The influence of the water vapor feedback on the climate response to the Pinatubo eruption.

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Abstract

Soden et al. (2002) reproduced with a GCM the climate response to the Pinatubo eruption and showed that the water vapor feedback (WVF) was responsible for an amplification of the direct cooling effect. The WVF was defined in their article as the consequences of the added radiative absorption from water vapor. Here another possible definition of the WVF is proposed, taking into account both the radiative effect of the water vapor content and the latent fluxes needed to maintain the relative humidity. The influence of this WVF during the Pinatubo event is investigated with a simple model. Using our definition, the WVF is found to smooth the atmospheric response to the Pinatubo perturbation and to reduce by 0.1 K the global cooling. The WVF amplification effect is only prevailing 30 months after the eruption and is found not to be totally active over short-term shocks like the Pinatubo eruption. This experiment shows the need to extend the feedback studies to a dynamic framework and to consider the climate sensitivity as a function of the time scale and thus to interprete with care the extrapolations of climate long-term features from short-term features: if events like the Pinatubo eruption are useful tools for GCM validations, they cannot be considered as proxies for the long-term climate sensitivity.

1. Introduction

In their article, Soden et al. (2002) reproduced with a GCM the response in temperature to the Pinatubo eruption. This event was responsible for an additional layer of aerosols in the high troposphere and thus for a reduction of the incoming short-wave (SW) flux and a slighter reduction of the outcoming long-wave (LW) flux (Hansen et al. (1996)). This lead to a temperature decrease that has been measured (Christy et al. (2000)). This event is a good experiment of the climate response to a change in a global forcing.

The water vapor feedback (WVF) is supposed to have played a major role during this period and Soden et al. (2002) showed that their GCM does reproduce the temperature profile only if the WVF is operative.

For these authors, the WVF is defined as the additional temperature change due to the additional absorption from water vapor if the relative humidity is fixed and the temperature increases or decreases. However, we showed in Hallegatte et al. (2005) that another WVF definition can be proposed, in which the WVF does not only involve changes in the radiative flux, as assumed by Soden et al. (2002) and Hall and Manabe (1999). We showed that maintaining fixed the relative humidity necessitates a non-zero budget between evaporation and precipitation. This consumes or creates a significant amount of energy and thus changes the temperature in the opposite direction that the initial temperature perturbation. This effect adds to the classical long-term positive feedback due to the constant relative humidity a short-

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term negative feedback. This negative part of the WVF has been found to reduce the short-term natural variability of the atmospheric temperature.

In the case of the Pinatubo event, this effect should be responsible for a reduction of the short-term cooling of the atmosphere and the long-term positive part of the WVF should be observable only after several months. The aim of this article is to assess whether this effect is significant during the Pinatubo event. And in this case, one may ask if the climate response to the Pinatubo eruption is a good proxy of the long-term climate response to the increase in greenhouse gas (GHG) concentrations.

2. The Model

The simple model used in this study has been comprensively described in Hallegatte et al. (2005). However, its main characteristics are reproduced here to ease the reading of this article.

A single column of atmosphere, containing only water vapor, CO_2 and three cloud layers is considered. Figure 1 displays a schematic diagram of the model. Crude assumptions are applied : (i) convection is not explicitly modeled but its effects are taken into account by fixed lapse rates. This can be justified by Zhang et al. (1994), who showed that variation in lapse rate does not alter significantly the water vapor feedback ; (ii) the ocean mixed layer depth is fixed; (iii) stratosphere SW absorption is prescribed; (iv) no ventilation influence on evaporation is considered, although Bates (2003) suggests that it has significant effects; (v) no explicit cloud cover change is introduced.

