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

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**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, suggest that these moisture parcels originate from the Arabian Sea, 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 observations 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 is 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 at Kolkata we invoke 65-75% moisture contribution from the BoB, the remaining moisture is from the continental landmass.

## 1 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. 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 received by the entire country (Gadgil, 2003). 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 and Deshpande (2003), Rangarajan et al. (2013) and Rahul et al. (2016a)). 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) (Krishnamurthy and 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 suggested presence of $\sim$ 40% moisture due to recycling 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 $\sim$ 20% moisture from the Arabian Sea to a parcel, modified due to Rayleigh based fractionation of original moisture parcel originating from the BoB, beside $\sim$ 45% moisture being included as ET component from recycling. 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 regions (Krishan et al., 2014). Satellite based observations and pan evaporation data indicate 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 and Matthias, 2006). Using the Eulerian moisture tracking method in a global study, Van der 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 land recycled moisture is possible using stable isotope tracers (Kendall and McDonnell, 2012). 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 ( Dansgaard (1964), Rozanski et al. (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 and Matsui (1991), Krishnamurthy and Bhattacharya (1991), Sengupta and Sarkar (2006), Froehlich et al. (2008), Peng et al. (2011), Rahul et al. (2016a), etc) and global physical models(eg. Yoshimura et al. (2003, 2008, 2010), Jasechko et al. (2013), Keys et al. (2014), etc) 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 the 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 land based moisture) and supply from evaporation of the BoB surface water during the year 2004.

## 2 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 reveal 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., 2010, 2011). The isotopic composition of rain water at Bangalore during the SWM of 2010 was explained using 70% moisture contribution from Arabian Sea while continental rainwater recycling contributed the rest (Rahul et al., 2016a). 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 land recycling. The measured isotopic composition of rain/vapour at Bangalore, situated equidistant $\sim$ 300 Km inland from the Arabian Sea in the west and the 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 the BoB before re-entering the Indo-Gangetic plain (Figure A3). 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 using the meteorological input from the Reanalysis 2 data. 2004 was a normal monsoon year. 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 A3 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 A1). 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 for 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 the BoB surface water have been used in this study. Precipitation data from the Tropical Rainfall Measurement Mission Project (TRMM) (Huffman et al., 2010) (3B42 V7 derived), Goddard Space Flight Center Distributed Active Archive Center (GSFC DAAC) *(http://trmm.gsfc.nasa.gov/)*, Total Precipitable Water, Air Temperature, Relative Humidity and 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/IHSresourcesgnip.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 form Rahul et al. (2016a, b) respectively. The figure A2 depicts the oxygen isotopic composition ($\delta^{18}O$) for Bangalore, Kakinada and Kolkata. Table A1 shows the oxygen isotopic composition ($\delta^{18}O$) of BoB rainfall for the year 2012 collected during the CTCZ-2012 expedition. Anaverage isotopic composition of rainfall recorded over the BoB is used to obtain a representative isotopic value for demonstrating the evaporated moisture over the BoB using the Craig and Gordon equation.

### 2.1 Designing Rayleigh's model for rainout

Rayleigh's distillation equation is 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 A4 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:

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

where $\delta V_i$ is the isotopic composition of vapour after rainout in the $i^{th}$ box, $\delta V_{i_0}$ is the initial isotopic composition of vapour, $\alpha_i$ is the fractionation factor (Majoube, 1971) calculated for the dew point temperature at 850mb pressure level for the $i^{th}$ box and $f_i$ is the fraction of vapour remaining in the air-mass, given by:

$$f_i = \frac{W_1 - \sum P_i}{W_i} \tag{2}$$

where $W$ 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 traverse over the BoB and pick 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:

$$f_i = \frac{W_1 - (P_i - E_{i-1})}{W_i} \tag{3}$$

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 (1965) model:

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

Where $\delta V_{iBoB}$ is the isotopic composition of the evaporation flux supplied by the Bay of Bengal, $\delta_l$ is the Bay of Bengal surface water isotopic composition, h is the relative humidity as a fraction of unity, $\delta_a$ is the isotopic composition of the vapour over the Bay of Bengal, calculated assuming equilibrium relationship between rain and vapour over the BoB, $\epsilon*$ is equilibrium enrichment factor and $\epsilon$ is the kinetic enrichment factor given by (Merlivat and Jouzel, 1979), where $\epsilon* = (\alpha - 1)10^3$, $\alpha$ 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.

