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Atmospheric Physics

Thermodynamics, Clouds and Precipitation

Ulrike Lohmann and
Marc Wüest

ETH Zürich
Institut für Atmosphäre und Klima

ETH, Oct 26, 2005

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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

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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

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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)

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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.

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Global mean energy budget

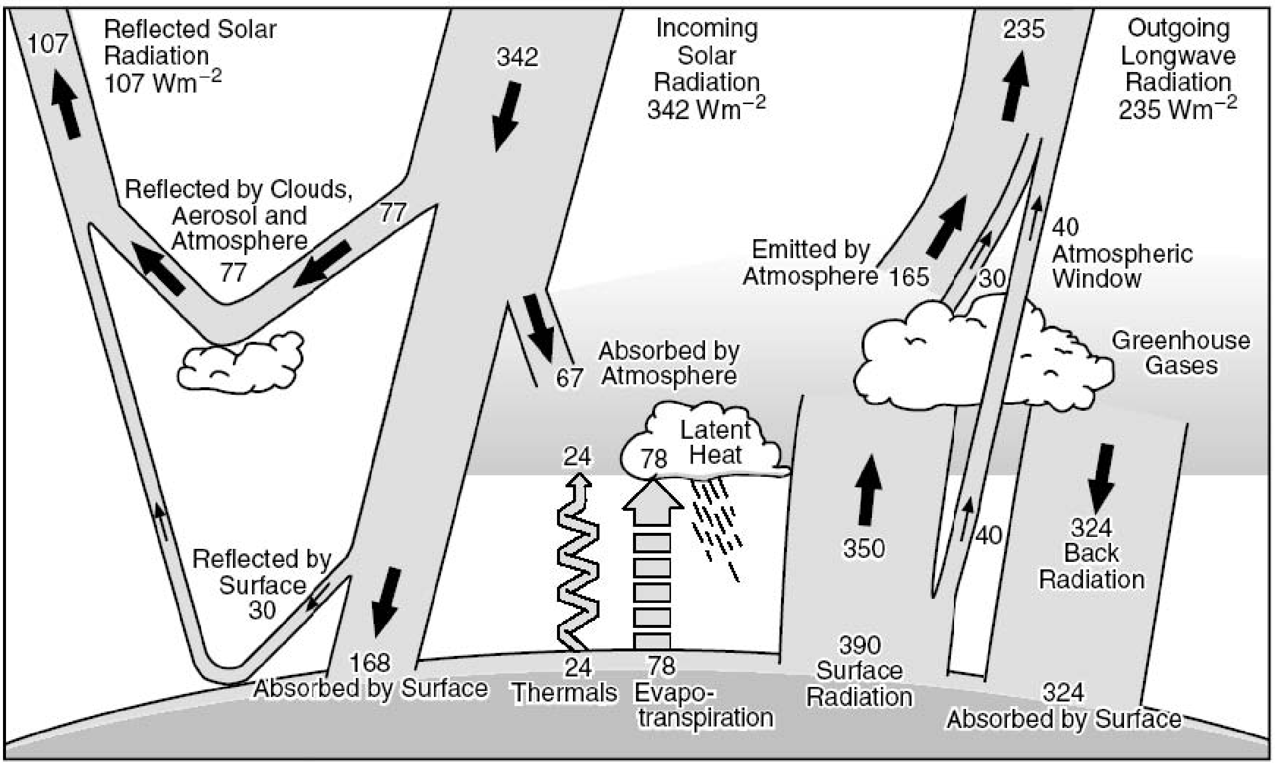


Figure: Kiehl and Trenberth, BAMS, 1997

Motivation

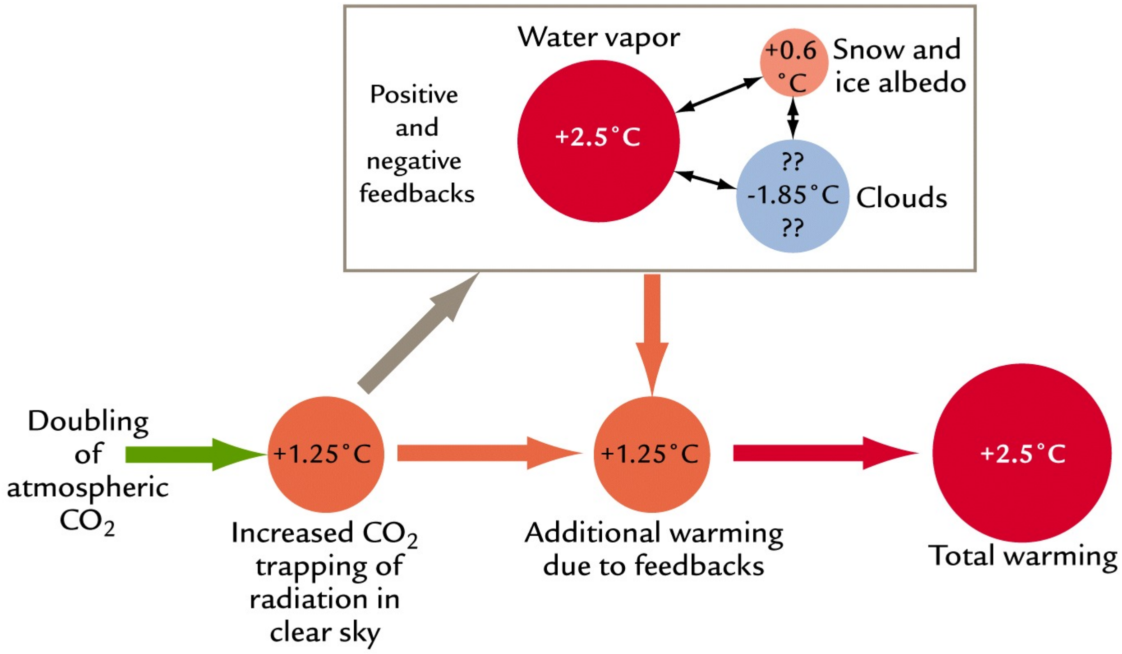


Figure: Components of 2xCO_2 warming, from Ruddiman [2001]

