

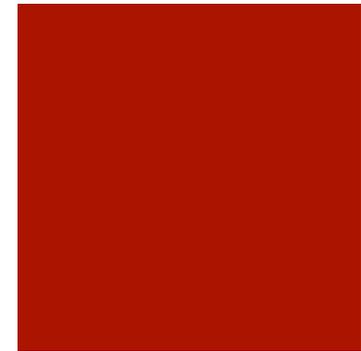


The challenges of climate change

Lecture 3 – Forcings and Feedback

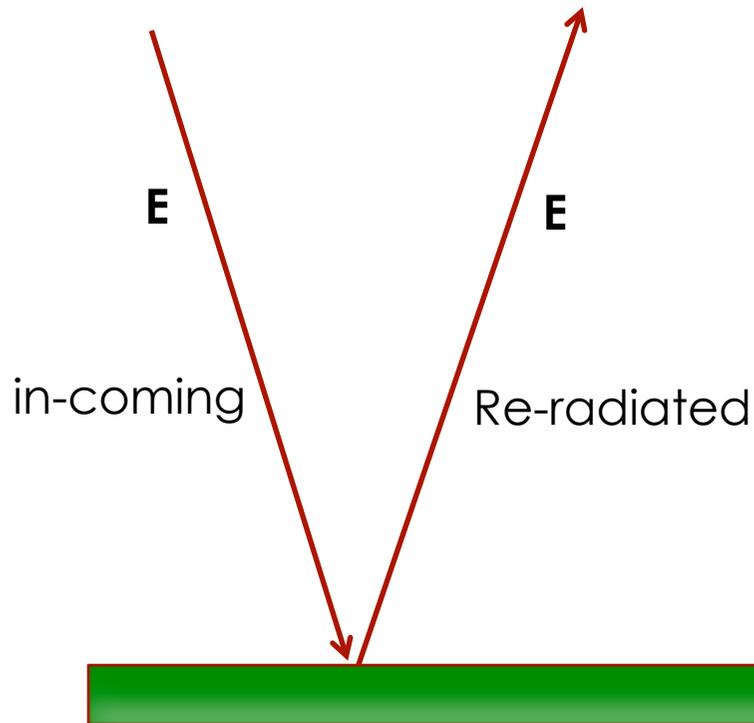
Outline of course

- **Do we understand the science behind climate change?**
 - Historical climate
 - **Basics of climate science**
 - **Modeling the climate**
 - Understanding the uncertainty
- **What are the implications of climate change?**
 - Biological/environmental implications
 - Economic political implications
- **What human actions can be taken to address climate change?**
 - Individual action
 - Political action
 - Technology
 - Economic action
 - Sources of inertia

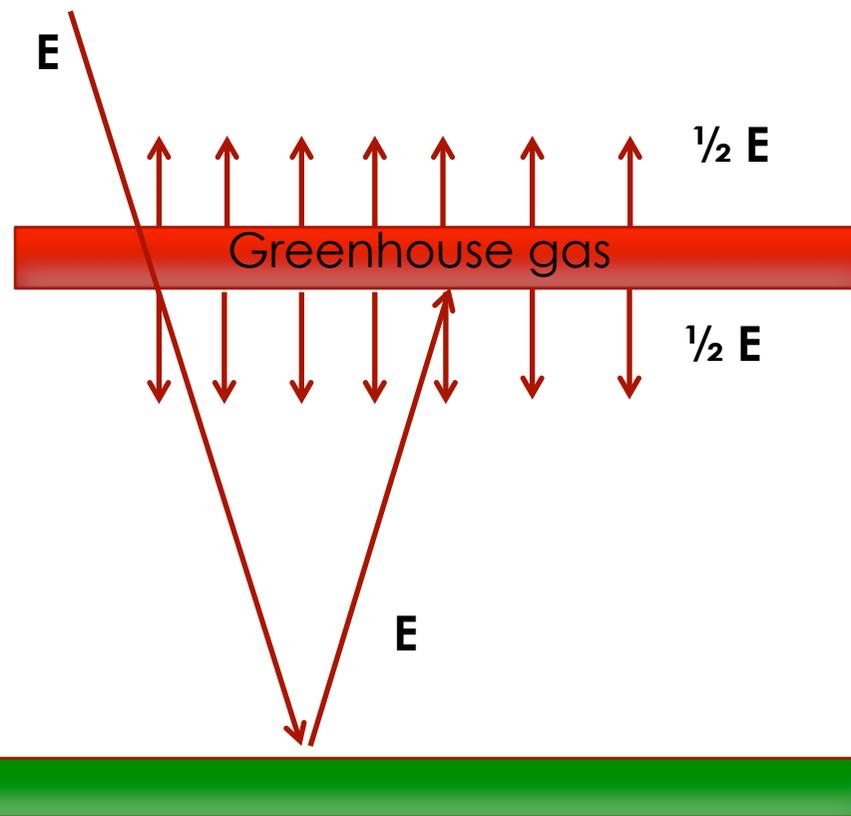
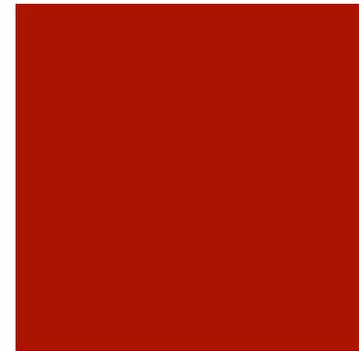


