

CLOUD PHYSICS

HANNA PAWŁOWSKA

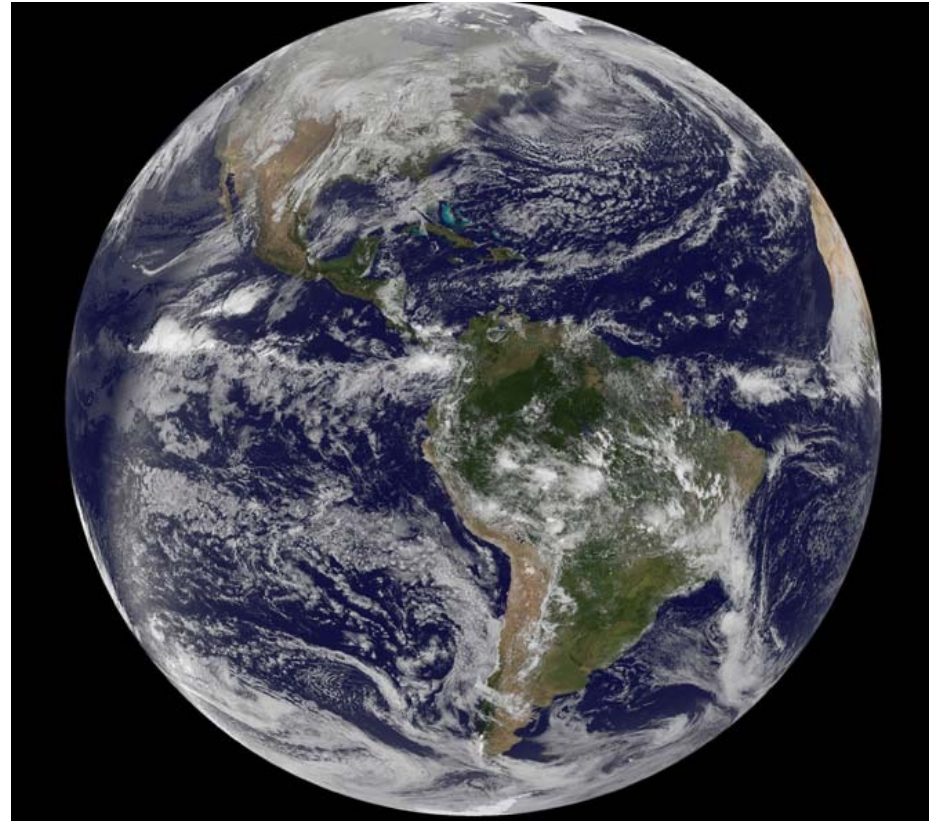
INTRODUCTION



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WHAT ARE CLOUDS?

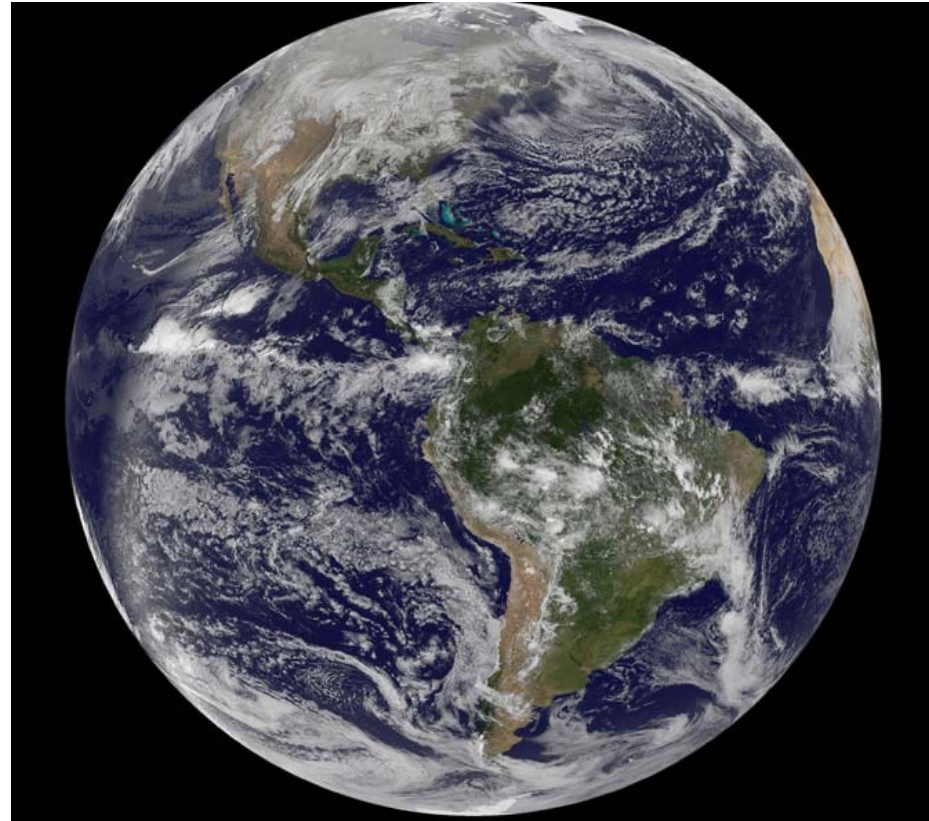


The GOES-13 satellite captured a "full-disk image" of North and South America in an image created December 30 2010 at 1445 UTC (9:45 a.m. EST), as the world awaits the new year.

Credit: NOAA/NASA GOES Project

CLOUDS ARE:

- turbulent, multiphase flows,
- collection of hydrometeors,
- key modulators of electromagnetic radiation,
- sources of latent heat,
- and a crucial component of atmospheric circulation.



The GOES-13 satellite captured a "full-disk image" of North and South America in an image created December 30 2010 at 1445 UTC (9:45 a.m. EST), as the world awaits the new year.

Credit: NOAA/NASA GOES Project

MICROPHYSICS

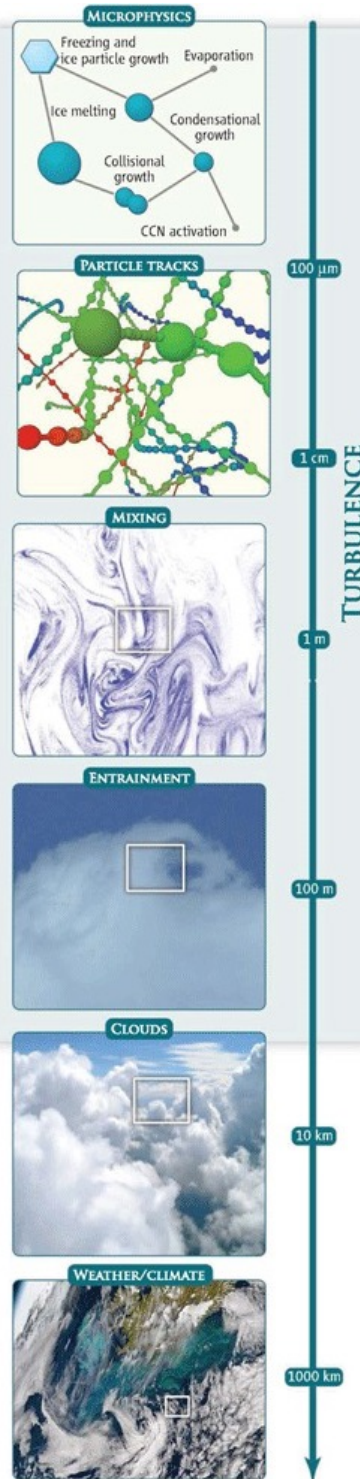
PARTICLE TRACKS

MIXING

ENTRAINMENT

CLOUDS

WEATHER/CLIMATE



A MATTER OF SCALE

100 μm

1 cm

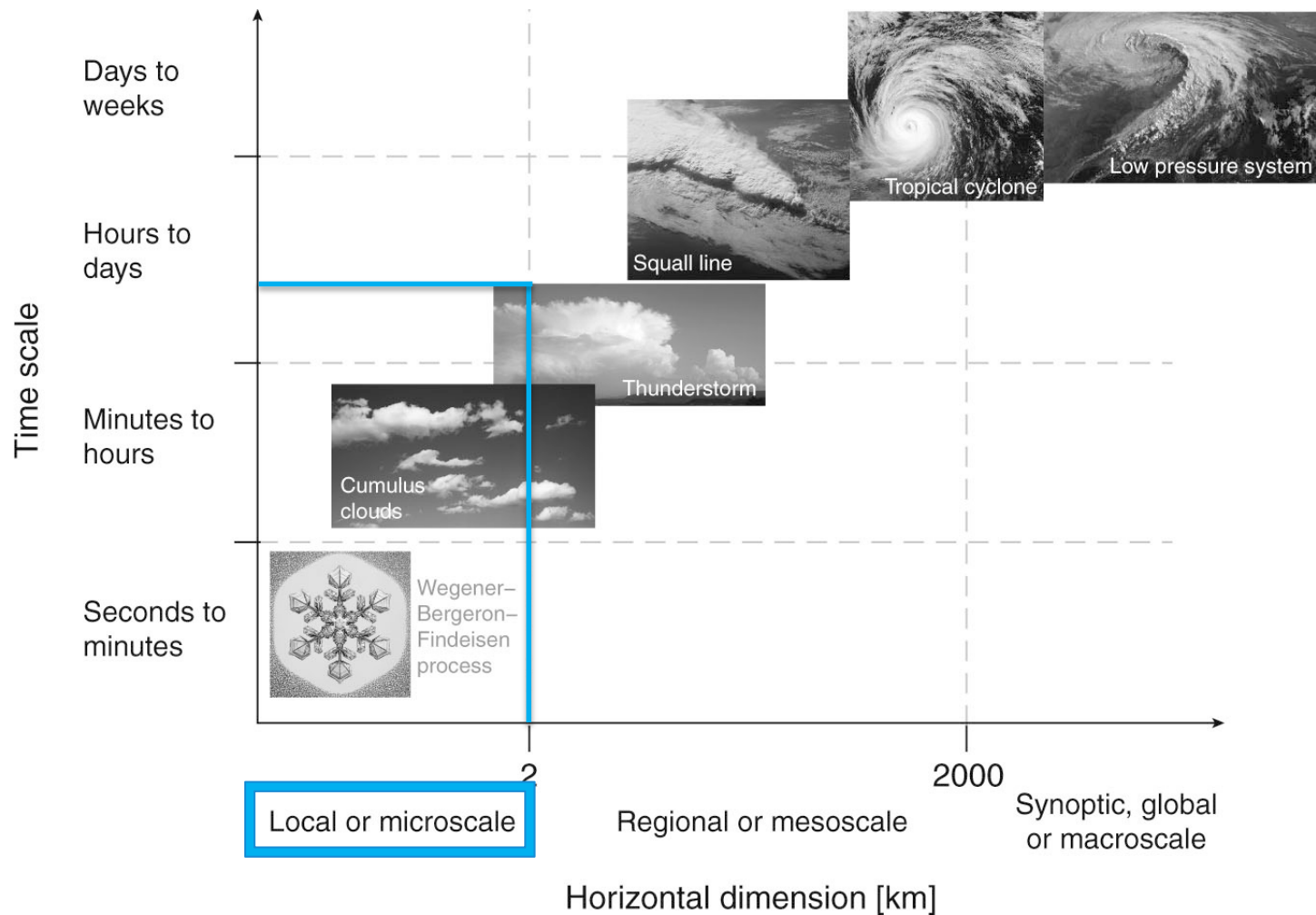
1 m

100 m

1 km

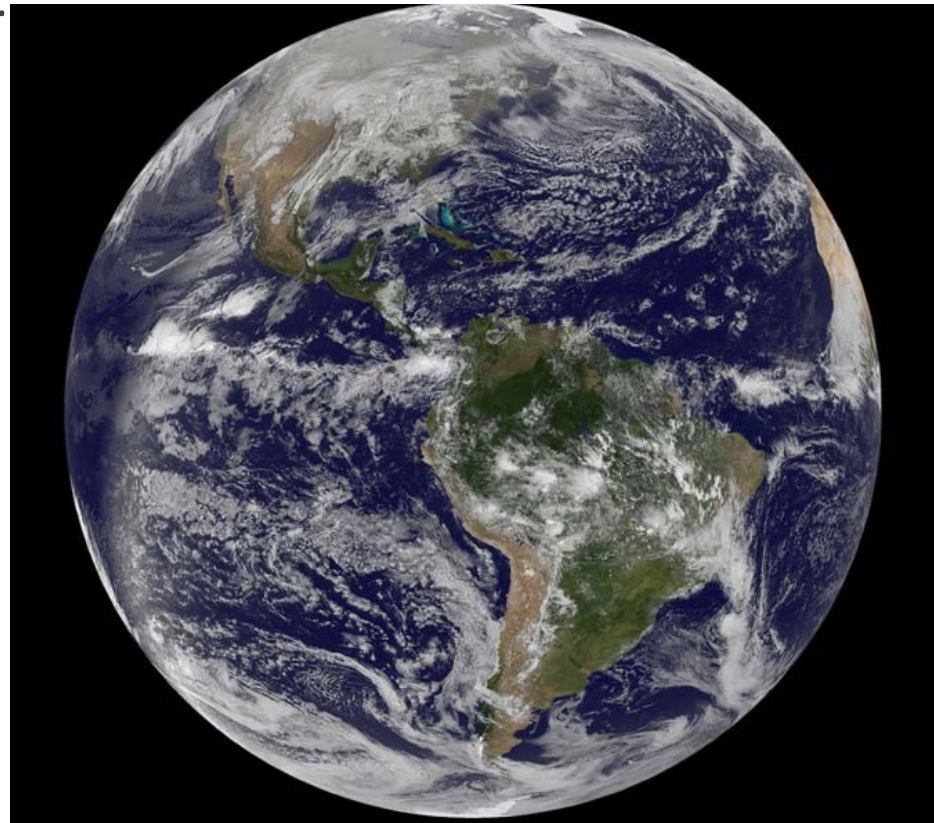
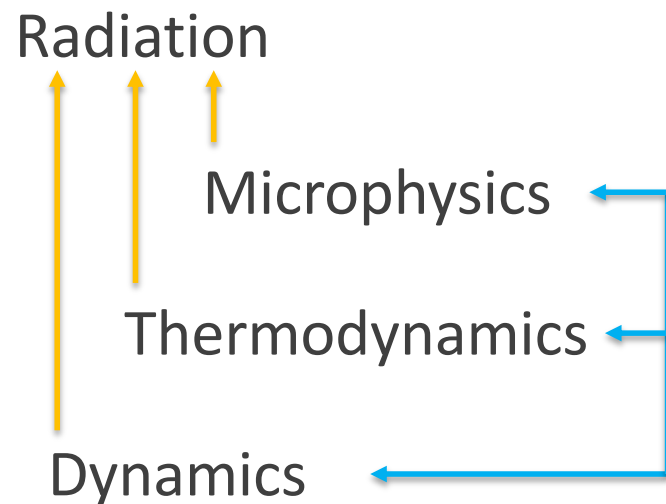
1000 km





WHY STUDY CLOUDS?

1. Clouds are coupled to the **water cycle** - they are the vessels in which **precipitation** develops.
2. They strongly modulate the **radiative** balance through their intense interactions with both shortwave and longwave radiation.