Mean total cloud amount 1983-2001

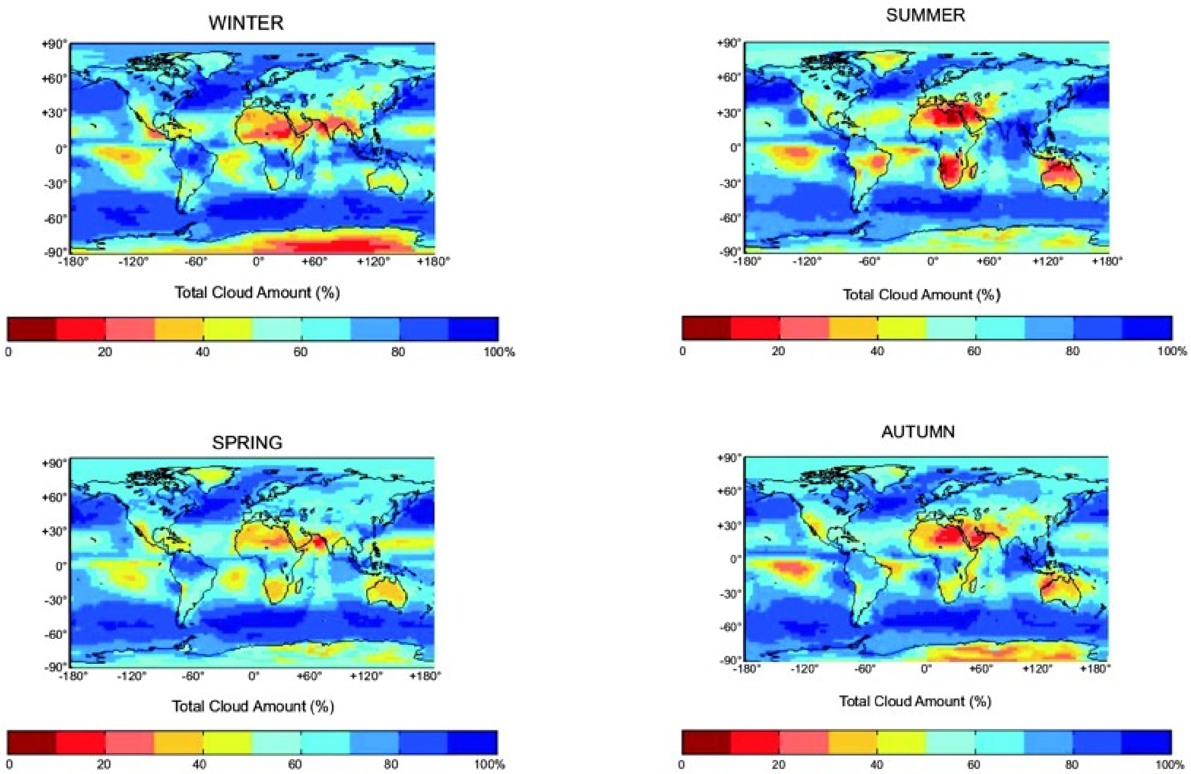
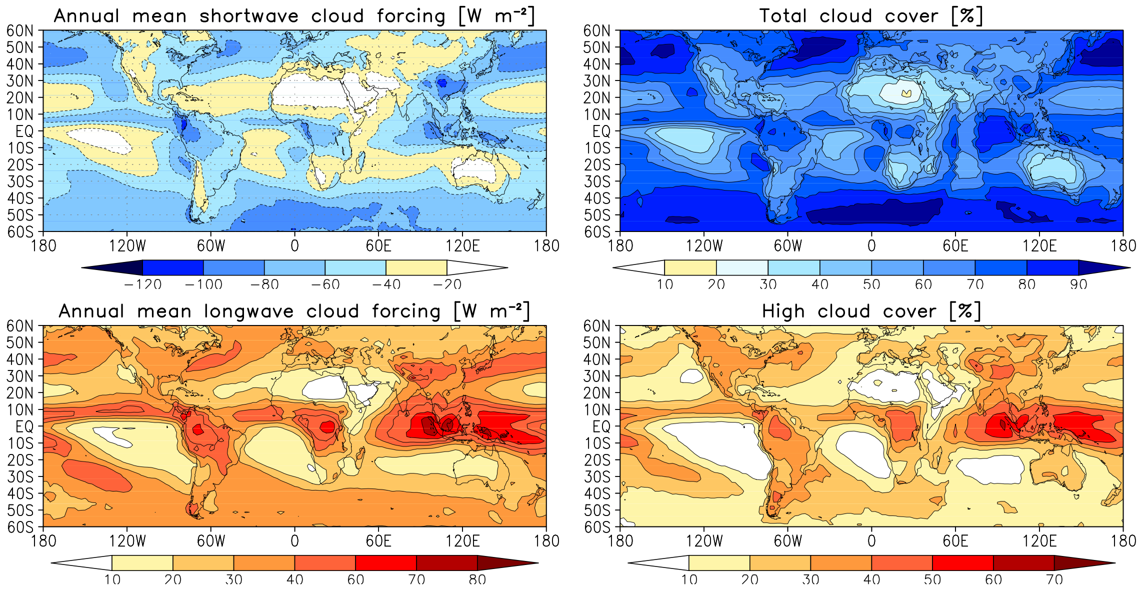


Figure: International Cloud Climatology Program

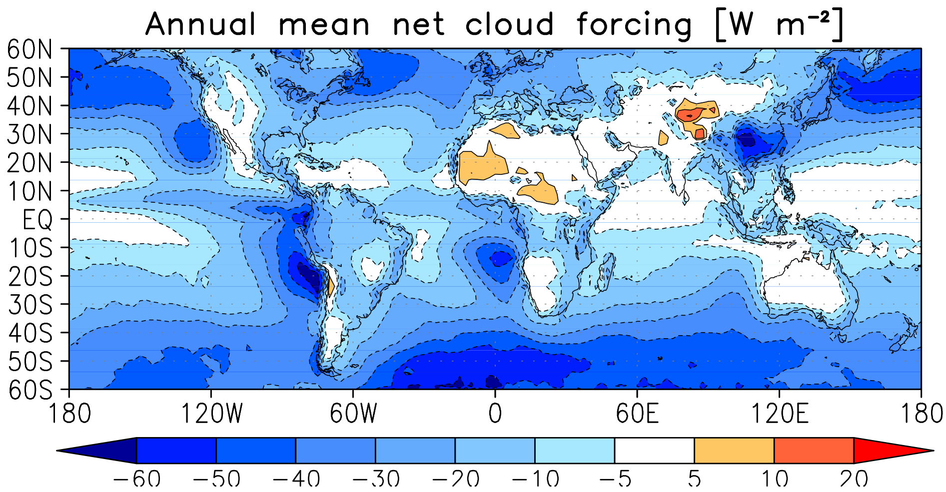
Geographic distribution of the "cloud forcing"



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

Outline | Importance | Cloud types | Individual clouds | Cloud formation

Geographic distribution of the "cloud forcing"



