Water in the Climate System – The Hydrological Cycle

Richard Allan - University of Reading

Thanks to Julia Slingo, Adrian Tomkins, Peter Bechtold and others

University of Reading
National Centre for Atmospheric Science
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Overview

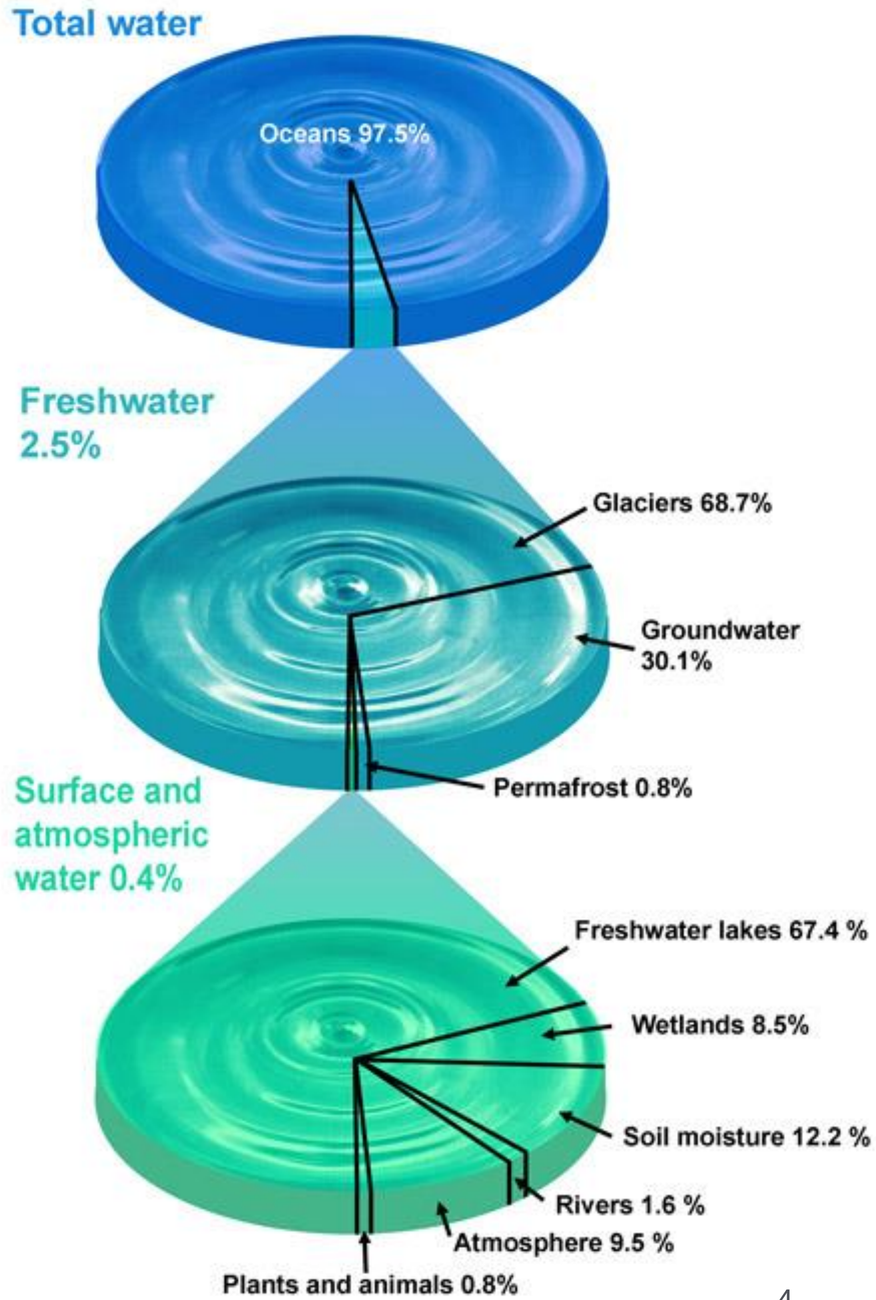
- Basic Quantities and Concepts
- Water cycle in the climate system
  - Atmospheric hydrological cycle
  - Ocean freshwater budget
  - Terrestrial water cycle
- Modelling the water cycle:
  - Clouds and precipitation
  - Atmospheric convection
  - Land surface processes
- Water cycle and climate change

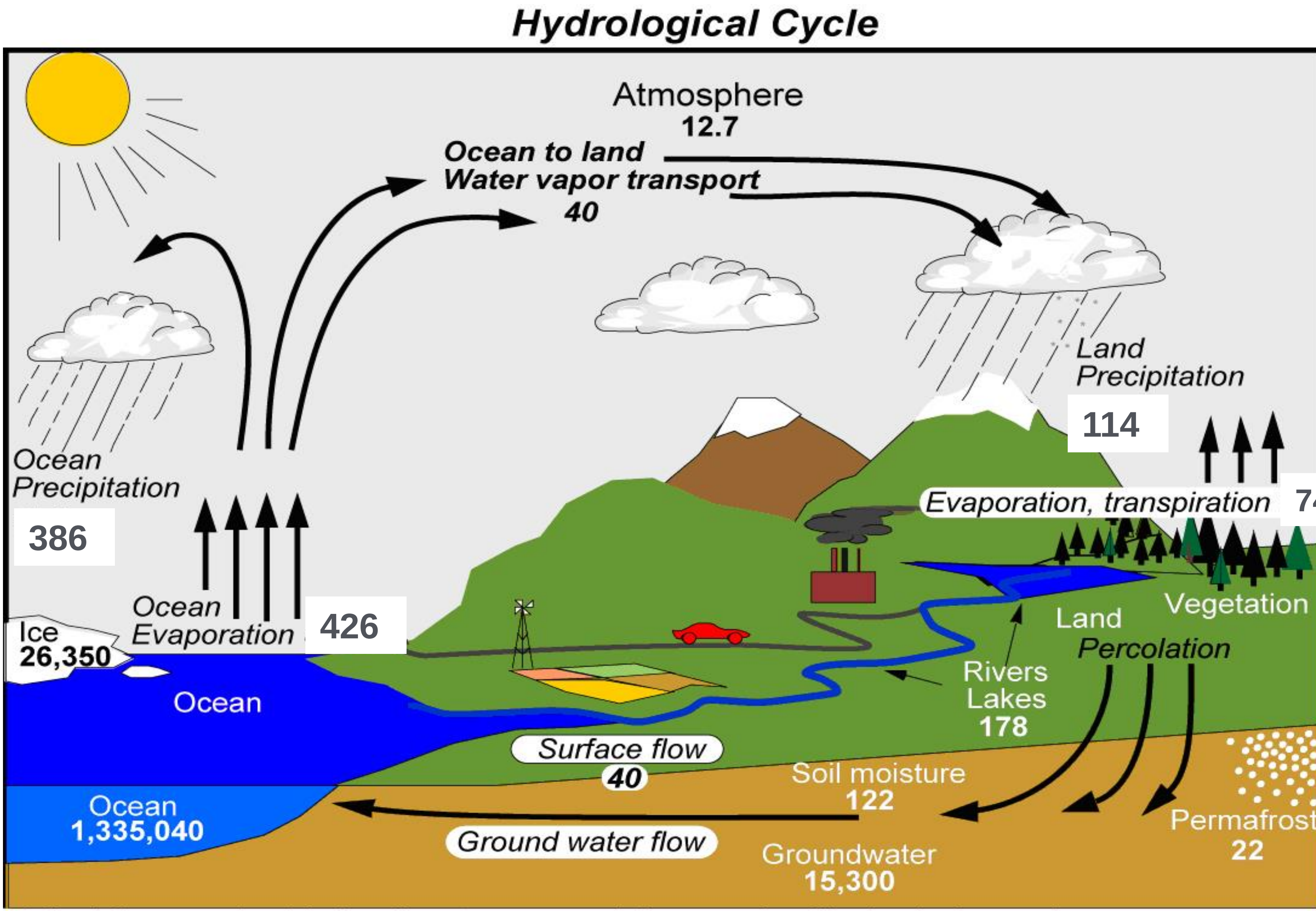
Why water is so important

- Water is a fundamental ingredient of the Earth System, supporting plant, animal and marine life.
- Water in both liquid and frozen forms covers ~75% of the Earth's surface
- Water vapour constitutes the Earth's most abundant and important greenhouse gas
- Water in its various forms (vapour, liquid, solid) determines the characteristics and spatio-temporal evolution of the Earth System
  - Latent heat release from precipitation is a major driver of the global circulation, which acts to transport heat, moisture and momentum around the climate system.
  - Natural ecosystems depend on precipitation, and so water has a fundamental role to play in other cycles of the earth system. such as the carbon and nitrogen cycles.

WATER RESOURCES

- Most water on Earth is salty
- Most fresh water locked away in glaciers or deep in ground
- Atmosphere contains a minute amount of water ~ 0.001% (~2.5cm of water globally)
- BUT every year atmosphere cycles ~40x that amount (~1m of water globally)
- Usable water depends strongly on the water cycle



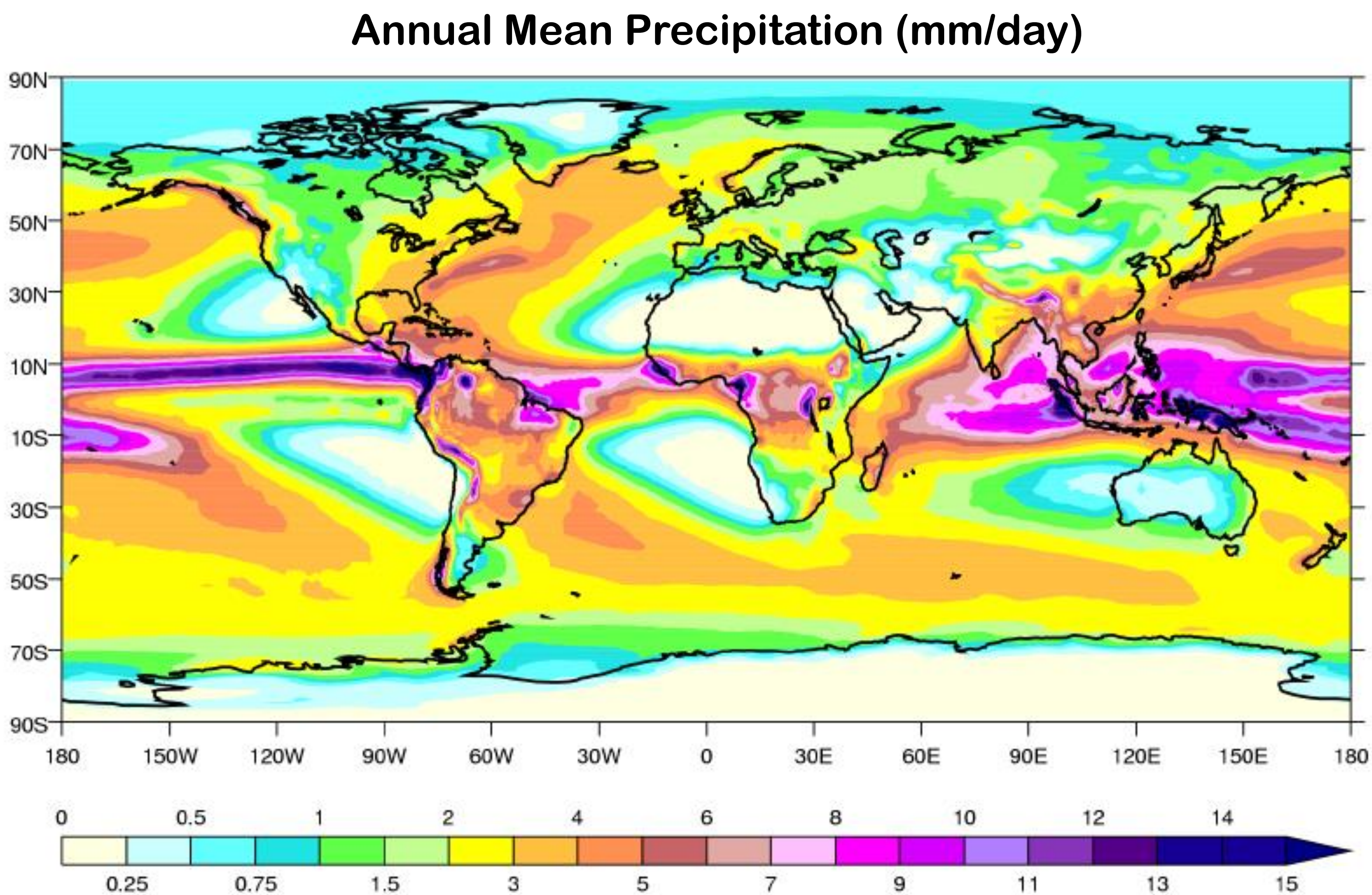


Units: Thousand cubic km for storage, and *thousand cubic km/yr* for exchanges

Trenberth et al. (2007) J Hydromet; updated: Trenberth et al. 2011 J. Clim

Atmospheric Hydrological Cycle

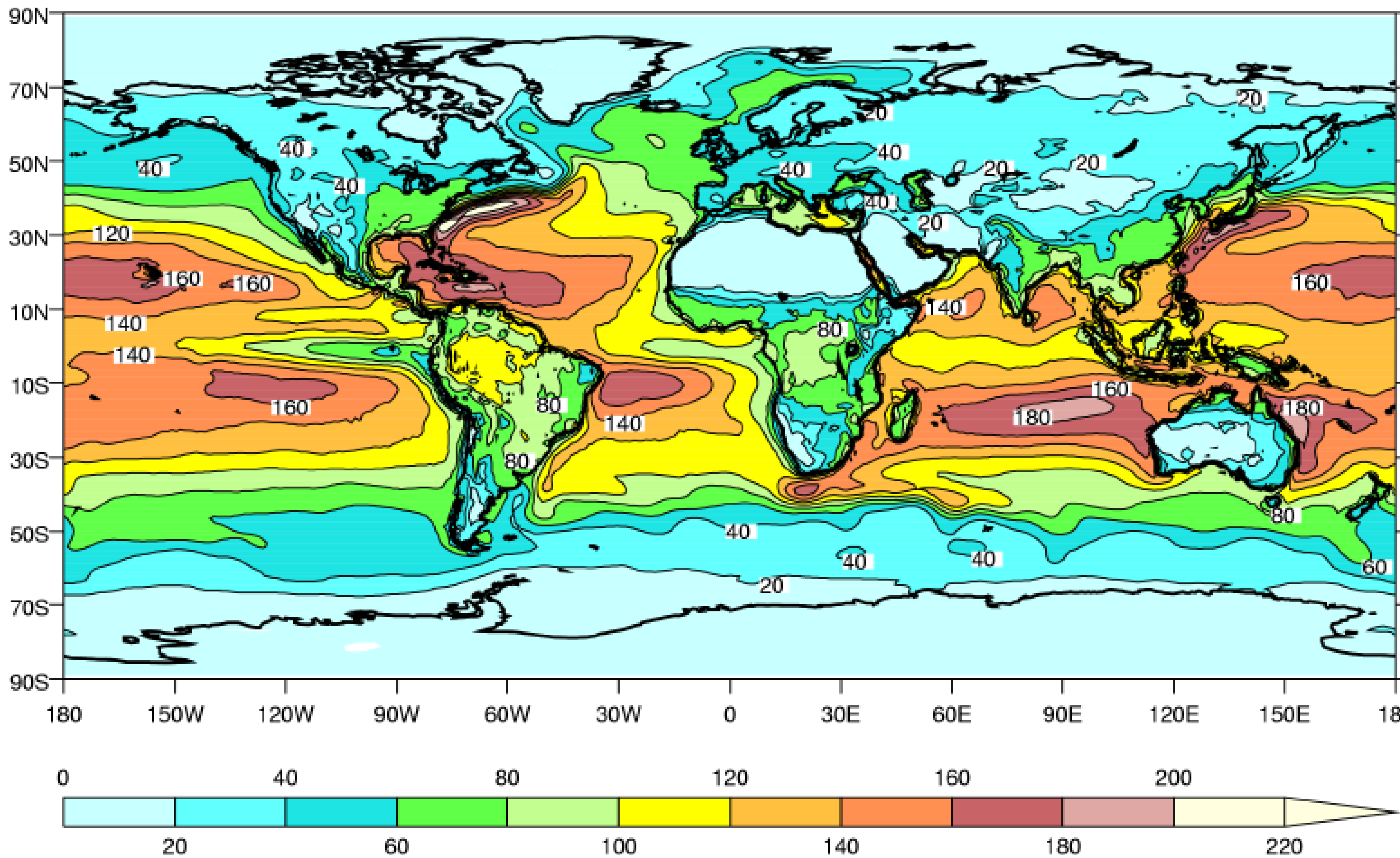
Precipitation = Surface Evaporation + Atmospheric Transport



Atmospheric Hydrological Cycle

Precipitation = Surface Evaporation + Atmospheric Transport

Annual Mean Latent Heat Flux (Wm^{-2})

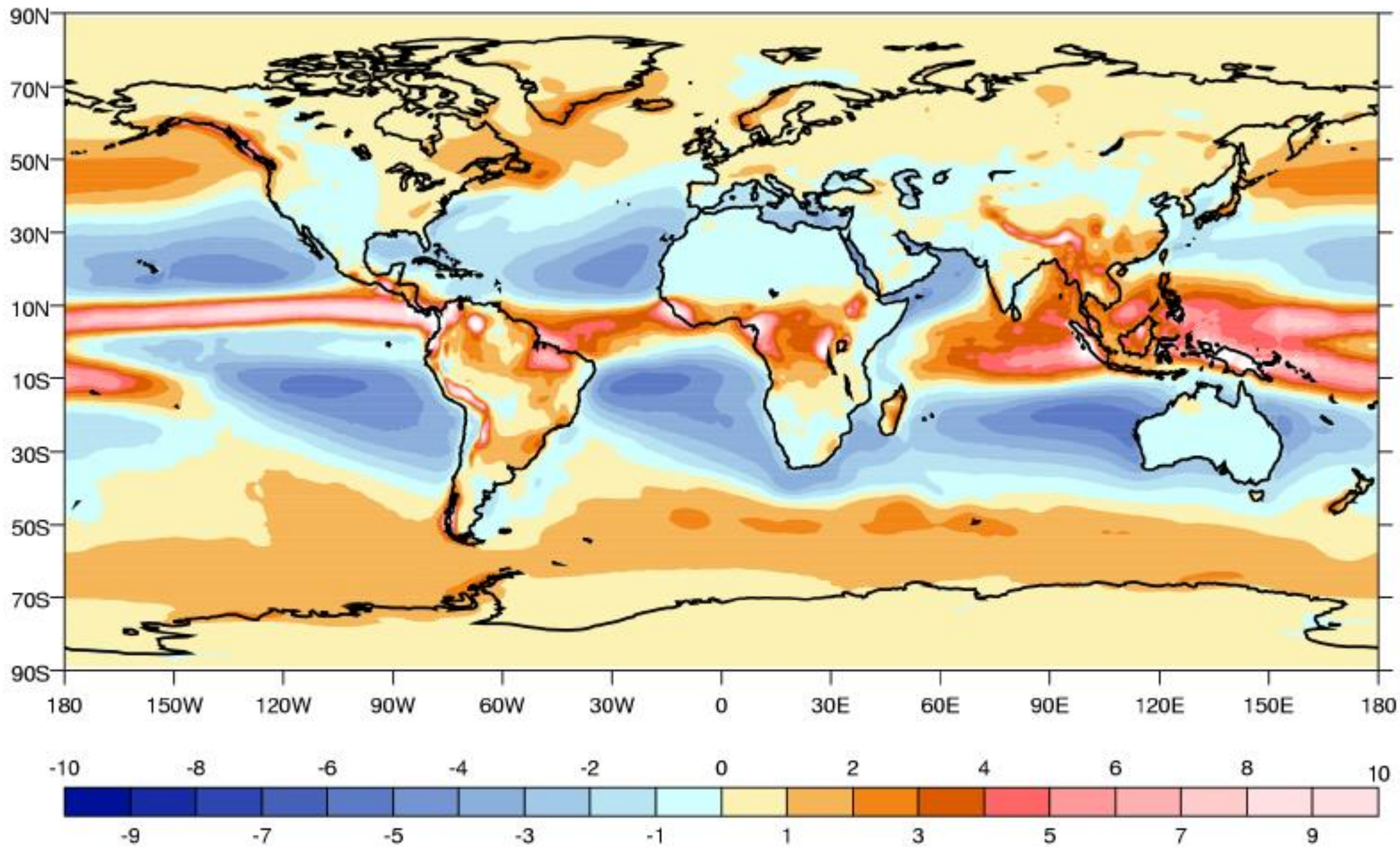


1 mm/day = 28.9 Wm^{-2}

Atmospheric Hydrological Cycle

Precipitation = Surface Evaporation + Atmospheric Transport

Annual Mean Precipitation minus Evaporation (mm/day)

