GEOPHYSICAL RESEARCH LETTERS, VOL. 40, 4007–4011, doi:10.1002/grl.50711, 2013

Four perspectives on climate feedbacks

N. Feldl[1] and G. H. Roe[2]

Received 7 May 2013; revised 27 June 2013; accepted 28 June 2013; published 30 July 2013.

[1] The spatial pattern of climate feedbacks depends on how the feedbacks are defined. We employ an idealized aquaplanet simulation with radiative kernels diagnosed for the precise model setup and characterize the meridional structure of feedbacks under four different definitions: local feedbacks, global feedbacks, nondimensional feedback factors, and relative humidity feedbacks. First, the spatial pattern of the reference response (i.e., the Planck feedback) is found to vary with definition, largely as a consequence of polar-amplified warming, which affects other high-latitude feedbacks as well. Second, locally defined feedbacks allow for decomposition of the surface temperature response as a function of feedbacks, forcing, and heat transport. Third, different insights into the dynamical and thermodynamical underpinnings of the subtropical moisture response are gained by comparing different versions of humidity feedbacks. Thus, alternative approaches to the conventional, global definition of feedbacks offer several advantages for understanding patterns of warming and, ultimately, regional climate predictability. **Citation:** Feldl, N., and G. H. Roe (2013), Four perspectives on climate feedbacks, *Geophys. Res. Lett.*, *40*, 4007–4011, doi:10.1002/grl.50711.

1. Introduction

[2] Climate feedbacks offer a powerful framework for decomposing the energetics of the climate system response to an imposed forcing, such as an increase in atmospheric CO_2. Yet the widespread appeal and convenience of the technique has led to a profusion of definitions. At their best, these various decompositions can isolate and illuminate different atmospheric processes. However, the risks are a conceptual lack of clarity and a hindrance of cross-comparison amongst studies. The purpose of this study is to evaluate how the spatial pattern of climate feedbacks depends on these different definitions.

[3] The decomposition of the top-of-atmosphere (TOA) energy balance should be considered carefully. For instance, a core component of the response is reference-state sensitivity, commonly termed the Planck feedback. In theory, this reference response is governed by the Stefan-Boltzmann law and must be negative in a stable climate. As we will show, not even the structure of the Planck feedback—the most fundamental of radiative processes—is robust to methodology.

[4] We employ the Geophysical Fluid Dynamics Laboratory Atmospheric Model 2 (GFDL AM2) in an idealized aquaplanet configuration. Radiative kernels and stratosphere-adjusted radiative forcing are diagnosed explicitly for our experimental setup (following *Feldl and Roe* [2013]). The aquaplanet allows for a clear comparison of feedback definitions without the complexities and asymmetries associated with land-sea contrasts, land-surface processes, seasonal and diurnal cycles, and aerosol forcing. Sea ice is treated as infinitesimally thin; the ocean albedo is increased to 0.5 where surface temperature drops below 263 K, but no ice thermodynamics are present. CO_2 is doubled and the model integrated to equilibrium. Feedbacks are calculated by comparing the last decade of two 30 year runs.

[5] In most formulations, climate feedbacks are the first-order terms in a Taylor series expansion of the changes to the local TOA energy budget. Let ΔT_s be the surface temperature response to a climate forcing, $\Delta R_f(x)$, where x is latitude. In equilibrium, conservation of energy requires this forcing to be balanced by a combination of changes in atmospheric and oceanic heat flux divergence, $\Delta(\nabla \cdot \vec{F}(x))$, and the sum of energy contributions from individual feedback process, $\lambda_i(x)\Delta T_s$:

$$-\Delta R_f(x) = -\Delta(\nabla \cdot \vec{F}(x)) + \sum_i \lambda_i(x)\Delta T_s + \mathcal{O}(\Delta T_s{}^2). \tag{1}$$

For completeness, the higher-order Taylor series terms $\mathcal{O}(\Delta T_s^2)$ have been included in equation (1), though these nonlinearities are typically neglected. Units are W m^{-2}. The feedback parameter of the ith climate field then has the form

$$\lambda_i(x) = \left.\frac{\partial R}{\partial \alpha_i}\right)_{\alpha_{j,j\neq i}} \frac{\Delta \alpha_i}{\Delta T_s}. \tag{2}$$

[6] We calculate feedbacks from radiative kernels, following *Soden and Held* [2006], with cloud feedbacks calculated as in *Soden et al.* [2008]; *Shell et al.* [2008]. The kernels represent the TOA radiative response to a differential nudge in a given climate field, i.e., $\partial R/\partial \alpha_i$. The relevant atmospheric feedbacks on interannual to multidecadal timescales are the Planck feedback (due to surface temperature change applied uniformly with height), the lapse rate feedback (due to departures at each vertical level from surface temperature change), water vapor, surface albedo, and clouds. *Bony et al.* [2006] provide a comprehensive description of these feedbacks.

