We thank Referee #3 for the review, which helps us to make the manuscript clearer, including a better description of the main objective of our study and an improved presentation of the ERA5 data. We also thank the referee for the insights about a possible explanation, based on previous studies that are suggested, of how humidity and clouds over land are affected by global warming. We have improved the investigation of the Bowen ratio (see our reply after the referee's comments below and updated related Figure 9 at the end of this document). Our answers below are marked with blue colours. In some of the answers, we refer to text belonging to line numbering related to the original version of the manuscript.

Referee #3

Summary:

The paper investigates recent observed trends in the land's climate and proposes a positive feedback between land humidity and cloud cover. While the research topic fits within the scope of ESD and is definitely worth pursuing, the presented analysis unfortunately lacks in clarity, and does not manage to show physical causation associated to the presented correlations. The central line of argument is hidden in a cross-comparison of datasets and variables with unnecessary figures, instead of presenting a quantitative analysis to physically support the proposed feedback. It is evident that there is reduced land cloud cover over land and that this is expected to lead to a positive forcing on land warming due to more short wave downward radiation, however this result was already presented in Loeb et. Al (2021). The correlations presented in the subitted manuscript are not sufficient to justify the author's claims that 1) reduced cloudiness significantly amplified land warming, because the expected warming is not quantified, and therefore 2) trends in land humidity and cloudiness signal a positive feedback, and not e.g. a common cause. Therefore it is not advisable that the manuscript is accepted as submitted. Further analyses are required to prove and quantify the expected magnitude of the feedback. Considering all above, the authors are strongly encouraged to contiue pursuing this research question, but further analyses and a full rewrite of the manuscript are advised.

Major scientific comments:

1. The use of the term paradox does not seem fitting, or at least does not become clear. In the abstract is seems like decreasing relative humidity and cloudiness are supposed to contradict each other, and are later also described as feedback, but they do not. In line 717 in the conclusion, it is said that the fact that land humidity does not increase at the same rate as the saturation vapour pressure is a paradox, but this is not true either. What is the scientific gap the authors are trying to understand? In line 135 it is called a positive feedback between drying and shortwave radiation which is very plausible and seems to be the subject of research, but this is not reflected by the title and abstract and conclusion, which discuss a paradox.

We agree with the referee, and the major concern below, point 4, has contributed to this insight. We think the correct descriptive phrase needs to be used. With "apparent" it meets the definition of a false paradox, while the statement sounds impossible at first glance. To explain the apparent paradox and improve the first paragraph of Section 5 we have changed to: "*The increase in absorbed solar radiation by the land surface in addition to the enhanced greenhouse effect at present implies thus even more stress on the terrestrial water cycle. The slower warming of the oceans at present means a limitation in evaporated moisture to keep pace with the rapid increase in the temperature over land. The apparent humidity paradox describes a superficial contradiction in the changing climate system: while global warming drives increased oceanic evaporation and a higher absolute* *atmospheric water vapor capacity, relative humidity and cloud cover over land are simultaneously decreasing. By denoting this phenomenon as 'apparent,' we explicitly frame it as a false paradox—an intuitive contradiction that can be entirely resolved by evaluating the distinct thermodynamic constraints of land-atmosphere coupling. In the regions we studied, the increase in evaporative demand, caused by enhanced absorption of radiation at the surface, is most obvious where precipitation decreases. We assume that the ocean-land warming contrast doesn't exist during more gradual natural climate change since it proceeds slowly enough in the ocean and over land so crossing of the vapour-liquid phase is not perturbed. The exception to a slow change in the climate is extreme volcano eruptions*."

We have changed to "apparent humidity paradox" at other places in the text, including the title. In addition to the apparent humidity paradox, a positive feedback between drying and shortwave radiation is indeed mentioned both in the abstract and conclusion section, while implicit also in the title. In any case, we have rewritten the abstract, considering our reply below to the major concern, point 4, by the referee.

2. The conclusions (line 725) read like the the proposed feedback between humidity and cloud cover/shortwave radiation is claimed to explain enhanced land warming, not only an amplifying feedback. However, there are existing explanations for enhanced land warming, like the moisture-convergence constraint leading to a higher temperature lapse rate in the boundary layer by Byrne&O'Gorman (2018), mentioned in the manuscript. Please clarify if you understand the feedback as separate mechanism or part of Byrne&O'Gorman's mechanism.

We see it as amplified feedback, but we also write in Section 5 "In addition, t*he present study did not isolate the initial trigger of the proposed feedback loop—specifically, whether surface humidity drops or cloud clearance acted as the primary driver."* Both processes coexist; the lower troposphere over land becomes more unstable due to surface sensible heating, caused by the increase in net solar radiation, while the previous study above suggests that the free troposphere becomes more stable due to remote oceanic warming aloft. See our reply below to the major concern, point 4, by the referee.

3. The manuscript is missing a quantitative link between the proposed increase in land surface SW radiation and the expected land warming. How much of the enhanced land warming is caused by the effect described by Byrne&O'Gorman and how much could the proposed feedback add? What is the cloud radiative effect over land? How much does the clear sky Planck response compensate? From the manuscript it does not become clear if there is a significant effect of the cloud reduction, or if land warming is not completely dominated by the effect proposed by Byrne&O'Gorman and competing effects like co2 increase (higher forcing on the dryer land), or aerosol cleanup.

Considering impact from the increase in SST, related to the study by the two authors above, see our reply to major concern 4 below. See also our reply to major concern 6 below, considering limitation in the CERES data record and considering referee's comment "…with unnecessary figures, instead of presenting a quantitative analysis to physically support the proposed feedback." in the text denoted with "Summary" above. In addition, such a detailed quantitative modelling analyses would be desirable, but is beyond the scope of the current study.

Even so, ERA5 surface net solar radiation has increased with as much as ~7 W m^{-2} in both South America and over the areas in the Northern Hemisphere since 1979 (Section 4), caused by decreases in the cloud cover. This regional brightening exceeds the globally averaged human-caused greenhouse gas forcing of 3.8 W m^{-2}, accumulated since 1750 (AR6). Although the forcing of 3.8 W m^{-2} is a global average, much of the extra heat at present has ended up as increased ocean heat content (line 37 in the manuscript). Furthermore, at lines 501 – 508 in Section 3.5 we present results of the responses in cooling in infrared (Planck response) for South America and the areas in the Northern hemisphere. The corresponding quantitative impact on the surface energy balance is presented and discussed as well by referring to results presented in Figures 7c, 7d, 8c and 8d. In the middle of the third paragraph in Section 4 we discuss impacts from the perturbed surface energy balance on warming for the two investigation areas.

Concerning "increase in CO2" by the referee versus decline in clouds and increase in solar radiative forcing, we refer to the modified statement in the following sentence (in Section 5) : "*As the apparent humidity paradox is a direct consequences of rapid anthropogenic warming, decreasing cloud cover and increased solar radiation are likely a response to the CO2-driven warming.*", as well as to previous studies that we refer to in the manuscript, e.g. Liu et al. (2023), Loeb et al. (2021, 2024), Simmons et al. (2010), Willet et al. (2014, 2020), McKinnon and Simpson (2025), Luo et al. (2024a).

