Point-to-point response to Reviewer 3:

Thank you very much for your careful review and critical comments and corrections! We performed a major 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) However, while the dataset itself is clearly of interest, the scientific analysis remains limited, and several methodological as well as conceptual issues reduce the robustness and interpretability of the results. In its current form, the manuscript does not provide substantial new insight beyond what is already well established in the literature.

It is our purpose to provide a simple data analysis which is based on linear regression of annual means of IWV from 1995 to 2025. The time series of annual means nicely shows the interannual variability of IWV. The article presents the 31 years-long IWV time series obtained by the independent measurement technique of ground-based microwave radiometry at Bern. This is a new result and it is important for validation of ERA5 reanalysis at Bern which is also a topic of the article. Water vapour in a changing climate is an important topic which needs more observational studies.

2) The main findings, namely an increase in IWV over time and an approximate scaling with temperature, are not novel in themselves. The manuscript does not clearly demonstrate what additional physical or methodological insight is gained from the present analysis. At this stage, the study reads more like the presentation of a valuable dataset than a manuscript that advances scientific understanding.

We performed a transparent trend analysis. We didn't use a sophisticated trend model as the previous study by Bernet et al. [1]. The present article has a 7 year-longer time series of IWV. The present study better describes the interannual variability of IWV. The present study suggests that the microwave radiometer at Bern possibly has a small dry bias in the winters from 1995 to 2011 compared to ERA. These are new important results.

3) The introduction lacks a clear structure and reads largely as a sequence of studies rather than a synthesis that motivates the present work. A clearer framing of the research gap and the specific contribution of this study is needed.

We improved the Introduction and the Discussion thanks to the many helpful comments of reviewers 1 and 2.

Please see our responses to reviewers 1 and 2 and the revised manuscript.

4) The manuscript discusses the relationship between total column water vapour and surface temperature but does not adequately refer to key studies in this field, such as Trenberth et al. (2005) and O'Gorman and Muller (2010). Proper positioning within the existing literature would help clarify both the motivation for the study and the limitations of the chosen approach.

Thank you for these references which we didn't know yet. We cite them in the revised manuscript.

Trenberth et al. [2] analysed data of the satellite microwave imager SSM/I and found a trend of 0.40mm/decade for the ocean from 1988 to 2003. They emphasized the need for considering the influence of changing observation systems in meteorological reanalysis datasets. They reported that their are not many regions in Europe where evident positive IWV trends are present.

O'Gorman and Muller [3] reported rates of changes of zonal means of IWV from 6 to 12%/K depending on latitude.

5) The trend analysis relies on a simple linear fit and does not sufficiently account for:

autocorrelation in the time series, low-frequency variability (e.g. the seasonal cycle), large-scale modes of climate variability and teleconnections (e.g. ENSO, NAO), rigorous estimation of trend uncertainty.

This introduces the potential for misleading or overly confident results (see, e.g. Wilks 2011). Established approaches for trend detection and uncertainty estimation (e.g. Weatherhead et al., 1998; Mieruch et al., 2008; Schroeder et al., 2016; Borger et al., 2022; and related work therein) are not considered. Overall, the current methodology raises concerns regarding the robustness and statistical significance of both the reported trends and the derived IWV-temperature scaling.

Closely related to this point, the manuscript does not investigate whether the observed IWV variability is linked to large-scale modes of climate variability. Given the length of the time series, such an analysis would be highly valuable. Assessing possible teleconnections could help to separate long-term trends from natural variability, improve the interpretation of interannual and decadal fluctuations, and strengthen the physical understanding of the observed changes. At present, the absence of such an analysis limits the interpretability of the results.

Linear regression of annual means is a conservative and robust method. It is *also a mathematical correct method. The trend estimation and error estimation is based on the work of C.F. Gauss. It is important that the annual mean is an average of the IWV values of all 12 months. This is fullfilled for the TROWARA dataset and ERA5. Thus a seasonal fit with a trend model is not needed. The estimated uncertainty is slightly larger than for the trend model with seasonal fit of Bernet et al. [1]. We compared both methods. The autocorrelation of a series of annual means is assumed to be zero since the residence time of water vapour and weather pattern in the atmosphere are smaller than a year. Of course, low frequency variability such as ENSO may contribute to oscillations of the annual means. In the revised manuscript, we discuss the interannual variability of IWV annual means in more detail and show that the trend value depends on the year where the series stops. However, we show that the positive IWV trend remains a robust result independent of the influence of interannual variability*

We calculated the linear trends of the annual means of IWV and its uncertainties by means of linear regression, and we used QR decomposition in order to solve the linear least-squares problem.