A greenhouse

Energy in = Energy out



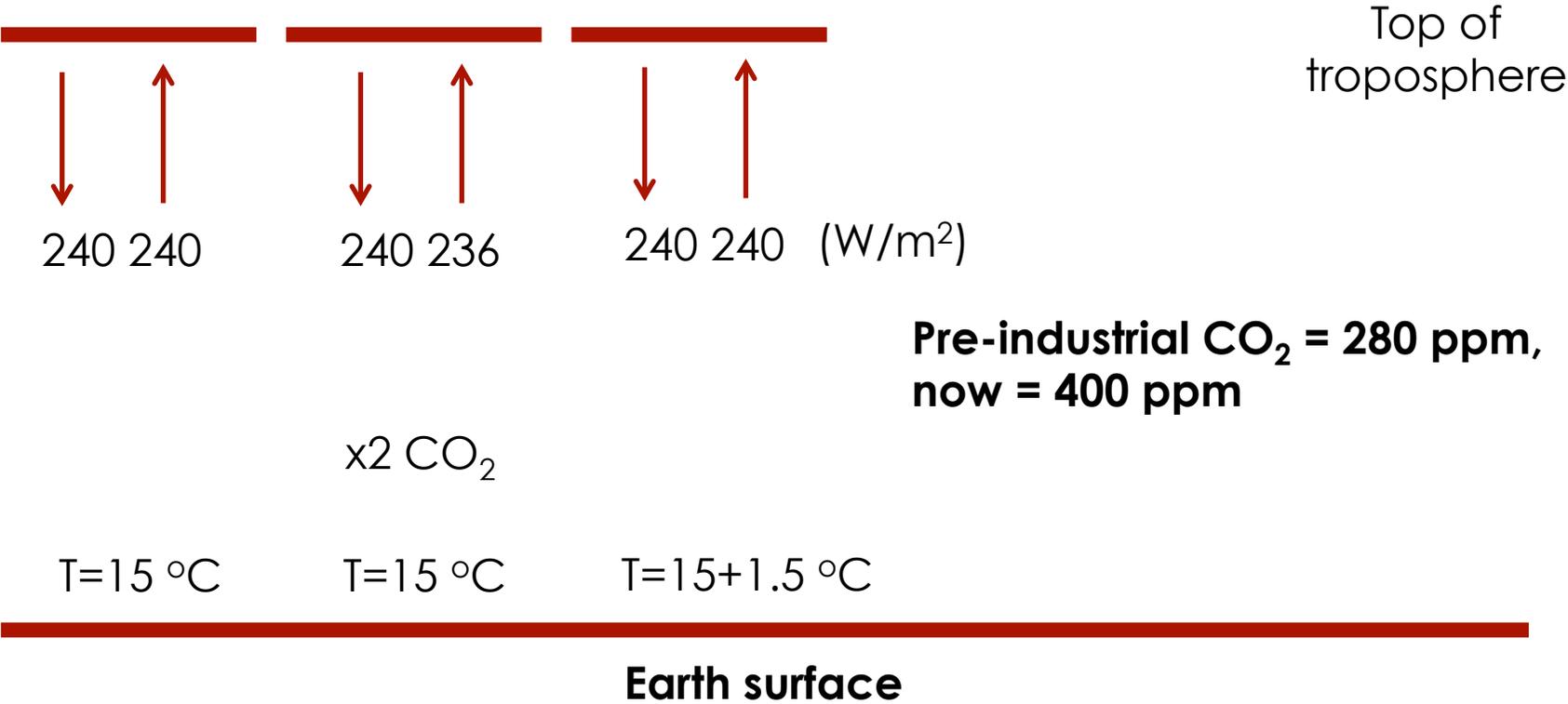
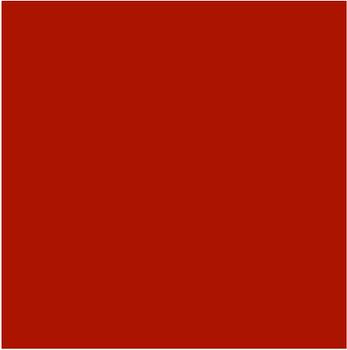
Energy in = 2 Energy out



Earth Surface

Radiative forcing

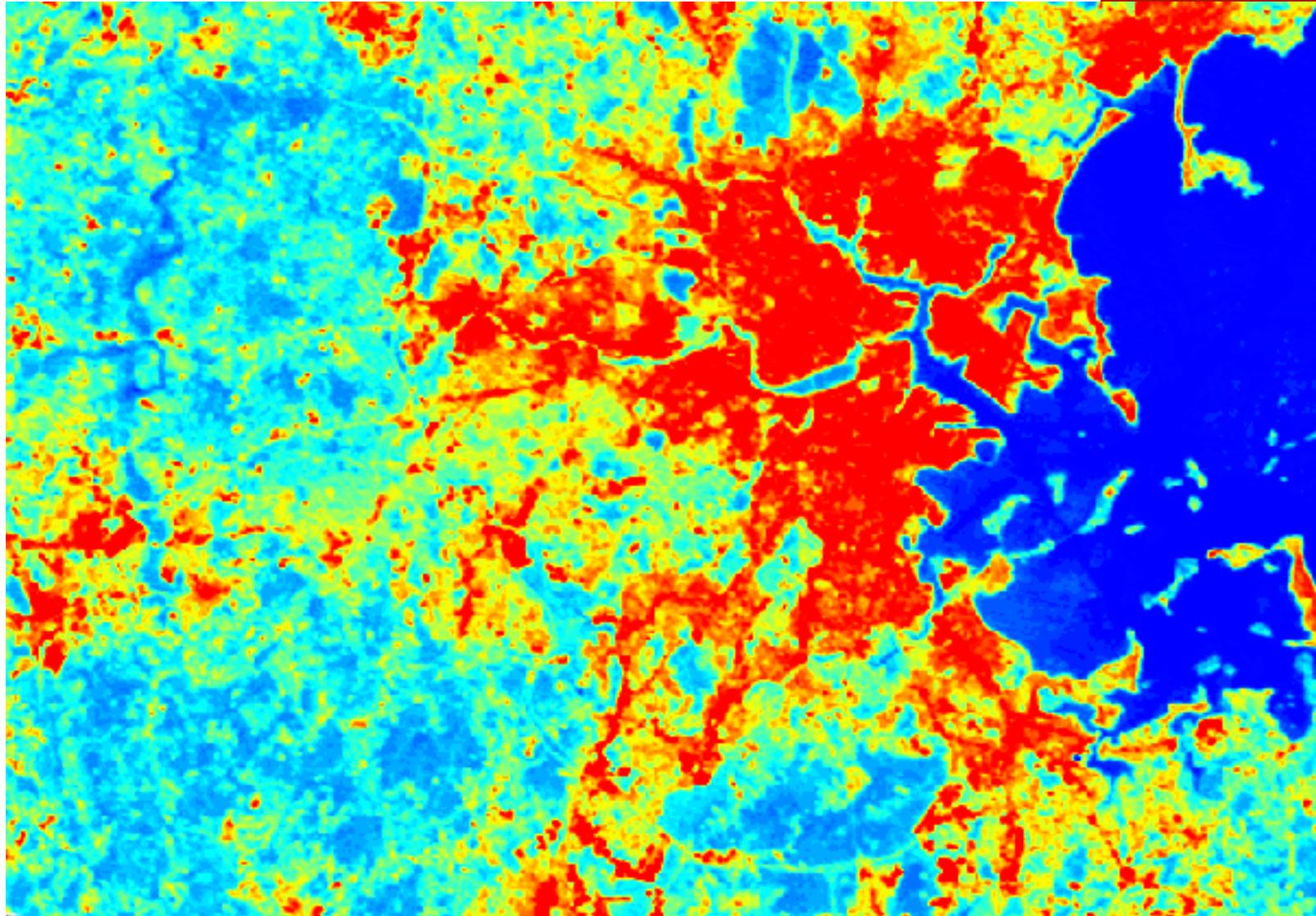
- Imbalance in incoming and outgoing radiation



