Using Relative Humidity as a State Variable in Climate Feedback Analysis

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ABSTRACT

An approach to climate change feedback analysis is described in which tropospheric relative humidity replaces specific humidity as the state variable that, along with the temperature structure, surface albedos and clouds, controls the magnitude of the response of global mean surface temperature to a radiative forcing. Despite being simply a regrouping of terms in the feedback analysis, this alternative perspective has the benefit of removing most of the pervasive cancellation between water and lapse rate feedbacks seen in models. As a consequence, the individual feedbacks have less scatter than in the traditional formulation. The role of cloud feedbacks in controlling climate sensitivity is also reflected more clearly in the new formulation.

1. Introduction

Feedback terminology is commonly used when analyzing the response of climate models to perturbations in greenhouse gases (Manabe and Wetherald (1980), Hansen et al. (1984), Wetherald and Manabe (1988), Zhang et al. (1994), Colman (2003), Bony et al. (2006), Soden et al. (2008), Roe (2009)). Most typically, the analysis is focused on the global mean surface temperature, and one speaks of lapse rate, water vapor, surface albedo, and cloud feedbacks. We would like to emphasize some arbitrary aspects of this decomposition. Being aware of this arbitrariness can be important; while the behavior of the system is unchanged by how one chooses to analyze it, different choices can simplify or complicate one's conceptual picture of the processes controlling the climate response.

Consider a model in which the net incoming flux at the tropopause N is a function of two degrees of freedom in the climate state (A and B), in addition to f, the forcing agent – say CO_2 concentration. Perturbing an equilibrium state, we refer to $(\partial N/\partial f)\delta f \equiv F$ as the forcing, so that in a new equilibrium state

$$F = -(\partial N/\partial A)\delta A - (\partial N/\partial B)\delta B \tag{1}$$

Assuming that A is the quantity of primary interest – say surface temperature – we are led to break the symmetry between A and B and write

$$\delta A = -\frac{F}{\lambda_A + \lambda_B} \tag{2}$$

$$\lambda_A \equiv \frac{\partial N}{\partial A} \tag{3}$$

$$\lambda_B \equiv \frac{\partial N}{\partial B}\frac{\delta B}{\delta A} \tag{4}$$

where λ_B might be referred to as the B-feedback. We can write

$$\delta A = \frac{\delta A|_B}{1 - \mu_B} \tag{5}$$

where $\delta A|_B = -F/\lambda_A$ might be referred to as the reference response (the response in the absence of B variations), while $\mu_B = -\lambda_B/\lambda_A$ is a non-dimensional measure of the amplitude of the B-feedback, defined so as to be positive if it increases the amplitude of δA.

Now suppose that B is a function of A and C, and we would rather consider the climate response as defined by δA and δC:

$$\delta N = \left(\frac{\partial N}{\partial A} + \frac{\partial N}{\partial B}\frac{\partial B}{\partial A} \right) \delta A + \frac{\partial N}{\partial B}\frac{\partial B}{\partial C} \delta C \tag{6}$$

We then have

$$\begin{aligned}
\delta A &= -\frac{F}{\tilde{\lambda}_A + \tilde{\lambda}_C} = \frac{\delta A|_C}{1 - \tilde{\mu}_C} \\
\tilde{\lambda}_A &\equiv \frac{\partial N}{\partial A} + \frac{\partial N}{\partial B}\frac{\partial B}{\partial A} \\
\tilde{\lambda}_C &\equiv \frac{\partial N}{\partial B}\frac{\partial B}{\partial C}\frac{\delta C}{\delta A} \\
\tilde{\mu}_C &\equiv -\tilde{\lambda}_C/\tilde{\lambda}_A
\end{aligned} \tag{7}$$

where $\delta A|_C$ is a new reference response (in the absence of C-feedback), and $\tilde{\mu}_C$ is a non-dimensional measure of the amplitude of the C-feedback. Of course, the system doesn't care whether we think of the flux as a function of (A, B) or (A, C). The choice between the two is a convention.

Consider a model in which A is the surface temperature, B is the temperature of the troposphere, and $C = A - B$. Then the C-feedback would be a lapse rate feedback, and the reference response at fixed C would be the familiar reference assuming identical temperature perturbations at the surface and through the entire troposphere. The B-feedback perspective would be very different. A climate change with uniform warming at the surface and through the troposphere would be described as resulting from a very large reference sensitivity (computed as if the forcing were required to be balanced entirely by the surface warming) in conjunction with a very strong negative B, or tropospheric temperature, feedback.

