# Chapter 7 - **Clouds and Aerosols**

Boucher, O., D. Randall, P. Artaxo, C. Bretherton, G. Feingold, P. Forster, V.-M. Kerminen, Y. Kondo, H. Liao, U. Lohmann, P. Rasch, S.K. Satheesh, S. Sherwood, B. Stevens and X.Y. Zhang, 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., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Presented by Keren Mezuman

# Outline

- **Introduction**
- Clouds
- Aerosols
- Aerosol-Cloud Interactions
- Radiative forcing and Effective Radiative forcing by Anthropogenic aerosols
- Processes Underlying Precipitation Changes
- Solar Radiation Management and Related methods

# Motivation

"Despite their small mass or volume fraction, particles in the atmosphere strongly influence the transfer of radiant energy and the spatial distribution of latent heating through the atmosphere, thereby influencing the weather and climate."

# Motivation continued

"Our inability to better quantify non-greenhouse gas RFs, and primarily those that result from aerosol– cloud interactions, underlie difficulties in constraining climate sensitivity from observations even if we had a perfect knowledge of the temperature record."

# Glossary

- **Aerosol** A suspension of airborne solid or liquid particles, with a typical size between a few nanometres and 10 µm that reside in the *atmosphere* for at least several hours. Aerosols may be of either natural or *anthropogenic* origin. Aerosols may influence *climate* in several ways: directly through scattering and absorbing radiation (*Aerosol–radiation interaction (ARI)*) and indirectly by acting as *cloud condensation nuclei (CCN)* or *ice nuclei (IN)*, modifying the optical properties and *lifetime* of clouds (*Aerosol–cloud interaction (ACI)*).

# Glossary

- **Radiative forcing:** the change in the net, downward minus upward, radiative flux (expressed in W $m^{-2}$) at the *tropopause* or top of *atmosphere* due to a change in an external driver of *climate change*, [e.g. [CO2], solar flux]. In this report radiative forcing is defined as the change relative to 1750.
- **Rapid adjustment** (occurs right away) The response to an agent perturbing the *climate system* that is driven directly by the agent, independently of any change in the *global mean surface temperature*. [e.g. *aerosols* altering internal (no surface response) heating and cooling causing changes to cloud cover, before *climate feedbacks]*.
- **Effective radiative forcing (ERF):** the radiative forcing once *rapid adjustments* are accounted.

# Glossary

- **Cloud feedback**: A *climate feedback* involving changes in any of the properties of clouds as a response to a change in the local or *global mean surface temperature*.
  - Remain the largest source of *uncertainty* in *climate sensitivity* estimates.
  - In liquid clouds, an increase in cloud droplet concentration and surface area would increase the cloud *albedo*.
- **Cloud radiative effect** The *radiative effect* of clouds relative to the identical situation without clouds.

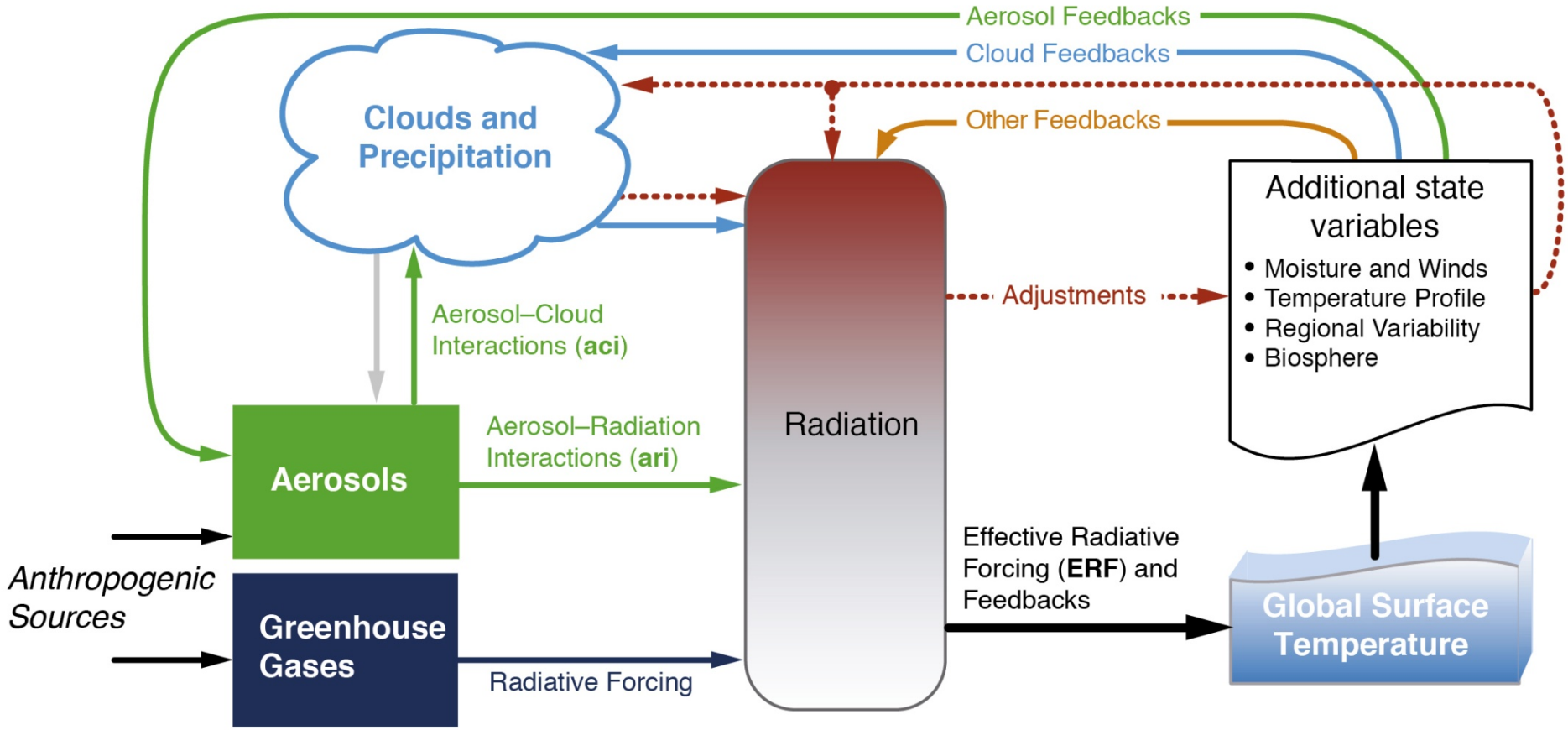


**Figure 7.1 |** Overview of **forcing and feedback pathways involving greenhouse gases, aerosols and clouds**. **Forcing agents are in the green** and **dark blue** boxes, with **forcing mechanisms** indicated by the straight **green** and **dark blue** arrows. The forcing is modified by **rapid adjustments whose pathways are independent of changes in the globally averaged surface temperature** and are denoted by brown dashed arrows. Feedback loops, which are ultimately rooted in changes resulting from changes in the surface temperature, are represented by curving arrows (blue denotes **cloud feedbacks**; green denotes **aerosol feedbacks**; and orange denotes **other feedback loops such as those involving the lapse rate, water vapour and surface albedo**). **The final temperature response depends on the effective radiative forcing (ERF) that is felt by the system, that is, after accounting for rapid adjustments, and the feedbacks**.

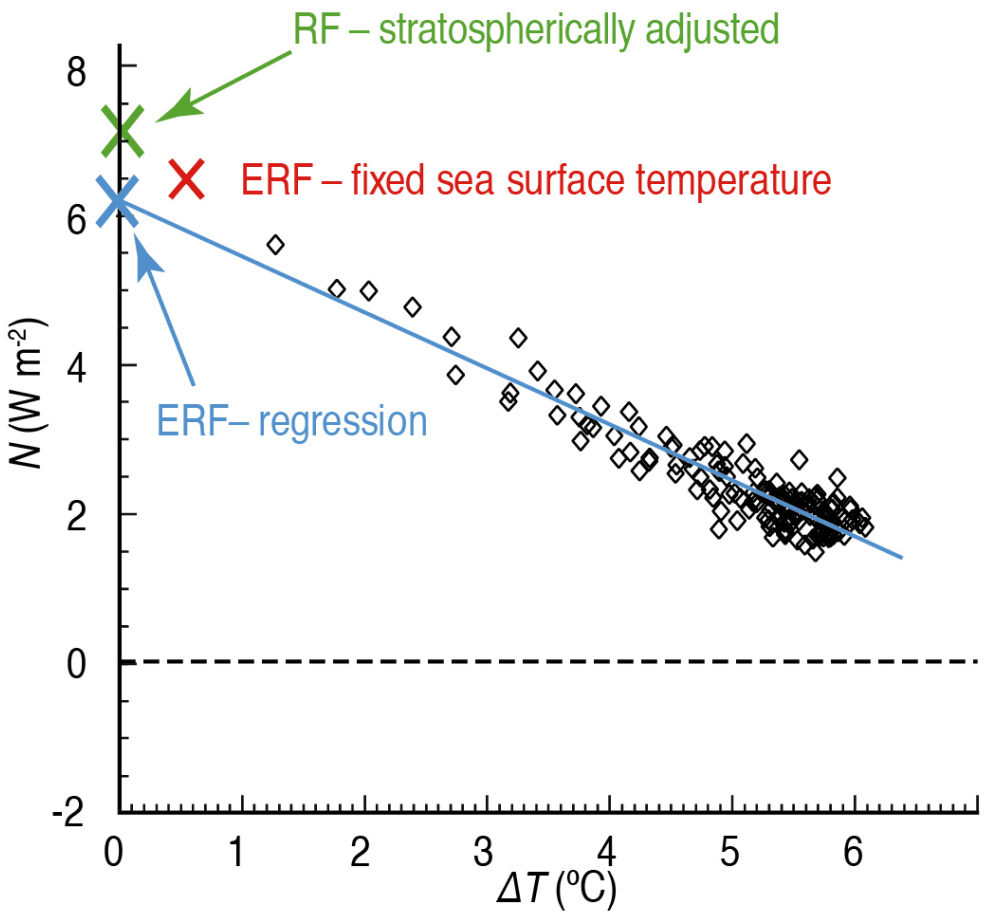


**Figure 7.2 | Radiative forcing (RF)** and **effective radiative forcing (ERF)** estimates derived by two methods, for the example of 4 × $CO_2$ experiments in one climate model. **N is the net energy imbalance at the top of the atmosphere** and **DT the global mean surface temperature change**. The **fixed sea surface temperature ERF** estimate is from an atmosphere–land model averaged over 30 years. **The regression** estimate is from 150 years of a coupled model simulation after an instantaneous quadrupling of $CO_2$, with the **N from individual years in this regression shown as black diamonds**. The stratospherically adjusted RF is the tropopause energy imbalance from otherwise identical radiation calculations at 1 × and 4 × $CO_2$ concentrations.

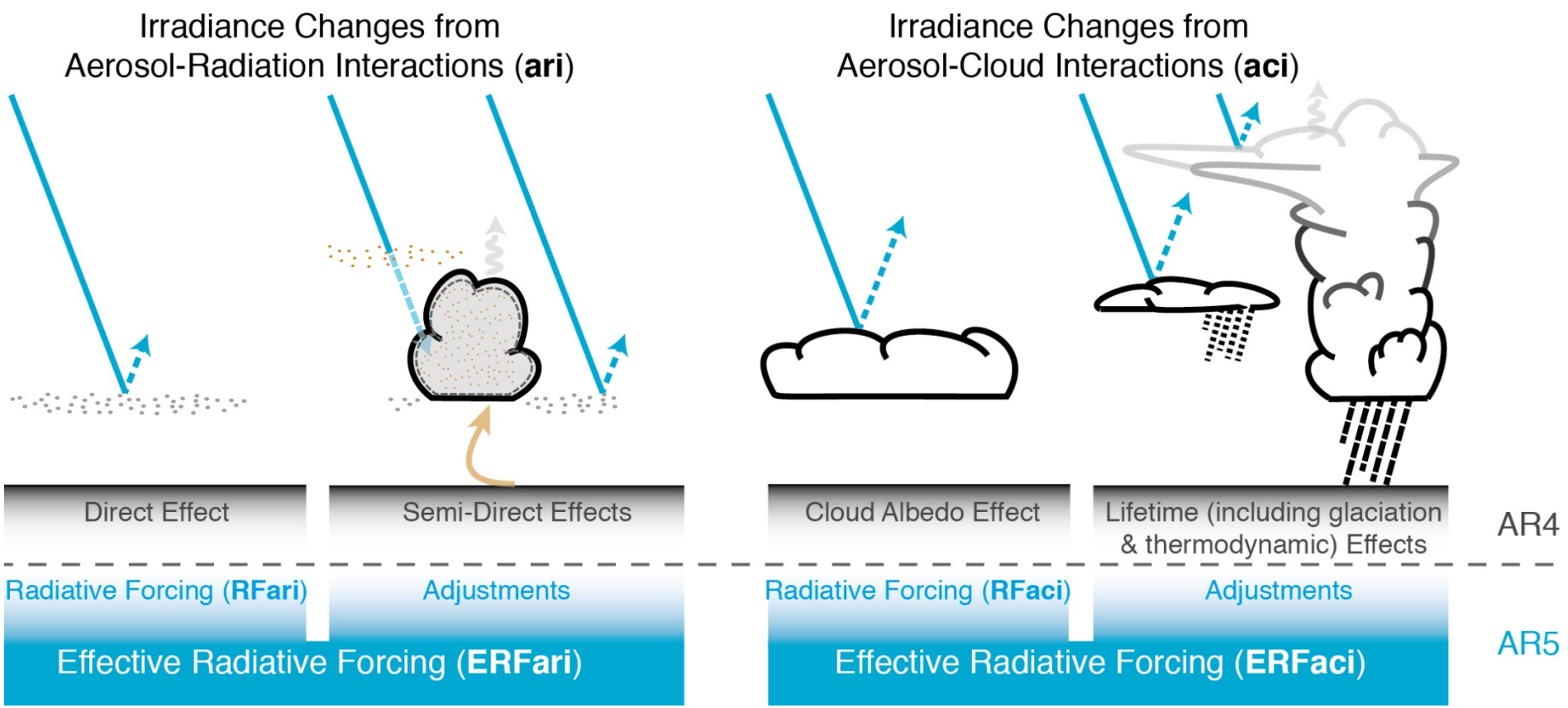


**Figure 7.3 |** Schematic of the new terminology used in this Assessment Report (AR5) for aerosol–radiation and aerosol–cloud interactions and how they relate to the terminology used in AR4. The blue arrows depict **solar radiation**, the grey arrows **terrestrial radiation** and the brown arrow symbolizes **the importance of couplings between the surface and the cloud layer for rapid adjustments**.

