Atmos. Chem. Phys. Discuss., 10, 3699–3715, 2010
www.atmos-chem-phys-discuss.net/10/3699/2010/

Atmospheric Chemistry and Physics Discussions

Thermodynamics of climate change: generalized sensitivities

V. Lucarini[1,2,3], K. Fraedrich[4], and F. Lunkeit[4]

[1]Department of Meteorology, University of Reading, Earley Gate, P.O. Box 243, Reading RG6 6BB, UK
[2]Department of Mathematics, University of Reading, Whiteknights, P.O. Box 220, Reading RG6 6AX, UK
[3]Department of Physics, University of Bologna, Viale Berti Pichat 6/2, 40127 Bologna, Italy
[4]Meteorologisches Institut, Klima Campus, University of Hamburg, Grindelberg 5, 20144 Hamburg, Germany

Received: 24 December 2009 – Accepted: 25 January 2010 – Published: 9 February 2010

Correspondence to: V. Lucarini (v.lucarini@reading.ac.uk)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Using a recent theoretical approach, we study how the impact of global warming of the thermodynamics of the climate system by performing experiments with a simplified yet Earth-like climate model. In addition to the globally averaged surface temperature, the intensity of the Lorenz energy cycle, the Carnot efficiency, the material entropy production and the degree of irreversibility of the system are linear with the logarithm of the CO_2 concentration. These generalized sensitivities suggest that the climate becomes less efficient, more irreversible, and features higher entropy production as it becomes warmer.

1 Introduction

The most basic way to characterize the climate system is describing it as a non-equilibrium thermodynamic system, generating entropy by irreversible processes and – if time-dependent forcings can be neglected – keeping a steady state by balancing the input and output of energy and entropy with the surrounding environment.

A primary goal of climate science is to understand how the statistical properties of the climate system change as a result of variations in the value of external or internal parameters. Rigorous mathematical foundations to this problem can be traced to the Ruelle response theory for non equilibrium steady state systems (Ruelle, 1998). Such an approach has been recently proved to have formal analogies with the usual Kubo response theory for quasi-equilibrium systems (Lucarini, 2008a) and to be amenable to numerical investigation (Lucarini, 2009a).

It has long been recognized that a comprehensive view on the climate system can be attained by adopting a thermodynamic perspective. Two main approaches can be envisioned along this line.

In the first approach, the focus is on the dynamical mechanisms and physical processes responsible for the transformation of energy from one form to the other. The concept of the energy cycle of the atmosphere due to Lorenz (1955) allowed for defining an effective climate machine, driven by the temperature difference between a warm and a cold thermal pool. The atmospheric and oceanic motions at the same time result from the mechanical work (then dissipated in a turbulent cascade) produced by the engine, and re-equilibrate the energy balance of the climate system (Peixoto and Oort, 1992). More recently, Johnson introduced a rather convincing Carnot engine-equivalent picture of the climate by defining robustly the warm and the cold reservoirs and their temperatures (Johnson, 2000).

In the second approach, the emphasis lies on the analysis of the irreversibility of the climate system, and, especially, of its entropy production. This largely results from the intellectual stimulation coming from the maximum entropy production principle (MEPP), which proposes that an out-of-equilibrium nonlinear system adjusts in such a way to maximize the production of entropy (Paltridge, 1979). Even if the general validity of MEPP is unclear (Dewar, 2005; Grinsteinn and Linsker, 2007), its heuristic adoption in climate science has been quite fruitful (Kleidon and Lorenz, 2005; Kleidon et al., 2006), and has stimulated a detailed re-examination of the importance of entropy production in the climate system (Peixoto and Oort, 1992; Ozawa et al., 2003). Moreover, this has resulted into a drive for adopting of a new generation of diagnostic tools based on the 2nd law of thermodynamics for auditing climate models (Fraedrich and Lunkeit, 2008) and for outlining a set of parameterisations to be used in conceptual and intermediate complexity models, or for the reconstruction of the past climate conditions (Kleidon and Lorenz, 2005; Kunz et al., 2008).

Recently a link has been found between the Carnot efficiency, the entropy production and the degree of irreversibility of the climate system (Lucarini, 2009b). This has made possible a new fruitful exploration of the onset and decay of snowball conditions (Lucarini et al., 2010) as parametrically controlled by variations in the solar constant. In that analysis, the two branches of cold and warm climate stationary states have been found to feature very distinct macro-thermodynamical properties.

