Response to reviewers

General response

We are very grateful to all three reviewers for their valuable comments. All comments have been carefully considered and necessary changes made. Some of the comments from different reviewers were related and required larger changes to the manuscript, and we therefore list here the major and structural changes made. We feel that these changes have greatly improved the quality and importance of this manuscript.

- We have put more emphasis on changes in water vapour, and particularly changes in integrated water vapour between different climate drivers. This has been done by editing the title, abstract and conclusions, and by reversing the study setup so that changes in water vapour are discussed first, and changes in water vapour lifetime are discussed last. As a consequence, Figures 1-3 are now numbered 4-6 and vice versa.
- A new Section 3.5 has been added. This section includes a discussion of how changes in water vapour lifetime can be interpreted, and what the value of analysing changes in lifetime is. Some of the text that was previously in the introduction has now been included in this section.
- We have highlighted more the advantages of studying water vapour lifetime compared to analysing changes in IWV and P separately, and focused on implications of our results. This is now reflected in Section 3.5 and in the revised abstract and conclusions. A relevant reference, Singh et al. (2016), has been added to the manuscript.

Reviewer #1

The authors present a study of water vapour lifetime, defined as the ratio of IVW/P, from a series climate models for present and future climate. The main driving forces of an increase of the lifetime in a warmer climate are analysed by a range of sensitivity studies. In addition to some major comments, the overall writing can be substantially improved in some sections. I therefore recommend major revisions.

Response: We thank the reviewer for the very useful comments, which have helped improve the manuscript. Each comment has been carefully considered and necessary changes have been made. Please see general response above and point-by-point responses below.

Major comments

1. Abstract: The abstract should be revised to better reflect the actual content of the manuscript.

Response: The abstract has been substantially rewritten and should now well reflect the content and the reversed study setup.

2. Introduction: "The fact that water vapour content increases more than precipitation with rising surface temperatures implies an expected increase in the lifetime (Douville et al., 2002; Held and Soden, 2006; Schneider et al., 2010), and hence a slowing down of the hydrological cycle. However, global-mean precipitation or evaporation fluxes are commonly referred to as the strength of the hydrological cycle, which, in contrast, implies an intensification or acceleration of the hydrological cycle with global warming. Douville et al. (2002) note that this conclusion is somewhat misleading because it suggests faster turnover of water, which is not the case. Hence, when the global hydrological cycle is said to intensify or accelerate with warming, it should be made clear that this refers to the fluxes and not the cycle as a whole" The takeaway from this paragraph is rather confusing. If the fluxes intensify, what is the significance of the overall slowdown? The authors need to resolve the more fundamental underlying issue of explaining the meaning or significance of a residence time change. If what matters for the impact of climate change is the intensification of fluxes, what is the purpose of talking about a slowdown of the hydrological cycle? Maybe there is a clear answer, but it needs to be stated somewhere early on to motivate the reader to adopt the perspective of IWV/P rather than IWV and P individually.

Response: We agree and have moved most of this paragraph to the new Section 3.5 (please see general response). Here, the paragraph has been rewritten to make the takeaway message less confusing. We have also highlighted the importance of the slowdown and included a new and relevant reference (Singh et al., 2016). The end of this new paragraph now reads:

> "While the terminology could be confusing, both the amplification (through intensification of fluxes) and the slowdown (through longer lifetime) are important indicators of changes in the hydrological cycle. The intensification of fluxes means more precipitation globally and higher water availability, with potential consequences for extreme precipitation and water vapour feedback. The slowdown, however, is an important sign of changing precipitation patterns, since water vapour resides in the atmosphere for a longer time before precipitation, and this behaviour cannot be deduced based on analysing IWV and P separately. A longer water vapour lifetime implies an increased length scale of water vapour transport, so that the distance between evaporation and precipitation of moisture is greater, as has been shown in detail by Singh et al. (2016). They further mention implications of this increased transport length scale, such as the expansion of the Hadley circulation and a poleward shift of midlatitude precipitation maximum."

3. Regarding the deep convective mass flux in the tropics: If the motivation of the study is to compare the convective mass flux between the different models, it may be relevant to consider additional quantities, such as convective vs. stratiform precipitation (noting that convective precipitation parameterisations have a large uncertainty and differ substantially between climate models), or the mass flux itself. As the study is designed presently, the mass flux and the implications thereof are rather implicit, and it remains unclear whether this quantity should be considered as an internal model variable or as the actual flux of mass as represented by climate models.

Response: An analysis of the convective mass flux between the different models could provide some interesting results, but is clearly beyond the scope of this study, as the required diagnostics are not available from the simulations. The point on moisture transport is rather mentioned as an example of how WVL is an indicator of changes in dynamical processes in the hydrological cycle. After also considering the comments from the other reviewers (particularly comment no. 3 and 4 of reviewer #3), we have decided to remove the sentences describing the link between WVL and mass flux changes.

4. On pg. 3, L. 10 onward, the authors state that "understanding the WVL has the potential to contribute to improved quantification of the hydrological cycle and its climate-induced changes", based on a previous paragraph about the potential use of isotope composition. However, if one were to investigate the implications of residence time for the stable isotope composition, it would be more meaningful to perform the study using isotope-enabled general circulation models, so it remains unclear how this motivation fits to the present study design. The connection between the cited literature and the topic of the study remain vague and would require further discussion. For example, the residence time definition in Aggarwal et al., 2012, yields values ranging from 1 to 100 days, which are in contrast to the magnitude of residence time changes discussed here. The study of Markle et al, 2018 addresses in particular multi-centennial time scales, and it is not obvious without further discussion if their findings are applicable to the presented sensitivity experiments.

Response: The paragraph has now been moved to the new section 3.5 and made part of a discussion of the value of WVL. We agree that a study using isotope-enabled GCMs would be very interesting and could, in combination with observations, give information that may be used to improve parameterizations of vertical mass-exchange in the GCMs. However, isotope-enabled GCMs are so far limited, both in number of models and in the comprehensiveness of the isotope schemes (Aggarwal et al., 2016), and this makes such a study difficult to conduct. With the design of our study, we are instead able to focus on changes in water vapour and its lifetime for a range of GCMs and sensitivity experiments. Isotope-enabled GCMs are expected to become more common in the future, and we expect that this will increase the value of our work.

It is correct that the lifetimes presented in Aggarwal et al. (2012) (approx. 1-100 days) have a much wider range than in our study. The reason is that we focus on the global- and annual-mean lifetime (around 8 days) and lifetime changes while Aggarwal et al. present daily measurements from individual stations. We would also get a much wider range in the lifetimes from the models if we were to consider daily and local scales. The point is that the correlation between isotopes and water vapour lifetime is valid for all stations/seasons considered in Aggarwal et al., and these stations represent a range of climate regimes, from Addis Ababa in the tropics to Halley Bay in the Antarctic. Therefore, we can deduce that an increase in the global water vapour lifetime strongly indicates a higher heavy isotope ratio. The text specifies that the correlation between WVL and isotope ratio in precipitation is found for daily station measurements (and not necessary globally).

5. Title: See major issue 2 above - what is the significance of the statement that the WVL is increasing? Is the ratio IWV/P an accurate and pointed description for how the hydrolocial cycle will be experienced in the future, given that fluxes will intensify? Consider that you possibly could ease the struggle of motivating this study at present by de-emphasizing the WVL aspects. By essentially reversing the study setup, you could talk about IWV and P changes and their sensitivities first, and finally concluding by discussing to what extend the WVL can provide additional information or be mistaken as a confusing message (which is now implicitly stated in the introduction).

Response: This is a good idea. We agree and have now reversed the study setup, included a discussion of the potential importance of WVL, and changed the title (please see general response). The title is now "Water vapour adjustments and responses differ between climate drivers".

6. Now it is very difficult to compare the results from individual models in Fig. 1. Consider plotting at least panel a on a horizontal scale that emphasizes the differences, rather than bars for example as a set of box and whisker plots. Regarding the large number of individual models in panels a-b, it may be more useful to present results as histograms and move the individual model perspective into a supplement figure.

Response: We agree that it is difficult to compare the models in Fig. 1a and the rightmost plot in Fig. 1b (now Fig. 4a-b) but we would like to keep the individual models in the figure in the main manuscript. We have now narrowed the scale in two of the plots (WV lifetime and WV lifetime sensitivity), and this made it much easier to compare results from the different models.

7. Conclusions: "If emissions evolve according to a business-as-usual pathway, the WVL could increase by 25% by the end of the 21st century because of the large expected temperature changes, and despite the projected aerosol emission reductions leading to a lower water vapour lifetime sensitivity." What are the implications of that conclusion? Does it actually matter if the WVL increases by 25%, what would be the consequences? The question if the residence time is a useful indicator to measure aspects of climate models remains ultimately unanswered. What do the differences between model mean states and their sensitivities signify? Is there actual value in using the residence time over inspecting total column water and precipitation/evaporation separately? Maybe that (open) question should be put into the focus of the introduction and answered in the conclusions. This is also related to major issue 2 and 5. Furthermore, given that models and observational estimates of the residence time disagree substantially, even on the same magnitude as the absolute changes predicted here (Trenberth, 2011; van der Ent and Tuinenborg, 2017), what is the overall uncertainty of these predicted changes? How do we know that the differences only can be interpreted meaningfully?

Response: The conclusions have now been rewritten and a new Section 3.5 on the potential importance of WVL has been added (please see general response). Regarding the modelled vs. observed water vapour lifetimes, a discussion of uncertainties has been added to the new Section 3.5, also accounting for comment no. 4 of reviewer #3:

> "Among the most important caveats with our WVL findings is that climate models have known deficiencies, such as problems with representing vertical convective mass fluxes (Bony et al., 2015), surface moisture fluxes and entrainment/detrainment rates. Part of the reason is that GCMs have relatively coarse resolution and many processes, such as convection, need to be parameterized. However, we use a large multi-model ensemble with horizontal resolutions ranging from 1.4°×1.4° (MIROC-SPRINTARS) to 2.8°×2.8° (CanESM2), and model spread in future WVL change is lower (relative standard deviation (RSD) of 22%) than for, e.g., precipitation change (RSD of 30%) (Fig. 4). Nevertheless, compared with present-day WVL from reanalysis, the climate models have too short WVLs (Trenberth et al., 2011; see also Section 3.3). Kao et al. (2018) compared trends in precipitation and column water vapour data from 13 CMIP5 models with observational datasets and also found differences in the moisture recycling rate between observations and the CMIP5 models, and concluded that this discrepancy was caused by relatively poor simulations of precipitation. However, the long-term trend and inter-annual variability of column water vapour was very well captured by nearly all models."

8. Pg. 8, L. 19: "a longer WVL implies a higher heavy isotope ratio ... and in turn indicates a larger fraction of convective vs. stratiform" - This conclusion seems to be based now on (weak) correlations between a set of isotope measurements in surface precipitation and climate variables. I suggest that a reliable extrapolation to future climate be based on the underlying physical processes instead.

Response: The conclusions have been rewritten and the connection between isotopes and precipitation type has been removed.

Minor comments

Sec. 3.2 should in part be within methods section.

Response: We agree that part of this section could belong to the methods section. However, we think that it is easier for the reader to interpret the results when explained in relation to the figures, and therefore prefer to present Figures 5-6 at the same time as explaining the methodology used.

Sec. 3.4 needs a transition sentence from previous section/paragraph.