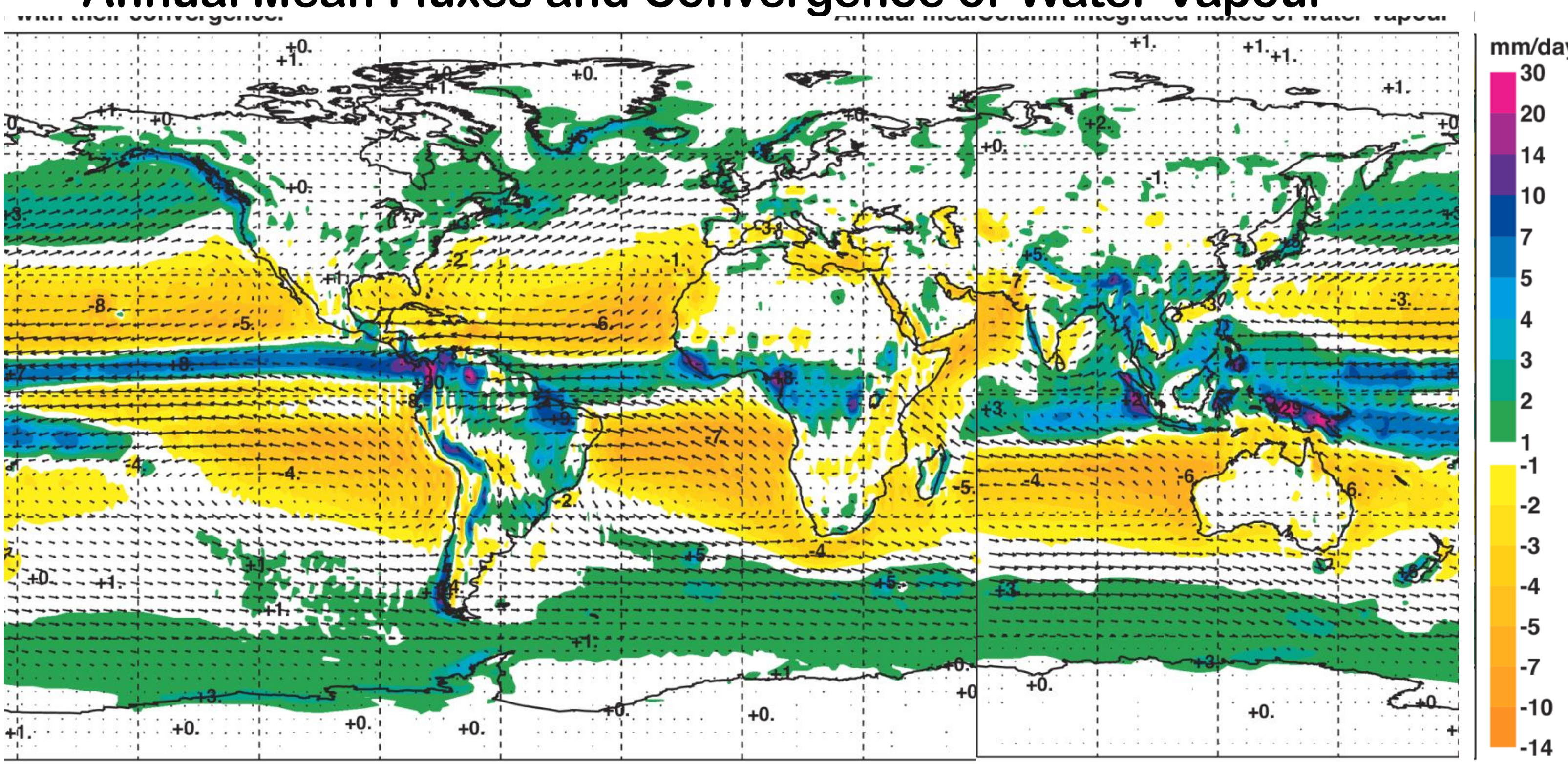


- •Sub-tropics are source of moisture for the global hydrological cycle
- •Atlantic exports moisture to the Pacific

Atmospheric Hydrological Cycle

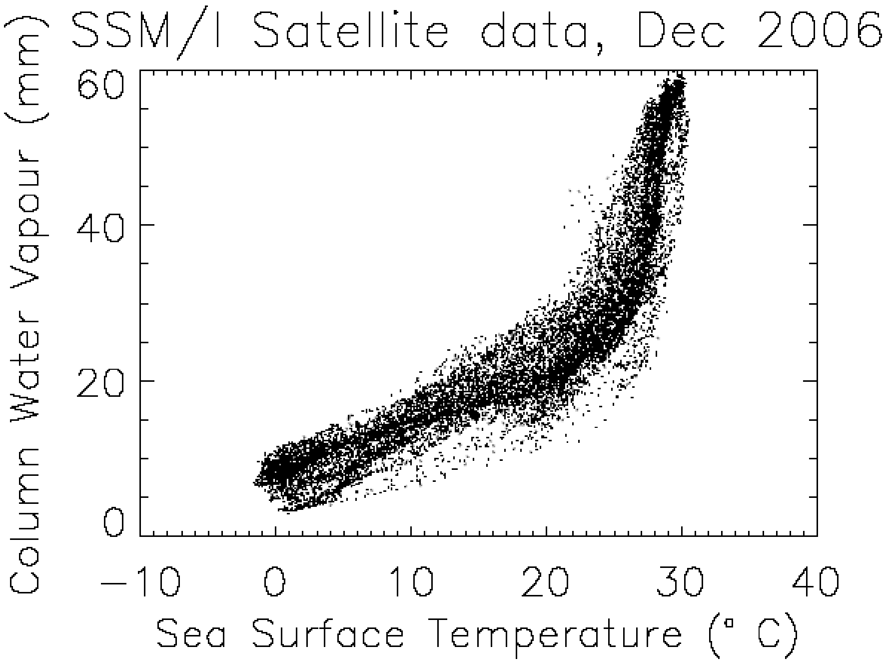
Precipitation = Surface Evaporation + Atmospheric Transport

Annual Mean Fluxes and Convergence of Water Vapour



- In the tropics, mean meridional circulation (i.e. Hadley cell) provides major equatorward transport in the lower troposphere
- In mid-latitudes, transient eddies provide the poleward transport

THE ROLE OF WATER VAPOUR

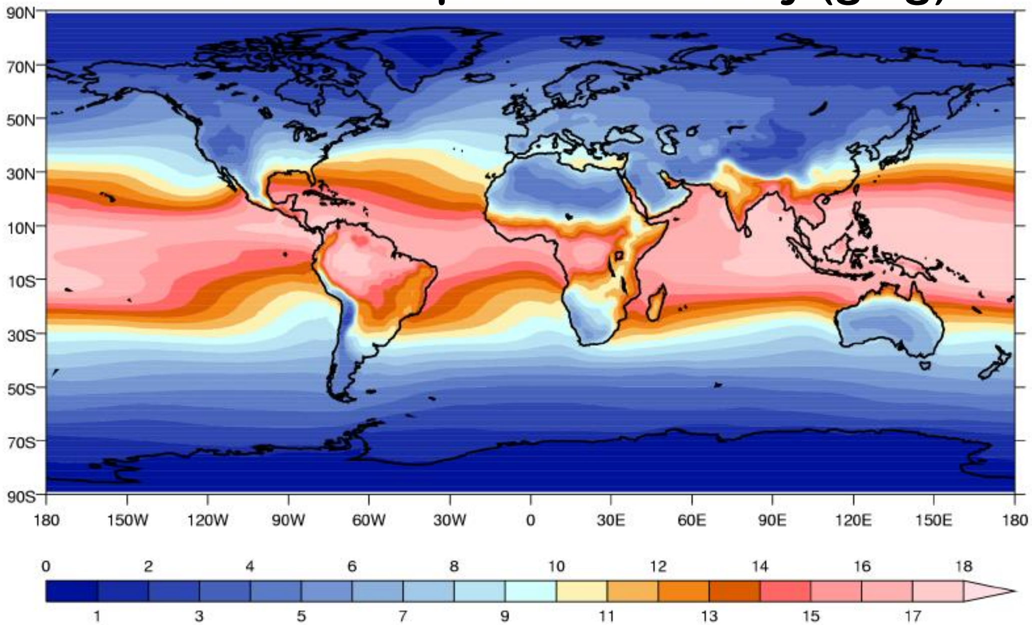


$$\frac{1}{e_s}\frac{de_s}{dT} = \frac{L}{R_v T^2} = \begin{cases} 0.14K^{-1} & T = 200K \\ 0.07K^{-1} & T = 273K \\ 0.06K^{-1} & T = 300K \end{cases}$$

- Physics: Clausius-Clapeyron
  - Relates saturated water vapour pressure to temperature
  - Fundamental control on the atmospheric hydrological cycle
- Low-level saturation vapour pressure increases with atmospheric warming at about 6-7%/K

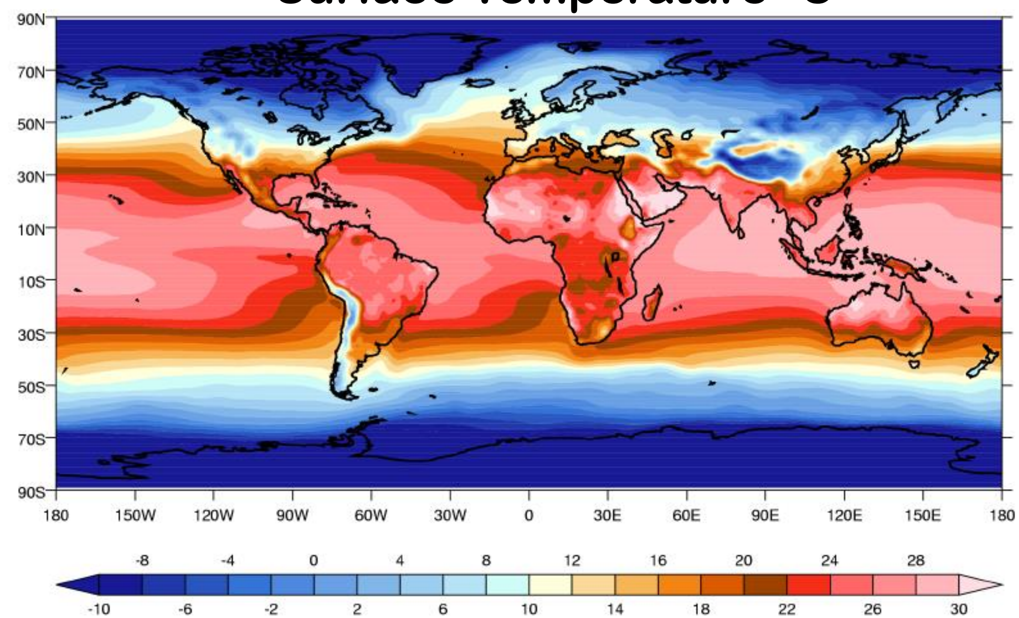
See also Allan (2012) Surv. Geophys

Near Surface specific humidity (g/kg)



Clausius-Clapeyron relationship and global distribution of water vapour

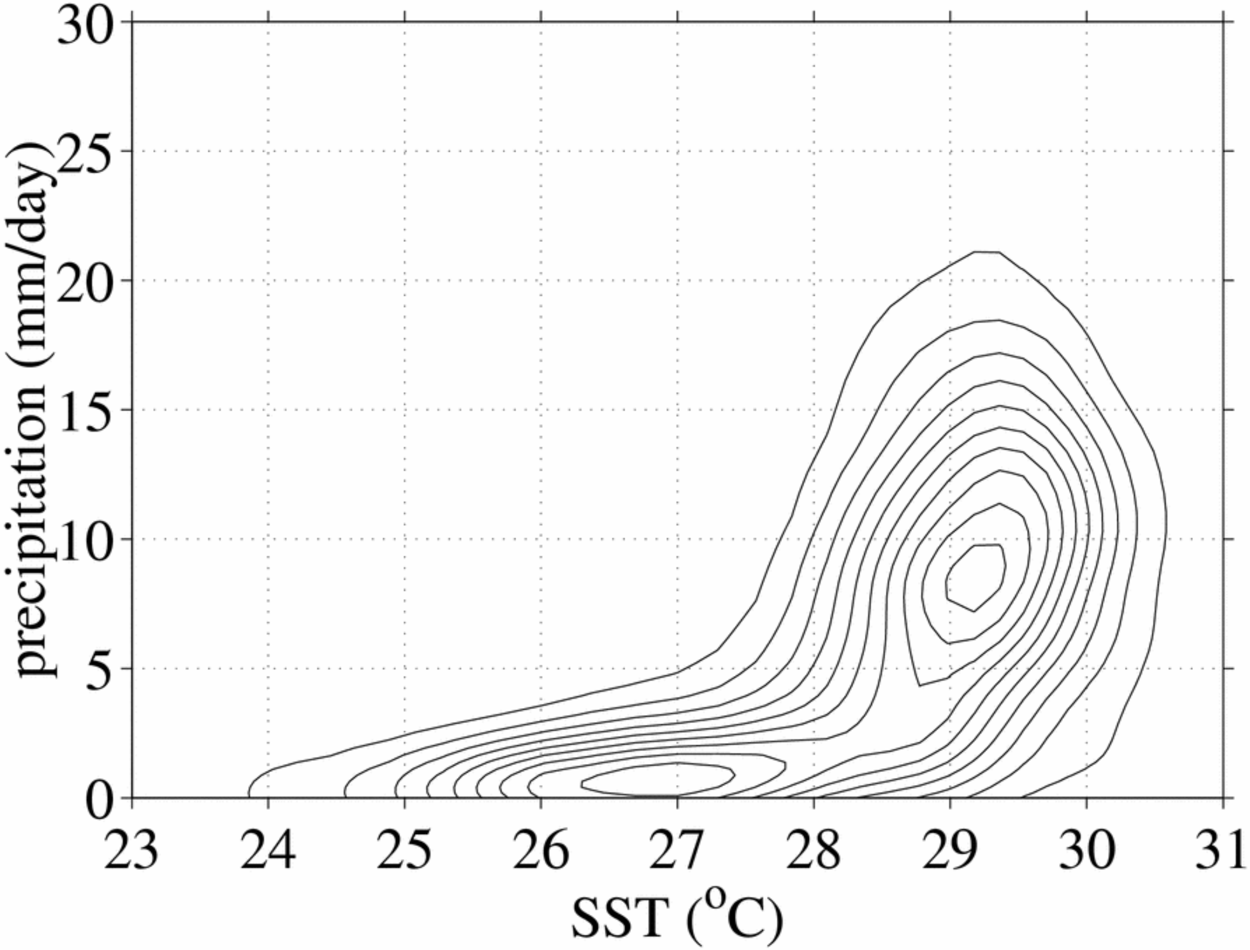
Surface Temperature ^{0}C



- Over oceans, where water is freely available, surface humidity follows surface temperature very closely.

- Over land, surface humidity is strongly controlled by soil moisture availability.

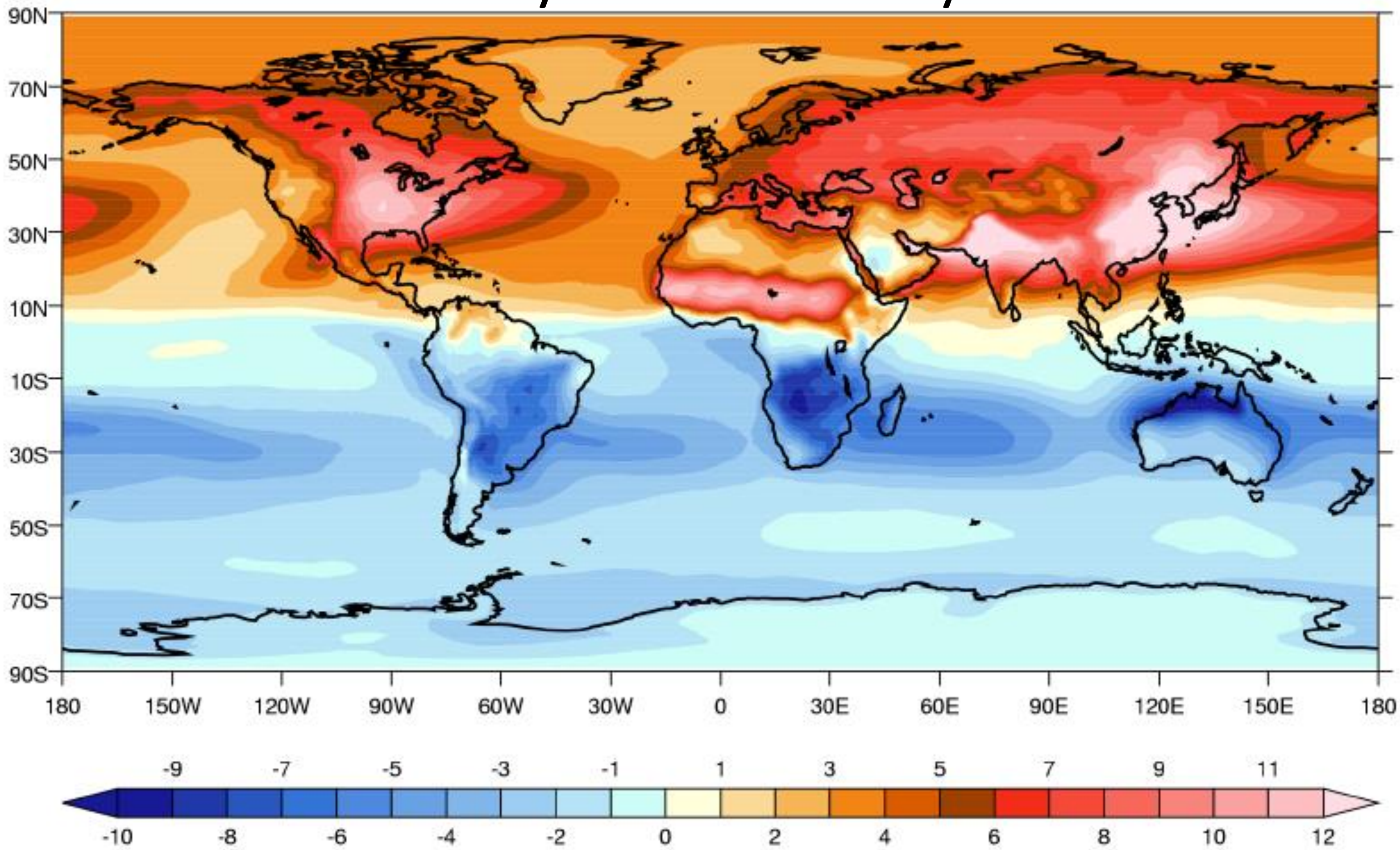
Clausius-Clapeyron relationship also influences precipitation rates, especially over the tropical oceans



Observed probability distribution function (PDF) of monthly mean Sea Surface Temperature (SST) and precipitation over the tropical Pacific for Dec.–Feb.

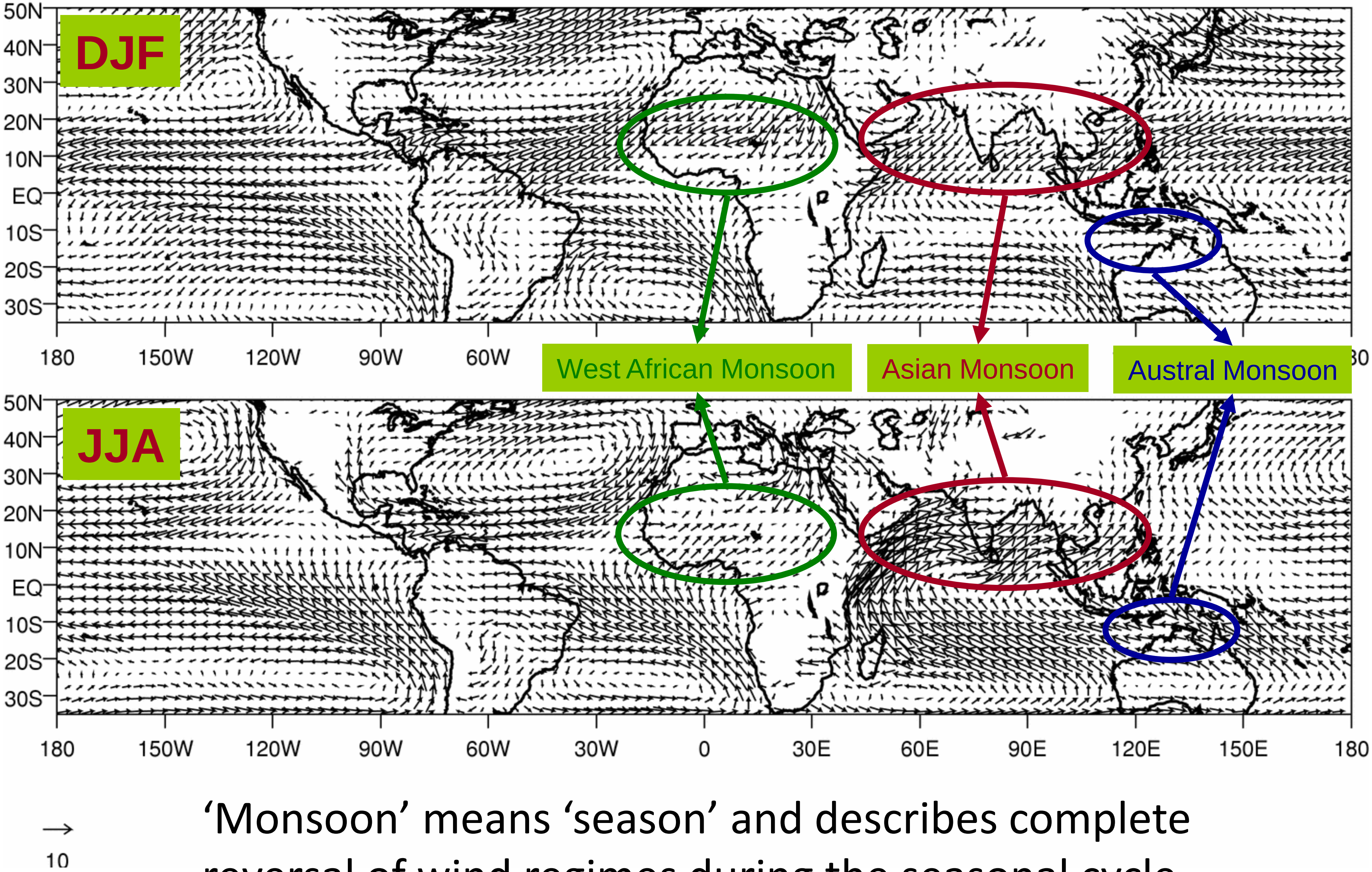
Seasonal variation in surface humidity:

