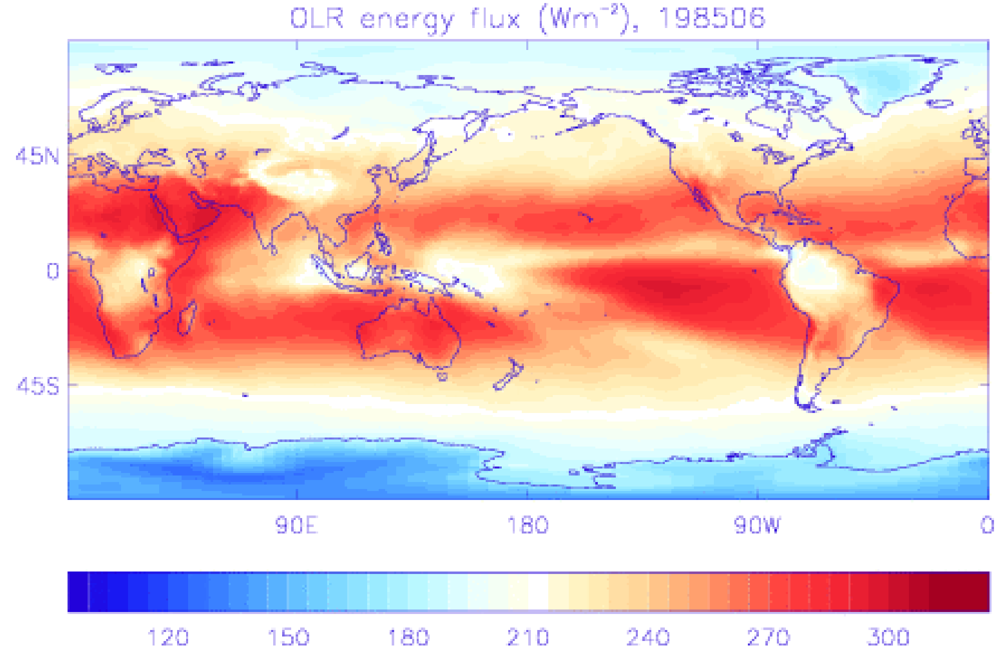
# Earth's Radiation Budget & Climate





Professor Richard Allan

*University of Reading*


**NERC Advanced Training Course**
**Earth Observations for Weather & Climate Studies**
**5–9 September 2016**

# Learning outcome

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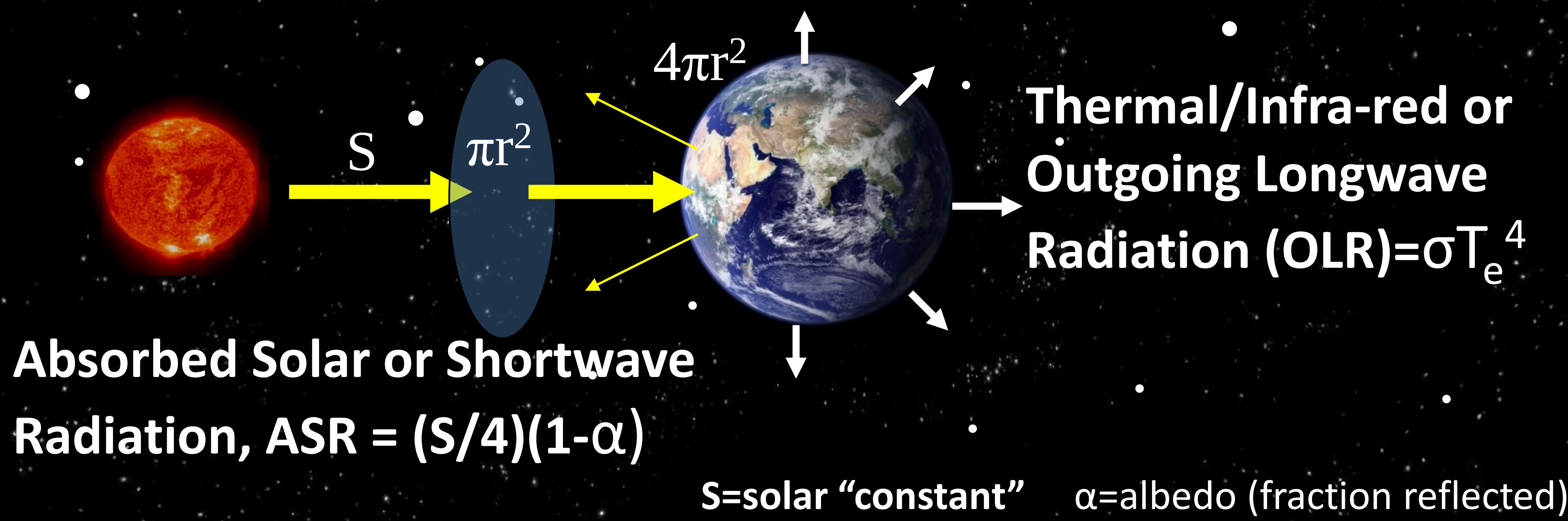
- Quantify the main terms of Earth's energy budget
- Describe how satellite instruments make measurements of radiative fluxes
- Appraise methods for evaluating global climate simulations
- Identify influence of clouds and water vapour on Earth's radiative energy balance
- Estimate radiative forcing, feedback and response using simple energy balance model
- Define Earth's energy imbalance/discuss implications for climate
- Discuss how the global energy and water cycles are linked

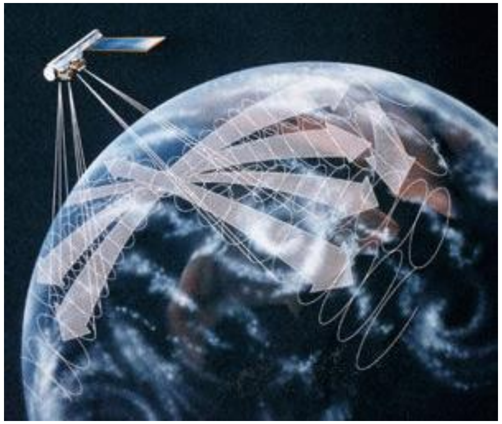
# Earth's Radiation Balance

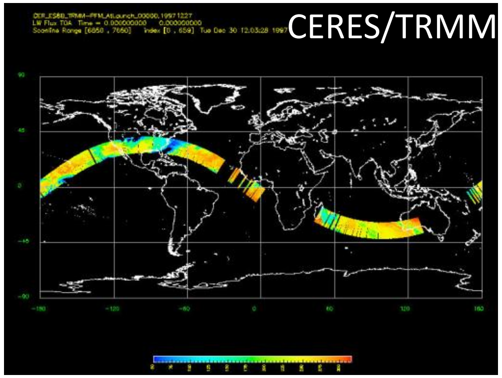



- There is a balance between the absorbed sunlight and the thermal/longwave cooling of the planet
- $(S/4)(1-\alpha) \approx OLR = \sigma T_e^4$
- OLR= $(S \approx 1362\ Wm^{-2}, \alpha \sim 0.3)$
- $T_e$= $(\sigma = 5.67 \times 10^{-8}\ Wm^{-2}K^{-4})$

# Satellite measurements of radiative fluxes

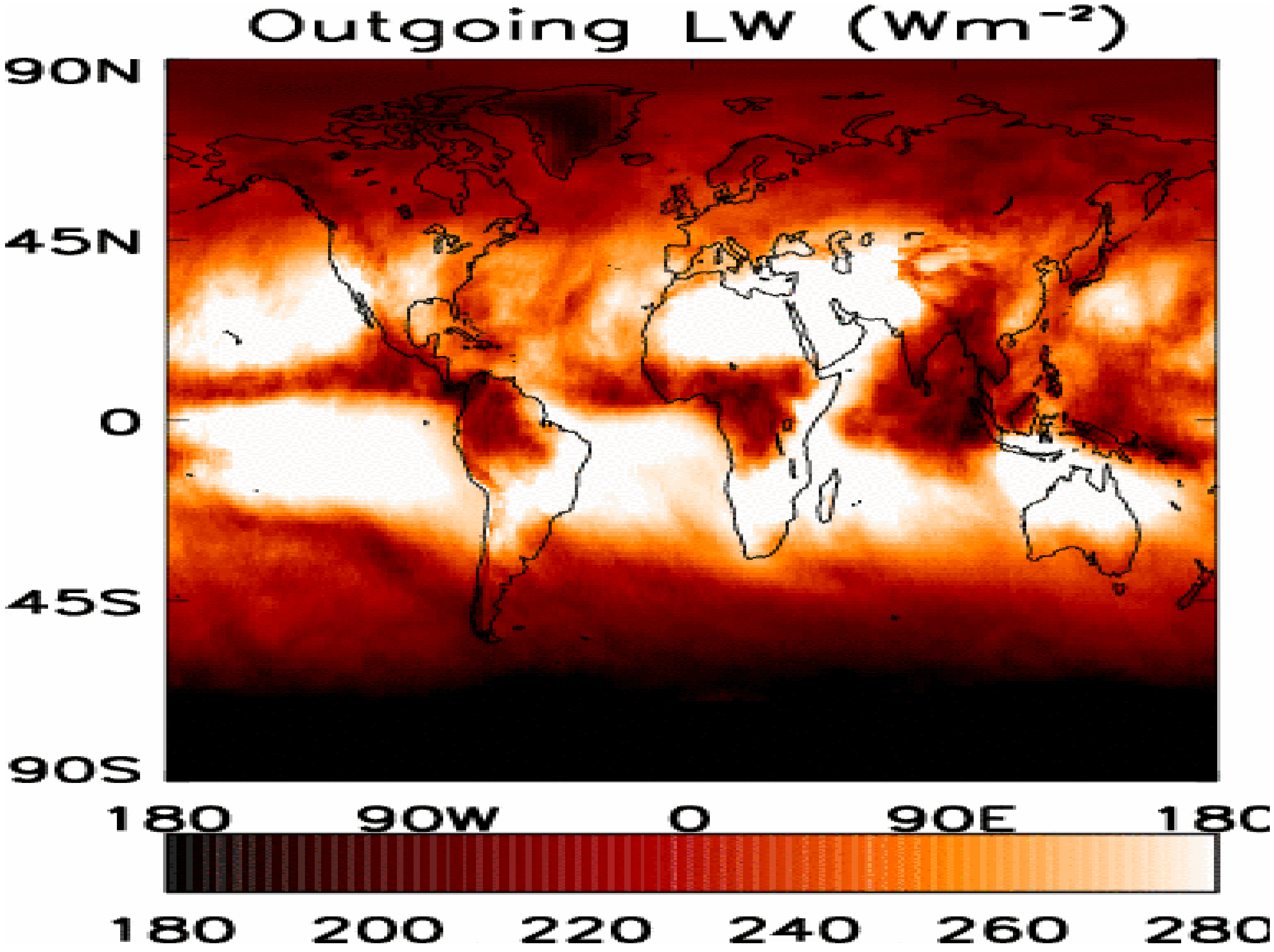
- Broadband radiation budget instruments:
  - Low Earth orbit: ERB/Nimbus 1970s/80s; ERBE 1980s/90s; ScaRaB; CERES 2000s…
  - Geostationary: GERB 2000s…
- Measure directional radiance from geolocated satellite footprint; shortwave & total spectrum, longwave by subtraction
- Convert to radiative energy flux using angular dependence models (theoretical or built up from many directional measurements)
- Depends on scene type (e.g. clear ocean, high cloud, etc) so an imager is also required (e.g. CERES/MODIS, GERB/SEVIRI)
- Diurnal/seasonal sampling must be considered
- Excellent stability over time (~0.2 $Wm^{-2}$/decade); combine with ocean heat content observations for ±0.1 $Wm^{-2}$ absolute accuracy (Loeb et al. 2012; Johnson et al. 2016)