## 3 DISCUSSION AND RESULTS

After spawning from the Arabian Sea, as the air mass enters the Indian landmass through its western coast, the constitution of the moisture parcel gets modified due to the process of rainout, addition of continental vapour or the BoB vapour 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 isotopic composition of the air mass is modified as it moves towards Kolkata under the prevailing wind direction during the SWM. The rain water $\delta^{18}O$ value decreases consistently as the SWM period progresses and follows a pattern similar to each other for the sites at Kolkata and Bangalore. The $\delta^{18}O$ rainfall approaches minima for the month of October for both locations (Figure A2). A consistent pattern recorded in the isotopic values during the SWM period at both the sites suggests a common source for moisture responsible for rain. This was confirmed from the observation documenting the backward trajectories for both the stations. However, there were situations during SWM period where a large difference in the monthly rainwater isotopic data of the two stations was noted. Such lack of consistent temporal pattern on the other hand suggests involvement of different sources. In the time series analysis of rainfall $\delta^{18}O$ a monthly lag in registering the isotopic minima was 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 the 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 modelled 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 A2 shows fraction of vapour remaining in the air mass (*f*) and the isotopic composition of vapour ($\delta^{18}Ov$) 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 region. Figure A5 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 leads to modification of the vapour isotopic composition. The final isotopic composition of the vapour is governed by the relative contributions of both these sources. (Sengupta and 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 $\sim 20^0$N in the BoB during onset time. The position of such low pressure zones shifts southward to $\sim 15^0$n during the later phase of the SWM. This explains the isotopic variability recorded in the Kolkata rainfall (Sengupta and Sarkar, 2006) during SWM period. It is noteworthy to mention that the significant differences in the evaporation contribution arise from box number 5,6 and 7 The evaporation contribution from the first four boxes remaining 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 ($\delta^{18}O$), as the vapour loses water progressively during condensation. The figure A6 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 run used three values as initial conditions ($\delta^{18}O$ ($\delta^{18}O_{mean} + SD$), $\delta^{18}O_{mean}$ and ($\delta^{18}O_{mean} - SD$), capturing the uncertainty or spread in the continental vapour isotopic value measured at Bangalore. This includes monthly uncertainty in rainwater 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 improved 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) ‰.

## 3.1 Model Validation

The figure A6 depicts the mean modeled isotopic value for rain at each box with error bars representing the standard deviation from the mean isotopic value obtained from ($\delta^{18}O$ ($\delta^{18}O_{mean} + SD$), $\delta^{18}O_{mean}$ and ($\delta^{18}O_{mean} - SD$) uncertainty in the initial vapour isotopic value.To validate our model prediction, the results 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 A1) 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.

## 4 Conclusions

In this study we quantified the source of moisture precipitating as rain at Kolkata. The BoB is a 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 the SWM during June but as strength of the monsoon decreases, the moisture contribution from BoB diminishes while the role of continental vapour becomes 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 was 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 Kolkata. 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.

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**Table A1.** Rainwater isotopic composition and collection locations over BoB collected during 2012 Expedition.

| S no. | Latitude (Decimal Degrees) | Longitude (Decimal Degrees) | $\delta^{18}O$(‰) |
|---|---|---|---|
| 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 | 88.8 | -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 |

