CLIMATE CHANGE:
Past, Present and Future

University of Reading

- Session 8: Clouds and Climate
  - What are clouds?
  - Why are they important?
  - Cloud Feedback

Why are clouds important?

- Influence Earth's radiative energy balance
- Key components of global cycle of water
  - Rainfall, snowfall
- They Influence and are influenced by atmospheric circulation
- Highly complex and interacting processes
  - Uplift and turbulance
  - Heat exchanges (radiative and latent heat exchanges)
  - Condensation, evaporation
  - Microphysical processes (linking aerosol and clouds)

Clouds are integral to the climate system.

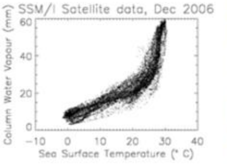
They are a crucial component of the global water cycle, vital to humans and to ecosystems which depend upon fresh water.

They are important signals of the atmospheric circulation that aid our ability to predict the weather.

Clouds are also crucial for climate and climate change. In addition to their powerful role in the hydrological cycle, they strongly interact with the Earth's radiative energy balance. They cool the surface by shading it from the direct solar beam but almost as strongly enhance the greenhouse effect of the atmosphere by reducing the efficiency by which the surface can cool to space through thermal emission.

Their formation processes and radiative properties are complex and thus predicting how they will respond and influence climate change is an extremely difficult challenge.

How and why do clouds form?



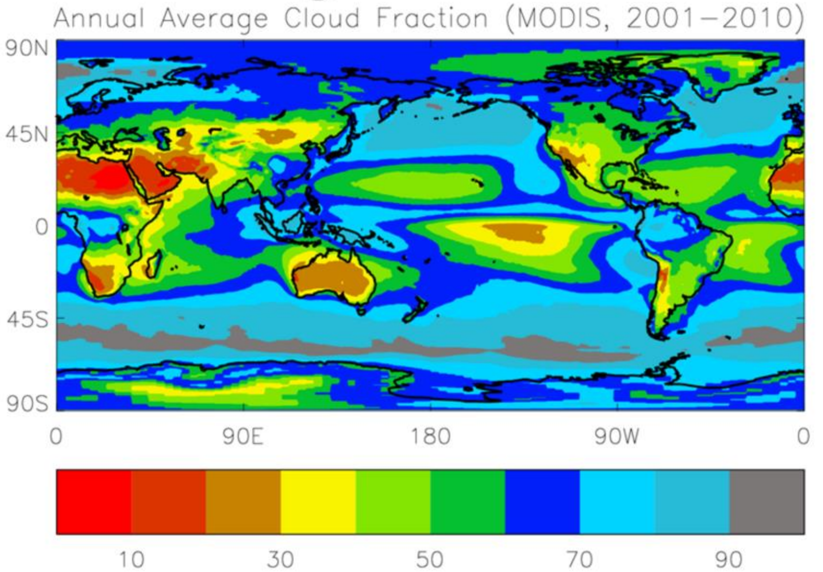
- The atmosphere can only hold certain amount of gaseous water vapour before saturation occurs
  - The fraction of water vapour relative to its saturated amount is termed Relative Humidity (RH)
  - 100% RH leads to saturation and condensation
  - Dew is also an example of condensation
  - High humidity is uncomfortable to humans since we are less able to lose heat via evaporation
- The amount of water vapour the air can hold rises rapidly with temperature

Clouds form because the air can only hold a certain amount of gaseous water vapour, just like water can only dissolve a certain amount of salt.

If there is more water vapour in the air than the air can hold, condensation of cloud droplets and ice may occur which are the clouds we observed. Crucially, the amount of water the air can dissolve is dependent on the temperature of the air.

Condensation also requires a surface on which to act, for example, condensation on vegetation as is the case for morning dew. Clouds form on condensation nuclei, tiny particles in the atmosphere such as sea salt, dust and other aerosols. Sometimes "super-saturation" can occur: the air is so pristine that cloud cannot form due to the lack of condensation nuclei.

Average percentage cloud coverage from satellite



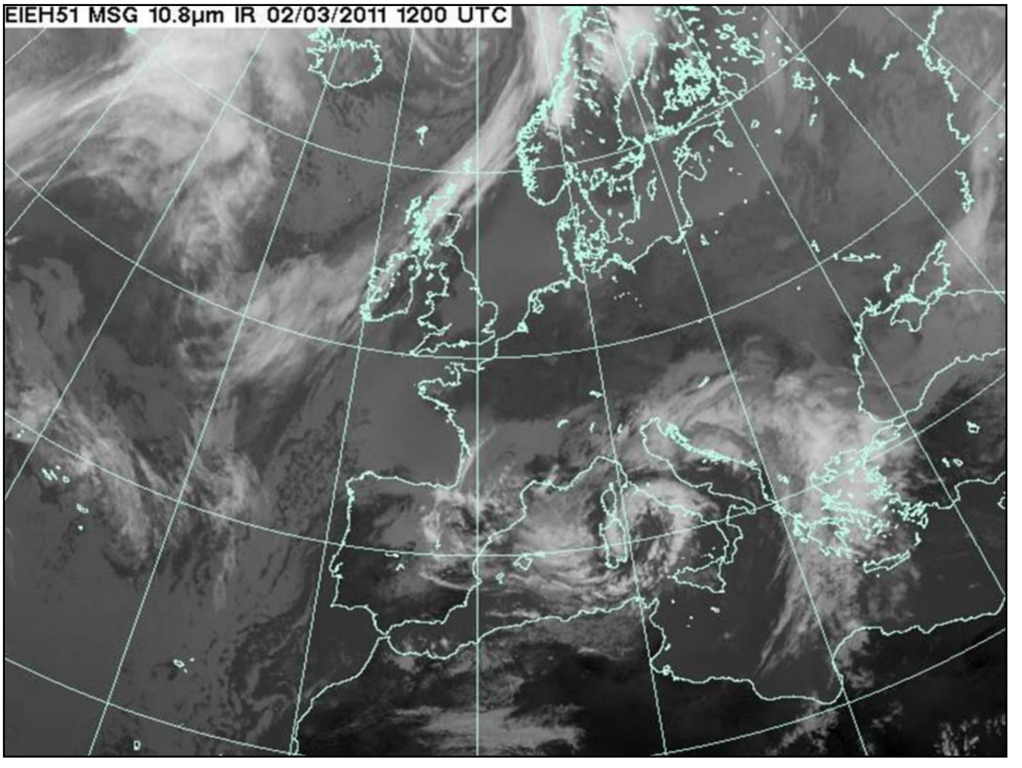
Satellite measurements show that the global annual average cloud coverage is about 60% (the above data from the MODIS instrument onboard the TERRA satellite gives a value of 61.6% cloud cover over the period January 2001 to December 2010). These estimates were constructed from measurements of energy emanating from the planet in distinct parts of the electromagnetic spectrum.

