Importance of clouds and aerosols in assessing climate change

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Acknowledgements

Lead Authors of IPCC WGI
Fifth Assessment Report

… especially those from the
“Clouds and Aerosols” chapter

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Clouds and Aerosols

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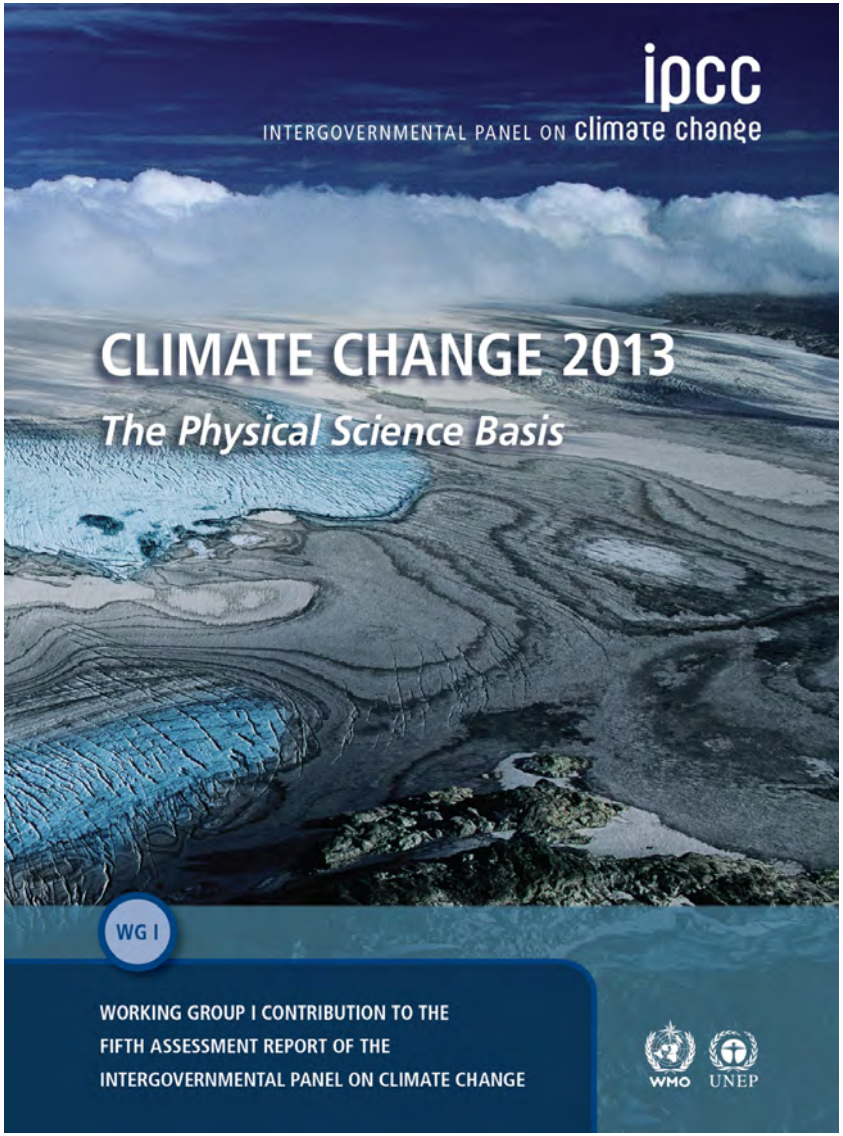

Outline

Introduction & Forcing, feedbacks and climate response

Role of aerosols in a changing energy budget

- Aerosol-radiation interactions
- Aerosol-cloud interactions

Role of clouds in a changing energy budget

Concluding remarks

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Introduction & Forcing, feedbacks and climate response

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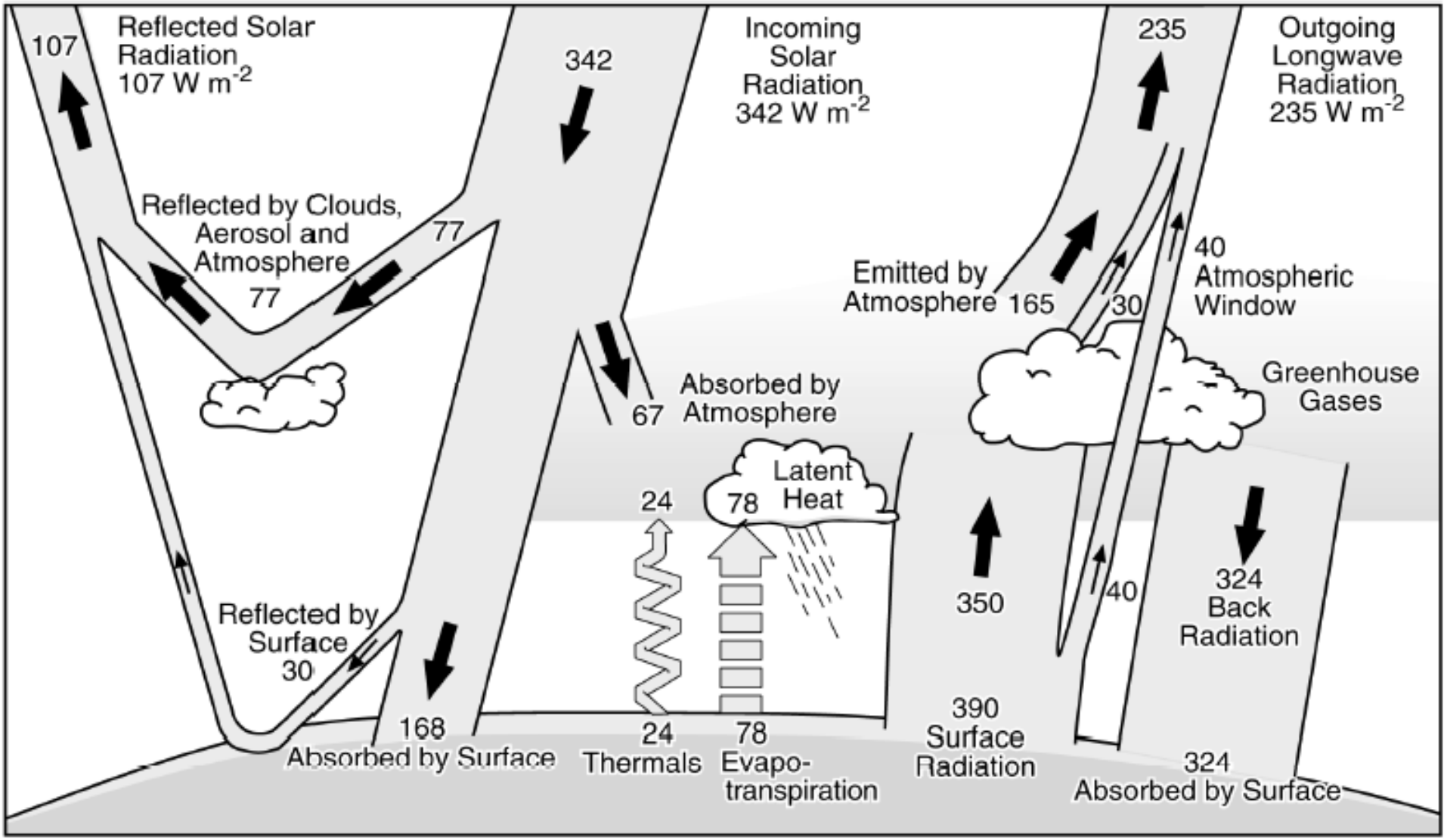
The Earth's Energy Budget



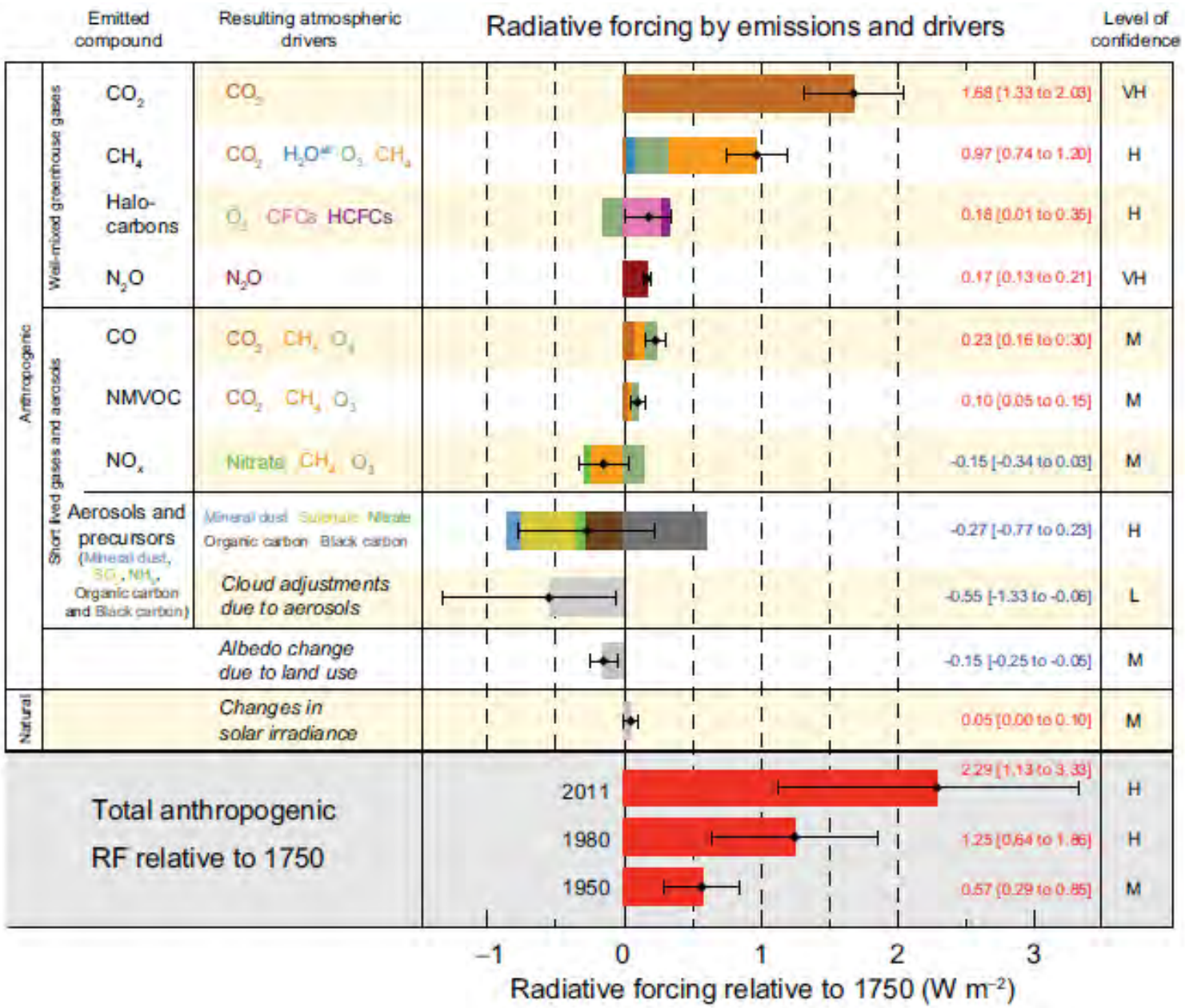
"Clouds and aerosols continue to contribute the largest uncertainty to estimates and interpretations of the Earth's changing energy budget."

Changes in the Earth's radiative budget

$$Q = F + (\lambda_{Planck} + \lambda_{WV/LS} + \lambda_{surface} + \lambda_{cloud}) \Delta T$$

F is the effective radiative forcing (Wm^{-2})

Climate forcings



IPCC AR5, SPM, 2013
IPCC AR5, Chapter 8, 2013

Changes in the Earth's radiative budget

$$Q = F + (\lambda_{Planck} + \lambda_{WV/LS} + \lambda_{surface} + \lambda_{cloud})\,\Delta T$$

F is the effective radiative forcing (Wm^{-2})

Feedback terms
Sum of λs is negative
(for climate to be stable)

Changes in the Earth's radiative budget

$$Q = F + (\lambda_{Planck} + \lambda_{WV/LS} + \lambda_{surface} + \lambda_{cloud})\,\Delta T$$

F is the effective radiative forcing (Wm^{-2})

λ is the net feedback parameter ($Wm^{-2}K^{-1}$), alltogether negative

ΔT is the surface temperature change (K)

Changes in the Earth's radiative budget

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Q is the radiative imbalance at the top-of-atmosphere but given the small heat capacity of the atmosphere is estimated as the heat flux to the ocean (Wm^{-2})

ΔT is the surface temperature change (K)