In this paper we revise and revive the classic problem of analyzing the climate sensitivity to CO_2 concentration changes by adding on top of the usual analysis of globally averaged surface temperature changes the investigation of how the global thermodynamics of the system is influenced by the atmospheric composition, so that a wider physically-based set of generalized sensitivities are introduced. Our investigation is performed using the simplified and portable climate model Planet Simulator (PLASIM) (Fraedrich et al., 2005; Fraedrich and Lunkeit, 2008). We believe our work contributes to presenting reliable metrics to be used in the validation of climate models of various degrees of complexity.

2 Efficiency and entropy production in the climate system

We define the total energy of the Ω-domain of the climatic system by $E(\Omega) = P(\Omega) + K(\Omega)$, where P represents the moist static potential energy, given by the thermal – inclusive of the contributions due to water phase transitions – and potential contributions, and K is the total kinetic energy. The time derivative of the total kinetic and potential energy can be expressed as $\dot{K} = -\dot{D} + \dot{W}, \dot{P} = \dot{\Psi} + \dot{D} - \dot{W}$, where we have dropped Ω-dependence for convenience, $\dot{D}$ is the (positive definite) integrated dissipation, $\dot{W}$ is the instantaneous work performed by the system (or, in other words, the total intensity of the Lorenz energy cycle), $\dot{\Psi}$ represents the hearting due to convergence of heat fluxes (which can be split into the radiative, sensible, and latent heat components), such that $\dot{E} = \dot{\Psi}$. We denote the total heating rate as $\dot{\Phi} = \dot{\Psi} + \dot{D}$. Under the hypothesis of a non-equilibrium steady state system, we have $\overline{\dot{E}} = \overline{\dot{P}} = \overline{\dot{K}} = 0$, where the upper bar indicates time averaging over a long time scale. At any instant, we can partition the domain Ω into Ω^+ and Ω^-, such that the intensive total heating rate $\dot{Q}$ is positive in Ω^+ and negative in Ω^-:

$$\dot{P} + \dot{W} = \int_{\Omega^+} dV \rho \dot{Q}^+ + \int_{\Omega^-} dV \rho \dot{Q}^- = \dot{\Phi}^+ + \dot{\Phi}^- = \dot{\Phi}. \qquad (1)$$

Since $\overline{\dot{D}} > 0$ we obtain $\overline{\dot{W}} = \overline{\dot{D}} = \overline{\dot{\Phi}^{+}} + \overline{\dot{\Phi}^{-}} > 0$. Assuming local thermodynamic equilibrium – which applies well everywhere except in the upper atmosphere, which has a negligible mass – and, neglecting the impact of mixing processes (Lucarini, 2009b) we have that locally $\dot{Q} = \dot{s}T$, so that at any instant entropy fluctuations have locally the same sign as heat fluctuations. The time derivative of the total entropy of the system is:

$$\dot{S} = \int_{\Omega^{+}} dV \frac{\rho \dot{Q}^{+}}{T} + \int_{\Omega^{-}} dV \frac{\rho \dot{Q}^{-}}{T} = \int_{\Omega^{+}} dV \rho |\dot{s}^{+}| - \int_{\Omega^{-}} dV \rho |\dot{s}^{-}| = \dot{\Sigma}^{+} + \dot{\Sigma}^{-} \tag{2}$$

where at all times $\dot{\Sigma}^{+} > 0$ and $\dot{\Sigma}^{-} < 0$. At steady state we have $\overline{\dot{S}} = 0$, so that $\overline{\dot{\Sigma}^{+}} = -\overline{\dot{\Sigma}^{-}}$. Moreover, $\overline{\dot{\Sigma}^{+}}$ measures the absolute value of the entropy fluctuations throughout the domain since $2\overline{\dot{\Sigma}^{+}} = \overline{\int_{\Omega} dV \rho |\dot{s}|}$.