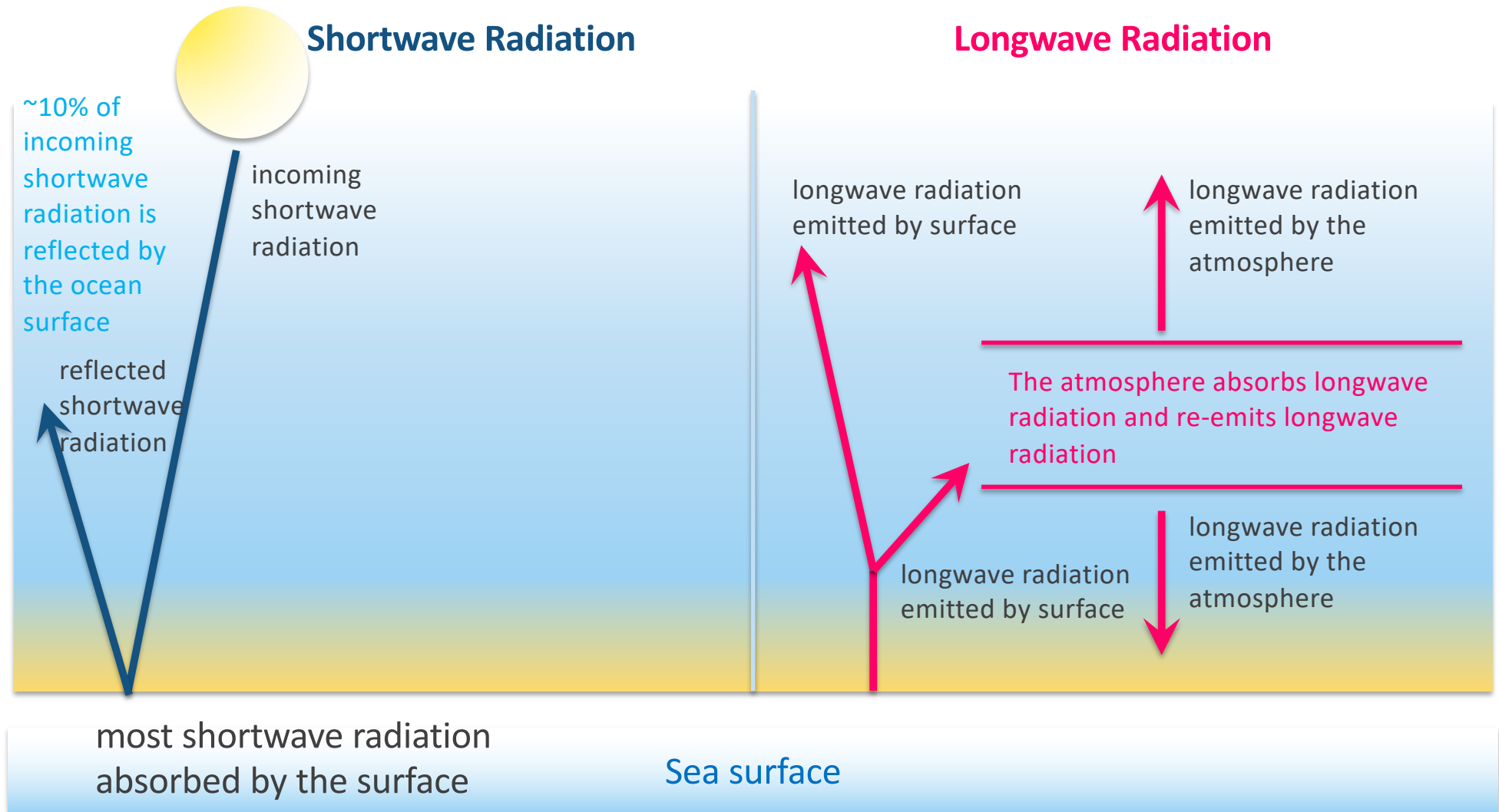


RADIATION; ENERGY BUDGET

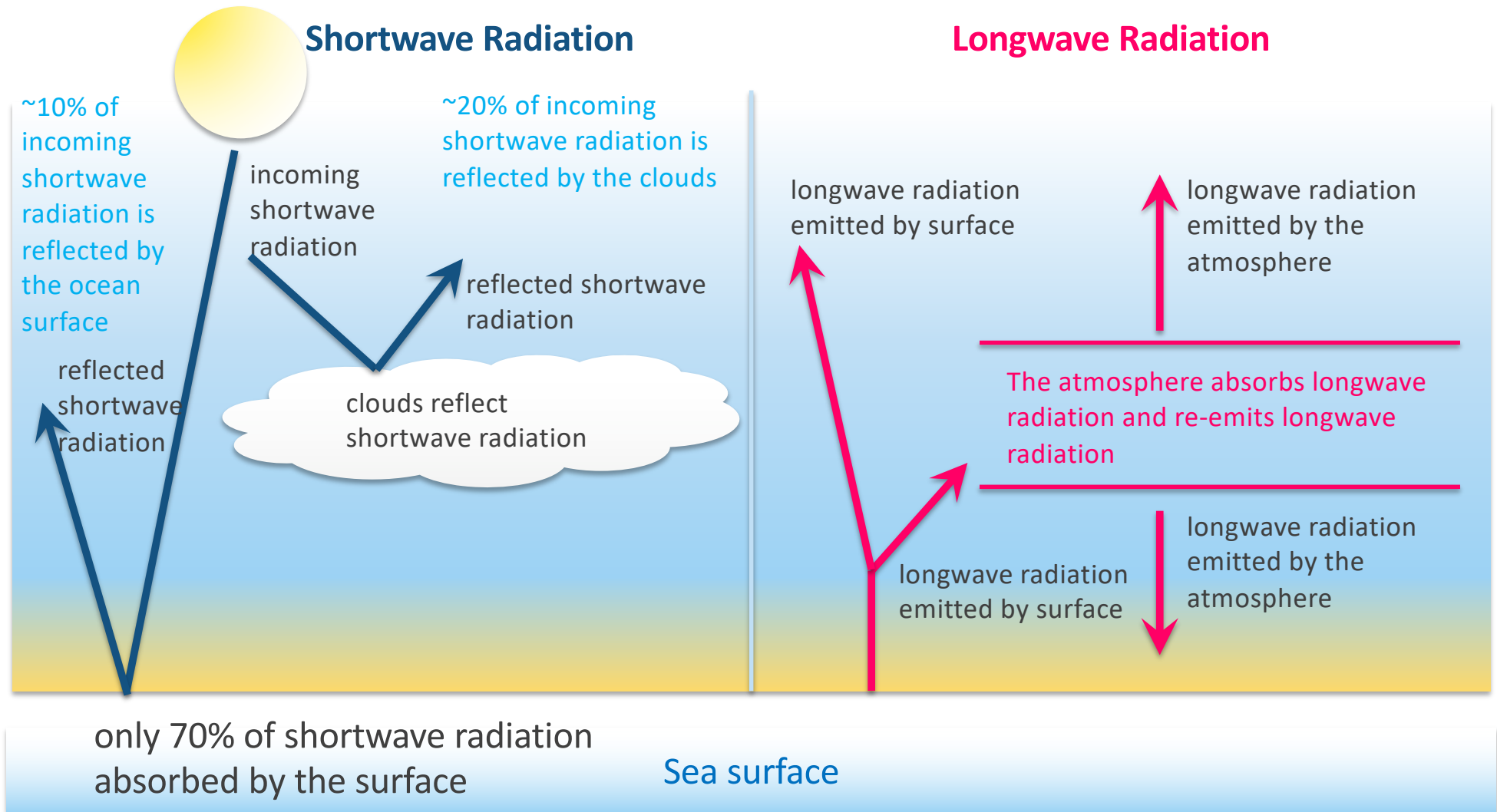


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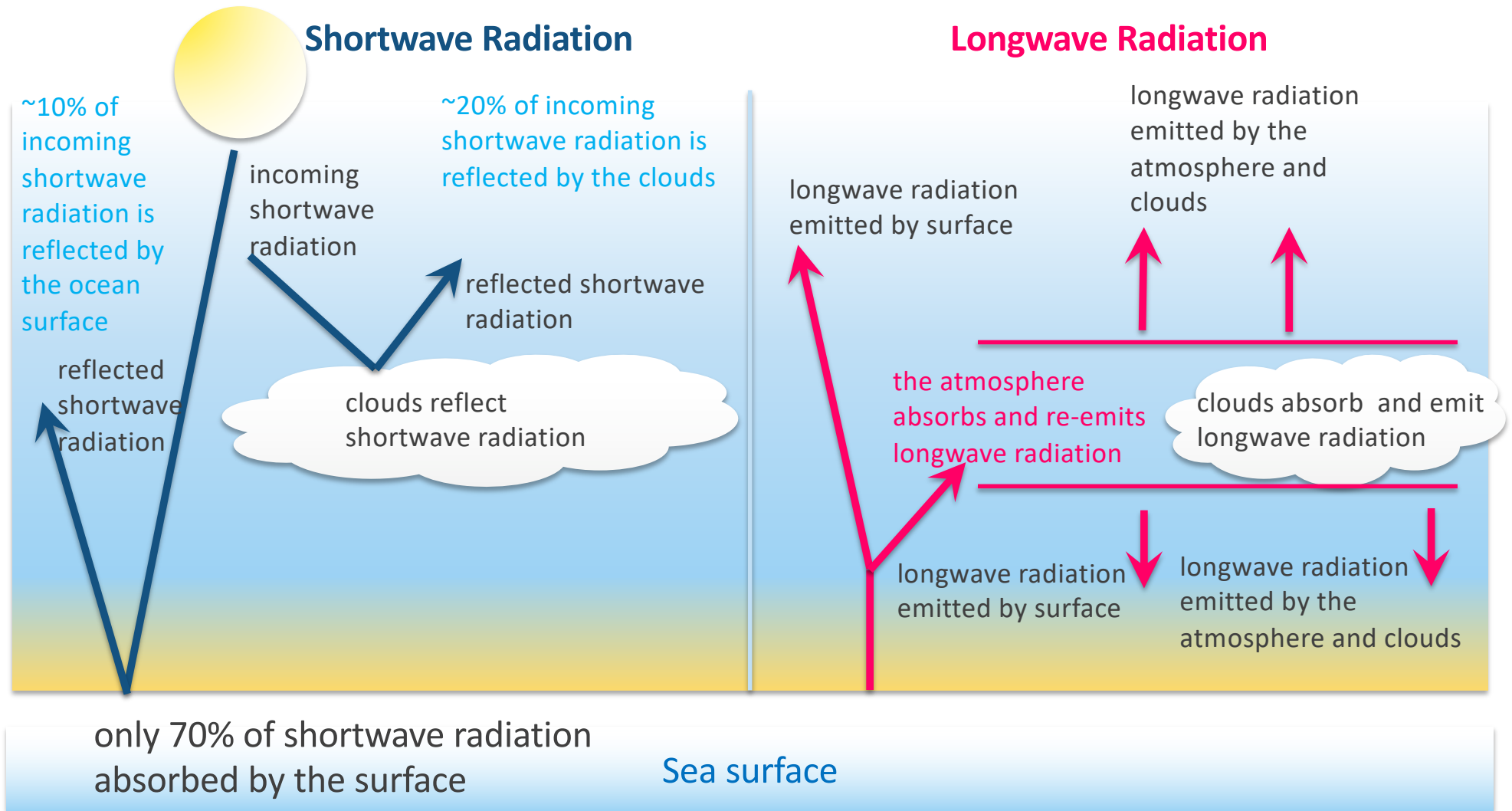
CLEAR SKY



CLOUDY SKY



CLOUDY SKY



Clouds may have a **warming** or **cooling** effect, depending on:

- their altitude,
- Cloud type,
- and the time of day (day vs. night).

Clouds reflect solar radiation back into space, exerting a **cooling effect**.

They can also absorb longwave radiation emitted by the Earth's surface, preventing it from escaping into space.

One of the largest sources of uncertainty in climate models is how clouds influence the climate system and how their role might change as the climate warms.

MICROPHYSICS → RADIATION



Droplets scatter and absorb light (**shortwave radiation**) depending on their size and the wavelength of the incoming radiation.

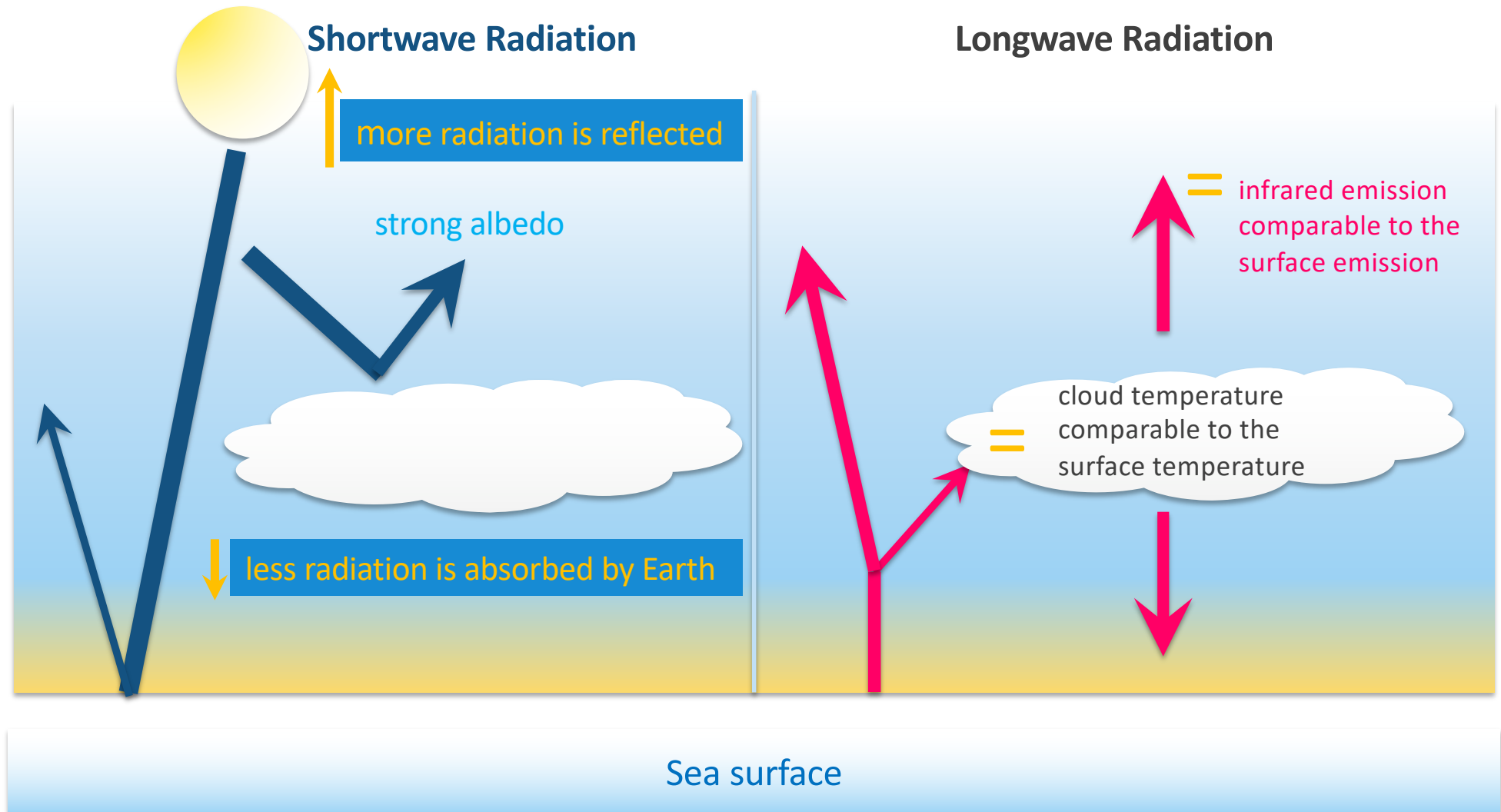
The number and size of droplets are among the key factors determining cloud radiative properties.

