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Maximum entropy production, cloud feedback, and climate change

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[1] A steady-state energy-balance climate model based on a global constraint of maximum entropy production is used to examine cloud feedback and the response of surface temperature T to doubled atmospheric CO_2. The constraint ensures that change in zonal cloud amount θ necessarily involves change in the convergence KX of meridional energy flow. Without other feedbacks, the changes in θ, KX and T range from about 2%, 2 Wm^{-2} and 1.5 K respectively at the equator to −2%, −2 Wm^{-2} and 0.5 K at the poles. Global-average cloud effectively remains unchanged with increasing CO_2 and has little effect on global-average temperature. Global-average cloud decreases with increasing water vapour and amplifies the positive feedback of water vapour and lapse rate. The net result is less cloud at all latitudes and a rise in T of the order of 3 K at the equator and 1 K at the poles. Ice-albedo and solar absorption feedbacks are not considered. **Citation:** Paltridge, G. W., G. D. Farquhar, and M. Cuntz (2007), Maximum entropy production, cloud feedback, and climate change, *Geophys. Res. Lett.*, *34*, L14708, doi:10.1029/2007GL029925.

1. Introduction

[2] *Dewar* [2003, 2005] recently published a proof of the concept of maximum entropy production (MEP) as it applies to non-linear systems. The proof revived interest in the MEP-based climate model of one of us [*Paltridge*, 1975, 1978] and the physics and mathematical treatment of the model were examined and updated as described briefly in the Appendix. The MEP constraint allows the model to calculate the broad steady-state distribution of cloud and surface temperature without the need for detailed consideration of the internal dynamics of the system. In principle therefore the model inherently includes cloud feedback, which is perhaps the most arguable (and potentially the most significant) of the various feedbacks built into large-scale general circulation climate models. Despite the fact that cloud feedback was formally identified in the early days of the World Climate Research Program as one of the most significant scientific problems restricting climate research, even the sign of cloud feedback is still not known for certain today [*Randall et al.*, 2003].

[3] This paper examines, albeit at the basic level of an energy balance climate model, what the MEP principle suggests with regard to cloud feedback. Radiative forcing information from various sources is used to calculate changes in the infrared input parameters of the MEP model caused by a doubling of CO_2 and by the subsequent feedback involving atmospheric water vapour and lapse rate (WV/LR feedback). Sensitivities of cloud amount θ and surface temperature T to doubled CO_2 are established from model trials with and without the changes of the input parameters.

2. Long-Wave Parameters of the MEP Model

[4] The model assumes a two-band radiating atmosphere in the long-wave part of the spectrum. All the atmospheric emission or absorption takes place in one of the bands which is regarded as 100% opaque. The other represents the 8 to 14 micron atmospheric window and the various smaller windows in the absorption spectrum of the atmosphere, and is regarded as 100% clear. The absorbing gases of the atmosphere are regarded as a blanket, the top of which in clear skies corresponds to the height from which the radiation of the opaque band is emitted upward. The bottom of the blanket radiates downwards from a radiative temperature very close to ground temperature, so that the net exchange of radiation between ground and atmosphere within the opaque band is effectively zero.

[5] The emissivity ε_a of the atmosphere is determined by the ratio of the width of the opaque band relative to that of the total black-body spectrum, but weighted appropriately by the shape of the spectrum. Transmission of radiation between ground and space in clear skies (or between ground and cloud base in cloudy skies) can take place only through the atmospheric window whose width is 1-ε_a. Upward emission of radiation R_u from the top of the radiating blanket in clear skies is given by $\varepsilon_a\sigma T_{bt}^4$, where σ is the Stefan Boltzmann constant and T_{bt} is the temperature at the top of the radiating blanket. T_{bt} is defined in terms of the black-body radiation at that temperature, but expressed as a fraction of the black-body radiation at the temperature of the Earth's surface. That is, it is expressed in terms of a parameter $F = \sigma T_{bt}^4/\sigma T^4$ such that $R_u = F\varepsilon_a\sigma T^4$.