# Top of Atmosphere Radiative Energy Fluxes

## CERES/TERRA, September 2004



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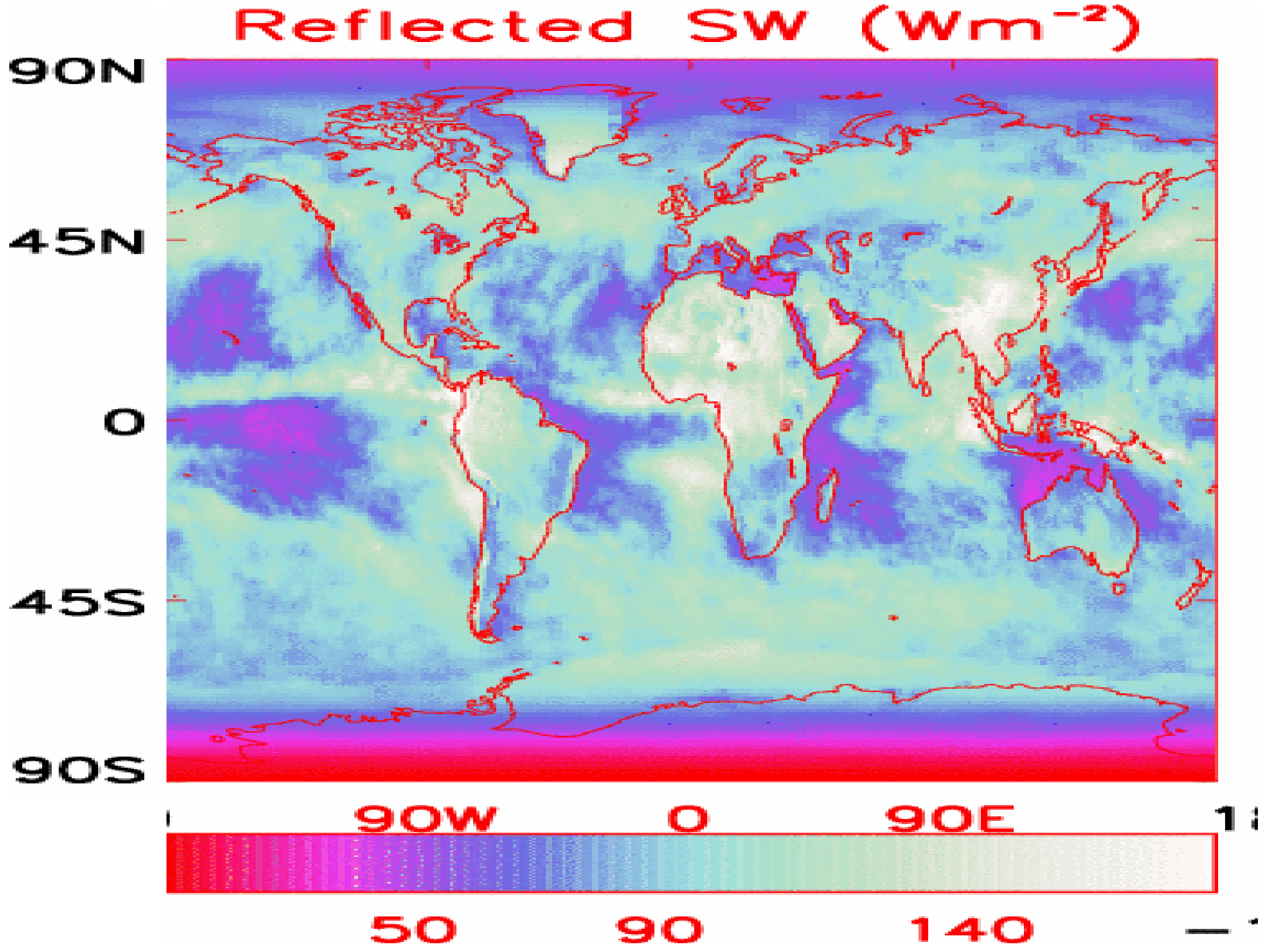
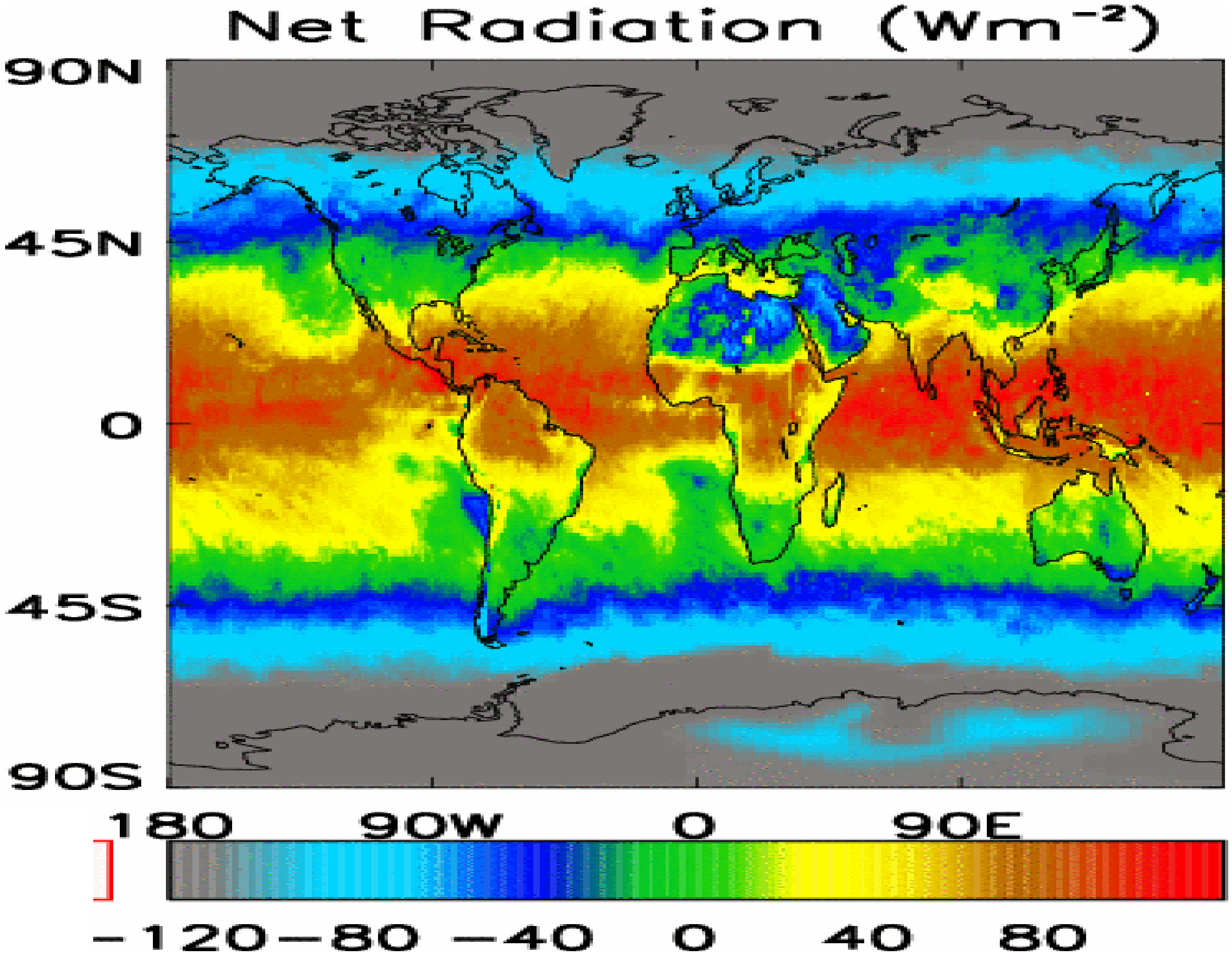
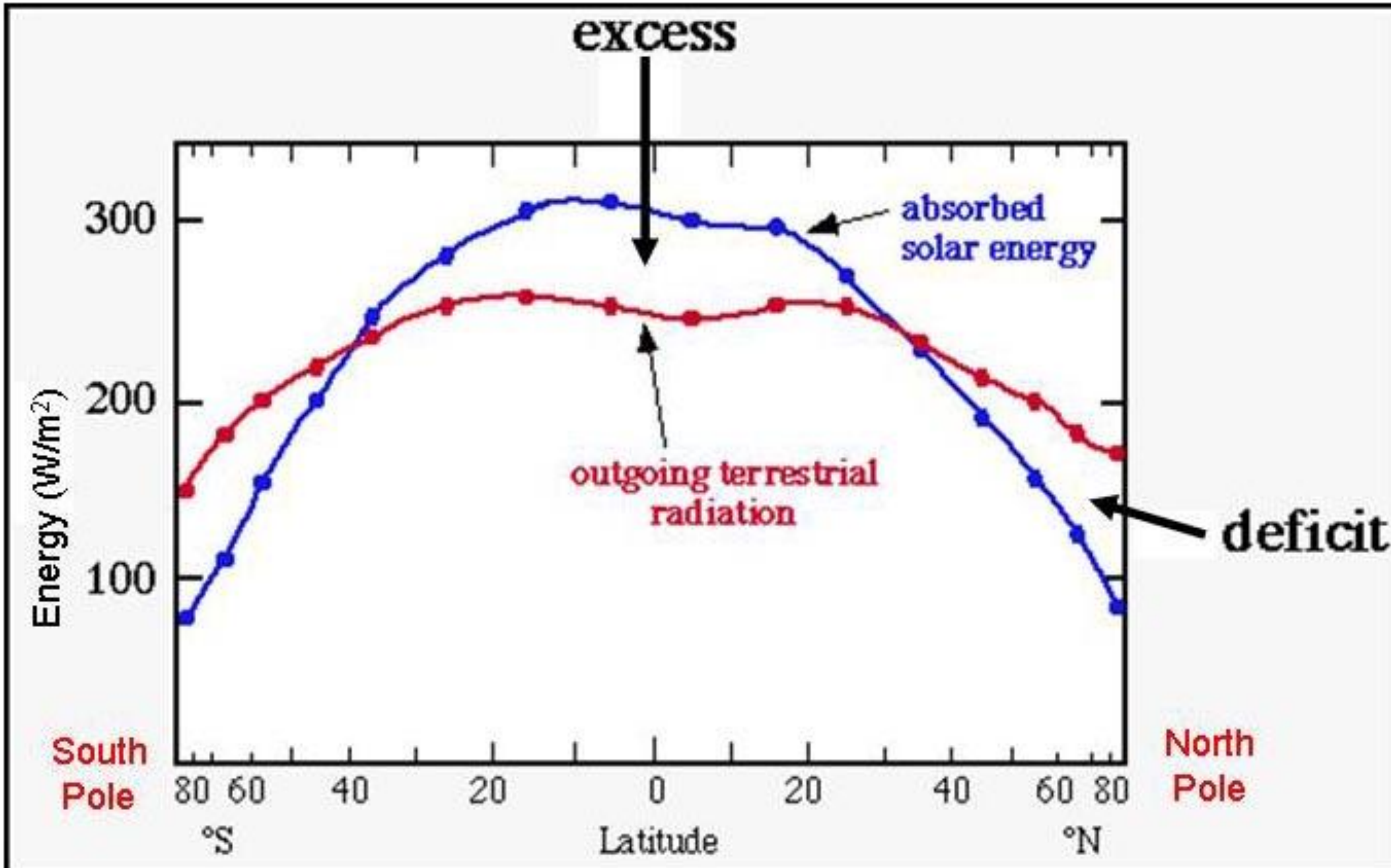