Cloud **longwave** radiative interactions depend primarily on their water content and temperature.

LOW CLOUDS – COOLING EFFECT

cooling effect

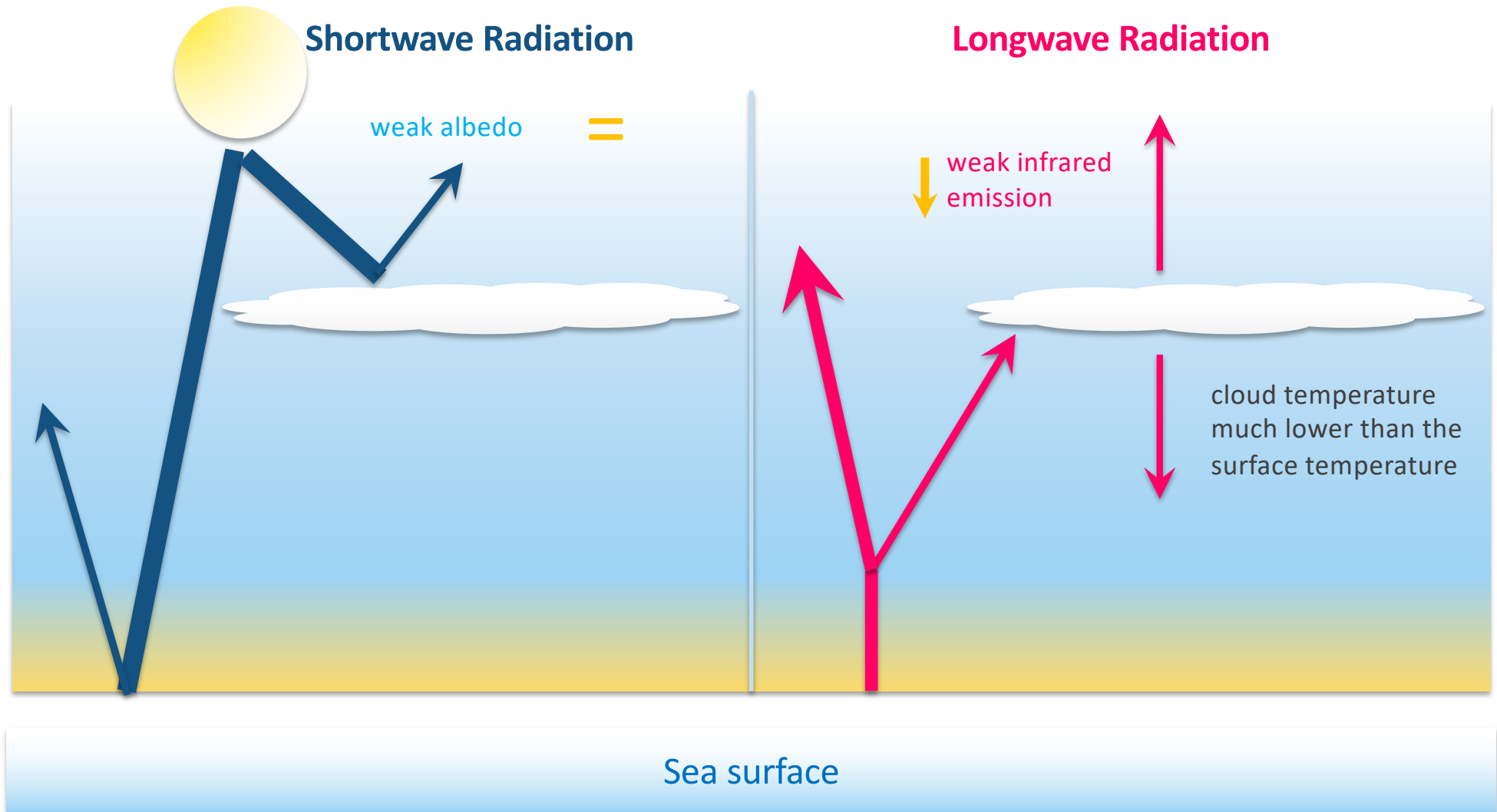
small effect



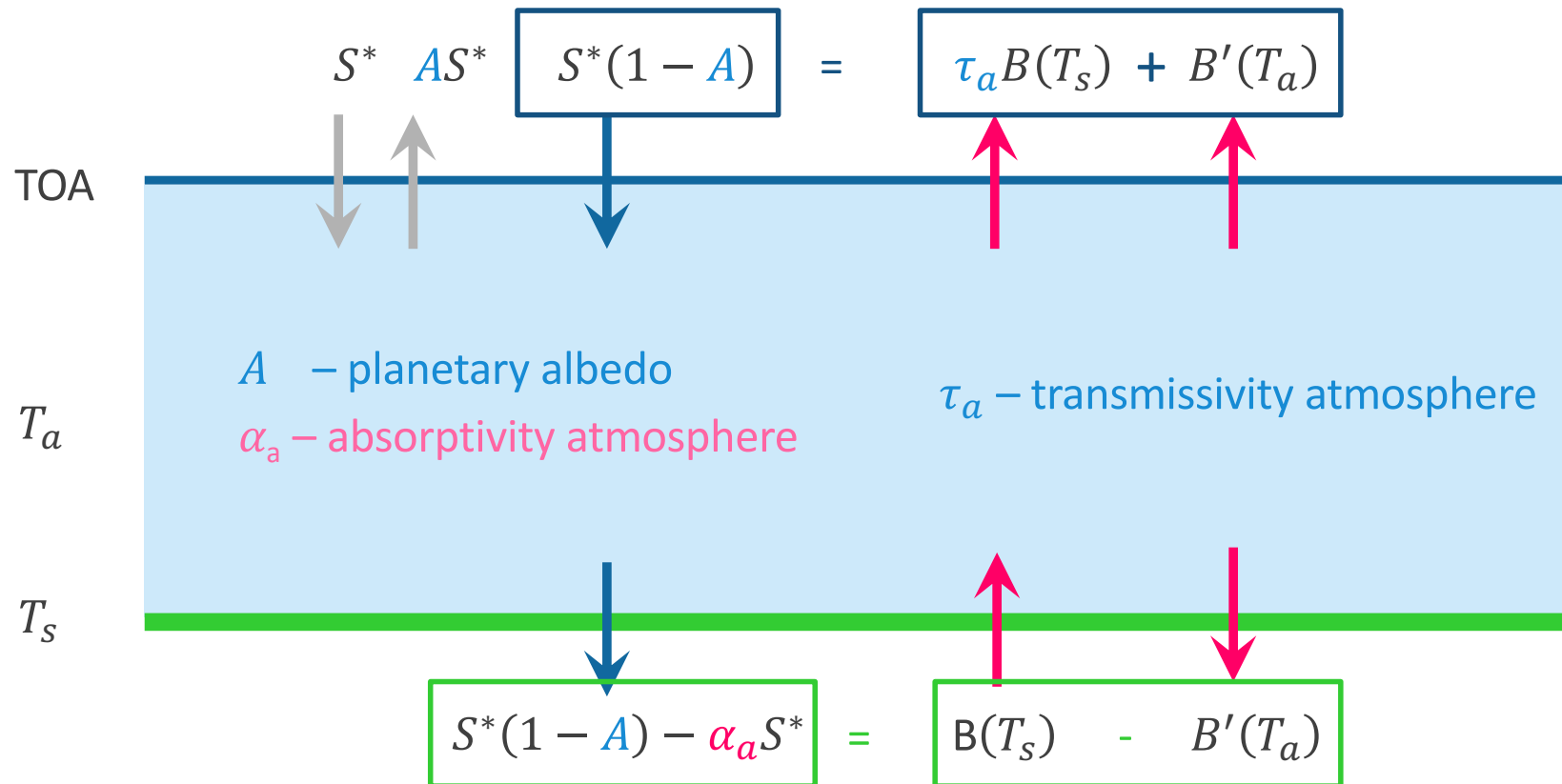
HIGH CLOUDS – WARMING EFFECT

small effect

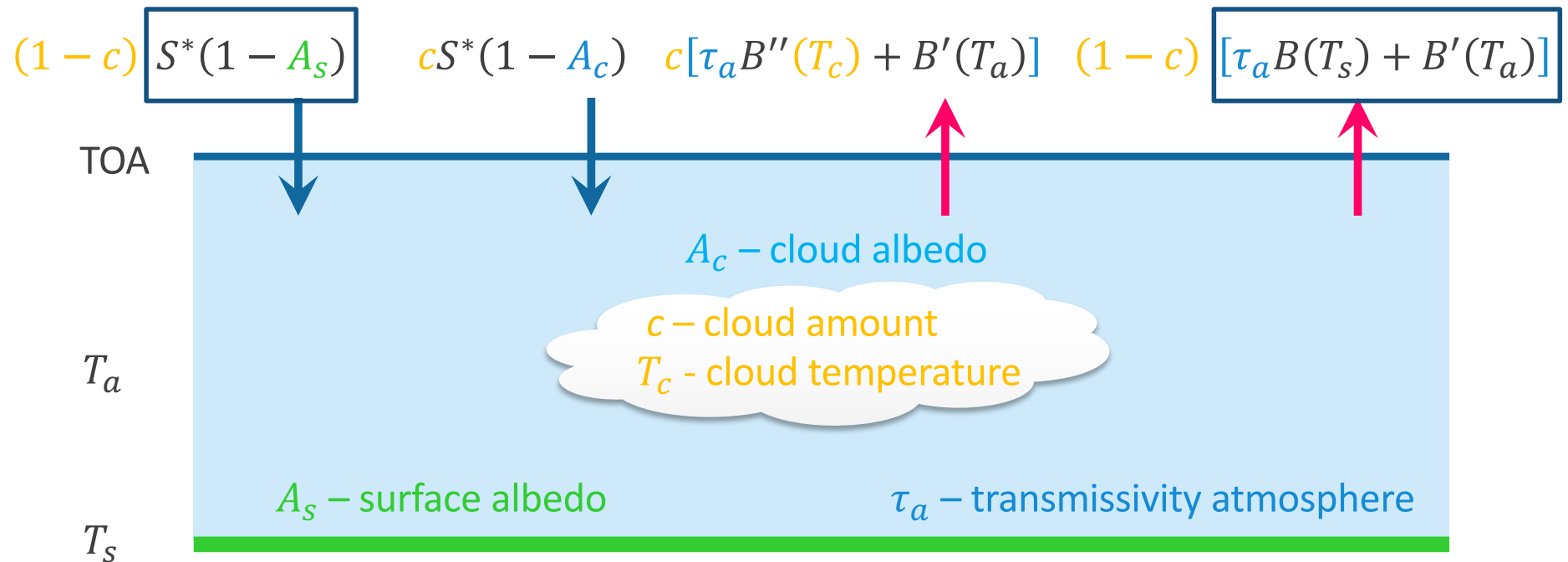
warming effect



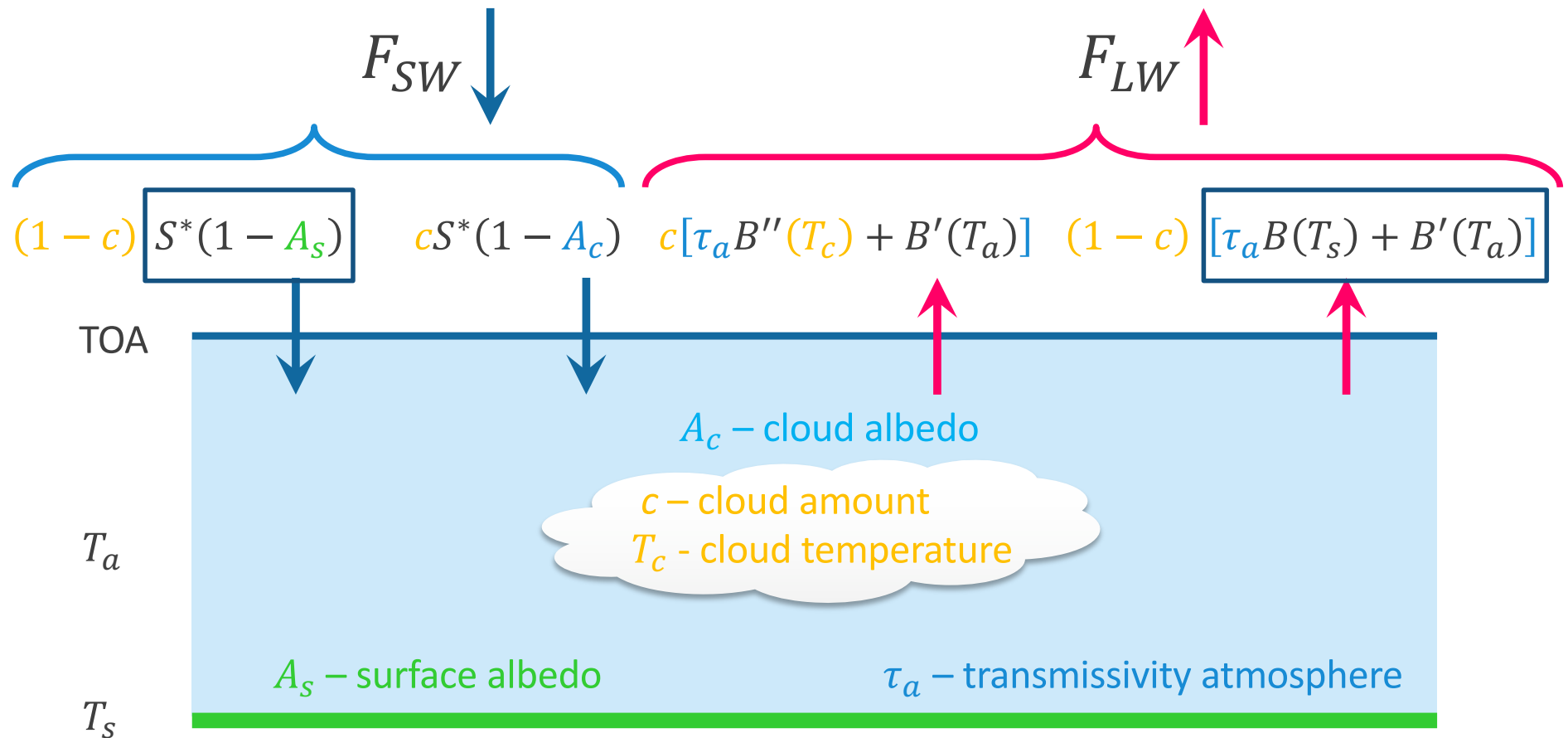
THE EARTH'S ENERGY BALANCE



IMPACT OF CLOUDS ON THE RADIATION BALANCE

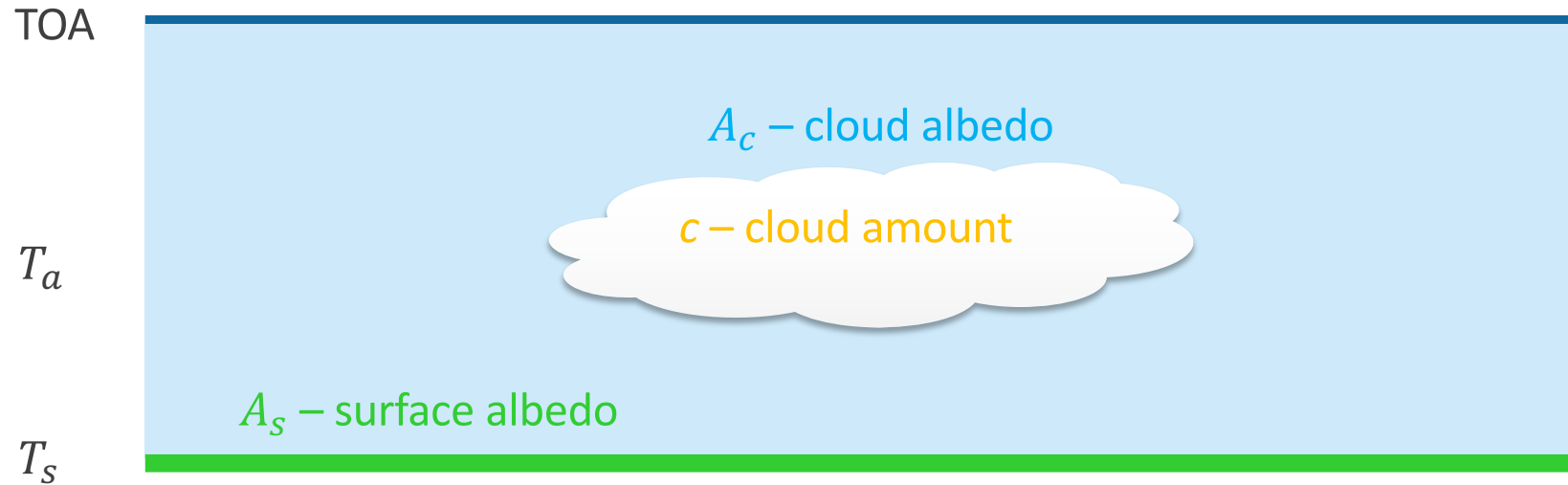


IMPACT OF CLOUDS ON THE RADIATION BALANCE



$$F^\downarrow = F_{SW}^\downarrow - F_{LW}^\uparrow$$

Forcing: $c \frac{\partial F^\downarrow}{\partial c} \equiv F^\downarrow - F^\downarrow(c = 0)$



ESTIMATION OF CLOUD RADIATIVE FORCING REQUIRES:

SURFACE ALBEDO

CLOUD ALBEDO → MICROPHYSICS

CLOUD AMOUNT → DYNAMICS



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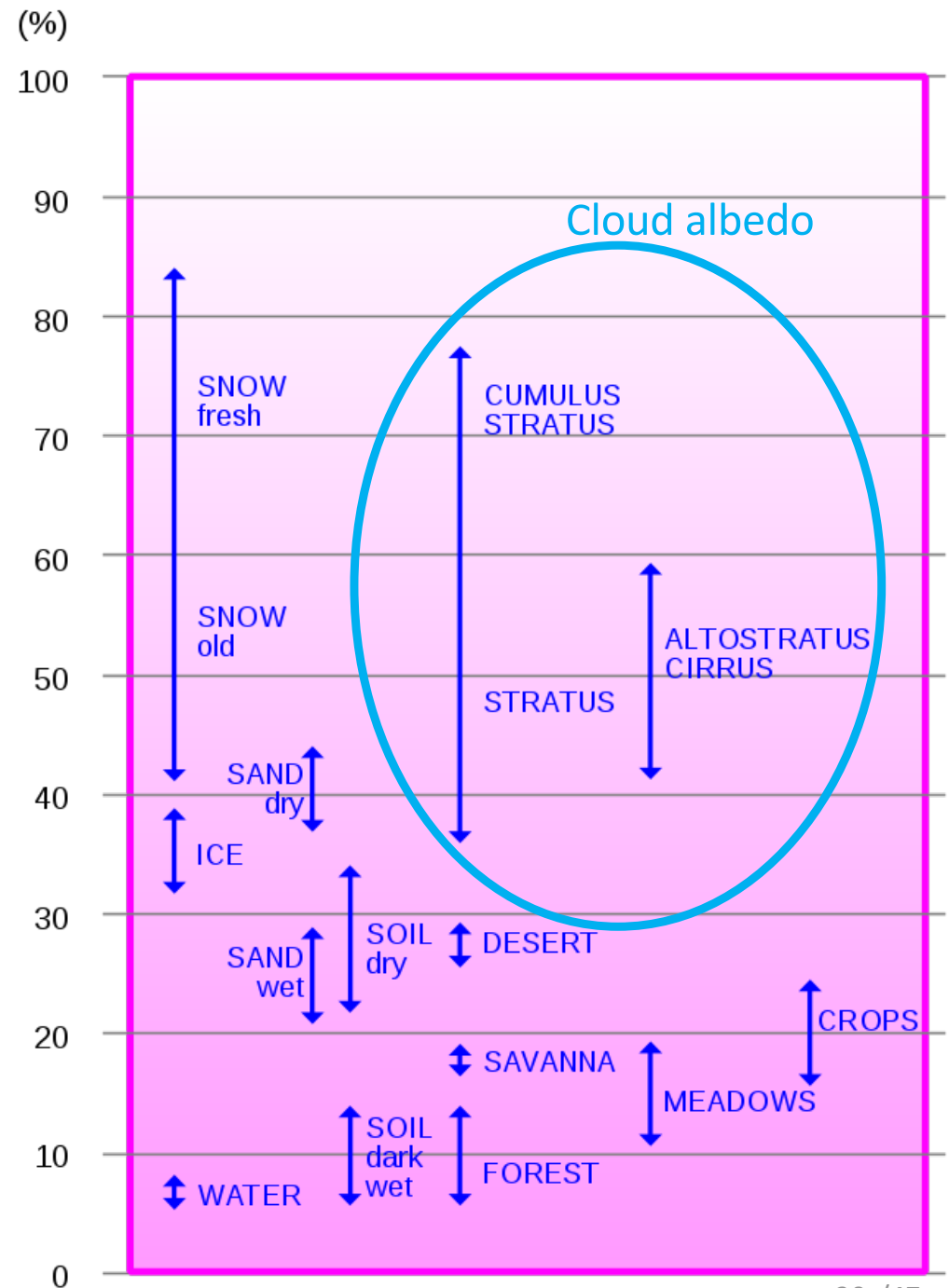
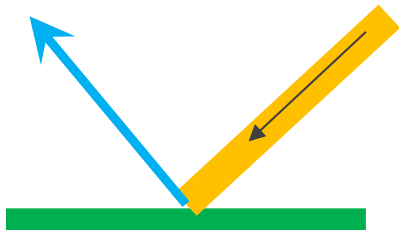