[6] The upward flux R_u^C of radiation to space from cloud and from the atmosphere above cloud is envisaged as black-body radiation emanating from an effective cloud top that is slightly higher and colder than real cloud top. It takes into account the presence above real cloud top of a blanket of CO_2 whose emissivity and thickness are much less than those of the clear-sky blanket. The effective cloud top temperature is again defined in terms of black-body radiation at that temperature. It is expressed in terms of parameters f and f' such that $R_u^C = f.\ f'\sigma T^4$. Here $f'\sigma T^4$ is the black-body radiation at the temperature of cloud base, and f is essentially a fractional measure of the temperature difference between cloud base and effective cloud top.

[7] Increasing the concentration of atmospheric CO_2 has the immediate effect of slightly closing the atmospheric window (increasing the emissivity ε_a), slightly thickening

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Table 1. Values of Flux Derivatives and Derived Infrared Parameters[a]

Flux Derivatives	Value for Clear Sky	Value for Mean Cloud	Value for θ = 100%	Derived Parameters	Value
$\partial R_d/\partial C$	1.8 (1)			$\partial \varepsilon_a/\partial C$	.0045
$\partial R_u/\partial C$	−4.5 (2)			$\partial F/\partial C$	−.0127
$\partial R_u/\partial C$		−3.7 (2)	−3.2	$\partial f/\partial C$	−.0097
$(\partial R_d/\partial T)_{wv}$	2.2 (3)			$(\partial \varepsilon_a/\partial T)_{wv}$	.0056
$(\partial R_u/\partial T)_{wv}$	−1.8 (4)			$(\partial F/\partial T)_{wv}$	−.0027
$(\partial R_u/\partial T)_{wv}$		−1.2 (4)	−0.8	$(\partial f/\partial T)_{wv}$	−.0024
$(\partial R_u/\partial T)_{lr}$	0	0.8 (5)	1.5	$(\partial f/\partial T)_{lr}$	.0048

[a]Parenthesized numbers refer to sources as follows: (1) *Fels et al.* [1991]; (2) *Intergovernmental Panel on Climate Change* [2001]; (3) derived from experimental data of *Swinbank* [1963]; (4) M. Dix (personal communication, 2006) involving calculations with the radiation package of the CSIRO Mark 3 Climate Model; and (5) *Bony et al.* [2006]. Subscripts *wv* and *lr* refer to feedback of water vapour and lapse rate respectively. The 100% cloud values are calculated from the clear-sky and mean-cloud values assuming a mean cloud cover of 60%. $(\partial R_d/\partial T)_{wv}$ and $(\partial R_u/\partial T)_{wv}$ are the differences between fluxes calculated for an atmosphere of constant relative humidity and one of constant specific humidity when the temperature at all levels is raised by 1 K. They are therefore the changes due only to the change in water vapour when the temperature is raised. Units of the $\partial R/\partial C$ in columns 2, 3, and 4 are Wm^{-2}, and of the $\partial R/\partial T$ are $Wm^{-2}\ K^{-1}$.

the clear-sky radiative blanket and raising its top to a lower temperature (decreasing the value of F) and, by the same mechanism, slightly raising the effective cloud-top to a lower temperature (decreasing the value of f). Feedback via surface temperature raises the concentration of atmospheric water vapour and further increases ε_a and decreases F and f. It is assumed that lapse-rate feedback derives primarily from latent heat release associated with the formation of rain in the upper levels of the cloudy atmosphere, thereby increasing the temperature of effective cloud-top relative to the ground and hence increasing f without affecting ε_a and F.

3. Calculations

[8] In terms of the above description, the downward long-wave flux R_d at the ground and the upward long-wave flux R_u at the top-of-the-atmosphere (TOA) are given by

$$R_d = \varepsilon_a \sigma T^4 (1-\theta) + f' \varepsilon_a \sigma T^4 \theta \quad (1)$$

and

$$R_u = \left[(1-\varepsilon_a)\sigma T^4 + F\varepsilon_a \sigma T^4\right](1-\theta) + f' f \sigma T^4 \theta \quad (2)$$

where θ is the fractional cloud amount. These equations can be differentiated with respect to CO_2 concentration C and (separately) to surface temperature T both for clear-sky conditions (θ = 0) and for fully clouded conditions (θ = 1). The differentiated equations can then be manipulated so as to yield expressions for the partial derivatives $\partial\varepsilon_a/\partial C$, $\partial F/\partial C$ and $\partial f/\partial C$ (each of them constant with respect to water vapour and lapse rate) and $\partial\varepsilon_a/\partial T$, $\partial F/\partial T$ and $\partial f/\partial T$ (each of them constant with respect to C) as a function of the corresponding partial derivatives of the radiative fluxes R_d and R_u.

