<u>Lecture 14.</u>

Research needs for improved understanding of aerosol–clouds-climate interactions

<u>Required reading:</u>

Chapter 24 from Heintzenberg&Charlson (2009)

<u>Recommended reading:</u>

WCRP (World Climate Research Programme) Grand Challenges - http://www.wcrp-climate.org/grandcha.shtml

White Paper on WCRP Grand Challenge: Clouds, Circulation and Climate Sensitivity: How the interactions between clouds, greenhouse gases and aerosols affect temperature and precipitation in a changing climate.
http://www.wcrp-climate.org/documents/GC4_Clouds_14nov2012.pdf

National Research Council (NRC) Report (2012):
A National Strategy for Advancing Climate Modeling.
http://www.nap.edu/catalog.php?record_id=13430

A. Arneth, S. P. Harrison, S. Zaehle, K. Tsigaridis, S. Menon, P. J. Bartlein, J. Feichter, A. Korhola, M. Kulmala, D. O'Donnell, G. Schurgers, S. Sorvari and T. Vesala
Terrestrial biogeochemical feedbacks in the climate system: Review
Nature Geoscience 3, 525 - 532 (2010), Published online: 25 July 2010 | doi:10.1038/ngeo905

*<u>IPCC report:</u> To cope with the complexity of Earth system processes and their interactions, and particularly to evaluate sophisticated models of the Earth system, observations and long-term monitoring of climate and biogeochemical quantities will be essential. Climate models will have to reproduce accurately t**he important processes and feedback mechanisms**.*

Feedbacks

Needs &Recommendations from Ch24 by Quaas et al

- Cloud-climate feedbacks represent a major uncertainty in projections of climate change. Proxies for climate change (e.g., seasonal cycle, interannual variability) have thus far been found to be unfit to quantify cloud feedbacks. This is because the dynamic and thermodynamic forcings of clouds
- Improved understanding of the cloud-climate feedback processes may lead to a better exploitation of existing data.
- New analysis methods of cloud responses to forcing in models, and of natural variability, may provide important insights into the processes. A promising pathway is to improve cloud parameterizations in large-scale models through the use observations in a combination of LES and CRM (cloud resolving model), as well as by exploiting NWP experiences. Systematic comparisons between process models (LES and CRM) and large-scale models may be used to analyze and improve cloud parameterizations in an effort to assess cloud-climate feedbacks on a large scale.
- Sustained observations from existing and additional satellites and ground-based sites are needed.

"Other" feedbacks

Example-
Arneth et al. (2010)
***Abstract**. The terrestrial biosphere is a key regulator of atmospheric chemistry and climate. During past periods of climate change, vegetation cover and interactions between the terrestrial biosphere and atmosphere changed within decades. Modern observations show a similar responsiveness of terrestrial biogeochemistry to anthropogenically forced climate change and air pollution. Although interactions between the carbon cycle and climate have been a central focus, other biogeochemical feedbacks could be as important in modulating future climate change. Total positive radiative forcings resulting from feedbacks between the terrestrial biosphere and the atmosphere are estimated to reach up to 0.9 or 1.5 $W\ m^{-2}\ K^{-1}$ towards the end of the twenty-first century, depending on the extent to which interactions with the nitrogen cycle stimulate or limit carbon sequestration. This substantially reduces and potentially even eliminates the cooling effect owing to carbon dioxide fertilization of the terrestrial biota. The overall magnitude of the biogeochemical feedbacks could potentially be similar to that of feedbacks in the physical climate system, but there are large uncertainties in the magnitude of individual estimates and in accounting for synergies between these effects.*

IPCC report: A number of feedbacks that amplify or attenuate the climate response to radiative forcing have been identified. In addition to the well-known positive water vapor and ice-albedo feedbacks, a feedback between the carbon cycle and the climate system could produce substantial effects on climate. Other feedbacks (involving, for example, atmospheric chemical and aerosol processes) are even less well understood. Their magnitude and even their sign remain uncertain. The response of the climate system to anthropogenic forcing is expected to be more complex than simple cause and effect relationships would suggest; rather, it could exhibit chaotic behavior with cascades of effects across the different scales and with the potential for abrupt and perhaps irreversible transitions.