July minus January



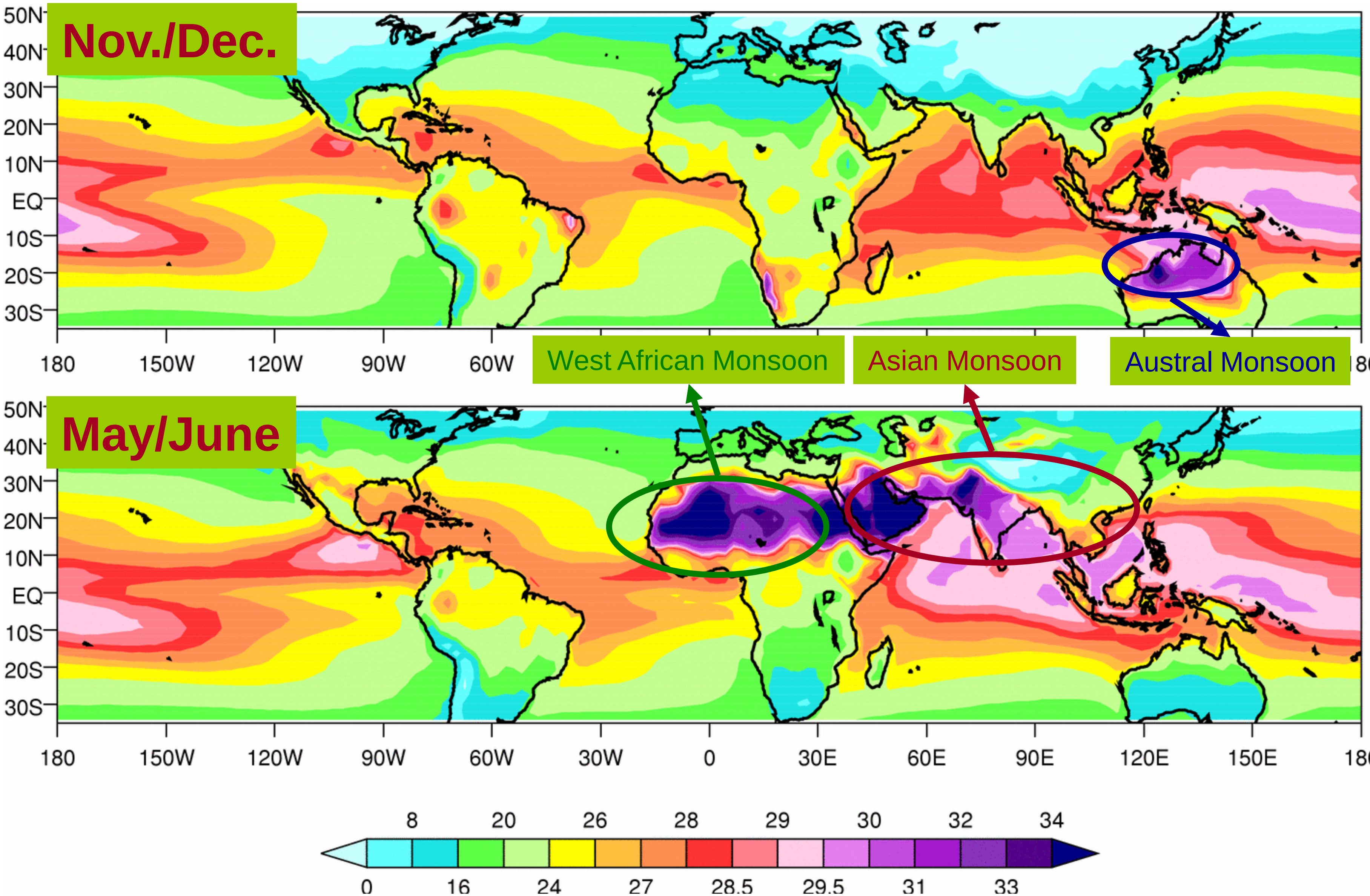
- Why are variations larger over land than ocean ?
- Why are largest variations over India/China and Sahel?

Monsoons: Winds at 925hPa

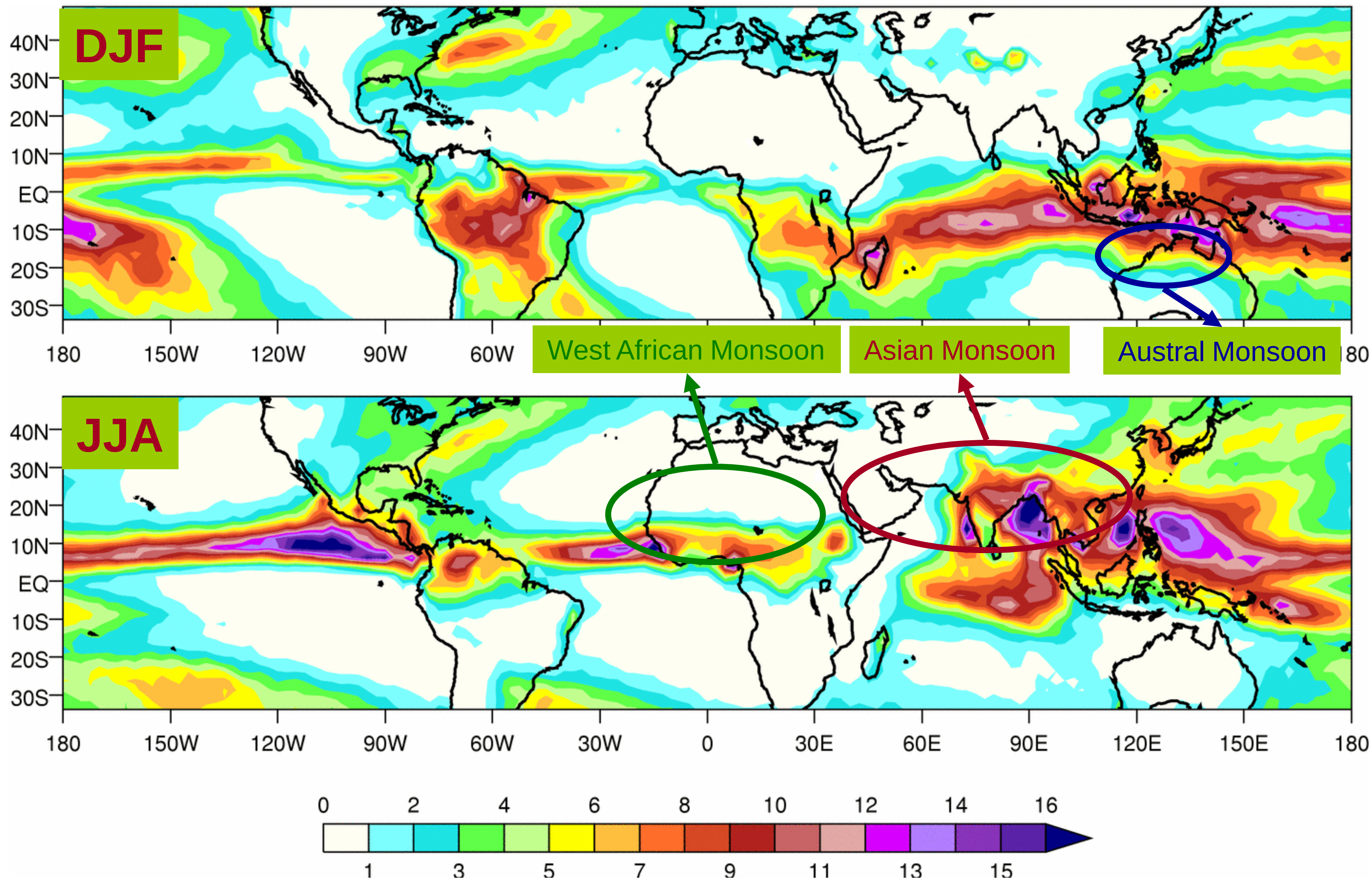


'Monsoon' means 'season' and describes complete reversal of wind regimes during the seasonal cycle

Monsoons: Land/Sea Temperature contrasts

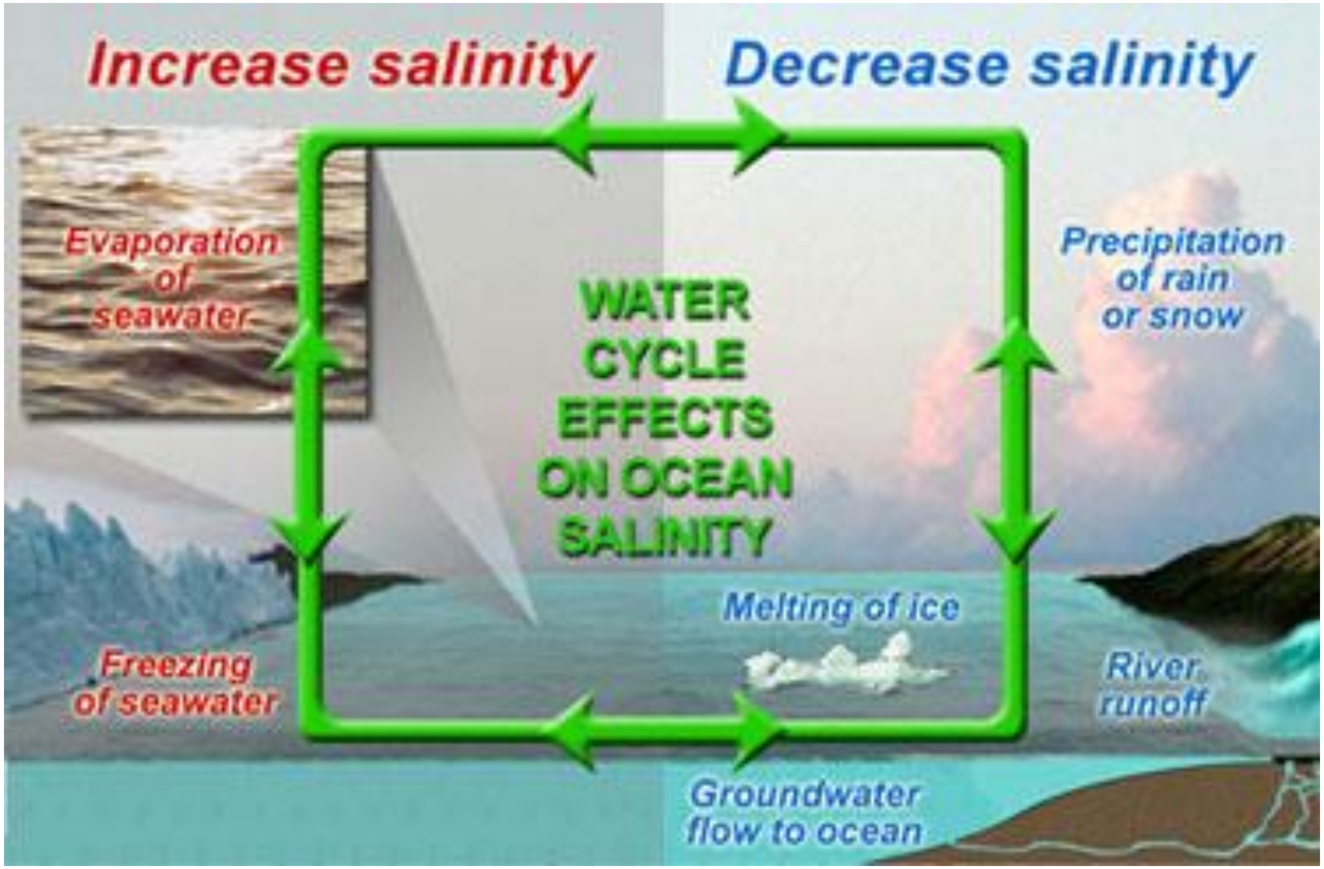


Monsoons: Rainfall (mm/day)



Ocean Water Cycle

- Controls Surface Salinity and Temperature, hence water density.
- Changes in water density drive ocean mixing and deep circulations



Annual Mean Sea Surface Salinity

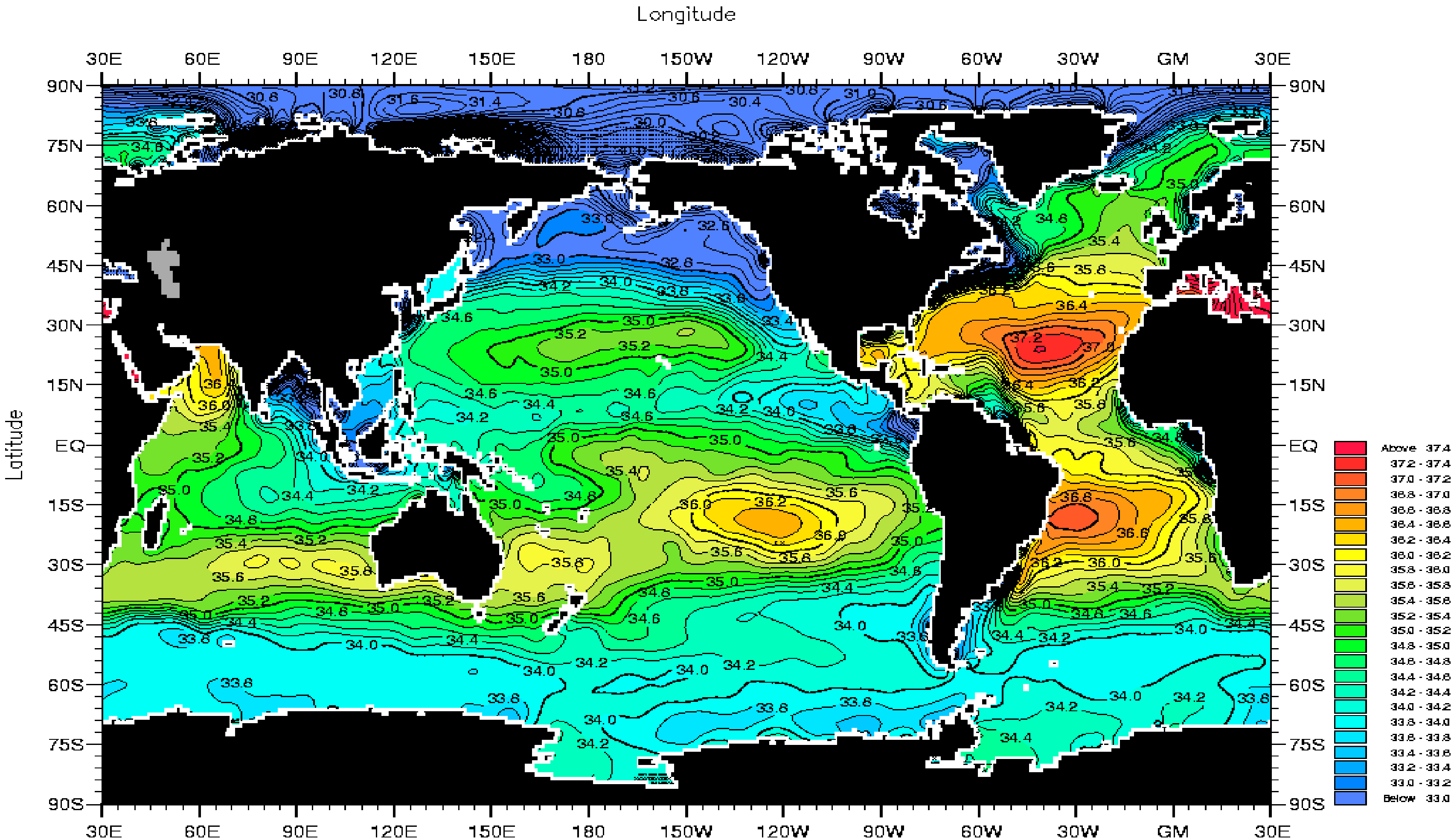
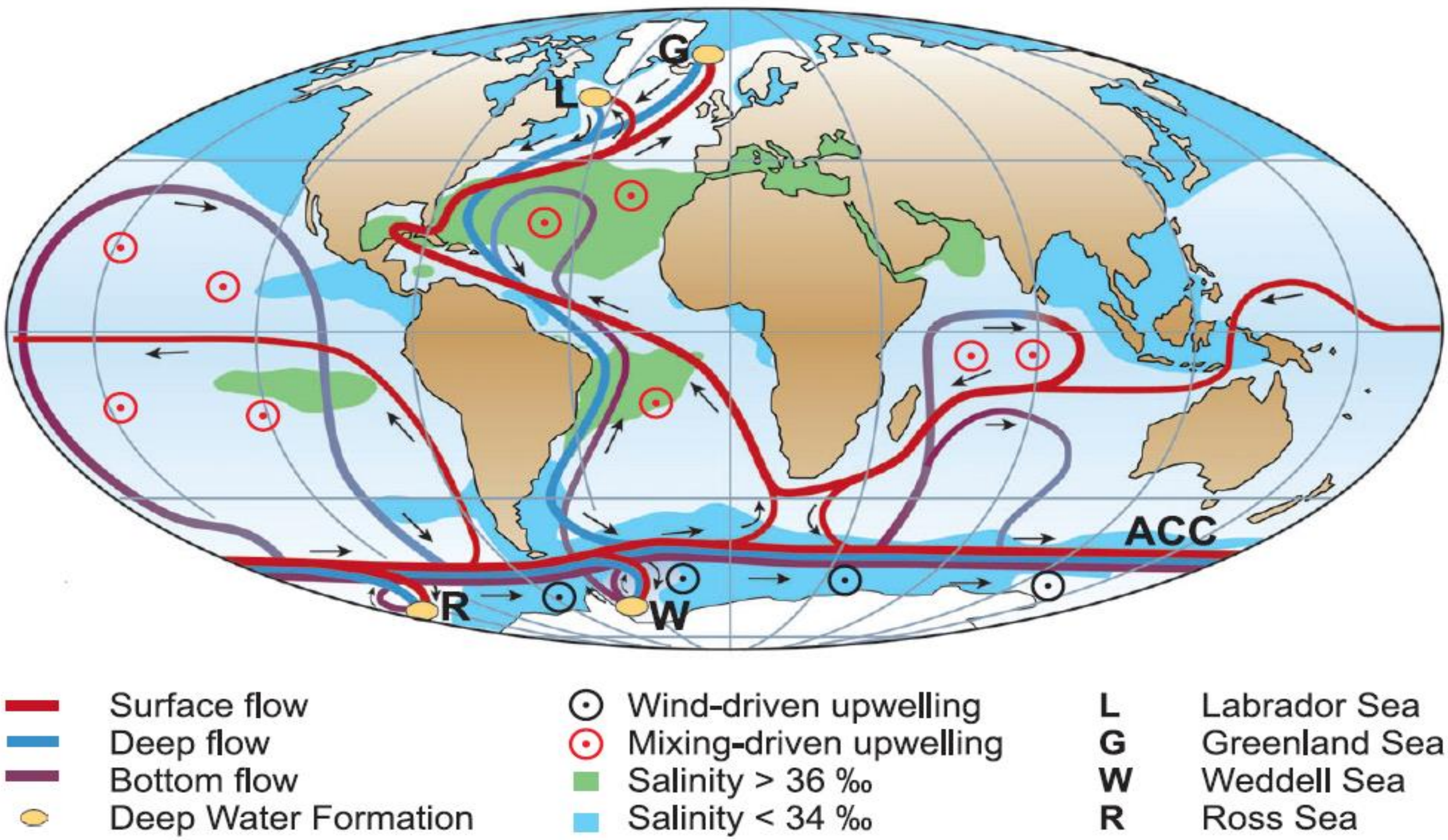


Fig. A2-1. Annual mean salinity (PSS) at the surface .

Minimum Value= 3.57 Maximum Value= 40.02 Contour Interval: 0.20

- Strongly reflects Precipitation minus Evaporation
- Note much higher salinity in Atlantic

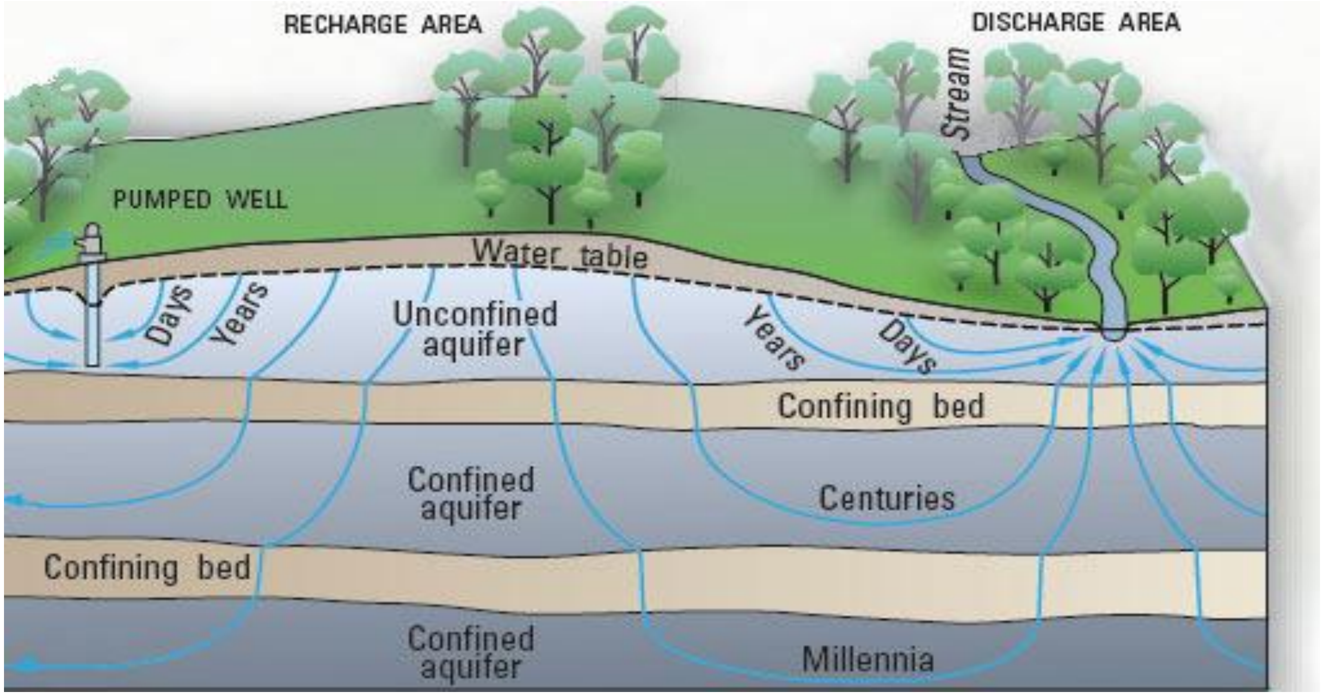
Global Thermohaline Circulation



From S. Rahmstorf: Thermohaline Ocean Circulation. In: *Encyclopedia of QuaternarySciences*, Edited by S. A. Elias. Elsevier, Amsterdam 2006 (see **www.pik-potsdam.de/~stefan/thc_fact_sheet.html**)

Terrestrial Water Cycle

Storage = P – E – R_o(Surface run-off) – R_u(Subterranean run-off)



- Operates on a vast range of timescales and space scales
- Terrestrial biosphere interacts with the water cycle by:
    - Extracting water from the soils
    - Returning water to the atmosphere through evapo-transpiration
- Water extraction is significantly altering the terrestrial water balance

Soil Moisture and the Surface Energy Budget

Soil water availability strongly influences the surface energy budget by determining the partitioning between surface sensible (H) and latent (LE) heat fluxes.

