic composition of vapour after rainout in the i^{th} box, δV_{i_0} is the initial isotopic composition of vapour, α_i is the fractionation factor Majoube (1970) calculated for the dew point temperature at 850mb pressure level for the i^{th} box and f_i is the fraction of vapor remaining in the air-mass, given by:

$$F_i = \frac{P_1 - \sum R_i}{P_i} \tag{2}$$

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

Upon leaving the continental landmass, the air parcels traverse over the Bay of Bengal and pick up moisture along the way and hence the isotopic composition of the vapor changes. In order to account for this change, evaporation over each box is calculated by:

$$E_i = P_1 - (P_i - R_i) \tag{3}$$

E_i is the evaporation over the i^{th} box, the other symbols have same meaning.

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

$$\delta V_{iBOB} = \frac{\delta_l - h\delta_a - \epsilon^* - \epsilon}{1 - h} \tag{4}$$

Where δV_{iBOB} is the isotopic composition of the evaporation flux supplied by the Bay of Bengal, δ_l is the Bay of Bengal surface water isotopic composition, h is the relative humidity as a fraction of unity, δ_a is the isotopic composition of the vapour over the Bay of Bengal, calculated assuming equilibrium between rain over BOB and the isotopic composition (Table 1-CTCZ-2012), $\epsilon*$ is equilibrium enrichment factor and ϵ is the kinetic enrichment factor given by Merlivat and Jouzel (1979), where $\epsilon* = (\alpha - 1)10^3$, α is the equilibrium fractionation factor.

Therefore, the modified equation to calculate the fraction of vapour remaining in the i^{th} box is:

$$F_i = \frac{P_1 - (R_i - E_{i-1})}{P_i} \tag{5}$$

The final isotopic composition of each box is calculated assuming complete mixing between the two moisture contributors.

3 Discussion and results

Trajectories of air parcel for both the locations suggest that the moisture originating from the Arabian Sea during Southwest monsoon undergoes significant modification in composition due to additional moisture from the continent or Bay of Bengal or both prior to arrival at Kolkata. Large scatter in the monthly rainwater isotopic record of the two stations and a lack of correlation is indicative of the importance of atmospheric circulation processes which includes continental input and the Bay of Bengal influence in modifying the rainfall isotopic composition recorded at the Bangalore station. For both stations, the $\delta^{18}O$ of rainwater is heavier during pre monsoon months. During March the $\delta^{18}O$ of rainwater at Kolkata is around 0‰, however more enriched values are recorded at Bangalore station. The isotopic composition steadily decreases with progressive time and follows a similar pattern for both sites reaching minimum value during the month of October. During JJAS, the $\delta^{18}O$ values at Bangalore station are enriched than that of Kolkata, which is possibly the result of gradual rainout of vapor source from Bangalore to Kolkata. The progressive depletion during the southwest monsoon period (JJAS) at both the sample sites suggests common source for moisture origin, confirming the observation documented based on HYSPLIT trajectories. However, the difference in the $\delta^{18}O$ values recorded at both the stations is suggestive of modification due to involvement of another moisture source contributing to Kolkata precipitation. In the time series analysis of rainfall and isotopes for both the stations, one month lag in the minimum isotopic signature was noticeable corresponding to timing of maximum rainfall recorded at the station data. This indirectly implies participation of second moisture source in regional precipitation. Therefore, we should be able to explain the precipitation at Kolkata employing Rayleigh distillation model after taking into consideration the isotopic variability recorded in the moisture generated by the Bay of Bengal and mixing with the advected Arabian Sea vapour.