Concerning the referee's comment about "aerosol cleanup", we refer to the IPCC reports of a temporally cooling effect by human aerosols and the previous studies by Glantz et al. (2022). The latter authors estimated an unmasking effect due to decreases in the aerosols over Europe since 1980. Notably, the strongest decrease occurred in the 1980s, a somewhat weaker decrease thereafter in the 1990s and during the latest two decades substantially lower aerosol loadings with relatively small changes appeared. The highest aerosol loadings occurred in eastern and central Europe, somewhat lower concentrations in western Europe and relatively low loadings in southern and northern Europe. The spatial distribution of the anthropogenic aerosols was thus very uneven. The strongest reduction in aerosols in the world has until today occurred in Europe, and North America has a similar negative trend during the same period (Figure 6.11 in AR6). From Copernicus, the warming goes fastest in Europe among the continents. From that we can conclude that decreases in short-lived human aerosols have resulted in enhanced greenhouse effect by long-lived greenhouse gases that has contributed to the rapid warming of the continent. The human strengthening of the greenhouse effect over Europe is with no doubt the main cause of the rapid warming, while declines in relative humidity and clouds over the region are likely related positive feedbacks. At the end of the sixth paragraph in Section 1 the following sentence has been included in the revised version of the manuscript; "*Substantial continental brightening from 1980 to 2024 with co-located reductions in total cloud cover were found over central United States, Brazil and central Asia, although no large trends in aerosol concentrations have occurred over the same period (McKinnon and Simpson, 2025)*." Finally, we refer to the current masking effect by human aerosols over south Asia at present and impacts on the ERA5 variables (search for south Asia in the manuscript), including TOA net solar radiation in Figure 5b.

4. Previous studies have shown that the stability over land is strongly influenced by the mean SST warming level (see Chadwick 2019). In AMIP experiments with isolated uniform SST increase, land moisture convergence decrease and stability increase. The presented correlations do not distinguish whether declining humidity causes reduced cloudiness, whether reduced cloudiness causes declining humidity, or whether both are responses to large-scale warming and circulation changes. Can you refute a SST increase as common cause of the two trends?

We thank the referee for highlighting the impact on warming over land due to an increase in SST, which we believe is relevant to point out in our current study. On lines 41 – 45 in Section 1 we present results by Sherwood et al. (2020) and Brogli et al. (2021) related to changes in the temperature lapse rate. ERA5 surface net solar radiation has thus increased by about 7 W m^{-2} in both South America and over the areas in the Northern Hemisphere since 1979, (Section 4), caused by decreases in the cloud cover. A significant portion of this radiation energy goes into sensible heating, in southwestern North America and other regions as well, that consequently has warmed the lower troposphere and increased the lapse rate. So, ERA5 data highlights a surface-driven boundary layer destabilization that acts over land where absorption of solar radiation has increased, while the larger-scale free troposphere undergoes stabilization due to remote oceanic warming.

We agree that the physical mechanism outlined by the referee is interesting and should be taken into consideration. The large-scale thermodynamic constraint described—where remote oceanic warming shifts the free-tropospheric lapse rate along a moist adiabat, stabilizing the upper atmosphere over land and suppressing large-scale moisture convergence—is probably, at least to a part, a driver of the warming over land. Our ERA5 reanalysis results do not contradict this macro-scale thermodynamic constraint. Instead, the results complement it by revealing how this remote, top-down stabilization triggers a cascade of localized, second-order surface feedbacks that amplify warming near the ground. We now frame the system as a hierarchical loop operating via a vertical partitioning of atmospheric stability. To clarify this relationship and better integrate the referee's point, we have included a separate paragraph (after the original sentence below) at the end of Section 5. The final part of this paragraph discusses regional land climate sensitivity.

"In addition, this study does not isolate the initial trigger of the proposed feedback loop—specifically, whether surface humidity drops or cloud clearance acts as the primary driver.

Even so, we propose secondary positive feedbacks, supported by observed ERA5 trends over the past four decades, which seems to be driven, at least in part, by a primary global response to uniformly increasing sea surface temperature (Byrne and O'Gorman, 2018; Chadwick et al., 2016; Chadwick, 2019). The previous studies suggest that ocean warming increases static stability over land by transport of warm and high-humidity air in the free troposphere. This response is coupled to decreased surface relative humidity (Byrne & O'Gorman, 2016; Chadwick et al., 2016; Joshi et al., 2008; O'Gorman & Muller, 2010) and reduction in clouds (Joshi et al., 2008). According to modelling work the cloud reduction and atmospheric stabilization are the triggers, while the drying of the land surface and the increase in atmospheric water demand are the consequences (Dong et al., 2009). Consequently, while the large-scale free troposphere is stabilized by remote oceanic adjustments aloft, the planetary boundary layer over land is intensely destabilized by an increase in absorbed solar radiation and surface sensible heating, as identified in the ERA5 data. This destabilization logically promotes vertical convection; by transporting heat upward, it enhances upper-tropospheric infrared cooling, serving as a pathway for the planet to shed radiation energy to space amidst an enhanced greenhouse effect. Furthermore, from an energy budget perspective, the regional increase in absorbed solar radiation at the land surface, reaching as much as 7 W m^{-2} over the last four decades, provides an empirical constraint on regional land climate sensitivity. As illustrated by the sharp divergence between global land and ocean warming trends in the ERA5 and AR6 historical records (Figure 13), the land surface exhibits a highly amplified temperature response. This suggests that localized land-surface feedbacks, specifically the decrease in humidity and cloud clearance over land globally, significantly elevate the effective climate sensitivity of continental environments relative to the global oceanic baseline, amplifying terrestrial warming at a rate that outpaces global mean projections."

In addition, the following text has been included at the end of the second paragraph in Section 1. "*Furthermore, trends in humidity and temperature in recent decades have been found in previous studies to be linked to ocean warming (Byrne and Gorman, 2018; Chadwick et al., 2016; Chadwick, 2019). Increases in sea surface temperature is suggested to lead to a remote thermodynamic adjustment characterized by an increase in static stability over land*."

At the end of the abstract the following sentence has been included: *"Ultimately, we propose a causal hierarchy linking large-scale mechanisms, such as sea surface temperature anomalies and increased static stability over land, into a primary global response amplified by secondary local positive feedbacks, directly supported by ERA5 trends spanning the past four decades."*

5. Why are the South American continent and the northern mid/high latitudes chosen for analysis if the statements are made for the global land? The chosen domains seem to be too broad to identify distinct regimes but still miss out on significant parts of global land. Would e.g. a zonal mean analysis not be a better suited approach to separate regimes?

Our focus is on global land but we additionally looked at these regional anomalies more closely. Zonal means would blur some regionally compensating areas and inhibit physical interpretation. Based on ERA5 results, supplemented by other data sources, we observe large coherent changes in humidity, clouds, surface net solar radiation, and precipitation across South America, as well as in southwestern North America. Collectively, these variables provide a strong indicator of the continent's sensitivity to climate change.

