We thank Stephan Fueglistaler for the very helpful comments. Here are our replies with which we hope to clarify some misunderstandings.

- **General reply**: Reading the comments of the three referees, we have the impression that we probably raised wrong expectations with respect to what we achieved with our study. All three referees agree in revealing weaknesses in our argumentation, which we believe can be explained and therefore eliminated:

    - Part of the problem is probably caused by misunderstandings (maybe due to unclear formulations), as for instance the precise definition of “drop” (sudden decline versus period of low values thereafter), or the presumable influence of “nudging” as we applied it.
    - Another, more severe part, is in fact caused by the lack of important information, which we erroneously hold back (mainly to shorten the manuscript), although it was found by our analyses. Most importantly, we did not put sufficient emphasis on our simulation RC1SDNT (i.e., nudged, but without mean temperature nudging), which was only mentioned briefly, but not discussed in full detail.

  We hope that we can clarify our findings with additional information and revision of the text, where the misunderstandings occur. The details about that are outlined in our point-by-point replies below.

- *Brinkop et al. present a study of the sudden drop of water entering the stratosphere in the year 2000 using the Chemistry-Climate Model EMAC. The model is forced with observed SSTs, and the QBO is imposed by nudging with observed stratospheric winds. An additional run where the model is nudged against ERA-Interim is presented. The paper is generally well written, with some technical details requiring clearer description (outlined below). My main concern with the paper is that the numerical model results presented do not support the key statements in the text - I am looking forward to reading their rebuttal. First, Figure 4 shows clearly that only the fully nudged model run (which I must assume to be almost identically to the ERA-Interim data used to nudge the model) qualitatively reproduces the drop in water entering the stratosphere as observed by HALOE.*

  Reply: It is a common misunderstanding, that a nudged model exactly reproduces the nudged data, which implies that it would act like a chemistry transport model (CTM). This is not the case, because the nudged model develops its own physical state on sub-synoptic scale. Nudging means adding a tendency to the model calculated tendency of selected prognostic variables in the simulation, which in our case is a Newtonian relaxation towards ERA-Interim reanalysis data. Nudging, however, still allows the model to develop its own subgrid-scale physics. Please note: water vapour is not nudged in our simulations and thus the hydrological cycle evolves freely, yet reacting to the additional weak forcing through nudging. This is different from ERA-Interim water vapour, which is assimilated by a 4D-Var data assimilation scheme. Therefore, we do not expect that nudged models provide the same results in detail as the data used for nudging. This also holds for the nudged QBO: all simulations are nudged with the same data (Singapore winds), in order to improve the timing of west and east phases. The resulting winds are, however, not the same in RC1SD and RC1, RC2, because the model still generates its own wind profiles!

- *I just can't see how you can reach the conclusion from your model calculations that ENSO via SST pattern is key to the problem, when the runs that are forced with observed SSTs (and even QBO!) completely fail to produce a drop around the year 2000. While suspecting ENSO/SSTs to be involved is completely reasonable, the challenge is to demonstrate that this is indeed the case, and your model results - along with other model results (e.g. SPARC CCMVal2) - fail to demonstrate this connection. The conclusion that "appropriate boundary conditions" are required is not helpful given that only your fully nudged run - where essentially every variable is set to prescribed values (P24913/L5ff) - gives the qualitatively correct result.*

  Reply: Thank you for this comment. We refer to your statement that the RC1 simulation (completely) fails to produce a drop in water vapour. We do not agree, that the drop is not simulated at all. The amplitude (of the decline around year 2000, what we call "drop") is too small and the period of low water vapour values is clearly too short. This is all the more interesting, because the temperature anomaly of the cold point (Fig. 5) is reproduced. This raised the question, if the characteristic of the drop is masked by a too low cold point temperature in RC1.

  In this context, it maybe have been overlooked that the simulation RC1SDNT also reproduces a smaller drop (and shorter recovery period). The only difference between the setups of RC1SDNT and RC1SD is that RC1SD includes the relaxation of the (vertically dependent) global mean temperature, whereas RC1SDNT does NOT include this. Note that this option is possible because the nudging is performed in spectral space, and "wave-0" (corresponding to the global mean) can be omitted easily. In other words, the additional nudging of wave-0 in RC1SD (compared to RC1SDNT) causes an additional temperature bias correction, whereas in RC1SDNT only the synoptic patterns are nudged. As we show by comparing the water vapour of RC1SD with that of RC1SDNT, the temperature bias is responsible for the reduced drop amplitude. Note further that the mean temperature bias (compared to ERA-Interim) of RC1 is even larger than that of RC1SDNT.

  Thus, as a further proof for the role of the temperature bias, we shifted (in our output data) the temperature anomaly at the cold point of RC1 to the mean cold point temperature of RC1SD (adding the difference in mean cold point temperature (RC1SD-RC1) to the RC1 cold point temperature). Then, we calculated the saturation water vapour values and found a similar drop (though not identical) as in the RC1SD simulation. We add a Figure with the respective saturation water vapour values to the revised manuscript (see also Figure in this reply). Apparently, the too low cold point temperatures contribute significantly to the reduced water vapour variability.

Although, this point was already discussed in the manuscript (Section 3), we accept that the explanation was not clear enough. We will improve it in the revised manuscript.

Another misunderstanding might be the definition of "drop". We do not explain the "period of low water vapour after 2000" with ENSO / SST and QBO coincidence, only the sudden drop (decline) of water vapour in 2000. As we conclude, such a sudden decline nearly always occurs after a strong ENSO event with concurrent phase change of QBO from west phase to east after La Niña. The recovery thereafter is not connected to ENSO.

- *Second, given that the fully nudged run (RC1SD) is presumably very similar to reanalysis data, it is not surprising that you get a drop - this has been known for a decade (see e.g. Figure 2 of Fueglistaler and Haynes (2005)); the challenge with the drop today is proper attribution to processes (see above), and accurate quantification and reproduction of the magnitude. As shown in Fueglistaler et al. (2013), all mode reconstructions using a wide range of available temperature data give what you also find: a drop, but the magnitude of pre/post 2000 is smaller than observed by HALOE; however, if one compares to SAGEII, the agreement is much better. The manuscript does not mention this conundrum, and is vague in terms of assessment of the success of the model result (first, it is noted that there is a "small" discrepancy, while later the discrepancy is quantified to be 50% - see comments below).*

  Reply: You refer to model simulations by Fueglistaler et al. (2013), already describing the water vapour drop. These are trajectory calculations based on ERA-Interim data. However, we use an Eulerian model with a hydrological cycle that develops freely under different boundary conditions (SSTs, GHGs, solar forcing).

  The nudging procedure is solely used to reproduce the observed (or reanalysed) synoptic scale situation (i.e. meteorological patterns), which cannot be reproduced by a free running setup, even if forced with observed SSTs. The water vapour, however, is in all cases developing freely. Further, nudging does not correct for model errors as long as the global mean temperature nudging is not included (see above). Thus, with a hierarchy of simulation setups (from free running (forced with simulated SSTs), forced by observed SSTs, nudged w/o T-mean and nudged with T-mean) we are able to analyse the influence of different drivers. To our knowledge, this has not been done with other GCMs or CCMs so far. Our new finding is, that the drop itself is only in parts masked by a model error, namely the cold point temperature bias.

According to the conundrum of discrepancies between different observation based datasets: an analysis of this is beyond the scope of the present study (although we are going to mention it in the revised manuscript). To confuse the situation even more, we add another (recent) dataset of Hegglin et al. (2014) to our Fig. 1. This shows that our simulated water vapour drop lies in fact within the range of at least two observational data sets.

Referring to the confusion with "small discrepancy" "and 50% difference", this indeed needs clarification. In the original manuscript we refer to two observational data sets: HALOE/Aura-MLS and HALOE/MIPAS. The former is used to compare our water vapour anomaly as a near global mean. With the latter we performed an analysis with respect to the zonal mean drop characteristics dependent on latitude: drop date, length and amplitude. This seems to be inconsistent and contradictory, but it is not the case. We included a text in Sec. 2.2 of the revised manuscript to clarify this aspect and refer explicitly to the different data sets used.

Concerning your statement that the "challenge with the drop today is the proper attribution to processes" we clearly agree. Yet, we see a need to clarify the simulated difference in drop appearance of RC1SD and RC1. We explicitly state that our simulations are not the first choice to explain the effect of certain processes for the appearance of the water vapour drop. In that case detailed sensitivity studies would be more appropriate. But this is not the focus of the manuscript.

- *Abstract, line 11: You date the "start date" to the "early days of 2000"; Fueglistaler (2012) argue, based on their Figure 9, that the drop dates around October 2000; it would be helpful if you could comment. (See also my comment below for P24916/L28 that the text does not explain how you determine this date.)*

  Reply: We define as the "drop" the decline of water vapour, shown in the time evolution of the anomaly in our Figures 1 and 1A. This starts with the highest value (i.e., the "drop onset") which defines our start date. From Figure 9 of Fueglistaler (2012), we assume that here, the minimum is used to define the "drop date". In order to avoid confusion and since the date definition is irrelevant for the process, we will replace "early days of 2000" by "in 2000" in the revised manuscript.

- *Further: "We show that the driving forces ... are tropical sea surface temperatures ..." As stated above, I don't think that your model results support this statement. Rather, your Figure 4 demonstrates the failure of the SST-based model runs. The question then is whether (i) the model fails to correctly reproduce the effect of SSTs on the TTL, or whether (ii) some other process is involved.*

Reply: We conclude from Figure 4 that the amplitude of the water vapour variability (including that of the drop) is underrepresented in the free running setup RC1. For RC2 we do not expect a correct timing at all, since the model is forced by simulated SSTs in that case.

A sudden decline in water water vapour anomaly is nevertheless visible also in RC1 at roughly the right time, however, with underrepresented magnitude, i.e. a too large minimum.

Figure 5 furthermore shows that the effect of SSTs on the TTL temperature anomaly is reproduced in RC1, i.e., the results are comparable between RC1 and RC1SD. This seems to be a contradiction: the TTL temperature anomaly is reproduced in RC1, but the water vapour anomaly is not. This apparent contradiction can be resolved by the non-linearity of the Clausius-Clapeyron relation: The amplitude of the water vapour anomaly does not only depend on the temperature anomaly, but also on its absolute value: RC1 simulates a significantly lower cold point temperature compared to RC1SD. As a consequence the water vapour variability is also lower, because of the temperature bias at the cold point – not because of its variability.

To demonstrate this, we added (from the output data) the difference of the mean cold point temperatures (RC1SD-RC1) to the RC1 cold point temperatures, keeping the variability of RC1 as it was simulated and calculate the corresponding saturation water vapour mixing ratio over ice. This result is shown in the attached Figure (which we will also include as new Figure in the revised manuscript), showing saturation water vapour mixing ratios of the temperature-shifted RC1 simulation closer to RC1SD.

Thus, in brief the answer to your question is: the model fails to correctly simulate the mean cold point temperature and this causes the absence of a "deep" drop. Nevertheless, we agree with the referee that other processes cannot be excluded.

We will describe this analysis in more detail in the revised manuscript.

- *P24911/L10: "This has become the big conundrum ..." suggest to reformulate.*

  Reply: We will reformulate it.

- *P24911/L13: "An increase in stratospheric water is expected..." This is a bold statement, not supported by any reference. I assume that your statement is not based on theoretical arguments, but on model results - in which case it would be fair to cite the papers (I assume that you think of CCMVal results, so please refer this work here).*

  Reply: We agree. Our statement indeed refers to model results. In the revised manuscript we will provide an appropriate reference.

- *P24912/L12: "Randel and Jensen (2013) state ..." I found this section unclear; are you saying here that your paper is to some extent a rebuttal* *to their statement concerning model results? Also, since you argue here that your model runs perform better than those referred to by Randel and Jensen (line 27: "... indicating that it is possible to ...") it would be useful if you could briefly list here what exactly is better in your model than in those that you compare to - "appropriate boundary conditions" (Line 28) is very vague. In any case, as already state above, I don't think that your results support your claim.*

Reply: With "appropriate boundary conditions" we refer to the observed (or reanalysed) SSTs **and** the nudging (of temperature, divergence, vorticity and the log of the surface pressure and the mean temperature (wave number zero in spectral space)). This is indeed misleading and will be clarified in the revised text.

As mentioned above, we use a hierarchy of 4 different model setups to analyse the millennium drop, i.e. the sudden decline in 2000. We find, that a nudged setup (RC1SD) performs best. Again: This cannot be expected a priori for water vapour, since the hydrological cycle is freely evolving.

A nudged setup excluding the mean temperature from nudging (RC1SDNT) also reproduces the millennium drop, however, with a smaller amplitude. This is related to the cold point temperature bias as outlined above.

Next, a free running simulation (RC1) forced with observed SSTs shows a similar onset of the drop but largely under-represents the amplitude, again caused by an even larger cold point temperature bias. Note that the observed SSTs used here is very similar to the SSTs used when nudging is applied, and thus can be excluded as cause.

Last but not least, a free running simulation with simulated SSTs (RC2) shows no drop at all. This is a result that does not surprise, because the dynamical situation is not related to the observed (or reanalysed).

The analysed gradual degradation of the drop signal from RC1SD and RC1SDNT over RC1 to RC2 is further augmented by the difference in the QBO signal between the different simulations (see Figure 14). Note that the QBO at roughly 90 hPa is key for the temperature signal affecting water vapour, i.e., at an altitude where the QBO nudging strength is already reduced and therefore relies on signal propagation.

Thus, to answer your question: Yes, we think our nudged (!) model simulations are performing better than our free running simulations. But this is obvious and to be expected, but not the point. The point is that we reveal some strong indications to why this is the case.

Similar analyses and evaluation of other model simulations are definitely required to corroborate our findings. This is, however, beyond scope for our present study.

- *P24914/L2: Please be more specific what "slightly nudged" means; reference to Jöckel et al. (2015) is not sufficient since the QBO is a key* *factor. Of particular importance here would be over which pressure levels you nudge the model (to the Singapore wind, I presume?).*

Reply: We will describe the QBO nudging procedure in more detail in the revised Section 2.1. We omit the word "slightly" as it is indeed vague and rather state explicitely the relaxation time of 58 days.

- *P24914/L25: It is not quite correct to state that previous studies focused mostly "on its absolute value"; see e.g. Fueglistaler and Haynes (2005; their Figure 2a); Fueglistaler (2012); Fueglistaler et al. (2013). Also, note that the focus on some period-average is not a deficit of the studies you quote here, but is due to the fact that the year 2000 drop is unusually long; and the long duration is - aside from the magnitude of the drop - the main reason we're interested in this event. None of the oscillations in the satellite record after the pre/post-2000 change comes even close.*

  Reply: Thank you for this hint. As it is written, it is indeed misleading. We only wanted to underline the differences in methodology of our study compared to previous studies. We will omit this text passage.

- *P24915/L14ff: "In Fig 1 we show that our RC1SD simulation is able to closely reproduce the water vapour fluctuations as observed ..." and "is in accordance with observed values." and later "... drop in 2000 is slightly underestimated (about -0.12ppmv),..". Later on you quantify the mismatch as 50. As pointed out above, your results are in line with previously reported results; the remaining problem is the exact magnitude.*

  Reply: This is an important point to clarify. In Figure 1 we compare our results with the HALOE/Aura-MLS data (and additionally also with the data set as published by Hegglin et al. 2014 in the revised manuscript). In contrast, the drop characteristics as described in Figure 3 are the combined HALOE/MIPAS water vapour series. Both observational based data sets have been derived with different methodologies. This will be clarified in the revised text in Section 2.2.

  Note that only our free running simulation (RC1) results are in line with previously reported results. With nudging (RC1SD and RC1SDNT) we are able to reproduce also the magnitude within the uncertainty of presently available observational data. All we do is to analyse the differences between nudged and free running simulations, yielding - in our opinion - strong indications to responsible processes.

- *P24915/L12ff: The temperature dependence of Clausius-Clapeyron indeed poses a challenge for water vapor amplitudes in the presence of a mean temperature bias; however one can address this problem by analysing the amplitudes in terms frost point temperature variations (see Fueglistaler et al. (2013) for a discussion of the impact of a mean temperature bias on H2O variations; their Figure 5b/para33 is for the annual cycle, but extension to inter-annual variability is simple.)*

Reply: As stated above, we will add a new Figure in which the saturation water vapour mixing ratios are shown, that correspond to the cold point temperatures of RC1SD, RC1 and RC1 with a shifted cold point temperature. With that we visualise how the cold point temperature bias effects the water vapour variability.

- *P24916/L28: Here you state that the observations have a larger drop by 50% in the tropics - whereas above (p24915/L23) you wrote "slightly underestimated". Also -please explain how exactly you determine the "drop date"; as noted above, we have argued that the drop occurs around October (Fueglistaler 2012; and follow-up papers)- please explain the difference.*

  Reply: This is redundant. See our replies above.

- *P24917/L19ff: It is rather confusing that your temperatures (Fig 5) seem to give a different picture than your water vapor (Fig 4); for example, in Figure 5 the black and red lines are reasonably similar, which cannot be said for Figure 4; please explain.*

  Reply: As outlined above, this is due to the non-linearity of the Clausius-Clapeyron relation. See our reply above.

- *P24918/L24: Statistics based on ad-hoc thresholds are generally not useful; and I am concerned that your analysis here (0.5ppmv for one model run, 0.2ppmv for another model run) falls into this category. Please show that this is not a concern here, or remove the analysis.*

  Reply: The thresholds have been only used to simplify the search of drop events with preceding ENSO events. Thus, the result of event identification counting is independent of the selected values. We could have also started with the ENSO index and search for drop events after La Niña events. The result is the same. Furthermore, we do not base any statistical analyses on this counting.

- *P24919/L2ff: "... eruption of Mt Pinatubo had a significant impact on temperature and water vapour ...". Please provide a reference for this statement; see also detailed discussion in Fueglistaler (2012), and Fueglistaler et al. (2014; ACP): Observations suggest that part of the aerosol warming tendency was offset by an increase in dynamical forcing of upwelling. Models generally have problems to reproduce this effect and therefore produce a massive moistening of the stratosphere - which is what you also find in your additional sensitivity run mentioned below on line 7.*

  Reply: The reference is Löffler et al., 2015, ACPD.[1] and will be added in the revised manuscript.

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[1] Löffler, M., Brinkop, S., & Jöckel, P.: Impact of major volcanic eruptions on stratospheric water vapour, Atmospheric Chemistry and Physics Discussions, 15, 34 407–34 437, doi: 10.5194/acpd-15-34407-2015, URL http://www.atmos-chem-phys-discuss.net/15/34407/2015/ (2015)

Löffler et al. analysed two nearly identical nudged (without mean temperature!) simulations, where only one simulated the effect of volcanoes. The major volcanic eruption of El Chichon and Mount Pinatubo were represented in one simulation by prescribing zonally and monthly averaged values of the aerosol radiative properties. The main finding of the paper is, that stratospheric water vapour is increased after the eruptions, resulting from increased heating rates and the subsequent changes in stratospheric and tropopause temperatures in the tropics. Any effect of increased upwelling is already represented in the nudging tendencies in both simulations and should vanish in the differences of the two model simulations. Only the effect of the volcano on upwelling thus remains. We agree, that models generally produce a probable too moist stratosphere after the volcanic eruption. Therefore, to be on the safe side, we neglected this period in our study. Furthermore, we will shorten the respective text passage in the manuscript due to the suggestions of another referee (Mark Schoeberl) and omit the addional sensitivity run.

- *P24920/L26/Figure 9 Please be specific which equation and terms you use.*

  Reply: We will state the used formula of Pearson's correlation coefficient in a new Appendix B of the revised manuscript.

  The residual circulation has been calculated with the formula for the transformed Eulerian mean as by Holton (2004), their equation 10.16b, for the tropics (20N-20S). This information will be added to the revised manuscript.

- *P24921/L11f: Can you clarify - are you saying that nudging to ERA-Interim slows down the upwelling in the TTL? Or is this simply an artefact arising from a difference in the pressure level of the cold point tropopause in the free-running simulation relative to reality/nudged version?*

  Reply: True, upwelling is slower in the nudged simulation RC1SD (see also Jöckel et al., 2015, GMDD). The nudging basically affects the whole momentum budget (e.g. resolved wave amplitudes are nudged, that largely drive upwelling) so it is not surprising that upwelling is different in the free running versus the nudged simulation. The overall shift in the tropopause is also likely contributing to upwelling differences at a given height. We have not yet performed the detailed analysis to answer the question which factor contributes to the upwelling differences most. However, for the purpose of this study, the important point is that upwelling is different in the simulations, and thus water vapour is transported at a different speed.

  We will add a sentence to clarify this.

- *P24922/L9: You could test in your model calculations whether the subtropics are involved; if it's only speculation please omit.*

  Reply: We will omit the sentence in the revised manuscript.

- *P24923/L1ff: If I understood correctly, you said earlier that the QBO nudging is equal in all model runs - why then this difference here? At what level do you truncate the nudging?*

  Reply: Yes, the QBO nudging setup is equal in all runs presented. Nevertheless, the resulting winds are not the same in RC1SD, RC1, and RC2, because the model generates its own wind profiles depending on the model configuration and setup. Nudging is not prescribing! Only for RC1SD, where divergence and vorticity and the logarithm of the surface pressure are nudged, too, the wind profiles are close to those of ERA-interim. The lower edge of the nudging region is 90 hPa. The nudging setup will be described in more detail in the revised manuscript (see above).