[9] Global-average (or mid-latitude) values of the radiative flux partial derivatives and their source references are quoted in Table 1 together with the derivatives of the infrared parameters calculated from them. The derivatives with respect to C assume the present-day concentration of CO_2 to be one unit, so that numerically they are equal to the changes from doubled CO_2 – this on the further assumption that the radiative response is linear over the range. The derivatives with respect to T reflect the changes in water vapour and lapse rate brought about by a rise in T of 1 K, and among other things involve an assumption of constant relative humidity at all levels of the atmosphere during the changes of T. $\partial f/\partial T$ is the sum of the changes due to the separate water-vapour and lapse-rate feedbacks (see the appropriately subscripted derivatives in Table 1).

[10] The parameters ε_a, F and f are fixed inputs for any particular trial of the MEP model. Each trial yields a distribution with latitude of T, θ and the meridional energy flux convergence KX. Here we simply re-run the model with changes to the parameters as indicated by the derivatives of the right hand column of Table 1. It is re-run first with the changes corresponding only to doubled CO_2. That is, ε_a, F and f at each latitude are changed to $\varepsilon_a + (\partial\varepsilon_a/\partial C)\Delta C$, $F + (\partial F/\partial C)\Delta C$ and $f + (\partial f/\partial C)\Delta C$ where $\Delta C = 1$. The zonal-average increases ΔT in surface temperature so derived are then used as the starting point of an iterative set of trials taking WV/LR feedback into account. $(\partial\varepsilon_a/\partial T)\Delta T$, $(\partial F/\partial T)\Delta T$ and $(\partial f/\partial T)\Delta T$ are added to the relevant parameters at each trial, with the ΔT at each latitude deriving from the output of the preceding two trials. The iteration stops when all the ΔT are infinitesimally small.

[11] The process assumes that CO_2 is a well-mixed gas and therefore that the parameter changes for doubled CO_2 are the same at all latitudes. A similar and far more drastic assumption is made with regard to water vapour and lapse rate in that the sensitivities to T (the $\partial\varepsilon_a/\partial T$ etc. of Table 1) are also set to be the same at all latitudes.

[12] There are problems of stability in the optimisation process (see the Appendix) associated with numerical application of the MEP constraint when the non-linear WV/LR feedback on temperature is large. The results here are derived by repeating the WV/LR feedback calculations over three equal steps (ΔT/3) of the 'starting point' temperature change ΔT. This is a considerable approximation that partially linearises (and reduces) the feedback.

4. Results and Discussion

[13] Case A of Figure 1 is the no-feedback distribution of temperature change calculated when cloud, meridional energy convergence, water vapour and lapse rate of each latitude zone are held constant while the changes $\partial\varepsilon_a/\partial C$,

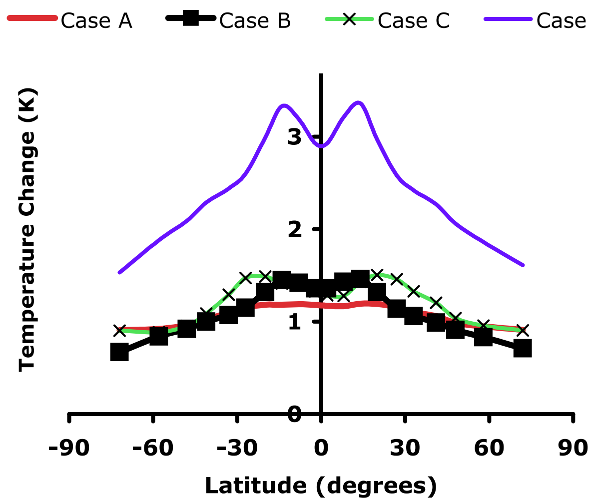

Figure 1. Distribution with latitude of surface temperature change for doubled CO_2 for four feedback conditions. As in the text, case A is for no feedbacks, case B is for cloud feedback only, case C is for WV/LR feedback only, and case D is for cloud and WV/LR feedback (noting that cloud feedback in this case is a response to both the CO_2 increase and the WV/LR change). Southern Hemisphere latitudes are negative.