6. It is does not become clear why both reanalysis and observations are analysed. Since ERA5 has radiation simulated by IFS without assimilating any observations (Hersbach et al., 2020). Why is not only CERES used for the radiation trends, if ERA5 features radiation simulated by IFS that is not assimilated? It would be easier to follow if the feedback would be shown on a minimal set of datasets and variables, and in an optional second step it would be checked if a possible feedback is apparent in other sources.

The present study is based on ERA5 reanalysis and data back to the 1980s, while CERES data are available for the shorter period from 2000 and hence too late to capture important long-term changes, including strong reductions in aerosols before 2000 in Europe and US. We have therefore also included results from the CLARA-A3 satellite observations since 1982 in the present study. Even so, we believe the comparisons between ERA5 and CERES radiation quantities are relevant as well to explore (in-) consistencies. Based on the radiation quantities, we employ a multi-dataset observational constraint framework to evaluate co-dependent equilibrium trends also with regards to ERA5 humidity, clouds and precipitation, given the highly coupled nature of these variables. We have rewritten the last three paragraphs in Section 1 to improve the description of the study's aim, as well as to provide a motivation for the use of the data sets included in the investigation:

"*The present study aims to investigate potential positive feedbacks over land globally by investigating changes in surface and air humidity, clouds, solar radiation, and precipitation from ECMWF ERA5 reanalysis to a steady increase in ocean-land warming contrast since 1979. Impacts from changes in solar radiation at the top of the atmosphere (TOA) on surface energy balance and air temperature have been investigated. Uncertainties in the energy balance will be presented. Investigating the water vapor's response to temperature directly addresses the Clausius-Clapeyron relationship, which gives an indication of possible moisture deficit over land. By analysing the Bowen ratio we link moisture availability with temperature trends and a shift in the heat fluxes, which expose underlying mechanisms of land-atmosphere coupling, thus, whether available energy is used to evaporate water* *or heat the air. As contrasting regional extremes, we evaluate South America vs. land areas in mid- and high latitudes in the Northern Hemisphere (43°N–90°N, 180°W–180°E) during the period 1979−2023. The aim is to investigate possible regional differences in humidity supply and cooling in infrared, relevant for the warming trend. Possible changes in land albedo for the areas in the Northern Hemisphere have also been investigated. Changes in precipitation during the investigation period are a fingerprint of perturbed surface water balance.*

We first introduce the various datasets and methods in Sect. 2. In Sect. 3 we present results of ERA5 TOA radiation quantities compared to Clouds and the Earth's Radiant Energy System (CERES) and CLoud, Albedo and surface RAdiation (CLARA-A3) satellite radiation observations of the period 2001–2023, while also considering 1982–2023 for the latter platform. ERA5 specific humidity and relative humidity are compared to Integrated Surface Database Humidity (HadISDH) gridded humidity in-situ observations since 1979. Results of total precipitation over land globally from ERA5 compared to Global Precipitation Climatology Project (GPCP) and Global Precipitation Climatology Centre (GPCC) since 1983 are presented in Sect. 3. Section 4 provides a discussion of changes in radiation, humidity, cloud cover, and precipitation driven by the anthropogenic reinforced greenhouse effect. Conclusions are presented in Section 5.

The objective is to investigate a possible feedback loop between humidity, clouds, and solar radiation in the ERA5 dataset. Given the highly coupled nature of these variables, we employ a multi-dataset observational constraint framework to evaluate their co-dependent equilibrium trends. While individual trends of the current variables have been studied in isolation, the aim with our study is to simultaneously evaluate ERA5 across three distinct earth system components (humidity, radiation, precipitation) using independent observations (HadISDH, CERES/CLARA-A3, GPCP/GPCC) to investigate a possible feedback loop driven by the accelerated ocean-land warming contrast. Finally, we incorporate recent studies on rapid global land-warming to corroborate our findings."

Further comments:

Introduction

This section lacks a through line. Further, the research gap is not clearly stated.

In the two paragraphs in the beginning of Section 1 we describe the overall global warming and thereafter present results of the differentiated land and ocean warming, relevant for the objective in the present study. Based on previous studies we explore possible causes of the differentiated warming. At the end of the second paragraph in the revised version of the manuscript, we have included the study suggested by the referee in the major concerns (see our answer above to point 4).

We continue in the third paragraph of Section 1 to present results of anthropogenic aerosols that the referee is pointing out in the major concern, point 3 (see our reply above concerning this issue). In the second original sentence in the third paragraph, we have included the study by Wild et al. (2026): "*In addition to internal variability, regional changes are forced by more heterogeneous perturbations, such as anthropogenic aerosols that temporarily mask greenhouse warming (Glantz et al., 2022; IPCC, 2021; Quaas et al., 2022; Wild et al., 2026)*." We continue in third paragraph to describe results of the jump in the global warming during recent years. At the end of this paragraph, we have included outcomes from previous studies about impact from changes in atmospheric circulation relevant for the warming trends. Concerning this issue, we mention in Section 5 a research gap related to the present study: "*Natural internal variability not investigated in the present study may also play a role for record-low planetary albedo associated with reduced low-level clouds, although the contribution is expected to subside and leave the observed longer-term warming unaffected (Goessling et al., 2024)*."

In the fourth and fifth paragraphs we focus on water vapour response to temperature, relevant for the differentiated warming between land and ocean. Here we also present results from previous studies in which decreases in relative humidity have been identified. At the end of Section 1 we have included the following sentence that describe the use of the Clausius-Clapeyron relationship: "*Investigating water vapor response to temperature directly addresses the Clausius-Clapeyron relationship, which gives an indication of possible moisture deficit over land*."

We continue in the sixth and seventh paragraphs to focus on clouds, one of the key variables in the proposed feedback loop between humidity, clouds and solar radiation. At the end of the sixth paragraph the following sentence has been included: "*Substantial continental brightening from 1980 to 2024 with co-located reductions in total cloud cover were found over central United States, Brazil and central Asia, although no large trends in aerosol concentrations have occurred over the same period (McKinnon and Simpson, 2025).*"

In the eight paragraph we continue presenting results of humidity deficit and findings in the study by Manabe (2019), who explain why the land surface get perturbed by the enhanced greenhouse effect. This is relevant for our study considering that land surface is additionally perturbed at present by increases in absorbed solar radiation. See also our reply above, related to Section 1, to the major concern, point 6, by the referee.

Line 91: „Clouds affect outgoing longwave radiation in the same way as GHGs" - This statement is not correct, even with the conditional clause that follows, because their effect depends on altitude and is spectrally much more uniform. Saying they operate "in the same way" is physically misleading.

We agree with the referee and the sentence has been changed to the following: "*Clouds in addition to GHGs re-radiates longwave radiation back to the land surface, but the net effect on the radiation budget also depends on the reflection of incoming solar radiation*."

Methods

This section seems a bit overly detailed, specifics of the products that are not relevant to this study can be looked up in the release papers of the products.

We have excluded the following sentence "*Over the long-term, GPCP represents the current state of the art.*" in Section 2.5

Line 165: It is mentioned that ERA5 temperature is used, but it is inconsistent which variable (skin layer, 2m). Why is skin temperature not used throughout? Like for humidity, there is opportunity to make the paper more consistent, and introduce the specific variables here.

