

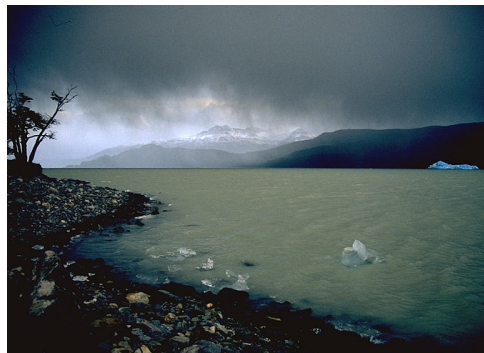
Atmospheric Physics

Thermodynamics, Clouds and Precipitation

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Marc Wüest

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ETH, Oct 26, 2005



Miscellaneous

- ▶ Lecturers: Ulrike Lohmann
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Marc Wüest
(CHN P18, Tel: 044 633 3781, Marc.Wueest@env.ethz.ch)
- ▶ Textbook: A Short Course in Cloud Physics, R. R. Rogers and M. K. Yau, Pergamon Press, 1989
- ▶ Prerequisite: Any introduction to Atmospheric Science
- ▶ Objective: Understanding the importance of cloud and precipitation physics
- ▶ Grading Scheme: 3 credit points; marked; 5 assignments
- ▶ Slides: English in order for you to get familiar with scientific English terminology
- ▶ Notes: one day before lecture at:
http://www.iac.ethz.ch/education/atmospheric_physics

Course Outline: first half (Ulrike Lohmann)

1. Oct 26: Introduction to aerosols and clouds
2. Nov 2: Review thermodynamics necessary for clouds
3. Nov 9: Parcel buoyancy and atmospheric stability
4. Nov 16: Mixing and convection
5. Nov 23: Aerosols, cloud condensation and ice nuclei
6. Nov 30: Formation and growth of cloud droplets
7. Dec 7: Formation and growth of ice crystals

Course Outline: second half (Marc Wüest)

1. Dec 14: Initiation of rain in non-freezing clouds
2. Dec 21: Rain and snow
3. Jan 11: Weather radar
4. Jan 18: Precipitation processes
5. Jan 25: Severe storms and hail
6. Feb 1: Weather modification
7. Feb 8: Radiative effects of clouds and aerosols (Ulrike Lohmann)

Importance of clouds

- ▶ Definition: Clouds consist of cloud droplets and/or ice crystals of different sizes.
- ▶ Clouds are a major factor in the Earth's radiation budget, reflecting sunlight back to space and trapping infrared radiation emitted by the Earth's surface.
- ▶ Clouds deliver water from the atmosphere to the Earth's surface as rain or snow → hydrological cycle
- ▶ Clouds scavenge gaseous and particulate materials and return them to the surface (wet deposition).
- ▶ Clouds provide a medium for aqueous-phase chemical reactions and production of secondary species.
- ▶ Updrafts and downdrafts associated with clouds largely determine the vertical redistribution of trace species, temperature and moisture.