Response: This has now been added (Section 3.4 is now Section 3.2):

> "In order to explore reasons for differences in IWV between the drivers, we compare vertical profiles of specific and relative humidity and temperature for each of the climate drivers (Fig. 2)."

Pg. 2, L. 24: "although some argue for a substantially shorter lifetime of 4-5 days" - I believe the discussion in the literature argues revolves around a consideration of whether IWV/P accurately represents how long water resides in the atmosphere - rephrase.

Response: Good point. The sentence has now been changed to:

> "Studies identify a global-mean water vapour lifetime of 8-9 days for present-day conditions (van der Ent and Tuinenburg, 2017), although some argue that water only resides in the atmosphere for about 4-5 days (Laderach and Sodemann, 2016)."

Pg. 3, L. 21: Some details to this long list of referenced studies should be given.

Response: We have now reduced the long list of references and given some details to two of the studies. It now reads:

> "… but most of these studies have focused mainly on precipitation (e.g., Andrews et al., 2010; Bala et al., 2010; Xie et al., 2013; Samset et al., 2016). Recently, new insight into precipitation changes has been given by analysing the atmospheric energy budget (Richardson et al., 2018b) and by the use of radiative kernels (Myhre et al., 2018a)."

At numerous locations throughout the manuscript, the writing is unclear. The reasons are varied, but often two or more ideas and arguments are complied into one sentence. Sometimes, within one sentence it is referred to several figures for different aspects. Below I list some of the places were writing can be substantially improved by careful editing:

Response: We have now improved the writing in several of the places mentioned:

Pg. 3, L. 9 **Response:** Sentence removed because of other comments.

Pg. 5, L. 13 **Response:** Sentence split in two.

Pg. 5, L. 22 **Response:** Sentence split in two.

Pg. 6, L. 2 **Response:** Sentence slightly rewritten.

Pg. 6, L. 31 **Response:** Sentence rewritten.

Pg. 7, L. 1 **Response:** Sentence split in two.

Pg. 7, L. 15-29 **Response:** Many of the sentences rewritten and/or split in two.

Pg. 8, L. 18-19 **Response:** Sentence removed because of other comments.

Reviewer #2

A catalog of idealized climate model experiments to assess precipitation response to different radiative forcings is here exploited to investigate how the atmospheric lifetime of water vapor is affected. This is diagnosed as integrated water vapor divided by precipitation rate which effectively characterizes how long it would take to precipitate out all the water vapor in the atmospheric column. Although it is obvious, based on past research, that this lifetime should increase, since thermodynamic and energetic constraints cause water vapor to increase at a faster fractional rate than precipitation, this work provides a useful investigation into the differences in this response between forcing agents, relating to fast adjustments and slow response to temperature, and further explores regional contributions. The most novel aspect, in my view, may be demonstrating how water vapor adjustments and responses differ between forcing agents. I recommend emphasizing this and I consider that this work merits publication following consideration of the suggestions below including the possibility of comparing with observed responses.

Response: We thank the reviewer for the very useful comments, which have helped improve the manuscript. Each comment has been carefully considered and necessary changes have been made. Please see general response above and point-by-point responses below. In particular, we have now emphasized more the different water vapour adjustments. This has been done by reversing the study setup, as suggested by Reviewer #1, so that water vapour changes are discussed first and the water vapour lifetime changes are discussed last.

Specific points

1) p.1, L24-26: the first 2 lines do not make much sense to me in the abstract and have marginal relevance to the results. Something outlining what water vapor lifetime is and why it is important would be more useful I think.

Response: The abstract has been substantially rewritten, and the first two lines have been removed, to highlight more the different water vapour adjustments rather than the lifetime differences.

2) p.1, L29: "projected" –> "simulated" (1986-2005 is not a projection)

Response: Corrected.

3) p.1, L31: "slows down the hydrological cycle" - if precipitation is increasing, the hydrological cycle could be thought of as speeding up since water is fluxing between atmosphere and surface more quickly so I suggest removing this confusing terminology.

Response: Removed.

4) p.1, L34 - "fast responses" should be clarified

Response: This has now been defined by changing the beginning of the sentence to:

> "Fast responses, which include the initial radiative effect and rapid adjustments to an external forcing…"

5) p.2, L18-20 - Is there a difference between water vapor residence time, lifetime and recycling rate (e.g. Li et al. 2011; Kao et al. 2018; van der Ent & Tuinenburg (2017); Allan & Zveryaev (2011) IJOC http://doi.org/10.1002/joc.2070). This could be clarified. Regional responses in water vapor lifetime may be misleading since the precipitation can result from transport of moisture from outside of the region and so not really reflect recycling rate within a box

Response: This has now been clarified and the text now reads:

> "The water vapour lifetime is also known as the residence time and is commonly expressed as the ratio between the time-averaged global-mean integrated water vapour and precipitation (Trenberth, 1998; Douville et al., 2002; Bosilovich et al., 2005; Schneider et al., 2010; Kvalevåg et al., 2013). The water vapour recycling rate is the inverse of the lifetime (P/IWV) and most often expressed regionally rather than globally (Li et al., 2011; Kao et al., 2018), in which another factor is how much of the regional precipitation results from transport of water vapour from outside the region."

6) p.4 L26 - RCP8.5 is a high emissions scenario but cannot simply be described as a business as usual pathway.

Response: This has now been changed to "a high emission pathway".

7) p.5, L15 - is an increase in WVL detectable in the historical period 1986-2005? Using trends from Allan et al. (2014) Surv. Geophys. http://doi.org/10.1007/s10712-012-9213-z for 1988-2008 and assuming WVL=8.9 days:

WVLS = WVL((1/IWV)(dIWV/dT) - (1/P)(dP/dT)) = 8.9x(0.064-0.028) = 0.32 days/K,

which is smaller than simulated perhaps due to additional noise from internal variability (with a large uncertainty). Alternatively:

dWVL/dt=WVL((1/IWV)(dIWV/dt) - (1/P)(dP/dT)) = 8.9x(0.0084 - 0.0018) = 0.06 days/decade (rather small)

Response: We agree that it would be good to compare modelled WVL increases to observed values over the historical period, but the period 1986-2005 is short and likely heavily influenced by natural variability. What we show in the manuscript are modelled values between pre-industrial times (1850-1869) and recent times (1986-2005). Ideally, we should have had observed values between the same two time periods, but observations are too sparse to derive this.

8) Fig.2 - additional annotation to show the meaning of dark/light bars in (a) and (b) would help the reader.

Response: We agree and have now included legends both in plot (a) and (b) to show the meaning of the dark/light bars.

9) Fig.3 - it is not clear from the scattering aerosol bar how the light and dark part contribute. Perhaps the total can be distinguished as a thick horizontal line or symbol (at the top of most bars but at -0.01 for scattering aerosol).

Response: Good suggestion. We have now added a symbol to show the total, and included this in the legend.

10) Fig. 4 - it would be more informative for me to group all the WV, E and P lines into 3 separate plots so that they can be compared across forcing agents. Are zonal values calculated using zonal dT or global dT?

Response: Both ways of presenting the results have their advantages, but we agree that comparing the results across forcing agents are more informative and have changed the plot accordingly. In addition, we included a similar plot for the slow response, so that readers can compare differences between slow and total responses without referring to the supplementary. However, we prefer to keep the original Supplementary Figure S2 unchanged so that the results also can be compared across variables (it also makes less sense to compare across forcing agents when the results have not been normalized with the global dT). With the new plots, it does not make sense to include the global mean values next to each line (the plot would be too busy), so we have added a Table 1 with these values and edited the text accordingly. Zonal values are normalized using global dT – this has now been specified in the figure caption.

11) p.7, L4-6 seems an important result and some more mechanistic discussion of this would be useful. Is the SO4 slow response small due to forcing predominantly affecting land which has less moisture availability? Or does this relate to the vertical temperature changes and the temperature dependence of the Clausius Clapeyron equation? Does the low level relative humidity increase explain the large fast response in BCx10 and why? On the other hand is this all explained by land-ocean temperature responses as implied? This could be summarized in the conclusions along with implications (why do we care?).

Response: This is an interesting point and we agree that further discussion of these results would be useful. The small SO4x5 slow response and the large Sol+2% slow response is related to the vertical temperature changes and the temperature dependence of the Clausius Clapeyron equation. This can be seen in Fig. S7 and we have added/modified the text to explain this (a sentence has also been added in the conclusions to highlight the different slow responses between drivers):

> "Changes in specific humidity profiles for the slow response (Fig. 2b) show that the assumption of constant relative humidity does hold. When normalized with ΔT_s, the specific humidity profiles are similar between the drivers, with a small exception for SO4x5, which shows a smaller increase throughout the troposphere. One reason is that SO4x5 is the driver that gives the least change in the temperature profile (and lapse rate up to 300 hPa) when normalized with surface temperature change (Fig. S7, lower left), and therefore the least change in the water vapour availability. It is also worth noting the strong difference between land and sea in the temperature change profile for this driver. The small increase in vertical temperature profiles compared to the other drivers could explain why SO4x5 has the smallest slow IWV response (Table 1). Sol+2%, which have the largest slow IWV response, has the second strongest increase in temperature profile per K surface temperature change (Fig. S7). BCx10 gives the strongest increase in atmospheric temperature, but a decrease in relative humidity, especially over land (Fig. S7), leads to a discrepancy between the actual specific humidity change and the temperature-driven change between the surface and 800 hPa (Fig. 2b)."

The low-level RH increase for BCx10 certainly contributes to the large fast response in IWV for this driver, as can be seen from Fig. 2a. However, it is difficult to know from the current simulations how much this contributes compared to the contribution due to warming of the atmospheric column. We have added/modified the text as follows:

> "In contrast to the CO2x2 experiment, BCx10 mostly yields a small increase in relative humidity (Fig. 2c), especially close to the surface, and therefore the specific humidity change for BCx10 is larger than the temperature-induced change throughout most of the troposphere (Fig. 2a). This low-level relative humidity increase contributes to the large fast IWV response for BCx10 (Table 1). Additional contributions come from atmospheric solar absorption due to BC, which leads to rapid atmospheric temperature increase (Fig. 2d) and therefore increased water vapour availability."

For CO2x2, the situation is opposite (RH decrease leading to small IWV fast response) and we have added a sentence to point this out:

> "This relative humidity decrease, and thus specific humidity decrease, contributes to the small fast IWV response for CO2x2 (Table 1)."

12) p.7, L26 "small exception for SO4x5." Please be more explicit in what is meant.

Response: The end of the sentence has now been expanded to explain this:

> "…, with a small exception for SO4x5, which shows a smaller increase throughout the troposphere."

13) P.7, L30 - there is very little mention of Figure 6. Either this can be removed or a little more discussion of the Figure panels included.

Response: The discussion of Fig. 6 (now Fig. 3) gives new insight into the fast vs. slow response of near-surface relative humidity to global warming. Therefore, we would like to keep the figure and have now included a bit more discussion and a sentence about the findings in the conclusions.

14) Fig.5 - dashed=Clausius Clapeyron in the legend would help. It is difficult to see dashed and solid in (b) so perhaps this can be replaced with a relative humidity change plot.

Response: The legend has been updated to show the meaning of the dashed lines. Regarding Fig. 5b (now Fig. 2b), we prefer to keep the specific humidity plot (a RH plot is shown in Fig. S7 in the Supplementary), but we have included an inset plot, which is zoomed in over the 700-1000 hPa region and shows the differences between dashed and solid lines much better.

