Lecture 2. An introductory survey: Building a "big" picture.

Outline:

1. The hydrological cycle.
2. Types of clouds.
3. Types of precipitation.
4. Impacts of aerosols on the Earth system.

Recommended reading:

Hydrological cycle:

http://ga.water.usgs.gov/edu/watercycle.html

Climatology of clouds:

Warren S.G. and Hahn C.J., Clouds/Climatology, in: Encyclopedia of Atmospheric Sciences (Eds. J.R. Holton, J.A. Curry, and J.A. Pyle), Academic Press, pp.476-483, 2002.

Hahn, C.J., W.B. Rossow, and S.G. Warren, 2001: ISCCP cloud properties associated with standard cloud types identified in individual surface observations. J. Climate., 14, 11-28.

The Global Precipitation Climatology Project (GPCP)

http://cics.umd.edu/~yin/GPCP//main.html

Aerosols:

Lohmann, U., and J. Fletcher, Global indirect aerosol effects: A review, Atmos.Chem.Phys., 5, 715-737, 2005.

Rosenfeld D., 2006: Aerosol-Cloud Interactions Control of Earth Radiation and Latent Heat Release. *Space Science Reviews*. Springer, 6 December 2006. 9p., DOI: 10.1007/s11214-006-9053-6

1. The hydrological cycle is an exchange of water between different reservoirs (land, ocean, atmosphere) in the Earth system.