<u>WCRP “Grand Science Challenges”</u>

- be both highly specific and highly focused identifying a specific barrier preventing progress in a critical area of climate science
- enable the development of targeted research efforts with the likelihood of significant progress over 5-10 years, even if its ultimate success is uncertain
- enable the implementation of effective and measurable performance metrics
- be transformative, a Grand Challenge should bring the best minds to the table (voluntarily), building and strengthening communities of innovators that are collaborative, perhaps also extending beyond “in-house expertise”
- capture the public’s imagination: teams of world-leading scientists working to solve pressing challenges
- can offer compelling storylines to capture the interest of media and the public

<u>WCRP Write Paper: The grand challenge in clouds&climate:</u>

http://www.wcrp-climate.org/documents/GC4_Clouds_14nov2012.pdf

Over the next 5-10 years, the grand challenge will be to overcome three main barriers that prevent progress in assessing Climate Sensitivity and future precipitation changes:

<u>Barrier 1</u>: Inability to constrain the effects of clouds on climate sensitivity estimates.

The spread of climate sensitivity estimates is unacceptably large, mostly as a result of uncertain changes in clouds. This uncertainty can be thought of as the ‘cloud problem’. The cloud problem contributes to an inability to usefully constrain the upper bound, and the relative reliability, of differing estimates of climate sensitivity.

<u>Defining Questions</u>: What are the origins of inter-model differences in climate sensitivity, radiative feedbacks and adjustments? What are the physical processes responsible for cloud feedbacks and adjustments in models? Can critical tests be designed to assess the relative reliability of model-based representations of such processes? Can estimates of possibly extreme climate sensitivity and feedbacks be constrained by observations and proxy data from past climates?

Barrier 2: Lack of understanding of regional circulation and precipitation changes, especially over land.

Regional precipitation projections remain very uncertain, and most of this uncertainty stems from an inability to quantitatively predict how large-scale atmospheric circulation systems will respond to climate change.

Defining Questions: What are the primary factors that control the strength, the regional patterns, temporal trends, and the modes of variability of the large-scale atmospheric circulation? What is the role of clouds in particular and to what extent is the coupling between aerosols and clouds important? How do these factors link to large-scale patterns of precipitation? Can projections of future precipitation changes at the regional scale be made more robust through advancements in physical understanding, or improved analyses of observations and simulations? Can paleoclimate reconstructions help assess the ability of climate models to predict large-scale circulation and precipitation patterns under climate change?

Barrier 3: Unreliable representation of the coupling between cloud-processes and large-scale dynamics.

Long-standing biases limit the reliability of climate model predictions/projections on all time and space scales. But model development is hindered by a lack of understanding of how processes contributing to model biases couple to large-scale circulation features and influence future projections.

Defining Questions: Can the physical origin of major model biases (double ITCZ, Madden-Julian Oscillation, extended equatorial cold tongue, diurnal cycle of convection and surface temperature biases over continents, etc.) be identified? How much do these biases hinge on the representation of cloud and moist processes and what is their dependence on model resolution? How do model biases at the process level translate into model biases at the climate scale and vice-versa? How do they affect simulations of past and future climate changes?

Opportunities for rapid progress

- CMIP5 and other Model Intercomparison Projects (or MIPs): The range and richness of experiments and outputs made available through many MIPs (including specialized projects focused on cloud feedbacks, short-term and medium-term biases, paleoclimate, geo-engineering, aerosol effects and the carbon cycle) provide a basis for unravelling the causes of inter-model differences in the simulation of current, past and future climates.
- Qualitatively new types of models: A new generation of models has been developed, which makes it possible to simulate clouds more explicitly than in traditional climate models. These include global cloud resolving models and yet finer-scale models on large domains, and hybrid approaches (superparameterization), models which makes it possible to address the cloud problem on a more nearly abinitio basis, but also decadal prediction systems, which make it possible to design qualitatively new tests.
- A golden age of Earth observations: The present may well be looked back upon as the golden age of Earth observations. It has emerged as a result of an explosion of passive and active remote sensing, both from ground and from space, as well as the development of entirely new technologies, for instance laser spectroscopy, which allows the analysis of the isotopic composition of rain and water in the atmosphere. Moreover, the record is beginning to become long enough to sufficiently sample many modes of natural variability, which offers qualitatively new opportunities for creative and critical analysis.
- Lessons from experience: research efforts developed over the last decade or two have helped articulate a winning strategy for addressing this grand challenge. This strategy is based on the recognized importance of developing physical understanding through a spectrum of models and theories as well as often highly idealized modelling frameworks. So doing involves decomposing the cloud problem into a series of more tractable questions. This framework is also crucial for breaking down other barriers to our understanding, for instance those related to the role of the atmospheric aerosol.