# Top of Atmosphere Radiative Energy Fluxes

## CERES/TERRA, September 2004



# Zonal Mean Radiative Fluxes



# Global annual average energy budget

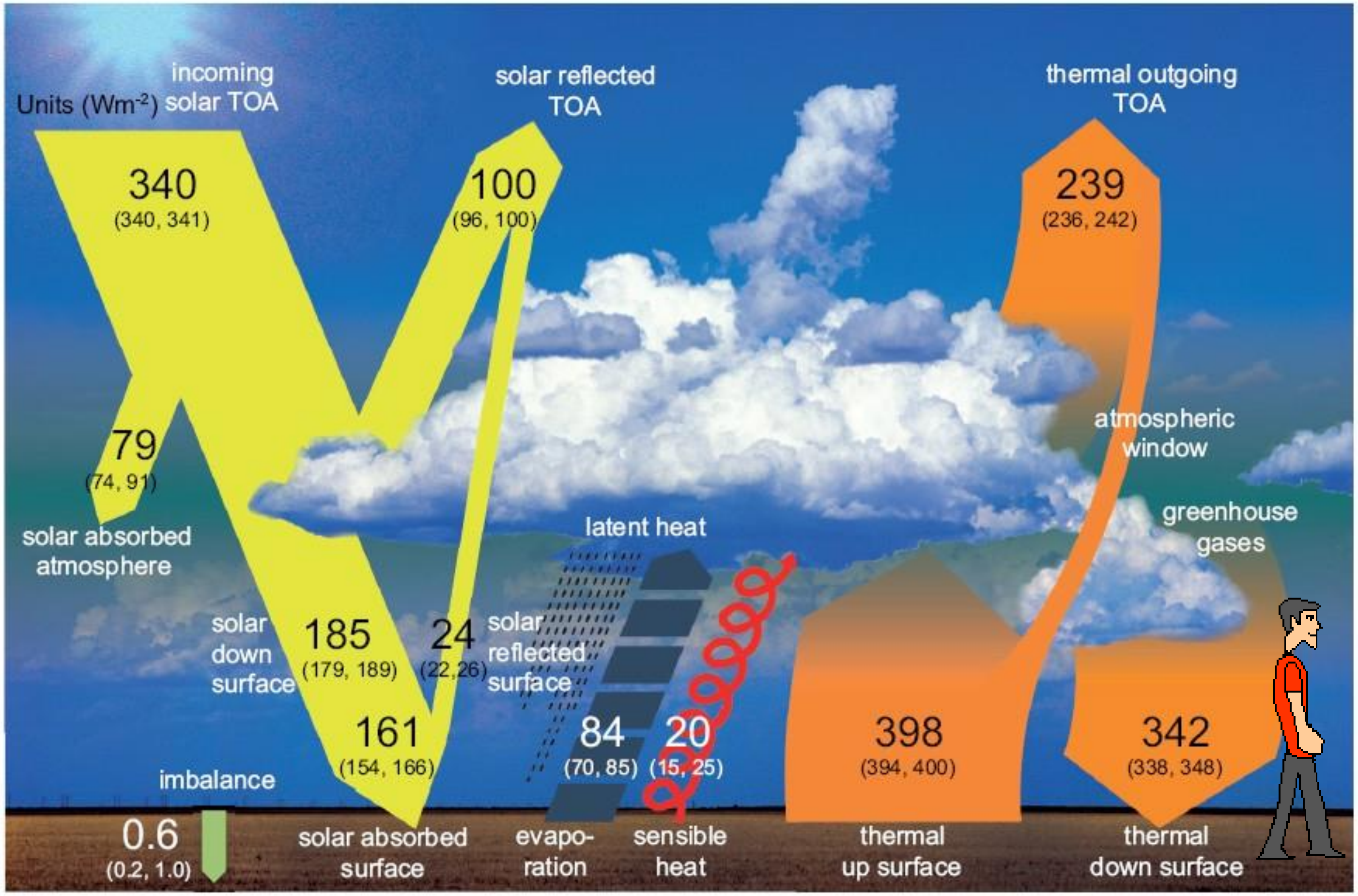
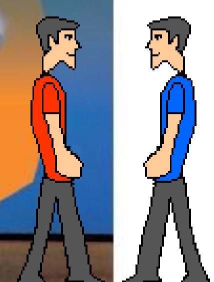


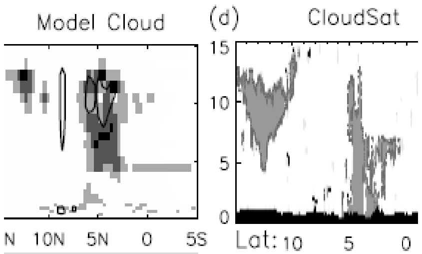

**Figure 2.11:** | Global mean energy budget under present-day climate conditions. Numbers state magnitudes of the individual energy fluxes in W m$^{-2}$, adjusted within their uncertainty ranges to close the energy budgets. Numbers in parentheses attached to the energy fluxes cover the range of values in line with observational constraints. (Adapted from Wild et al., 2013.)

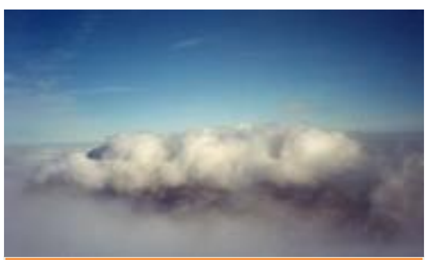


IPCC AR5 WG1
[Fig. 2.11]

