Lecture 6.

Representation of aerosol and clouds in models.

Challenges and future directions in modeling aerosol-clouds-climate interactions.

Required reading:

Chs. 20, 23 and 12 from Heintzenberg&Charlson (2009)

Ch. 3 from CCSP Report (2009): Atmospheric Aerosol Properties and Climate Impacts http://www.climatescience.gov/Library/sap/sap2-3/final-report/default.htm

Additional reading:

AeroCom project – GCMs intercomparisons
http://aerocom.met.no/aerocomhome.html

Ghan, S., et al., Droplet Nucleation: Physically-Based Parameterizations and Comparative Evaluation. J. Adv. Model. Earth Syst., 3, M10001, 33 pp., doi:10.1029/2011MS000074, 2011.

Hoose, C. and O. Möhler, Heterogeneous ice nucleation on atmospheric aerosols: A review of results from laboratory experiments. Atmospheric Chemistry and Physics 12, 9817-9854, 2012.

Types of climate models:

- Climate models based on by their dimensions:

Zero Dimensional Models (0-D):

consider the Earth as a whole (no change by latitude, longitude, or height)

One Dimensional Models (1-D):

allow for variation in one direction only (e.g., resolve the Earth into latitudinal zones or by height above the surface of the Earth)

Two Dimensional Models (2-D):

allow for variation in two directions at once (e.g., by latitude and by height)

Three Dimensional Models (3-D) (mesoscale (regional) models, General Circulation Models (GCMs) and Earth System Models (ESMs)):

allow for variation in three directions at once (i.e., divide the earth-atmosphere system into domains, each domain having its own independent set of values for each of the climate parameters used in the model.

- Climate models based on included basic physical processes:

Energy Balance Models:

0-D or 1-D models (e.g., allow to change the albedo by latitude) calculate a balance between the incoming and outgoing radiation of the planet;

Radiative Convective Models:

1-D models to model the temperature profile the atmosphere by considering radiative and convective energy transport up through the atmosphere.

General Circulation Climate Models:

2-D (longitude-averaged) or 3-D climate models solve a series of equations and have the potential to model the atmosphere very closely as well as some atmosphere-land-ocean coupling

Earth System Models:

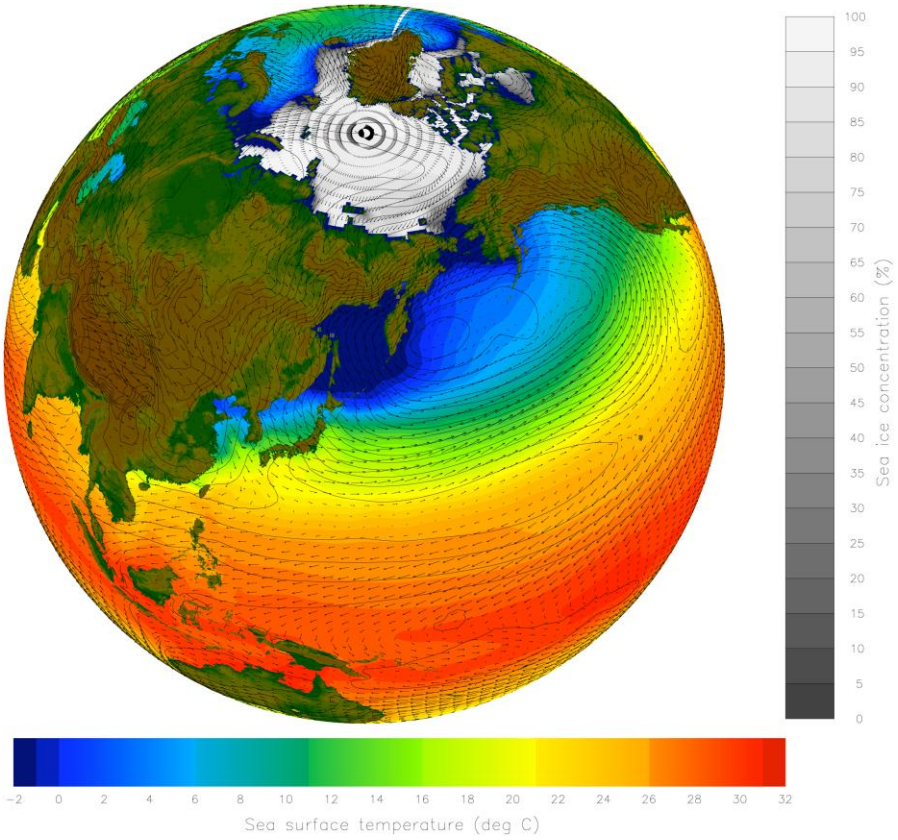
3-D fully-coupled, global climate models of atmosphere, land, ocean, sea ice and human dimension

Example of ESM:

http://www.cesm.ucar.edu/

The Community Earth System Model (CESM) is a fully-coupled, global climate model that provides state-of-the-art computer simulations of the Earth's past, present, and future climate states.