Global mean energy budget

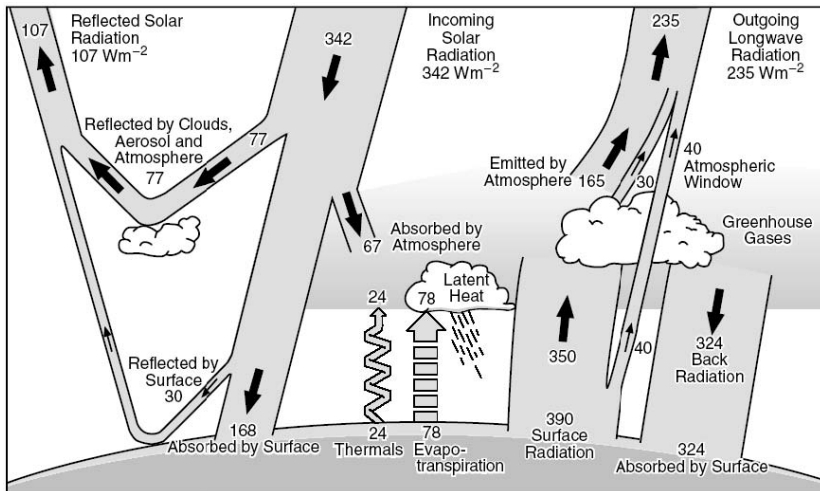


Figure: Kiehl and Trenberth, BAMS, 1997

Motivation

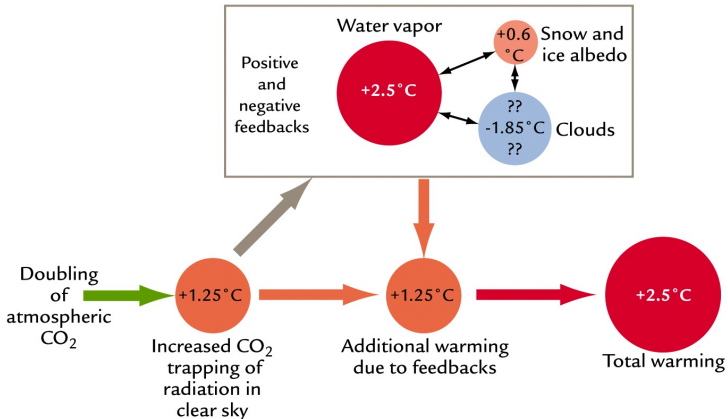


Figure: Components of 2xCO₂ warming, from Ruddiman [2001]

Mean total cloud amount 1983-2001

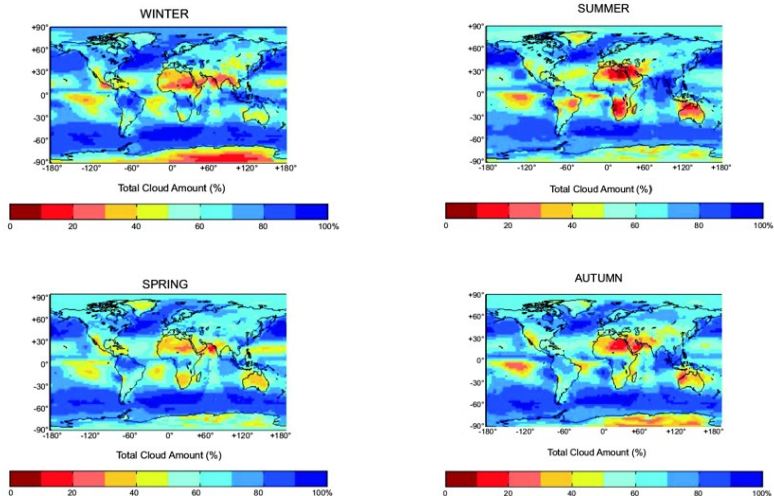
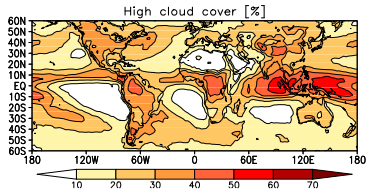
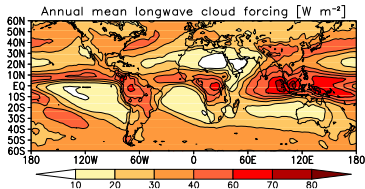
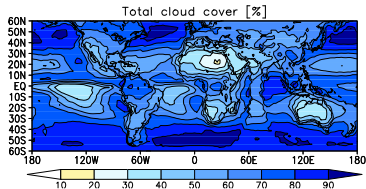
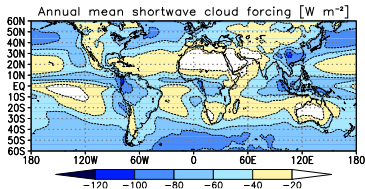


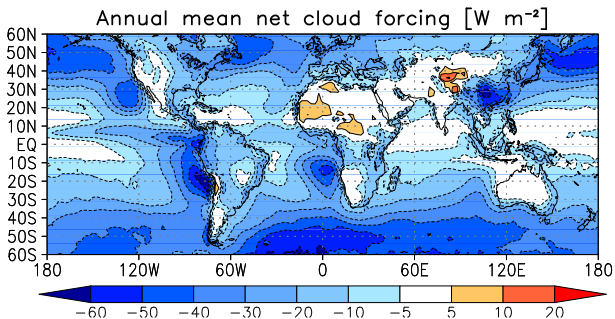
Figure: International Cloud Climatology Program