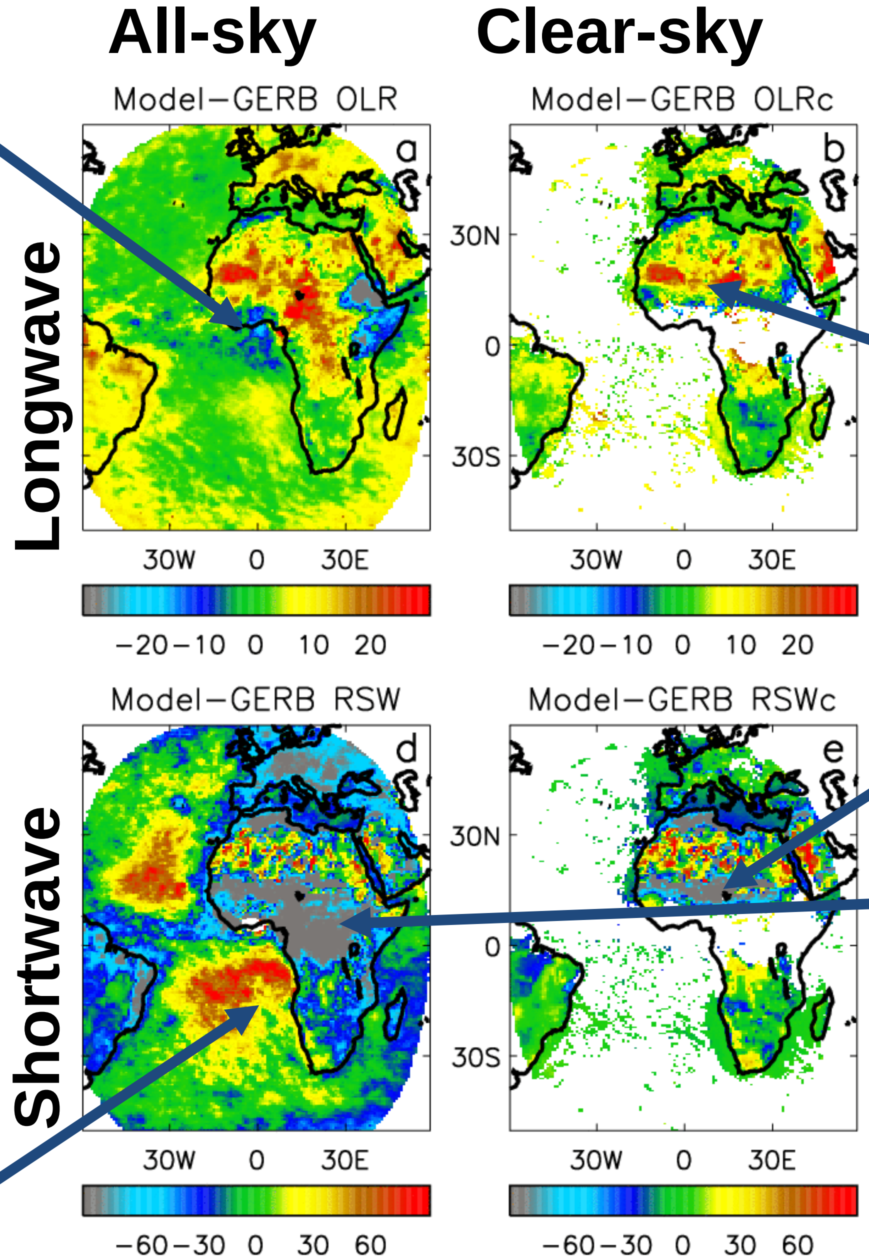
# Model evaluation with GERB

Convective outflow



Marine stratocumulus



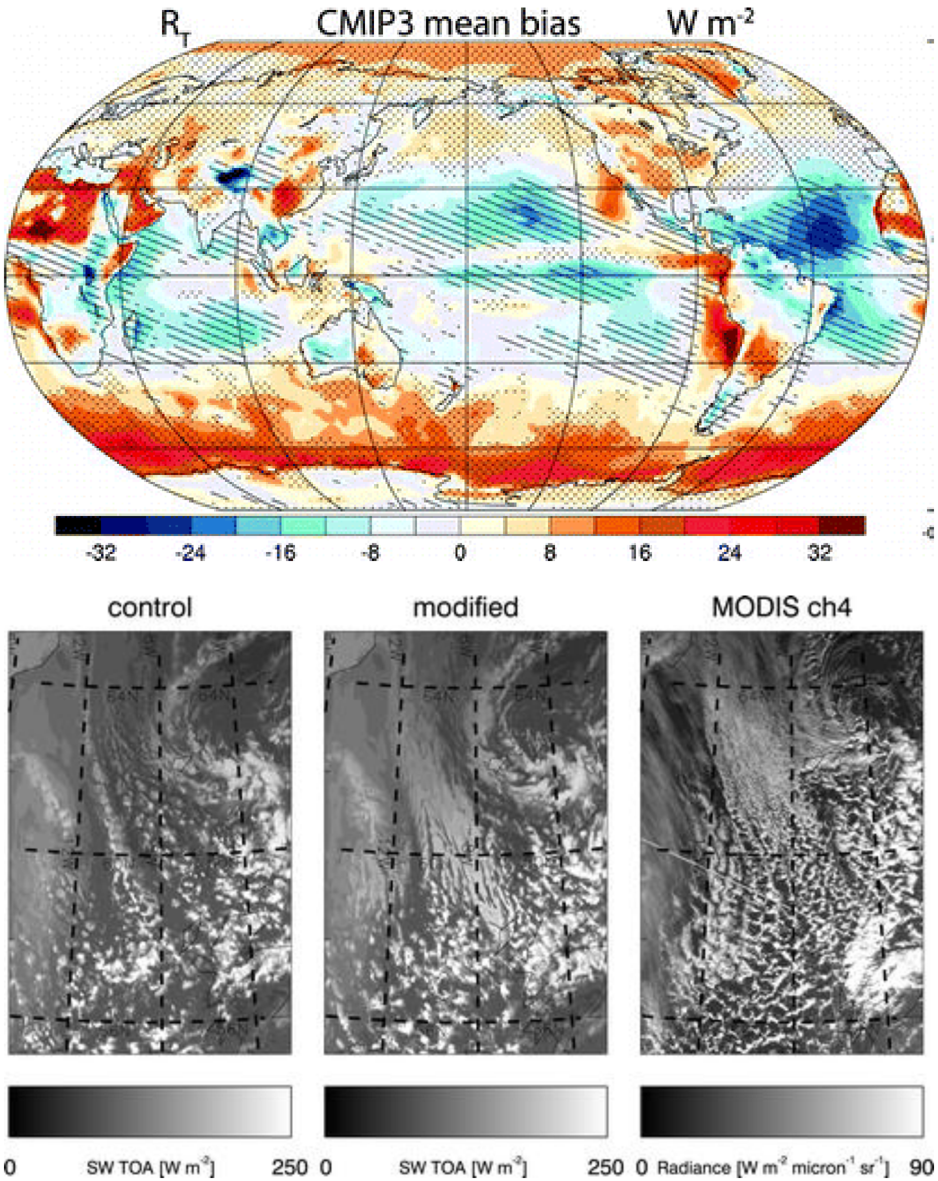

Mineral dust

Surface albedo

Convective cloud

[Allan et al. (2007) QJRMS]

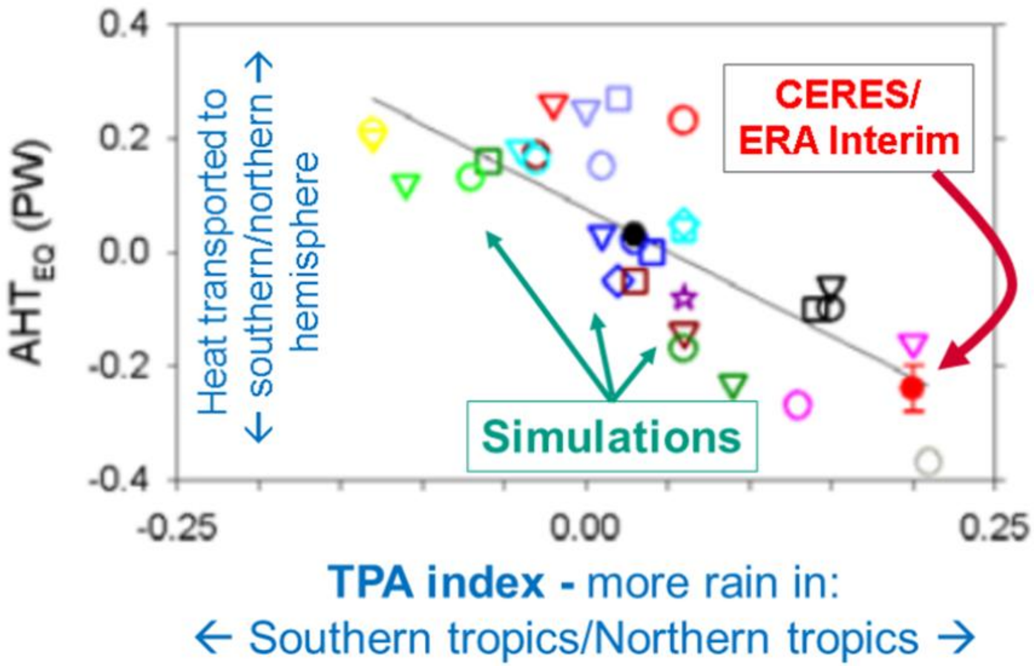
# Systematic model bias in southern ocean




Large biases in net energy budget identified over Southern Ocean - linked to cloud processes e.g. cold air outbreaks. See:
Trenberth & Fasullo, 2010;
Karlsson & Svensson, 2011 ;
Bodas-Salcedo *et al.*, 2012;

← Field et al. (2014) QJRMS

# Causes/consequences of hemispheric asymmetry in Earth's energy budget

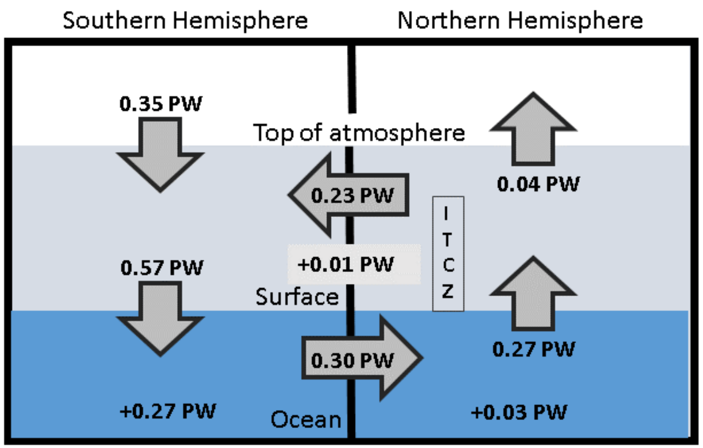



Estimated cross equatorial atmospheric heat transport in peta Watts ($AHT_{EQ}$) against an index of tropical precipitation asymmetry (TPA) between hemispheres in simulations and observations

**Above:** Loeb et al. (2016) Clim. Dyn

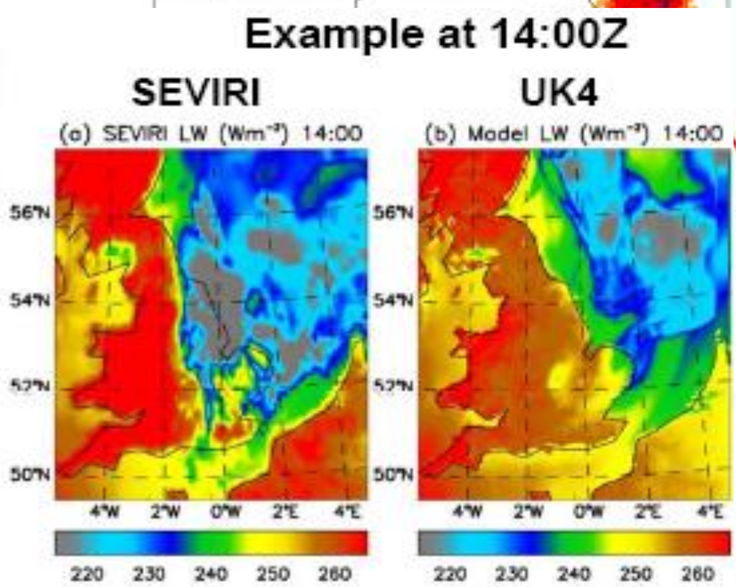
**Right:** hemispheric energy budget based upon Liu et al. (2015) JGR →