Therefore, we obtain $\overline{\dot{\Sigma}^{+}} = \overline{\dot{\Phi}^{+}} \Big/ \Theta^{+}$ and $\overline{\dot{\Sigma}^{-}} = \overline{\dot{\Phi}^{-}} \Big/ \Theta^{-}$, where $\Theta^{+}(\Theta^{-})$ can be defined as the time and space averaged value of the temperature where absorption (release) of heat occurs. Since $\left|\overline{\dot{\Sigma}^{+}}\right| = \left|\overline{\dot{\Sigma}^{-}}\right|$ and $\left|\overline{\dot{\Phi}^{+}}\right| > \left|\overline{\dot{\Phi}^{-}}\right|$, we derive that $\Theta^{+} > \Theta^{-}$ and we characterize the climate system as a Carnot engine such that $\overline{\dot{W}} = \eta \overline{\dot{\Phi}^{+}}$, with efficiency $\eta = \left(\Theta^{+} - \Theta^{-}\right) / \Theta^{+} = \left(\overline{\dot{\Phi}^{+}} + \overline{\dot{\Phi}^{-}}\right) \Big/ \overline{\dot{\Phi}^{+}}$ (Johnson, 2000; Lucarini, 2009b).

The 2nd law of thermodynamics imposes that the long-term average of the material entropy production inside the system $\overline{\dot{S}_{\mathrm{in}}(\Omega)}$ (this excludes the contributions due to the “degradation” of the solar radiation into terrestrial longwave radiation) is bounded from below by $\overline{\dot{S}_{\mathrm{min}}(\Omega)} \approx \overline{\dot{W}} \Big/ \langle\Theta\rangle \approx \eta \overline{\dot{\Sigma}^{+}}$, where $\langle\Theta\rangle = \left(\Theta^{+} + \Theta^{-}\right)/2$ (Lucarini, 2009b). Therefore, η sets also the scale relating the minimal material entropy production of

the system to the absolute value of the entropy fluctuations inside the system. If the system is isothermal and at equilibrium the internal entropy production is zero, since the efficiency η is vanishing: the system has already attained the maximum entropy state. While $\overline{\dot{S}_{\mathrm{min}}}$ is related to the dissipation of kinetic energy, the excess of material entropy production with respect to the minimum, $\overline{\dot{S}_{\mathrm{exc}}}$, is due to the turbulent sensible and latent heat transport down the gradient of the temperature field. Therefore, we can define:

$$\alpha = \overline{\dot{S}_{\mathrm{exc}}} \Big/ \overline{\dot{S}_{\mathrm{min}}} \approx \int_{\Omega} dV \overline{\boldsymbol{H} \cdot \nabla\left(\frac{1}{T}\right)} \Big/ \left(\bar{\dot{W}} \big/ \langle\Theta\rangle\right) \approx \int_{\Omega} dV \overline{\boldsymbol{H} \cdot \nabla\left(\frac{1}{T}\right)} \Big/ \left(\eta \overline{\dot{\Sigma}^{+}}\right) \geq 0 \tag{3}$$

as a parameter of irreversibility of the system. Since $\overline{\dot{S}_{\mathrm{in}}} \approx \eta \overline{\dot{\Sigma}^{+}}(1 + \alpha)$, we have that material entropy production is maximized if we have a joint optimization of heat transport down the gradient of the temperature field and of production of mechanical work.

3 Methods

PLASIM is a simplified yet Earth-like climate model used in a configuration featuring T21 horizontal resolution with five sigma levels in the vertical. The ocean is represented by a 50m slab ocean (with energy transport set to 0), including a 0-dimensional thermodynamic sea ice model. Slab ocean climate models are well suited for providing an accurate steady state climate response (Danabasoglu and Gent, 2009). The global atmospheric energy balance is greatly improved with respect to previous versions of the model by re-feeding the kinetic energy losses due to surface friction and horizontal and vertical momentum diffusion (Becker, 2003; Lucarini and Fraedrich, 2009). The average energy bias is in all simulations is $\leq 0.2\,\mathrm{W\,m^{-2}}$, which is about one order of magnitude smaller than most state-of-the art climate models (Lucarini and Ragone, 2010).