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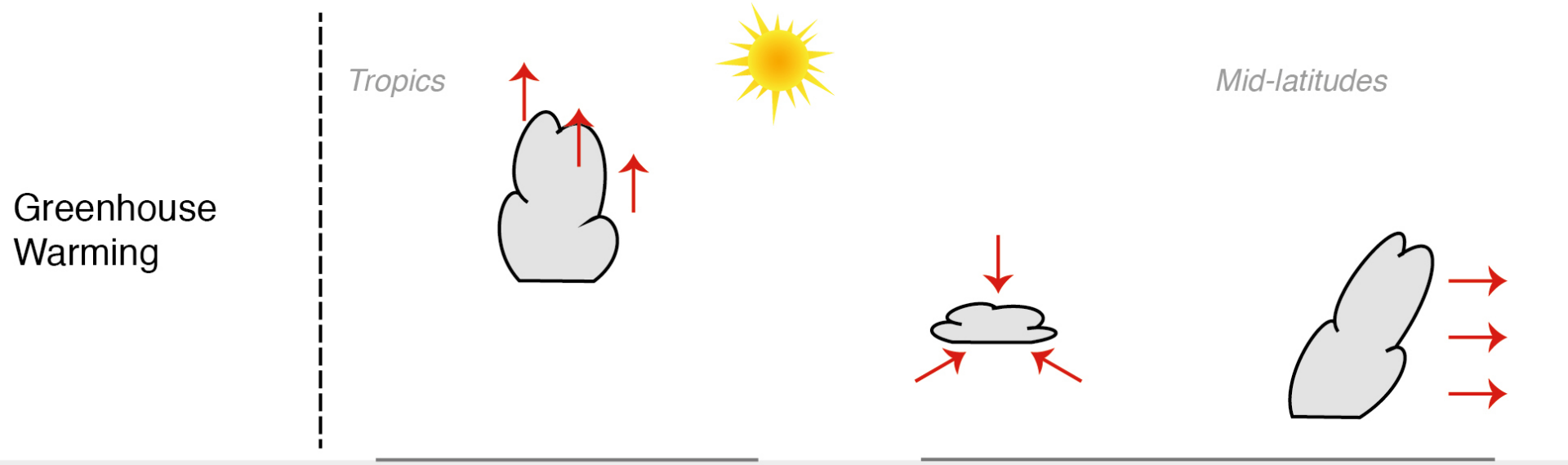
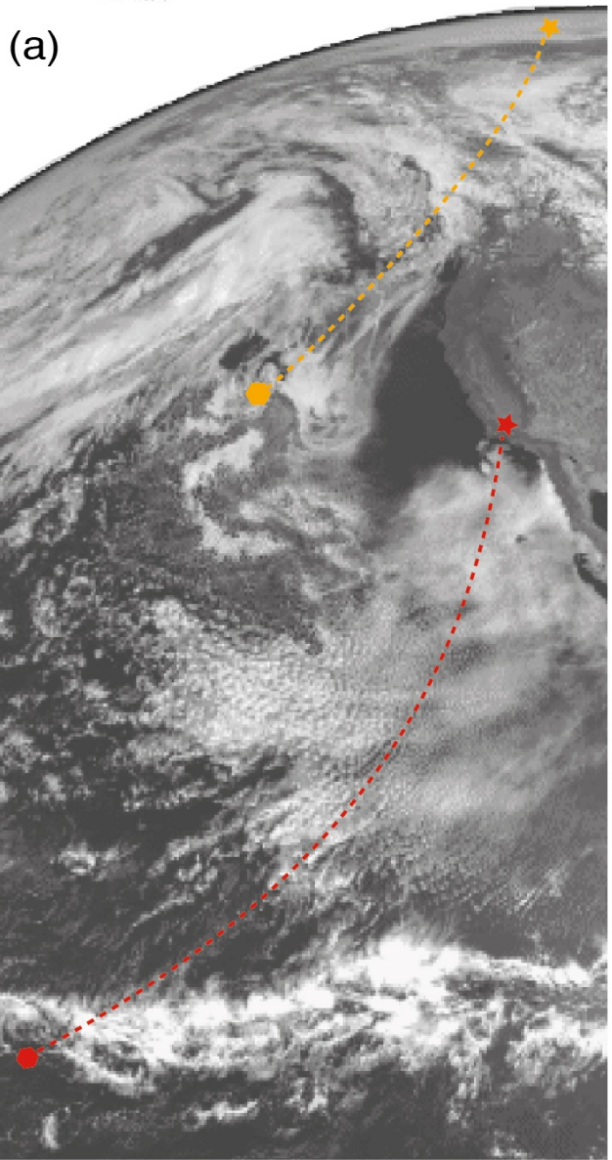
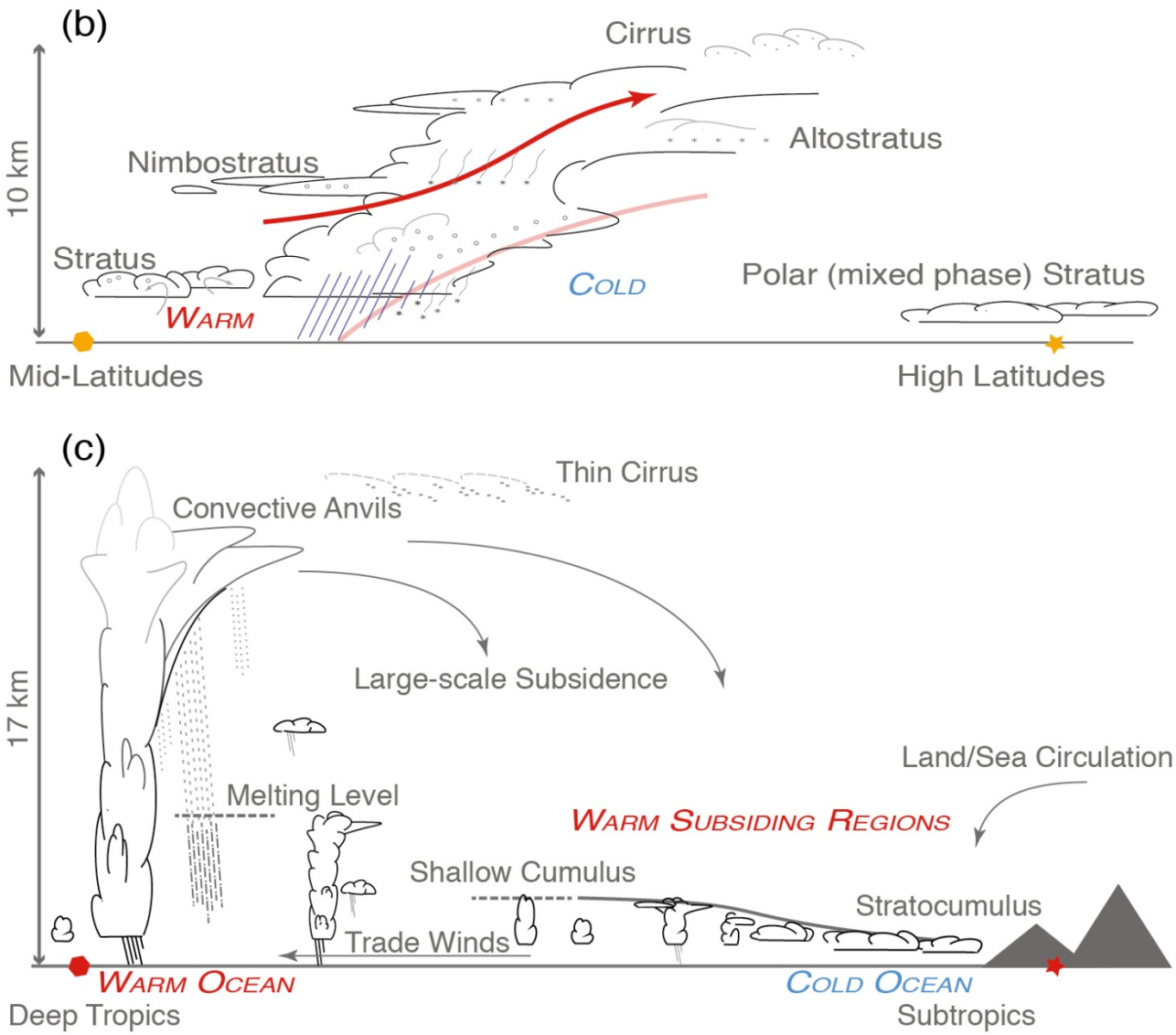
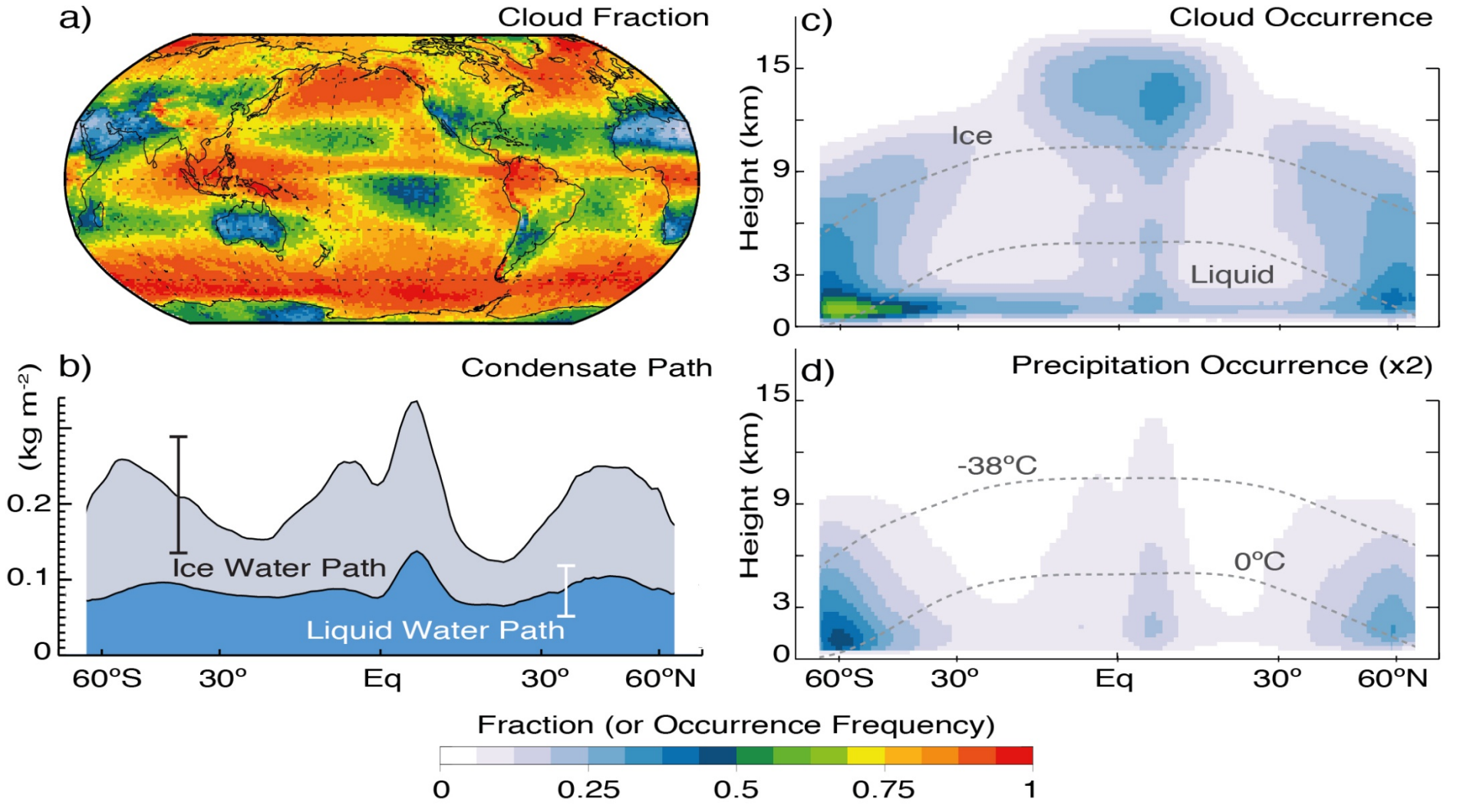
# FAQ 7.1 | How Do Clouds Affect Climate and Climate Change?




| | | |
|---|---|---|
| Greenhouse Warming | High clouds rise as troposphere deepens, increasing difference between cloud top and surface temperature. | Reduction in mid- and low-level cloudiness (left). Shift of cloudy storm tracks poleward into regions with less sunlight (right). |
| Cloud Response | | |
| Feedback Mechanism | High clouds more effectively trap infrared radiation, increasing surface warming. | Less sunlight reflected by clouds back to space, increasing surface warming. |


(a)


(b)
Cirrus
Altostratus
Nimbostratus
10 km
Stratus
COLD
Polar (mixed phase) Stratus
WARM
Mid-Latitudes
High Latitudes
(c)
Thin Cirrus
Convective Anvils
Large-scale Subsidence
17 km
Land/Sea Circulation
Melting Level
WARM SUBSIDING REGIONS
Shallow Cumulus
Stratocumulus
Trade Winds
WARM OCEAN
COLD OCEAN
Deep Tropics
Subtropics


a)
Cloud Fraction
b)
Condensate Path
(kg m-2)
0.2
0.1
0
Ice Water Path
Liquid Water Path
60°S
30°
Eq
30°
60°N
c)
Cloud Occurrence
Height (km)
15
9
3
0
Ice
Liquid
d)
Precipitation Occurrence (x2)
-38°C
0°C
Fraction (or Occurrence Frequency)
0
0.25
0.5
0.75
1