Consists of 4+ geophysical component models (atmosphere, land, ocean, sea ice) *on potentially different grids* that exchange *boundary data* with each other.



Modeling climate's complexity. This image, taken from a larger simulation of 20th century climate, depicts several aspects of Earth's climate system. Sea surface temperatures and sea ice concentrations are shown by the two color scales. The figure also captures sea level pressure and low-level winds, including warmer air moving north on the eastern side of low-pressure regions and colder air moving south on the western side of the lows.

The range of scales

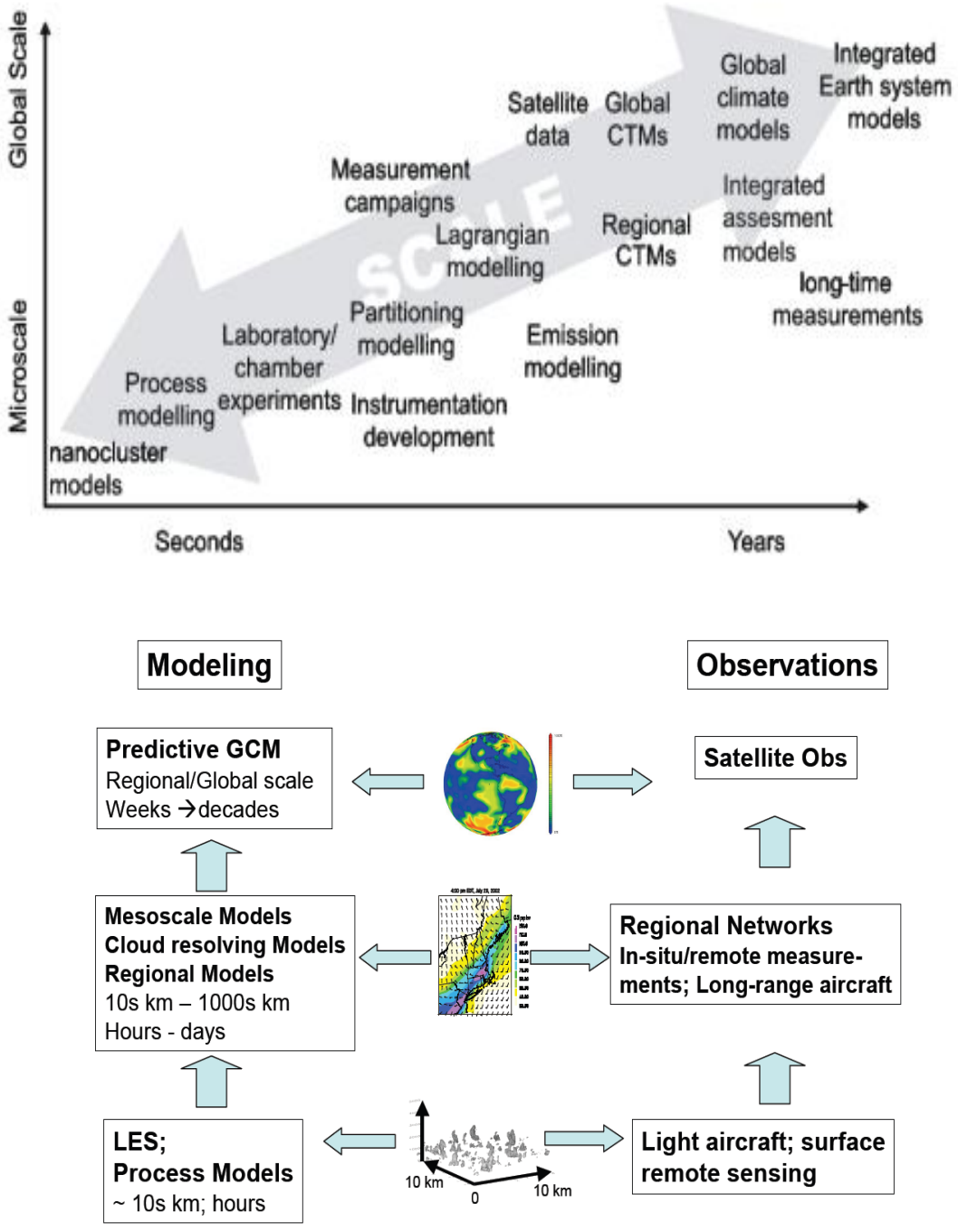


Figure 6.1 The range of scales of models vs. observations.

Representation of aerosols in models*:*

Composition:

Most common aerosol types: sulfates, BC, organics, dust, sea-salt

Representation of particle size distribution:

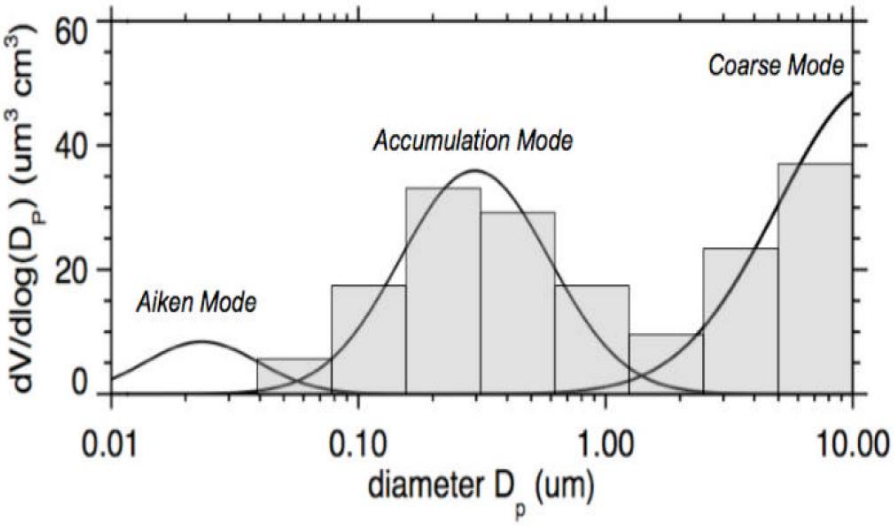


Figure 6.2 Different representations of size distribution in models: modal (lines) vs. sectional (or bin) (boxes).

The particle size distribution of aerosols represented by a sum of three log-normal functions:

$$N(r) = \sum_i \frac{N_i}{\sqrt{2\pi}\ \ln(\sigma_i)\ r} \exp\left(-\frac{\ln(r / r_{0,i})^2}{2\ln(\sigma_i)^2}\right) \qquad [6.1]$$

where **N(r)** is the particle number concentration, $\mathbf{N_i}$ is the total particle number concentration of i-th size mode with its median radius $\mathbf{r_{0,i}}$ and geometric standard deviation $\boldsymbol{\sigma_i}$.

Effective particle radius

$$r_e = \frac{\int \pi r^3 N(r) dr}{\int \pi r^2 N(r) dr} \qquad [6.2]$$

Aerosol radiative forcing (at top-of-the-atmosphere, TOA)

Emissions -> AOD -> Direct radiative forcing

Emissions -> AOD -> Direct radiative forcing efficiency (radiative forcing per AOD)

A typical approach for calculating DRF in GCMs:

Emission -> load (mass per unit area, g/m2)