However, it is slightly problematic to define cloud coverage since there is a rich spectrum of clouds ranging from tropical cyclones to small cumulus and tenuous, thin cirrus. The latter categories may sometimes be mis-classified as clear-sky. How frequent is the sky completely clear??

Clouds and Climate

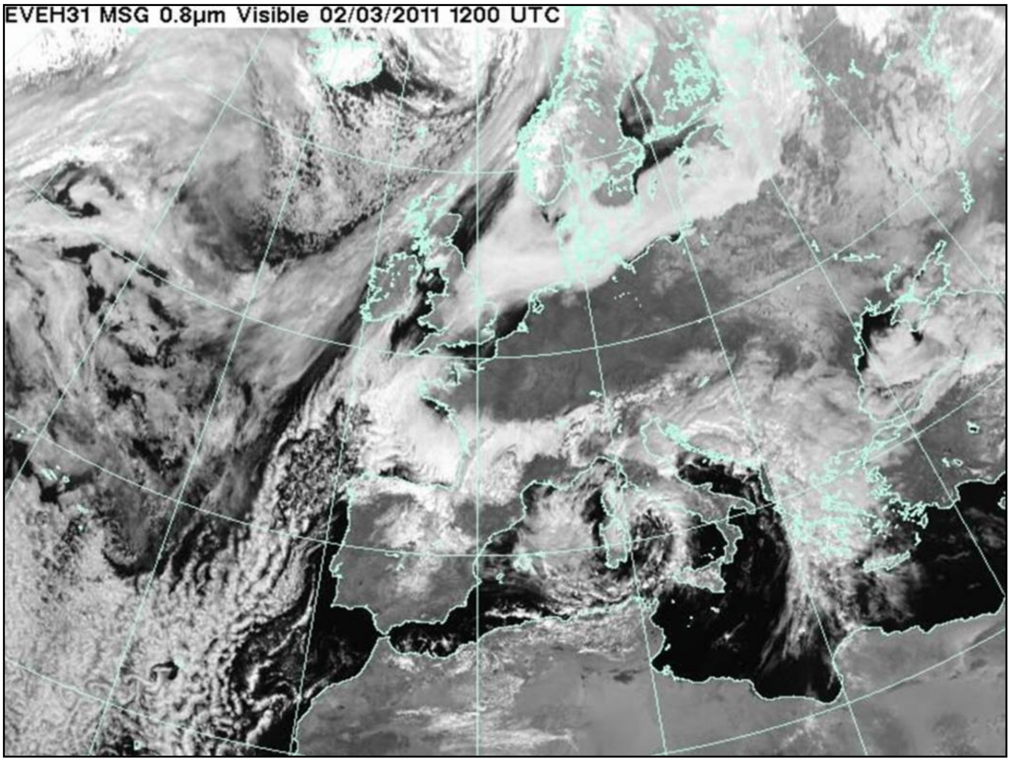
- Most of the water in the atmosphere is invisible vapour. The small amount of liquid water and ice are critical to climate
  - clouds are the tip of the iceberg
  - …water vapour with attitude
- Clouds interact strongly with longwave and shortwave radiation through emission, absorption and scattering
  - radiative effect is highly variable in time and space
- How will clouds respond to climate change?
  - Will they amplify (positive feedback) or retard (negative feedback) the response of the climate system to a forcing?

For further reading, see the IPCC (2013) Working Group 1 Frequently Asked Question 7.1: http://www.metlink.org/wp-content/uploads/2014/05/FAQ7_1.pdf