Surface Energy Budget:

$$\frac{\partial T_s}{\partial t} = \frac{1}{C}\left(S_{net} - L_{net}(T_s) - H(T_s) - LE(\alpha) - G\right)$$

where T_s is surface temperature, S_{net} is net solar radiation, L_{net} is net longwave radiation and G is ground heat flux, C is heat capacity

Bowen Ratio (β) is widely used to describe the influence of soil moisture on surface fluxes and hence temperature:

$$\beta = \frac{H}{LE}$$

Constraints on evaporation

- Energy & precipitation (P) constraints on evaporation (E)

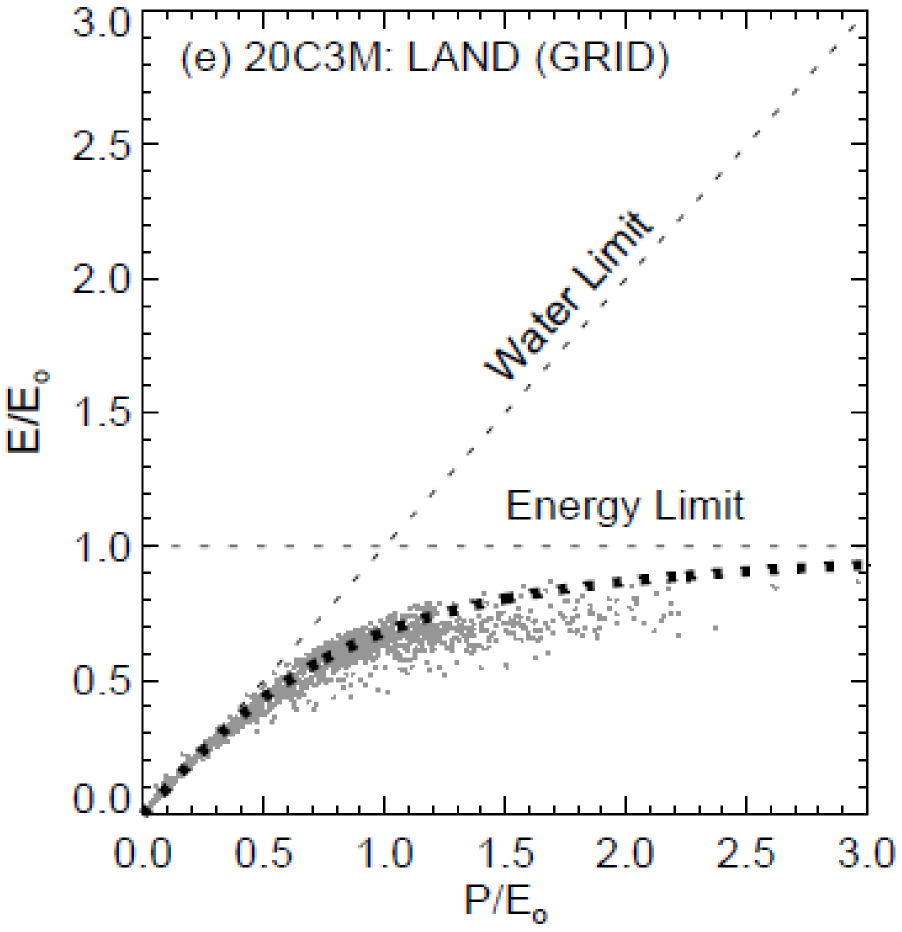
$$E = \frac{P\,E_o}{\left(P^n + E_o^n\right)^{1/n}}$$

Budyko Framework

- **E_o** is maximum theoretical evaporation (E is energy limited)
- **E** is also limited by water availability (determined by P)
- **n** is a catchment-specific parameter

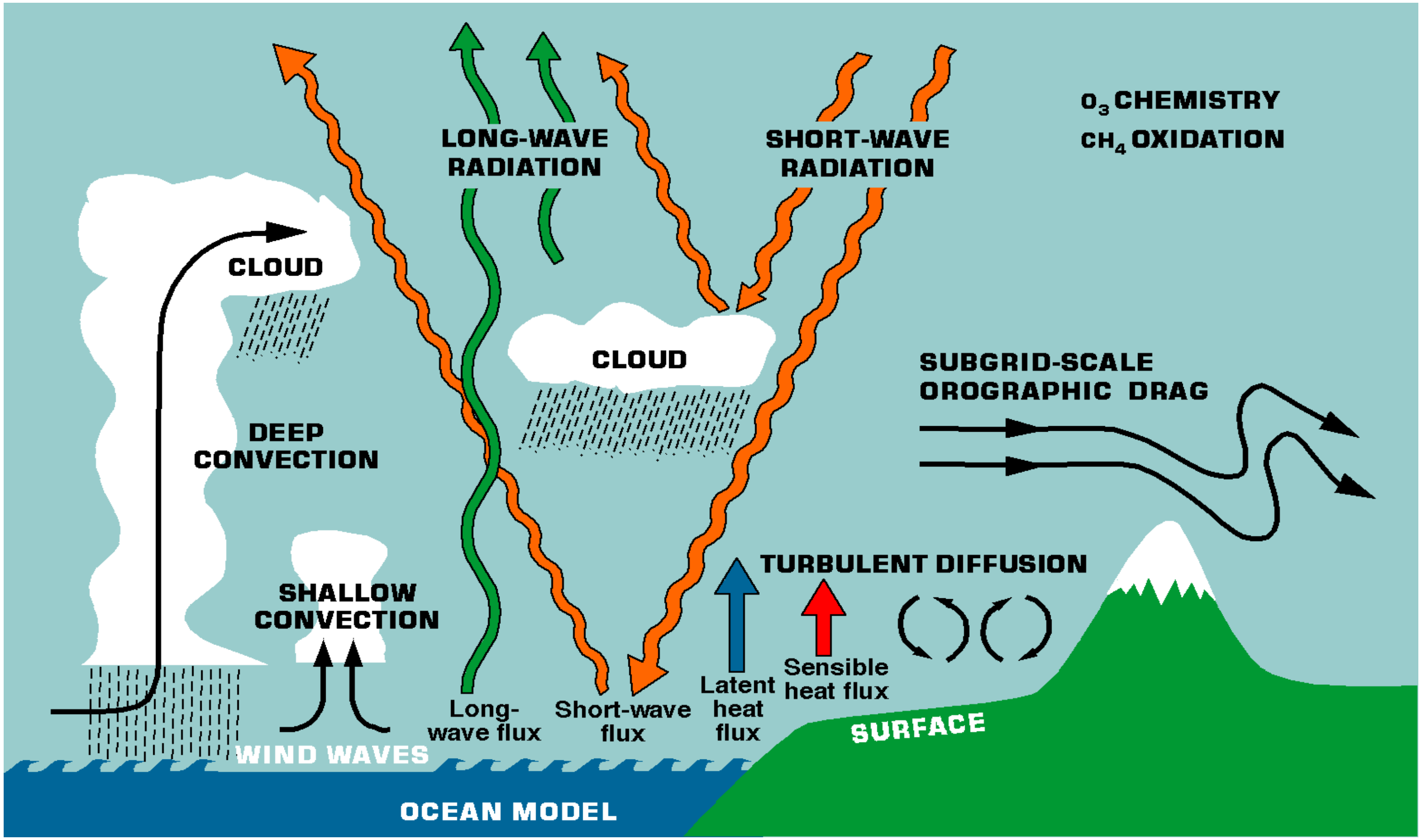
If $P \gg E_o$, $E \rightarrow E_o$

If $E_o \gg P$, $E \rightarrow P$



Roderick et al. (2014) HESS

Representing the Water Cycle in Models

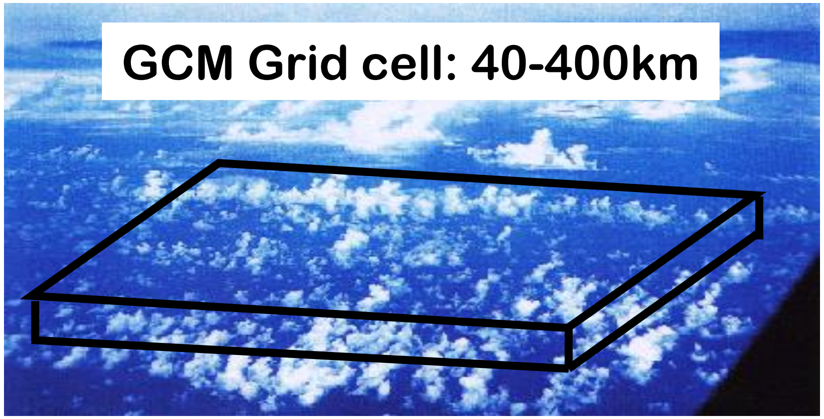


Phase changes of water (evaporation, condensation, freezing and sublimation) all operate at the sub-gridscale and hence need to be parametrized.

Cloud and Precipitation Processes

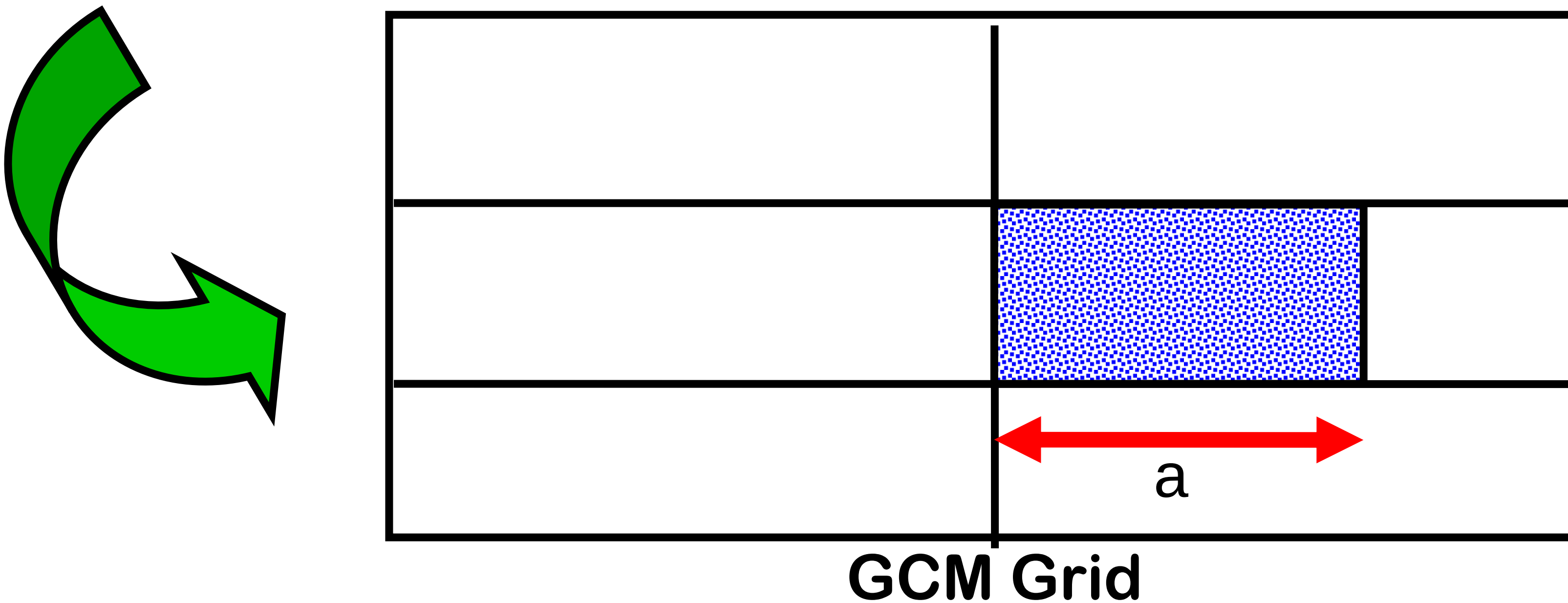
- We need to include in models:
  - Formation of clouds
  - Release of precipitation
  - Evaporation of both clouds and precipitation
- Therefore we need to describe:
  - change of phase from water vapour to water droplets and ice crystals
  - transformation of small cloud droplets/ice crystals to larger rain drops/ice particles
  - advection and sedimentation/falling of these species
  - evaporation/sublimation of cloud and precipitation size particles

Deciding how much cloud



Most schemes presume cloud fills GCM box in vertical

Still need to represent horizontal cloud cover: **a**



From Tompkins, ECMWF Training Course

Some assumptions regarding cloud formation

q_v = water vapour mixing ratio
q_c = cloud water (liquid/ice) mixing ratio
q_s = saturation mixing ratio = F(T,p)
q_t = total water (vapour+cloud) mixing ratio
RH = relative humidity = q_v/q_s

(#1) Local criterion for formation of cloud: $q_t > q_s$

This assumes that no supersaturation can exist

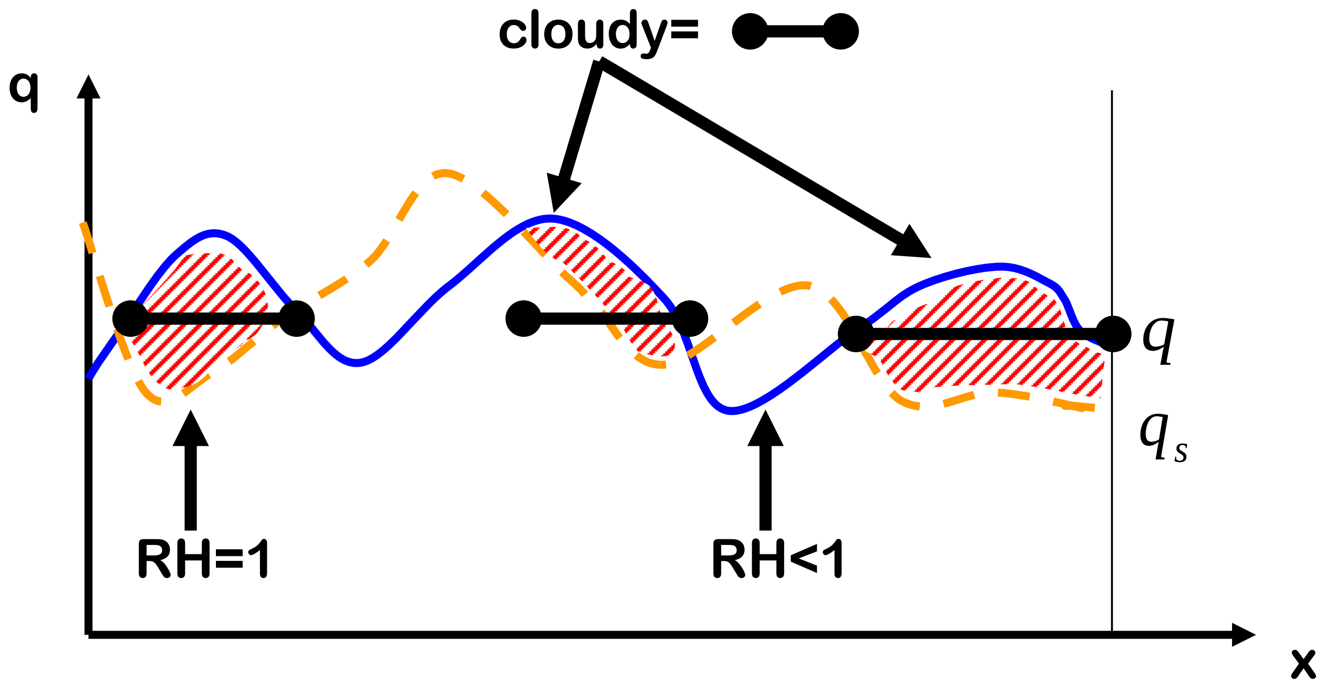
(#2) Condensation process is fast (cf. GCM timestep)

$$q_v = q_s,\ q_c = q_t - q_s$$

From Tompkins, ECMWF Training Course

Partial cloud cover

Partial coverage of a grid-box with clouds is only possible if there is a inhomogeneous distribution of temperature and/or humidity.

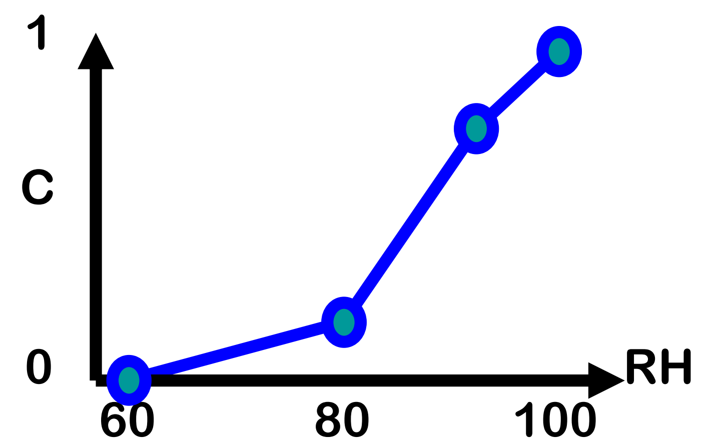


Another implication of the above is that clouds must exist before the grid-mean relative humidity reaches 1.

From Tompkins, ECMWF Training Course

Simple Diagnostic Schemes: Relative Humidity Schemes

- Many schemes, from the 1970s onwards, based cloud cover on the relative humidity (RH)
- e.g. Sundqvist et al. MWR 1989:



$$C = 1 - \sqrt{\frac{1 - RH}{1 - RH_{crit}}}$$

RH_{crit} = critical relative humidity at which cloud assumed to form (function of height, typical value is 60-80%)