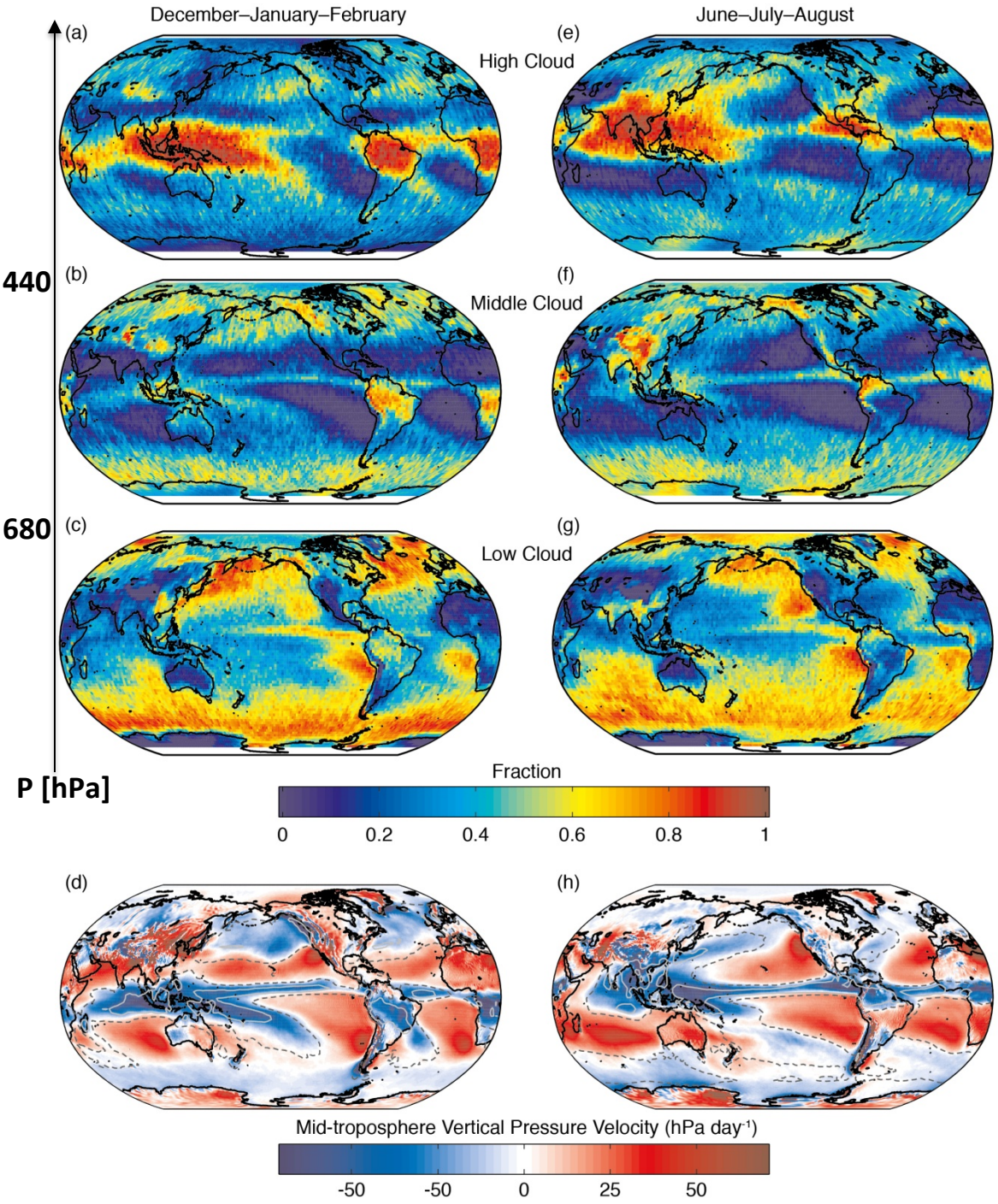



Figure 7.6 | (a–d) December–January–February mean high, middle and low cloud cover from CloudSat/CALIPSO 2B-GEOPROF R04 and 2B-GEOPROF-LIDAR P1.R04 data sets for 2006–2011 (Mace et al., 2009), 500 hPa vertical pressure velocity (colours, from ERA-Interim for 1979–2010; Dee et al., 2011), and Global Precipitation Climatology Project (GPCP) version 2.2 precipitation rate (1981–2010, grey contours at 3 mm day–1 in dash and 7 mm day–1 in solid); (e–h) same as (a–d), except for June–July–August. For low clouds, the GCM-Oriented CALIPSO Cloud Product (GOCCP) data set for 2007–2010 (Chepfer et al., 2010) is used at locations where it indicates a larger fractional cloud cover, because the GEOPROF data set removes some clouds with tops at altitudes below 750 m. Low cloud amounts are probably underrepresented in regions of high cloud (Chepfer et al., 2008), although not as severely as with earlier satellite instruments.

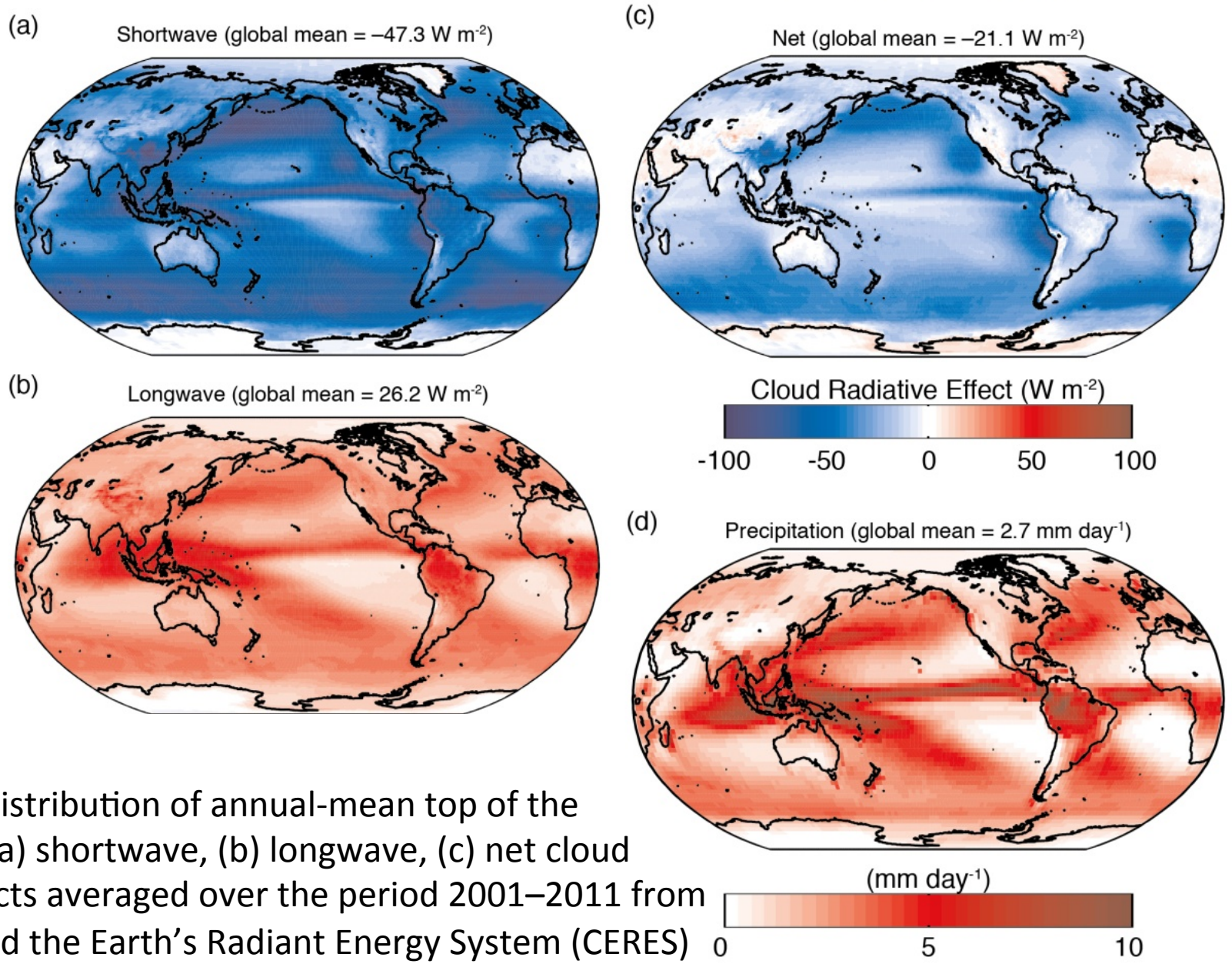



Figure 7.7 | Distribution of annual-mean top of the atmosphere (a) shortwave, (b) longwave, (c) net cloud radiative effects averaged over the period 2001–2011 from the Clouds and the Earth's Radiant Energy System (CERES) Energy Balanced and Filled (EBAF) Ed2.6r data set (Loeb et al., 2009) and (d) precipitation rate (1981–2000 aver- age from the GPCP version 2.2 data set; Adler et al., 2003).

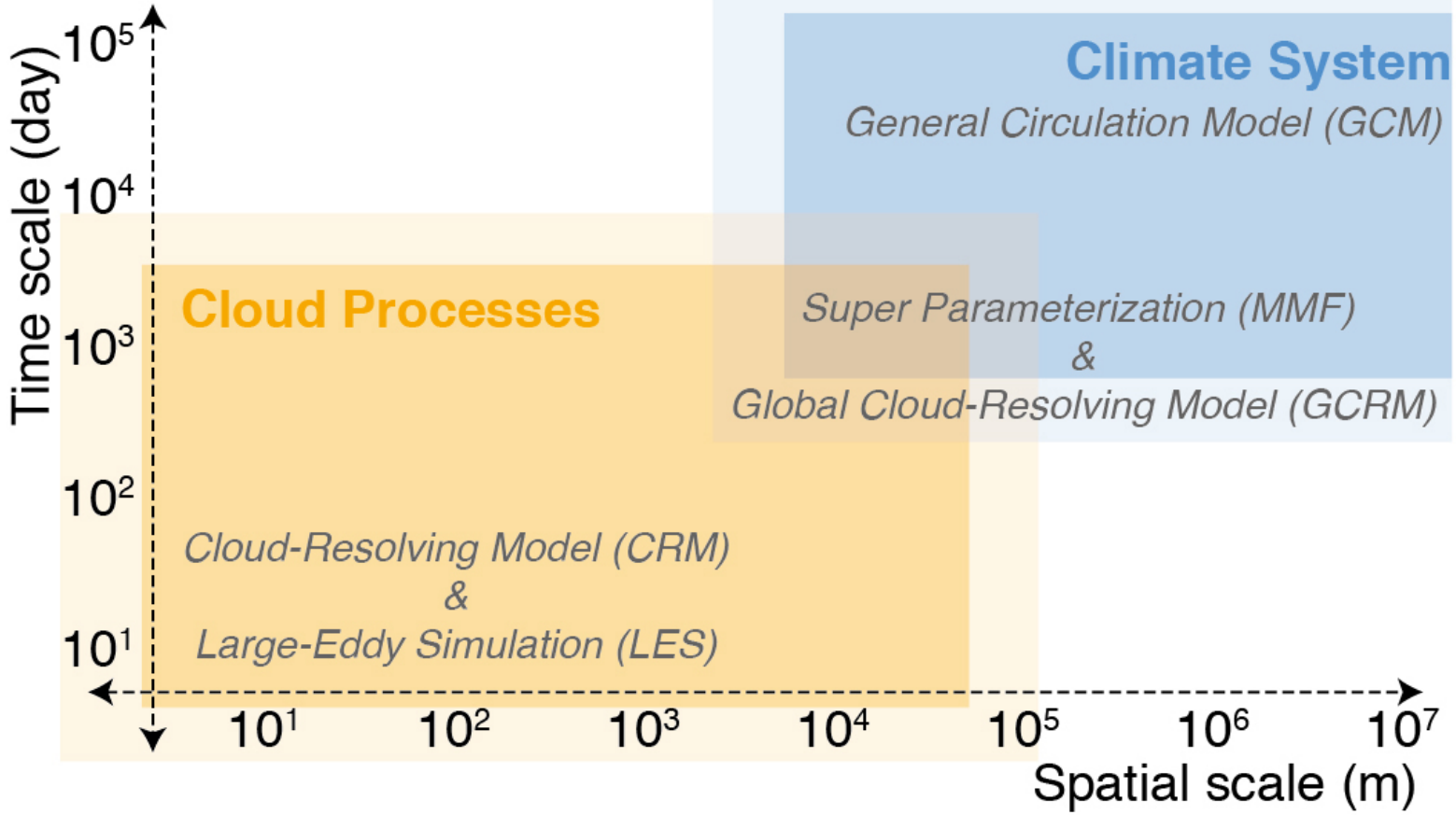



**Figure 7.8 |** Model and simulation strategy for representing the climate system and climate processes at different space and time scales. Also shown are the ranges of space and time scales usually associated with **cloud processes** (orange, lower left) and **the climate system** (blue, upper right). **Classes of models are usually defined based on the range of spatial scales they represen**t, which in the figure is roughly spanned by the text for each model class. The temporal scales simulated by a particular type of model vary more widely. For instance, climate models are often run for a few time steps for diagnostic studies, or can simulate millennia. Hence the figure indicates the typical time scales for which a given model is used. Computational power prevents one model from covering all time and space scales. Since the AR4, the development of Global Cloud Resolving Models (GCRMs), and hybrid approaches such as General Circulation Models (GCMs) using the 'super-parameterization' approach (sometimes called the Multiscale Modelling Framework (MMF)), have helped fill the gap between climate system and cloud process models.

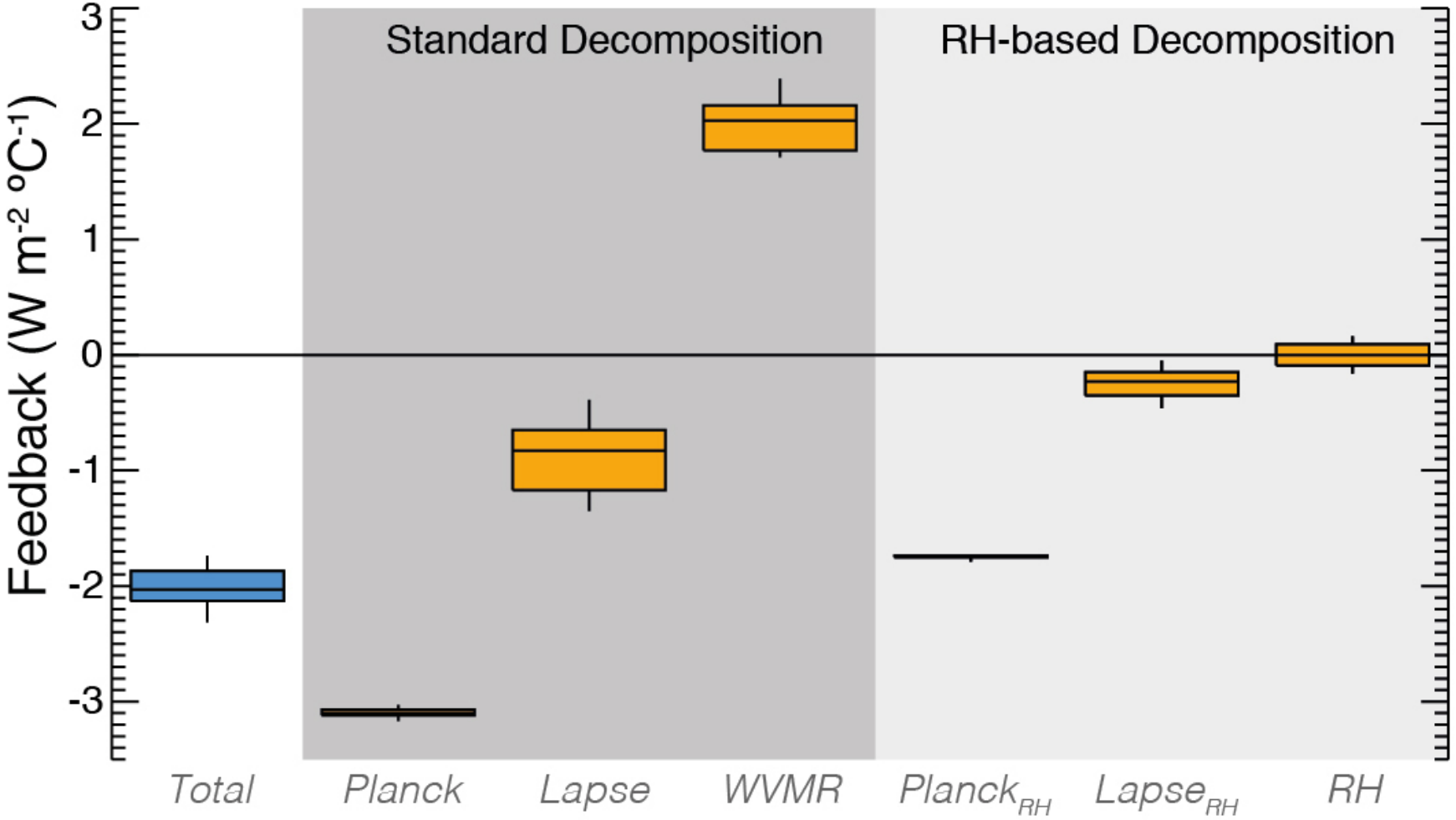



**Figure 7.9 |** Feedback parameters associated with water vapour or the lapse rate predicted by CMIP3 GCMs, with **boxes showing interquartile range and whiskers showing extreme values**. At left is shown the **total radiative response including the Planck response**. In the darker shaded region is shown the **traditional breakdown of this into a Planck response** and **individual feedbacks from water vapour (labelled 'WVMR') and lapse rate (labelled 'Lapse')**. In the lighter-shaded region at right are the equivalent three parameters calculated in **an alternative, relative humidity-based framework.** In this framework all three components are both weaker and more consistent among the models. (Data are from Held and Shell, 2012.)