We have changed the phrase to "ERA5 temperature at 2m height". The ERA5 T at 2m is better to use than the skin temperature for investigating atmospheric moisture, since it represents the actual air temperature where water vapor mixes and resides, while the skin temperature is a theoretical surface energy balance parameter that often decouples from the air mass above it.

Line 259: Why does a low spatial resolution prevent area-weighing?

HadISDH data doesn't coverage land to 100%, thus, spatial gap in the data appears. We have therefore changed the colour bar for Figures 3 and 4, so white colour previously related to zero values has been excluded and the white colour denotes now instead missing data (see the figures at the end of this reply document). This is the reason why we have excluded area weighting of the HadISDH data, since the weighting requires full data coverage to establish accurate averaging.

We have changed the current sentence to "*Global land annual mean values of the parameters from ERA5, CERES, and CLARA-A3 grid fields have been area-weighted before the analyses, with the exception of the HadISDH dataset, due to limitations in the spatial coverage*."

Results

The discussion of humidity changes is partly unclear. It's comprehensible that relative humidity is a 0th order measure for cloud formation because it directly encapsulates how far air is from condensation, and constant relative humidity still is a common null hypothesis. However, the analysis of changes in specific humidity (Figure 4) and the ratio of column water vapour over 2m temperature doesn't seem to be relevent for the argument. Further, it is unclear why the latter quantity would be a meaningful quantity when there are accepted measures like the column relative humidity.

We agree with the referee that relative humidity is a relevant indicator for saturation of air and cloud formation. Evaluating ERA5 2m air temperature alongside column water vapor (referred to as total column water vapor or precipitable water vapor) is however a standard approach in climate science (e.g. Wan et al., 2024) to investigate atmospheric thermodynamics. When investigating the atmosphere's humidity response to warming, column water vapour is more proper to use than column relative humidity because it represents an absolute physical quantity, whereas relative humidity is a relative mathematical ratio that changes with temperature. According to the Clausius-Clapeyron equation column water vapour could increase with about 7% per one degree Kelvin. To a first approximation, climate models assume global tropospheric relative humidity stays near-constant as the planet warms. A deviation from this scaling is however expected over land due to the ocean-land warming contrast, which prevents the land's atmospheric moisture from keeping pace with its faster-rising temperatures. Because continents lack the unlimited water supply of the oceans, relative humidity over land drops as it warms, causing the actual column water vapor to fall short of the theoretical saturation limit dictated by the Clausius-Clapeyron relation (Figure 9 and lines 80, 475-484, 647-659). The extreme cases with decline in both relative humidity and specific humidity, for example in South America and southwestern North America, is of course important finding considering humidity deficit. The results of ERA5 specific humidity are relevant for the apparent humidity paradox, since positive trends appear simultaneous with decreases in relative humidity.

Subsection 3.6: It's doesn't become clear why precipitation is taken as indicator for land humidity and not moisture convergence (or mean P-E as analog). It seems like the statement in line 23 could be made if P-E had ben analysed, but not only analysing P. Changes in precipitation and evaporation can balance each other in terms of the moisture budget and be more dependent on changes in stability and vertical motion than humidity. Also, an increase in shortwave radiation is often associated with an increase in precipitation (e.g. Wild et. al. 2018), which opposes your argument. How do you reconcile this, and why do you use precipitation instead of P-E?

The negative trend in precipitation in both the ERA5 and GPCP data over the regions mentioned in Section 3.6, South America, Africa, and Australia, and in southwestern North America, have occurred at the same time with decreases in ERA5 specific humidity and latent heat flux, while sensible heat flux has increased. Since increase in precipitation has not compensated for the disturbed surface energy balance associated with deficit in humidity and increase in water demand (which in turn are related to evaporation) the decrease in precipitation then strongly indicates stress on the water cycle in these areas. Concerning this issue, see the discussion related to the study by Manabe (2019) in Section 1, between the lines 127 - 134, as well to the sentence on line 639 in Section 4. We don't find in the study by Wild et al, (2005) (link in the referee's reference list) that the authors state the supposed relation between shortwave radiation and precipitation. We neither found that the study by Wild et al. (2018) states this. Even so, we are not surprised if this could be the case in situation over land where there is no stress on the terrestrial water cycle and increase in the water demand. Particularly over the ocean this should be the case.

The following sentence in the first paragraph of Section 3.6 has been modified: "*The negative trends coincide with decreases in ERA5 latent heat flux and specific humidity shown in Fig. 5e and 5f, respectively, which indicate increases in water demand*."

Line 690: An increase in the Bowen ratio could also be caused by a decrease in the sensible heat flux

The referee is right, this could happen, but the sensible heat flux increases for the present case because absorbed solar radiation at the land surface has increased.

Line 704: This is what is expected from Byrne&O'Gorman but it reads like it was a new finding of this study

We have changed the sentence to: "*The decreases in relative humidity over land globally coincide with rapid warming compared to the weaker warming over the oceans*." In Section 1 and Section 3.4 we refer to previous studies concerning the decrease in relative humidity.

Figures/Tables:

Generally it'd be helpful if regions of non-significant trends would contain hatches. Some figures don't seem necessary for the line of argument and could be excluded or put in a supplementary section (Figure 4,9,10,11,12).

Trends not statistically significant have been marked in Figures 5, 6 and 9 (see figures at the end of this reply document). The first paragraph of Section 3.4 and fourth paragraph of Section 3.5 have consequently been rewritten.

If a figure or table is not given much notice in the manuscript, we agree with the referee to move the material to the appendix. Figure 4 is relevant for the apparent humidity paradox, considering areas in the Northern Hemisphere where an increase in specific humidity is found simultaneously as relative humidity has decreased (Figures 5f and 5g). Figure 4 is relevant as well considering humidity deficit, decreases in cloud cover and precipitation, thus, increase in water demand, for example in South America and southwestern North America. Considering Figures 4 and 9, see our answer to the first comment by the referee belonging to the part denoted with "Results" above. There is a chapter included in Section 3.5 to present the results of albedo changes in the Northern Hemisphere shown in Figure 10. The results are in line with two previous studies that we refer to. The present results are relevant for the ERA5 surface energy balance and the degree of warming. The influences of decreases in snow cover in the Northern Hemisphere are also discussed in Section 4. Reduced surface albedo is noticed today as a contribution factor to explain why Europe, among the continents, warming up fastest in the world. Decreases in land albedo influences warming as well in other regions in the Northern Hemisphere (Figure 5a). Considering Figures 11 and 12, we refer to our reply to the comment by the referee related to “Subsection 3.6” above.

We thank the referee for the suggestion, but have decided to keep the Figures 4,9,10,11,12 in the main text.

Table 1: The table is much too large and difficult to interpret. It seems like the data would be perfectly suited to create a boxplot or violinplot, please consider such a visualization style instead of a table. Further, the angle brackets defined in the caption could be used in Eq. 1. This could also be considered for Table 2.

