Response to referee's comments

The reviewer has two major concerns regarding the contents of the manuscript. The authors agree with the reviewer's comments, and follow his recommendation to check the residence time of moisture in the atmosphere for their mechanism, as well as check their results against existing literature. The recommendations are included in the revised manuscript. The detailed comments (red) and responses (black) as follow:

Main comments

(1) The first one is the lack of a modelling work to check the results. To base the conclusions only on correlation analysis is not enough to support for the proposed mechanism

The reviewer rightfully points out that modelling work is needed to check the results presented in the manuscript, as correlation is not proof of the mechanism. It is the authors' intention to follow up on this manuscript with modelling work, since the presentation of the statistical results and additional trajectory calculation is already lengthy.

(2)The second one is the lack of a proper methodology to estimate moisture sources. The single use of backward trajectories does not guarantee the proper estimation of sources of moisture

Moisture sources are estimated and found to be consistent with the authors' claims (see next section "Back-trajectory calculation").

(3) Even more the time scale (about 16-18 days) is clearly too long (the average residence time of moisture in the atmosphere is about ten days, Numaguti, 1999).

The authors have briefly addressed the issue of the timescale in their previous response, but only through estimation. A quantitative calculation is presented in this response using methodogies recommended by the referee. The time taken by air parcels from Australia to travel from the evaporative region of Indian Ocean to West India is about 8-13 days (pale bars in Figure 5c). This may be on the longer side of the average moisture residence time of ~10 days, but the air parcels from Australia are only a subset of all air parcels. Using the proper methodologies, the timescale of the mechanism (between Australia and India) is calculated to be 13-19 days with the mode of 14 days (13-18 days with the mode of 17 days in the original manuscript, using naive trajectory-only calculations).

(4) Please check the methodologies by Stohl and James (2004, 2005) or Sodemann et. al. (2008a, 2008b) to diagnose net water changes along a large number of back trajectoriers that permit to infer the moisture sources for any given region. Results on global sources of moisture for precipitation using these approches (Gimeno et. al. 2010 and Gimeno et. al. 2011) seem to agree with results from this study (the Indian ocean as one of the main source of moisture for JJA Indian subcontinent precipitation). However the result should be conveniently checked.

The referee recommends that the authors' results be checked against existing literature. The results of the next section seem to agree with the results of Gimeno et al. (2010) although the moisture sources are only estimated for air parcels that travel between India and Australia through the Indian Ocean, which form a small subset of the air parcels that travel between India and the Indian Ocean. Nevertheless, the back-trajectories produce an evaporative source in the tropical Indian Ocean of a shape that resembles the one produced from forward-trajectories by Gimeno et al. (2010) (Figure 3 of the referenced paper). The pattern of net precipitation over India (Figures 1 and 2) also resembles that in Figure 4 of Gimeno et al. (2010).

Back-trajectory calculation

Methodology

Back-trajectories are calculated for up to 30 days using 6-hourly winds from the NCEP/ NCAR Reanalysis 1, at horizontal resolution $2.5° \times 2.5°$ and 12 pressure levels (1000, 925, 850, 700, 600, 500, 400, 300, 250, 200, 150, and 100 millibars). Air parcels are initialised over land regions of the Indian sub-continent at horizontal resolution of $0.25° \times 0.25°$ apart, to match TRMM resolution, and on 8 pressure levels (1000, 925, 850, 700, 600, 500, 400, and 300 millibars), for a total of 38,592 parcels per timestep or 4,824 parcels per level. Parcels are not initialised on the remaining 4 pressure levels (250 to 100 millibars). This is because no humidity data is available for pressure levels higher than 300mb, and humidity is assumed to be effectively zero above this level. While it is possible that an air parcel on these levels can reach Australia in a back-trajectory calculation, it must have passed the 300mb pressure level before reaching India, at which time all moisture is assumed to have been removed from the air parcel. Therefore, such a parcel trajectory cannot be admitted as support for the hypothesis. Calculations are started once a week in July and August, for a total of 9 weeks, to sample 30-day trajectories that travel through the Indian Ocean during austral winter. Calculations are started at all 4 timesteps of the sampled day, to sample diurnal changes in wind. Air parcel positions are collected once every 6 hours. The calculation is carried out for the years 1972-2008.