- *P24923/L13ff: I could not quite follow your reasoning here. ENSO is related to surface temperature anomalies, so I don't understand what you mean by "under normal SST conditions the influence (of ENSO, I assume?) on upwelling is smaller." What do you mean by "normal"? Please explain.*

  Reply: What we want to say: The SST anomalies have a direct influence on the upwelling. Thus, the stronger the ENSO event the larger the impact on upwelling. This simple rule of thumb is, however, in some cases violated due to other processes. By "normal" we meant "undisturbed conditions", i.a. without ENSO. We will formulate better in the revised manuscript.

- *P24923/L13ff: Are you saying that you accept a time lag (between cause and effect) *varying* between 6 and 34 months? Please correct me if I misunderstood, but a scientific cause-effect relationship requires a well-defined time lag.*

  Reply: You are absolutely right with your comment! However, the El Niño is not the cause of the drop. What we wanted to explain is that a drop (or better a large amplitude in water vapour anomaly) occurs after a period beginning with an El Niño event, followed by one or two La Niñas. During ENSO we see a strong correlation between SST and upwelling, resulting in a large amplitude in water vapour anomaly after the La Niña decays. Because El Niños and La Niñas, respectively, develop all differently and also last differently long, we see the different time lags between the onset of the El Niño and the following drop. The period with anomalous SSTs starts with an El Niño, but important for a drop is La Niña.

  The text will be improved accordingly.

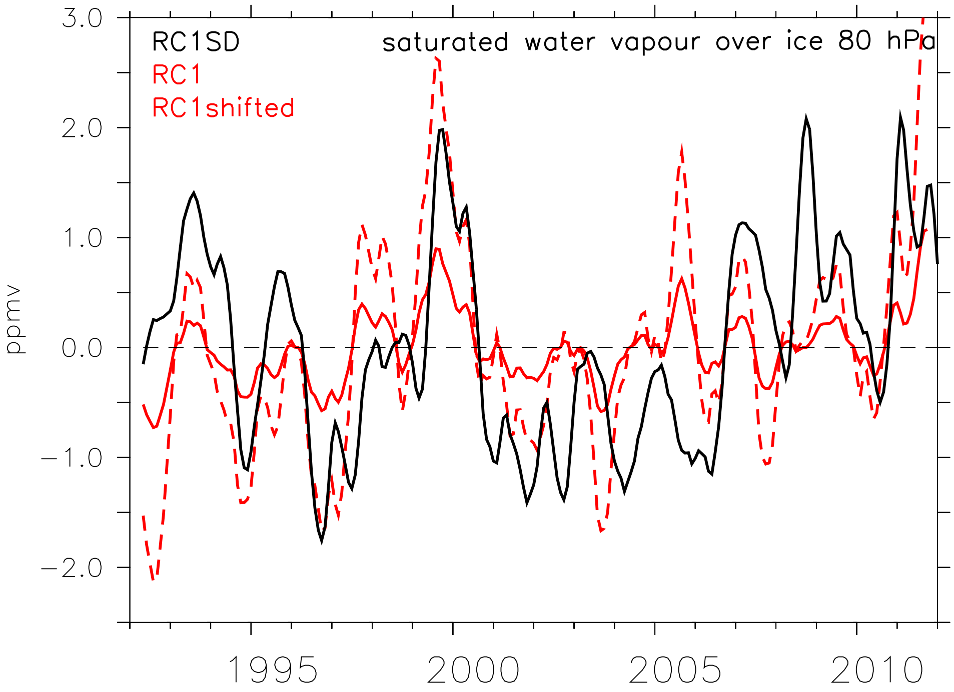

Figure 1: Saturation water vapour anomaly over ice (de-seasonalised, 6-month running mean) calculated from the respective cold point temperatures (10° S-10° N) of RC1SD and RC1 simulations. RC1shift: mean cold point temperature of RC1 is shifted to RC1SD mean cold point temperature. The mean cold point temperatures are: RC1SD: 192.1 K, and RC1: 186.0 K, RC1shift: 192.1 K)

We thank Mark Schoeberl for the very helpful comments and suggestions. Here are our replies with which we hope to clarify some misunderstandings.

- **General reply**: Reading the comments of the three referees, we have the impression that we probably raised wrong expectations with respect to what we achieved with our study. All three referees agree in revealing weaknesses in our argumentation, which we believe can be explained and therefore eliminated:
  - Part of the problem is probably caused by misunderstandings (maybe due to unclear formulations), as for instance the precise definition of “drop” (sudden decline versus period of low values thereafter), or the presumable influence of “nudging” as we applied it.
  - Another, more severe part, is in fact caused by the lack of important information, which we erroneously hold back (mainly to shorten the manuscript), although it was found by our analyses. Most importantly, we did not put sufficient emphasis on our simulation RC1SDNT (i.e., nudged, but without mean temperature nudging), which was only mentioned briefly, but not discussed in full detail.

  We hope that we can clarify our findings with additional information and revision of the text, where the misunderstandings occur. The details about that are outlined in our point-by-point replies below.

- *General comments: (1) The authors are not native English speakers and thus the paper needs some through grammatical editing and improved organisation. For example, the first sentence is almost incomprehensible. Long sentences are common in German, but are considered bad grammar in English. A better first sentence would be: Since the early 1980's climate models have predicted a increase in stratospheric water vapor [refs]. Satellite and balloon borne measurements have not yet observed such an increase [refs].*

  Reply: We will shorten the first sentence of the introduction in the revised manuscript.

- *(2) A key missing reference in this work is 'Dessler, A.E., M.R. Schoeberl, T. Wang, S.M. Davis, K.H. Rosenlof, and J.-P. Vernier, Variations of stratospheric water vapor over the past three decades, J. Geophys. Res., 119, doi:10.1002/2014JD021712, 2014.' Reprint This work describes how the QBO, diabatic heating, and the tropospheric temperatures can be use to successfully model stratospheric water vapor including the year 2000 water vapor drop. The implication of this work is that unless models get the three components that contribute to the drop correct, they will not be able to simulate the drop. This paper is extremely relevant to this work, and it is somewhat surprising that the authors were unaware of it.*

  Reply: Thank you for the hint. In the above mentioned study, Dessler et al. use reanalysis data to drive a trajectory model and apply a regression analysis. Here, we simulate stratospheric water vapour with a chemistry climate model. In our revised manuscript, we will refer to Dessler et al. where appropriate.

- *(3) I think that the model discussion (Section 2.1) is totally confusing - at least to someone outside the CCMI world. I feel like a diagram of what models are being used for what components of the simulation. There are references to hindcast simulations, nudging to ERAI, etc. The model sounds like a pile of components - which does not give me confidence in its veracity - nor does its rather poor simulation of the tape recorder (see below).*

  Reply: We are using only one model: The Chemistry Climate Model EMAC. EMAC, as any other model of this complexity, is build of several different components, which are not even mentioned here (see for instance Jöckel et al., 2010[1] for such technical details.) Thus, we are a bit surprised by this comment. Moreover, we stress that EMAC is widely used and has been extensively evaluated (e.g., Jöckel et al., 2015[2]; Righi et al., 2015[3]; Eichinger et al., 2015[4]; Pozzer et al., 2007[5] ; Jöckel et al., 2006; etc.).

  Also it is unclear to us, what you mean with "components of the simulation". As we state in the text, we analysed and compared the results of 4 different simulations, all performed with EMAC, however with different external forcing and with different boundary conditions.

  Nevertheless, we agree that the different simulations could be summarised better in a Table, which we will include (and referred to) in the revised Section 2.1.

  Concerning the apparent "poor tape recorder signal" you will find our reply below.

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[1] Jöckel, P., Kerkweg, A., Pozzer, A., Sander, R., Tost, H., Riede, H., Baumgaertner, A., Gromov, S., Kern, B.: Development cycle 2 of the Modular Earth Submodel System (MESSy2), Geoscientific Model Development, 3, 717752, doi: 10.5194/gmd-3-717-2010, URL http://www.geosci-model-dev.net/3/717/2010/ (2010)

[2] Jöckel, P., Tost, H., Pozzer, A., Kunze, M., Kirner, O., Brinkop, S., Cai, D. S., Frank, F., Garny, H., Gottschaldt, K.-D., Graf, P., Grewe, V., Kern, B., Matthes, S., Mertens, M., Meul, S., Nützel, M., Oberländer-Hayn, S., Ruhnke, R., Runde, T., and Sander, R.: Earth System Chemistry Integrated Modelling (ESCiMo) with the Modular Earth Submodel System (MESSy, version 2.51), Geosci. Model Dev., accepted 2016.

[3] Righi, M., V. Eyring, K.-D Gottschaldt, C. Klinger, F. Frank, P. Jöckel, and I. Cionni, Quantitative evaluation of ozone and selected climate parameters in a set of EMAC simulations, Geosci. Model Dev., 8, 733-768, doi:10.5194/gmd-8-733-2015, 2015.

[4] Eichinger, R., Jöckel, P., Brinkop, S., Werner, M., and Lossow, S.: Simulation of the isotopic composition of stratospheric water vapour Part 1: Description and evaluation of the EMAC model, Atmos. Chem. Phys., 15, 5537-5555, doi:10.5194/acp-15-5537-2015, 2015.

[5] Pozzer, A., Jöckel, P., Tost, H., Sander, R., Ganzeveld, L., Kerkweg, A., Lelieveld, J.: Simulating organic species with the global atmospheric chemistry general circulation model ECHAM5/MESSy1: a comparison of model results with observations, Atmospheric Chemistry and Physics, 7, 25272550, doi: 10.5194/acp-7-2527-2007, URL http://www.atmos-chem-phys.net/7/2527/2007/ (2007)

- *(4) The main point of this paper is to show that ENSO, combined with the west phase of the QBO can product sufficient upwelling (cold temperatures in the UTLS) to produce the water vapor drop. The 'event analysis' appears to support their conclusions - at least with the nudged model. The main problem I have is that there are other water vapor anomalies not associated with ENSO (for example the most recent). By not analyzing these events, their conclusion is foregone. This problem can be repaired if the authors analyze some drop events not linked to ENSO and compare them with ENSO linked events.*

  Reply: ENSO, through SST changes, triggers upwelling, which is then followed by a strong decline of water vapour when the La Niña event decays, and if the QBO coincidently changes its phase from west to east. This finding is not new (Dessler et al., 2014). This also holds for the "most recent event" (you refer to) in our time series (see for instance Figure 11). Thus, we think that you misinterpreted our text and we will revise it accordingly.

  Yet, we see your point to mention those anomalies not associated with ENSO: they do not exhibit large amplitudes of water vapour: This is for instance the case after year 2000. Here, we have a moderate El Niño in 2002/03, but no La Niña and therefore no large drop. Similarly, the period 1977 to 1981 of the simulation RC1 shows no ENSO and therefore no large drop.

- *Specific comments: (pg:line) 2:1 Water vapor is an important greenhouse gas in the troposphere. It isn't so clear it is as important in the stratosphere. I would delete this sentence and instead reference the Solomon et al. [2010] paper showing the impact of stratospheric water vapor on the surface radiative balance.*

  Reply: Since our analysis does not include tropospheric water vapour and its greenhouse effect, we will indeed remove the corresponding sentence. However, it is beyond dispute that stratospheric water vapour is important for the stratospheric temperature (Forster and Shine, 1999[6]; Grewe and Stenke, 2008)[7] and has a strong influence on the surface radiation balance (Solomon et. al., 2010).

- *2:12 The analysis by Dessler et al. shows that the to reproduce the water vapor field, you need the QBO, among other things. This means that models that fail generate a QBO (which is most of them) will naturally fail in generating the water vapor time series. I note that this model does include a QBO (4:27) which is good.*

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[6] Forster, P. M. and Shine, K. P.: Stratospheric water vapour changes as a possible contributor to observed stratospheric cooling, Geophys. Res. Lett., 26(21), 3309-3312, 1999.

[7] Grewe, V. and Stenke, A.: AirClim: an efficient tool for climate evaluation of aircraft technology, Atmos. Chem. Phys., 8, 4621-4639, doi:10.5194/acp-8-4621-2008, 2008.

Reply: Yes, indeed. Thanks to Giorgetta et al., 2002.[8] We will add this information.

- *4:22 What hindcast simulations? - what are you talking about here?*

  Reply: A hindcast simulation covers the past, in contrast to a forecast simulation, which projects the future.

- *4: I think it would be helpful to have a table describing the models and their differences (RC1SD, RC1SDNT, RC1, RC2) that show up in Figure 4 as a quick reference.*

  Reply: We will include such a table in the revised manuscript (Section 2.1). Note, however, that RC1SD, RC1SDNT, RC1 and RC2 refer to different EMAC simulations, not to different models.

- *5:2 I object to the words 'model data' better is 'model output'*

  Reply: Maybe even better "model results" depending on the context. Will be corrected.

- *5:22 Fair point!*

  Reply: Thanks.

- *6:5 What is 'It' - the chart, the measurements, the curve?*

  Reply: The measurements. Will be corrected.

- *6:8 'specified dynamics' - below you call this 'EMAC .. nudged mode' I think you should be consistent, or I am not understanding something.*

  Reply: "Specified dynamics" is the more general term (introduced by CCMI), of which "nudging" (more precisely Newtonian relaxation) is one methodology. This will be explained in the revised Section 2.1. Moreover, we will use "nudged mode" in conjunction with EMAC throughout the revised text.

- *6:28 The model average (in Gettelman et al., 2009) is cold biased but only by about a degree. More models are above the model mean than below - and the spread is large - almost 10K. I think that the text could be more precise.*

  Reply: We will modify the text to include the additional information.

- *7: I think that it is obvious that the cold tropopause temperature anomaly reduces water vapor and that signal propagates into the stratosphere (a bit asymmetrically). Something like this statement would be a nice way to summarize the discussion of Figure 3. Figure 3. Please put titles on the individual figures.*

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[8] Giorgetta, M. A., Manzini, E., and Roeckner, E.: Forcing of the quasi-biennial oscillation from a broad spectrum of atmospheric waves, Geophys. Res. Lett., 29(8), doi:10.1029/2001GL014756, 2002.

Reply: We will add a summarising sentence to the end of Section 3 and put titles on the individual figures.

- *8:11 How does it point to a shift in 'temperature relevant processes'? What are you talking about here? Why does this point to ENSO? I think something is missing here.*

  Reply: What we mean is simply: Between the different simulations (here RC1 and RC1SD) we see a small phase shift of those processes, which affect temperature (i.e., QBO, upwelling (due to ENSO), ozone). As a consequence the time of occurrence of the drop is also shifted accordingly between the two simulations. Since this is trivial, we will omit the sentence in the revised manuscript.

- *8:25 Please provide a reference to this statement 'propagates. . . lower stratosphere' Maybe reference Calvo et al. 2010?*

  Reply: We will add adequate references for the ENSO effects on the stratosphere. (Scaife et al., 2003, Randel et al., 2010, Calvo et al., 2013).

- *9:25 I think it is obvious from Figure 6 that the causal relationship is weak to non existent. Why all the discussion about it?*

  Reply: Figure 6 shows the relationship between ENSO (vertical bar = major phase of El Niño) and subsequent large drop (red asterisks). So, unfortunately we do not get your point.

- *9 Okay, I get that RC1SD has problems for Mt. Pinatubo and I also get that you should see a surface temperature anomaly for (Fig. 7) - I think that the authors can just state this rather than waste time discussing it. Fig. 7 only shows that RC2 is not useful - which the other figures already indicate.*

  Reply: We will reduce this paragraph as suggested. For the revision (see our replies to the other referees) we will improve our argumentation for which we also need the SST time series of RC2. Thus, we need to keep it.

- *9:26 I am confused by this sentence. Are you now saying that there is no relationship between ENSO and water vapor drops?*

  Reply: No. The sentence is indeed misleading. What we want to say is: In the RC2 simulation (forced with simulated SSTs) large drops occur, however, a connection with a preceding ENSO event as analysed from the observations and from the other simulations is not as clearly visible .

  Furthermore, the correlation between upwelling and temperature is weaker in RC2 (compared to the other simulations, see Table 1). The reason are the different horizontal SST patterns which are not as those observed. This affects the dynamics, e.g., stratospheric winds and thus wave propagation. We will clarify this in the revised text.

- *10:7 You should also reference the Dessler et al. paper noted in the general comments here.*

  Reply: Will be done.

- *10:14 There are also positive anomalies in non ENSO years such as 1976, 2000, 2006. Figure 8 Please title the figures. Figure 8 - the tape recorder signal looks funky to me. The amplitude is way too weak. The authors need to comment on this or provide more explanation. It would be useful to produce the observations in Figure 9 along with the model runs. I am attaching a tape recorder figure. The amplitudes is a lot larger.*

  Reply: 1976 and 2000 are ENSO years, more precisely La Niña years. To avoid a misunderstanding, we will replace "ENSO year" by either "La Niña year" or by "EL Niño year" as appropriate throughout the text. 2006 is indeed no ENSO year. The upwelling is influenced by other processes. We will clarify in the revised text that positive anomalies are not solely caused by SST changes in the tropics.

  We think that panel a) and b) together with the caption are sufficient.

  Tape recorder: This is a misunderstanding. The tape recorder signal is well reproduced by our model (see Eichinger et al, 2015). In our Figure 8, however, we de-seasonalised (i.e., subtracted the seasonal cycle) in order to show the anomalies to illustrate the inter-annual variations. The revised caption will be improved.

- *10:21 Ozone anomaly? Where is this shown?*

  Reply: We have no additional figure for ozone. But the negative correlation between upwelling and ozone is stated in the manuscript.

- *10:25-30 Just use correlation coefficient (not Pearson's correlation coefficient). These correlations aren't very strong.*

  Reply: This comment is in contradiction to one of the comments by Stephan Fueglistaler, who asked us to present also the formula. Thus, we must name it correctly.

- *10:29 decreases at lower altitudes.*

  Reply: Will be corrected.

- *11:4 also see Schoeberl et al. , J. Geophys. Res, 113 Doi: D24109, 2008 for vertical velocity calculations using the observed tape recorder.*

  Reply: We will add this reference.

- *11:14 Basically what the authors are saying here is that they assume that all these other processes (like convection) and that the water vapor drop is primarily tempera- ture driven. However, during ENSO there is a significant collapse in western Pacific convection which provides about 30% of the water vapor to the UTLS. Thus I don't think that it is a good idea* *to assume that convection is unimportant. In any event, I presume these models include convective processes and water vapor transport so that they are probably included in the correlation.*

Reply: We do not assume that convection is unimportant. Actual, in our simulations the effect of convection on the TTL temperature and moisture is included. What we wanted to say is that the contribution of directly injected water vapour and ice particles into the stratosphere and thus their contribution on the water vapour concentration is not considered in our analysis.

- *1:21 But there are strong upwelling periods not near ENSO .. so the data doesn't quite fit the hypothesis. In fact the biggest (model) upwelling is in 2005 in Fig. 9 - nowhere close to an ENSO event.*

  Reply: We only say that strong SST anomalies trigger increased upwelling. But we never stated the reverse argument, namely that every increased upwelling was necessarily triggered by an SST anomaly in the tropics.

- *11:30 The episode analysis described in the next few pages and in the Figures 10 - 14 but I have to wonder if the results are also true for drop episodes not associated with ENSO. For example, just pick a period of temperature decline not associated with ENSO. The authors are selecting events and making an assumption that the water vapor drops are all produced by the ENSO events - the correlation is weak it seems from the previous figures. While ENSO events appear to contribute, they are just one component of the whole system producing the drop such as the phase of the QBO.*

  Reply: That is an interesting point. We expect that we will not find the QBO anomaly changing from positive to negative values, and a clear signal in upwelling anomaly together. We will perform this analysis for the revision.

  In the context of the "assumption" you mention, it is unclear what "drops" you refer to. Just to clarify: The large drops (sudden decline of water vapour) we selected are all preceded by a strong El Niño/La Niña event, as outlined also above. However, we do NOT claim or assume, that no other trigger is possible which also can cause steep declines ("drops").

- *13:31 So you conclude that it is the coincidence of ENSO upwelling and west phase of the QBO that produces lower temperature anomalies and the water vapor drop. Yes?*

  Reply: Yes, in case "ENSO" means "La Niña" with reduced upwelling, and "west phase" means "transition from west to east phase". We will make the formulation more precise in the revision.

- *14:1 what level is Figure 15 plotted for, 80hPa? What are the units, vertical velocity? Figure 16. The 72/73 case sort of blows your hypothesis since the lag is 36 months - longer than a QBO cycle.*

Reply: Figure 15 is for 80 hPa for the upwelling as written in the figure title. We will add the information also to the revised figure caption.

The normalised upwelling anomaly is calculated by division of either the maximum or the absolute value of the minimum. For the SSTs it is defined accordingly. Therefore, the results are dimensionless. We will add this definition to the revised figure caption.

El Niño usually starts a period in which upwelling correlates strongly with the SSTs (not in all cases, see e.g., 1982/1983). This strong correlation lasts until La Niña ends. Thus, the water vapour maximum is reached with the maximum of La Niña. The length of the ENSO period (start at El Niño until maximum of La Niña), however, shows large variations, roughly between 1.5 and 3 years. Conditions for a large drop are therefore only given at the end of this period, i.e., at the maximum of La Niña. This period we call "lag" and therefore most probably caused a misunderstanding, since "lag" implies a cause-to-effect relationship, which we do, however, not claim. In the revision, we will eliminate the word "lag".

