

## Point-to-point response to Reviewer 1:

Thank you very much for your careful review and the excellent comments and corrections! We performed a moderate revision and took advantage of your expertise.

Your points are in bold face, *our response is in italic font style*, the changed text is in a normal font style.

**1) Abstract - some of the introductory material could be removed to focus on the importance, key results and wider implications e.g. the importance of water vapour for climate, why independent measurements are important, the originality of this record, key results and wider implications. Improving the abstract could enhance the impact of this work.**

*Thank you, we re-checked the abstract and removed the sentence that "climate change is stronger in Switzerland than at many other places in the world."*

**2) L5 - suggest "man-made" → "human-caused" (though I recognise that men are probably more guilty!). "many places around the world" is a bit vague so could state that "Surface air temperature in Switzerland has increased at about twice the global average rate since 1995."**

*Done. We use "human-caused" now. We removed the vague sentence about climate change in Switzerland.*

**3) L12 - suggest removing "certainly" since this is not directly demonstrated (e.g. "has implications for")**

*We agree and changed it.*

**4) L15 - "nearly twice" would be more precise**

*Done.*

**5) L17 - a more up to date IPCC report could be cited. In fact the IPCC assesses multiple lines of evidence, not just climate models, to show that human caused emissions have driven warming of climate.**

*We agree and we cite now the IPCC report of 2021 [1]*

**6) L17-20 - the 7%/K rate is applicable for temperatures at low altitudes away from, the poles since the Clausius Clapeyron rate depends upon the absolute temperature such that the rate is larger for**

cooler temperatures (e.g. Allan 2012 *Surv. Geophys.* 10.1007/s10712-011-9157-8). An altitude difference between the observing site and the ERA5 grid point could also cause a discrepancy in mean temperature and water vapour though I presume this is quite small (I see this correction is made on L123).

*Thank you, We write now about an approximately rate of 7%/1K and added your sentence.*

According to the Clausius-Clapeyron equation, a temperature increase of 1K induces an increase of the saturation water vapour pressure of about 7% [2], so that the approximately Clausius-Clapeyron rate is 7%/1K. This rate depends upon the absolute temperature, and the rate is larger for cooler temperatures [3].

7) Fig.1 - the first and second box on the left are showing the same thing and the feedback does not look correct as the warming is feeding back to greenhouse gas increases. I suggest: Emissions lead to increased CO<sub>2</sub>/CH<sub>4</sub> → warming of climate → increased water vapour → feedback to warming of climate

*Thank you for your help. We change the figure.*

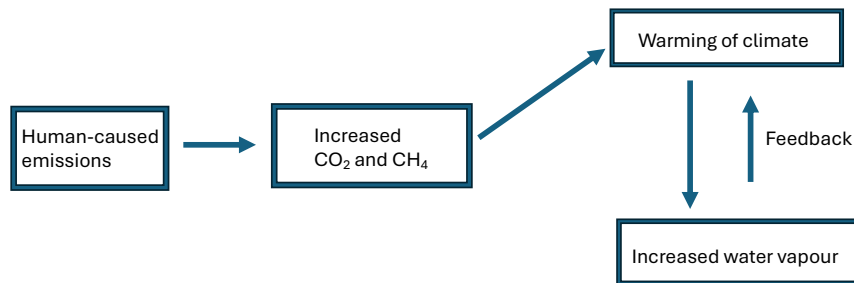


Figure 1: A scheme of the feedback of water vapour to a warming climate. The feedback loop is fully realised once the Earth's radiative balance is attained which will also involve an equilibrium between evaporation and precipitation.

8) L24 - the feedback loop is fully realised once the Earth's radiative balance is attained which will also involve an equilibrium between evaporation and precipitation

*Thank you, we take your sentence in the revised manuscript.*

9) L29 - Suggest new sentence at "For example"

*Thank you*

10) L31 - Multiple aspects of the changing observing system could affect ERA5 including new and changing satellite instruments and their artificial drifts, changes from manual to automated ground-based humidity sensors, etc. There is evidence of an artificial drying over the global land in ERA5, particularly in the early 2000s. Although this is more pronounced in tropical regions, this effect could contribute to the smaller increases in water vapour compared to the measurements in Europe (Wang et al. 2026 Sci. Bull. <https://doi.org/10.1016/j.scib.2026.01.045>). In any case, changes in the observing system could indeed lead to spurious water vapour changes in ERA5.

