Climate Lecture 5

The Role of Clouds in Climate

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Introduction

David Rind has played a central role in the science of the modeling of climate change. He was the scientific driving force behind the development and evaluation of the first Goddard Institute for Space Studies (GISS) global climate model (GCM), 'Model II' (Hansen *et al*., 1983). Model II was one of the three original GCMs whose projections of climate change in response to a doubling of CO_2 concentration were the basis for the influential Charney Report that produced the first assessment of global climate sensitivity. David used Model II to pioneer the scientific field of climate dynamics, performing a broad range of investigations of processes controlling individual elements of the general circulation and how they changed over a wide range of past and potential future climates (e.g., Rind and Rossow, 1984; Rind, 1986, 1987). The defining characteristic of David's papers is his unique talent for tracking down the myriad links and causal chains among different parts of the nonlinear climate system. Rather than viewing climate using a simple forcing-and-response paradigm, David showed that the global energy, water, and even momentum cycles are coupled via the general circulation and its transports.

Clouds are among the most important agents by which the climate system accomplishes this coupling. Clouds usually form when moist air rises to lower pressure, adiabatically expands and cools, and saturates. The resulting condensation of water vapor releases latent heat, and the clouds that form reflect sunlight and absorb thermal infrared radiation. For the planet as a whole, clouds are the major contributor to Earth's planetary albedo and thus the primary regulator of the energy input to the Earth system. The greenhouse effect of clouds is second only to water vapor as the means by which thermal cooling of Earth to space is limited.

Cloud formation occurs in two fundamentally different ways. Moist convective clouds require conditional instability, that is, a lapse rate that exceeds the moist adiabatic lapse rate. When instability is present and the atmosphere is sufficiently humid, convective clouds are triggered when (1) lifting due to surface turbulence or other sources saturate air, (2) the latent heat release is sufficient to overcome a stable inversion layer above, making the air parcel buoyant relative to its surroundings and allowing it to rise on its own. When the atmosphere is not convectively unstable, stratiform clouds can occur, usually due to lifting by other phenomena (e.g., frontal uplift, other wave motions, boundary layer turbulence) that produces saturated but not buoyant air or occasionally by other sources of cooling of moist air (radiative or contact with a cooler surface). Thus in satellite images, clouds are tracers of the different character of the general circulation in different regions and the way in which the circulation links the global energy and water cycles—a visible reminder of David Rind's life's work. Convective and stratiform clouds play largely different, though partly overlapping, roles in the climate system. Convective cloud systems produce much of the precipitation on Earth and transport heat and moisture upward. Stratiform clouds produce less precipitation but most of the cloud radiative effect on Earth.

Deep convective clouds cool the surface and boundary layer, warm and dry the mid-troposphere, and moisten the upper troposphere. Shallow fair weather cumulus clouds tend to produce little or no precipitation but are important because they transport water evaporated from the ocean surface into the free troposphere. Shallow cumulus clouds are frequent enough to reflect a non-negligible amount of sunlight. Deep convective clouds are infrequent and radiatively unimportant by comparison, but they inject large amounts of water vapor and ice into the upper troposphere, forming extensive shields of stratiform cirrostratus 'anvil' clouds and ubiquitous thinner cirrus clouds (Liao, Rossow and Rind, 1995a, 1995b) that are very important radiatively. These extensive cloud decks, convectively generated but not convective themselves, produce the visible appearance of the Intertropical Convergence Zone (ITCZ), an irregular band of cloudiness that circles the equatorial region, in satellite images. This comprises the rising branch of the Hadley and Walker cells. The sinking branch of the Hadley and Walker cells creates an inversion layer at the top of the boundary layer, suppressing the development of deep clouds. Over land this is responsible for the major subtropical deserts, while over ocean, it leads to broken fields of shallow cumulus over the open subtropical oceans and solid decks of stratocumulus in the eastern oceans, where boundary layer turbulence lifts air to its condensation level but not above the inversion.

Shallow cumulus and stratocumulus clouds also occur in the mid-latitudes, in 'cold air outbreaks' behind the cold fronts associated with synoptic baroclinic storms. The major mid-latitude cloud features, though, are the stratiform 'comma clouds' that form along cold fronts and warm fronts and in the cold 'conveyor belt' of rising motion that wraps around the north side of low-pressure centers. These spiral-like features are made of cirrus, altostratus, altocumulus, and precipitating nimbostratus clouds, and they tend to occur in a wave-like sequence of 5–6 storms around the latitude belt. At even higher latitudes, the water transported poleward in frontal regions or evaporated from the open ocean moistens the polar low-level atmosphere and forms stratus cloud decks that emit longwave (LW) radiation down to the surface and play a role in the seasonal melting of sea ice. In the absence of such clouds, the sea-ice surface radiates 40–50 W/m^2 of heat to the atmosphere to maintain itself against melting.

Once formed, clouds evolve according to the microphysical processes that occur on the scale of individual liquid droplets or ice crystals. The pathways are somewhat different for liquid and ice but they share some things in common. We consider the simpler liquid case first. Excess vapor, usually formed in rising air at a rate τ_*^{-1}, condenses liquid water onto small particles called cloud condensation nuclei to form small cloud droplets at a rate τ_{cond}^{-1} (where τ represents a characteristic time scale of a given process). Droplets may be supplied or removed by transport from or to other locations, or by local evaporation when dynamical processes cause dry air to enter the region. Cloud droplets grow by coalescence, that is, gravitational settling of larger droplets relative to smaller droplets that produces collisional growth into raindrop sizes (10s–100s of microns) at a rate τ_{growth}^{-1}. Drops that reach a size such that their fall speeds exceed the vertical velocity of the updraft fall from the cloud as precipitation at a rate τ_{fall}^{-1} and eventually evaporate at the rate τ_{evap}^{-1} into smaller droplets and then vapor again, completing the lifecycle. Ice crystals display a similar lifecycle but in a more complex fashion, since they can form and grow not only by vapor deposition onto ice nuclei but also by contact of ice nuclei with supercooled droplets, freezing of small liquid haze droplets at very cold temperatures, and by the diffusion of water vapor from nearby evaporating liquid droplets. Growth by diffusion (the Bergeron–Findeisen process) is responsible for producing many of the large particles that lead to heavy precipitation (snow, or 'cold' rain from snow crystals that melt as they fall).

The net effect of the fractional coverage, frequency of occurrence, top altitude, and optical thickness (the combined result of the amount of liquid and ice, the physical thickness, and the droplet or crystal size) determines the magnitude of the effect of clouds on the Earth's planetary energy balance (i.e., the balance at the top of the atmosphere between sunlight absorbed and heat emitted to space). This is quantified by the concept of cloud forcing, the difference between how much radiation heats the Earth and how much it would heat a hypothetical Earth with no clouds. The shortwave (SW, sunlight) component of cloud forcing is negative, because clouds are brighter than most of the rest of the Earth and reflect more sunlight, cooling the Earth. The longwave (LW, Earth's radiated heat) component is positive because the greenhouse effect of clouds (mostly high altitude clouds) adds to the warming caused by greenhouse gases. This occurs because in the absence of clouds, the Earth emits heat to space primarily from the moderately warm middle troposphere, where the water vapor concentration starts to become small enough for LW photons to escape to space. High clouds prevent that from occurring, and radiation to space occurs instead from near the colder top of the cloud, and thus less heat is emitted.

The net cloud forcing varies geographically because different cloud types occur in different regions. Overall, net cloud forcing is negative because the SW cooling exceeds the LW warming, that is, on balance, the Earth is cooler with than without clouds. The largest negative SW cloud forcing occurs in the places where optically thick precipitating clouds are prevalent over a dark ocean: the ITCZ and the mid-latitude storm tracks. The largest positive LW cloud forcing also occurs over the ITCZ because of high altitude tropical anvils and cirrus clouds, and to a lesser extent in the nimbostratus clouds of the mid-latitude storm tracks. The SW and LW forcing largely compensate each other in the ITCZ and to a lesser extent in the storm tracks. The largest negative net cloud forcing occurs in the stratocumulus decks over the cold eastern tropical/subtropical oceans, where SW forcing is large and LW forcing is almost non-existent because of these clouds' low altitude.