Back-trajectories that do not reach Australia, defined as entering the region ($115 - 150$°E, $15 - 30$°S), are excluded. There are many back-trajectories that pass over the Indian Ocean as this is a major source of water vapour for India (Gimeno et al., 2010, Stohl and James, 2005), but not all of these reach Australia. We are only interested in air parcels that reach India *from Australia*, and the climatology pattern of their accumulated water-vapour change ($\overline{p-e}$, the climatology difference between accumulated precipitation p and evaporation e).

The net precipitation and net evaporation sections are calculated along all of the remaining back-trajectories using a method modified from Sodemann et al. (2008). We wish to establish a lower bound for the amount of evaporation into these air parcels over the main water vapour source of Indian Ocean, to determine how much water vapour at least is entering air parcels from Australia to India. Therefore unlike Sodemann et al. (2008), who calculated the boundary layer height using the methodology of Troen and Mahrt (1986), a boundary layer height is chosen to represent a daytime lower limit, and only negative changes in water vapour along the back-trajectory (i.e. $p-e < 0$) that occur below this limit are considered evaporation, with evaporation during the day expected to dominate that during the night. Troen and Mahrt (1986) models the boundary layer height for 16 and 17 August over Wangara, Australia (Clarke et al., 1971). Using their results as a basis, for the same season, similar latitude, and full moisture availability over the ocean, the daytime lower limit of 1000m is chosen for our calculation. Unlike Sodemann et al. (2008), a relative humidity threshold of 80% is not used to determine if $p - e > 0$ changes should be considered, as this is not as useful a criteria for cloud existence for a case over the tropical Indian Ocean.

Back-trajectories are classified as belonging to the West India or East India domain from whether travelling from Australia to India, the first net precipitation event over India occurs in the West India or East India domain. Thus, travelling from Australia to India, an air parcel may finally reach East India, but should it reach India through the Arabian Sea branch and precipitate on West India, it is considered to belong to the West India domain. However, should such a parcel not precipitate on West India despite passing through West India, and only precipitate in East India, it is considered to belong to the East India domain. Air parcels that do not precipitate in either West or East India domains are not considered to belong in either domain. West India air parcels that travel into East India are terminated at the first precipitation point after leaving the West India domain. This is done likewise for parcels traveling into West India from East India. This permits evaporation segments along the trajectory inside the domain to be included into the calculation of the accumulated water vapour change and prevents the accumulated water vapour change from being biased towards precipitation at the edges of the domains.

The trajectory times from India to when air parcels first cross the line (110°E, 37.5°S)-(145°E, 11.25°S) located in interior Australia are collected. We wish to estimate an upper bound of time-lag between low temperature events in Australia and precipitation events in India. Air parcels are observed from the back-trajectories to circulation inside Australia for a few days before leaving Australia. Since low temperature events in Australia can last a few days, air parcels can leave Australia any time during the event. Trajectory times from when air parcels first cross the line (110°E, 37.5°S)-(145°E, 11.25°S) to when they depart Australia (e.g. to re-enter the Indian Ocean), are also collected. The sum of the two trajectory times, from India to interior Australia, and from interior Australia out of Australia, gives the desired upper bound estimate. The trajectory times from India to when air parcels first cross the line (90°E, 27.5°S)-(115°E, 8.75°S) located in the Indian Ocean are collected as well. This gives an estimate of the time between evaporation from the Indian Ocean and precipitation in India.

Results

Of the total air parcels initiated, 3.5% reach Australia. 3.0% of these air parcels produce net precipitation in India, while the other 0.5% produce net precipitation over Indochina. 2.4% of the total air parcels that reach India are classified as belonging to the West India domain and 0.6% are classified as belonging to the East India domain.

