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Interactive Comment

Interactive comment on "A Lagrangian description on the troposphere-to-stratosphere transport changes associated with the stratospheric water drop around the year 2000" *by* F. Hasebe and T. Noguchi

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Reply to Anonymous Referee #1

We thank the thorough reading and constructive comments on our manuscript. We have made substantial changes to the manuscript in response to the review as described below. Each panel of figures are labeled "a", "b", "c" and "d" from the top to the bottom if exists, and the following reply refers to these labels. These revisions have significantly improved the manuscript, and we hope we have answered all of the concerns. We think all these improvements will satisfy the reviewer and hopefully make the manuscript suitable for publication in ACP.

General comments

1. **Comment:** This manuscript describes the change of pathways of backward kinematic trajectories initialized at 400 K height level from a period before and after the stratospheric water vapour (SWV) drop in the year 2000. The authors discuss the cause of the stepwise drop in SWV by an analysis of the water vapour entry values to the stratosphere. They focus on the month of September in the period 1998-2002, because the drop in H2O entry values first occurred at that month. The authors' conclusions are that the low H2O entry values to the stratosphere in September 2000 and the sustained low values thereafter can be interpreted as being driven by changes in thermal forcing from the earth's surface.

   I recommend major revisions before a potential publication of the manuscript in ACP.

   Reply: We have made substantial changes to the manuscript in response to the review as described below, and we hope we have answered all of the concerns raised by the reviewer.

Specific comments

1. **Comment:** Two former publications of 1. by Bonazzola and Haynes (2004), who performed a trajectory analysis on the basis of ECMWF operational analysis data for the period prior to the drop (1997-1999) and 2. by Fueglistaler, Wernli and Peter (2004), who analysed the troposphere-to-stratosphere transport in the time period January/February and July/August for the year 2001 (i.e. posterior to the

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drop), and probably relevant to this study, are considered neither in the introduction nor in the results. The authors should compare their results with those of these older ones. In particular I would like to see what is new in the current manuscript.

Reply: Thank you for pointing out important papers not referenced in this study. Both papers are referred to in Sections 1 and 3 of revised manuscript as the pioneering studies using the trajectories in TTL dehydration. The comparison of the results with those of former research is made, although it is not straightforward because of the differences in the analyzed quantities as well as the datasets having been used. It is well known that the entry value of water to the stratosphere $[H_2O]_e$ depends on two factors: the pathways taken by trajectories and the temperature distribution in the TTL. The former describes the efficiency of sampling the coldest region by air parcels and the latter is related with the coldest temperature irrespective of the trajectory distribution, and are called "the sampling effect" and the "temperature effect", respectively, by Bonazzola and Haynes (2004). These authors estimated the importance of both effects on the intraseasonal and interannual time scales. What is new in the present study is to have decomposed $[H_2O]_e$ into the regional contributions (Fig. 7) by estimating the frequency distribution of LCP (Fig. 5) and temperature minima ($\sim SMR_{min}$ in Fig. 6), respectively, on a regional basis, and applied it to solve the problem of the SWV drop in 2000.

The following revisions are made in Section **1 Introduction**,

- **Page 28039, lines 24 to 27**: The reproduction of SWV variations by using the Lagrangian temperature history along the trajectories (e.g., Fueglistaler et al., 2005; Dessler et al., 2014) has proven quite

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effective, even though ...

has been changed to

The Lagrangian description of the transport processes in the tropical troposphere to the stratosphere using trajectory calculations proved to be quite effective not only in the reproduction of SWV variations but also in the characterization of the dehydration processes in the TTL (e.g., Bonazzola and Haynes, 2004; Fueglistaler et al., 2004, 2005; Dessler et al., 2014) even though ...

and **3 Results**

- **Page 28045, lines 10 to 13**: The spatial maximum during the period ... this maximum shows eastward expansion as far as 150° E.

has been changed to

The comparison between the two will shed light on the change in "the sampling effect" of Bonazzola and Haynes (2004). The spatial distribution is characterized by the maxima over the Bay of Bengal and Malay Peninsula accompanied by a ridge extending to South China Sea. It is interesting to note some similarity in the location to the spatial maxima of the first encounter of backward trajectories to 370 K isentrope for June to August 1999 shown by Bonazzola and Haynes (2004). During the period posterior to the drop (Fig. 5(b)), the maxima show eastward expansion as far as 150°E.