[7] One key issue for the present study is the choice of what value to use for ΔT_s in equations (1) and (2). In most studies of feedback parameters, ΔT_s is taken to be the global-mean surface temperature response, hereafter $\Delta \overline{T_s}$ [e.g., *Soden et al.*, 2008; *Shell et al.*, 2008; *Colman and McAvaney*, 2009; *Zelinka and Hartmann*, 2012]. However, it can also represent the local temperature change, hereafter $\Delta T_s(x)$ [e.g., *Crook et al.*, 2011; *Armour et al.*, 2012],

---

[1] Department of Atmospheric Sciences, University of Washington, Seattle, Washington, USA.

[2] Department of Earth and Space Sciences, University of Washington, Seattle, Washington, USA.

Corresponding author: N. Feldl, Department of Atmospheric Sciences, University of Washington, 408 ATG Bldg., Box 351640, Seattle, WA 98195-1640, USA. (feldl@u.washington.edu)

0094-8276/13/10.1002/grl.50711

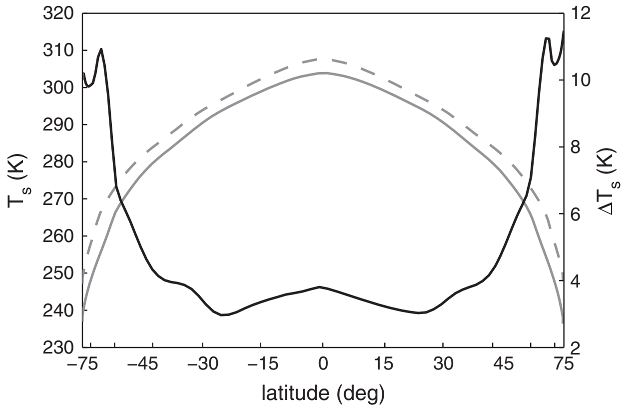

Figure 1. Zonal-mean, annual-mean T_s climatologies for the control run (solid grey), 2×CO_2 run (dashed grey), and their difference (black).

which offers some advantages. Our first goal is to evaluate how this local versus global definition affects the interpretation of the spatial pattern of feedbacks, $\lambda_i(x)$, starting with the reference Planck response. In later sections, we address two other definitions: feedback factors and relative humidity feedbacks.

2. Comparison of Global and Local Definitions

[8] A fundamental response of the climate system is an increase in radiation from a warmer body. Naively, one might expect the structure of this Planck "feedback" to be governed by the Stefan-Boltzmann law, wherein the change in outgoing flux is proportional to T_s^3, implying a tropical maximum in magnitude, and a polar minimum. However, as seen from the solid black line in Figure 2a, the Planck feedback is instead most negative, or stabilizing, at high latitudes. This result was explained by *Feldl and Roe* [2013] as a consequence of polar amplification: the Planck feedback is the product of the temperature kernel (i.e., $\partial R/\partial T$ in equation (2)), which behaves according to the Stefan-Boltzmann law, and, in the case of globally defined feedbacks, the ratio $\Delta T_s(x)/\Delta\overline{T_s}$, which peaks strongly enough at high latitudes (Figure 1) that it dominates the pattern. However, when the local definition is instead applied, $\Delta\alpha$ and $\Delta T_s(x)$ cancel in equation (2), and the expected meridional structure is recovered (solid black line in Figure 2b): the Planck feedback is strongest at low latitudes except at the equator, where high clouds obscure the underlying atmosphere. The thin line that follows the Planck feedback in Figure 2b is the response calculated as $4\varepsilon\sigma T_s^3$ for best-fit emissivity, $\varepsilon = 0.64$, and Stefan-Boltzmann constant, σ.