The atmospheric water vapor content is controlled by evaporation and precipitation. Evaporation depends on surface air and ocean temperatures. Precipitation is modeled as a process driving the relative humidity toward a *target relative humidity*, which is supposed to be fixed, with a characteristic time τ_P. The equation is $P = E - 1/\tau_P \cdot (Q^\infty - Q)$, where E is the evaporation, P the precipitation, Q the column water content and Q^∞ is the column water content that would ensure an unchanged relative humidity (Q^∞ is a function of the troposphere temperature). This is justified by Hall and Manabe (2000), who showed that the precipitation annual-mean is controlled by the evaporation annual-mean, and by the classical assumption of constant relative humidity (see IPCC (2001), chp.7 or Hansen et al. (1984)). In consequence, the absolute humidity is only controlled by the atmosphere temperature change, with a delay τ_P. A wide range of values are possible for τ_P.

The radiative module is a 65-layer column model of the atmosphere, with three cloud layers and two gases (H_2O and CO_2). It computes the LW radiative budgets of the troposphere, stratosphere and ocean, using a Malkmus narrow-band model with a water vapor continuum. The principles behind this module were explored by Green (1967) and developed later by Cherkaoui et al. (1996). Radiative modules based on these principles were built by Hartmann et al. (1984) and Soufiani et al. (1985), who also created the radiation band coefficients tables.

Several parameters have been adjusted to ensure that the equilibrium state of the model is consistent with the observed mean values. The calibration of τ_P will be described in the next section.

In Hallegatte et al. (2005), the WVF gain is found to be 38% (*i.e.* a 1.6 factor), which is consistent with GCM studies (*e.g.* Schneider et al. (1999)).

3. Simulation of the Pinatubo event and model validation

A first simulation is carried out to assess the ability of our model to roughly reproduce the observed temperature trajectory during the few years following the Pinatubo eruption. To do so, we use only the SW perturbation observed by the Earth Radiation Budget Satellite (ERBS) (and detrended by Soden et al. (2002)), that is reproduced in Fig. 2.

Figure 3 reproduces, for the 5 years following the Pinatubo's eruption: (a) the observations of monthly temperature anomalies from the microwave sounding unit (MSU) (Christy et al. (2000)); (b) the total column water content anomalies from the NVAP merged data set already used by Soden et al. (2002); and (c) the outgoing longwave radiative (OLR) flux anomalies as measured by ERBS (and detrended by Soden et al. (2002)). The time lag between the temperature anomaly maximum and the water vapor