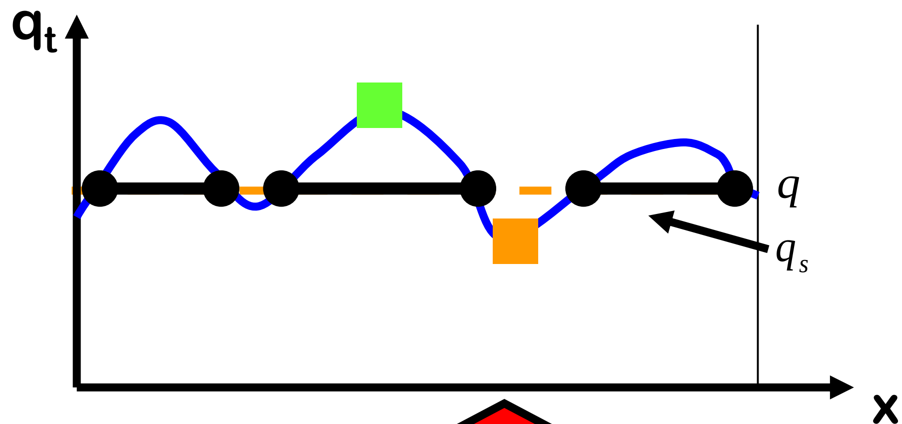
From Tompkins, ECMWF Training Course

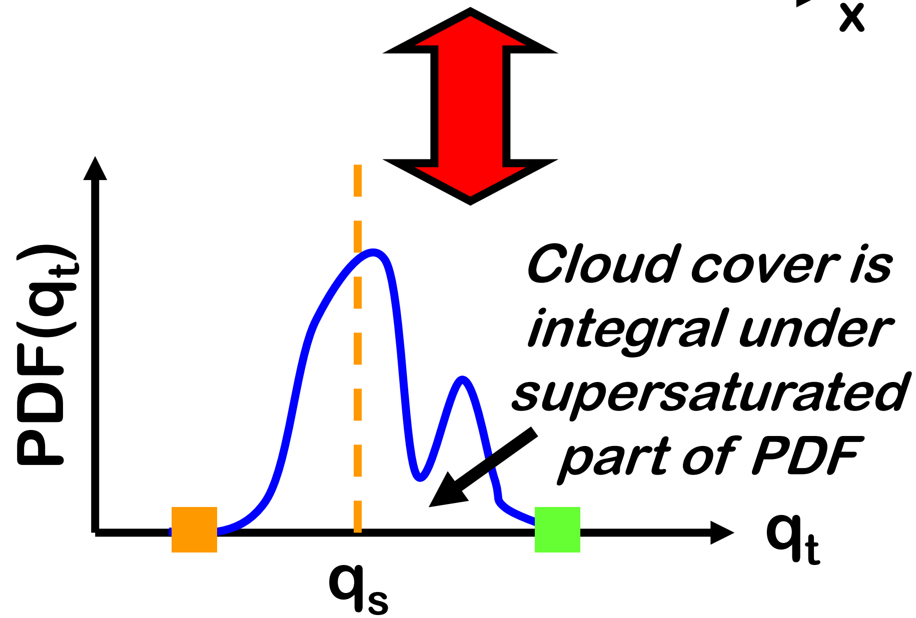
Statistical Schemes

- These explicitly specify the probability density function (PDF) for the total water q_t (and sometimes also temperature)

$$C = \int_{q_s}^{\infty} PDF(q_t)\,dq_t$$

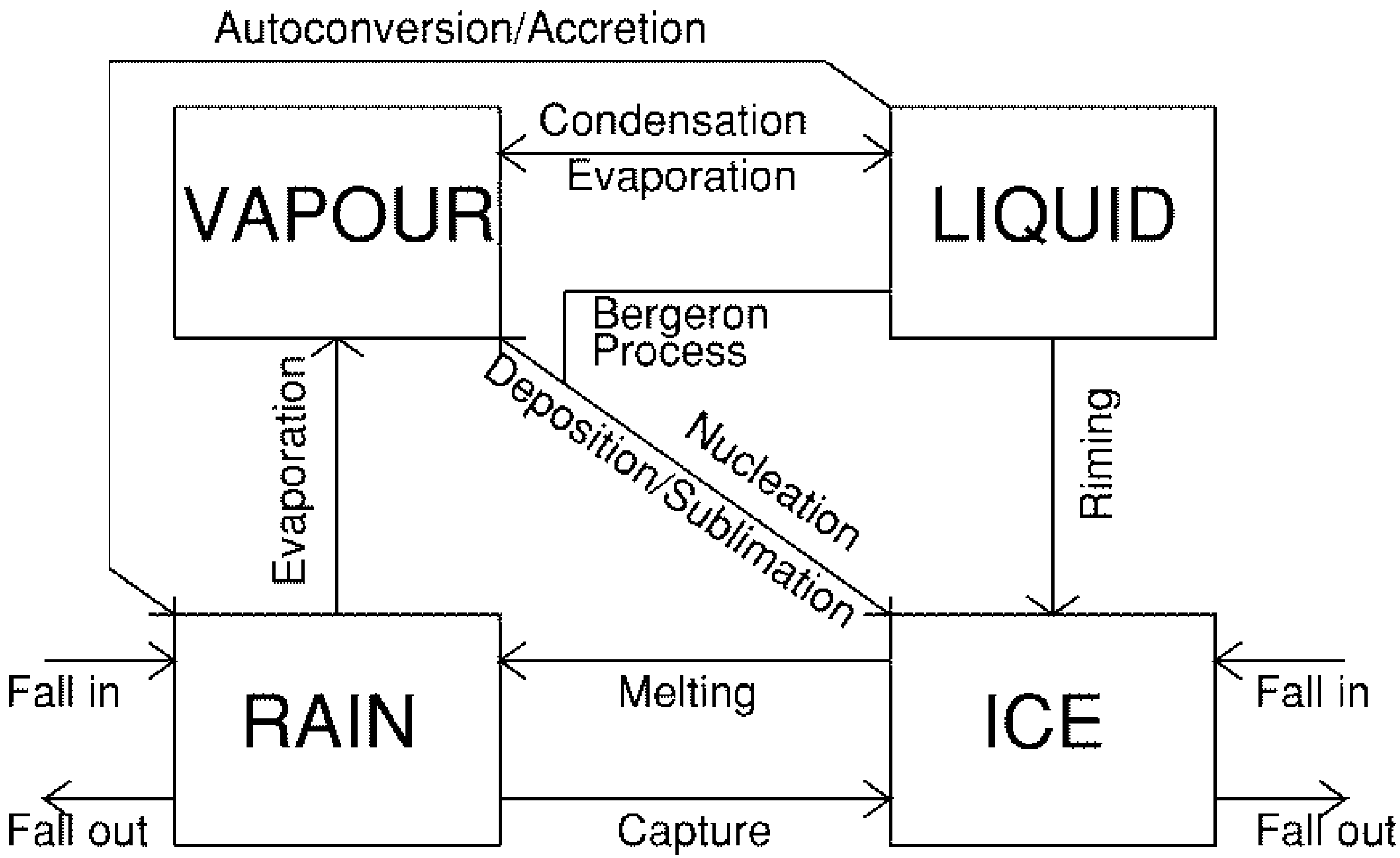
$$q_c = \int_{q_s}^{\infty} (q_t - q_s)\,PDF(q_t)\,dq_t$$





From Tompkins, ECMWF Training Course

Unified Model cloud microphysics scheme



It is here that some of the major uncertainties in climate sensitivity arise


Convection
Much more in following lecture by Alison Sterling

Radiative-convective equilibrium

If we assume that only radiative processes are operating, the equilibrium surface temperature is very high, tropospheric temperatures very low and the profile is strongly superadiabatic*.

In reality, convection removes heat from the surface, warms the atmosphere and adjusts the lapse-rate towards that observed#.

From the classic paper by [Manabe and Wetherald, JAS, 1967]

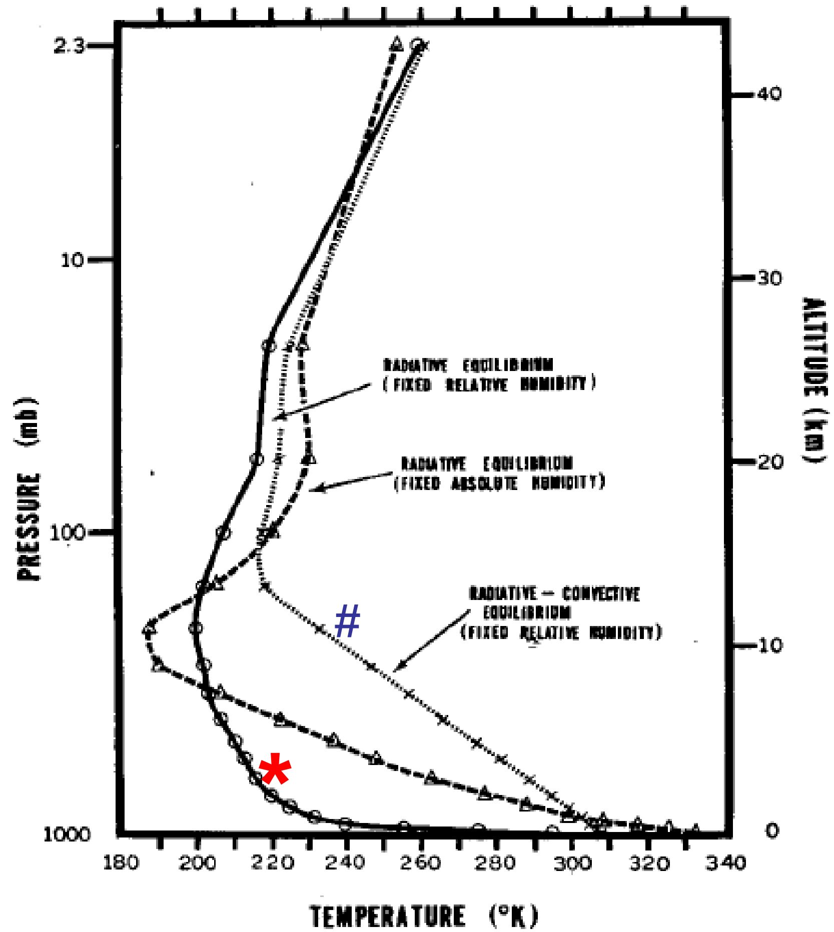


FIG. 5. Solid line, radiative equilibrium of the clear atmosphere with the given distribution of relative humidity; dashed line, radiative equilibrium of the clear atmosphere with the given distribution of absolute humidity; dotted line, radiative convective equilibrium of the atmosphere with the given distribution of relative humidity.

What is convection doing, where does it occur

- Convection transports heat, water vapour, momentum … and chemical constituents upwards …. Water vapour then condenses and falls out → net convective heating/drying
- Deep Convection (precipitating convection) stabilizes the environment; shallow convection redistributes the surface fluxes
- The tropical atmosphere is in radiative(cooling) / convective(heating) equilibrium: 2K/day cooling in lowest 15 km corresponds to about 5 mm/day precipitation.
- The effect of convection (local heat source) is fundamentally different in the midlatitudes and the Tropics.
- In the Tropics the Rossby radius of deformation R=NH/f is ~ infinite, and therefore the effects are not locally bounded, but spread globally via gravity waves – "throwing a stone in a lake"

From Bechtold, ECMWF Training Course

Convection schemes attempt to represent the effects of a family of individual clouds on the environment

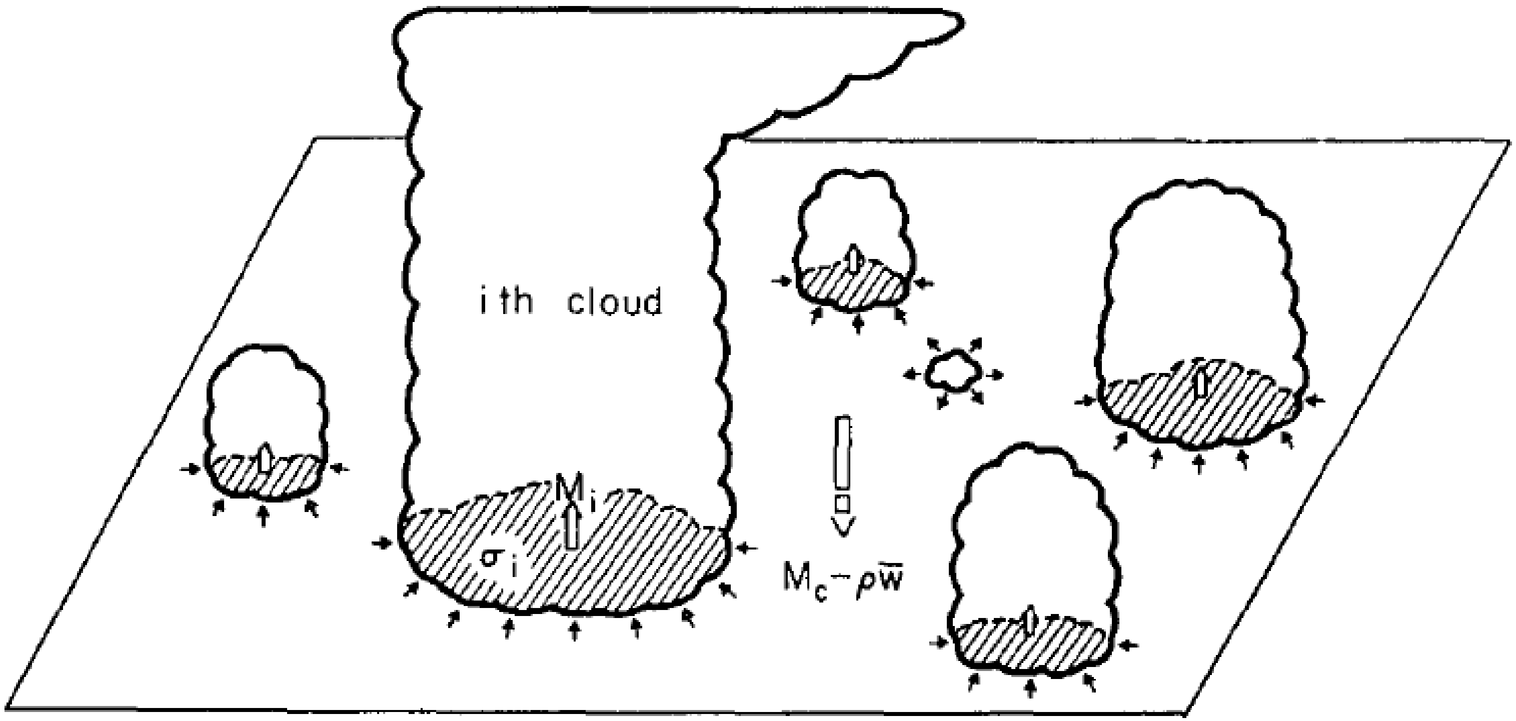


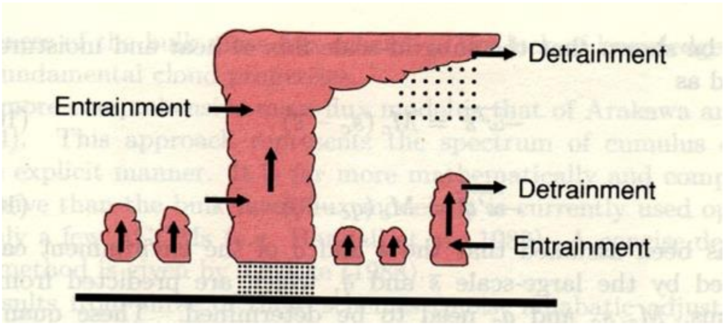
FIG. 1. A unit horizontal area at some level between cloud base and the highest cloud top. The taller clouds are shown penetrating this level and entraining environmental air. A cloud which has lost buoyancy is shown detraining cloud air into the environment.

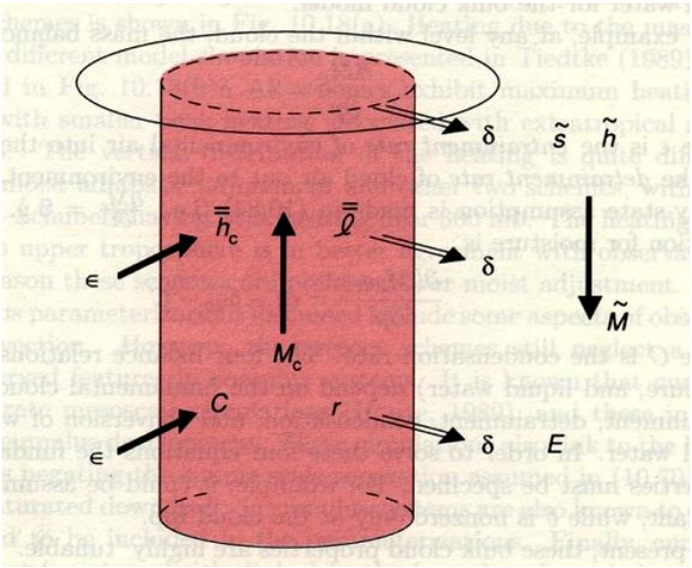
Arakawa and Schubert (1974)

Task of the (Penetrative) Convection scheme

To calculate the collective effects of an ensemble of convective clouds in a model column as a function of grid-scale variables.

Hence parameterization needs to describe Condensation/Evaporation and Transport of T, q and (often) momentum

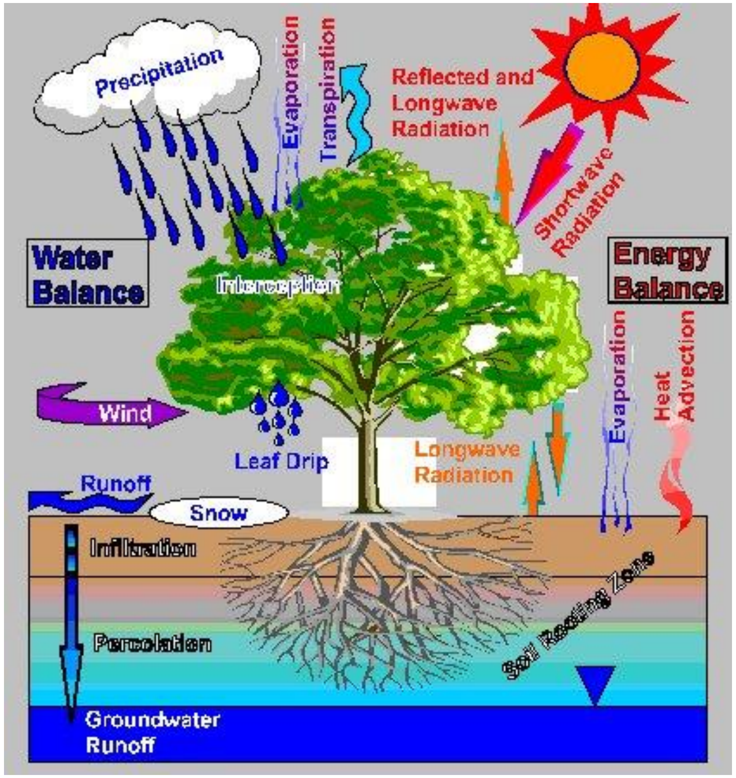




Most models treat shallow (non-precipitating) convection as a separate process

From Bechtold, ECMWF Training Course

Representing Surface processes



Surface schemes are needed to:

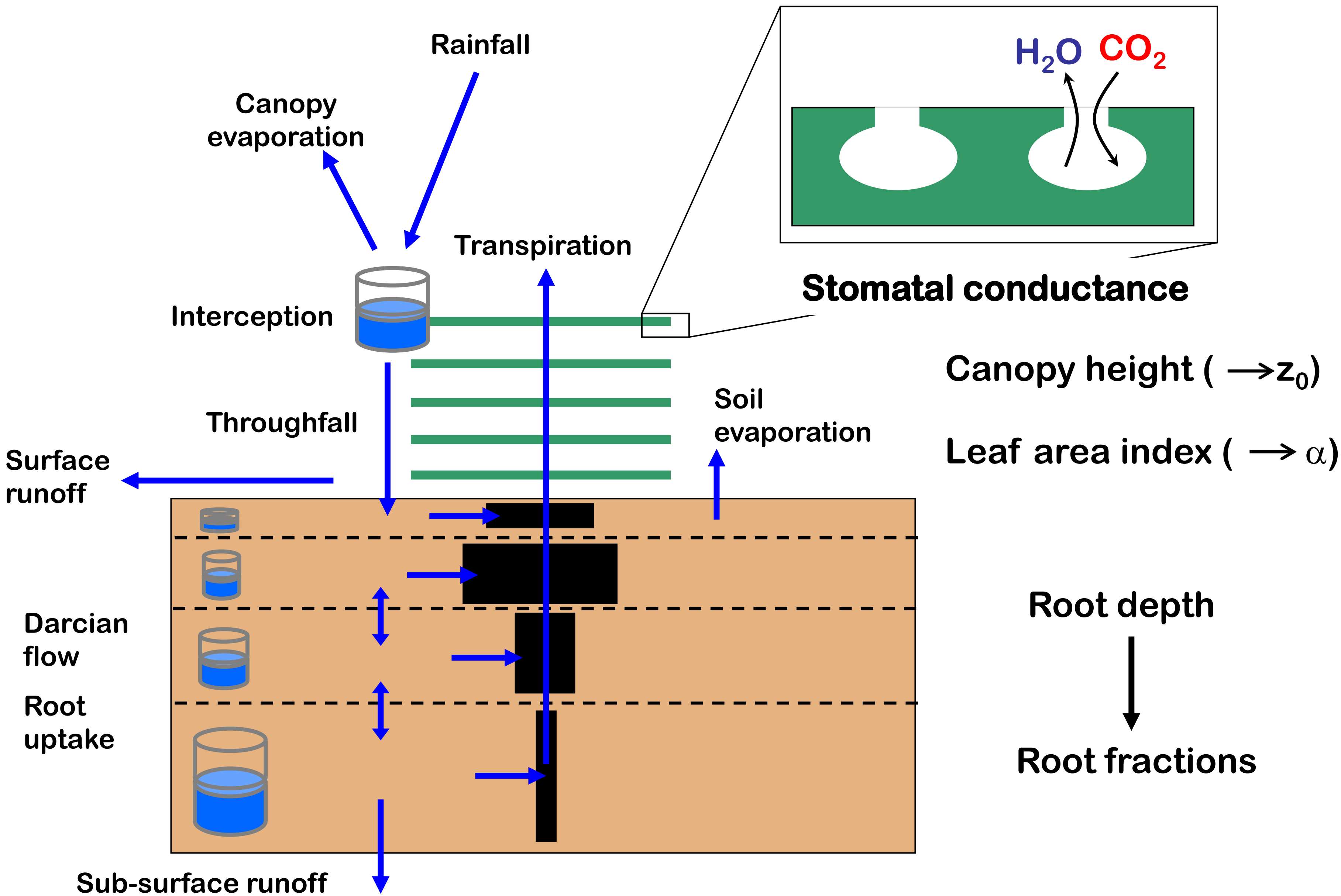
1. Calculate the fluxes of heat, moisture and momentum between the surface and atmosphere

2. Calculate surface temperature and other variables

- Over the oceans, the schemes are quite simple

•Over land, models now contain quite detailed representations of evaporation, interception and *vertical* transfers of heat and moisture in the soil

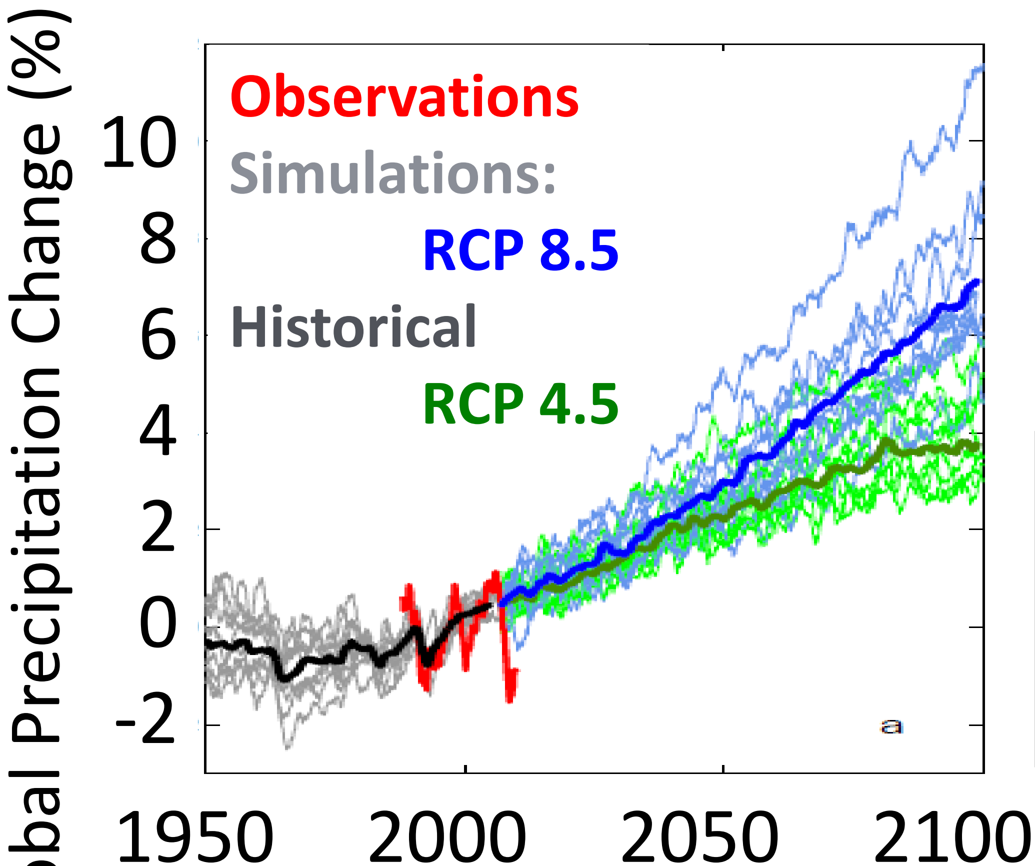
Modelling the land surface and the terrestrial water cycle



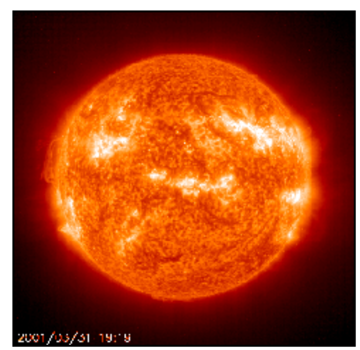
Why the Water Cycle is at the heart of climate change

- Potential acceleration of the hydrological cycle has implications for the incidence of extreme events.
- Regional changes in mean precipitation patterns have implications for desertification, flooding.
- Changes in the partitioning between fresh and salty water (e.g. melting ice-caps, river water extraction, accelerated hydrological cycle from global warming) could have major consequences for the Earth System.
- Impacts of climate variability and change on natural ecosystems directly involve precipitation.
- The impacts of climate change and variability on the quality of human life occur primarily through changes in the water cycle.
- Water availability and water quality are fundamental issues for the 21st century.