[9] Figure 2a shows the meridional structure of all globally defined feedbacks. The lapse rate feedback is negative where temperatures follow a moist adiabat and positive in the presence of high-latitude temperature inversions. The water vapor feedback is strongest where fractional changes in water vapor concentration are largest, which occurs in the tropical upper troposphere because (1) fractional changes in saturation vapor pressure are largest where it is cold, following Clausius-Clapeyron, and (2) warming, and hence moistening, is amplified aloft due to changes in lapse rate. Changes in relative humidity (discussed in section 4) could complicate this picture. The net cloud feedback is positive in the tropics, consistent with a decrease in cloud fraction at all levels but especially in the upper troposphere, and negative in the high latitudes, consistent with an increase in low, bright clouds and a poleward shift of the storm track [*Feldl and Roe*, 2013; *Zelinka et al.*, 2012]. The surface albedo feedback is locally large and constrained to the vicinity of the ice line.

[10] When the local definition of feedbacks is instead used, the relative importance of high-latitude and low-latitude feedbacks is altered (cf. Figures 2a and 2b). In addition to the effect on the Planck feedback, there is a striking difference in the apparent strength of the surface albedo feedback relative to the water vapor feedback. Within the feedback calculation of equation (2), a factor that peaks in the tropics (e.g., $1/\Delta T_s(x)$) will reduce the magnitude of high-latitude feedbacks, as is the case in Figure 2b. On the other hand, a uniform factor (e.g., $1/\Delta\overline{T_s}$) will not affect the meridional structure, as in Figure 2a. Thus, globally defined feedbacks afford some insights by preserving the spatial pattern of $(\partial R/\partial\alpha)\Delta\alpha$, whereas locally defined feedbacks emphasize the physical connection between local radiative fluxes and local temperature change. This is the crux and consequence of the ΔT_s choice.

3. Feedback Factors

[11] In a conventional feedback analysis, a reference system response is defined against which to measure the strength of the feedbacks. As mentioned above, the reference response is taken to be what many studies refer to as the Planck feedback. Notably, equation (1), for the case of locally defined feedbacks, can be rearranged to solve for surface temperature change as a function of change in horizontal divergence of heat flux, radiative forcing, and feedbacks,

$$\Delta T_s(x) = \frac{1}{\lambda_P(x)}\left[\Delta(\nabla\cdot\vec{F}(x)) - \Delta R_f(x) - \left(\sum_{i\neq P}\lambda_i(x)\right)\Delta T_s(x)\right], \tag{3}$$

in which each term on the right-hand side is normalized by the Planck response, $\lambda_P(x)$. Equation (3) can alternatively be written in the form

$$\Delta T_s(x) = \Gamma_0\frac{\Delta\widetilde{R}_f(x)}{(1-\sum_i f_i(x))} \tag{4}$$

where $\Gamma_0 = 1/\lambda_P(x)$, the feedback factors are $f_i = -\lambda_i/\lambda_P$, and $\Delta\widetilde{R}_f(x)$ is the net local forcing, $\Delta(\nabla\cdot\vec{F}(x)) - \Delta R_f(x)$. This formulation has the advantage of no lingering ΔT_s term on the right-hand side of the equation (cf. equation (3)), which makes it the most exact representation of the pattern of surface temperature change as a function of the pattern of feedbacks and forcing. Further, the system gain, the factor by which the response adjusts due to inclusion of feedbacks, is cleanly given by $1/(1-\sum_i f_i(x))$. *Roe* [2009] provides an in-depth review of this particular form of feedback analysis.

[12] While the feedback parameters, λ_i, described in the previous section, are given in units of W m^{-2} K^{-1}, feedback factors, f_i, represent a natural non-dimensionalization. Figure 2c shows the meridional structure of feedback factors. A net feedback factor of 1 is equivalent to a net feedback parameter of 0 W m^{-2} K^{-1} and occurs where the net non-Planck feedbacks exactly balance the Planck response.