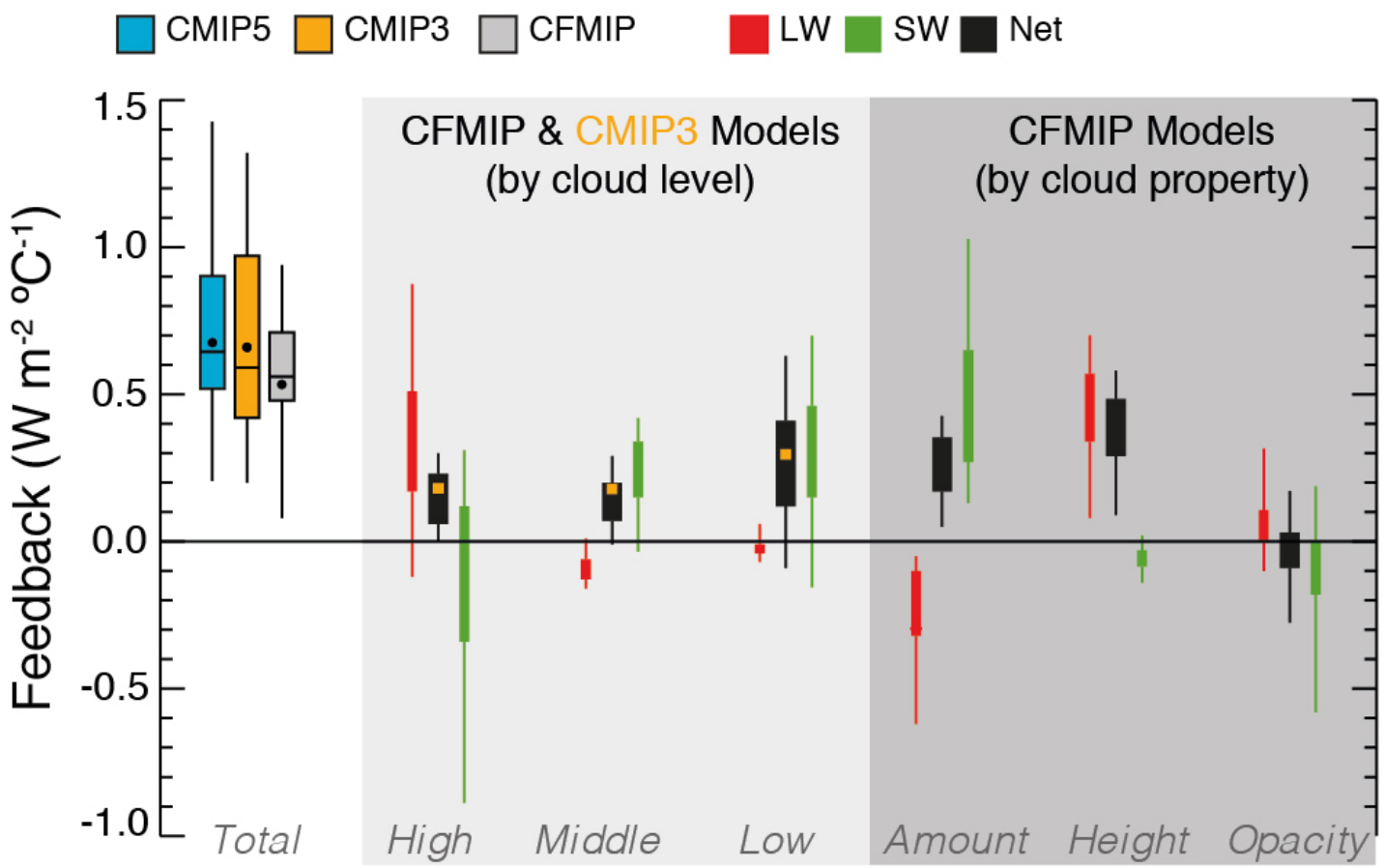



**Figure 7.10 |** Cloud feedback parameters as predicted by GCMs for responses to $CO_2$ increase including rapid adjustments. **Total feedback shown at left**, with **center light shaded section showing components attributable to clouds in specific height ranges** (see Section 7.2.1.1), and **right dark-shaded panel those attributable to specific cloud property changes where available**. The net feedback parameters are broken down in their **longwave** (LW) and **shortwave** (SW) components. Type attribution reported for CMIP3 does not conform exactly to the definition used in the Cloud Feedback Model Intercomparison Project (CFMIP) but is shown for comparison, with their 'mixed' category assigned to middle cloud. CFMIP data (original and CFMIP2) are from Zelinka et al. (2012a, 2012b; 2013); CMIP3 from Soden and Vecchi (2011); and CMIP5 from Tomassini et al(2013).

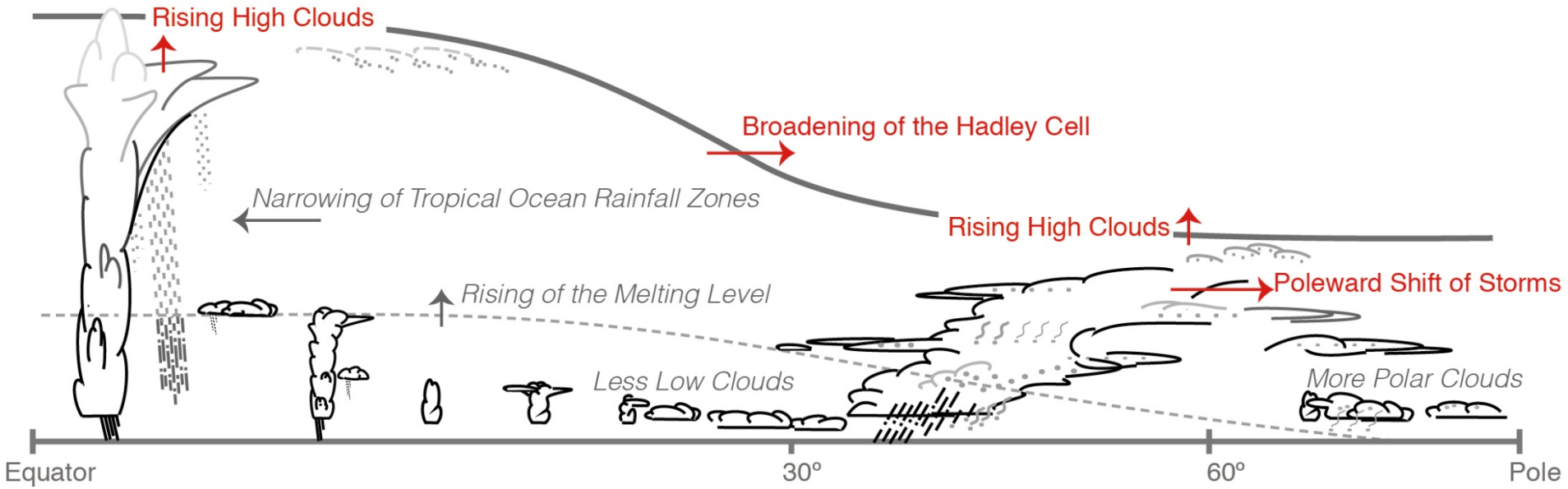



**Figure 7.11 |** Robust **cloud responses to greenhouse warming** (those simulated by most models and possessing some kind of independent support or understanding). **The tropopause** and **melting level** are shown by the thick solid and thin grey dashed lines, respectively. **Changes anticipated in a warmer climate are shown by arrows**, with red colour indicating those making a **robust positive feedback** contribution and grey indicating those where the **feedback contribution is small and/or highly uncertain**. **No robust mechanisms contribute negative feedback**. Changes include **rising high cloud tops** and **melting level, and increased polar cloud cover and/or optical thickness** (high confidence); **broadening of the Hadley Cell and/or poleward migration of storm tracks,** and **narrowing of rainfall zones such as the Intertropical Convergence Zone** (medium confidence); and **reduced low-cloud amount and/or optical thickness** (low confidence). Confidence assessments are based on degree of GCM consensus, strength of independent lines of evidence from observations or process models and degree of basic understanding.

# Clouds – quick summary

- The net radiative feedback due to all cloud types is judged *likely* to be positive.
- The central (most likely) estimate of the total cloud feedback is taken as the mean from GCMs (+0.6 W $m^{-2}$ $°C^{-1}$).
- Because there is no accepted basis to discredit individual GCMs *a priori*, the probability distribution of the true feedback cannot be any narrower than the distribution of GCM results.

# Clouds – quick summary

- Cloudiness and humidity changes in climate models are understood as responses to changes in large scale circulation.
  - Positive feedback: height of high clouds, latitudinal distribution of clouds.
- Some aspects of cloud response vary among models (due to subgrid scale processes).

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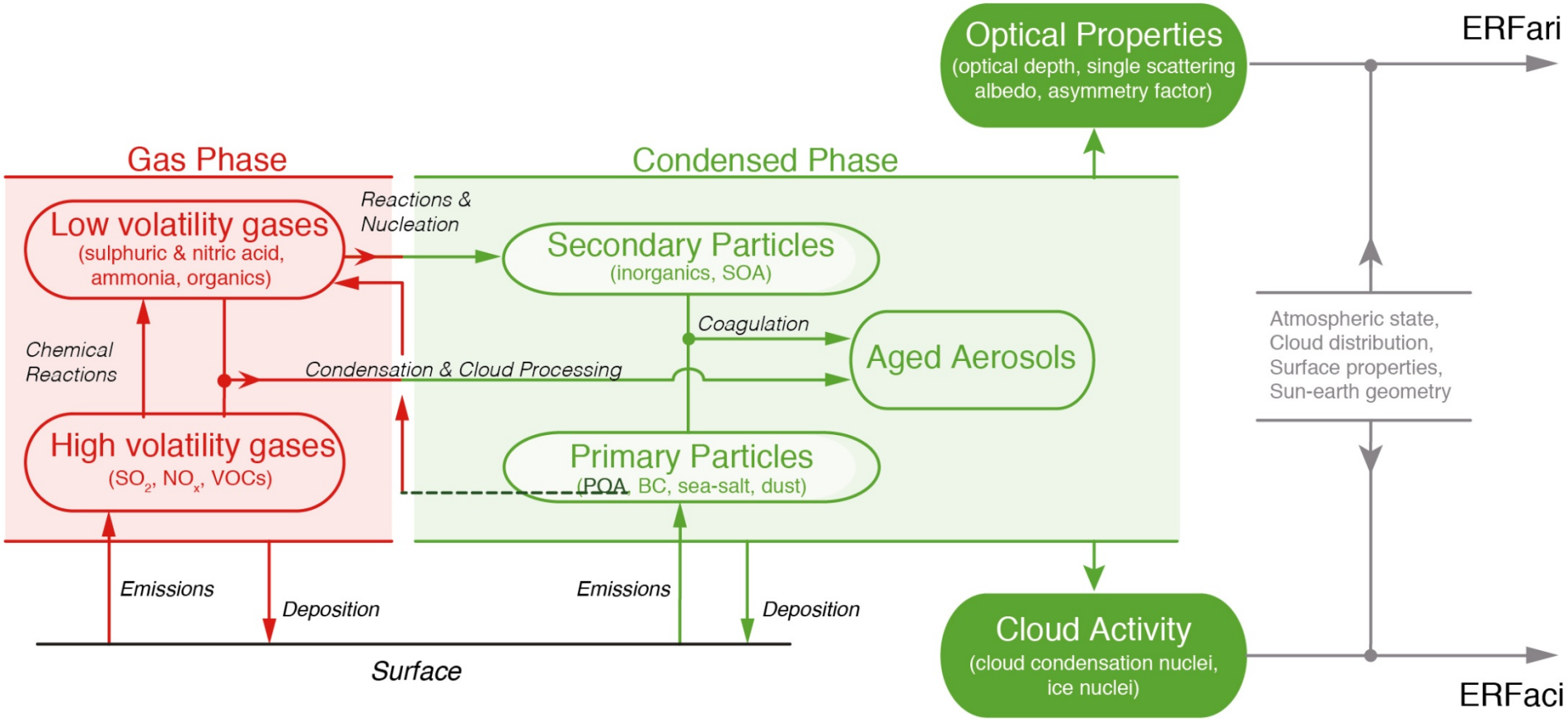


**Figure 7.12 |** Overview of atmospheric aerosol and environmental variables and processes influencing aerosol–radiation and aerosol–cloud interactions. **Gas-phase variables and processes** are highlighted in red while **particulate-phase variables and processes** appear in green. **Although this figure shows a linear chain of processes from aerosols to forcings (ERFari and ERFaci), it is increasingly recognized that aerosols and clouds form a coupled system with two-way interactions** (see Figure 7.16).