3.1 Designing Rayleigh's model for rainout

We redesigned the Rayleigh distillation model by including a vapour mixing process where new vapour generated from the Bay of Bengal will mix with the continental vapour in transit. Figure 5 shows a schematic representation of the procedure. The model is run at a monthly time step for the south west monsoon taking the average monthly precipitation (δ) oxygen isotopic composition from IAEA GNIP dataset for the respective stations, isotopic composition of rainfall collected over Bay of Bengal during the CTCZ-2012 expeditions, and the climatological (2000-2010) monthly averages of the meteorological parameters; Relative humidity(h), Total precipitable water (P) from the reanalysis data, precipitation (P) from TRMM. Evaporation (E) is calculated, assuming that lessening of the air mass content by rainout is compensated by addition of evaporation from the Bay of Bengal, calculated using Equation (3). 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. All the calculations in the model are done after calculating the isotopic composition of vapor. This fractionation is based assuming equilibrium between the isotopic composition of vapour and the resulting rain and vice versa for meteorological conditions at 850mb pressure. Over Bay of Bengal, kinetic fractionation incorporated into the Graig and Gordon model is used to calculate the vapor isotopic composition. Using a simple two component mixing between isotopic compositions of the advected vapor and the vapor supplied by the Bay of Bengal, the final isotopic composition of the moisture is obtained.

Therefore, as the air mass moves towards Kolkata under the prevailing wind direction during the SW monsoon, the original isotopic composition is modified due to the processes of i) rainout which follows Rayleigh type distillation and ii) mixing of the vapor generated over the Bay of Bengal. Table 2 shows the calculated average values of evaporation(E), Fraction of vapour remaining(F) and the isotopic composition of vapor($\delta^{18}O_v$)over each modelling box for the summer monsoon months. Evaporation is calculated using equation (3), (P) being the Total Precipitable water over each box and the R being the precipitation from the TRMM data. the fraction of vapour remaining the airmass (F) is calculated using Equation(5) incorporating the evaporative addition of Bay of Bengal to the total precipitable water over each box. The mixing of the advected Arabian Sea component and the evaporated Bay of Bengal component leads to isotopic modification of the vapor governed by the simple two component mixing process. 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 by condensation. It can be seen, as the monsoon progresses, the evaporative component i.e. the Bay of Bengal contribution becomes lesser. This can be attributed to the decreasing strength of the monsoon and more contribution from the continental branch. For $E = 0$ i.e. for no moisture contribution by the Bay of Bengal, isotopic composition of rainfall is -8.04±0.96 ‰. This value is depleted as compared to the observed value by about 2.5‰.

Table 3 depicts the model results at monthly and the seasonal basis. The model run is started assuming the average isotopic value of rain at Bangalore as the initial composition. The model is run with three values of initial conditions ($\delta^{18}O_{vapour}$ [($\delta^{18}O_{mean} + SD$), $\delta^{18}O_{mean}$ and ($\delta^{18}O_{mean} - SD$)]., reflecting the uncertainty in the isotopic composition. This includes monthly uncertainty in rainwater values based on number of sample for every month. The modelled values of rain over each box are calculated assuming equilibrium between vapour and the liquid phase. The model performs well and within the uncertainty limits at a monthly scale and the model performance improves significantly when the same simulation is run with average δ^{18}O rain composition for the entire SW-monsoon (JJAS) period. In the later case, the modelled $\delta^{18}O$ value of rain at Kolkata is -5.50 ‰ and the actual observed value is -5.54‰.

Figure 6 depicts the mean modelled isotopic composition of rain at each box with error bars representing the standard deviation from the mean isotopic composition obtained for ($\delta^{18}O_{mean} + SD$), $\delta^{18}O_{mean}$ and ($\delta^{18}O_{mean} - SD$). To validate our model predicted values, we compared our model results with the isotopic composition of rain at Kakinada, which lies within our modelling transect. Data of Kakinada station is available as IAEA-GNIP network station from the subcontinent. This station lies between Box3 and Box 4 and the average isotopic composition of rain at Kakinada during the SW monsoon is (-3.63±2.81‰). This observed value is very close to the modelled value (4.01±0.75‰), indicating the validity of the modelling procedure. Based on this observation we have shown that the rainwater isotopic signature at Kolkata is modified due to interplay of processes like evaporation contribution from the Bay of Bengal. The model simulation yields varying monthly contribution of the continental branch of the Arabian sea and Bay of Bengal vapour sources. The Bay of Bengal acts as an active source of moisture at the beginning of SW monsoon. Its contribution to precipitation as simulated by the model given as a percentage of the total rainfall is 77.07±8.08% in June 60.69±13.10% in July 38.48±15.3% in August and 19.12±13.23% in September for the box over Kolkata. It is noted that the Bay of Bengal vapour supply diminishes as the monsoon gradually becomes weaker and wind patterns change.

