Response to referee's comments

The reviewer finds the evidence presented by the authors in the manuscript to be insufficient to support their hypothesis of moisture advection from the southeastern Indian Ocean to west India. Substantial reworking of the back-trajectory calculations will be presented at the next section, "Back-trajectory calculation", to further support the authors' hypothesis. The detailed comments of the reviewer may be classified into two categories – the first are valid observations of oversight on our part which are corrected in the revised manuscript; the second are comments that we agree with, but do not contradict what is claimed in the manuscript. The comments (red) and responses (black) are listed as follow:

Main comments

(1) The authors argue that the ocean west of Australia is a "non-negligible source of water vapour for the Indian summer monsoon" (pg. 26428, l. 23). However, the study in fact remains fully qualitative in this respect. Back-trajectories are started at all times, irrespective of the amount of water vapour or precipitation that is advected with them.

A quantitative calculation of net water vapour changes is performed (see section "Back-trajectory calculation").

(2) Of all these trajectories, only 3-10% actually end up in Australia. Even without considering the uncertainties involved in a 30-day backward trajectory calculation, it cannot be deduced from this finding that the Indian summer monsoon is modulated by such a small air mass contribution (NB not even a rainfall contribution).

The reviewer raises two objections:

Firstly, the reviewer correctly states that uncertainties arising from a 30-day backward trajectory calculation are substantial. However, the actual portion of the trajectories that is relevant to the proposed mechanism extends at most to 20 days. As will be shown, the timescale mode of the mechanism is about 14 days.

Secondly, the reviewer objects that 3-10% of the trajectories that end up in Australia do not constitute a large enough air mass to modulate the Indian summer monsoon. From a quantitative calculation of water vapour changes along the trajectories, the net precipitation contribution from air parcels that end up in Australia is also 3-10% of the seasonal rainfall. This amount cannot be said to be "not even a rainfall contribution" (reviewer). The reviewer is right in that this percentage cannot "modulate" the monsoon, but the authors do not claim that the Indian summer monsoon is being "modulated" since larger net precipitation contributions only arise when cold events occur in Australia (infrequent). The authors claim that the contribution is "non-negligible" and that the mechanism "does not detract from the dominant influence of ENSO and IOD on Indian rainfall" (pg 14, paragraph 3, lines 2-3), which are the main phenomena modulating the Indian summer monsoon.

(3) A second issue is that the time scale of the water transport needed to support the hypothesis brought foward by the authors is at odds with findings from the literature. ... Without further evidence, one has to conclude that the authors'

mechanism only works when extending the life time of atmospheric moisture far beyond realistic values.

The reviewer is rightfully concerned about the transport lifetime of water vapour in the mechanism. However, the timescale of the mechanism refers to the time between low temperature events in Australia and precipitation in India. As water vapour only enters the air parcels while they are over the Indian Ocean, the timescale of the authors' mechanism does not contradict existing literature. Further evidence is also provided in the next section that the transport lifetime provided in existing literature supports the authors' mechanism, as it is found that it takes about 8-13 days for the air parcels to move between West India and the main evaporative region in the southeastern Indian Ocean.

(4) A further problematic issue is that only boundary-layer air from 850hPa and below is traced back in time...Thus, the mere existence of a potential transport path does not alow the conclusion that water vapour is materially conserved along this transport path. Again, this leaves no basis for arguing for a direct Australian-Indian teleconnection via the presented mechanism.

The reviewer's first concern regarding the lack of representation of air from higher pressure levels than 850hPa is noted. The back-trajectory calculations have been revised to trace back air from pressure levels up to 300mb. The authors do not understand the reviewer's second concern, since water vapour is of course not conserved along the transport path – for example, evaporation takes place all along the of the air parcel's trajectory over the tropical Indian Ocean and adds to the water vapour content of the air parcels (see Figure 2) – and the authors do not claim that water vapour is conserved.

(5) While the general thought of a southern hemisphere equivalent to the cold surges in the South China Sea is certainly attractive, the evidence presented in this manuscript argues for the opposite as claimed by the authors, namely that the proposed mechanism is unable to modulate the Indian monsoon. This does of course not preclude that another mechanism could cause such a teleconnection, e.g. through modulating both, the cold spells in Australia and some factors influencing the Indian summer monsoon, but it would have to be shown by further extending the study into that direction.