- Research community: A mature and interconnected research community now exists in ways that did not exist in the past, and allows us to more effectively combine methodologies. A wide variety of activities within the WCRP, centered for the most part around its working group on coupled modelling (WGCM), with strong links to the WCRP core project on the Global Energy and Water Cycle Experiment (GEWEX) and the WCRP/CAS Working Group on Numerical Experimentation (WGNE), will contribute to the grand challenge. Contributions from other core projects such as the WCRP Climate and Cryosphere Project (CLIC), the THORPEX project of the World Weather Research Programme, as well as a number of programmes focused on understanding the character and influence of various forcing agents within the International Geosphere-Biosphere Programme (IGBP) also help create a basis for progress on this grand challenge.

National Research Council (NRC) Report (2012):

Current issues in climate models:

Finding 3.1: Climate models are continually moving toward higher resolutions via a number of different methods in order to provide improved simulations and more detailed spatial information; as these higher resolutions are implemented, parameterizations will need to be updated.

Finding 3.2: While different approaches to achieving high resolution in climate models have been explored for more than two decades, there remains a need for more systematic evaluation and comparison of the various downscaling methods, including how different grid refinement approaches interact with model resolution and physics parameterizations to influence the simulation of critical regional climate phenomena.

Finding 3.3: Climate models have evolved to include more components in order to more completely depict the complexity of the Earth system; future challenges include more complete depictions of Earth's energy, water, and biogeochemical cycles, as well as integrating models of human activities with natural Earth system models.

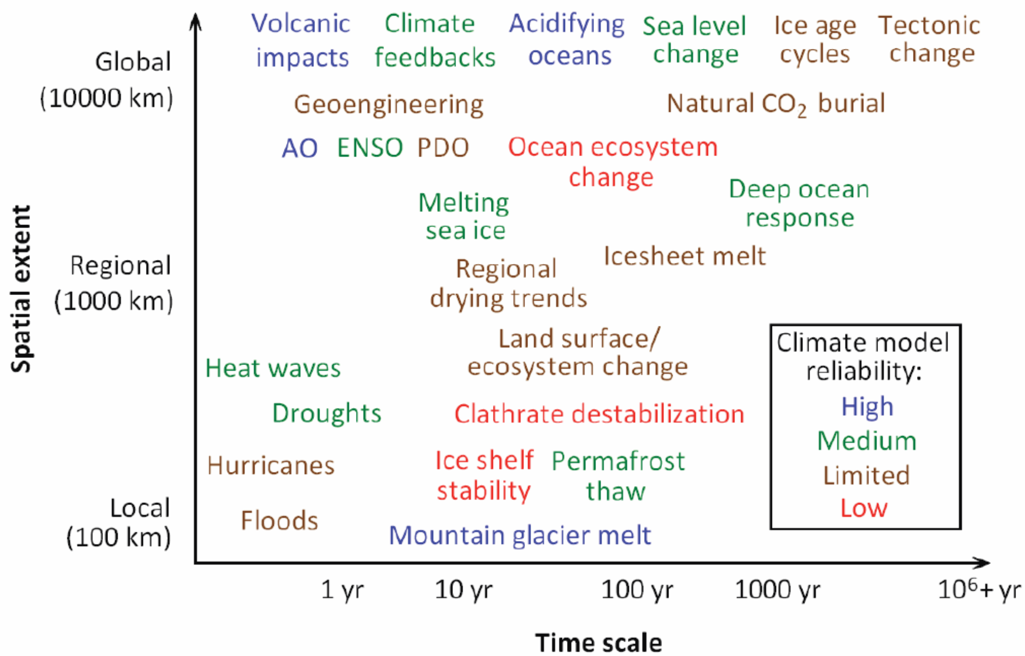

FIGURE 1.7 Time and space scales of key climate phenomena. Color coding shows relative reliability of climate model simulations of these phenomena (or their statistics in the present climate, for climate variability/extremes).