4 Conclusions

Previous studies have concluded Bay of Bengal to be the sole contributor of moisture towards precipitation at Kolkata. We identified two source regions contributing to precipitation at Kolkata using HYSPLIT back trajectories, originating over the continent or the Bay of Bengal and modelled the isotopic composition of precipitation at Kolkata. While Bay of Bengal remains a major moisture contributor to precipitation at Kolkata, but as the monsoon loses its strength, the peninsular moisture contribution becomes significant. The performance of the model is limited at a monthly time scale but performs well at a seasonal scale. The limitations at a monthly scale may arise due to the model assumption that the isotopic composition of Bay of Bengal surface water and the isotopic composition of rain is constant for the whole SW monsoon period. This assumption was made due to the unavailability of high resolution datasets over the Bay of Bengal. The performance of the model can be improved taking into consideration the seasonal variation in the rain and surface water isotopic composition of rainfall over the Bay of Bengal.

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Table 1. Rainwater isotopic composition ($\delta^{18}O$) over Bay of Bengal and their collection locations from the CTCZ-2012 expedition.

S no.	Latitude (Decimal Degrees)	Longitude (Decimal Degress)	$\delta^{18}O(‰)$	$\delta^{2}H(‰)$	d-excess
1	18.99	89.39	-1.74	-5.41	8.52
2	18.99	89.39	-1.55	-6.38	6.03
3	18.99	89.39	-1.53	-5.50	6.72
4	19.02	89.39	-1.31	-6.13	4.34
5	19.00	89.60	-4.26	-33.52	0.54
7	19.00	90.00	-4.80	-32.54	5.85
8	19.00	88.84	-3.71	-26.41	3.26
9	19.00	88.84	-3.58	-23.96	4.68
10	19.00	88.84	-3.55	-25.71	2.69
11	19.01	88.80	-2.60	-13.75	7.05
12	19.01	89.00	-3.18	-18.71	6.75
13	19.01	89.00	-0.06	1.65	2.15
14	19.01	89.01	-2.04	-9.61	6.71
15	19.01	89.01	-2.14	-11.40	5.74
17	19.01	89.01	-1.42	-7.21	4.16
18	19.00	89.01	-1.54	-11.23	1.09
19	19.02	89.01	-1.32	-8.60	1.98
20	19.02	89.01	-0.06	3.75	4.24
21	19.02	89.02	-0.04	3.54	3.86
22	19.02	89.02	-3.55	-15.50	12.89
23	19.00	89.02	-2.98	-15.60	8.23
24	19.00	89.00	-2.68	-13.88	7.54
25	19.01	89.00	-2.84	-12.17	10.59
26	19.01	89.01	-0.71	0.56	6.27
27	19.01	89.01	-0.78	0.81	7.05
28	19.01	89.00	-0.88	-4.16	2.88
29	19.01	89.00	-0.97	-7.72	0.05
30	19.01	89.01	-0.81	-7.16	-0.66
31	19.01	89.01	-0.14	-9.93	-8.81
32	18.06	89.01	-0.57	-2.17	2.42
33	16.69	88.98	-1.98	-8.33	7.54
34	14.51	88.86	-0.36	3.53	6.39

Table 2. Table shows the mean values of evaporation contribution from the Bay of Bengal (E), fraction of vapor remaining over each box(F) and the modelled isotopic composition of vapor over each box ($\delta^{18}O_v$). The values in brackets is the standard deviation from the mean values.