Geographic distribution of the “cloud forcing”



- ▶ shortwave cloud forcing (SCF) = $F_{SW} - F_{SW,cs} = \frac{S_0}{4} (\alpha_{cs} - \alpha_{cl}) \Rightarrow$ albedo effect of clouds
- ▶ longwave cloud forcing (LCF) = $F_{LW,cs} - F_{LW} \Rightarrow$ greenhouse effect of clouds

Geographic distribution of the “cloud forcing”



Global mean values:

$$\overline{\text{SCF}} = -49 \text{ W m}^{-2} ; \overline{\text{LCF}} = 32 \text{ W m}^{-2} ; \overline{\text{CF}} = -17 \text{ W m}^{-2}$$

Hydrological cycle

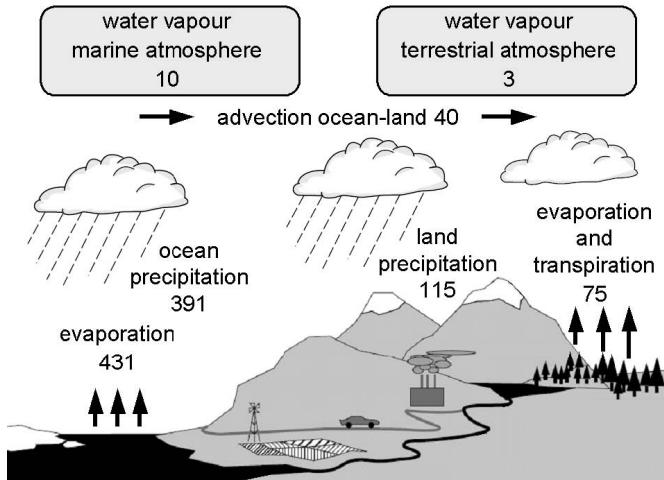


Figure: Quante, J. Phys IV, 2004

Mean total precipitation 1979-2001

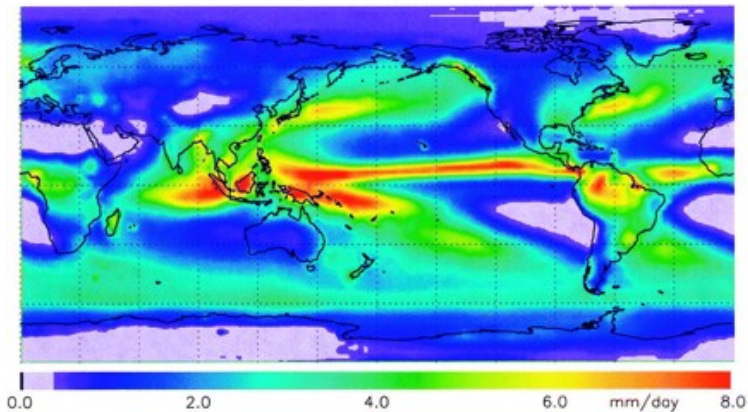


Figure: Global Precipitation Climatology Project

Seasonal variation in total precipitation

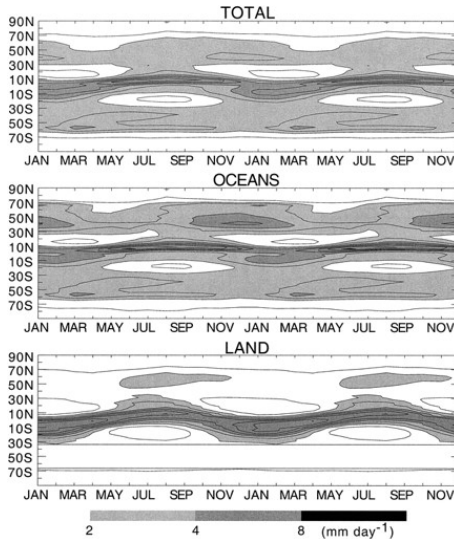


Figure: Adler et al., 2003

Time series of total precipitation

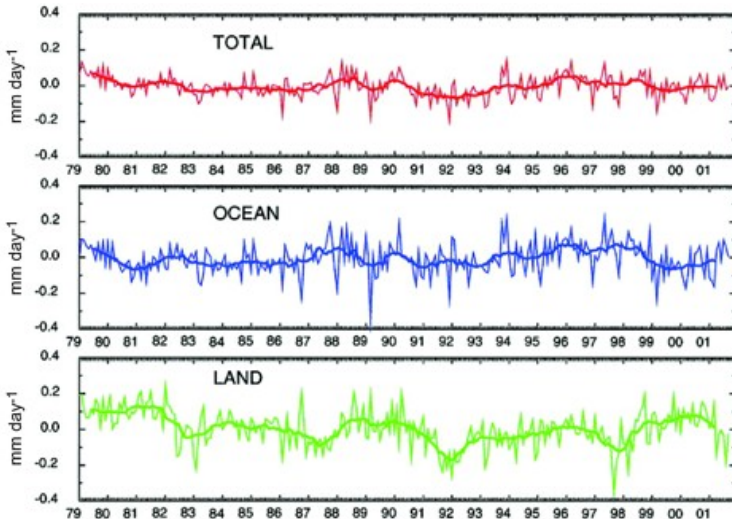


Figure: Adler et al., 2003

Cloud types

- ▶ Cumulus (Cu): vertical development
- ▶ Stratus (St): layered cloud
- ▶ Cirrus (Ci): ice clouds

10 cloud types in 4 families:

- ▶ Low base with vertical extent: Cu, Cb, Ns