The climatology accumulated net precipitation associated with the air parcels of East and West India domain is concentrated in four regions, two in the East India domain and two in the West India domain. Assuming that the sampled air parcels are representative of the boreal summer (austral winter) season, contribution to seasonal precipitation by air parcels originating in Australia can reach up to 3cm/season, which is about 3% of seasonal precipitation. This climatology amount is small, but it is not evenly distributed through the years and can get as high as 10cm/season. Figure 1 shows the climatology accumulated net water vapour sink, $\overline{p - e}$, for the air parcels originating in Australia with its first accumulated net precipitation in the East India domain. Air parcels approach the Indian Subcontinent from the Bay of Bengal and net precipitation occurs over Northeast India and the Ganges basin. Bangladesh is seen as a net evaporative region, indicating that air parcels from Australia do not contribute to the precpitation in Bangladesh. Figure 2 shows the same, but for the West India domain. Net precipitation occurs on the slopes of the Western Ghats and over Northwest India (Figure 3). Net precipitation and net evaporation also occur along the stationary waves off the Western Ghats, over the Arabian Sea. The main evaporative source for air parcels of both domains is however the Indian Ocean; net evaporation is seen along most of the back-trajectory pathway in the Indian Ocean. For air parcels originating in Australia, net evaporation is particularly concentrated in the southeast Indian Ocean, west of Australia.

Figure 4 shows the number density of West India air parcels as they travel along the back-trajectory from the Indian end. The number density is the the number of air parcels on a $0.25° \times 0.25°$ resolution grid at a snapshot in time, with day 0 as when the air parcels are at their Indian end of the back-trajectory. Parcels are removed when they cross the line in interior Australia. Air parcels begin to reach the main evaporative region at day 7. By day 13, most of the parcels have entered or passed the evaporative region.

The distribution of trajectory times from India to the evaporative region as demarcated by the upper magenta line in Figure 4 is shown as pale bars in Figure 5a-c, for both domains, East India domain, and West India domain. West India air parcels take about 8-13 days to enter the evaporative sink, while East India air parcels take about 13-18 days. Considering that the average residence time of moisture in the atmosphere is about 10 days (Numaguti, 1999), precipitation in East India is not expected to have any relationship with low temperatures in Australia through the proposed mechanism of advection. The consistency between the 10-day average residence time of moisture and the trajectory times between West India and the evaporative sink supports the proposed mechanism of advection.

The distribution of trajectory times from India to interior Australia, as demarcated by the lower magenta line in Figure 4 is shown as dark bars in Figures 5a-c. West India air parcels take about 12-16 days to reach interior Australia, while East India air parcels take substantially longer, about 17-24 days. This further highlights that West India and East India air parcels are inherently different and should be analysed separately. Figures 5d-f show the distribution of time that air parcels spend inside Australia after passing the demarcated line in Australia. Parcels at the zero bin have not left Australia by the 30th day of the back-trajectory calculation – since it's not possible to use as a time limit when they leave Australia, we assume that the low temperature event occurs at the time when they hit the demarcation line. About half of the air parcels are still in Australia at the 30th day, and the rest have left Australia. However, as trajectory calculation become increasingly inaccurate from numerical as time increases, these distribution should be considered more qualitative than quantitative. Neverthess, to obtain some kind of upper bound of time-lag between low temperature events in Australia and precipitation events in India, the times in Figures 5a-c and Figures 5d-f are added with the resulting distribution shown in Figures 5g-i. This produces a time lag of about 13-19 days (13-18 days was quoted in the original manuscript) with the mode of 14 days (17 days in the original manuscript). This change in mode may be attributed to increased sampling over the whole season and more pressure levels, than was done in the original manuscript.

Figure 3 mark ground stations that show positive correlation at 95% confidence level between gauge rainfall and VCD (very cold days) in Australia, using a lag-time of 14 days. The stations that show significant correlation are unchanged from those obtained in the original manuscript, which used a lag-time of 17 days. The value of the correlation coefficients have changed and most show increases in value, but the increases are minor (Table 1).