The biases in the global energy and entropy budgets can be written as $\overline{\dot{S}} = \overline{\dot{\Sigma}}^{+} + \overline{\dot{\Sigma}}^{-} = \Delta_S$, with $\Delta_S << \left|\overline{\dot{\Sigma}}^{+}\right|, \left|\overline{\dot{\Sigma}}^{-}\right|$, and $\overline{\dot{E}} = \overline{\dot{P}} + \overline{\dot{K}} = \Delta_E$, with $\Delta_E << \left|\overline{\dot{\Phi}}^{+}\right|, \left|\overline{\dot{\Phi}}^{-}\right|$. Moreover, the Lorenz energy cycle has a spurious term, with $\overline{\dot{W}} = \overline{\dot{\Phi}^{+}} + \overline{\dot{\Phi}^{-}} - \Delta_E$. Therefore, the thermodynamic efficiency is ill defined and, similarly, the estimates for entropy production contributions are, in principle, inconsistent. If the numerical errors in the material entropy budget discussed in (Johnson, 2000) are, as in this case, negligible, the 2nd law of thermodynamics imposes that $\Delta_E \approx \langle\Theta\rangle\Delta_S$. Thanks to that, as thoroughly discussed in (Lucarini et al., 2010), the two thermodynamic temperatures Θ^{+} and Θ^{-} are still well defined, as the expression $\left(\Theta^{+} - \Theta^{-}\right)/\Theta^{+}$ provides a good first order approximation to the true efficiency $\eta = \overline{\dot{W}} \Big/ \overline{\dot{\Phi}^{+}} = \left(\overline{\dot{\Phi}^{+}} + \overline{\dot{\Phi}^{-}} - \Delta_E\right) \Big/ \overline{\dot{\Phi}^{+}}$). Similarly, the material entropy production rate is computed as $\overline{\dot{S}_{\text{in}}} + \Delta_S$, and the irreversibility factor is evaluated as $\alpha = \left(\overline{\dot{S}_{\text{in}}} + \Delta_S\right) \Big/ \left(\eta\left(\overline{\dot{\Sigma}}^{+} + \left|\overline{\dot{\Sigma}}^{-}\right|\right) \Big/ 2\right)$, where we introduce a correction in the denominator to account for the fact that $\overline{\dot{\Sigma}}^{+} \neq \left|\overline{\dot{\Sigma}}^{-}\right|$. With these corrections, all proposed formulas apply with a high degree of approximation.

4 Results

In the usual operative definition climate sensitivity $\Lambda_{\overline{T_S}}$ is the increase of the globally averaged mean surface temperature $\overline{T_S}$ between the preindustrial CO_2 concentration steady state and the steady state conditions realized when CO_2 concentration is doubled. As $\overline{T_S}$ is almost linear with respect to the logarithm of the CO_2 concentration on a large range, it is actually easy to generalize the definition of $\Lambda_{\overline{T_S}}$ as the impact on $\overline{T_S}$ of CO_2 doubling so that $\Lambda_{\overline{T_S}} = d\overline{T_S} \Big/ d\log_2\left([CO_2]_{\text{ppm}}\right)$.

The main goal of this work is to check whether it is possible to define, in a similar fashion, generalized sensitivities Λ_X to describe the steady state response to CO_2 concentration changes of the thermodynamical properties X of the climate system. At this scope, we have performed climate simulations for CO_2 concentrations ranging from 50 to 1850 ppm by 50 ppm steps, thus totalling 37 runs. Each simulation has a length of 50 years and the statistics are computed on the last 30 years of the simulations in order to rule out the presence of transient effects. In order to fully characterize the non-equilibrium properties of the climate system, we have analysed the most important thermodynamic variables of the system introduced in the previous section:

- the time average of the temperatures of the warm (Θ^{+}) and cold (Θ^{-}) reservoir, and, as reference, the time average of the global mean surface temperature $\overline{T_S}$ (Fig. 1);
- the thermodynamic efficiency η (Fig. 2a);
- the average intensity of the Lorenz energy cycle $\overline{\dot{W}}$ (Fig. 2b);
- the time average of the rate of material entropy production $\overline{\dot{S}_{\text{in}}}$ (Fig. 2c);
- the degree of irreversibility of the system α (Fig. 2d).

See the appendix for additional details in the calculations. It is rather interesting to observe that, in addition to the surface temperature, all of these thermodynamic variables feature a striking linear behaviour with respect to the logarithm of the CO_2 concentration. Therefore, we can safely attribute a robust value (with an uncertainty of at most 10%) to the generalized sensitivities defined as $\Lambda_X \equiv dX \Big/ d\log_2\left([CO_2]_{\text{ppm}}\right)$. Results are summarized in Table 1.

