

## Today's Lecture (Lecture 12): Anthropogenic climate change — robust projections

### Reference

IPCC AR5, Ch. 12

Holton, Ch. 11

Held and Soden (2006), Allen and Ingram (2002), Andrews et al. (2009), linked from course webpage

# 5 – Anthropogenic climate change

1. Introduction
2. The climate system
3. Internal variability
4. Forcing and feedbacks
5. Anthropogenic climate change
  - 5.1 A brief history of anthropogenic climate change
  - 5.2 Projections
  - 5.3 Clouds and aerosols
  - 5.4 Attribution
  - 5.5 The importance of the 2°C warming goal
  - 5.6 “Skepticism” and how to respond to it

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## 5.1 – A brief history of anthropogenic climate change

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- ▶ Scientific consensus forms: 1965 Revelle report (solution: geoengineering), 1979 Charney report, 1988–today IPCC

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- ▶ Late 1980's: early denialism develops, on ideological grounds
- ▶ 1992 UN Framework convention on climate change
- ▶ 1998 Kyoto protocol, tension between countries whose emissions are mostly in the past and countries whose emissions are mostly in the future; intense funding of denialism by the industries with financial interests (oil, coal)
- ▶ 2004 Oreskes paper on scientific consensus, 2007 Nobel Prize, societal consensus forms
- ▶ 2009 failure to achieve binding targets in the Copenhagen climate accord, but consensus around 2 degree goal

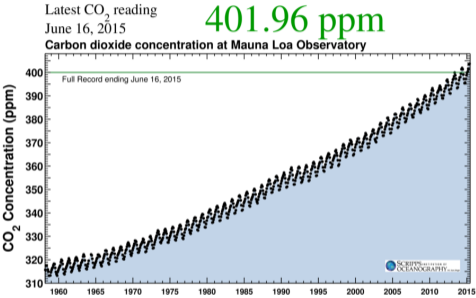
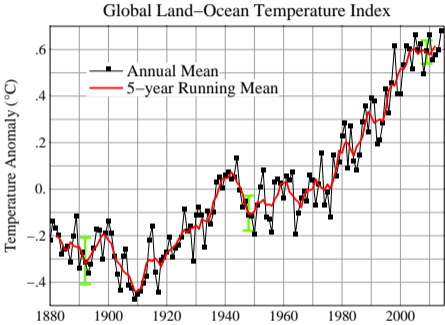
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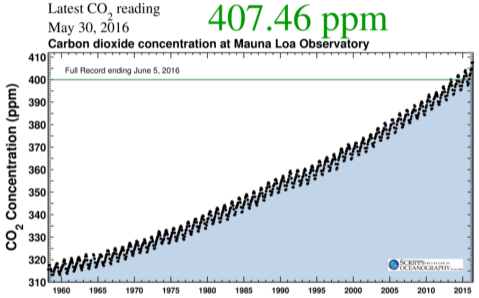
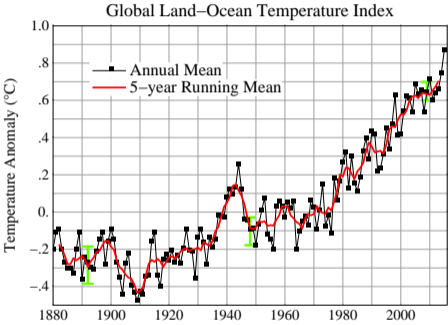
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# Some aspects of the instrumental record



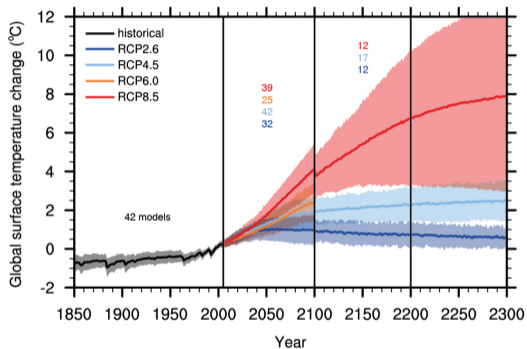
# Some aspects of the instrumental record