ALBEDO

Albedo (Latin: *albedo*, meaning 'whiteness') is the measure of

- the **diffuse reflection of solar radiation**, defined as the ratio of **reflected radiation** to the **total solar radiation** received by an astronomical body (e.g. a planet like Earth).

It is a dimensionless quantity measured on a scale

- from 0 (representing an idealized blackbody that absorbs all incident radiation)
- to 1 (representing a surface that reflects all incident radiation).



FIRST ESTIMATES OF MEAN CLOUD ALBEDO WERE OVERESTIMATED

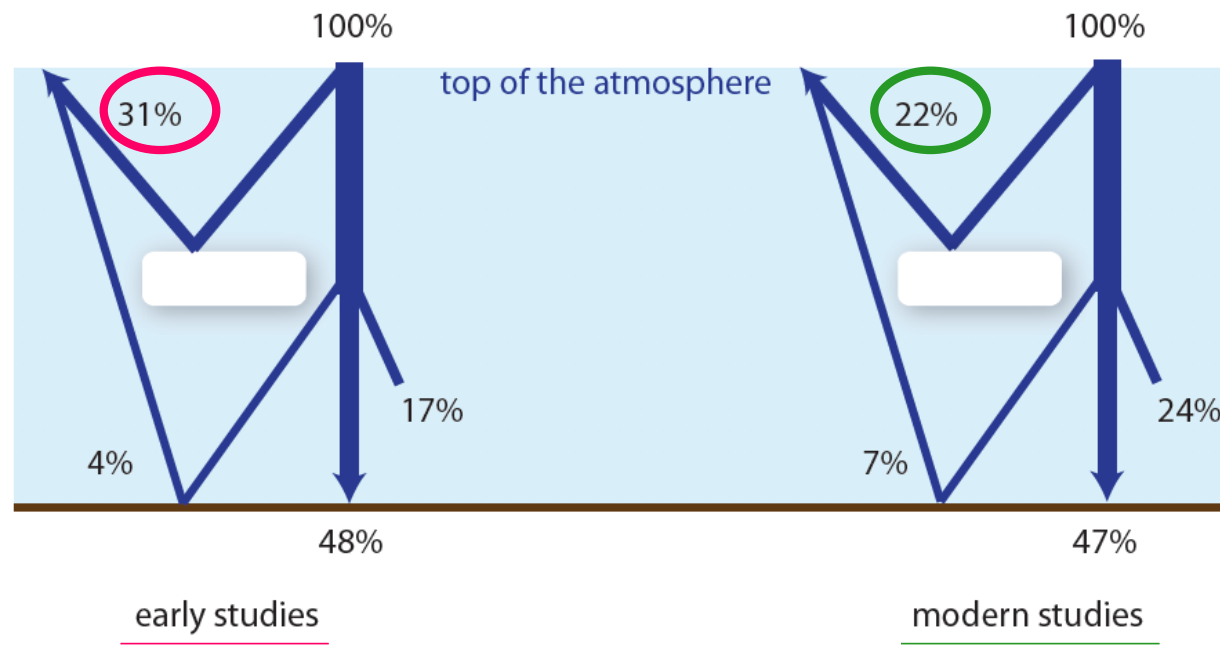
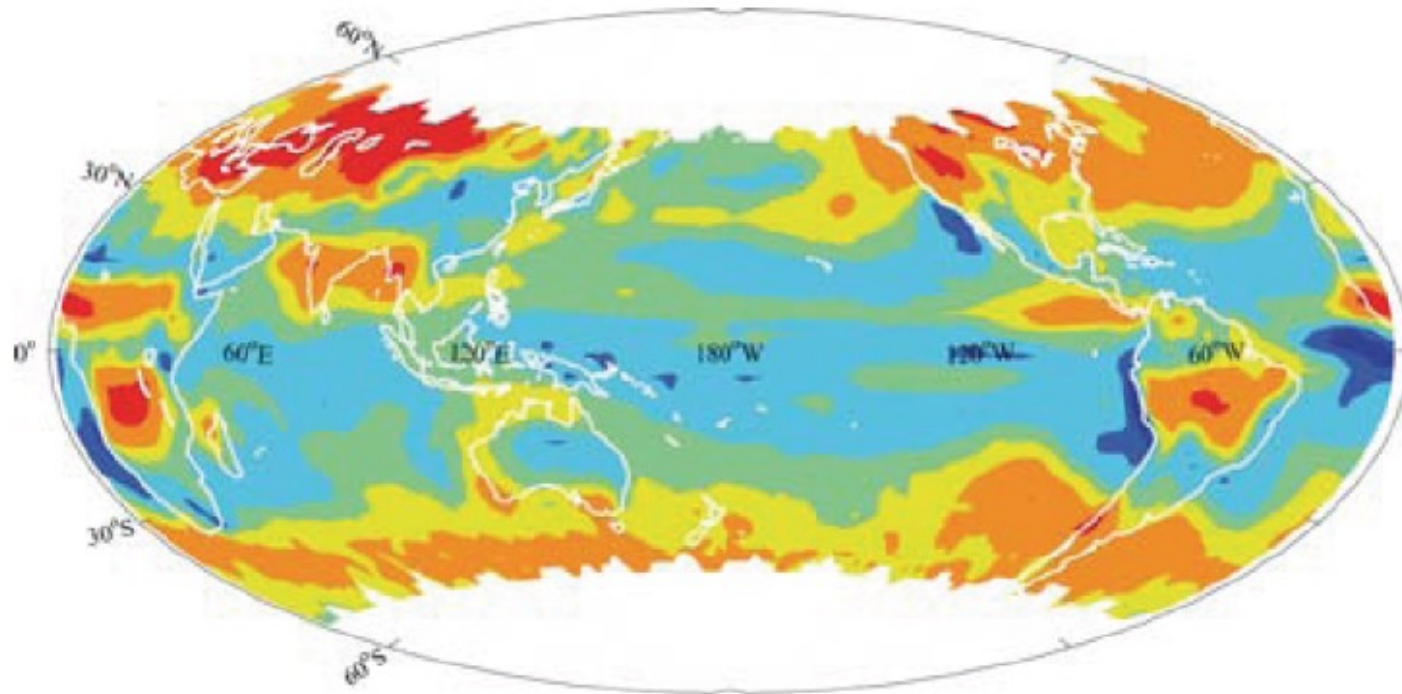


Figure 1.6: The contribution of different components of the short-wave radiative fluxes to the total reflected radiation, as derived from early studies on the Earth energy budget and modern satellite observations. The white boxes indicate that most, but not all, atmospheric reflection of solar radiation is associated with clouds.

