# Linearity of outgoing longwave radiation: From an atmospheric column to global climate models

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**Key Points:**

- The longwave clear-sky (LWCS) feedback has distinct spatial patterns in CMIP5 models, while the global-mean feedback is robustly 1.9 $\mathrm{W/m^2/K}$.
- The various spatial patterns of LWCS feedback across models can be explained by the spatial patterns of column RH changes.
- The global-mean LWCS feedback is robust as a result of that OLR is linear when conditioned upon RH and the RH histogram is invariant.

## Abstract

The linearity of the global-mean outgoing longwave radiation (OLR) with surface temperature has important implications for climate sensitivity. Global climate models robustly produce a $1.9\,\mathrm{W/m^2/K}$ of global-mean longwave clear-sky (LWCS) feedback. This number is consistent with idealized single-column atmospheric models (Koll & Cronin, 2018). However, there is considerable spatial variation in the LWCS feedback including negative values over tropical oceans known as the “super-greenhouse effect” which is compensated by larger values in the subtropics/extratropics. Therefore it is unclear how the idealized model results are relevant for the global-mean LWCS feedback in comprehensive climate models. Here we show with a simple analytical theory and model output that the compensation of this spatial variability to produce a robust global-mean feedback can be explained by two facts: 1) when conditioned upon free-tropospheric column relative humidity (RH), the LWCS feedback is independent of RH, and 2) the global histogram of column RH is largely invariant under warming.



## Plain Language Summary

In response to $CO_2$ forcing, the Earth's climate warmings and emits more OLR to space. This OLR emission is linear with the global mean surface temperature as a result of the water vapor feedback. Previous work has demonstrated this understanding in single-column atmospheric models with fixed RH. The question remains, however, why the Earth behaves like a single atmospheric column given the diversity of RH values across the globe. Here we theoretically show that the analogue for fixed RH of a single column is that the global RH histogram is invariant under warming. We further demonstrate with model output that this invariance indeed holds. These results thus fill the missing link between the theory for a single column and the fact that the global-mean OLR being linear.


## 1 Introduction

A standard paradigm for analyzing the Earth's climate and climate sensitivity is to treat is as a linear system (e.g. Gregory et al., 2004). An implicit assumption in those treatments is that the global-mean outgoing longwave radiation (OLR) is linear with the global-mean surface temperature ($\overline{T_s}$). Indeed, as is shown in Figure 1a, the annual-mean global mean clear-sky OLR ($\overline{\mathrm{OLR}}$) from the Coupled Model Intercomparison Project phase 5 (CMIP5) (Taylor et al., 2012) increases in a strikingly linear fashion with $\overline{T_s}$ for each model after abruptly quadrupling $CO_2$ concentration. Though models warm by various amounts after 150 years, the LWCS feedback (slope of the linear regression of $\overline{\mathrm{OLR}}$ against $\overline{T}_s$) varies by only 5% around the mean value of 1.88 W/m$^2$/K for the 9 models from different modeling centers shown, consistent with previous work (Andrews et al., 2015). Notably, this value is also consistent with idealized single-column model calculation by Koll and Cronin (2018) over a wide range of surface temperatures.

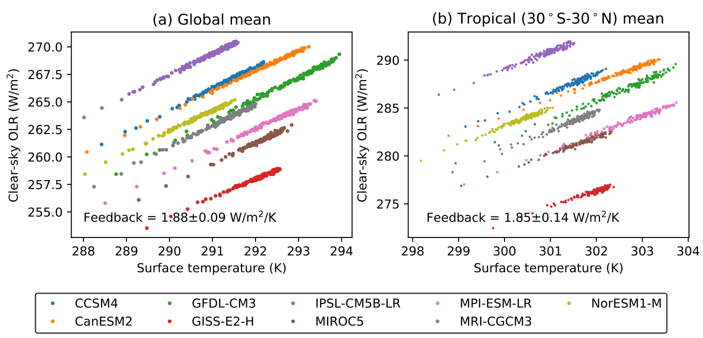


**Figure 1.** (a) Annual mean and global mean clear-sky OLR vs. surface temperature of CMIP5 models for the abrupt 4x$CO_2$ experiment. (b) The same as (a) but for the tropical (30°S-30°N) mean.