Box	*1*	*2*	*3*	*4*	*5*	*6*	*7*	
E(mm)	3.12 (±0.94)	2.52 ±(1.50)	5.56 (±1.70)	4.36 (±1.77)	8.85 (±1.89)	9.29 (±0.47)	19.07 (±2.00)	**June**
F	0.9354	0.9676	0.8748	0.9903	0.8588	0.8872	0.6804	
$\delta^{18}O_v$(‰)	-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)	
E(mm)	3.76 (±1.41)	3.36 (±1.50)	5.00 (±0.81)	4.59 (±1.20)	8.25 (±1.24)	6.35 (±1.24)	11.57 (±3.5)	**July**
F	0.9262	0.9586	0.8895	0.9295	0.8369	0.7504	0.9125	
$\delta^{18}O_v$(‰)	-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)	
E(mm)	4.24 (±1.40)	3.74 (±1.5)	5.21 (±0.82)	4.11 (±1.10)	8.30 (±1.24)	4.80 (±1.63)	5.00 (±2.00)	**August**
F	0.9135	0.9591	0.888	0.9407	0.8192	0.9286	0.8327	
$\delta^{18}O_v$(‰)	-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)	
E(mm)	4.39 (±1.70)	3.34 (±1.5)	4.06 (±0.81)	5.33 (±1.24)	3.90 (±1.24)	1.64 (±1.24)	2.17 (±1.50)	**September**
F	0.8987	0.9511	0.8986	0.8859	0.9103	0.8673	0.7761	
$\delta^{18}O_v$(‰)	-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)	

Table 3. Table below shows the mean observed monthly isotopic composition ($\delta^{18}O$ ‰) of rain Kolkata and the modelled isotopic rain composition taking the isotopic composition of rain at Bangalore as the initial condition for the model run. The number in brackets is the standard deviation from the mean value

	Bangalore	***Kolkata*** $\delta^{18}O$ ***Rain***	
	$\delta^{18}O$ ***Rain***	***Observed***	***Modelled***
JJAS	-1.61(±0.97)	-5.54(±1.99)	-5.47(±1.29)
June	-0.76 (±2.64)	-2.49 (±3.24)	-3.88(±1.67)
July	-0.97 (±3.18)	-5.08 (±2.43)	-5.61(±1.17)
August	-1.82 (±2.96)	-6.83 (±2.27)	-5.34(±2.15)
September	-2.90 (±3.22)	-7.76 (±3.05)	-7.03(±2.52)