HOWEVER, CURRENT MODELS POORLY REPRODUCE VARIABILITY PARAMETERS SUCH AS PLANETARY ALBEDO



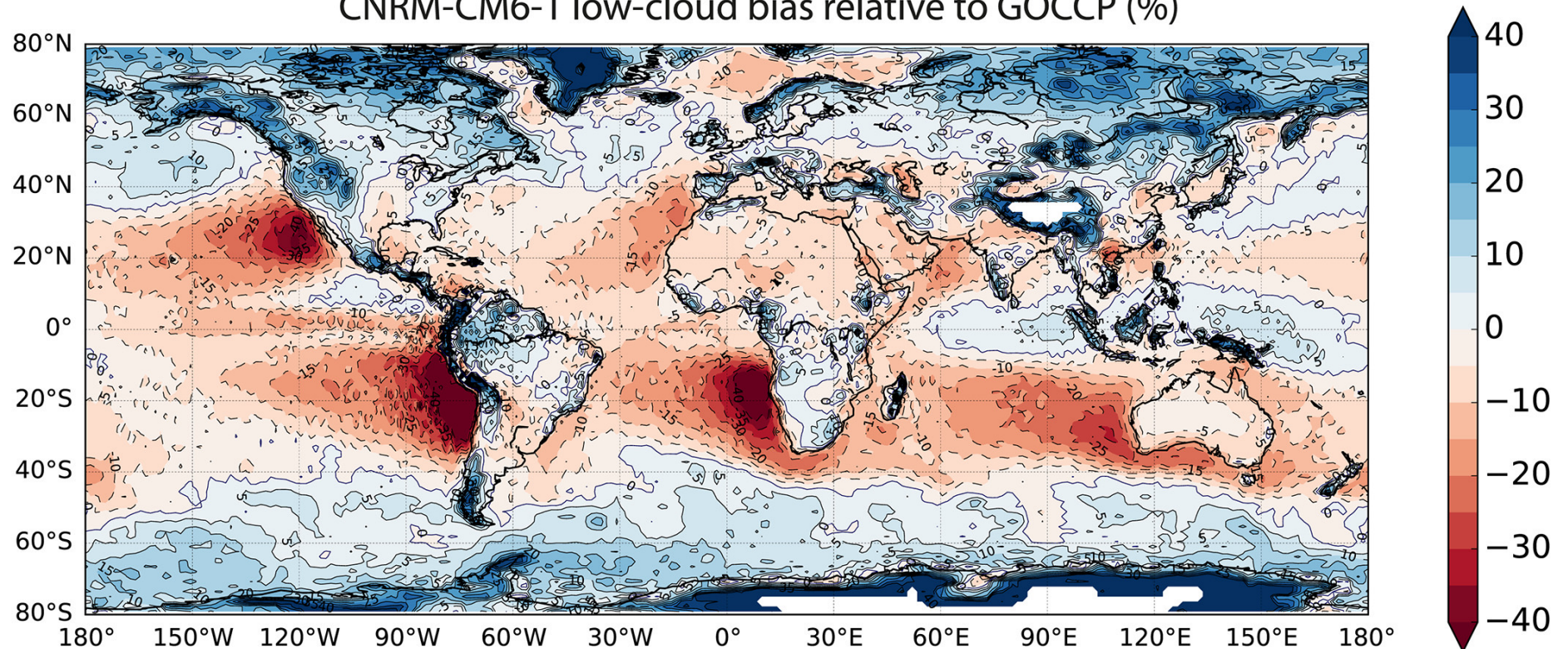
ERBE
Earth Radiation Budget Experiment (NASA)

Correlation between albedo from ERBE and climate models



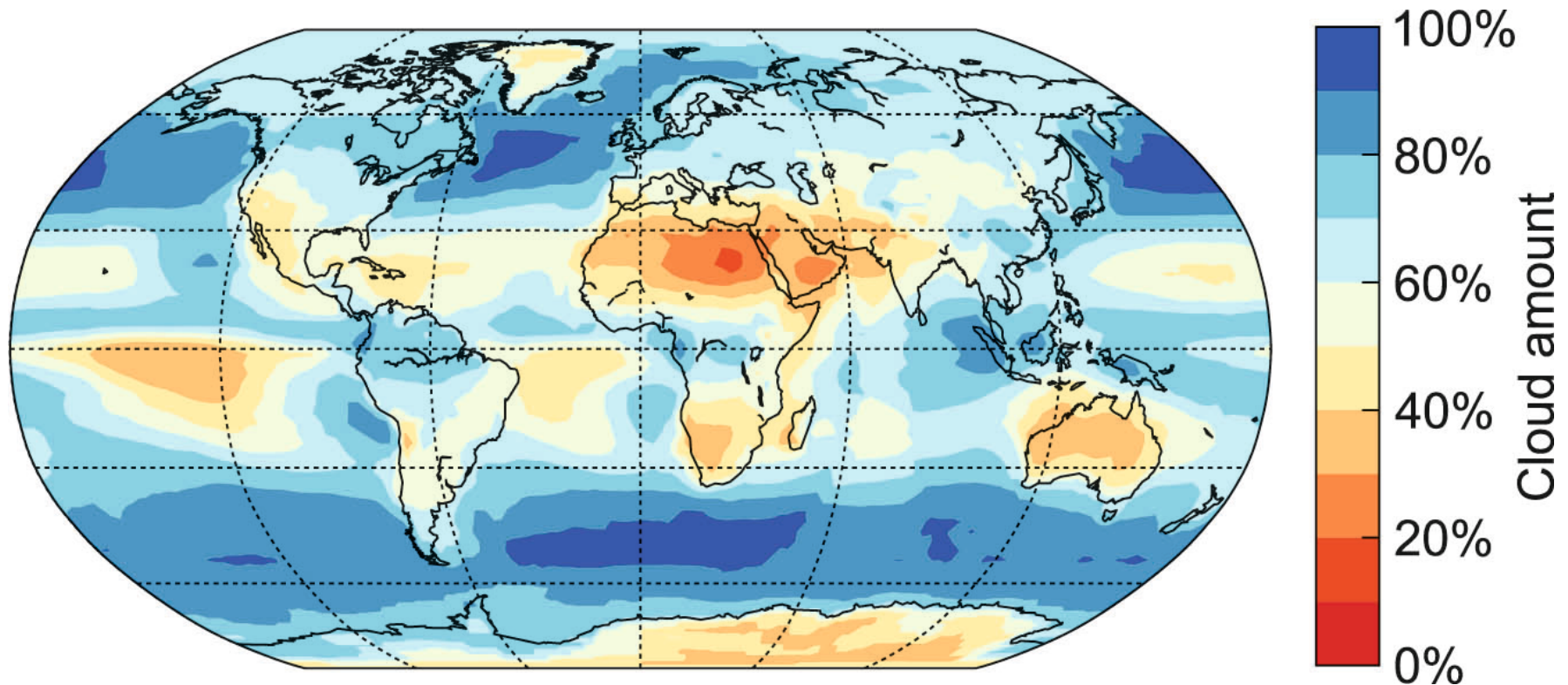
The mean geographical distribution of correlation between monthly mean albedo in ERBE and 20 GCM's, November 1984 – February 1990.

CNRM-CM6-1 low-cloud bias relative to GOCCP (%)

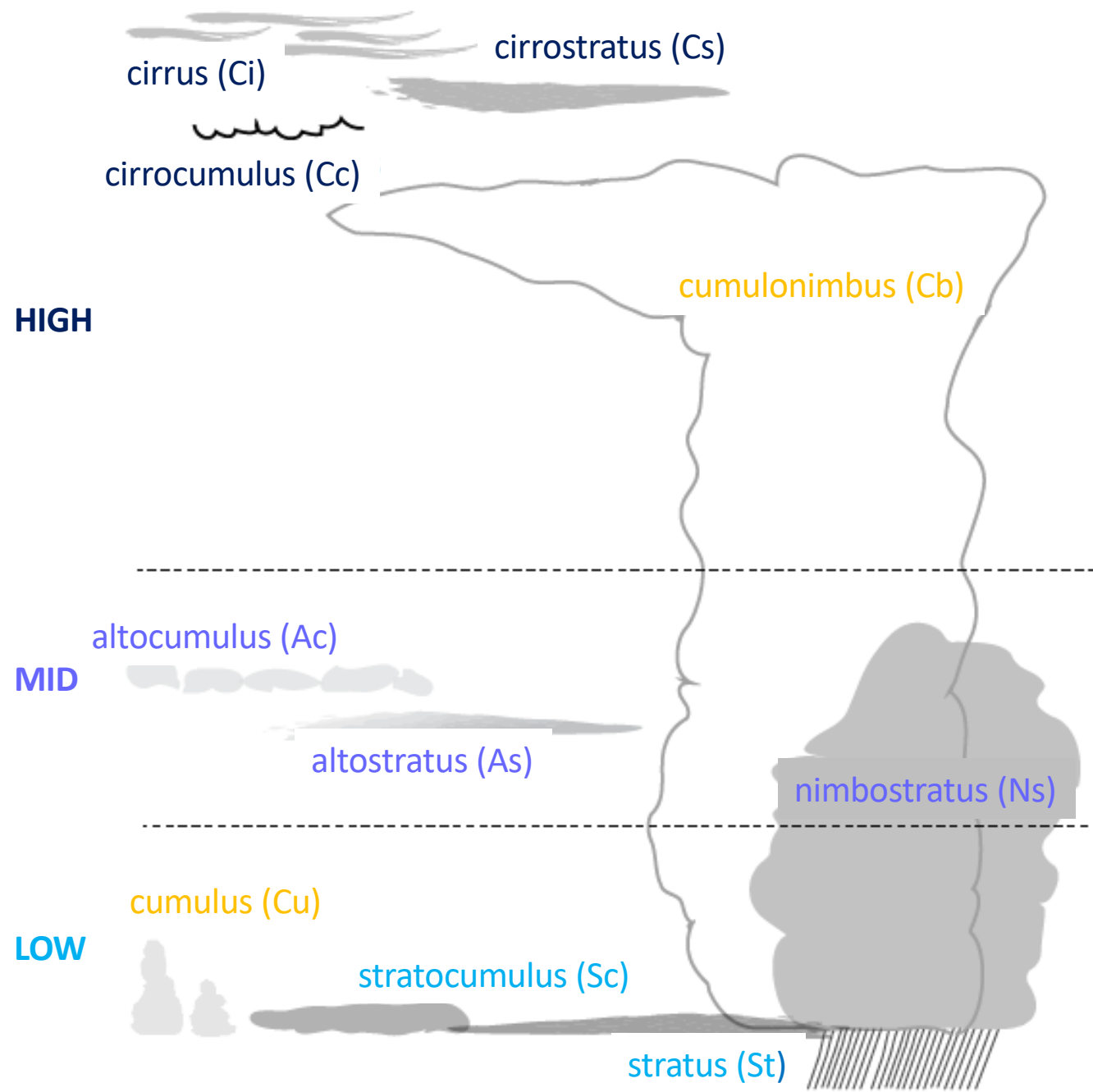


Low-cloud bias of the CNRM-CM6-1 AMIP simulation relative to the GOCCP (GCM Oriented CALIPSO Cloud Product) climatology (%). Data are averaged between 2007 and 2015.

CLOUD AMOUNT



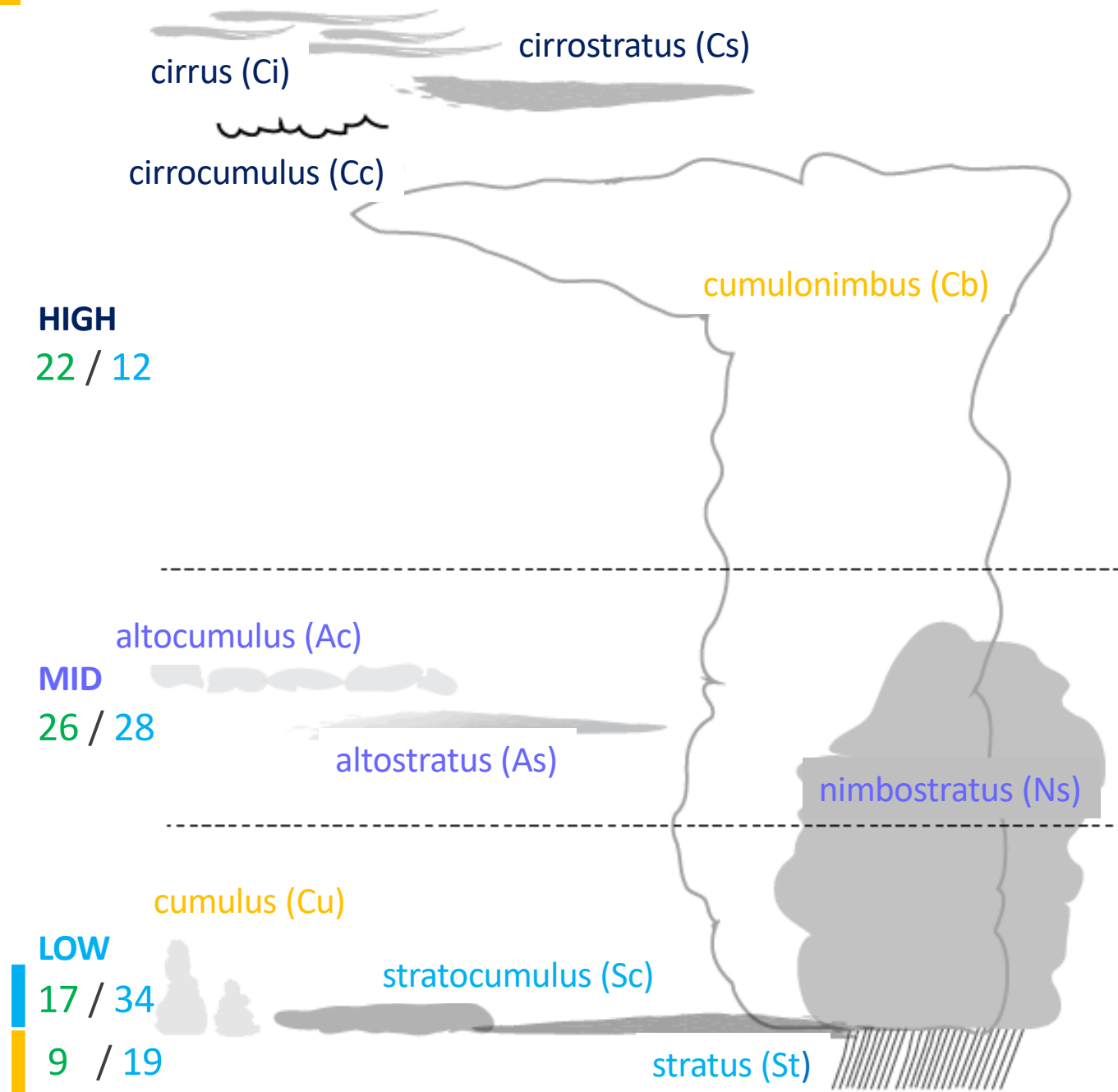
Annual mean total cloud cover (%) averaged over 1983-2009. Data were obtained from the International Satellite Cloud Climatology Project (ISCCP).



Siebesma, A., Bony, S., Jakob, C., & Stevens, B. (Eds.). (2020). *Clouds and Climate: Climate Science's Greatest Challenge*. Cambridge University Press.

Figure 1.2 A schematic of Luke Howard's cloud classification.

CLOUD AMOUNT (%) OVER LAND/OCEAN



Siebesma, A., Bony, S., Jakob, C., & Stevens, B. (Eds.). (2020). *Clouds and Climate: Climate Science's Greatest Challenge*. Cambridge University Press.

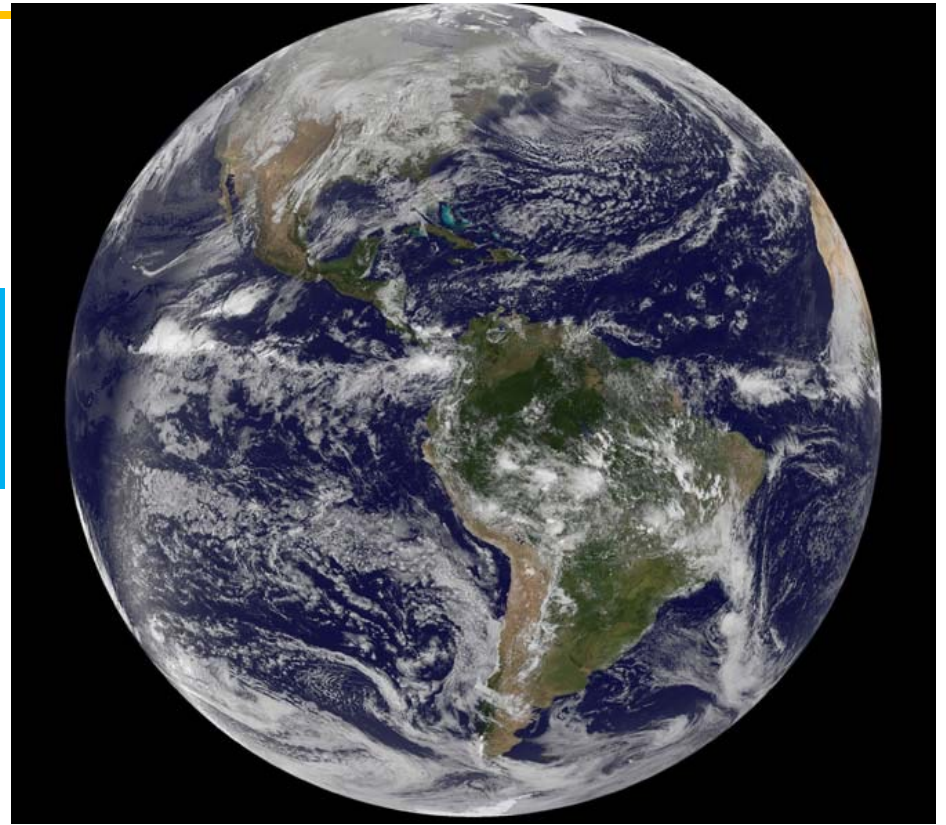
Figure 1.2 A schematic of Luke Howard's cloud classification.