- *15:1-14 RE SSTs – more convection – more waves. How is that relevant to this study?*

  Reply: This paragraph describes how the SST signal propagates into the tropopause region (namely by convection triggering waves which break and cause upwelling). Thus, it provides background information, but is not directly relevant for our analyses.

- *15:17 First use of UTLS - please define.*

  Reply: Will be corrected.

- *15:24 Please provide a reference to ' cold point is slightly too high' - how do we know this. How would too high a cold point lead to reduced variability (next sentence) I can see that it might lead to an overall bias but not reduced variability.*

  Reply: The reference to Gettelman et al.,(2009) will be added here (note that it is already cited in the text). The variability is affected by the absolute value due to the non-linearity of the Clausius-Clapeyron relation.

- *16:12-15 What are you trying to say here?*

  Reply: Urban et al. (2014) show that in the period 2008 – 2011 water vapour is uncorrelated to cold point temperature. The reason is so far unknown. We do not analyse it here, because it is beyond scope. We will reformulate accordingly.

We thank Referee #3 for the very helpful comments and suggestions. Here are our replies with which we hope to clarify some misunderstandings.

- General reply: Reading the comments of the three referees, we have the impression that we probably raised wrong expectations with respect to what we achieved with our study. All three referees agree in revealing weaknesses in our argumentation, which we believe can be explained and therefore eliminated:

    - Part of the problem is probably caused by misunderstandings (maybe due to unclear formulations), as for instance the precise definition of “drop” (sudden decline versus period of low values thereafter), or the presumable influence of “nudging” as we applied it.
    - Another, more severe part, is in fact caused by the lack of important information, which we erroneously hold back (mainly to shorten the manuscript), although it was found by our analyses. Most importantly, we did not put sufficient emphasis on our simulation RC1SDNT (i.e., nudged, but without mean temperature nudging), which was only mentioned briefly, but not discussed in full detail.

  We hope that we can clarify our findings with additional information and revision of the text, where the misunderstandings occur. The details about that are outlined in our point-by-point replies below.

- *This paper explores the ability of models to capture the post-2000 drop in stratospheric water vapor, and the factors that led to the drop. The authors find that a specified dynamics version of the model can capture the drop, while a free-running model with observed SSTs and a QBO nudged to observations grossly underestimates it but can capture some elements of it. They then argue that El Niño/La Niña and the QBO were crucial forcing mechanisms for the drop.*

  Reply: This is a good summary of what we did. However, it possibly contains a first misunderstanding, namely about term “post-2000 drop”. If this means the “sudden decline of water vapour in 2000”, i.e. the period until its minimum is reached, the referee is right. If, however, the ≈5 year period of low water vapour is meant, it is a misunderstanding. We never claimed that the QBO can explain this 5 year period. All we say is that QBO is essential for the sudden decline.

  To clarify this, we will define (and use) two different phases of “the drop” in our revised manuscript as:

    - Phase 1 is the short period of the steep decline between the drop onset (i.e., its maximum) and its subsequent minimum. The difference between max. and min. will be called “amplitude” of the drop.
    - Phase 2 is the period of low values between the minimum and the start of the recovery.

Furthermore, we will clarify in the revised introduction which of the phases are addressed and discussed in which Section. For instance, Sections 3 and 4 are about the millennium drop (phase 1 and 2), whereas Section 5 analyses only the phase 1 of other “drops”.

We use a hierarchy of 4 different model setups to analyse the millennium drop, i.e. the sudden decline in 2000. We find, that a nudged setup (RC1SD) performs best. This cannot be expected a priori for water vapour, since the hydrological cycle is freely evolving.

A nudged setup excluding the mean temperature from nudging (RC1SDNT) also reproduces the millennium drop, however, with a smaller amplitude. This is related to the cold point temperature bias.

Next, a free running simulation (RC1) forced with observed SST shows a similar onset of the drop but largely under-represents the amplitude, caused by an even larger cold point temperature bias. Note that the observed SST used here is very similar to the SST used when nudging is applied, and thus can be excluded as cause.

Last but not least, a free running simulation with simulated SST (RC2) shows no drop at all. This is a result that does not surprise, because the dynamical situation is not related to the observed (or reanalysed).

The analysed gradual degradation of the drop signal from RC1SD and RC1SDNT over RC1 to RC2 is further enhanced (or manifested) by the difference in the QBO signal between the different simulations (see Figure 14 for RC1SD and RC1). Note that the QBO at roughly 90 hPa is key for the temperature signal affecting water vapour, i.e., at an altitude where the QBO nudging strength is already reduced and therefore relies on signal propagation.

The nudging procedure is solely used to reproduce the observed (or reanalysed) synoptic scale situation (i.e. meteorological patterns), which cannot be reproduced by a free running setup, even if forced with observed SSTs. The water vapour, however, is in all cases developing freely. Further, nudging does not correct for model errors as long as the global mean temperature nudging is not included (see above). Thus, with a hierarchy of simulation setups (from free running (forced with simulated SSTs), forced by observed SSTs, nudged w/o T-mean and nudged with T-mean) we are able to analyse the influence of different drivers. To our knowledge, this has not been done with other GCMs or CCMs so far. Our new finding is, that the drop itself is only in parts masked by a model error, namely the cold point temperature bias.

- *I found this work to be somewhat unconvincing. If SSTs were so important, then both the free-running model and the specified dynamics version should show the millennium drop. While the lower stratospheric QBO is weaker in the free-running version as compared to the specific dynamics version, and thus the model is under-representing this pathway, it is difficult to draw* *conclusions as to the importance of the QBO unless additional simulations are performed in which the QBO does propagate far enough downward. Finally, the weak drop in the free-running simulation doesn't last as long as the drop in the specified dynamics simulation, and part of why the millennium drop was so interesting is its >5 year duration.*

Reply: This might be another misunderstanding due to our formulations. We still think that the SSTs are important, because the simulation RC2 with simulated SSTs (i.e., not related to real SSTs) does not show any signature of the drop (Figure 4). In contrast, the free running simulation RC1 forced by observed (or reanalysed) SSTs does show some characteristics of the drop (Figure 4): phase 1 is partly represented, e.g., the timing of the onset (i.e., the maximum water vapour right before the fast decline) is almost correct. However, the drop amplitude is underrepresented (i.e., the minimum is too large) compared to the nudged simulations (RC1SD and RC1SDNT). Also phase 2 is visible, but the duration is indeed shorter and the minimum is too large.

Our conclusion is therefore that the correct SSTs are important to trigger the drop (i.e., phase 1) and also, at least partly, for the period of low values in phase 2. The absolute value of the water vapour anomaly minimum during phase 2, however, cannot be explained solely by SSTs.

We agree that “it is difficult to draw conclusions as to the importance of the QBO”, if this is meant in a quantitative sense (e.g. as the QBO contribution to the drop amplitude) from the simulated millennium drop period only. All we find and discuss, however, is that common to all phases 1 of all analysed drops in other years, is the fact that the QBO is coincidently changing from west to east phase. As shown in Figure 14, this correlation is weaker in RC1 compared to RC1SD, because the QBO timing in RC1 is different from the “real” timing. This occurs, despite the applied QBO nudging for two reasons: First, the nudging does not force a one-by-one representation of the nudged data by the model, the applied relaxation time was 58 days. The model thus still develops its own dynamical state. Second, the relevant altitude is in the “nudging transition” region, meaning that the direct effect of the nudging is even weaker and the QBO signal depends more on the signal propagation from above.

Nevertheless, we see a clear QBO oscillation in all simulations and in the observations of temperature and moisture. Therefore, qualitatively it is doubtless that the QBO modulates water vapour in all simulations. The question we cannot answer, however, is how large this effect is. We see that during some periods the QBO temperature effect does not propagate as far down as during others. As we show for the phase 2 of the millennium drop, the QBO signal is partly compensated by an increased upwelling which causes a lower cold point temperature. In RC1 this effect is weaker compared to RC1SD. To illustrate this, we will add a Figure to the new supplement (see also below), which shows the time evolution of zonal mean temperature and water vapour anomalies versus height for simulation RC1SD, i.e., a similar figure for RC1SD as Figure 8 for RC1.

In the revised manuscript we will clarify our discussion and conclusions accordingly.

- *General Comments on Content: A. Fundamentally, it is unclear to me how the QBO and ENSO could even potentially be the answer to the millennium drop, as both of them have a characteristic timescale (2.5 years and ≈5 years respectively for a full period) that is shorter than the duration of the drop (>5 years). Any given ENSO event lasts one or two years at most, and stratospheric memory for a quantity like water vapor is on the order of months, so it isn't clear how ENSO could even mechanistically lead to a long-lived drop. Stated another way, any drop that lasts longer than 5 years must be driven by a process that can persist in a given phase for 5 years. It is worth noting that there is not a single long-lived (>5 year) drop in either RC1 or RC2 in figure 4. IN addition, the composite analysis in section 5 also suggests that the events are of relatively short duration (at most two years). (That being said, the millennium drop in figure 4 in RC1 does seem to last for 4 years, so there is some hope. There are modes of SST variability that last longer than ENSO.)*

  Reply: This is in our opinion a misunderstanding due to different meanings of "drop". We argue with ENSO and QBO only for the above defined phase 1 of the drop and before, **not** for phase 2! This will therefore be clarified in the revised manuscript.

- *B. My intuition based on previous work is that ENSO and the QBO are important for changes in stratospheric water vapor, and probably contributed a big chunk of the drop for least a couple of years. In terms of ENSO, two publications not cited should be discussed in the manuscript:*

  Garfinkel, C. I., M. M. Hurwitz, L. D. Oman, D. W. Waugh (2013), Contrasting Effects of Central Pacific and Eastern Pacific El Niño on Water Vapor, GRL, 40, Stratospheric4115-4120, doi: 10.1002/grl.50677 Garfinkel, C.I., D. W. Waugh, L.D. Oman, L. Wang, and M.M. Hurwitz, (2013). Tem- perature trends in the tropical upper troposphere and lower stratosphere: connections with sea surface temperatures and implications for water vapor and ozone, Journal of Geophysical Research: Atmospheres, 118(17), 9658-9672, doi: 10.1002/jgrd.50772

  The first paper demonstrated that La Niña leads to moistening of the stratosphere, while the impacts of El Niño were dependent on the specific nature of the El Niño event (some lead to dehydration, others t' little effect in the annual mean). This paper is entirely consistent with the authors' arguments, as they find that large drops follow La Niña events when the stratosphere is moistened. Note that this is somewhat in contrast with the analysis of

Dessler, A.E., M.R. Schoeberl, T. Wang, S.M. Davis, K.H. Rosenlof, and J.-P. Vernier, Variations of stratospheric water vapor over the past three decades, J. Geophys. Res., 119, doi:10.1002/2014JD021712, 2014

who find that warmer mid-tropospheric temperatures lead to more stratospheric wa- ter vapor. This point should be discussed in more detail in the revised manuscript, specifically near line 24920:15-20.

The second paper shows that SSTs have led to a dehydration trend over the historical record, and more relevantly, to a period of enhanced dehydration in the early 2000s (that is weaker than suggested from satellite/balloon products). This second paper is also consistent with the present analysis. However, both of these papers as well as the authors' RC1 simulations indicate that SSTs are not the full answer to the millennium drop.

Reply: Thank you for this comment! We will include the discussion on these publications in our revised text.

- *In terms of the QBO, the authors claim that the QBO is crucial, but don't provide the analysis to convincingly demonstrate this. The present experiment will (by design un- fortunately) miss some of the influence of the QBO. Figure 14 strongly indicates that the QBO in the lowermost stratosphere is mis-represented and much too weak in the RC1 experiment, while the QBO at these levels is likely crucial in order to capture the effect of the QBO on water vapor. I strongly suggest that the authors perform a modified RC1 experiment in which the QBO nudging is strong enough so that lower stratospheric winds mimic those observed. It would be very interesting to compare such a revised RC1 experiment to the present one to see whether the QBO does, in fact help with explaining the magnitude of the drop.*

  Reply: Here, we probably have the same misunderstanding as above. We only claim that the "timing of the QBO" is crucial for the phase 1 of the drop. We just wanted to point out, that in our RC1SD simulation a coincidence between drop phase 1 and QBO phase change (west to east) is present. This has also been reported by Dessler et al. (2014) as being important to generate large amplitudes in water vapour.

  Nevertheless, we see the gap in our reasoning for phase 1: Figure 14 shows that the QBO anomaly is more pronounced in the nudged simulation RC1SD (left) compared to the free running simulation (right). Indeed, this is not the only difference, because also the absolute cold point temperature is different, because the nudging in RC1SD includes also the nudging of the mean temperature implying a bias correction. In our revised analysis, we will include also the millennium drop of the RC1SDNT simulation, in which the temperature bias is not corrected.

  We agree, however, that additional sensitivity studies are required to corroborate our findings and mention this in our revised "Summary and Conclusions".

- *C. I found the manuscript somewhat tedious to read, somewhat repetitive, and difficult to follow. I have several suggestions for how to improve the text below, but I suggest that the authors carefully edit the paper before submitting their revised version.*

  Reply: We will carefully edit the paper!

- *D. On a relatively minor note, the bottom row of figure 3 doesn't appear to be consistent with figure 1. Figure 1 suggests that the RC1SD integration is quite good at capturing the length of the drop, but the bottom row of figure 3 gives a gloomier picture.*

  Reply: This is indeed a misunderstanding, again related to the usage of the different drop phases. We guess, in your comment you refer to phase 2 of the drop when you say "length of the drop". Figure 3, however, shows the duration of the phase 1 in unit "months". The confusion is most probably caused by the word "length". We will clarify this in the revision.

  Moreover, Figures 1 and 3 are based on differently combined data sets: In Figure 1 RC1SD is compared to the HALOE/Aura-MLS data and in Figure 3 to the HALOE/MIPAS data. Last but not least, Figure 3 shows the result of a new analysis (as explained in Appendix A4) which includes the folding of the model data with a remote sensing average kernel.

- *Minor comments: 24911:2 the first sentence of the manuscript is very unclear*

  Reply: We will reformulate it.

- *24913:5 section 5 is about ENSO and the QBO (i.e. contributors to the drop). Section 6 is a discussion.*

  Reply: We will correct this in the revised manuscript.

- *24914:21 'in water vapour we supplement the EMAC simulations with a combination of satellite observations . . .'*

  Reply: Will be reformulated.

- *24915:26 to my eye, both temperature and water vapor are captured quite well. Can this be quantified via a correlation analysis?*

  Reply: We will calculate the Pearson's correlation coefficients (between model results and observations) for cold point temperature anomaly and water vapour anomaly, respectively and add the results to the Figure.

- *24916:24 Figure 3 is introduced quite abruptly. How was this figure constructed? I think reference to the appendix is necessary (assuming I understood the appendix).*

  Reply: Yes, indeed! We will expand Section 2.2 and introduce all data sets used first. We will also reformulate the first sentence introducing Figure 3 to clarify this additional evaluation of the year-2000 drop characteristics (water vapour strength, length and drop date).

- *24917:25 this discrepancy between water vapor and temperature is very confusing. Section 5 'attributes' this to the QBO (as far as I can tell), but it is hard to believe the analysis in section 5 considering the poor quality of the QBO in the lowermost stratosphere.*

  Reply: We guess, you refer to simulation RC1 here, in which the water vapour anomaly does not follow the temperature anomaly as direct as in RC1SD. However, we do not claim in Section 5 that this is due to the QBO. We attribute this rather to the bias in cold-point temperature. At least that is what we intended to say. We will recheck Section 5 and eliminate misleading arguments pointing to the QBO for this aspect. Parts of this misunderstanding are maybe also related to the confusion with the different drop phases.

- *Figure 6: I suggest removing the RC2 curve. It doesn't contribute in any way to the authors' points.*

  Reply: It seems to be a misunderstanding, but RC2 is not presented in Figure 6. In Figure 6 we present the moisture anomalies from RC1SD, RC1 and RC1 with the eruption of Mt. Pinatubo. The red curve thus shows the effect of additional heating of the stratosphere on the water vapour variability. We removed this curve, because this was also suggested by another referee.

  In case you are, however, referring to Figure 7: We are very hesitating to remove the result for RC2, because we need the results of our hierarchy of 4 simulations, in order to disentangle some of the effects. Note that in RC2 the simulated SST is completely unrelated to the observed, however, the QBO is nudged and therefore its phase correct.

- *24924:18 'we experience' is the wrong word*

  Reply: We will change it to 'we find' in the revised manuscript.

- *24925:28-24926:25 This is somewhat long-winded and tedious. The authors' point is that the model is missing processes that are potentially important. This could be stated more concisely.*

  Reply: We agree. We will reformulate and shorten this part in the revised manuscript.

- *Section A4: I assume this is for figure 3. This should be stated explicitly*

  Reply: We will refer from the figure caption to Appendix A4 and likewise from the text in A4 to the Figure 3 in the revised manuscript.

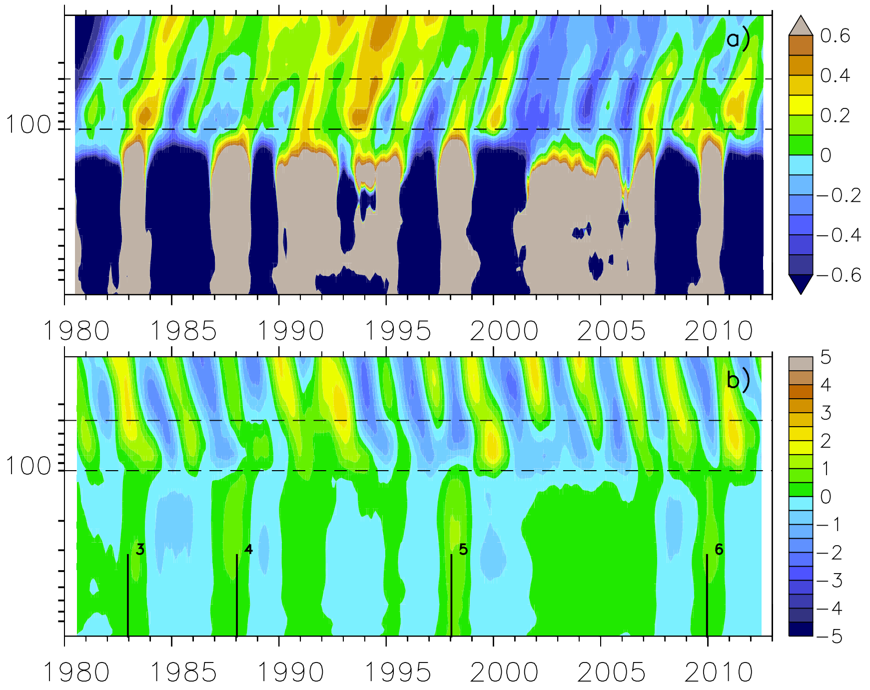

Figure 1: **(a)** Temporal evolution of moisture anomalies (ppmv). **(b)** Temporal evolution of temperature anomalies (K). RC1SD simulation, 10° S – 10° N, (12 month running mean). Strong El Niño events are labelled. The altitude range covers the pressure levels from 900 to 30 hPa. The dashed lines mark the region between 100 and 50 hPa.

The millennium water vapour drop in chemistry-climate model simulations

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Abstract. This study investigates the abrupt and severe water vapour decline in the stratosphere beginning in year 2000 (the “millennium water vapour drop”) and other ~~similar~~ similarly strong stratospheric water vapour ~~drops~~ reductions by means of various simulations with the state-of-the-art Chemistry-Climate Model (CCM) EMAC (ECHAM/MESSy Atmospheric Chemistry Model). The model simulations differ with respect to the prescribed sea surface temperatures (SSTs) and whether nudging is applied or not. The CCM EMAC is able to reproduce the signature and pattern of the water vapour ~~disturbances~~ drop in agreement with those derived from satellite observations ~~. Model data~~ best, if the model is nudged. Model results confirm that this extraordinary water vapour decline is in particular obvious in the tropical lower stratosphere ~~. The starting point of the severe water vapour drop is identified in the tropical lower stratosphere and the start date is found to be in the early days of 2000. We show~~ and is related to a large decrease in cold point temperature. The drop signal propagates under dilution to the higher stratosphere and to the poles via the Brewer-Dobson circulation (BDC). We found that the driving forces for this significant ~~drop~~ decline in water vapour mixing ratios are tropical sea surface temperature (SST) changes due to a coincidence with a preceding strong El Niño–Southern Oscillation event (1997/98) ~~, which was~~ followed by a strong La Niña event (1999/2000) and supported by the prevailing western phase of the equatorial stratospheric quasi-biennial oscillation (QBO) at ~~that time. This constellation of ENSO and QBO obviously lead to the outstanding anomalies in meteorological quantities which are identified in the equatorial atmosphere: (a) a distinct warming (up to 1) of the tropical upper troposphere (200 to 120) beginning in mid-1997 and lasting for about one and a half years, (b) a strong warming (up to 2.5) of the tropical lower stratosphere (100 to 50), beginning in early 1999 and ending in early 2000, and (c) a significantly enhanced upwelling at the tropopause in the late 1990s and an obviously reduced upwelling around the year 2000 followed by a period of enhanced upwellingagain. These dynamically induced changes are unambiguously connected to the stratospheric water vapour anomaly. Similarly strong water vapour reductions~~ the drop onset. Correct (observed) SSTs are important to trigger the strong decline in water vapour and also, at least partly, for the long period of low water vapour values from 2001 to 2006. For this period, the specific synoptic situation is important as well, as it causes the observed persistent low cold point temperatures. These are induced by a period of increased upwelling, which, however, has no corresponding pronounced signature in SSTs anomalies in the tropics. Our free-running simulations do not capture the drop as observed, because a) the cold point temperature has a low bias and thus the water vapour variability is reduced and b) because they do not simulated the appropriate synoptic situation. Large negative water vapour declines are also found in other years, and seem to be a ~~typical feature~~feature, which can be found after strong

combined El Niño/La Niña events, if the QBO west phase ~~has prolonged down to the tropopause.~~ during La Niña changes to the east phase.