It is worth considering why the latter, untraditional, viewpoint seems so awkward. Fundamentally, the problem is that it is physically implausible for the surface warming and tropospheric warming to vary independently. The large changes in gravitational stability that would result if there were no "tropospheric feedback" would be strongly resisted by the atmospheric circulation. It makes little sense to use variables A and B in this kind of analysis if they are so closely tied together that the limit of no B-feedback is so implausible. From the perspective of analyzing and explaining the behavior of GCMs, it would make climate responses look as if they were the results of large cancellations between two terms.

While there is nothing preventing one from using this perspective, it can cause confusion. For example, it might encourage the (incorrect) idea that because B-feedback is large its strength must be a source of substantial uncertainty in the response. Thinking of "tropospheric feedback" as large and negative in this example is simply a result of our odd choice of variables. Needless to say, we are not recommending the use of this tropospheric feedback perspective. We are however recommending an analogous transition from the concept of water vapor feedback towards the use of relative humidity feedback. ((Ingram 2012) discusses the reorganization of climate feedback analyses along similar lines.)

2. Specific humidity vs. relative humidity feedback

In rresponse to warming, GCMs poroject changes in the spatial distribution of relative humidity. While there is some consistency across models in these simulations (Wetherald and Manabe (1988), Sherwood et al. (2010a)), the dynamics underlying these responses is not entirely straightforward (Pierrehumbert et al. (2007), Sherwood et al. (2010b)). However, the net effect of these changes in relative humidity on water vapor feedback in models is small (e.g., Soden and Held (2006)), suggesting that analysis of feedbacks in those models would be simplified by a methodology using relative rather than specific humidity as a state variable. But this choice is also favored by the desire to work with a set of feedbacks that are independently realizable.

Imagine a feedback analysis of the simulated climatic response to a reduction of 50% in atmospheric CO_2, or a comparison of the radiative balance during the last glacial maximum with that at present. The standard procedure is to use, as a reference, a temperature perturbation with uniform amplitude throughout the troposphere and with no change in specific humidity, clouds, or surface albedo. This reference response is then modified by lapse rate, water vapor, surface albedo and cloud feedbacks. But this reference perturbation can easily contain regions in which water vapor is supersaturated, due to the reduction in temperatures. This reference perturbation is not realizable; the cooling would have to be accompanied by reduction in water vapor at least in those regions where the climatological relative humidities are already high. The surface boundary layer over the oceans is one region where decreases in vapor might be required to retain realizeability. In the upper tropical troposphere, where much of the water vapor feedback originates, the cold climatological temperatures increase the sensitivity of saturation vapor pressure to values of 12-15% per degree K. A 4K cooling, say, can convert 50% relative humidity to supersaturation. Admittedly, this realizability issue would not arise for sufficiently small perturbations, but one would like to use a feedback formalism in which the feedback processes are individually meaningful for climate changes of the magnitude of the glacial-interglacial differences. If one uses relative rather than specific humidity as a variable, this issue of realizability due to supersaturation would never arise.

A different but related problem occurs for warm perturbations in models in which warming in the upper tropical troposphere is larger than at the surface, and the relative humidity stays more or less unchanged. In such a model it can happen that the increase in upper tropospheric water vapor is unrealizable (resulting once again in supersaturation) except if it is accompanied by the upper level maximum in warming (and the associated negative lapse rate feedback). It is undesirable for the realizability of a large positive feedback to be dependent on the presence of a large negative feedback. The tendency for cancellation between positive water vapor and negative lapse rate feedback in models, with the spread across models in their sum being smaller than would be expected from independent processes, has been noted repeatedly (Zhang et al. (1994), Soden and Held (2006), Sanderson et al. (2010)). The simple physics underlying this cancellation when relative humidities are unchanged has recently been described clearly by Ingram (2010), building upon the early work of Simpson (1928). A feedback analysis that involves this cancellation makes the decomposition of the response into parts due to different processes look more complicated than it actually is.