Étages	Genus	Abbr	Cloud amount (%)		Frequency (%)		Amount-when-present (%)	
			Land	Ocean	Land	Ocean	Land	Ocean
High	Cirrus	Ci						
	Cirrocumulus	Cc	22	12	45	34	49	35
	Cirrostratus	Cs						
Mid	Alto cumulus	Ac	17	17	32	37	52	47
	Altostratus	As	4	6	5	10	82	59
	Nimbostratus	Ns	5	5	5	5	98	99
Low	Cumulus	Cu	5	13	14	33	34	40
	Cumulonimbus	Cb	4	6	7	11	59	58
	Stratus	St	5	12	6	14	72	84
	Stratocumulus	Sc	12	22	21	31	34	40
	Fog	Fo	1	2	1	2	100	100
Total cloud cover			Tc	54	68			
Clear sky			Cr		22	3		
Precipitation			Pt		9	10		

Table 1.1. *The original cloud classification defined by Luke Howard, whereby clouds belong to one of ten gender types ('genus') based on their aesthetic appearance and their altitude at three different "Étages" (levels). Also shown are the official abbreviations for cloud types as identified by the WMO, along with the additional cloud type fog and types of precipitation. For the WMO recognized cloud types the annual mean cloud amount is shown, which is derived from surface observations over land (1971-1997) and from ships (1954-2008), collected by Hahn and Warren, 2007 (Hahn and Warren, 2007). The cloud amount is the product of the frequency of occurrence and the amount-when-present.*

A cloud is an aggregate of water droplets, ice crystals, or a combination of both, suspended in the air.

For a cloud to be visible, cloud particles must be present in a sufficiently high concentration.



MICROPHYSICS

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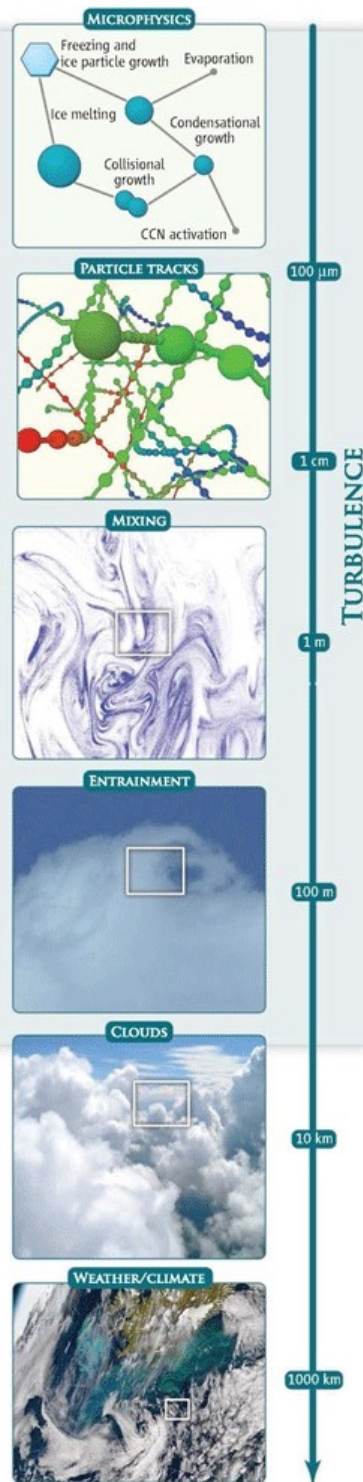
PARTICLE TRACKS

MIXING

ENTRAINMENT

CLOUDS

WEATHER/CLIMATE



A MATTER OF SCALE

100 μm

1 cm

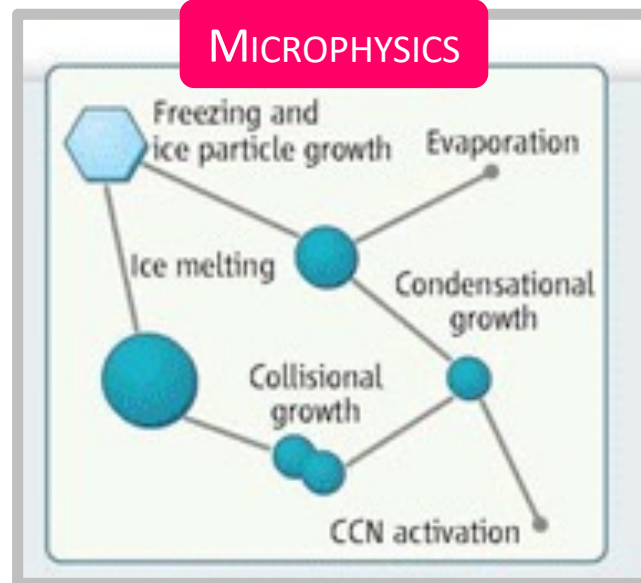
1 m

100 m

1 km

1000 km

MICROPHYSICS



The shape and appearance of clouds are influenced by cloud microstructure and its interaction with radiation.

The details of the microphysical properties of a cloud affect its future development and its interaction with the environment.

Each interaction is highly dependent on the shape, size, concentration, and phase of the particles within the cloud.

➤ Radiation

Interactions with radiation can lead to variations in the absorption, emission, and scattering of heat and light and, as a result, have far-reaching consequences for the global energy budget.

➤ Dynamics

Thermal interactions through the redistribution of heat and moisture can both modify the local behaviour of clouds and have cumulative effects on large-scale atmospheric circulations.

→ Radiation

Interactions with radiation can lead to variations in the absorption, emission, and scattering of heat and light and, as a result, have far-reaching consequences for the **global energy budget**.

→ Dynamics

Thermal interactions through the redistribution of heat and moisture can both modify the **local behaviour of clouds** and have cumulative effects on **large-scale atmospheric circulations**.

→ Chemistry

Chemical interactions result in removal, generation, and transformation of aerosols and gases.

→ Electricity

Electrical interactions lead to the redistribution of electric charge and the dramatic discharges in the form of lightning strikes.

A LINK BETWEEN MICROPHYSICS AND RADIATION



Clouds formed in **clean air** exhibit lower droplet concentrations, scatter less light, and are **less reflective**.



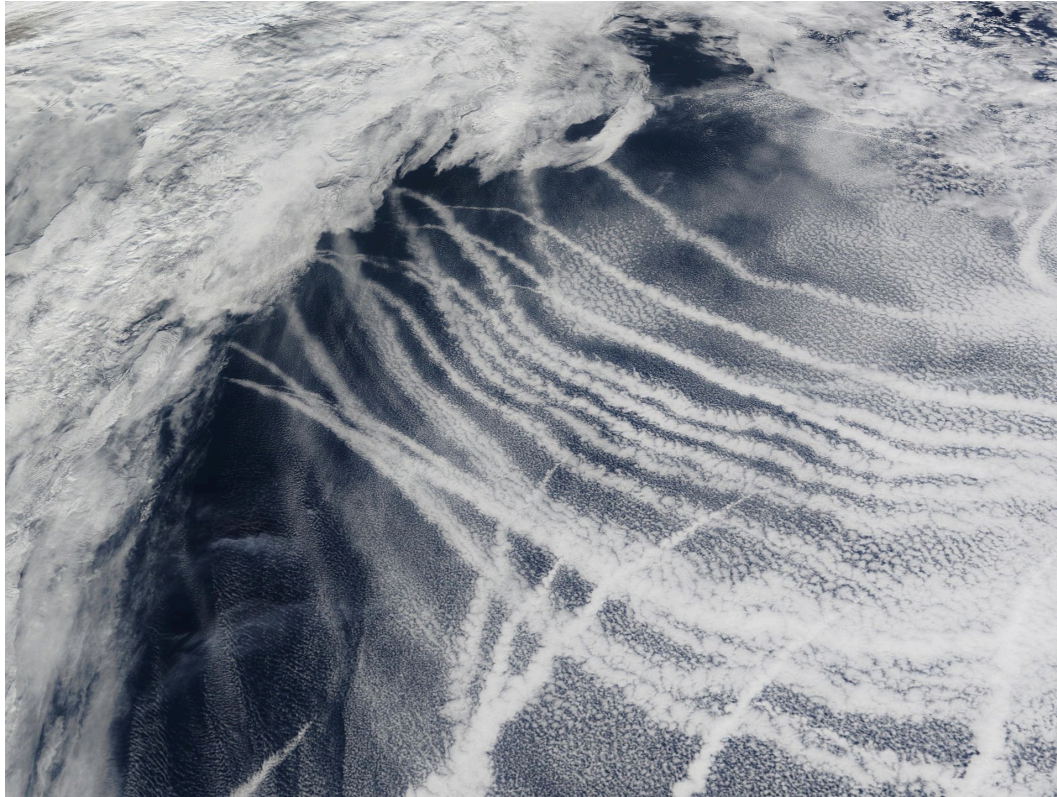
Clouds formed in **polluted air** exhibit higher droplet concentrations, scatter more light, and are **more reflective**.

SHIP TRACKS



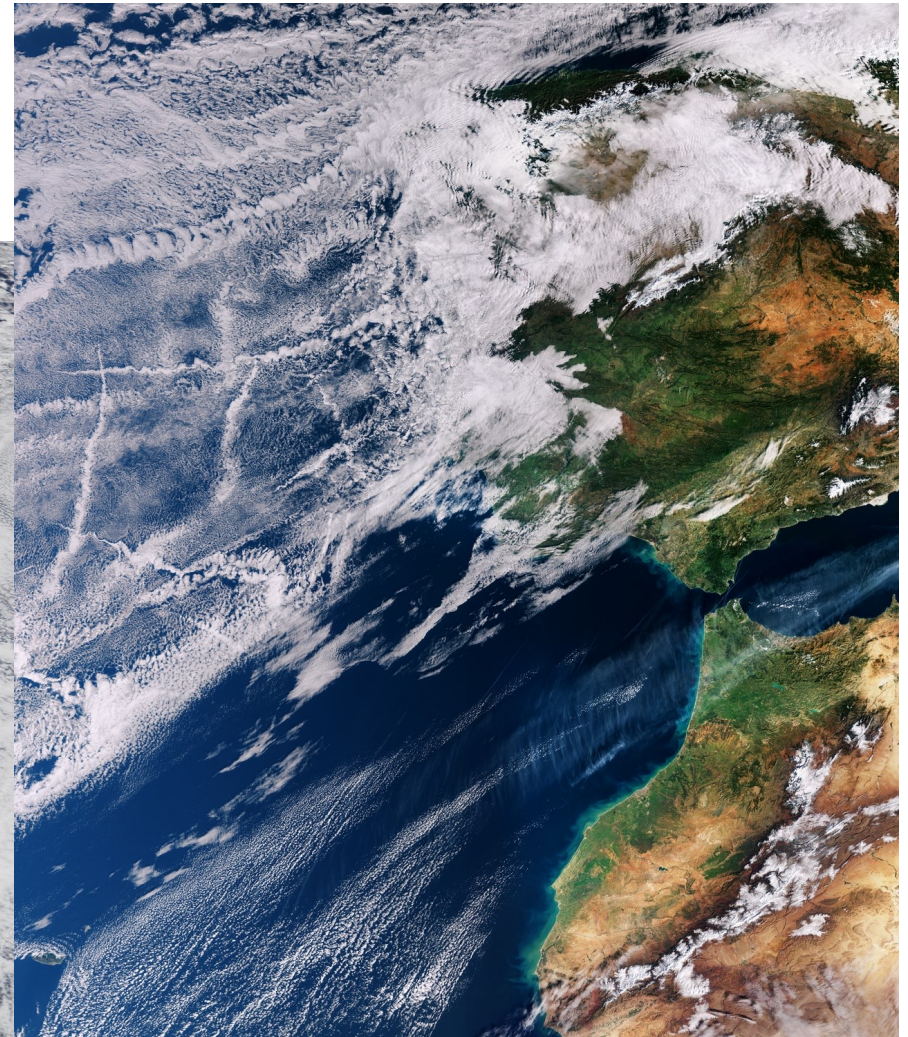
This schematic illustration shows how aerosols from ship emissions lead to a higher cloud droplet concentration accompanied by a reduction in droplet size. These microphysical alterations can suppress the onset of precipitation (Albrecht effect) and increase cloud albedo, causing them to appear brighter (Twomey effect). Credit: NASA

SHIP TRACKS



Visible ship tracks in the Northern Pacific, on March 4th 2009.

<https://svs.gsfc.nasa.gov/cgi-bin/details.cgi?aid=3667>



Over the Atlantic Ocean close to Spain and Portugal on 16 January 2018.

