The Water Vapor Feedback Characterisation

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Introduction

- The IPCC/TAR interprets the climate machine behavior in terms of feedback loops.
- These analyses are carried out only in a linear and static framework (*i.e.* by comparing steady states), which has been duly critized by Rossow.
- This work aims at extending in a rigorous manner the feedback concept in a dynamic but still linear framework.
- In a first step, this approach is based on a simple 0D model. The methodology is then tentatively extended to a SCM.

The water vapor feedback: short-term vs. long-term

A doubling-CO_2-experiment $\Rightarrow \Delta RF = 3\,W \cdot m^{-2} \Rightarrow \Delta T_s = 3\ K$

Based on the assumption of constant relative humidity

$\Rightarrow$ Absolute humidity approximately doubles

$\Rightarrow$ Addition of $30\,kg \cdot m^{-2}$ of water vapor in the atmosphere

$\Rightarrow$ This can be done through an increase in evaporation and/or a decrease in precipitation

$\Rightarrow$ A latent energy loss of $\Delta E = -8 \cdot 10^7\,J \cdot m^{-2}$

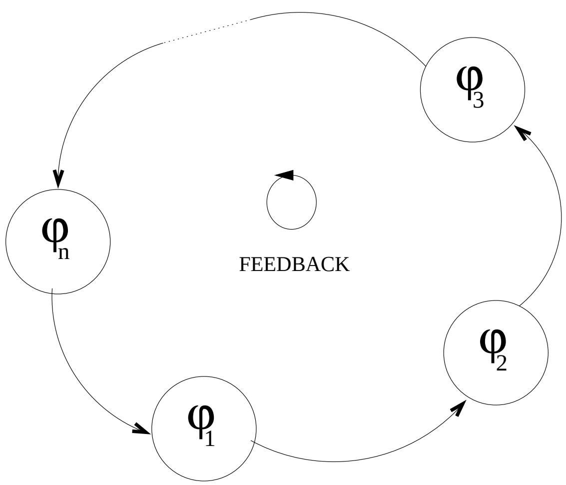
If $\Delta E = \Delta RF \cdot \Delta t$

$\Rightarrow$ **9 months are necessary to collect this energy**

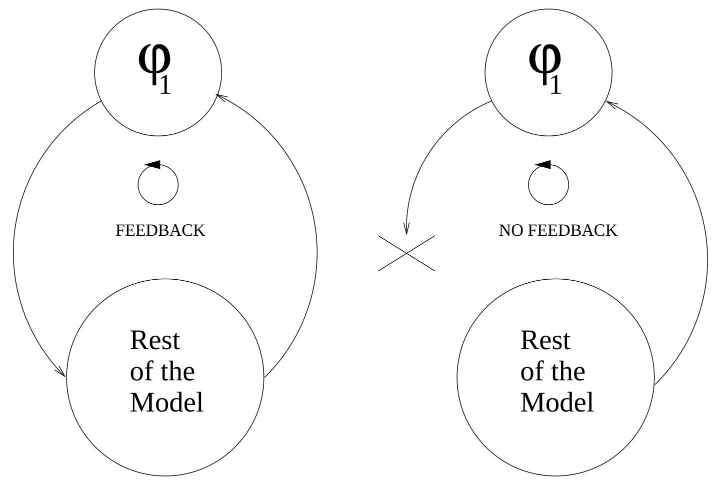
$\Longrightarrow$ This short-term feature of the water vapor feedback is not captured by static analyses

Feedback loop definition

A feedback loop is defined as a set of processes interfaced by transfer variables $\{\varphi_i$,i=1,..,n$\}$ in which the evolution of each variable $\delta\varphi_j$ depends only on $\delta\varphi_{j-1}$, and the evolution $\delta\varphi_1$ depends only on $\delta\varphi_n$.