1 Introduction

Since the early ~~1980s,~~ 1980‘s balloon-borne stratospheric water vapour measurements (e.g., Hurst et al., 2011) and ~~corresponding satellite measurements starting in the early 1990s (~~climate models have predicted a continuous increase in stratospheric water vapour concentrations (SPARC CCMVal, 2010; Stenke and Grewe, 2005, Gettelman et al., 2010). Satellite measurements have not yet observed such an increase (UARS/MLS, UARS HALOE, and SAGE II instruments; see for instance Solomon et al., 2010; Hartmann et al., 2013)~~an increase of stratospheric water vapour was long reported and climate model simulations uniformly predict a continuous increase of stratospheric water vapour concentrations in the future (SPARC CCMVal, 2010; Stenke and Grewe, 2005)~~. However, if we look from the late 1980s/early 1990s to now, we actually find a decreasing trend from merged satellite observations in the lower stratosphere (see Hegglin et al., 2014). ~~This has become the big conundrum now and there is~~ The explanation of this has become a large scientific challenge and a lot of discussion persists, if Boulder balloon observations are representative, or if there is an issue in the satellite data merging.

An increase in stratospheric water vapour with time is expected as a net result of global warming ~~, including enhanced atmospheric concentrations of methane, which affect water vapour concentrations through methane oxidation~~as predicted for the 21th century by coupled CCMs (Gettelman et al., 2010). However, ~~the~~ multi-year data sets ~~also~~ show significant fluctuations on different time scales, which make it difficult to assess robust trends ~~.~~ (Hegglin et al., 2014).

In the year 2000, an extraordinary sudden drop of stratospheric water vapour content has been observed (e.g., Randel et al., 2006; Fueglistaler et al., 2005, Rosenlof and Reid, 2008, Maycock et al., 2014), which brought again into focus that temperature fluctuations have a large potential to significantly impact the amount of water vapour in the stratosphere. The strong and widely noticed water vapour drop in the year 2000 is particularly remarkable due to the fact, that it is followed by a 5 year period of low stratospheric humidity. Randel and colleagues showed that the tropical tropopause temperatures ~~were~~ remain noticeably lower than normal after the ~~drop~~ decline due to an increase in tropical upwelling. The coldest temperatures after the drop lie over the western tropical Pacific/Indonesia region and Africa during all seasons of the year, but are not a major feature in the Caribbean or the mid-Pacific (Rosenlof and Reid, 2008). These negative water vapour anomalies after 2001 lead to a reduction in the global surface temperature warming trend of 25 % (Solomon et al., 2010).

Since water vapour is the most prominent greenhouse gas, and therefore is an important contributor to variations and trends in climate, it is necessary to better understand its large variability. Stratospheric water vapour variations are connected with temperature changes in the tropical region, especially with the cold-point temperature (Randel et al., 2004; Fueglistaler, 2013). Changes of stratospheric water vapour levels ranging from inter-annual to decadal time scales are less well understood, in particular the contribution of processes involved. Well-known and understood is the “tape-recorder” effect (Mote et al., 1996) describing the annual cycle of the tropical stratospheric water vapour amount in accordance with the seasonally varying cold point temperature (e.g., Fueglistaler et al., 2005). Moreover, variations of the tropopause temperatures are clearly related to tropical upwelling, the equatorial quasi-biennial oscillation of stratospheric zonal winds (QBO), and the El Niño–Southern Oscillation (ENSO) as for example discussed by Randel et al. (2004). Recent analyses of the observed stratospheric water vapour record show that many of the variations on time scales of one to several years can be linked to changes in tropical tropopause temperatures, but some discrepancies still exist (e.g., Schoeberl et al., 2012; Fueglistaler et al., 2013). Randel and Jensen (2013) state that the water vapour fluctuations observed by satellite instruments over the last 20 years are not adequately reproduced by "free-running" Chemistry-Climate Models (CCMs), although those were forced by observed sea-surface temperatures (SSTs) and concentrations of greenhouse gases and ozone depleting substances were prescribed. Randel and Jensen point out, that current CCMs are not able to reconstruct the severe water vapour drop after the beginning of year 2000. Therefore, they conclude that important components of internal variability might be missing or at least under-represented in the model systems, especially in the tropical tropopause layer (TTL). Similar investigations summarise that it is still unclear whether the inability to simulate the observed trends is due to the large uncertainties in the observed stratospheric water vapour and tropical tropopause temperatures (e.g., Wang et al., 2012), inaccuracies in the CCMs, or whether the models miss relevant mechanisms (see Chapter 4 in WMO, 2014).

Here we present results of a set of ~~simulations with~~ 4 simulations with different model setups with the state-of-the-art chemistry-climate model (CCM) EMAC (**E**CHAM/**M**ESSy **A**tmospheric **C**hemistry model), indicating that it is possible to retrace the observed water vapour fluctuations in the stratosphere (including the millennium drop)~~, if appropriate boundary conditions are applied. The advantage of a CCM is that it includes chemical feedbacks of radiative important greenhouse gases like ozone, which are important for the stratospheric temperature distribution.~~ . In the following section the CCM EMAC is briefly described~~and the investigated simulations~~ , the investigated model simulations and the used observational data sets are presented. ~~In Sect. 3 model data are~~ The millennium water vapour drop as represented in one of the model simulations is compared to observations ~~.~~ in Sect. 3. To clarify, which part of the millennium drop we refer to, we define two different phases of "the drop": phase 1 is the short period of the steep decline between the drop onset, i.e., the water vapour maximum, and its subsequent minimum. Phase 2 is the period of low values between the minimum and the start of the recovery. In Sect. 4 ~~three long-term~~ all model simulations are ~~analysed, differing mainly~~ compared with respect to ~~surface temperatures or applied nudging.~~ their ability to represent the millennium drop. Sec. 5 provides an analysis of other large moisture anomalies in the lower stratosphere and their relation to preceding El Niño/La Niña events. An overall discussion of our findings is given in Sect. ~~5.~~ 6.

2 Method and data

2.1 Description of the model system

The ECHAM/MESSy Atmospheric Chemistry (EMAC) model is a numerical chemistry and climate simulation system that includes sub-models describing tropospheric and middle atmosphere processes and their interaction with oceans, land and human influences (Jöckel et al., 2010). It uses the second version of the Modular Earth Submodel System (MESSy2) to link multi-institutional computer codes. The core atmospheric model is the 5th generation European Centre Hamburg general circulation model (ECHAM5, Roeckner et al., 2006). For the present study we analysed EMAC (ECHAM5 version 5.3.02, MESSy version 2.50) in the T42L90MA-resolution, i.e. with a spherical truncation of T42 (corresponding to a quadratic Gaussian grid of approx. 2.8 by 2.8 ° in latitude and longitude) with 90 vertical hybrid pressure levels up to 0.01 hPa.

The multi-year ~~simulation has~~ simulations have been performed with the CCM EMAC in the framework of the ESCiMo project (Earth System Chemistry integrated Modelling, Jöckel et al., ~~2015~~2016). Within ESCiMo so-called reference (RC) simulations have been carried out, as defined by the IGAC/SPARC Chemistry-Climate Model Initiative (CCMI) and described in detail by Eyring and Lamarque (2012). The ~~forcings of the two transient hindcast~~ forcing of the transient reference simulations in either free-running (RC1; from 1960 to 2011) or in a nudged mode (RC1SD, RC1SDNT; from 1980 to 2012) are similar (“hindcast simulations”). They are taken from observations or empirical data, including anthropogenic and natural ~~forcings~~ forcing based on changes in trace gases, solar variability and volcanic eruptions ~~. The quasi-biennial oscillation (QBO) is in all simulations slightly nudged to get the correct phasing of the observed QBO (Jckel et al., 2015~~(see Table 1 for an overview). The sea surface temperatures (SSTs) and the sea ice concentrations (SICs) are from observations or reanalysis data (RC1: HadISST, RC1SD and RC1SDNT: ERA-interim). In the case of RC1SD the model prognostic variables (vorticity, divergence, the logarithm of the surface pressure, the temperature and additionally the ~~zonal~~ mean temperature (wave number zero in spectral space)) are nudged by Newtonian relaxation towards ERA-Interim reanalysis data. ~~Therefore, the RC1SD simulation can be used to compare the model data with corresponding observations including year-to-year variations~~RC1SDNT is nudged similarly with the exception that the mean temperature is NOT nudged. The transient forecast reference simulation RC2 (from 1960 to 2100~~; RC2~~) is a future projection that follows the IPCC scenario RCP 6.0 and a specified scenario of the development of ozone depleting substances (halogen scenario A1; WMO, 2007). It also considers solar variability in the past and future (for details see Jöckel et al., ~~2015~~2016). Because of potential discontinuities between the observed and simulated data record, RC2 uses SSTs and SICs derived from a coupled climate model simulation (with an interactive ocean, HadGEM2, RCP6.0 scenario; Johns et al., 2011) for the entire period. In the following analysis we confine the data of the RC2 simulation from 1960 to 2040.

The internal generation of a QBO is a feature of the L90MA setup of EMAC (Giorgetta et al., 2002). Therefore, in all simulations a QBO is internally generated. Nevertheless, the zonal winds near the equator are nudged towards a zonal mean field with a Gaussian profile in the latitudinal direction and with a relaxation time scale of 58 days in our simulations to get the correct phasing of the observed QBO (Jöckel et al., 2016). The nudging is applied in the altitude range between 10-90 hPa, with full nudging weights (i.e., 1.0) from 20-50 hPa, levelling off to 0.3 (0.2) at the upper (lower) edge of the nudging region. Full nudging is utilised between 7 °S-7 °N latitudes. As will be shown in the results, this does not necessarily mean, that the QBO is equal in all simulations!

2.2 Observational data sets

~~To analyse different characteristics of the millennium drop in water vapour we use besides the~~ For comparison with our EMAC simulation with specified dynamics RC1SD ~~also a~~ (nudged mode), we use (i) the water vapour data from combined HALOE (Halogen Occultation Experiment) and MLS satellite measurements as described in Randel and Jensen (2013), (ii) a merged data set from seven limb-viewing satellite instruments, which were compiled into a long-term record (Hegglin et al., 2014) and (iii) a combination of satellite observations performed by HALOE ~~(Halogen Occultation Experiment)~~ and MIPAS (Michelson Interferometer for Passive Atmospheric Sounding) instruments (Russell et al., 1993; Fischer et al., 2008). For more details see the Appendices A1-A3.

~~Previous analyses of the millennium drop characteristics focused mainly on its absolute value (Randel et al., 2006; Maycock et al., 2014) , i.e. those studies used the water vapour difference between multi-year means before 2000 and after 2001. Those approaches reflected mainly the change in the large-scale circulation that contributed to the millennium drop. Contributions from the QBO and ENSO on the other hand were attenuated or even completely removed. Here, we rely on running annual means to make the contributions of these two variability patterns more visible. We focus on several characteristics~~ With the data set (iii) we performed a novel analysis on several zonal mean characteristics of phase 1 of the millennium drop as a function of altitude and latitude (Appendix A4). Based on derived start and end dates of this phase 1 (i.e., from its maximum to its minimum anomaly), we calculate the length ~~of the drop~~(duration) of phase 1, the start date (months since January 2000), and the ~~total change in water vapour . For more details see the Appendix.~~size (amplitude). The same analysis was applied to the simulated stratospheric water vapour of RC1SD. This analysis is based solely on running annual means and does not imply an inter-comparison of periods before (2000) with periods after (2001) the decline, in contrast to previous studies (Randel et al., 2006; Maycock et al., 2014).

3 The millennium water vapour drop

This study is motivated by a chart which is shown in Fig. 1 (the original figure was published by Randel and Jensen, 2013): The near-global lower stratospheric water vapour anomalies were derived from multi-year satellite measurements (1992–2012) from HALOE and Aura/MLS at the 83 hPa pressure level (approximately 17 km altitude). ~~It impressively indicates~~ The measurements impressively indicate inter-annual fluctuations of up to 15 % (about 0.5 ppmv) from the 20 year mean mixing ratio. There are clear signs of the QBO over the full time period. The figure highlights the severe water vapour drop (approximately −0.7 ppmv) in the year 2000. ~~In~~

The HALOE data (see Fig. 1~~we show that our~~) show a step like change from an enhanced water vapour period before the drop (1993-2000) into a phase with reduced water vapour. The recovery from this phase (our phase 2) with prevailing negative anomalies starts in 2007. The RC1SD ~~simulation (with specified dynamics) is able to closely reproduce the water vapour fluctuations as observed, here representing the near-global mean (60S–60N) anomalies. Except for the time before 1994, where the eruption of Mt. Pinatubo had a significant impact on temperature and water vapour, the temporal evolution of water vapour at the pressure level 83by RC1SD is in accordance with observedvalues. For example the~~ simulation (nudged, including mean temperature nudging) closely reproduces the water vapour fluctuations as observed. The timing of relative minimum and maximum water vapour values is reproduced very well. Evidently the model underestimates the strength of the inter-annual fluctuations (only about 0.3 ppmv instead of 0.5 ppmv) ~~. The severe drop~~ compared to the combined HALOE/Aura-MLS satellite data. The amplitude of the severe drop (phase 1) in 2000 is ~~slightly underestimated (about —~~by about 0.12 ppmv

~~)~~smaller than in the combined HALOE/Aura-MLS satellite data, yet the period with lower than normal water vapour (phase 2) is captured well. The ~~deviations after 2006 can partly be attributed to the corresponding positive anomalies of the cold point temperature in the tropical region (~~deviation of the RC1SD simulation results from the merged data set by (Hegglin et al., 2014, see Fig. ~~2) . The cold point temperature anomalies are represented better than the moisture anomalies, likely due to the direct nudging of zonal mean temperature in the model to ERA-Interim.~~

~~We conducted an additional simulation similar to RC1SD, but without nudging of zonal mean temperature (RC1SDNT) . The RC1SDNT simulation shows a cold point temperature anomaly time series similar to RC1SD, but the water vapour anomalies are by a factor of about 1/3 too small (not shown). The lower absolute values of the anomalies are likely caused by a mean tropical cold point tropopause temperature (189.4) which is lower than for~~ 1) is even smaller. RC1SD ~~(192.1) within the 1992–2012 period. We know from model inter-comparison studies that it is a common feature of many models,~~ and the merged data set agree in particular with respect to a) the start of the recovery phase after the drop, which starts earlier as in the HALOE data, b) the amplitude of the drop, and c) the lower water vapour anomalies in the period before the drop. The merged data set consists of individual short satellite records, merged with the simulated water vapour from a chemistry-climate model, which was nudged to observed meteorology. For the lower stratosphere this record of water vapour mixing ratios largely follows tropical tropopause temperatures. This might be the reason why the RC1SD and the merged data set are in better agreement.

Fig. 2 (also corresponding to Fig. 2 of Randel & Jensen, 2013) moreover shows that the cold point ~~tropopause in the tropics has a cold bias (Gettelman et al. , 2009). We conclude that in order to correctly simulate water vapour anomalies in time and amplitude, it is important not only to correctly reproduce the temperature anomaly, but also the mean temperature at the cold point tropopause.~~ temperature anomalies of RC1SD follow those of the radiosonde data. This can be expected, due to the nudging of EMAC towards ERA-Interim data.

There are expectations that the water vapour drop in observations exhibits different characteristics at different latitudes and altitudes with respect to the start date, the ~~strength~~ drop size (amplitude) and the length (duration) of the anomaly. For example, Urban et al. (2014) show that in the tropics the significant reduction of water vapour started in the altitude range from 16.5 to 18.5 km (375–425 K) in early 2000, whereas between 25 and 30 km (625–825 K) it began in late 2001. Moreover, they demonstrate that the drop was more pronounced in the lower tropical stratosphere than in the middle stratosphere, i.e. -1.3 and -0.6 ppmv, respectively. The minimum water vapour mixing ratios were found in the lower stratosphere about one year, in the middle stratosphere almost two years after the onset of the drop.

~~A more comprehensive and novelanalysis is provided in Fig. 3. The~~ Here, we perform a novel, comprehensive analysis to quantify the characteristics of the water vapour drop ~~with respect to strength, drop length and drop date are shown as a~~ (phase 1): a) the amplitude (drop size), b) the duration of the drop (drop length), and c) the onset of the drop (drop date). The results are shown in Fig. 3 as a function of latitude and altitude for both, the combined HALOE/MIPAS data set (Schieferdecker, 2015) and for the RC1SD simulation. The details of the methodology are described in Appendix A4. ~~The amplitude~~

The amplitude (drop size) of the drop maximises in the tropical lower stratosphere consistently in observations and the RC1SD simulation ~~. However~~ (Fig. 3, top). However, the amplitude in the tropics is ~~50~~larger in the observations. Towards higher latitudes and altitudes up to about 20 hPa the drop amplitude typically decreases. Above this level some increase in the drop amplitude can be observed that goes along with a stronger QBO variability. It is unclear if the drop amplitude here can be unambiguously attributed to the millennium drop or simply reflects natural QBO variability or a combination of both.

A similar pattern can be seen for the start date of the millennium drop ~~.~~ (Fig. 3, middle). Up to 40 hPa the drop occurs in most cases during the year 2000. Above 30 hPa there is a clear shift to dates in 2002 and 2003, again mostly controlled by QBO variability. The stronger branch of the Brewer–Dobson circulation on the Northern Hemisphere is clearly visible in the earlier start dates of the drop compared to the Southern Hemisphere.

The ~~drop length~~ duration of phase 1 is the less consistent ~~parameter.~~quantity (Fig. 3, bottom). Values typically range from 6 months (inherent from the approach) to about 20 months. In the simulation the length is in the order of 9 months in the lowermost tropical stratosphere. The observations exhibit here longer drops related to the larger drop amplitudes.

In conclusion, Fig. 3 nicely reflects that the cold point tropopause anomaly reduces water vapour and that this signal propagates into the upper stratosphere and, a bit asymmetrically due to the different branches of the Brewer-Dobson circulation, further towards the poles.

4 The millennium water vapour drop in other ESCiMo simulations

In the last Section, we showed that the millennium water vapour drop is reasonably well reproduced by ~~an EMAC simulation in the nudged mode~~the RC1SD simulation with nudged mean temperature. In the following we investigate whether also ~~free-running simulations~~ the other simulations RC1SDNT, RC1 and RC2 (see Table 1) are capable to simulate the variability ~~in~~ of lower stratospheric water vapour, and in particular the drop in year 2000.

The RC1SDNT (without mean temperature nudging) simulated water vapour anomaly time series amplitude is by a factor of about 1/3 too small (Fig. 4). Additionally, the period of low water vapour anomaly (phase 2) has a too high minimum. However, the tropical cold point temperature anomalies (Fig. 5) are in better agreement with RC1SD. Since RC1SD and RC1SDNT differ only with respect to the nudging of the global mean temperature, the RC1SD simulation implies a bias correction and RC1SDNT is affected by this bias. Therefore, the smaller water vapour anomaly amplitude in RC1SDNT is likely caused by a tropical cold point temperature of 189.4 K, which is biased low compared to that of RC1SD (192.1 K) within the 1992–2012 period. Contemporary CCMs show a large spread of about 10 K in simulating cold point tropopause temperatures (Gettelman et al., 2009). This corresponds to the likewise wide spread of simulated ozone at the tropopause level and to differently simulated tropopause altitudes. Since the cold point temperature strongly affects stratospheric water vapour, we conclude that in order to correctly simulate water vapour anomalies in time and amplitude, it is not sufficient to reproduce the temperature anomaly. The mean cold point temperature must be simulated correctly as well. The explanation for this is the non-linear dependence of water vapour on temperature as described by the Clausius-Clapeyron equation.

The magnitude of inter-annual variability in water vapour in the tropical lower stratosphere is overall far lower in the free-running simulation RC1 ~~and RC2 simulations~~ (Fig. 4). However, a decrease in water vapour around the year 2000 is found also in RC1. The strength of the drop (phase 1) is underestimated by a factor of 2. ~~RC2 does not show a dropat all. Furthermore, RC1 and~~ The minimum period (phase 2) is visible but the minimum is far too high. Compared to RC1SDNT, the free-running RC1 simulation does not simulate the observed synoptic situation. Yet, this seems also to be important for reproducing the observed water vapour variability, in particular the millennium drop. This is consistent with results of Garfinkel et al. (2013b), who showed with model simulations forced by observed SSTs only, that SSTs alone cannot explain the timing and the subsequent recovery of the millennium drop.

The main difference between the RC2 ~~both have a time lag compared to RC1SD and are not able to simulate the~~ and RC1 simulation is that RC2 uses simulated instead of observed SSTs. RC2 is therefore neither showing the water vapour decline, nor the long period with low water vapour values after 2000. ~~Interestingly a different picture shows up for the simulated~~ Accordingly, no low cold point temperature anomalies are visible in Fig. 5.