AOD = MEE * load, where MEE is the mass extinction efficiency

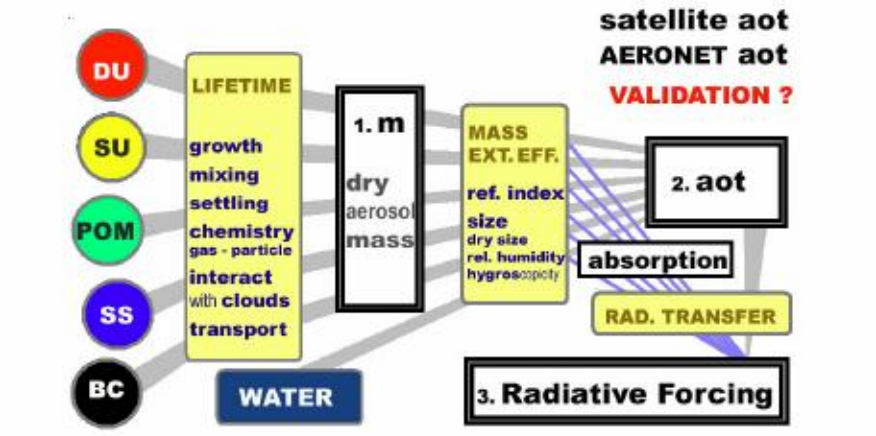


Figure 6.3 Schematics of modeling steps in GCMs from emissions to estimates of direct aerosol radiative forcing at TOA (From Kinne et al., 2006, ACP)

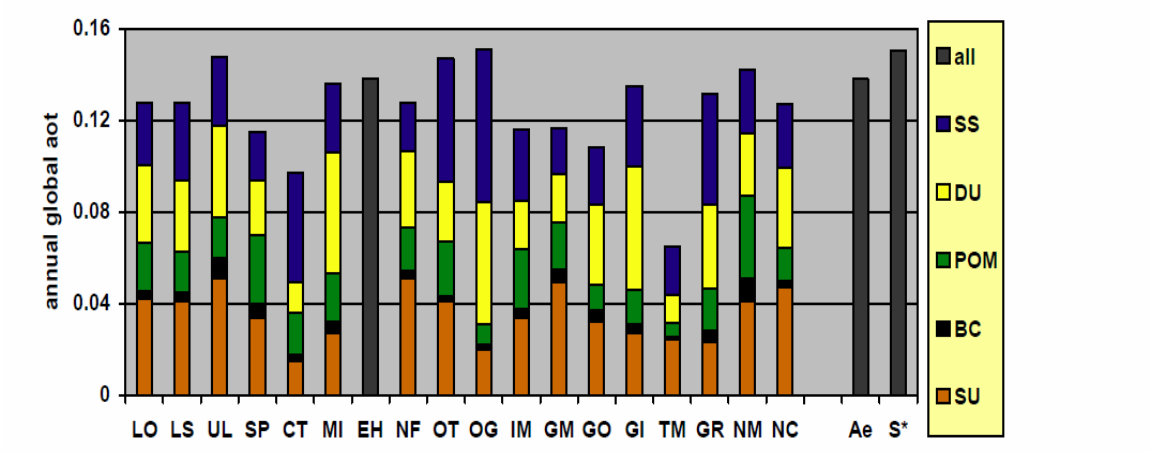


Figure 6.4 Modeled contribution of aerosol components to global mean AOD at 550 nm by different GCMs (see model names and further details in Kinne et al., 2006, ACP)

Table 6.1 AeroCom GCMs intercomaprison) (see details in Ch3 of CCS Report, 2009)

Quantity	Mean	Median	Range	Stddev /mean*
Sources (Tg yr^{-1})				
Sulfate	179	186	98-232	22%
Black carbon	11.9	11.3	7.8-19.4	23%
Organic matter	96.6	96.0	53-138	26%
Dust	1840	1640	672-4040	49%
Sea salt	16600	6280	2180-121000	199%
Removal rate (day^{-1})				
Sulfate	0.25	0.24	0.19-0.39	18%
Black carbon	0.15	0.15	0.066-0.19	21%
Organic matter	0.16	0.16	0.09-0.23	24%
Dust	0.31	0.25	0.14-0.79	62%
Sea salt	5.07	2.50	0.95-35.0	188%
Lifetime (day)				
Sulfate	4.12	4.13	2.6-5.4	18%
Black carbon	7.12	6.54	5.3-15	33%
Organic matter	6.54	6.16	4.3-11	27%
Dust	4.14	4.04	1.3-7.0	43%
Sea salt	0.48	0.41	0.03-1.1	58%
Mass loading (Tg)				
Sulfate	1.99	1.98	0.92-2.70	25%
Black carbon	0.24	0.21	0.046-0.51	42%
Organic matter	1.70	1.76	0.46-2.56	27%
Dust	19.2	20.5	4.5-29.5	40%
Sea salt	7.52	6.37	2.5-13.2	54%
MEE at 550 nm (m^2 g^{-1})				
Sulfate	11.3	9.5	4.2-28.3	56%
Black carbon	9.4	9.2	5.3-18.9	36%
Organic matter	5.7	5.7	3.7-9.1	26%
Dust	0.99	0.95	0.46-2.05	45%
Sea salt	3.0	3.1	0.97-7.5	55%
AOD at 550 nm				
Sulfate	0.035	0.034	0.015-0.051	33%
Black carbon	0.004	0.004	0.002-0.009	46%
Organic matter	0.018	0.019	0.006-0.030	36%
Dust	0.032	0.033	0.012-0.054	44%
Sea salt	0.033	0.030	0.02-0.067	42%
Total AOT at 550 nm	0.124	0.127	0.065-0.151	18%