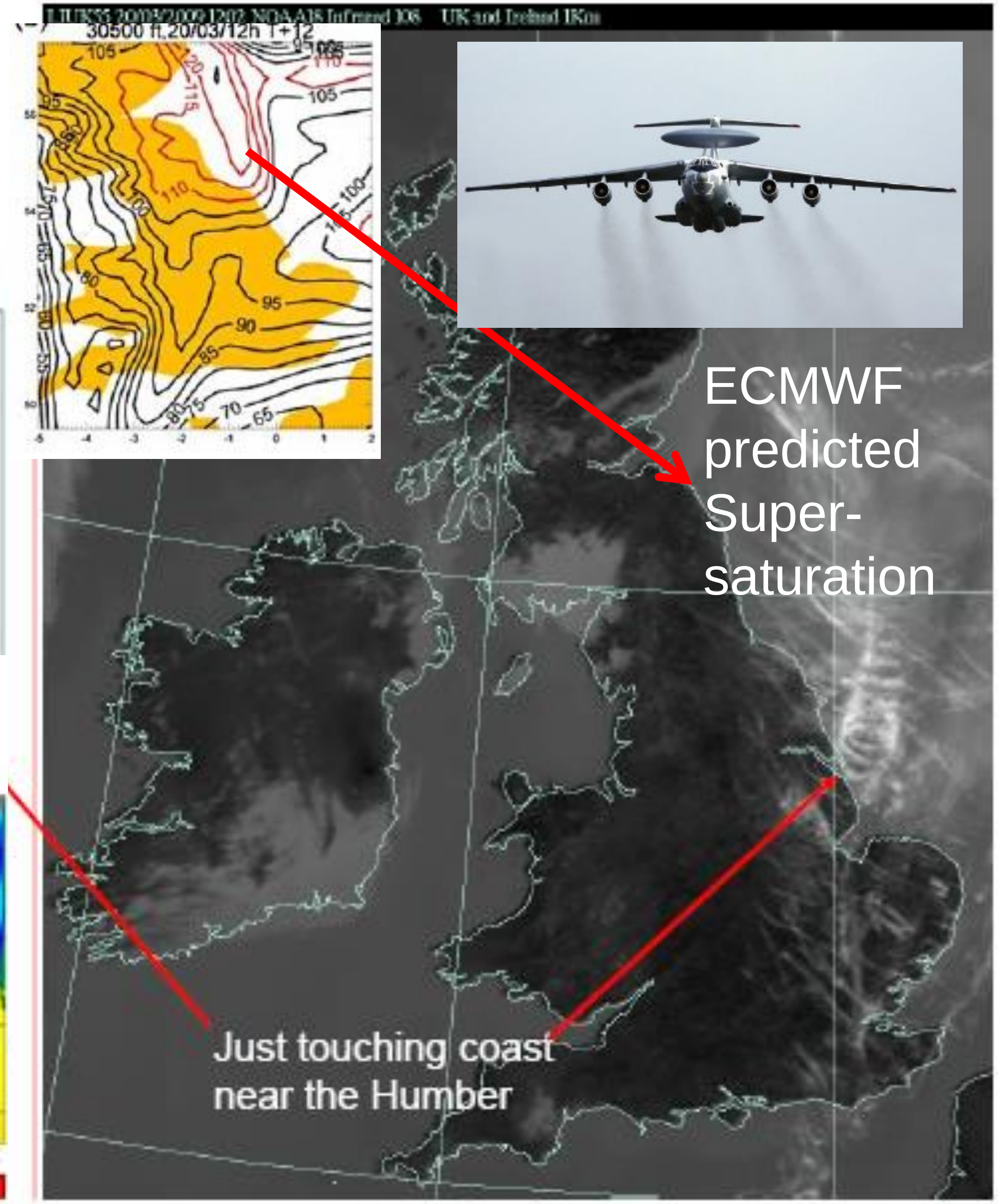
Hemispheric asymmetry in energy budget and precipitation are linked:
Frierson et al. (2013) Nature Geoscience ; Haywood et al. (2016) GRL; Stephens et al. (2015) Rev Geophys



# Radiative forcing of cirrus contrails

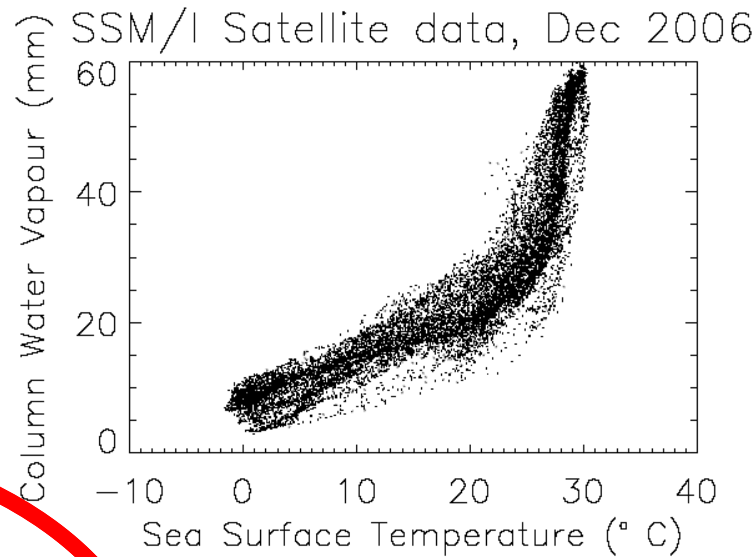
Haywood et al. (2009) JGR

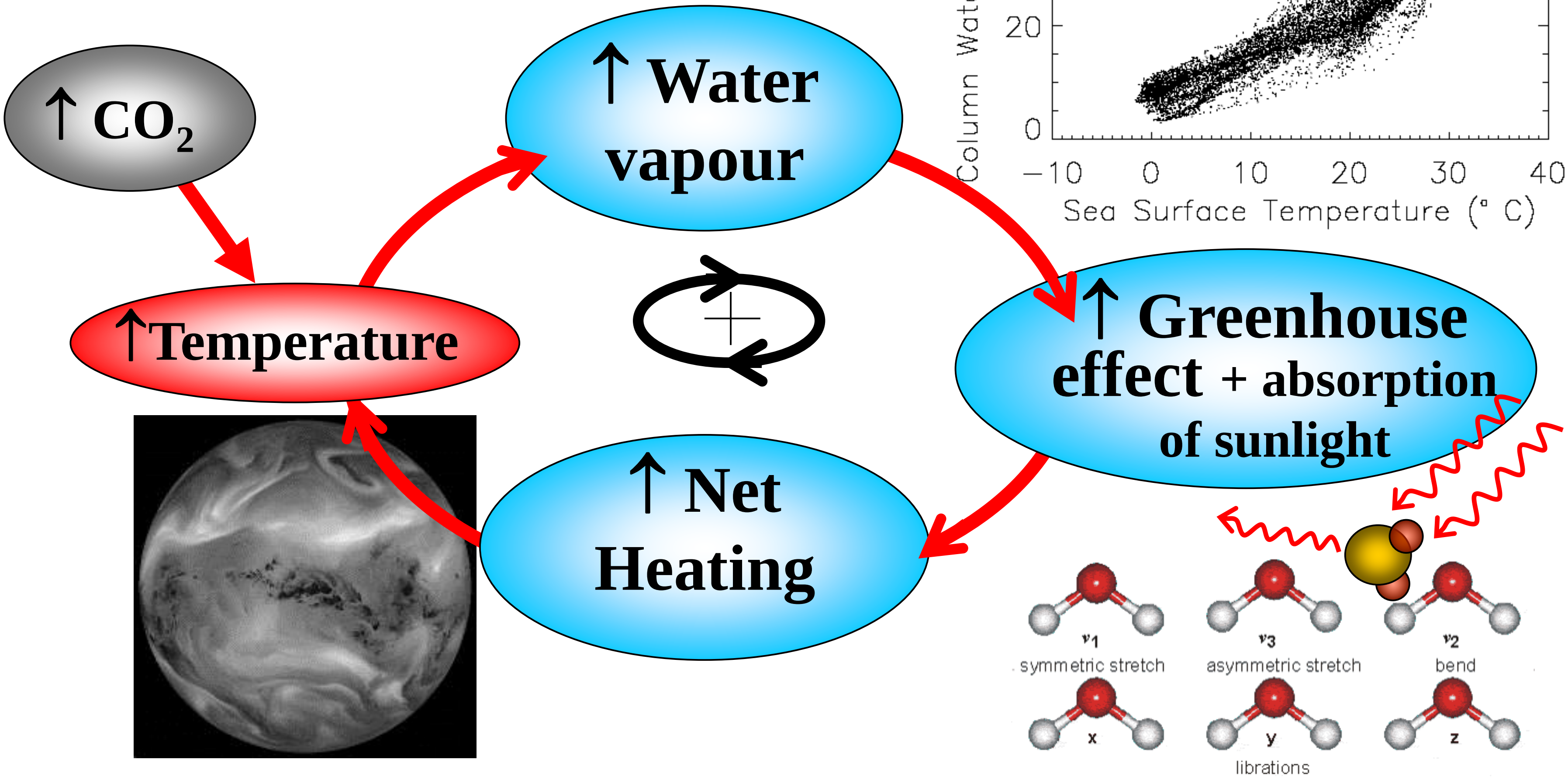


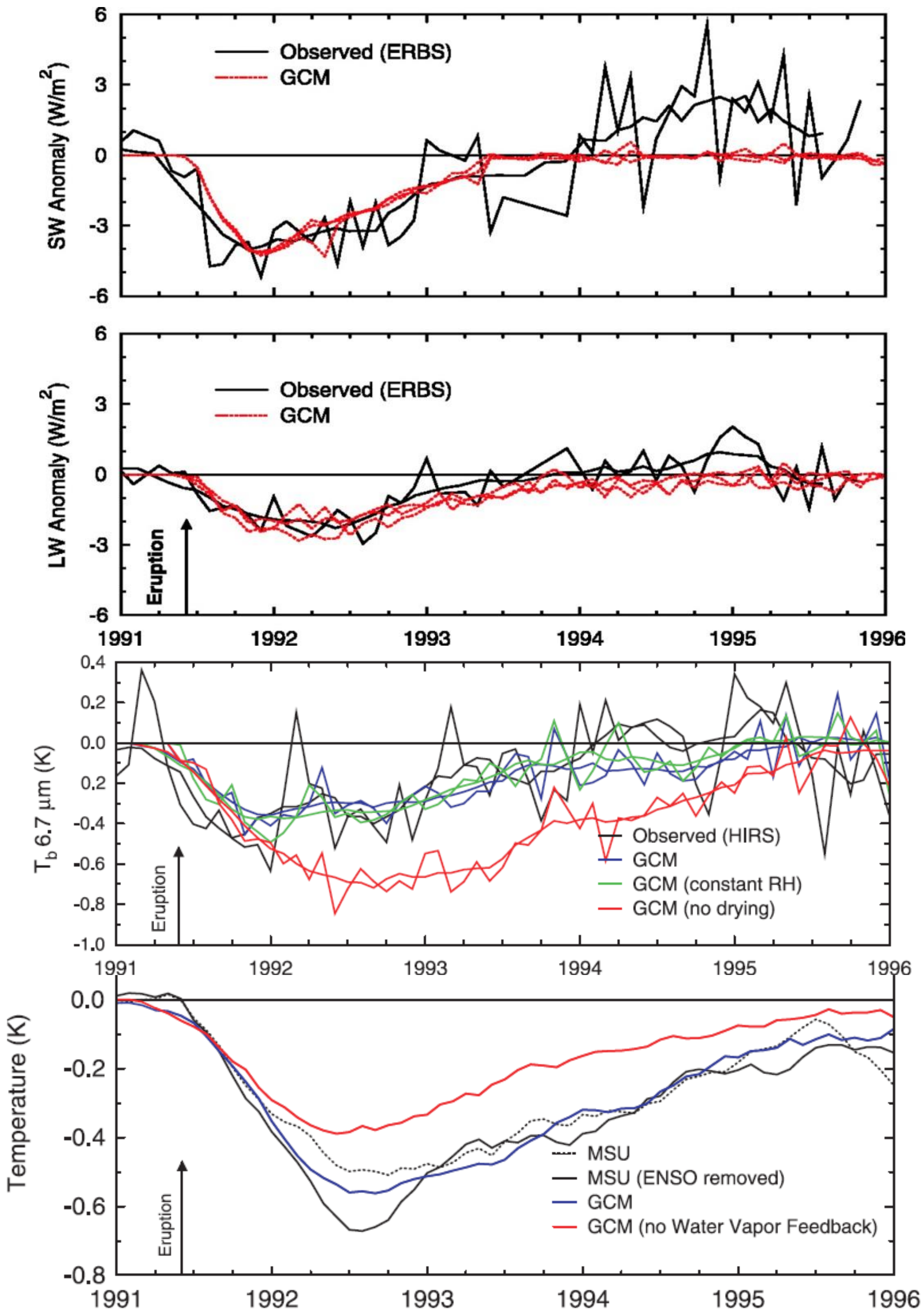



# Radiative forcings and feedbacks

$$\frac{1}{e_s}\frac{de_s}{dT} = \frac{L}{R_v T^2}$$



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# Volcanic eruption as a test of radiative forcing & feedback