Figures: GISS, SIO



## 5.2 – Projections



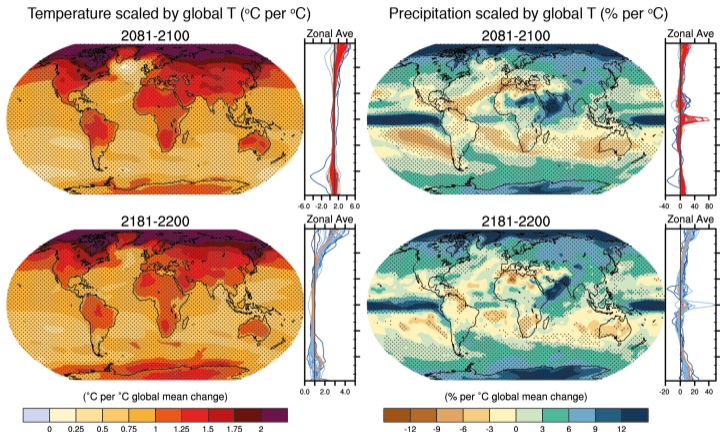
Projections are based on models – of emissions or concentrations of anthropogenic forcing agents (aerosols and greenhouse gases), possibly land use change, etc.

# Robust projections

*Robust projections* are projections where models are in agreement and the underlying physical mechanisms are well understood. The main ones are

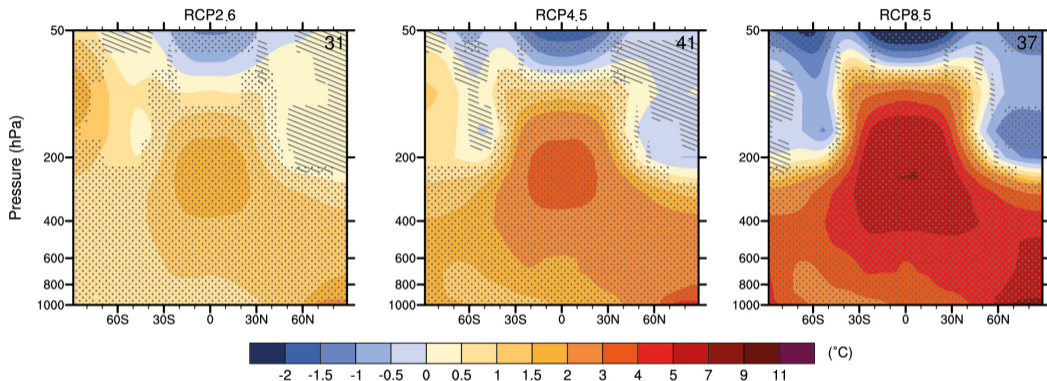
- ▶ increase in global-mean surface temperature
- ▶ arctic amplification
- ▶ precipitation pattern changes

Examples where models disagree: regional climate, magnitude of the warming. Clouds and aerosols are the biggest source of uncertainty, so they will get their own lecture.



## Vertical-meridional structure of the warming

### Annual mean atmospheric temperature change (2081-2100)



Moist adiabats become less steep with increasing temperature, recalling (2.70):

$$\Gamma_s = -\frac{\partial T}{\partial z} \approx \frac{g}{c_{pd} + L_v(dq_s/dT)} = f(T) \neq \text{const}, \quad \frac{dq_s}{dT} \sim \exp(cT) \quad (5.1)$$

