LETTERS

On the Robustness of the Water Vapor Feedback: GCM Vertical Resolution and Formulation

W. J. INGRAM

Hadley Centre for Climate Prediction and Research, Met Office, Bracknell, Berkshire, United Kingdom

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ABSTRACT

Expectations of the size of climate change are generally based on models in which relative humidity (RH) changes little under climate change. A wide variety of general circulation models (GCMs) show such a response, but it has been suggested that this may be an artifact of their having inadequate vertical resolution, and that in reality the climate is much less sensitive to external forcing.

This paper compares GCM simulations with a wide range of vertical resolutions, as well as completely different schemes for convection or advection. All these cases show similar water vapor feedbacks, suggesting that the consensus of GCMs on this feedback may well be correct.

1. Background

Water vapor is the most important greenhouse gas in our atmosphere, and to understand the sensitivity of the earth's climate we need to know how water vapor feeds back on climate change. If relative humidity (RH) remains unchanged as climate changes then specific humidity (SH) increases exponentially with temperature, and climate is substantially more sensitive to external forcing than it would be if SH remained unchanged (so that RH decreased exponentially with temperature).

From the early numerical work on climate change, simple physical arguments suggested roughly unchanging RH. Later, radiosonde and then satellite observations of the midlatitude seasonal cycle became available and were found to be consistent with this. Also, GCMs have been developed and also found to agree well despite very different formulations, and very different cloud feedbacks (Manabe and Wetherald 1967; Cess et al. 1990; Held and Soden 2000).

However, the possibility has been raised that this GCM consensus is an artifact of overdiffusive simulations of water vapor, due to lack of resolution (especially in the vertical) and perhaps other causes such as the numerical diffusion needed to maintain smooth and stable solutions. The Intergovernmental Panel on Climate Change (IPCC) notes (Stocker et al. 2001) that ''the apparent lack of sensitivity of water vapour feedback in current GCMs . . . may be an artefact of insufficient vertical resolution,'' and some authors have argued for a water vapor response much closer to unchanged SH. The issues this letter investigates can then be summarized as two competing hypotheses:

- Hypothesis 1: The water vapor feedback is close to what unchanged RH would give, and modeling it is not badly affected by vertical resolution.
- Hypothesis 2: The usual vertical resolution in the free troposphere is not enough to get the water vapor response right, leading to an inflated climate sensitivity—the real value is substantially smaller, maybe close to what unchanged SH would give.

Specifically, Spencer and Braswell (1997) argued that the GCMs (and radiosonde observations) do not represent adequately the small regions at low latitudes of very dry air that therefore radiate heat to space very effectively. If these ''cooling fins'' increased their area substantially with global warming (''hypothesis 2a''), this would provide an important negative feedback omitted from current models. Another specific mechanism (''hypothesis 2b'') was proposed by Lindzen et al. (2001), who argued that the low latitudes are roughly equally split between dry clear areas that radiate heat more effectively, and moist cloudy ones that radiate less heat, and that the former could expand with global warming, again giving a strong negative feedback absent from existing models.

Tompkins and Emanuel (2000) and Lane et al. (2000)

Corresponding author address: Mr. W. J. Ingram, Hadley Centre for Climate Prediction and Research, Met Office, London Road, Bracknell, Berkshire RG12 2SY, United Kingdom.
E-mail: william.ingram@metoffice.com