The reviewer states that the evidence presented in the manuscript argues for the opposite as claimed by the authors. While the authors agree that some of the presented evidence may not be convincing enough, the authors consider all of the presented evidence to be consistent with their hypothesis. Furthermore, the authors do not argue that the mechanism "modulates" the Indian Monsoon, but that the mechanism provides a "non-negligible" source of water (see comment 2). Could the reviewer please specify which of the presented evidence argue that the proposed mechanism has negligible impact on the on the Indian monsoon, so that the authors may respond to his or her concerns?

The reviewer makes a good philosophical point in that there is really no way of precluding another mechanism from causing such a teleconnection. Practically, however, one may only test finite and known major phenomena that affect regional variability. In Section 4.4, the authors test for the correlations with the major known modulators of the Indian Monsoon, the ENSO and IOD, and found no significant correlation.

Detailed comments

(6) In Fig. 1, it is argued for a moisture transport path as indicated by the arrows over the Arabian sea. Fig. 2 however shows a much more direct transport path from Australia to India, which basically points out that the mean flux and source-sink pattern shown in Fig. 1 is partially misleading. Also, it is not stated for which season this figure is representative.

The reviewer's point is noted and the authors agree that Figure 1 in the manuscript is partially misleading. The figure shows the mean flux and source-sink patterns in the region, but only the mean source-sink pattern pertaining to air-parcels from Australia to India relevant. Figure 1 is removed in the revised manuscript. (N.B. The figure is for JJA.)

(7) Furthermore, the quantity E-P, which presumably is plotted here, does not exclude that the precipitation events can have occurred on a net evaporative area, and vice versa, at shorter time scales.

As Figure 1 will be removed from the manuscript, this may no longer be relevant. However, this comment is relevant to Figures 1-3 in this reply which are included in the revised manuscript. It is possible to obtain the predominating quantity E from E-P, by only considering net evaporative changes that occur within the planetary boundary layer, as done by Sodemann et al. (2008). It is however difficult to obtain the predominating quantity P from E-P for the phenomena and region in question. Firstly, the relative humidity over the tropical Indian Ocean and at the coasts of India is high. Thus, high relative humdity is not indicative of the presence of clouds. Secondly, Indian monsoon rainfall is intense (e.g. in the Goa station, more than 10 inches can fall in a day, for consecutive days). During such intense rainfall, the ground is saturated with water or flooded. Therefore, no attempt is made to distinguish P from E-P. When E-P<0 (or P-E >0 in this work, since precipitation is of chief concern), it is considered to be "net precipitation".

(8) On pg. 26424, I. 10, the authors interpret time-lagged correlation between Australian temperature and TRMM rainfall over India. Are these correlations tested for significance, and at what level? It should be more clearly explained why the areas of much stronger positive and negative correlation on shorter lag times are ignored.

The correlations were significant at 95% confidence level. The revised manuscript explains more clearly why other areas of correlation are ignored: Indian monsoon rainfall is strongly auto-correlated at time lags of 10-20 days and 30-60 days. (See references in the manuscript for a discussion, e.g. Goswami and Mohan, 2001, Krishnamurthy and Shukla, 2000.) Lag-correlations of Indian monsoon rainfall with any variable that produces a positive correlation at any lag time will always produce mirrored positive correlation 10-20 days and 30-60 days away, and mirrored negative correlation half of those periods. Similarly for any variable that produces negative correlation. These correlations can only be rejected on the ground of physicality; the direction of large-scale circulation excludes correlations before when information can propagate from Australia to India. This leaves only two correlation bands that are physical. However, thanks to the reviewer, West and East Indian air parcels are now better classified through net precipitation (detailed next section). The new evidence reveals that the trajectory population of 13-19 days travel time characterise the West India domain and the trajectory population of 17-24 days travel time characterise the East India domain, rather than a mixture of both populations for both domains. Since neither of the two correlation bands are seen for the lag-correlation graphs of East India (this is not surprising for the reason as given by the reviewer of moisture transport lifetime), the second correlation band in West India is likely to be due to auto-correlation cause by the 10-20 day mode. Mother Nature is consistent indeed!