We thank the referee for the suggestion. However, we respectfully disagree that a boxplot is the appropriate format for Table 1. The data in Table 1 do not represent a large population or distribution of independent samples; rather, they are a set of 8 distinct, aggregated statistical metrics (including R^2, RMSD, NRMS, MBE, mean values, trend values) comparing ERA5 against the other data sets directly.

Converting these disparate statistical values into a boxplot would obscure the exact, absolute numbers that are necessary for the reader to evaluate the performance of the reanalysis against the satellite observations. We believe the current table format provides the most precise and unambiguous way to present this quantitative comparison. In the surrounding paragraphs we guide the reader through the most critical values in the table.

The angle bracket symbol “<>” is already included in the text caption to Table 2, but the delta symbol “Δ” has been included in the footnote of Table 2. We have included the bracket symbol in Eq.1.

In Figure 6, a diverging colorbar would immensely help identifying the sign of change. Again, hatching would be helpful to denote significance.

We have included a contour line that denotes the 95% confidence level in Figures 6a and 6b (see figure below). We have tested with different diverging colorbars for these figures, but found that the “parula” suits best here for the focus on land globally. We believe the additional information given in the body text, in addition the contour lines, facilitates for the readers to catch the relevant findings.

In Figure 10, it is unclear what ‚100%‘ refer to. Judging from the colorbar label it seems like all yellow regions show a 100% increase, when it probably means 0 change. Further, it seems like seasonal means would be sufficient, and for consistency with the other figures it would be nice to show the trend per decade.

We agree with the referee that the results can be more clearly presented, which means to flip the colours so higher values represent larger changes between the two periods (see Figure 10 at the end of this reply document). This means, instead of calculating the rate between the two periods the difference divided by the mean of the period 1979-1988 has been calculated. We have accordingly made the changes in the sub-figures, changed text in Section 3.5 and in the figure caption to Figure 10: ”*Changes in ERA5 annual surface upward solar radiation (in percent) in the Northern hemisphere, obtained by comparing differences in mean values of the periods 1979-1988 and 2014-2023 divided by mean values of the former period*.”

We thank the referee for the suggestion, but prefer to present the results based on comparison between the two decades, since a linear decrease is not expected for a change in surface albedo related to a shorter season with snow cover. We believe monthly averaging is more suitable to present. With seasonal averaging results will not be able to present for areas in the winter season due to the polar night.

Figure 11 It would be clearer if the period (yr) was in the colorbar label

It will not be clear to separate the original text, since the phrase "of the period" is a relevant link between the first and last parts of the text. This text is not necessary to present in the figure, since the information is available in the figure caption. Even so, we believe the original presentation facilitates understanding for the readers.

Issues of understanding/precision:

Line 722: „crossing of the vapor-liquid phase": Do you just mean to say evaporation?

We mean saturation of the air and decided to keep the phrase.

Line 665: „Luo et al. (2024b) and Næss et al. (2025) found a reduction in the clouds due to deforestation" Considering the many metrics for clouds, which one are you referring to?

We have changed the text to: "*A slight but statistically insignificant increase in total cloud cover across the Amazon was found by Næss et al. (2025). Luo et al. (2024) provide evidence for local decreases in global low-level clouds and tropical high-level clouds from deforestation through both idealized deforestation simulations with climate models and from observations-driven reanalysis using space-for-time substitution*."

Line 667: „The overall biophysical effect of deforestation": please specify which effect you are referring to.

The sentence has been changed to "*The overall biophysical effect of deforestation, cooling by increased surface albedo versus warming due to decrease in evapotranspiration, leads to cooling in the boreal zone*."

Line 688: „natural level" Do you mean preindustrial?

We have changed the phrase to "background levels".

References:

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Bowen ratio

We have improved the investigation of the Bowen ratio and Figure 9 (see below) has been modified with results of Bowen ratio and evaporative fraction. The name of Section 2.7 has been changed to "*2.7 Statistical analysis, Bowen ratio and evaporative fraction*". The following text has been included in this section:

"*Trends in Bowen ratio (BR) and evaporative fraction (EF) between sensible and latent heat flux (SHF and LHF, respectively) have been investigated:*

$$BR = \frac{SHF}{LHF} = \frac{1-EF}{EF}, \tag{7}$$

$$EF = \frac{1}{1+BR} = \frac{LHF}{SHF+LHF} \tag{8}$$

with a screening mask for BR, EF > 0, to avoid division with zero and BR <= 50 as a crucial boundary cap, since small values of EF yield disproportionately massive Bowen ratios. The screening mask for EF: total heat flux (SHF + LHF) is larger than 5, which eliminates low-energy cases where the Bowen ratio breaks down, and the range 0 – 1 is also applied for EF, which limit the data to a realistic physical window and removing all unphysical spikes."

The fourth paragraph in Section 3.5 has been modified with the following sentence: "*Statistically significant increases in the Bowen ratio between sensible and latent heat flux with 19 and 26% from 1979 to 2023 for annual and summer averaging, respectively, are shown in Figure 9b*." and text:

"*Depletion of water supply has affected latent heat flux that is associated with a statistically significant negative trend of -0.37 W m^{-2} decade^{-1} for South America, although minor increases appear regionally in Fig. 5e. In addition to a strong increase in mean sensible heat flux, with 1.1 W m^{-2} decade^{-1} (Fig. 7e), substantially reduced evaporative cooling has consequently occurred in South America during the latest four decades. Statistically significant increases in the Bowen ratio between sensible and latent heat flux with 19 and 26% from 1979 to 2023 for annual and summer averaging, respectively, are shown in Figure 9b Specific humidity has however increased over the current Northern Hemisphere region, while relative humidity and low cloud cover have decreased (Figure 8). This is probably driven by the differentiation of warming in the oceans and in the air over land, which causes the air to be further away from saturation at present. Figure 8e shows a strong increase in mean total heat flux over the areas in the Northern Hemisphere, where the positive trend in sensible heat flux, 0.54 W m^{-2} decade^{-1}, is higher than 0.43 W m^{-2} decade^{-1} for latent heat flux. In addition to large part of South America, Fig. 9c and 9e show that significant increases in Bowen ratio appear in southwestern North America, central and northern Africa, central Australia and large parts of Europe. The shift in heat fluxes is found in the results of the evaporative fraction as well (Fig. 9d and 9f), while also here South Asia deviates from these changes. The very low annual values in northern Russia (Fig. 9c) indicate, however, that the Bowen ratio breaks down due to air-to-land sensible heat flux in winter that rendering the standard mathematical definition. The screening mask introduced for the evaporative fraction (Section 2.7) removes these extreme unphysical mathematical spikes (Fig. 9d), while also in part of Europe for the winter season.*"

Finally, at the end of the fifth paragraph in Section 4 the following text has been included: "*The weak or negative trends in the ERA5 total column water vapour to surface temperature ratio over land from 1979 to 2023 shown in Fig. 9a indicate that atmospheric moisture is not keeping pace with temperature increases, invalidating Clausius-Clapeyron scaling. These findings point to severe land-based moisture limitations and declining relative humidity, where drier surfaces likely enhance local warming via increased and reduced sensible and latent heat fluxes, respectively. The Bowen ratio between sensible and latent heat flux has significantly increased from 1979 to 2023 over large parts of global land (Fig. 9c and 9e).*