In the traditional formulation we think of tropopause radiative flux as a function of the temperature profile ($T(p)$), the water vapor profile ($Q(p)$), the surface albedo (α), and a set of cloud parameters $\mathcal{C}\ell$: $N(T(p), Q(p), \alpha, \mathcal{C}\ell)$. We then perturb N

$$\delta N = F + \delta T_S(\lambda_T + \lambda_L + \lambda_Q + \lambda_\alpha + \lambda_{\mathcal{C}\ell}), \tag{8}$$

or, in equilibrium,

$$\delta T_S = \frac{\delta T_s|_Q}{1 - \mu_L - \mu_Q - \mu_\alpha - \mu_{\mathcal{C}\ell}}. \tag{9}$$

Here δT_S is the surface temperature response; λ_T is the change in N for a uniform temperature change with no change in water vapor, surface albedo, or clouds; $\lambda_L, \lambda_Q, \lambda_\alpha, \lambda_{\mathcal{C}\ell}$ are the traditional lapse rate, water vapor, albedo, and cloud feedbacks, respectively; $\delta T_s|_Q \equiv -F/\lambda_T$ is the corresponding reference response holding Q, as well as L, α, and $\mathcal{C}\ell$, fixed. Finally, $\mu_i = -\lambda_i/\lambda_T$ are non-dimensional measures of these feedbacks.

In the alternative formulation, based on a constant relative humidity for the reference response, we have

$$\delta N = F + \delta T_s(\tilde{\lambda}_T + \tilde{\lambda}_L + \tilde{\lambda}_H + \tilde{\lambda}_\alpha + \tilde{\lambda}_{\mathcal{C}\ell}). \tag{10}$$

We have split the water vapor feedback into three terms

$$\lambda_Q = \lambda_{QT} + \lambda_{QL} + \tilde{\lambda}_H \tag{11}$$

and set

$$\tilde{\lambda}_T = \lambda_T + \lambda_{QT} \tag{12}$$

$$\tilde{\lambda}_L = \lambda_L + \lambda_{QL}. \tag{13}$$

Here $\tilde{\lambda}_T$ accounts for the effects on the outgoing flux of a tropospheric temperature perturbation equal to that at the surface (λ_T) plus the humidity perturbation required to maintain fixed relative humidity (λ_{QT}); $\tilde{\lambda}_L$ accounts for the fact that the tropospheric temperature responses are not uniformly equal to the surface temperature response (λ_L) and for the additional humidity changes required to maintain constant relative humidity in the non-uniform component of the tropospheric warming (λ_{QL}); while $\tilde{\lambda}_H$ accounts for the departures from fixed relative humidity.

The cloud and albedo feedbacks are unchanged: $\tilde{\lambda}_A = \lambda_A$ and $\tilde{\lambda}_C = \lambda_C$, but if we write the feedbacks in non-dimensional form

$$\delta T_S = \frac{\delta T_s|_H}{1 - \tilde{\mu}_L - \tilde{\mu}_H - \tilde{\mu}_\alpha - \tilde{\mu}_{\mathcal{C}\ell}} \tag{14}$$

with $\delta T_s|_H = -F/\tilde{\lambda}_T$ (the reference response with fixed tropospheric temperature structure, relative humidity, surface albedos, and clouds) and $\tilde{\mu}_i = -\tilde{\lambda}_i/\tilde{\lambda}_T$, these non-dimensional strengths of albedo and cloud feedbacks are altered by the modified reference response. For example, at fixed relative humidity, temperature changes due to cloud perturbations result in specific humidity changes, and the effects of this vapor perturbation on the tropoopause fluxes are now included in the non-dimensional cloud feedback. The result will be that $|\tilde{\mu}_{\mathcal{C}\ell}| > |\mu_{\mathcal{C}\ell}|$, and the amplitude of this non-dimensional measure of the strength of cloud feedback, whether positive or negative, is increased.

3. Relative humidity feedbacks in CMIP3 models

We have computed these alternative relative humidity-based feedback strengths in 21st century SRESa1b simulations, using one ensemble member from each of 18 models from the Coupled Model Intercomparison Project - phase 3 (CMIP3). We use the radiative kernel technique and following identical procedures to those utilized in Soden et al. (2008). The kernels (Shell et al. 2008)are derived from the radiative transfer code and control climate of the Community Atmospheric Model, Version 3 (Collins et al. 2006). The climate responses are calculated as the differences between the 2080–99 averages in the SRESa1b simulations and 1980–99 averages in the corresponding 20th Century (20c3m) simulations.

We start with the traditional temperature and water vapor kernels, as defined by Soden et al. (2008). The temperature kernel provides the perturbation to the tropopause flux for a local change in temperature of 1K; the water vapor kernel provides the response to the specific humidity increase needed to maintain fixed relative humidity for a local temperature perturbation of 1K. We sum these two kernels to produce the fixed-relative humidity temperature kernel. To compute the alternative temperature (or Planck) feedback the combined kernel is multiplied by an atmospheric temperature response throughout the troposphere equal to the surface temperature response at each grid point, while the alternative lapse rate feedback uses the differences between the actual atmospheric temperature change and the surface temperature change at each location. We derive the relative humidity feedback by subtracting the original water vapor kernel times the atmospheric temperature response from the traditional water vapor feedback.