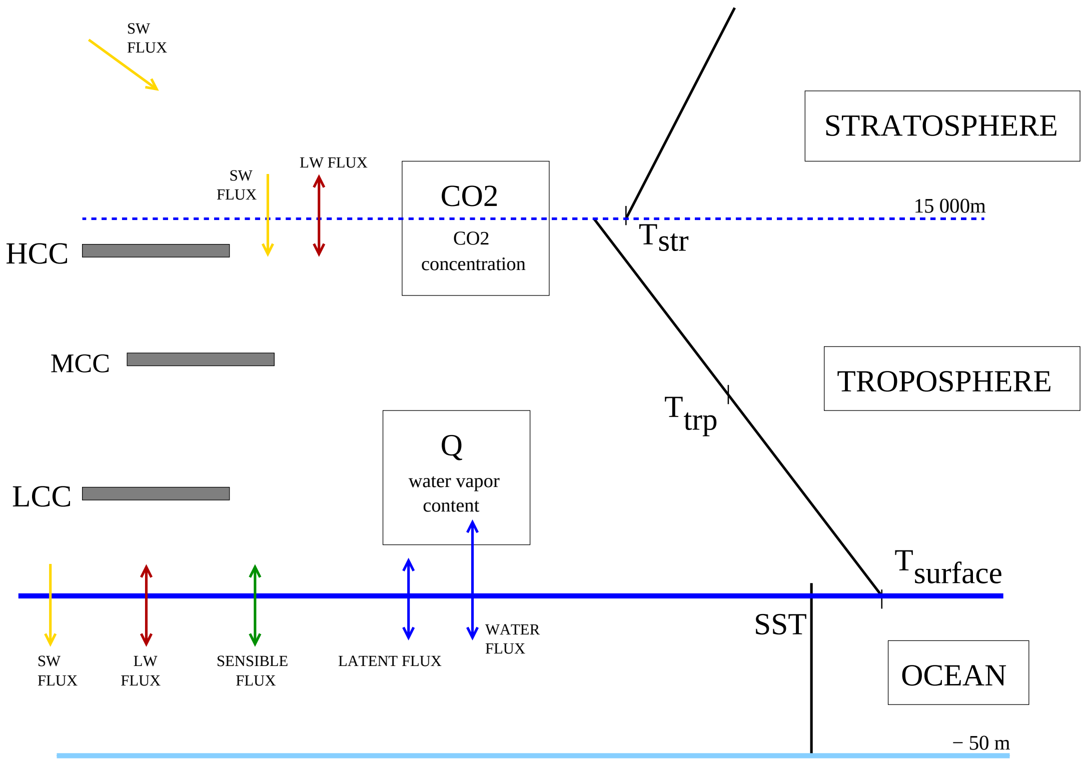

Figure 1: Schematic diagram of the model

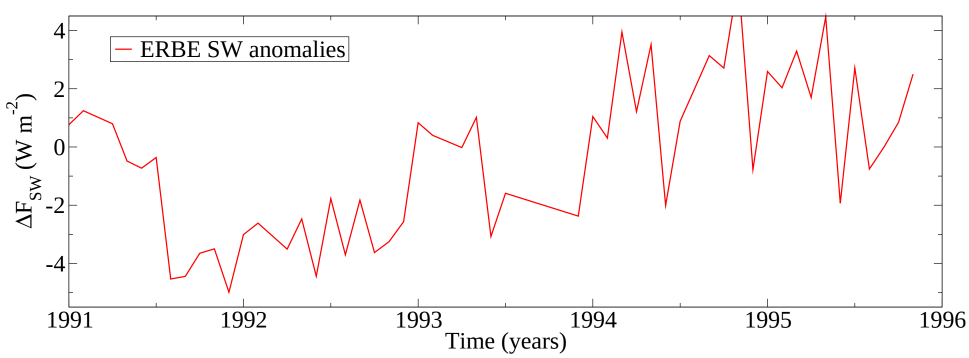

Figure 2: SW Radiative forcing due to stratospheric aerosols after the Pinatubo eruption, from ERBS.