15) p.8 (Conclusions) - what is the significance of changes in water vapor lifetime above the differing fractional responses of P and IWV and implications for changes in the tropical circulation mass flux and precipitation intensity distribution, which is well known? Emphasizing what is novel will help increase the impact of this work.

Response: The conclusions have now been rewritten with a stronger focus on the changes in integrated water vapour, and with more emphasis on the implications of changes in the water vapour lifetime (please also see general response).

Reviewer #3

A number of climate model simulations from the CMIP5 intercomparison are used in order to estimate the change in water vapor lifetime with climate change. Water vapor lifetime is shown to increase by about 2 days in the next 100 years. Contributions from different climate drivers are analyzed using simulations from the Precipitation Driver Response Model Intercomparison Project (PDRMIP). Estimates for the combination of all drivers for the past are shown to be consistent with CMIP5 results. Changes in WVL are split into fast and slow responses. Changes in IWV per surface temperature change of different climate drivers are compared to the theoretical 7%/K increase that is expected assuming relative humidity to stay constant. BC shows the strongest increase in water vapor lifetime. The findings are very interesting but the paper is too concise to appreciate results fully. More information, explanations for assumptions and discussion needs to be added.

Response: We thank the reviewer for the very useful comments, which have helped improved the manuscript. Each comment has been carefully considered and necessary changes have been made. Please see point-by-point responses below (and general response above).

1. You calculate contributions from changes in IWV and P to ΔWVL by calculating the ΔWVL twice, with the IWV and P terms held constant one at a time (page 5 line 9-10). This means that you neglect nonlinear terms which needs to be mentioned. It is difficult to judge from the material presented if this is a good assumption, since figure 2a gives the fast WVLS and figure 2b the WVL itself. I suggest plotting the overall WVL change in figure 2b additionally.

Response: This is a good point. The contribution to the fast *ΔWVL* from changes in each of IWV and P is calculated for each model as follows (using CO2x2 as an example):

$$\Delta WVL_{IWV} = \frac{IWV_{CO2x2}}{P_{base}} - \frac{IWV_{base}}{P_{base}} = WVL_{IWV,CO2x2} - WVL_{base}$$

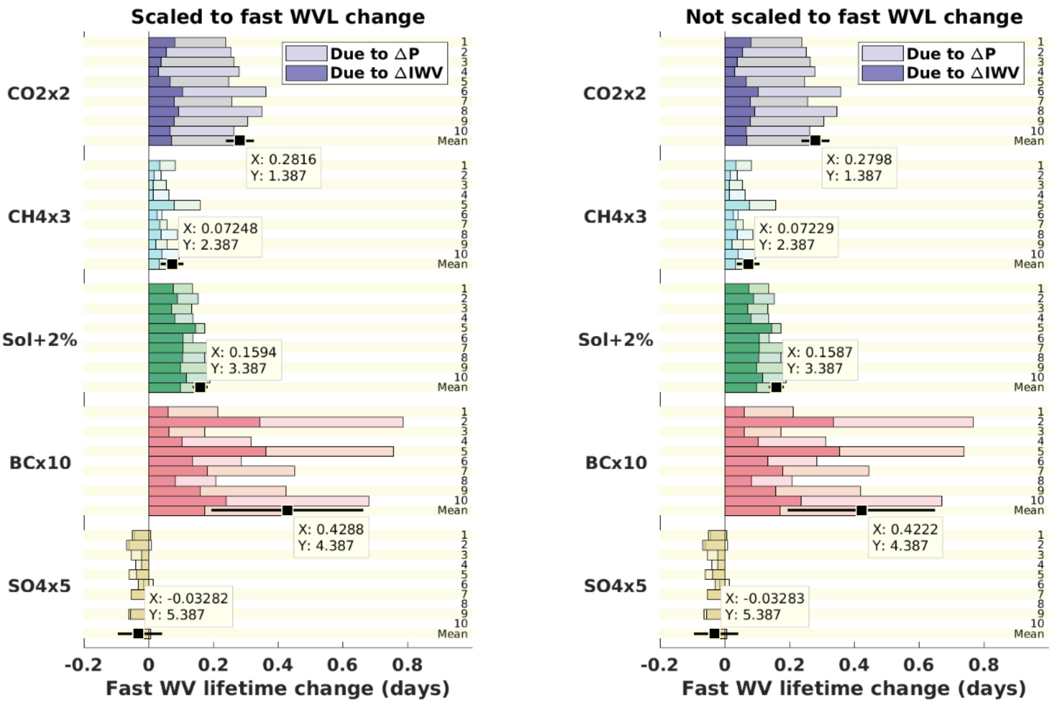
$$\Delta WVL_{P} = \frac{IWV_{base}}{P_{CO2x2}} - \frac{IWV_{base}}{P_{base}} = WVL_{P,CO2x2} - WVL_{base}$$

In Fig. 2b (now Fig. 5b), the two terms have been scaled so that the sum of $\Delta WVL_{IWV,scaled}$+ $\Delta WVL_{P,scaled}$ equals the actual fast *ΔWVL:*

$$\Delta WVL_{IWV,scaled} = \Delta WVL_{IWV} \frac{\Delta WVL}{\Delta WVL_{IWV} + \Delta WVL_{P}}$$

$$\Delta WVL_{P,scaled} = \Delta WVL_{P} \frac{\Delta WVL}{\Delta WVL_{IWV} + \Delta WVL_{P}}$$

To test how good our assumption is, we need to check whether ΔWVL_{IWV}+ ΔWVL_{P} is notably different from *ΔWVL*. The following figure shows $\Delta WVL_{IWV,scaled}$+ $\Delta WVL_{P,scaled}$ (left plot) vs. ΔWVL_{IWV}+ ΔWVL_{P} (right plot) for each model and driver:



The plots show that differences are very small. In the model mean, the largest difference is for BCx10: (0.4288-0.4222 days)/0.4222 days = 1.56%. Based on this, the following sentence has been added at the end of Section 2.3 in the manuscript:

> "This assumption involves nonlinear terms, but the model-mean difference between the actual *ΔWVL* and the sum ΔWVL_{IWV}+ΔWVL_{P} is less than 2% for all drivers."

2. Could you please give an explanation why it makes sense to scale ΔWVL with RF (page 6 line 17).

Response: We have added a sentence to clarify this:

> "By scaling the fast ΔWVL with RF, we are able to estimate the historical contribution to ΔWVL from each driver, in a similar way to what has been done before for other quantities (e.g., sensible heat flux changes in Myhre et al. (2018b))."

3. Water vapor lifetime is increased which is supposed to be connected with a decrease in vertical mass fluxes. But a decrease in vertical mass fluxes should be connected with a moistening of the lower troposphere which appears not to be the case. Is there an explanation for this behavior?

Response: An analysis of the convective mass flux in relation to the water vapour lifetime could provide some interesting results, but is clearly beyond the scope of this study, as the required diagnostics are not available from the simulations. The point on moisture transport is rather mentioned as an example of how WVL is an indicator of changes in dynamical processes in the hydrological cycle. After also considering the comments from the other reviewers (particularly major comment no. 3 of reviewer #1), we have decided to remove the sentences describing the link between WVL and mass flux changes.

4. Changes of water vapor lifetimes are connected with vertical mass fluxes. For the analysis of WVL changes you use climate models which have problems representing those mass fluxes. In particular convective mass fluxes are known to be a source of large uncertainty within climate models. Surface moisture fluxes may also be problematic. Vertical profiles of humidity may be strongly dependent on entrainment and detrainment rates which are highly problematic. It would be good to add a discussion about how dependent results are on known deficiencies in global models. Original model resolutions need to be given.

Response: A discussion of uncertainties has been added to the new Section 3.5, also accounting for major comment no. 7 of reviewer #1:

> "Among the most important caveats with our WVL findings is that climate models have known deficiencies, such as problems with representing vertical convective mass fluxes (Bony et al., 2015), surface moisture fluxes and entrainment/detrainment rates. Part of the reason is that GCMs have relatively coarse resolution and many processes, such as convection, need to be parameterized. However, we use a large multi-model ensemble with horizontal resolutions ranging from 1.4°×1.4° (MIROC-SPRINTARS) to 2.8°×2.8° (CanESM2), and model spread in future WVL change is lower (relative standard deviation (RSD) of 22%) than for, e.g., precipitation change (RSD of 30%) (Fig. 4). Nevertheless, compared with present-day WVL from reanalysis, the climate models have too short WVLs (Trenberth et al., 2011; see also Section 3.3). Kao et al. (2018) compared trends in precipitation and column water vapour data from 13 CMIP5 models with observational datasets and also found differences in the moisture recycling rate between observations and the CMIP5 models, and concluded that this discrepancy was caused by relatively poor simulations of precipitation. However, the long-term trend and inter-annual variability of column water vapour was very well captured by nearly all models."

~~Increased water vapour lifetime due to global warming~~

Water vapour adjustments and responses differ between climate drivers

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Abstract. ~~The relationship between changes in integrated water vapour (IWV) and precipitation can be characterized by quantifying changes in atmospheric water vapour lifetime. Precipitation isotope ratios correlate with this lifetime, a relationship that helps understand dynamical processes and may lead to improved climate projections. We investigate how water vapour and its lifetime respond to different drivers of climate change, such as greenhouse gases and aerosols. Results from 11 global climate models have been used, based on simulations where CO_2, methane, solar irradiance, black carbon (BC), and sulphate have been perturbed separately. A lifetime increase from 8 to 10 days is projected between 1986-2005 and 2081-2100, under a business-as-usual pathway. By disentangling contributions from individual climate drivers, we present a physical understanding of how global warming slows down the hydrological cycle, due to longer lifetime, but still amplifies the cycle due to stronger precipitation/evaporation fluxes. The feedback response of IWV to surface temperature change differs somewhat between drivers. Fast responses amplify these differences and lead to net changes in IWV per degree surface warming ranging from 6.4±0.9%/K for sulphate to 9.8±2%/K for BC. While BC is the driver with the~~

~~strongest increase in IWV per degree surface warming, it is also the only driver with a reduction in precipitation per degree surface warming. Consequently, increases in BC aerosol concentrations yield the strongest slowdown of the hydrological cycle among the climate drivers studied, with a change in water vapour lifetime per degree surface warming of 1.1±0.4 days/K, compared to less than 0.5 days/K for the other climate drivers (CO_2, methane, solar irradiance, sulphate).~~

Water vapour in the atmosphere is the source of a major climate feedback mechanism and potential increases in the availability of water vapour could have important consequences for mean and extreme precipitation. Future precipitation changes further depend on how the hydrological cycle responds to different drivers of climate change, such as greenhouse gases and aerosols. Currently, neither the total anthropogenic influence on the hydrological cycle, nor those from individual drivers, are constrained sufficiently to make solid projections. We investigate how integrated water vapour (IWV) responds to different drivers of climate change. Results from 11 global climate models have been used, based on simulations where CO_2, methane, solar irradiance, black carbon (BC), and sulphate have been perturbed separately. While the global-mean IWV is usually assumed to increase by ~7% per degree K surface temperature change, we find that the feedback response of IWV differs somewhat between drivers. Fast responses, which include the initial radiative effect and rapid adjustments to an external forcing, amplify these differences. The resulting net changes in IWV range from 6.4±0.9%/K for sulphate to 9.8±2%/K for BC. We further calculate the relationship between global changes in IWV and precipitation, which can be characterized by quantifying changes in atmospheric water vapour lifetime. Global climate models simulate a substantial increase in the lifetime, from 8.2±0.5 to 9.9±0.7 days between 1986-2005 and 2081-2100 under a high emission scenario, and we discuss to what extent the water vapour lifetime provides additional information compared to analysis of IWV and precipitation separately. We conclude that water vapour lifetime changes are an important indicator of changes in precipitation patterns and that BC is particularly efficient in prolonging the mean time, and therefore likely the distance, between evaporation and precipitation.