This robust global mean LWCS feedback, however, is made up of non-uniform local responses which moreover differ amongst models. The OLR increase per unit warming in the deep tropics is relatively low, and sometimes even negative, an effect known as the “super-greenhouse effect”. This phenomenon has received some attention as a local feedback (Raval & Ramanathan, 1989; Valero et al., 1997; Stephens & Greenwald, 1991; Stephens et al., 2016; Dewey & Goldblatt, 2018; Raghuraman et al., 2019), but its relevance for the global climate sensitivity is unclear given that other regions seem to emit more OLR per unit warming to compensate. Here we would like to understand this compensation and whether it is guaranteed under global warming.

The origin of OLR being linear with $T_s$ rather than quartic (as suggested by the Stefan–Boltzmann law) lies in the water vapor feedback given that the relative humidity (RH) remains constant with warming (Ingram, 2010; Koll & Cronin, 2018). OLR calculation for a single-column atmospheric model does confirm that there exists a wide range of $T_s$ where the LWCS feedback varies by less than $\pm 10\%$ around $2\,\mathrm{W/m^2/K}$ if the atmospheric column follows a warming trajectory of constant RH (Koll & Cronin, 2018). Here we conceptually describe the behavior of this single-column atmospheric model with the following equation:

$$\left.\frac{\partial \mathrm{OLR}}{\partial T_s}\right|_{\mathrm{RH}} \approx \alpha \approx 2\ \mathrm{W/m^2/K} \tag{1}$$

However, unlike the idealized column model, the vertical profile of RH is rarely uniform and inversions can complicate the vertical temperature profiles. Furthermore, the RH profile in a given column need not be constant. Therefore, Eq. (1) is not directly applicable to the global mean of CMIP5 models shown in Fig. 1a. It is thus unclear whether the agreement between the global climate models and the idealized single-column model is coincidental.

Here we show that this agreement is not a coincidence. We first investigate the spatial patterns of LWCS feedback in CMIP5 models to get a sense of how the spatial patterns compensate and further show that the spatial patterns are tied to column RH changes. We find that $\alpha$ is independent of column RH so long as the column RH is interpreted as being in the free troposphere. We show analytically that the global mean LWCS feedback will be equal to $\alpha$ so long as the global histogram of column RH doesn't change with warming, a criterion satisfied to a large degree by all CMIP5 models.

## 2 Materials and Methods

The LWCS feedback is diagnosed following the forcing-response analysis introduced by Gregory et al. (2004). Monthly mean output of global climate models from Coupled Model Intercomparison Project phase 5 (Taylor et al., 2012) for the abrupt4x$CO_2$ experiment (abruptly quadrupling $CO_2$ then integrate for 150 years) is analyzed. The local longwave clear-sky feedback is determined by linear regression of local clear-sky OLR onto *local* surface temperature to emphasize the physical connection between OLR and local surface temperature (The advantage of using locally defined feedback is discussed in Feldl and Roe (2013)), which is not the same as earlier work that regresses local radiative quantities onto global mean surface temperature (e.g. Andrews et al., 2015; Stephens et al., 2016). As the clear-sky feedback is roughly constant throughout the entire length of the simulation (150 years; Figure 1), we will not separate the fast response epoch ($\sim$ the first 20 years) and the slow response epoch (the rest 130 years or so) in the following analysis.

Column relative humidity is calculated as the water vapor mass divided by the saturated water vapor mass within the column. To calculate the water vapor mass between every two pressure levels, specific humidity data are interpolated to the center of pressure levels assuming linearity with the logarithm of pressure and then weighted by the pressure difference.