- **Page 28045, line 27**: The following sentence is inserted after "the SMR_{min}."
This corresponds to focus on the change in "the temperature effect"

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of Bonazzola and Haynes (2004).

- **Page 28046, lines 6 to 9**: The values show general decrease ... between the two (third panel),

has been changed to

The values show general decrease in the tropics with some enhanced drop in the central Pacific reaching less than 3.0 ppmv in the period posterior to the drop (Fig. 6(b)). The gross features correspond well to the horizontal distribution of the LCP-averaged SMR of July/August 2001 estimated by Fueglistaler et al. (2004). The difference between the two periods (Fig. 6(c)),

2. **Comment:** In Section 2.1 you state that your method is similar to that of Fueglistaler et al., 2005. I suggest that you describe at least the main aspects of your method (e.g. in an Appendix), so that the reader can understand what you did without reading the afore-mentioned paper. Please provide as well more information on the calculation of the trajectories. For instance: which time interval of ERA-interim data was available for interpolation? As ERA-interim has 6 hours output interval, do you consider this sufficient for temporal interpolation? Also, how many trajectories do you analyse in total? Is this sufficient for robust results?

Reply: Spatiotemporal interpolations necessary to conduct trajectory calculations have been written in Section 2.1, while the brief description on the main aspects of the method is introduced in Section 3.1. The following revisions are made in Section **2.1 Trajectory calculations**,

- **Page 28041, lines 5 to 11**: The trajectory calculations are started from uniformly distributed gridpoints ... ERA Interim dataset (Dee

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et al., 2011).

has been changed to

The backward trajectory calculations are started from uniformly distributed gridpoints (every 5.0° longitude by 1.5° latitude) within 30° N and S from the equator on 400 K potential temperature surface. The initializations are made on the 5th, 15th, and 25th of every month during the period since January 1997 till December 2002 relying on the European Centre For Medium-Range Weather Forecasts ERA Interim dataset (Dee et al., 2011). The number of initialization points is 2952 for a single calculation resulting in 8856 for the estimation of monthly values. This number compares well with that of the reduced set of trajectories in the study on the sensitivity of number of trajectories by Bonazzola and Haynes (2004) and turned out to be enough to derive statistically significant results as can be seen later in Section 3.

and the following sentences are inserted in **3 Results**

- **Page 28043, line 13, top**: The calculations are made on a monthly basis using the three initialization days (5th, 15th and 25th of each month) at a time. The following description refers to a specific month omitting the suffix for time. Let start by assuming that the minimum saturation mixing ratio along i-th TST trajectory ($i = 1, \cdots, N_{\mathrm{TST}}$) is denoted by $\mathrm{SMR}_{\mathrm{min}i}$. The entry value of water to the stratosphere $[\mathrm{H_2O}]_\mathrm{e}$ is defined as the ensemble mean value of $\mathrm{SMR}_{\mathrm{min}}$ as in Fueglistaler et al. (2005):

$$[\mathrm{H_2O}]_\mathrm{e} = \frac{1}{N_{\mathrm{TST}}} \sum_{i}^{N_{\mathrm{TST}}} \mathrm{SMR}_{\mathrm{min}i}. \quad (1)$$

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- **Page 28045, line 7**, after “TST trajectories.”: Let assume that i-th TST trajectory ($i = 1, \cdots, N_{\mathrm{TST}}$) takes minimum saturation mixing ratio ($\mathrm{SMR}_{\mathrm{min}i}$) at bin j ($j = 1, \cdots, M$), that is, the Lagrangian cold point (LCP) for i-th TST trajectory is found at bin j. If we denote the number of LCP events at bin j as $N(\mathrm{LCP} \in j)$,

$$N_{\mathrm{TST}} = \sum_{j}^{M} N(\mathrm{LCP} \in j). \tag{2}$$

Because some trajectories do not satisfy the TST condition in general, $N_{\mathrm{TST}} \leq N$, where N is the total number of initialization points used for the calculation. The probability of LCP events at bin j, $P(\mathrm{LCP} \in j)$, is defined by

$$P(\mathrm{LCP} \in j) = \frac{N(\mathrm{LCP} \in j)}{N_{\mathrm{TST}}}, \tag{3}$$

so that the normalization condition $\sum_{j}^{M} P(\mathrm{LCP} \in j) = 1$ holds.