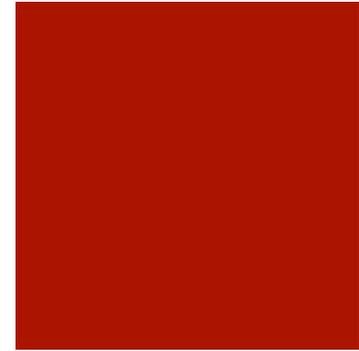
Pre-industrial CO₂ = 280 ppm,
now = 400 ppm

Radiative forcing arises from all greenhouse gases, and can be assessed via global warming potential

Land Use



Aerosol forcing

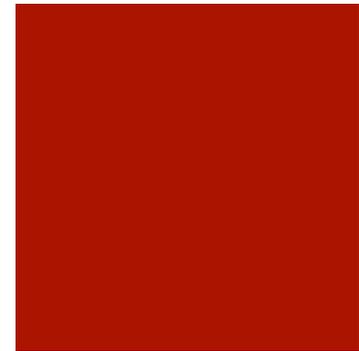


- Aerosols are particulate matter in the atmosphere – natural (e.g. volcanoes, ice, sand) and anthropogenic (carbon etc).
- Can create two types of forcing (not feedback).
- DIRECT
 - Global dimming (negative, 2 W/m²)
- INDIRECT
 - Changes in cloud chemistry, albedo and lifetime (negative 1.5 W/m²)

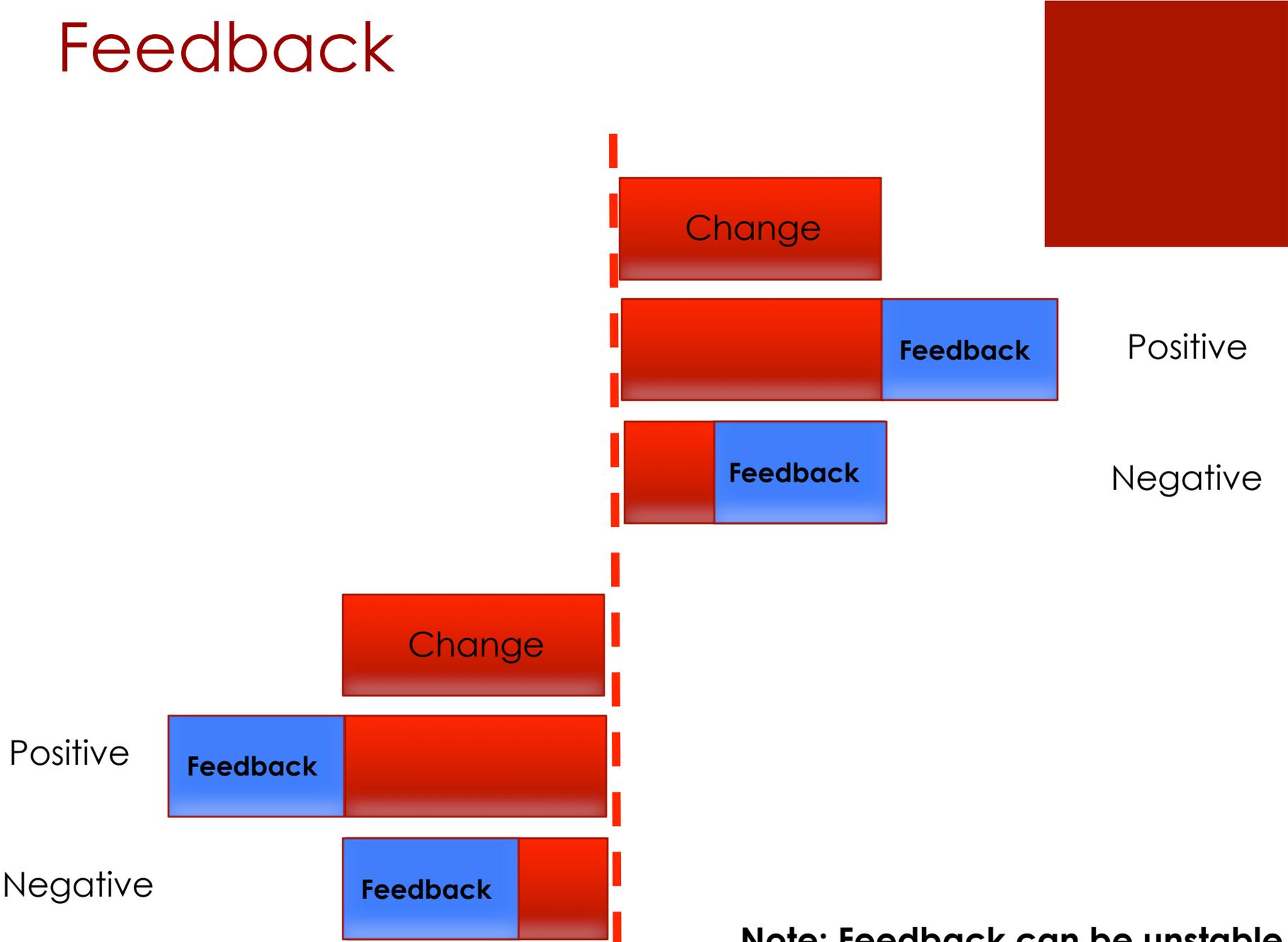
Climate Sensitivity

- Change in temperature for a given radiative forcing
- G_0 = Change in temperature / Change in forcing
= $0.27 \text{ } ^\circ\text{C}/\text{W}/\text{m}^2$