On pg. 26425, I. 10, the authors interpret the correlation between rain gauges and VCD in Australia shown in Fig. 2. The interpretation appears very much biased towards a desired outcome. 5 out of 7 West Indian stations are far in the North where as the authors argue the influence of Australian moisture should be small. The southernmost station where correlations should be strongest shows no significant correlation. This does not mean that the correlations have to be artifacts, but at least the proposed mechanism does not help to explain the observations.

The net precipitation over West India contributed by air parcels belonging to the West Indian domain is shown in Figure 3 in the next section. The influence of Australian moisture is not small in the northern part of the West India domain, as a net precipitation region is seen over the northwestern region of India. The region of net precipitation does not exactly match the set of stations demonstrating correlation between rain gauges and VCD but is a possible explanation for the correlations. The coarse spatial and temporal resolution of the reanalysis winds used for the back-trajectory calculations can result in some offset and mismatch of the net precipitation.

The contribution to net precipitation over the stations at the southern region of the West India domain by air parcels originating from Australia forms only part of the total net precipication, which is very high in that region durcing the Indian summer monsoon. Therefore, correlation is not assured when any station receives net precipitation from air parcels originating from Australia. In order for the positive correlation to be seen, this contribution must be strong enough relative to contributions by air parcels from elsewhere, or its variations in Australian moisture will be completely dominated by variations of the other contributions. As the reviewer points out in comment (2), the contribution by Australian moisture is small and thus easily overwhelmed. Therefore, the authors carry out a field correlation test, which tests whether the number of stations in West India showing positive correlation between gauge rainfall and VCD can arise by chance. At 95% confidence level, the positive correlations do not arise by chance. The positive results of field correlation test is consistent with the proposed mechanism, although the pattern of the stations by itself may not be completely convincing.

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° × 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° × 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° × 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).

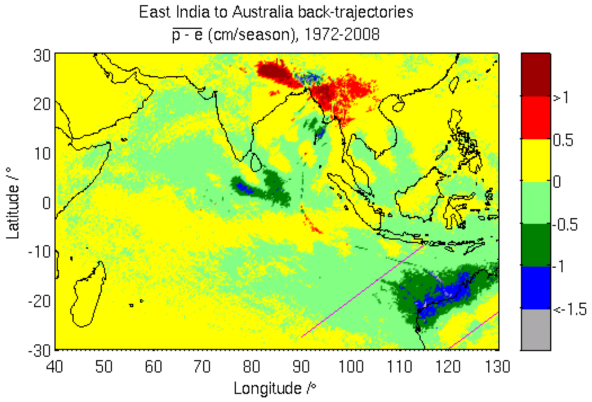

Figure 1: Shading shows climatology accumulated net water vapour sink $\overline{p - e}$ (cm/season) calculated from back-trajectories between India and Australia that precipitate first in the East India domain. Colour scale is half that for the West India domain. Magenta lines show demarcation of the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