By itself cloud forcing tells us nothing about the role of clouds in climate change. How clouds respond to increases in greenhouse gas concentrations or any other external forcing agent (e.g., changing solar luminosity, volcanic, or anthropogenic aerosols) is the biggest scientific uncertainty in projections of future climate change. It has often been assumed that because more water evaporates into the atmosphere as the oceans warm, cloud cover will increase with warming and clouds will have more liquid water and become optically thicker, providing a negative feedback that would mitigate much of the climate change. These assumptions are however inconsistent with what GCMs actually predict and/or what is observed, and these feedbacks in any case tell only part of the story. Cloud feedbacks consist of five components:

1. *Cloud cover feedback*: Changes in cloud cover depend on changes in both water vapor concentration (specific humidity) and temperature, since the latter determines the saturation vapor pressure, that is, the upper limit for water vapor in equilibrium over a flat surface of liquid water at a given temperature. Thus, *relative* humidity, the ratio of specific to saturation humidity, is the controlling factor for cloud cover, and relative humidity itself is controlled by the dynamics of the atmosphere on large and small scales.
2. *Cloud height feedback*: Higher cloud tops reduce outgoing LW radiation relative to the emission change without this cloud effect. An early one-dimensional radiative–convective model study in which David Rind participated (Hansen *et al*., 1981) demonstrated this feedback for the case in which cloud top temperature is fixed with warming but rises to higher altitude. In this case, the initial reduction in emission due to the higher colder cloud top causes the new emission level to warm to the temperature of the previous emission level to re-establish radiative balance. Extrapolating this temperature along the convectively adjusted atmospheric lapse rate to the surface implies a warmer surface temperature because of the greater distance from the emission level to the surface in the warmer climate.
3. *Cloud optical thickness feedback*: The canonical wisdom that clouds should become brighter with warming due to increased condensation of water vapor was shown to be inconsistent with satellite observations for much of the world by Tselioudis, Rossow and Rind (1992), because processes that reduce the physical thickness of clouds and/or their liquid water content oppose this effect in low and middle latitudes.
4. *Cloud phase feedback*: Fewer aerosol particles serve as effective ice nuclei than as cloud condensation nuclei for liquid clouds. Consequently, liquid clouds have more and smaller droplets than ice clouds have crystals, and the bigger ice crystals precipitate more quickly. Both effects cause ice clouds to be optically thinner than equivalent liquid clouds. Thus, a change in the relative amounts of liquid and ice as climate warms will induce a cloud feedback.
5. *Cloud location feedback*: Since the SW feedback of clouds depends not only on the cloud properties but on the amount of sunlight available for them to reflect, a shift in clouds to higher solar zenith angles (e.g., to higher latitudes) or to a location over a brighter surface will result in less SW cloud forcing even if the cloud properties do not change.

The current generation of climate models that participated in the Coupled Model Intercomparison Project Phase 5 (CMIP5) generally agree on some aspects of cloud feedback and disagree on others. Climate model responses to increasing greenhouse gas concentrations exhibit four basic behaviors:

1. An increase in cloud top altitude (decrease in cloud top pressure) in the tropics and extratropics such that cloud top temperature remains nearly constant with warming, producing a positive LW feedback. This behavior, anticipated in David Rind's early one-dimensional study (Hansen *et al*., 1981), occurs in all models. It is well understood via two mechanisms. In the tropics, the 'fixed anvil temperature' hypothesis states that convective clouds inject ice into the atmosphere at levels at which they lose buoyancy and their compensating subsidence no longer warms the atmosphere, and this occurs at the level at which water vapor concentration (which approximately follows temperature) becomes too small to effectively radiatively cool the atmosphere. In mid-latitudes, the rising tropopause altitude due to CO_2 warming of the upper troposphere and cooling of the lower stratosphere has the same effect. In both cases, since convective and/or large-scale dynamical mixing controls the lapse rate below the higher cloud top emission-to-space level, greenhouse warming at high altitude is communicated to the surface as a higher temperature there even though temperature at the emission level remains constant.
2. A poleward shift in the mid-latitude storm tracks, which takes place in all models and is also seen in the observational record. This is associated with the poleward expansion of the Hadley cell, for which several explanations exist, for example the suppression of baroclinic instability at the equatorward edge of the storm track due to the reduced lapse rate in the warmer climate. The shift to higher latitudes produces a positive cloud location feedback, as long as the latitudes vacated by the shifting storm tracks are replaced by decreased cloudiness.
3. A general decrease in cloud cover in the subtropics and tropics, except for the equatorial central and east Pacific in some models (due to a weakening of the Walker cell and eastward shift of deep convection). Most GCMs predict this to varying degrees, but the magnitude and spatial extent of this decrease are probably the greatest source of disagreement among models and the single largest contributor to the spread in global climate sensitivity in the CMIP5 models. The response of low clouds to warming is the net result of several opposing processes. Increased surface turbulent fluxes in the warmer climate deepen the boundary layer, causing stratocumulus clouds that lie at its top to thicken and reflect more sunlight — a negative feedback. At the same time, turbulent entrainment of dry air above the cloud top inversion into the cloud evaporates liquid water and dissipates cloud, a positive feedback. In some models shallow cumulus clouds develop and penetrate the inversion top, and the dry air that descends to compensate this also dissipates the cloud. GCMs with low climate sensitivity tend to be dominated by the boundary layer deepening effect, especially in the stratocumulus regions of the eastern oceans. GCMs with high sensitivity tend to be dominated by the drying effects, e.g., within and at the edges of the stratocumulus decks, but perhaps also over the open subtropical oceans. Optical thickness also decreases somewhat with warming in these models, as originally predicted by Tselioudis, Rossow and Rind (1992).

4. An increase in high latitude cloud cover and optical depth, especially at low altitudes. Possible reasons for this include the increased poleward transport of water vapor by synoptic storms, increased evaporation of water from regions in which sea ice has melted and been replaced by open ocean, and boundary layer deepening. Much of it is microphysical, though, a result of the increased ratio of liquid to ice in the mixed-phase stratus that are ubiquitous in this region. The magnitude of this cloud phase feedback is highly uncertain, due to poor knowledge of ice nucleus concentrations and how they will change, and poor understanding of the many pathways by which ice is nucleated and supercooled liquid is maintained in these clouds.

Most of the focus in cloud feedback studies has been on low-level clouds, which continue to be a great uncertainty because of the competing mechanisms that control them. High cloud feedbacks have received less attention, in part because cancellation between their LW and SW forcing mutes their net cloud forcing in the current climate. Caution should be exercised, however, because at least two aspects of high clouds are more or less missing from today's GCMs. Thin cirrus, the only clouds whose net cloud forcing is positive in the current climate, are unresolved by the coarse vertical resolution of GCMs, and thus the physics that maintains them is largely absent from the models. Likewise, organized mesoscale convection, which occurs when favorable environmental conditions (e.g., high wind shear and/or humidity) cause a transition from individual short-lived convective cells into longer lived clusters of cells that develop an areally extensive stratiform rain region and anvil clouds, is not parameterized at all by most GCMs. In addition, most GCM cumulus parameterizations tend to produce a transition from shallow to deep convection too readily, due to insufficient sensitivity of convection depth to dry tropospheric conditions, a process that is controlled by entrainment into the clouds. Gradually, these weaknesses are giving way as more models begin to be evaluated against a broader range of satellite and field experiment data and in hindcasts of real-world events. However, convergence of model predictions of cloud feedback is still most likely to require a decade or more of further research.

Clouds also affect climate change through their interactions with aerosols. The *first indirect effect* occurs because clouds nucleate onto aerosol particles. With more aerosols, the available liquid water is partitioned among more, but smaller, droplets, and the greater collective surface area of the larger number of droplets causes more sunlight to be reflected, cooling the climate. The *second indirect effect* is proposed to occur because smaller droplets fall more slowly and thus are less likely to precipitate, increasing the liquid water that remains in the clouds and thus also causing more solar reflection. However this effect is highly uncertain. A *semi-direct* effect can also occur when absorbing aerosols (black carbon and dust) heat a cloud and cause liquid water to evaporate, or when they increase or decrease the convective stability of the atmosphere and thus change the amount or vertical development of clouds. One of the 'solar radiation management' proposals for geoengineering the climate to offset greenhouse warming involves adding aerosol particles to low stratocumulus cloud decks, making them more reflective. Studies to date indicate that while reductions in temperature may be possible via such techniques, it is much harder to predict the resulting feedbacks on the circulation and effects on precipitation patterns. Aerosols also interact with precipitation. Precipitation *scavenging* of aerosols from the atmosphere (also called wet deposition) is the primary removal mechanism for aerosols. Convective *invigoration* by aerosols has been proposed to limit growth of cloud droplets and allow them to interact more with ice crystals to increase precipitation, but this mechanism is highly uncertain.

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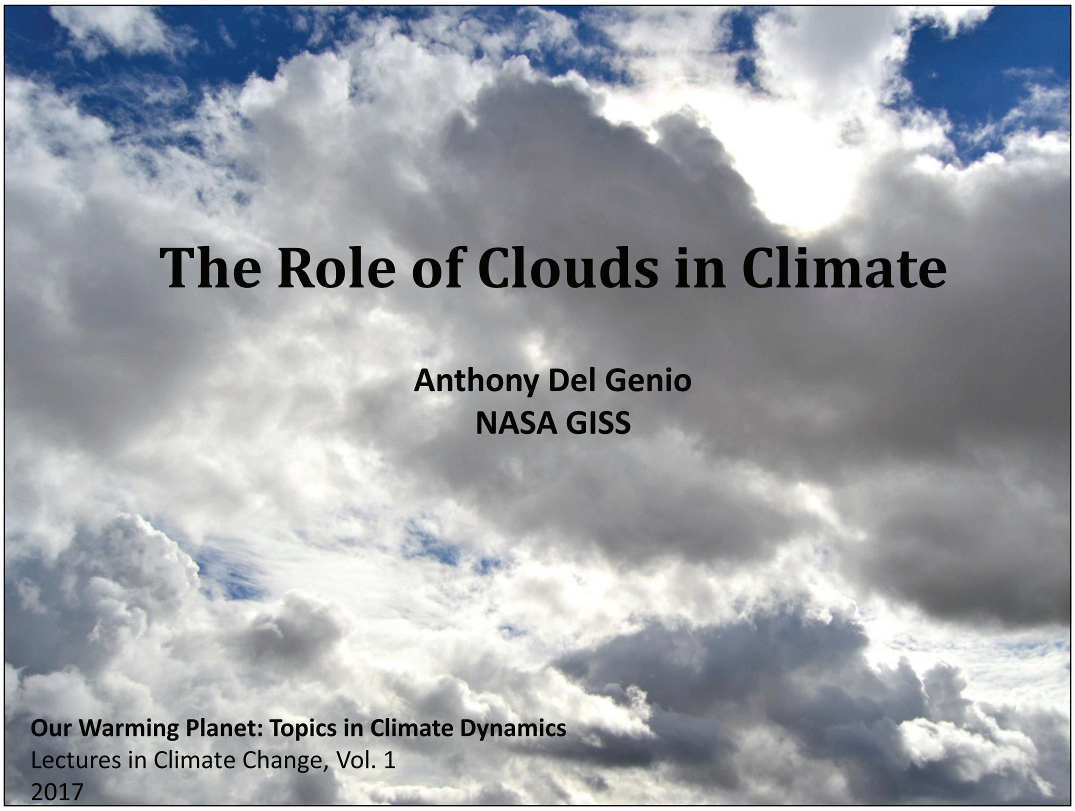
Slide 1