$$G_0 = \frac{\delta T}{\delta F} = 0.27^\circ \text{ C W}^{-1} \text{ m}^2$$

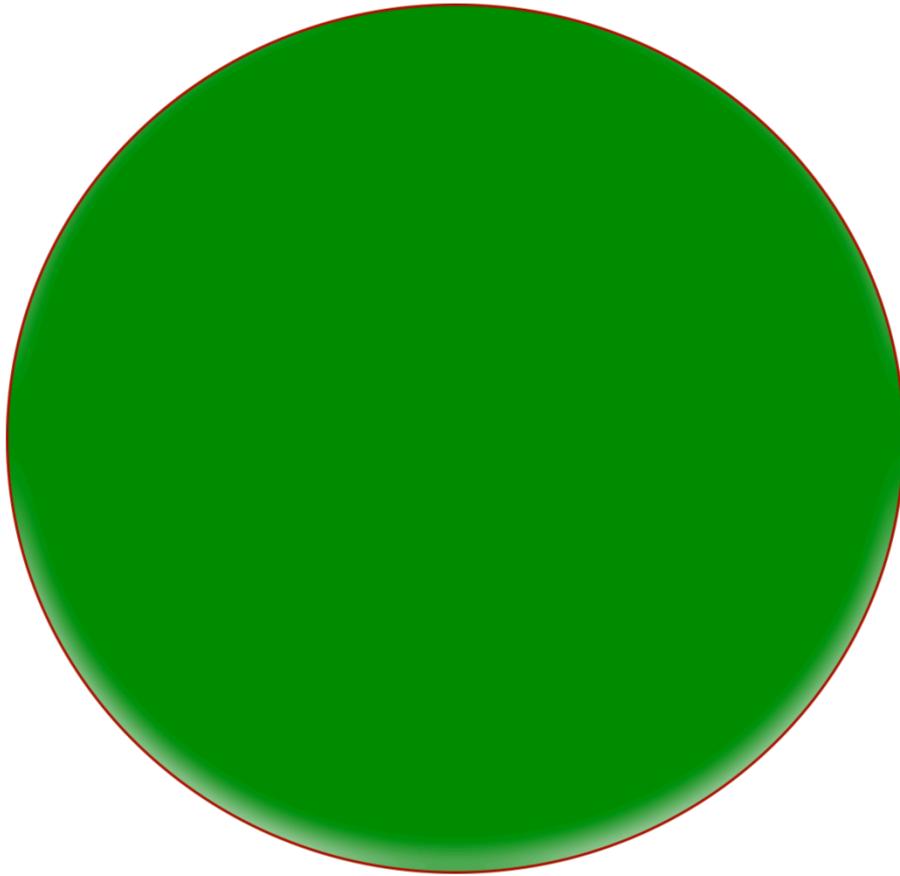


Feedback

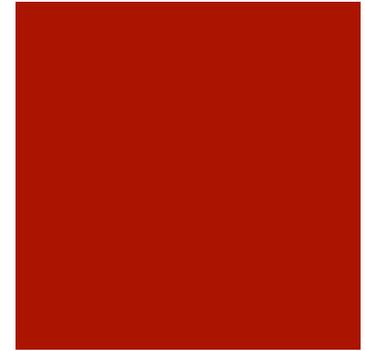
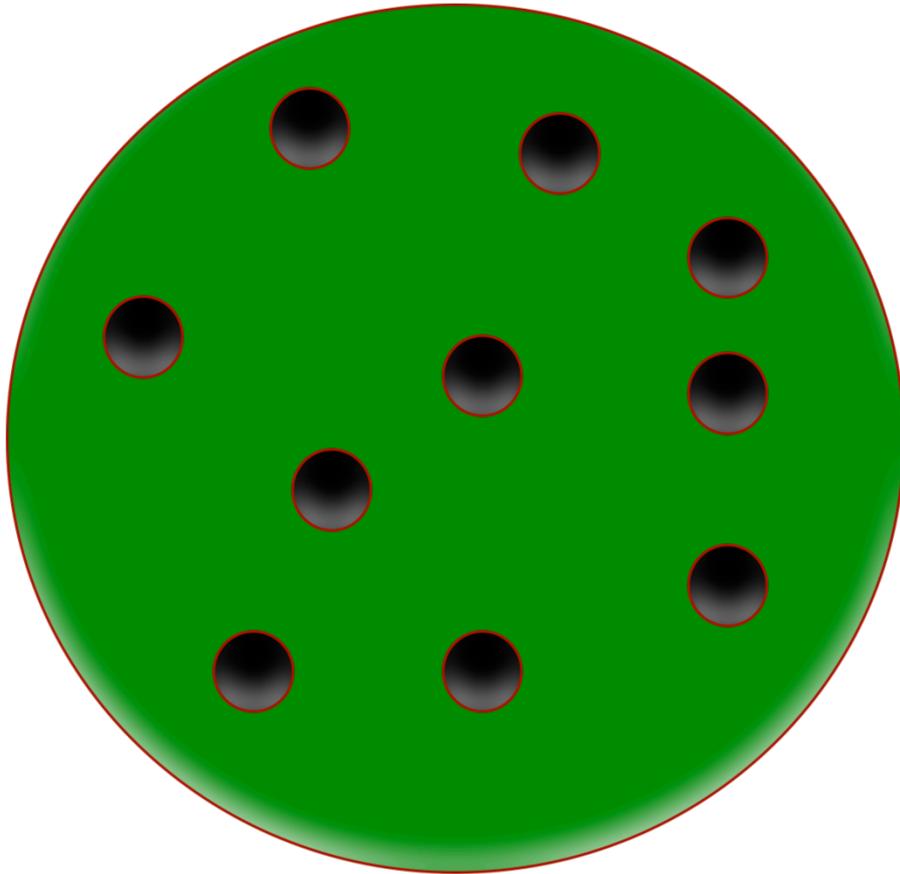


