

Lecture 12. Aerosol and cloud feedbacks in the climate system: Discussion

Outline:

1. Background materials for class discussion.

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For review of cloud feedbacks see materials for Lecture 11.

The most recent review paper on feedbacks: Bony, S., et al. How well do we understand climate change feedback processes? *J. Climate* (in press)

ftp://eos.atmos.washington.edu/pub/breth/papers/in-review/bony_etal_feedbacks.pdf

- ✓ Focuses on the feedbacks associated with climate variables (i) that directly affect the top-of-atmosphere (TOA) radiation budget, and (ii) that respond to surface temperature mostly through physical (rather than chemical or biochemical) processes.

NOTE: Every climate variable that responds to a change in global mean surface temperature through physical or chemical processes and that directly or indirectly affects the Earth's radiation budget has the potential to constitute a climate change feedback.

- ✓ Considers the feedbacks decomposed into water vapor, lapse rate, surface albedo and cloud feedback components)

Some conclusions from Bony et al:

Climate sensitivity estimates critically depend on the magnitude of climate feedbacks, and global feedback estimates still differ among GCMs despite steady progress in climate modeling. This constitutes a major source of uncertainty for climate change projections.

- ✓ *Cloud feedbacks:*

Global cloud feedbacks are still associated with a large range of estimates among GCMs, larger than that of other feedbacks. Evaluating the feedbacks produced by the different models is thus crucial to narrow the range of climate sensitivity estimates. Real advances in the evaluation of cloud feedbacks have long been hindered by our lack of

understanding of the physical processes implicated in these feedbacks. In that regard, progress has been made over the last few years.

- To better understand what controls the climate change cloud feedbacks, simple conceptual frameworks have been used to analyze the complexity of the climate system and to decompose the global cloud feedback into components related to specific physical processes. This makes the study of cloud feedbacks more tractable and helps to suggest specific and targeted diagnostics for data analysis and model-data comparison.
- New methodologies of model-data comparison (e.g. model-to-satellite approaches using the ISCCP simulator) and many new diagnostics devoted to the analysis of specified components of cloud feedback mechanisms (such as compositing and clustering techniques) have been developed. These make the comparison of model simulations with observations more stringent and more relevant for the evaluation of model cloud feedbacks.
- These new analyses give guidance on which dynamical regimes or cloud types are primarily responsible for the diversity of cloud feedbacks among models. The responses of convective and boundary-layer clouds both contribute to the spread of global cloud feedbacks in GCMs, with a dominant role of inter-model differences in the response of low-level clouds. The application to GCMs of observational tests focused on the response of boundary-layer clouds to changes in large-scale environmental conditions (using observed climate variations not as an analogue of long-term climate changes but as an example of changing environmental conditions) may thus help to determine which of the model cloud feedbacks are the more reliable. Relative confidence in the different model formulations can also be assessed against CRMs, as in the Global Energy and Water Cycle Experiment (GEWEX) Cloud System Study (GCSS, Randall et al. 2003).
- So far, only a small number of observational datasets (essentially the ERBE6 and ISCCP datasets) have been used widely to evaluate the GCMs' cloud properties and cloud radiative feedbacks. Indeed, over the last 20 years we have been relying on passive radiometer retrievals that did not resolve cloud vertical structure (this latter had to be derived from field program radar measurements or radiosonde based retrievals), and that mainly provided column integrated or cloud top retrieval products. The new A-Train constellation of satellites that will include CloudSat and Calipso in particular (Stephens et

al. 2002), will be the first real observational advance in cloud property retrievals in a long time: new observations from active spaceborne radar and lidar, in synergy with other instruments, will provide vertical profiles of multi-layer cloud amount, cloud condensate, cloud phase properties and microphysical size distributions and precipitation. The use of new and existing observations of clouds, used together with the methodologies of model-data comparison provide a foundation for future progress in our ability to evaluate cloud feedbacks in GCMs.

✓ *Water vapor - lapse rate feedbacks*

The overall picture of the water vapor-lapse rate feedback under climate change - considered as the most positive climate feedback affecting climate sensitivity and associated, to a first approximation, with a nearly unchanged relative humidity - has remained fairly stable over time. Recent studies make us more confident in the reliability of this picture.

- Our understanding of the physical processes that control the relative humidity distribution, as well as recent analyses of interannual to decadal climate variations and of the water vapor response to the Pinatubo eruption, suggest that the mean tropospheric relative humidity may not undergo substantial changes as long as the large-scale atmospheric circulation remains largely unchanged.

However, some uncertainty remains as to the role of cloud microphysical processes in the response of the tropospheric relative humidity distribution to climate warming.