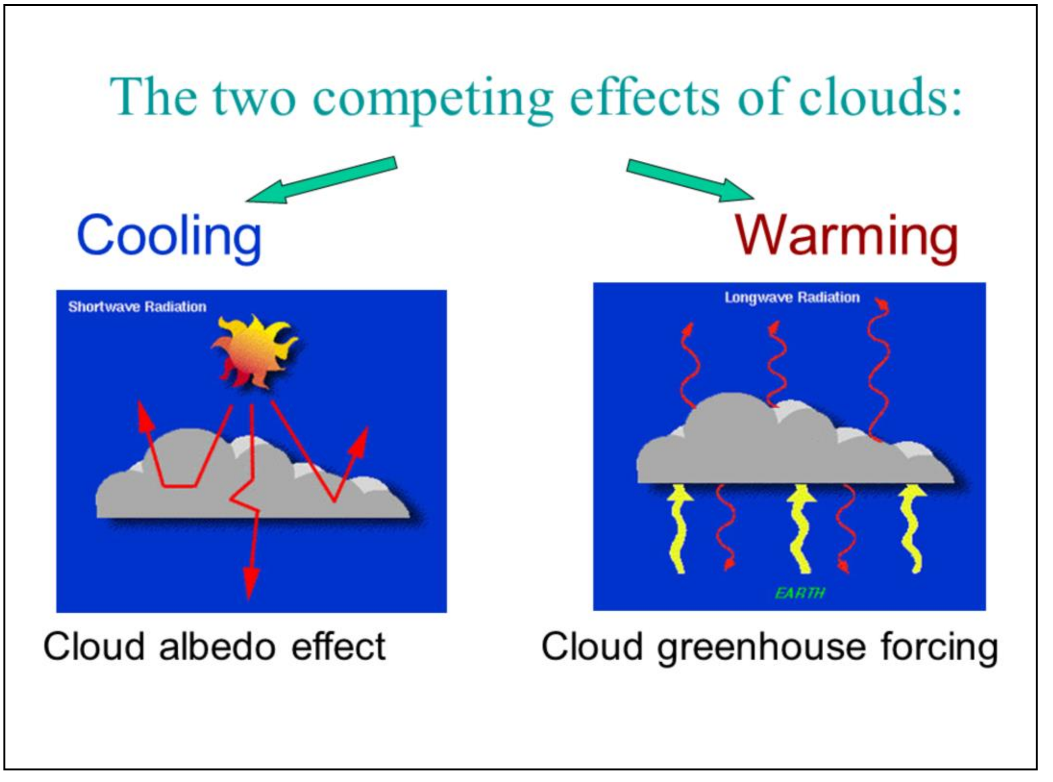


Clouds reduce the thermal emission to space thereby enhancing the natural greenhouse effect of the atmosphere. This occurs because the cloud top temperature, which determines thermal emission, is lower than the surface temperature (temperature generally falls with height in the troposphere).

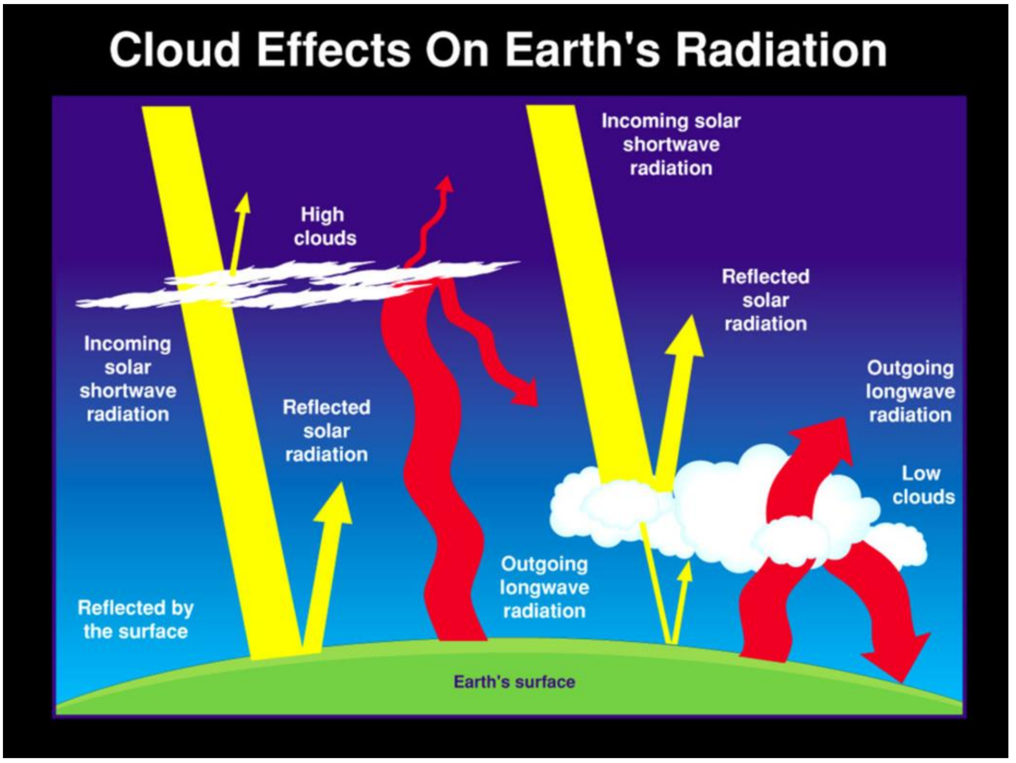
Note that in the picture above (from the Meteosat SEVIRI instrument) that hot land is dark, cold, high altitude cloud is white.



Clouds reflect solar radiation back to space. Above, the thickest clouds are white since the amount of solar raditaion being reflected back to space is substantial. The clear oceans appear dark since oceans readily absorb solar radiation. Land regions appear intermediate since land surfaces are generally more reflective than the oceans but darker than thick clouds (although fresh snow and ice is also highly reflective).



Clouds exert a cooling effect and warming effect on weather and climate. Whichever effect dominates depends on the cloud properties but also, crucially, how much solar radiation is incoming.



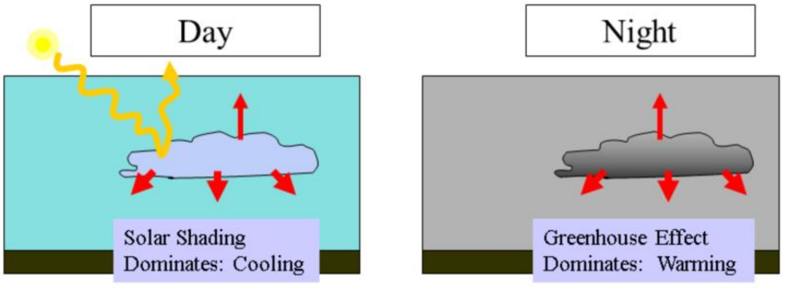
Clouds tend to cool in the day and warm at night relative to the clear-sky atmosphere. This is simply because there is large amounts of solar radiation in the day but none at night. When averaged over day and night clouds tend to have overall cooling effect relative to the cloud-free atmosphere. This does not mean they are causing temperatures to drop, merely that if you suddenly removed all cloud, the Earth would heat up.