Global mean values:

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

Hydrological cycle

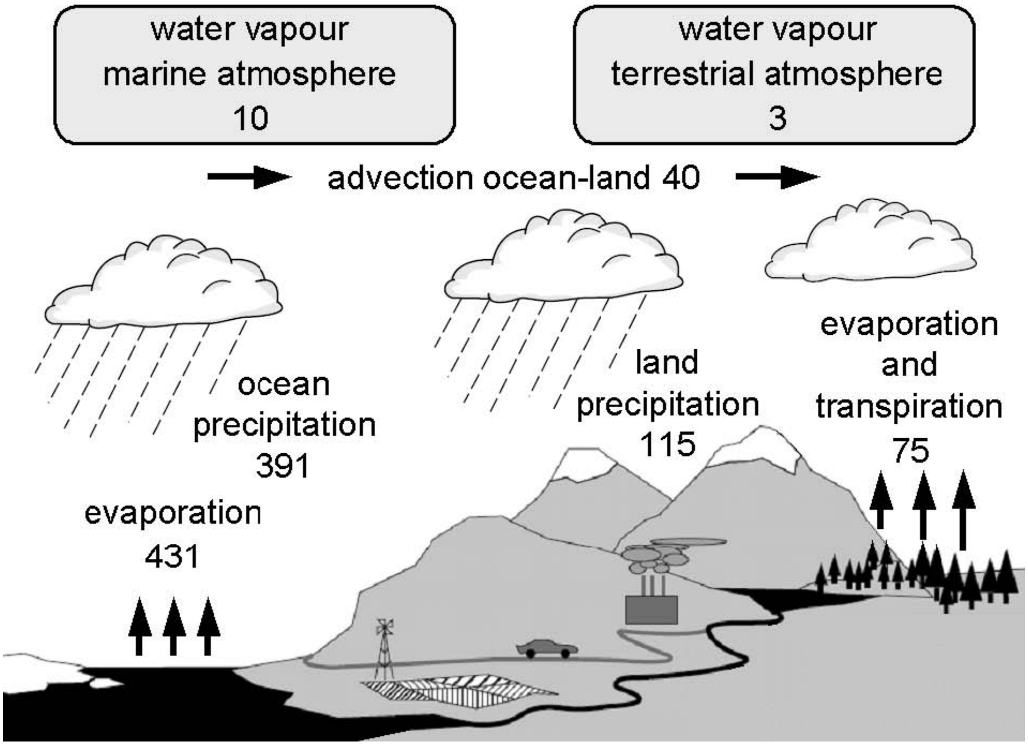


Figure: Quante, J. Phys IV, 2004

Mean total precipitation 1979-2001

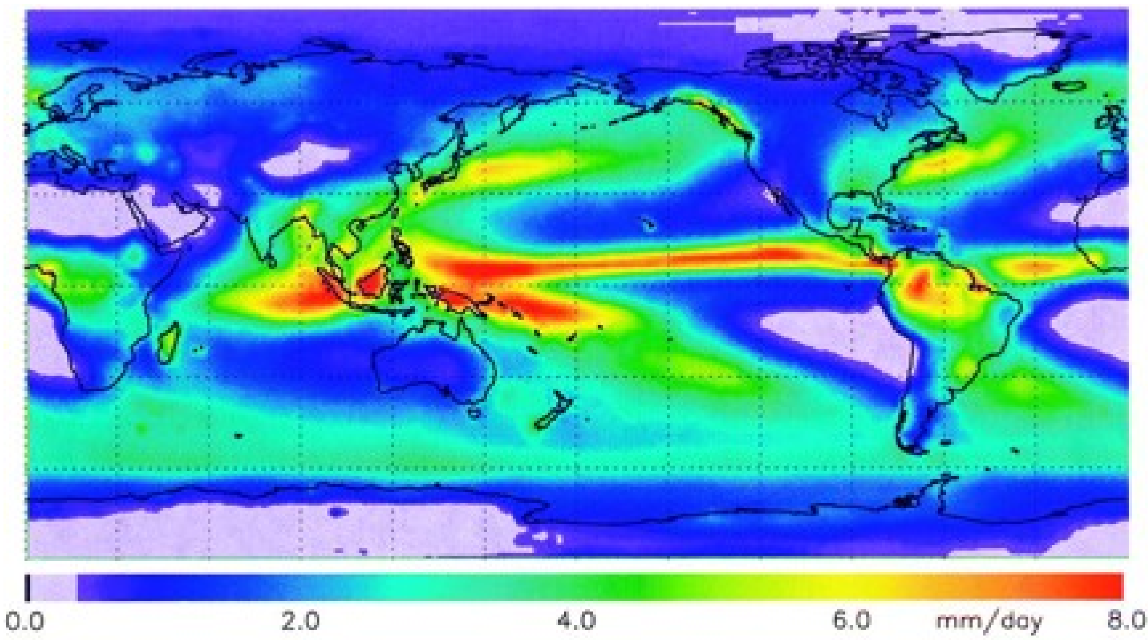


Figure: Global Precipitation Climatology Project

Seasonal variation in total precipitation

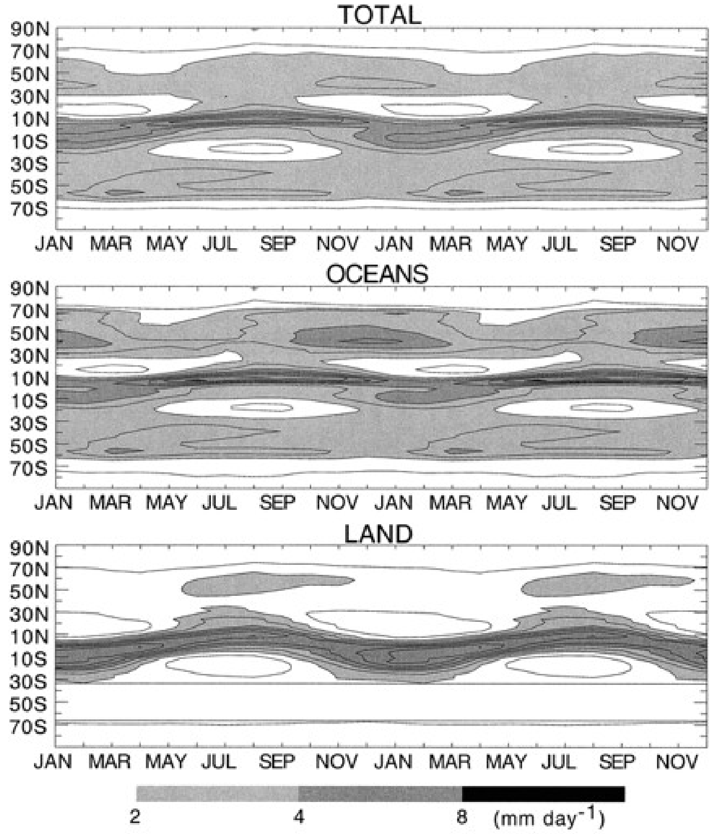


Figure: Adler et al., 2003

Time series of total precipitation

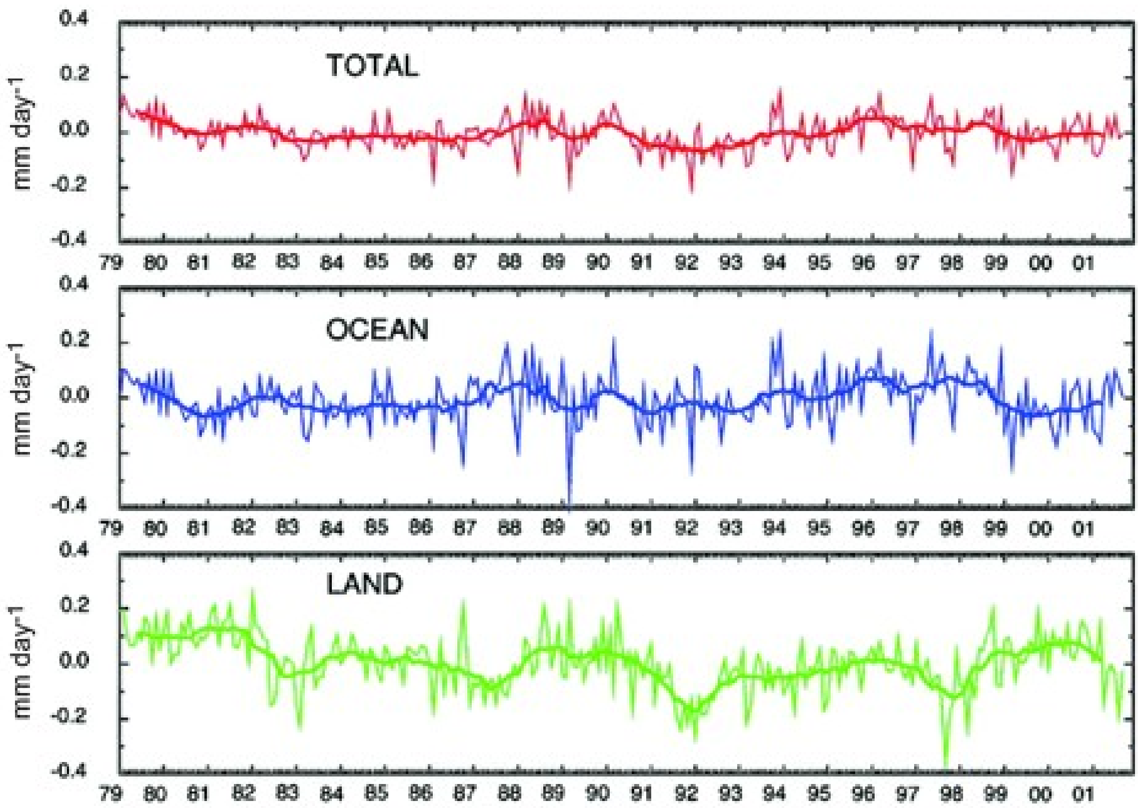