*Thank you for the detailed discussion. We added it in the revised manuscript.*

The IWV series provided by ERA5 can be affected by such changes in the radiosonde instrumentation. Generally, multiple aspects of the changing observing system could affect ERA5 including new and changing satellite instruments and their artificial drifts, changes from manual to automated ground-based humidity sensors, etc. There is evidence of an artificial drying over the global land in ERA5, particularly in the early 2000s. Although this is more pronounced in tropical regions, this effect could contribute to the smaller increases in water vapour compared to the measurements in Europe [4]. In any case, changes in the observing system could lead to spurious water vapour changes in ERA5.

11) L36 - See also surface water vapour changes in Switzerland from Philipona et al. (2007) GRL doi: 10.1029/2008GL036350 of around 3%/decade 1981-2005, which leads to a large increase in downward longwave radiation.

*Thank you, we included the works of Philipona et al.*

[5] and [6] found surface water vapour changes of 3%/decade in Switzerland from 1981 to 2005 causing a large increase in downward longwave radiation.

12) L42 - see also Wan et al. (2023) HESS doi:10.5194/hess-28-2123-2024

*Thank you, we added this reference*

[7] found a global IWV trend of about 2%/decade from 1993 to 2021 using reanalysis and satellite datasets.

**13) L46 - the larger increases in the northern hemisphere seems somewhat consistent with Allan et al. 2022 Fig.2. (changes in the Arctic are largest)**

*Thank you, we added this thought.*

The larger IWV increase in the northern hemisphere seems somewhat consistent with [8].

**14) L65 - presumably there are other original aspects of the analysis that are introduced? Otherwise this can appear rather incremental.**

*We added two sentences. The former study of Bernet et al. 2020 did not look into detail concerning the difference between the radiometer and ERA5*

It is also important to check the agreement between the actual ground-based microwave radiometer observations and ERA5. Further, the present study elucidates why the IWV trend from the radiometer is stronger than ERA5.

**15) L75 - a line introducing how the work aims to advance the knowledge already discussed may improve the flow and the impact.**

*We add two sentences.*

The present study analyses in more detail the deviation or agreement between IWV from TROWARA and ERA5 during the 31 years from 1995 to 2025. The former trend studies of [9] and [10] were not able to distinguish between natural variability and climatic trend of IWV because of the short time interval.

**16) L89 - if only non-rain conditions are observed, will this bias the actual water vapour content, which will tend to be higher in rainfall events? Changes in rainfall frequency, as well as natural shifts in the larger-scale circulation, can also affect the record, in addition to the overall greenhouse gas induced warming**

*Yes, IWV is increased by about 5 mm during rain. This effect can be neglected, since the rain intervals are short compared to the rain-free times. We add a reference and explanation*

Though, water vapour is increased by about 5mm during rain [11], this effect can be neglected for calculation of the IWV trend because the time intervals of rain are much smaller than the rain-free time intervals in Switzerland. The mean difference between IWV(all times) and IWV(rain-free) is just 0.17mm over the Swiss Plateau [11].

**17) L98/L188 - "an indoor"**

Done.

**18) L102 - what is "on it's random"?**

*Thank you, it is called radome (we forgot the 'e' at the end). Radome stands for radar dome or in our case radiometer dome*

The outdoor radiometer suffered under water films on its radome during and after rain events. A radome is the microwave-transparent dome for the radiometer which protects the antenna against rain.

**19) L123 - quote magnitude (e.g. 0.05 mm and also in %)**

*We added the values for Bern.*

The relative correction is  $\frac{\Delta IWV}{IWV} = 5\%$  at Bern. For a typical IWV value of 10mm, we get  $\Delta IWV = 0.5\text{mm}$

**20) L141 - around 5-10%?**

*Yes, we added this relative uncertainty range*

**21) L147 - the value as a percentage could also be useful**

*Yes, we provide the percentage values in addition. In addition, we corrected the correlation coefficient and the standard deviation.*

The monthly IWV series of TROWARA and ERA5 have a correlation coefficient of 0.99. The mean difference and the standard deviation of (TROWARA – ERA5) is  $-0.25 \pm 0.93\text{mm}$  (or  $-1.7 \pm 6.2\%$ ).