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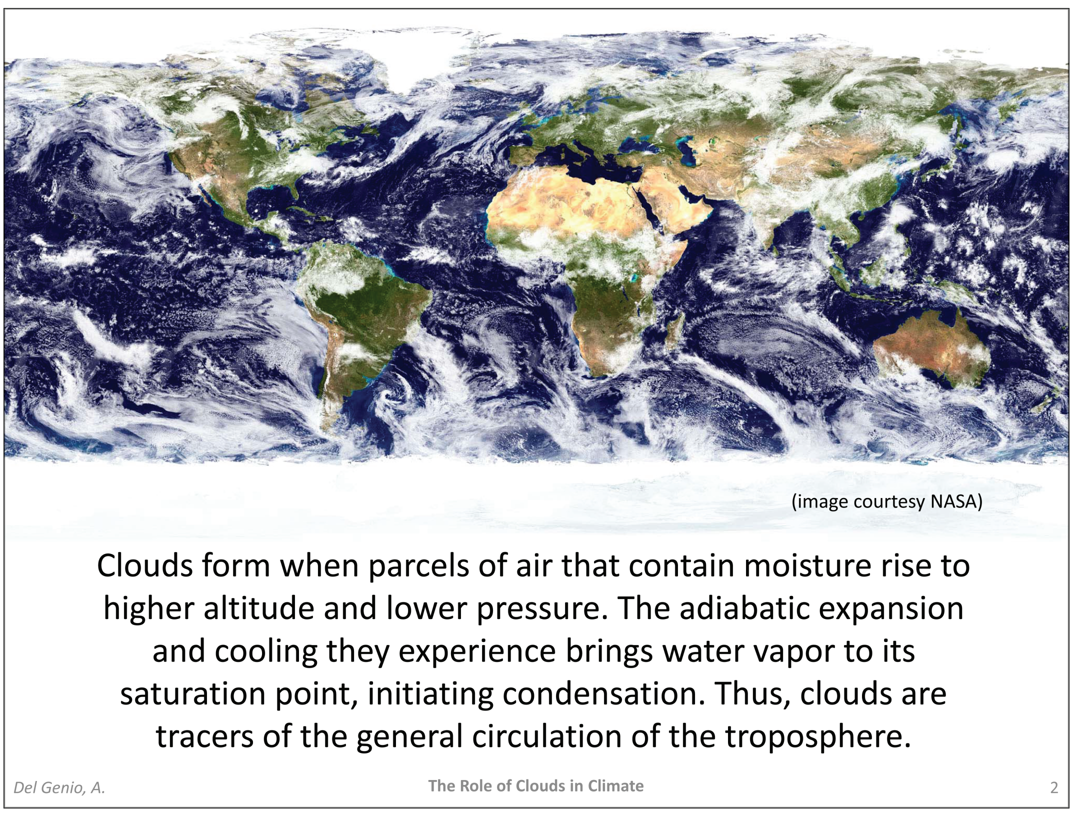

Slide 3

Two fundamentally different types of clouds exist, with different roles in the climate

- Convective clouds: Formed by rising due to buoyant instability of a column of air when air is humid and the lapse rate exceeds the moist adiabatic lapse rate

- Stratiform clouds: Formed by other sources of upward vertical motion such as lifting of warm air masses over cold air masses or boundary layer turbulence

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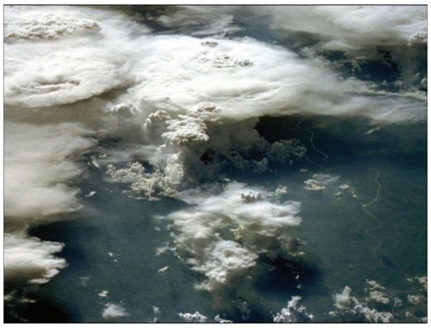
Convective clouds

- Shallow (fair weather) cumulus
  - No or little precipitation
  - Moisten the lower troposphere by transporting water evaporated from the surface upward
  - Frequent enough to have a radiative impact

- Deep cumulonimbus
  - Responsible for the majority of Earth's precipitation
  - Warm and dry the atmosphere
  - Source of ~50% of cirrus clouds



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Stratiform clouds

- Low/middle clouds
  - Mostly liquid, but can be mixed-phase or ice at low temperatures
  - No or little precipitation (stratus, stratocumulus) or significant precipitation (nimbostratus)
  - Important for reflection of sunlight
  - Little greenhouse effect because they lie below the clear sky emission level

- High clouds
  - Almost exclusively ice
  - Optically thin with little reflection of sunlight (cirrus) or thick convective anvil clouds (cirrostratus) with significant reflection
  - Always produce snow which does not reach the ground; thick anvils produce rain at the ground
  - Strong greenhouse effect because they lie above the clear sky emission level

(images courtesy NASA)

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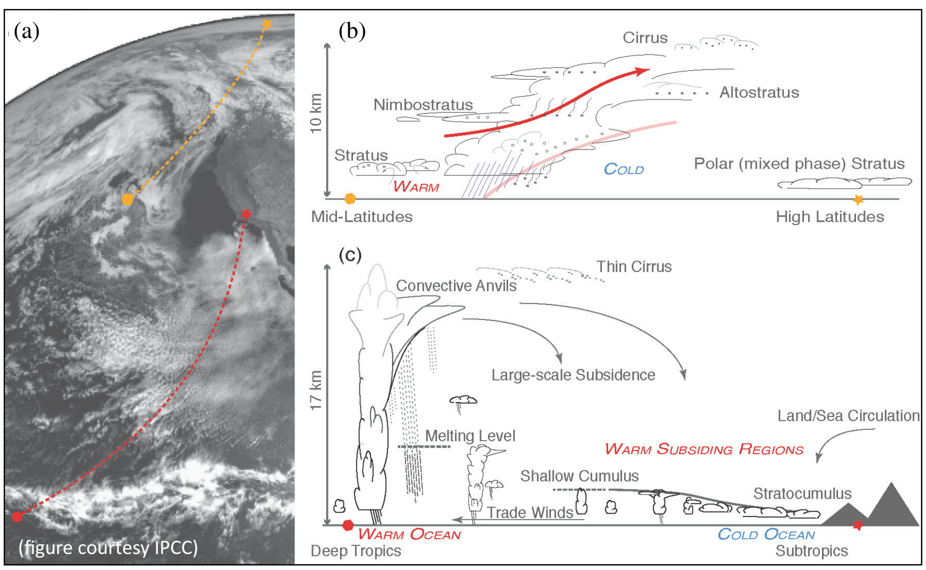

(figure courtesy IPCC)

In the tropics, clouds are controlled by the Hadley/Walker circulation; in the mid-latitudes by synoptic storms; and in the polar regions by boundary layer turbulence and the snow/ice or ocean surface

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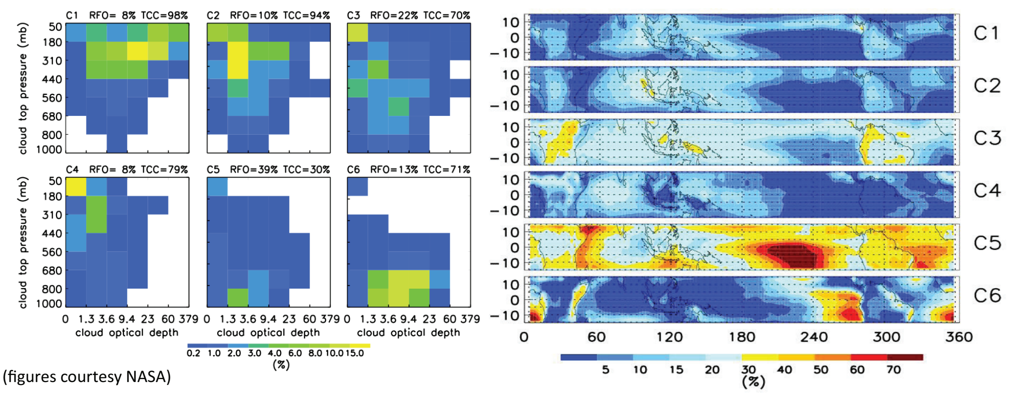

(figures courtesy NASA)