HOW WILL GLOBAL PRECIPITATION RESPOND TO CLIMATE CHANGE?



Allan et al. (2014) Surv. Geophys



CHANGING WATER CYCLE

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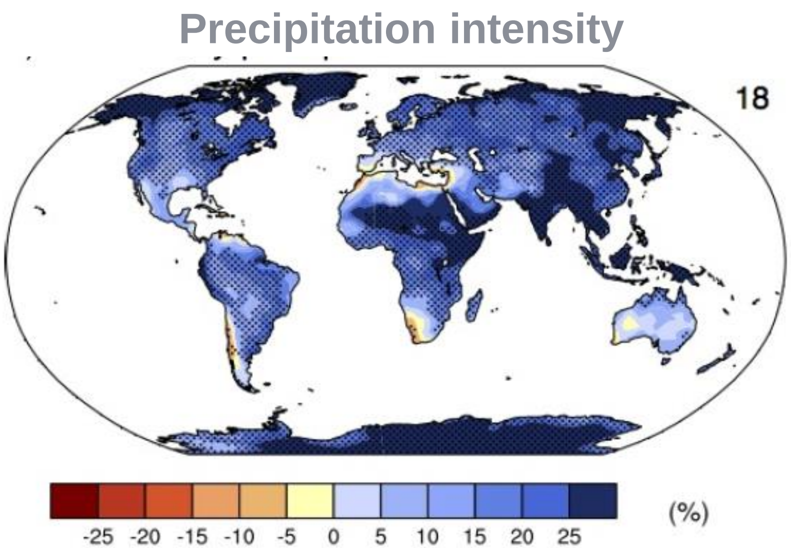
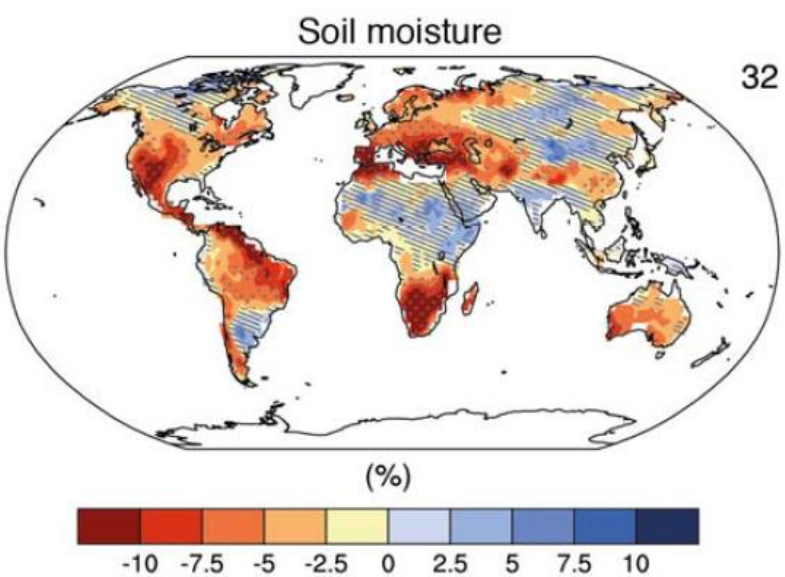
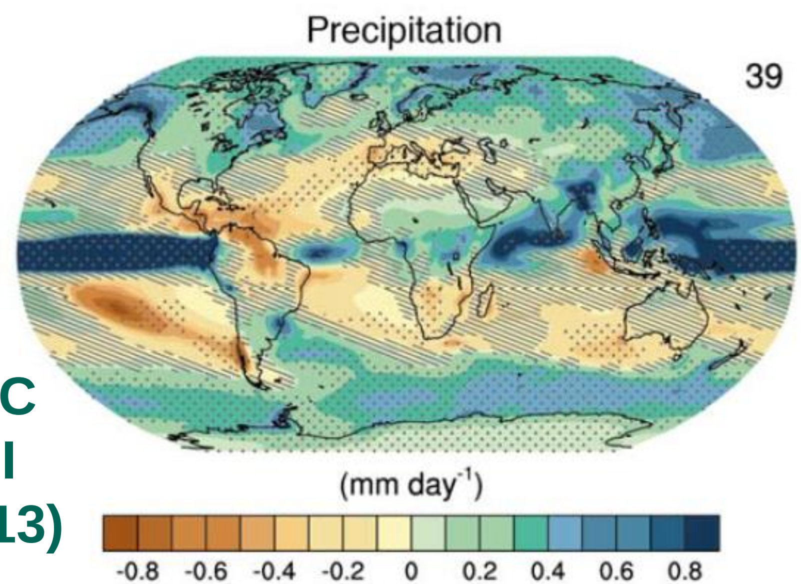


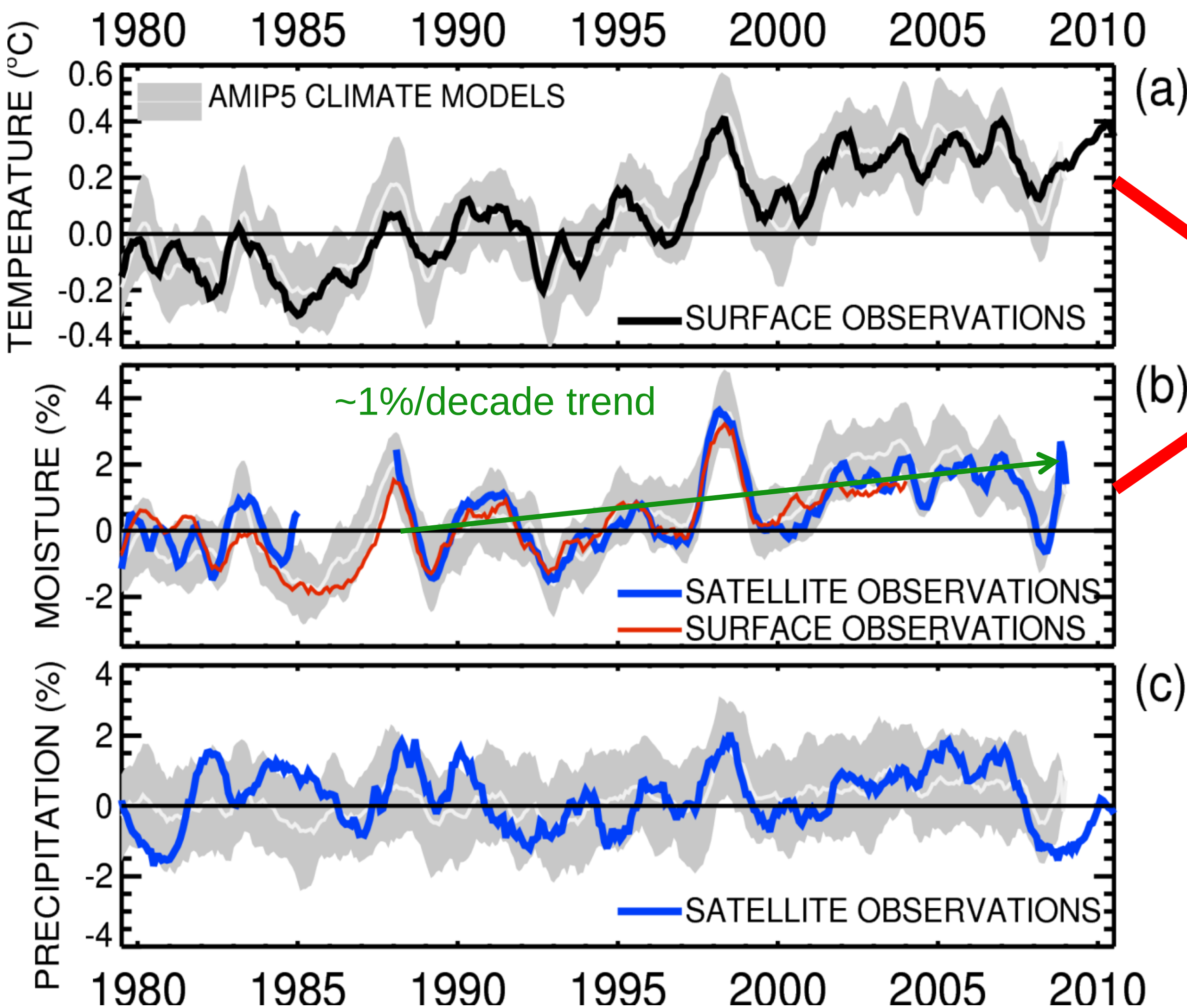


- Increased Precipitation
- More Intense Rainfall
- More droughts
- Wet regions get wetter, dry regions get drier?
- Regional projections??



IPCC WGI (2013)

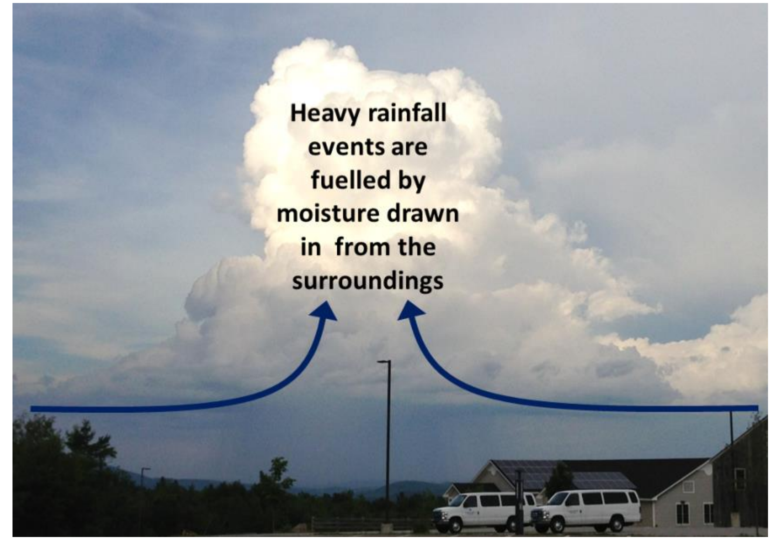
MONITORING CHANGES IN THE GLOBAL WATER CYCLE



Water vapour increases by around 7% for each degree C of warming.

Adapted from:
Allan et al. (2014) Surv. Geophys

Extreme Precipitation



- Moisture convergence fuels large-scale rainfall events

e.g. *Trenberth et al. (2003) BAMS*

- Intensification of rainfall with warming

e.g. Allan & Soden (2008) Science

- Amplifying latent heat feedbacks?

e.g. *Berg et al. (2013) Nature Geo*

- Time/space scale important
- Observational constraints? →

e.g. *O'Gorman (2012) Nature Geosci*; Liu & Allan (2012) JGR

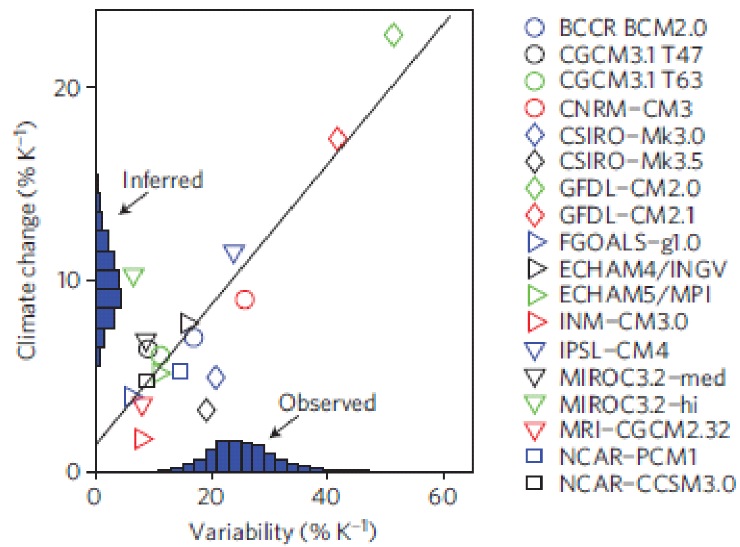
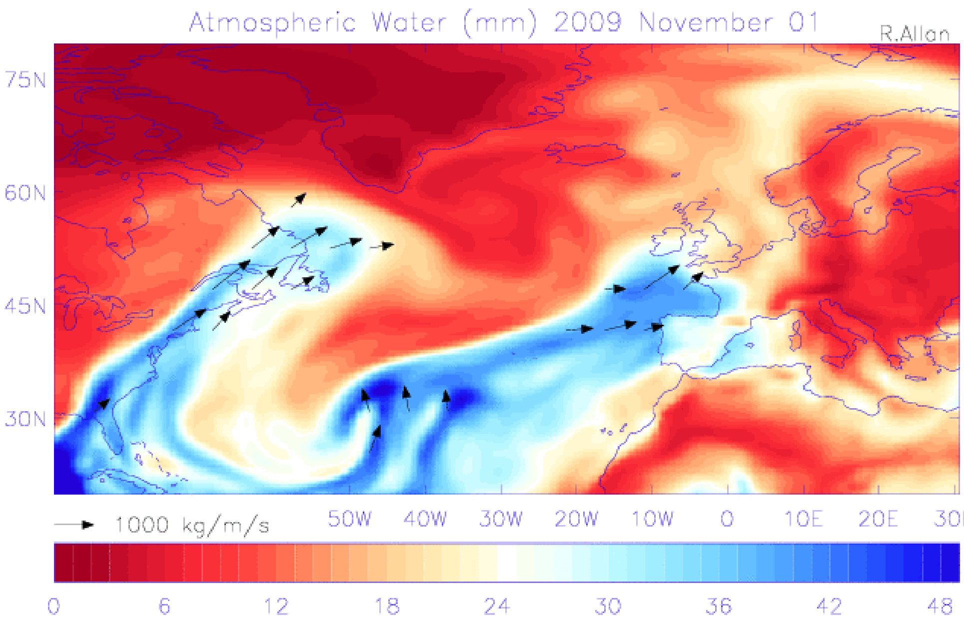


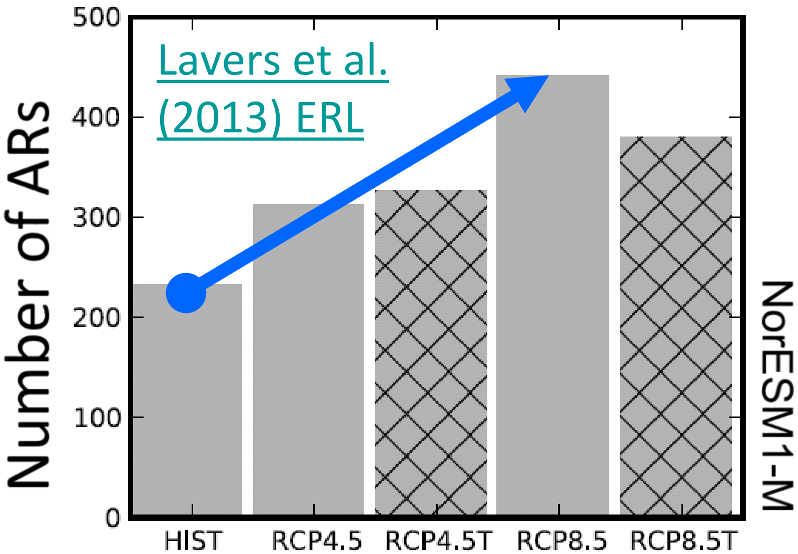
Figure 2 | Sensitivities (% K^{-1}) of the 99.9th percentile of precipitation for variability versus climate change in the CMIP3 simulations. The solid

Water vapour and mid-latitude flooding

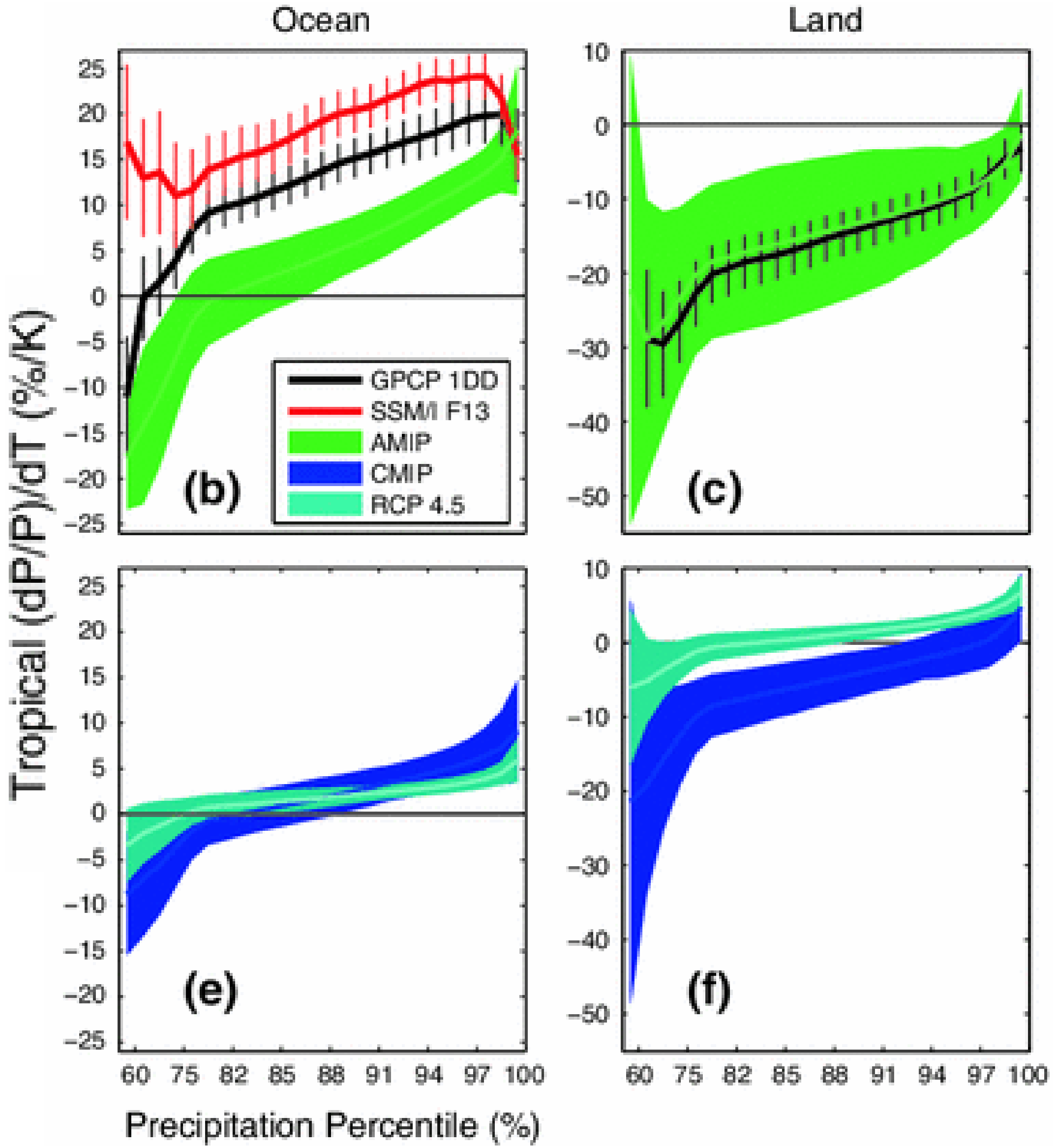


- Simulating extreme precipitation challenging
- Represent large-scale precursors
- Future changes in ARs strongly constrained by water vapour