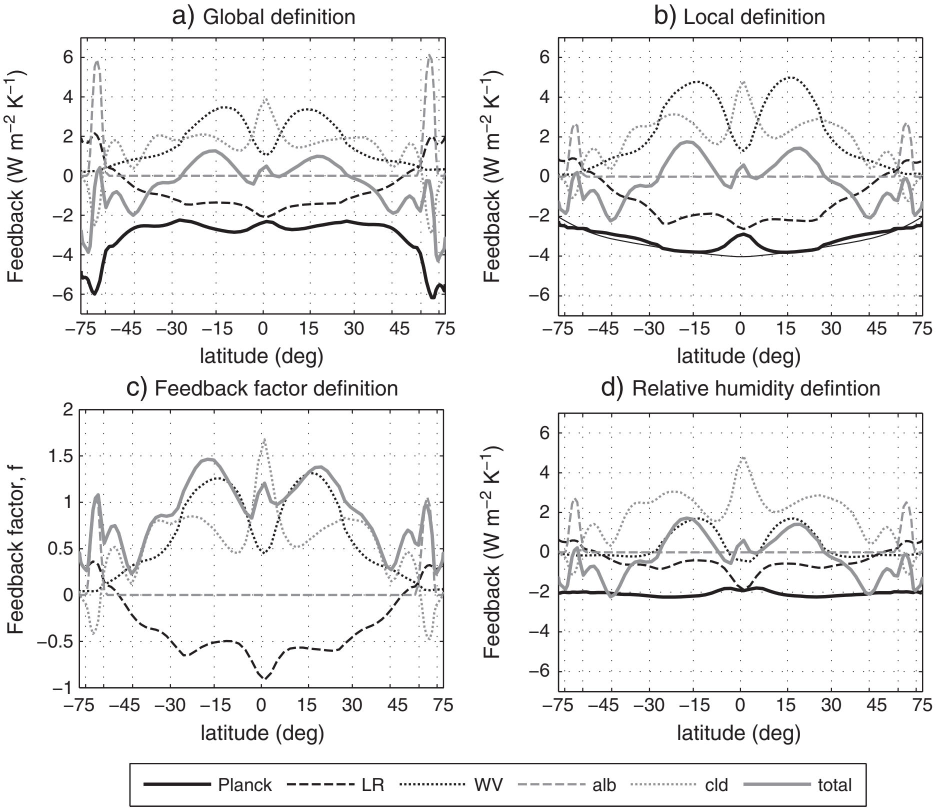

Figure 2. Zonal-mean, annual-mean feedbacks for Planck, lapse rate (LR), water vapor (WV), surface albedo (alb), cloud (cld), and the sum of these individual feedback terms (total) for the four feedback definitions. (a) Global, $\Delta\overline{T_s}$-defined feedback parameters. (b) Local, $\Delta T_s(x)$-defined feedback parameters. The thin line is the Planck feedback estimated as $4\varepsilon\sigma T_s^3$. (c) Nondimensional feedback factors. Note that the Planck "feedback" is not included here as an individual term, because it is defined as the reference response to which all other feedback factors are relative. (d) Relative humidity framework, locally defined as in Figure 2b).

For $f < 0$, the inclusion of the feedback has damped the response relative to the Planck response; for $0 < f < 1$, the feedback has amplified the response. The subtropical condition $f > 1$ suggests a locally unstable regime, which must be accommodated by an increase in divergence of heat flux if runaway warming is to be avoided [*Pierrehumbert*, 1995; *Feldl and Roe*, 2013].

[13] One benefit of the $f_i = -\lambda_i/\lambda_P$ formulation is that the local versus global choice discussed in section 2 is of no consequence for the meridional structure of f. Whichever form of ΔT_s is used in equation (2), be it $\Delta\overline{T_s}$ or $\Delta T_s(x)$, is simultaneously used to solve for λ_P, and hence, the terms cancel. The clean separation between warming and feedbacks is desirable because we are trying to use the latter to understand the former; convolving the two should be avoided.

4. Relative Humidity Feedback

[14] Recent work has focused on reformulating the water vapor feedback around relative humidity rather than specific humidity [*Ingram*, 2010; *Held and Shell*, 2012; *Ingram*, 2013]. As an important distinction, the new framework represents a regrouping of energy flux changes, without affecting the total linear sum (cf. thick grey line in Figures 2b and 2d). Secondly, in addition to the water vapor feedback itself, the Planck and lapse rate feedbacks are affected. The component of the former water vapor feedback associated with vertically uniform changes in temperature is combined with the Planck feedback, and the component associated with vertical temperature anomalies is combined with the lapse rate feedback; in both cases, these are the humidity perturbations required to maintain fixed relative humidity. The portion that remains is due solely to changes in relative humidity. The global-mean relative humidity feedback is anticipated to be small, as long as relative humidity changes are small [*Held and Soden*, 2000; *Sherwood et al.*, 2010].