The three temperature indicators (Fig. 1) feature, as expected, positive sensitivities: the surface temperature sensitivity is well within the range of what is simulated by the climate models included in IPCC (2007), whereas the two bulk thermodynamic temperatures have smaller sensitivities. Therefore, an increase of the vertical temperature gradient is predicted for higher CO_2 concentrations. Moreover, as the temperature of the cold bath increases faster than that of the warm bath, higher CO_2 concentration implies a more isothermal atmosphere. The main process contributing to this effect is large enhancement of latent heat fluxes due to the impact of increasing average temperature on the Clausius-Clapeyron relation. Consequently, increases in the CO_2 concentration cause a steep decrease in the efficiency of the climate system, as shown in Fig. 2a. In the explored range, the efficiency decreases by about 35%, with a relative change of about −7% per CO_2 doubling. In a thicker (and warmer) atmosphere, the absorbed heat $\overline{\dot{\Phi}^+}$ is larger, so that the actual strength of the Lorenz energy cycle changes as the result of the competing effects of increasing energy input and decreasing efficiency. The intensity of the Lorenz cycle decreases in a warmer climate (Fig. 2b), with an approximate change of −4% per CO_2 doubling. By energy conservation, the same applies to the total dissipation, so that in a warmer climate weaker surface winds are expected.

As with increasing CO_2 concentration the average temperature increases and the total dissipation decreases, $\overline{\dot{S}_{\text{min}}}$ – which is related uniquely to mechanical dissipation – is a decreasing function of CO_2 concentration. Instead, as shown in Fig. 2c, the actual average rate of material entropy production $\overline{\dot{S}_{\text{in}}}$ has the opposite behaviour, with an approximate relative increase of 2% per CO_2 doubling. This implies that the entropy production due to the heat transport down the gradient of the temperature field is much higher in warmer climates, the reason being, again, that latent heat fluxes become extremely effective in transporting heat. Therefore, the degree of irreversibility of the system α increases steeply with CO_2 concentration (Fig. 2d). In the considered range, the fraction of entropy production due to mechanical energy dissipation $1/(\alpha+1)$ drops

from about 22% to about 12%. Note that this behaviour is specific for climate conditions analogous to the present ones, whereas under snowball conditions, where latent heat fluxes are negligible, higher temperatures lead to higher total entropy production, the value of α is about unity and only slightly affected by temperature (Lucarini et al., 2010).

5 Conclusions

We have proposed a new approach for analysing the classical problem of the steady-state response of the climate system to CO_2 concentration changes and have demonstrated its validity with a simplified yet Earth-like climate model. We have introduced a comprehensive set of generalized climate sensitivities describing the response of the global thermodynamical properties of the climate system, building upon a recently introduced theoretical framework (Lucarini, 2009b).

We find that, in addition to the globally averaged surface temperature, the intensity of the Lorenz energy cycle, the Carnot efficiency, the material entropy production and the degree of irreversibility of the system are linear with the logarithm of the CO_2 concentration. The generalized sensitivities proposed here (whose values are reported in Table 1) demonstrate that the climate system becomes less efficient, more irreversible, and features higher entropy production as it becomes warmer. Changes in intensity of the latent heat fluxes tend to be the dominating ingredients, thus showing, at a fundamental level, how important it is to address correctly the impact of climate change on the hydrological cycle.

Due to the monotonic (and, in particular, linear) dependence of the diagnosed variables with respect to the logarithm of the CO_2 concentration, it is possible to re-parameterise efficiently all the variables with respect to just this one. In Table 2 we provide the linear coefficients of all the thermodynamic macro-variables of the system with respect to the changing surface temperature. These data may be of use when devising simplified yet comprehensive climate models or estimating unknown quantities in comprehensive models or from actual observational data.

We believe that the investigation proposed here may serve as a stimulation to re-examine, from a more fundamental point of view, the problem of climate change, and may help addressing problems of paleoclimatological relevance, such as the interplay between solar constant and atmospheric composition changes in determining ice ages, or the onset and the decay of snowball conditions. We expect that extensive application of the thermodynamically-based tools adopted here may, in general, help closing the Gap between Simulation and Understanding in Climate Modeling (Held, 2005) and may provide the basis for a new generation of metrics aimed at the validation of climate models (Lucarini, 2008b).

References

Becker, E.: Frictional heating in global climate models, Mon. Wea. Rev., 131, 508–520, 2003.

Danabasoglu, G. and Gent, P. R.: Equilibrium Climate Sensitivity: is it accurate to use a slab ocean model?, J. Climate, 22, 2494–2499, 2009.

Dewar, R.: Maximum entropy production and the fluctuation theorem, J. Phys. A: Math. Gen., 38, L371–L381, 2005.

Fraedrich, K.: Simple Climate Models, in: Progress in Probability 49, , Birkhäuser, Berlin, 65–110, 2001.