- UK winter flooding linked to strong moisture transport events
  - Cumbria November 2009 ([Lavers et al. 2011 GRL](#))
  - "Atmospheric Rivers" (ARs) in warm conveyor

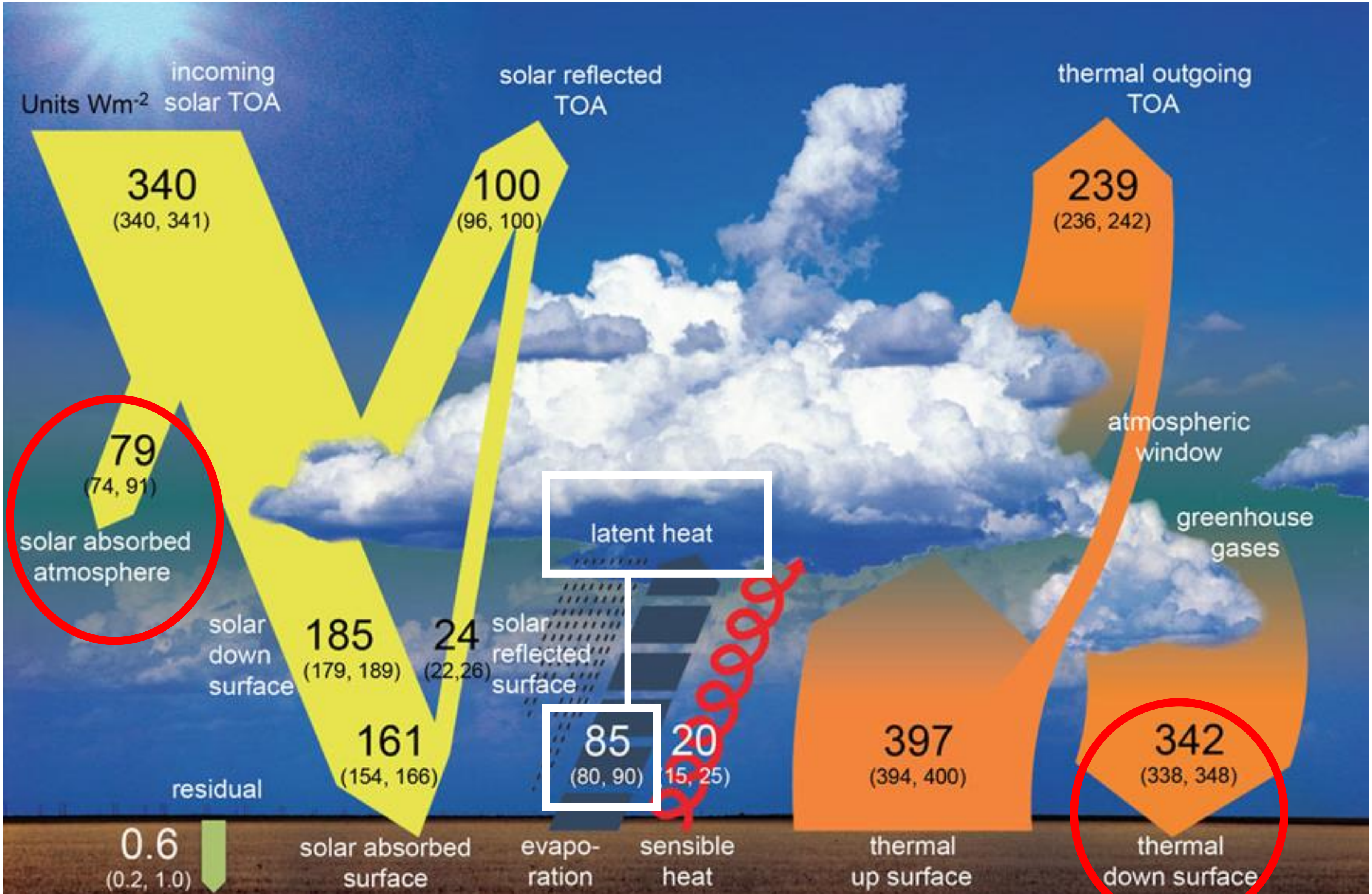


EVALUATING SIMULATED RESPONSES OF EXTREME PRECIPITATION TO WARMING



Allan et al. (2014) Surveys in Geophysics

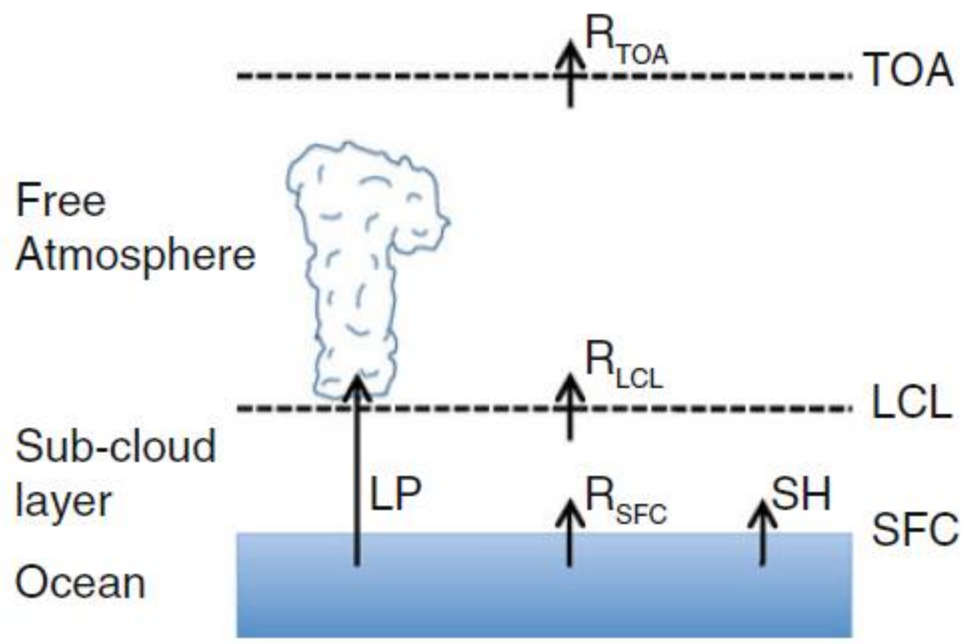
Earth's Energy Budget & the Global Water Cycle



Wild et al. (2012) Clim. Dynamics see.also: Trenberth et al. (2009) BAMS

Radiative energy budget of the atmosphere and hydrological response

- There is an approximate balance between latent heating LP (precipitation) and radiative cooling R_{TOA}-R_{LCL} above lifting condensation level (LCL)
- Below LCL sensible heat adjustments important (SH)

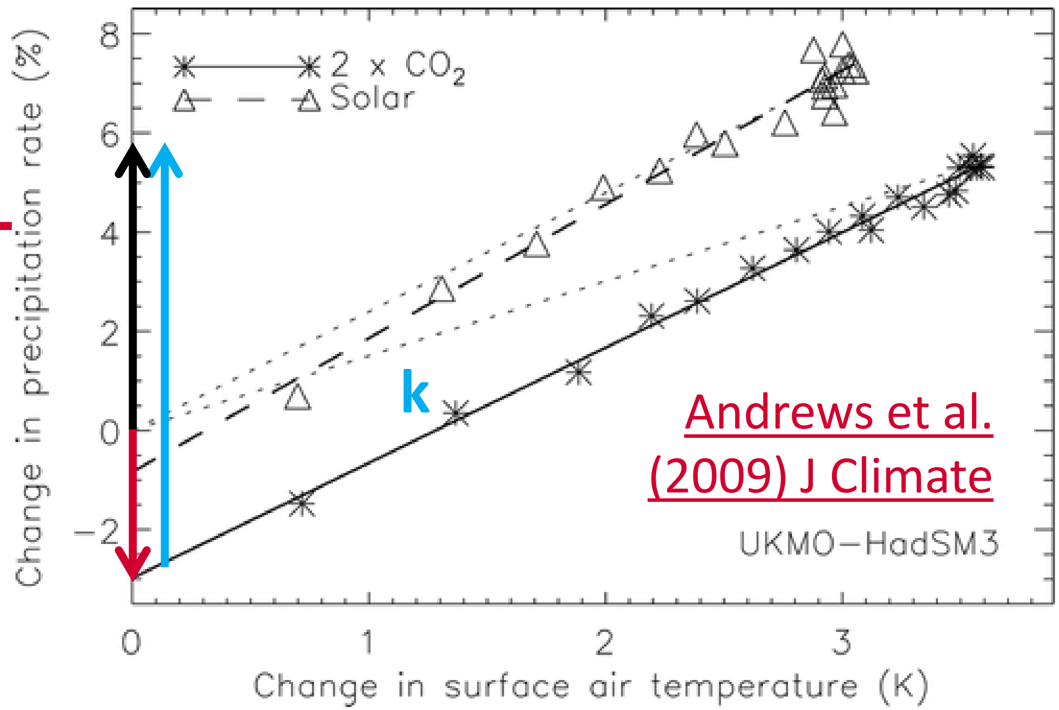


O'Gorman et al. (2012) Surv. Geophys;
after Takahashi (2009) JAS.
See also Manabe & Wetherald (1975) JAS

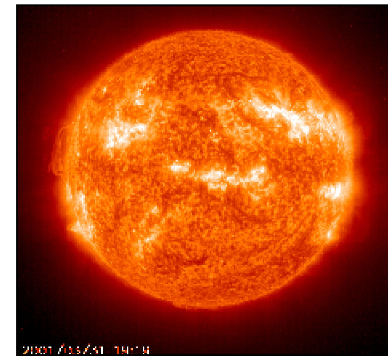
EARTH'S ENERGY BUDGET AND PRECIPITATION RESPONSE

$\underline{L\Delta P} \approx$

$\underline{k\Delta T} - \underline{f_F \Delta F}$

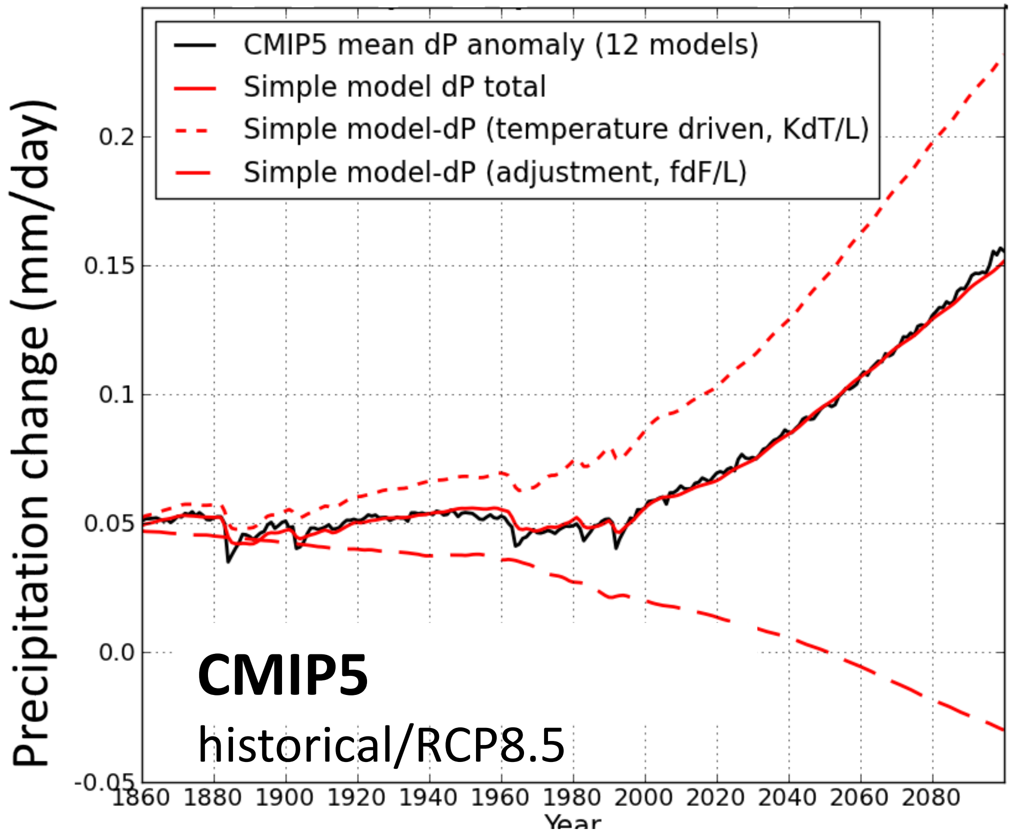


Andrews et al. (2009) J Climate



See also: Allen and Ingram (2002) *Nature* ; O'Gorman et al. (2012) Surv. Geophys ; Pendergrass & Hartmann (2012) GRL

SIMPLE MODEL TO UNDERSTAND GLOBAL PRECIPITATION RESPONSES



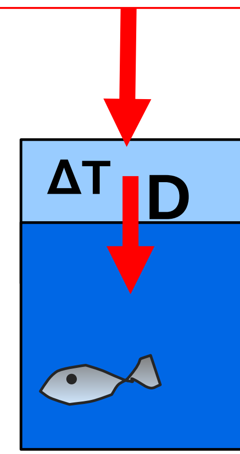
After [Allan et al. (2014) Surv. Geophys](#) and [Thorpe and Andrews (2014) ERL](#)

Using simple model:

$L\Delta P = k\Delta T - f_F\Delta F$

$$\frac{\mathrm{d}\Delta T_\mathrm{m}}{\mathrm{d}t} = \frac{1}{C_\mathrm{m}}(\Delta F - Y\Delta T_\mathrm{m} - D)$$

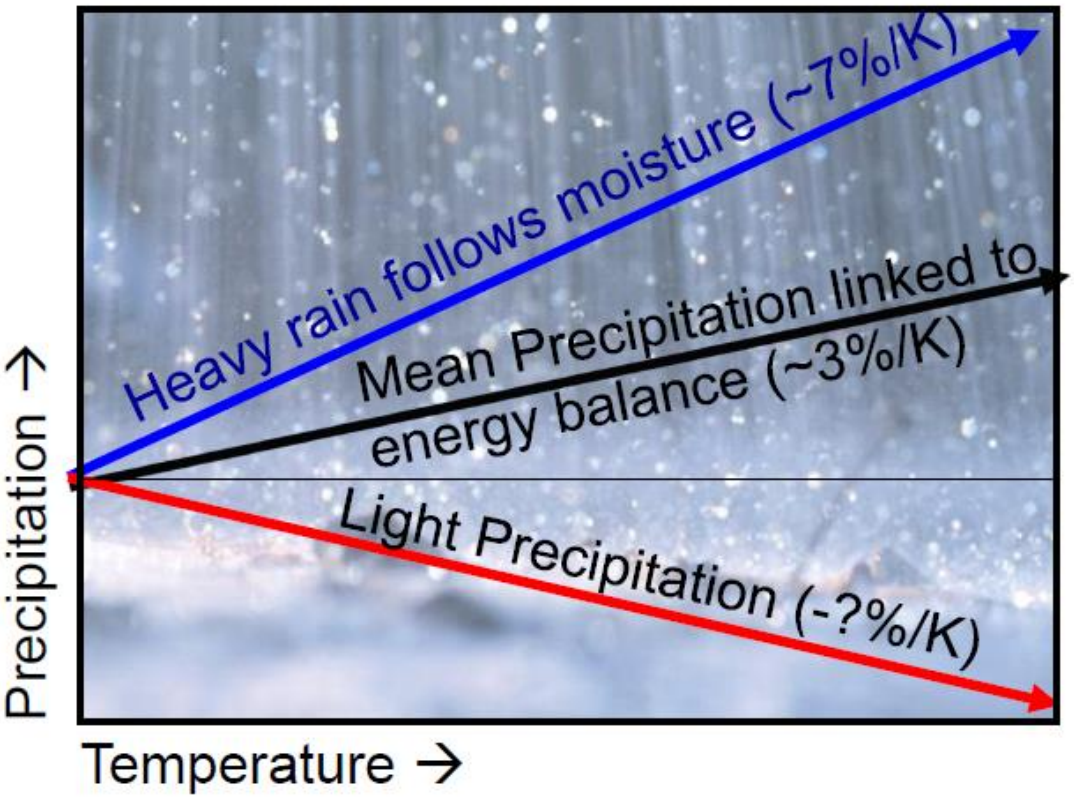
$$\boxed{N = \Delta F - Y\Delta T}$$



$$D = c(\Delta T_\mathrm{m} - \Delta T_\mathrm{D})/d$$

Zahra Mousavi
(PhD project)

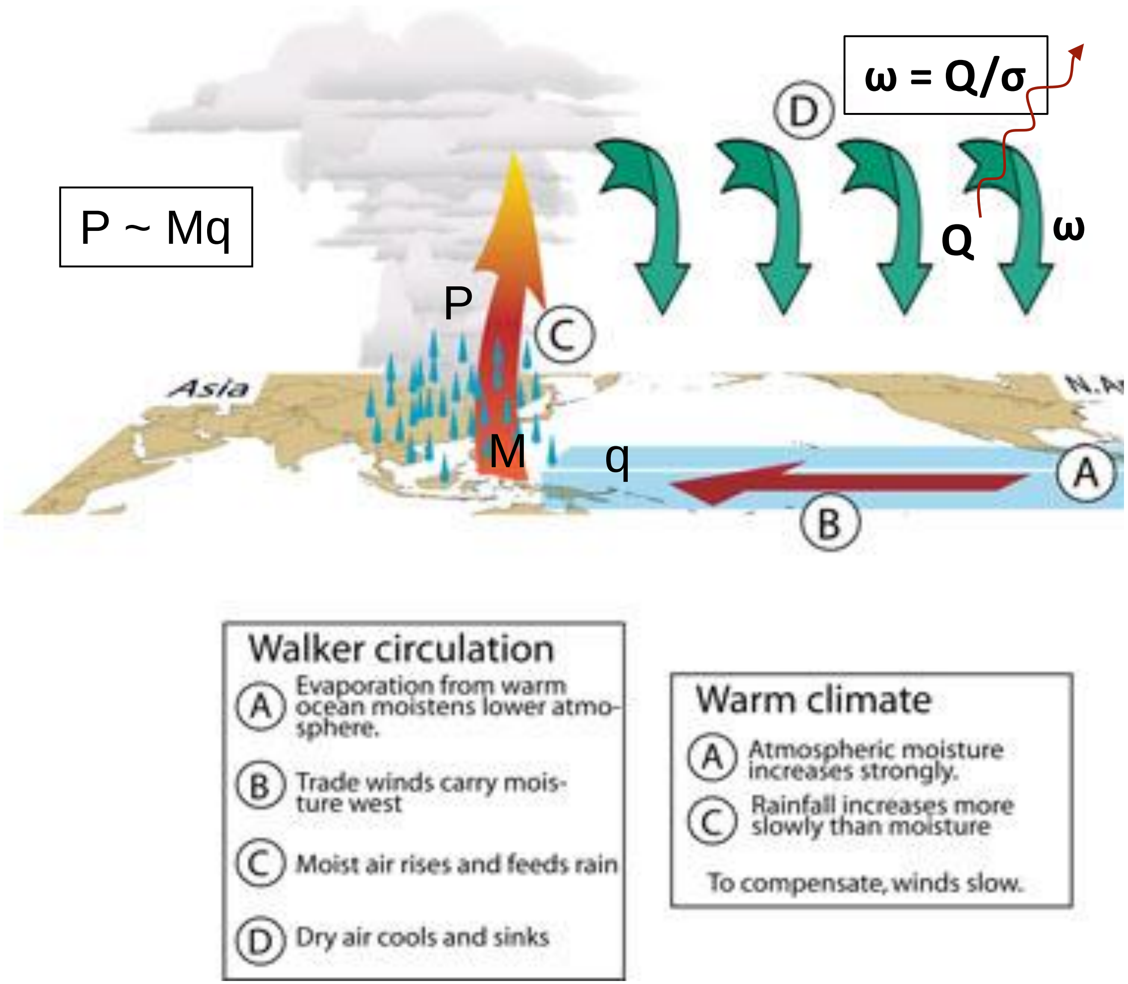
CONTRASTING PRECIPITATION RESPONSE EXPECTED



- Basic physics indicates that precipitation changes will not be uniform in space.
- Some regions will experience increases and others decreases

e.g. Allen and Ingram (2002) *Nature*; Allan (2011) *Nature*

Circulation response



Schematic from Gabriel Vecchi

First argument:

$$P \sim Mq$$

So if P constrained to rise more slowly than q, this implies reduced M:

Bony et al. (2013) Nat Geosci

Chadwick et al. (2012) J Clim

Second argument:

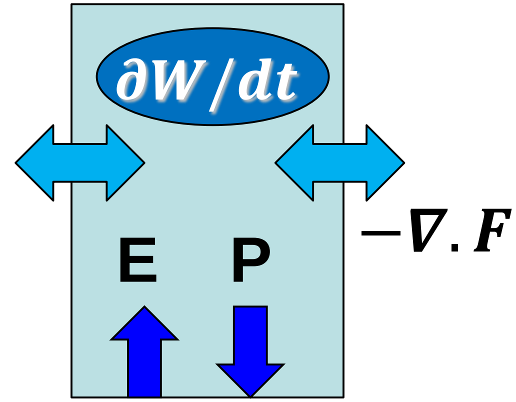
$$\boldsymbol{\omega = Q/\sigma}$$

Subsidence (ω) induced by radiative cooling (Q) but the magnitude of ω depends on static stability ($\sigma = \Gamma_d - \Gamma$).