Changes in the Earth's radiative budget

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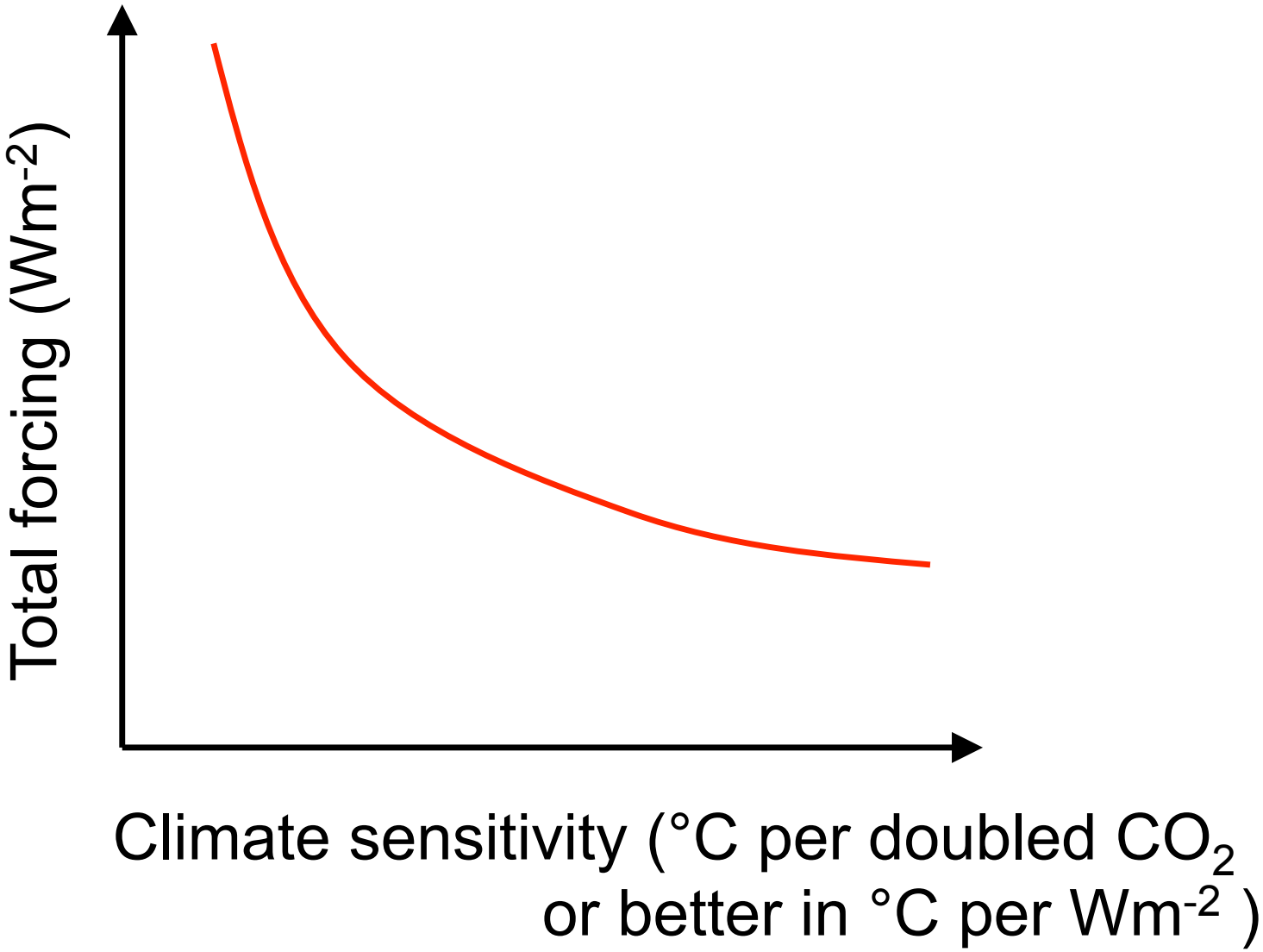
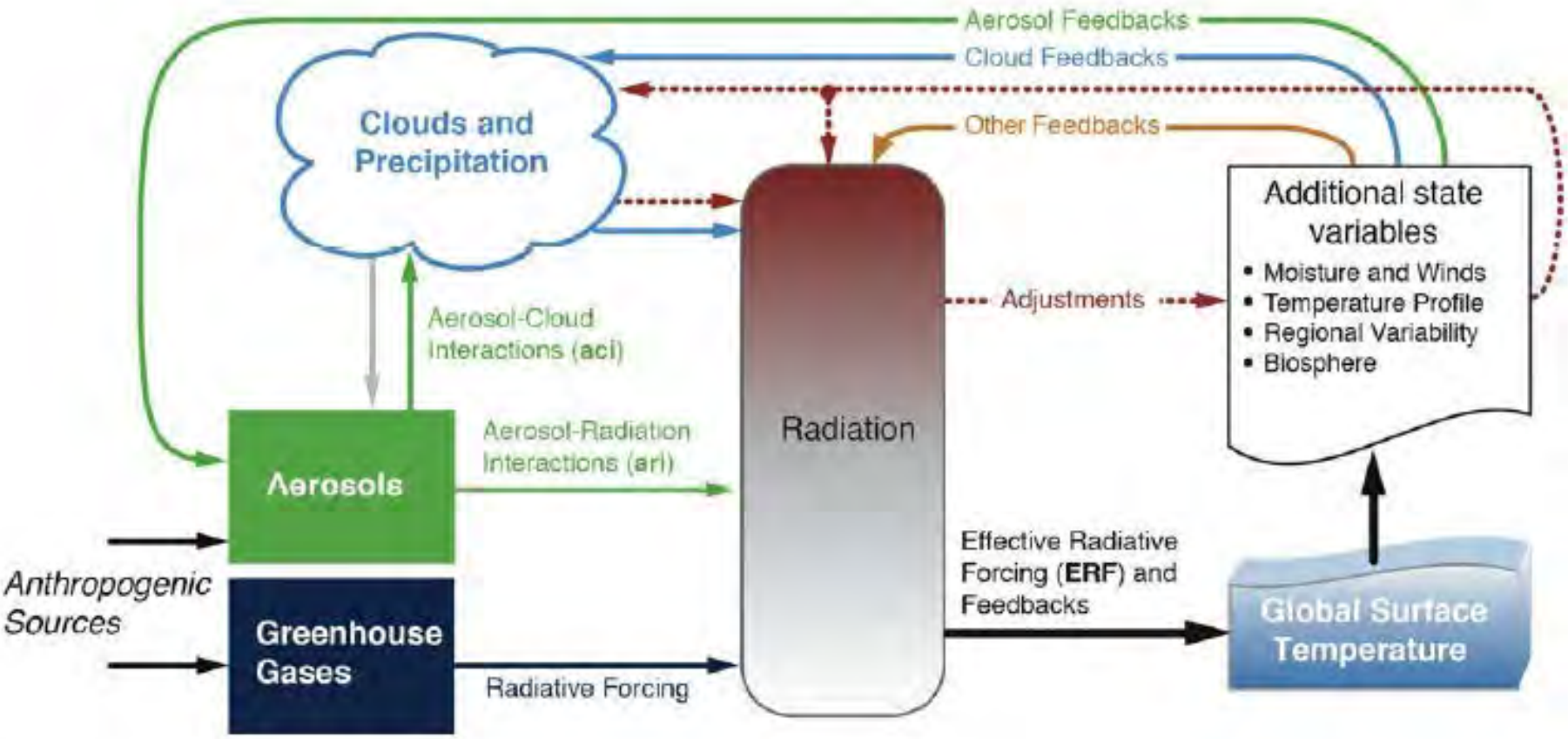
ΔT is the surface temperature change (K)

Total forcing vs. sensitivity



Forcings, adjustments and feedbacks



Rapid adjustments = do not act through a surface-temperature change
Feedbacks = act through a surface temperature change

IPCC AR5, Chapter 7, 2013

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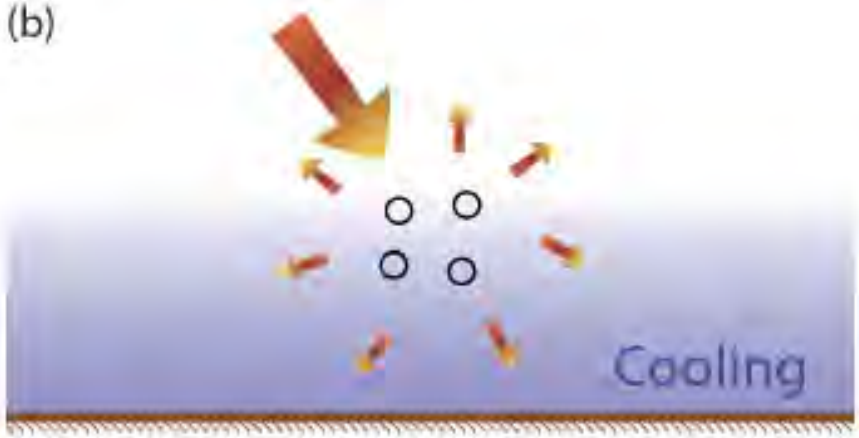
Aerosol-radiation interactions

Scattering aerosols

(a)

Aerosols scatter solar radiation. Less solar radiation reaches the surface, which leads to a localised cooling.

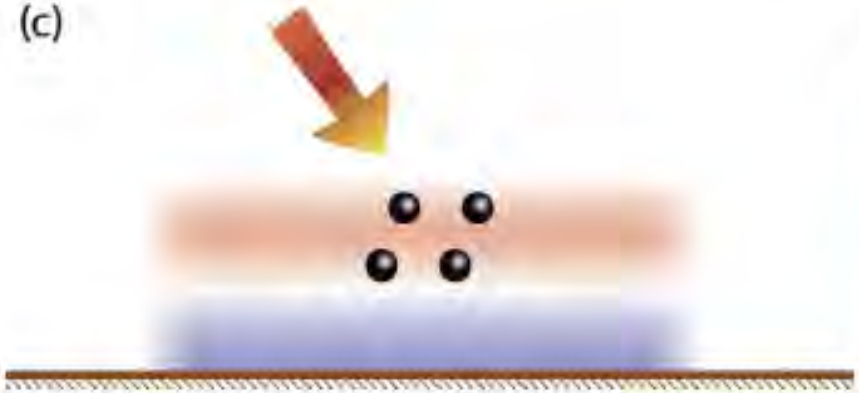
(b)



The atmospheric circulation and mixing processes spread the cooling regionally and in the vertical.

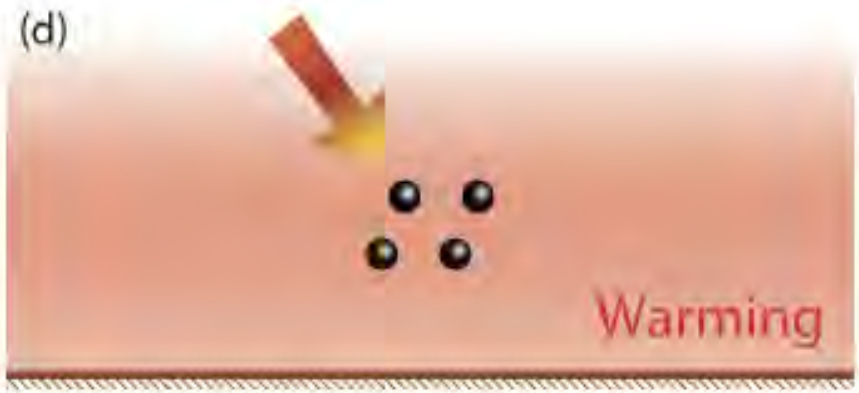
Absorbing aerosols

(c)



Aerosols absorb solar radiation. This heats the aerosol layer but the surface, which receives less solar radiation, can cool locally.

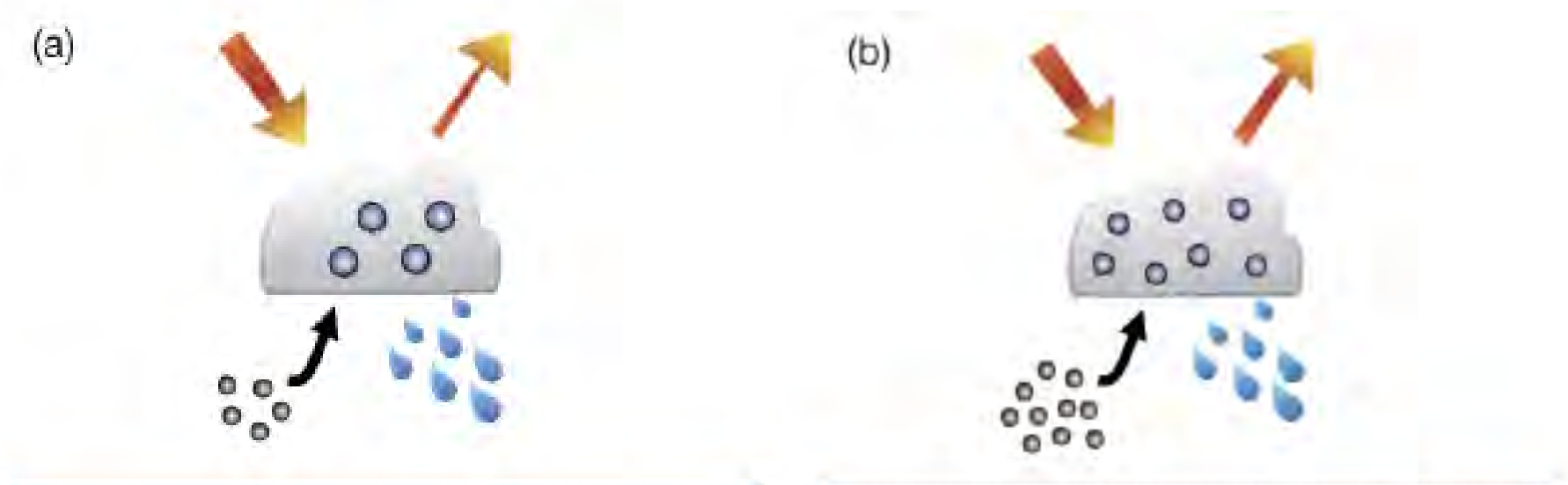
(d)



At the larger scale there is a net warming of the surface and atmosphere because the atmospheric circulation and mixing processes redistribute the thermal energy.