Figures

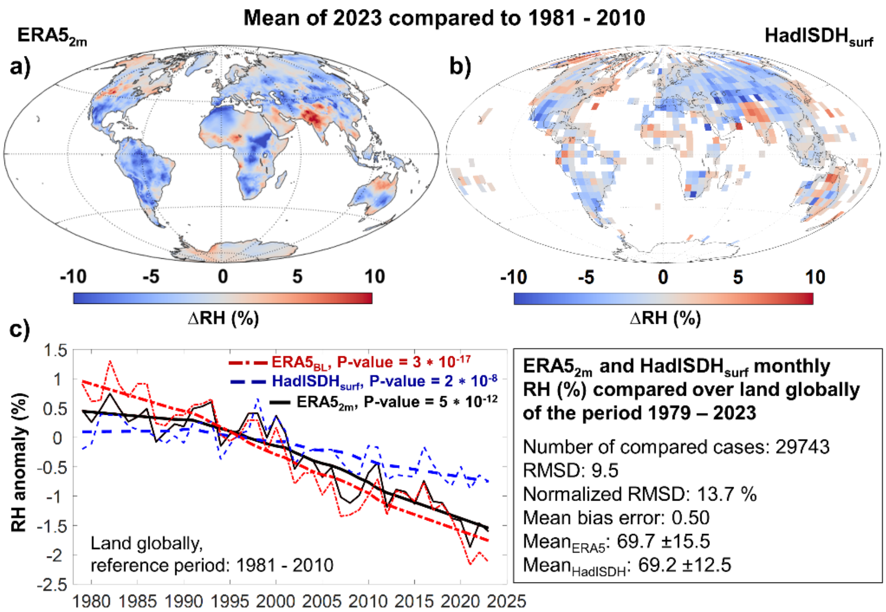

Figure 3. Comparison of relative humidity (RH) in the lower troposphere between a) ERA5 and b) HadISDH for 2023 relative to the period 1981–2010. Heavy black solid and blue dashed lines for ERA5 and HadISDH, respectively, in c) denote trend lines where the Savitzky-Golay finite impulse response smoothing filter of polynomial order has been applied on annual and global land time series represented by the light black solid and blue dashed lines. P-values of the trends are obtained by the Mann-Kendall test at the 95% confidence interval applied to the annual values. The evaluation statistics in the lower right were obtained by comparing the monthly mean values of the ERA5 and HadISDH time series.

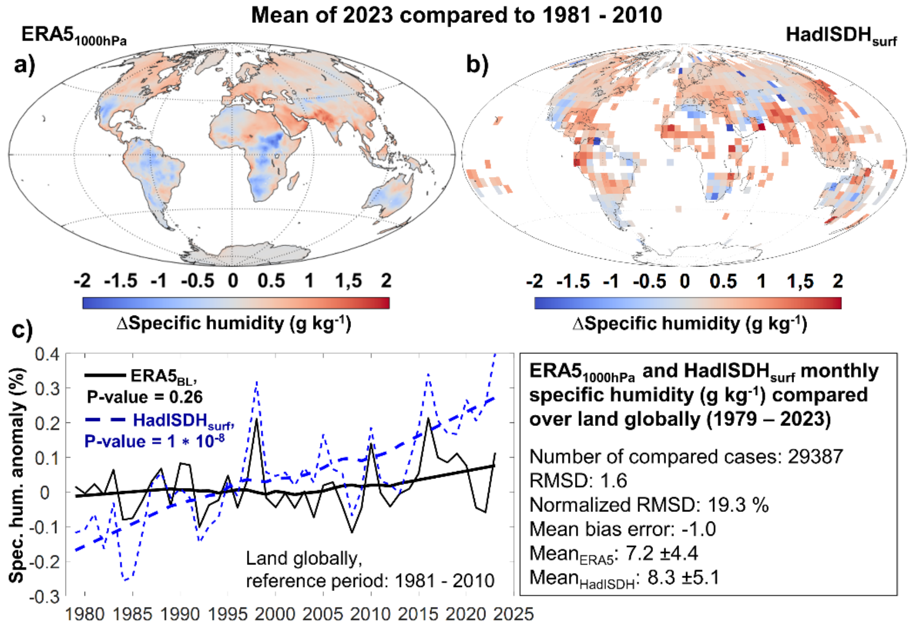

Figure 4. Comparison of specific humidity in the lower troposphere between a) ERA5 and b) HadISDH for 2023 relative to the period 1981-2010. Heavy black solid and blue dashed lines for ERA5 and HadISDH, respectively, in c) denote trend lines where the Savitzky-Golay finite impulse response smoothing filter of polynomial order has been applied on annual and global land time series represented by the light black solid and blue dashed lines. P-values of the trends are obtained by the Mann-Kendall test at the 95% confidence interval applied to the annual values. The evaluation statistics in the lower right were obtained by comparing the monthly mean values of the ERA5 and HadISDH time series.