Figure: Adler et al., 2003

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 km[1]): St, Sc
- Mid level clouds (2-7 km): As, Ac
- High altitude ice clouds (7-16 km): Ci, Cs, Cc

[1] heights refer to mid latitudes

Outline Importance Cloud types Individual clouds Cloud formation

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Annual average cloud amounts [%] from surface observations

<table>
<tr><th>Cloud type</th><th>Land</th><th>Ocean</th></tr>
<tr><td>Stratus</td><td>5</td><td>11</td></tr>
<tr><td>Stratocumulus</td><td>12</td><td>22</td></tr>
<tr><td>Cumulus</td><td>5</td><td>12</td></tr>
<tr><td>Cumulonimbus</td><td>4</td><td>4</td></tr>
<tr><td>Nimbostratus</td><td>5</td><td>6</td></tr>
<tr><td>Altostratus</td><td>4</td><td rowspan="2">22</td></tr>
<tr><td>Altocumulus</td><td>17</td></tr>
<tr><td>Cirrus</td><td>22</td><td>13</td></tr>
</table>

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

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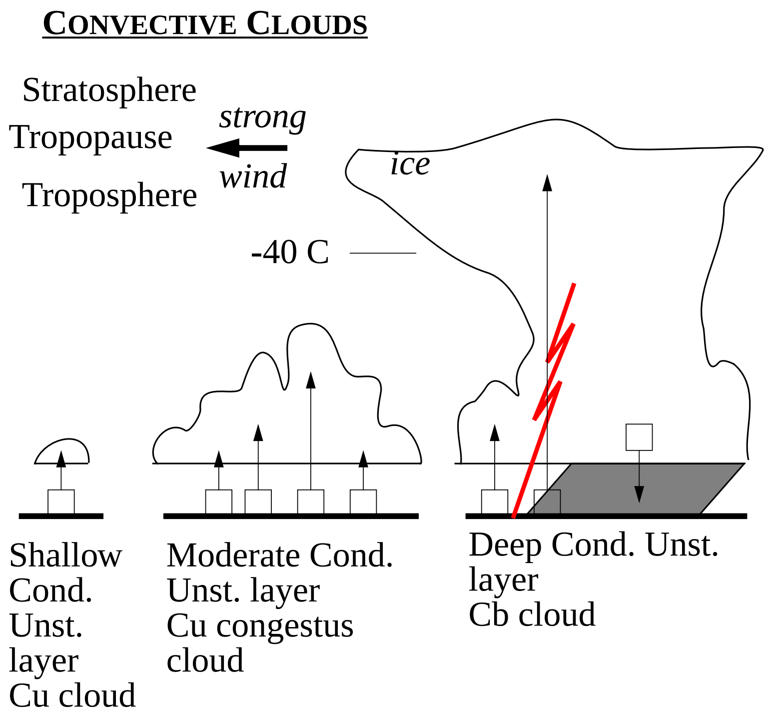