Tropical clouds can be organized into 6 categories in weather satellite images by their optical thickness (which determines how much visible sunlight they reflect) and their emission of thermal infrared radiation to space (which depends on how high their tops are):

- *Disturbed (precipitating) conditions*: Organized deep convection (WS1), cirrostratus and anvil clouds (WS2), and isolated deep, midlevel and shallow convection (WS3)
- *Suppressed (fair weather, drizzle) conditions*: Cirrus (WS4), shallow cumulus (WS5), and stratocumulus (WS6)

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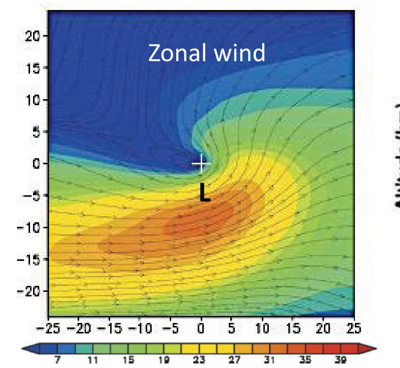

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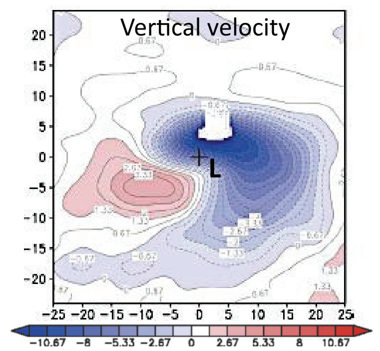

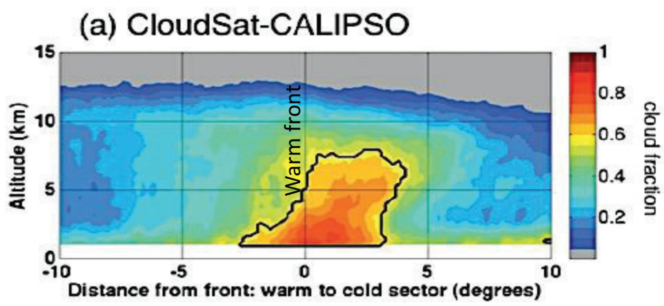

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- In mid-latitudes, shallow cumulus, stratocumulus, and stratus form behind the cold front, where cold air moves equatorward and descends.
- Ahead of the warm front cloud structure is tilted as air moves poleward and rises, with cirrus far ahead of the surface front, followed by two cloud types specific to mid-latitudes:
  - Mid-level top altostratus and altotcumulus that precede frontal passage
  - Thicker, higher-top frontal nimbostratus clouds that follow and produce rain and snow

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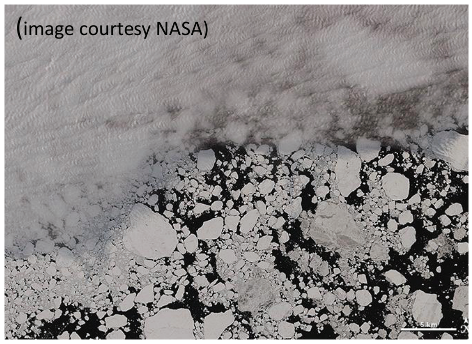

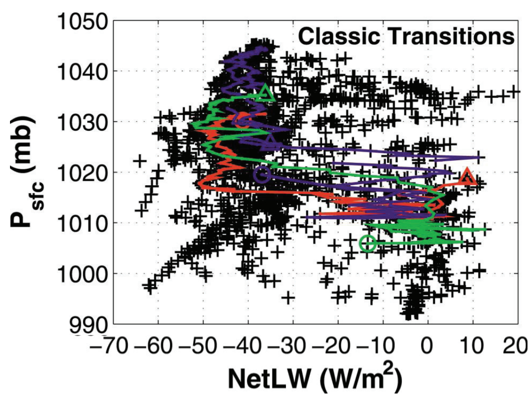

Polar clouds often occur over sea ice or snow and are difficult to detect in weather satellite images. They are easiest to notice by measuring the longwave radiation they emit down to the surface.

The Arctic often divides into two modes of behavior:

1. High pressure with clear skies or thin ice clouds that have little effect on radiation and allow sea ice to cool radiatively;
2. Low pressure with thicker liquid water clouds formed from water vapor transported by storms, which emit enough longwave radiation down to balance the upward heat loss from the surface.

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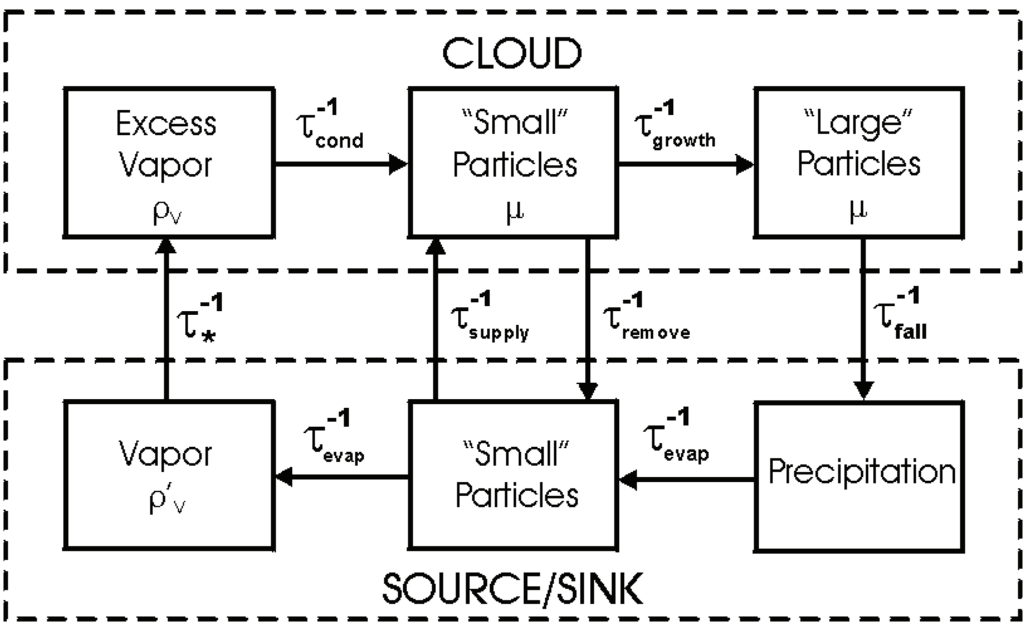
Cloud microphysical processes



(figure courtesy NASA)

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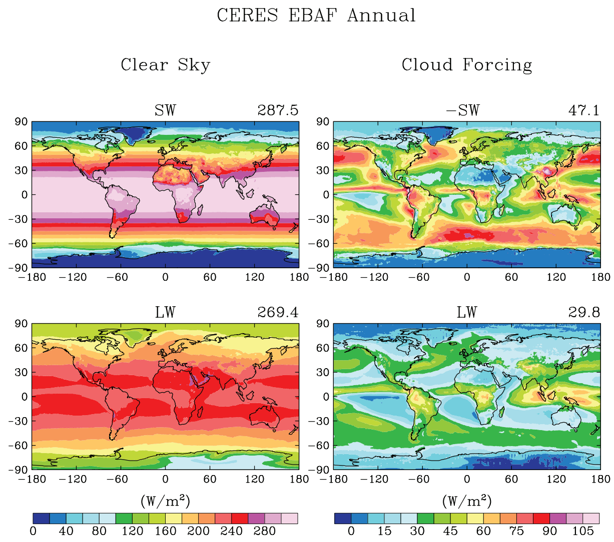
Clouds modulate the geographic pattern of solar absorption and thermal infrared emission

Cloud forcing is a measure of the radiative effect of clouds

Defined as the actual absorbed (SW) or emitted (LW) flux (including clouds) minus the flux in clear sky

(up/down fluxes are defined as –/+)



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Components of cloud feedback

- *Cloud cover feedback:* Depends on how *relative* humidity responds to climate warming, the result of competing effects of changes in water vapor concentration and temperature, and whether the clouds that increase or decrease are those that primarily warm or cool the planet. Primarily a response to dynamics.
- *Cloud height feedback:* Higher cloud tops reduce emission to space relative to the change in emission without this change, and convective/dynamic mixing communicates this to the surface.
- *Cloud optical depth feedback:* Clouds become brighter or darker depending on how cloud water content, physical thickness, and particle size change with warming.
- *Cloud phase feedback:* An increase in the amount of liquid relative to ice causes a negative feedback due to the smaller liquid droplets, but this is reduced for clouds over snow/ice.
- *Cloud location feedback:* A shift in cloud locations to higher solar zenith angle (poleward or away from noon) or to a location with a brighter surface reduces SW cloud forcing.