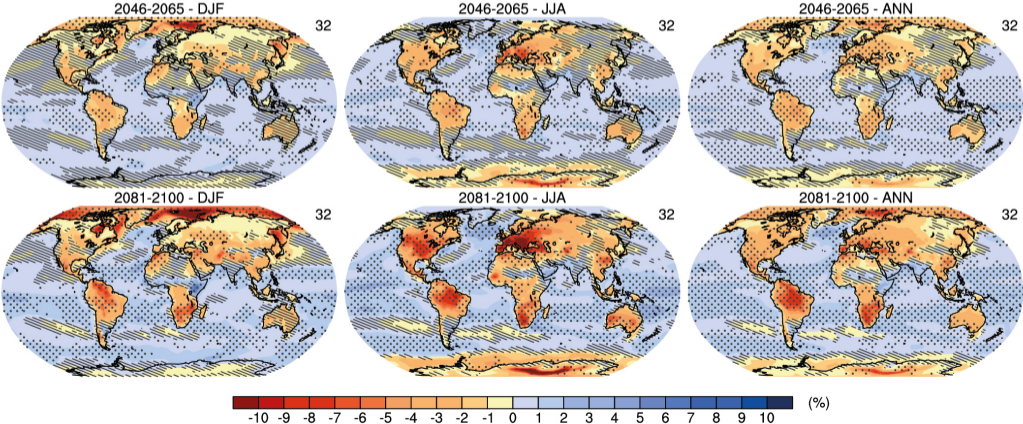
$\Gamma_s$  is always **smaller** than the dry adiabatic lapse rate and **decreases** with increasing temperature.

# Moisture scales with Clausius–Clapeyron equation

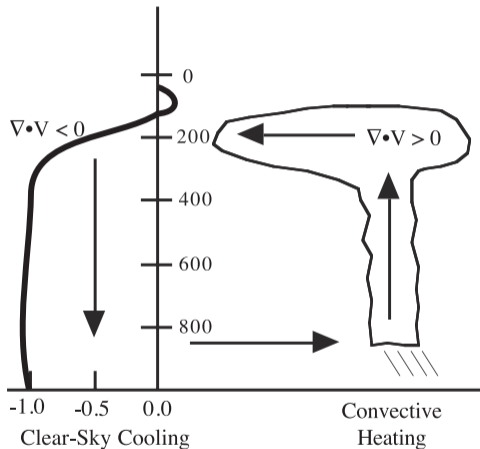
$$\frac{d \ln e_s}{dT} = \frac{L}{R_v T^2} \approx 7\% \text{ K}^{-1} \tag{5.2}$$

Evidence that relative humidity is relatively constant in a warming climate – processes that control relative humidity are not sensitive to climate change – so that  $d \ln q/dT$  also approximately follows CC ( $7\% \text{ K}^{-1}$ )

## Mean relative humidity change (RCP8.5)



## Balance between vertical motion, radiative cooling and convective heating



**Updrafts:** latent heating  $Q \approx 10 \text{ K day}^{-1}$ , high  $\omega$

**Subsidence:** radiative cooling  $Q \approx -1 \text{ K day}^{-1}$ , low  $\omega$

Steady-state ( $\partial/\partial t = 0$ ), neglecting horizontal advection:

$$\omega \frac{T}{\theta} \frac{\partial \theta}{\partial p} = \frac{Q_{\text{rad}}}{c_p} \quad (5.3)$$

where

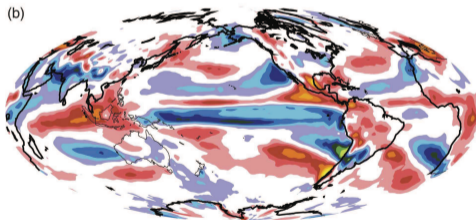
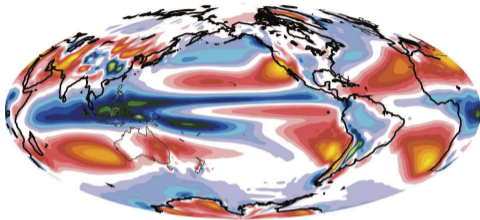
$$\sigma = \frac{T}{\theta} \frac{\partial \theta}{\partial p} \quad (5.4)$$

is called the *stability parameter*

# Response of the tropical circulation to warming

(a) Multi-model ensemble-mean background 500hPa  $\omega$  (hPa $\cdot$ day $^{-1}$ )

Upward -50 -40 -30 -20 -10 -5 5 10 20 30 40 50 Downward



Multi-model ensemble-mean 21st Century 500hPa  $\omega$  change (hPa $\cdot$ day $^{-1}\cdot$ °C $^{-1}$ )  
Scaled by global mean surface air temperature warming of each model before averaging.