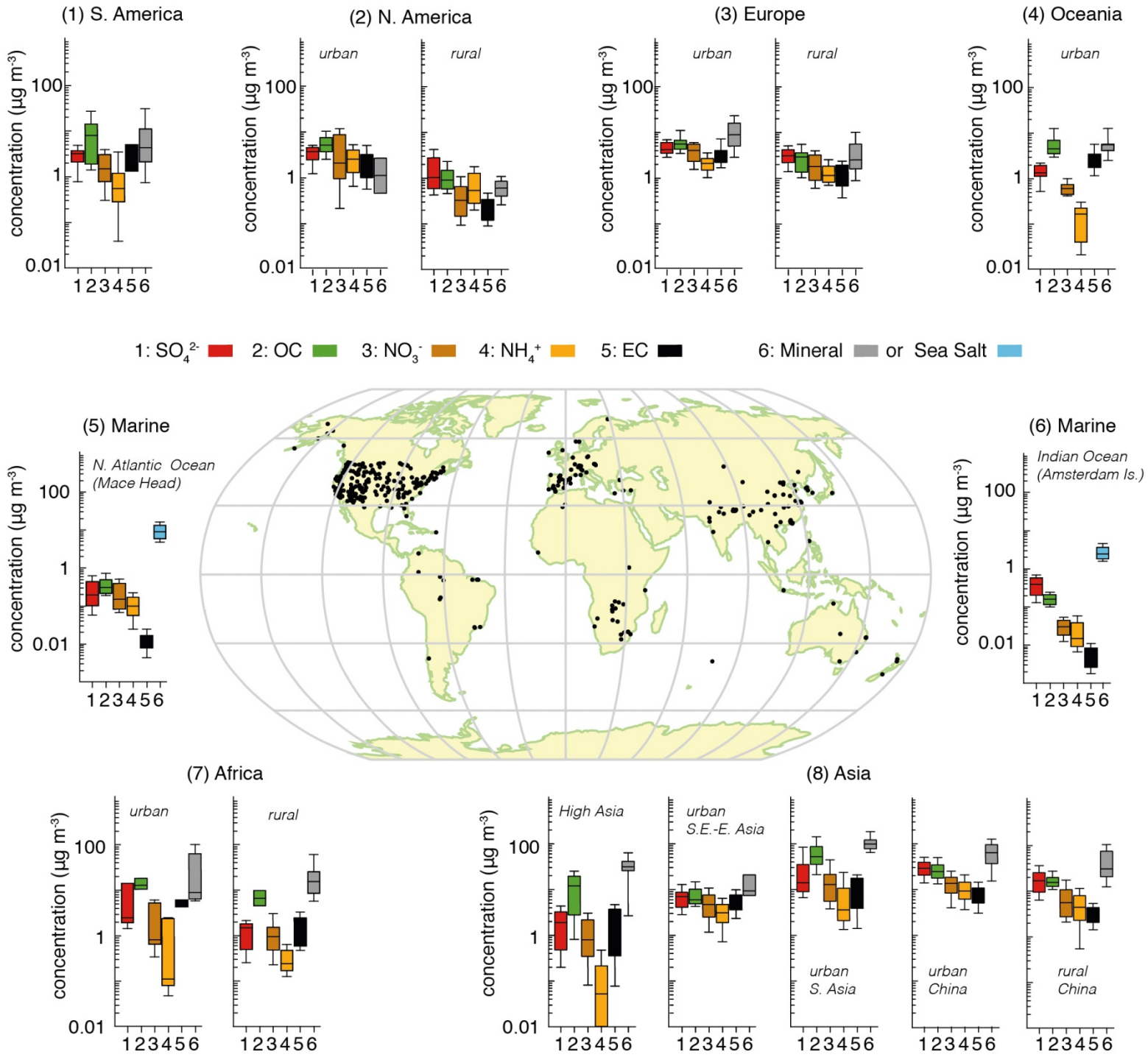
(1) S. America
(2) N. America
(3) Europe
(4) Oceania
urban
rural
concentration (µg m-3)
100
1
0.01
1 2 3 4 5 6
1: SO4 2- 2: OC 3: NO3 - 4: NH4 + 5: EC 6: Mineral or Sea Salt
(5) Marine
N. Atlantic Ocean
(Mace Head)
(6) Marine
Indian Ocean
(Amsterdam Is.)
(7) Africa
(8) Asia
High Asia
urban
S.E.-E. Asia
urban
S. Asia
urban
China
rural
China

**Table 7.2 |** Key aerosol properties of the main aerosol species in the troposphere. Terrestrial primary biological aerosol particles (PBAPs), brown carbon and marine primary organic aerosols (POA) are particular types of organic aerosols (OA) but are treated here as separate components because of their specific properties. The estimated lifetimes in the troposphere are based on the AeroCom models, except for terrestrial PBAPs which are treated by analogy to other coarse mode aerosol types.

| Aerosol Species | Size Distribution | Main Sources | Main Sinks | Tropospheric Lifetime | Key Climate Relevant Properties |
|---|---|---|---|---|---|
| **Sulphate** | Primary: Aitken, accumulation and coarse modes<br>Secondary: Nucleation, Aitken, and accumulation modes | Primary: marine and volcanic emissions.<br>Secondary: oxidation of $SO_2$ and other S gases from natural and anthropogenic sources | Wet deposition<br>Dry deposition | ~ 1 week | Light scattering. Very hygroscopic. Enhances absorption when deposited as a coating on black carbon. Cloud condensation nuclei (CCN) active. |
| **Nitrate** | Accumulation and coarse modes | Oxidation of $NO_x$ | Wet deposition<br>Dry deposition | ~ 1 week | Light scattering.<br>Hygroscopic. CCN active. |
| **Black carbon** | Freshly emitted: <100 nm<br>Aged: accumulation mode | Combustion of fossil fuels, biofuels and biomass | Wet deposition<br>Dry deposition | 1 week to 10 days | Large mass absorption efficiency in the shortwave. CCN active when coated. May be ice nuclei (IN) active. |
| **Organic aerosol** | POA: Aitken and accumulation modes. SOA: nucleation, Aitken and mostly accumulation modes.<br>Aged OA: accumulation mode | Combustion of fossil fuel, biofuel and biomass. Continental and marine ecosystems.<br>Some anthropogenic and biogenic non-combustion sources | Wet deposition<br>Dry deposition | ~ 1 week | Light scattering. Enhances absorption when deposited as a coating on black carbon. CCN active (depending on aging time and size). |
| **... of which brown carbon** | Freshly emitted: 100–400 nm<br>Aged: accumulation mode | Combustion of biofuels and biomass. Natural humic-like substances from the biosphere | Wet deposition<br>Dry deposition | ~ 1 week | Medium mass absorption efficiency in the UV and visible. Light scattering. |
| **... of which terrestrial PBAP** | Mostly coarse mode | Terrestrial ecosystems | Sedimentation<br>Wet deposition<br>Dry deposition | 1 day to 1 week depending on size | May be IN active. May form giant CCN |
| **Mineral dust** | Coarse and super-coarse modes, with a small accumulation mode | Wind erosion, soil resuspension.<br>Some agricultural practices and industrial activities (cement) | Sedimentation<br>Dry deposition<br>Wet deposition | 1 day to 1 week depending on size | IN active. Light scattering and absorption.<br>Greenhouse effect. |
| **Sea spray** | Coarse and accumulation modes | Breaking of air bubbles induced e.g., by wave breaking. Wind erosion. | Sedimentation<br>Wet deposition<br>Dry deposition | 1 day to 1 week depending on size | Light scattering. Very hygroscopic. CCN active. Can include primary organic compounds in smaller size range |
| **... of which marine POA** | Preferentially Aitken and accumulation modes | Emitted with sea spray in biologically active oceanic regions | Sedimentation<br>Wet deposition<br>Dry deposition | ~ 1 week | CCN active. |

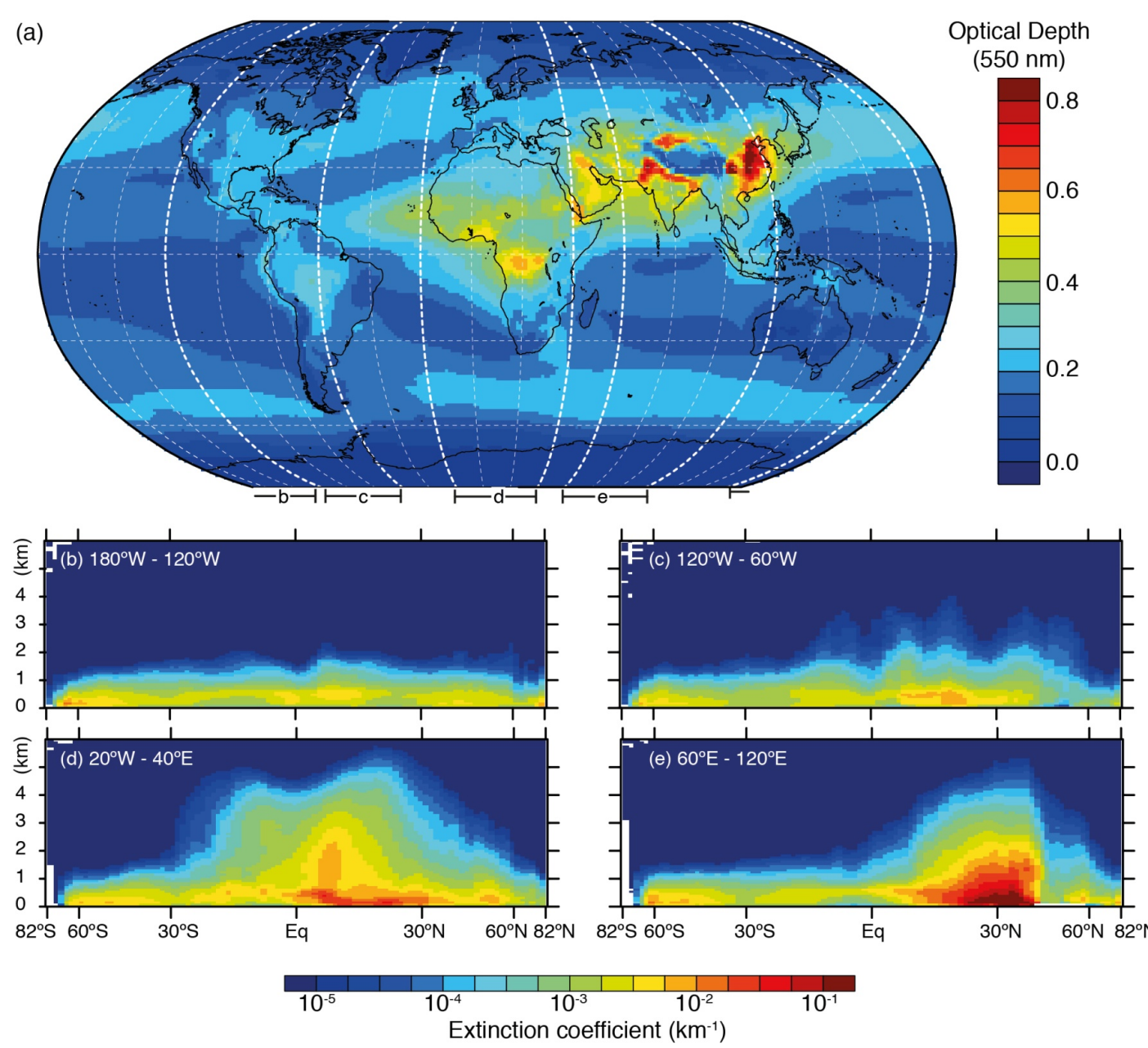


Figure 7.14 | (a) Spatial distribution of the 550 nm aerosol optical depth (AOD, unitless) from the European Centre for Medium Range Weather Forecasts (ECMWF) Integrated Forecast System model with assimilation of Moderate Resolution Imaging Spectrometer (MODIS) aerosol optical depth (Benedetti et al., 2009; Morcrette et al., 2009) averaged over the period 2003–2010; (b–e) latitudinal vertical cross sections of the 532 nm aerosol extinction coefficient (km–1) for four longitudinal bands (180°W to 120°W, 120°W to 60°W, 20°W to 40°E, and 60°E to 120°E, respectively) from the Cloud–Aerosol Lidar with Orthogonal Polarization (CALIOP) instrument for the year 2010 (nighttime all-sky data, version 3; Winker et al., 2013).

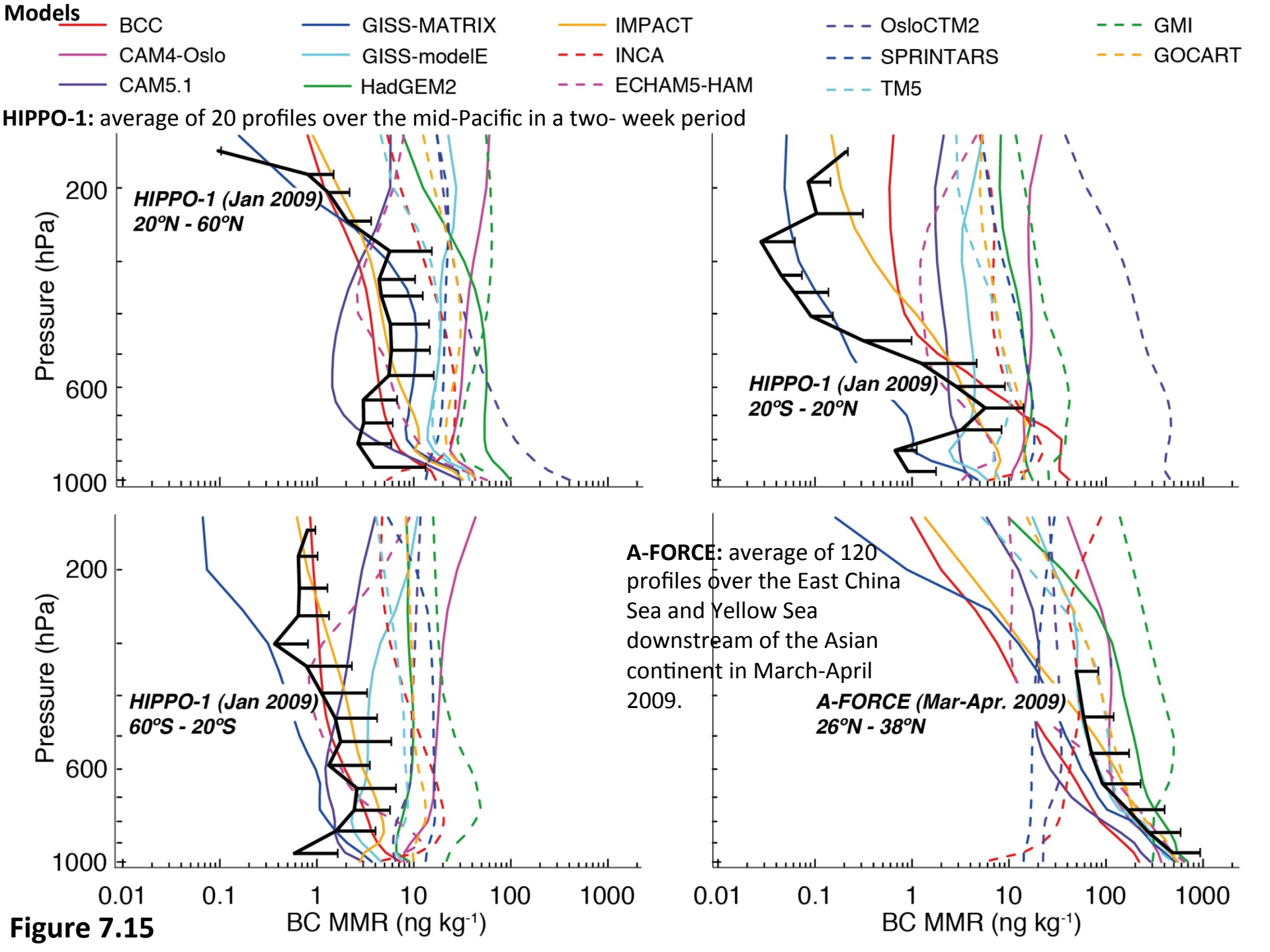
Models
BCC
CAM4-Oslo
CAM5.1
GISS-MATRIX
GISS-modelE
HadGEM2
IMPACT
INCA
ECHAM5-HAM
OsloCTM2
SPRINTARS
TM5
GMI
GOCART
HIPPO-1: average of 20 profiles over the mid-Pacific in a two- week period
HIPPO-1 (Jan 2009)
20°N - 60°N
HIPPO-1 (Jan 2009)
20°S - 20°N
HIPPO-1 (Jan 2009)
60°S - 20°S
A-FORCE (Mar-Apr. 2009)
26°N - 38°N
A-FORCE: average of 120 profiles over the East China Sea and Yellow Sea downstream of the Asian continent in March-April 2009.
Pressure (hPa)
200
600
1000
0.01
0.1
1
10
100
1000
BC MMR (ng kg-1)

**Figure 7.15**

# Aerosols – quick summary

- Climate-relevant aerosol processes are better understood, and their properties are better observed.
  - Representation of process varies greatly with models.
  - The level of sophistication required is unclear.
  - Anthropogenic origin: 20-40% of aerosol optical depth (AOD), 25-67% of CCNs.