Note: Feedback can be unstable

Daisyworld

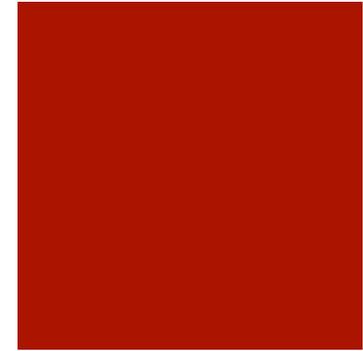
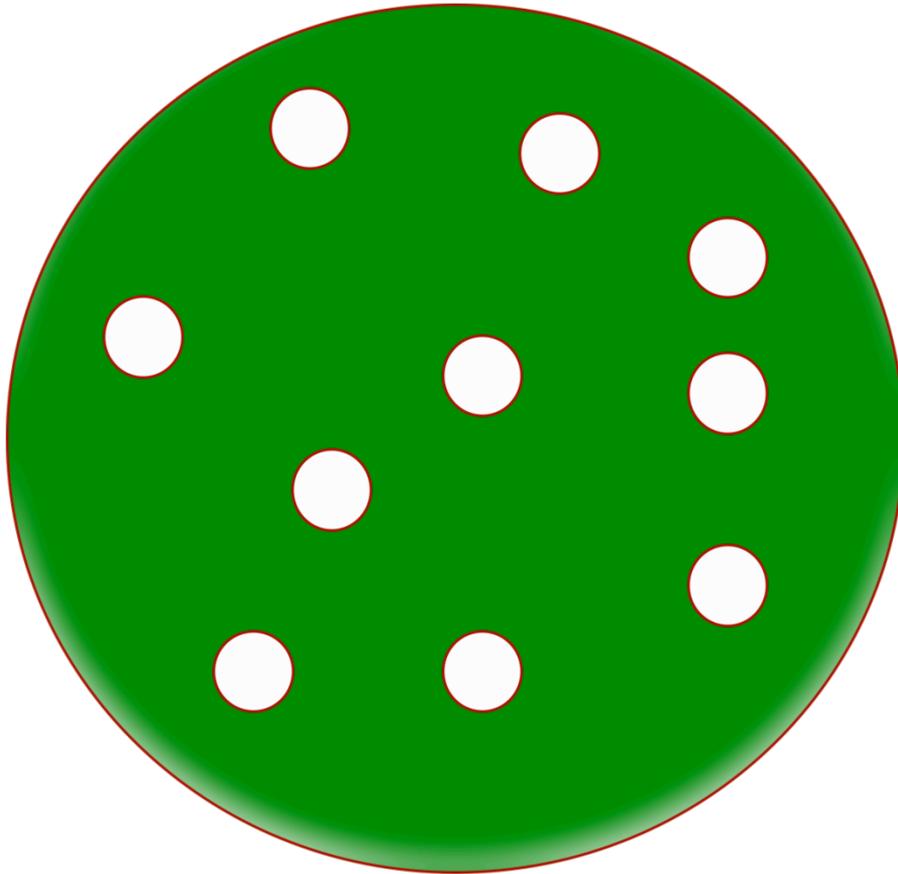


Daisyworld



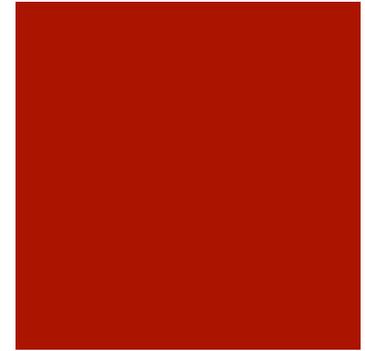
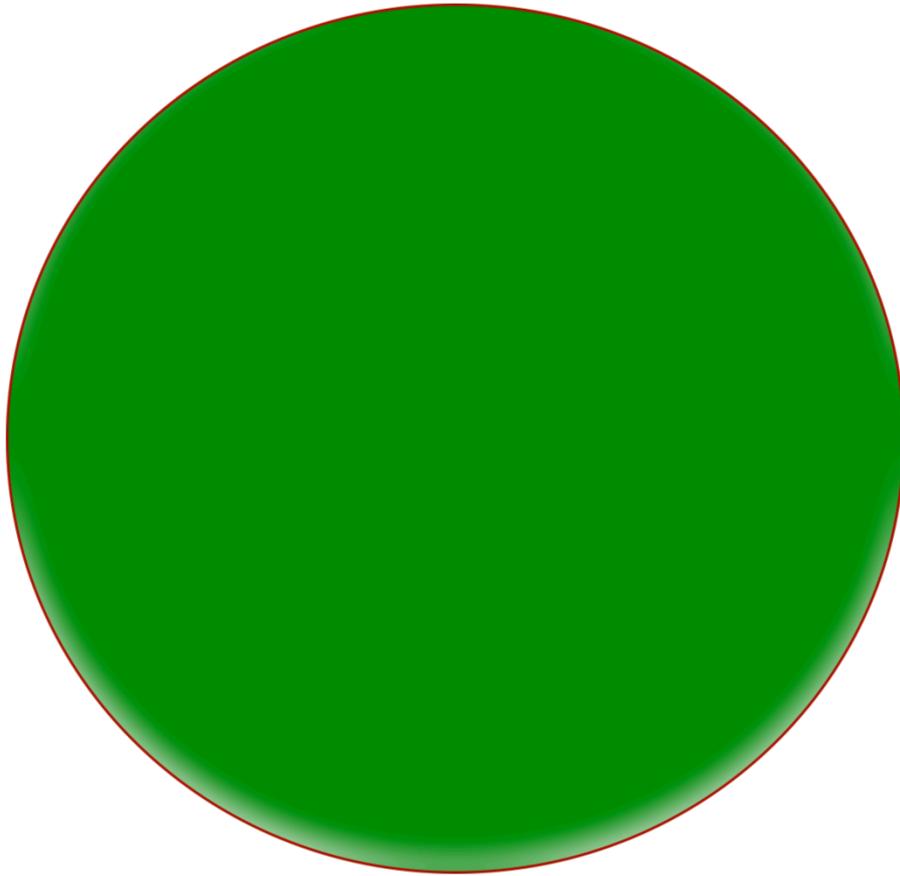
Black daisies like it cool