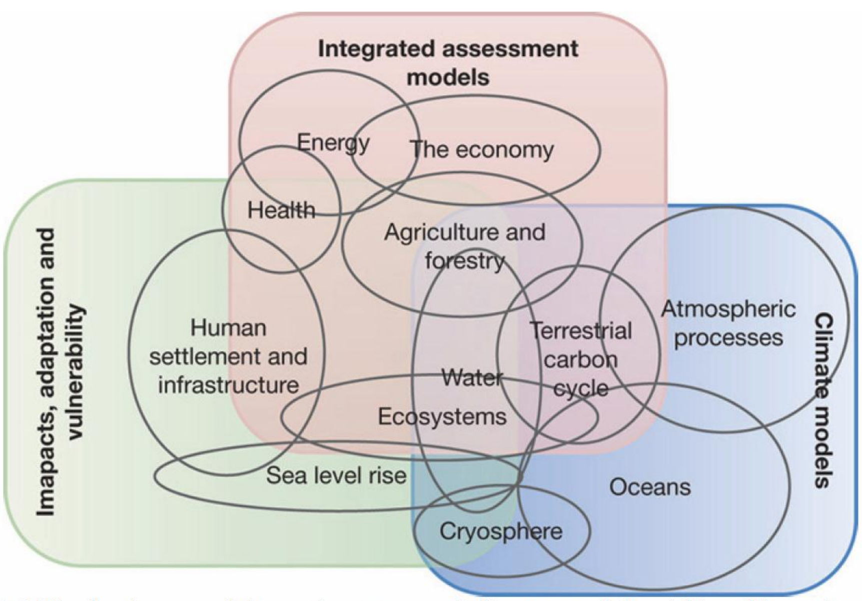

FIGURE 3.2 The landscape of the various types of climate models within a hierarchy of models is complex and overlapping. This is one view of that landscape centered on the three broad types of models and analytic frameworks in climate change research that contribute to the IPCC reports: integrated assessment models, physical climate models, and models and other approaches used to help assess impacts, adaptation, and vulnerability. SOURCE: Moss et al., 2010. Reprinted by permission from Macmillan Publishers Ltd., copyright 2010.

Observational systems

Finding 4.2: Progress is likely on a number of important problems in climate modeling over the coming decades through a combination of increasing model resolution, advances in observations and process understanding, improved model physical parameterizations and stochastic methods, and more complete representations of the Earth system in climate models.

Finding 5.1: Observational networks and systems are increasingly responsive to needs for climate data and information, but still fall short of meeting information needs for climate and Earth system modeling.

Finding 5.3: To be useful for evaluating climate and Earth system models, observations need to be regionally comprehensive, global in scope and internationally coordinated in a way that ensures consistency and transparency across measurement standards, spatial and temporal sampling strategies, and data management protocols (metadata standards, quality control, uncertainty estimates, processing techniques, etc.).

GCOS (Global Climate Observing System)   http://www.wmo.int/pages/prog/gcos/

TABLE 5.1: Essential Climate Variables (ECVs) that are both currently feasible for global implementation and have a high impact on UNFCCC requirements (GCOS, 2010).

Domain	Essential Climate Variables
Atmospheric (over land, sea and ice)	**Surface:** Air temperature, Wind speed and direction, Water vapor, Pressure, Precipitation, Surface radiation budget. **Upper-air:** Temperature, Wind speed and direction, Water vapor, Cloud properties, Earth radiation budget (including solar irradiance). **Composition:** Carbon dioxide, Methane, and other long-lived greenhouse gases; Ozone and Aerosol, supported by their precursors.
Oceanic	**Surface:** Sea-surface temperature, Sea-surface salinity, Sea level, Sea state, Sea ice, Surface current, Ocean color, Carbon dioxide partial pressure, Ocean acidity, Phytoplankton. **Sub-surface:** Temperature, Salinity, Current, Nutrients, Carbon dioxide partial pressure, Ocean acidity, Oxygen, Tracers.
Terrestrial	River discharge, Water use, Ground water, Lakes, Snow cover, Glaciers and ice caps, Ice sheets, Permafrost, Albedo, Land cover (including vegetation type), Fraction of absorbed photosynthetically active radiation (FAPAR), Leaf area index (LAI), Above-ground biomass, Soil carbon, Fire disturbance, Soil moisture.