1 Introduction

Water vapour is the largest contributor to the natural greenhouse effect and the source of a major climate feedback mechanism (Boucher et al., 2013). ~~Changes in the hydrological cycle will have widespread consequences for humanity, e.g., through changing precipitation patterns and extremes.~~ The global-mean integrated water vapour (IWV) is found to increase by around 7%/K both in models (Held and Soden, 2006; O'Gorman and Muller, 2010) and observations (Wentz et al., 2007; O'Gorman et al., 2012), consistent with the rate of change of saturation vapour pressure with temperatures representative of the lower troposphere and constant relative humidity (Allen and Ingram, 2002; Trenberth et al., 2003; Held and Soden, 2006). Hence, recent observed moistening trends have been attributed to human activities (Santer et al., 2007; Chung et al., 2014).

In contrast to the expected increase in IWV, models project that global-mean precipitation will only rise by 1-3% per degree of surface warming, due to energetic constraints (Allen and Ingram, 2002; Held and Soden, 2006; O'Gorman et al., 2012).

Extreme precipitation events, however, are likely to increase with the availability of water vapour (Allen and Ingram, 2002) (at around 7%/K), but large uncertainties exist due to non-thermodynamic contributions (O'Gorman and Schneider, 2009; O'Gorman, 2015). Changes in the hydrological cycle will have widespread consequences for humanity, e.g., through changing precipitation patterns and extremes.

The relationship between changes in IWV and precipitation (*P*) can be most easily examined by computing changes in atmospheric water vapour lifetime (*WVL*). The WVL then provides information on the extent to which this relationship is dependent on both the forcing mechanism and timescales of response, and the extent to which there is inter-model agreement on this relationship. The water vapour lifetime, or moisture residence time, is commonly expressed as the ratio between the time-averaged global-mean integrated water vapour and precipitation . Studies identify a lifetime of 8-9 days for present-day conditions , although some argue for a substantially shorter lifetime of 4-5 days . A historical increase in WVL is found from both models (Bosilovich et al., 2005; Kao et al., 2018) and observations (Li et al., 2011; Kao et al., 2018). The fact that water vapour content increases more rapidly than precipitation with rising surface temperatures implies an expected increase in the lifetime , and hence a slowing down of the hydrological cycle. However, global-mean precipitation or evaporation fluxes are commonly referred to as the strength of the hydrological cycle, which, in contrast, implies an intensification or acceleration of the hydrological cycle with global warming . note that this conclusion is somewhat misleading because it suggests faster turnover of water, which is not the case. Hence, when the global hydrological cycle is said to intensify or accelerate with warming, it should be made clear that this refers to the fluxes and not the cycle as a whole. Here we adopt the terminology from , and use the term amplification to indicate an increase in precipitation and evaporation rather than acceleration (which implies a decreased lifetime) of the hydrological cycle.

The WVL is a fundamental component of the hydrological cycle and is useful for studying how dynamical processes in the hydrological cycle are altered due to climate change . For instance, potential increases in water vapour lifetime (expressed as $WVL=IWV/P$) imply that the moisture transport from the atmospheric boundary layer to the free troposphere must decrease, since the vertical moisture transport (M) is governed by $M=P/q$, where q is specific humidity in the boundary layer , assuming that changes in q and IWV with temperature are proportional (some differences exist). A direct consequence of this is a weakening of the atmospheric circulation in the tropical Pacific, known as the Walker circulation, and this weakening is found both in observations and models . Stable water isotopes provide valuable knowledge on the evaporation and condensation history of atmospheric moisture, and more specifically on, e.g., proportions of convective and stratiform precipitation (Aggarwal et al., 2016) and past variability in high-latitude aerosol abundance (Markle et al., 2018). A positive correlation between WVL and stable isotope ratio in precipitation has been found from daily measurements at stations representing a range of climate regimes (Aggarwal et al., 2012), and better diagnostics of the impact of WVL on isotopes have been called for (Dee et al., 2018). It is suggested that the relationship between isotope ratio and the WVL could be used to improve the parameterizations of vertical mass-exchange in global climate models (GCMs) (Aggarwal et al., 2012), which is currently one of the major uncertainties in GCMs (Bony et al., 2015). Therefore, understanding the WVL has the potential to contribute to improved quantification of the hydrological cycle and its climate-induced changes.

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A number of recent studies have looked at the impacts of different climate drivers on the fast and slow components of the hydrological cycle separately, but most of these studies have focused mainly on precipitation (e.g., Andrews et al., 2010; Bala et al., 2010; Xie et al., 2013; Samset et al., 2016). Recently, new insight into precipitation changes has been given by analysing the atmospheric energy budget (Richardson et al., 2018b) and by the use of radiative kernels (Myhre et al., 2018a)~~.~~. In contrast to the slow (feedback) response, the fast response includes rapid adjustments to an external forcing and the initial radiative impact of the external forcing before changes in the global- and annual-mean surface temperature occur (Sherwood et al., 2015; Flaschner et al., 2016; Myhre et al., 2017). The common approach is to perform GCM simulations with prescribed sea surface temperatures (SST) to derive the fast response, and with coupled atmosphere-ocean to derive the total response. The slow response is the difference between the total and fast response.

The slow response in global precipitation scales with the surface temperature change induced by each driver (Andrews et al., 2010; Samset et al., 2016), while the fast response scales with the change in the atmospheric component of the radiative forcing. Black carbon (BC) differs from most other climate drivers due to strong regional solar absorption in the atmosphere, and has been identified as a driver with large inter-model variability (Stjern et al., 2017). Smith et al. (2018) explored rapid adjustments due to different climate drivers, and found that changes in water vapour contribute a large part of these adjustments and oppose rapid adjustments due to tropospheric temperature changes.

~~In this study,~~The relationship between changes in IWV and precipitation (*P*) can be most easily examined by computing changes in atmospheric water vapour lifetime (*WVL*). The WVL then provides information on the extent to which this relationship is dependent on both the forcing mechanism and timescales of response, and the extent to which there is inter-model agreement on this relationship. The WVL is a fundamental component of the hydrological cycle and is useful for studying how dynamical processes in the hydrological cycle are altered due to climate change (Laderach and Sodemann, 2016), and is an important indicator of the transport length of water vapour (Singh et al., 2016).

The water vapour lifetime is also known as the residence time and is commonly expressed as the ratio between the time-averaged global-mean integrated water vapour and precipitation (Trenberth, 1998; Douville et al., 2002; Bosilovich et al., 2005; Schneider et al., 2010; Kvalevåg et al., 2013). The water vapour recycling rate is the inverse of the lifetime (P/IWV) and most often expressed regionally rather than globally (Li et al., 2011; Kao et al., 2018), in which another factor is how much of the regional precipitation results from transport of water vapour from outside the region. Studies identify a global-mean water vapour lifetime of 8-9 days for present-day conditions (van der Ent and Tuinenburg, 2017), although some argue that water only resides in the atmosphere for about 4-5 days (Laderach and Sodemann, 2016). A historical increase in WVL is found from both models (Bosilovich et al., 2005; Kao et al., 2018) and observations (Li et al., 2011; Kao et al., 2018). The fact that water vapour content increases more rapidly than precipitation with rising surface temperatures implies an expected increase in the lifetime (Douville et al., 2002; Held and Soden, 2006; Schneider et al., 2010).

Motivated by the great value of quantifying lifetimes of other quantities, e.g., BC aerosols (Bond et al., 2013), and the large number of studies that have focused on the topic of water vapour lifetime (e.g., van der Ent and Tuinenburg, 2017, and references therein), we want to explore historical and future changes in water vapour lifetime and discuss the potential value

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of quantifying WVL changes. In the first part of this study we use GCM results from the Precipitation Driver Response Model Intercomparison Project (PDRMIP) (Myhre et al., 2017) to explore how different climate drivers influence the distribution and magnitude of water vapour content throughout the atmosphere on both fast and slow timescales. In the second part, PDRMIP data are used to understand how the relationship between integrated water vapour and precipitation (i.e., the water vapour lifetime of water vapour) has changed and is expected to change in the future according to GCM results in the Coupled Model Intercomparison Project phase 5 (CMIP5) (Taylor et al., 2011). PDRMIP data are also used to explore how different climate drivers influence the distribution and magnitude of water vapour content throughout the atmosphereWe further discuss how changes in the WVL can be interpreted and the potential value of diagnosing the WVL in the context of global climate change.

2 Methods

2.1 Precipitation Driver Response Model Intercomparison Project (PDRMIP)

Data from 11 GCMs involved in PDRMIP have been used – details about PDRMIP and the participating models (except ECHAM-HAM – see Supplementary Text S1) are given in Myhre et al. (2017). The core PDRMIP experiments consist of one base experiment, representing present-day conditions (pre-industrial for HadGEM2), and five perturbation experiments relative to base: doubling of the CO_2 concentration (hereafter denoted CO2x2), tripling of the CH_4 concentration (CH4x3), total solar irradiance increased by 2% (Sol+2%), five times increase in anthropogenic sulfate concentration or SO_2 emissions (SO4x5), and ten times increase in BC concentration or emissions (BCx10). Each experiment has been run with two model set-ups: with fixed SSTs, and with a coupled model configuration, being run for at least 15 and 100 years, respectively. Analyses are here based on years 6-15 from the fixed SST experiments and years 51-100 from the coupled experiments. Each model has run one ensemble member, but the model-mean water vapour lifetime sensitivity (WVLS; see Section 2.3) for each experiment differs by only 3% or less if results from years 51-75 or 76-100 are used instead of years 51-100 from the coupled experiments; this indicates a strong signal-to-noise ratio.

All model data have been regridded to T42 horizontal resolution, and, in the case of 3D data, to 60 vertical layers stretching from the surface to 0.1 hPa. In Fig. S1, IWV in the PDRMIP base experiment has been compared with observations from MODIS Aqua and Terra level 3 data (downloaded from https://giovanni.gsfc.nasa.gov/giovanni/), and the cycle 36 output from the European Centre for Medium Range Weather Forecasts Integrated Forecast System model for year 2010. Four of the PDRMIP models did not have 3D fields with specific humidity available, but for these models the specific humidity was calculated based on temperature, pressure and relative humidity in each grid box and for each month.

2.2 Coupled Model Intercomparison Project Phase 5 (CMIP5)

Data from 26 GCMs participating in CMIP5 (Taylor et al., 2011) were obtained (see Fig. 14 for model names) for the historical (1850-2005) and RCP8.5 (a "business as usual"high emission pathway) (van Vuuren et al., 2011) (2006-2100) experiments, and for the variables surface air temperature, evaporation and water vapour path (here denoted integrated water vapour). The WVL was calculated by taking the global and 20-year mean IWV divided by evaporation (evaporation and precipitation are equal in the global mean).