Feedback loop scheme



Loop opening scheme

Static feedback gain

In a static framework, the feedback gain is defined as:

$$(1 - g_1) \cdot \delta\varphi_1^\infty = \delta\varphi_1^0$$

- $\delta\varphi_1^\infty$ is the change in equilibrium value of φ_1, after a forcing perturbation has been applied;
- $\delta\varphi_1^0$ is the change in the equilibrium value of φ_1 for the same perturbation but when the feedback has been made inoperative.

But static feedback gains don't take into account the dynamics of the feedback and is unable to cope with transient trajectories.

The static feedback gain is a **linear** concept.

Dynamic response study.

Following the TEF formalism, the TLS of the model can be solved using the Borel (Laplace-like) transform. Then all variables but one (φ_1) can be eliminated, leading to, in the Borel space:

$$(1 - g_1(\tau)) \cdot \mathcal{B}[\mathring{\delta}\varphi_1](\tau) = \mathcal{B}[\mathring{\delta}\varphi_{1,ins}](\tau)$$

- $\mathring{\delta}\varphi_1(t)$ is the φ_1 change predicted by the TLS, in the closed loop case.
- $\mathring{\delta}\varphi_{1,ins}(t)$ is the φ_1 change predicted by the TLS, in the open loop case.
- **$g_1(\tau)$ is the dynamic feedback gain, that generalizes the static feedback gain. The dynamic feedback gain is also a linear concept.**

$$\Longrightarrow \mathcal{B}[\mathring{\delta}\varphi_1](\tau) = \mathcal{B}[\mathring{\delta}\varphi_{1,ins}](\tau) + \frac{g_1}{1-g_1}\mathcal{B}[\mathring{\delta}\varphi_{1,ins}](\tau)$$

Feedback function :

An inverse Borel transform leads to:

$$\mathring{\delta}\varphi_1(t) = \mathring{\delta}\varphi_{1\,ins}(t) + \mathcal{B}^{-1}\left[\frac{g_1(\tau)}{1 - g_1(\tau)}\right] * \frac{d}{dt}\mathring{\delta}\varphi_{1\,ins}(t) \tag{1}$$

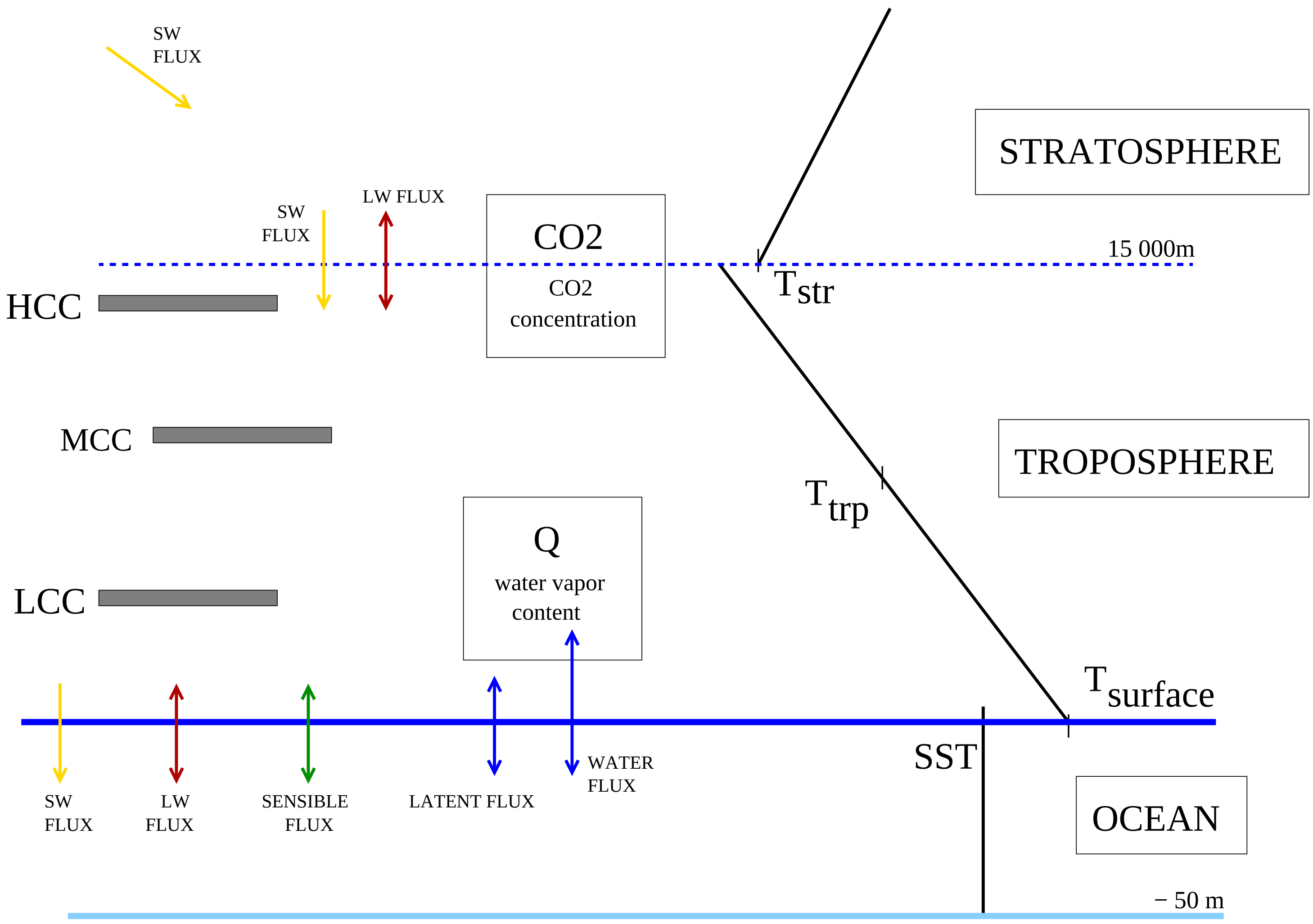
The feedback function is defined by:

$$\mathring{\delta}F^R_{\varphi_1}(t) = \mathcal{B}^{-1}\left[\frac{g_1(\tau)}{1 - g_1(\tau)}\right] \tag{2}$$

Interpretation :

If a perturbation is applied, which would have lead in the open loop model to a unit step in φ_1, then this perturbation leads, in the closed loop model, to the response $(1 + \mathring{\delta}F^R_{\varphi_1}(t))$.

Application to a Simple model of the Water Vapor Feedback



Water vapor feedback function

Open loop: all processes, that drive the water vapor, do not see temperature variations.

Closed loop: complete model

$$\mathring{\delta} F^{R}_{T_{WV}}(t) = -0.56 \cdot (1 - e^{-\frac{t}{\tau_1}}) + 1.17 \cdot (1 - e^{-\frac{t}{\tau_2}}) \qquad (3)$$

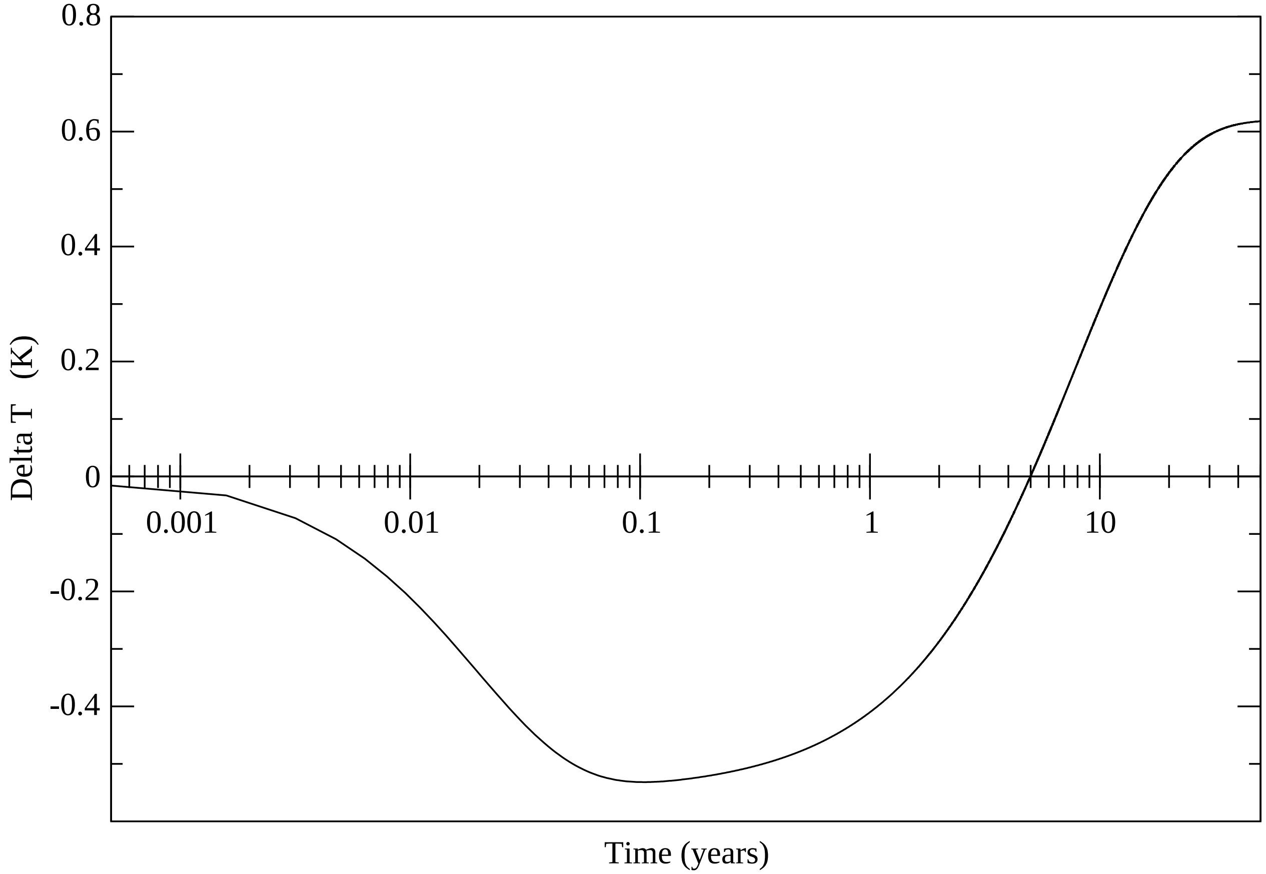
With $\tau_1 = 7$ days and $\tau_2 = 7$ years.

If a perturbation would lead to a 1K step in the model without water vapor feedback, then it leads in the complete model to a temperature response equal to $1 + \mathring{\delta} F^{R}_{T_{WV}}(t)$.

Static gain = 38 %

$\Longrightarrow$ A feedback needs time to settle and is not instantaneous

Water vapor feedback function



Mode interpretation

The water vapor feedback function is composed of 2 modes:

- A slow (7 years) and positive (+54%) mode : the "classical" water vapor feedback, due to the radiative effect of H_2O.
- A fast (7 days) and negative (-100%) mode: the "atmosphere loading". During the transient phase, some liquid water in ocean is changed into atmospheric water vapor.

Influence on natural variability

If a perturbation would lead in the model without water vapor feedback to:

$$\mathring{\delta} T_{WV,ins} = A \cdot cos(\omega \cdot t)$$

$$\mathring{\delta} T(t) = \left(1 + \mathring{\delta} F^{R}_{T_{WV}}(t)\right) * \frac{d}{dt} \mathring{\delta} T_{WV,ins}(t) \qquad (4)$$

$\Rightarrow$ The only modes that are able to act are those with characteristic times lower (or of the same order than) ω^{-1}.

- For short period perturbation: only the fast and negative mode is active $\Longrightarrow$ The water vapor feedback reduces the *fast* natural variability (period shorter than one year).
- For long period perturbations: both modes are active $\Longrightarrow$ The water vapor feedback enhances the *slow* natural variability (period greater than one year).