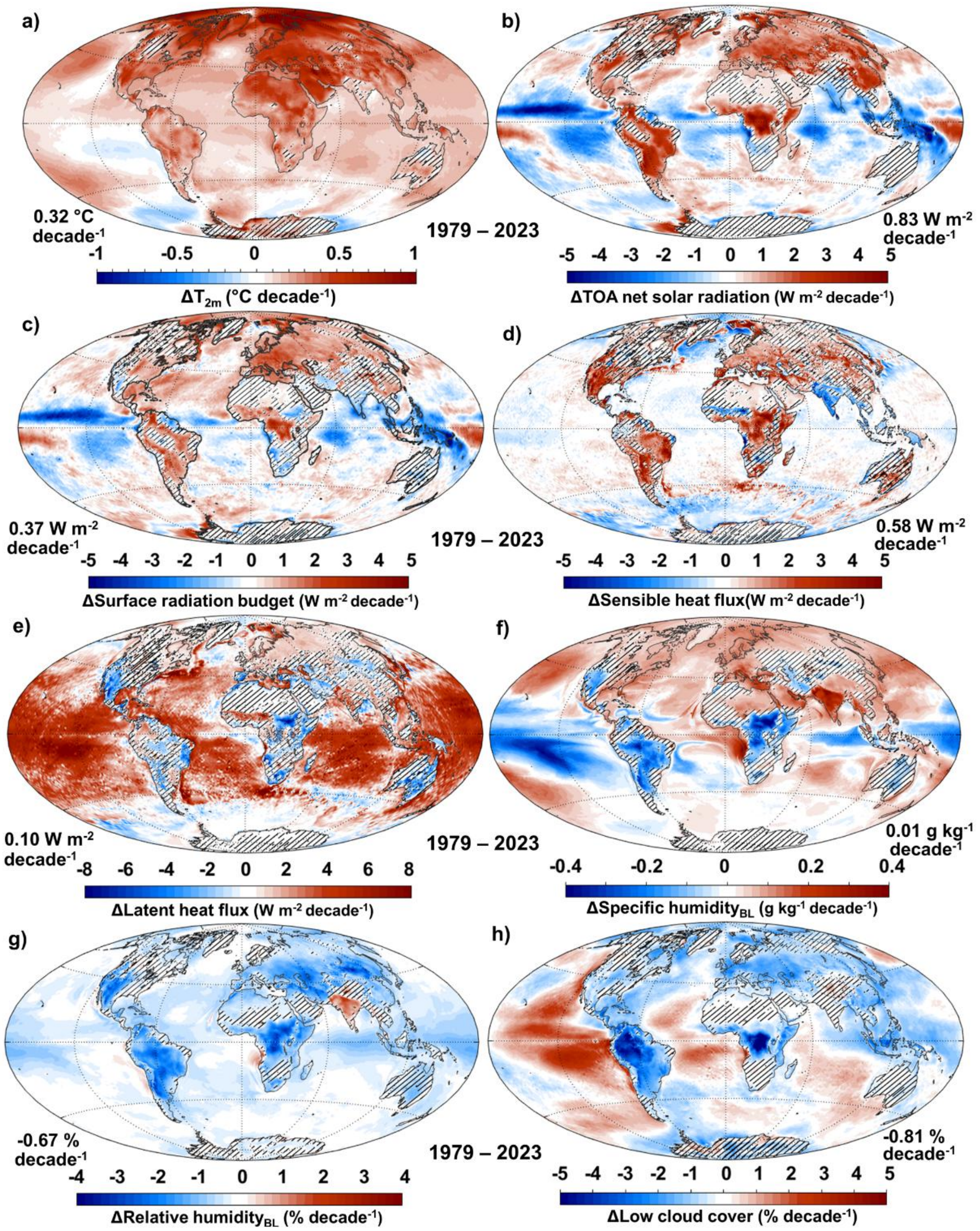

Figure 5. Trends in ERA5 a) temperature at two-metre height (T_{2m}), b) top of the atmosphere (TOA) net solar radiation, c) surface radiation budget, d) surface sensible heat flux, e) surface latent heat flux, f) specific humidity in the boundary layer (BL), g) relative humidity in the BL and h) low cloud cover represented by linear regression of the period 1979–2023. Trend values represent area-weighted means with respect to land globally. The hatched areas over land represent trends that are not statistically significant at the 95% confidence level.

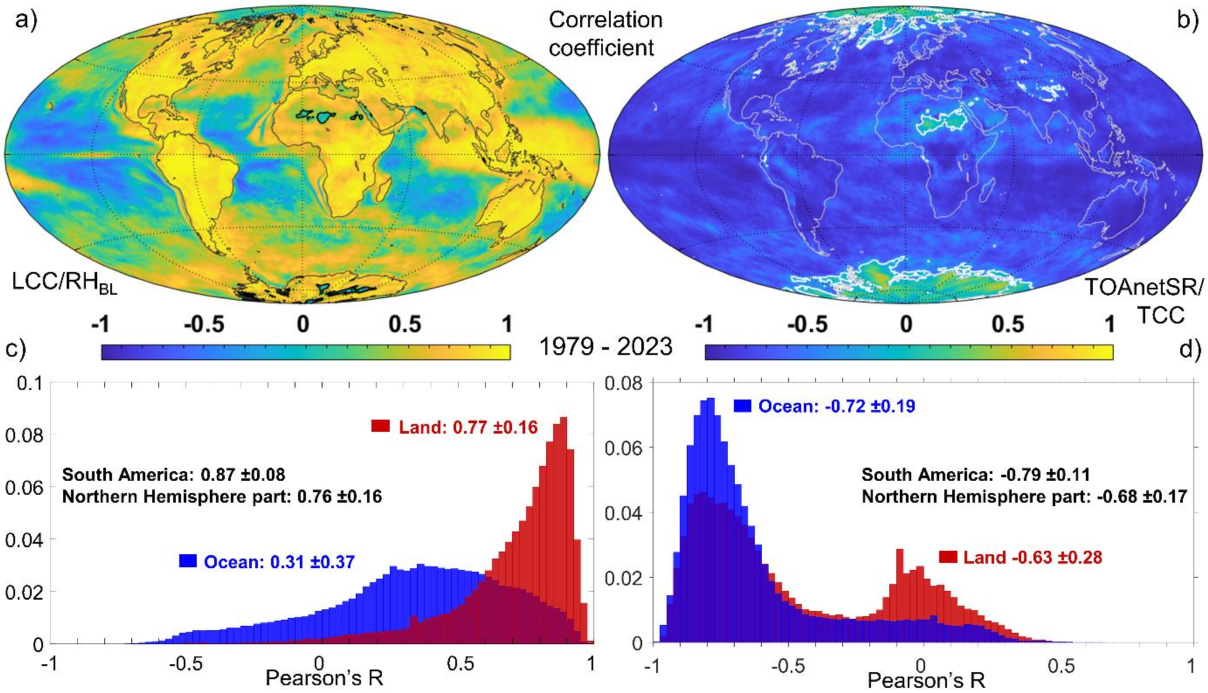

Figure 6. Scenes of Pearson's correlation between annual a) relative humidity in the boundary layer (RH_{BLH}) and low cloud cover (LCC) and b) total cloud cover (TCC) and net top of the atmosphere solar radiation (TOAnetSR) of the period 1979 – 2023. c) and d) Normalized distribution Pearson's correlation coefficient from results presented in panel a) and b), respectively, for land and ocean globally with corresponding mean values presented. Mean values of correlation coefficient are also presented for South America and the areas in the Northern Hemisphere (43°N-90°N, 180°W-180°E). The black and white solid lines in a) and b), respectively, denote land areas where correlation is not statistically significant at the 95% confidence level.