2.3 Water vapour lifetime sensitivity

The global-mean water vapour lifetime sensitivity follows the approach of Kvalevåg et al. (2013) and is calculated as

$$WVL_i = \frac{IWV_i}{P_i}$$

$$\Delta WVL = WVL_i - WVL_{base}$$

$$WVLS = \frac{\Delta WVL}{\Delta T_s}$$

where WVL_i is the lifetime (in days), IWV_i is the global-mean integrated water vapour (kg m^{-2}), and P_i is the global-mean precipitation (kg m^{-2} day^{-1}) for a perturbation experiment *i*. The water vapour lifetime change, ΔWVL, is the difference between the lifetime in the perturbation and base experiments. The WVLS is the lifetime change divided by the global-mean surface temperature change, ΔT_s. The ΔWVL due to fast responses has been split into contributions from *IWV* and *P* by calculating the ΔWVL twice, with the *IWV* and *P* terms held constant one at a time. This assumption involves nonlinear terms, but the model-mean difference between the actual ΔWVL and the sum $\Delta WVL_{IWV}+\Delta WVL_P$ is less than 2% for all drivers.

3 Results and discussion

3.1 Water vapour lifetime and sensitivity

The CMIP5 pre-industrial multi-model mean value for the WVL is 7.8±0.5 days, and all models show an increase over both the historical and future time period (Fig. 1a) (a paired sample *t*-test shows that the multi-model mean increases are significant). A substantial increase of the lifetime from a present-day (i.e. 1986-2005) value of 8.2±0.5 to 9.9±0.7 days towards the end of the century is projected by the mean of CMIP5 models assuming RCP8.5, because increases in IWV are larger than for precipitation (Fig. 1b). Also, nearly 75% of the models show a stronger WVLS for the historical period than for the future, with model-mean values of 0.55±0.1 days/K and 0.47±0.06 days/K, respectively, and a paired sample *t*-test shows that the two values are significantly different. The present-day lifetime of 8.2±0.5 days from CMIP5 is close to, but slightly lower than, a recent assessment using reanalysis data of 8.9±0.4 days (van der Ent and Tuinenburg, 2017).

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To further understand these differences, it is instructive to investigate WVLS for each of the fast and slow responses, and for each of the five climate drivers studied in PDRMIP. The response to surface temperature changes (i.e., slow response) dominates the change for all drivers except BCx10 (Fig. 2a), but the fast response is still a significant enhancement to the slow response for CO2x2 (27% of the total). For CH4x3, the fast response is 30% of the total, but with large differences between models (range of 8%-58%). All models (except HadGEM3) show that the fast response is more important than the slow response for BCx10, because BC is the driver with the strongest atmospheric temperature increase for the fast response. These results support earlier single-model findings (Kvalevåg et al., 2013). The slow response is remarkably similar between models and drivers, again with the exception of BCx10, which has an inter-model range of 0.10-0.45 days/K. Separating the fast response into contributions from changes in atmospheric water vapour and precipitation (keeping in mind that the lifetime is defined as global water vapour divided by precipitation) reveals that both terms are large for BCx10, but that reduced precipitation dominates the fast WVL changes (Fig. 2b). Interestingly, reduced precipitation dominates the fast WVL changes for CO2x2 as well, while increased atmospheric water vapour dominates for Sol+2%. For SO4x5, the small fast WVL change is dominated by reduced water vapour (note that increased sulphate leads to cooling) except for one model (NCAR-CESM1-CAM5), which has a different sign because it has perturbed emissions rather than concentrations and it includes the influence of sulphate on BC through coating. This leads to a heating of the atmosphere, and this effect dominates the direct sulphate effect because fast responses for sulphate are small.

3.2 Historical lifetime changes explained

By combining the PDRMIP results for individual drivers with radiative forcing since pre-industrial time, we can reproduce the pre-industrial to present-day WVL increase of 0.34±0.08 days from CMIP5 models within the uncertainties (Fig. 3a). There is an almost equal contribution from the slow temperature response and the fast response to the total lifetime change. The PDRMIP estimate of historical lifetime change due to the slow (temperature) response in Fig. 3a was derived by first taking the mean of the slow lifetime change across all PDRMIP drivers in Fig. 2a. This value of 0.31 days K^{-1} was then multiplied with the multi-model mean CMIP5 historical surface temperature change of 0.64 K (not shown). The PDRMIP fast response contribution in Fig. 3a is the sum of the individual terms in Fig. 3b. These terms have been derived by combining the present-day radiative forcing for separate climate drivers from Myhre et al. (2013) with the radiative forcing and fast WVL change from PDRMIP models using the following equation for each PDRMIP model

$$\Delta WVL_{fast,historical,j} = \Delta WVL_{fast,PDRMIP,j} \times \frac{RF_{historical,j}}{RF_{PDRMIP,j}}$$

where RF is the radiative forcing (in W m^{-2}) and j designates the climate driver and corresponding PDRMIP experiment, e.g., CO_2 and CO2x2, respectively (see Table S1 for details and multi-model mean values). The bars in Fig. 3b have further been split into contributions from changes in precipitation and water vapour using the numbers in Fig. 2b. All calculations were done for each PDRMIP model, and Fig. 3 shows the multi-model mean results.

Disentangling the fast response into contributions from the main historical climate drivers shows that increased CO_2 concentrations constitute around half (~0.1 days) of the net increase due to the fast response, with the reduced precipitation term being three times as large as the contribution from increased water vapour (Fig. 3b). For aerosols, a substantial lifetime increase due to BC is partly counteracted by scattering aerosols, which reduce the WVL. The impact of aerosols contributes to the stronger WVLS in the historical period compared to the future simulations in the CMIP5 models (Fig. 1b), since aerosol and aerosol precursor emissions are projected to decrease strongly towards the end of the century in the RCPs (Rogelj et al., 2014).

3.3 Zonal- and annual-mean changes in IWV

Figure 4Table 1 shows that the slow responses of global-mean water vapour per degree K change in surface temperature differ between drivers, but are fairly close to the 7%/K that we expect from the Clausius-Clapeyron relation. However, thesethe numbers differ somewhat between drivers, ranging from 6.5±1%/K for SO4x5 to 8.1±1%/K for Sol+2%. These differences are amplified bybecome larger when the fast response is included, which adds to the pure surface temperature related response, most notably. The fast response is largest for BCx10, which changes from 7.5±1%/K to 9.8±2%/K between the slow and total response.

Integrated water vapour increases much more than evaporation and precipitation at nearly all latitudes and for all five PDRMIP drivers (Fig. 41; Fig. S2-3). However, the total global-mean increase in IWV differs strongly between each driver, with BCx10 at 9.8±2%/K and SO4x5 at 6.4±0.9%/K. (Table 1). The estimated global IWV increase for BCx10 ranges from 6.8 to 13%/K for the different PDRMIP models, while locally decreasing in some regions (Fig. S4). BCx10, and to some extent SO4x5, show steep north-south gradients in the IWV change, emphasising the strong regional influences of these short-lived compounds (Fig. 4; Fig. S3-4).1; Fig. S3-4). The north-south gradient for BCx10 is steeper for the total response (Fig. 1b) than the slow response (Fig. 1a) due to strong influence of the fast response for this compound. In contrast to the other climate drivers, precipitation decreases and water vapour increases strongly for BCx10, and this explains why the WVLS for BCx10 is more than twice as large as for any other driver (Fig. .2a).

3.42 Changes to global-mean vertical profiles

In order to explore reasons for differences in IWV between the drivers, we compare vertical profiles of specific and relative humidity and temperature for each of the climate drivers (Fig. 2). For the fast response from CO2x2, the change in the specific humidity profile differs considerably from what would be expected by the Clausius-Clapeyron relation when assuming that relative humidity stays constant (Fig. 5a2a; Fig. S5-6), a common assumption in climate change studies (Allen and Ingram, 2002). This indicates that the changes are not only temperature-driven. The specific humidity change for CO2x2 is around half of the expected temperature-induced change throughout most of the lower troposphere, explained by a tropospheric relative humidity decrease that peaks near 800 hPa (Fig. 5c). Over land, this2c). This relative humidity decrease, and thus specific humidity decrease, contributes to the small fast IWV response for CO2x2 (Table 1). Over land, the lower than expected increase in specific humidity is particularly evident in the lower troposphere (Fig. S5), and~~ this~~ could be explained by the physiological effect since increased CO_2 leads to less evaporation from vegetation (Richardson et al., 2018a). CH4x3 shows some of the same tendency as CO2x2 (Fig. ~~5a~~2a) but without any considerable change in relative humidity (Fig. ~~5c), while~~2c). Sol+2% largely follows the temperature-induced change in specific humidity (Fig. 2a).~~5a).~~

In contrast to the CO2x2 experiment, BCx10 mostly yields a small increase in relative humidity (Fig. ~~5c~~2c), especially close to the surface, and therefore the specific humidity change for BCx10 is larger than the temperature-induced change throughout most of the troposphere~~. It is also worth noting the different lapse rates~~ (Fig. 2a). This low-level relative humidity increase contributes to the large fast IWV response for BCx10 (Table 1). Additional contributions come from atmospheric solar absorption due to BC, which leads to rapid atmospheric temperature increase (Fig. 2d) and therefore increased water vapour availability. It is also worth noting the different lapse rates between the drivers, broadly with temperature changes decreasing with height for CO2x2 and increasing with height for BCx10 (Fig. ~~5d~~2d; Fig. S6), and this has implications for atmospheric stability.

Changes in specific humidity profiles for the slow response (Fig. ~~5b) show that the assumption of constant relative humidity does hold, and, when normalized with ΔT_s, they are similar between the drivers, with a small exception for SO4x5. Also, some differences can be seen for BCx10 with~~2b) show that the assumption of constant relative humidity does hold. When normalized with ΔT_s, the specific humidity profiles are similar between the drivers, with a small exception for SO4x5, which shows a smaller increase throughout the troposphere. One reason is that SO4x5 is the driver that gives the least change in the temperature profile (and lapse rate up to 300 hPa) when normalized with surface temperature change (Fig. S7, lower left), and therefore the least change in the water vapour availability. It is also worth noting the strong difference between land and sea in the temperature change profile for this driver. The small increase in vertical temperature profiles compared to the other drivers could explain why SO4x5 has the smallest slow IWV response (Table 1). Sol+2%, which have the largest slow IWV response, has the second strongest increase in temperature profile per K surface temperature change (Fig. S7). BCx10 gives the strongest increase in atmospheric temperature, but a decrease in relative humidity, especially over land (Fig. S7), leads to a discrepancy between the actual specific humidity change and the temperature-driven change between the surface and 800 hPa (Fig. ~~5b), and this is due to decreased relative humidity, especially over land (Fig. S7).~~ 2b).

Earlier studies have shown a strong land-ocean contrast in the response of near-surface relative humidity to global warming, mainly due to greater warming over land than ocean (Byrne and O'Gorman, 2016). Inspection of near-surface relative humidity changes shows that patterns of reduced relative humidity over land and increased over oceans are rather similar between drivers for the slow response (Fig. ~~6~~3). However, the fast response constitutes a large part of the total response for all drivers. For CO2x2, fast responses amplify the land-ocean contrast considerably, while for BCx10, fast responses lead to strong increases in relative humidity over large land regions, and these outweigh the reductions over land in the slow response. Interestingly, Sol+2% shows much less land-ocean contrast than CO2x2 in the fast response, while their slow responses are very similar.