Low clouds explain much of this cooling effect since the the cloud albedo effect (cooling) dominates over the cloud greenhouse effect (warming).

It is often reported that high clouds exert a net warming effect on climate. This is true for thin clouds, but for thicker high clouds, the cloud albedo effect and greenhouse effect roughly cancel out.

Radiative effect of clouds

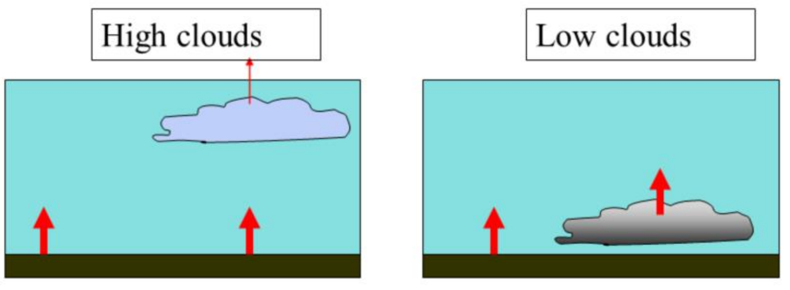
- Clouds that are "optically thick" reflect and scatter larger proportion of solar radiation than thinner clouds
- Clouds shade the surface from the sun during the day, thereby cooling the ground
- Solar shading (cooling) effect dominate during day while greenhouse effect (warming) continues unopposed at night



Although the cloud greenhouse effect operates constantly, in the day this effect is swamped by the solar shading (cooling) effect. At night, the greenhouse warming effect continues unopposed leading to a warming effect.

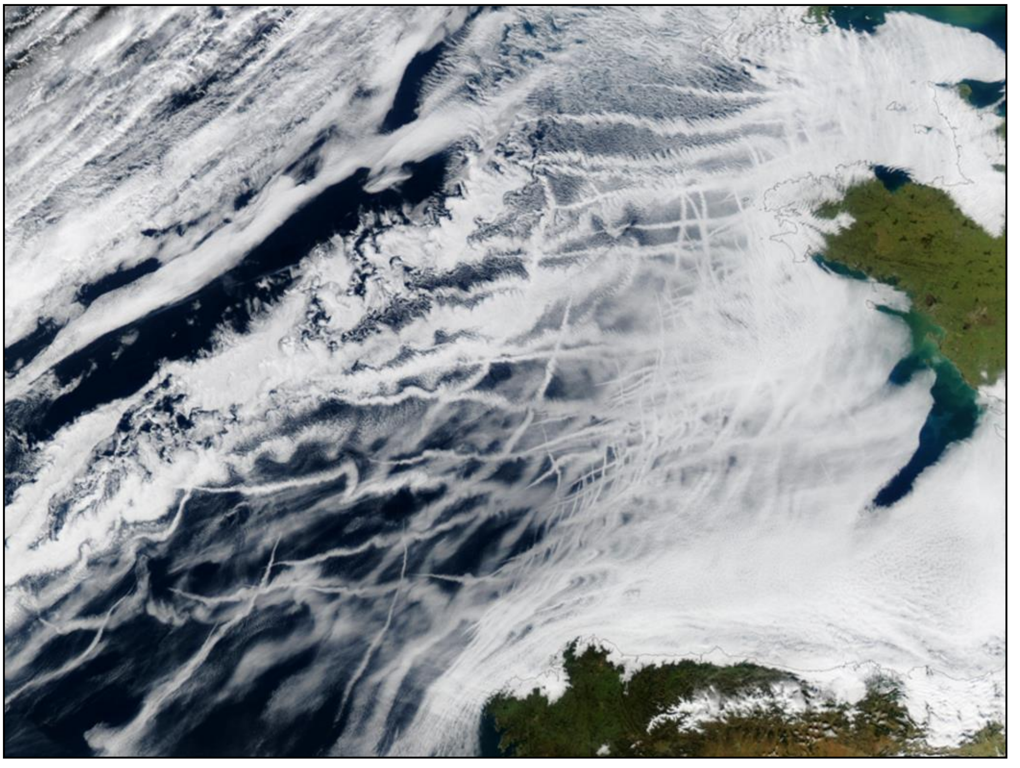
Radiative effect of clouds

- High clouds have a large greenhouse effect
  - Cloud top emission temperature very low
- Low clouds have a small greenhouse effect
  - Cloud top emission similar to the surface