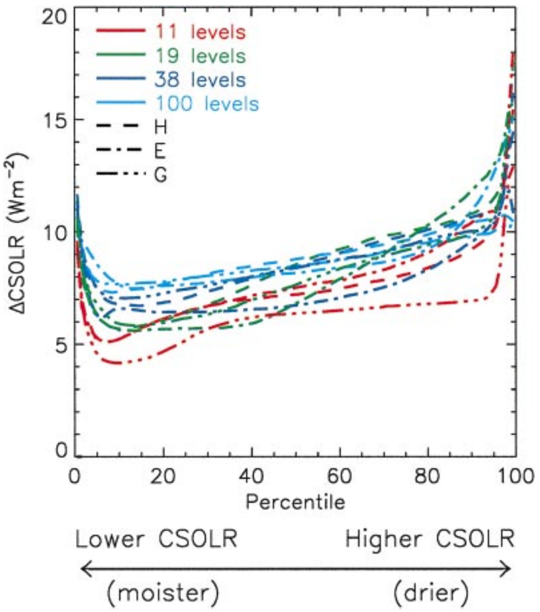

FIG. 1. The change in low-latitude CSOLR on warming, in each percentile of its own distribution, for each of the 12 pairs of simulations (see text). Thus, the area under each curve is the low-latitude mean change in CSOLR for that case, with contributions from higher CSOLR (generally, lower RH) to the right. For example, the 100th (rightmost) point on each curve has a *y*-value equal to the mean of the highest 1% of low-latitude CSOLR in the cooled run subtracted from the mean of the highest 1% of low-latitude CSOLR in the warmed run. Readers familiar with cumulative frequency distributions (CFDs) may note that this is simply inverting the CFDs (swapping *x* and *y*) and then differencing them. (The area under this curve corresponds to the area to the left of the CFD, which also equals the mean of the underlying distribution.) This calculation was done on instantaneous data sampled at intervals of 10 days and 15 h, and the results were time averaged.

both discuss the convergence of the RH distribution with vertical resolution in equilibrium single-column convective simulations. The former find convergence at a resolution of 25 hPa, while the latter find no convergence even at 15 hPa. This discrepancy may just reflect differences between the convection schemes concerned. Or it may be due to the tests being differently designed—it is not clear how to ensure a single-column test would respond like the much more diverse and fully four-dimensional world of a GCM, or even if this is possible. In any case, if hypothesis 1 is true, the water vapor feedback is in fact not very sensitive to the actual distribution of RH (Held and Soden 2000), so GCMs' RH distributions could be badly distorted by their vertical resolution with little effect on their simulation of climate change.

This paper addresses these issues by comparing GCM simulations with varying numbers of levels, including much higher midtropospheric vertical resolution than any previous GCM study. Section 2 describes the simulations, section 3 discusses results and the mechanisms responsible, and section 4 provides a concluding summary.

2. Experiments

We examine the water vapor feedback in idealized ''inverse'' GCM experiments where radiation responds to a prescribed uniform change in sea surface temperatures (Cess et al. 1990), rather than temperature responding to a prescribed radiative forcing. The response will not match that of coupled experiments in detail (Senior and Mitchell 1993). However, they do indicate how similar the response of different models to radiative forcing will be, and give clearer signals than coupled simulations as well as needing far less computing time. The experiments are for ''perpetual July'' using climatological sea surface temperatures with a uniform offset of +2 or −2 K (Cess et al. 1990). They are designed so that water vapor effects will dominate the differences, allowing the convenient simplification of quantifying the water vapor feedback in terms of clear-sky outgoing longwave (terrestrial thermal) radiative flux (CSOLR) at the top of the atmosphere (TOA).

The physics of the model simulations is based on HadAM3 (Pope et al. 2000), with some minor corrections and technical alterations to maintain numerical stability. (Pope et al. 2001 show the overall improvement in this model's control simulation of moisture going from 19 to 30 levels.) Three established sets of unevenly spaced levels are used: 11 (Walker and Rowntree 1977), 19 (Pope et al. 2000), and 38 (Webb et al. 2000), as well as a set of 100 levels evenly spaced in the model's hybrid pressure vertical coordinate, so increasing the resolution most in the free troposphere. There, typical layer thicknesses are 140, 90, 50, and 10 hPa, respectively, for the 4 sets of levels. The differences in layer spacing, particularly the evenness of the 100 levels, could have significant effects in addition to the change in resolution, but the results below suggest this is not an issue. The physical formulation is the same for all sets of levels except that the dynamics time step is reduced from 30 to 10 min with 100 levels, again for numerical stability: tests with 11 levels found this change in time stepping caused no important differences to the quantities considered here (not shown). All data shown are averaged over 720 days after discarding at least 90 days initially.