[15] One appeal of the relative humidity feedback is that it removes the persistent anti-correlation between water vapor (i.e., specific humidity) and lapse rate feedbacks, leading to a decrease in spread for intermodel comparisons [*Held and Shell*, 2012]. Figure 2d shows that, for the local feedback definition, both relative humidity and lapse rate feedbacks collapse toward zero, compared to Figure 2b. However, by incorporating both temperature and specific humidity changes, the Planck feedback becomes meridionally uniform and thus diverges from a Stefan-Boltzmann interpretation—though it retains its net stabilizing tendency. Hence, while some physical processes are clarified in this framework, others are obfuscated.

[16] *Held and Shell* [2012] report a global-mean relative humidity feedback near zero. In our idealized experiment, we find that the relative humidity feedback is mostly near zero, except for regions of positive values lingering in the subtropics (black dotted line in Figure 2d), whose cause

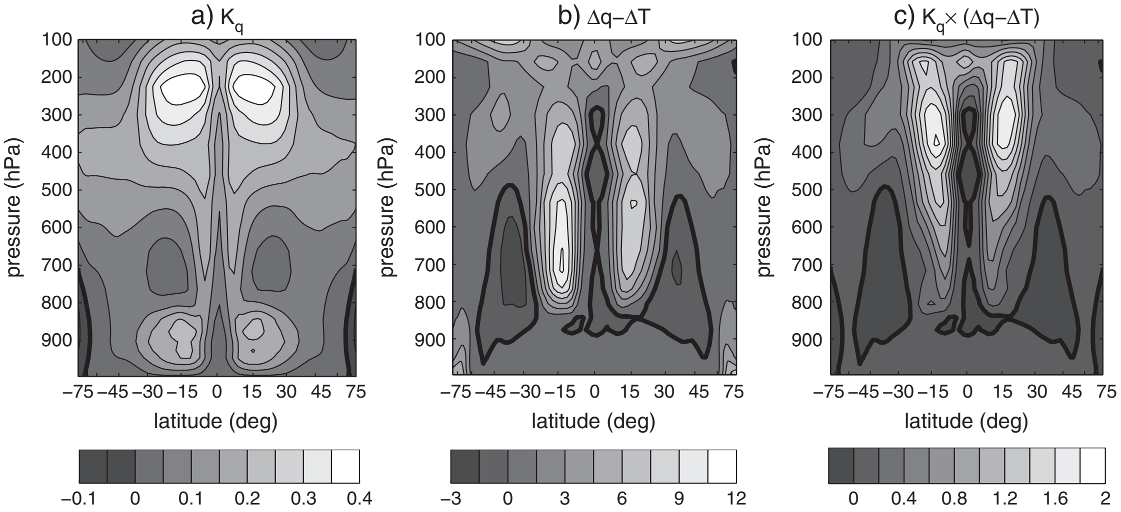

Figure 3. Zonal-mean, annual-mean components of the LW relative humidity feedback following equation (2). (a) The specific humidity radiative kernel, $K_q = \partial R/\partial q$, in W m^{-2} K^{-1}/100 hPa. (b) $\Delta q - \Delta T$, which can be regarded as changes in relative humidity [see *Held and Shell*, 2012], where Δq (in units K) is the fractional change in specific humidity relative to a 1 K warming and fixed relative humidity. Positive values indicate an increase in relative humidity and negative values, a decrease. (c) The convolution of Figures 3a and 3b, demonstrating the subtropical influence. In all panels, the zero contour is indicated by the heavy black line.

we now investigate. Figure 3 shows the vertical structure of the decomposed relative humidity feedback. While the TOA is most sensitive to changes in the tropical upper troposphere (Figure 3a) [*Soden and Held*, 2006; *Feldl and Roe*, 2013], departures from fixed relative humidity peak at lower levels (Figure 3b). Hence the regions that have the greatest impact on the top-of-atmosphere energy balance occur in the subtropics near 300–400 hPa (Figure 3c). The feedback in Figure 2d is computed by locally normalizing, then vertically integrating, Figure 3c. Thus, the relative humidity feedback is substantial in the subtropics because (1) the mean climate state requires this region to be highly sensitive and (2) actual changes in relative humidity are large here due to changes in circulation strength (i.e., a 13% reduction in intensity of the Hadley circulation). Differences between our humidity kernel and that of *Soden et al.* [2008] are a consequence of permanent high clouds at the equator and low relative humidity in the subtropics, due to perpetual equinox conditions in the aquaplanet.