Large differences in assessments of DRF among GCMs

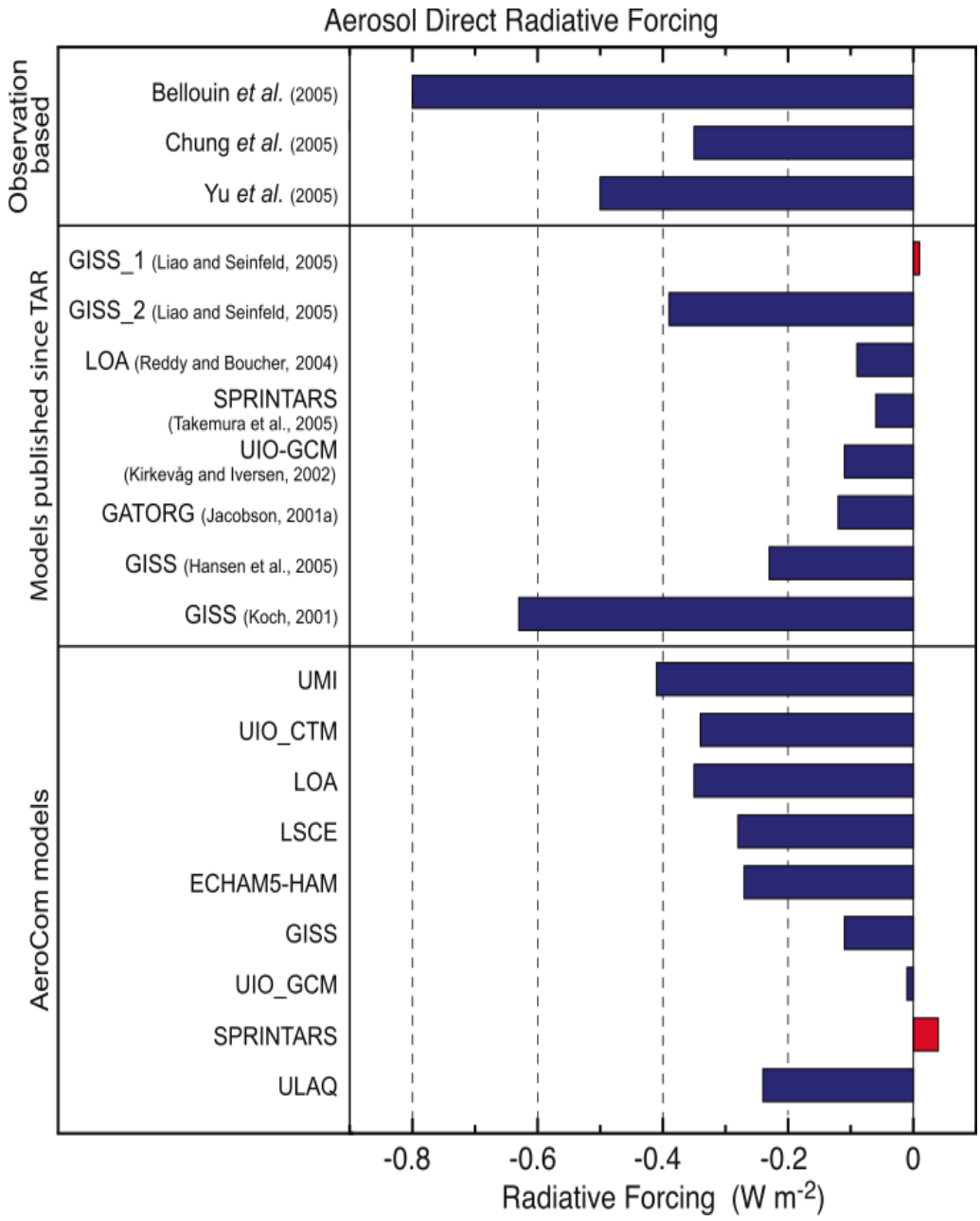


Figure 6.5 Estimates of the direct aerosol radiative forcing from observationally based studies, independent modeling studies, and AeroCom project results with identical aerosol and aerosol precursor emissions. GISS_1 refers to a study employing an internal mixture of aerosol, and GISS_2 to a study employing an external mixture (IPCC, 2007).