## 3 Spatial pattern of LWCS feedback and connection to column RH

We demonstrate the spatial pattern of the LWCS feedback and the ensuing compensation which produces the robust value of $\alpha$ shown in Fig. 1a by gradually increasing the spatial dimensions of our analysis. Figure 2a shows the zonal-mean feedback obtained by regressing the zonal-mean clear-sky OLR onto the zonal-mean surface temperature using decadal mean data (to smooth over inter-annual internal variability). The zonal-mean LWCS feedback is not uniform across latitudes, with a minimum of $1\,\mathrm{W/m^2/K}$ in the deep tropics and a typical value of $2\,\mathrm{W/m^2/K}$ in the extratropics in the multi-model mean. The linearity of clear-sky OLR with $T_s$ can be assessd by the $R^2$ of the local OLR-$T_s$ linear regression. The linearity is remarkably strong in the extratropics, indicated by the close to 100% of explained variance (Figure 2b), and somewhat weaker in the tropics. Models also tend to agree better in the extratropics as measured by the standard deviation of LWCS feedback (Figure 2c).

Figure 2d shows the map of LWCS feedback. In the extratropics, similar to the zonal mean (Figure 2a), the LWCS feedback is relatively spatially uniform and lacks any land-ocean contrast. In the tropics, however, regions of negative feedback emerge, which is the “super-greenhouse effect” referred to in the Introduction. The linearity is again remarkably strong in the extratropics for each location but is weak within the 30°S-30°N latitude band (Figure 2e). Models show very good agreement of the LWCS feedback in the extratropics, while in the tropics the standard deviation across models is of the same magnitude as the feedback itself in the tropics (Figure 2f), consistent with previous findings that models disagree on the locations and strengths of “super-greenhouse effect” (Stephens et al., 2016).

To understand the spatial pattern and the model spread of the LWCS feedback shown in Figure 2, we consider the joint dependence of OLR on $T_s$ and RH. Invoking Eq. (1)