Uncertainties

Finding 6.1: There are important uncertainties in the response of the climate system to future forcings, including uncertainties due to inadequate representation and spatial resolution of some processes and features in current climate models, and uncertainties inherent in both dynamical and statistical downscaling methods for making local climate projections. Climate predictions and projections are subject to uncertainty resulting from the incomplete knowledge of initial conditions of the relevant components and internal variability of the climate system, which depends on the time scale being considered.

Finding 6.3: There is no simple, formulaic way to communicate uncertainty. To develop effective and consistent communication strategies, social-science based empirical studies are needed.

Finding 6.5: Communication of uncertainty is a challenge within the climate modeling community: more sophisticated approaches that include the involvement of experts across disciplines and the consideration of communication from the beginning of any particular climate model-based research project or program could help address this challenge.

Finding 6.6: Resource managers and decision-makers have diverse and evolving methods for handling climate change uncertainty.

Recommendation 6.1: Uncertainty is a significant aspect of climate modeling and should be properly addressed by the climate modeling community. To facilitate this, the Unites States should more vigorously support research on uncertainty, including:

- understanding and quantifying uncertainty in the projection of future climate change, including how best to use the current observational record across all time scales;
- incorporating uncertainty characterization and quantification more fully in the climate modeling process;
- communicating uncertainty to both users of climate model output and decision makers; and
- developing deeper understanding on the relationship between uncertainty and decision making so that climate modeling efforts and characterization of uncertainty are better brought in line with the true needs for decision making.

Some other recommendations

Recommendation 4.2: Within the realm where progress is likely, the climate modeling community should continue to work intensively on a broad spectrum of climate problems, in particular on long-standing challenges such as climate sensitivity and cloud feedbacks that affect most aspects of climate change (regional hydrological changes, extremes, sea level rise, etc.) and require continued or intensified support. Progress can be expected as resolution, physical parameterizations, observational constraints, and modeling strategies improve.

Recommendation 4.3: More effort should be put towards coordinated global and regional climate modeling activities to allow good representation of land surface hydrology and terrestrial vegetation dynamics and to enable improved modeling of the hydrological cycle and regional water resources, agriculture, and drought forecasts.

Recommendation 3.1: To address the increasing breadth of issues in climate science, the climate modeling community should vigorously pursue a full spectrum of models and evaluation approaches, including further systematic comparisons of the value added by various downscaling approaches as the resolution of climate model increases.

Recommendation 3.2: To support a national linked hierarchy of models, the United States should nurture a common modeling infrastructure and a shared model development process, allowing modeling groups to efficiently share advances while preserving scientific freedom and creativity by fostering model diversity where needed.