- **Page 28045, lines 7 to 10**: The top two panels of Fig. 5 show ... posterior to the drop).

has been changed to

The top two panels of Fig. 5 show the horizontal distributions of $P(\mathrm{LCP} \in j)$ thus defined for those trajectories initialized in September 1998 and 1999 (a; prior to the drop) and September 2000, 2001 and 2002 (b; posterior to the drop). Because N_{TST} is different among individual September, N_{TST} for each month has been

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used as a weight in taking the averages. In other words, the calculations are made by combining the trajectories of two or three prior- or posterior-months together for the illustrations. To be more specific, the TST trajectories of September 1998 and 1999, selected from $N = 2952 \times 3 \times 2$ trajectories, are combined together for the illustration of Fig. 5(a), while those of September 2000, 2001, and 2002, selected from $N = 2952 \times 3 \times 3$ trajectories, are used for panel Fig. 5(b).

- **Page 28046, lines 1 to 3**: Figure 6 is the same as Fig. 5 ... rather than the probability of LCP events.

has been changed to

The ensemble mean value of $\mathrm{SMR_{min}}$ at bin j, SMR(LCP$\in j$), is defined by

$$\mathrm{SMR}(\mathrm{LCP} \in j) = \frac{1}{N(\mathrm{LCP} \in j)} \sum_{i}^{\mathrm{LCP} \in j} \mathrm{SMR}_{\mathrm{min}i}, \tag{4}$$

where $\sum_{i}^{\mathrm{LCP}\in j}$ indicates the sum with respect to the subset of TST trajectories that take LCP at bin j.

Figure 6 is the same as Fig. 5 except that SMR(LCP$\in j$) is illustrated rather than $P(\mathrm{LCP} \in j)$.

- **Page 28046, lines 16 to 20**: the comparisons based only on the

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changes ... SMR_{min} (Fig. 6) together for each bin.

has been changed to

the comparisons based only on the changes in SMR(LCP$\in j$) could be misleading, because the values of $P(\mathrm{LCP} \in j)$ are much higher in the former than in the latter (Fig. 5). The expectation value for bin j, $E(\mathrm{LCP} \in j)$, is defined by the multiple of $P(\mathrm{LCP} \in j)$ and SMR(LCP$\in j$) to quantify the contribution of each bin to $[H_2O]_e$. The sum of $E(\mathrm{LCP} \in j)$ with respect to all bins reduces to

$$\sum_{j}^{M} E(\mathrm{LCP} \in j) = \sum_{j}^{M} P(\mathrm{LCP} \in j) \times \mathrm{SMR}(\mathrm{LCP} \in j) \tag{5}$$

$$= \sum_{j}^{M} \frac{N(\mathrm{LCP} \in j)}{N_{\mathrm{TST}}} \times \frac{1}{N(\mathrm{LCP} \in j)} \sum_{i}^{\mathrm{LCP} \in j} \mathrm{SMR}_{\mathrm{min}i} \tag{6}$$

$$= \frac{1}{N_{\mathrm{TST}}} \sum_{j}^{M} \sum_{i}^{\mathrm{LCP} \in j} \mathrm{SMR}_{\mathrm{min}i} \tag{7}$$

$$= \frac{1}{N_{\mathrm{TST}}} \sum_{i}^{N_{\mathrm{TST}}} \mathrm{SMR}_{\mathrm{min}i}. \tag{8}$$

This is the entry value of water to the stratosphere $[H_2O]_e$ (Eq. (1)) shown as a time series in Fig. 3. $[H_2O]_e$ is thus decomposed of the sum of $E(\mathrm{LCP} \in j)$, which is interpreted as the contribution of bin j to $[H_2O]_e$. What is important here is that it is neither $P(\mathrm{LCP} \in j)$ nor SMR(LCP$\in j$) but the product between the two, $E(\mathrm{LCP} \in j)$, that is directly responsible for composing the value $[H_2O]_e$. By comparing the distribution of $E(\mathrm{LCP} \in j)$ between the two periods, prior and

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posterior to the drop, we can see how the drop in $[H_2O]_e$ is brought about by the change of water transport from individual region.
Figure 7 shows the horizontal distribution of $E(\mathrm{LCP} \in j)$.