In addition to the set of simulations with the standard HadAM3, another set of simulations was performed using a different convection scheme (a slightly updated version of that of Emanuel and Zivkovic-Rothman 1999), and a third set using a different scheme for the advection of heat and moisture [a monotonic finite-volume scheme with intercell fluxes calculated assuming a quintic polynomial subcell distribution following the one-dimensional non-oscillatory integrally reconstructed volume-averaged numerical advection (NIRVANA) scheme of Leonard et al. (1995)].

3. Results

Table 1 gives global-mean responses with each set of levels and each physical formulation. The total climate

TABLE 1. Global-mean changes from −2 to +2 K runs, and implied "climate sensitivity parameters" (the warming divided by the net radiative change at TOA). Each box gives the value for HadAM3 (H), Emanuel convection (E), and alternative advection (G). We estimate typical standard errors as 0.007 K W^{-1} m^2, 0.02 K W^{-1} m^2, 0.01 W m^{-2}, 0.07 W m^{-2}, and 0.03 K, respectively.

Number of levels		11	19	38	100
Clear-sky climate sensitivity (K W^{-1} m^2)	H	0.62	0.57	0.55	0.55
	E	0.62	0.63	0.63	0.57
	G	0.80	0.62	0.57	0.57
Climate sensitivity (K W^{-1} m^2)	H	1.34	0.79	0.54	0.43
	E	0.85	0.75	0.77	0.88
	G	2.12	0.87	0.57	0.43
TOA clear-sky outgoing SW flux (W m^{-2})	H	−1.42	−1.43	−1.43	−1.43
	E	−1.40	−1.46	−1.45	−1.41
	G	−1.50	−1.48	−1.44	−1.45
TOA clear-sky outgoing LW flux (W m^{-2})	H	8.47	9.16	9.62	9.20
	E	8.36	8.51	8.46	9.04
	G	7.09	8.73	9.12	8.89
Near-surface (1.5 m) temperature (K)	H	4.40	4.39	4.48	4.26
	E	4.34	4.41	4.39	4.38
	G	4.47	4.52	4.41	4.20

sensitivity varies considerably, but most of this is due to the modeled cloud feedbacks, which are not the focus of this paper. [We hope to publish an analysis of the cloud feedbacks later. These are well known to be very variable between models (Cess et al. 1990), even after the usual tuning to make their cloud simulations more realistic, so similarly large variability between resolutions is no surprise. The fundamental reason is presumably that clouds are due to the difference between two nearly equal quantities: total humidity and saturation humidity.] When we exclude cloud processes, the clear-sky climate sensitivity parameters cluster around 0.6 K W^{-1} m^2 (with one comparative outlier), and are all well above the value of 0.2–0.25 K W^{-1} m^2 calculated assuming unchanged specific humidity. These numbers indicate a dependence on resolution in that the 11-level simulations are all more sensitive than the 100-level ones, but the effect is small compared with the variation due to cloud feedback. Thus these simulations are broadly consistent with hypothesis 1 and only with a weak form of hypothesis 2.

The near-surface warmings are all similar, as intended. The clear-sky shortwave (solar) changes are similar too. (They will largely be determined by total-column water vapor changes, which will be dominated by the low-level contributions closely tied to the near-surface warmings.) The variation in clear-sky climate sensitivity is thus mainly due to variation in the CSOLR changes.

These global means are consistent with the mechanisms of hypotheses 2a and 2b playing a limited role in this model. To see if they do, we plot the contributions to the mean CSOLR change from different parts of the low-latitude CSOLR distribution in Fig. 1. (Hypotheses 2a and 2b both concern low latitudes: the assumption of unchanged RH seems generally accepted to be more robust at higher latitudes. We take "low latitudes" to be equatorward of 30°.)