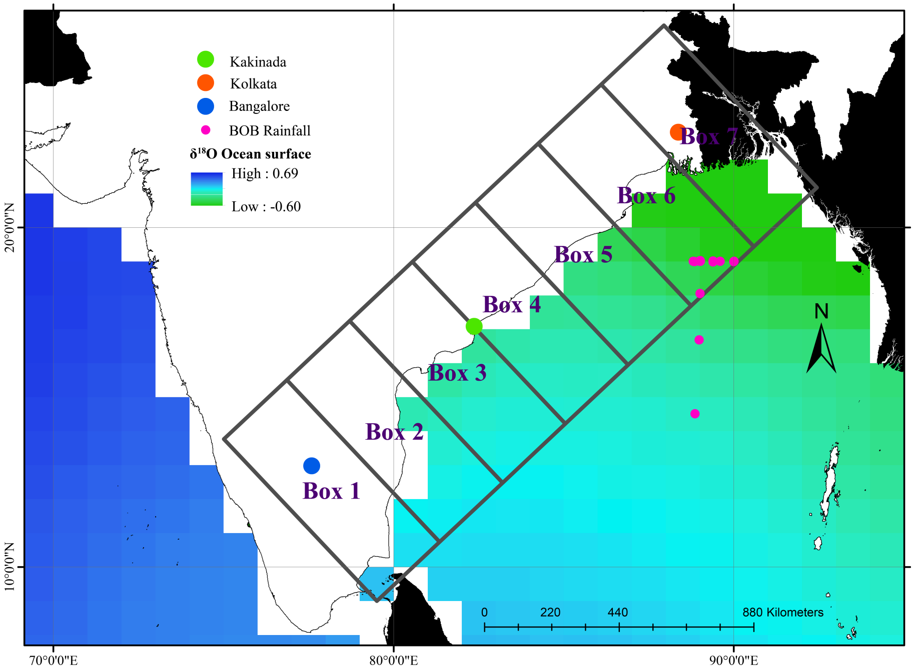


**Figure A1.** Study area and modelling transect divided into boxes of equal dimensions. The modelling transect was chosen such that majority of the HYSPLIT trajectories pass through it. Orange, green and blue circles represent the location of Kolkata, Kakinada and Bangalore stations respectively. The 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.

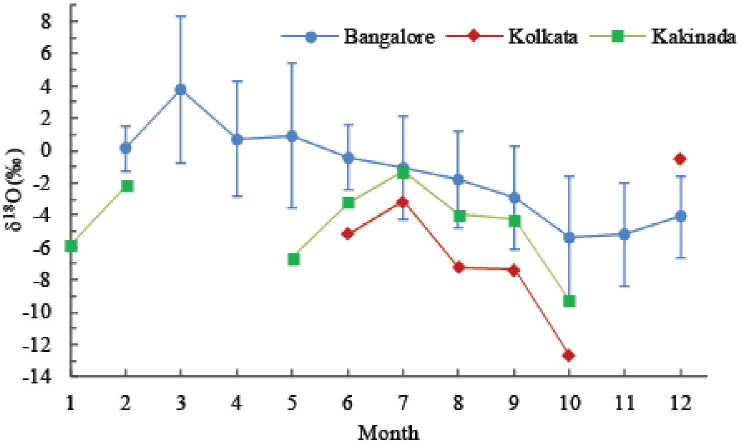
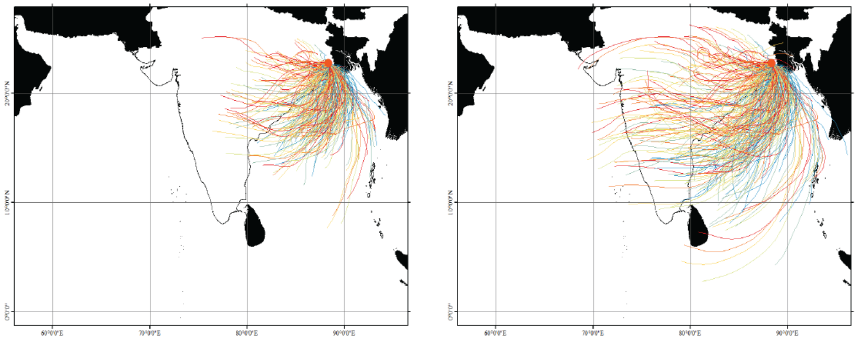
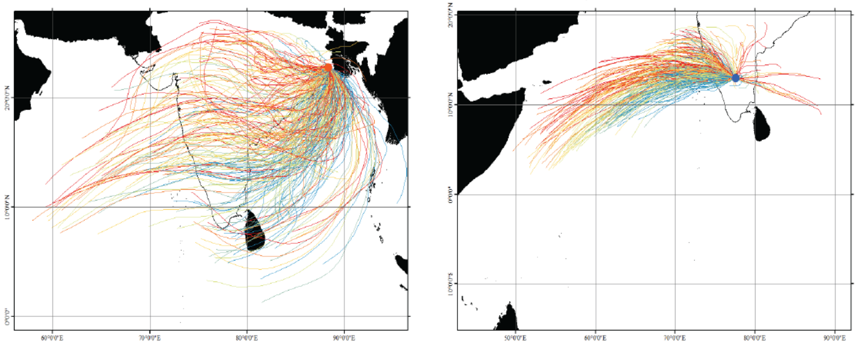


**Figure A2.** Monthly averaged $\delta^{18}O$ isotopic composition for Bangalore (blue circle) station. The bars represent the standard deviation from monthly mean. Isotopic composition of Kakinada (green square) and Kolkata (red diamond for the year 2004.