Aerosol-cloud interactions

Aerosol-cloud interactions

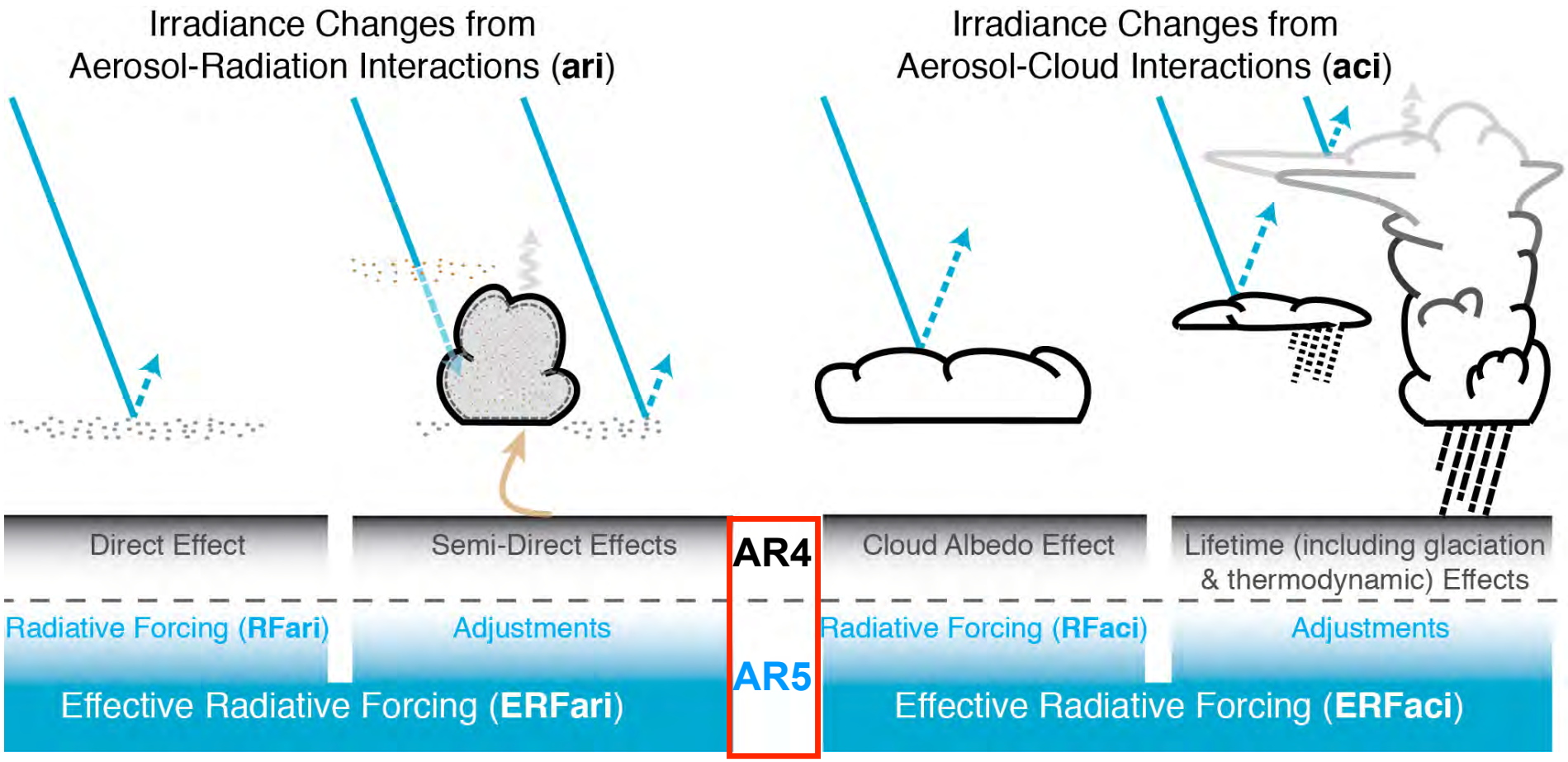


Aerosols serve as cloud condensation nuclei upon which liquid droplets can form.

More aerosols result in a larger concentration of smaller droplets, leading to a brighter cloud. However there are many other possible aerosol-cloud-precipitation processes which may amplify or dampen this effect.