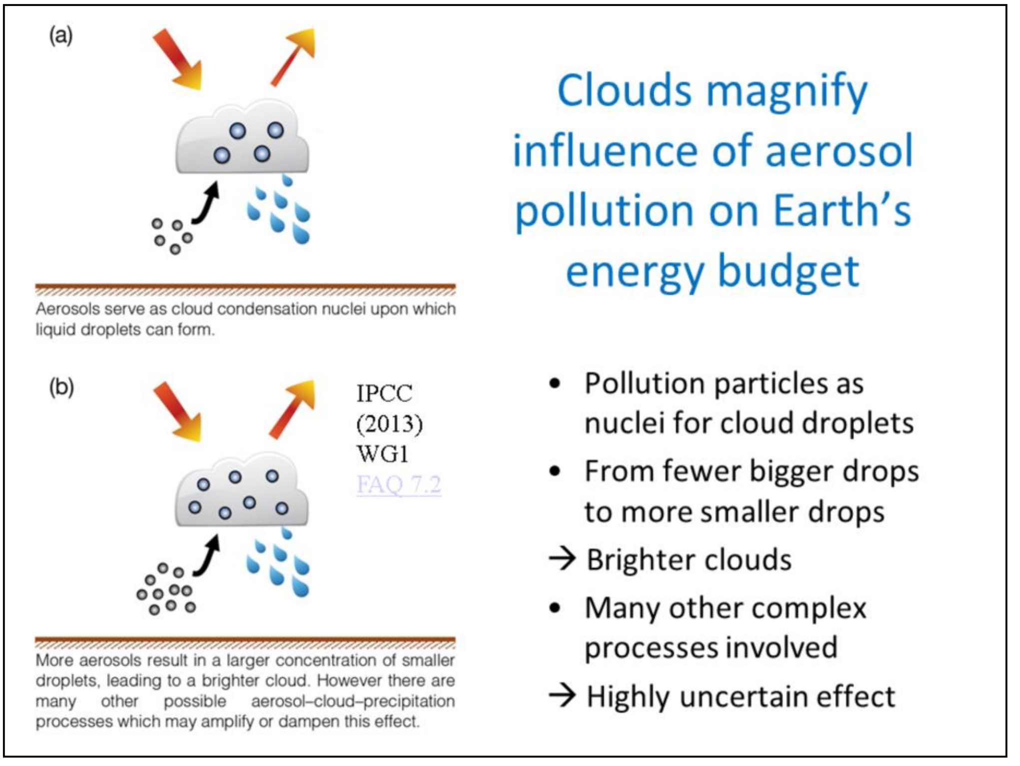


The greenhouse effect of clouds depends on how much the cloud can reduce the outgoing flow of thermal radiation to space. This effect is strongest for clouds with high altitude tops since the cloud tops will be extremely cold, relative to the surface, and therefore only emit a small fraction of the surface emission out to space.

Since low cloud tops emit thermal radiation at a similar rate to the surface, due to the similar cloud top and surface temperature, the greenhouse effect of low clouds is small.

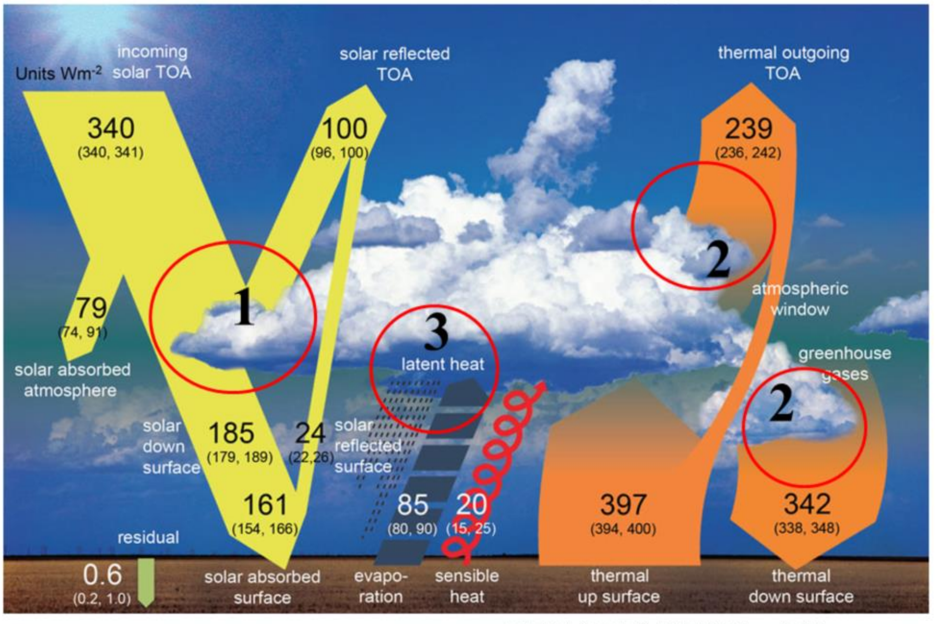


Clouds are also modified by pollution. The picture above shows that where ships have travelled across the ocean, clouds are more visible. This is primarily because the pollution particles from the ships alters the characteristics of the cloud.



The amount of sunlight that clouds scatter depends upon the sizes and number of the droplets as well as how thick they are (how much water they contain). Aerosol pollution particles can modify the characteristics of cloud: in particular they act as condensation nuclei for droplets to form and cause more numerous, smaller droplets which makes clouds brighter than they would otherwise have been in a more pristine environment. Therefore clouds effectively amplify the influence of aerosol pollution particles on climate. However, there are many other complex ways in which clouds are modified by aerosol which makes the size of the aerosol cooling effect highly uncertain.

Clouds affect Earth's energy balance



IPCC (2013) WG1 Fig. 2.11

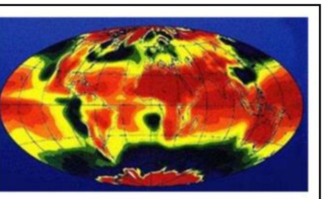
In the global mean radiation balance, clouds:

1) cool the surface by the solar shading effect

2) warm the atmosphere beneath the cloud by the greenhouse effect

3) heat the atmosphere once water condenses and is lost via precipitation thereby transfering energy from the surface (evaporative cooling) to the atmosphere (latent heating)

Global effect of clouds on radiation balance



- Satellite observations show that clouds exert a net cooling effect on the present climate
  - Calculated from differences between cloudy-sky and clear-sky radiative fluxes to space
  - thermal effect warms planet by ~30 Wm^{-2}
  - Solar shading cools planet by ~50 Wm^{-2}
  - Net cooling of ~20 Wm^{-2}
    - ~10% of clear-sky greenhouse effect