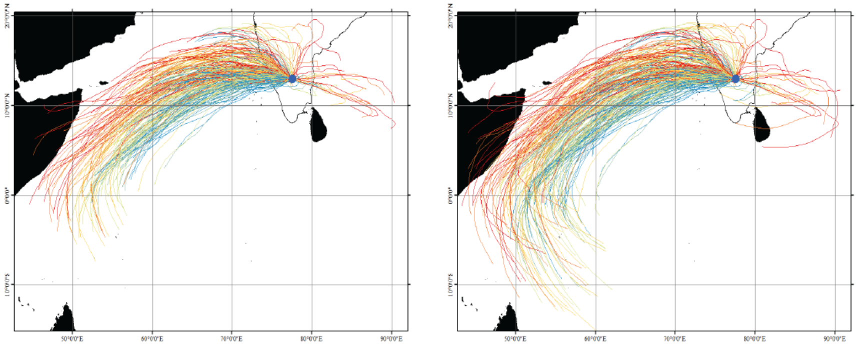
a) Kolkata -48 hours

b) Kolkata -72 hours



c) Kolkata -96 hours

d) Bangalore -48 hours



e) Bangalore -72 hours

f) Bangalore -96 hours

| 200 m | 500 m | 1000 m | 1500 m | 2000 m | 2500 m

**Trajectory Height Above Mean Sea Level**

**Figure A3.** 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 Bangalore and Kolkata during all rainy days of the SWM. The modelling transect is chosen such that majority of the trajectories pass through it.

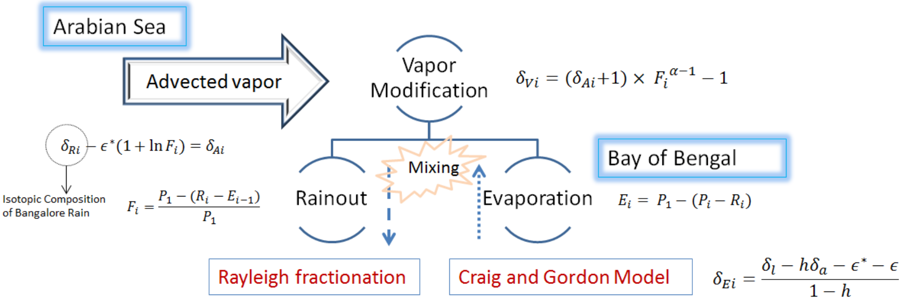


**Figure A4.** Schematic of the modelling procedure involved.

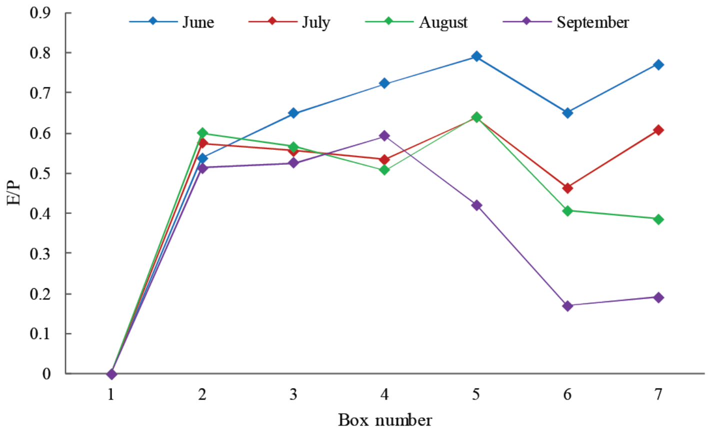
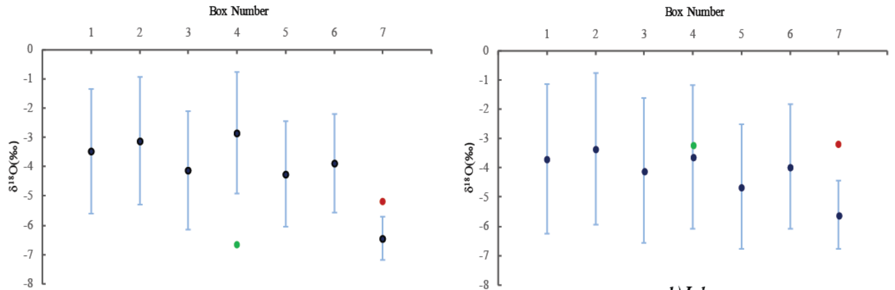
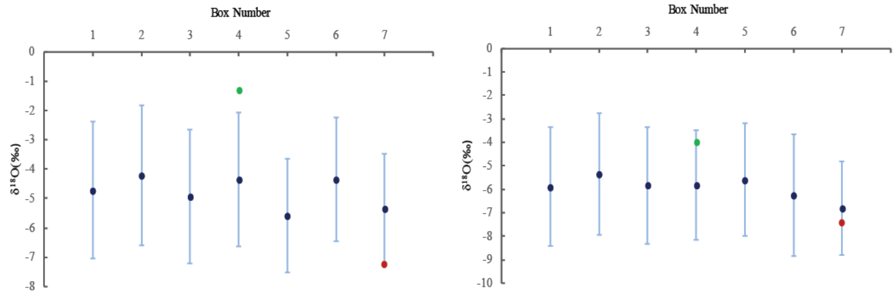