Figure: Houze's cloud atlas: *www.atmos.washington.edu/gcg/Atlas/*

Schematic of layer clouds

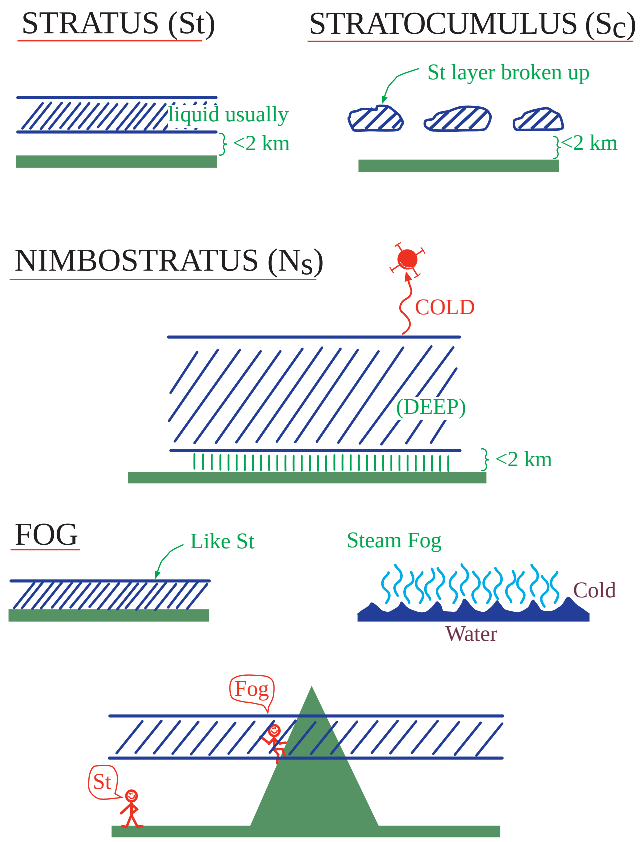

Figure: Houze's cloud atlas

Schematic of mid-level clouds

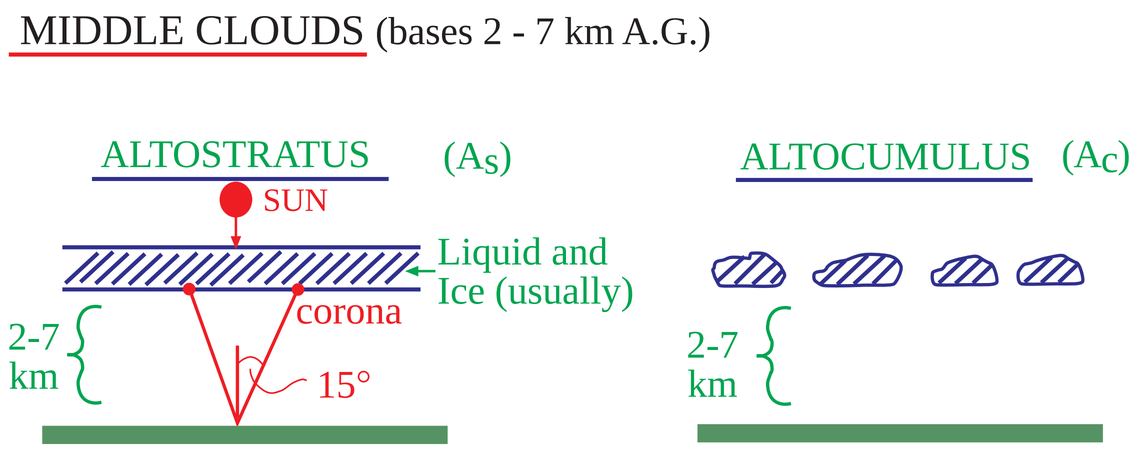

Figure: Houze's cloud atlas

Schematic of cirrus clouds

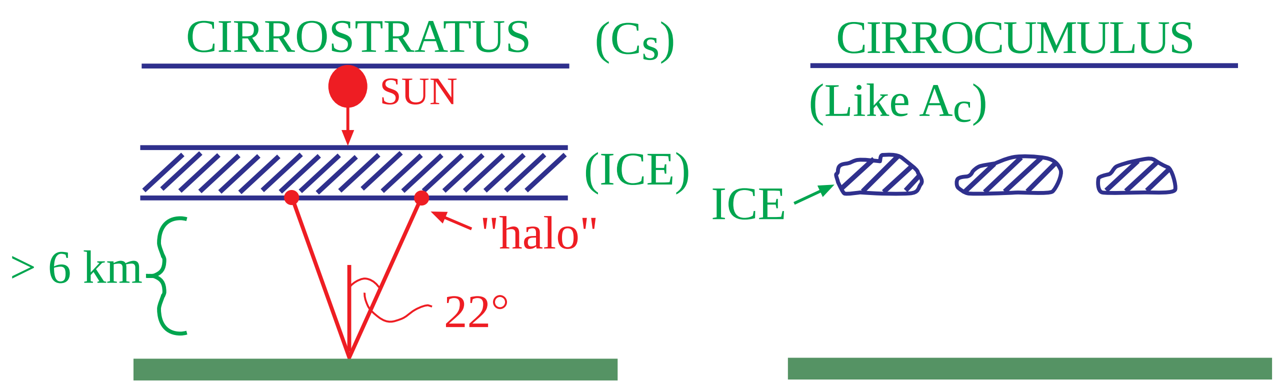

Figure: Houze's cloud atlas

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

Outline Importance Cloud types Individual clouds Cloud formation

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

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

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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

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

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

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