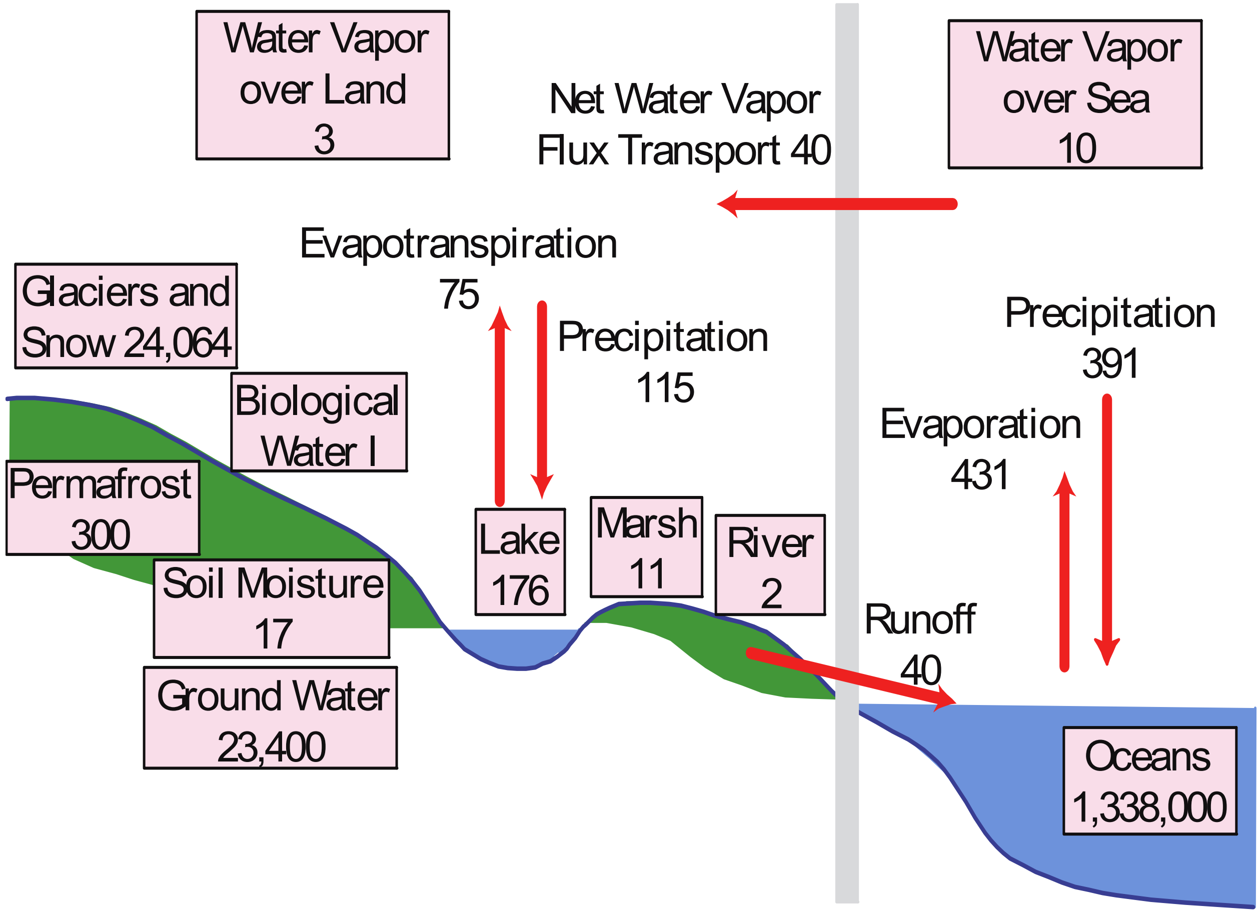


Figure 1. Schematic of the hydrological cycle. The numbers in the boxes are estimates of the total amounts of water in the various reservoirs in units of 10^{15} kg. The numbers alongside the arrows are estimates of average annual fluxes in units of 10^{15} kg/year. From Oki (1999).

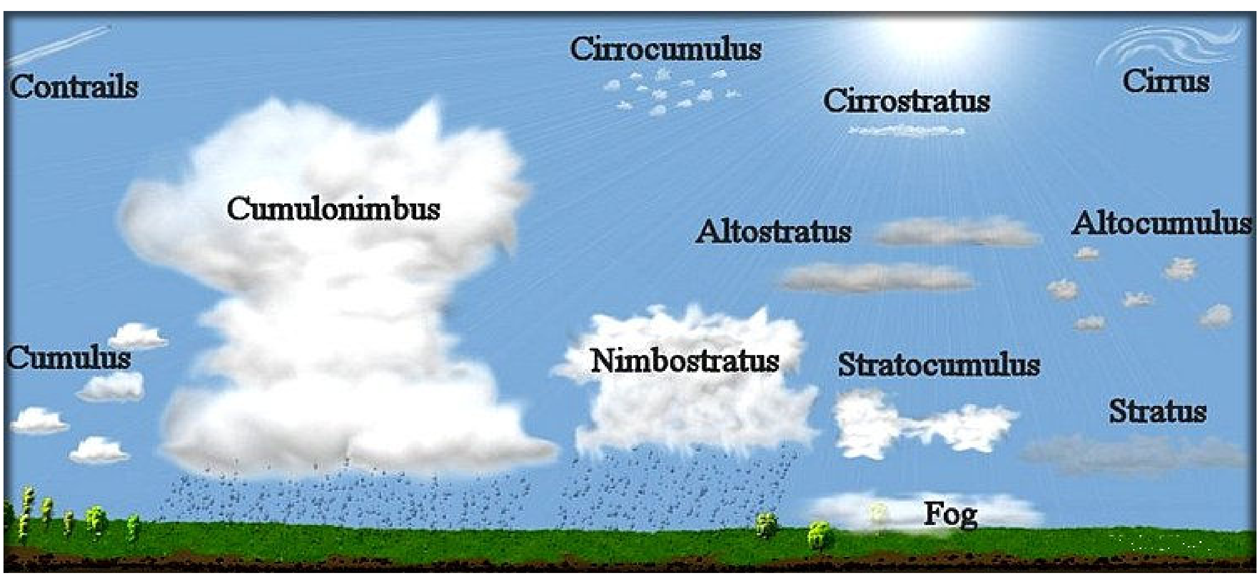
- Atmosphere has a relatively small amount of water (water vapor + precipitation)
- Note unequal amount of precipitation over land and ocean

2. Types of clouds.

Cloud classification from ground-based observations is based on the form and height of clouds.