Daisyworld



Black daisies like it cool
White daisies like the heat

Daisyworld

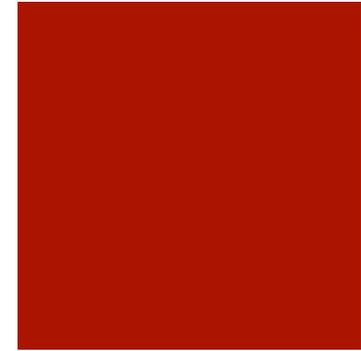
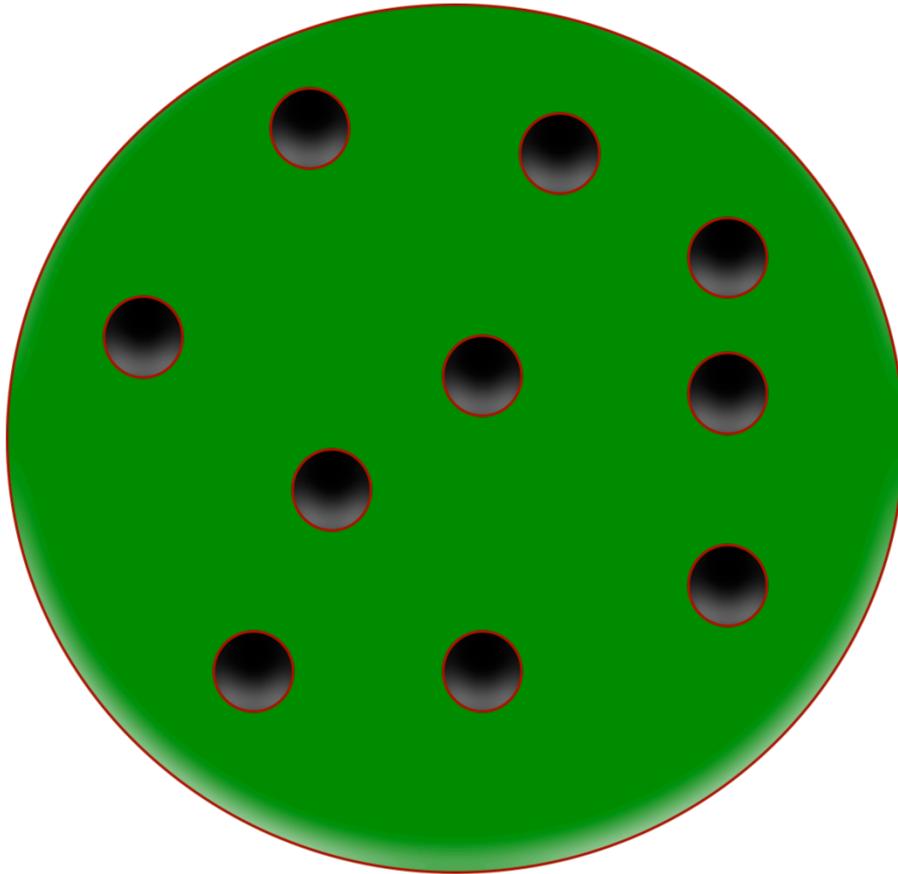


Black daisies like it cool

White daisies like the heat

At early times the star is faint
(like the sun)

Daisyworld



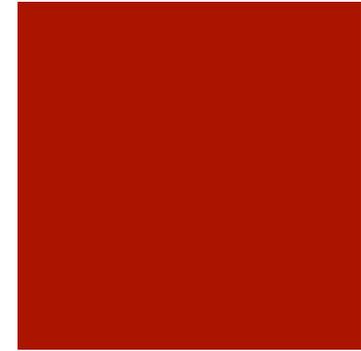
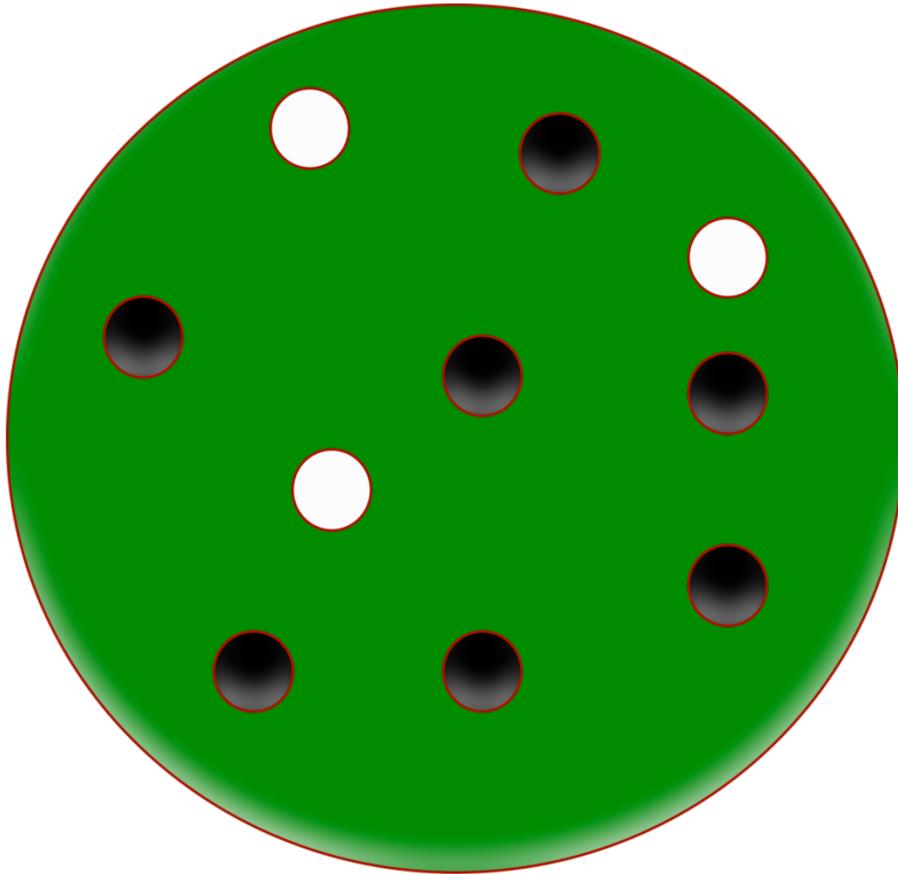
Black daisies like it cool