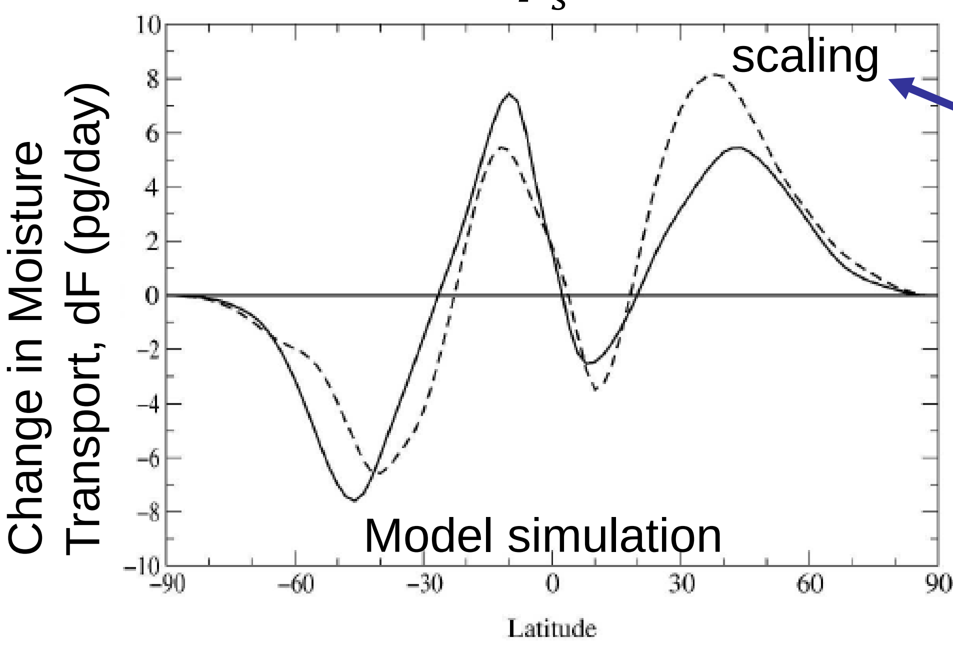
If Γ follows MALR → increased σ. This offsets Q effect on ω.

See Held & Soden (2006) and Zelinka & Hartmann (2010) JGR

Moisture Balance



$$P - E \approx \nabla . \frac{1}{g}\int_{p_s}^{0} q\,\boldsymbol{u}\,dp = -\nabla . F$$



$$\frac{\delta F}{F} \approx \frac{\delta e_s}{e_s} \approx \alpha \delta T.$$

$$\alpha \approx 0.07\ \mathrm{K}^{-1}$$

If the flow field remains relatively constant, the moisture transport scales with low-level moisture.

Held and Soden (2006) J Climate

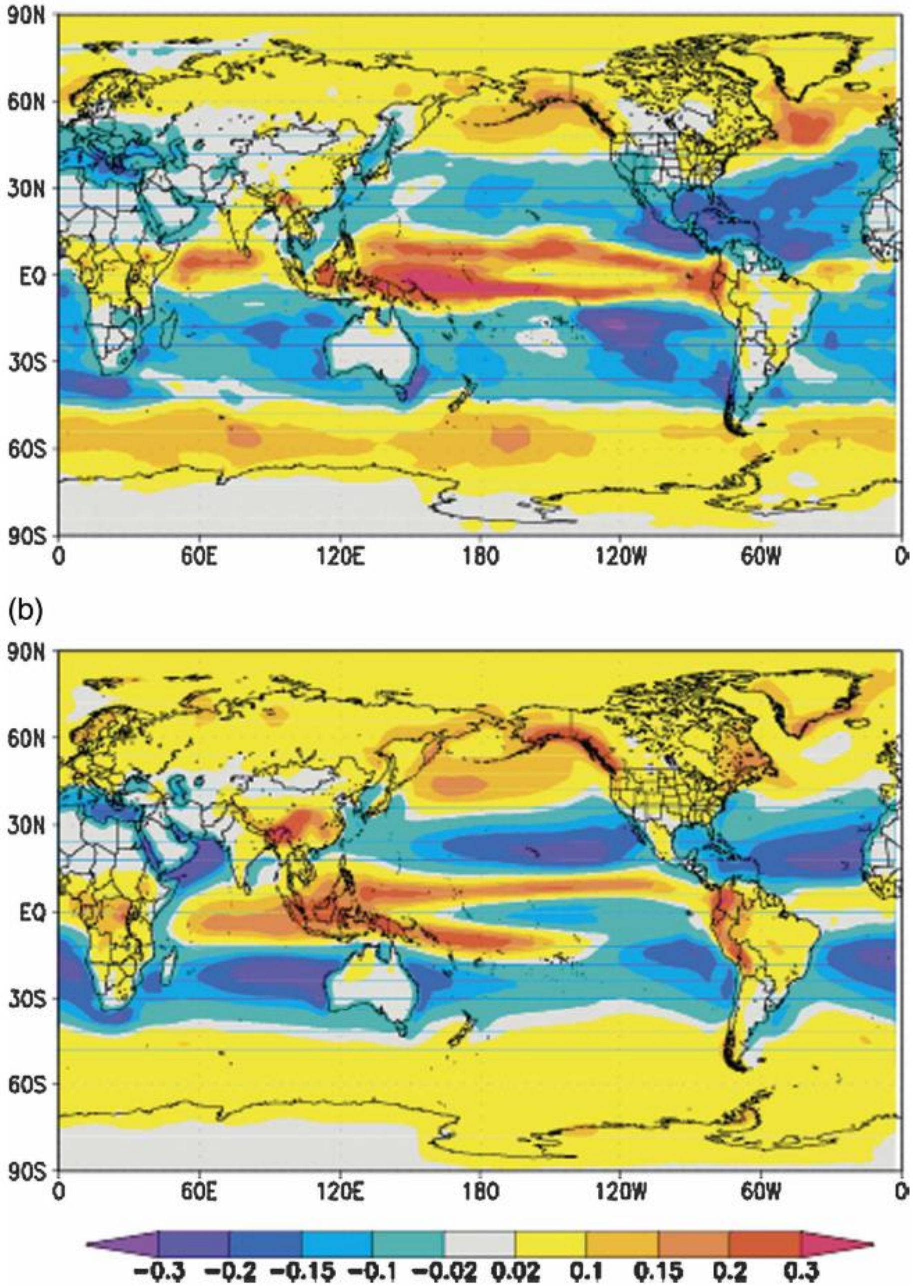


FIG. 7. The annual-mean distribution of $\delta(P - E)$ from the ensemble mean of (a) PCMDI AR4 models and (b) the thermodynamic component predicted from (6) from the SRES A1B scenario.

Moisture Balance

$$\frac{\delta F}{F} \approx \frac{\delta e_s}{e_s} \approx \alpha \delta T. \quad \alpha \approx 0.07\ \mathrm{K}^{-1}$$

$$\delta(P - E) = -\nabla \cdot (\alpha \delta T F). \approx \alpha \delta T (P - E).$$

Enhanced moisture transport ***F*** leads to amplification of

(1) P–E patterns (left)

Held & Soden (2006) *J Climate*

(2) ocean salinity patterns

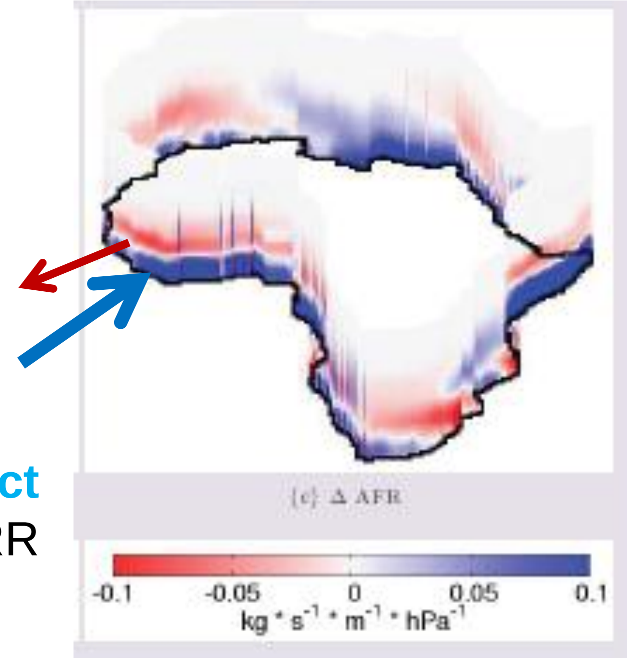
Durack et al. (2012) *Science*

See also Mitchell et al. (1987) *QJRMS*

r.p.allan@reading.ac.uk

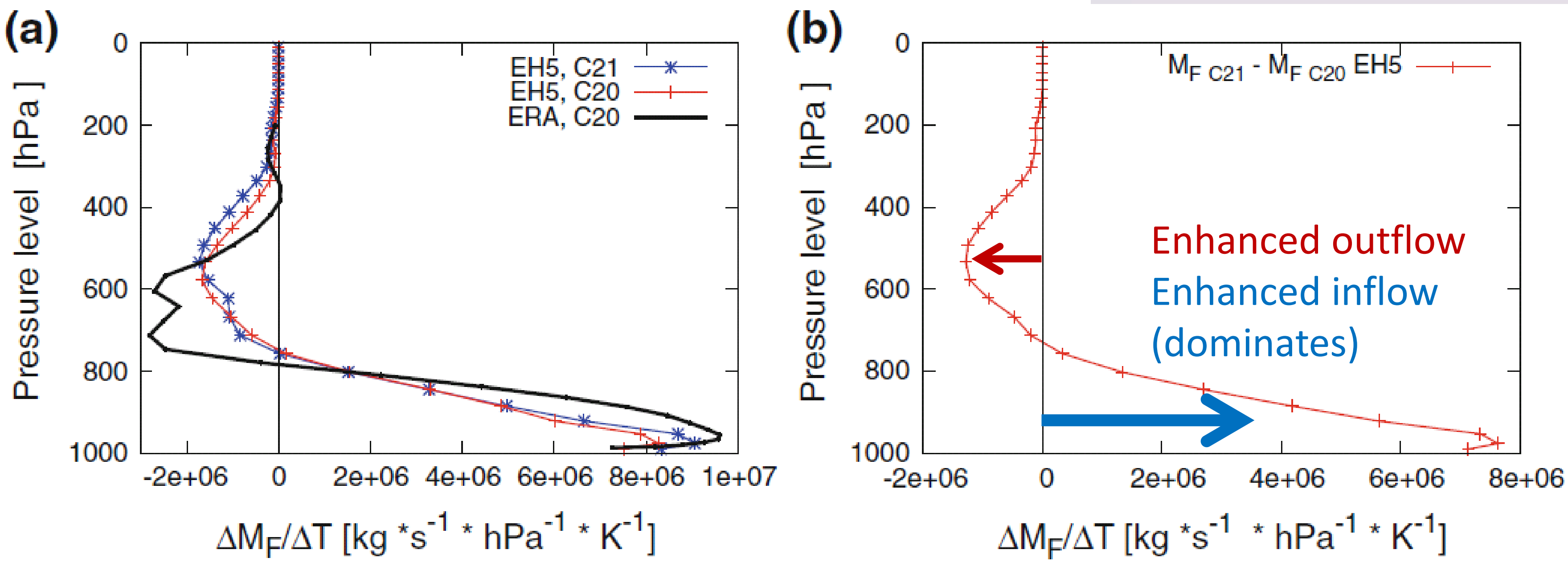
Enhanced moisture transports into the "wet" tropics, high latitudes and continents

$$\frac{\partial w}{\partial t} + \nabla \cdot \frac{1}{g}\int_0^{p_s} \mathbf{v} q \, dp = E - P,$$



PREPARE project

Zahn & Allan (2014) WRR

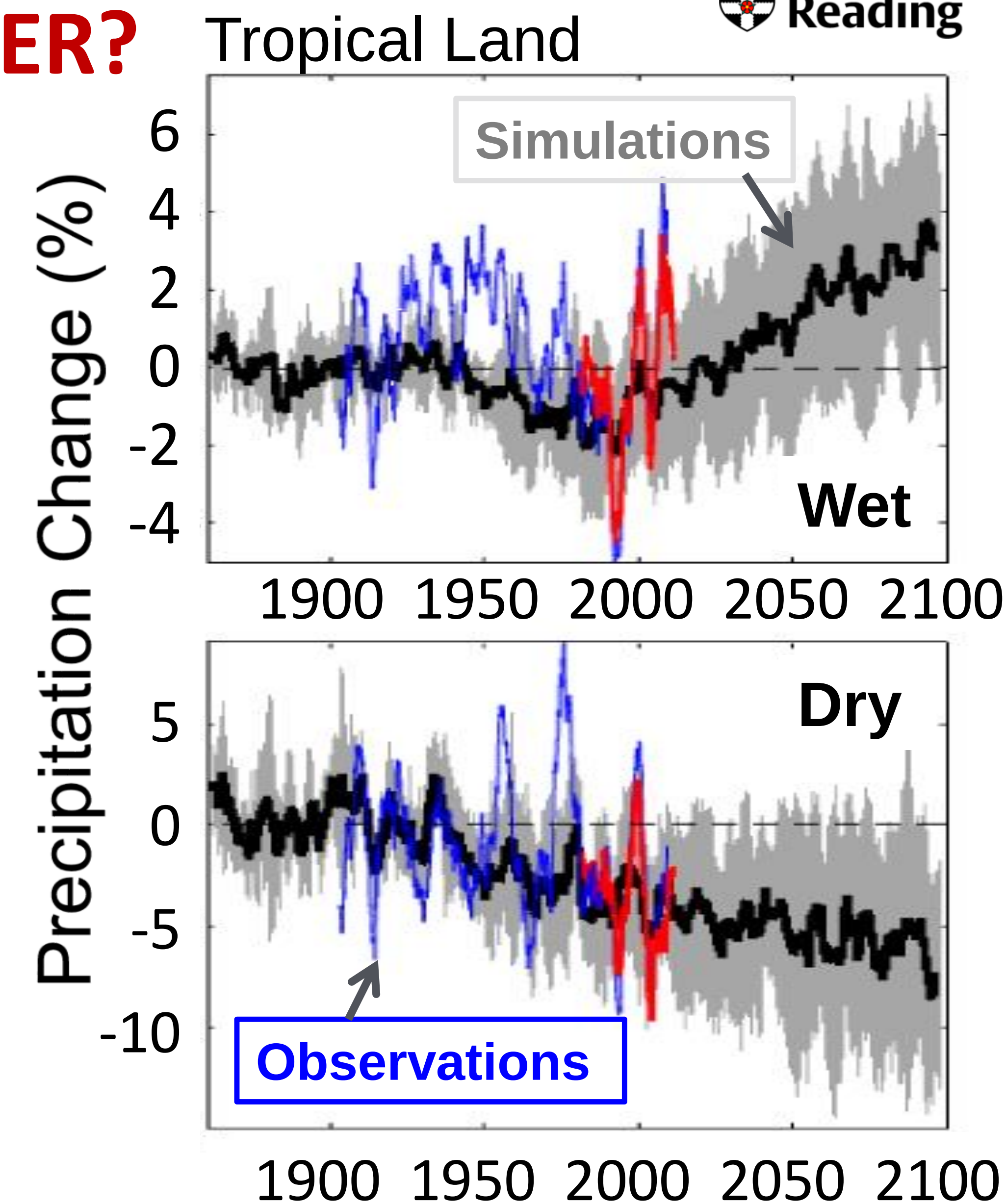


Allan et al. (2014) Surv. Geophys ; Zahn & Allan (2013) J Clim

r.p.allan@reading.ac.uk

THE RICH GET RICHER?

- Held & Soden (2006) scaling holds over oceans but less applicable/relevant over land (Greve et al. 2015)
- However, contrasting trends over land also imply more intense wet and dry spells in future Liu & Allan (2013) ERL
- Sampling of wet/dry regimes and consideration of internal variability and other processes key in understanding changes Allan (2014) Nature Geosci. ; Byrne & O'Gorman (2015)



IMPACT-RELEVANT METRICS
CHANGES IN GLOBAL ARIDITY

- Changes in aridity index:

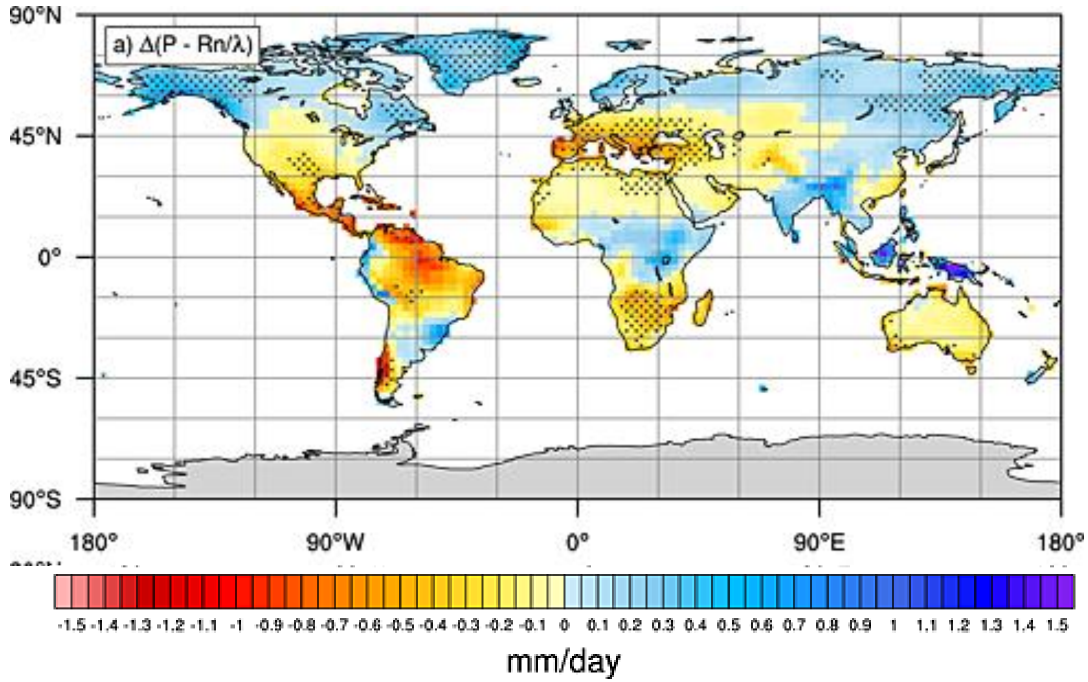
$$P - Eo \sim P - Rn/\lambda$$

(E_o is potential evaporation, R_n is net radiation and λ is latent heat of vapourization)

Right: $\Delta(P - Rn/\lambda)$

Greve & Seneviratne (2015) GRL

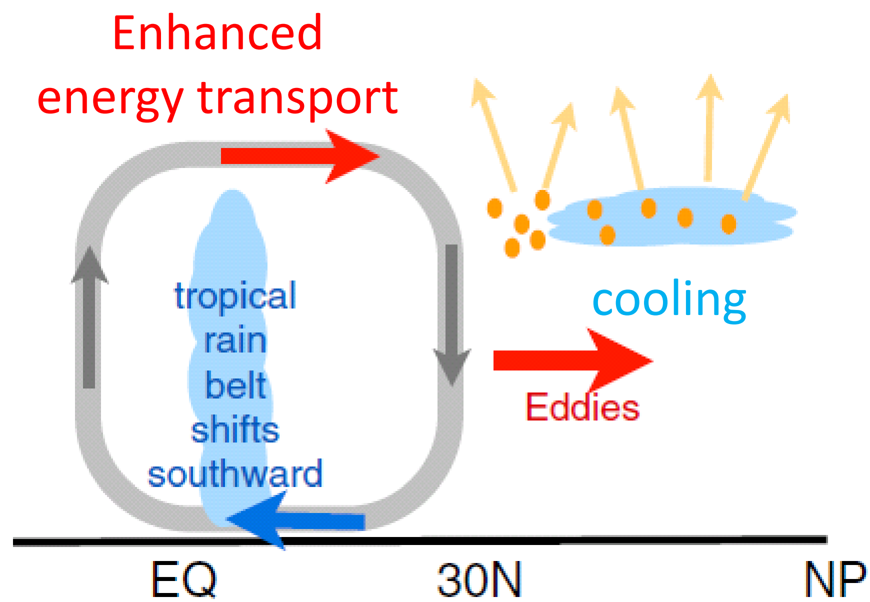
Also: Roderick et al. (2014) HESS

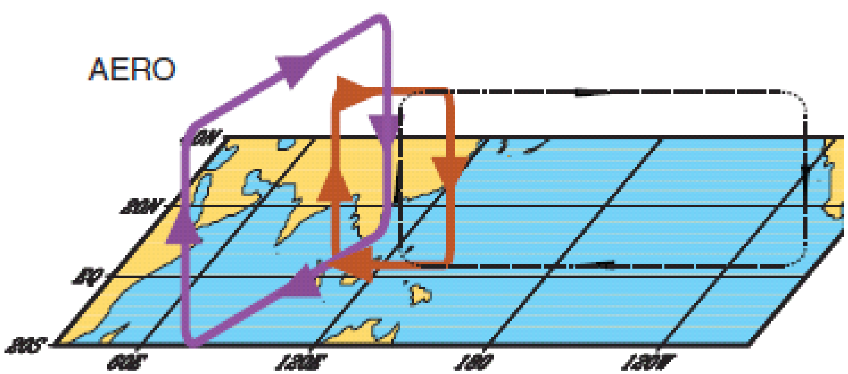


EARTH'S ENERGY BUDGET & REGIONAL CHANGES IN THE WATER CYCLE

University of Reading

- Regional precipitation sensitive to asymmetries in Earth's energy budget Loeb et al. 2015 Clim. Dyn
- N. Hemisphere cooling: stronger heat transport into hemisphere
- Reduced Sahel rainfall from:
- Anthropogenic aerosol cooling 1950-1980s: Hwang et al. (2013) GRL →
- Asymmetric volcanic forcing e.g. Haywood et al. (2013) Nature Climate





- Sulphate aerosol effects on Asian monsoon e.g. Bollasina et al. 2011 Science (left)
- Links to drought in Horn of Africa? Park et al. (2011) Clim Dyn
- GHGs & Sahel rainfall recovery?

Dong & Sutton (2015) Nature Clim.