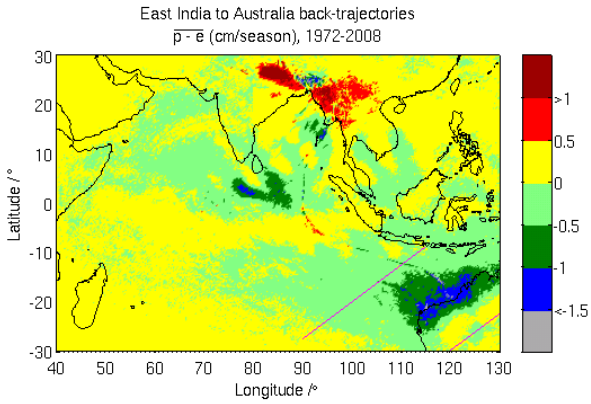

Figure 1: Shading shows climatology accumulated net water vapour sink $\overline{p-e}$ (cm/season) calculated from back-trajectories between India and Australia that precipitate first in the East India domain. Colour scale is half that for the West India domain. Magenta lines show demarcation of the evaporative region in the southeast Indian Ocean and interior Australia used to calculation trajectory times.

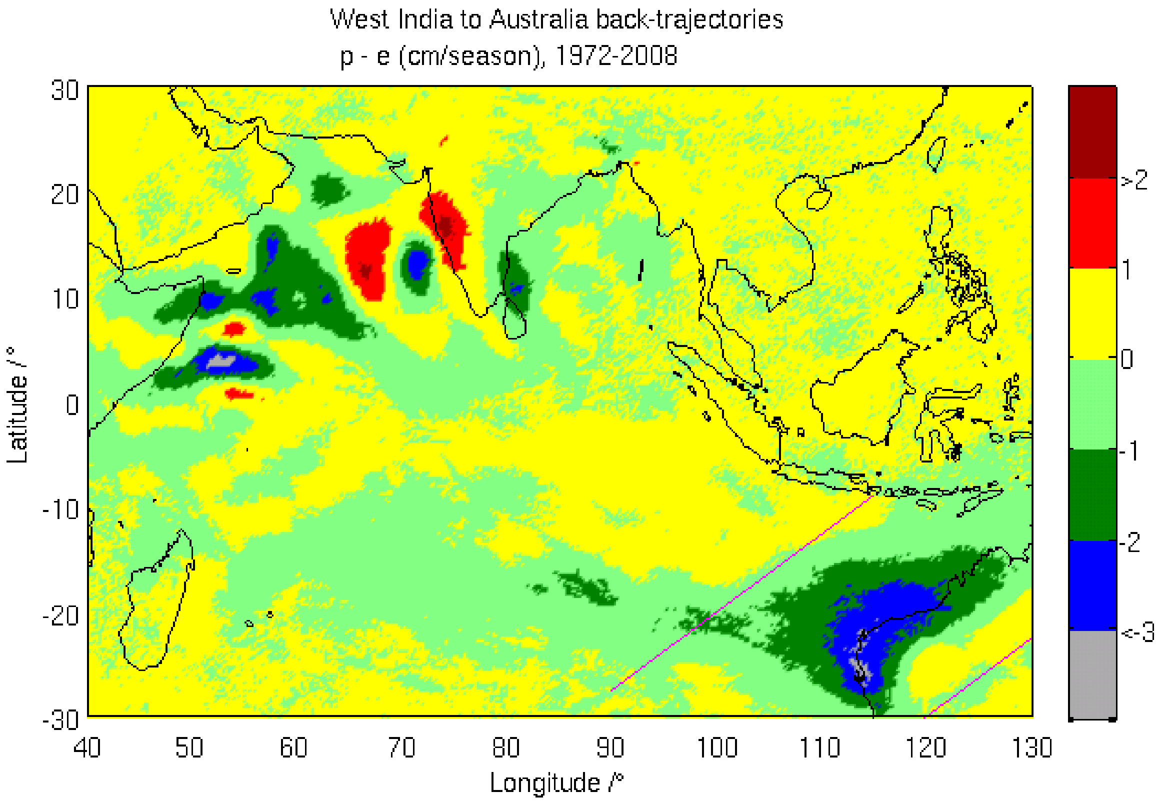

Figure 2: Shading shows climatology accumulated net water vapour sink $\overline{p-e}$ (cm/season) calculated from back-trajectories between India and Australia that precipitate first in the West India domain. Colour scale is double that for the East India domain. Magenta lines show demarcation of the evaporative region in the southeast Indian Ocean and interior Australia used to calculation trajectory times. Purple polygons show net precipitation over the West India domain and net evaporation over the southeast Indian Ocean.