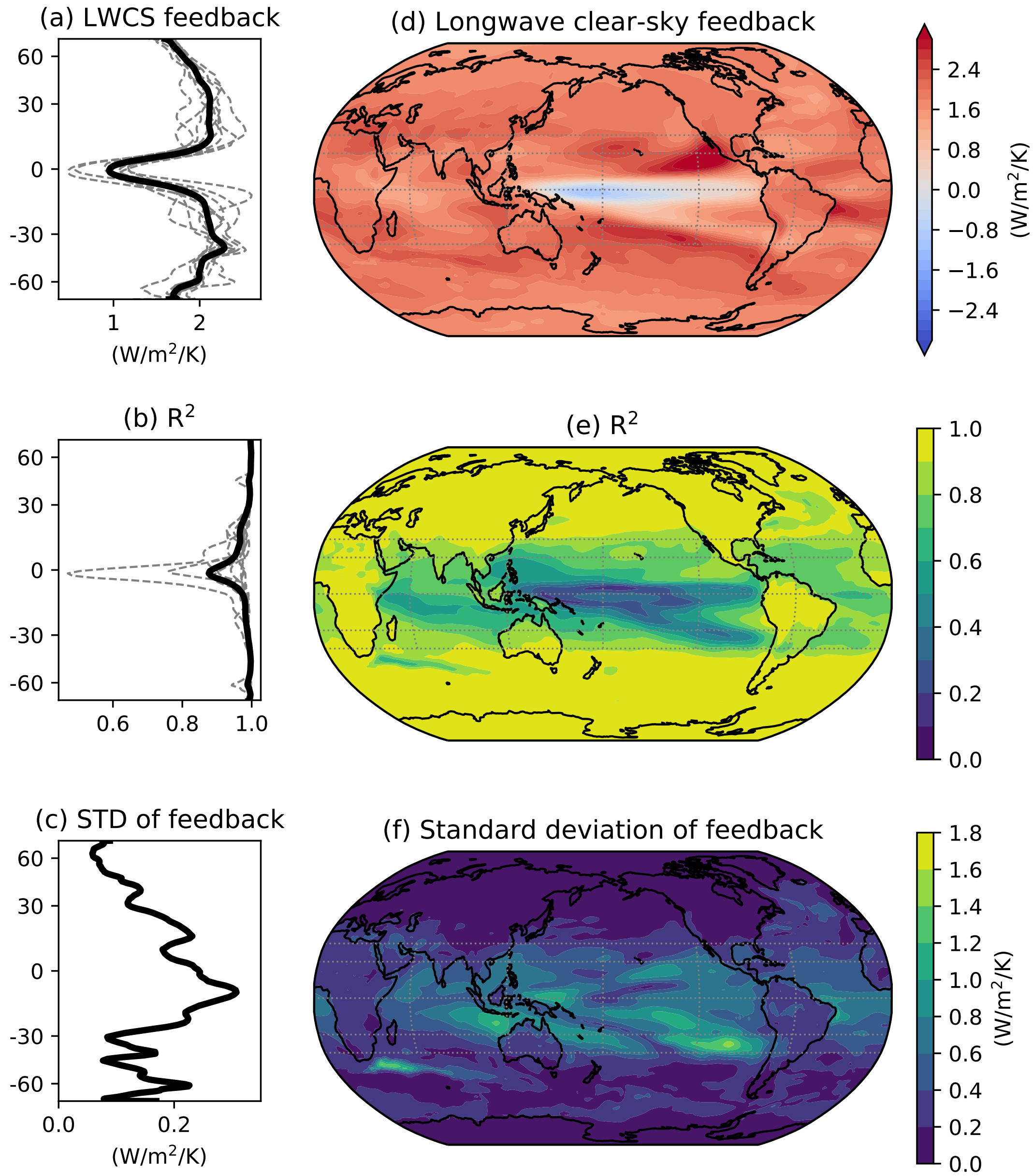


**Figure 2.** (a) Zonal-mean LWCS feedback for each model (dashed) and the multi-model mean (solid). (b) The $R^2$ of the linear regression of zonal-mean OLR onto the zonal-mean $T_s$ for each model (dashed) and the multi-model mean (solid). (c) Standard deviation of the zonal-mean LWCS feedback among models. (d), (e), and (f) show the same variables as in (a), (b), and (c) respectively on 2D maps.

but also allowing for RH changes with warming yields

$$\frac{\mathrm{dOLR}}{\mathrm{d}T_s} = \alpha + \beta\frac{\mathrm{dRH}}{\mathrm{d}T_s}, \tag{2}$$