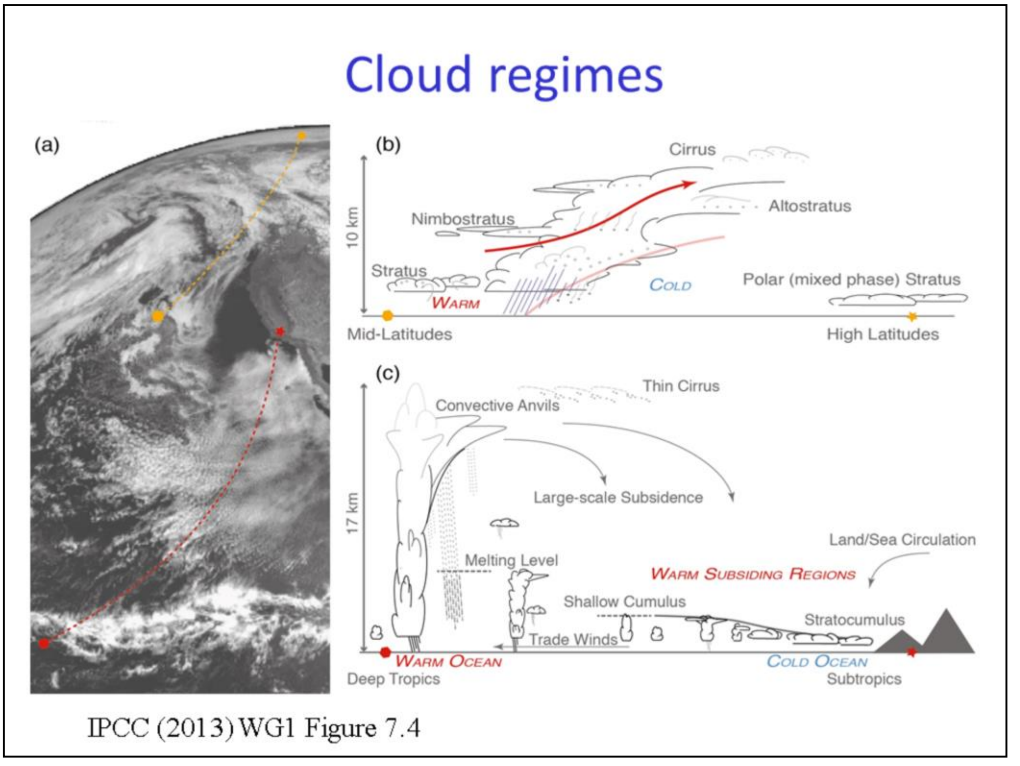
Averaged globally and over day and night, the cooling effect of clouds dominates over the greenhouse effect. This net cooling effect is approximately 10% of the strength of the clear-sky greenhouse effect from water vapour and other greenhouse gases including CO_2.

It is important to note that although the effect of clouds is to keep climate slightly cooler than it would be otherwise, their effect on climate change is not clear. If this cooling effect diminishes with warming (for example if clouds trap more infra-red outgoing radiation or reflect less sunlight back to space), then they will amplify any change in climate (a positive feedback). If the cooling effect becomes stronger with warming of climate (e.g. cloud greenhouse effect diminishes in a warming atmosphere or low cloud extent becomes larger) then clouds will damp down changes in climate (a negative feedback).

Potential for Cloud Feedbacks

- Deep convective and cirrus cloud
  - Small net cloud radiative effect
  - Large influence on surface/atmosphere energy and water budgets
- Boundary Layer Cloud
  - Large net cloud radiative effect
  - Extensive coverage
  - Sensitive to circulation and aerosol
- Mid-level and super-cooled cloud
  - Ice to liquid phase crucial to radiative properties

Cloud feedbacks are more complex than water vapour feedbacks because the formation processes of different types of clouds are diverse and each cloud type exerts contrasting effects on Earth's energy balance. For example, thunderstorms, low level stratocumulus and mid-level altostratus are very different in their formation and properties and may respond very differently to changes in surface temperature, both amplifying or reducing the changes depending on the cloud meteorological regime.