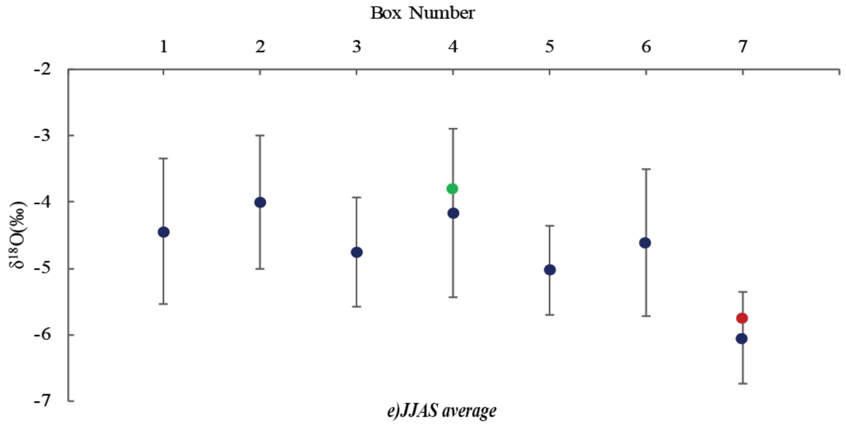
**Figure A5.** E/P ratio for each box of the modelling transect for the SWM months of 2004.



*b)July*



*c)August* *d)September*



*e)JJAS average*

**Figure A6.** Dark blue represents the mean modelled $\delta^{18}O$ (‰) 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 A2.** 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 mean values.

| **Box** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **Month** |
|---|---|---|---|---|---|---|---|---|
| $f$ | 0.9354 | 0.9676 | 0.8748 | 0.9903 | 0.8588 | 0.8872 | 0.6804 | **June** |
| $\delta^{18}O_v$(‰) | -13.11<br>(±2.57) | -13.1<br>(±2.58) | -13.08<br>(±2.50) | -13.08<br>(±2.52) | -13.06<br>(±2.39) | -13.03<br>(±2.33) | -12.98<br>(±1.96) | |
| $f$ | 0.9262 | 0.9586 | 0.8895 | 0.9295 | 0.8369 | 0.7504 | 0.9125 | **July** |
| $\delta^{18}O_v$(‰) | -13.24<br>(±2.75) | -13.23<br>(±2.74) | -13.22<br>(±2.75) | -13.2<br>(±2.74) | -13.18<br>(±2.73) | -13.16<br>(±2.73) | -13.12<br>(±2.72) | |
| $f$ | 0.9135 | 0.9591 | 0.888 | 0.9407 | 0.8192 | 0.9286 | 0.8327 | **August** |
| $\delta^{18}O_v$(‰) | -14.19<br>(±2.95) | -14.18<br>(±2.96) | -14.16<br>(±2.95) | -14.15<br>(±2.94) | -14.12<br>(±2.94) | -14.11<br>(±2.93) | -14.08<br>(±2.93) | |
| $f$ | 0.8987 | 0.9511 | 0.8986 | 0.8859 | 0.9103 | 0.8673 | 0.7761 | **September** |
| $\delta^{18}O_v$(‰) | -15.32<br>(±3.21) | -15.31<br>(±3.21) | -15.29<br>(±3.20) | -15.27<br>(±3.20) | -15.25<br>(±3.20) | -15.23<br>(±3.19) | -15.19<br>(±3.18) | |