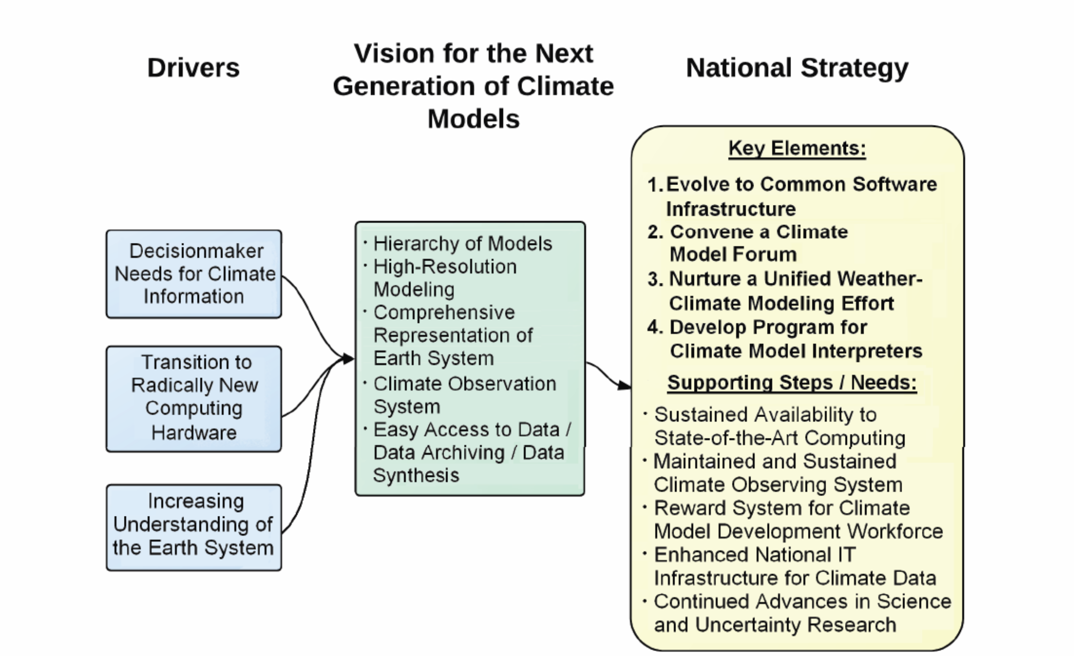

FIGURE S.1 Driven by the growing need for climate information and the coming transition to radically new computing hardware, a new generation of climate models will be needed to address a wide spectrum of climate information needs. A national strategy consisting of four key unifying elements and several other recommendations can help to achieve this vision.

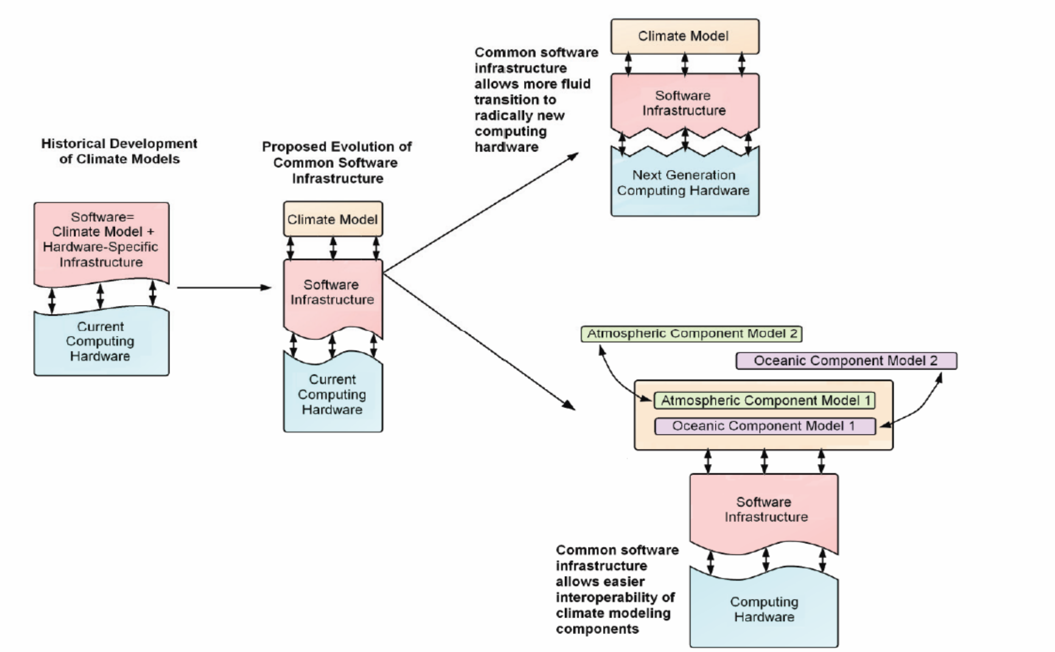

FIGURE S.2 The development of a common software infrastructure that interfaces between the climate modeling computer code and the computing hardware has two important advantages: (1) it will facilitate the migration of models to the next generation of computing platforms by isolating the climate modeling computer code from the changes in hardware, and (2) it will allow the interoperability of climate model components, for example to enable the testing of two different atmospheric component models, without having to adapt the component models to different hardware platforms.