We find for the means and standard deviations across the model ensemble,

$$\begin{aligned}
\tilde{\lambda}_T &= -1.75 \pm 0.01 W m^{-2} K^{-1} \\
\tilde{\lambda}_L &= -0.26 \pm 0.12 W m^{-2} K^{-1} \\
\tilde{\lambda}_H &= -0.02 \pm 0.10 W m^{-2} K^{-1}
\end{aligned} \quad (15)$$

as compared to

$$\begin{aligned}\lambda_T &= -3.10 \pm 0.04 W m^{-2} K^{-1} \\ \lambda_L &= -0.89 \pm 0.27 W m^{-2} K^{-1} \\ \lambda_Q &= +1.98 \pm 0.21 W m^{-2} K^{-1} \end{aligned} \quad (16)$$

The terms that are moved from water vapor feedback to the new temperature and the lapse rate feedbacks are

$$\begin{aligned}\lambda_{QT} &= 1.36 \pm 0.04 W m^{-2} K^{-1} \\ \lambda_{QL} &= 0.63 \pm 0.16 W m^{-2} K^{-1}. \end{aligned} \quad (17)$$

Fig. 1 shows the results from the individual models. As expected (Ingram (2010)),the scatter among the models both in the strength of the fixed relative humidity lapse rate feedback ($\tilde{\lambda}_L$) and in the relative humidity feedback ($\tilde{\lambda}_H$) is much smaller than the scatter in the traditional lapse rate and water vapor feedbacks (λ_L and λ_Q). There is little correlation across the models between $\tilde{\lambda}_L$ and $\tilde{\lambda}_H$, suggesting that the remaining scatter has different sources in these different feedback terms, unlike the situation in the tradiational formulation.

The non-dimensional albedo and cloud feedbacks are increased by the ratio $\lambda_T/\tilde{\lambda}_T = 1.77$. Our climate responses, computed as a simple difference between two climate states, do not distinguish between cloud responses that scale with the temperature response and those that scale with the instantaneous CO_2 concentration (Gregory and Webb 2008). The ratio of 1.77 would apply to the component that scales with temperature. If the component that scales with CO_2 is negligible in the water vapor and lapse rate responses, as indicated by Colman and McAveney (2011), then the results displayed in Fig. 1 can be interpreted as referring to feedbacks that scale with temperature in the usual sense.

4. Discussion

A feedback analysis is a construct that we impose on simulations and observations of climate change to help us relate model results to each other and to observations, and to attribute sensitivity to particular processes. There are several kinds of arbitrariness in this construction, none of which change the final climate response but which may alter our understanding of that response. Some of the arbitrariness involves the choice of variables with which we describe the climate response, the example we focus on here being the use of relative, as opposed to specific, tropospheric humidity.

The alternative feedback perspective using relative humidity as the state variable clearly simplifies the analysis of GCM responses. In the absence of cloud and albedo feedbacks, the typical radiative restoring strength in the CMIP3 models, about 2 $\mathrm{Wm^{-2}\ K^{-1}}$, is interpreted without the need for any cancellation between large positive water vapor and negative lapse rate feedbacks. It emerges instead as the sum of a reference response, corresponding to uniform warming with fixed relative humidity, of about 1.75 $\mathrm{Wm^{-2}\ K^{-1}}$, a small (≈ 0.25 $\mathrm{Wm^{-2}\ K^{-1}}$) negative lapse rate feedback, and a negligible relative humidity feedback.

This perspective also enhances the importance of cloud feedbacks for the model responses, as compared to the standard specific humidity perspective, by increasing the non-dimensional measure of the strength of the feedback to take into account the humidity changes that accompany the temperature response to any cloud change, so as to maintain a fixed relative humidity.

Admittedly, simplifications that result from this perspective arise from the fact that relative humidity changes are modest in these models. Whether this approach simplifies the analysis of observations of climate change will depend on whether observed relative humidity changes remain small, especially in the tropical upper troposphere, where these changes would have the largest effect on the troposphere's radiative balance (Soden et al. 2005). A drawback is that one loses contact between the reference, "no feedback", sensitivity and the simplest textbook estimate based on Stefan-Boltzmann.