3. **Comment:** In sections 3.4/3.5 you show that the horizontal distribution of LCP-event probability (Fig. 5) shifts from Bay of Bengal and the Western Pacific area to the Central Pacific. Fig. 7 shows that the contribution of the region from which the water vapour enters the stratosphere shifts in the same way. However, this effect is accompanied by a general decrease in H2O entry values over most of the tropical area (Fig. 6(b)) and a strong temperature decrease at 100 hPa (Fig. 9), which is most prominent in the Central Pacific. I wonder whether it is not this cooling at 100 hPa which is the dominant process for the water vapour drop instead of the shift of trajectories entering the stratosphere. Thus I would like to see more evidence for your suggestion that it is the shift of the trajectories rather than the strong cooling at 100 hPa that leads to the water vapour drop. My feeling is that it is not possible to disentangle these two influences with your analysis.

Reply: Thank you pointing out the important issue to be explained in more detail. As is shown by Eq. (8), we can interpret the values of $E(\mathrm{LCP} \in j)$ as the contribution of bin j to $[H_2O]_e$. Because the quantity that directly drives $[H_2O]_e$ is $E(\mathrm{LCP} \in j)$, any statement that attributes solely $P(\mathrm{LCP} \in j)$ or SMR(LCP$\in j$) to the cause of changes in $[H_2O]_e$ is mathematically wrong. However, we believe it is quite interesting to see individual changes in $P(\mathrm{LCP} \in j)$ and SMR(LCP$\in j$) to interpret the variations in $E(\mathrm{LCP} \in j)$. The following revision is made in the revised manuscript.

- **Page 28046, line 23 to page 28047, line 1**: The contribution from

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this core area ... decrease in $\mathrm{SMR}_{\mathrm{min}}$.

has been changed to

The contribution from this core area remains dominant during the posterior period (Fig. 7(b)). While the reduction of $[H_2O]_e$ cannot be free from the general cooling (lowering of SMR(LCP$\in j$)) in posterior years over most of the tropics (Fig. 6), it is interesting to note the increase of $E(\mathrm{LCP} \in j)$ despite the decrease in SMR(LCP$\in j$) over the central Pacific. This is because the increase of $P(\mathrm{LCP} \in j)$ more than compensate for the decrease of SMR(LCP$\in j$) over there. In this sense, it is not appropriate to attribute the cooling over the western and the central Pacific to the drop in $[H_2O]_e$. The similarity in the spatial distributions of $P(\mathrm{LCP} \in j)$ and $E(\mathrm{LCP} \in j)$, especially that of the location of maxima over the Bay of Bengal and Malay Peninsula together with the post 2000 decrease over there and the western tropical Pacific, suggests that the relocation of LCPs (change in $P(\mathrm{LCP} \in j)$) is a leading factor that has caused the drop in $[H_2O]_e$ in September 2000.

4. **Comment:** Page: 28040, line 10: What do you mean by occasional value?

   Reply: "its occasional value ($\mathrm{SMR}_{\mathrm{min}}$)" has been changed to "the minimum value ($\mathrm{SMR}_{\mathrm{min}}$)".

   Comment: line 20: however, it will... What is meant by "it"?

   Reply: The sentence has been changed to
   However, such a restriction will serve to focus our investigation on some specific processes that may have led to ...

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Comment: line 21: “the advantages”. Please specify the advantages or omit the “the”.

Reply: “the advantages” has been replaced by “an advantage”.

5. **Comment:** Page 28041, line 12: What is meant by “those on pressure levels”? Which variables are on pressure levels?

   Reply: The sentence has been replaced by

   > - **Page 28041, line 11ff**: All meteorological variables given on 60 model levels have been interpolated to those on 91 pressure levels keeping the horizontal resolution of 0.75° by 0.75° longitude-latitude gridpoints prior to calculations. The time step has been set to 30 minutes, similar to 36 minutes taken by Bonazzola and Haynes (2004), by applying spatiotemporal interpolations to the 6-hour interval ERA Interim dataset. As for the limitation and caution of this method, see, for example, the pioneering studies by Fueglistaler et al. (2004) and Bonazzola and Haynes (2004).

6. **Comment:** Page 28042, line 19: If you use ERA-interim data for the calculation of backward trajectories, how is a time step of 30 minutes possible? Please provide some information why 0.2 K in potential temperature within one time step defines a fast ascending air parcel.

   Reply: The ERA Interim gridpoint values in the time interval of 6 hours are interpolated in both time and space to the location of air parcels every time step of trajectory calculation as is described above. The increment of 0.2 K has been chosen empirically. The following revision is made.