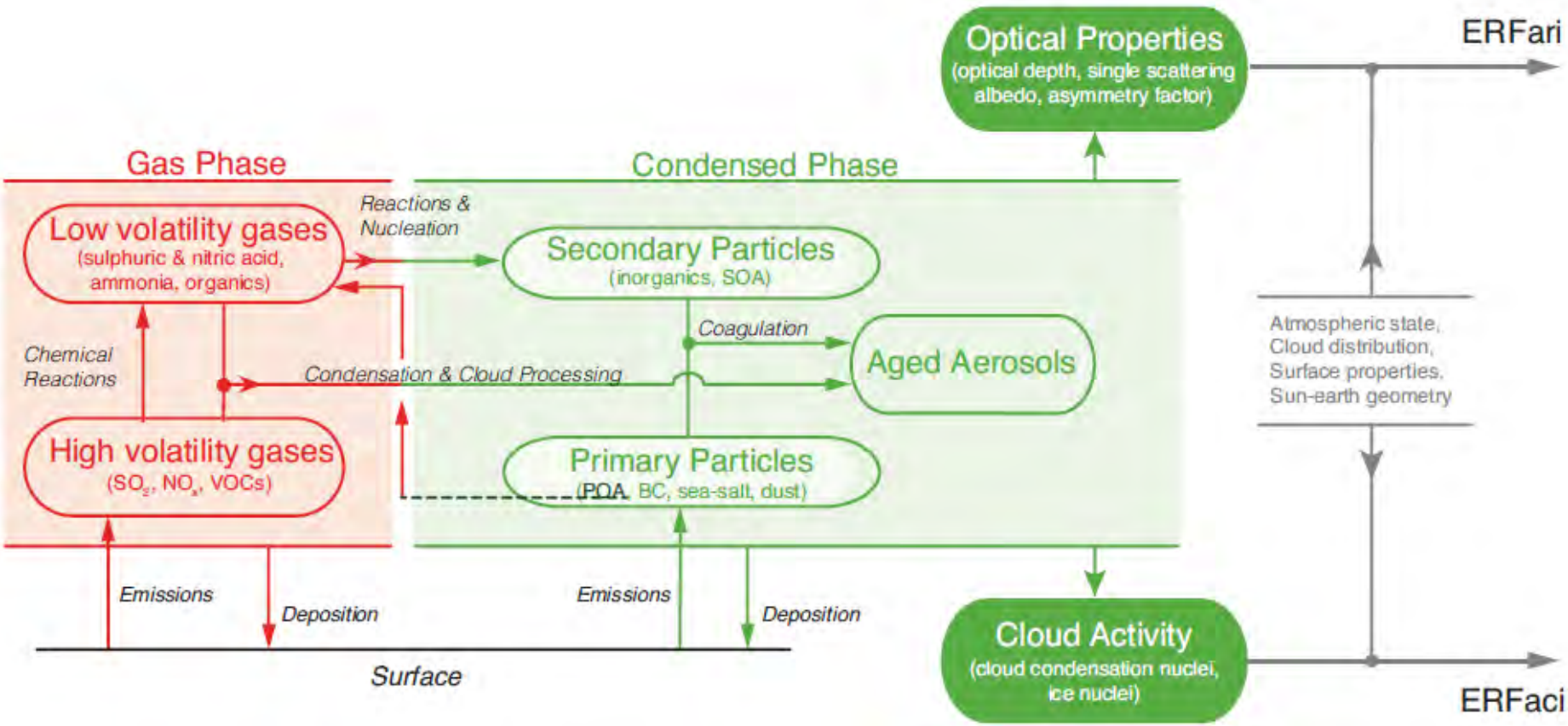
IPCC AR5, Chapter 7, 2013

Aerosol radiative forcings

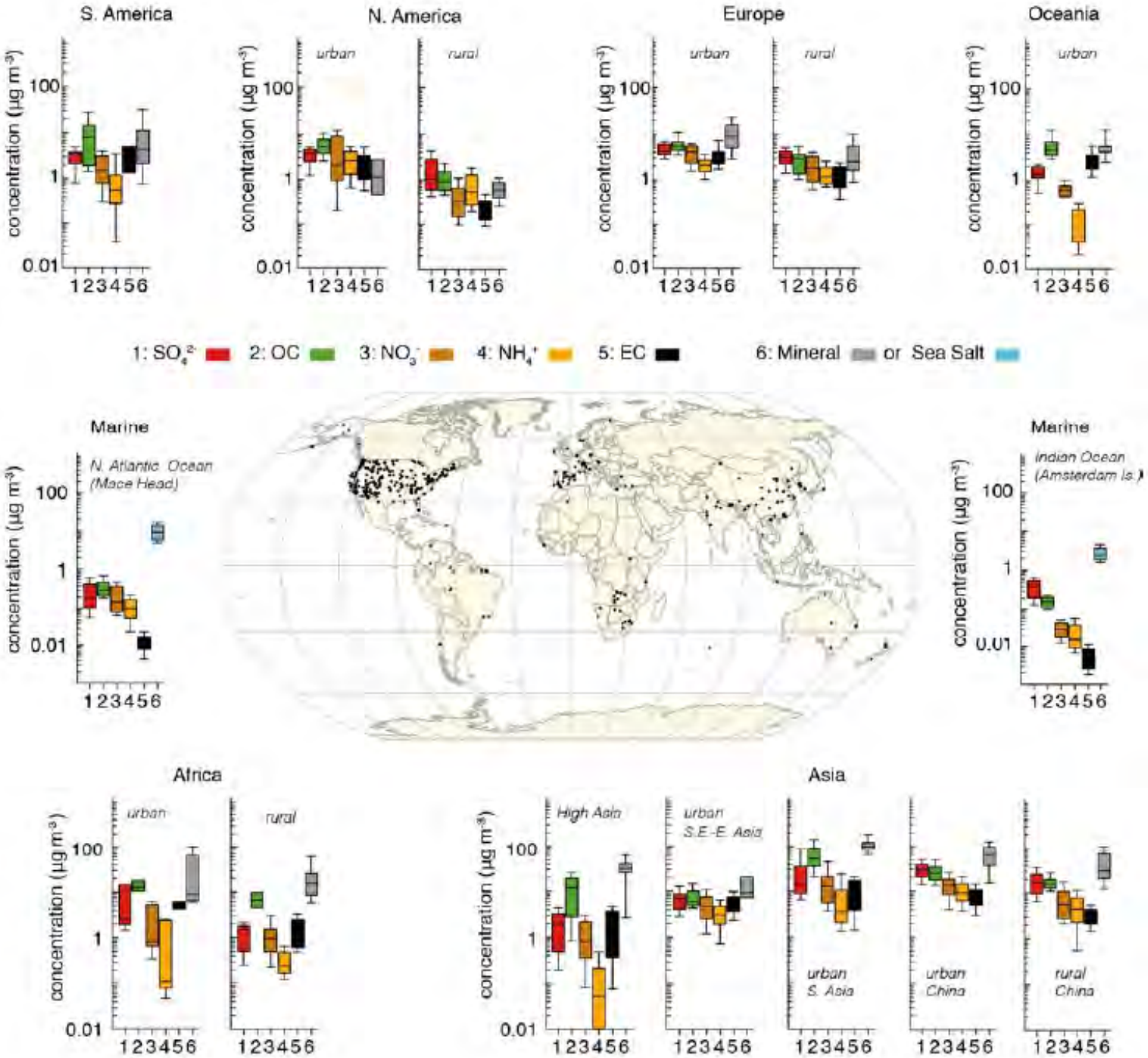


IPCC AR5, Chapter 7, 2013

Aerosol radiative forcings



IPCC AR5, Chapter 7, 2013



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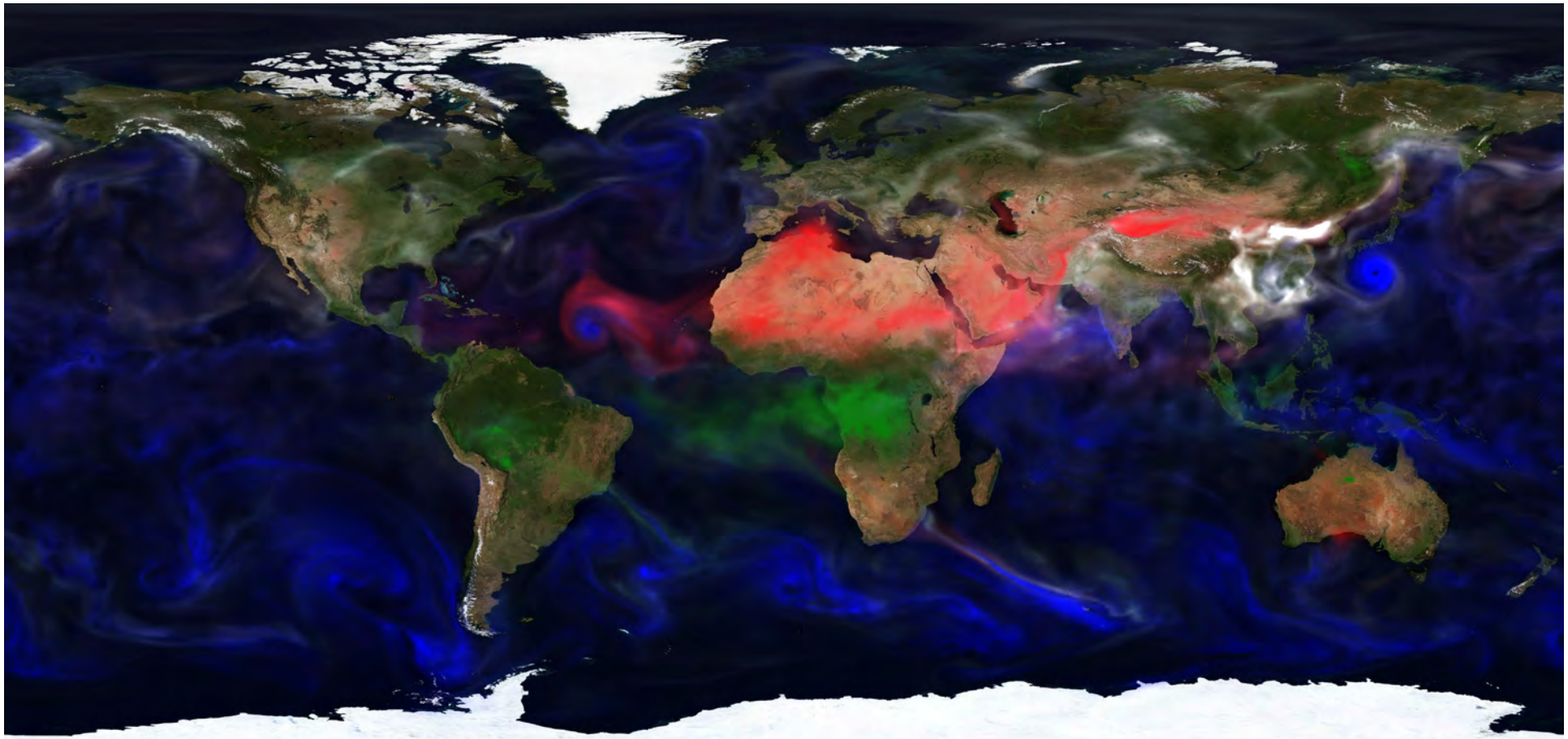
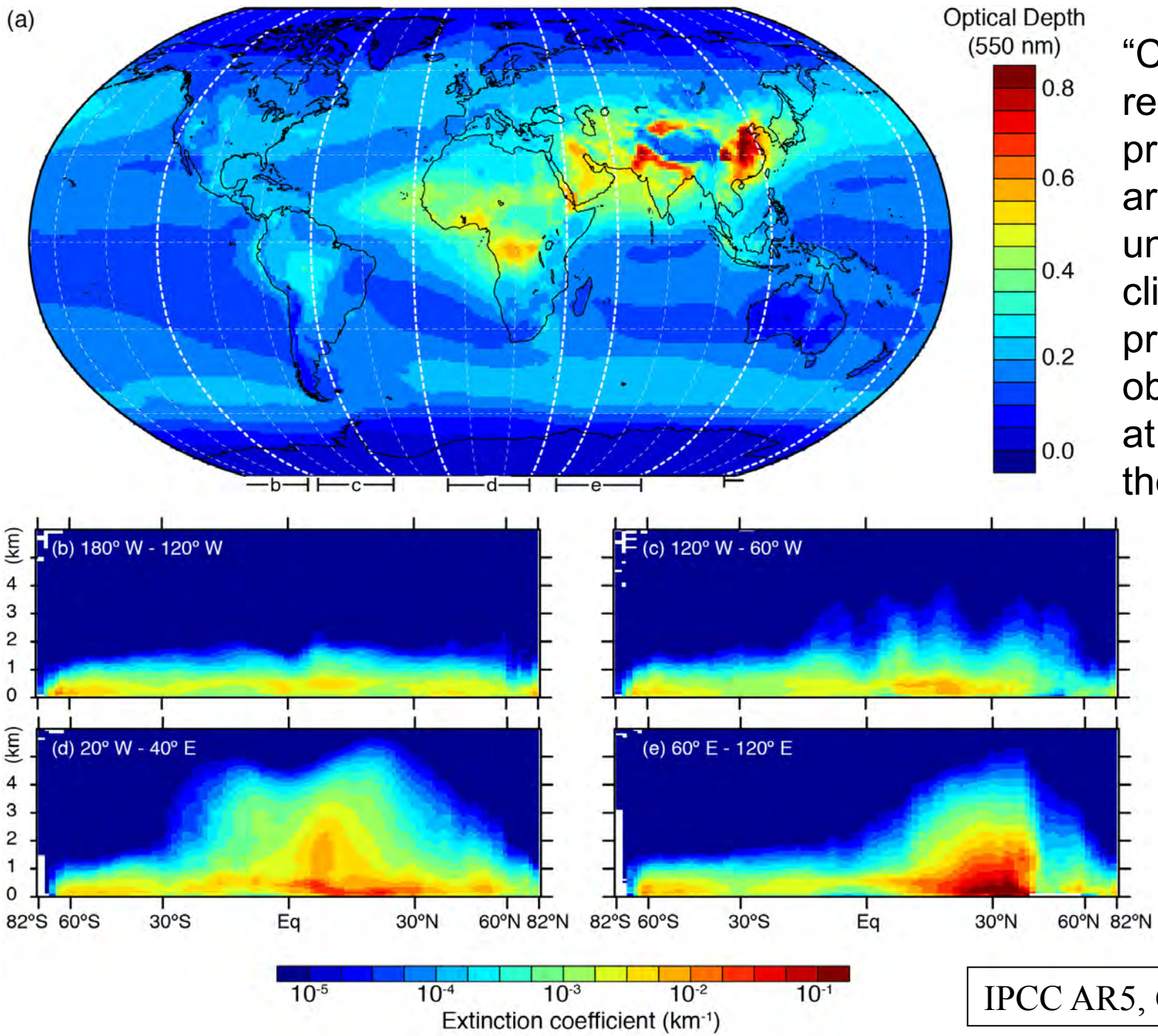
Aerosol day-to-day variability

MACC II aerosol monitoring and forecasting system =
MODIS + IFS aerosol model + 4D-VAR



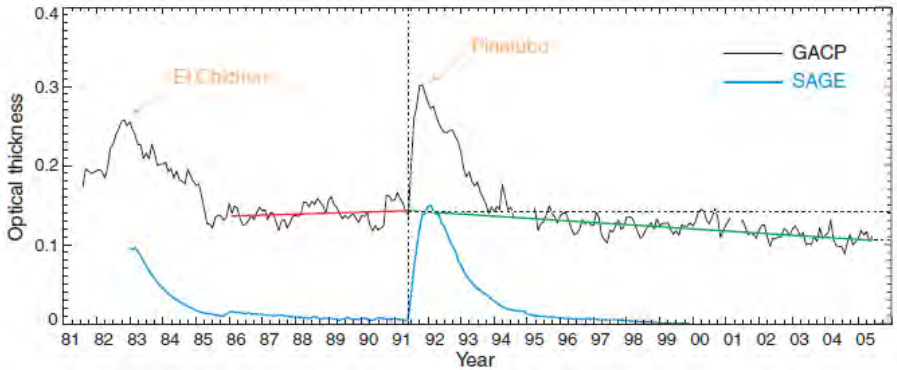
MACC II / Copernicus © S. Mantonavi (MEEO, Italy) & Angela Benedetti (ECMWF)

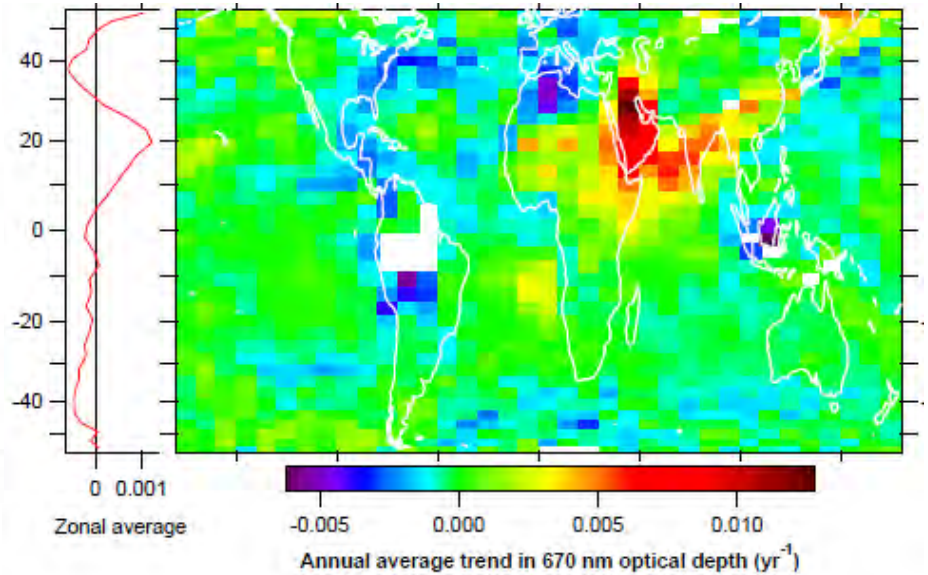


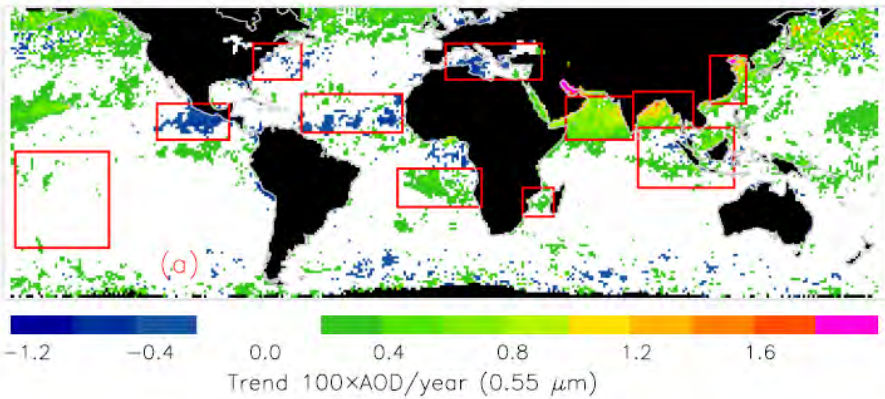
"Climate-relevant aerosol processes are better understood and, climate-relevant properties better observed, than at the time of the AR4."

IPCC AR5, Chapter 7, 2013

What can be said of aerosol trends?