- ▶ Low base and layered (0-2 km¹): St, Sc
- ▶ Mid level clouds (2-7 km): As, Ac
- ▶ High altitude ice clouds (7-16 km): Ci, Cs, Cc

¹heights refer to mid latitudes

Annual average cloud amounts [%] from surface observations

Cloud type	Land	Ocean
Stratus	5	11
Stratocumulus	12	22
Cumulus	5	12
Cumulonimbus	4	4
Nimbostratus	5	6
Altostratus	4	22
Alto cumulus	17	
Cirrus	22	13

From: Quante, J. Phys IV, [2004]

CONVECTIVE CLOUDS

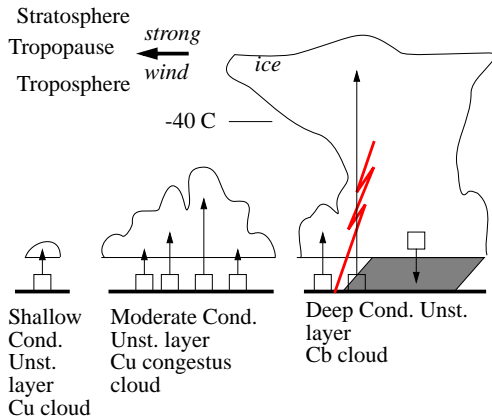


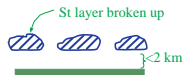
Figure: Houze's cloud atlas: www.atmos.washington.edu/gcg/Atlas/

Schematic of layer clouds

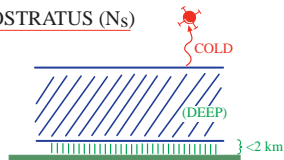
STRATUS (St)



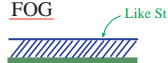
STRATOCUMULUS (Sc)



NIMBOSTRATUS (Ns)



FOG



Steam Fog



Figure: Houze's cloud atlas

Schematic of mid-level clouds

MIDDLE CLOUDS (bases 2 - 7 km A.G.)

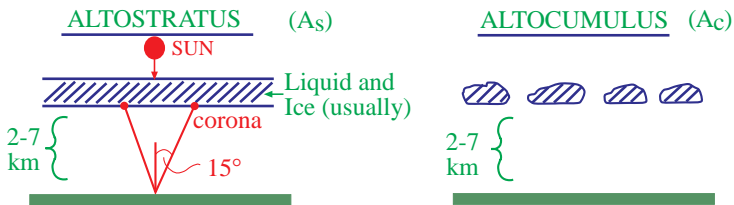


Figure: Houze's cloud atlas

Schematic of cirrus clouds

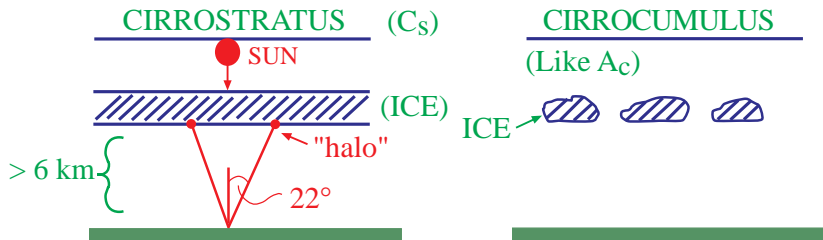


Figure: Houze's cloud atlas



Alto cumulus castellanus (Houze): gray or white broken sheets, elements, bands, rounded masses