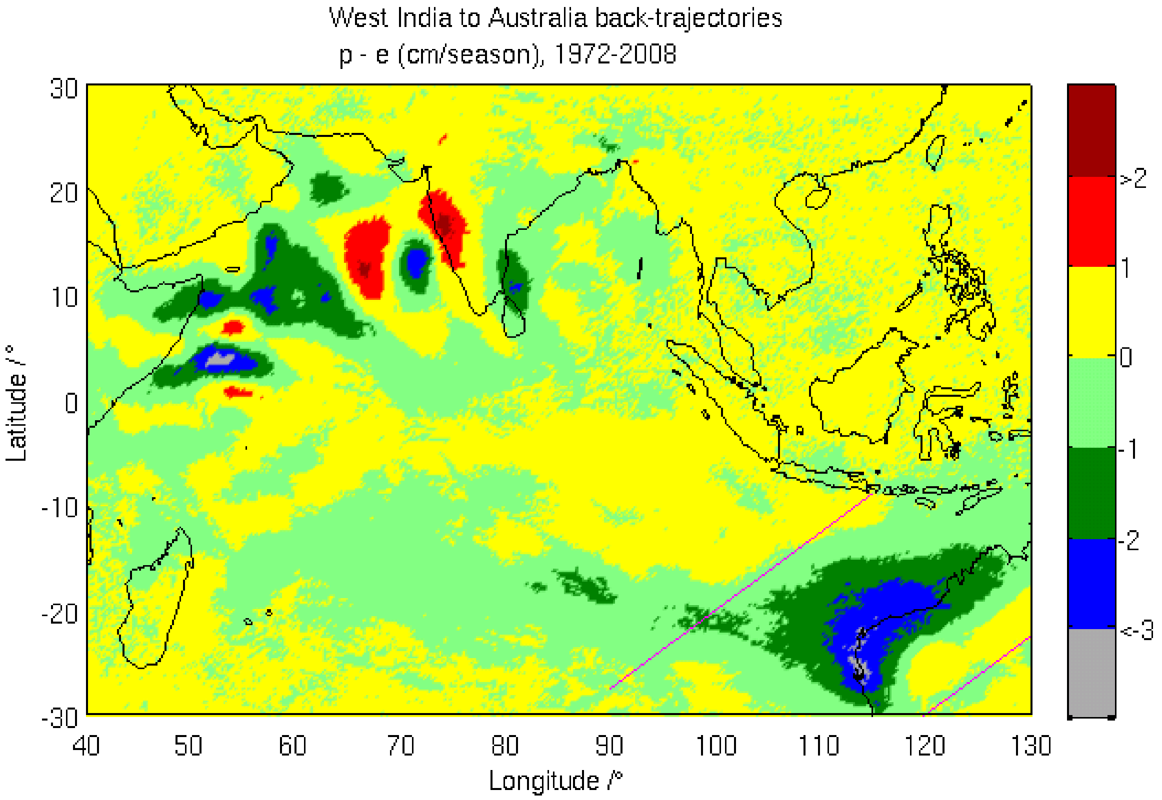

Figure 2: Shading shows climatology accumulated net water vapour sink $\overline{p - e}$ (cm/season) calculated from back-trajectories between India and Australia that precipitate first in the West India domain. Colour scale is double that for the East India domain. Magenta lines show demarcation of 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.

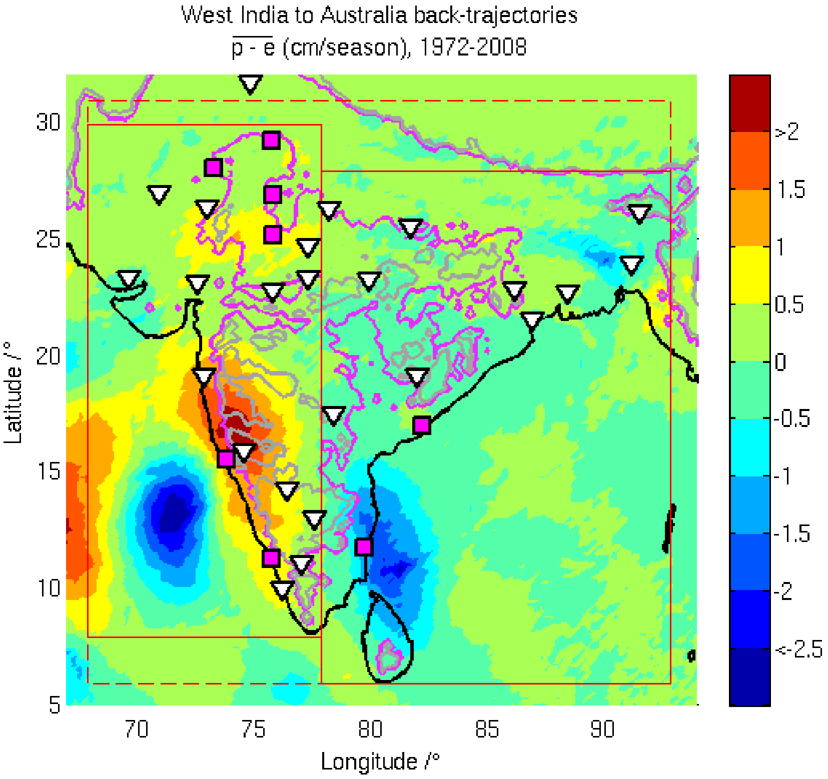

Figure 3: Shading shows climatology accumulated net water vapour sink $\overline{p-e}$ (cm/season) calculated from back-trajectories between India and Australia that precipitate first in the West India domain but in greater detail over India. Red boxes show the West India and East India domain. Grey 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.