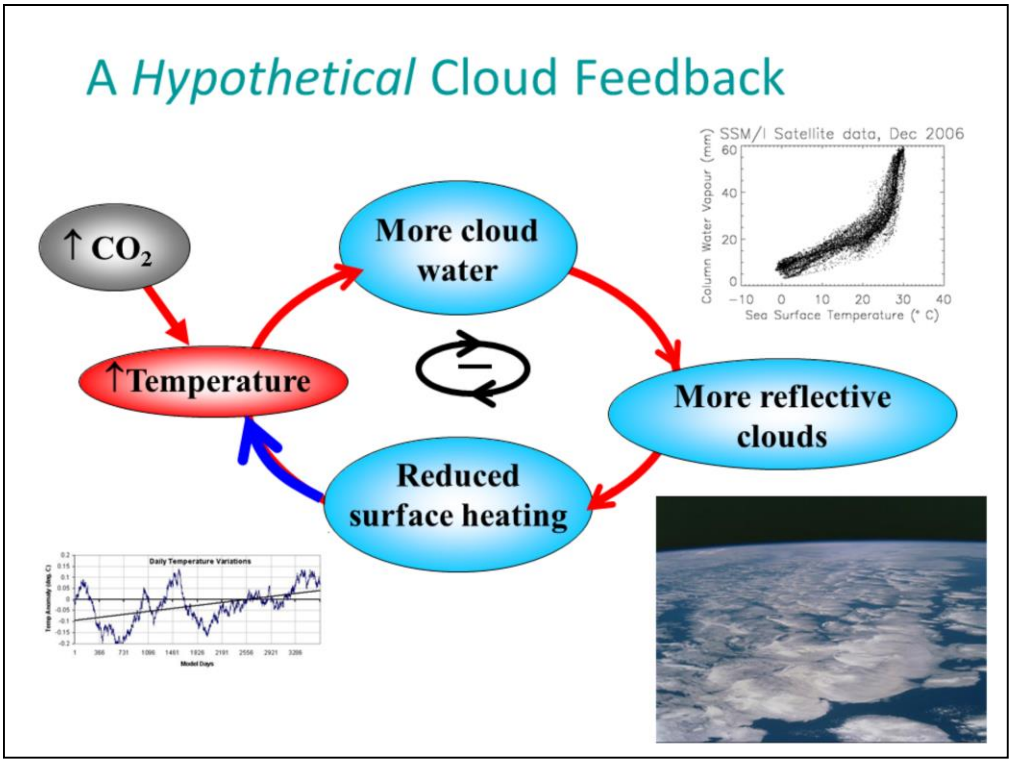


Diverse cloud regimes reflect diverse meteorology. Above left shows a visible-wavelength satellite image which captures mid-latitude weather systems at the top and depicted schematically top right for a path through the yellow line). To the bottom of the satellite image, along the red line travelling upward from the bottom you see thunderstorms as the brightest clouds, then broken cumulus and finally extensive sheets of low-level stratocumulus cloud as depicted in the schematic bottom right (from left to right) [IPCC (2013) WG1 Figure 7.4]

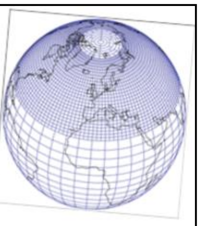
Cloud Feedback: a complex problem

- Although clouds cool the present day climate, this does not tell us whether they will amplify or counteract global climate changes
- How will clouds respond to global warming?
  - More clouds? Less Clouds?
  - Thicker clouds? Thinner clouds?
  - Higher clouds? Lower clouds?
  - More high thin clouds? More low clouds?

The fact the clouds exert a net cooling effect on the current climate does not tell us much about whether clouds will amplify global warming (positive feedback) or counteract global warming (negative feedback). To know what sign and magnitude feedback clouds may provide, we need to know how clouds will respond to climate change. For example, if cloud properties stay the same but coverage increases, clouds will likely counteract global warming (since clouds have a net cooling effect on present day climate). Alternatively, if low cloud cover diminishes with warming, the reduced cloud albedo effect will heat the surface, amplifying the initial warming.



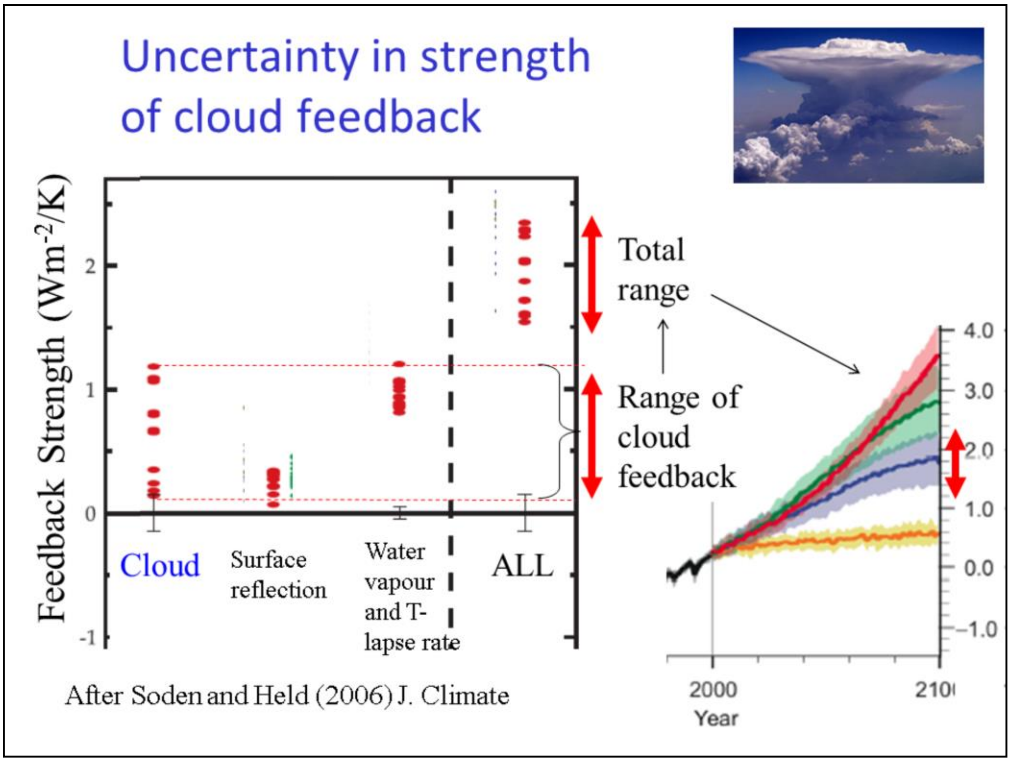
Above is a hypothetical cloud feedback – it is not one that has been confirmed. If cloud water increased in a warmer world, this would make clouds brighter, thereby counteracting some of the warming – a negative feedback. Positive cloud feedback appears likely for high tropical cirrus but climate simulations produce both positive and negative feedbacks for low altitude clouds so the jury is still out on the overall cloud feedback.