1. Radiative forcing by 1991 eruption of Mt. Pinatubo
2. Resulting cooling drives decreased water vapour in upper troposphere
3. Diminished greenhouse effect amplifies cooling
4. Climate model simulates cooling magnitude due to realistic water vapour feedback representation

[Soden et al. (2002) Science]

# Simple model of forcing & feedback

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Net radiation budget change ($\Delta R = \Delta ASR - \Delta OLR$) depends on Forcing ($\Delta F$) and response which depends on Feedback, Y ($Wm^{-2}K^{-1}$):

$$\Delta R = \Delta F + Y\Delta T_s$$

- Feedbacks are additive:

$$Y = \frac{dR}{dT_s} = \frac{\partial R}{\partial T_s} + \sum_x \frac{\partial R}{\partial x}\frac{\partial x}{\partial T_s} + \sum_x \sum_y \frac{\partial^2 R}{\partial x \partial y}\frac{\partial x \partial y}{\partial T_s^2} + \cdots$$

- *x* denotes feedback variable, e.g. cloud, water vapour, ice-albedo, etc. Non-linear effects are generally ignored.
- First term is known as the *Planck* or *Black Body* or *No Feedback* response:

$$\frac{\partial R}{\partial T_s} \approx -4\sigma T_e^3$$

- See Bony et al. (2016) J. Clim (note, the reciprocal of feedback parameter **Y** is termed climate sensitivity, **λ=1/Y** in $K/Wm^{-2}$)

# Exercise: Equilibrium Climate Change

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1. Calculate the radiative forcing from a doubling of $CO_2$ using: $\Delta F = 5.35\ln(C_2/C_1)$ [$C_1$ and $C_2$ are initial and final $CO_2$ concentrations]

When climate responds and reaches a new equilibrium, $\Delta R = 0$:

$$\Delta R = \Delta F + Y \Delta T_s = 0$$

2. Calculate equilibrium temperature response $\Delta T_s$ with "Planck" feedback, $Y = \partial R/\partial T_s \approx -4\sigma T_e^3$ [$T_e$ = 255 K, $\sigma = 5.67\times10^{-8}$ $Wm^{-2}K^{-4}$]

3. Re-calculate equilibrium temperature with water vapour feedback assuming water vapour increases with warming at ~10%/K and R increases with water vapour at ~0.15 $Wm^{-2}$/%

$$Y = \frac{\partial R}{\partial T_s} + \frac{\partial R}{\partial W}\frac{\partial W}{\partial T_s}$$

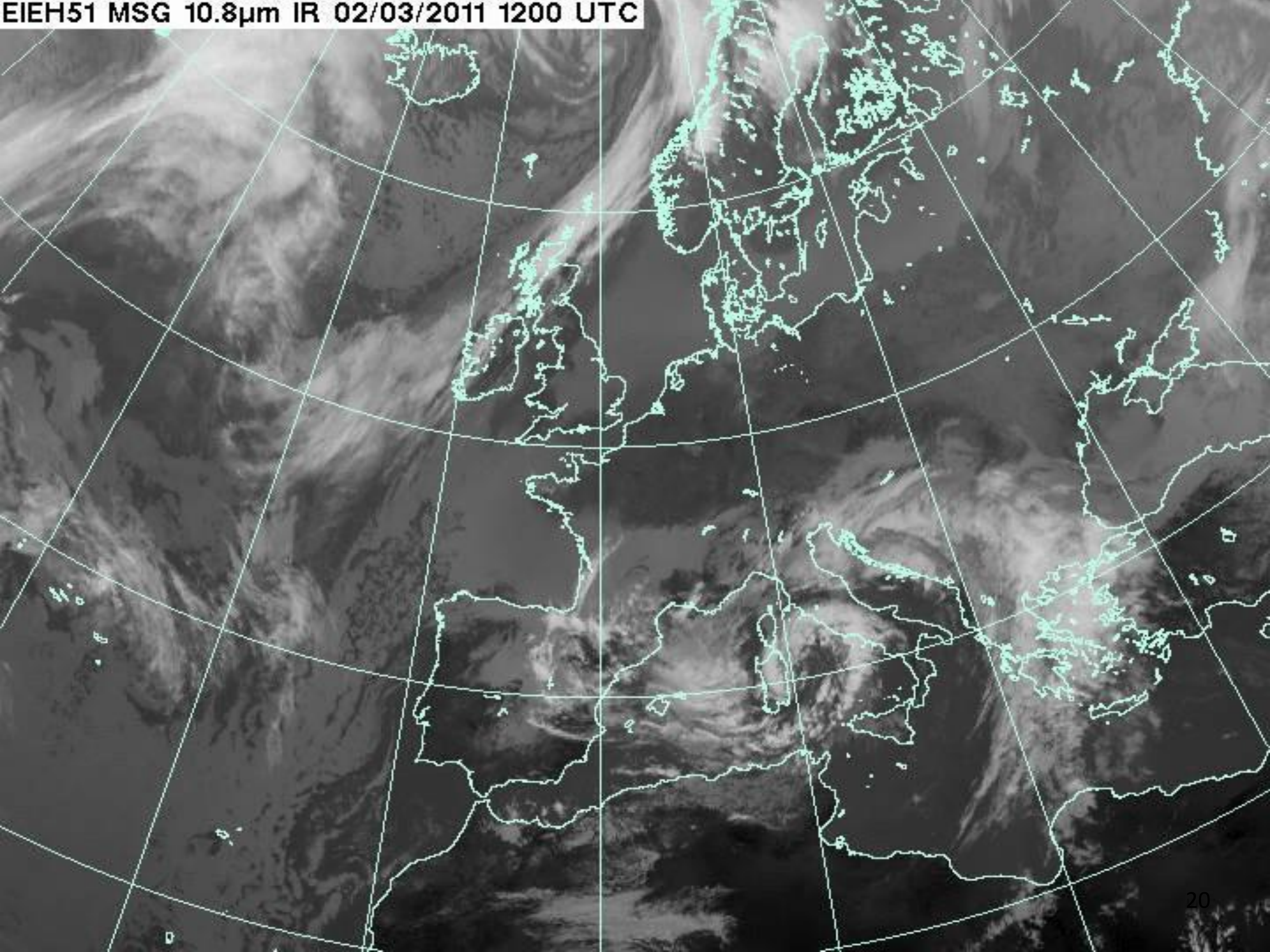
# Cloud Feedback

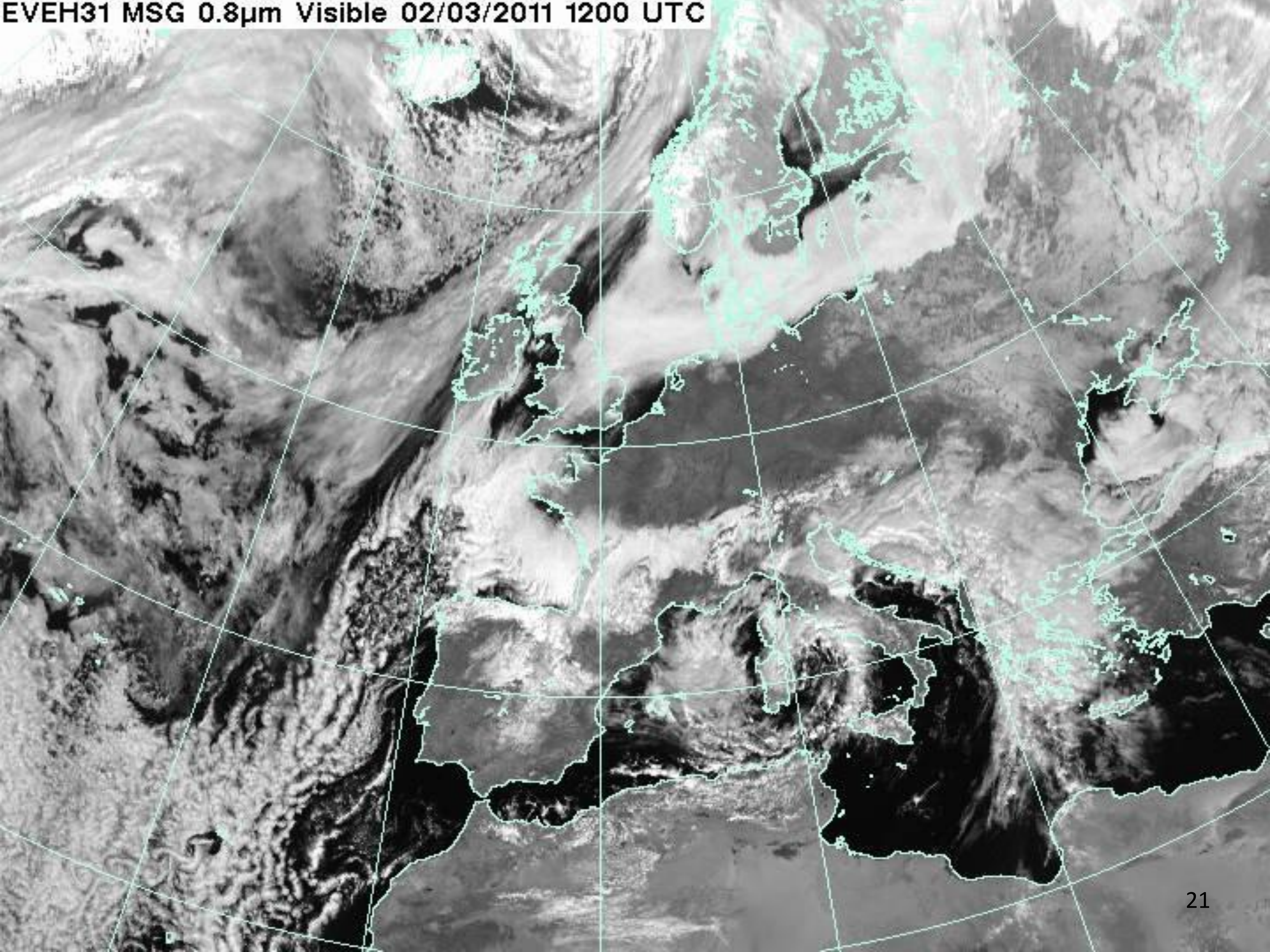
$$\frac{\partial R}{\partial x}\frac{\partial x}{\partial T_s}$$