- Clouds are classified into a system that uses Latin words to describe the appearance of clouds as seen by **an observer on the ground**. The four principal components of this classification system are cumulus (means heap or pile), stratus (layer), cirrus (means a lock of hair) and nimbus (rain). These four words and a word *altum* (means height) are used either separately or in combination to define 10 clouds types, which are organized into three corresponding to the base of clouds above the local height.

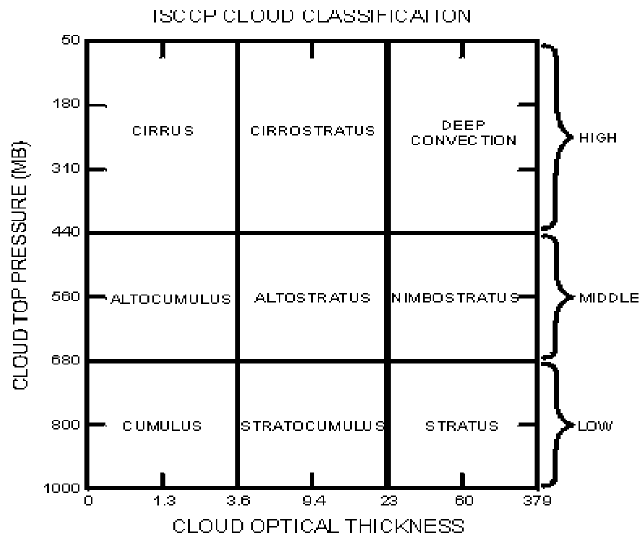
Type	Height	Height of cloud base Polar regions	 Temperate regions	 Tropical regions	Precipitation
Cumulus Cumulonimbus Stratus	Low	Below 2km	Below 2km	Below 2km	Light showers are possible Always reported when showers /thunderstorms/hail occurs Near costs/hills
Nimbostratus Altostratus Altocumulus	Middle	2-4 km	2-7 km	2-8 km	Normally continuous Often continuous Occasionally
Cirrus Cirrostratus Cirrocumulus	High	3-8 km	5-13 km	6-18 km	No



Fog is often considered as a cloud whose base starts at the ground.

Cloud classification used in satellite remote sensing is based on retrieved cloud top pressure and cloud optical depth.

Example: The International Satellite Cloud Climatology Project (ISCCP) http://isccp.giss.nasa.gov/



Satellite vs. ground-based observations of clouds

Type of observation	Advantages	Disadvantages
Ground-based	• direct observations • history (long records) • can often distinguish between cloud types • other complimentary measurements • cost/automatic/frequent observations • provide validation to satellite observations	• non-uniform coverage • human error • multi-layer cloud impacts
Satellite	• global coverage • system consistency • easier to model (radiative transfer codes) • sensitive to vertical structure with potential for vertical resolution	• short lifetime of an individual satellite • difficulty of inter-calibrating instruments on different satellites • problems in distinguishing multi-layered clouds, lower clouds and fog • high cost

3. Types of precipitation.

Means of observations:

- Ground-based: rain gauges and snow gauges (snow is measured as water equivalent). An extensive network of meteorological stations with long-term records.
- Ground-based: radar (relates radar backscattering to rain drop size distributions)
- Satellite:

  Examples: TRMM – Tropical Rainfall Measuring System (sampling footprint between 35°N and 35°S) http://trmm.gsfc.nasa.gov/

  CloudSat http://cloudsat.atmos.colostate.edu/

Types of precipitation and common abbreviations used by meteorologists:

1. ***Rain*** (R, RA)- Rain is liquid precipitation that reaches the surface in the form of drops that are greater than 0.5 millimeters in diameter. The intensity of rain is determined by the accumulation over a given time. Categories of rain are light, moderate and heavy.
2. ***Snow*** (SN, SNW, S)- Snow is an aggregate of ice crystals that form into flakes. Snow forms at temperatures below freezing. For snow to reach the earth's surface the entire temperature profile in the troposphere needs to be at or below freezing. It can be slightly above freezing in some layers if the layer is not warm or deep enough the melt the snow flakes much. The intensity of snow is determined by the accumulation over a given time. Categories of snow are light, moderate and heavy.
3. ***Snow Pellets*** (GS)- A snow pellet is precipitation that grows by supercooled water accreting on ice crystals or snow flakes. Snow pellets can also occur when a snowflake melts about half way then refreezes as it falls. Snow pellets have characteristics of hail, sleet and snow. With sleet (ice pellets), the snowflake almost completely melts before refreezing thus sleet has a hard ice appearance. Soft hail grows in the same way snow pellets can grow and that is ice crystals and supercooled water accreting on the surface. Snow pellets will crush and break apart when pressed. They can bounce off objects like sleet does. Snow pellets have a whiter appearance than sleet. Snow pellets have small air pockets embedded within their structure and have visual remnants of ice crystals unlike sleet. Snow pellets are typically a couple to several millimeters in size.
4. ***Snow Grains*** (SG)- Snow grains are small grains of ice. They do not produce much accumulation and are the solid equivalent to drizzle.
5. ***Ice Crystals*** (IC)- Also called diamond dust. They are small ice crystals that float with the wind.
6. ***Sleet / Ice Pellets*** (PE, PL, IP, SLT)- Sleet (Ice Pellets) are frozen raindrops that strike the earth's surface. In a sleet situation the precipitation aloft when it is first generated will be snow. The snow falls through a layer that is a little above freezing and the snow partially melts. If the snow completely melts it will be more likely to reach the earth's surface as supercooled water instead of sleet. If the snow partially melts there will still be

ice within the falling drop for water to freeze on when the drop falls into a subfreezing layer. The lowest layer of the troposphere will be below freezing in a sleet situation and deep enough to freeze drops completely. The lower boundary layer can be above freezing and sleet occur if the sleet does not have time to melt before reaching the surface.
7. ***Hail*** (GR, A)- Hail is dense precipitation ice that is that least 5 millimeters in diameter. It forms due to ice crystals and supercooled water that freeze or stick to the embryo hail stone. Soft hail is more white and less dense since it has air bubbles. Soft hail occurs when hail grows at a temperature below freezing by ice crystals and small supercooled water and cloud droplets merging onto the hail. Hard hail occurs when liquid water drops freeze on the outer edges of the hailstone after the outer edge is above freezing. The freezing of supercooled water releases latent heat and this can result in the outer edge of the hail stone warming above freezing. Then the water refreezes creating solid ice. Hail will commonly have soft ice and hard ice layers when it is sliced open.
8. ***Graupel*** (GS)- Graupel forms in the same way as hail except the diameter is less than 5 millimeters. It usually grows by soft hail processes.
9. ***Drizzle*** (DZ, L)- Drizzle is liquid precipitation that reaches the surface in the form of drops that are less than 0.5 millimeters in diameter.
10. ***Freezing Drizzle*** (FZDZ, ZL)- Freezing Drizzle is liquid precipitation that reaches the surface in the form of drops that are less than 0.5 millimeters in diameter. The drops then freeze on the earth's surface.
11. ***Freezing Rain*** (FZRA, ZR)- Freezing Rain is liquid precipitation that reaches the surface in the form of drops that are greater than 0.5 millimeters in diameter. The drops then freeze on the earth's surface.
12***. Freezing Fog*** (FZFG)- Freezing fog is a fog composed of supercooled water drops. These drops freeze just after they wet the earth's surface.
13. ***Mixed Precipitation*** (MXD PCPN)- The combination of two or more winter precipitation types occurring at the same time or over a period of time at the same place.

Two basic precipitation generation types: dynamic precipitation and convective precipitation.