3.3 Water vapour lifetime and sensitivity

The CMIP5 pre-industrial multi-model mean value for the WVL is 7.8±0.5 days (Fig. 4a). All models show an increase over both the historical and future time period (a paired sample *t*-test shows that the multi-model mean increases are significant). A substantial increase of the lifetime from a present-day (i.e. 1986-2005) value of 8.2±0.5 to 9.9±0.7 days towards the end of the century is projected by the mean of CMIP5 models assuming RCP8.5, because increases in IWV are larger than for precipitation (Fig. 4b). Also, nearly 75% of the models show a stronger WVLS for the historical period than for the future, with model-mean values of 0.55±0.1 days/K and 0.47±0.06 days/K, respectively, and a paired sample *t*-test shows that the two values are significantly different. The present-day lifetime of 8.2±0.5 days from CMIP5 is close to, but slightly lower than, a recent assessment using reanalysis data of 8.9±0.4 days (van der Ent and Tuinenburg, 2017).

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Separating the fast response into contributions from changes in atmospheric water vapour and precipitation (keeping in mind that the lifetime is defined as global water vapour divided by precipitation) reveals that both terms are large for BCx10, but that reduced precipitation dominates the fast WVL changes (Fig. 5b). Interestingly, reduced precipitation also dominates the fast WVL changes for CO2x2, while increased atmospheric water vapour dominates for Sol+2%. For SO4x5, the small fast WVL change is dominated by reduced water vapour (note that increased sulphate leads to cooling) except for one model (NCAR-CESM1-CAM5), which has a different sign because it has perturbed emissions rather than concentrations and it includes the influence of sulphate on BC through coating. This leads to a heating of the atmosphere, and this effect dominates the direct sulphate effect because fast responses for sulphate are small.

3.4 Historical lifetime changes explained

By combining the PDRMIP results for individual drivers with radiative forcing since pre-industrial time, we can reproduce the pre-industrial to present-day WVL increase of 0.34±0.08 days from CMIP5 models within the uncertainties (Fig. 6a). There is an almost equal contribution from the slow temperature response and the fast response to the total lifetime change.

The PDRMIP estimate of historical lifetime change due to the slow (temperature) response in Fig. 6a was derived by first taking the mean of the slow lifetime change across all PDRMIP drivers in Fig. 5a. This value of 0.31 days K^{-1} was then multiplied with the multi-model mean CMIP5 historical surface temperature change of 0.64 K (not shown). The PDRMIP fast response contribution in Fig. 6a is the sum of the individual terms in Fig. 6b. These terms have been derived by combining the present-day radiative forcing for separate climate drivers from Myhre et al. (2013) with the radiative forcing and fast WVL change from PDRMIP models using the following equation for each PDRMIP model

$$\Delta WVL_{fast,historical,j} = \Delta WVL_{fast,PDRMIP,j} \times \frac{RF_{historical,j}}{RF_{PDRMIP,j}}$$

where *RF* is the radiative forcing (in W m^{-2}) and *j* designates the climate driver and corresponding PDRMIP experiment, e.g., CO_2 and CO2x2, respectively (see Table S1 for details and multi-model mean values). By scaling the fast ΔWVL with RF, we are able to estimate the historical contribution to ΔWVL from each driver, in a similar way to what has been done before for other quantities (e.g., sensible heat flux changes in Myhre et al. (2018b)). The bars in Fig. 6b have further been split into contributions from changes in precipitation and water vapour using the numbers in Fig. 5b. All calculations were done for each PDRMIP model, and Fig. 6 shows the multi-model mean results.

Disentangling the fast response into contributions from the main historical climate drivers shows that increased CO_2 concentrations constitute around half (~0.1 days) of the net increase due to the fast response, with the reduced precipitation term being three times as large as the contribution from increased water vapour (Fig. 6b). For aerosols, a substantial lifetime increase due to BC is partly counteracted by scattering aerosols, which reduce the WVL. The impact of aerosols contributes to the stronger WVLS in the historical period compared to the future simulations in the CMIP5 models (Fig. 4b), since aerosol and aerosol precursor emissions are projected to decrease strongly towards the end of the century in the RCPs (Rogelj et al., 2014).

3.5 Interpretation and value of water vapour lifetime

In atmospheric chemistry and aerosol science, the lifetime of a compound is a measure of how long the compound resides in the atmosphere after it is emitted or produced, e.g., through surface emissions or chemical production. Diagnosing this lifetime has proved useful in many aspects, and the most relevant example is probably the lifetime of BC. Several studies show that the BC lifetime in many global aerosol models is too long, and reducing the lifetime by altering the sinks (mainly wet removal for BC) has given substantial improvements in modelled vertical profiles compared with observations, with large implications for the climate effect of BC (e.g., Hodnebrog et al., 2014; Samset et al., 2014). In a similar way to chemical compounds, the changes in atmospheric water vapour lifetime (WVL) is the relationship between changes in the burden (i.e., IWV) and the sources/sinks (i.e., evaporation/precipitation). In the following we discuss the potential value of diagnosing changes in the water vapour lifetime in addition to examining changes in IWV and P separately.

Since the water vapour lifetime includes both IWV and P, it can be used to measure variations in the hydrological cycle and be an important indicator of climate change (Kao et al., 2018). However, the interpretation of changes in the hydrological cycle can be rather confusing and deserves some discussion. While the longer WVL induced by global warming means that the hydrological cycle is slowing down, the global-mean precipitation or evaporation fluxes are also commonly referred to as the strength of the hydrological cycle; because they both increase, this implies an intensification or acceleration of the hydrological cycle with global warming (e.g., Wu et al., 2013). Hence, when the global hydrological cycle is said to intensify or accelerate with warming, it should be made clear that this refers to the fluxes and not the cycle as a whole. Hence, as noted by Douville et al. (2002), the conclusion that the hydrological cycle is intensifying is somewhat misleading because it suggests faster turnover of water, which is not the case; instead they use the term amplification to indicate an increase in precipitation and evaporation rather than acceleration (which implies a decreased lifetime) of the hydrological cycle. While the terminology could be confusing, both the amplification (through intensification of fluxes) and the slowdown (through longer lifetime) are important indicators of changes in the hydrological cycle. The intensification of fluxes means more precipitation globally and higher water availability, with potential consequences for extreme precipitation and water vapour feedback. The slowdown, however, is an important sign of changing precipitation patterns, since water vapour resides in the atmosphere for a longer time before precipitation, and this behaviour cannot be deduced based on analysing IWV and P separately. A longer water vapour lifetime implies an increased length scale of water vapour transport, so that the distance between evaporation and precipitation of moisture is greater, as has been shown in detail by Singh et al. (2016). They further mention implications of this increased transport length scale, such as the expansion of the Hadley circulation and a poleward shift of midlatitude precipitation maximum.

Another aspect of WVL is the link to isotopes. Stable water isotopes provide valuable knowledge on the evaporation and condensation history of atmospheric moisture, and more specifically on, e.g., proportions of convective and stratiform precipitation (Aggarwal et al., 2016) and past variability in high-latitude aerosol abundance (Markle et al., 2018). Singh et al. (2016) highlight, due to changes in water vapour lifetime and transport length scale, that caution is needed when interpreting isotope data. Also, a positive correlation between WVL and stable isotope ratio in precipitation has been found from daily measurements at stations representing a range of climate regimes (Aggarwal et al., 2012), and better diagnostics of the impact of WVL on isotopes have been called for (Dee et al., 2018). It is suggested that the relationship between isotope ratio and the WVL could be used to improve the parameterizations of vertical mass-exchange in global climate models (GCMs) (Aggarwal et al., 2012), which is currently one of the major uncertainties in GCMs (Bony et al., 2015). Therefore, understanding the WVL has the potential to contribute to improved quantification of the hydrological cycle and its climate-induced changes.

Among the most important caveats with our WVL findings is that climate models have known deficiencies, such as problems with representing vertical convective mass fluxes (Bony et al., 2015), surface moisture fluxes and entrainment/detrainment rates. Part of the reason is that GCMs have relatively coarse resolution and many processes, such as convection, need to be parameterized. However, we use a large multi-model ensemble with horizontal resolutions ranging from 1.4°×1.4° (MIROC-SPRINTARS) to 2.8°×2.8° (CanESM2), and model spread in future WVL change is lower (relative standard deviation (RSD) of 22%) than for, e.g., precipitation change (RSD of 30%) (Fig. 4). Nevertheless, compared with

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present-day WVL from reanalysis, the climate models have too short WVLs (Trenberth et al., 2011; see also Section 3.3). Kao et al. (2018) compared trends in precipitation and column water vapour data from 13 CMIP5 models with observational datasets and also found differences in the moisture recycling rate between observations and the CMIP5 models, and concluded that this discrepancy was caused by relatively poor simulations of precipitation. However, the long-term trend and inter-annual variability of column water vapour was very well captured by nearly all models.

In conclusion, diagnosing changes in the water vapour lifetime reveals important changes in the hydrological cycle, and specifically changes in precipitation patterns since these are directly affected by how long water resides in the atmosphere. Since black carbon is the climate driver among those studied here with the by far strongest water vapour lifetime sensitivity, it is also the driver that is most efficient in increasing the distance between evaporation and precipitation per degree K global surface temperature change. However, the full potential of diagnosing the water vapour lifetime is most likely still unexplored. When inclusion of isotopes in GCMs becomes more common in the future, WVL and its changes can potentially prove extremely useful in constraining projections of the hydrological cycle and precipitation, in a similar way to how diagnosing and evaluating the lifetime of BC has helped constrain the climate effect of BC.

4 Conclusions

Based on new model simulation data sets we can explain the historical increase in water vapour lifetime and quantify how this may change in the future. If emissions evolve according to a business-as-usual pathway, the WVL could increase by 25% by the end of the 21st centuryBased on new model simulation data we have investigated how different climate drivers influence water vapour in the atmosphere. We find that the feedback response of IWV, the relative change per degree K global- and annual-mean surface temperature change, differs somewhat between drivers, ranging from 6.5%/K for sulphate to 8.1%/K for solar forcing. Fast responses are particularly important for black carbon because of rapid heating of the atmospheric column, leading to an increase from 7.5 to 9.8%/K between the feedback response and the total IWV response, and with strong regional differences in the IWV distribution. For CO_2, fast responses are also important, leading to a decrease from 7.7 to 7.2%/K, for the slow and total response respectively, partly due to a reduction of relative humidity throughout the troposphere in the fast response. We also show that the fast response is an important contributor to the previously known strong land-ocean contrast in the response of near-surface relative humidity to global warming, with CO_2 and BC showing strong and opposite fast responses over land.

Results show that the lifetime of water vapour could increase by 25% by the end of the 21st century in a high emission scenario. This is because of the large expected temperature changes, and despite the projected aerosol emission reductions leading to a lower water vapour lifetime sensitivity. The increased lifetime means that the hydrological cycle slows down considerably with global warming, but the cycle is still amplified because both precipitation and water vapour content increase globally.