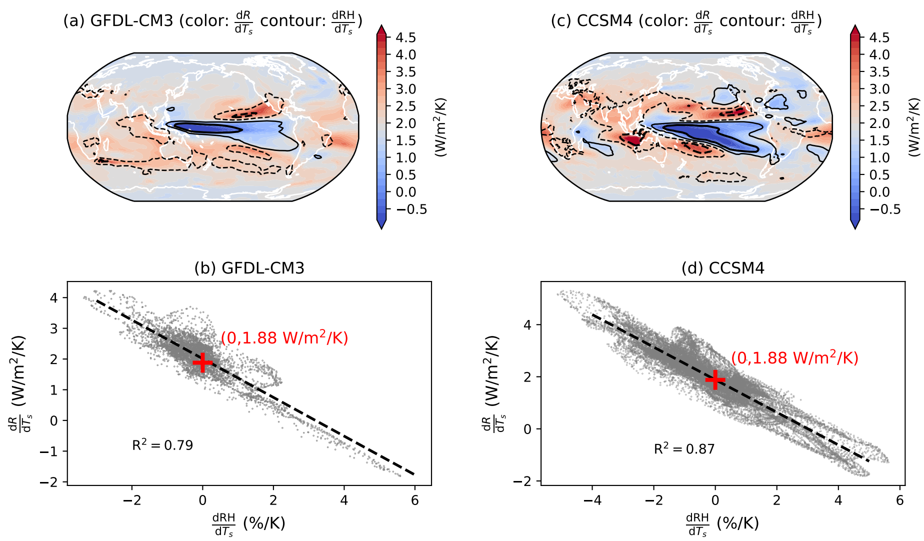


**Figure 3.** (a) Location-specific longwave clear-sky feedback parameters (color shading) and the sensitivity of column relative humidity (RH) to surface temperature (black contours) for GFDL-CM3. Contours of -3%/K (thick dashed), -1%/K (thin dashed), 1%/K (thin solid), 3%/K (thick solid) are shown. (b) Scatter plot of the two fields shown in (a) and the linear regression line. The red cross marks the point of zero column RH change and a LWCS feedback of $1.88\,\mathrm{W/m^2/K}$. (c) and (d) are the same as (a) and (b) but for CCSM4.

where $\beta = \frac{\partial \mathrm{OLR}}{\partial \mathrm{RH}}\big|_{T_s}$. Eq. (2) indicates that the spatial pattern of the LWCS feedback should be closely related to the spatial pattern of $\frac{\mathrm{dRH}}{\mathrm{d}T_s}$. A similar idea is mentioned in Held and Soden (2000). In testing this idea, we begin by using column RH and later refine this by using the free tropospheric column RH.

Figure 3 illustrates the accuracy of Eq. (2) with two models that feature different patterns of LWCS feedback. In GFDL-CM3 the regions of super-greenhouse effect are mainly located on equator in the western basin of the Pacific, while in CCSM4 these regions expand off equator and are mainly located in the central Pacific. For both models, the spatial patterns of LWCS feedback (color shading) and the column RH changes (contours) are almost identical (Figure 3a and c). To make this more explicit, we plot $\frac{\mathrm{dOLR}}{\mathrm{d}T_s}$ vs. $\frac{\mathrm{dRH}}{\mathrm{d}T_s}$ in Figure 3b and d, taking only grid points within 30°S-30°N. The correlations for GFDL-CM3 and CCSM4 are -0.89 and -0.93 respectively, and -0.87 for all the 9 CMIP5 models in Figure 1 on average. Moreover, the intercept of the linear regression is on average $1.9\,\mathrm{W/m^2/K}$ which indeed recovers the value of $\alpha$ (see Figure 3b and d for GFDL-CM3 and CCSM4). In other words, for locations where column RH doesn't change with warming, the LWCS feedback is close to the value given by the single atmospheric column model.

A key feature of Figure 3 a and c is that column RH increases in the deep tropics are accompanied by column RH decreases in the subtropics. This implies that the local effects of RH changes on OLR might cancel out in the global mean, or even just in the tropical mean as indeed seen in Figure 1b. This suggests that the robustness of the global mean LWCS feedback evident in Figure 1 results from a geographical *rearrangement* of column RH values, without any change in the column RH histogram. We test these ideas in Section 5, but first we return to the question to what extent Eq. (1) applies to realistic atmospheres with non-uniform RH profiles.

## 4 OLR-$T_s$ relationship conditioned upon column RH

Eq. (1), a central result of (Koll & Cronin, 2018), was tested in an idealized single-column atmospheric model with vertically uniform RH profiles and moist adiabatic temperature profiles. However, we know that the real atmosphere exhibits more complicated vertical structures of temperature and RH which influence the OLR (Shine & Sinha, 1991; Huang et al., 2007).

To test the applicability of Eq. (1) to more realistic atmospheres, Figure 4(a) shows the OLR dependence on $T_s$ conditioned upon various column RH ranging from 40% to 70%. As expected, the OLR increases as column RH decreases for a given $T_s$. Furthermore, at relatively low $T_s$, the slope (the LWCS feedback) is around $1.9\,\mathrm{W/m^2/K}$ for all column RH values, consistent with Eq. (1). However, OLR decreases with $T_s$ at $T_s$ above 303 K, which is inconsistent with Eq. (1). Although a flattening of OLR-$T_s$ curve is expected from the closing of the water vapor window (Koll & Cronin, 2018), this happens at a much higher temperature and cannot explain the *decrease* of OLR with $T_s$ seen here. This decrease of OLR with $T_s$ is distinct from the super-greenhouse effect discussed above because here it occurs even at fixed column RH.