Importance of composition in assessment of direct radiative forcing:

sulfates -> always negative forcing (leading to cooling);

biomass burning (if OC is major constituents) -> negative

carbonaceous (if BC is dominant) -> positive

mineral dust -> negative or positive ?

multi-component (internally-mixed) aerosols -> negative or positive ?

Outstanding issues in assessments of direct radiative forcing (DRF):

- Sources (emission) and composition (GCMs mainly include sulfates, BC, organics, dust, sea-salt, rarely nitrates and secondary organics; consider external mixtures, and rarely internal mixtures. Large uncertainties in assessment of anthropogenic sources and their change with time/area)
- Simplified treatment of optical properties, especially light absorbing aerosols (e.g., external vs. internal mixtures of BC)
- Simplified representation of high spatial and temporal variations of aerosol amount and properties
- In addition to TOA DRF, aerosols can affect the surface radiative budget and provide additional radiative heating (or cooling) of the atmosphere – need to account for the total aerosol radiative impact

Aerosol indirect effects

NOTE: The IPCC reports consider only the cloud albedo indirect aerosol forcing (only water clouds).

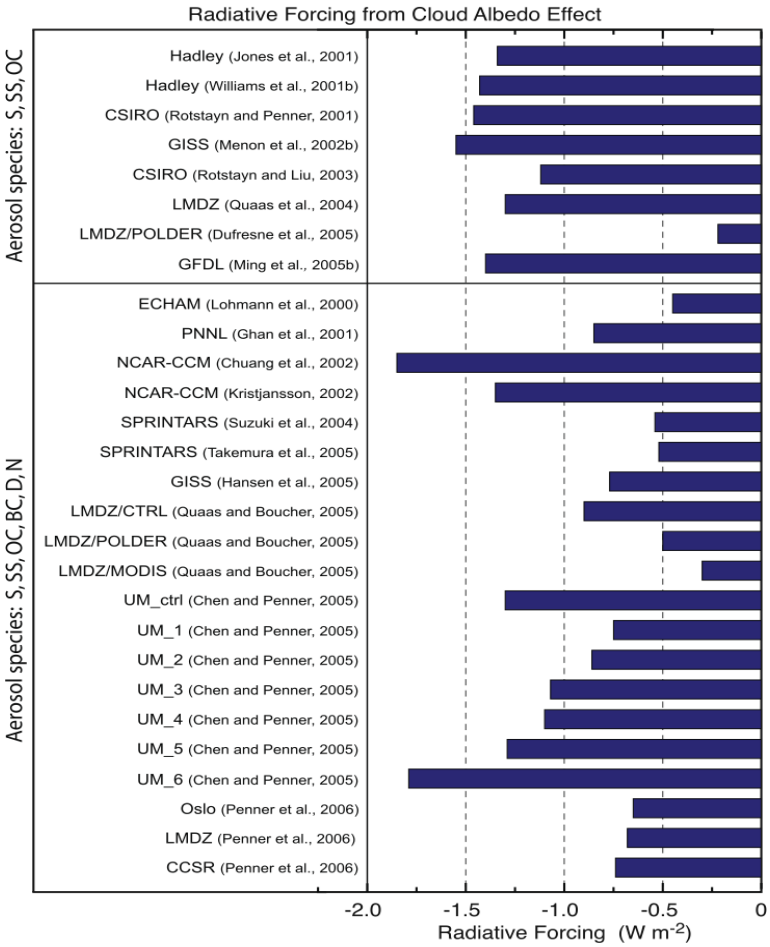


Figure 6.6 Aerosol indirect radiative forcing due to the cloud albedo effect, in the context of liquid water clouds, from the global climate models (see IPCC, 2007). Top panel: results for models that consider a limited number of species, primarily anthropogenic sulfates (S), (also sea salt (SS) and organic carbon (OC). Bottom panel: results from studies that include a variety of aerosol compositions and mixtures (S, SS, OC, black carbon (BC, dust (D) and nitrates (N); the estimates here cover a larger range than those in the top panel.