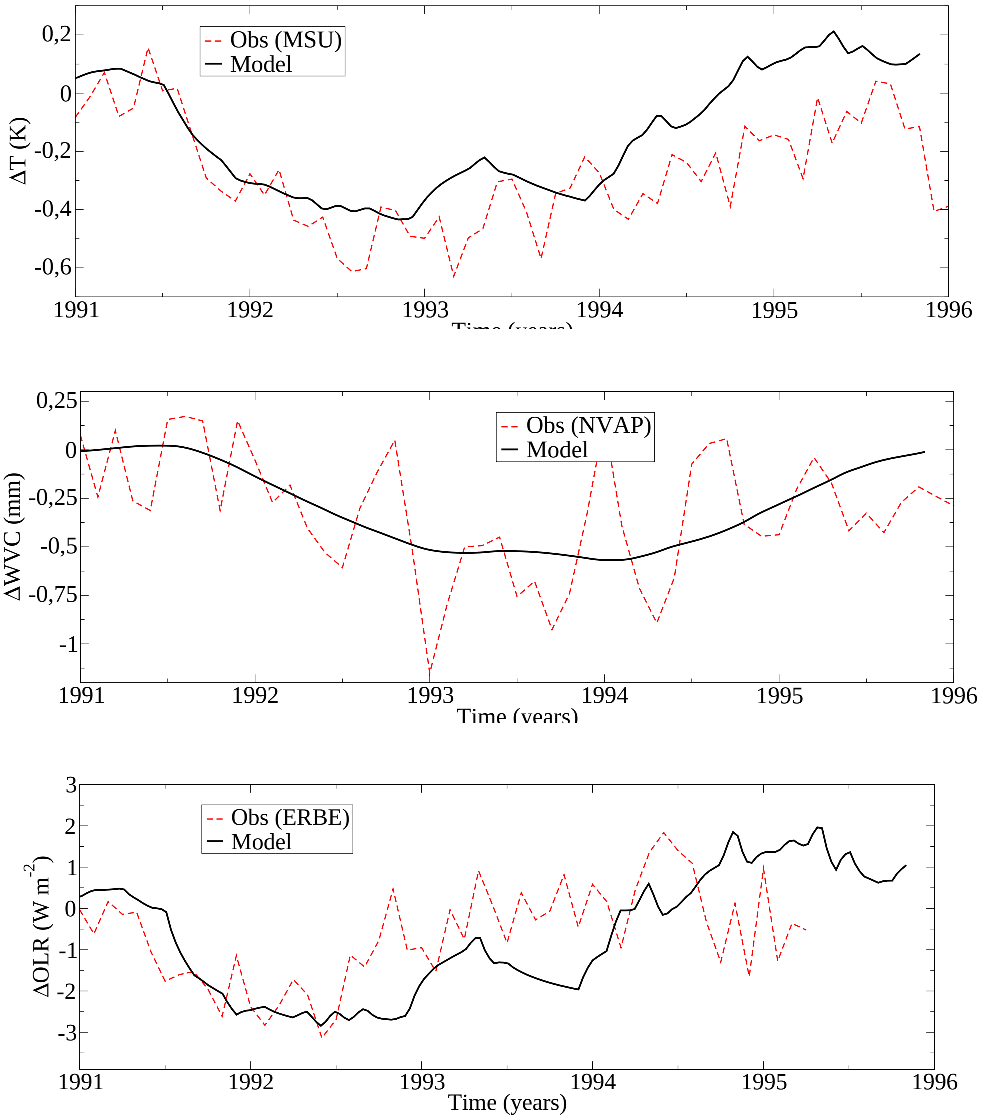

Figure 3: Model response to the Pinatubo eruptions and observed monthly anomalies. (a) Temperature response of the model and observed anomalies, as measured by the microwave sounding unit (MSU); (b) Total column water contant calculated by the model and observation merged by NVAP; (c) Outgoing Longwave Radiative flux anomalies calculated by the model and observed ones, provided by ERBS and detrended by Soden.

content anomaly maximum (several months) suggests a long characteristic time τ_P for the precipitations. The retained value $\tau_P = 1$ year is the one that makes the model be the closest to the observed trajectories.

We can propose several explanations for this surprisingly long characteristic time for the adjustment of water vapor: (i) during the years following the aerosols may perturb the precipitations, preventing the water vapor return to equilibrium; (ii) on the contrary to a change in CO_2 concentration, which impacts the mean troposphere, a change in the SW flux influences mainly the lower troposphere. In the Pinatubo case, this influence stabilizes the atmosphere, reducing the precipitations. This process may impair the water vapor adjustment. Moreover, the hypothesis of constant lapse rate, acceptable when studying climate change, may be inappropriate in this experiment.

Figure 3.(a) shows the observed temperature anomalies and the troposphere temperature change calculated by the model. It shows that the model is able to reproduce reasonably well the global mean response in temperature to the Pinatubo eruption, even if the cooling is significantly underestimated (by about 25%). This is easily explained by the simplicity of the model and the lack of many essential processes like the cloud cover response and the lapse rate changes. Temperature variations coming from non-represented dynamic processes are also responsible for a part of the inconsistency.

From January 1994, the modeled temperature returns to its equilibrium value, in a consistent manner with the SW radiative forcing (see Fig. 2). However, the observed temperature does not exhibit this return to equilibrium. It is unclear whether this discrepancy comes from non-represented processes or from deficiencies in the modeled processes.

Figure 3.(b) shows the observed total column water vapor anomalies and the anomalies calculated by the model. The slight underestimation of the water vapor content anomalies is consistent with the cooling underestimation. The assumption of constant relative humidity is thus strongly supported by observations.