Among the climate drivers studied here (CO_2, methane, solar irradiance, BC, and sulphate), WVL changes are most sensitive to perturbations in BC aerosols (1.1±0.4 days per Kelvin increase in T_s), due to strong increases in IWV with temperature combined with a precipitation reduction (contraryin contrast to a positive precipitation increasechange per unit temperature change for the other drivers). According to model calculations, an increase in WVL of 4-5% between pre-industrial and present-day has already occurred, and around half of this increase is due to fast atmospheric responses. Aerosol concentration changes, and BC in particular, strongly modify the fast WVL change and contribute to large inter-model uncertainty.

The increase in WVL with global warming reveal important changes in the hydrological cycle. Quantifying WVL changes gives information about changing precipitation patterns – information that cannot be deduced by analysing IWV and P separately. More specifically, a longer lifetime leads to greater distances between the source (evaporation) and sink (precipitation) of water vapour, with implications such as the Hadley cell expansion (Singh et al., 2016). Our results show that BC is considerably more efficient than any of the other climate drivers in prolonging the WVL, and therefore likely the transport length of water vapour. Estimating WVL could become more important in the future as inclusion of isotopes in GCMs becomes more common, and this may lead to more robust projections of the hydrological cycle and precipitation.

Data availability

The PDRMIP model results are available at http://cicero.uio.no/en/PDRMIP. The CMIP5 data are available at http://pcmdi9.llnl.gov/.Due to known relations between precipitation, moisture and convective mass flux, an increase in WVL strongly indicates a subsequent reduction in global-mean vertical mass flux. Specifically, this involves a weakened tropical Pacific atmospheric circulation , but a further set of model integrations with the additional diagnostics would be required to firmly establish this. In addition, a longer WVL implies a higher heavy isotope ratio, due to the correlation between isotopes and WVL , and this in turn indicates a larger fraction of convective vs. stratiform precipitation .

Author contribution

GM and ØH designed the study. ØH performed the analysis and was the primary writer and received input from all authors, especially GM.

Competing interests

The authors declare that they have no conflict of interest.

~~Author contribution~~

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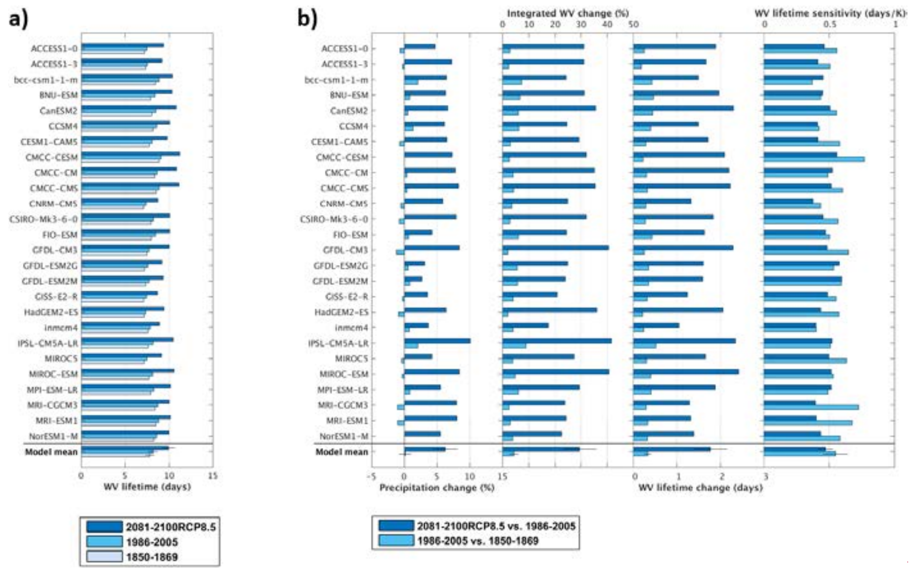


Table 1. Global- and annual mean relative changes in integrated water vapour and with evaporation/precipitation in parentheses (note that global-mean evaporation and precipitation are equal) for five different drivers, and split into fast, slow and total responses, using the mean of PDRMIP results. In the two rightmost columns, values have been divided by the global- and annual-mean ΔT_s induced by each driver.

	Fast (%)	Slow (%)	Total (%)	Slow (%/K)	Total (%/K)
CO_2x2	0.8 (-2.5)	16.8 (6.1)	17.6 (3.6)	7.7 (2.8)	7.2 (1.4)
CH_4x3	0.4 (-0.5)	4.6 (1.9)	5.0 (1.4)	7.4 (3.1)	7.3 (1.8)
Sol+2%	1.2 (-0.7)	18.7 (6.7)	19.9 (6.0)	8.1 (3.0)	8.2 (2.5)
BCx10	2.1 (-3.0)	4.4 (1.5)	6.5 (-1.5)	7.5 (2.8)	9.8 (-3.4)
SO_4x5	-0.4 (-0.1)	-13.3 (-6.1)	-13.7 (-6.1)	6.5 (2.9)	6.4 (2.8)

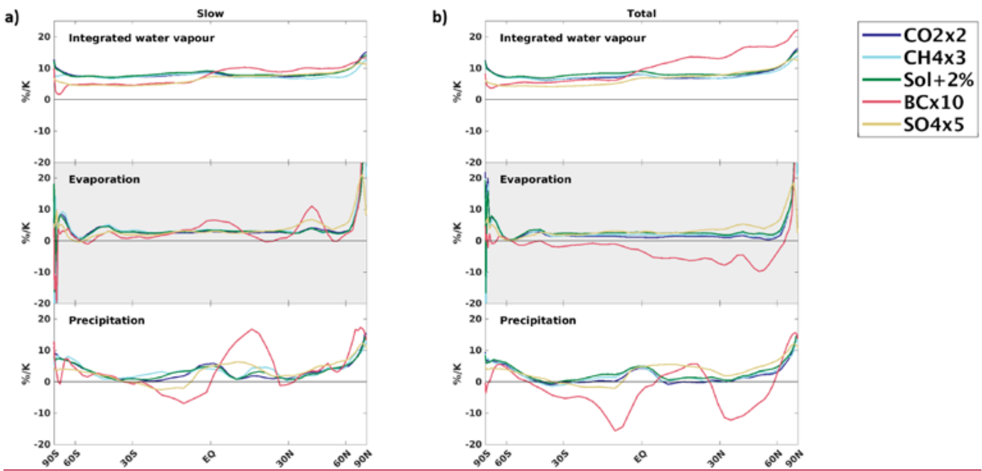


Figure 1: Historical and future water vapour lifetime in CMIP5 models. a) Water vapour (WV) lifetime (in days) for each of the three time periods, and b) changes in precipitation (%), integrated WV (%), WV lifetime (days), and WV lifetime sensitivity (WVLS; days/K) between each of the time periods. Error bars show the standard deviation representing the spread between the models. All values are global- and annual-means.

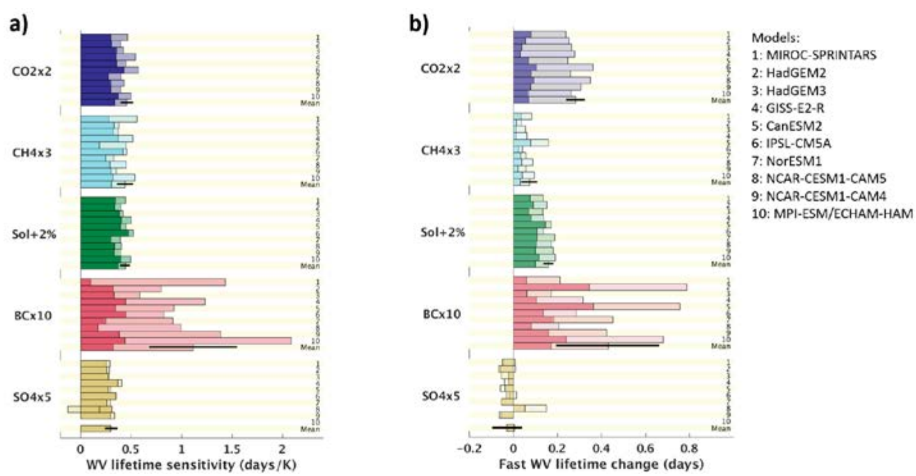
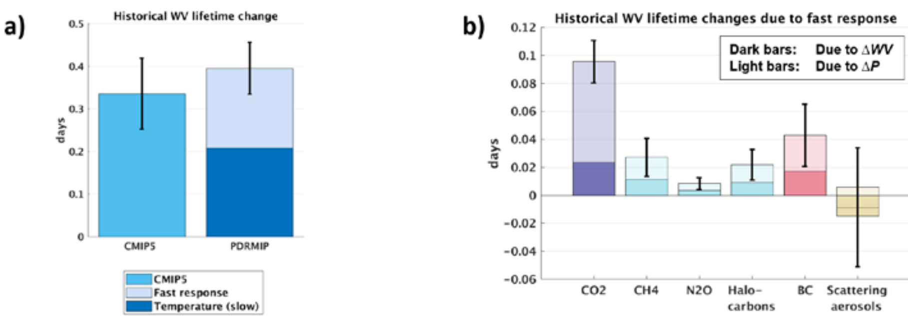
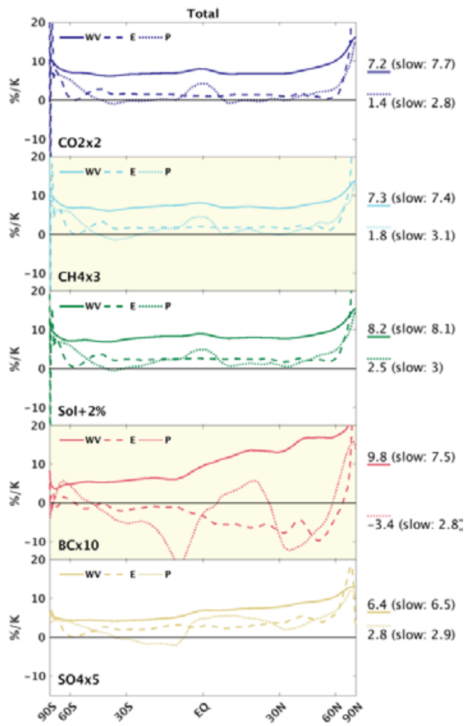


Figure 2: Water vapour lifetime changes for individual drivers. a) Water vapour (WV) lifetime sensitivity (in days/K) in PDRMIP models, split into slow (dark-coloured bars) and fast (light-coloured bars) responses for each driver. b) WV lifetime change (days)

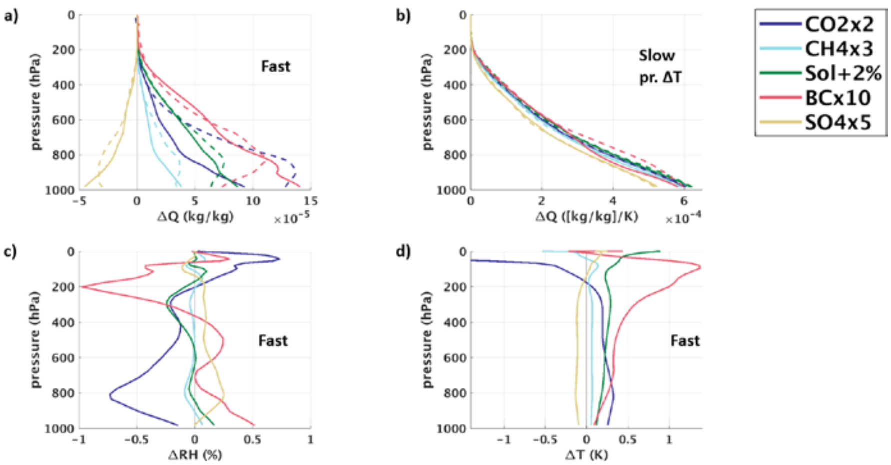
~~due to fast responses, split into contributions from changes in atmospheric water vapour (dark-coloured bars) and precipitation (light-coloured bars). The fast response in a) is not divided by ΔTs but calculated as the difference between the total and slow WV lifetime sensitivity (in days/K). In the few cases where the dark and light-coloured bars have opposite sign (e.g., SO4x5 model no. 8 in Fig. 2a), the vertical black line gives the net value. Error bars show the standard deviation representing the spread between the models.~~



~~Figure 3: Contributions to historical water vapour lifetime change. a) Total historical change in water vapour (WV) lifetime from CMIP5 models compared to PDRMIP results with contributions from slow and fast responses. b) Historical WV lifetime change due to fast responses, split into different drivers and into contributions from changes in atmospheric integrated WV (dark-coloured bars) and precipitation (light-coloured bars). Error bars show the standard deviation representing the spread between the models.~~



~~Figure 4:~~ Zonal-mean relative changes (in %/K) in integrated water vapour ~~(WV)~~, evaporation ~~(E)~~, and precipitation ~~(P)~~ for five different drivers for the a) slow and b) total response, divided by the global- and annual-mean ΔT_s induced by each driver, using the mean of the PDRMIP results. ~~Global-mean values are given to the right of each plot with the slow response given in parentheses (note that global-mean evaporation and precipitation are equal).~~ In some cases, relative evaporation changes are large at very high latitudes and exceed the scale.