Radiative impact of clouds

High level clouds (cirrus):

The overall effect of the high thin cirrus clouds is to enhance atmospheric greenhouse warming. They are highly transparent to shortwave radiation (their cloud albedo forcing is small), but they readily absorb the outgoing LW radiation. Because cirrus clouds are high, and therefore cold, the energy radiated to outer space is lower than it would be without the cloud (the cloud greenhouse forcing is large).

Low level clouds

Low stratocumulus clouds act to cool the Earth system. Because lower clouds are much thicker than high cirrus clouds, they are not as transparent to solar radiation. Instead, they reflect much of the solar energy back to space (cloud albedo forcing is large). Although stratocumulus clouds also emit longwave radiation out to space and toward the Earth's surface, they are near the surface and at almost the same temperature as the surface (thus, their cloud greenhouse forcing on a planetary scale is small).

Deep convective clouds:

Because cumulonimbus cloud tops are high (can reach 10 km) and cold, the LW radiation emitted to outer space is lower than it would be without the cloud (the cloud greenhouse forcing is large). But because they also are very thick, they reflect much of the SW radiation back to space (their cloud albedo forcing is also large). As a consequence, overall, the cloud greenhouse and albedo forcings almost balance, and the overall effect of cumulonimbus clouds is neutral-neither warming nor cooling.

Representation of droplet activation process

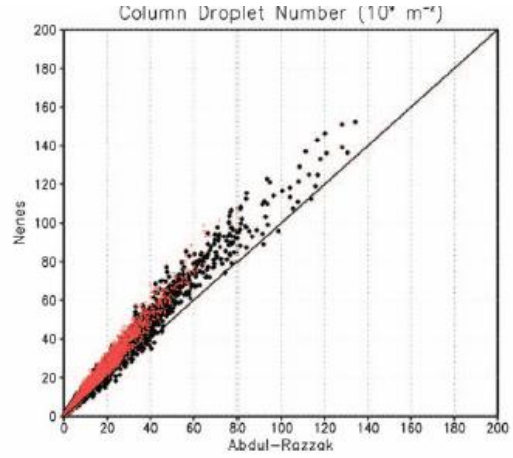
Complexity: involves spontaneous growth of aerosols that serve as cloud condensation nuclei (CCN) at cloud edges or within clouds; depends on aerosol number size distribution, hygroscopicity and cooling rate (updrfats)

Table 6.2 Comparison of aerosol activation schemes based on Kohler theory (Ghan et al. 2011)

Scheme and Key Reference	Mass Transfer	Condensation Coefficient	Integration Over Size Distribution	Iterative Solution	Kinetic Limitations
Abdul-Razzak *Abdul-Razzak and Ghan* [2000]	scaling of G	scaling of G	analytic	no	neglected
Nenes *Fountoukis and Nenes* [2005]	explicit	explicit dependence	analytic	yes	treated
Ming *Ming et al.* [2006]	explicit	explicit dependence	numerical	yes	empirical
Hänel *Hänel* [1987]	constant G	fixed	numerical	yes	neglected
Cohard *Cohard et al.* [2000]	constant G	undefined	analytic	no	neglected
Khvorostyanov *Khvorostyanov and Curry* [2009]	explicit	explicit dependence	analytic	no	neglected
Shipway *Shipway and Abel* [2010]	explicit	explicit dependence	analytic	yes	treated
Kivekas *Kivekas et al.* [2008]	empirical	fixed	analytic	no	empirical

Findings from Ghan et al. 2011:

- Found good aggrement ~30% among considered parametrizations
- Two parameterizations (Nenes and Abdul-Razzak) ran in the same GCM agree within 10%