White daisies like the heat

At early times the star is faint
(like the sun)

Black daisies dominate,
albedo is low, and
temperature rises.

Daisyworld



Black daisies like it cool

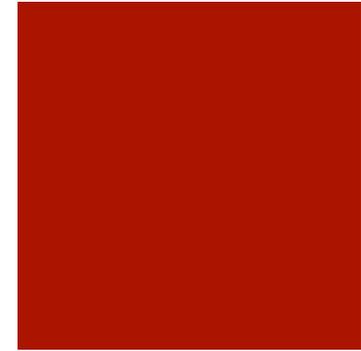
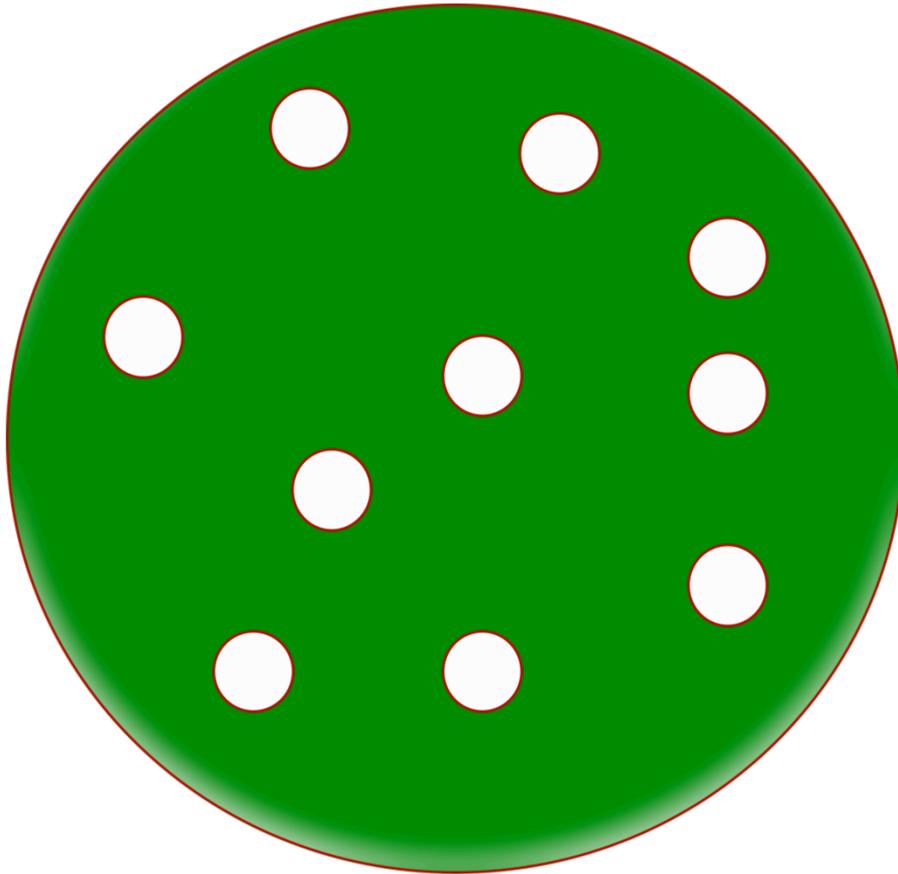
White daisies like the heat

At early times the star is faint
(like the sun)

Black daisies dominate,
albedo is low, and
temperature rises.

White daisies begin to grow,
albedo rises

Daisyworld



Black daisies like it cool

White daisies like the heat

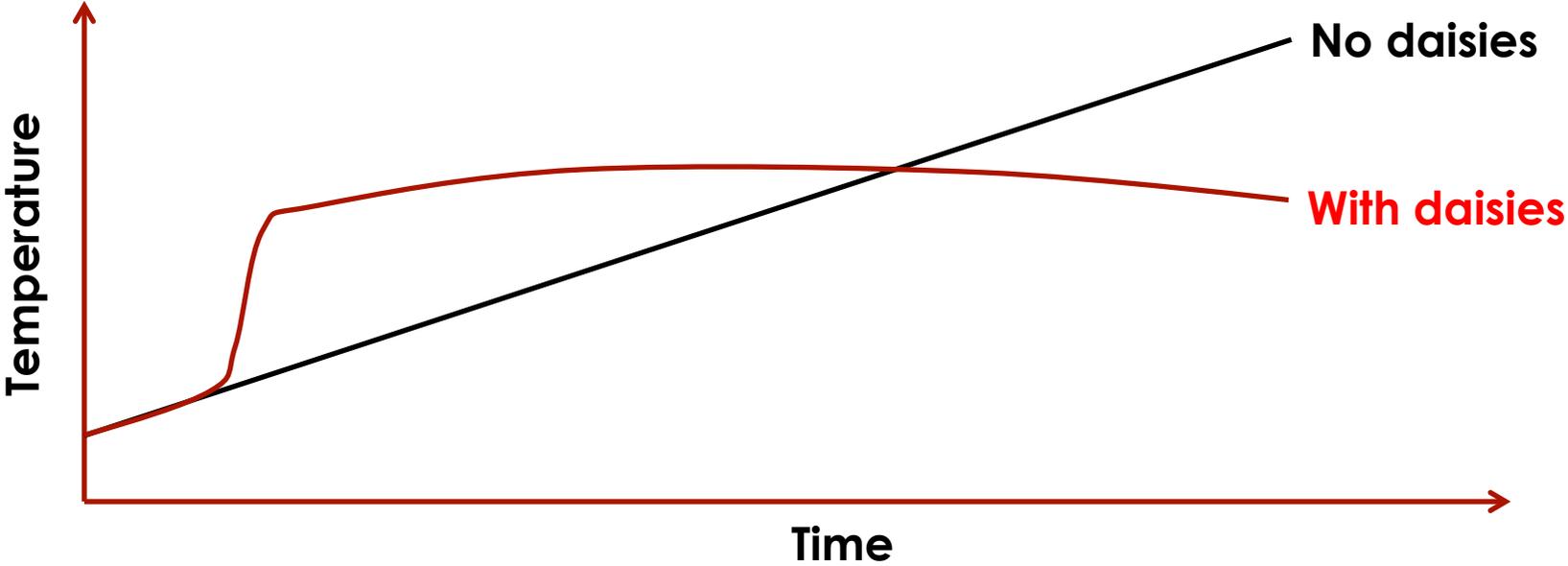
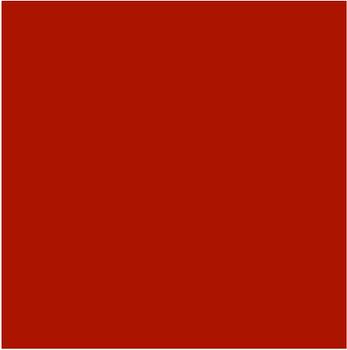
At early times the star is faint
(like the sun)