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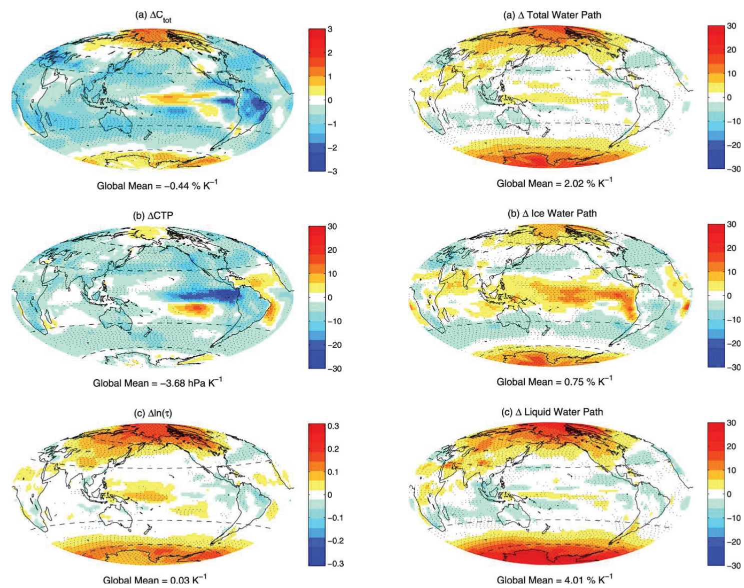

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The major cloud responses to warming in GCMs include: Decreasing cloud cover and pressure in the tropics and extratropics, and increasing cloud cover and optical depth and a shift from ice to liquid at the poles.

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Some features of the predicted cloud feedback are considered high-confidence predictions

- The positive LW feedback due to increasing cloud altitude is understood via the “fixed anvil temperature” mechanism whereby the altitude at which convective clouds detrain moisture and ice shifts upward, following the shift of the vertical profile of radiative cooling by increased water vapor.

- The positive SW feedback due to the expansion of the Hadley cell and poleward shift of the storm tracks (moving the storm clouds to latitudes with less insolation) is supported by observations, although the physical mechanism(s) responsible for the Hadley cell expansion are still debated

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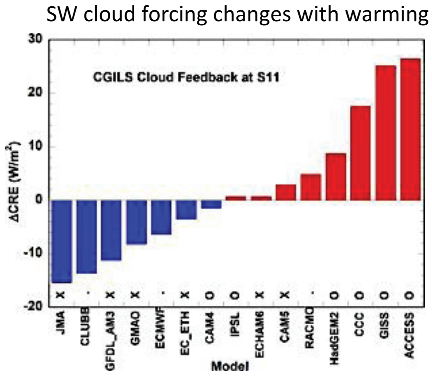
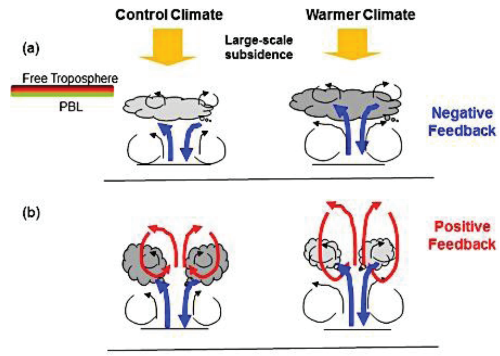
But there is still substantial disagreement among GCMs about tropical low cloud feedback

SW cloud forcing changes with warming





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Low-sensitivity models: Increased surface evaporation deepens the boundary layer and thus stratocumulus clouds with warming.

High-sensitivity models: Drying by shallow convective subsidence and cloud top entrainment dissipates stratocumulus with warming.

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Other sources of uncertainty in cloud feedback

- The cloud phase contribution to cloud feedback (less reflective ice to more reflective liquid) depends on the unknown concentration of ice nuclei and uncertainty in the multiple pathways by which ice nucleates and grows in different conditions
- Thin cirrus, which have a net positive LW cloud forcing, are unresolved by the vertical layering of GCMs and the mechanisms of their production and maintenance are poorly understood
- Optically thick convective anvil clouds are produced by the mesoscale organization of convection, which is not represented in any GCM

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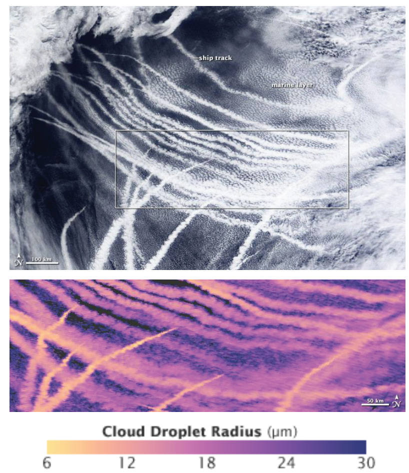
Cloud–aerosol interactions

- *First indirect effect*: Higher aerosol concentration produces more but smaller cloud droplets whose collective surface area is greater, making the cloud more reflective; a potentially significant negative climate forcing.
- *Second indirect effect*: Smaller droplets precipitate less, increasing cloud water content and lifetime; this has not yet been observationally verified and may be offset by faster evaporation of smaller droplets when dry air is entrained into the cloud.
- *Semi-direct effect*: Warming of air by solar absorption by lower albedo aerosols (e.g., black carbon) evaporates cloud droplets or affects atmospheric stability; cloud may increase or decrease depending on the type of cloud and altitude of the warming.

NE Pacific ship tracks



(images courtesy NASA)

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Precipitation–aerosol interactions

- *Wet deposition (scavenging)*: Precipitating droplets collect aerosol particles and remove them from the atmosphere (below-cloud scavenging), or cloud droplets that form by nucleating onto an aerosol remove the aerosol when they rain out (in-cloud scavenging); this is the primary mechanism for removing aerosols from the atmosphere
- *Invigoration of convection*: Higher aerosol concentration limits coalescence growth of cloud droplets into rain drops in a convective updraft, allowing more liquid to be carried up to colder temperatures; the resulting increase in ice formation releases additional latent heat that strengthens the convection; this is currently a controversial hypothesis

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Take-away messages

- Clouds form either because of convective instability or because of stable lifting of air masses; they are tracers of Earth's general circulation
- Convective clouds transport heat, moisture, momentum and produce much of Earth's precipitation; stratiform clouds produce some precipitation but dominate radiative effects
- Clouds with low and high tops play different roles in the climate system via how much precipitation they form and/or whether they influence primarily SW or LW radiation
- Cloud feedbacks in a changing climate are due to changes in cloud cover, height, optical thickness, phase, and location; some are well understood, others are not
- Interactions of aerosols with clouds affect cloud optical thickness, and potentially cloud cover and precipitation; many of these interactions are uncertain

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Slide Notes

Slide 2 Clouds link the energy and water cycles via the atmospheric general circulation. This composite global satellite image identifies the primary atmospheric circulation regimes by the characteristic cloud patterns associated with them. The equatorial region is characterized by an irregular but zonally oriented band of cloudiness associated with the Intertropical Convergence Zone (ITCZ). The ITCZ marks the rising branch of the tropical Hadley circulation, in which moisture evaporated in the subtropics converges and rises, creating an environment suitable for deep convection and the highest climatological precipitation rates on Earth. Actual convective clouds cover only a small fraction of the tropics. The clumps of equatorial cloudiness that collectively make up the ITCZ are the result of organization of convection into clusters with extensive stratiform rain and anvil cloud regions. Poleward of the ITCZ in the subtropics, the descending branch of the Hadley cell advects dry air down from high altitudes. Over land, where the surface source of moisture is limited, this suppresses clouds and rain and is responsible for Earth's deserts. Over ocean, surface evaporation provides water vapor that is advected upward to the top of the low-level boundary layer inversion by small-scale turbulence. Depending on the sea surface temperature, this cloudiness can take two distinct forms. Over the colder ocean waters of the eastern oceans (particularly visible off the coast of Peru and Chile, but to a lesser extent off the coasts of Namibia and California), overcast stratocumulus decks form. Over the somewhat warmer open oceans, scattered fields of shallow trade cumulus form instead. The mid-latitudes of both hemispheres are dominated by the spiral, 'comma' cloud and precipitation patterns associated with synoptic low-pressure centers generated by the baroclinic instability of the atmosphere's latitudinal temperature gradient. The clouds themselves are the result of rising motion along the cold front equatorward of the low (the tail of the comma), along the warm front east of the low, and in the 'cold conveyor belt' that wraps around the north side of the low.

Slide 3 Clouds are usually the result of upward motions that cause adiabatic expansion and cooling that brings moist air to its saturation point. Global climate models (GCMs) typically divide clouds into two general categories: (1) Convective clouds that result when air is displaced upward in a conditionally unstable environment (i.e., a lapse rate in excess of the moist adiabatic lapse rate) and reaches its level of free convection (positive buoyancy). (2) Stratiform clouds that form in moist convectively stable conditions due to other sources of lifting—this includes motions along fronts formed by baroclinic instability processes in an area that is not unstable vertically, clouds that form at the tops of the turbulent boundary layer, clouds that form as convective updrafts lose buoyancy and diverge, injecting ice into the upper troposphere, clouds that form due to other wave motions, and orographic clouds that form in flow over topography.