Application on a Single Column Model (SCM)

The aim is to extend our conclusions to the single column version of LMDZ.

Based on one property:

To assess a feedback function, it is equivalent to compare the full model trajectory with the trajectory of the model in which:

- the loop has been opened (*e.g.* by replacing fields of the model) and a forcing has been perturbed (which is awkward in climate models);
- the key processes has been made dependent on a new variable φ^* instead of φ, with:

$$\varphi^* = \varphi + \Delta\varphi$$

Problem in the assessment of the water vapor feedback

The usual WV feedback is based on the *observed* equality:

$$r_h = \text{constant}$$

- This equality comes from the whole climate dynamics: **it is not a "process"**
- Since it is not a process, it cannot be "cut"

$\Longrightarrow$ It is not possible to cut the water vapor feedback in a GCM, without loosing the conservation laws

In the simple model, precipitations were built as a process ensuring r_h = constant at equilibrium

$\Longrightarrow$ We created a process "r_h = constant" we are able to cut.

Proposal: a ”Convection feedback”

On the contrary, it is possible to define a *convection feedback* as follows:

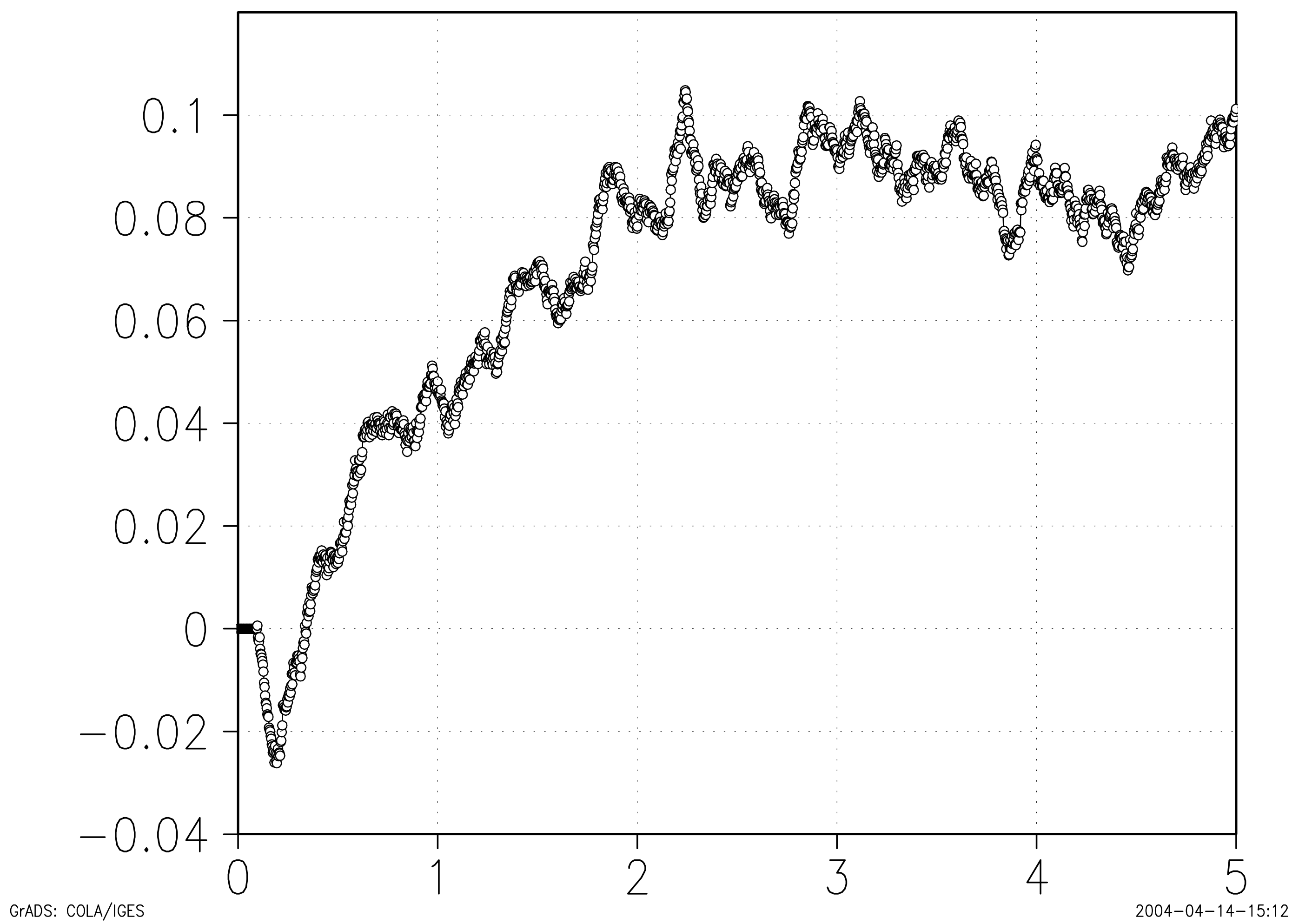
$$\text{Temperature is changed by } \Delta T$$