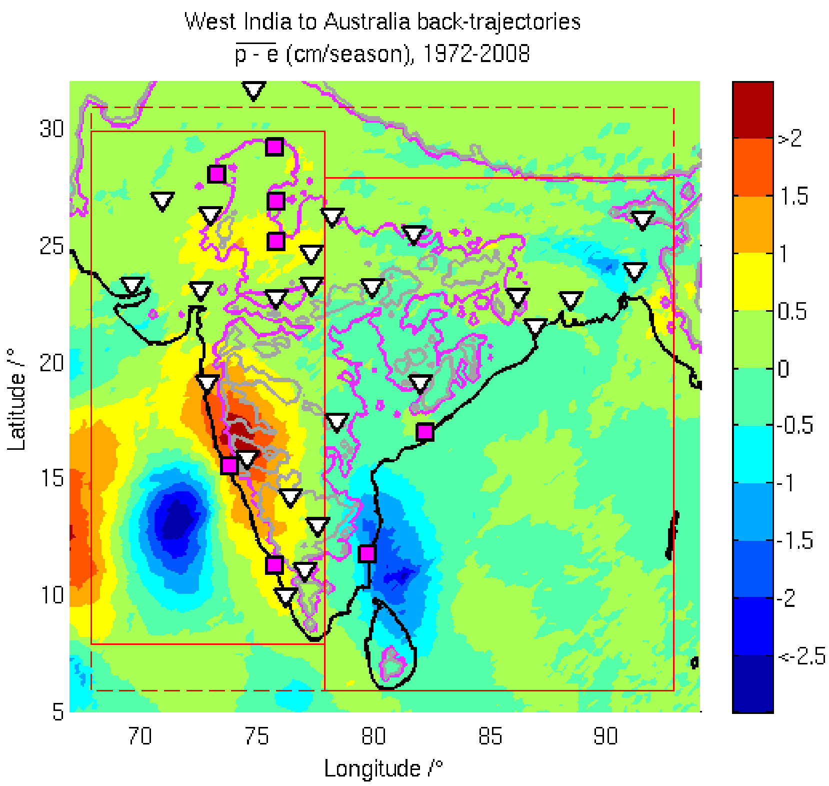

Figure 3: Shading shows climatology accumulated net water vapour sink $\overline{p-e}$ (cm/season) calculated from back-trajectories between India and Australia that precipitate first in the West India domain but in greater detail over India. Red boxes show the West India and East India domain. Grey and magenta contours show the 300m and 600m height contours. The correlation between VCD and seasonal mean rainfall is calculated for rain gauges marked by squares and triangles. Magenta squares are the stations that show significant correlation at 95% confidence level.