$\partial F/\partial C$ and $\partial f/\partial C$ are applied to the input parameters. It is derived by removing the MEP constraint and using energy balance of the individual zones to calculate their temperature response. The change in T decreases towards the poles because the doubled CO_2 operates on radiative fluxes determined by a surface temperature that itself decreases towards the poles. The fact that most general circulation models do not reflect this expectation (particularly in the Northern Hemisphere) is generally attributed to their inclusion of ice-albedo feedback.

[14] Case B of Figure 1 is the distribution of temperature change when θ, KX and T are allowed to adjust (but with no WV/LR feedback) so as to satisfy the MEP constraint. Referring to curves (1) and (2) of Figure 2, the constraint and the requirements of energy balance ensure a strong link between the changes in the distributions of cloud and of meridional energy convergence. The link occurs because the radiative temperatures used to define entropy production (see equation A1 of the Appendix) are a function of cloud cover. Thus the decrease of radiative input at the equator occasioned by a 1 or 2 percent increase in cloud is roughly balanced by an increase in KX (a decrease in divergence), and as a consequence the rise of T in the tropics is only slightly greater than that of Case A. Similarly, the increase of radiative input at the poles occasioned by a 2 percent decrease in cloud is roughly balanced by a decrease in KX, so the rise of T in those regions is only slightly less than that of Case A. Overall, an insignificant global-average increase of cloud (0.04%) is associated with an insignificant change (0.04 K) of the increase of global average temperature with doubled CO_2. Note that the label 'cloud feedback only' for case B in Figure 1 and elsewhere implies inclusion of the effect of any associated change in KX.

[15] The global nature of the MEP constraint and the link between θ and KX ensure that the concept of a cloud feedback factor can be considered here only in the global-average context when the net convergence is zero. Thus a cloud feedback factor β_c relevant to increasing CO_2 in the absence of WV/LR feedback can be defined by its appearance in an equation of standard feedback form

$$\Delta T/\Delta C = \frac{\partial T/\partial C}{1 - \beta_c} \tag{3}$$

where $\partial T/\partial C$ is the no-feedback response (the average of the case A distribution in Figure 1) and $\Delta T/\Delta C$ is the response when cloud change is taken into account (the average of case B). Inversion of the equation gives $\beta_c \sim 0$ as in Table 2.

[16] Case C of Figure 1 is the distribution of temperature change when WV/LR feedback is included in the individual zonal energy balance calculations of case A – that is, when the MEP constraint is removed and θ and KX are held constant. The feedback is positive, relatively small, and concentrated in the mid-latitudes. Referring to Table 2, the global-average rise in temperature $\delta T/\delta C$ in this case is 0.2 K above the 1.1 K of case A. Case D is the equivalent distribution from a full run of the MEP model where WV/LR feedback is included and where θ and KX are allowed to adjust so as to satisfy the MEP constraint. There is a change in cloud associated both with the CO_2 increase and with the WV/LR feedback since both processes affect the infrared