Figure 1 has CSOLR increasing (generally, RH decreasing) along the *x* axis, so in particular the contribution from any cooling fins simulated will be at the right-hand side. First, suppose that hypothesis 2a applies, so that the cooling fins exist and their area increases substantially on warming, like the idealized case in Fig. 2a, but only at high vertical resolution. Then in Fig. 1 we would see increases in CSOLR of tens of W m^{-2} in a spike a little before the right-hand side of the curves, like Fig 2c, but at high resolution only. Clearly we do not—we only see spikes right at the end, and if anything they are smaller at the highest resolution. Now suppose on the other hand that a model has cooling fins whose coverage is much the same in warm and cold climates as hypothesis 1 implies. Then their extremely weak water vapor greenhouse effect will make their CSOLR not only the largest but also the most sensitive to temperature changes, and the curve will jump up noticeably at the right-hand side—just what we see.

Hypothesis 2b implies a peak in the middle of the curve (Figs. 2b and 2d), again at high resolution only. Clearly the models produce nothing of the sort at any resolution. In fact, they could not, since their undifferenced distributions do not show the bimodality of the model of Lindzen et al. (2001), which is a prerequisite for such a response. [The realism of that assumption of Lindzen et al. (2001) is beyond the scope of this modeling sensitivity study.]

On the contrary, the higher clear-sky climate sensitivity at 11 levels (Table 1) corresponds to the 11-level curves in Fig. 1 being consistently lower across most of their range. This indicates a consistent, though small, dependence of the model's moist response on vertical resolution, occurring right across the range of RH.

Can we then identify the mechanism, which must act similarly at almost all points? Figure 3a shows the profiles of simulated RH horizontally averaged over low latitudes. We see a typical pattern of RH decreasing with height above the surface, which is the ultimate source of moisture, increasing again in the upper troposphere around the typical levels of convective detrainment, and

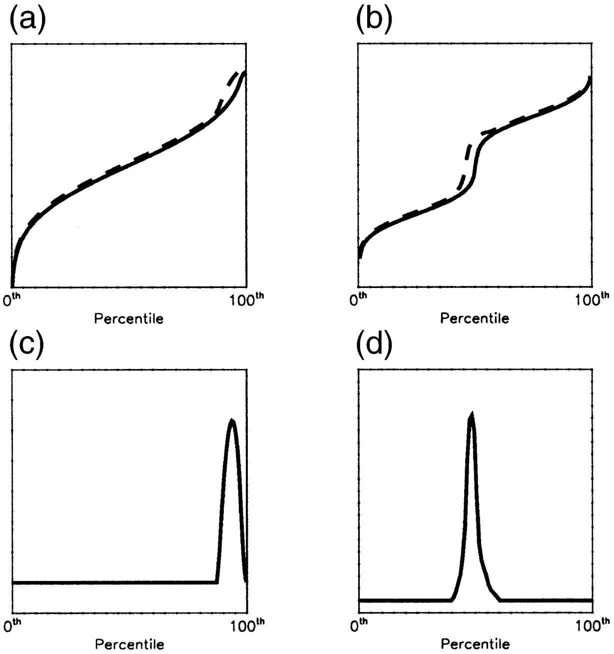

FIG. 2. Idealized examples of the variation of CSOLR across its own distribution, and the change on warming, illustrating hypotheses 2a and 2b. Each of these implies that there is a particular part of the CSOLR distribution where it changes much more on warming, substantially increasing the overall radiation of heat to space and decreasing the climate sensitivity: (a) and (b) colder (solid) and warmer (dashed) climates; (c) and (d) difference on warming, comparable with Fig. 1.; (a) and (c) hypothesis 2a—the area of the cooling fins (very dry air at low latitudes, which therefore has a very low water vapor greenhouse effect and radiates more heat than anywhere else) increases on warming. The shape of the curves is irrelevant away from the right-hand side, and has been drawn as it is for a bell-shaped underlying distribution, corresponding to the well-known ogee CFD. (b) and (d) Hypothesis 2b—the dry clear air covering about half the low latitudes expands on warming. This hypothesis presupposes a strong bimodality of the underlying distribution [the idealized numerical model of Lindzen et al. (2001) corresponds to a step function variation in 2b].

then dropping very low in the stratosphere. The exceptions are two of the 11-level simulations with almost no mean vertical gradient in the troposphere. This is perhaps not surprising, as even in the Tropics there are only six levels in the free troposphere at this resolution. Also, one of the 11-level simulations is much moister in the stratosphere (where it has only two levels in the Tropics).