- Currently there is no substantive evidence to suggest that, as a first approximation, the weak relative humidity response simulated under climate change is an artifact of GCMs.
- It seems unlikely that the water vapor feedback associated with CO₂ forcing is substantially affected by changes in the lower stratospheric water vapor. But lower stratospheric water vapor changes are likely to play a more important role in the climate response to other types of forcings (e.g. ozone).
- However, recent comparisons of the observed and simulated variations of water vapor

and relative humidity in the current climate reveal biases in GCMs, and there is still a non-negligible spread in the model estimates of the water vapor-lapse rate feedback under climate change. This spread is likely to result from inter-model differences in the meridional patterns of surface warming and in the magnitude (albeit small) of relative humidity changes.

- More quantitative investigations are thus required to determine how accurately the lapse rate and relative humidity variations (as well as their variations with surface temperature or other factors) need to be reproduced in the current climate to constrain more rigorously the magnitude of the water vapor-lapse rate feedback estimates under climate change.

✓ *Cryosphere feedbacks*

The cryosphere is an important contributor to climate sensitivity through various feedbacks, in particular the snow/ice-albedo feedbacks. However, the magnitude of these and other cryosphere-related feedbacks remains uncertain. The cryospheric feedbacks in high latitudes are strongly coupled to processes in the atmosphere and in the ocean, particularly to polar cloud processes and ocean heat and freshwater transport. While some advances have been demonstrated in developing sea-ice components of the coupled GCMs during the last few years, further progress is hampered by the scarcity of observational data in the polar regions, sea ice and snow thickness being currently a particular problem. Detailed satellite and in situ datasets should help to improve parameterizations of sea ice and snow processes, as well as their interaction with other components of the climate system. For instance, diagnostic tests have been proposed recently to evaluate the climate change snow-albedo feedback produced by GCMs by using the northern hemisphere springtime warming and simultaneous snow retreat in the current seasonal cycle as an analog for anthropogenic climate change. Development of an appropriate set of metrics allowing the testing against observations of the sea ice and snow parameterizations and their effect on climate sensitivity is needed on the way towards reducing uncertainties associated with the cryosphere feedbacks.

Some strategy suggested by Zhang, 2004 (!!!compare to Stephens, 2005!!!)

(Zhang, M. H., 2004: *Cloud-climate feedback, how much do we know?* In "Observation, Theory, and Modeling of Atmospheric Variability", edited by Zhu et al., World Scientific Series on Meteorology of East Asia, Vol. 3, World Scientific Publishing Co., Singapore, 2004, 632pp.)

- ✓ The study of cloud-climate feedback is rooted in the subgrid-scale dynamics and physics (e.g., cloud microphysics).
- ✓ The cloud feedback problem could become at least conceptually more tractable if we divide it *into three different tasks*. *One* is the microphysical cloud calculation with given dynamical circulation features. With detailed knowledge of aerosol distribution, the dynamical circulation provides the information on the generation of super saturation. This can then be used to estimate the number of cloud droplets nucleated ... The spectral size distribution of cloud droplets can then be calculated. This procedure itself incurs considerable demand on computational resource. This is one direction several modeling groups are currently pursuing. *The second aspect* is the specification of the atmospheric dynamics on the subgrid scale. Clouds are mostly generated by subgrid scale processes, which have to be parameterized in climate models. To describe the variability of the atmospheric thermodynamic and dynamical structures within a grid, statistical description is needed. Yet, these statistical relationships should be based on realistic physical principles. At the present time, these subgrid models are either from empirical relationships or from highly intuitive conceptualizations. This deficiency in the subgrid scale dynamics has prompted Randall et al. (2003) to use cloud resolving models inside a climate model to replace the parameterization package. *The third issue* is the abstraction of the coupling of subgrid scale dynamics with the subgrid scale cloud processes into a practical parameterization formulation. It is not clear whether this abstraction is possible. This issue is still valid even if spatial resolution of current models is reduced by an order of magnitude. On the practical side, very few existing convective schemes even include a component of the cloud microphysics.

Aerosol feedbacks in the climate system:

- ✓ Highly uncertain, mainly because most climate GCMs run aerosol off-line (i.e., no coupling)

Some examples of recent studies:

- ✓ Mineral dust:

Miller, R.L., I. Tegen, and Ja. Perlwitz 2004. *Surface radiative forcing by soil dust aerosols and the hydrologic cycle*. *J. Geophys. Res.* **109**, D04203, doi:10.1029/2003JD004085.

Mechanism: Mineral dust causes large radiative forcing at the surface. The climate response depends not only upon the TOA forcing, but its difference with respect to the surface value, which represents radiative heating within the atmosphere. Surface forcing alters evaporation and the hydrologic cycle, which feeds back upon the aerosol burden through the efficiency of wet deposition.