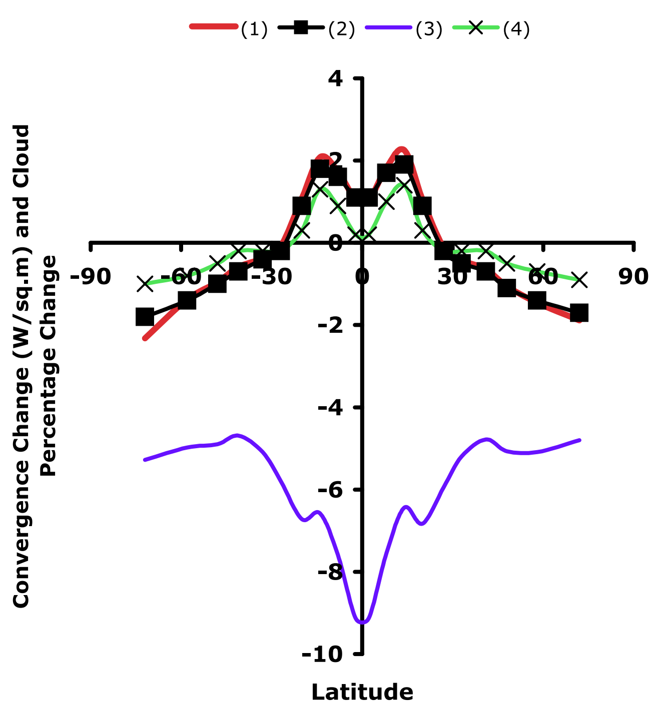

Figure 2. Distributions with latitude of (1) the change in cloud amount without WV/LR feedback (case B), (2) the associated change in convergence of meridional energy flow without WV/LR feedback (case B), (3) the overall cloud change when WV/LR feedback is included (case D), and (4) the change in convergence when WV/LR feedback is included (case D), all for doubled CO_2. Note that "percentage change" of cloud amount here and in the text is an absolute rather than relative measure.

Table 2. Global-Average Changes in T and θ with doubled CO_2[a]

Case	Change in T, K	Text Symbol	Change in θ, %	Feedback Factor
A	1.1	$\partial T/\partial C$	0	0
B	1.1	$\Delta T/\Delta C$	~0.0	$\beta_c \sim 0.0$
C	1.3	$\delta T/\delta C$	0	$\beta_{wl}\vert_\theta \sim 0.1$
D	2.5	dT/dC	~−6.0	$\beta_{wl} \sim 0.6$

	$p = \varepsilon_a$	$p = F$	$p = f$
$\Delta T/\Delta p$	182 K	23 K	−57 K
$\Delta\theta/\Delta p$	−9.3	−4.4	0.8

[a]The changes are given for the four cases of Figure 1, together with the relevant symbols used in the text, and with the corresponding feedback factors calculated from the changes in T using inversion of equations 3 and 5 (or the appropriate equivalent to equation 3 for case C – that is, $\beta_{wl}|_\theta = 1 - (\partial T/\partial C) / (\delta T/\delta C)$). Also given are partial derivatives of global-average θ and T with respect to ε_a, F and f derived from sensitivity runs of the MEP model.

input parameters ε_a, F and f which determine θ and T, but the change associated with WV/LR feedback is by far the larger. The net result is a reduction of cloud by several percent at all latitudes (see Figure 2), and an amplification of the rise in temperature to about 3 K at the equator and 1 K at the poles. The net global-average rise in temperature dT/dC is 2.5 K.

[17] Consider the global-average situation when KX is zero. The full-derivative change in T is given by

$$\frac{dT}{dC} = \frac{\Delta T}{\Delta \varepsilon_a}\cdot\left\{\frac{\partial \varepsilon_a}{\partial C} + \frac{\partial \varepsilon_a}{\partial T}\cdot\frac{dT}{dC}\right\} + \frac{\Delta T}{\Delta F}\cdot\left\{\frac{\partial F}{\partial C} + \frac{\partial F}{\partial T}\cdot\frac{dT}{dC}\right\} + \frac{\Delta T}{\Delta f}\cdot\left\{\frac{\partial f}{\partial C} + \frac{\partial f}{\partial T}\cdot\frac{dT}{dC}\right\} \quad (4)$$

where $\Delta T/\Delta\varepsilon_a$, $\Delta T/\Delta F$ and $\Delta T/\Delta f$ are partial derivative responses to changes in the individual input parameters and include the effect of MEP-modelled cloud change. Re-arranging this equation and making use of equation 3

$$dT/dC = \frac{\partial T/\partial C}{(1-\beta_c)(1-\beta_{wl})} \quad (5)$$

where β_{wl} is a WV/LR feedback factor equal to $(\Delta T/\Delta\varepsilon_a)(\partial\varepsilon_a/\partial T) + (\Delta T/\Delta F)(\partial F/\partial T) + (\Delta T/\Delta f)(\partial f/\partial T)$. It combines (1) the effect of WV/LR feedback on global energy balance (and hence T) via direct change of the input parameters with (2) the effect on global energy balance (and hence T) from the consequent change of cloud.