   > - **Page 28042, line 18**: The required rate for the fast ascent is empirically set to more than 0.2 K in potential temperature within 1 time step (30 min),

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Comment: line 24: “rapidly decays” is probably the wrong expression. Do you mean the proportion of fast air parcel go to zero?

Reply: “rapidly decays” has been replaced by “rapidly goes to near zero”.

7. **Comment:** Page 28045, line 2: The reference to figure 4 of Randel and Jensen is misleading. It shows the intrusion of ozone-rich air, which I expect to be of stratospheric origin and thus dry air.

   Reply: As the influence from the extratropics is out of the scope of the present study, the sentence is deleted. The related changes are

   - **Page 28044, line 24 to page 28045, line 4**: dehydration efficiency in the TTL. ... associated with the modal shift seen in Fig. 4,

   has been changed to

   dehydration efficiency in the TTL. To quantify the change in the LCP distribution associated with the modal shift seen in Fig. 4,

8. **Comment:** Page 28046, line 10: Please provide information about the statistics (“significance”) including the respective formulas you used. I do not understand how the t-test is applied for your samples. I expect to see arguments why you think your applied statistics method is suitable. You might do this in an appendix.

   Reply: The method of estimating the statistical significance has been written in Appendix, which will read as follows:

   Appendix A: Statistical tests between prior and posterior to the drop
   A1 The difference of $P(\text{LCP} \in j)$
   Let the random variable, X, is the number of event occurrences in some number of trials, n. The binomial distribution can be used to calculate the probabilities for each of $n+1$ possible values of

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X $(X = 0, 1, \cdots, n)$ if the following conditions are met: (1) the probability of the event occurring does not change from trial to trial, and (2) the outcomes on each of the n trials are mutually independent. These conditions are rarely met, but real situations can be close enough to this ideal that the binomial distribution provides sufficiently accurate representations. The probability that the number of occurrence X is x among n trials, $\mathrm{Pr}(X = x)$, follows the binomial distribution

$$\mathrm{Pr}(X = x) = \binom{n}{x} p^x (1-p)^{n-x}, \quad (x = 0, 1, \cdots, n), \tag{9}$$

where p is the probability of occurrence of the event.
The statistical test for the difference in the population proportion of two binomial populations, $p_1 - p_2$, could be made as follows. Let the sample size and the sample proportion of the two sets being n_1 and n_2 and m_1/n_1 and m_2/n_2, respectively. The test statistic, T_1, defined by

$$T_1 = \frac{m_1/n_1 - m_2/n_2}{\sqrt{p^*(1-p^*)(1/n_1 + 1/n_2)}}, \quad p^* = \frac{m_1 + m_2}{n_1 + n_2}, \tag{10}$$

follows approximately the standard normal distribution. The statistical test for the difference between $P(\mathrm{LCP} \in j)$ in prior and posterior periods could be done by applying the two-sided tests under the null hypothesis of $p_1 - p_2 = 0$ at some significance level α, where p_1 and p_2 are the population proportion of LCP taking place at bin j in the posterior and prior to the drop, respectively. In our case, n_1 and n_2, and m_1 and m_2, are N_{TST} and $N(\mathrm{LCP} \in j)$, respectively, for posterior (suffix 1) and prior (suffix 2) periods.

A2 The difference of SMR(LCP$\in j$)

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The statistical test to be applied is the comparison of the population means of two normal distributions, μ_1 and μ_2, with unknown population variances. This test is sometimes called the Welch's t test. The test statistic, T_2, defined by

$$T_2 = \frac{\overline{x}_1 - \overline{x}_2}{\sqrt{s_1^2/n_1 + s_2^2/n_2}}, \tag{11}$$

follows the t distribution of the degree of freedom m, where

$$m = \frac{(s_1^2/n_1 + s_2^2/n_2)^2}{s_1^4/(n_1^2(n_1-1)) + s_2^4/(n_2^2(n_2-1))}. \tag{12}$$

Here, n_1 and n_2, $\overline{x}_1$ and $\overline{x}_2$, and s_1^2 and s_2^2 are the sample size, the sample mean, and the unbiased sample variance, respectively, of the two sets. The statistical test for the difference between SMR(LCP$\in j$) in prior and posterior periods could be done by applying the two-sided tests under the null hypothesis of $\mu_1 - \mu_2 = 0$ at some significance level α. In our case, n_1 and n_2, $\overline{x}_1$ and $\overline{x}_2$, and s_1^2 and s_2^2 are $N(\text{LCP} \in j)$, SMR(LCP$\in j$), and the unbiased variance of SMR_{min} at bin j, respectively, for posterior (suffix 1) and prior (suffix 2) periods.