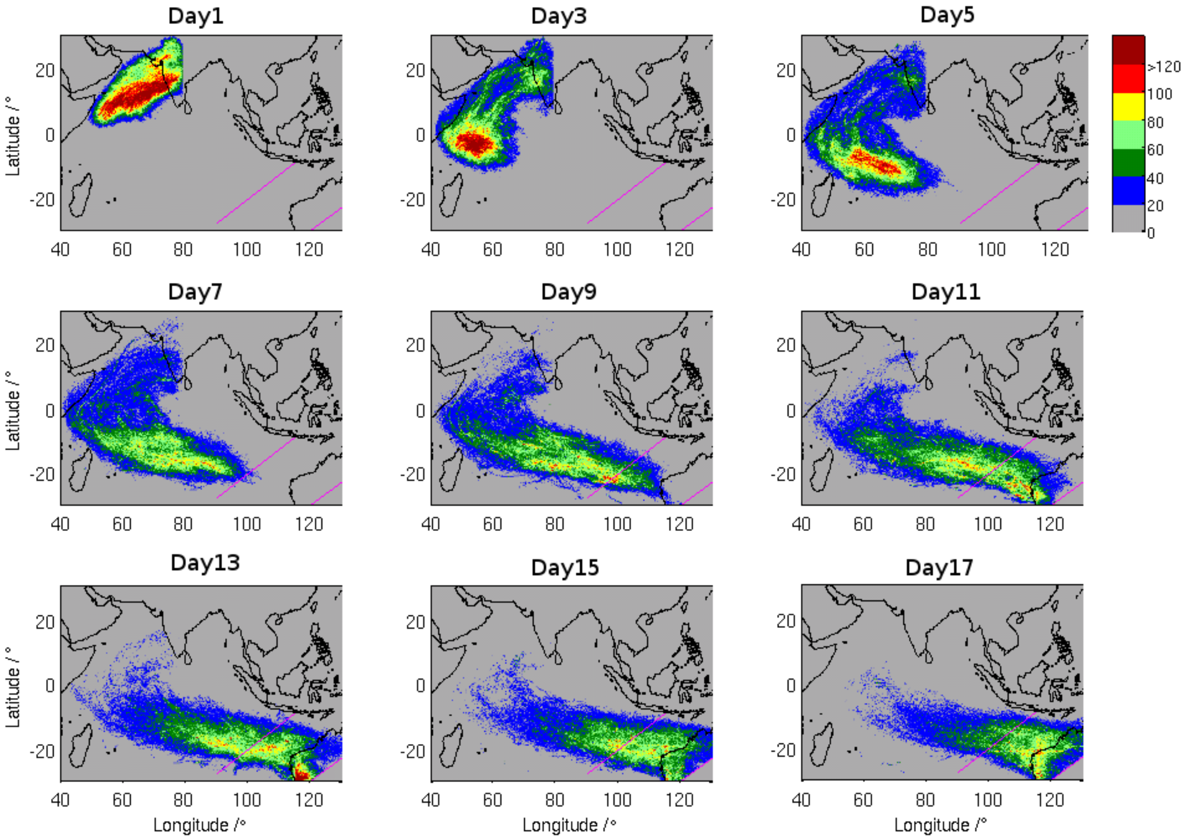

Figure 4: Shading shows the number density of air parcels, showing the number of air parcels on a 0.25° × 0.25° resolution grid. Only air parcels of back-trajectories from India that reach Australia and precipitate first in the West India domain are shown. Magenta lines show demarcation of the evaporative 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.