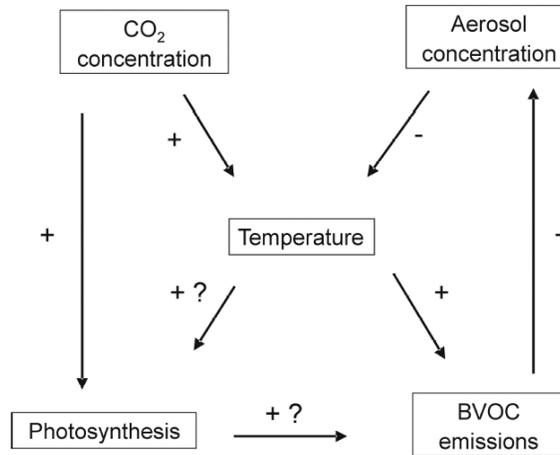
Findings based on GCM modeling results: While global evaporation and precipitation are reduced in response to surface radiative forcing by dust, precipitation increases locally over desert regions, so that dust emission can act as a negative feedback to desertification.

- ✓ Organic aerosol:

Kulmala et al., *A new feedback mechanism linking forests, aerosols, and climate*. *Atmos. Chem. Phys.*, 4, 557–562, 2004.

Below is schematic figure of coupling of atmospheric CO₂ concentration, assimilation of carbon by vegetation productivity (ecosystem gross primary production GPP), emission of biogenic volatile organic compounds (BVOCs), and aerosol particle concentration with atmospheric T. Increased CO₂ concentration will increase temperature (+) and vegetation productivity (+). Increased T will enhance BVOC emissions (+) and probably also plant productivity (+?). Increased vegetation productivity may enhance BVOC emissions (+?). Increased BVOC emissions will enhance aerosol formation and growth and therefore also enhance aerosol and CCN concentrations (+). Enhanced aerosol and CCN concentrations will decrease temperature (-) due to increased reflection of sunlight

from low clouds back to space. This results also in the increase of diffuse radiation, which has a positive influence on photosynthesis



✓ Biogenic aerosols

Barth et al. Coupling between land ecosystems and the atmospheric hydrologic cycle through biogenic aerosol pathways. *BAMS*, 86, 1738- 1742, 2005.

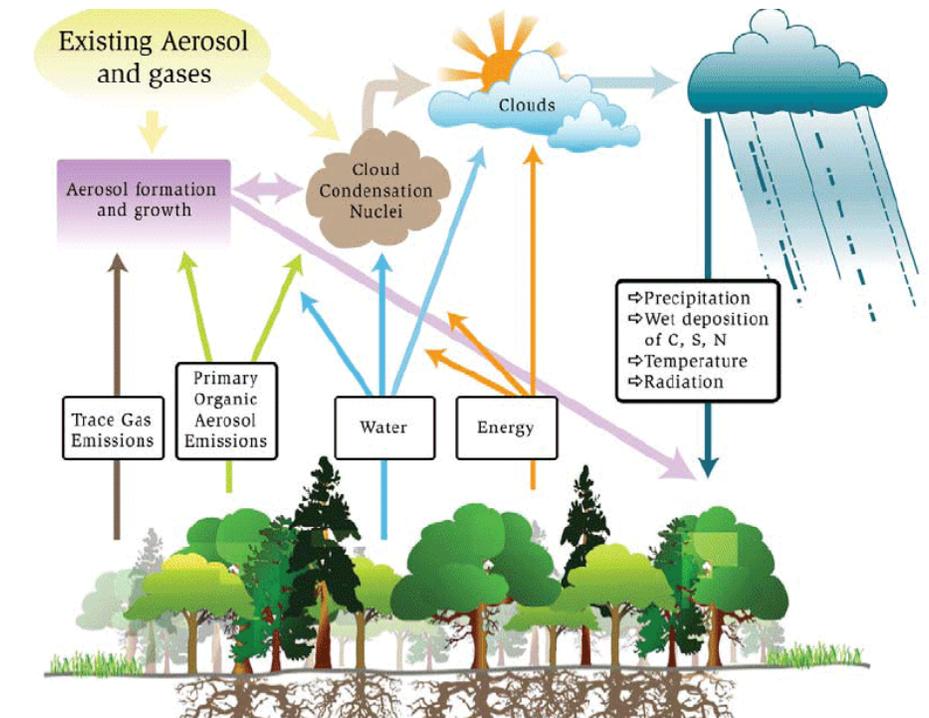


Figure. Schematic of the coupling of terrestrial ecosystems and the hydrologic cycle via energy and water exchange and aerosol processing.