[18] While cloud feedback is associated with a change in the distribution of T because of the MEP constraint, it is not a "local feedback on temperature" in the same direct sense as are water vapour and lapse rate. As a consequence the two feedback factors of equation 5 are not simply additive – albeit in this particular case β_c is effectively zero. Further, since WV/LR feedback reduces cloud, the factor β_{wl} as defined here (~0.6 from inversion of equation 5 – see Table 2) is not only positive but is numerically much larger than the typical 'fixed-cloud' WV/LR feedback factor $\beta_{wl}|_\theta$ as discussed by *Bony et al.* [2006] and calculated in Table 2 as case C.

[19] Mathematically, the difference between β_c and β_{wl} arises because the absolute value of $\partial F/\partial T$ is very much smaller than that of $\partial F/\partial C$. Thus in the case of CO_2, the decrease in cloud occasioned by an increase of the parameter ε_a (that is, by $(\Delta\theta/\Delta\varepsilon_a)(\partial\varepsilon_a/\partial C)\Delta C$) is roughly offset by an increase in cloud occasioned by the decrease in the parameter F (that is, by $(\Delta\theta/\Delta F)(\partial F/\partial C)\Delta C$). In the case of water vapour, the equivalent offset of $(\Delta\theta/\Delta\varepsilon_a)(\partial\varepsilon_a/\partial T)\Delta T$ by $(\Delta\theta/\Delta F)(\partial F/\partial T)\Delta T$ is very much less so that there is a large net decrease of cloud.

[20] Physically, the relatively smaller response of F to increasing water vapour may arise because water vapour is not a well-mixed gas. As an increase of CO_2 occurs at all levels of the atmosphere, one can imagine its effective radiative blanket-top rising continually (and dropping in temperature) as more and more of its absorption lines become saturated higher in the troposphere. As water vapour increases, and because water vapour is largely confined to the very lowest levels of the atmosphere, the corresponding rise of its effective blanket-top (and the drop of its temperature) is restricted by the physical limit of its upward extent.

[21] The various assumptions associated with this paper's simple physical picture of WV/LR feedback ensure that the calculations relevant to that feedback can be illustrative only. Among other things the picture ignores changes of solar absorption, it relies upon water vapour being something of a well-mixed gas horizontally, it makes assumptions with regard to constancy of relative humidity, and it uses approximations in the numerical simulation of the WV/LR feedback. Perhaps equally as significant, it relies upon calculations of change in radiative flux at the ground and at top-of-atmosphere that are themselves somewhat questionable by virtue of the spread of values to be found in the published literature [see *Bony et al.*, 2006].

[22] In summary, the present work suggests qualitatively that cloud feedback slightly reduces the initial temperature response to doubled CO_2 at high latitudes but slightly amplifies the response at low latitudes. It greatly amplifies the subsequent feedback via water vapour and lapse rate at all latitudes. The positive sign of the overall cloud feedback is consistent with the analyses of current coupled atmosphere-ocean general circulation models [*Bony et al.*, 2006]. Meridional poleward energy flow is decreased despite an increase in equator/pole temperature gradient, a result which is not consistent with analyses of general circulation models [*Held and Soden*, 2006].

Appendix

[23] Paltridge's original MEP model used two broad thermodynamic constraints together with the requirement for energy balance both at the TOA and at the ground. The first concerned maximization of the overall rate of flow of entropy to space. It was calculated as the sum over all the

Table A1. Input Parameters of the MEP Model[a]

Lat., °	I, Wm^{-2}	g_o	d_o	α, S. Hem	α, N. Hem	f	ε, S. Hem	ε, N. Hem
72.0	186	0.130	0.57	30.0	25.0	0.80	0.99	0.99
58.5	242	0.095	0.43	7.3	9.8	0.80	0.99	0.98
48.7	288	0.080	0.39	6.2	10.4	0.80	0.99	0.98
40.6	324	0.070	0.37	6.1	9.3	0.80	0.99	0.98
33.4	355	0.060	0.35	6.7	9.6	0.78	0.99	0.97
26.7	376	0.055	0.34	7.8	10.8	0.75	0.98	0.97
20.4	393	0.050	0.33	8.3	9.8	0.71	0.98	0.97
14.4	406	0.047	0.32	7.5	8.3	0.70	0.99	0.99
8.6	413	0.045	0.31	7.4	7.9	0.70	0.99	0.99
2.8	420	0.045	0.30	7.2	7.1	0.70	0.99	0.99