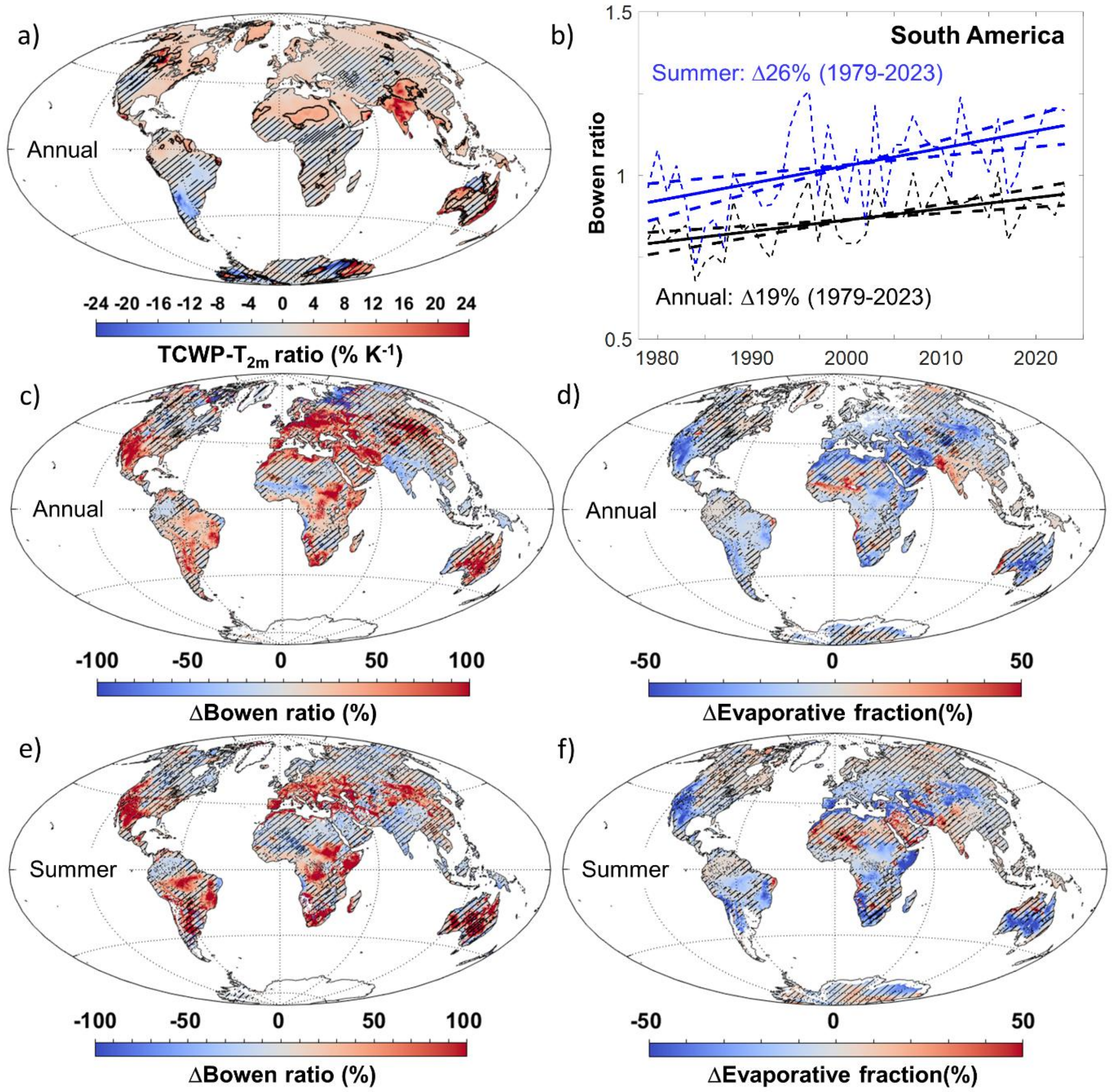

Figure 9. a) Trends in the ratio between ERA5 annual total column water vapour (TCWP in %) and temperature at 2 m height (T_{2m} in kelvin (K)) from 1979 to 2023, where the black solid line denotes 7 % per K according to Clausius-Clapeyron equation between uptake of moisture in the air due to warming. b) Heavy solid and dashed lines denote linear regressions and corresponding 95% confidence intervals, respectively, for annual and summer averaging (June – August) of ERA5 Bowen ratio (light dashed lines) obtained over area-weighted South America of the period 1979 – 2023. c) and e) Trends in Bowen ratio (in percent) by linear regression for annual and summer averaging, respectively. d) and f) Trends Evaporative fraction (in percent) by linear regression for annual and summer averaging, respectively. The hatched areas over land represent trends that are not statistically significant at the 95% confidence level.

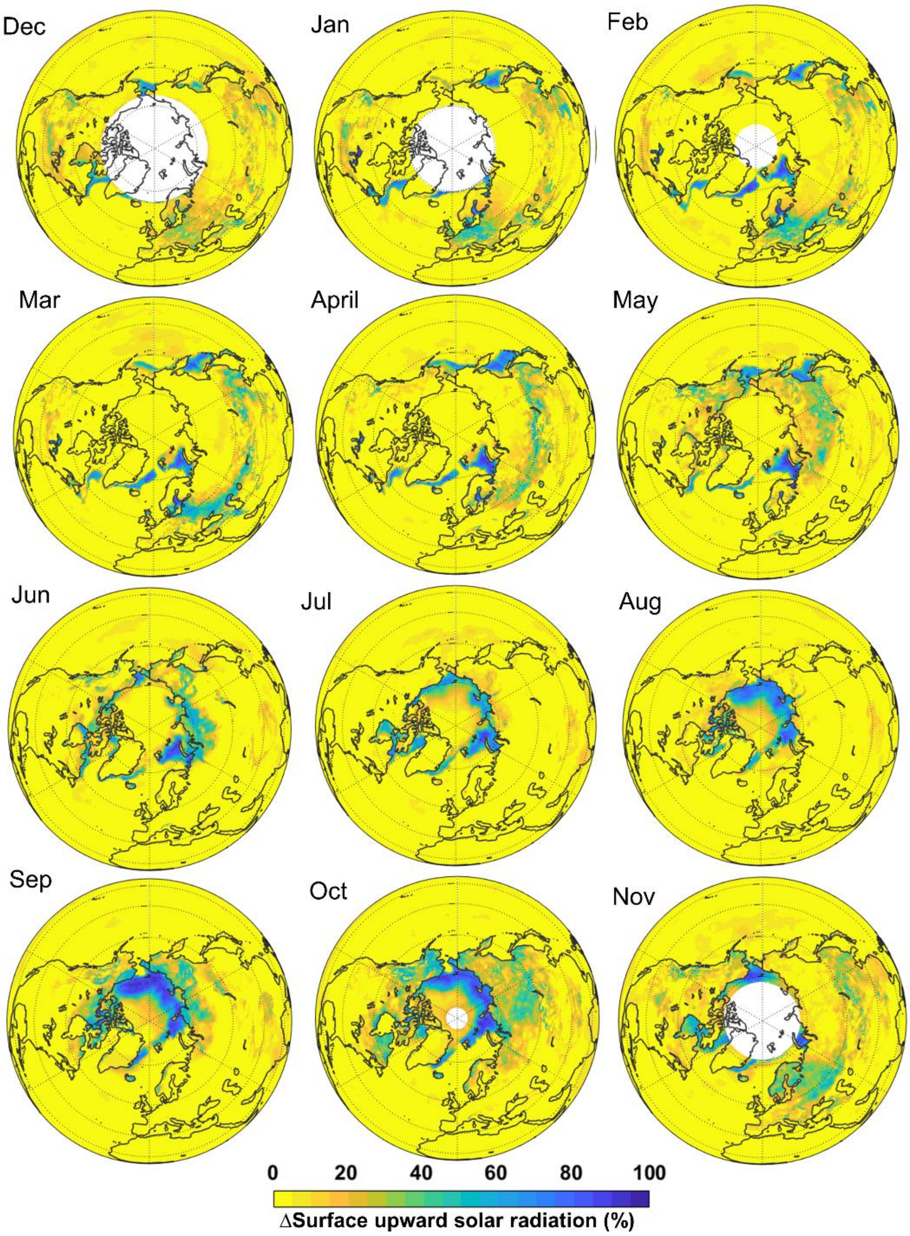

Figure 10. Changes in ERA5 annual surface upward solar radiation (in percent) in the Northern hemisphere, obtained by comparing differences in mean values of the periods 1979-1988 and 2014-2023 divided by mean values of the former period. No data are available during the polar night, denoted with white colour.