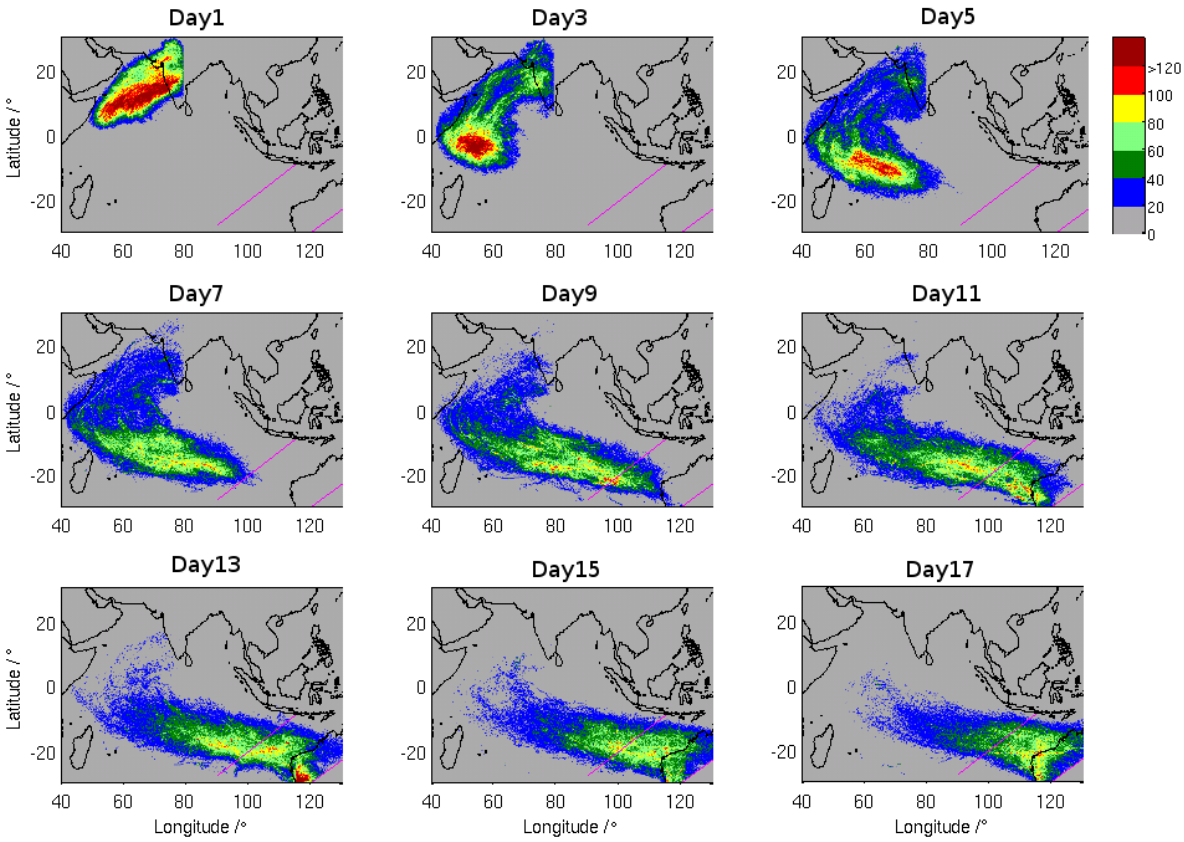

Figure 4: Shading shows the number density of air parcels, showing the number of air parcels on a 0.25° × 0.25° resolution grid. Only air parcels of back-trajectories from India that reach Australia and precipitate first in the West India domain are shown. Magenta lines show demarcation of the evaporative region in the southeast Indian Ocean and interior Australia used to calculation trajectory times. Parcels are removed when they cross the line in interior Australia.