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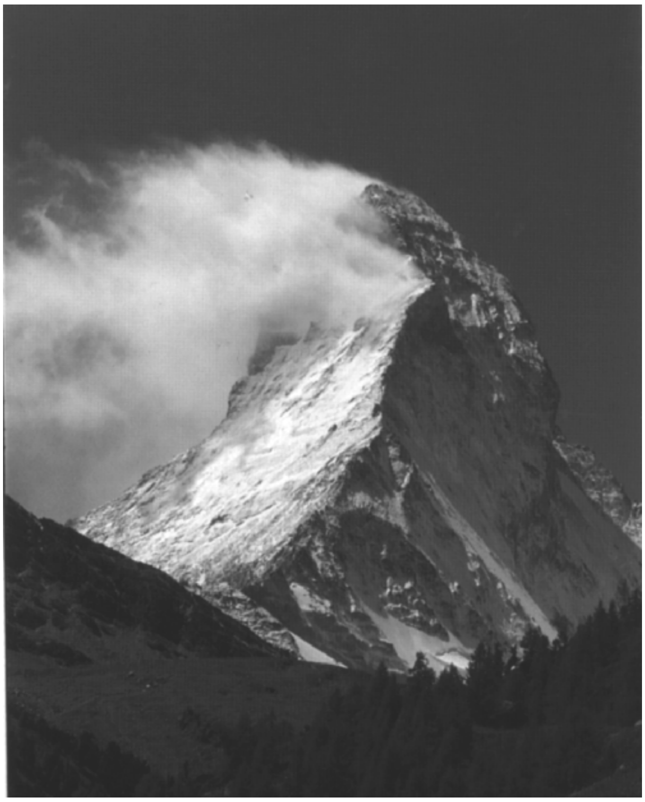
Cirrus uncinus (Karlsruhe): detached, white, filaments or patches with fibrous appearance or silky sheen

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

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Schematic of banner clouds

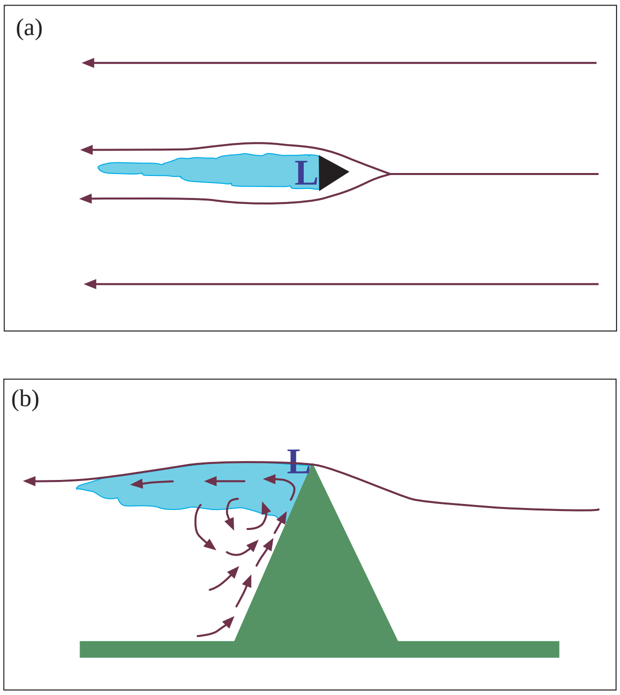

Figure: Houze's cloud atlas

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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

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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

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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.

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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 it's 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.