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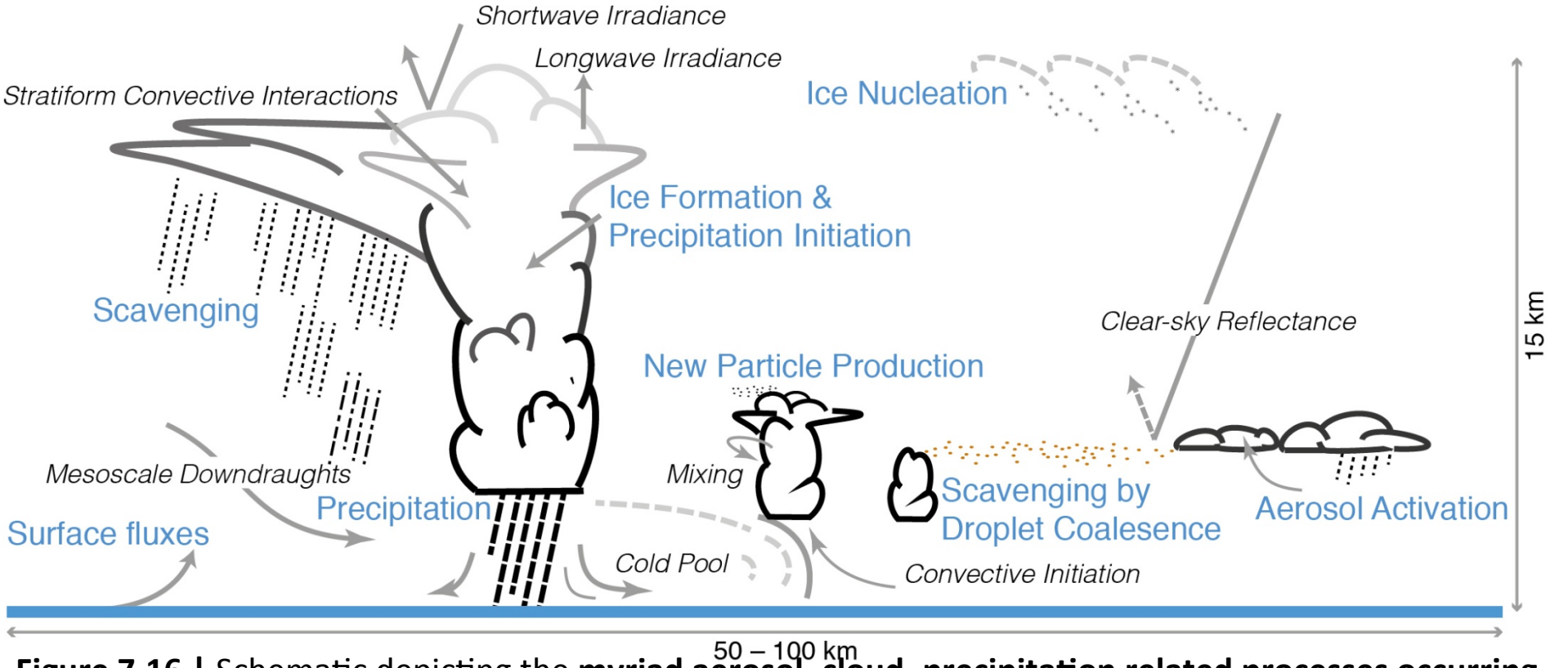


**Figure 7.16 |** Schematic depicting the **myriad aerosol–cloud–precipitation related processes occurring within a typical GCM grid box.** The schematic conveys the **importance of considering aerosol–cloud–precipitation processes as part of an interactive system** encompassing a large range of spatiotemporal scales. Cloud types include low-level stratocumulus and cumulus where **research focuses on aerosol activation, mixing between cloudy and environmental air, droplet coalescence and scavenging which results in cloud processing of aerosol particles, and new particle production near clouds; cirrus clouds where a key issue is ice nucleation through homogeneous and heterogeneous freezing; and deep convective clouds where some of the key questions relate to aerosol influences on liquid, ice, and liquid–ice pathways for precipitation formation, cold pool formation and scavenging. These processes influence the shortwave and longwave cloud radiative effect and hence climate**. **Primary processes that affect aerosol–cloud interactions** are labelled in blue while **secondary processes that result from and influence aerosol–cloud interactions** are in grey.

# Physical Mechanisms Linking Cosmic Rays to Cloudiness

- 'Ion-aerosol clear air' mechanism: GCR ionize atoms that facilitate aerosol nucleation and growth, impacting CCN concentrations → possible changes in cloud cover and properties. [*Svensmark 1998*]
- Global electric circuit: GCR ionization→conductive atmosphere→fairweather current→ions scavenged by cloud droplets→cloud dynamics leads to charge accumulation at the cloud boundaries→conductivity gradients→ effects on droplet collisions→possible changes in cloud cover and properties.

**"Cosmic rays enhance new particle formation in the free troposphere, but the effect on the concentration of cloud condensation nuclei is too weak to have any detectable climatic influence during a solar cycle or over the last century (*medium evidence, high agreement*)".**

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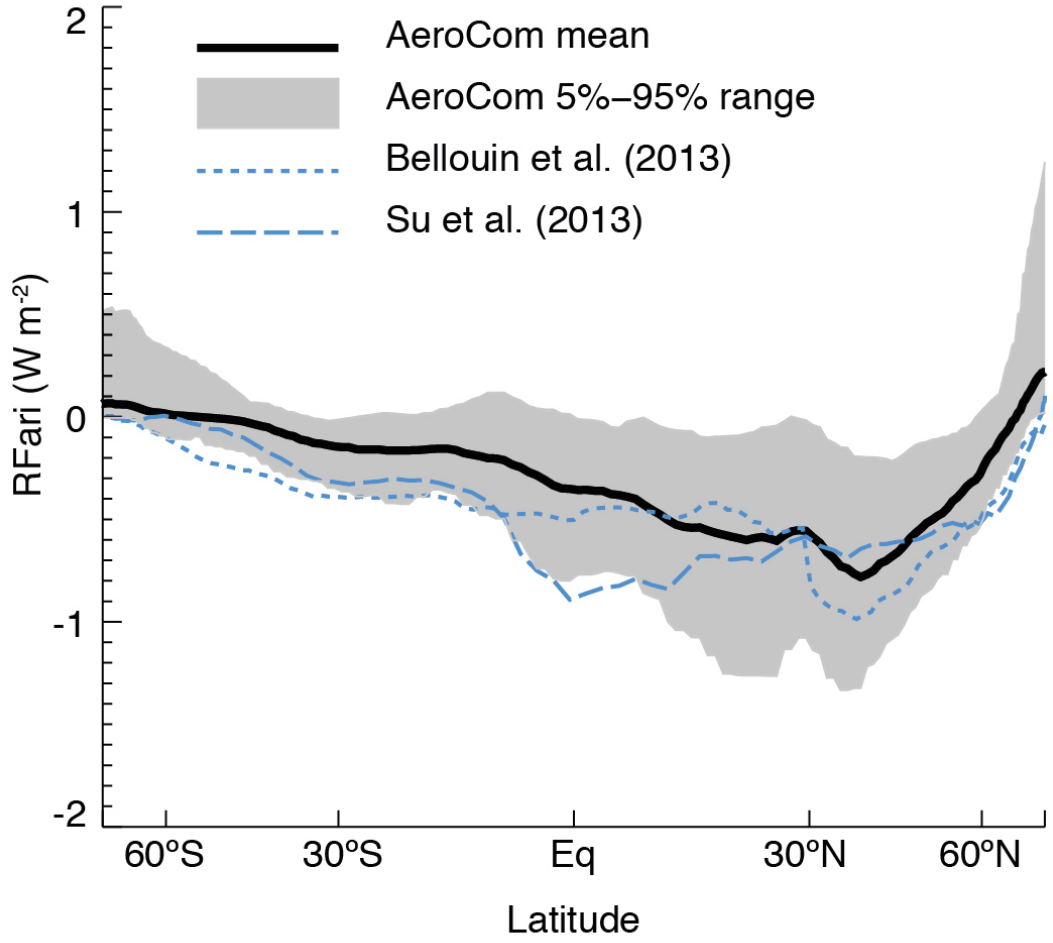



**Figure 7.17 |** Annual zonal mean top of the atmosphere radiative forcing due to aerosol–radiation interactions (RFari, in W m–2) due to all anthropogenic aerosols from the different AeroCom II models. No adjustment for missing species in certain models has been applied. **The multi-model mean** and **5th to 95th percentile range** from AeroCom II models (Myhre et al., 2013) are shown with a black solid line and grey envelope. The **estimates from Bellouin et al. (2013) and Su et al. (2013)** are shown with dotted and dashed lines, respectively. **The forcings are for the 1850 to 2000 period.**

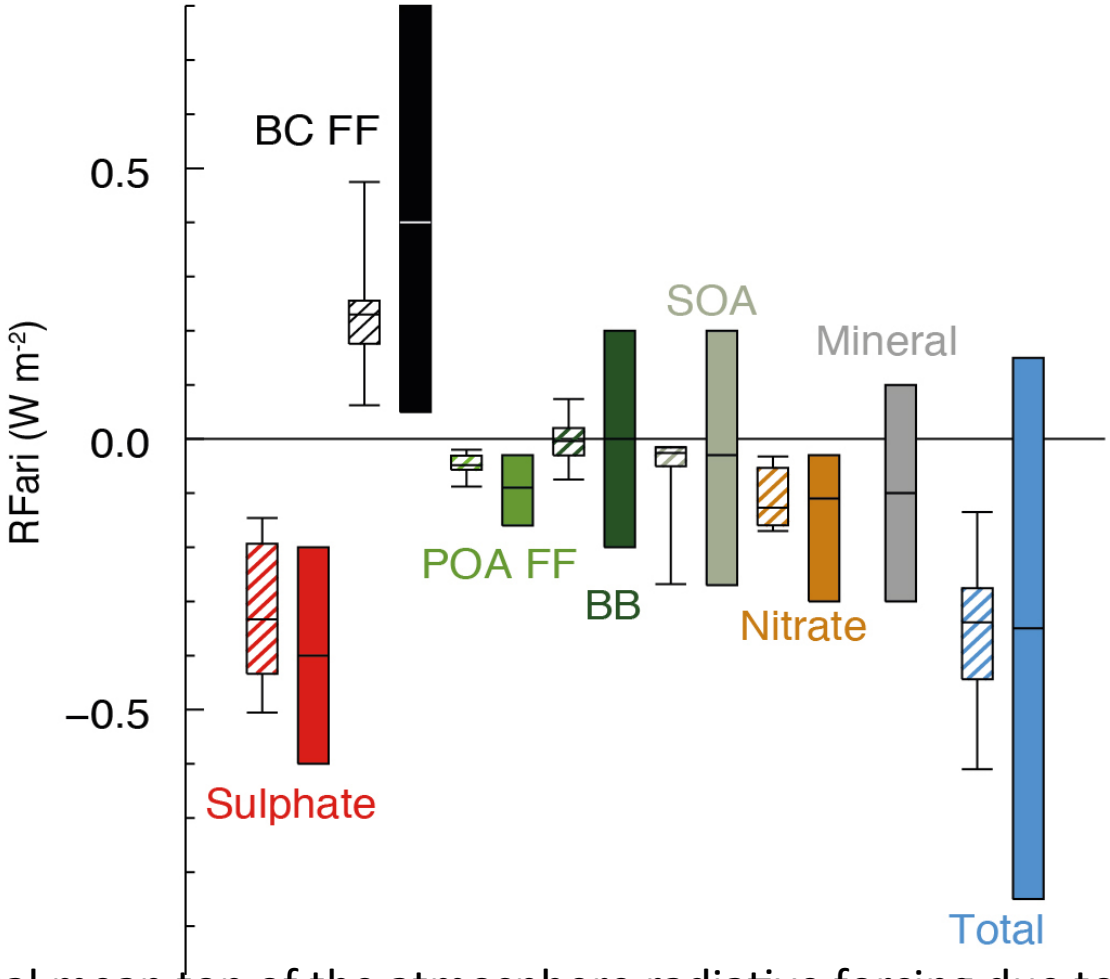
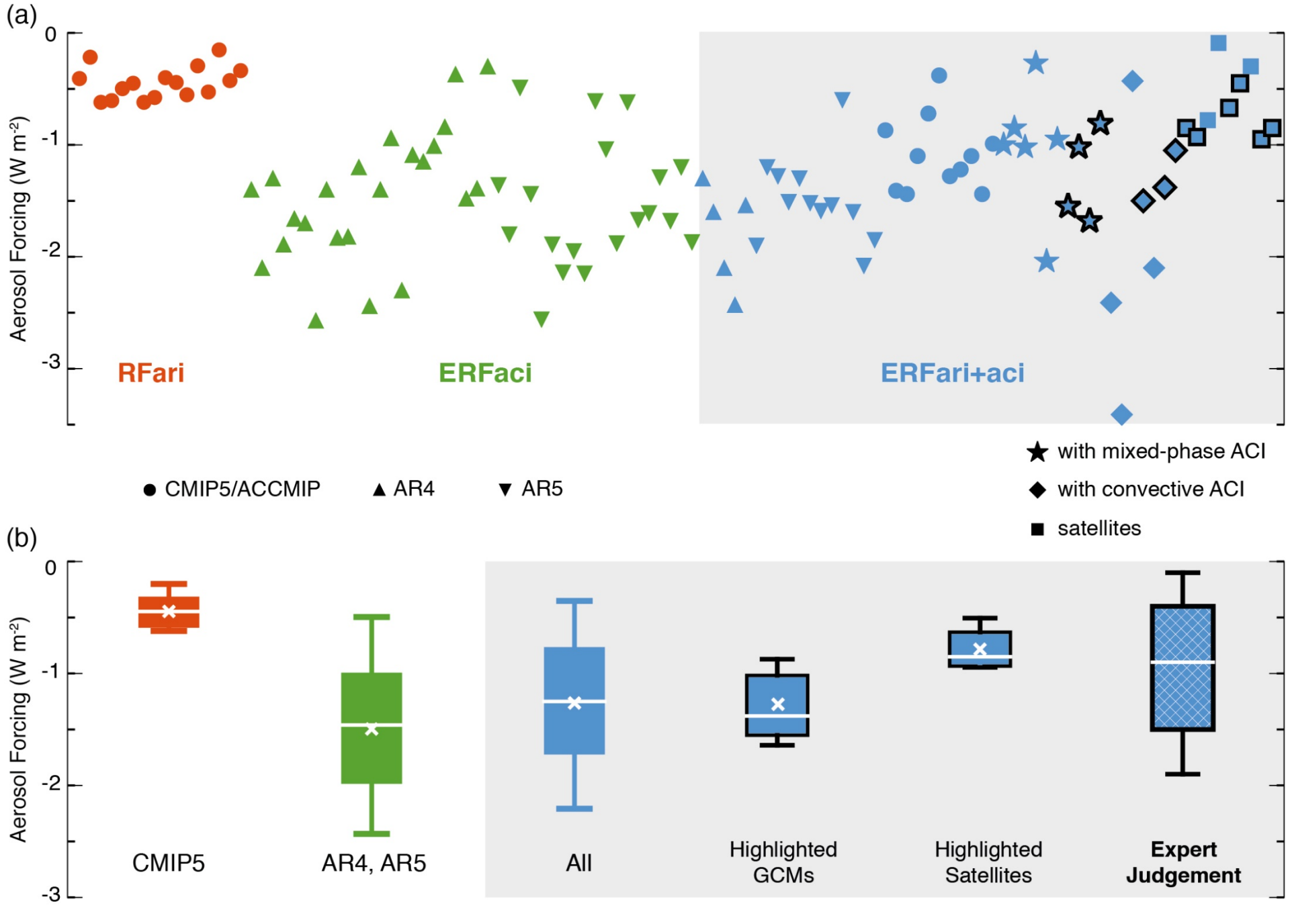