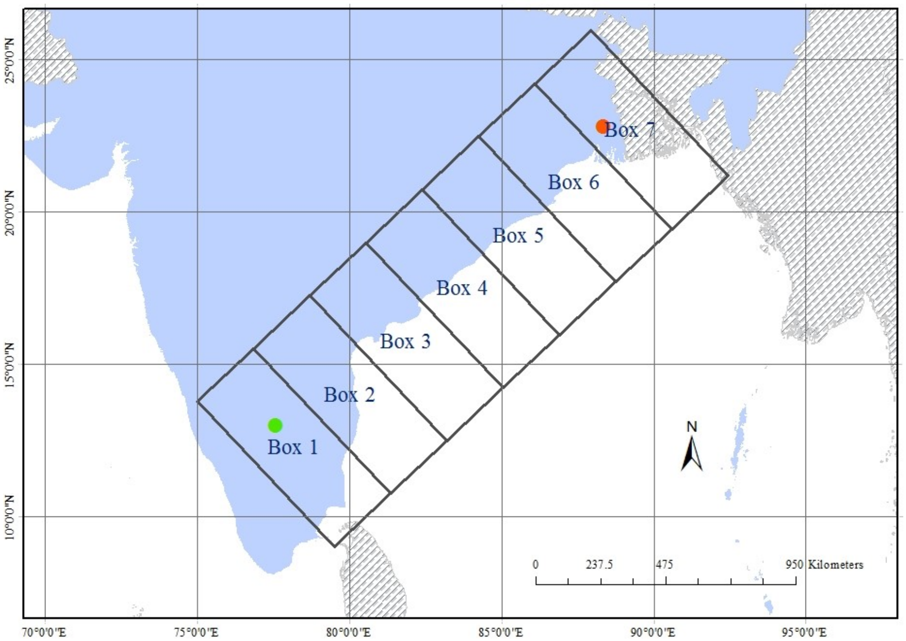


Figure 1. Study area and modelling transect divided into boxes of equal dimensions. the size of the boxes was chosen so that majority of the air-mass trajectories pass through it between the Bangalore and Kolkata transect. Red and green circles represent the location of Kolkata and Bangalore stations respectively. The isotopic composition of rain at Kakinada which is used to validate the model, lies between Box3 and Box4

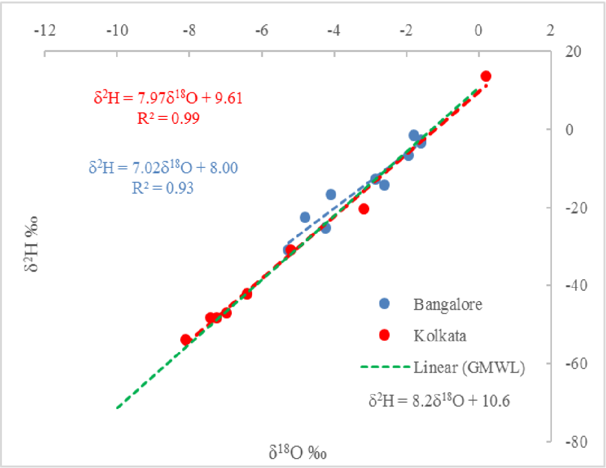


Figure 2. Local meteoric water lines at the Bengaluru and Kolkata for the SW monsoon from the IAEA-GNIP data for both stations and Global Meteoric Water Line given by Rozanski et al. (1993).

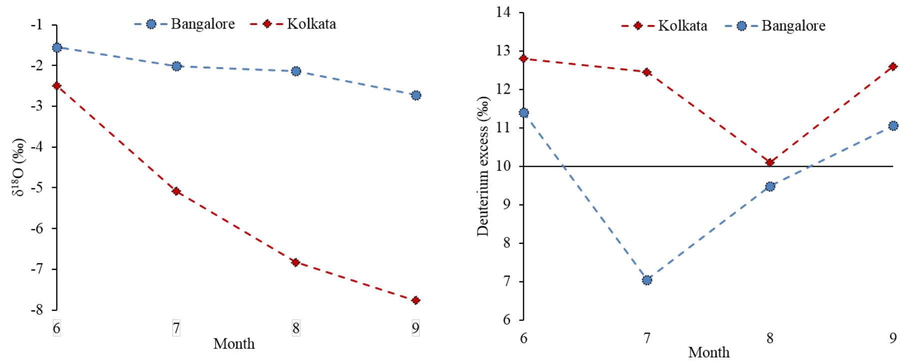
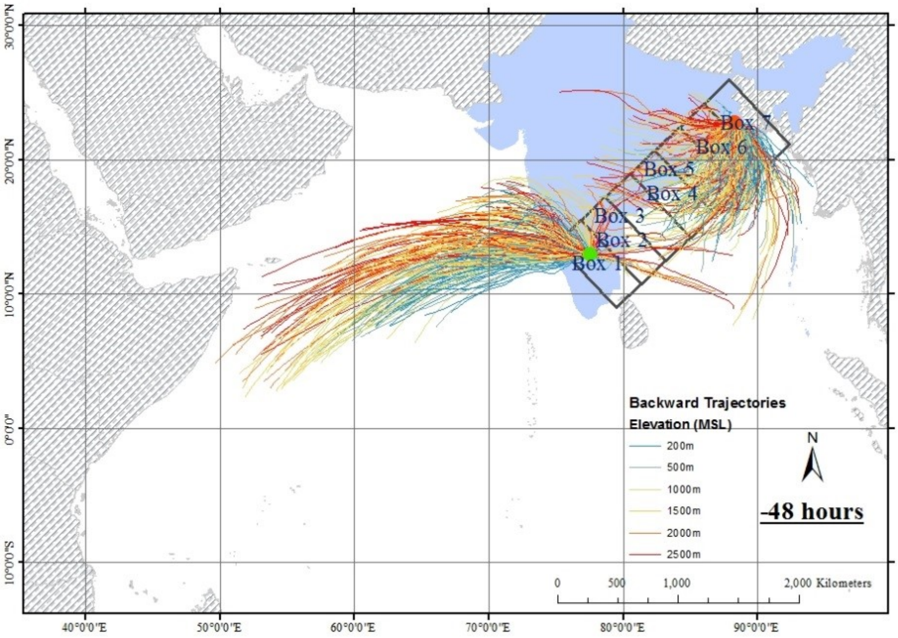