What then causes this breakdown of Eq. (1) in realistic atmospheric columns? A single column RH is insufficient for representing the vertical structure of the water vapor in realistic climate models, as the boundary-layer RH (Held & Soden, 2000; Byrne & O'Gorman, 2016) and the free tropospheric RH (R. Pierrehumbert, 1998; R. T. Pier-

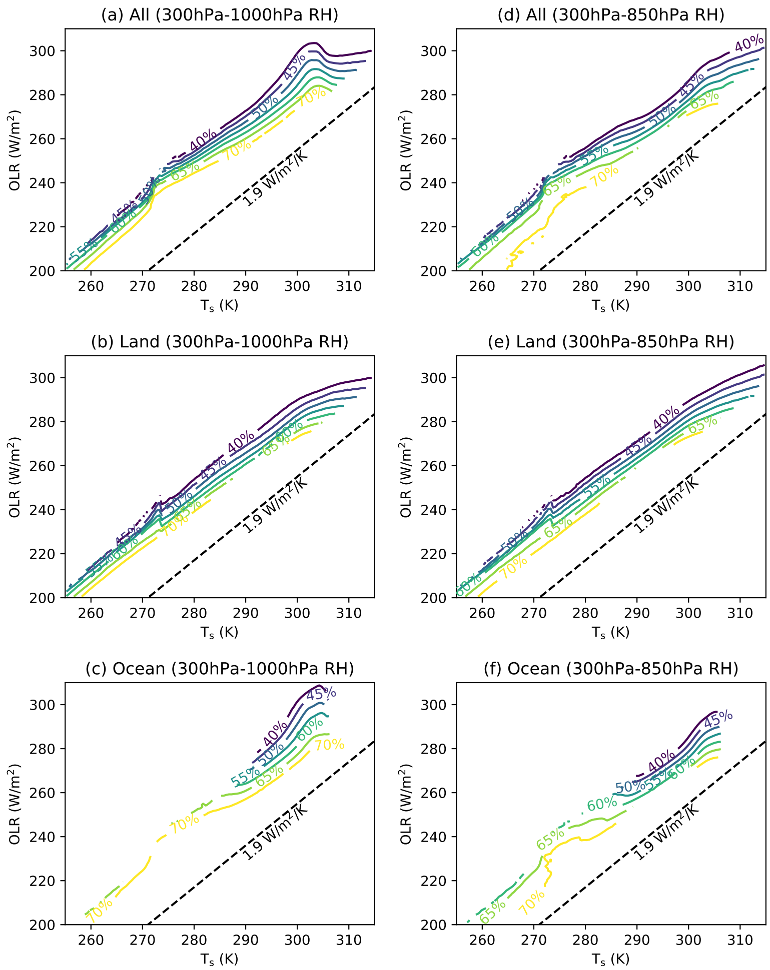


**Figure 4.** Clear-sky OLR vs. surface temperature conditioned upon various column RH values. Data from 9 CMIP5 models are included in the statistics. Column RH for 300 hPa-1000 hPa is used for (a), (b), (c) and column RH for 300 hPa-850 hPa (free troposphere) is used for (d), (e), (f). (a) and (d) include both land and ocean data, while (b) and (e) include land only, and (c) and (f) include ocean only. The dashed black line indicates a reference slope of 1.9 W/m$^2$/K.

rehumbert & Roca, 1998; Galewsky et al., 2005; Romps, 2014) are determined by essentially independent processes which are sometimes decoupled. Furthermore, it is known that in contrast to the upper troposphere, the influence of the boundary-layer RH on OLR is quite weak (B. Soden & Held, 2006; B. J. Soden et al., 2008). Physically this is because the boundary-layer air temperature is close to $T_s$ and an increase in the emission from the boundary-layer water vapor is approximately equal to the decrease in surface emission. This suggests that we should focus on free-tropospheric RH rather than boundary-layer RH. Figure 4d shows the same OLR-$T_s$ relationship as in Figure 4a but now conditioned on the free-tropospheric (300 hPa-850 hPa) column RH. With this RH variable, the decrease in OLR with $T_s$ at higher $T_s$ disappears, and Eq. (1) applies for most RH and $T_s$ values.