**22) L153 - please quantify**

*Good idea, there is really a perfect agreement after 2011*

From 1995 to 2010, TROWARA had less water vapour (0.49mm or 3.3%) than ERA5. Since 2011 the agreement between the absolute annual means of IWV from TROWARA and ERA5 has been improved, and the mean difference is 0.00mm (for unknown reasons ).

**23) L155 - can the radiosonde or other independent data offer a clue?**

and **24) L158 - mostly correct is vague**

*We reformulated, clarified and added several sentences. We used GNSS in 2007 to check whether ERA5 or TROWARA have a bias. It seems that there is a dry winter bias of TROWARA. The reason cannot be found but it is good news that the bias disappears after 2011. Reprocessing of TROWARA's data and study of independent data such as a harmonized radiosonde series are future tasks.*

Since 2011 the agreement between the absolute annual means of IWV from TROWARA and ERA5 has been improved and the mean difference is 0.00mm (for unknown reasons). The higher IWV trend of TROWARA compared to the IWV trend of ERA5 is mainly due to the higher IWV values of ERA5 in the years before 2011. It is hard to determine whether ERA5 or TROWARA were better in the years before 2011. The beginning part of TROWARA's IWV series, where the deviations from ERA5 occur, was carefully harmonized and validated in the trend study of [9]. In 2007, ERA5's IWV is about 1mm larger than TROWARA's IWV. IWV measurements by the GNSS at Payerne indicate (in agreement with ERA5) that TROWARA had a dry bias from January to March 2007. A dry bias of TROWARA during the winter months (with respect to ERA5) is also obvious in Figure 3. A retrieval error is unlikely as a possible reason since the retrieval of TROWARA's raw data has not been changed in the years after 2011. TROWARA's dry bias in winter before 2011 also cannot be due to the outdoor operation of TROWARA in the beginning years, because TROWARA was since November 2002 indoors, and a relatively strong dry winter bias occurred in 2007. Generally, the deviation between TROWARA and ERA5 in the years before 2011 requires in future a more sophisticated analysis, eventually a reprocessing of the whole TROWARA dataset which is beyond the scope of the present article. The good news is the very good agreement of TROWARA and ERA5 after 2011 (mean deviation is 0.00mm for the time interval from 2011 to 2025). The main result of Figure 4 is that TROWARA and ERA5 show both significant positive IWV trends at Bern.

**25) L159 - January looked consistent in Fig. 2?**

*Yes, Figure 2 is for the year 2025 and the dry bias problem of TROWARA disappears after 2011. We describe the problem in a better way now. As the new paragraph above (point 24) shows.*

**26) Fig.6 - the trends look consistent to within uncertainty**

*Thank you, we took your formulation for the new caption of Figure 6*

**27) L171 - the difference to Bernet et al. 2020 is negligible considering interannual variability**

*We agree and added a sentence*

Generally, the difference of the trend value of the present study to that of [12] is negligible considering the interannual variability of IWV.

**28) L174 - the latest IPCC report suggests an increase in contrasts between wet and dry events in a warming world (Douville et al. 2021 IPCC Chapter 8) which is consistent, though the record is short.**

*Thank you, We added your comment in the new text.*

*[13] suggested an increase in contrasts between wet and dry events in a warming world (which would be consistent with the higher IWV variability at Bern after 2014).*

**29) L179 - and presumably also surface station humidity which also displays a change from manual to automated sensors**

*Thank you, we added your comment.*

**30) L182 - quantify?**

*Yes, we provide the number: ERA5- TROWARA= 0.49mm or 3.3%*

**31) L184 - I do not understand the link to the radiosode from the microwave radiometer here? Is it meant that the radiosonde's affect ERA5?**

*Yes , the radiosonde data is assimilated into ERA5 analysis. We added several sentences and indicate that the bias problem is possibly TROWARA's problem since GNSS supports ERA5 in 2007*

Thus, the assimilated radiosonde data of ERA5 could have a wet bias. On the other hand, the bias problem disappeared after 2011. In addition, the independent IWV observations of GNSS at Payerne indicated that TROWARA and not ERA5 had a winter bias problem in 2007. Further work and analysis are needed to understand the dry bias of TROWARA in the years before 2011. We are quite sure that a retrieval error of TROWARA's IWV can be excluded since the retrieval did not change in 2011, and we obtain no bias between TROWARA and ERA5 in the years after 2011. An instrumental change of TROWARA also did not happen in 2011. In addition, the change of TROWARA from outdoors to indoors in 2002 cannot explain the possible bias problem since a dry bias occurred for example in 1998 before the instrument site change and in 2007 after the instrument site change. However, a reprocessing of the whole TROWARA series might be an attempt for the future in order to clarify the small bias problem of TROWARA in the years before 2011. The possible dry bias of TROWARA before 2011 explains why the IWV trend of TROWARA ( $5.1\% \pm 0.9\%$ /decade) is a bit larger than those of ERA5 ( $3.7\% \pm 0.6\%$ /decade).