Dynamic precipitation (also known as stratiform precipitation) results from a forced lifting of air. These forcing mechanisms include processes that cause low level convergence and upper level divergence. As unsaturated air rises the relative humidity of the air will increase. Once the air saturates, continued lifting will produce clouds and eventually precipitation. Dynamic precipitation tends to have a less intense rain rate than convective precipitation and also tends to last longer.

Convective precipitation is also known as thermodynamic precipitation. While dynamic precipitation only needs saturated air and lift, convective precipitation requires an additional component called instability. Uplift due to instability release occurs when the air rises on its own after being lifting to a certain point in the troposphere. Instability is commonly assessed by examining the Lifted Index (LI) and CAPE (Convective Available Potential Energy). Both these indices can be used to assess the acceleration rate of air once air from the lower troposphere is brought to a level in the troposphere where it will rise on its own due to positive buoyancy. Instability causes the air to rise much faster than it would by forced lifting alone. Think of convective precipitation as falling from thunderstorms with strong updrafts while dynamic precipitation falls from a deck of stratus clouds. Convective precipitation tends to have lighting, thunder and heavy rain while dynamic precipitation is more of a gentle long lasting rain with no lightning and thunder.

Two mechanisms of the formation of precipitation: ice crystal process and collision-coalescence process.

Ice crystal process (mainly in cold clouds): When ice crystals and supercooled water droplets coexist in a cloud, ice crystals collect the available water vapor at a much faster rate than liquid water. Thus, ice crystals grow larger at the expense of water droplets. Eventually, this process generates ice crystals large enough to fall as snowflakes.

Collision-coalescence process (mainly in warm clouds): The bigger droplets fall faster, they collide and join with smaller water droplets. After many collisions the droplets are large enough to fall to the grounds as rain.