The effect of the correct cold point temperature ~~anomalies~~ on the saturation water vapour value is also demonstrated for the RC1 simulation (Fig. ~~5), which are comparable for RC1SD and~~ 6). We took the temperature variability of RC1 ~~and only slightly smaller for RC2.Similar to the water vapour drop,~~ as shown in Fig. 5, but used the actual cold point mean temperature as simulated in RC1SD. Thus, we shifted the cold point temperature ~~drop lags behind the year 2000 (Fig. 5), which points to a shift in the incidence of temperature relevant processes: El Nio and corresponding large-scale upwelling, the radiative effect due to the local ozone distribution and the QBO (Randel and Jensen, 2013~~anomalies. Then we calculated the corresponding saturation moisture over ice for RC1SD (just for comparison), for RC1 (original simulation) and for RC1shifted (shifted cold point temperature anomaly). The results show that a corrected absolute cold-point temperature of RC1 (i.e., RC1shifted) is expected to improve the representation of phase 2 of the drop.

We conclude: (1) Without observed SSTs die millennium drop (phase 1 and 2) cannot be simulated at all. (2) The specific synoptic situation as simulated by RC1SD and RC1SDNT seems to be important for the representation of the millennium drop (phase 2). Note, that the period of increased upwelling after 2001 has no corresponding signature in observed tropical SSTs. (3) The correct cold point temperature is necessary to simulate the correct minimum of low water vapour values (phase 2) and the amplitude of the drop (phase 1).

5 Other ~~“drops” of~~ large negative moisture anomalies (phase 1) in the lower stratosphere and their relation to preceding El Niño/La Niña events

The millennium drop in water vapour 2000/01 (phase 1) after the strong 1997/98 El Niño event is followed by an unusual long time period of relatively low water vapour values (phase 2) (Fig. 1). Since Solomon et al. (2010) found that these anomalous low water vapour values in the lower stratosphere caused a reduced trend in global surface temperatures over the years 2000–2009 by about 25 %, we wonder, if this millennium drop is unique or if we can expect that such a ~~drop~~ decline is a more or less typical feature of stratospheric water vapour variability? Is there a relation to preceding El Niño/La Niña events? The El Niño Southern Oscillation is an ocean–atmosphere feedback that occurs every 2–5 years and propagates throughout the troposphere into the lower stratosphere. Therefore El Niño/La Niña events have the potential to couple the surface temperature with the stratosphere ~~.~~ (Scaife et al., 2003, Randel et al., 2009, Calvo et al., 2010, Garfinkel et al., 2013a).

We have analysed the time evolution of water vapour anomalies for the RC1SD and RC1 simulations at 80 hPa (Fig. ~~6~~7) for the full time period available for the respective simulations. In the RC1 simulation we found 5 and in the RC1SD simulation 3 relatively large water vapour ~~drops~~ declines (phase 1) marked by a red asterisk, which are comparable to the millennium drop amplitude in the respective simulation. An additional asterisk marks a smaller water vapour ~~drop~~ decline after the 1986/87 El Niño in RC1SD, which additionally was examined.

Because the amplitudes in the RC1 simulation are generally smaller than in RC1SD, we define a "large ~~drop~~decline" in the simulations differently: RC1SD: ~~drop~~ decline > 0.5 ppmv, and for RC1: ~~drop~~ decline > 0.2 ppmv.

The thresholds have been only used to simplify the search of decline events with preceding ENSO events. Thus, the result of event identification counting is independent of the selected values. We could have also started with the ENSO index and searched for decline events after La Niña events. The result is the same.

Although there are 2 other large water vapour ~~drops~~ declines in the RC1SD simulation starting 1994 and 1996, we neglect this time period, because the eruption of Mt. Pinatubo (1991) had a significant impact on temperature and water vapour ~~. Through the use of nudging data from reanalysis the effect of Mt. Pinatubo is partially captured in the dynamics and the temperature field. In another sensitivity study with the RC1 simulation set-up, which includes the effect of the Mt. Pinatubo eruption in terms of additional aerosols in the stratosphere, a strong positive water vapour anomaly lasting over 5is found, followed by a huge water vapour drop (Fig. 6, red curve~~in our simulations (Löffler et al., 2015)). Likewise, we cannot exclude, that the eruption of Mt. Chichon in 1982, although less strong than the eruption of Mt. Pinatubo had an influence on the results.

The dominant effect of El Niño/La Niña events on the tropical surface temperatures (including land and sea surface temperatures) are clearly visible in Fig. ~~7~~ 8a in all simulations. The data derived from the RC1 simulation indicate strong temperature signals related to the El Niño and La Niña episodes (1: 1969/70, 2: 1973/74, 3: 1982/83, 4: 1986/87, 5: 1997/98, 6: 2009/10). The RC1SD simulation only covers El Niño and La Niña events from no 3 to no 6, but the surface temperatures are similar to RC1. The 1997/98 El Niño event (5) was unusually strong compared to former events, with a tropical surface temperature amplitude of about 0.7 K, similar for both RC1 and RC1SD. Case no 4 shows a two year lasting El Niño starting as weak in 1986 and becoming 1987/88 a moderate event followed by a strong La Niña. The SSTs for the RC2 simulation were taken from a coupled ocean–atmosphere simulation of the HadGEM-model, and the tropical surface temperatures are generally lower than in observations (Fig. ~~7b~~8b). However, the simulated surface temperature represent similar fluctuations (in magnitude) as observed, but originating in different periods of time and often with longer time duration. ~~A causal relationship between large drops and preceding El Nio/La Nia events could not be found.~~

In order to understand the origin of large water vapour declines, we analysed the corresponding development and incidence of two important components of natural variability influencing the temperature in the TTL: the El Niño/La Niña events and the QBO. The QBO appears as a reversal of the tropical zonal wind direction with a mean period of about 28 months (ranging from 22 to 34 months) and is a primarily wave-driven stratospheric phenomenon. In the tropical lower stratosphere the QBO is the dominant dynamic feature.

As mentioned above (Sect. 2), in all ~~three~~ four EMAC simulations the QBO is nudged to zonal mean winds with respect to the amplitude and phase. Therefore the signature of the QBO in the temperature anomaly (Fig. ~~8b~~9b, RC1 as representative for all simulations) propagating downwards to the TTL is present in all three EMAC simulations (for the RC1SD simulation see Fig. S1 in the supplement). Although the QBO nudging setup is equal in all simulations presented, the resulting winds are not the same in RC1SD, RC1, and RC2. The QBO nudging does not force a one-by-one representation of the nudged data by the model, the model still develops its own dynamical state. Note that the QBO at roughly 90 hPa is key for the temperature signal affecting water vapour, i.e., at an altitude, where the QBO nudging strength is already reduced and therefore relies on signal propagation. Only for RC1SD (and RC1SDNT), where divergence and vorticity and the logarithm of the surface pressure are nudged, too, the wind profiles are close to those of ERA-interim.

It is well-known (Rosenlof and Reid, 2008, Dessler et al., 2014) that the QBO phase contributes to the extraordinary temperature fluctuation in the tropical tropopause region around year 2000 due to an unusual long QBO-phase: strong east-winds in the equatorial lower stratosphere (around 30 hPa) were persistently detected for nearly two years (2000/01); the downward propagation of the zero-wind line (change from east- to west-wind direction) stopped for one year (from mid-2000 to mid-2001) at about 40 hPa.

Around a strong El Niño event (black vertical lines, Fig. ~~8~~9b) we find a positive moisture (Fig. 9a) and temperature anomaly throughout the troposphere up to about 100 hPa ~~. Above, in a~~ and subsequent moistening of the lower stratosphere. This result is consistent with the findings of Dessler et al. (2014), who showed by regression analysis that stratospheric entry values of water vapour increase with tropospheric temperature. El Niño as an important driver of the inter-annual variability is captured in the tropical tropospheric temperature regressor. In contrast, the effect of La Niña events to increase stratospheric water vapour as discussed by Garfinkel et al. (2013a) is not captured with the tropospheric temperature regressor, but with the BDC (Brewer-Dobson circulation) regressor.

In Fig. 9, in a narrow layer between 100 and 50 hPa (marked with dashed black lines) a negative temperature anomaly occurs, except for the 1982/83 El Niño, where a positive QBO phase with warming probably masks this feature. For the 1997/98 and the 2009/10 El Niño the cooling is not pronounced, but also visible.

Positive and negative temperature anomalies in the narrow layer are related to a large part by changes in upwelling (Fig. 10), which directly modifies ~~tropopause temperatures~~ the tropopause temperature through lifting of air masses~~and corresponding advection of ozone anomalies into the TTL. A~~. Additionally, a positive upwelling anomaly (cooling) is accompanied by a negative ozone anomaly (cooling~~). Therefore,~~ , not shown). For this reason upwelling anomaly and ozone anomaly are ~~highly~~ anti-correlated with a Pearson's correlation coefficient ~~$R = -0.6$~~ of about $r = -0.56$ at 70 hPa for both, RC1 and RC1SD (Table ~~1~~2, see Appendix B for the formula of the Pearson's correlation coefficient). Tropical upwelling is calculated from the model ~~data~~ results in terms of the residual vertical velocity w^* as introduced in the transformed Eulerian mean (TEM) equations (e.g. Holton, 2004~~)~~, his equation 10.16b) for the tropics (20 °S – 20 °N). As expected temperature and large-scale upwelling are also strongly anti-correlated with a Pearson's correlation coefficient ~~$R = -0.7$~~ $r = -0.7$ (70 hPa) for RC1SD (RC1: ~~$R = -0.58$~~$r = -0.58$) (Table ~~1~~2). Likewise temperature and QBO are positively correlated with ~~$R = 0.5$~~ $r = 0.5$ (RC1) (~~$R = 0.4$~~ $r = 0.4$ for RC1SD) at 70 hPa. The correlation ~~coefficients decrease towards 90~~coefficient decreases at lower altitudes, because the effect of the QBO on temperature decreases.

In the TTL positive temperature anomalies always result in positive water vapour anomalies propagating upward into the stratosphere (Fig. ~~8a). They~~ 9). This is independent of a heating and moistening of the tropical troposphere during El Niños and occurs also under La Niña conditions. Because El Niño (La Niña) conditions lead to an increase (decrease) in upwelling (Fig. 9) a cooling (warming) of the TTL region can often be found (El Niños 1,2,4,5,6, La Niñas: 2,4,5,6). A moistening can occur in cases, where the mature phase of an El Niño is over and positive TTL anomalies appear. This is consistent with the results of Garfinkel et al. (2013a) who also find a moistening of the stratosphere after La Niña events. TTL temperature anomalies are an indicator of the regional dynamical properties (Mote et al., 1996; Randel et al., 2004). The traveling time for water vapour in the lower stratosphere calculated from the maximum correlation between temperature at 100 hPa and water vapour at 82 hPa is 2 months ~~according to~~ (Rosenlof and Reid~~(~~, 2008, Schoeberl et al., 2008).

We find a similar result only for RC1SD, but RC1 and RC2 exhibit the maximum correlation for lag ~~= 0.~~ = 0. Accordingly, the correlation between temperature and moisture at 70 hPa is stronger in RC1 ($r = 0.8$) than in RC1SD ($r = 0.4$). Consistently, upwelling is smallest in the RC1SD and largest in the RC1 simulation leading to a faster transport of water vapour through the TTL in RC1. ~~Accordingly, the correlation between temperature and moisture at 70is stronger for RC1 ($R = 0.8$)than for RC1SD ($R = 0.4$)~~Because nudging basically affects the whole momentum budget (e.g., resolved wave amplitudes, which largely drive upwelling, are nudged), it is not surprising that upwelling is different in the free running compared to the nudged simulation.

We use this connection to analyse the conditions under which large temperature drops occur, in order to understand the origin of large water vapour drops. In doing so, we disregard other processes that may contribute to the water vapour distribution and its variability in the TTL such as convective overshooting and large-scale water vapour transports, ice supersaturated regions and cirrus development.

Every El Niño event is generally accompanied by a strong positive upwelling anomaly (Fig. ~~9~~10) followed by a period with reduced upwelling and thus positive temperature anomalies in the TTL. Many of these positive temperature anomalies mark the onset of strong drops in temperature and water vapour. Note the double maximum in the temperature anomaly after the 1972/73 (no 2) El Niño (Fig. ~~8b~~9b), which is related to the reduced upwelling in Fig. ~~9.~~ 10. This confirms that upwelling plays the other important role in generating temperature anomalies around 100–60 hPa beside the QBO, directly through adiabatic cooling.

Although the SSTs of the RC1SD and RC1 simulation are similar, the period with a positive upwelling anomaly after the year 2001, leading to the observed low tropopause temperatures and low water vapour values in the lower stratosphere (Randel et al., 2006) is not adequately simulated in the RC1 simulation. Interestingly after 2001, where tropical SSTs only exhibit a small but long lasting positive anomaly in both, ~~RC1and~~ RC1 and RC1SD, upwelling already shows a positive anomaly, stronger in RC1SD than in RC1. ~~This might be related to an enhanced momentum flux convergence in the subtropical region (Randel et al., 2006), but a detailed analysis of our simulations regarding this topic is beyond the scope of this study.~~

If a strong El Niño plus La Niña event is typically followed by a large temperature/water vapour drop we might expect that typical conditions exist that favour these large variations. We performed an episode analysis for the previously selected 4 (RC1SD) and 5 (RC1) strong El Niño events, followed by a La Niña event (Fig. ~~7)~~ 8) and strong declines in water vapour, respectively. Additionally, 4 smaller declines in water vapour of simulation RC1SD, where no ENSO event preceded, were selected and analysed. The onset of the individual temperature ~~drops~~ declines at 80 hPa (Fig. ~~10~~11) is placed at month 0, so that the periods before the drop and afterwards can be consistently analysed. We selected the start of the temperature drop (rather than the drop in water vapour), where temperature is at its maximum, for the definition of the corresponding event, because QBO, upwelling and ozone have a direct effect on temperature. Water vapour anomalies follow temperature anomalies directly or with a time lag.

The onset of the millennium water vapour drop (Fig. ~~11~~12, green dashed line) is phase shifted by 3 to 4 months and the 2009/10 water vapour drop about 2 months after the temperature maximum of the ~~respective drops~~ corresponding decline (Fig. ~~10~~11). For the other ~~drops~~ declines in RC1SD and all ~~drops~~ declines in RC1, we find no time lag.

All onsets of the temperature drops of RC1SD and RC1 are associated with a minimum in the large-scale upwelling anomaly (Fig. ~~12~~13), accompanied by a maximum in ozone anomaly (Fig. ~~13~~14) and for RC1SD only, a west-phase of the QBO (Fig. ~~14~~15). Accordingly, the minima of the drops show maxima in upwelling, minima in ozone and an east-phase of the QBO (for RC1SD only).

RC1 does not show the transition from west QBO to east QBO phase at the 80 hPa level as a typical feature, because the QBO-phases do not propagate down as far into the TTL as in RC1SD. Therefore, the contribution of the QBO phase to the drop is less for RC1.

Generally, the correlation between temperature anomaly and QBO anomaly is smaller in RC1 than in RC1SD for the 90 hPa level compared to 70 hPa (Table ~~1~~2). This points to a different coincidence of upwelling and QBO in RC1, which might partly explain, why the anomalies in temperature and hence water vapour at TTL level are smaller in RC1.

The analysis of small declines of the RC1SD simulation (we placed the figures in the supplement, Fig. S2 – Fig. S6) confirms our results. Small declines are not necessarily accompanied by the changing west to east phase anomaly of the QBO. A clear negative anomaly in upwelling (at the onset in phase 1) only exists for one decline. However, the amplitudes of the upwelling anomalies are smaller than the respective amplitudes for the large declines (Fig. 13).

The time evolution of the upwelling anomaly is strongly correlated with SST anomalies during El Niño and La Niña periods (El Niño region 3.4, Figs. ~~15 and 16~~16 and 17) except for the 1982/83 (no 3) El Niño event, which had its maximum already before the maximum of surface temperature was reached. However, for the whole simulation period in RC1SD upwelling anomalies and surface temperature anomalies in the tropics are only correlated with $R = -0.4$. We conclude, that under most El Niño/La Niña conditions the high/low SST anomalies have the dominant influence on upwelling maxima and minima, and thus on the drop amplitude, whereas under ~~normal SST conditions the influence~~ undisturbed SST conditions (without the influence of ENSO) the influence on upwelling is smaller.

~~Both simulations, RC1SD and RC1, show variable time-lags between El Nio (in terms of SST anomaly maximum) and temperature drop (represented by the negative anomaly in upwelling) onset ranging from 6 to 34 months, which is a result of the SST time evolution during the El Nio/La Nia phases. The relationship is particularly visible in Fig. 16 for the 1972/73 (no 2) El Nio, which was followed by a 2long-lasting La Nia event and had the longest analysed time lag.~~In the RC2 simulation large water vapour drops (phase 1) also occur, however, none of those show a clear relation with preceding ENSO events as analysed from the observations and from the other simulations. Furthermore, the correlation between upwelling and temperature (Table 2) is weaker in RC2 (compared to the other simulations). The reason are the different horizontal SST patterns, which are not as those observed. This affects the dynamics, e.g., stratospheric winds and thus wave propagation.

6 Summary and discussion

~~We demonstrated that observed fluctuations and changes of lower~~ We use results of 4 different simulations performed with the CCM EMAC to analyse the millennium drop in stratospheric water vapour~~content can be reproduced by multi-year CCM simulations, if specific boundary conditions are met. The nudged simulation~~ . The simulations differ with respect to the SSTs and whether nudging is applied or not (see Table 1). We find, that a nudged setup (RC1SD~~) fits best with observationsregarding the time evolution of lower stratospheric water vapour and its amplitude. In contrast, the~~ , including nudging of the global mean temperature) performs best compared to observations. A nudged setup excluding the mean temperature from nudging (RC1SDNT) also reproduces the millennium drop, however, with a smaller amplitude and a little too high water vapour values during the drop phase 2. This is solely related to the cold point temperature bias, because this is the only difference between RC1SD and RC1SDNT. The free-running RC1 ~~and~~ simulation with observed SSTs grossly underestimates the drop, but can capture some elements of it, and the free running simulation with simulated SSTs (RC2~~simulations provide too small amplitudes and thus too low variability in water vapour.~~

~~The analyses of these three model simulations show that the observed millennium water vapour drop is driven mainly by two forcings, namely an unusual strong positive tropical SST anomaly (from El Nio 1997/98) coinciding with a negative phase of~~) shows no drop at all. The analysed gradual degradation of the ~~QBO in the years before the~~ drop ~~. This is followed by~~ signal from RC1SD(NT) over RC1 to RC2 is further augmented by the difference in the QBO signal between the different simulations.

Our conclusion is that the correct SSTs are important to trigger the drop (i.e., phase 1) and also, at least partly, for the period of low values in phase 2. Second, the specific synoptic situation as simulated by RC1SD and RC1SDNT contributes to the characteristics of the millennium drop. This is especially true for phase 2, a period of increased upwelling after 2001, which has no corresponding pronounced signature in SSTs anomalies in the tropics. Finally, the correct absolute cold point temperature is necessary to simulate the correct minimum of low water vapour values (phase 2) and thus the amplitude of the drop (phase 1). The millennium drop of stratospheric water vapour of RC1SD in phase 1 is correlated with a strong negative tropical SST ~~fluctuations (~~fluctuation from La Niña 1999/2000 (after an unusual strong positive tropical SST anomaly from El Niño 1997/98) with reduced upwelling at the onset of the decline and a positive phase of the QBO ~~. After the year 2000, we find a period of stronger than usual upwellingand a corresponding negative temperature anomaly~~changing to the negative phase and stronger upwelling.

~~Strong~~ We also analysed the time series of water vapour anomalies in order to understand if there are similarities in the processes leading to large amplitudes in water vapour anomaly. In the RC1SD simulation strong drops in temperature and water vapour at the tropopause (phase 1) and above can ~~be found also~~ also be found after other El Niño events (e.g. ~~1986~~1982/~~87~~ 83 and 2009/10) followed by a La Niña, when conditions comparable to the millennium drop occur: Reduced upwelling due to a La Niña event in coincidence with a west phase of the QBO (warming) followed by an increase in upwelling in connection with the east phase of the QBO (cooling). The reduced upwelling induces a positive ozone anomaly (warming) and vice versa. ~~Interestingly, from~~

In the RC1 simulation ~~, we experience that the contribution of the QBO to a~~ we also find large amplitudes in water vapour at the tropopause (phase 1) after ENSO events. However, the QBO anomalies are often not in phase with the temperature or water vapour ~~drop is small. The smaller temperature and thus water vapour amplitudes in~~ decline. This affects the timing of declines displayed in Fig. 5, which is slightly different compared to RC1SD. In RC1 the temperature variability seems to be dominated more by upwelling, which is in absolute terms, also larger in RC1 ~~seem to be a result of the smaller QBO contribution to the drop compared to the~~ than in RC1SD ~~simulation~~ (Fig. ~~14). We conclude that it is~~ 13). This is at least not in contradiction Dessler et al. (2014), who found that the BDC provides the largest part to the water vapour variability in the lower stratosphere. Nevertheless, from our nudged simulation RC1SD, which is more in accordance with ERA-Interim, we find the coincidence of reduced upwelling and QBO ~~that controls the strength of the temperature and the corresponding moisture drop.~~ west phase anomaly changing to east in connection with the large declines (Fig. 13 and Fig. 15).