$$\Longrightarrow \text{Convection is changed}$$

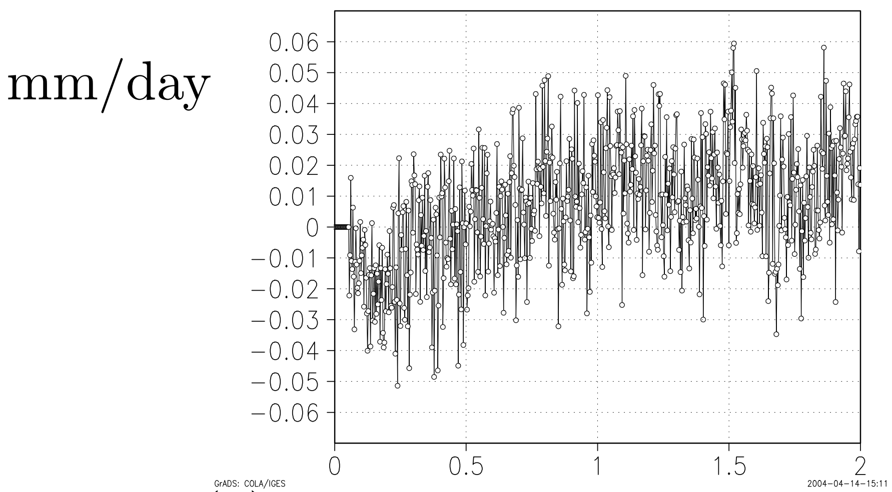
$$\Longrightarrow \text{Temperature is changed by } \Delta T + \delta_F T(t)$$

This feedback can be evaluated in SCMs by making the convection parametrization depend on $T' = T + \Delta T$ instead of T.

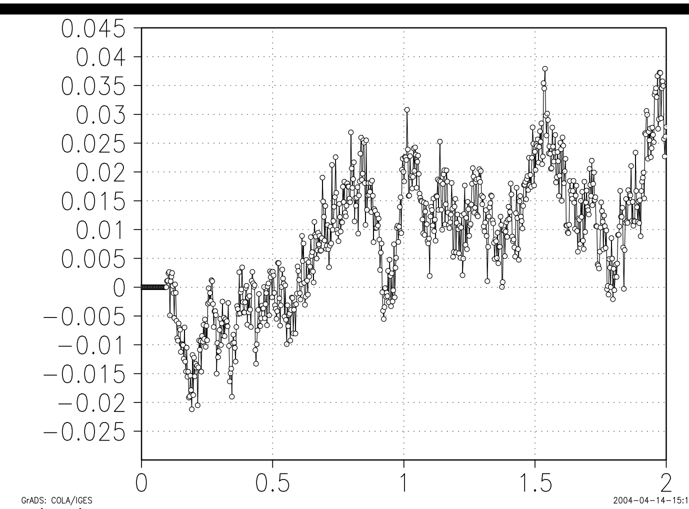
Convection feedback in a SCM: $\Delta T = 0.2\,K$