Slide 4 Convective clouds sometimes penetrate only a short vertical distance but at other times all the way through the troposphere, and there is actually a continuum of convective cloud depths with occurrence peaks of tops in the lower and upper troposphere and a weak tertiary peak in the mid-troposphere. Predicting the depth of a convective cloud is important because the effect of convection on the environment changes character as convection deepens. Shallow cumulus slightly heat the lower troposphere, but their primary role is to transport moisture out of the boundary layer into the lower free troposphere. This has several implications for the climate. It helps maintain sub-saturated conditions in the boundary layer, allowing surface evaporation to continue; it facilitates the transport of subtropical water vapor toward the equator by the return branch of the Hadley circulation; and by moistening the lower troposphere it provides more favorable conditions for future cumulus clouds to rise to greater altitude without being diluted by turbulent entrainment of dry air. Shallow cumulus often does not precipitate, or else precipitate only weakly. They produce scattered cloudiness but are frequent enough to significantly affect the cloud cover of the subtropics and mid-latitudes. Deep cumulonimbus produces most of the Earth's precipitation. They create a deep profile of convective heating that peaks in the mid-troposphere early in the lifecycle and then shifts upward as convection organizes on the mesoscale and produces upper troposphere stratiform rain regions. Deep convection dries the atmosphere and thus stabilizes it. The cloudiness due to deep convection itself is minimal, but the stratiform rain and anvil regions created by deep convection cover a large area. Injection of ice into the upper troposphere by deep convective updrafts accounts for about 50% of the cirrus in the tropics. (The remainder of cirrus occurs when large-scale upward motions in the atmosphere, e.g., due to waves, cause air to become supersaturated with respect to ice.)

Slide 5 Stratiform clouds are important primarily for their radiative effects. The global mean temperature is determined by the balance between absorbed sunlight and the Earth's emitted heat radiation. Clouds affect the former by their influence on Earth's planetary albedo, with ~2/3 of the reflected sunlight being due to clouds. Clouds affect the latter because like greenhouse gases, they too absorb thermal infrared radiation and re-emit it at a lower temperature, thus reducing overall emission to space. Stratiform clouds, which cover a much larger area than convective clouds, are responsible for most of clouds' radiative effect on the climate. Low-altitude stratiform clouds such as stratus and stratocumulus tend to be made of liquid and are optically thick and thus reflect significant sunlight. At the same time, they do not trap much more thermal radiation than the clear atmosphere does because they exist at altitudes where most of the atmosphere's water vapor (the most important greenhouse gas) resides. Thus these clouds have a net cooling effect on the current climate. High stratiform clouds are almost always ice and can either be optically thin (cirrus) or optically thick (cirrostratus). Cirrus clouds reflect relatively little sunlight but strongly absorb thermal infrared radiation and re-emit it to space at the very low temperatures of the upper troposphere, and they thus have a net warming effect on the climate. Thick cirrostratus clouds both strongly reflect sunlight and strongly absorb thermal infrared radiation and thus have an approximately neutral effect on the planetary energy balance. Optically and physically thick stratiform clouds such as nimbostratus can produce significant precipitation (rain or snow) in mid-latitude synoptic storms but usually not as much as convective storms do. Stratus and stratocumulus either do not precipitate at all or drizzle. Ice crystals in cirrus and cirrostratus clouds are typically much bigger than liquid droplets in low clouds and therefore precipitate more easily. Thus, technically all high clouds produce snow. However, for most high clouds, the snow sublimes long before reaching the surface, visible as wispy virga. Thick cirrostratus anvils associated with convective storms, though, produce considerable snow that melts upon reaching the 0°C line and ultimately reaches the surface as stratiform rain.

Slide 6 Tropical cloud types and locations are dictated primarily by the Hadley and Walker circulations. In the rising branch of these circulations (near the equator and over warm oceans and land), moisture converges and produces unstable conditions, giving rise to heavily precipitating cumulonimbus clouds, sometimes with stratiform rain regions and anvils, and often produces thin cirrus as well. As air drifts poleward or toward longitudes with cooler sea surface temperatures, it radiatively cools and begins to subside. This subsidence dries the column and suppresses cloud formation in the free troposphere. If the subsidence is over ocean, it is opposed at low altitudes by turbulence in the boundary layer, and where the two meet, an inversion layer forms. Water evaporated from the ocean is transported upward by the turbulence and saturates beneath the inversion, forming a stratocumulus deck, typically off the west coasts of the continents where the ocean surface is cool. If the subsidence is over land, there is no significant surface source of water vapor and skies remain clear; these are locations of the world's deserts. After air subsides, it begins its return flow toward the equator or warm ocean longitudes. As the ocean beneath these 'trade winds' begins to warm, the boundary layer deepens and shallow cumulus clouds that can penetrate the inversion begin to occur, reducing the cloud cover and injecting water vapor into the lower free troposphere, the source of the water that ultimately converges in the ITCZ. Mid-latitude cloud types are regulated primarily by the synoptic low- and high-pressure centers that develop due to baroclinic instability of the equator-pole temperature gradient. Warm moist air flows poleward east of the low and rides up and over denser colder air at the warm front, producing cirrus, altocumulus or altostratus, and eventually thicker stratus and nimbostratus near the surface warm front. This air continues to flow around the north side of the low, producing an extensive nimbostratus cloud shield there. West of the low-pressure center, cold dry air flows equatorward. It meets warm humid air at the cold front and lifts that air, often producing convective clouds and precipitation. Behind the cold front, the colder drier air produces clear skies and/or low stratus clouds. If the cold air outbreak occurs over the ocean, evaporation from the warmer ocean surface can sometimes produce extensive areas of cellular shallow convective clouds. In the polar regions, the dominant cloud types are stratus and stratocumulus and are heavily influenced by boundary layer turbulence and by the nature of the surface beneath them (open ocean, or snow/ice). Figure reproduced with permission from IPCC from Boucher, O., Randall, D., Artaxo, P., Bretherton, C., Feingold, G., Forster, P., . . . Zhang, X.Y. (2013). Clouds and Aerosols. In: *Climate Change 2013: The Physical Science Basis. Contribution of*

Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., . . . Midgley, P.M. (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, pp. 571–658, doi:10.1017/CBO9781107415324.016.

Slide 7 The different types of clouds that are prevalent in the tropics can be objectively identified by their combination of visible optical thickness and cloud top pressure (or temperature) that is retrieved from visible and thermal infrared weather satellite images. The International Satellite Cloud Climatology Project (ISCCP) produces two-dimensional frequency histograms of these quantities for 2.5×2.5 degree regions and defines six dominant cloud types from these distributions. Organized deep convection is characterized by high optical thickness and low cloud top pressure and occurs mostly in the ITCZ north of the equator and the corresponding South Pacific Convergence Zone (SPCZ) south of the equator. Cirrostratus and anvil clouds, which occur in association with organized convection, have similar cloud top pressures, somewhat lower optical thicknesses, and have a similar geographic distribution. Both these cloud types occur where and when the atmosphere is very humid. In moderately humid conditions, a mix of individual deep convective clouds, shallow cumulus, and mid-level top 'congestus' clouds are common, identified by moderate to low optical thickness and a variety of cloud top pressures. These situations also occur in the ITCZ and SPCZ, and they are more likely to exist over the tropical continents. In drier conditions skies are sometimes dominated by thin cirrus (low cloud top pressure and low optical thickness), primarily over the tropical warm pool and central Africa, where deep convection has previously humidified the upper troposphere. In the cooler sea surface temperature regions of the tropics, low clouds dominate. Over the open oceans on either side of the ITCZ or SPCZ, where air subsides, shallow cumulus is prevalent. These are identified as high cloud top pressure, low optical thickness clouds, but the latter is in part an artifact of the fact that individual clouds are smaller than the resolution of weather satellite images, and thus clear sky mixes with cloud in one pixel. Over the colder eastern oceans off the west coasts of the continents, where ocean upwelling is present, denser stratocumulus decks are prevalent, with high cloud top pressure and moderate optical thickness.

Slide 8 In mid-latitudes, the flow around low-pressure centers (L in the ECMWF reanalysis storm composites above) brings cold, subsiding air equator-ward west of the low, giving rise to shallow cumulus, stratocumulus, and stratus clouds. East of the low, poleward moving warm air ascends as it meets cold air at the warm front. Cirrus occurs when surface high pressure is in place but the warm front is advancing from the west and the elevated part of the warm front is overhead. With time the altitude of the front lowers at a given location. Altostratus and altocumulus, mid-level cloud types unique to the mid-latitudes (moderate optical thickness, moderate cloud top pressure) commonly set in after the cirrus, heralding a degradation of weather conditions. As the front approaches the surface, nimbostratus (fairly high optical thickness and fairly low cloud top pressure, but not to the extent seen in cumulonimbus), another cloud type unique to the mid-latitudes, move in. A composite cross section of cloud occurrence across the warm front thus shows a tilted structure. Figures from Bauer, M. and Del Genio, A.D. (2006). Composite analysis of winter cyclones in a GCM: Influence on climatological humidity. *Journal of Climate*, 19, 1652–1672, doi:10.1175/JCLI3690.1, and Booth, J.F., Naud, C.M. and Del Genio, A.D. (2013). Diagnosing warm frontal cloud formation in a GCM: A novel approach using conditional subsetting. *Journal of Climate*, 26, 5827–5845, doi:10.1175/JCLI-D-12-00637.1.