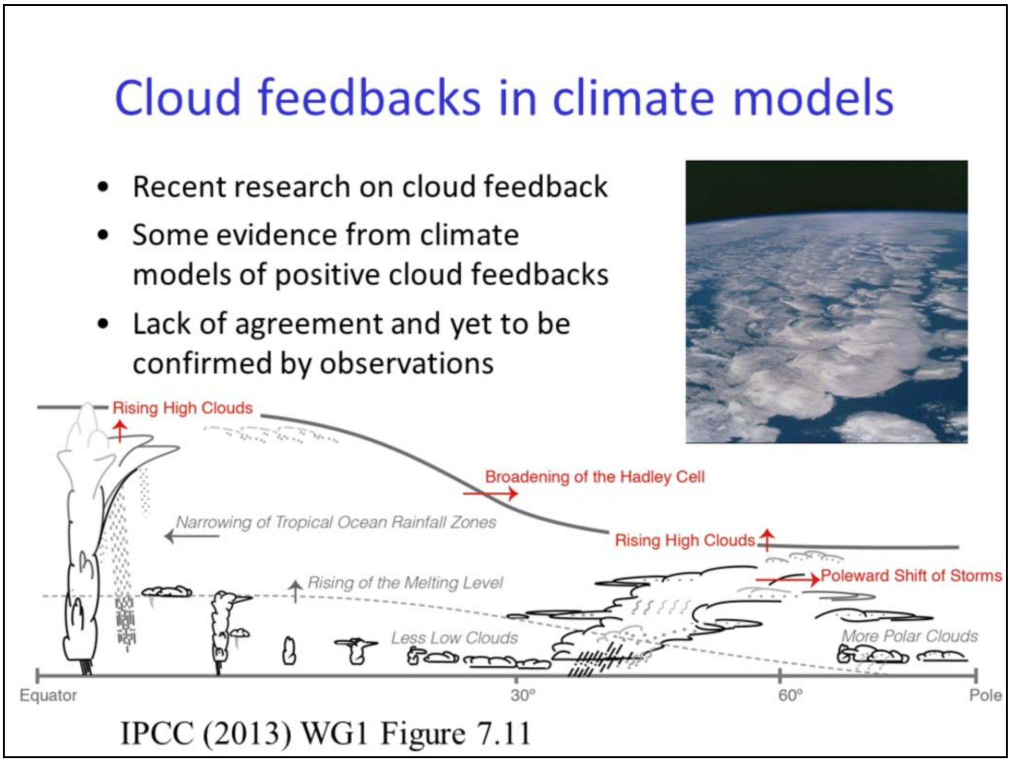
What do climate simulators tell us?

- Current climate models suggest that clouds generally enhance warming (positive feedback)
- But there is a large range in cloud feedback in the models, explaining much of the uncertainty in predictions of future warming
- …and we don’t know whether any model accurately represents cloud feedback

The state of the art coupled climate models used in the IPCC (2007,2013) generate fairly neutral feedbacks up to strongly positive feedbacks (they amplify the warming). However, the range in the magnitude of cloud feedback is large and explains much of the uncertainty in the prediction of future warming by the models.

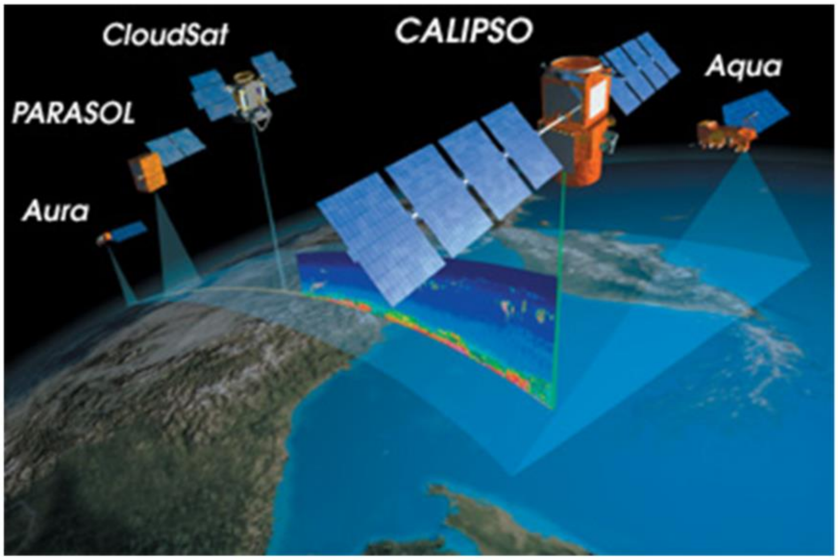


For a given future scenario (e.g. blue or red lines in right plot) there is a range of temperature responses expected over the coming century. The reason for this is that different climate simulators (models) give different climate responses to the radiative forcing from increased concentration of greenhouse gases. In some models there are stronger positive feedbacks than in other models (note that no models have an overall negative feedback). Research shows that most of this range in feedback strength in the models stems from cloud processes. In some models cloud feedback is strongly positive (like water vapour feedback) whereas in other models the cloud feedback is close to zero. It is not well known which, if any, of the models provides the most realistic overall feedback.



There is some agreement amongst climate model simulations of how clouds may respond to a warming climate. In the above diagram the red text and arrows depict changes that amplify warming (positive feedbacks) while grey text and arrows depict cloud feedbacks that are either small or very uncertain. For example models do not agree whether low clouds (which have a cooling effect on climate) will become more extensive (negative feedback) or less extensive (positive feedback) and this is one of the largest contributions to the uncertainty in how sensitive the climate is to a particular change in greenhouse gas concentration. Even with this information from simulations, there is a lack of observational confirmation of the strength of cloud feedback and even whether clouds will amplify or diminish temperature responses to rising greenhouse gas concentrations.

Current Satellite Measurements



A constellation of satellites is currently active, measuring cloudiness in unprecedented detail. More are planned (e.g. Earthcare) Meanwhile the search for a smoking gun on cloud feedback remains elusive…

Clouds and Climate: Conclusions

- Clouds crucial to weather and climate
  - Global water cycle
  - Radiative Energy Balance
- Clouds currently exert a cooling effect
  - Cooling by day, especially thick, low clouds
  - Warming by night, especially for high altitude clouds
- Complex cloud processes
  - Difficult to represent in computer models
  - Magnify influence of aerosol on climate
  - How will clouds respond to global warming?
  - Uncertainty in cloud feedback leads to large uncertainty in climate prediction
  - more observations required…