Treatment of ice processes

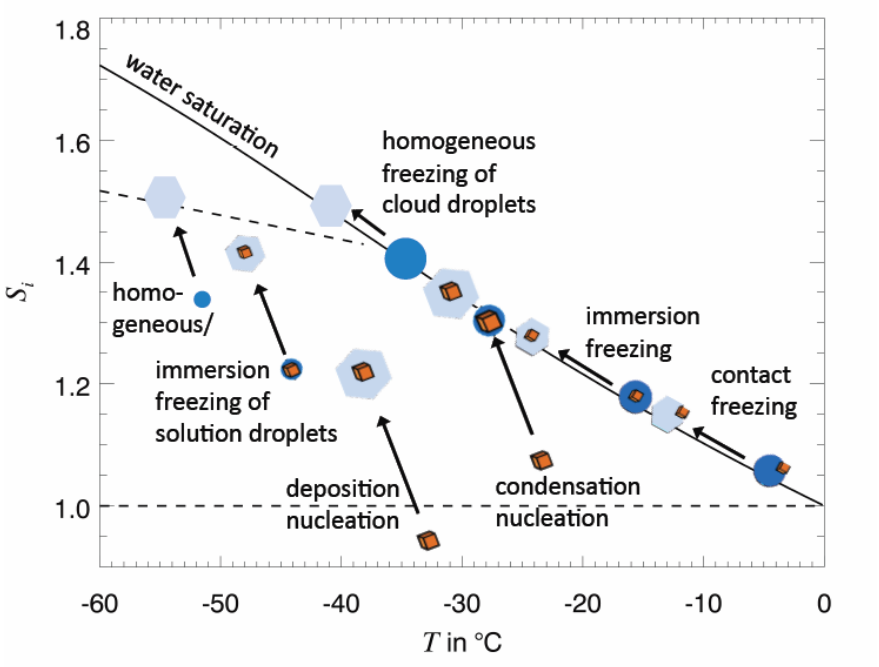


Figure 6.7 Schematic representation of different ice nucleation modes, from Hoose and Mohler (2012, ACP).

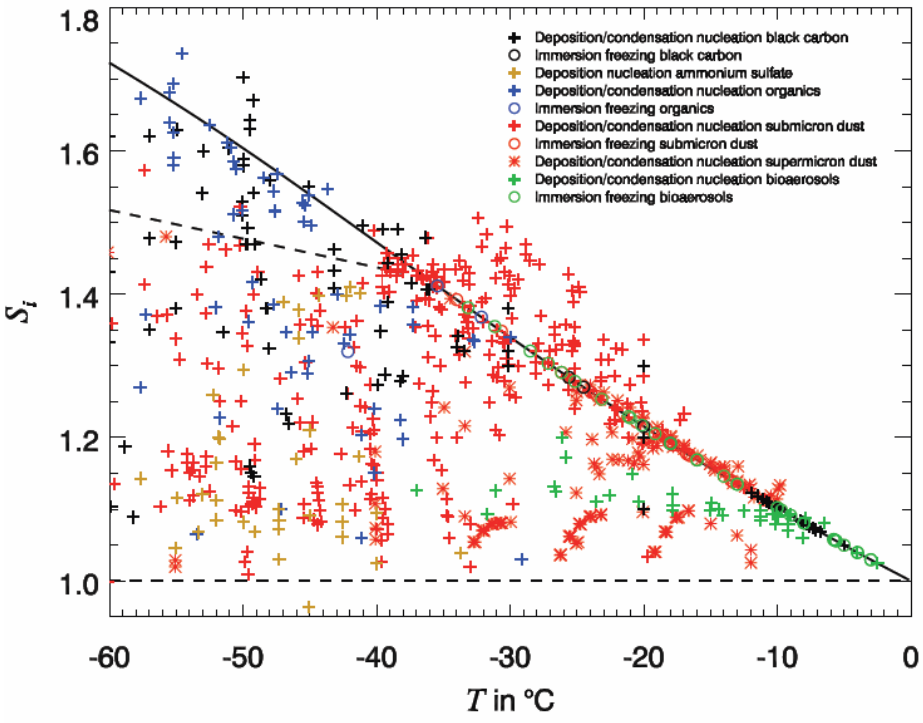


Figure 6.8 Comparison of measured ice nucleation onset temperature and saturation ratios, from Hoose and Mohler (2012, ACP).

Findings from Hoose and Mohler (2012):

(Based results from six decades of laboratory experiments of heterogeneous ice nucleation and its parameterizations):

- Observed onset conditions for heterogeneous ice nucleation spread over large ranges of temperature and ice supersaturation, due to differences in methodology and nonstandardized reported variables.
- Classical nucleation theory, if employed with only one fitted contact angle, does not reproduce the observed temperature dependence for immersion nucleation, the temperature and supersaturation dependence for deposition nucleation, and the time dependence of ice nucleation. Formulations of classical nucleation theory with distributions of contact angles offer possibilities to overcome these weaknesses.