[17] A further value of the relative humidity feedback is that it provides an elegant dissection of the relative importance of thermodynamics and dynamics. Previous work has shown that moistening the subtropics drives anomalous divergence of heat flux, which in part explains polar amplification [*Hwang and Frierson*, 2010; *Zelinka and Hartmann*, 2012; *Feldl and Roe*, 2013]. Comparison of relative and specific humidity feedbacks (cf. dotted black line in Figures 2b and 2d) shows that half to a third of the subtropical specific humidity feedback is due to changes in relative humidity that are dynamically controlled (5 W m^{-2} K^{-1} compared to <2 W m^{-2} K^{-1} at 15°N); the remainder is associated with moistening tied to temperature changes alone (i.e., the moistening required to maintain fixed relative humidity). This striking result emphasizes the importance of evaluating the meridional structure of feedbacks, rather than the global mean only.

5. Summary and Discussion

[18] While feedbacks offer a convenient breakdown of the TOA energy balance, each of the approaches discussed herein highlights a different way of characterizing that balance, which when considered together lead to new insights. For characterizing the meridional structure of feedbacks, the local definition offers several advantages. First, the physical insight it affords is arguably clearer: while clouds are perhaps more complicated, the temperature, surface albedo, and water vapor feedbacks can be simply conceived of as a local change in TOA fluxes due to a local climate response. The locally defined Planck feedback, for instance, exhibits a meridional structure consistent with the Stefan-Boltzmann equation. Second, the locally defined feedbacks are not skewed by polar-amplified warming. While the diminished albedo feedback still matters for polar amplification at the latitude of sea-ice retreat, we gain a different picture of the relative importance of surface albedo and water vapor feedbacks under the local definition. Third, the local definition allows for a decomposition of the spatial pattern of warming (equation (3)), as demonstrated by *Crook et al.* [2011]; *Feldl and Roe* [2013]. Finally, the choice of global versus local definitions has an important effect when transient integrations are of interest. Recent work by *Armour et al.* [2012] has shown that an artificial time-varying behavior is introduced in globally defined feedbacks as a consequence of the evolving pattern of surface warming, which actuates different feedbacks at different times. This is a particular issue for regression-based methods of calculating feedbacks [e.g., *Gregory et al.*, 2004].

[19] Feedback factors f_i are a useful nondimensional measure that closely follow the concept of amplification and damping of response relative to a reference sensitivity. In addition, the powerful partial temperature change analysis, in which each term is normalized by the Planck feedback,

is quite naturally expressed in the language of feedback factors (equation (4)). This analysis, applicable under the local definition as well, provides insight into how spatial patterns of forcing and feedbacks contribute to the pattern of warming. For instance, while the CO_2 forcing accounts for only a small and quite uniform surface temperature change [*Feldl and Roe*, 2013], aerosol and paleoclimate forcings may have more asymmetric signatures.

[20] The relative humidity feedback is appealing for the separation that it brings to thermodynamic and dynamic processes, and because it highlights interesting features of the subtropical moisture response. For instance, the subtropical peak in water vapor feedback is a prevalent feature, for both relative and specific humidities, and is tied to both mean-state conditions and changes in overturning circulation. To the extent that changes in relative humidity are an expression of changes in circulation strength, the relative humidity feedback can be thought of as a dynamically mediated water vapor feedback.

[21] The global definition is an appropriate choice for global-mean feedbacks and equilibrium experiments. By construction, global-mean feedbacks are the global average of the globally defined feedback patterns, which is convenient. Further, the global definition reflects the various terms in the TOA energy budget (equation(1)) more closely than other definitions, because the feedbacks are scaled by a constant factor, $\Delta\overline{T_s}$. However, the alternative approaches presented here are more natural for evaluating the spatial and temporal patterns of system response. The aquaplanet is a particularly useful tool for comparing these various definitions because the differences described herein are tied to broad features of the climate response, such as polar amplification and a weakening of the Hadley circulation, which are robust features of more realistic models. As research evolves to emphasize regional climate predictability and transient response, we expect that adoption of a consistent local framework will be increasingly useful to the community.

[22] **Acknowledgments.** The authors thank Kyle Armour for valuable discussions, Karen Shell and an anonymous reviewer for their constructive comments on the manuscript, and the editor. This work was funded by Washington NASA Space Grant Consortium, NASA Grant #NNX10AK64H.