Some associated changes are made to **Page 28045, line 17**:

The test statistic of the difference (see Appendix A1 for details) is shown in Fig. 5(d) indicating ...

and the figure caption of Figs. 5 and 6 referring to the Appendix.

- **Figure 5**. Horizontal distribution of LCP-event probability, $P(\text{LCP} \in j)$, estimated from the TST trajectories initialized on 400 K

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in (a) September 1998 and 1999 (prior to the drop) and (b) September 2000, 2001 and 2002 (posterior to the drop). The probabilities are estimated in 10° by 10° longitude-latitude bin as the number of LCPs experienced by all TST air parcels inside the bin divided by the total number of TST parcels used for the calculation ($N(\mathrm{LCP} \in j)/N_{\mathrm{TST}}$). Panels (c) and (d) are the difference of probabilities between the two (posterior minus prior to the drop) and the values of test statistic (T_1 of Appendix A1), respectively. The colored bins indicate that the difference is statistically significant at the significance level of 1 % or higher. Those bins shown in white indicate there found no LCP event in (a) and (b), while the difference is not statistically significant in (c) and (d). See Appendix for the details of statistical tests.

- **Figure 6**. The same as Fig. 5 except that the ensemble mean values of $\mathrm{SMR}_{\mathrm{min}}$ are illustrated on the bin-by-bin basis ($\mathrm{SMR}(\mathrm{LCP} \in j)$). The test statistic shown in (d) is T_2 of Appendix A2. See Appendix for the details.

Comment: line 8: “leading to a reversal of the zonal gradient of $\mathrm{SMR}_{\mathrm{min}}$ over the equator” ... I do not understand this sentence.

Reply: This part of the sentence has been deleted.

Comment: Page 28048, line 21: How can the contribution from the Tibetan high and the thermal forcing from the ocean to the SWV drop be quantified by a “projection of the H2O entry values onto bins in the tropics”? I don’t understand this sentence.

Reply: The sentence has been revised as follows:

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- **Page 28048, lines 22 to 25**: the modulations of the Tibetan high and ... distributed in the tropics (Fig. 7).

has been changed to

the modulations of the Tibetan high and the TTL circulation driven by the thermal forcing from the equatorial ocean. The regional contribution to $[H_2O]_e$, quantified by $E(\mathrm{LCP} \in j)$, shows distinct decrease in two regions; one over the Bay of Bengal and the other over the equator in the western tropical Pacific (Fig. 7(c)). The former will be related to the weakening of Tibetan high, while the latter may imply the modulation of the Matsuno-Gill pattern (Matsuno, 1966; Gill, 1980), although these will not be independent between each other.

9. **Comment:** Page 28049, line 5: "without taking the average". I do not understand what you intended to calculate.

Reply: Each panel of Figure 9 is the averaged distribution either before the drop or after the drop. The features commonly appear in each of the months depending on the category either prior or posterior to the drop even if the averages are not taken among years. The sentences have been revised as follows:

- **Page 28049, lines 4 to 7**: The corresponding features appear basically the same ... with the intensity weaker in the latter (2000/2001/2002).

has been changed to

We can see the Tibetan anticyclone in the height field of both periods (left) with the intensity weaker in the latter (2000, 2001 and

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2002) than in the former (1998 and 1999). This feature appears basically the same in individual monthly mean values of August depending on the category either prior or posterior to the drop.

Comment: Page 28049, lines 23-29: I cannot follow your description of Figure 10.