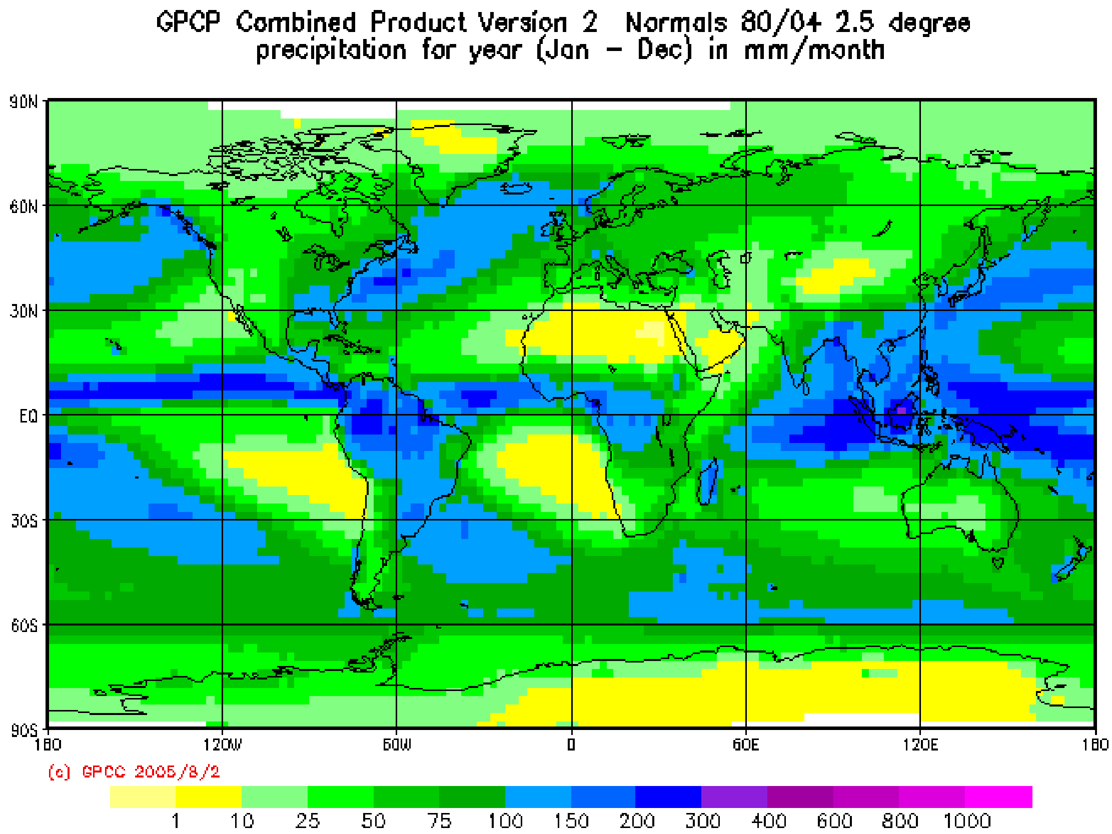


Figure 2. Mean annual global precipitation for Jan-Dec for 1980-2004. Data from the ***Global Precipitation Climatology Project*** (**GPCP**) that was established *by the* World Climate Research Program *(WCRP) in 1986 with the goal of providing mo*nthly mean precipitation data on a 2.5 x 2.5 degree latitude-longitude grid for the period 1980-2004.

The average annual precipitation of the entire surface of our planet is estimated to be about 1050 millimeters per year or approximately 88 millimeters per month. Actual values vary spatially from less than 10 millimeters per month or to a maximum of more than 300 millimeters per month depending on location. The reasons for these patterns are as follows:

- The deserts in the subtropical regions (but not all) occur because these areas do not contain any mechanism for lifting air masses. In fact, these areas are dominated by subsiding air that results from global circulation patterns.
- Continental areas tend to be dry because of their distance from moisture sources.

- Polar areas are dry because cold air cannot hold as much moisture as warm air.
- Areas near the equator achieve high rainfall amounts because constant solar heating encourages convection, and global circulation patterns cause northern and southern air masses to converge here causing frontal lifting.
- Mid-latitudes experience cyclonic activity and frontal lifting when polar and subtropical air masses meet at the polar front. Further, the air masses in this region generally move from West to East, causing levels of precipitation to decrease East of source regions.
- Mountain ranges near water sources can receive high rainfalls because of orographic uplift, if and only if the prevailing winds are in their favor. This can also result in a sharp reduction in rainfall in regions adjacent or on the leeward slopes of these areas. This phenomenon is commonly know as the rainshadow effect.

4. Impacts of aerosols on the Earth system.

Direct radiative impacts

IMPACT	IMPORTANCE
Top of the atmosphere (TOA) radiative forcing (solar plus IR)	affects energy balance of the Earth's climate system
Radiative forcing at the surface (solar plus IR)	affects surface temperature and surface-air exchange processes, ecosystem functioning
Radiative heating/cooling of atmospheric layers (solar plus IR)	affects temperature profile, cloud lifetime, and atmospheric dynamics thermodynamics
Actinic flux (UV)	affects photolysis rates and photochemistry

Indirect radiative impacts (via clouds)

Lohmann and Feichter (2005)

Table 1. Overview of the different aerosol indirect effects and range of the radiative budget perturbation at the top-of-the atmosphere (F_{TOA}) [W m^{-2}], at the surface (F_{SFC}) and the likely sign of the change in global mean surface precipitation (P) as estimated from Fig. 2 and from the literature cited in the text.

Effect	Cloud type	Description	F_{TOA}	F_{SFC}	P
Indirect aerosol effect for clouds with fixed water amounts (cloud albedo or Twomey effect)	All clouds	The more numerous smaller cloud particles reflect more solar radiation	−0.5 to −1.9	similar to F_{TOA}	n/a
Indirect aerosol effect with varying water amounts (cloud lifetime effect)	All clouds	Smaller cloud particles decrease the precipitation efficiency thereby prolonging cloud lifetime	−0.3 to −1.4	similar to F_{TOA}	decrease
Semi-direct effect	All clouds	Absorption of solar radiation by soot may cause evaporation of cloud particles	+0.1 to −0.5	larger than F_{TOA}	decrease
Thermodynamic effect	Mixed-phase clouds	Smaller cloud droplets delay the onset of freezing	?	?	increase or decrease
Glaciation indirect effect	Mixed-phase clouds	More ice nuclei increase the precipitation efficiency	?	?	increase
Riming indirect effect	Mixed-phase clouds	Smaller cloud droplets decrease the riming efficiency	?	?	decrease
Surface energy budget effect	All clouds	Increased aerosol and cloud optical thickness decrease the net surface solar radiation	n/a	−1.8 to −4	decrease