Figure 3.(c) shows the Outgoing Longwave Radiative flux (OLR) as simulated by the model and as measured by ERBS. The two values are in good agreement even if the series exhibit some significant inconsistencies (larger than 1 W m^{-2}), probably because of effects of the non-represented dynamics.

4. Simulation of the Pinatubo event without water vapor feedback

In Soden et al. (2002), the WVF is made inoperative using the methodology of Hall and Manabe (1999). In this study, the WVF is defined as the effect of the additional water vapor through the radiative fluxes only. Practically, the WVF is made inoperative by making the LW radiative module of the model depend on the specific humidity from a control run (without the Pinatubo perturbation) rather than on the actual absolute humidity as in the full model.

Our model is built in order to implement another possible definitions of the WVF. The loop in the model is the following: a troposphere temperature increase occurs; the relative humidity is decreased (as a consequence of the Clausius-Clapeyron relation); precipitation, modeled to maintain a constant relative humidity, decreases; the relative humidity goes back to its initial level, corresponding to a larger total water content; the radiative budget is modified (troposphere and ocean warm up); as a consequence, the troposphere temperature increase is modified.

The difference between the two definitions is the fact the our defintion takes into account latent and radiative effects of the change in absolute humidity when the Soden's definition of the WVF does take into account only the radiative part. Following our definition of the WVF, it is necessary to remove the two effects to really *"cut"* the WVF. Practically, this is done by making the relative humidity used by the precipitation module depend on the unperturbed temperature. As a consequence, the equilibrium water vapor content is such that: (i) the relative humidity is fixed if the WVF is active; (ii) the specific humidity is fixed if the WVF is inoperative.

In the case of the Pinatubo experiment, the forcing change yields a decrease in evaporation and in precipitation. This water flux change is responsible for a negative energy flux from the ocean to the atmosphere, spraying the energy loss of the ocean among the other reservoirs. However, the evaporation decrease is larger than the precipitation decrease since the absolute humidity decreases. This prevents the atmosphere from exhibiting a larger temperature decrease than in a climate in which the precipitation would be equal to the evaporation, maintaining the specific humidity. Since the atmospheric temperature drives the water vapor content, this effect should be responsible for a delay in the positive part of the WVF.

Of course, there is a part of subjectivity in our definition of the WVF: when we cut the WVF, we force evaporation and precipitation to be equal by modifying the precipitation model and keeping unchanged the evaporation model. Other solutions are possible even if the one we chose seems to be the more consistent with the usual concept of the WVF.

A first assessment of the negative part of the WVF can be made from the observed change in water vapor content during the few years after the Pinatubo event. The total column water vapor is found by NVAP to have been reduced by about 0.4 mm, *i.e.* by about 0.4 kg m^{-2}. Precipitating this amount of water vapor yields an energy change of $\Delta E = 0.4 \times L_v = 0.4 \times 2.5 \times 10^6 J\,m^{-2} = 10^6 J\,m^{-2}$. If this energy is taken from the atmosphere, the mean atmosphere temperature change would be $\Delta T = \Delta E/(M\,C_p) = 10^6/10^7 = 0.1\ K$. This temperature change would not be negligible with respect to the total temperature change due to the Pinatubo eruption (about -0.5 K nearly 18 months after the eruption, according to the MSU data). The assessment of this effect thus worths to carry out an experiment of the climate reponse to the Pinatubo event with and without the WVF.

Figure 4 shows the model atmospheric temperature response to the Pinatubo SW flux change with the full model, when the WVF is operative (refered to as *"WVF"*). Are also reproduced the model response when the LW radiative part only of the WVF is made inoperative (as in the Soden's study) (refered to as *"No LWF"*), and when the whole WVF is made inoperative (as in Hallegatte et al. (2005)) (refered to as *"No WVF"*). The observed atmospheric temperature response is also reproduced.