**Figure 7.18 |** Annual mean top of the atmosphere radiative forcing due to aerosol– radiation interactions (RFari, in W m–2) due to different anthropogenic aerosol types, for the 1750–2010 period**. Hatched whisker boxes show median (line), 5th to 95th percentile ranges (box) and min/max values (whiskers) from AeroCom II models (Myhre et al., 2013) corrected for the 1750–2010 period.** Solid coloured boxes show the AR5 best estimates and 90% uncertainty ranges. **BC FF is for black carbon from fossil fuel and biofuel, POA FF is for primary organic aerosol from fossil fuel and biofuel, BB is for biomass burning aerosols and SOA is for secondary organic aerosols**.


(a)
0
-1
-2
-3
Aerosol Forcing (W m-2)
RFari
ERFaci
ERFari+aci
CMIP5/ACCMIP
AR4
AR5
with mixed-phase ACI
with convective ACI
satellites
(b)
0
-1
-2
-3
Aerosol Forcing (W m-2)
CMIP5
AR4, AR5
All
Highlighted GCMs
Highlighted Satellites
Expert Judgement

# Outline

- Introduction
- Clouds
- Aerosols
- Aerosol-Cloud Interactions
- Radiative forcing and Effective Radiative forcing by Anthropogenic aerosols
- **Processes Underlying Precipitation Changes**
- Solar Radiation Management and Related methods

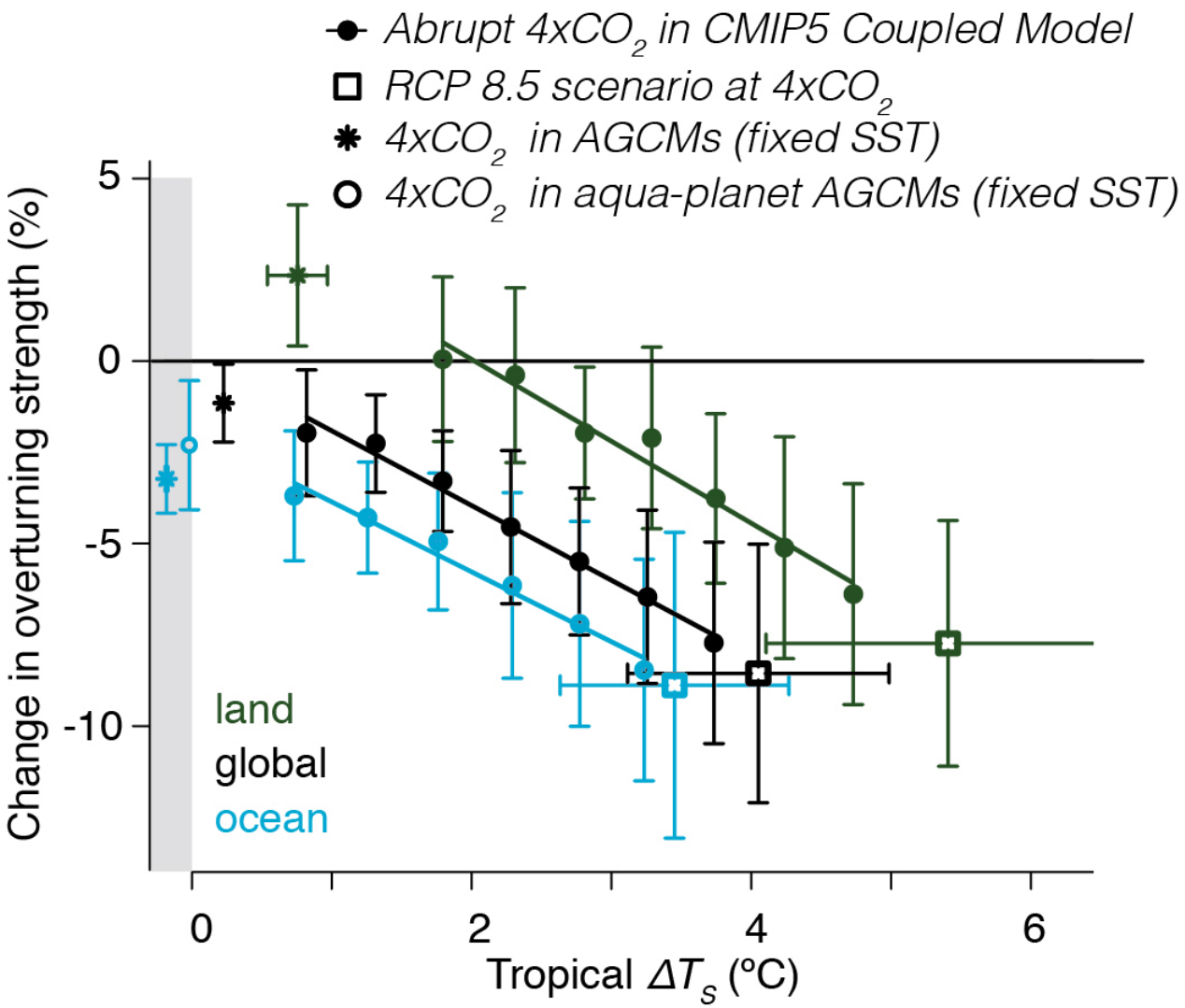



**Figure 7.20 |** Illustration of the response of the large-scale atmospheric overturning to warming (adapted from Bony et al., 2013). **The overturning intensity is shown on the y-axis and is measured by the difference between the mean motion in upward moving air and the mean motion in downward moving air. The warming is shown on the x-axis and is measured by the change in surface temperature averaged over the Tropics, ΔTs, after an abrupt quadrupling of atmospheric CO2.** The grey region delineates responses for which ΔTs is zero by definition. Nearly one half of the final reduction in the intensity of the overturning is evident before any warming is felt, and can be associated with a rapid adjustment of the hydrological cycle to changes in the atmospheric cooling rate accompanying a change in CO2. With warming the circulation intensity is further reduced. The rapid adjustment, as measured by the change in circulation intensity for zero warming, is different over land and ocean. Over land the increase in CO2 initially causes an intensification of the circulation. **The result is robust in the sense that it is apparent in all of the 15 CMIP5 models analyzed, irrespective of the details of their configuration.**

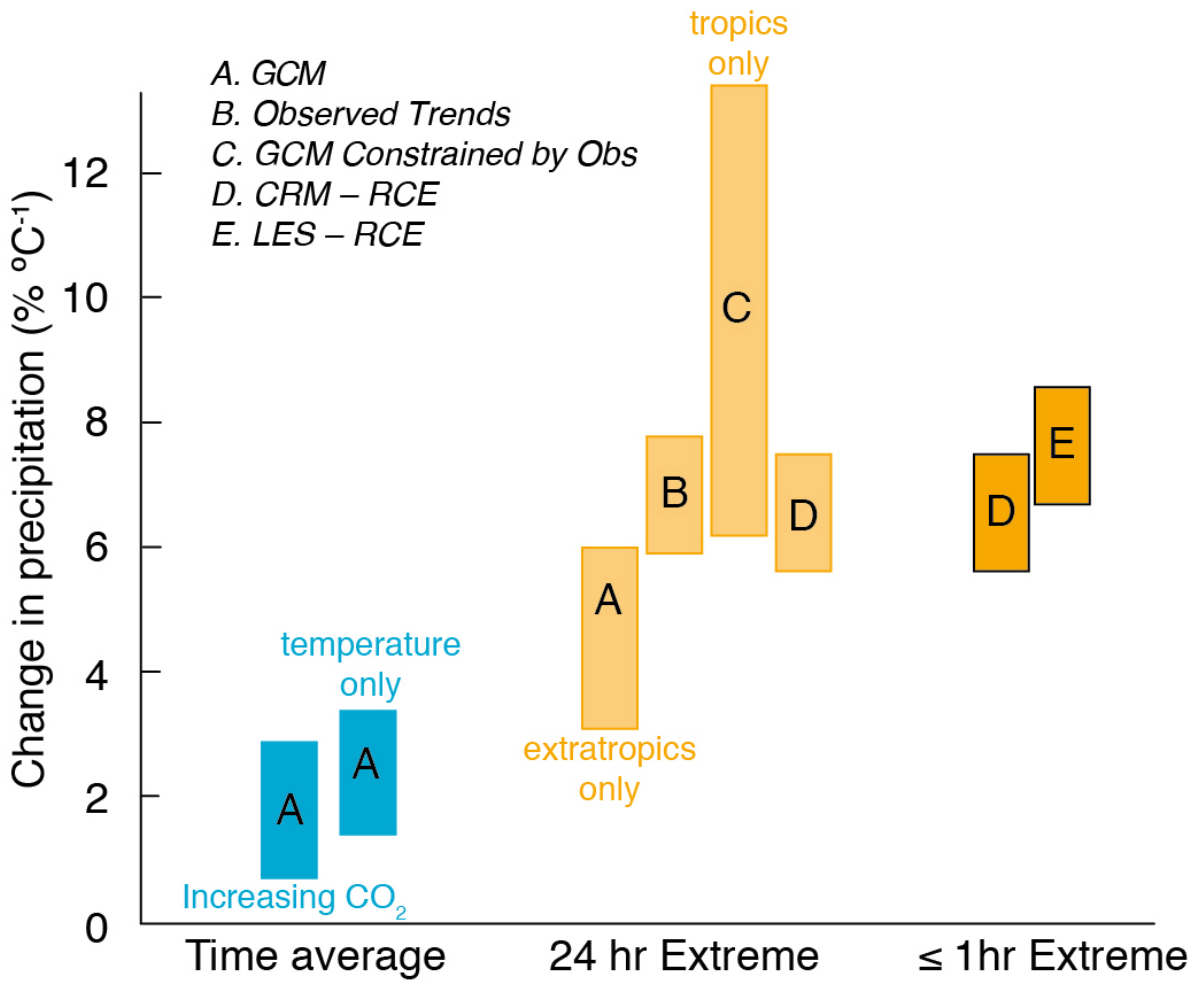



**Figure 7.21 |** Estimate (5 to 95% range) of the increase in precipitation amount per degree Celsius of global mean surface temperature change. At left (blue) are **climate model predictions of changes in time-averaged global precipitation**; at centre and right (orange) are **predictions or estimates of the typical or average increase in local 99.9th percentile extremes, over 24 hours (centre) and over one hour or less (right)**. Data are adapted from (A) GCM studies (Allen and Ingram, 2002; and Lambert and Webb, 2008, for time average; O'Gorman and Schneider, 2009 for extremes), (B) long-term trends at many sites globally (Westra et al., 2013), (C) GCMs constrained by present- day observations of extremes (O'Gorman, 2012), (D, E) cloud-resolving model (CRM) and large-eddy simulation (LES) studies of radiative convective equilibrium (Muller et al., 2011; Romps, 2011).