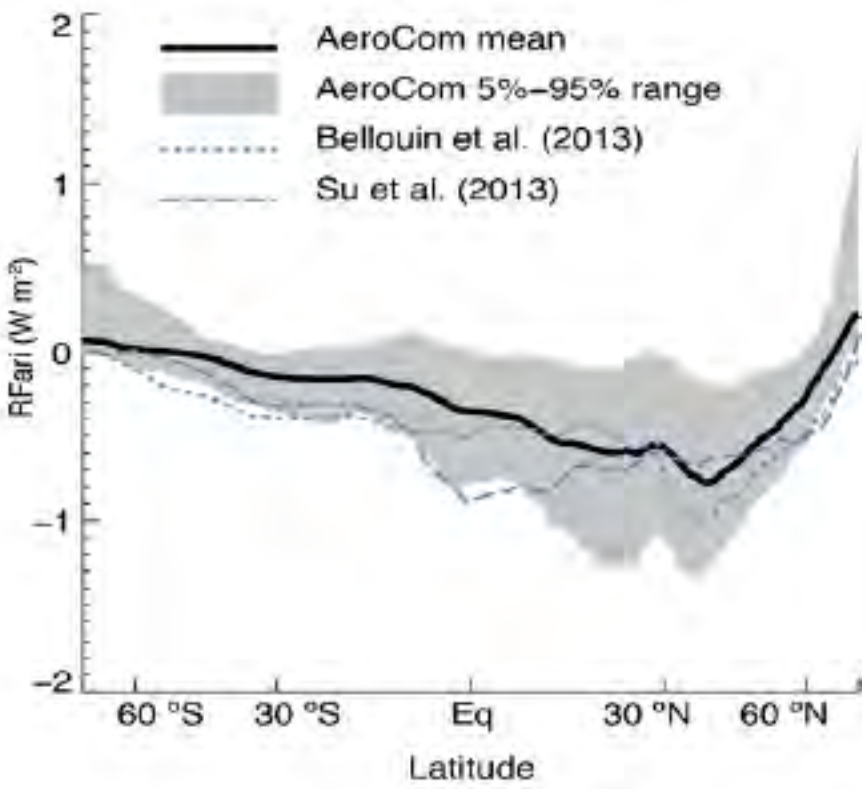


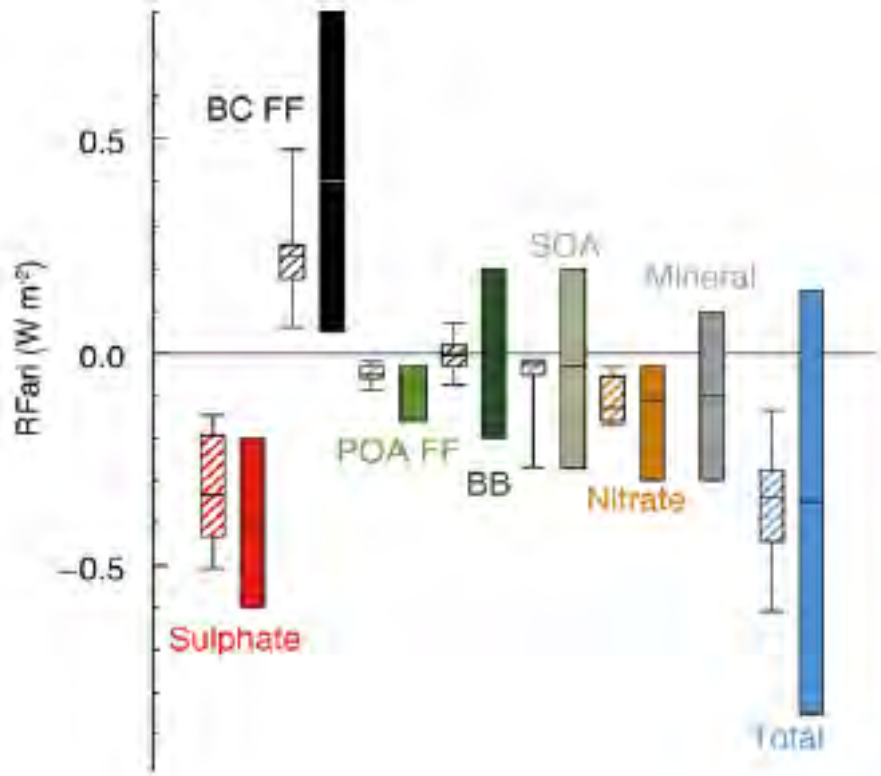


"Overall, *confidence* in satellite based global average AOD trends is *low.*

IPCC, Chapter 2, 2013

Aerosol RFari assessment

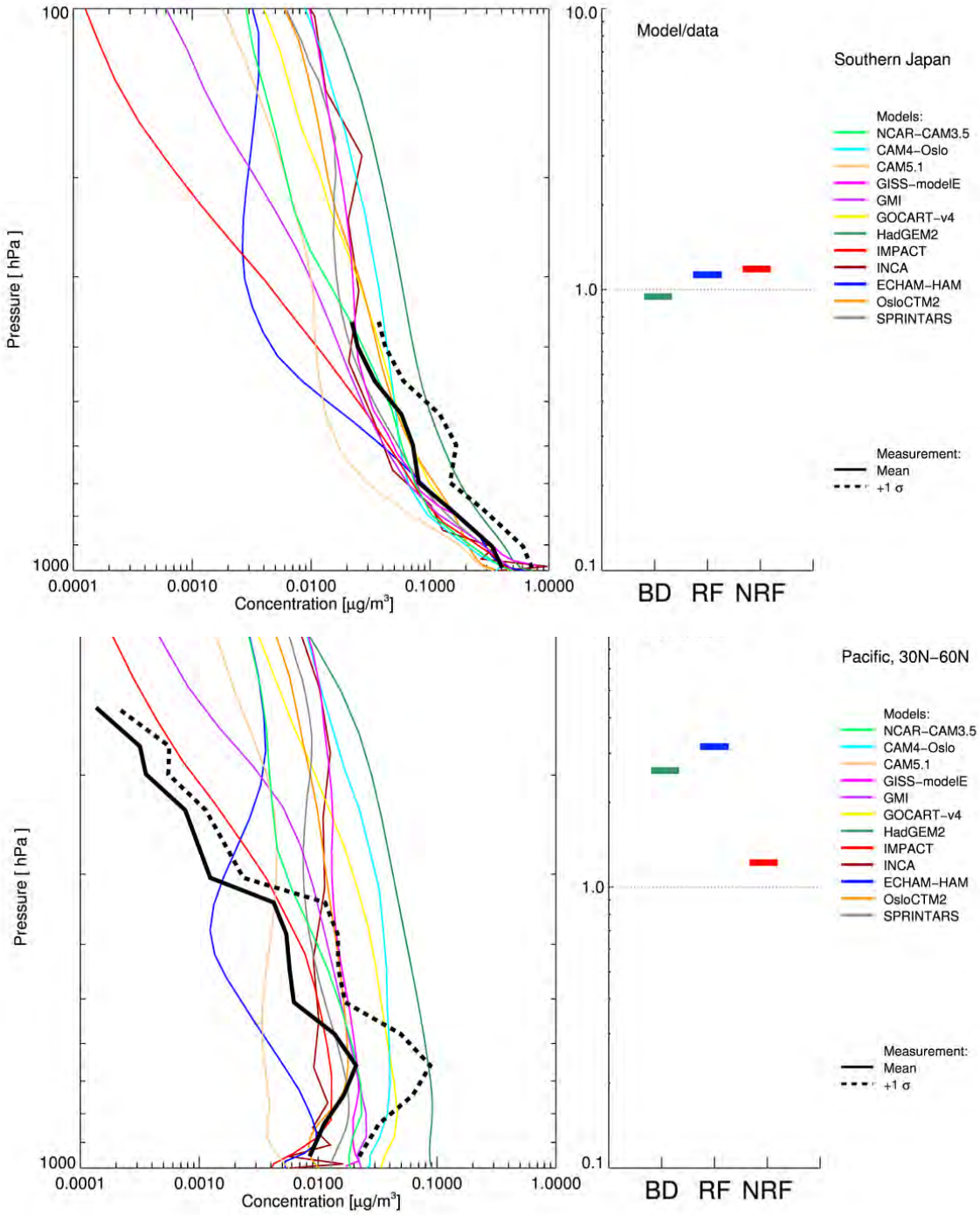




RFari = -0.35 (-0.85 to +0.15) Wm^{-2}
ERFari = -0.45 (-0.95 to +0.05) Wm^{-2}

IPCC AR5, Chapter 7, 2013

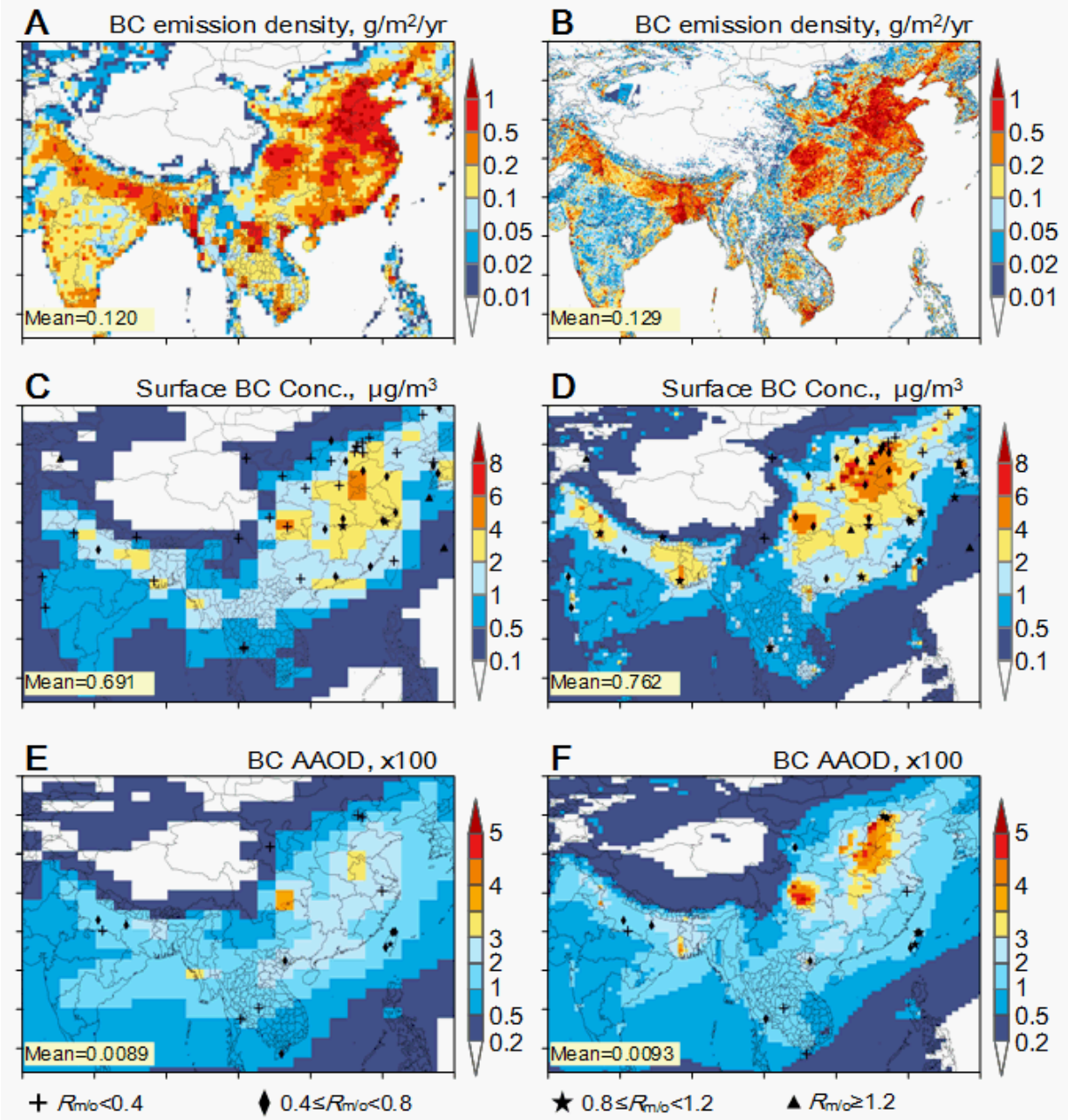
RFari due to BC aerosols



AeroCom II models underestimate BC in many source regions, do well in some outflow region such as Japan but overestimate BC concentrations in some remote regions, especially at heights, which has an impact on the simulated normalized RF and RF.

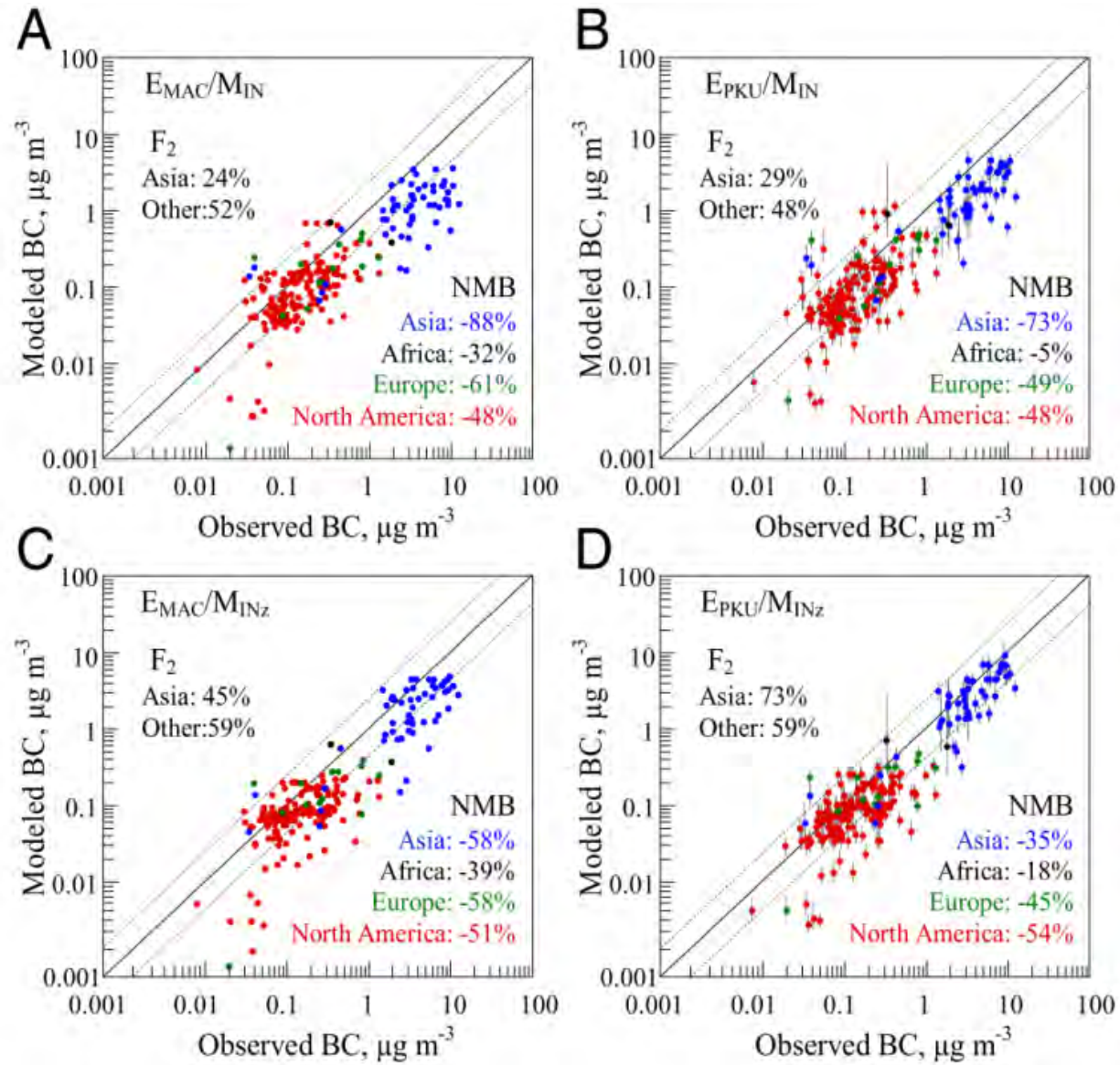
Samset et al. (2013) & Boucher et al. (2014)

Need for higher resolution in aerosol models



R. Wang, Y. Balkanski & O. Boucher

Model-observation comparison for BC surface concentration



Wang et al.
PNAS 2014

Study of aerosol-cloud interactions

Observations

- Form the basis for studying aerosol-cloud interactions but…
- Aerosol observations can be contaminated by clouds (or vice versa)
- Aerosols and cloud properties co-vary with the meteorology (humidity, winds, meteorological situation, …)

=> *One can try to deconvolve this effect but statistics go down*

Small-scale models

- Can represent clouds better but…
- Overlook large-scale feedbacks
- Are expensive to runs