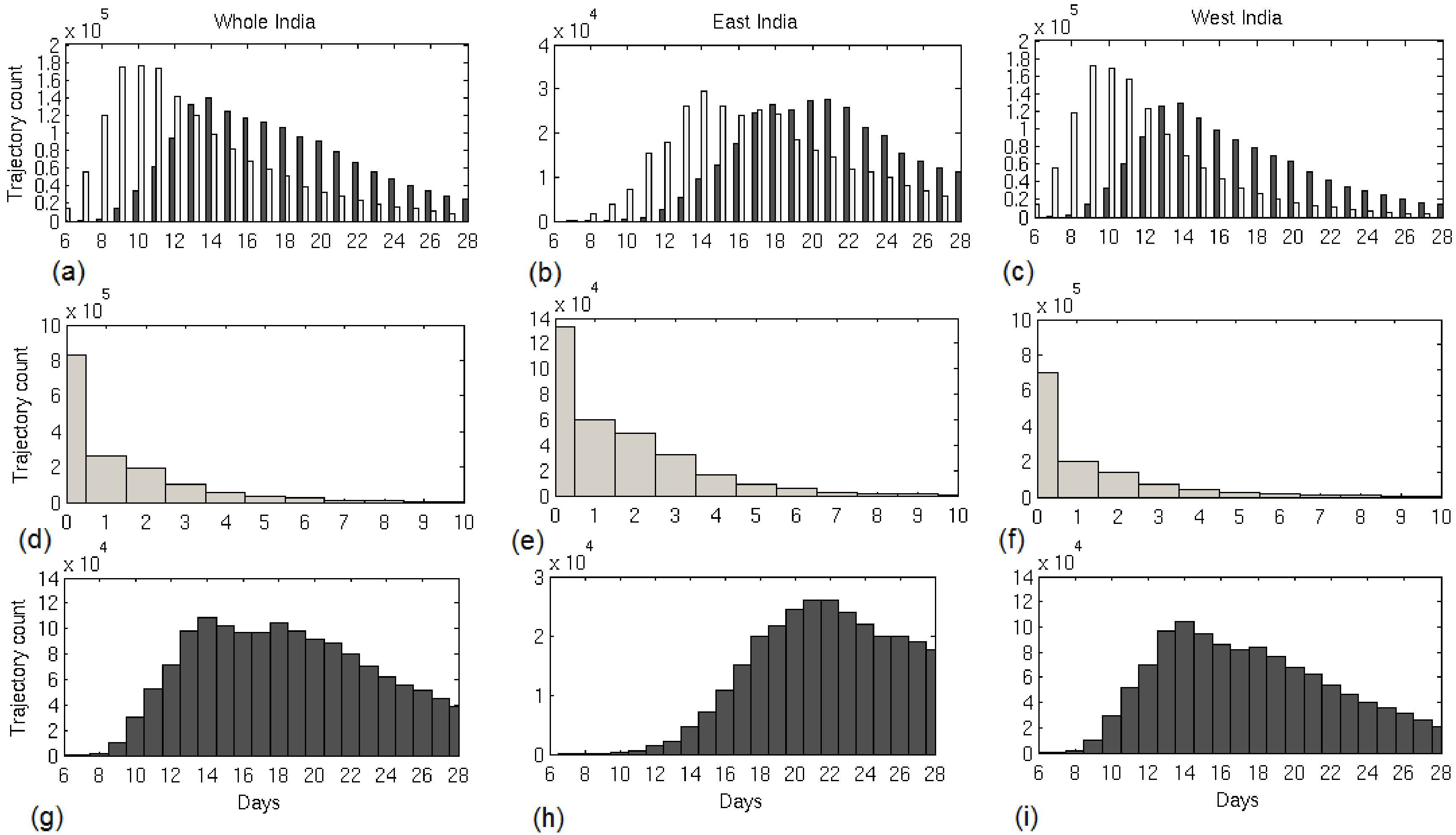

Figure 5: Trajectory times for air parcels of: left column, both West and East India domains (sub-figures a, d, g); middle column, East India (sub-figures b, e, h); right column, West India (sub-figures c, f, i). First row (sub-figures a, b, c): light bars show trajectory times from India to the evaporative region in southeast Indian Ocean (first magenta line in Figure 2); dark bars show trajectory times from India to interior Australia (second magenta line in Figure 2). Second row (subfigures d, e, f): time spent by air parcels in Australia (115 – 150°E, 15 – 30°S) after crossing demarcation line in interior Australia, before leaving the continent to re-enter the Indian Ocean. Parcels at the zero bin have not left Australia by the 30th day. Third row (sub-figures g, h, i): Trajectory times from India to when air parcels leave Australia, from summing the trajectory times of the first and second row. This estimates an upper bound to the time-lag between low temperature events in Australia and precipitation events in India.

Station	Location (°E, °N)	old CC	new CC
Goa/Panjim	73.8, 15.5	0.82	0.84
Kozhikode	75.8, 11.3	0.77	0.78
Hissar	75.7, 29.2	0.75	0.74
Kota Aerodrome	75.9, 25.2	0.72	0.72
Kakinada	82.2, 17.0	0.69	0.72
Cuddlore	79.8, 11.8	0.65	0.67
Jaipur/Sanganer	73.3, 28.0	0.57	0.55
Indore	75.8, 26.8	0.54	0.55

Table 1: Pearson correlation coefficients between gauge rainfall and VCD, for the stations marked as magenta squares in Figure 3. Old correlation coefficients calculated using 17 days of lag time are compared with new correlation coefficients calculated using 14 days of lag time. Correlations are significant at 95% confidence level.

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