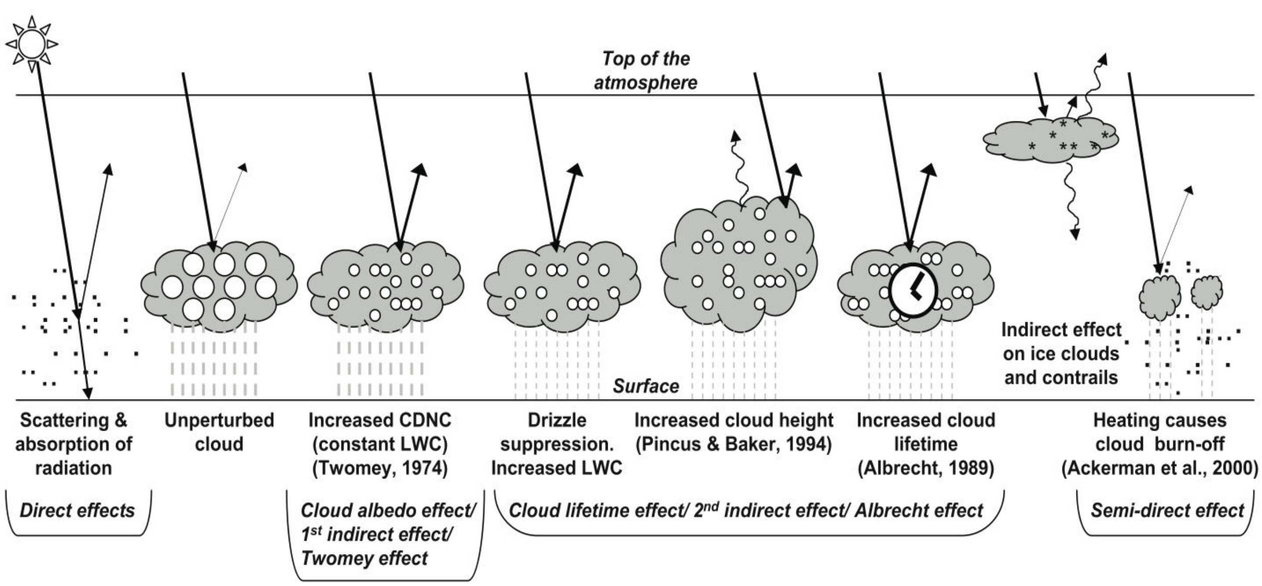


Figure 3. Schematic diagram showing the different radiative mechanisms associated with cloud effects. The small black dots represent aerosol particles; the larger open circles cloud droplets. Straight lines represent the incident and reflected solar radiation, and

wavy lines represent terrestrial radiation. The filled white circles indicate cloud droplet number concentration (CDNC). The unperturbed cloud contains larger cloud drops as only natural aerosols are available as cloud condensation nuclei, while the perturbed cloud contains a greater number of smaller cloud drops as both natural and anthropogenic aerosols are available as cloud condensation nuclei (CCN). The vertical grey dashes represent rainfall, and LWC refers to the liquid water content (modified from Haywood and Boucher, 2000, IPCC, 2007).

Suggested impacts on the hydrological cycle (via clouds and precipitation and/or surface evaporation)

Aerosol particles can either promote or suppress precipitation – depends on aerosol type as well as other factors.