- Depends on:
  - Type of cloud
  - Height of cloud
  - Time of day/year
  - Surface characteristics

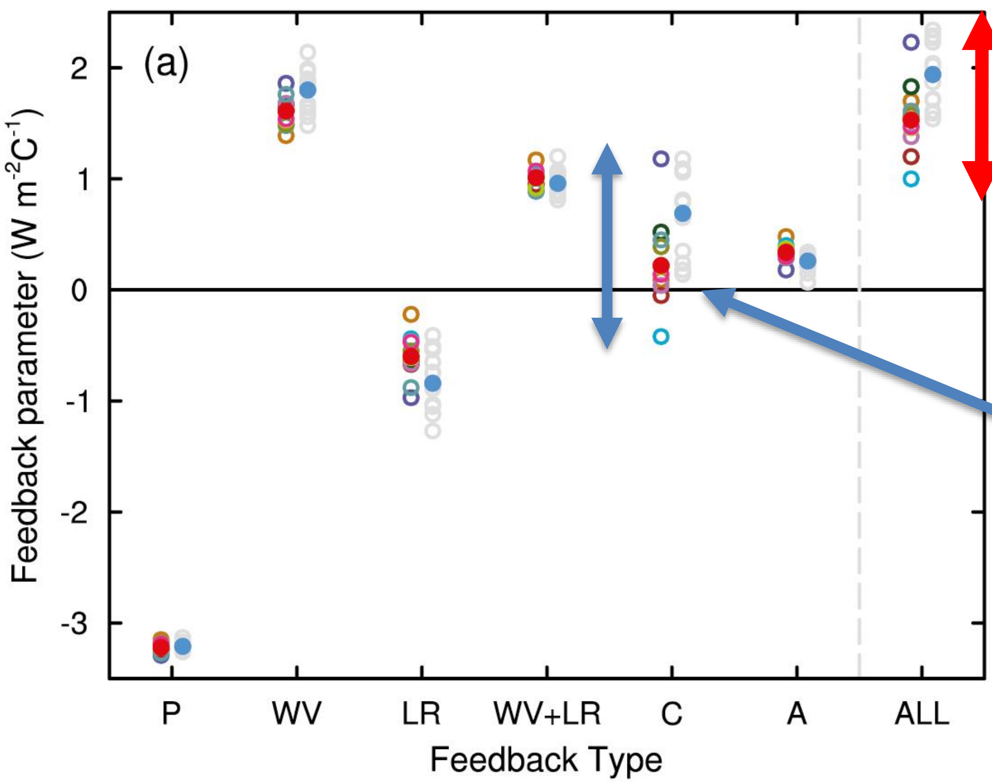
Non-trivial relationship between cloud and temperature

In addition, aerosol can influence clouds, thereby providing indirect radiative forcings which are also highly uncertain


EIEH51 MSG 10.8µm IR 02/03/2011 1200 UTC


EVEH31 MSG 0.8μm Visible 02/03/2011 1200 UTC

# Feedback uncertainty



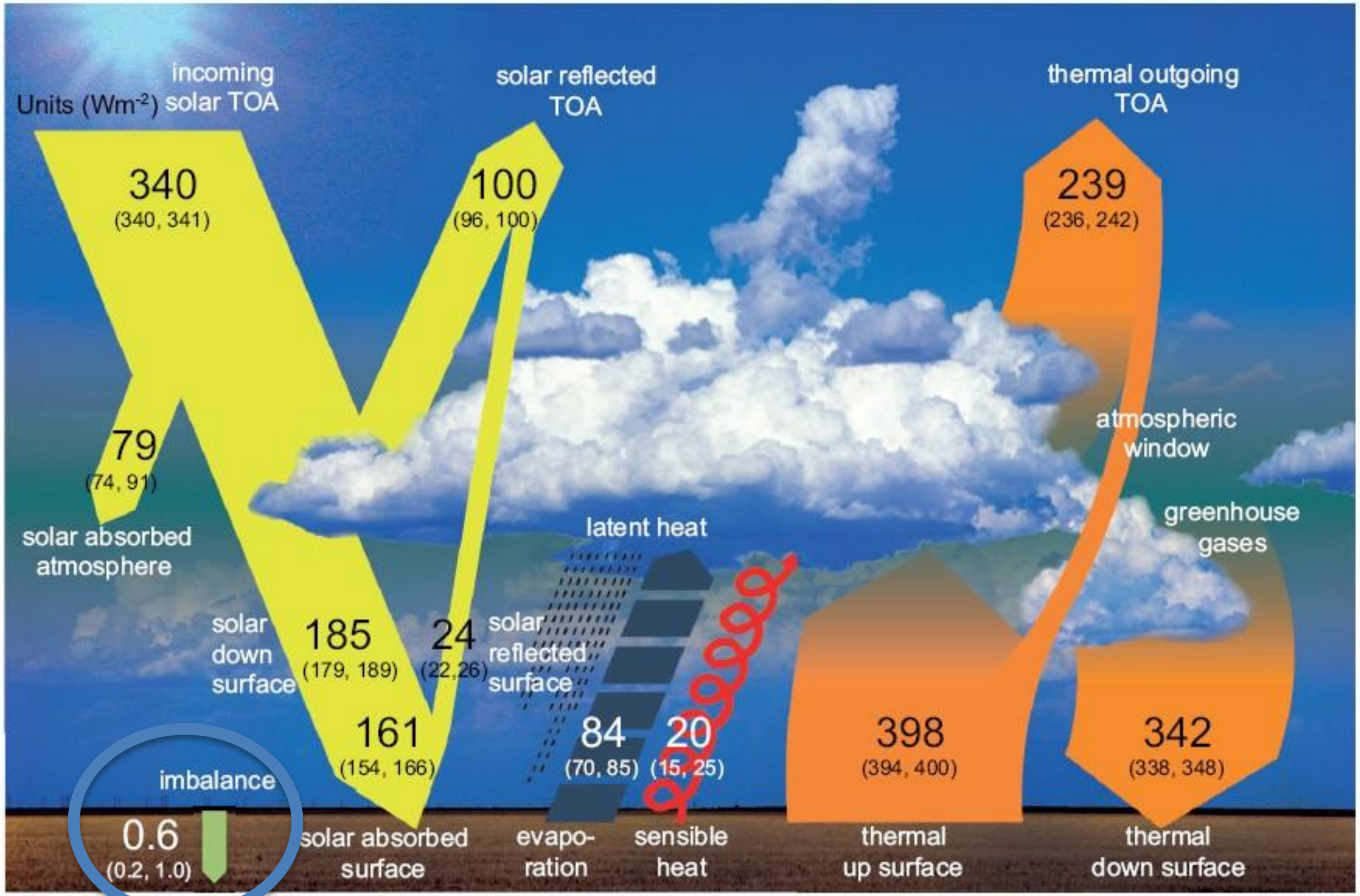

Total range

Cloud feedback range

**Above:** Planck (P), Water Vapour (WV), Temperature Lapse Rate (LR), Cloud (C) and Albedo (A) feedbacks simulated by climate models [IPCC AR5 WG1 Fig. 9.43]

# Earth's global annual average energy budget

IPCC AR5 WG1
Fig. 2.11

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# Earth's energy imbalance

- It takes time to reach climate equilibrium due to the vast heat capacity, $C_s$, of the oceans

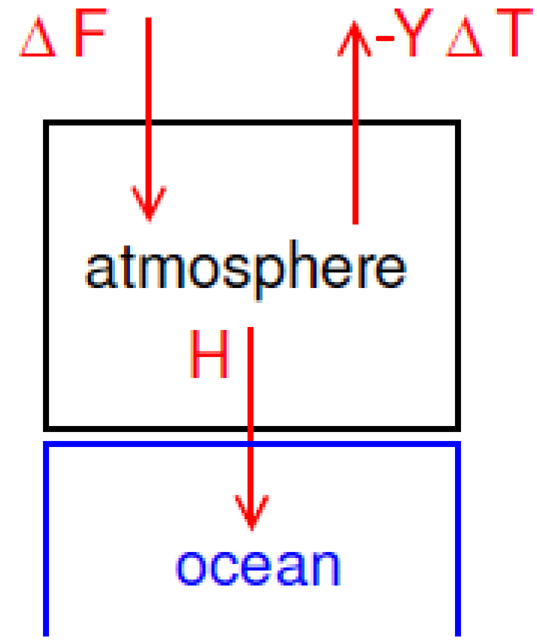
$$\Delta R = \Delta F + Y\Delta T \approx H$$

- Therefore we have a radiative imbalance as oceans take up heat, H

$$C_s \frac{d\Delta T(t)}{dt} \approx R(t)$$

- Note that $\Delta T$ depends on ocean mixed layer heat content so vertical redistribution of energy is important