Figure 4 shows that our model is able to reproduce qualitatively the Soden et al. (2002) results and to capture the positive part of the WVF that enhances the temperature change due to the Pinatubo event from nearly 12 months after the eruption. In our case, this enhancement is however much weaker than in the Soden's study, which may explain the model underestimation of the cooling. This is also consistent with the fact that, during the Pinatubo event, the water vapor content change is only about 1 kg$\times$K^{-1} when it is supposed to be about 3.5 kg$\times$K^{-1} at equilibrium. As a consequence it seems that only about 30% of the positive part of the WVF is expressed during the Pinatubo event, leading to a feedback factor about 1.2. This shows how far from the WVF equilibrium we are in the Pinatubo case, as suggested by the WVF long characteristic time of 8 years found in Hallegatte et al. (2005). This gives a clear illustration of the fact that the equilibrium climate sensitivity cannot be derived from the climate response to a short-term shock.

Figure 4 shows also that if the whole WVF is made inoperative (*i.e.* if the radiative and the latent effects of the WVF are removed) the maximum atmospheric temperature decrease is about 0.1 K larger than with the active WVF. Then, in the case of the Pinatubo event, the WVF is mainly responsible for a smoothing of the shock and for a reduction of the maximum atmospheric temperature change. The enhancing effect is only observable from January 1994, *i.e.* 30 months after the eruption.

In spite of the model simplicity and the lack of some major processes, this experiment shows that the WVF, as defined in this article, is a regulating process of the atmospheric temperature in case of short-term perturbations. Conversely, the WVF enhances the whole climate response to long-term changes like the increase in GHG concentrations.

5. Conclusive discussion

This article proposes a definition of the WVF that accounts for latent flux changes and assess the influence of this WVF on the climate response to the Pinatubo eruption. This experiment shows that the WVF is then not only a positive feedback that enhances the equilibrium temperature change when a

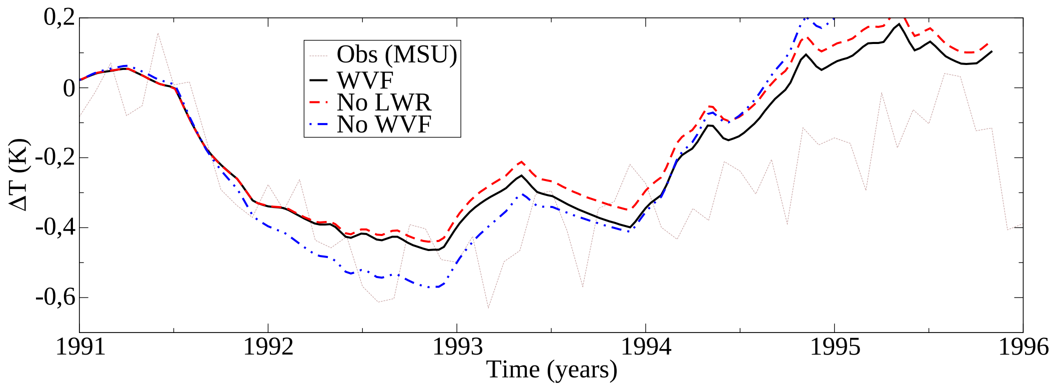

Figure 4: Model response with WVF (WVF), without the LW radiative part of the WVF (LWR) and without the whole WVF (No WVF). Observed temperature anomalies provided by MSU are also reproduced.

forcing is modified. The WVF has also a short-term component that changes the climate transients. In particular, the WVF is found in our model to reduce the amplitude of the atmospheric temperature response to short-term shocks. This shows that the WVF, while enhancing the long-term variability, may reduce the climate short-term variability of the atmospheric temperature. Moreover, the positive part of the WVF is found to be a very slow process that is not totally active in the case of short-term shocks like the Pinatubo eruption.

This work shows clearly how a single process may be reponsible for different consequences over different time scales. It shows the need to extend the feedback studies to a dynamic framework and to consider the climate sensitivity as a function of the time scale. It emphasizes the need for a careful interpretation of the extrapolations of climate long-term features from short-term climate characteristics: if events like the Pinatubo eruption are useful tools for GCM validations, they cannot be considered as direct proxies for the climate sensitivity in response to a change in GHG concentrations.

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