Figure 3. Monthly averaged $\delta^{18}O$ isotopic composition and d-excess for two stations during the SW monsoon period . Both stations follow a similar depletion pattern for $\delta^{18}O$ indicating they are supplied by the same moisture source. The d-excess for Kolkata is greater but higher variability is observed at Bangalore. The highest difference between the two stations being observed during the start of the SW monsoon. (Source:IAEA-GNIP)



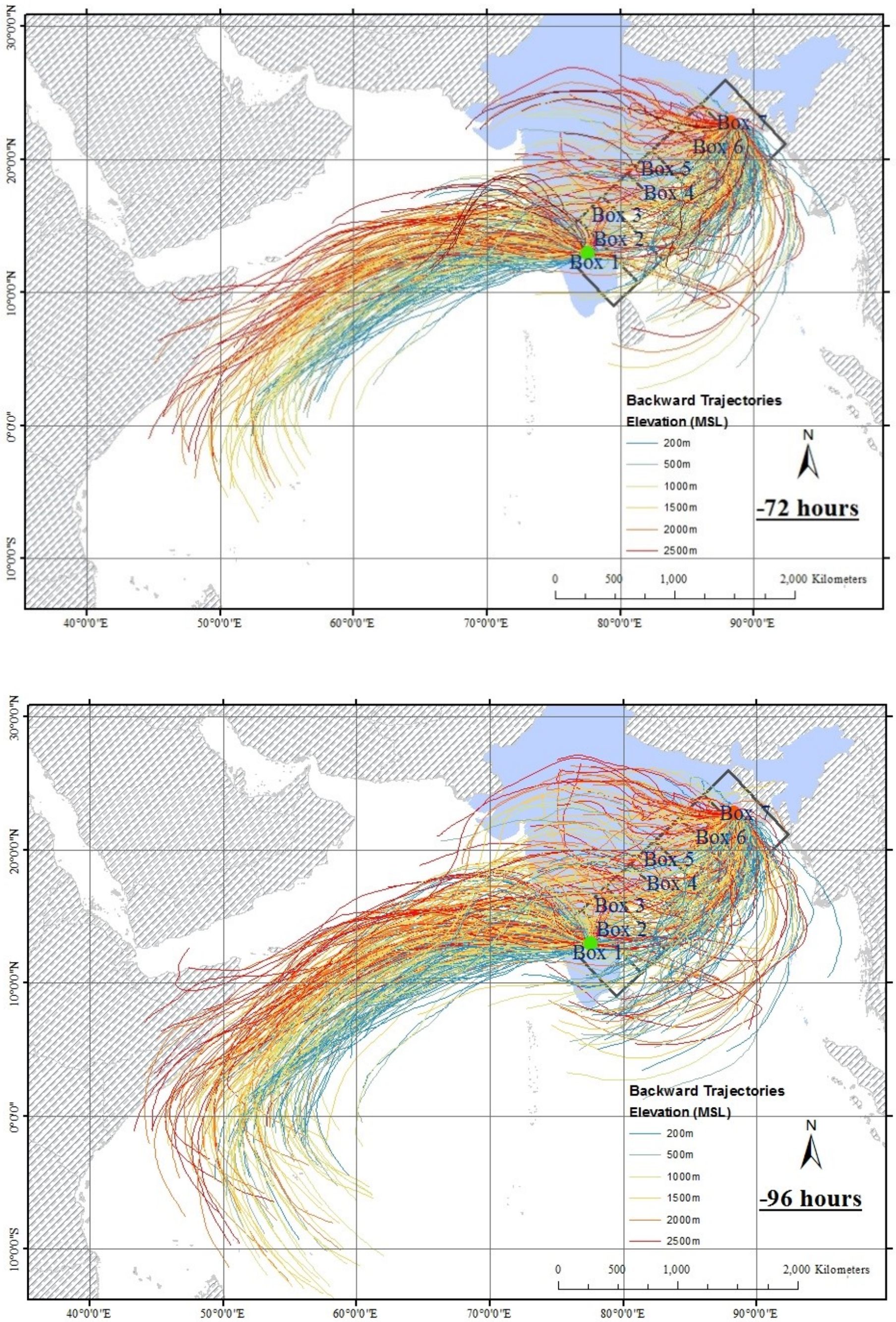


Figure 4. Backward air-mass Trajectories (-48 hours, -72 Hours and -96 hours prior to a rainy day at 200m, 500m, 1000m, 1500m, 2000m and 2500m above MSL for a single year (2004) at Bengaluru and Kolkata during all rainy days of the SW Monsoon. It can be seen that majority of the trajectories pass through the modelling transect. Three types of trajectories can be identified, originating from Arabian Sea, Bay of Bengal or land.