Reply: Figure 10 has been redrawn to make the important point clearer. The sentences are revised as follows:

- **Page 28049, lines 23 to 27**: The difference between the longitudes of warm SST core ... to underlying convective heating (Hatsushika and Yamazaki, 2003).

has been changed to

The possible connection of the water drop in 2000 to the modified SST distribution has been discussed by Rosenlof and Reid (2008). They found the correlation coefficients between tropopause temperature and SST are quite small "if one correlates times prior to 2000, or after 2001" separately, but a large negative correlation coefficient of – 0.44 appears if one correlates the entire time period which, they say, is "exclusively a consequence of the decrease in tropical tropopause temperatures of $\sim 2°$C in $171° - 200°$ longitude band coincident with an increase in SSTs of $0.4°$C in the $139° - 171°$ tropical longitude band." The longitudinal difference between the warm SST core and the temperature minimum near the tropopause will be due to the eastward tilt of cold region associated with a steady Kelvin wave response to underlying convective heating (Hatsushika and Yamazaki, 2003). Thus the notion by Rosenlof and Reid (2008) suggests that the SWV drop in 2000 is driven by some dynamical

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process that accompanies the generation of Matsuno-Gill pattern. This is consistent with the idea that the modified SST distribution is one of the key processes that drove the water drop in the year 2000.

10. **Comment:** Page 28050, lines 1-3: I doubt your conclusion drawn from Fig. 7, namely that the TTL temperature in the Central Pacific is not the cause of the water vapour drop. I think that this interpretation is not supported by the results of Figure 7. Please consider that the cooling in 2001/2002 is distributed over the whole tropical belt, as Figure 9 shows.

    Reply: This point has been already discussed in the reply to item 3 of Specific comment. The sentences are revised as follows:

    - **Page 28049, line 29 to page 28050, line 3**: The important point in our analysis is that ... by way of the Bay of Bengal and the western tropical Pacific (Fig. 7).

    has been changed to

    The important point in our analysis is that the decrease of SMR(LCP$\in j$), albeit widely distributed and remarkable in the tropics (Figs. 6 and 9), is not enough to explain the drop of $[H_2O]_e$ if we recognize the dipole structure, that is, the paired increase and decrease, in $E(\mathrm{LCP} \in j)$ over the equatorial Pacific (Fig. 7). The modified pathway of TTL trajectories, resulted in the reduction of LCP probabilities over the Bay of Bengal and the western tropical Pacific (Fig. 5), is quite important.

11. **Comment:** Discussion section: As far as I understand the following two sentences contradict each other:

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Page 28050 line 1ff: “The important point in our analysis is that the drop of H2O does not come from the decrease of TTL temperature in the Central Pacific but that from the the water transport by way of the Bay of Bengal and the Western tropical Pacific.”

and

Page 28052 line 6: “The correspondence to the change in the SST distribution ... suggests that the drop and the subsequent low values of H2O are brought about by the eastward expansion of warm SST region to the central Pacific through reduced water entry to the stratosphere.”

Could you please clarify?

Reply: The former sentence has been replaced as written above. The latter is revised as follows:

- **Page 28052, line 6ff**: The correspondence to the change in the SST distribution, the time of occurrence, and the persistency of phenomenon suggest that the drop and the subsequent low values of $[H_2O]_e$ are brought about by the reduced water entry to the stratosphere mainly through the Bay of Bengal (in boreal summer) and the Western tropical Pacific. The dipole pattern in $E(\mathrm{LCP} \in j)$ over the equatorial Pacific (Figs. 7 and 12) is suggestive of an eastward shift of Matsuno-Gill pattern related to the eastward expansion of warm SST region to the central Pacific.

12. **Comment:** Figure 5: The caption of this figure is not at all comprehensible from the beginning of “The difference of probabilities...”. Please give details of the computational method either in the main text or in an appendix. For instance, describe what is considered in the Binomial distributions and how you determined their parameters. What do you mean with Gauss transformation? Is it simply the fact that the Binomial approaches a Gaussian for a large number of data?

ACPD

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Reply: The details of the computational method have been written in the main text (Reply to item 2 of Specific comments). The issues such as binomial distributions and Gauss transformation are written in Appendix. The caption of Figure 5 is revised as is written in item 8 above.

Technical corrections:

1. **Comment:** Figures 5/6/7: please describe the respective month and year on top of the figures, then it is easier to follow the description in the text.

   Reply: Done.

2. **Comment:** Figure 9/10: color bar is missing.

   Reply: The color bar is found at the top in Figure 9. Figure 10 has been rewritten in monochromatic fashion and no longer needs color bar.

3. **Comment:** Figure 12: select a more appropriate color bar to display the results for the upper and middle figure.

   Reply: The color code of Figure 12 is set exactly the same as that of Fig. 7 so that we could easily compare between the two. Thus the color bar is kept intact.

ACPD

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