Returning to the decrease of OLR with $T_s$ at high $T_s$ as shown in Figure 4a, we find that this decrease is caused by the transition from the lower $T_s$ values populated by ocean regions to those higher $T_s$ values populated by land regions. At fixed column RH, the boundary layer is dryer and the free troposphere is moister over land than over ocean. Thus, as one transitions from ocean to land columns at fixed column RH, one swaps boundary-layer moisture for free-tropospheric moisture which reduces the OLR, leading to the kink in Figure 4a at roughly 303 K. Indeed, land alone has a more linear OLR-$T_s$ relationship (Figure 4(b)), though a mild decrease of OLR with $T_s$ still exists for the warmest oceans (Figure 4(c)) located in between the subtropical deserts (e.g., the Red Sea) over which the boundary layer is very dry and more "land-like". Using free-tropospheric column RH, the land-ocean contrast is significantly reduced (Figure 4e and f) and the OLR-$T_s$ relationship over land is an extension of that over ocean to higher $T_s$.

To summarize, despite the diversity of RH and temperature profiles in realistic climate models, the LWCS feedback ($\alpha$) is indeed independent of both $T_s$ and RH consistent with Eq. (1) so long as RH is interpreted as free-tropospheric column RH. Therefore, Eq. (1) seems applicable to realistic atmospheres and we can turn to the additional condition on column RH distribution.

## 5 Condition for robust global-mean LWCS feedback

Now we answer the question under what conditions the compensation of local LWCS feedback seen in Section 3 is guaranteed to produce a global-mean LWCS feedback around $2\,\mathrm{W/m^2/K}$, consistent with Eq. (1). In particular, we show that a sufficient condition is that the free-tropospheric column RH distribution, denoted as $F(\mathrm{RH})$, stays invariant with global warming.

We denote the joint distribution of $T_s$ and column RH as $f(T_s, \mathrm{RH})$ whose integral in $T_s$ gives $F(\mathrm{RH})$. For convenience, we express the OLR in the following functional form which is equivalent to Eq. (1):

$$\mathrm{OLR}(T_s, \mathrm{RH}) = \alpha T_s + R(\mathrm{RH}), \tag{3}$$

where the specific functional form of $R(\mathrm{RH})$ is not of concern here. The global-mean clear-sky OLR ($\overline{\mathrm{OLR}}$) is thus

$$\begin{aligned}\overline{\mathrm{OLR}} &= \int \mathrm{dRH} \int \mathrm{d}T_s f(T_s, \mathrm{RH}) \mathrm{OLR}(T_s, \mathrm{RH}) \qquad (4)\\ &= \alpha \int \mathrm{dRH} \int \mathrm{d}T_s f(T_s, \mathrm{RH}) T_s + \int \mathrm{dRH} R(\mathrm{RH}) \int \mathrm{d}T_s f(T_s, \mathrm{RH}). \qquad (5)\end{aligned}$$

The integral in the first term of Eq. (5) gives the global mean surface temperature ($\overline{T_s}$) and the integral over $T_s$ in the second term gives the column RH distribution, therefore

$$\overline{\mathrm{OLR}} = \alpha \overline{T_s} + \int \mathrm{dRH} R(\mathrm{RH}) F(\mathrm{RH}), \qquad (6)$$

and thus

$$\delta \overline{\mathrm{OLR}} = \alpha \delta \overline{T_s} + \int \mathrm{dRH} R(\mathrm{RH}) \delta F(\mathrm{RH}). \qquad (7)$$

If the column RH distribution remains constant with global warming, i.e.,

$$\delta F(\mathrm{RH}) \equiv 0, \qquad (8)$$

then we have

$$\frac{\delta \overline{\mathrm{OLR}}}{\delta \overline{T_s}} = \alpha. \qquad (9)$$

Therefore, the global-mean LWCS feedback is equal to the constant-RH value $\alpha$ (Eq. (1), Figure 4) so long as the global column RH histogram is invariant under global warming.