Fraedrich, K., Jansen, H., Kirk, E., Luksch, U., and Lunkeit, F.: The planet simulator: towards a user friendly model, Met. Zeit., 14, 299–304, 2005.

Fraedrich, K. and Lunkeit, F.: Diagnosing the entropy budget of a climate model. Tellus A 60, 921–931, 2008.

Grinstein, G. and Linsker, R.: Comments on a derivation and application of the "maximum entropy production" principle, J. Phys. A: Math. Theor., 40, 9717–9720, 2007.

Held, I. M.: The Gap between Simulation and Understanding in Climate Modeling, Bull. Amer. Meteor. Soc., 86, 1609–1614, 2005.

IPCC: The Physical Science Basis, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, 2007.

Johnson, D. R.: Entropy, the Lorenz Energy Cycle and Climate, General Circulation Model Development: Past, Present and Future, Academic Press, New York, 659–720, 2000.

Kleidon, A., Fraedrich, K., Kirk, E., and Lunkeit, F.: Maximum entropy production and the strength of boundary layer exchange in an atmospheric general circulation model, Geophys. Res. Lett., 33, L06706, doi:10.1029/2005GL025373, 2006

Kleidon, A. and Lorenz, R. D.: Non-equilibrium thermodynamics and the production of entropy: life, Earth, and beyond, Springer, Berlin, 2005.

Kunz, T., Fraedrich, K., and Kirk, E.: Optimisation of simplified GCMs using circulation indices and maximum entropy production, Clim. Dyn., 30, 803–813, 2008.

Lorenz, E. N.: Available potential energy and teh maintenance of the general circulation, Tellus, 7, 157–167, 1955.

Lucarini, V.: Response Theory for Equilibrium and Non-Equilibrium Statistical Mechanics, Causality and Generalized Kramers-Kronig relations, J. Stat. Phys., 131, 543–558, 2008a.

Lucarini, V.: Validation of Climate Models, Encyclopedia of Global Warming and Climate Change, SAGE, Thousand Oaks, 1053–1057, 2008b.

Lucarini, V.: Evidence of dispersion relations for the nonlinear response of the Lorenz 63 system, J. Stat. Phys., 134, 381–400, 2009a.

Lucarini, V.: Thermodynamic Efficiency and Entropy Production in the Climate System, Phys. Rev. E, 80, 021118, doi:10.1103/PhysRevE.80.021118, 2009b.

Lucarini, V. and Fraedrich, K.: Symmetry-break, mixing, instability, and low frequency variability in a minimal Lorenz-like system. Phys. Rev. E, 80, 026313, doi:10.1103/PhysRevE.80.026313, 2009.

Lucarini, V., Fraedrich, K., and Lunkeit, F.: Thermodynamic analysis of snowball earth hysteresis experiment, Efficiency, entropy production, and irreversibility, Q. J. R. Met. Soc., doi:10.1002/qj.543, 2010.

Lucarini, V. and Ragone, F.: Energetics of IPCC4AR Climate Models: Energy Balance and Meridional Enthalpy Transports, submitted to Rev. Geophys. 2010, also at arXiv:0911.5689v1. 2010.

Ozawa, H., Ohmura, A., Lorenz, R. D., and Pujol, T.: The second law of thermodynamics and the global climate system, A review of the maximum entropy production principle, Rev. Geophys., 41, 1018, doi:10.1029/2002RG000113, 2003.

Paltridge, G. W.: Climate and thermodynamic systems of maximum dissipation, Nature, 279, 630–631, 1979.

Peixoto, J. and Oort, A.: Physics of Climate, Springer, New York, 1992.

Ruelle, D.: General linear response formula in statistical mechanics, and the fluctuation-dissipation theorem far from equilibrium, Phys. Lett. A, 245, 220–224, 1998.

Table 1.

Generalized Sensitivities	
Definition	Value
$\Lambda_{\overline{T_S}}$	2.55 K
Λ_{Θ^+}	1.65 K
Λ_{Θ^-}	2.35 K
Λ_{η}	−0.002
$\Lambda_{\overline{W}}$	$-0.06\,\mathrm{Wm^{-2}}$
$\Lambda_{\overline{\dot{S}_{in}}}$	$0.0004\,\mathrm{Wm^{-2}\,K^{-1}}$
Λ_{α}	0.7

Table 2.