Stratus (Karlsruher Wolkenatlas: <http://www.wolkenatlas.de/wolken>):
very low, gray, uniform layer (sun outline very distinct when visible)



Cumulus humilis (Karlsruhe): white, detached, dense elements with shape outlines and vertical growth



Cirrocumulus stratiformis with cumulus humilis (Karlsruhe): thin, white sheet or patch without shading composed of very small ripples, grains



Nimbostratus praecipitatio (Karlsruhe): gray, dark, diffuse, uniform cloud with steady precipitation



Cirrostratus with 22 °halo (Karlsruhe): thin, white, translucent veil either fibrous or smooth in appearance (halo)



Cumulonimbus praecipitatio (Karlsruhe): very deep, dense and precipitating with flattened top



Stratocumulus (Karlsruhe): low, gray-white, patch or layer with elements, rolls or rounded masses



Cirrus uncinus (Karlsruhe): detached, white, filaments or patches with fibrous appearance or silky sheen



Cumulus mediocris (Karlsruhe): cumulus of moderate vertical development (cauliflower)



Altostratus (Houze): uniform or striated gray/blue sheet (no halo but sun behind grounded glass)



Banner cloud (Houze): A cloud plume often observed to extend downwind from isolated, sharp, often pyramid-shaped mountain peaks, even on otherwise cloud-free days

Schematic of banner clouds

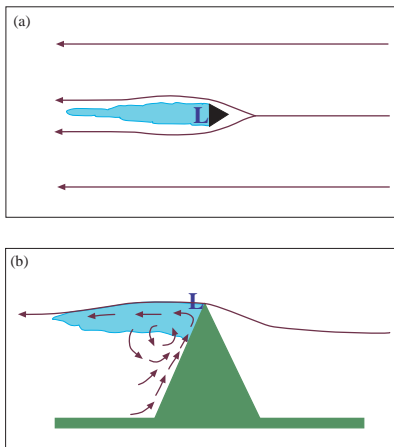


Figure: Houze's cloud atlas



Fog (Houze): Water droplets suspended in the atmosphere in the vicinity the earth's surface that affect visibility



Contrail (Karlsruhe): A cloud like streamer frequently observed to form behind aircraft flying in clear, cold, humid air



Smog (Karlsruhe): Originally a natural fog contaminated by industrial pollutants, a mixture of smoke and fog; today more generally air pollution accompanied with visibility reduction

Cloud formation

- ▶ need to increase $RH = e/e_s$ until 100% RH is reached
 - ▶ decrease temperature (e_s): adiabatically or non-adiabatically
 - ▶ increase e : evaporation, mixing, diffusion
- ▶ fog (cloud at surface): cooling due to radiation or mixing (2% of cloud formation)
- ▶ Expansion and lifting, cooling along the dry adiabat (98% of cloud formation)
- ▶ lifting condensation level (LCL): The level at which a parcel of moist air lifted dry-adiabatically would become saturated. → cloud base
- ▶ Level of free convection (LFC): The level at which a parcel of air lifted dry-adiabatically until saturated and saturation-adiabatically thereafter would first become warmer than its surroundings in a conditionally unstable atmosphere.

Cloud formation

- ▶ Except for Cu and Cb, all clouds need large-scale lifting (expansion and cooling)
- ▶ Cu and Cb have prerequisite to reach LFC and lift above it by its condensational warming → CAPE
- ▶ Fog is mainly caused by radiative cooling most often during early mornings of autumn and spring. Night without clouds cool more radiatively so that air is quickly saturated → fog (radiation fog). Usually not a large vertical extent, thus fast dissipation due to solar radiation during day.
- ▶ Fog above the surface cannot be destroyed easily due to radiative cooling from cloud top and no heating from below → can last very long.