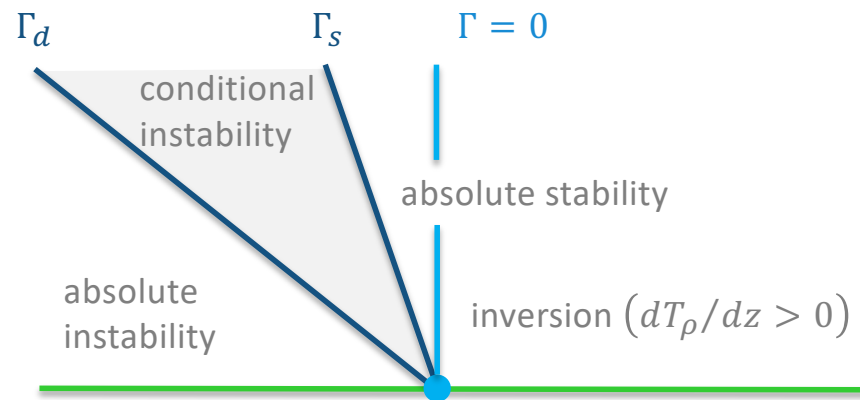
http://www.esa.int/spaceinimages/Images/2018/02/Atlantic_ship_tracks

DYNAMICS

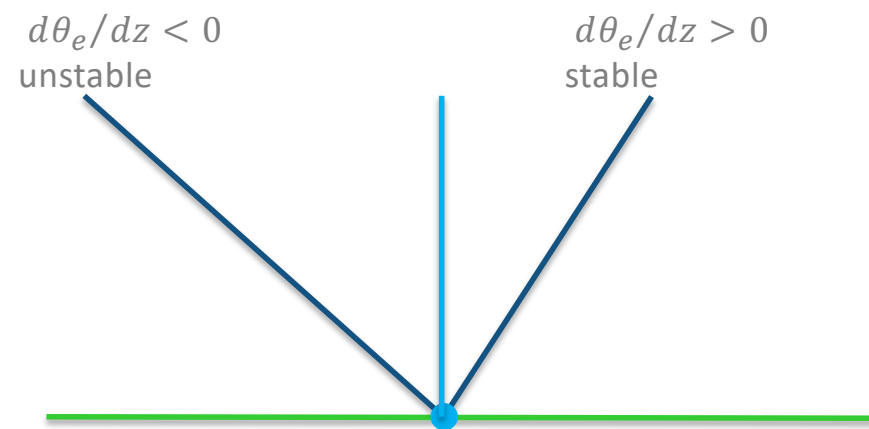


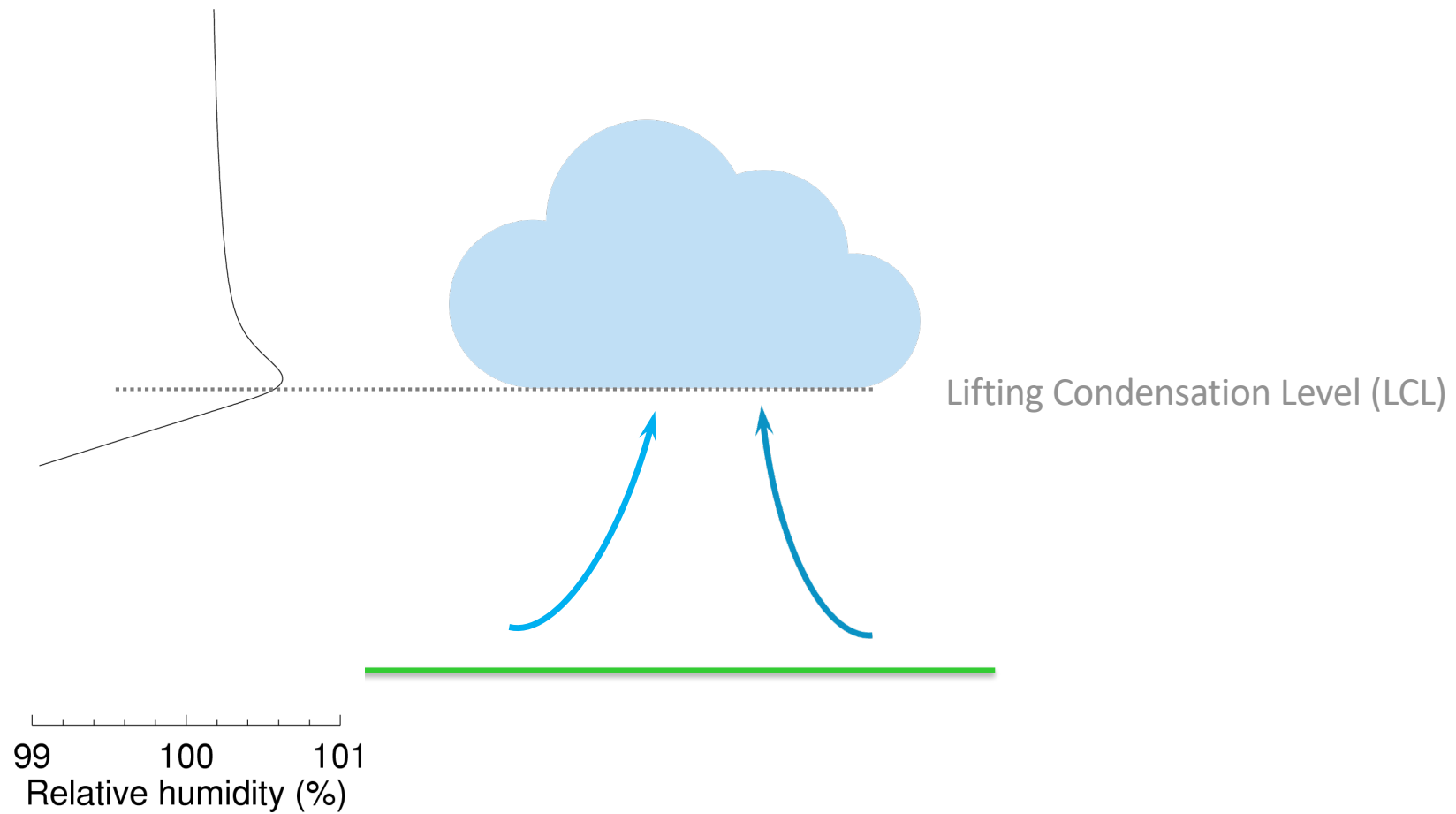
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STABILITY

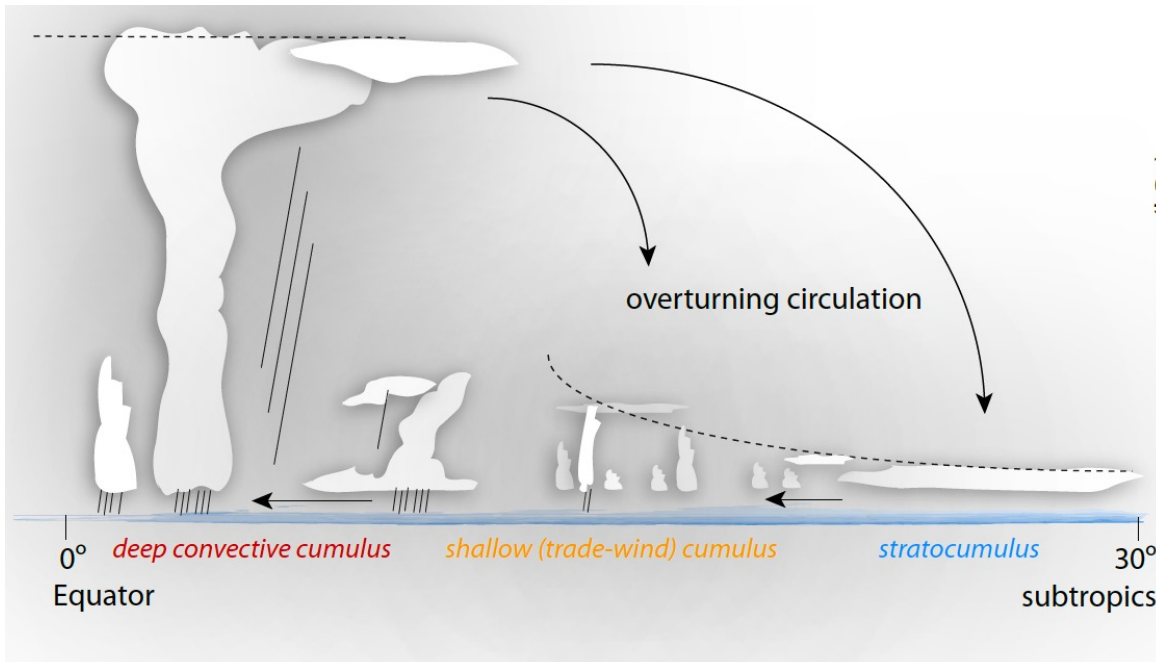


STABILITY



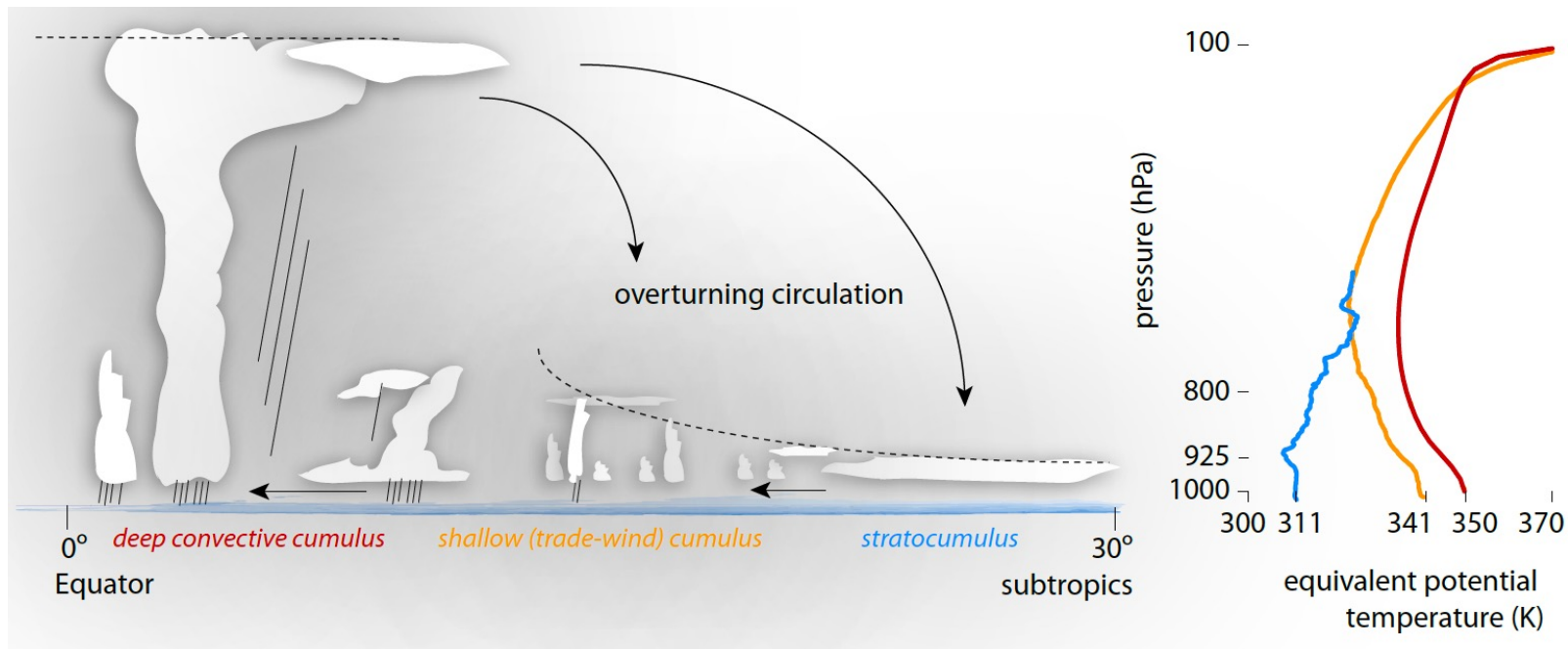


THE LARGE-SCALE CIRCULATION

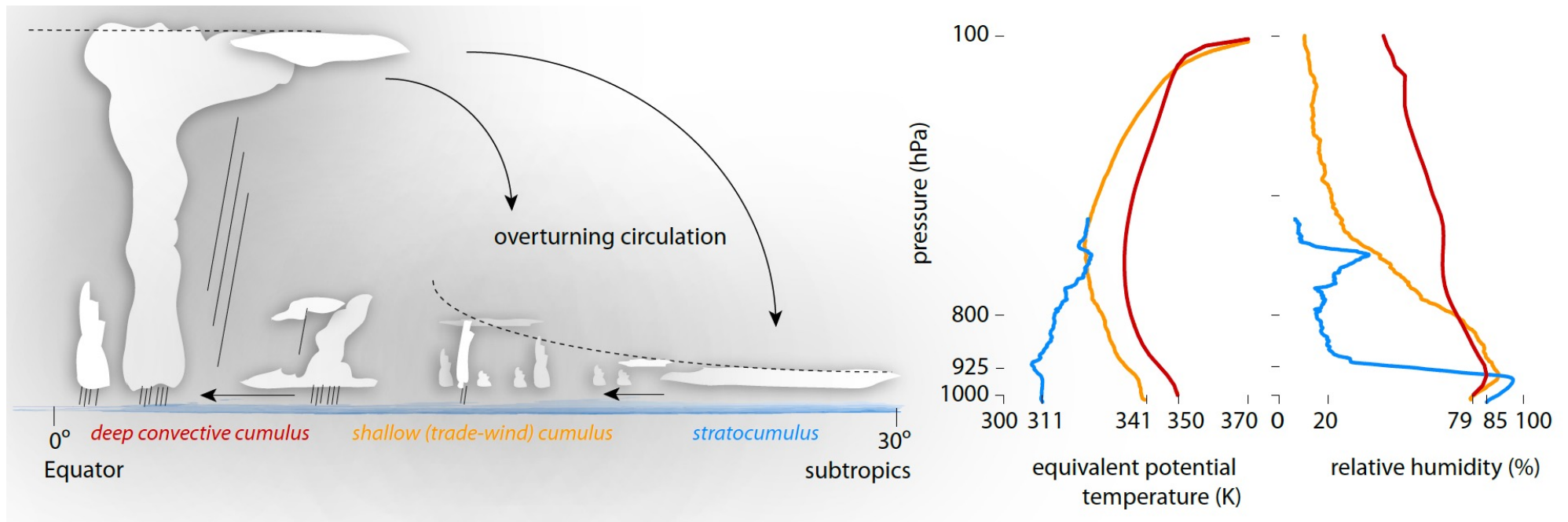


Clouds are not just a visual expressions of the state of the atmosphere, or a collection of small droplets that produce considerable rain, rather, they are a crucial component of the dynamics of the atmosphere as a whole.