[a]The latitudes are mid-latitudes of the equal-area zones of each hemisphere. I is the mean annual solar input to the TOA. g_o is the albedo of the Rayleigh-scattering atmosphere with no underlying surface. d_o is the albedo of the cloudy-sky atmosphere with no underlying surface. α and ε are the surface albedo and emissivity respectively. F (= 0.55), f and f' (= 0.85) are the fractional measures of height described in the text. ε_a (= 0.75) and ε_c (= 1.0) are the emissivities of clear sky and cloud respectively. k_c (= 0.20) and k are the fractional short-wave absorptions by cloudy and clear sky respectively. k is a function of α according to $k = 0.18 - 0.18\ (\alpha - 0.06)$.

model grid boxes i of the net radiative outputs R_{Ni} from the TOA, each divided by an atmospheric or planetary temperature T_{ai} defined in terms of the outward long-wave radiative flux from each box. From steady state considerations, the maximization of entropy flow defined in this way is equivalent to maximization of the rate of entropy production associated with the horizontal (basically meridional) energy flows within the system. In effect, the constraint determines in any particular trial the equivalent of the diffusion coefficients for horizontal energy transfer required in a pure energy balance model. The second of the constraints concerned maximization of the vertical flux HLE of sensible and latent heat from ground to atmosphere in each grid box. Mathematically, the two constraints can be expressed as the maximization of:

$$S_p = \sum_i KX_i/T_{ai} \qquad \text{(A1)}$$

and of

$$HLE_i \quad \forall \quad i \qquad \text{(A2)}$$

where S_p is the global rate of production of entropy associated with horizontal energy flow and KX_i is the net convergence of horizontal energy flow into or out of an individual grid box i. The two constraints allow calculation of the four passive unknowns (θ_i, T_i, KX_i and HLE_i) of the two energy-balance equations of each box.

[24] The updated version of the model is different in detail but not in substance. (1) It has 20 equal-area zonal-average grid boxes spanning pole-to-pole, where the solar input at the top of each zone is the annual average taking into account the tilt of the Earth. The original model assumed zero tilt and therefore a solar input to the polar zones which was far too low. (2) Its definition of atmospheric temperature T_{ai} amounts to a weighted average of the radiative temperatures of the effective cloud-top and of the clear-sky 'blanket-top' described in Section 2. In practice this is not greatly different to the original definition in the 1975 paper, but is significantly different to that in the 1978 paper which left out the 'window' component of upward radiation in clear skies in an attempt to de-couple atmospheric and surface temperature. Suffice it to say that the unrealistically low T_{ai} so defined led to unrealistically low values of meridional flux. (3) Its mathematical operation closely follows the computationally efficient semi-analytic technique developed by *O'Brien and Stephens* [1995]. (4) Re-tuning of some of the input parameters was required to achieve realistic simulation of the observed distributions of T, θ, KX and the separate short- and long-wave radiative cloud forcing at the TOA. The re-tuned values are given in Table A1. (5) The model now incorporates a specific tuning factor z_0 multiplying the radiation from the clear-sky 'blanket top' in the formula for the total infrared flux defining T_{ai}. The best overall simulation of the observed distributions is achieved with $z_0 = 1.07$, but setting it to 1.0 makes little difference to the changes calculated in the present work.

[25] Attempts were made (1) to modify the constraint of equation A2 so as to maximize the actual entropy production $HLE_i(1/T_{ai} - 1/T_i)$, and then (2) to combine equations A1 and A2 into one overall constraint of maximizing the total global entropy production associated with both horizontal and vertical turbulent heat flows. Step (1) led to a stable solution that could not be tuned to a good simulation of Earth's cloud and temperature distributions. A stable solution for step (2) has not yet been found.

[26] **Acknowledgment.** Graham Farquhar acknowledges support from the Gary Comer Award.

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