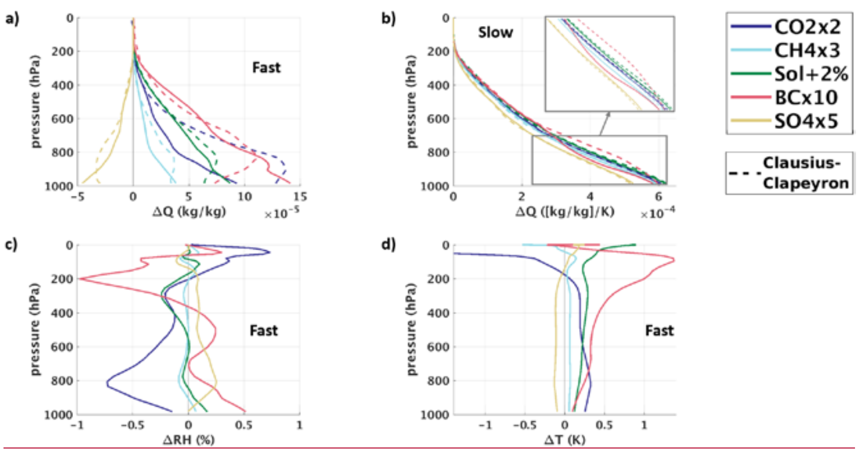


Figure 52: Vertical profile changes for individual drivers. a) Fast and b) slow changes in specific humidity (ΔQ), and fast changes in c) relative humidity (ΔRH) and d) temperature (ΔT), using the mean of the PDRMIP results. In a) and b), dashed lines show expected specific humidity changes from the Clausius-Clapeyron relation assuming constant relative humidity (calculated for each model, month and grid box, and with values at pressures <10 hPa set to zero because this approximation does not hold for low pressures). The slow response in b) is divided by ΔT_s induced by each driver, and the inset plot is zoomed in on 1000-700 hPa.

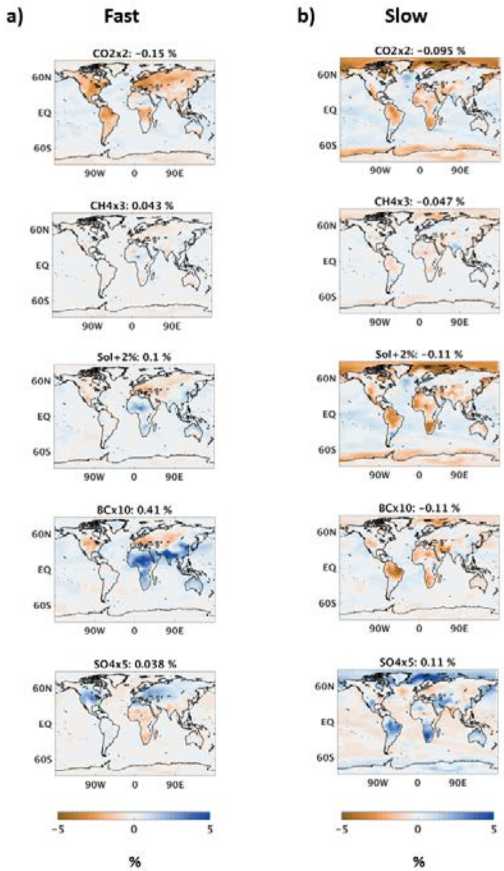


Figure 63: Maps of model mean absolute change in near-surface relative humidity (%) for each PDRMIP driver, separated into a) fast and b) slow responses. The plots are means of the six models with available data for near-surface relative humidity: CanESM2, HadGEM2, MIROC-SPRINTARS, NCAR-CESM1-CAM4, NCAR-CESM1-CAM5 and NorESM1.

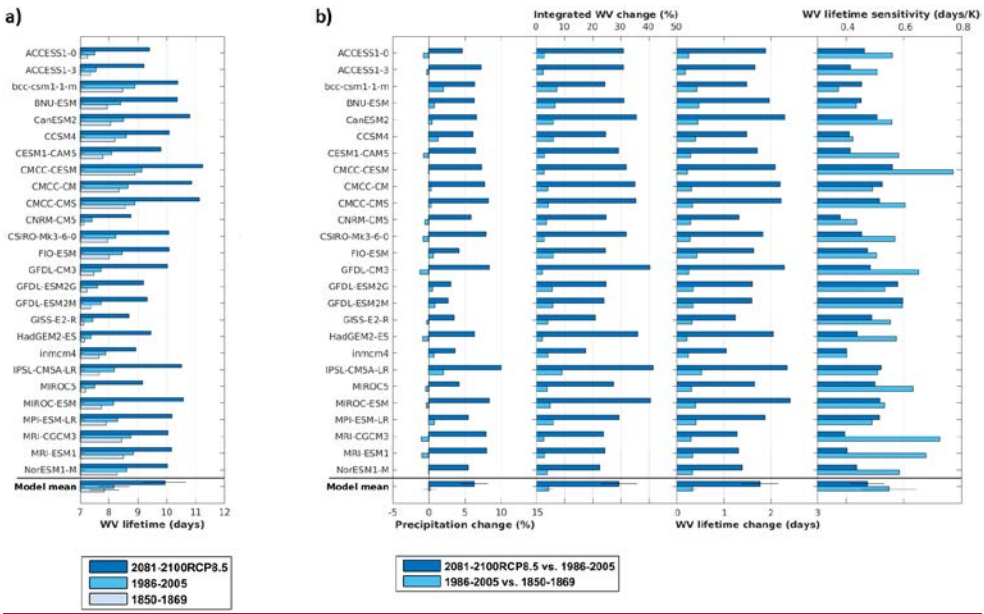


Figure 4: Historical and future water vapour lifetime in CMIP5 models. a) Water vapour (WV) lifetime (in days) for each of the three time periods, and b) changes in precipitation (%), integrated WV (%), WV lifetime (days), and WV lifetime sensitivity (WVLS; days/K) between each of the time periods. Error bars show the standard deviation representing the spread between the models. All values are global- and annual-means.

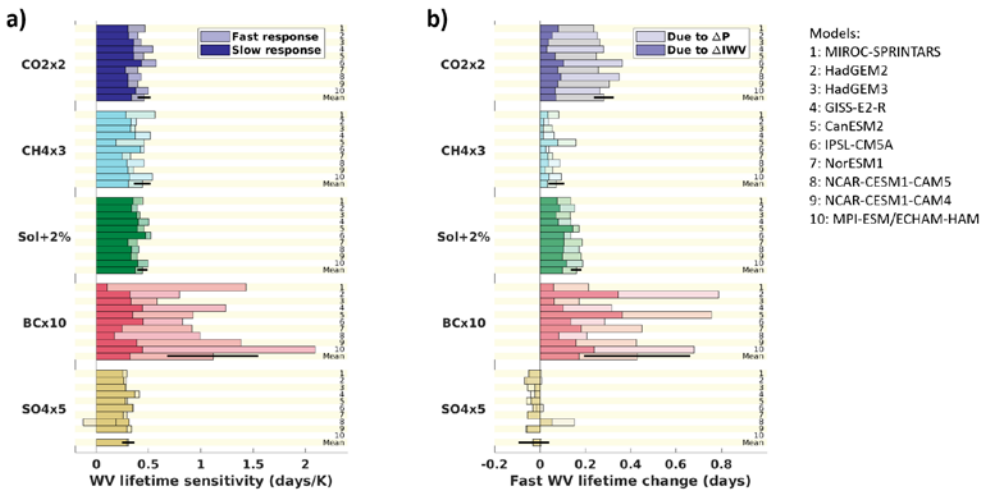


Figure 5: Water vapour lifetime changes for individual drivers. a) Water vapour (WV) lifetime sensitivity (in days/K) in PDRMIP models, split into slow (dark-coloured bars) and fast (light-coloured bars) responses for each driver. b) WV lifetime change (days) due to fast responses, split into contributions from changes in atmospheric water vapour (dark-coloured bars) and precipitation (light-coloured bars). The fast response in a) is not divided by ΔTs but calculated as the difference between the total and slow WV lifetime sensitivity (in days/K). In the few cases where the dark and light-coloured bars have opposite sign (e.g., SO4x5 model no. 8 in Fig. 5a), the vertical black line gives the net value. Error bars show the standard deviation representing the spread between the models.

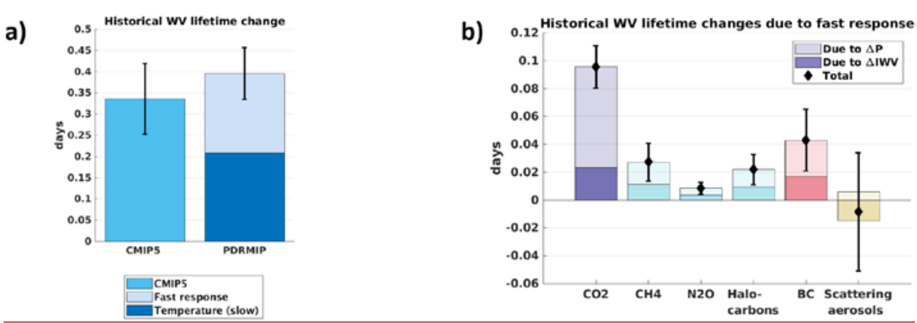


Figure 6: Contributions to historical water vapour lifetime change. a) Total historical change in water vapour (WV) lifetime from CMIP5 models compared to PDRMIP results with contributions from slow and fast responses. b) Historical WV lifetime change due to fast responses, split into different drivers and into contributions from changes in precipitation (light-coloured bars) and IWV (dark-coloured bars). Error bars show the standard deviation representing the spread between the models.