During ~~the~~ periods of strong surface forcing of a successive El Niño/La Niña event, the trend in the upwelling anomaly is often (but not always) strongly correlated to the SSTs in the El Niño 3.4 region (Figs. ~~15 and 16). The time it takes to shift from El Nio to La Nia determines the time the temperature drop lags the El Nio maximum.~~

~~The strong and widely noticed water vapour drop in the year 2000 is particularly remarkable due to the fact, that it is followed by a 5period of low stratospheric humidity. This cold period after 2000 is accompanied by stronger than usual tropical upwelling between the tropopause and 70(Fig. 9), causing the low temperatures and thus the low water vapour in the lower stratosphere, as described in Randel et al. (2006) and Rosenlof and Reid (~~16 and 17). This connection was already stated by Calvo et al. 2010, and Deckert and Dameris, 2008). ~~These negative water vapour anomalies after 2001 lead to a reduction in the global surface temperature warming trend of 25(Solomon et al., 2010) . Therefore, it is important to correctly model the relevant processes leading to the observed variations in moisture in the lower stratosphere. From our 3 ESCiMo simulations RC1SD (nudged), RC1, and RC2 we found that only the RC1SD simulation reproduces this millennium drop and the period with low water vapour values after year 2000 in accordance with observations. RC1 and RC2 simulate too small amplitudes in water vapour and RC1 a slightly different timing of the drop onset. RC2 shows no strong drop at all. Furthermore RC1 and RC2 both do not capture this~~ Thus, after an ENSO the potential for a large water vapour decline (phase 1) is increased, however it remains open, if a period with low water vapour values ~~, and thus the important contribution of the lower stratospheric water vapour feedback in RC1 is underrepresented.~~ follows (phase 2), because the conditions for its appearance can be different as for the phase 1.

Tropical upwelling, that strongly controls temperature in the tropopause layer, is influenced both by the ENSO (see e.g. Calvo et al., 2010)~~and the QBO~~. We find that in the free-running ~~simulations (~~simulation RC1 ~~, RC2)~~ the QBO does not propagate downward far enough ~~to influence the upwelling in the~~ into the tropopause region. Furthermore, the relation of tropical SSTs/ENSO to upwelling is stronger in RC1 compared to the nudged simulation.

This raises the question, whether there are processes or ~~forcings~~forcing, which are missing or underrepresented in the RC1 and the RC2 simulations. Because SSTs are prescribed from similar observations, RC1SD and RC1 differ mainly with respect to the nudging (of temperature, vorticity, divergence, the logarithm of surface pressure), and the temperatures of land surfaces, which are not prescribed, but can evolve interactively. RC2 uses simulated SSTs, which are colder than those used for RC1. Therefore RC2 can be expected to show different results at least for the time evolution.

~~EMAC is a CCM which considers interactively the feedback of dynamics, chemistry and radiation, including parameterisations for sub-grid scale processes. Global models like EMAC resolve the large-scale circulation, but unresolved convective transport effects or the drag due to breaking gravity waves are considered only through parameterisations. The response of the free-running model system to the prescribed SSTs appears to differ from the nudged model, i.e. the response in the reanalysis. Deckert and Dameris (2008) showed that higher SSTs in the tropics amplify deep convection locally with subsequent more convective excitation of quasi-stationary waves. These waves propagate upward and can dissipate in the UTLS, carrying the signal into the low-latitude lower stratosphere. An increase of SSTs intensifies the activity of tropical convection, which strengthens the associated latent-heat release and warms the tropical upper troposphere. Consequently, the meridional temperature gradient is increased, which strengthens and shifts the subtropical jets to higher latitudes. Waves can propagate further up and break at higher levels leading to stronger upwelling (Shepherd and McLandress, 2011).~~

~~These findings with respect to tropical dynamics and the involved mechanisms influencing the transmission from disturbances originating near the surface, propagating through the troposphere and affecting the UTLS region suggest that these processes may not adequately be represented by the EMAC model.~~ So far it is not clear, how many of the processes of the obtained cause and effect relationship are insufficiently described or parameterised. More investigations are needed to clarify, whether an inaccurate representation of these processes and/or feedback mechanisms in EMAC is responsible, or if it is a matter of model resolution that leads to the disagreement regarding the strength of year-to-year fluctuations of water vapour and temperature. Moreover, a general problem of “free running” models is, that the cold point is slightly too high (Gettelman et al., 2009) and therefore a little too cold compared to observations, which already leads to a reduced variability in absolute humidity.

Looking at the now 22 year long global water vapour record constructed on satellite-instrument measurements, there is another severe water vapour drop of similar size apparent after 2011 (Urban et al., 2014). Once longer records of global measurements become available in the future, it might turn out that such significant stratospheric water vapour fluctuations occur regularly. Natural changes that affect the stratospheric water vapour content are modified by climate change itself, may impact future climate. This demonstrates that robust climate predictions need realistic fluctuations of SSTs and an adequate representation of the QBO to reproduce the observed stratospheric water vapour fluctuations. Obviously severe changes can have a “memory” effect, impacting climate change on a decadal time scale (Solomon et al., 2010).

The variability of tropopause temperatures is dominated on an inter-annual period by modulations of the El Niño–Southern Oscillation, the tropical upwelling, and the stratospheric QBO. Variations in ozone amplify the impact of those drivers. In our analysis this relationship seems to be sufficient to show the connection between large water vapour drops, QBO phases, and preceding El Niños. While this part is understood (Randel et al., 2006, 2009; Fueglistaler and Haynes, 2005; Jones et al.,

~~2009~~2011; Urban et al., 2012; Fueglistaler et al., 2013; Randel and Jensen, 2013), the connection between temperature and moisture is far more complicated.

From Urban et al., 2014 we know that a period exists, where the variability of lower stratospheric water vapour is ~~not simply explainable by the course in~~ uncorrelated to the mean zonal temperature (2008–2011). The reason is so far unknown. Here, we omitted to analyse this period, because it is beyond the scope of this paper.

We further neglected in our analysis any possible changes in the transport of water vapour into the TTL, and the presence of supersaturated regions or cirrus clouds in the TTL. Since temperature and water vapour are non-linearly dependent, a monthly mean temperature does not give any information about the actual frequency distribution of saturation values of water vapour. In our simulations, the actual water vapour values are generally lower than the saturation values. It points to a lack of certain processes important for the budget of water vapour in the lower stratosphere (for instance convective overshooting). This is a topic of further research.

Appendix A: Millennium drop characteristics

A1 UARS/HALOE

HALOE was deployed on UARS (Upper Atmosphere Research Satellite) and performed measurements from September 1991 to November 2005. The measurements were based on the solar occultation technique. Absorption spectra were obtained in specific spectral bands in the wavelength range between 2.5 and 11 μm. Typically 30 occultations per day were performed, generally at two distinct latitude bands in the opposite hemispheres, based on sunrise and sunset measurements. Within a month the observations covered roughly the latitude range between 60° S and 60° N. Water vapour results were retrieved from the 6.54 to 6.67 μm spectral range, typically covering altitudes from about 10 to 85 km. For the analysis here we use data retrieved with version 19, that have been used extensively (e.g. Kley et al., 2000; Randel et al., 2006; Scherer et al., 2008; Hegglin et al., 2013).

A2 Envisat/MIPAS

To fill some observational gaps that are inherent of the solar occultation technique employed by the HALOE instrument we also consider MIPAS limb observations of thermal emission. Those provided typically more than 1000 individual measurements per day, lasting from June 2002 to April 2012. MIPAS was carried by Envisat (Environmental Satellite) which used a sun-synchronous orbit with full latitudinal coverage on a daily basis. The measurements covered the spectral range between 4.1 and 14.6 μm. Initially a spectral resolution of 0.035 cm^{-1} (unapodised) was used, however after an instrument failure in March 2004 later observations had to be performed with a reduced resolution of 0.0625 cm^{-1} (Fischer et al., 2008). Here we utilise data that have been retrieved with the IMK/IAA (Institut für Meteorologie und Klimaforschung in Karlsruhe, Germany/Instituto de Astrofsica de Andaluca in Granada, Spain) processor. Water vapour information is retrieved from several microwindows in the wavelength range between 7.09 and 12.57 μm providing data from 10 km up to the lower mesosphere. For the observations with high spectral resolution retrieval version 20, for the low resolution time period version 220 is used. Detailed information on these data sets can be found in Schieferdecker (2015) and Hegglin et al. (2013).

A3 Data set combination

The combination is based on monthly zonal mean time series from the individual data sets. In the overlap period a time-independent shift is determined that minimises the offset between the time series in a root mean square sense. This shift is derived for every altitude level and latitude bin considered and subsequently applied to the MIPAS time series. Applications of the combined HALOE-MIPAS time series can be found in Eichinger et al. (2014) or Schieferdecker et al. (2015).

A4 Analysis approach

The basic data for the analysis presented in Fig. 3 are monthly zonal mean data covering the time period from July 1998 to December 2005. The HALOE-MIPAS data set is interpolated in time to fill a few gaps. The data are averaged over a latitude range of 20° using a 10° latitude grid. The rather wide average in latitude aims to handle some of the sparseness of the HALOE observations. For the simulations this would not be necessary but for reasons of compatibility and comparability the same handling is applied. In the vertical the data sets extend from 100 to about 7 hPa and are interpolated on a regular grid using 16 levels per pressure decade.

The analysis is performed separately for every pressure level and latitude bin using the steps listed below. Figure A1 shows an example.

In a first step we calculate a running average over one year. In Fig. A1 the averaged time series is given by the black line. Based on that time series we calculate in the next step the gradient in water vapour along every data point.

Subsequently we look for periods with sequences of at least six data points that have a negative gradient allowing one data point in-between to have a positive or zero gradient. Typically we find several of such periods, as seen in the example in Fig. A1. We only consider those periods that have started within a certain time interval. For 100 hPa this interval ranges from January 2000 to January 2004, as indicated by the red lines in Fig. A1. This is based on a priori knowledge. For higher altitudes we adjust the start of the interval to the start date of the millennium drop at 100 hPa. At this altitude the drop is typically easiest to observe and we expect that higher up no earlier start dates occur.

To decide which of the periods represents the millennium drop we rely on two parameters, one, the absolute change in water vapour and, two, its overall gradient. These parameters are calculated for every period. Subsequently the periods are ranked according to these parameters with the largest absolute value gaining the highest rank. The ranks for a period are summed up and the period with the lowest sum is considered as the period that most likely represents the millennium drop. In the example shown in Fig. A1 the first period is chosen to represent the millennium drop as it exhibits both the largest decrease and the strongest negative gradient among the possible periods.

Appendix B: Pearson's correlation coefficient

Pearson's correlation coefficient is determined by:

$$r = \frac{\sum_{i=1}^{n}(a_i - \overline{a})(b_i - \overline{b})}{\sqrt{\sum_{i=1}^{n}(a_i - \overline{a})^2}\sqrt{\sum_{i=1}^{n}(b_i - \overline{b})^2}} \tag{B1}$$

a and b are the data sets to be correlated. n is the number of values per data set and $\overline{a} = \frac{1}{n}\sum_{i=1}^{n} a_i$.

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Table 1. Overview over the chemistry-climate model simulations used for this analysis.

Types of Reference simulations (T42L90MA)	Hindcast 1980-2012 (nudged) RC1SD	Hindcast 1980-2012 (nudged) RC1SDNT	Hindcast 1960-2011 (free-running) RC1	Hindcast+future projection 1960-2040 (RCP6.0) (free-running) RC2
SST	ERA-interim	ERA-interim	HadSST/SSI	HadGEM simulated
Nudged QBO	+	+	+	+
Nudging of: vorticity, divergence, temperature, logarithm of surface pressure	+	+	–	–
Additional nudging of mean temperature	+	–	–	–

Table 2. Correlation of anomalies (de-trended, de-seasonalised) for RC1SD, RC1 and RC2 at 90 and 70 hPa, respectively.

Correlation of anomalies	1980–2012 RC1SD 70 hPa	1960–2011 RC1 70 hPa	1960–2030 RC2 70 hPa	1980–2012 RC1SD 90 hPa	1960–2011 RC1 90 hPa	1960–2030 RC2 90 hPa
Temperature-ozone	0.69	0.92	0.88	0.60	0.70	0.41
Temperature-upwelling	−0.70	−0.55	−0.44	−0.64	−0.61	−0.39
Temperature-QBO	0.42	0.52	0.47	0.25	−0.25	−0.12
Ozone-upwelling	−0.56	−0.62	−0.54	−0.54	−0.65	−0.45
Ozone-QBO	0.51	0.57	0.50	0.23	−0.38	−0.14
Temperature-moisture	0.37	0.84	0.80	0.86	0.94	0.90

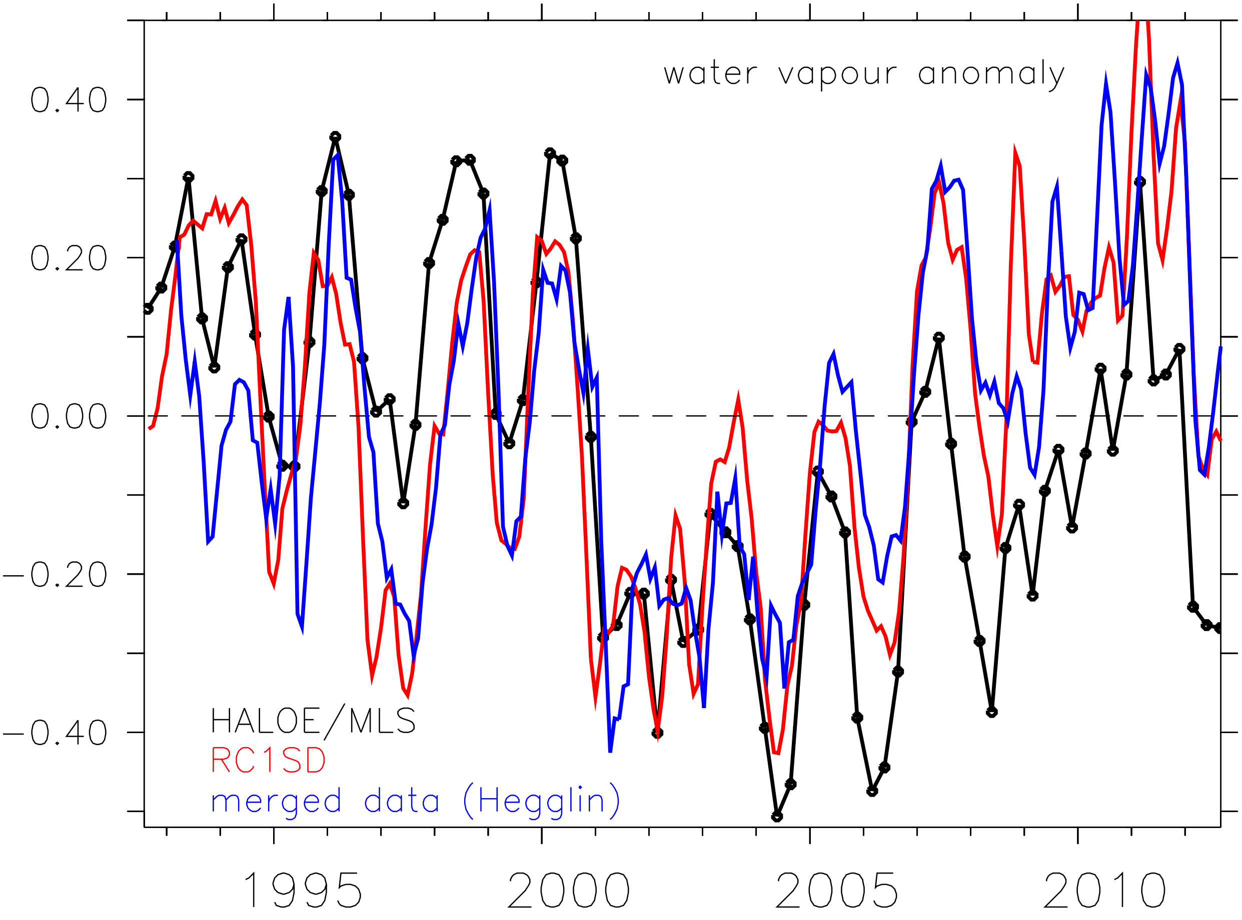

Figure 1. Interannual changes of the near-global mean (60° S–60° N) stratospheric water vapour mixing ratios (in ppmv) at 83 hPa. The black line is the data derived from satellite observations (combined HALOE and Aura/MLS satellite measurements, de-seasonalised, 3 month ~~running mean~~average), which was published by Randel and Jensen (2013) in their Fig. 5a (upper graph). The red line is the RC1SD simulation (de-seasonalised, 3 month running mean). The blue line is the merged data set as published by (Hegglin et al., 2013). The correlation between HALOE/Aura/MLS and RC1SD is r=0.68 and between the merged data set and RC1SD r=0.73. (r: Pearson's correlation coefficient, see Appendix B).

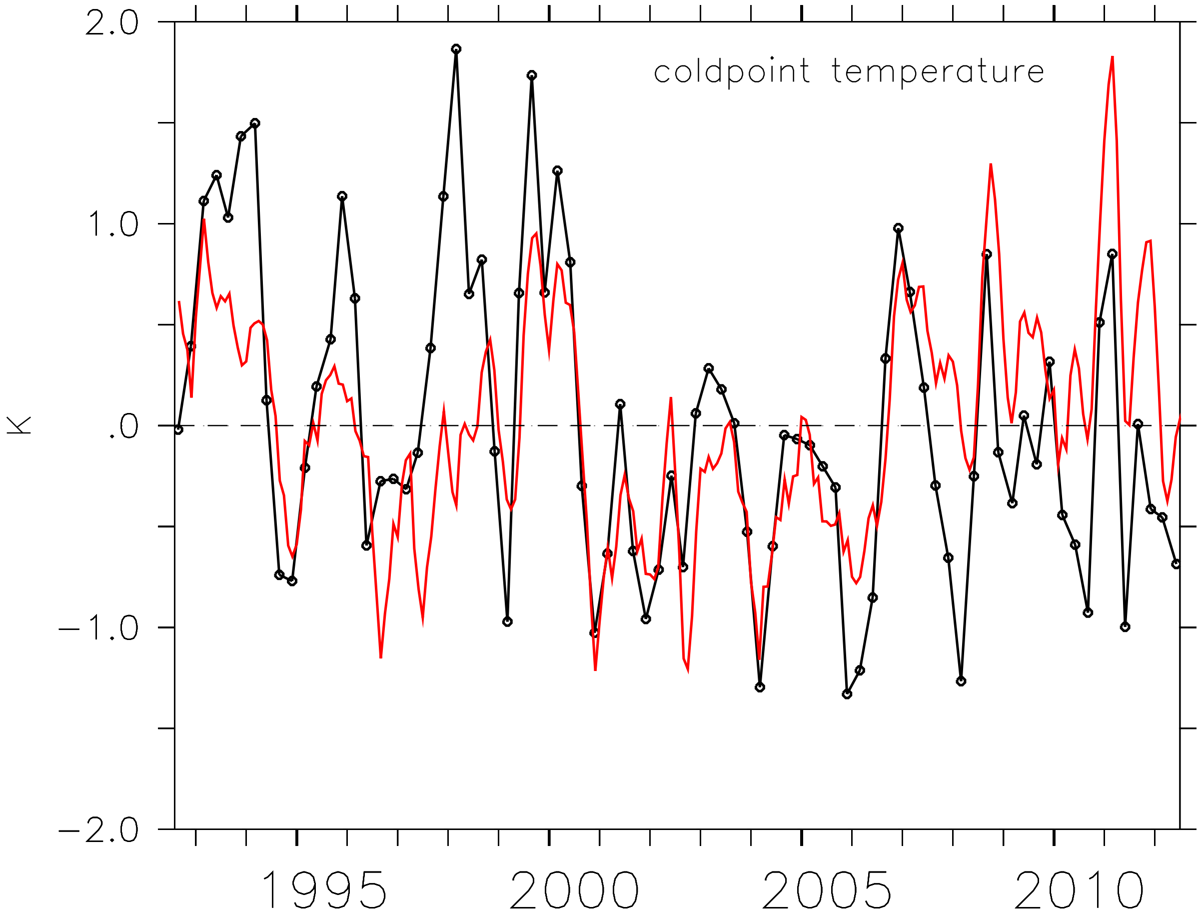

Figure 2. Cold point temperatures in the tropics (20° S–20° N) derived from radiosonde data (black line). The data was already published by Randel and Jensen (2013) in their Fig. 5a (lower graph). The red line is the RC1SD simulation (de-seasonalised, 3 month running mean). The correlation coefficient is r=0.61.