# Outline

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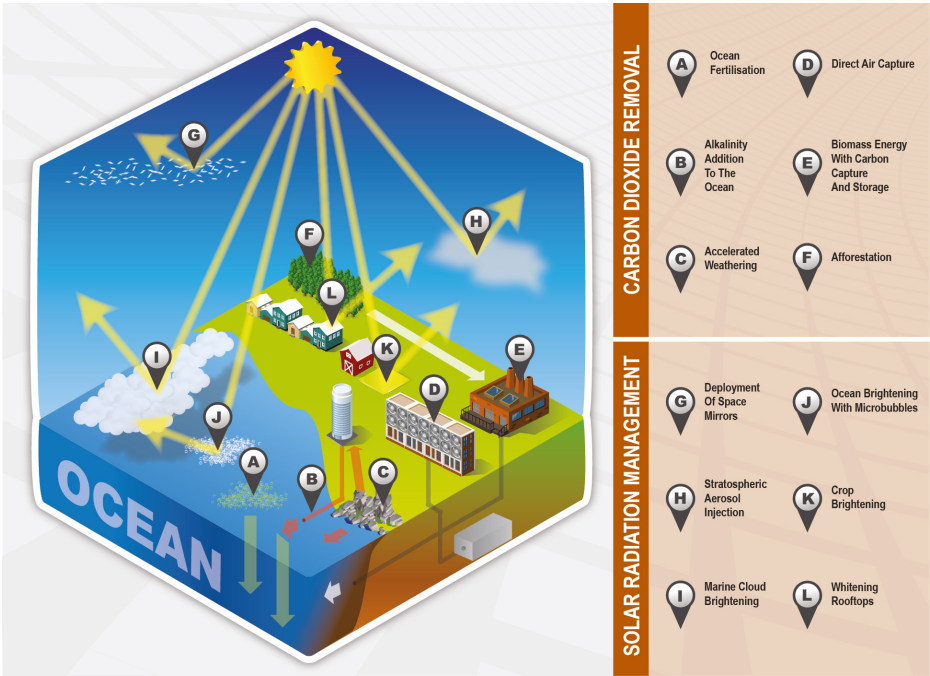
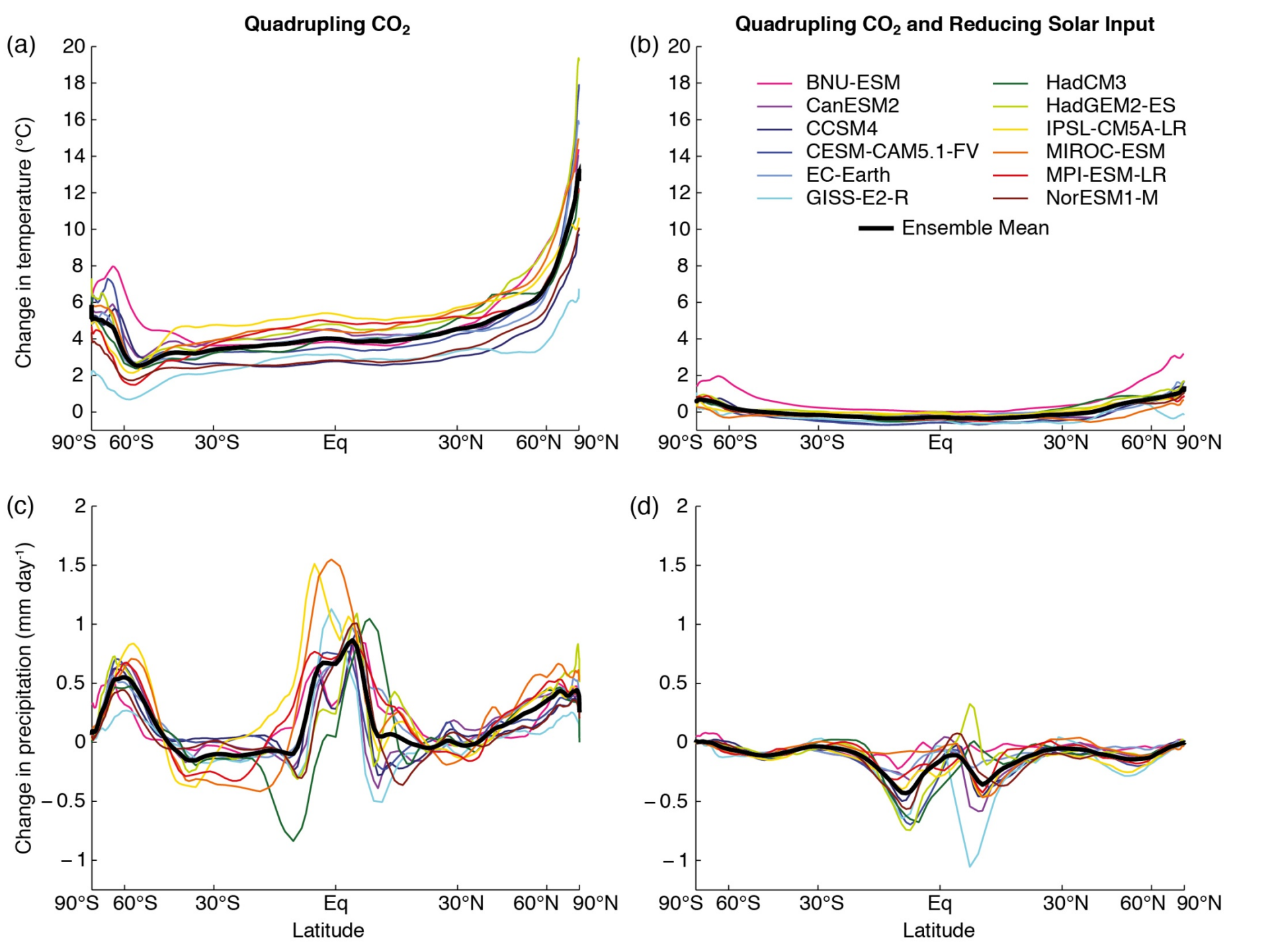
# Methods (all questionable)

- Stratospheric aerosols (SO2, H2SO4).
- Cloud brightening via cloud seeding
- Surface albedo changes applied to urban areas, cropland, grassland, deserts and the ocean surface.
- Cirrus thinning via adding efficient IN




Quadrupling $CO_2$
Quadrupling $CO_2$ and Reducing Solar Input
(a)
(b)
(c)
(d)
Change in temperature (°C)
Change in precipitation (mm day$^{-1}$)
Latitude
BNU-ESM
CanESM2
CCSM4
CESM-CAM5.1-FV
EC-Earth
GISS-E2-R
HadCM3
HadGEM2-ES
IPSL-CM5A-LR
MIROC-ESM
MPI-ESM-LR
NorESM1-M
Ensemble Mean
90°S 60°S 30°S Eq 30°N 60°N 90°N

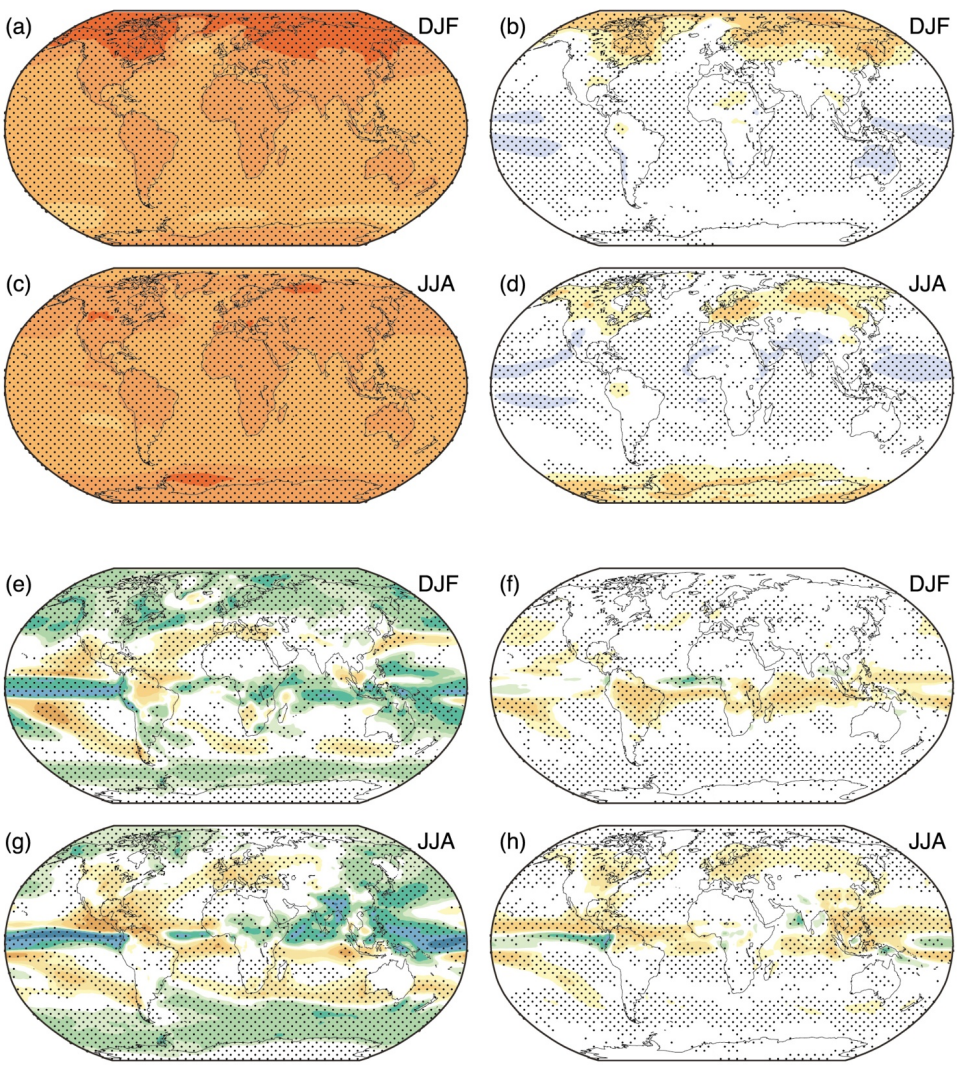



Figure 7.23 | Multi-model mean of the change in surface air temperature (°C) averaged over December, January and February (DJF) for (a) an abrupt 4 × $CO_2$ simulation and (b) an experiment where the 4 × $CO_2$ forcing is balanced by a reduction in the total solar irradiance to produce a global top of the atmosphere flux imbalance of less than ±0.1 W m–2 during the first 10 years of the simulation (Geoengineering Model Intercomparison Project (GeoMIP) G1 experiment; Kravitz et al., 2011). (c, d) Same as (a-b) but for June, July and August (JJA). (e–h) same as (a–d) but for the change in precipitation (mm day–1). All changes are relative to the pre-industrial control experiment and averaged over years 11 to 50. The figure extends the results from Schmidt et al. (2012b) and shows the results from an ensemble of 12 coupled ocean–atmosphere general circulation models. Stippling denotes agreement on the sign of the anomaly in at least 9 out of the 12 models.

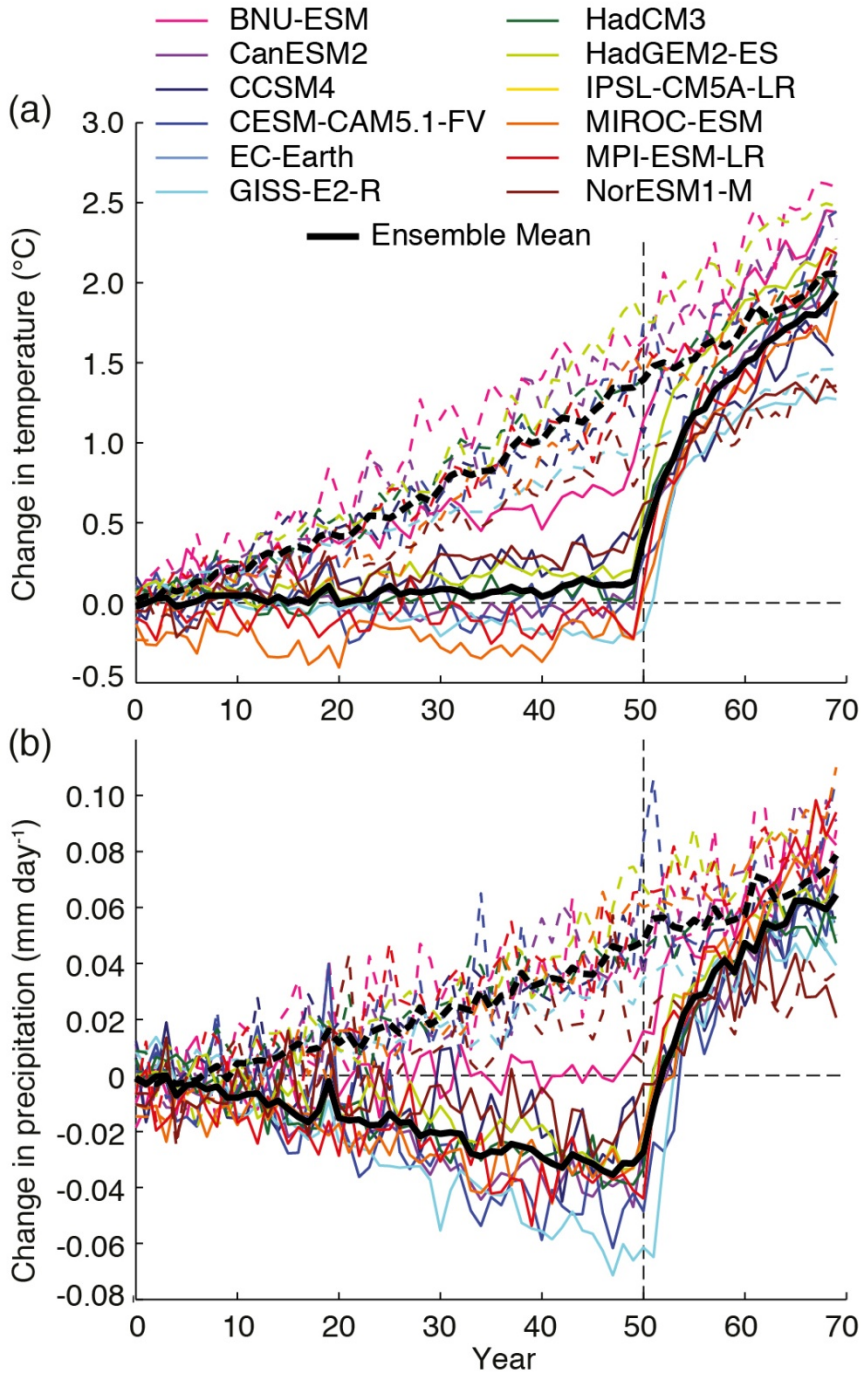



Figure 7.24 | Time series of globally averaged (a) surface temperature (°C) and (b) precipitation (mm day–1) changes relative to each model's 1 × $CO_2$ reference simula- tion. Solid lines are for simulations using solar radiation management (SRM) through an increasing reduction of the total solar irradiance to balance a 1% yr–1 increase in $CO_2$ concentration until year 50, after which SRM is stopped for the next 20 years (Geoengineering Model Intercomparison Project (GeoMIP) G2 experiment; Kravitz et al., 2011). Dashed lines are for 1% $CO_2$ increase simulations with no SRM. The multi-model ensemble mean is shown with thick black lines.

# Summary

# Summary

- The quantification of cloud and convective effects in models, and of aerosol–cloud interactions, continues to be a challenge.
- Climate models are incorporating more of the relevant processes than at the time of AR4, but confidence in the representation of these processes remains weak.

# Summary

- Precipitation and evaporation are expected to increase on average in a warmer climate, but also undergo global and regional adjustments to carbon dioxide (CO2) and other forcings that differ from their warming responses.
- There is *high confidence* that, as climate warms, extreme precipitation rates on for example, daily time scales will increase faster than the time average.
- Changes in average precipitation must be consistent with changes in net cooling of the troposphere (which is affected by its temperature, GHGs, and aerosols).

# Summary

- The net feedback from water vapour and lapse rate changes combined, as traditionally defined, is *extremely likely* positive (amplifying global climate changes).
- The sign of the net radiative feedback due to all cloud types is less certain but *likely* positive.
- Uncertainty in the sign and magnitude of the cloud feedback is due primarily to continuing uncertainty in the impact of warming on low clouds (positive but uncertain).
- Aerosol–climate feedbacks occur mainly through changes in the source strength of natural aerosols or changes in the sink efficiency of natural and anthropogenic aerosols.