[23] The Editor thanks Karen Shell and an anonymous reviewer for their assistance in evaluating this paper.

References

Armour, K. C., C. M. Bitz, and G. H. Roe (2012), Time-varying climate sensitivity from regional feedbacks, *J. Clim.*, doi:10.1175/JCLI-D-12-00544.1 in press.

Bony, S., et al. (2006), How well do we understand and evaluate climate change feedback processes? *J. Clim.*, *19*(15), 3445–3482.

Colman, R., and B. McAvaney (2009), Climate feedbacks under a very broad range of forcing, *Geophys. Res. Lett.*, *36*, L01702, doi:10.1029/2008GL036268.

Crook, J. A., P. M. Forster, and N. Stuber (2011), Spatial patterns of modeled climate feedback and contributions to temperature response and polar amplification, *J. Clim.*, *24*(14), 3575–3592.

Feldl, N., and G. H. Roe (2013), The nonlinear and nonlocal nature of climate feedbacks, *J. Clim.*, doi:10.1175/JCLI-D-12-00631.1, in press.

Gregory, J. M., W. J. Ingram, M. A. Palmer, G. S. Jones, P. A. Stott, R. B. Thorpe, J. A. Lowe, T. C. Johns, and K. D. Williams (2004), A new method for diagnosing radiative forcing and climate sensitivity, *Geophys. Res. Lett.*, *31*, L03205, doi:10.1029/2003GL018747.

Hansen, J., A. Lacis, D. Rind, G. Russell, P. Stone, I. Fung, R. Ruedy, and J. Lerner (1984), Climate sensitivity: Analysis of feedback mechanisms, in *Climate Processes and Climate Sensitivity,* vol. 5, edited by J. Hansen, T. Takahashi, and M. Ewing, pp. 130–163, AGU Geophys. Monog. 29, Washington D C.

Held, I. M., and K. M. Shell (2012), Using relative humidity as a state variable in climate feedback analysis, *J. Clim.*, *25*(8), 2578–2582.

Held, I. M., and B. J. Soden (2000), Water vapor feedback and global warming, *Ann. Rev. Energy Environ.*, *25*, 441–475.

Hwang, Y.-T., and D. M. W. Frierson (2010), Increasing atmospheric poleward energy transport with global warming, *Geophys. Res. Lett.*, *37*, L24807, doi:10.1029/2010GL045440.

Ingram, W. (2010), A very simple model for the water vapour feedback on climate change, *Q.J.R. Meteorol. Soc.*, *136*, 30–40.

Ingram, W. (2013), A new way of quantifying GCM water vapour feedback, *Clim. Dyn.*, *40*(3-4), 913–924.

Pierrehumbert, R. T. (1995), Thermostats, radiator fins, and the local runaway greenhouse, *J. Atmos. Sci.*, *52*(10), 1784–1806.

Roe, G. (2009), Feedbacks, timescales, and seeing red, *Annu. Rev. Earth Planet. Sci.*, *37*, 93–115.

Shell, K. M., J. T. Kiehl, and C. A. Shields (2008), Using the radiative kernel technique to calculate climate feedbacks in NCAR's Community Atmospheric Model, *J. Clim.*, *21*(10), 2269–2282.

Sherwood, S. C., W. Ingram, Y. Tsushima, M. Satoh, M. Roberts, P. L. Vidale, and P. A. O'Gorman (2010), Relative humidity changes in a warmer climate, *J. Geophys. Res.*, *115*, D09104, doi:10.1029/2009JD012585.

Soden, B. J., and I. M. Held (2006), An assessment of climate feedbacks in coupled ocean-atmosphere models, *J. Clim.*, *19*(14), 3354–3360.

Soden, B. J., I. M. Held, R. Colman, K. M. Shell, J. T. Kiehl, and C. A. Shields (2008), Quantifying climate feedbacks using radiative kernels, *J. Clim.*, *21*(14), 3504–3520.

Zelinka, M. D., and D. L. Hartmann (2012), Climate feedbacks and their implications for poleward energy flux changes in a warming climate, *J. Clim.*, *25*, 608–624.

Zelinka, M. D., S. A. Klein, and D. L. Hartmann (2012), Computing and partitioning cloud feedbacks using cloud property histograms. Part II: Attribution to changes in cloud amount, altitude, and optical depth, *J. Clim.*, *25*, 3736–3754.