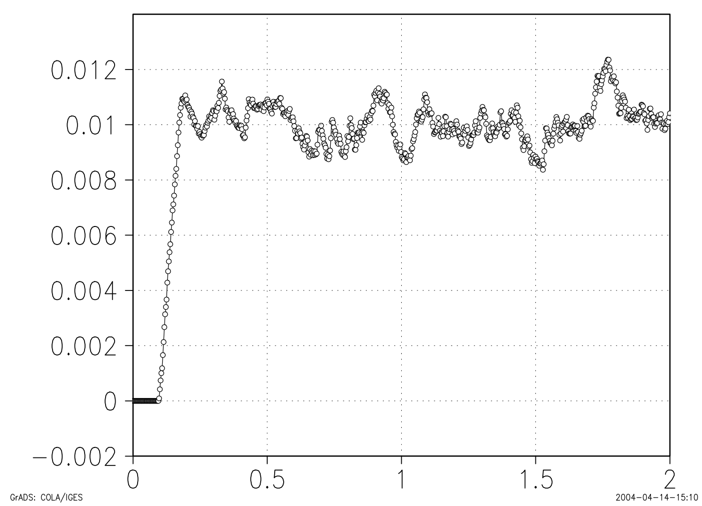
Air surface temperature change over 5 years (static gain ≈ 33%)



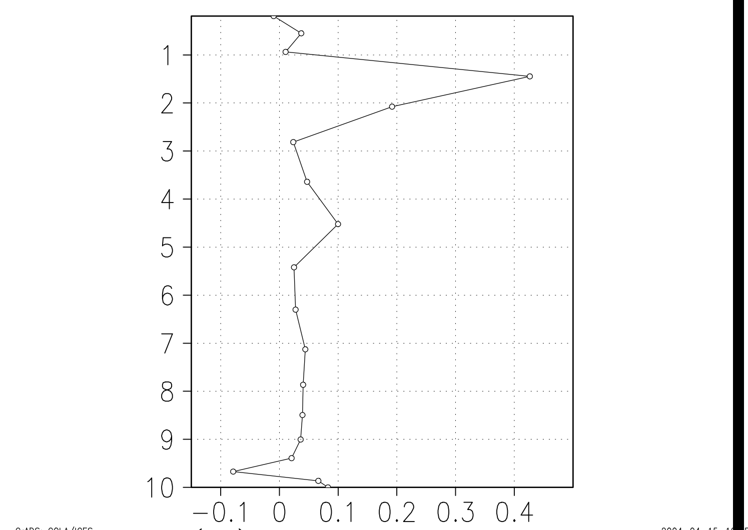
(a) δ Precipitations over 2 yr



(b) δ Evaporation over 2 yr



(c) δr_h over 2 yr



(d) Profile of δT

Conclusions

- Feedback, as a linear concept, can be applied on high-complexity non-linear systems with interesting results
- Feedbacks need time to settle and they can be characterized by gains and characteristic times: the water vapor feedback is negative for short time scales and positive for long time scales.
- This formulation allows to derive conclusions on the effects of feedbacks on variability: the water vapor feedback reduces the rapid natural variability and enhances the slow natural variability.
- We propose a methodology to measure feedbacks in complex models as GCMs or SCMs. First results are consistent with those from simple models.

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The Borel transform

The Borel transformation is defined by:

$$f(t) \xrightarrow{\mathcal{B}} \mathcal{B}[f](\tau) = \frac{1}{\tau}\int_0^\infty e^{-t/\tau} f(t)dt = \frac{1}{\tau}\widetilde{f}(\frac{1}{\tau}) \tag{5}$$

where $\widetilde{f}(p)$ stands for the Laplace transform of $f(t)$.

Contrary to the Laplace variable, the Borel variable τ is real and homogeneous to time.

$\mathcal{B}[\partial f/\partial t](\tau) = (1/\tau)\mathcal{B}[f](\tau)$,