- ▶ Even in a warmer climate, the tropical atmosphere conserves  $\theta_e$ :

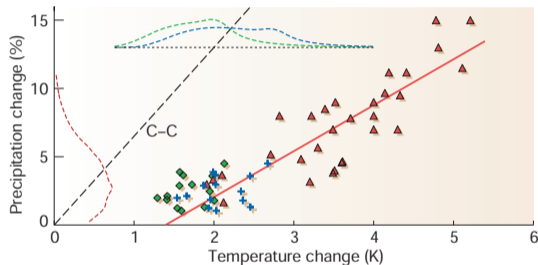
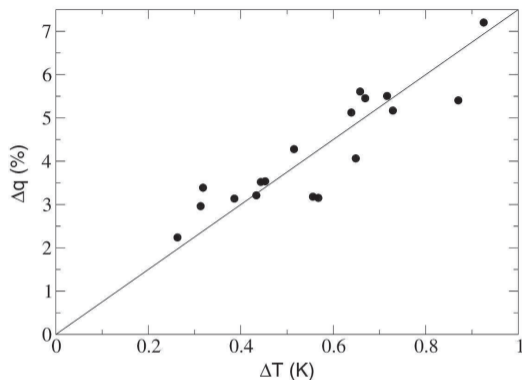
$$\theta_e = \theta \exp\left(\frac{L_v q_s}{c_{pd} T}\right) \quad (5.5)$$

- ▶ In the upper troposphere, where  $q_s \approx 0$ ,  $\theta_e \approx \theta$
- ▶ In the boundary layer, where  $q_s \sim CC$ ,  $\Delta\theta_e/\Delta\theta > 1$  with global warming
- ▶ Therefore  $\Delta\theta(200 \text{ hPa}) > \Delta T_S = \Delta\theta(1000 \text{ hPa})$  and:
  - ▶ Average  $\partial\theta/\partial p$  over the atmospheric column increases with  $Lq_s$
  - ▶  $Q_{\text{rad}}$  does not increase as fast (Knutson and Manabe, 1995) – greater LW absorption in more opaque atmosphere
  - ▶ Therefore

$$\omega = \frac{Q}{c_p} \left(\frac{T}{\theta} \frac{\partial\theta}{\partial p}\right)^{-1}$$

must decrease, resulting in a slowing circulation

## Implications for precipitation



Think of the vertical circulation as air parcels leaving the boundary layer with high  $q$ , condensing and precipitating most of the BL  $q$  as they rise, and then returning to the surface with the low upper-tropospheric  $q' \ll q$ ; so the precipitation is approximately  $P = Mq$ , where  $M$  is the vertical mass flux.

Since  $q$  scales approximately with CC in a warming climate ( $7\% \text{ K}^{-1}$ ), but  $M$  decreases, the increase in precipitation is less than CC. (It turns out to be  $2\% \text{ K}^{-1}$ )

## Response of precipitation to GHG forcing – atmospheric energy budget

The precipitation response is evidently not constrained by water vapor availability (which increases according to CC). As we can see from the following argument, it is instead constrained by the atmospheric energy budget.

Recall that the atmosphere loses energy to radiative cooling at a rate

$$R_a = F_{\text{TOA}} - F_s + R_{\text{TOA}} - R_s \approx -100 \text{ W m}^{-2} \quad (5.6)$$

which is balanced by sensible and latent heat fluxes from the surface. Recall also that latent heat dominates.