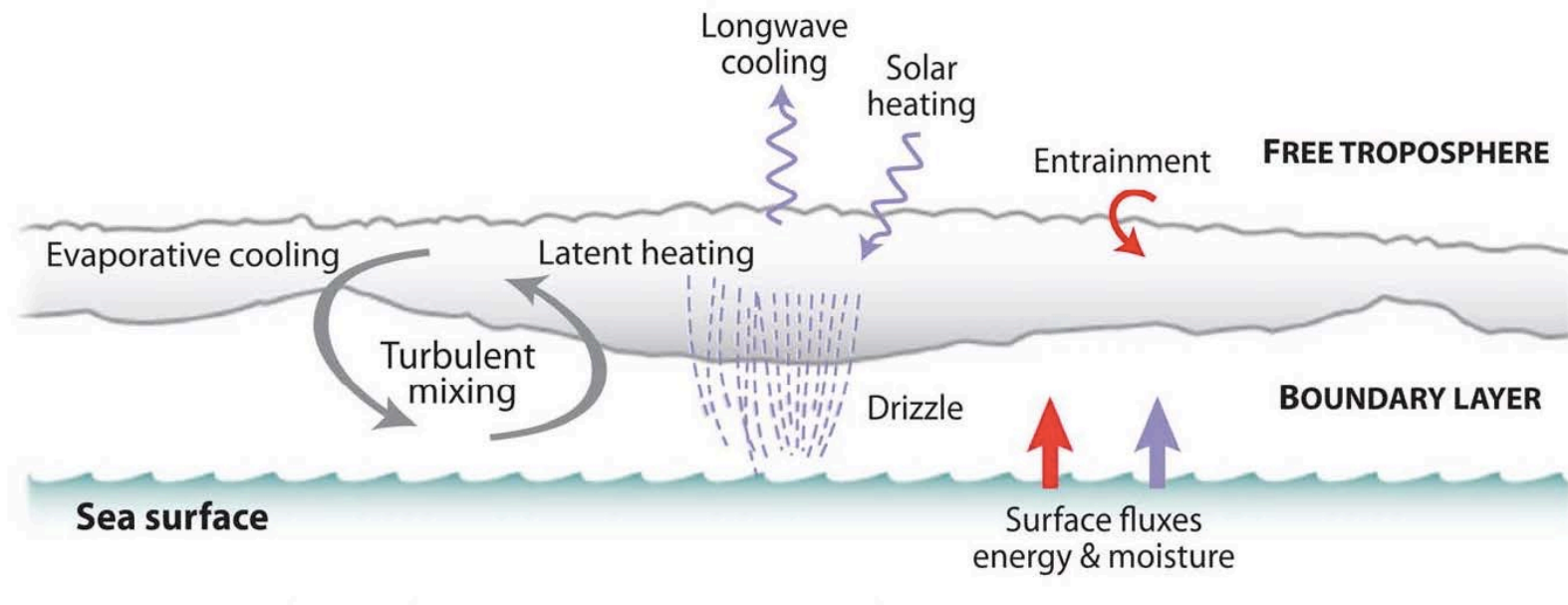
THE LARGE-SCALE CIRCULATION



THE LARGE-SCALE CIRCULATION



KEY PROCESSES CONTROLLING BOUNDARY LAYER CLOUDS

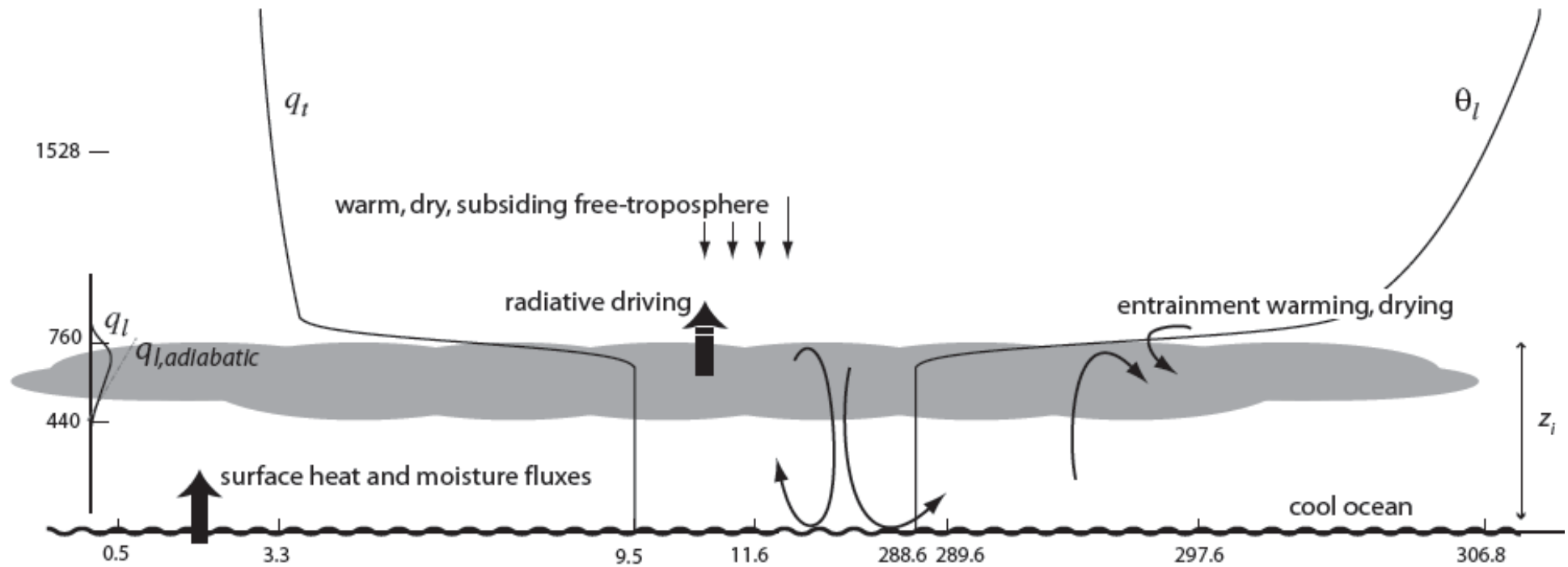


Large decks of stratocumulus are particularly interesting to studies aerosol effects on cloud albedo.

Radiative cooling at the top drives turbulence.

SW heating and LW cooling do not cancel.

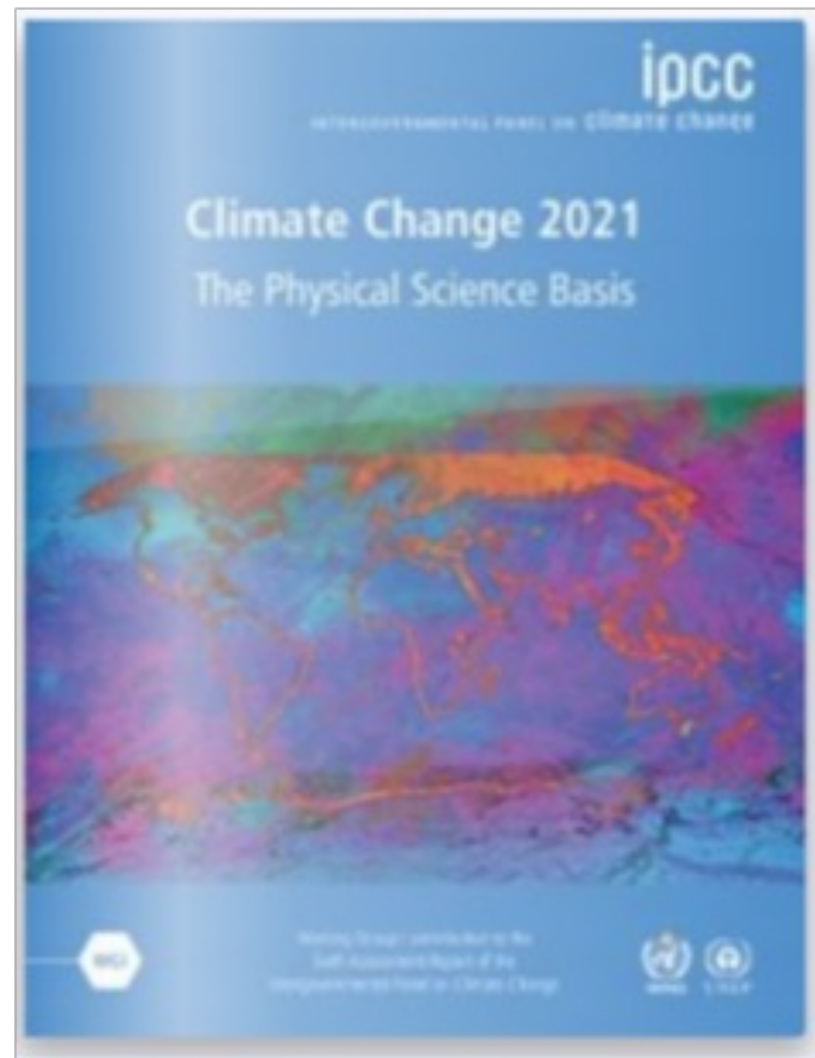
STRATOCUMULUS



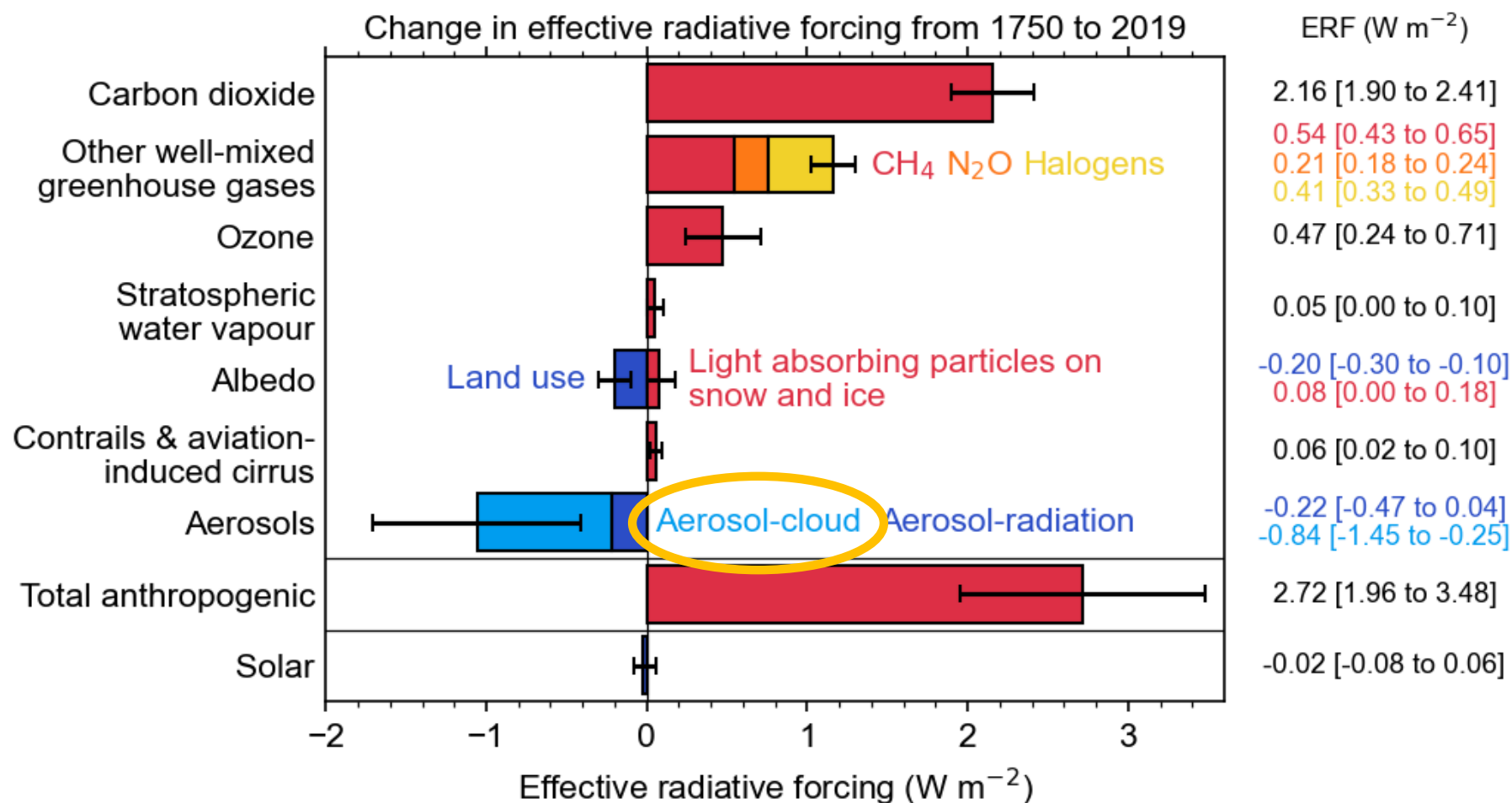
CLOUDS VS. CLIMATE CHANGE



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SIXTH ASSESSMENT REPORT IPCC: AR6 CLIMATE CHANGE 2021



Change in effective radiative forcing from 1750 to 2019 by contributing forcing agents (carbon dioxide, other well-mixed greenhouse gases (WMGHGs), ozone, stratospheric water vapour, surface albedo, contrails and aviation-induced cirrus, aerosols, anthropogenic total, and solar). Solid bars represent best estimates, and *very likely* (5–95%) ranges are given by error bars.

Fig. 7.6
https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Chapter_07.pdf

SIXTH ASSESSMENT REPORT IPCC: AR6 CLIMATE CHANGE 2021

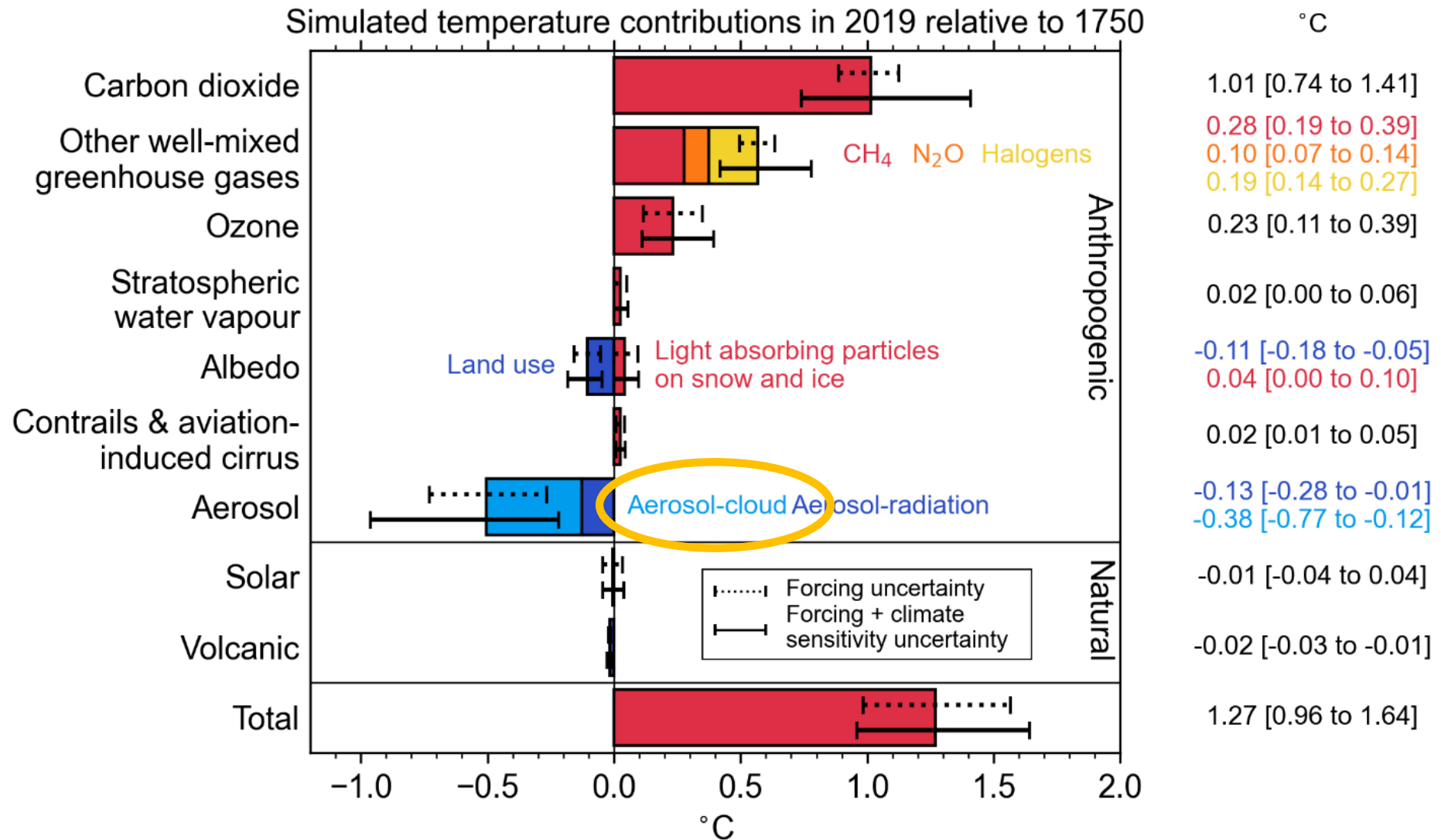


Fig. 7.7
https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Chapter_07.pdf

The contribution of forcing agents to 2019 temperature change relative to 1750