$\Delta R = \Delta F + Y\Delta T$



# Current changes in Earth's energy imbalance

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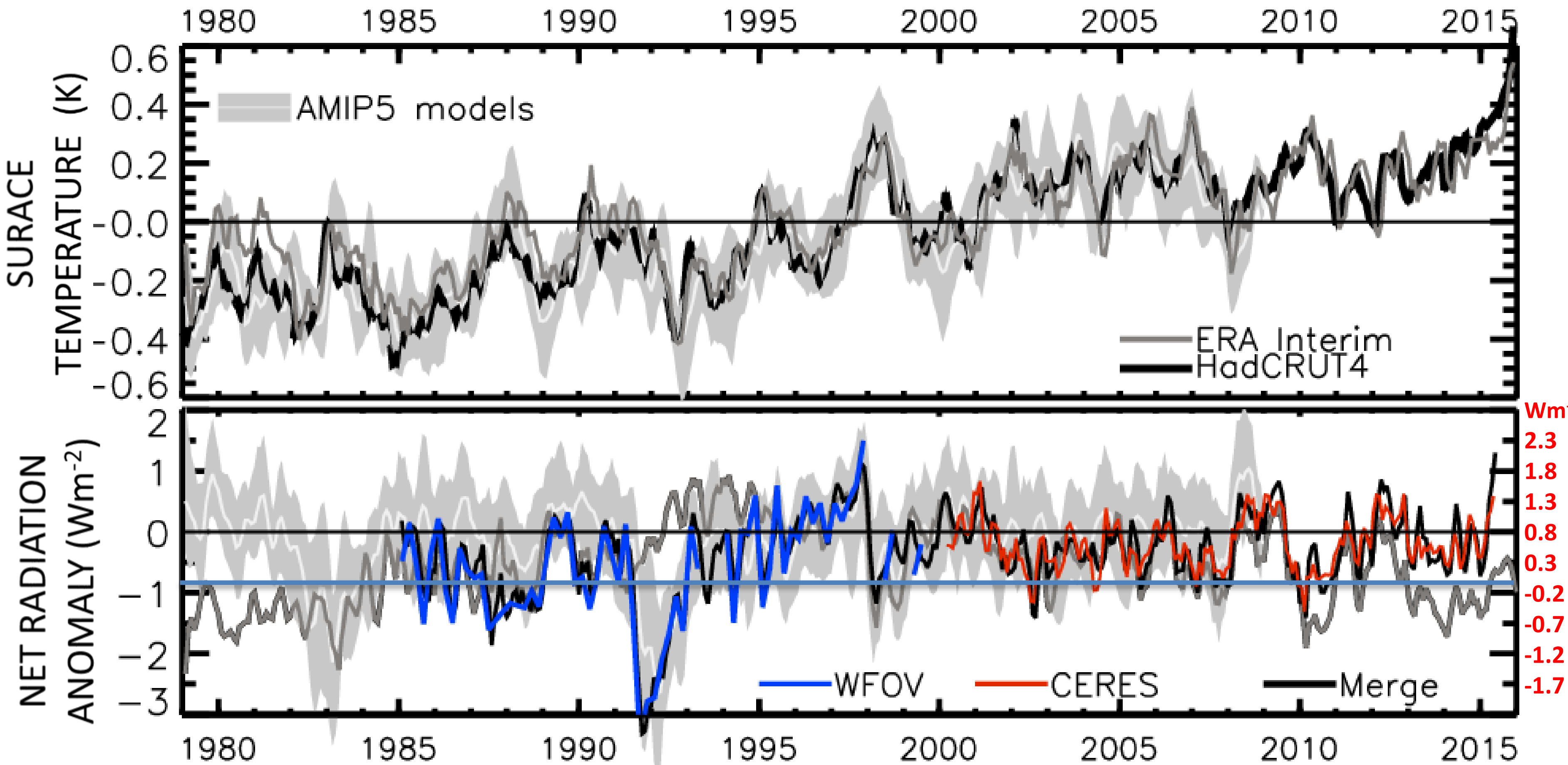
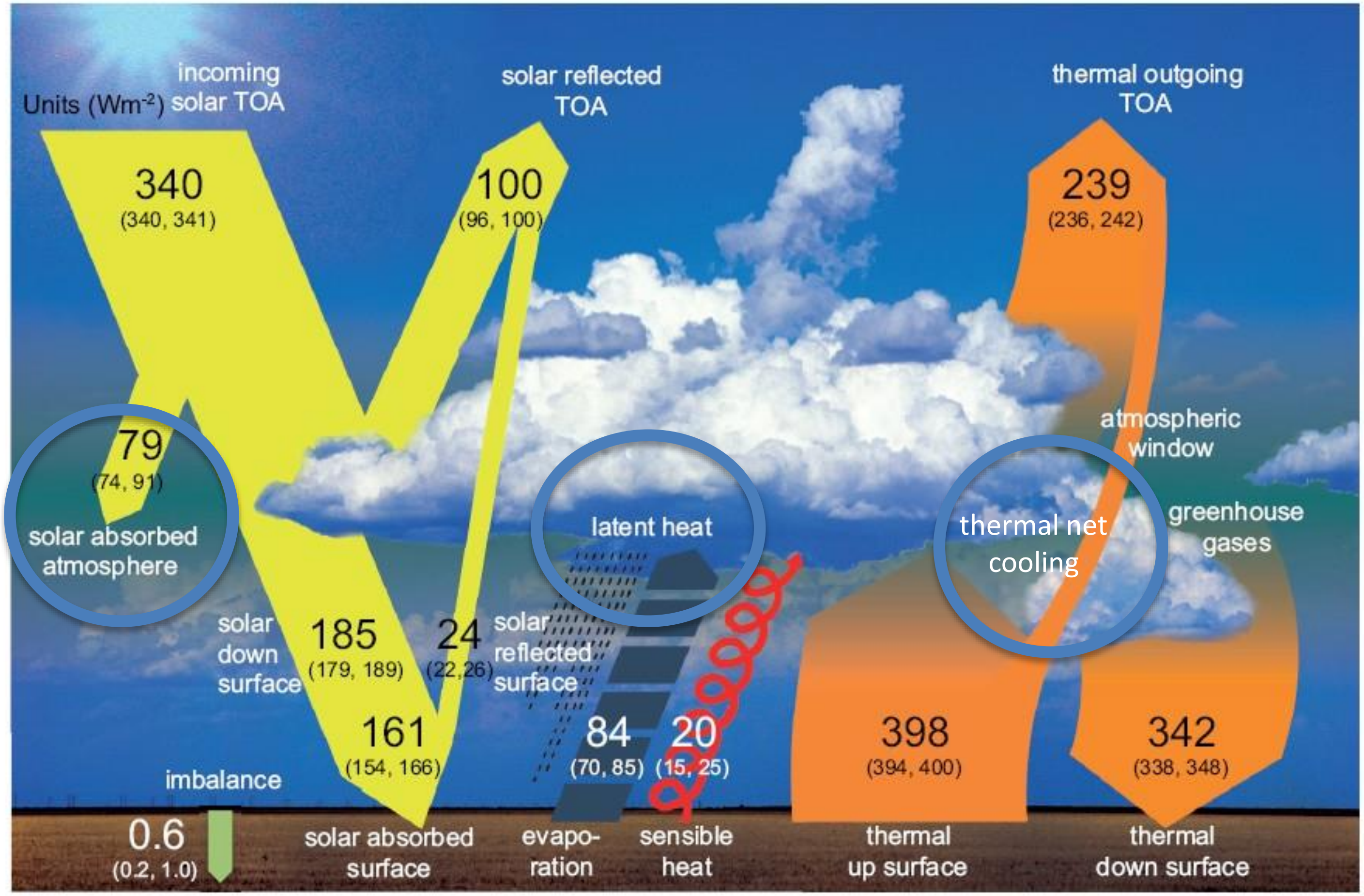



Update from Loeb et al. (2012) Nature Geoscience & Allan et al. (2014) GRL

# Earth's global annual average energy budget




IPCC AR5 WG1 Fig. 2.11

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# Energy balance & the global water cycle

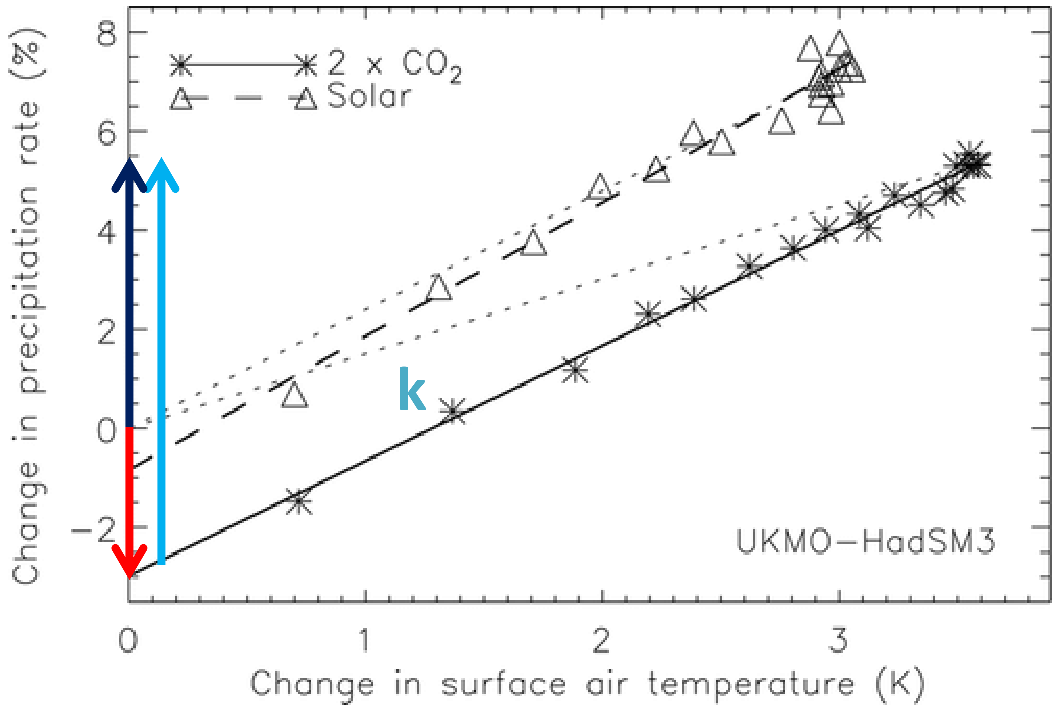
[Andrews et al. (2009) J Clim](#)

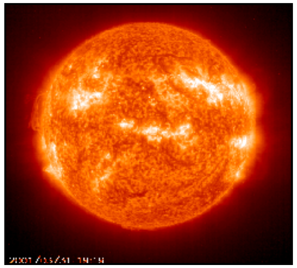
$L\Delta P \approx \Delta R_{atm}$

$\approx k\Delta T - f_{\Delta F}\Delta F$

ahem?

$\Delta SH$



Partitioning of radiative forcing **ΔF** between the atmosphere **$f_{\Delta F}\Delta F$** & surface **$(1-f_{\Delta F})\Delta F$** is crucial for hydrological response, **LΔP.**

(see also [Allen & Ingram 2002 Nature](#) , [Allan et al. 2014 Surv. Geophys](#).)

# Summary

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- There is a balance between absorbed sunlight and emitted thermal infrared (longwave) radiation that determines climate
- Satellites instruments (e.g. CERES) can measure Earth's radiation budget by converting radiance measurements to fluxes using angular dependence models  that require scene-type information from imagers (e.g. MODIS)
- Systematic biases in simulated radiation balance can reveal deficiencies in cloud processes but comparisons also help quantify and evaluate radiative forcings (e.g. cirrus contrail, aerosol) and feedbacks (e.g. water vapour, cloud)
- It takes 100s of years for climate to reach a new equilibrium following a radiative forcing due to the large heat capacity of the ocean: this results in an imbalance in the radiation budget
- Radiative forcings and response also dictate how the global water cycle will respond to a warming world.