GCM climate warming simulations normally include marked RH increases above decreases around the tropopause (Wetherald and Manabe 1988; Mitchell and Ingram 1992). This can be explained as an upward shift of the upper-tropospheric RH maximum as the tropopause rises with tropospheric warming (Wetherald and Manabe 1988). Figure 3b shows the RH changes on warming corresponding to Fig. 3a. The most marked feature is the drying maximum around 300 hPa—except in the two 11-level simulations where there was no upper-tropospheric maximum to move up in the first place. The third 11-level simulation, with the excess moisture in the stratosphere, shows a substantial moistening there on warming, also presumably spurious. Thus all three 11-level simulations show a moistening on warming compared to higher resolution, implying a comparative increase in water vapor greenhouse effect and so greater climate sensitivity. At higher latitudes (not shown) again comparing the RH changes in the 11-level simulations with those at higher resolution shows consistent differences attributable to blurring of the vertical variation of RH.

4. Concluding remarks

Our model's water vapor feedback is robust to changing vertical resolution, even with vertical resolution much higher than in any previously published work. In particular, there is no sign of two effects, which it had

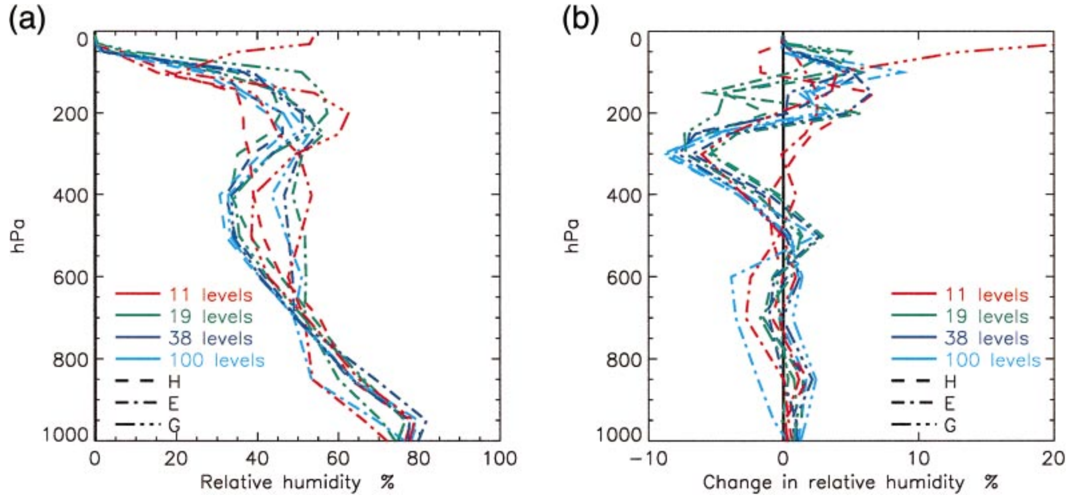

FIG. 3. The RH as a function of pressure horizontally averaged over low latitudes. (a) Mean of +2 and −2 K simulations. (b) Change on warming.

been hypothesized are important in reality but missed by GCMs, so inflating their clear-sky climate sensitivity. Only at the lowest vertical resolution (lower than ever used in any previously published work with this GCM) do we find any systematic exaggeration of the clear-sky climate sensitivity, and this effect is small compared to the uncertainty in the cloud feedback, consistent with previous studies (Cess et al. 1990). These results are robust to changing major aspects of model formulation, but should be tested in a wider range of simulations, including completely different models.

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