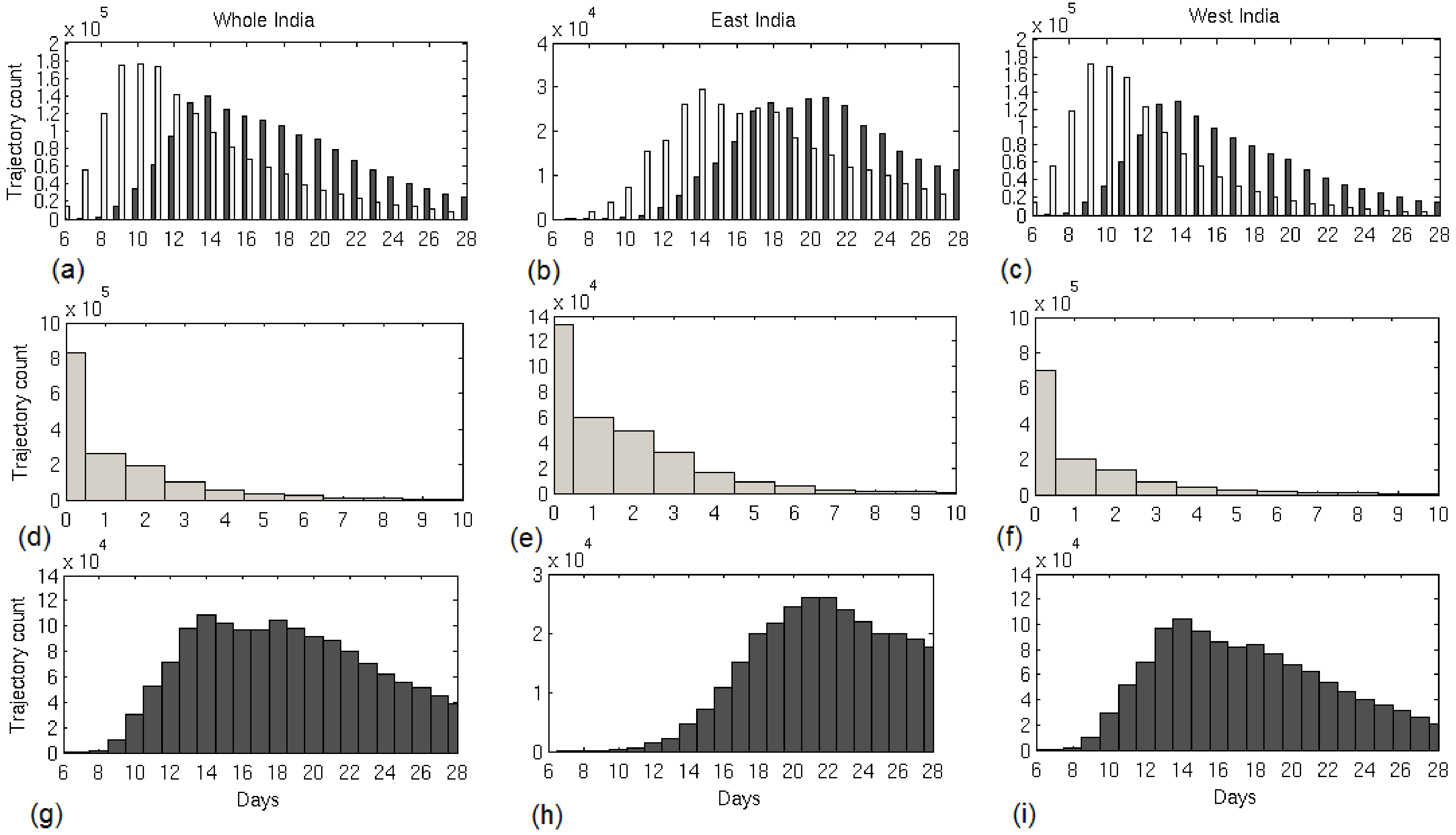

Figure 5: Trajectory times for air parcels of: left column, both West and East India domains (sub-figures a, d, g); middle column, East India (sub-figures b, e, h); right column, West India (sub-figures c, f, i). First row (sub-figures a, b, c): light bars show trajectory times from India to the evaporative 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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