**32) L188 - could the drop in TROWARA IWV in 2002 that is larger in magnitude than ERA5 relate to the instrument site change?**

*The drop in IWV in 2002 is possibly caused by natural variability of IWV. Generally IWV of TROWARA is smaller than ERA5 in the years 1995 to 2010. Only in 2000-2002 ERA5 and TROWARA agree well. As explained before, in 2007 the dry bias also occurs (though the radiometer is inside). For unknown reasons, the bias disappears after 2011. So, we think that the change from outdoors to indoors cannot explain the bias problem, as we tell now in the paragraph before*

**33) L194 - what is wet random?**

*We corrected the word its a radome. A dome over the radiometer against rain.*

**34) L196 - the increase in IWV in both makes the result more robust but does not on its own signify that it is caused by temperature changes. Saying both values are "reasonable" is vague.**

*We removed the vague sentence and added a new sentence about the observational results of Wan et al. (2024)*

*[7] found values from 6%/1K to 8%/1K for the IWV to temperature sensitivity at northern latitudes from 15 to 55°N.*

**35) L207 - better to quote as a % per decade as done later so this could be removed**

*We agree but we like to emphasize the total change of IWV over the 31 years. We make this clearer now.*

*Over the 31 years from 1995 to 2025, the ground-based microwave radiometer TROWARA at Bern measured a relative increase of IWV by 15.8% while the reanalysis ERA5 gave a relative IWV increase by 11.5% over the whole time interval. In both cases, one can say that the tropospheric water vapour at the end of 2025 is clearly larger than in 1995 which should have implications for climate, weather, and hydrology of the Swiss Plateau.*

**36) L210 - the Clausius Clapeyron equation provides the physical basis for expecting increases but does not show the cause without other lines of evidence**

*We agree and take your formulation now*

The Clausius-Clapeyron equation provides the physical basis for expecting that this water vapour increase is due to climate warming.

**37) L212 - trend studies over Europe?**

*Yes, we added over Europe now*

**38) L220 - are there independent coincident measurements of surface specific humidity that could compliment the IWV record?**

*We mention that GNSS in Payerne prefers ERA5 and indicates that TROWARA had a dry bias in 2007.*

In 2007, independent IWV observations by GNSS in Payerne confirmed ERA5 and indicated that TROWARA had a dry winter bias in 2007. In the years from 2011 to 2025, there is no mean bias at all between TROWARA and ERA5.

**39) Discussion/Conclusions - decreases in aerosol in the 1990s may also have impacted Europe's climate, directly through their diminishing effect on reflecting sunlight by the atmosphere and cloud (e.g. Schwarz et al. 2020 Nature Geosci. doi: 10.1038/s41561-019-0528-y) but also through altering wind patterns (e.g. Dong et al. 2023 Clim. Dyn. <https://doi.org/10.1007/s00382-022-06438-3>). To what extent can some of the changes relate to changes in atmospheric circulation that are related to or unrelated to greenhouse gas forced climate change?**

*Thank you for these interesting thoughts about reasons for the strong climate warming in Europe. We added a paragraph at the end of the Discussion section*

The temperature trend is  $0.47\text{K}\pm 0.10\text{K}$ . This strong climate warming in Europe might be not only due to increased human-caused emissions of  $\text{CO}_2$  and  $\text{CH}_4$  (as suggested in the simplified scheme of Figure 1). Decreases in human-caused aerosol emissions since the 1990s may have impacted Europe's climate, directly through their diminishing effect on reflecting sunlight by the atmosphere and clouds, so that an additional climate warming is possible because of the reduction of aerosol emissions (e.g., [14]). Further, altering wind patterns could contribute to the strong climate warming in Europe [15].

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Thank you for your thorough review!

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