Slide 9 Polar cloudiness is dominated by low stratus and stratocumulus clouds. More so than in other parts of the world, these low clouds can occur in either phase of water or a mixture of the two. Polar clouds are difficult to detect in weather satellite images, because in the visible they are about as reflective as the underlying sea ice or snow, and in the thermal infrared, they are often as warm or warmer than the underlying surface because low-level temperature inversions are common. They are much easier to detect from the ground via their effect on thermal infrared radiation. When skies are clear or when optically thin ice clouds are present, the surface radiates thermal infrared (LW) radiation upward, while the atmosphere emits little downward, producing a negative (upward) net LW radiative flux that cools the surface and maintains the sea ice against heat conducted up through the ice from the warmer ocean below. When liquid or mixed-phase clouds are present, they emit about as much LW radiation down as the surface emits up, producing a near-zero net radiation balance at the surface. These two contrasting conditions tend to persist for long times in the Arctic relative to other latitudes, with sudden transitions from the 'radiatively clear' state to the 'opaque cloud' state when low pressure moves in, usually accompanied by poleward transport of water vapor from lower latitudes. The lower figure shows individual observations of surface pressure and net LW radiation at the surface for an Arctic sea ice location (black crosses). The colored lines connect consecutive points in time and thus show several examples of how the two parameters jointly evolve on particular days. When low pressure departs and high pressure moves in, an equally sudden transition from near-zero net LW flux (caused by cloudy skies that prevent the surface from cooling) to strongly negative LW flux (from upward radiation in clear skies that cools the surface freely when clouds are not present) occurs. The net result is a strongly bimodal distribution of surface longwave radiation. Figure from Stramler, K., Del Genio, A.D. and Rossow, W.B. (2011). Synoptically driven Arctic winter states. *Journal of Climate*, 24, 1747–1762, doi:10.1175/2010JCLI3817.1.

Slide 10 The evolution of a cloud from birth to death is due to a combination of macrophysical dynamical processes that produce an environment favorable or hostile to the presence of clouds, and microphysical processes on the scale of water molecules or individual cloud droplets or ice crystals that cause the cloud to grow or decay. Consider first the simpler liquid water case. Excess (supersaturated) vapor concentration initiates condensation (at the rate $\tau^{-1}{}_{\mathrm{cond}}$ in units of inverse time) in the presence of a suitable cloud condensation nucleus (soluble aerosol particles such as sulfate or sea salt, or insoluble but hygroscopic particles). Cloud droplets may also be supplied (at the rate $\tau^{-1}_{\mathrm{supply}}$) by advection from another location and can be removed (at the rate $\tau^{-1}_{\mathrm{remove}}$) by advection to another location or by erosion of the cloud as dry air is turbulently entrained into the cloud and evaporates cloud liquid water. Condensation can produce droplets of size ~10 μm, similar to that observed in typical clouds, but condensation slows down as droplet size increases and thus cannot explain the onset of precipitation in some clouds. Instead, clouds grow to precipitation size (at the rate $\tau_{\text{growth}}^{-1}$) by gravitational coalescence, the process by which large droplets falling faster than nearby small droplets collide with them and incorporate them to make larger drops whose fall speeds eventually become large enough to allow them to fall out of the cloud (at the 'sedimentation' rate τ_{fall}^{-1}). The observed size of cloud droplets is the size at which coalescence becomes faster than condensation. Once the large drops fall through the base of the cloud and leave the saturated conditions of the cloud, they begin to evaporate in the sub-saturated air below (at the rate τ_{evap}^{-1}). If the sedimentation rate exceeds the evaporation rate (e.g., if the sub-cloud air is fairly humid or the cloud base is close to the surface), precipitation reaches the ground. If not, the drops completely evaporate and return water vapor and aerosols to the atmosphere. This description, for liquid clouds, applies as well to ice clouds. However, ice clouds 'heterogeneously' nucleate onto different types of aerosol (black carbon, biogenic, perhaps dust) and can also 'homogeneously' nucleate in the absence of an ice nucleus at temperatures colder than ~−35°C by the freezing of a previously nucleated liquid haze droplet. Furthermore, in addition to the coalescence mechanism of growth (called 'aggregation' for ice clouds becoming snow), ice crystals can also grow in a mixed phase cloud when water vapor is supersaturated with respect to ice but sub-saturated with respect to liquid. In these conditions, water evaporated from the liquid droplets diffuses toward ice crystals and is deposited onto the surface, causing snowflakes to grow rapidly via what is called the Bergeron–Findeisen process. This process is responsible for much of the precipitation (rain and snow) that occurs in cold seasons.

Slide 11 Earth planetary radiation balance (at the top of the atmosphere) demands that in equilibrium, the sunlight (SW radiation) absorbed by the Earth equal the thermal radiation (LW) that Earth emits to space. The role of clouds in maintaining this balance is often described in terms of the concept of 'cloud forcing' (sometimes called 'cloud radiative effect'). For energy balance purposes, radiative fluxes are designated as positive downward (into the Earth system, i.e., warming) and negative upward (out of the Earth system, i.e., cooling). The cloud forcing is then defined as the difference between the actual absorbed or emitted flux (which includes both cloudy and clear regions of the atmosphere) and the flux in clear skies (the latter being a rough proxy for what the flux would be if there were no clouds). The figures above show the clear sky SW and LW flux to space (left panels) and the SW and LW cloud forcing, i.e., the amount by which clouds alter the flux relative to clear skies (right panels). In the absence of clouds, the geographic distribution of reflected sunlight would be determined primarily by the decrease in incident sunlight from equator to pole caused by Earth's spherical shape, modulated by the seasonality due to Earth's obliquity and the different surface albedos of ocean, land, sea ice and snow. Likewise, in clear skies outgoing thermal infrared (LW) radiation would be determined primarily by the decrease in temperature from equator to pole and modulated by the mostly latitudinal variation in middle/upper troposphere water vapor concentration associated with both temperature (through the Clausius–Clapeyron equation) and the general circulation (through its effect on relative humidity). (The maximum clear sky LW flux thus occurs in the subtropics of each hemisphere, where water vapor concentrations are small and radiation to space occurs from a lower, warmer altitude.) Thus, SW cloud forcing is negative, because clouds are brighter than most of the Earth's surface and increase the planetary albedo. The largest SW cloud forcing occurs in regions of significant optically thick cloud, including the ITCZ and SPCZ, the mid-latitude storm tracks, and the eastern subtropical ocean stratocumulus decks. It is larger over ocean than land in general because the ocean surface is darker and thus the presence of cloud has more of an effect on the albedo. LW cloud forcing is positive, because the greenhouse effect of clouds reduces LW cooling to space. The largest LW cloud forcing occurs in regions with significant high cloud, i.e., regions of rising motion in the general circulation such as the ITCZ, SPCZ, and mid-latitude storm tracks, because in these places clouds lie above the altitude (and below the temperature) at which the clear atmosphere emits to space. (It is often mistakenly assumed that clear areas emit to space from Earth's surface, but only a small fraction of the emission to space comes from the surface because of the opacity of water vapor and other greenhouse gases. Applying the Stefan-Boltzmann equation flux = σT^4 to the observed clear sky flux of 269.4 W/m^2, one finds that clear regions emit to space on average at a temperature T ~ 270 K, much colder than Earth's mean surface temperature of ~288 K.) The geographic pattern of LW cloud forcing is similar to that of SW cloud forcing, except that there is little LW cloud forcing in the stratocumulus regions, where almost all cloud is at low altitude and emission is dominated by the overlying water vapor and other greenhouse gases. Globally, SW cloud forcing (–47.1 W/m^2) exceeds LW cloud forcing (+29.8 W/m^2), giving rise to the common statement that 'clouds cool the Earth". This is to be interpreted as a statement about the current climate: Earth is cooler because it has clouds than it would be if it had no clouds. It is not a statement about how clouds will affect climate change. Figure from 'Physical Processes Controlling Earth's Climate' by Anthony D. Del Genio, from *Comparative Climatology of Terrestrial Planets,* edited by Stephen J. Mackwell, Amy A. Simon-Miller, Jerald W. Harter, and Mark A. Bullock © 2014 The Arizona Board of Regents. Reprinted by permission of the University of Arizona Press.

Slide 12 The long-term effect of clouds on climate change is referred to as 'cloud feedback'. It is the combined result of how changes in temperature caused by climate forcings (such as greenhouse gases, aerosols, and solar luminosity) directly affect cloud properties, and how changes in other parts of the climate system caused by changes in temperature (such as water vapor and the circulation) affect cloud properties. It has often simplistically been assumed that clouds will offset greenhouse gas-induced climate change, based on the logic that warming evaporates more water from the ocean, which causes more clouds to form, which increases the albedo, which offsets the warming. However, this is largely erroneous for three reasons. First, cloud cover does not respond to the absolute amount of water vapor in the atmosphere (the specific humidity), but rather to the relative humidity, i.e., the amount of water vapor in the atmosphere relative to its upper limit over a flat surface such as the ocean (the saturation humidity). As the climate warms, water vapor does increase, but temperature increases too, raising the saturation humidity, and so relative humidity changes only by small amounts, rising slightly in some places and decreasing slightly in other places, determined mostly by interaction with the general circulation. Thus in global climate models (GCMs), some places see a slight increase in cloudiness, others a slight decrease in cloudiness as climate warms, and the global cloud feedback depends on which of these has the greater effect. Second, the simplistic argument considers only the SW effect of clouds, ignoring the warming LW effect. So, one must know whether the clouds that increase or decrease are those that warm or cool the Earth to know the sign of the feedback. Third, not only cloud cover changes when the climate warms. Higher cloud tops with warming reduce emission to space, a positive feedback that appears as surface warming due to mixing by convection or large-scale dynamics. Increases or decreases in cloud optical thickness change reflection of sunlight and sometimes emission of heat to space. Changes from less reflective ice clouds with bigger particles to more reflective liquid clouds with smaller droplets increase the optical depth as climate warms, but much less so if the clouds are over a bright snow/ice surface. Finally, shifts in cloud locations to a higher solar zenith angle where there is less sunlight to reflect, or to a location with a brighter surface underneath, with no change in the cloud itself, reduce SW cloud forcing and produce a positive cloud feedback.