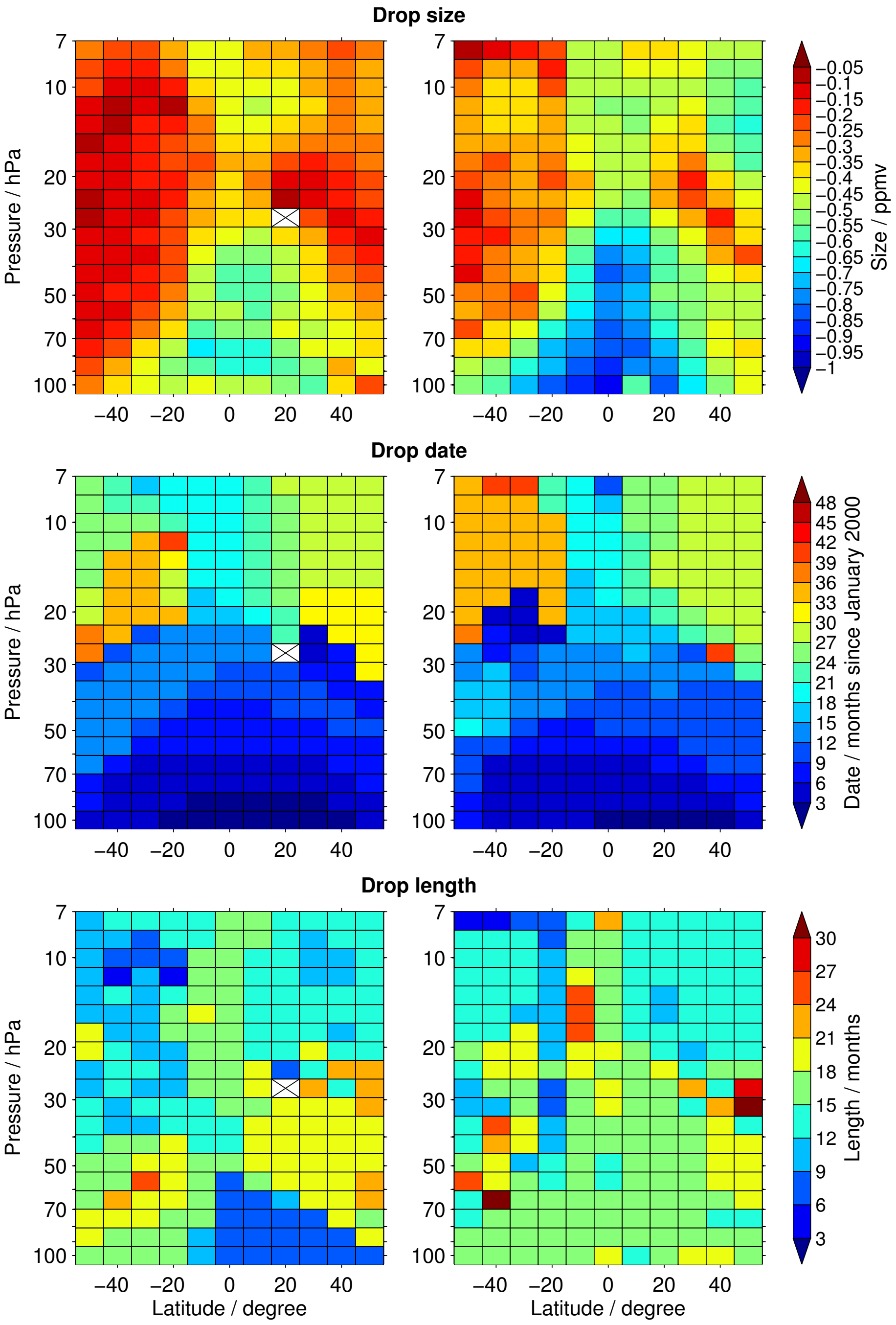

Figure 3. Characteristics of the millennium water vapour ~~drop~~ decline with respect to height (hPa). RIGHT: Satellite observations. LEFT: RC1SD simulation. TOP: Drop ~~strength~~ size (amplitude)(unit: ppmv), MIDDLE: drop date (months since January 2000). BOTTOM: drop length (duration) (unit: months). White boxes with crosses indicate that the analysis failed to find a water vapour decrease that fulfilled the criteria listed in the Appendix A4.

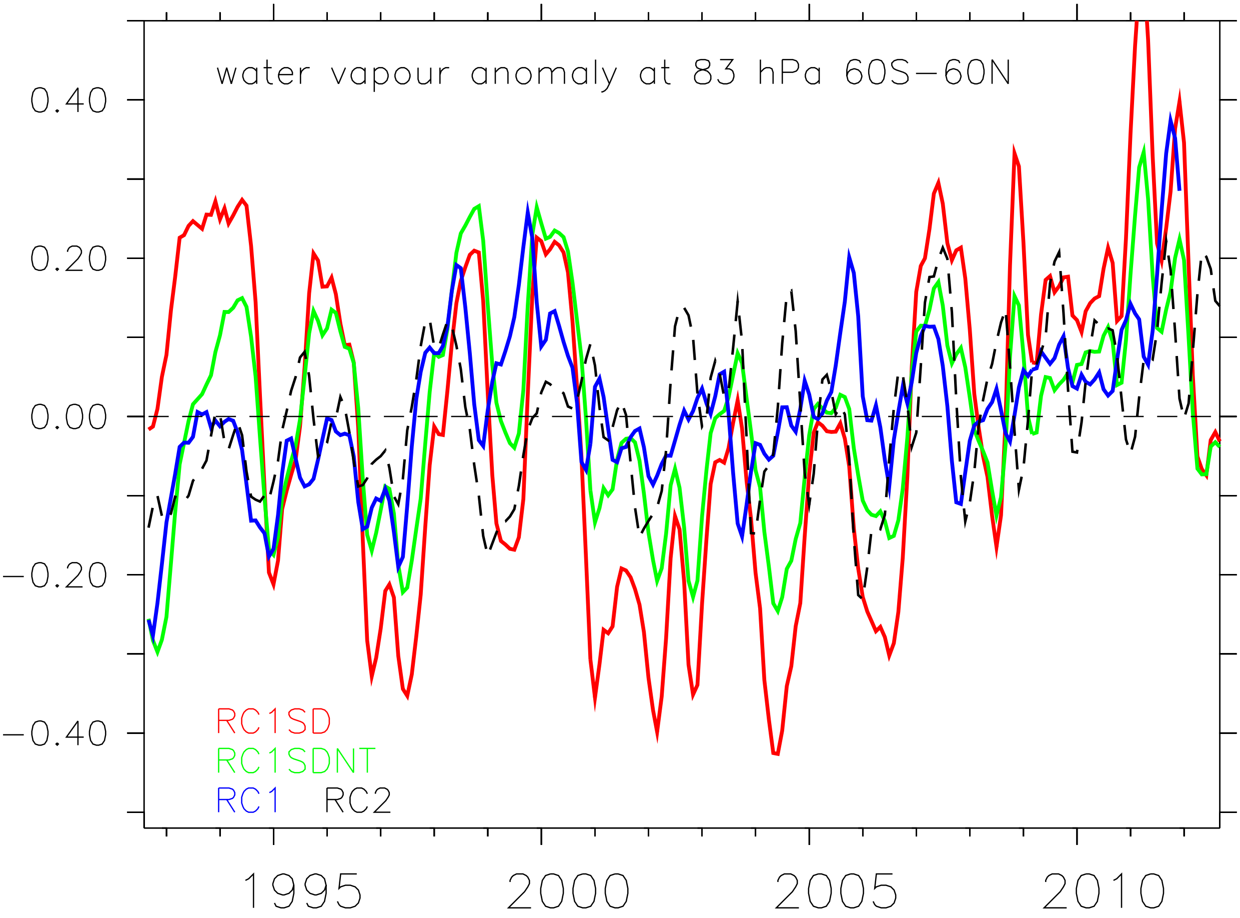

Figure 4. Near-global mean (60° S–60° N) water vapour anomalies (de-seasonalised, note, these anomalies are a 12 month running mean and therefore slightly different compared to RC1SD in Fig. 1) derived from RC1SD, RC1SDNT, RC1 and RC2 simulations.

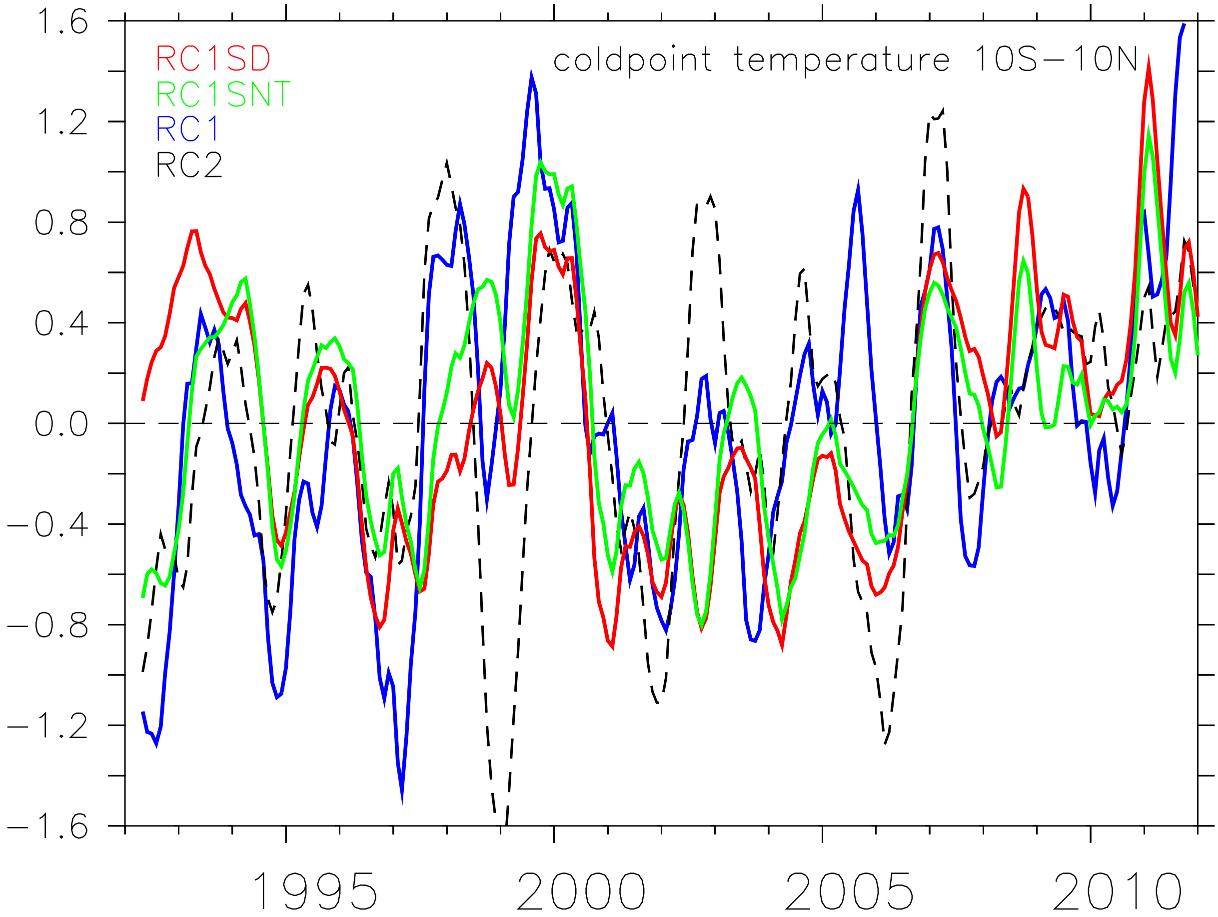

Figure 5. Cold point temperature anomalies (de-seasonalised, 12 month running mean) derived from RC1SD, RC1SDNT, RC1 and RC2 simulations.

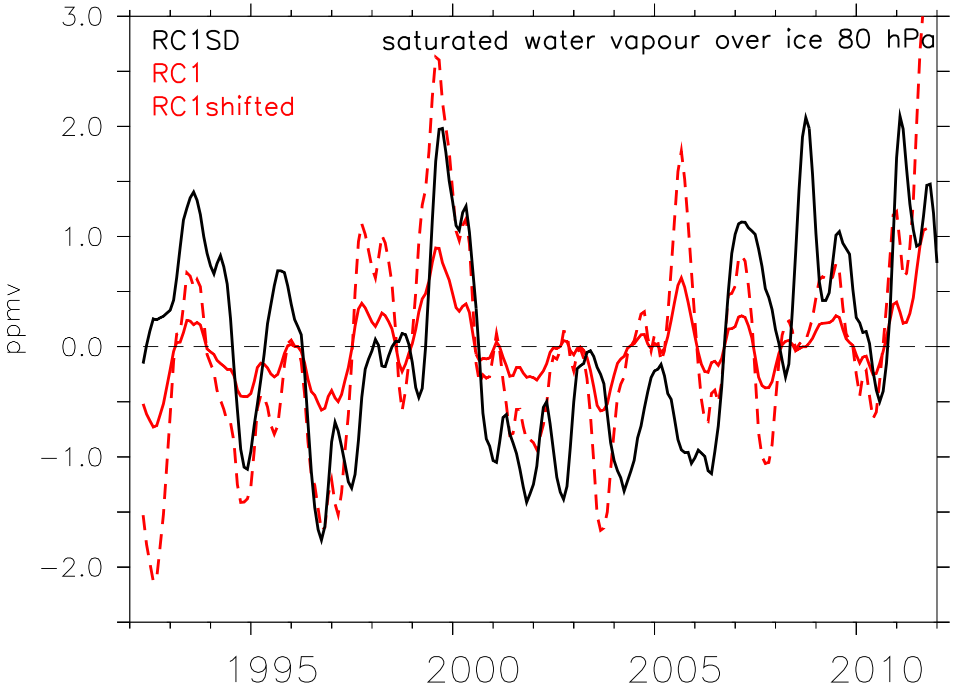

Figure 6. Saturation water vapour anomaly over ice (de-seasonalised, 6-month running mean) calculated from the respective cold point temperatures (10° –10° N) of RC1SD and RC1 simulations. RC1shift: mean cold point temperature of RC1 is shifted to RC1SD mean cold point temperature. The mean cold point temperatures are: RC1SD: 192.1 K, and RC1: 186.0 K, RC1shift: 192.1 K)

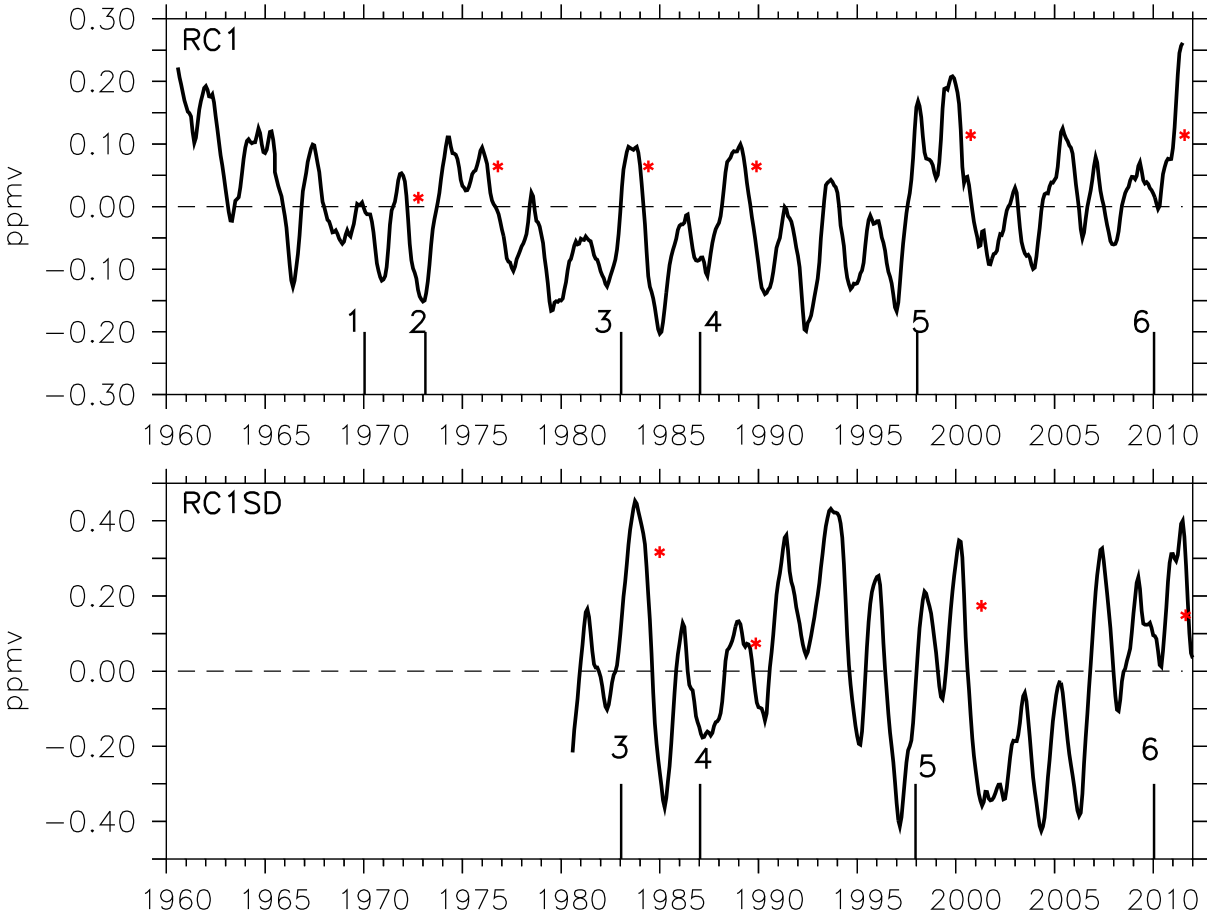

Figure 7. Moisture anomalies in ppmv (detrended, de-seasonalised, 12-months running mean) derived from RC1SD and RC1 simulations at 80 hPa. Black vertical lines mark El Niño events and red asterisks mark the respective subsequent water vapour drop.

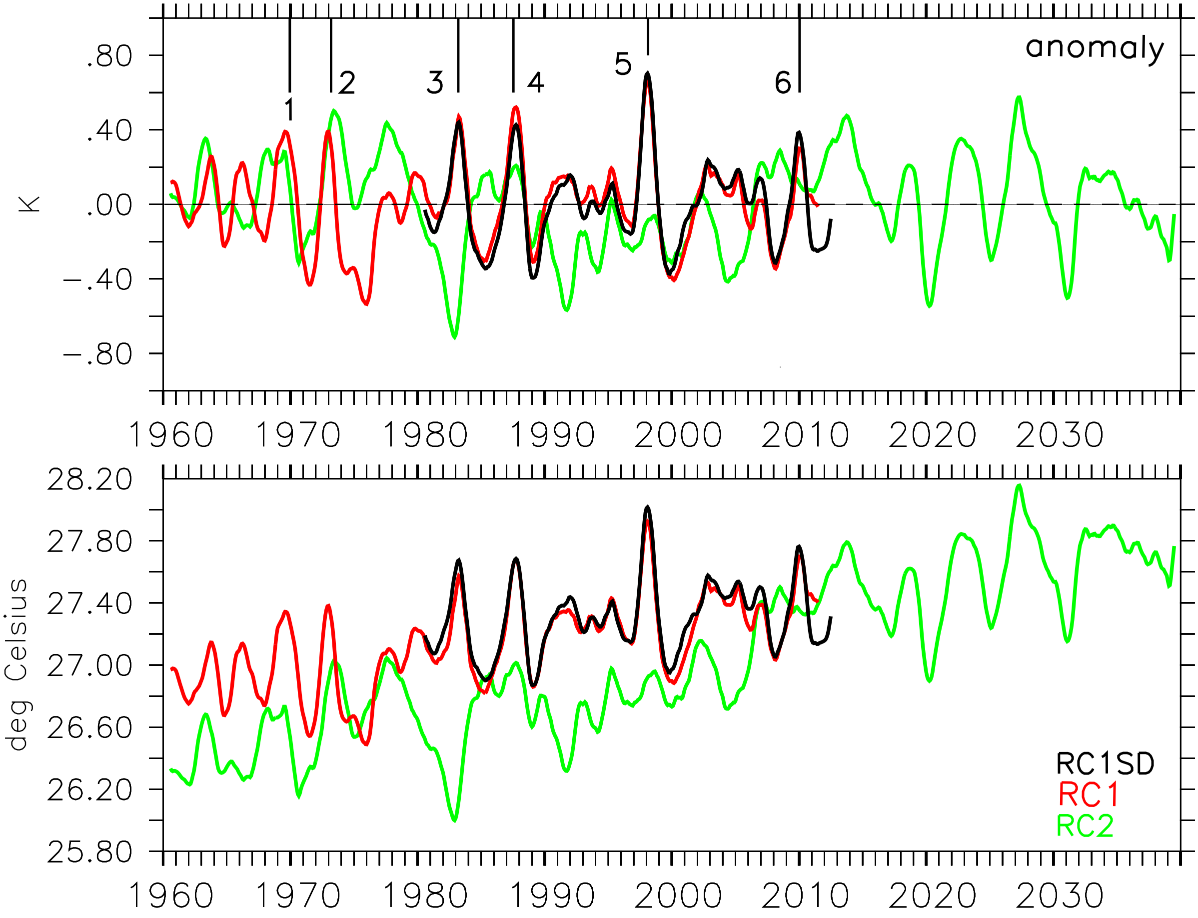

Figure 8. (a) Surface temperature anomaly in the tropical region (10° S–10° N) (de-trended, de-seasonalised, 12-point running mean) for RC1SD (black), RC1 (red) and RC2 (green). Strong El Niño/La-Niña events are labeled. **(b)** Surface temperature (degree Celsius) for RC1SD, RC1 and RC2 (12-point running mean).