When the atmospheric energy fluxes are perturbed, equilibrium is restored on fast timescales due to the small heat capacity of the atmosphere. Thus, if we perturb the atmosphere by doubling the  $\text{CO}_2$  concentration, it will quickly reequilibrate according to the equation

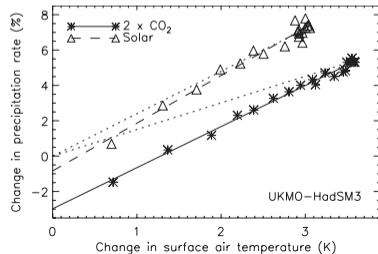
$$\Delta R_a = -(\Delta \text{LH} + \Delta \text{SH}) \approx -\Delta \text{LH} = -\Delta P \quad (5.7)$$

If we decompose the radiative perturbation into an ERF  $\Delta R_c$  (forcing plus rapid adjustments) and a feedback  $\Delta R_T$  (slow processes mediated by surface temperature increase), we can write the following equation for precipitation change:

$$\begin{aligned} L\Delta P &= -\Delta R_c - \Delta R_T \\ &= -\Delta R_c + k_T \Delta T_S \end{aligned} \quad (5.8)$$

$$\approx -3 \text{ W m}^{-2} + 2 \text{ W m}^{-2} \text{ K}^{-1} \Delta T_S \quad (5.9)$$

$$\frac{\Delta P}{P} \approx -3\% + 2\% \text{ K}^{-1} \Delta T_S \quad (\text{normalizing by } LP \approx 100 \text{ W m}^{-2}) \quad (5.10)$$





## Geographic distribution of the precipitation response

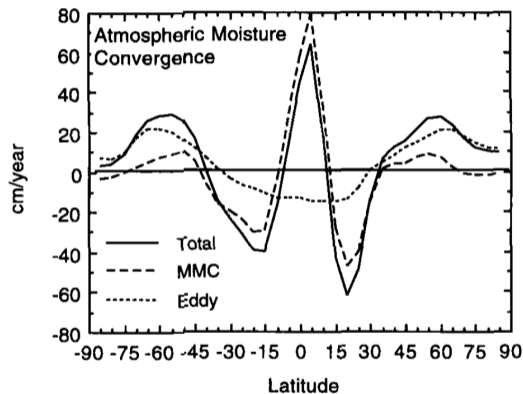


Figure: Hartmann (1994)

- ▶  $P - E$ , the difference between precipitation and evaporation, balances the convergence of atmospheric moisture transport:

$$P - E = \nabla \cdot \vec{F}, \quad \vec{F} = q\vec{v} \quad (5.11)$$

(this is the analog to convergence of atmospheric energy transport balancing the atmospheric energy budget). Consider  $F$ , the zonal-mean meridional component of  $\vec{F}$ .

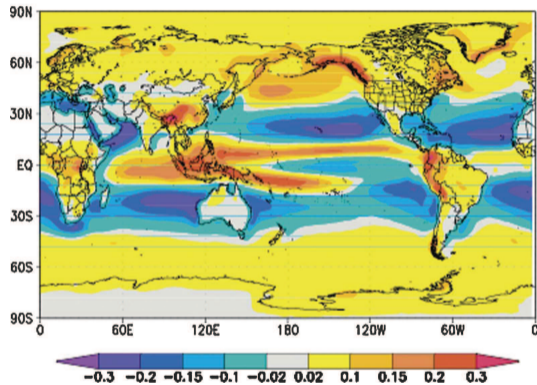
- ▶ In a warming climate, meridional moisture transport changes because  $q$  increases (CC) and because the meridional circulation changes; CC dominates, so that

$$\frac{\Delta F}{F} \approx \frac{\Delta q}{q} = 0.07 \text{ K}^{-1} \Delta T \quad (5.12)$$

- ▶ Therefore

$$\begin{aligned} \Delta(P - E) &= \nabla \cdot \Delta F \\ &\approx 0.07 \text{ K}^{-1} \Delta T \nabla \cdot F \\ &\approx 0.07 \text{ K}^{-1} (P - E) \Delta T \end{aligned} \quad (5.13)$$

## Wet get wetter, dry get drier



- ▶ From (5.13), the change in the precipitation pattern under global warming is proportional to the precipitation pattern itself
- ▶ As a result, this pattern is called “wet get wetter, dry get drier”