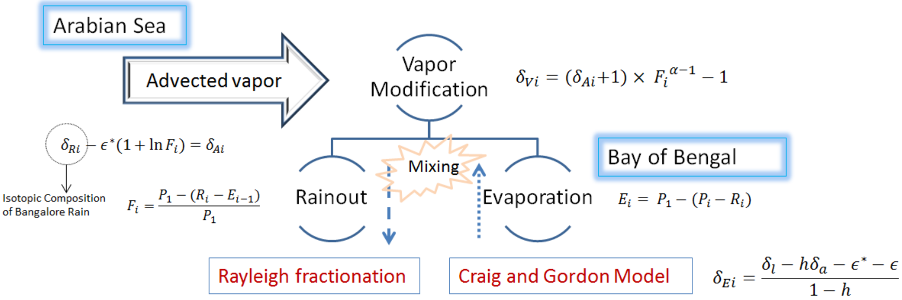


Figure 5. Schematic of the modelling procedure involved. Moisture supplied by the Arabian Sea under the prevailing wind direction is modified by rainout and vapour addition by the Bay of Bengal. The final composition is as result of mixing between the moisture from the two sources.

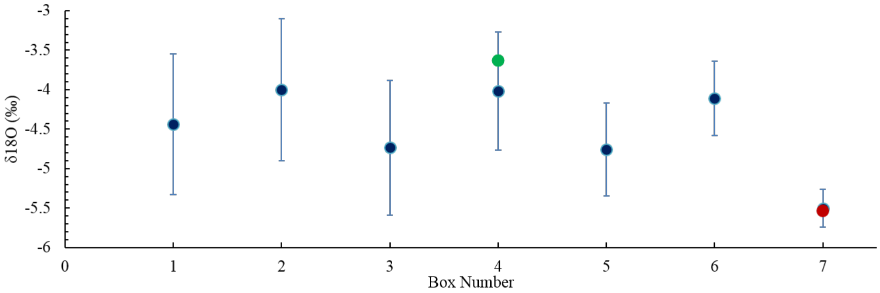


Figure 6. Dark blue represents the modelled isotopic composition of rain over each box as calculated from Rayleigh's distillation equation. The green solid circle represents the observed isotopic composition of rain at Kakinada Station(2004) and the red solid circle is the observed average isotopic composition of rain at Kolkata during the SW monsoon. It is clear that our model predicts the isotopic composition of stations in the boxes within the modelling transect.