Slide 13 The current generation of GCMs produces these primary cloud feedbacks in response to warming: (1) Cloud cover generally decreases equatorward of about 50° latitude, with the exception of the equatorial central-east Pacific, where some models predict an increase in cloud cover instead. The decrease in cloud cover occurs mostly in low- and middle-level clouds and is thus a positive cloud feedback. (2) Cloud height increases in the tropics and extratropics, another positive feedback. (3) Cloud cover and optical depth increase in the polar regions with warming. (4) There is a shift from ice to liquid, especially in the polar regions, as climate warms; this constitutes part but not all of the optical depth feedback there. The stippled areas in the figures indicate where at least 75% of the GCMs agree, which gives a sense of where there is model consensus and inter-model disagreement. Overall, the total cloud feedback predicted by today's GCMs ranges from near-neutral to strongly positive. Figure from Zelinka, M.D., Klein, S.A., and Hartmann, D.L. (2012). Computing and Partitioning Cloud Feedbacks Using Cloud Property Histograms. Part II: Attribution to Changes in Cloud Amount, Altitude, and Optical Depth. *Journal of Climate*, 25, 3736–3754. doi:10.1175/JCLI-D-11-00249.1.

Slide 14 Several aspects of cloud feedback are thought to be well understood and are agreed upon by all models, lending confidence in the predictions: (1) The positive LW feedback due to increasing cloud top altitude with warming can be understood by invoking the 'fixed anvil temperature' (FAT) hypothesis (or a more recent variant, the proportionately higher anvil temperature hypothesis). The idea is based on the fact that relative humidity remains nearly constant with warming, and so increasing water vapor concentration increases the altitude at which the water vapor concentration is so low that it no longer can effectively radiate to space. At this altitude there must be a divergence of the subsidence mass flux to compensate this cooling. The divergence is compensated by an inflow of mass at this altitude where convective systems detrain water vapor and ice to create anvils and cirrus clouds. The level of this detrainment follows the level at which water vapor radiative cooling begins to decrease as climate warms. The feedback occurs because despite the fact that the emission temperature remains constant, the emission level rises in altitude. Extrapolating from the new emission level over a greater distance along the atmospheric lapse rate down to the surface, a warmer surface temperature results. This positive feedback has been predicted by all GCMs for as long as climate simulations have been performed, and there is observational evidence for FAT in current climate variability over El Niño cycles. This is a tropical feedback, but cloud height increases in the extratropics with warming as well. This can be understood by the increase in tropopause height as climate warms, a well-founded feature of climate associated with the fact that increased upper troposphere radiative warming and increased lower stratosphere cooling by increased CO_2 shifts the tropopause upward. (2) The positive SW feedback due to the poleward shift of the extratropical storm tracks (i.e., a cloud location feedback due to the higher solar zenith angle) is also agreed upon by GCMs and occurs because of Hadley cell expansion with warming, which shifts the latitude of maximum latitudinal temperature gradient required for baroclinic instability poleward. There are several hypotheses for Hadley cell expansion, which is observed over recent decades, the most promising being the fact that the lapse rate of the atmosphere decreases with warming (because of the temperature dependence of the moist adiabatic lapse rate), stabilizing the southern edge of the storm track against baroclinic instability.

Slide 15 The major difference between low and high climate sensitivity climate models is in their prediction of how low clouds respond to warming. The plot on the left shows the change in cloud radiative effect (i.e., the change in cloud forcing, which can be considered a rough measure of the cloud feedback for the clouds in question here) between a warmer climate and the current climate for a large number of climate models that simulated a stratocumulus cloud regime in the subtropical Pacific. The models range from ones with a strong negative cloud feedback (ΔCRE < 0, implying stronger negative SW cloud forcing with warming) to ones with a strong positive cloud feedback (ΔCRE > 0, implying weaker negative SW cloud forcing with warming). At least two competing mechanisms determine the sign of this feedback in GCMs. As climate warms, more water evaporates from the oceans and more sensible heat is transferred to the atmosphere, while subtropical free troposphere subsidence weakens slightly, the net effect being a deeper boundary layer. By itself, this would cause the lifting condensation level to occur farther below the inversion, creating deeper, thicker stratocumulus clouds that are more resistant to breakup by the entrainment of dry air from above the inversion. However, in some GCMs entrainment is strong enough to break up the cloud in the warmer climate, and in others, shallow cumulus clouds begin to form or increase in frequency or depth in the warmer climate and penetrate the inversion. The subsidence that compensates the upward mass flux of these cumulus clouds dries and breaks up the stratocumulus layer. This effect is limited to the stratocumulus regions and does not extend to the open subtropical oceans, where most GCMs predict decreasing low cloud cover due to the fact that drier air subsides into the boundary layer as the climate warms.

Slide 16 Regardless of GCM consensus or lack thereof, physics that is not included in any GCM must be kept in mind in assessing the true uncertainty in cloud feedback, which in turn is the single biggest contributor to the uncertainty in Earth's climate sensitivity to a given external forcing. The transition from more ice to more liquid as climate warms is not simply a function of temperature. It also depends on the nature and availability of ice nuclei, which are poorly understood and poorly constrained by observations, and on the many possible pathways by which ice can nucleate and how this depends on its interactions with the dynamics within the cloud and at cloud top. None of these is thought to be represented well in GCMs, as evidenced by the fact that the fraction of ice vs. liquid in clouds varies with temperature in very different ways in different GCMs. Thin cirrus, the only cloud type that has a net warming effect on the current climate, exist in thin layers that are unresolved by the vertical layering of today's GCMs. Thus, subtle radiation–microphysics–turbulence interactions that depend on heating gradients across thin layers are absent in GCMs. In addition, the confidence with which GCM cumulus parameterizations transfer water vapor and ice upward into the near-tropopause atmosphere is low, and even the dynamical vertical transport of water vapor in a discretized model across a gradient of several orders of magnitude can be problematic. Finally, most tropical precipitation and the extensive cloudiness associated with it occurs in organized mesoscale convective systems. The processes of mesoscale convective organization and the lifecycle and propagation of such systems are absent from today's GCMs.

Slide 17 Clouds also interact with the aerosol environment in several ways as it changes with time. The interaction depends on the type of aerosol, the concentration of the aerosol, and the type of cloud. For liquid clouds, aerosols that are soluble in water are the most efficient cloud condensation nuclei, and if small concentrations of these aerosols exist, cloud droplet formation is limited by aerosol concentration and thus an increase in aerosol leads to an increase in cloud droplet number, which for a given amount of available vapor implies smaller droplets. The increased total surface area of the smaller, but greater in number, droplets makes the cloud more reflective. This is called the first indirect effect or 'Twomey' effect. The Twomey effect has been observed in ship tracks, local concentrations of aerosols that produce more reflective cloud with smaller droplet sizes under the right conditions. The magnitude of the first indirect effect for industrial, transportation-generated, or biomass burning aerosols advected out to the more pristine oceans is less certain, since it is difficult to unravel the relative influence of aerosol and meteorological effects on observed clouds. Smaller droplets also potentially produce a microphysical second indirect effect, since smaller droplets precipitate from the cloud more slowly. Thus, cloud liquid water content should increase with reduced precipitation loss, and it has been hypothesized that this can increase cloud lifetime and thus time-averaged cloud cover. The second indirect effect has not been observationally verified. The hypothesized liquid water content increase may be offset by the entrainment of dry air into some clouds, which may evaporate smaller droplets more easily than larger droplets in pristine non-polluted clouds. In addition, any cloud lifetime effect must compete with the time scales on which circulation changes dissipate clouds dynamically. Another aerosol influence on clouds, the semi-direct effect, occurs by using the atmosphere as an intermediary. In the presence of an absorbing aerosol such as black carbon, air warms by SW absorption due to the aerosols. If the aerosol is within the cloud the heating of the air may evaporate cloud liquid water. If it is above a stratocumulus deck and strengthens an inversion, it may reduce the entrainment of dry air into the cloud and make the cloud optically thicker. If it occurs beneath the base of a convective cloud, it may destabilize the column and promote convective growth. The magnitudes of all these effects are highly uncertain.

Slide 18 Clouds also interact with aerosols via precipitation. The most obvious and important process is scavenging (wet deposition), by which precipitation removes aerosols from the atmosphere. Scavenging can occur when precipitating particles collect aerosols below-cloud base (below-cloud scavenging), or since liquid droplets nucleate onto aerosols, any droplet that precipitates by definition removes aerosol from the atmosphere (in-cloud scavenging). A more controversial hypothesis is the invigoration of deep convection by aerosols. In deep convection, liquid droplets are carried by updrafts above the 0°C level and become super-cooled. When they collide with ice crystals and freeze (glaciate), the additional latent heat release strengthens the updraft and allows it to penetrate higher. It has been proposed that with a higher aerosol concentration, the smaller droplets that form are more easily carried upward to the colder regions of the cloud and promote additional freezing, invigorating the convection. The extent to which this occurs in varying environmental conditions is poorly understood, and whether any such effect is transient or affects convection over its entire lifecycle is not yet determined.