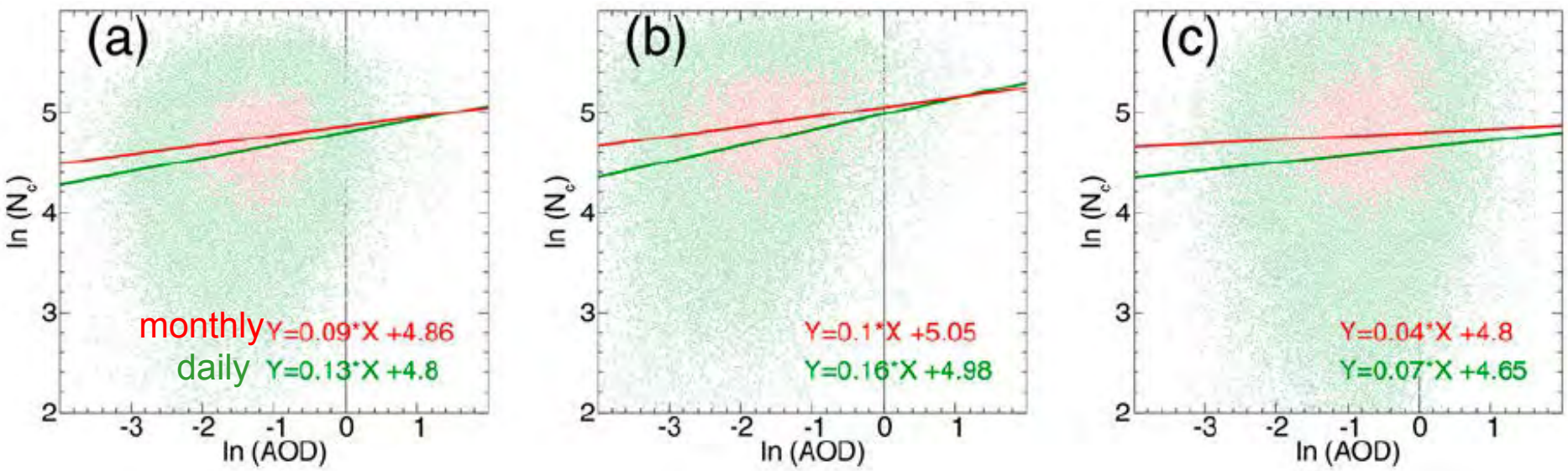
Large-scale models

- Can represent the variability in large-scale conditions and can be constrained by large-scale observations but …
- Clouds are heavily parametrised

Aerosol-cloud interactions

Satellite approaches to aerosol-cloud interactions involve correlating cloud properties with aerosol properties (e.g. in log-log space) accounting for by weather regime and region

Example: cloud droplet column concentration vs AOD



North America JJA | North America DJF | Asia MAM

Quaas, Boucher et al., PNAS, 2011

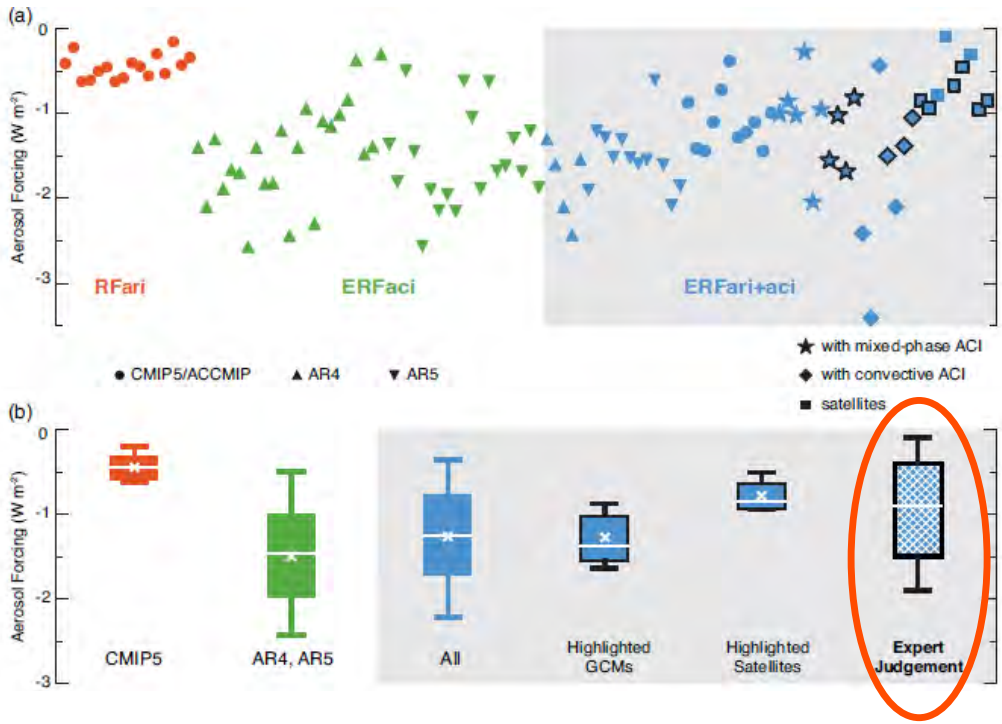
Aerosol ERFari+aci assessment

Latest GCM study from each group

More emphasis on studies that also included effects on convective clouds or mixed-phase clouds

Satellite studies corrected for LW effects

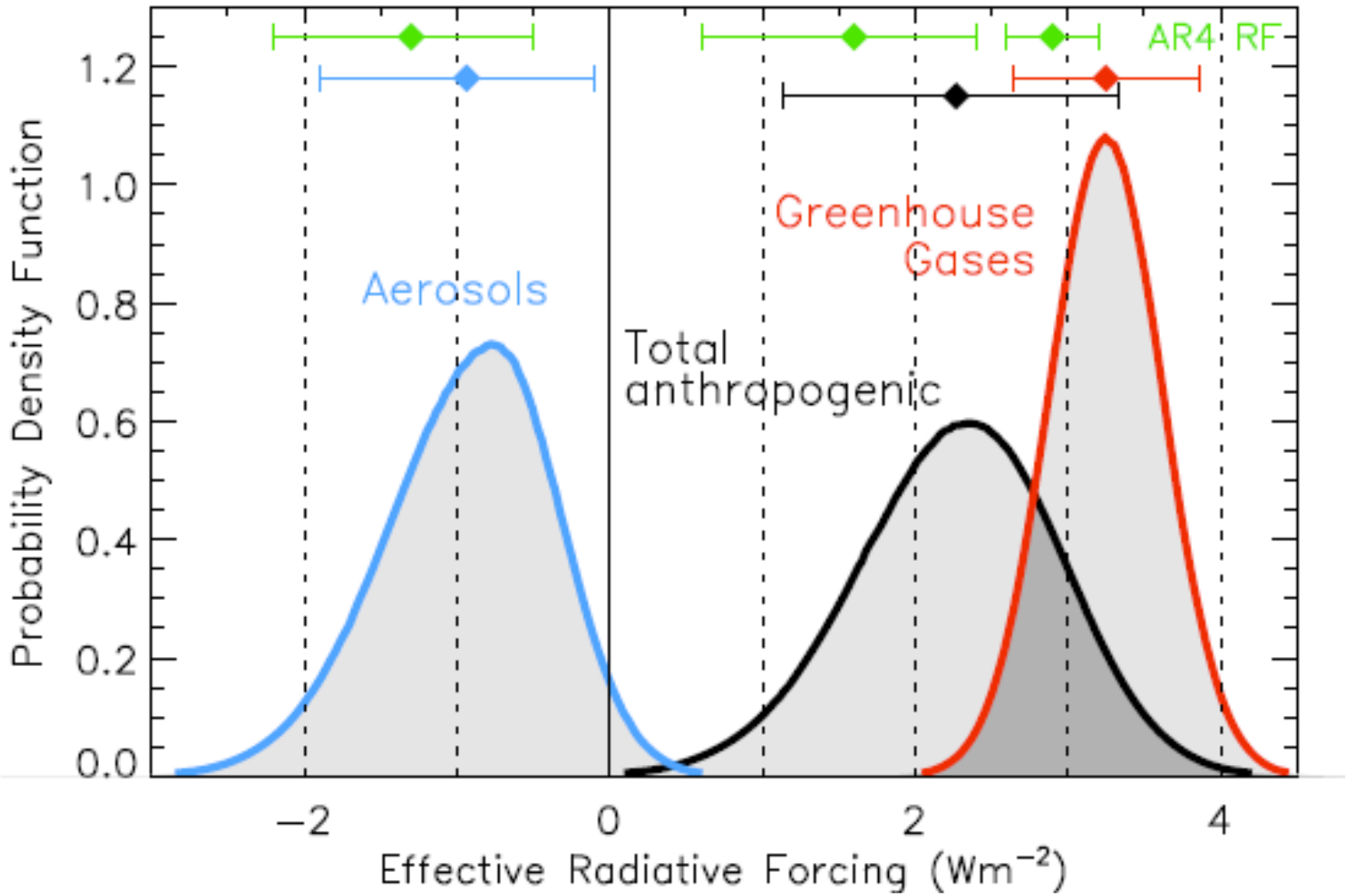
LES & CRM studies



Combined with expert judgement to estimate ERFari+aci as -0.9 (-1.9 to -0.1) Wm^{-2}

IPCC AR5, Chapter 7, 2013

Climate forcings



IPCC AR5, Chapter 8, 2013

"There is *high confidence* that aerosols … have offset a substantial portion of global mean forcing from well-mixed greenhouse gases. They continue to contribute the largest uncertainty to the total RF estimate."

Major research gaps - Aerosols

• Aerosol absorption is not well observed. Black carbon is underestimated in source regions but possibly overestimated in remote regions in global models ⇒ *better observations & models, need to know anthropogenic fraction, high resolution modelling*

• Aerosol-cloud interactions continue to be a stumbling block in climate models but ⇒ *new approaches are now possible (large-domain CRM and LES, new parameterizations, systematic verification of weather models, data assimilation techniques, etc.)*

• Trends in aerosols are not well understood at the global scale ⇒ *better monitoring & satellite calibration, source inversion, sampling uncertainties in the historical period, focus on the last 40-50 years in Earth's energy budget studies*

• Are there robust changes in circulation and weather extremes in response to the aerosol forcings?

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Role of clouds in a changing energy budget