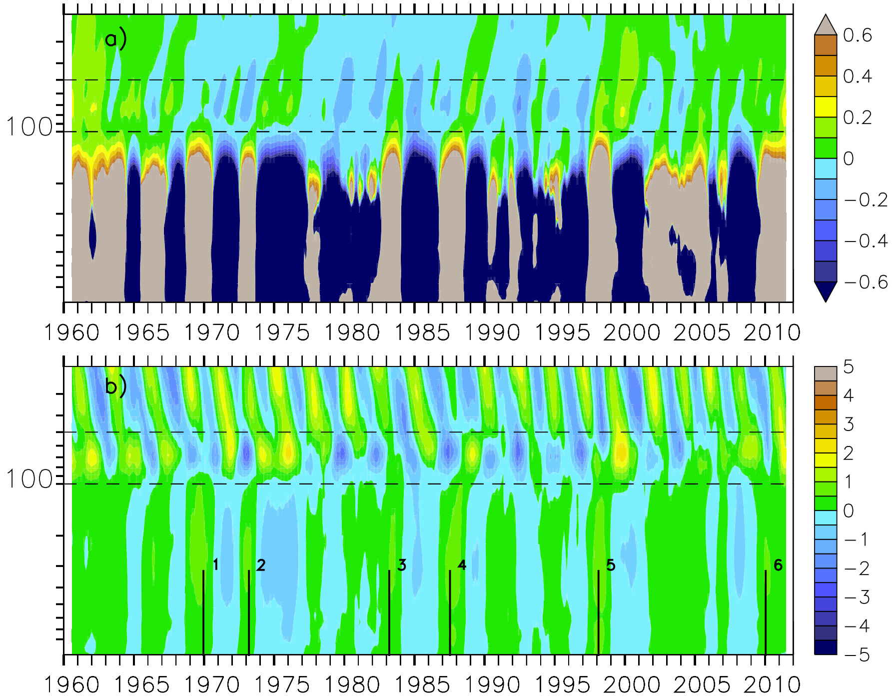

Figure 9. (a) Temporal evolution of moisture anomalies (ppmv). **(b)** Temporal evolution of temperature anomalies (K) in the tropical ~~UTLS~~ region (12 month running mean), derived from the RC1 simulation. Strong El Niño events are labelled. The altitude range covers the pressure levels from 900 to 30 hPa. The dashed lines mark the region between 100 and 50 hPa.

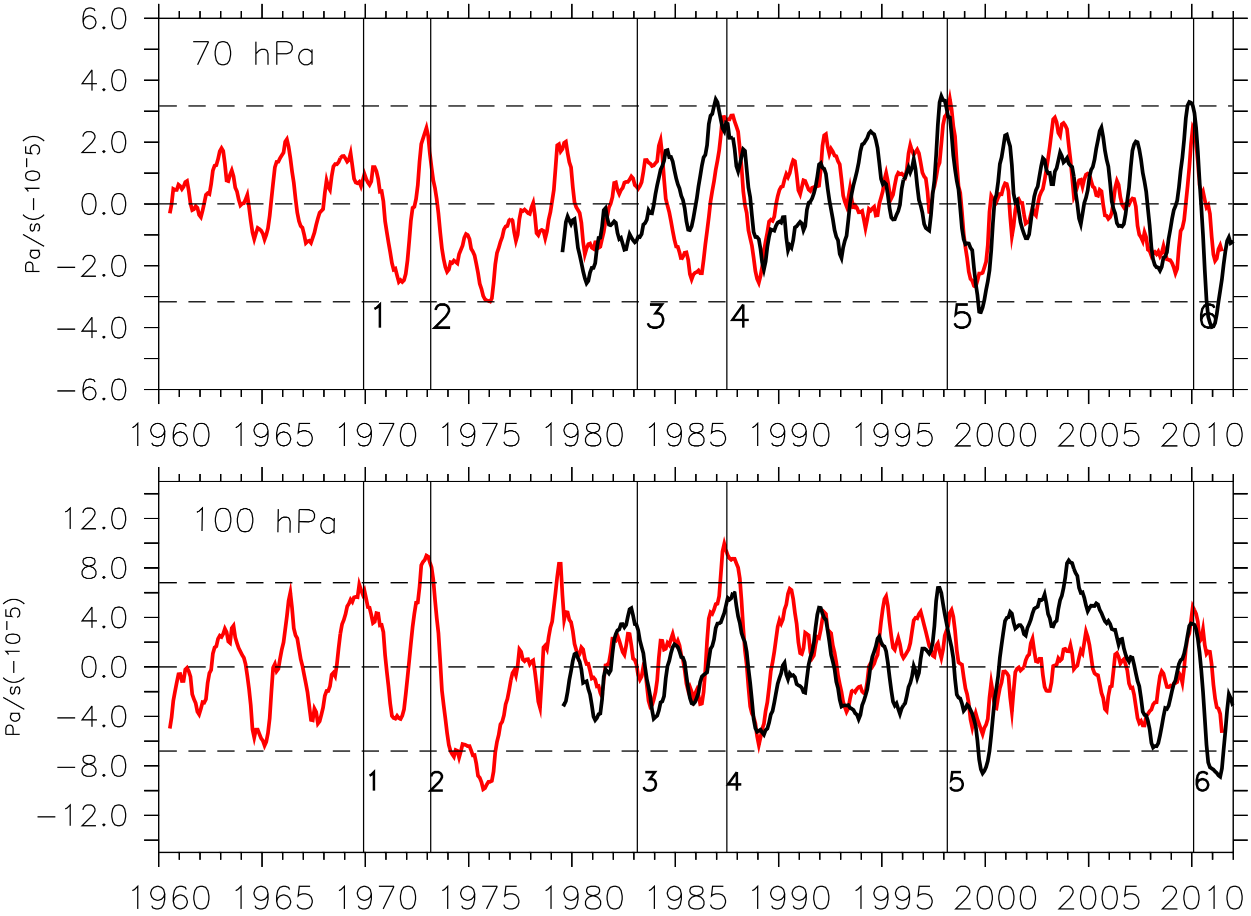

Figure 10. Temporal evolution of tropical upwelling anomalies in the tropics (20° S–20° N) (de-seaonalised and detrended) at 70 and 100 hPa (running mean). Red lines indicate data derived from RC1, black lines from RC1SD. Black dashed lines mark one standard deviation from the unsmoothed RC1SD monthly mean upwelling anomaly values. Black solid vertical lines mark El Niño events.

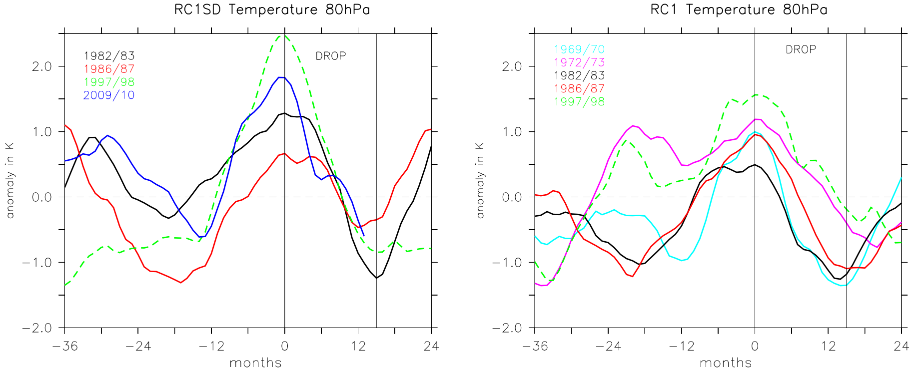

Figure 11. Episode analysis of the zonal mean temperature anomaly at 80 hPa, tropical mean (10° S–10° N), de-seasonalized, de-trended, 12-point running mean, related to 4 different El Niño events in the RC1SD (left) and the RC1 (right) simulation. All episodes are referenced to the beginning of the respective temperature drop.

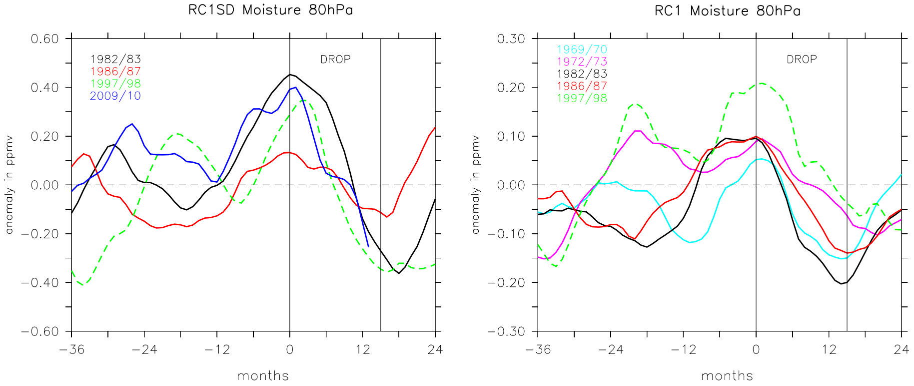

Figure 12. Same as Fig. ~~10~~11, but for the water vapour anomaly. Note that the vertical axis is smaller in the right figure.

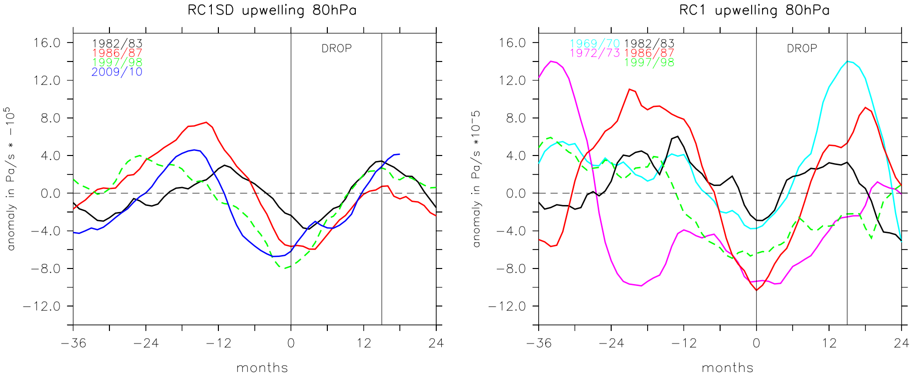

Figure 13. Same as Fig. ~~10~~11, but for tropical upwelling anomaly.

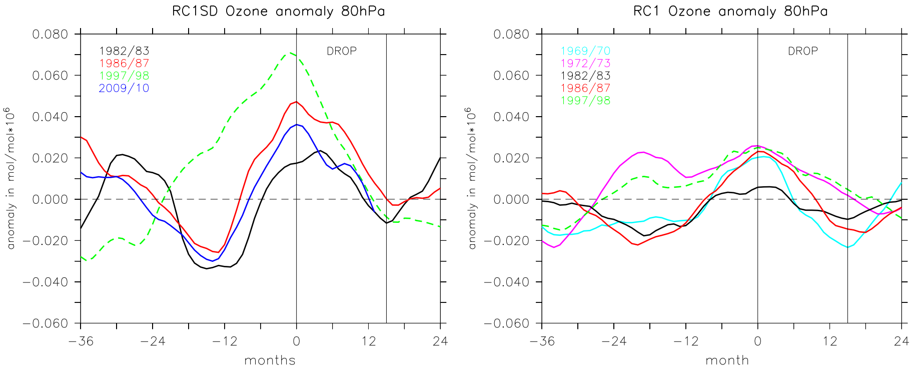

Figure 14. Same as Fig. ~~10~~11, but for the ozone anomaly.

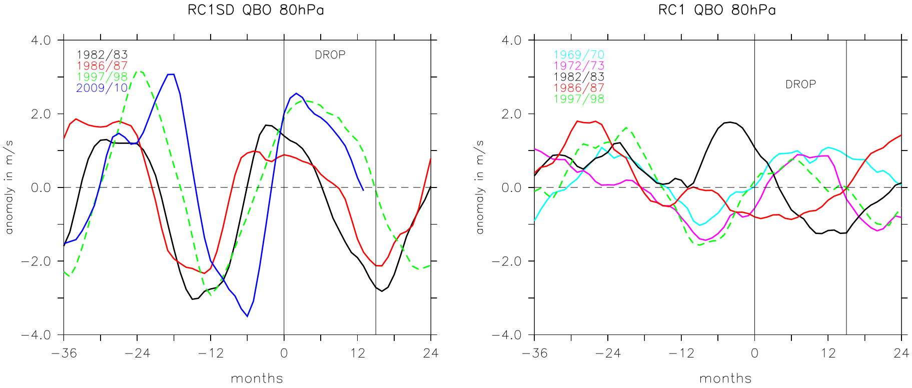

Figure 15. Same as Fig. ~~10~~11, but for the QBO anomaly. The QBO is represented through the zonal wind anomaly.

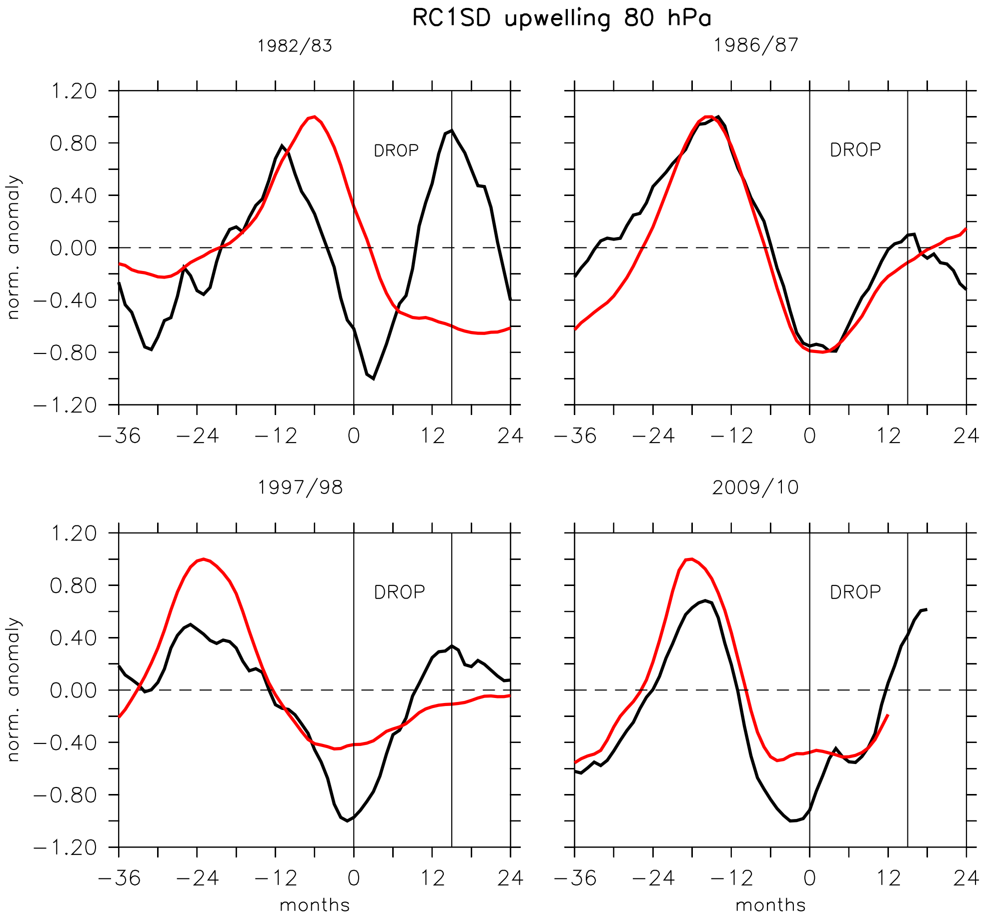

Figure 16. Episode analysis for the normalised ~~(with respect to the maximum absolute value)~~ upwelling anomaly (black) for (10° N–10° S) ~~in relation to~~ at 80 hPa and the max-normalised SST anomaly for the El Niño index 3.4 region (red). The normalised upwelling anomaly is calculated by division of either the maximum or the absolute value of the minimum. For the SSTs it is defined accordingly. Therefore, the results are dimensionless. All episodes are referenced to the beginning of the temperature drop. The drop onsets are accompanied by a negative upwelling anomaly.

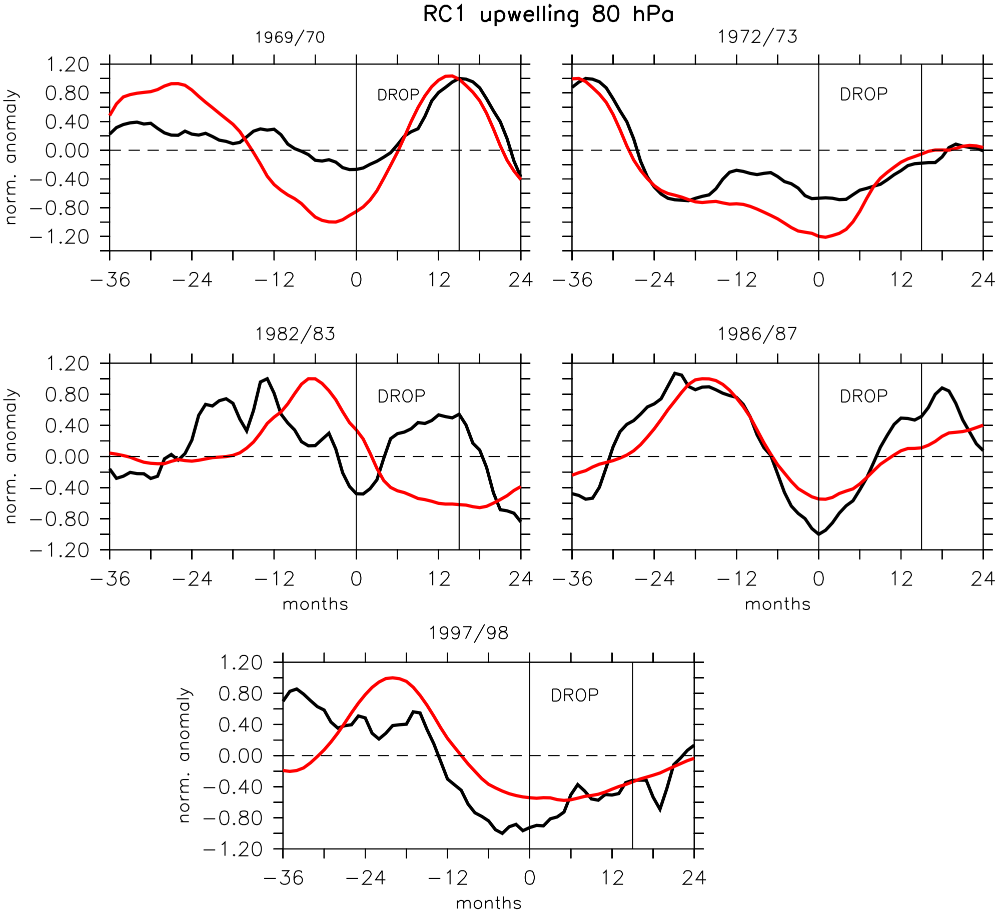

Figure 17. Episode analysis for the normalised ~~(with respect to the maximum absolute value)~~ upwelling anomaly at 80 hPa (black) for (10° ~~S–10~~N–0° ~~N~~S) ~~in relation to~~ and the max-normalised SST anomaly for the El Niño index 3.4 region (red). The normalised upwelling anomaly is calculated by division of either the maximum or the absolute value of the minimum. For the SSTs it is defined accordingly. Therefore, the results are dimensionless. All episodes are referenced to the beginning of the temperature drop. The drop onsets are accompanied by a negative upwelling anomaly.~~The El Nio event in 1972/73 (red line) starts already before the month −36. This event has the largest delay of the drop after the surface temperature maximum for all analysed events.~~

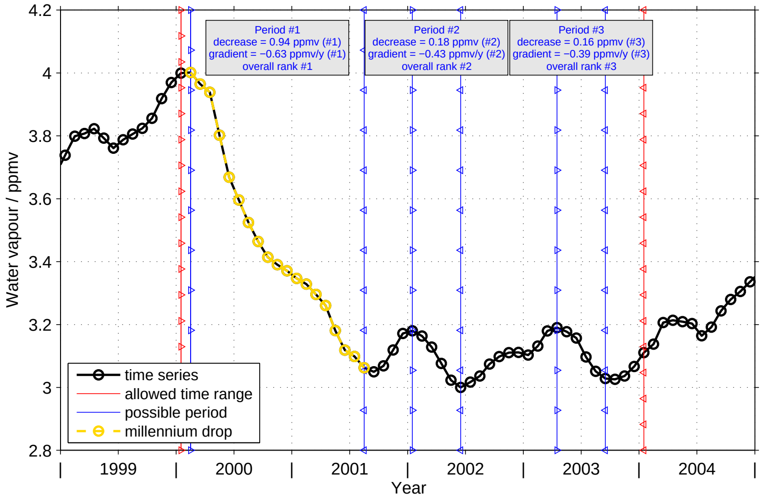

Figure A1. An example of the millennium drop characteristics analysis considering the HALOE/MIPAS time series at 100 hPa at the Equator. The time series is given in black and represents a running mean over one year. The red lines indicate the general time interval where a water vapour drop will be considered. Within this period three periods can be found where water vapour is decreasing. The first period from February 2000 to August 2001 (overplotted in yellow) exhibits both the largest decrease and absolute gradient and is therefore selected as the representative period for the millennium drop.