It is remarkable that the interannual variability of IWV strongly increased since 2014 (Figure 4). The interannual variability of IWV seems to be not related to the variability of the North Atlantic Oscillation (NAO) index. [4] 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). The interannual variability of IWV can enhance or reduce the absolute trend by about 10 to 20%. For example, if our trend study would end in 2021 instead of 2025, the trend would be smaller since there is a local minimum of IWV in 2021 (Figure 4). For the interval 1995 to 2021, TROWARA's IWV trend is only 0.7mm/decade (instead of 0.8mm/decade for 1995 to 2025). The ERA5 IWV trend for 1995 to 2021 is 0.5mm/decade (instead of 0.6mm/decade for the complete series). However, in both cases the positive trend would still has a 95% confidence. This means, the interannual variability of IWV cannot mask the positive IWV trend at Bern.

6) Closely related to this point, the manuscript does not investigate whether the observed IWV variability is linked to large-scale modes of climate variability. Given the length of the time series, such an analysis would be highly valuable. Assessing possible teleconnections could help to separate long-term trends from natural variability, improve the interpretation of interannual and decadal fluctuations, and strengthen the physical understanding of the observed changes. At present, the absence of such an analysis limits the interpretability of the results.

We think that attribution of IWV changes to large-scale modes of climate variability is a very complex problem and certainly beyond the scope of the article. We tried to find the signal of the NAO index in the interannual variability *of IWV at Bern since Bern has an Atlantic west coast climate. But we did not see a correlation. The signal of the ENSO 1997/1998 is also not in the Bern IWV data or maybe delayed by several years (Figure 4). We also did not find a correlation between the interannual variability of surface air temperature and IWV at Bern.*

7) The manuscript reports a scaling of approximately 10.9 % / K and implicitly compares this result to Clausius-Clapeyron expectations. However, Clausius-Clapeyron scaling applies to saturation vapour pressure, whereas column water vapour is also influenced by atmospheric dynamics, relative humidity, and vertical structure. Values exceeding about 7 % / K are not unexpected at a local scale, but this requires careful discussion and interpretation. In its present form, the manuscript risks overstating the physical significance of the reported scaling, and the discussion should be revised accordingly.

In the revised manuscript, we discuss in more detail how different factors influence climate warming in Europe. We also expalin that the IWV trend of TROWARA could be overestimated because of the dry winter bias of TROWARA before 2011. The high rate of change of IWV from TROWARA at Bern may indicate too that TROWARA's trend is a bit too high and the results from ERA5 are more reasonable.

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).

The positive IWV trends of TROWARA and ERA5 confirm each other and can be explained by the coincident increase of surface air temperature at Bern from 1995 to 2025. 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 CO_2 and 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., [5]). Further, altering wind patterns could contribute to the strong climate warming in Europe [6].

According to Clausius-Clapeyron, we expect an IWV increase of 7% per 1K increase of temperature. [7] found values from 6%/1K to 8%/1K for the IWV to temperature sensitivity at northern latitudes from 15 to 55°N. Since the location of Bern (575m a.s.l.) has an Atlantic west coast climate, we further expect a sensitivity value of about 7%/1K. The trend values of TROWARA and ERA5 at Bern indicate 10.9% per 1K increase in temperature for TROWARA and 7.8% per 1K increase in temperature for ERA5. The IWV temperature sensitivity of ERA5 is more conform with the expectation of the Clausius-Clapeyron scaling. This may also indicate that TROWARA's IWV trend is a bit larger than ERA5's IWV trend.

8) The applied height correction is not well justified. A correction based on a water vapour scale height would be more physically consistent (e.g. Weaver and Ramanathan, 1995). In addition, the cited reference appears to be incorrect, as the original work is by Bock et al. (2005). Moreover, for relative trends, such a correction is generally unnecessary.

Thank you, we will cite the original work of Bock et al.. An estimation of the water vapour scale height would be too difficult for the GNSS data and we agree with you that the height correction has no influence on the trends. However, we need the height correction for Figures 2 to 4 where absolute IWV values are shown.

9) The intercomparison between ERA5, TROWARA, radiosonde, and GNSS is based on monthly values for only one year.

For this purpose, a comparison using daily or hourly collocated data would be more appropriate. This would substantially increase the sample size, allow a more robust assessment of bias, scatter, and correlation, better reveal systematic differences between the observing systems.

Using only 12 monthly means limits the statistical value of the comparison and may obscure relevant discrepancies.

Please can you explain why the IWV mean of 12 months should be not equal to the annual mean? The trend analysis of the annual means is in our study not obscured by an imperfect fit of seasonal variations or interannual variabilities. In other trend studies, the seasonal variation is fitted by sine waves with constant amplitudes and phases. In reality, the seasonal variation changes its amplitudes and phases from year to year. The radiosondes only measure two times per day. Hourly values are not available. In the revised manuscript , we also mention a comparison of TROWARA, ERA5 and GNSS in 2007. The small differences between the instruments and ERA5 would disappear in the time series because *of large daily fluctuations of IWV .*

Thank you for your review. The revised manuscript provides a much better discussion of the results and the scientific background.

References

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