This additional condition, described by Eq. (8), is indeed satisfied in CMIP5 models. Figure 5a shows that the multi-model mean histogram of free-tropospheric column RH is largely unchanged between the first and the last 10 years of the simulation, and the same is true for individual models (see Figure 5c and Figure 5e for GFDL-CM3 and CCSM4 as examples). Furthermore, this invariance holds on a year-to-year basis (Figure 5b, d, and f) which guarantees the linearity of the global-mean OLR vs. global-mean $T_s$ for annual mean data as shown in Figure 1. This result is consistent with previous work that finds that the free tropospheric RH is overwhelmingly controlled by the large-scale circulation (R. T. Pierrehumbert & Roca, 1998; Galewsky et al., 2005; Sherwood & Meyer, 2006), and constant free-tropospheric RH has long been proved to be an accurate leading order assumption with global warming (Manabe & Wetherald, 1975).

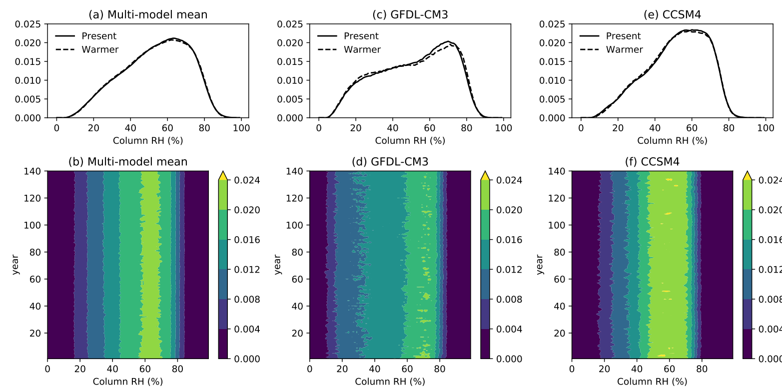


**Figure 5.** (a) The multi-model-mean histogram of free-tropospheric column RH in the first 10 years (solid; labelled "present") and the last 10 years (dashed; labelled "warmer") of the simulation. (b) Time series of the multi-model-mean free-tropospheric RH histogram throughout the simulation. (c) The same as (a) but for GFDL-CM3. (d) The same as (b) but for GFDL-CM3. (e) The same as (a) but for CCSM4. (f) The same as (b) but for CCSM4.

## 6 Summary

This paper aims to connect the idealized model results of (Koll & Cronin, 2018) to the behavior of comprehensive climate models, in line with the hierarchical approach to climate science (Held, 2005; Jeevanjee et al., 2017; Maher et al., 2019). In particular, we sought to understand whether the robustness of LWCS feedback in CMIP5 models could be traced back to the single-column physics of (Koll & Cronin, 2018). We found that indeed it could, on the condition that the global free-tropospheric column RH histogram remains invariant under warming. This invariance of the global RH histogram is a global analogue of the fixed-RH condition for single-column models. In this sense, we have shown that "fixed RH" is a good approximation for the atmosphere under global warming, and the linearity of global-mean OLR is a direct consequence of this.

This invariance of the global column RH histogram is manifest in Figure 2a and c where a moistening of the deep tropics is accompanied by the drying of the subtropics. The super-greenhouse effect discussed in the Introduction arises when this deep-tropical moistening is strong enough to make $\frac{\mathrm{dOLR}}{\mathrm{d}T_s}$ negative (see Eq. (2)). However, our results show that any such negative $\frac{\mathrm{dOLR}}{\mathrm{d}T_s}$ values must be offset elsewhere by anomalously positive values. This means that, in a global or even a tropical-mean context, the super-greenhouse effect is constrained to disappear (as evident in Figure 1) and thus has little impact on large-scale climate.

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