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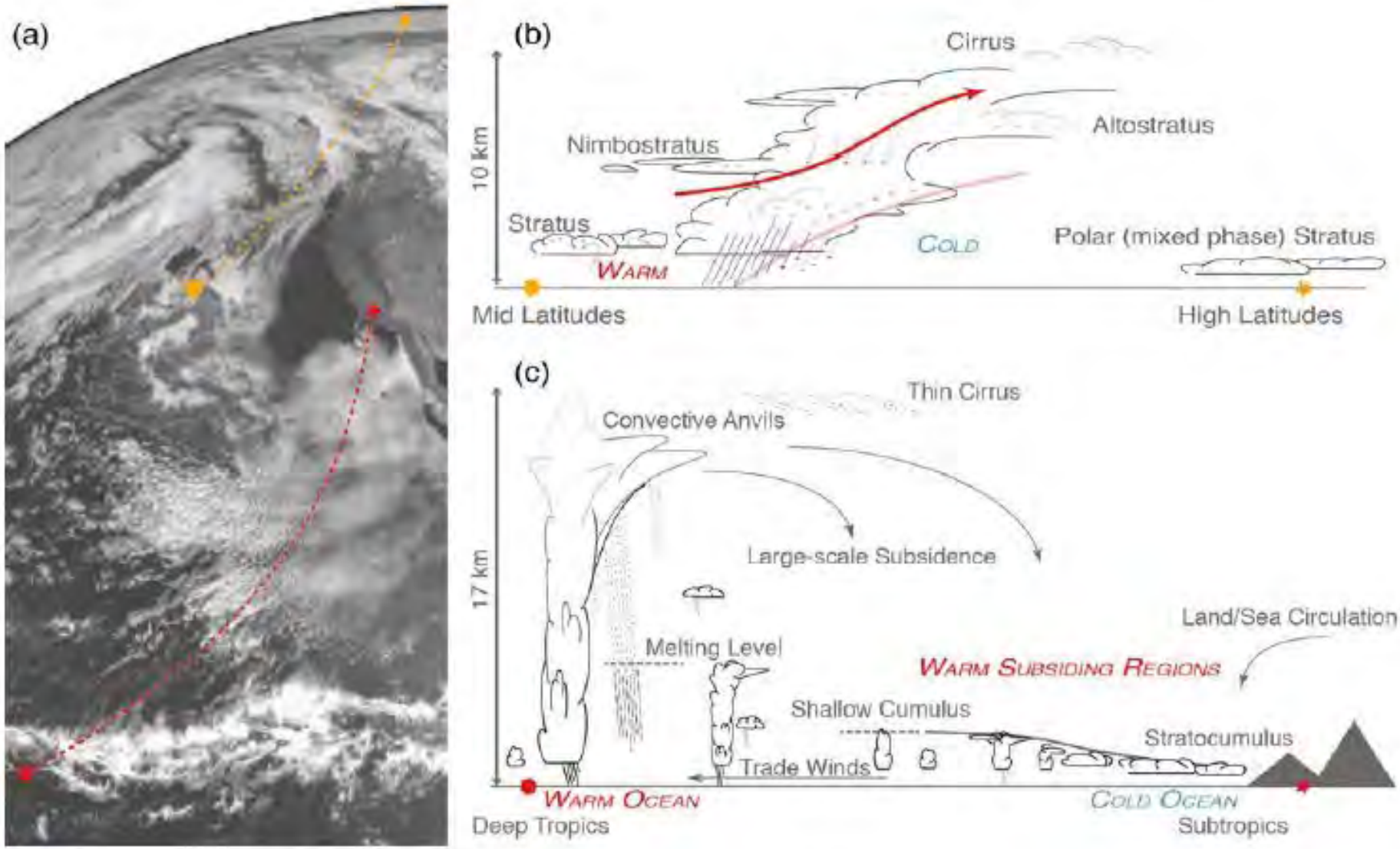
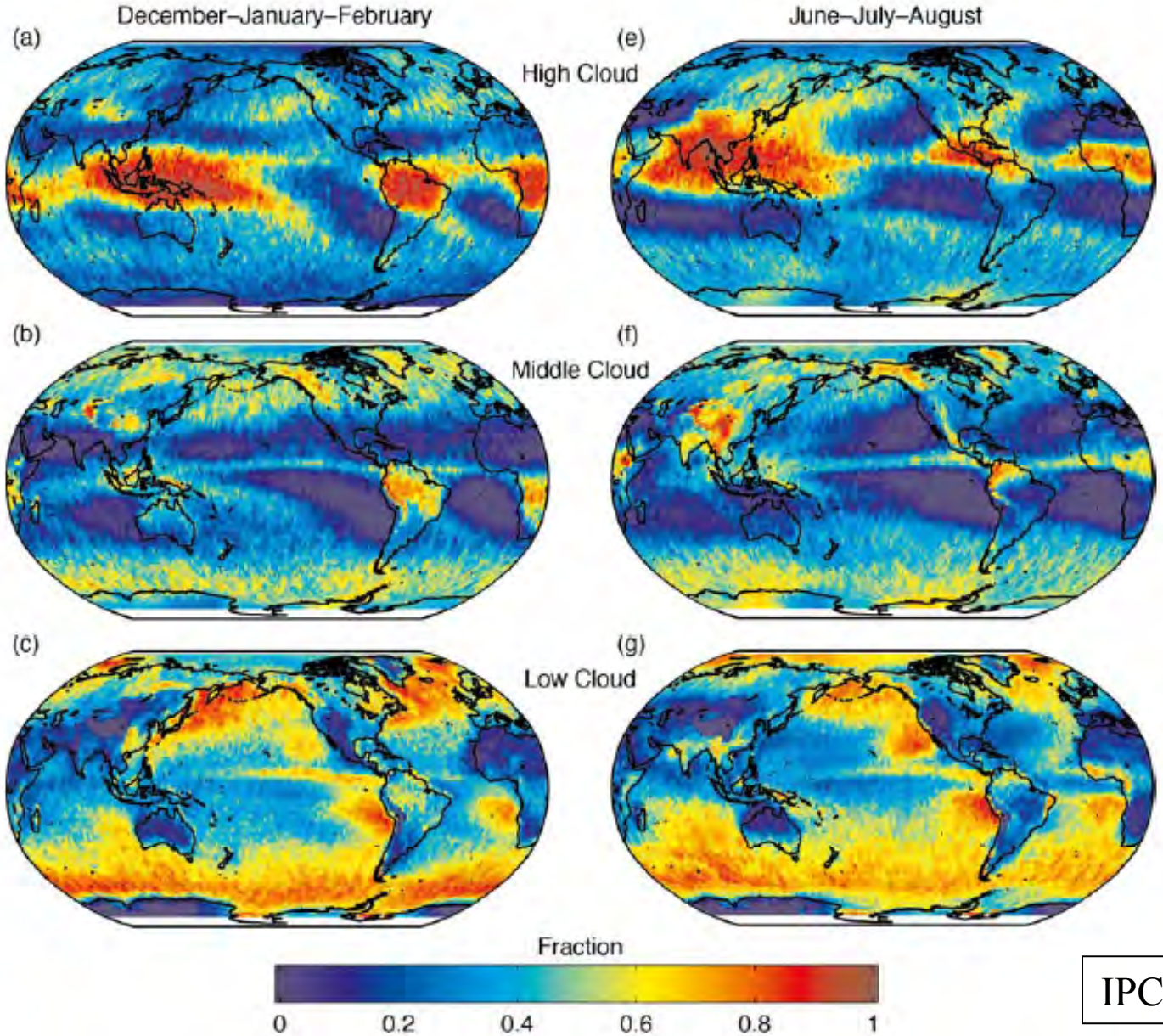
Diversity of cloud types



IPCC AR5, Chapter 7, 2013

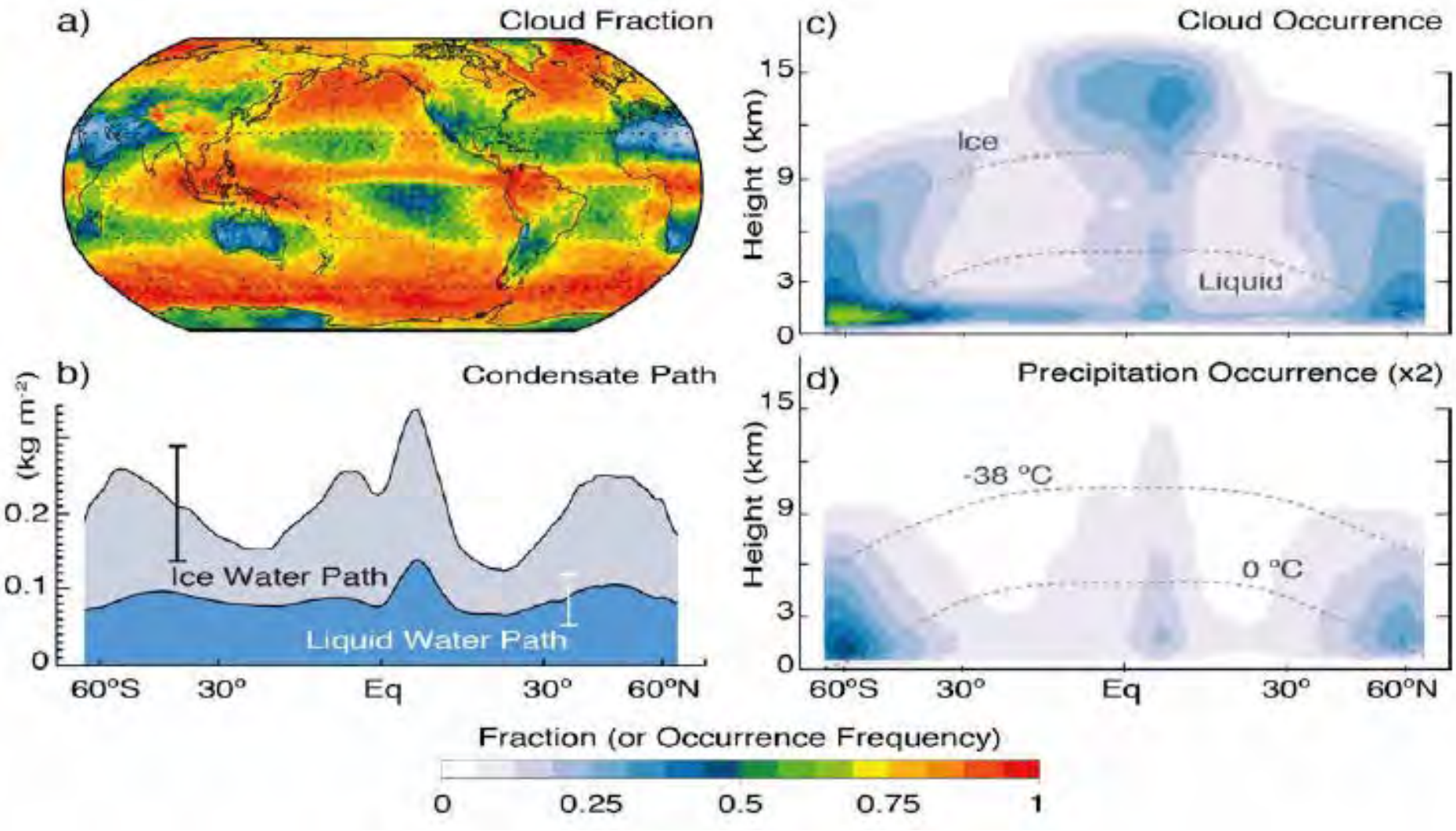
Cloud climatology



"New satellite sensors and new analysis of previous data sets have given us a clearer picture of the Earth's clouds since AR4."

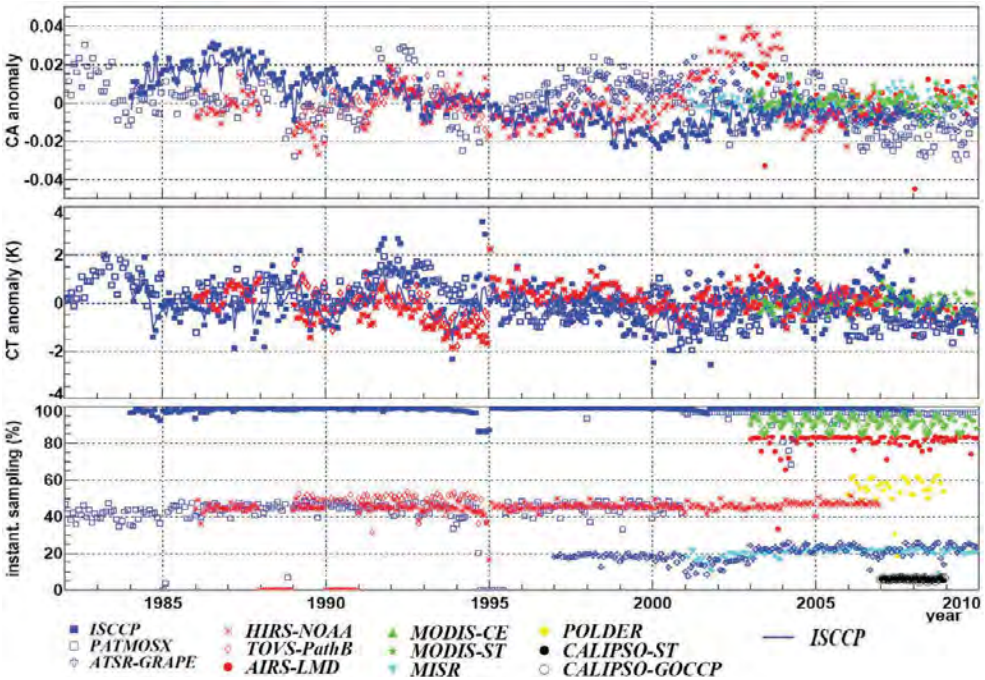
IPCC AR5, Chapter 7, 2013

Cloud climatology



IPCC AR5, Chapter 7, 2013

What can be said of cloud trends?



Stubenrauch et al., BAMS, 2013

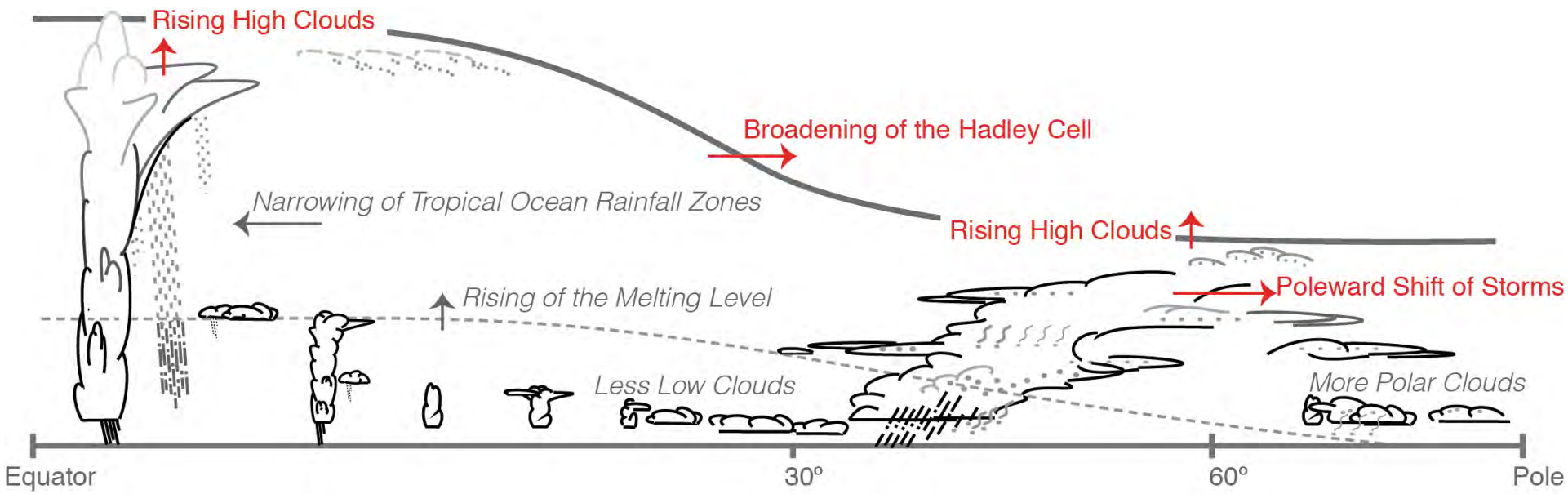
"An assesment of long-term variations in global-mean cloud amount from nine different satellite datasets by Stubenrauch et al. (2013) found differences between datasets were comparable in magnitude to the interannual variability. Such inconsistencies result from differences in sampling as well as changes in instrument calibration and inhibit an accurate assessment of global-scale cloud cover trends."

"It is *likely* that circulation features have moved poleward since the 1970s, involving a widening of the tropical belt, a poleward shift of storm tracks and jet streams, and a contraction of the northern polar vortex."