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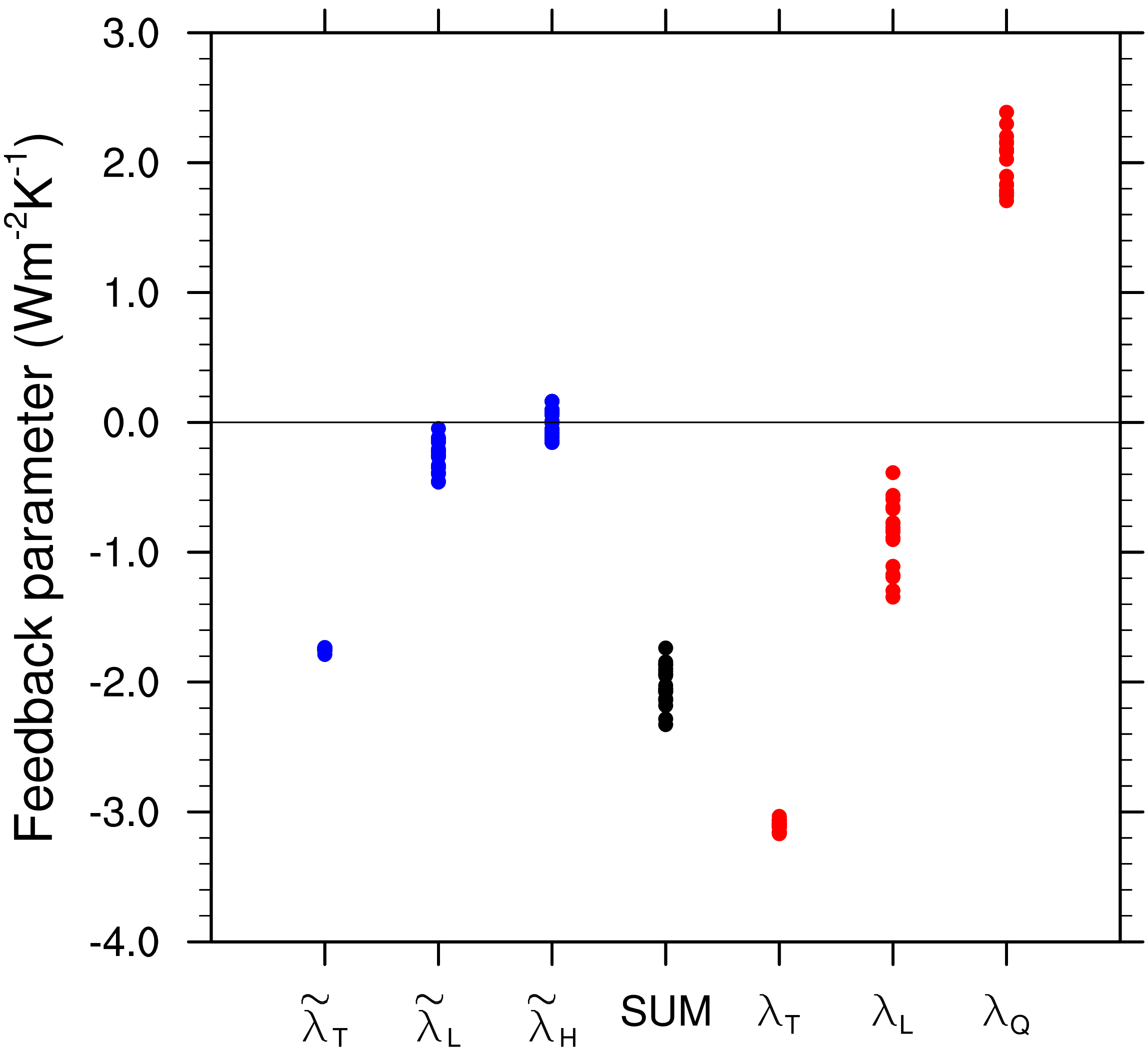

FIG. 1. Temperature, lapse rate, and water vapor feedback strengths in CMIP3 models from the traditional perspective with specific humidity as the state variable and from the alternative perspective with relative humidity as the state variable. The temperature and lapse rate feedbacks at fixed specific humidity and the specific humidity feedback are shown in the right three columns (red); the temperature and lapse rate feedbacks at fixed relative humidity and the relative humidity feedback are shown in the left three columns (blue). The sum of the three feedbacks, which is independent of the choice of decomposition, is shown as the central column (black). Each model result is indicated by a dot.