Parameterisations	
Definition	Value
$d\Theta^{+} \big/ d\overline{T_s}$	0.65
$d\Theta^{-} \big/ d\overline{T_s}$	0.92
$d\eta \big/ d\overline{T_s}$	$-0.0008\,\mathrm{K}^{-1}$
$d\overline{\dot{W}} \big/ d\overline{T_s}$	$-0.024\,\mathrm{Wm}^{-2}\,\mathrm{K}^{-1}$
$d\overline{\dot{S}_{\mathrm{in}}} \big/ d\overline{T_s}$	$0.00016\,\mathrm{Wm}^{-2}\,\mathrm{K}^{-2}$
$d\alpha \big/ d\overline{T_s}$	$0.275\,\mathrm{K}^{-1}$

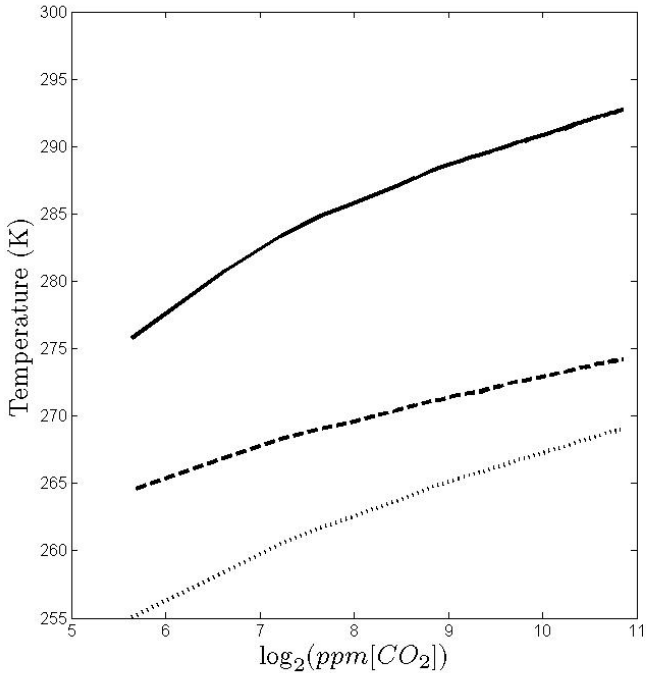

Fig. 1. Time average of the global mean surface temperature T_s (solid line) and of the temperature of the warm (Θ^{+}) and cold (Θ^{-}) reservoirs (dashed and dotted lines, respectively).

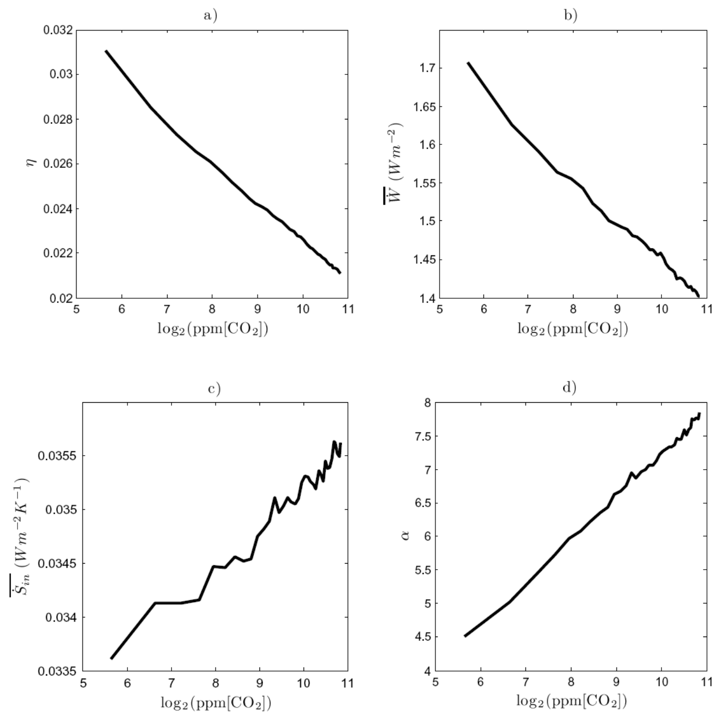

Fig. 2. Generalised climate sensitivities. CO_2 concentration dependence of macroscopic thermodynamic variables: **(a)** Thermodynamic efficiency; **(b)** average intensity of the Lorenz energy cycle; **(c)** average rate of material entropy production; **(d)** degree of irreversibility. See text for further details.