IPCC AR5, Chapter 2, 2013

Robust cloud feedbacks

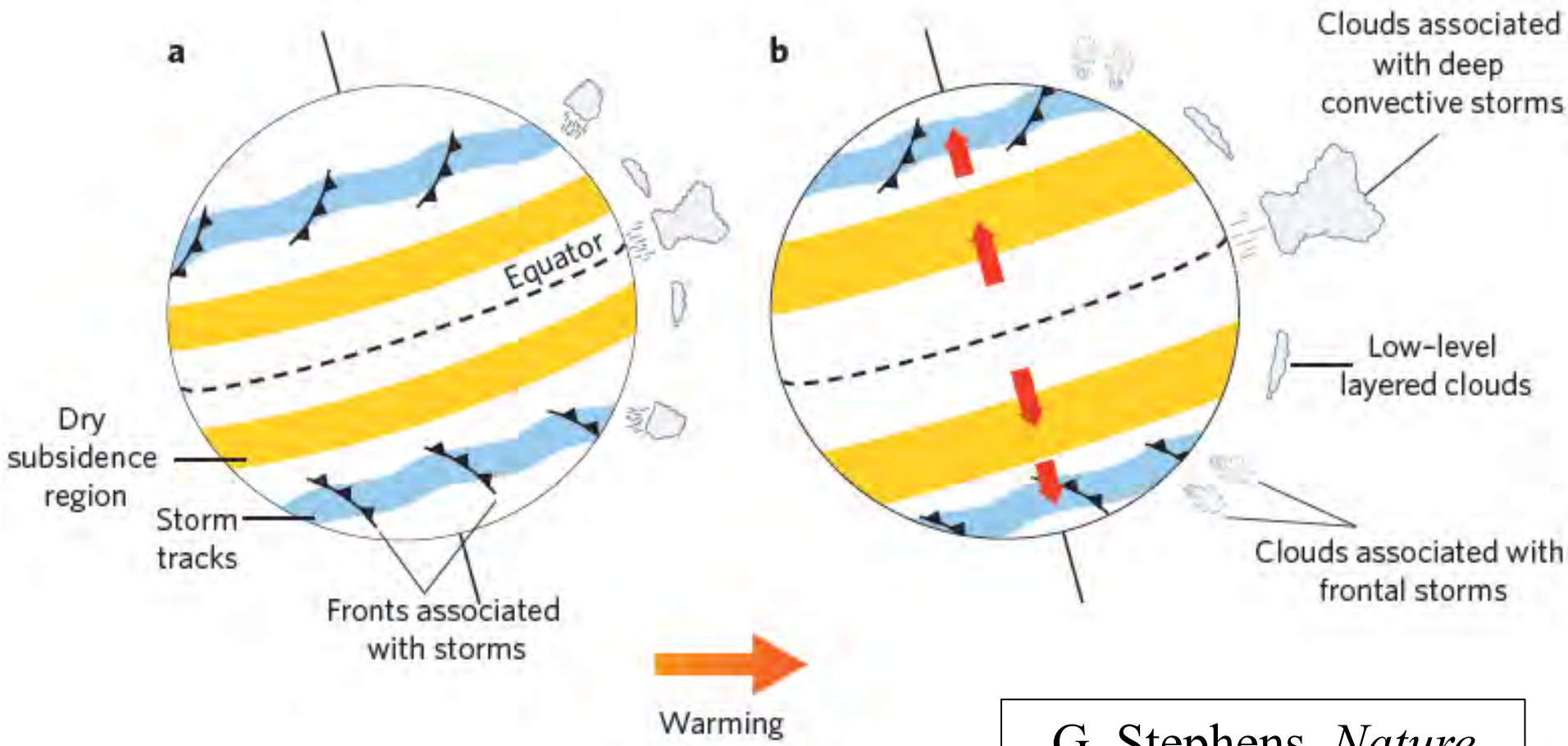
"Robust mechanisms are those simulated by most models and possessing some kind of independent support or understanding"



"No robust mechanisms constribute negative (cloud) feedback"

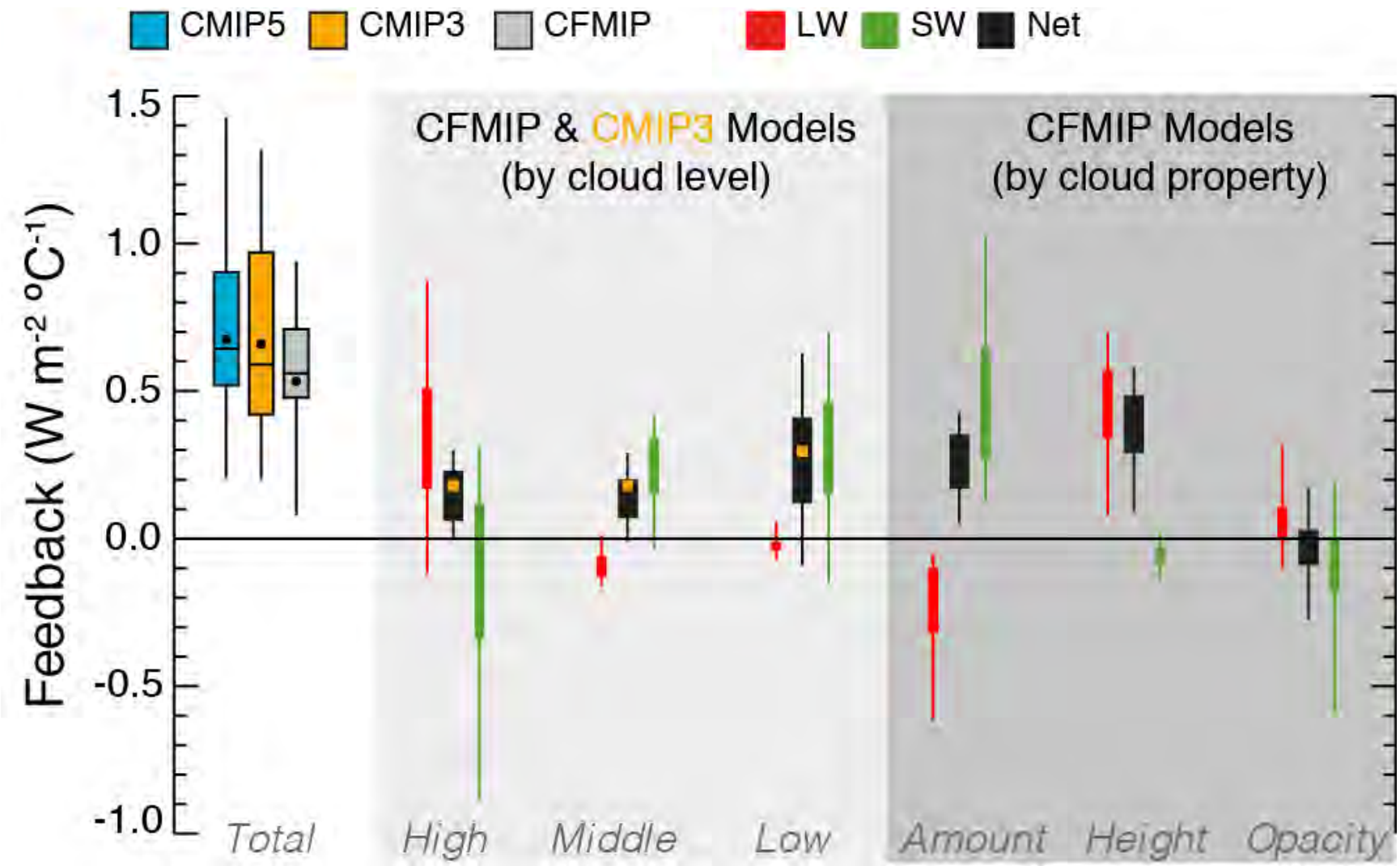
IPCC AR5, Chapter 7, 2013

Cloud climate feedbacks



G. Stephens, *Nature Climate Change*, 2011

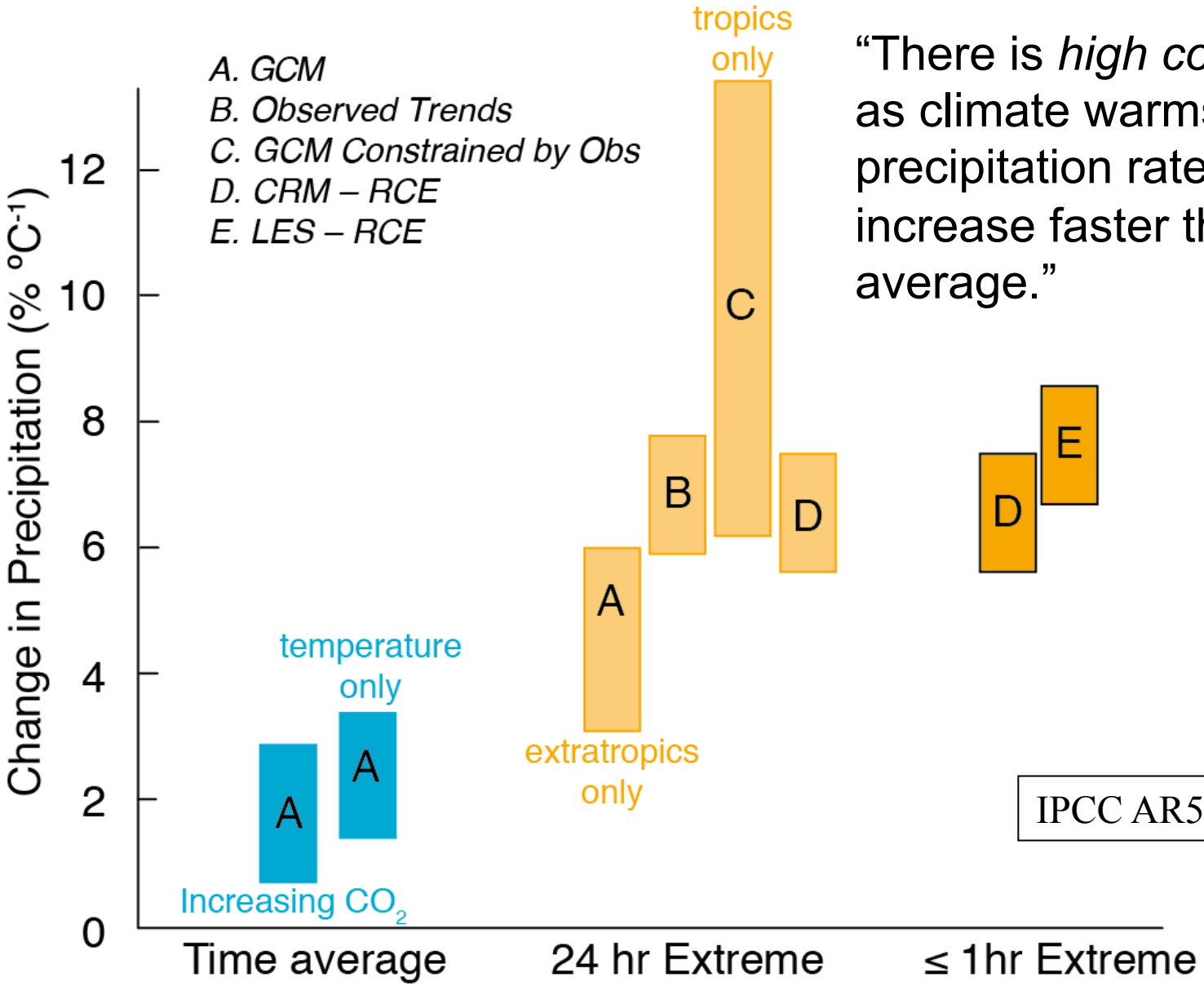
Cloud climate feedbacks



"The sign of the net radiative feedback due to all cloud types is likely positive."

IPCC AR5, Chapter 7, 2013

Changes in precipitation extremes



"There is *high confidence* that, as climate warms, extreme precipitation rates […] will increase faster than the time average."

IPCC AR5, Chapter 7, 2013

Major research gaps - Clouds

• Aerosol-cloud interactions continue to be a stumbling block in climate models but ⇒ *new approaches are now possible (large-domain CRM and LES, new parameterizations, systematic verification of weather models, data assimilation techniques, synergetic use of observations and models needed to disentangle aerosol-cloud interactions from the impact of meteorology, etc.)*

• Trends in clouds are not well understood at the global scale
⇒ *better monitoring & satellite calibration*
⇒ *look for circulation changes as a proxy for cloud feedbacks*

• We need to improve our understanding of feedbacks associated with low-level clouds (the "joker" of cloud feedbacks)

• The new frontier is to understand links between clouds, atmospheric circulation and climate sensitivity ⇒ *WCRP grand challenge*, *some theoretical and multi-model approach, rapid adjustments and slow feedbacks decomposition*

Concluding remarks

• Observing capability of clouds and aerosols have substantially improved. However monitoring of trends is imperfect.

• There has been substantial improvement in our understanding of aerosol and cloud processes, but not all of this new knowledge is yet "available" in global climate models.

• Aerosol forcing (ERFari+aci) and cloud feedbacks remain uncertain, prohibiting strong constraint on the climate sensitivity paramater
⇒ *More focus on the energy budget*

• Aerosols are thought to contribute to a RF that is less negative than in AR4. They continue to dominate the uncertainty in the total anthropogenic RF.

• The sign of the net radiative feedback due to all cloud types is *likely* positive. No robust mechanisms constribute a negative cloud feedback.

• Some cloudiness and humidity changes to global warming are now understood as responses to large-scale circulation changes

• High resolution modelling is needed
⇒ *good news = satellite are already high resolution in model's world*