Black daisies dominate,
albedo is low, and
temperature rises.

White daisies begin to grow,
albedo rises.

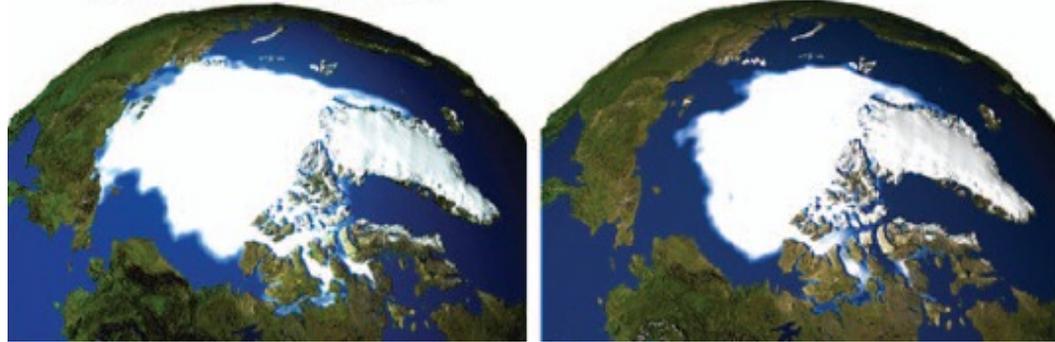
As planet gets much hotter,
white daisies dominate.

Daisyworld

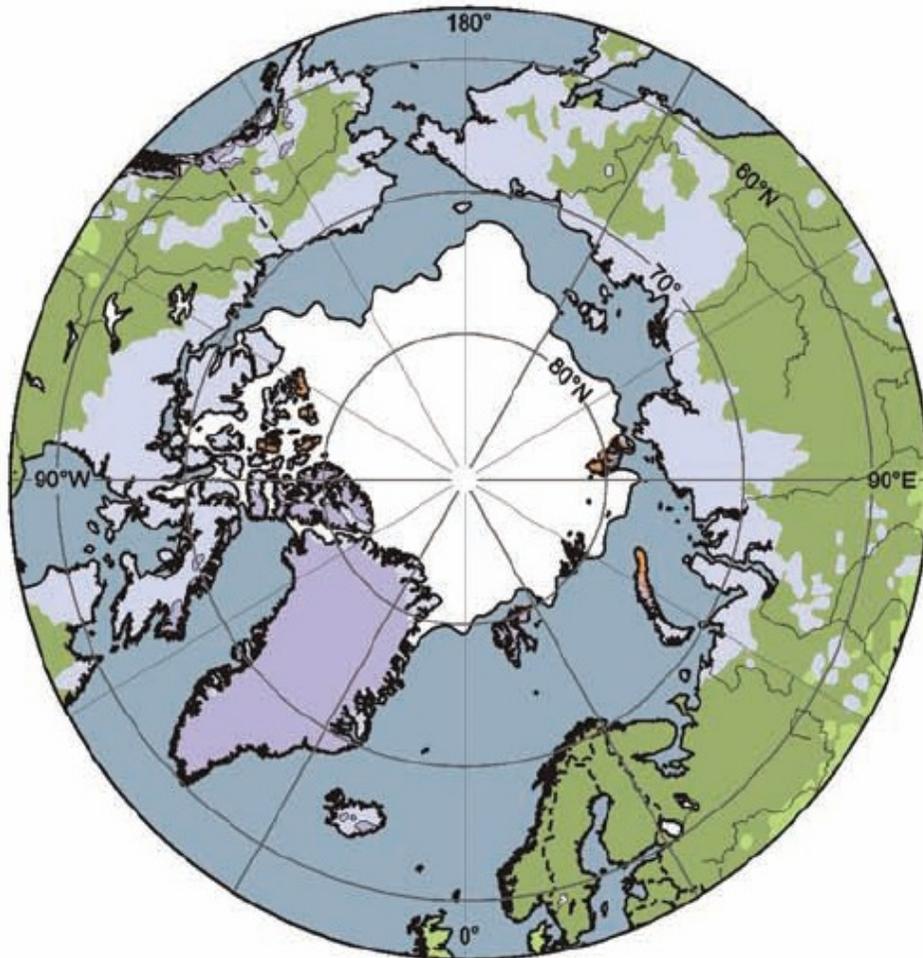


Observed Sea Ice September 1979

Observed Sea Ice September 2005



Current Arctic Conditions



Projected Arctic Conditions

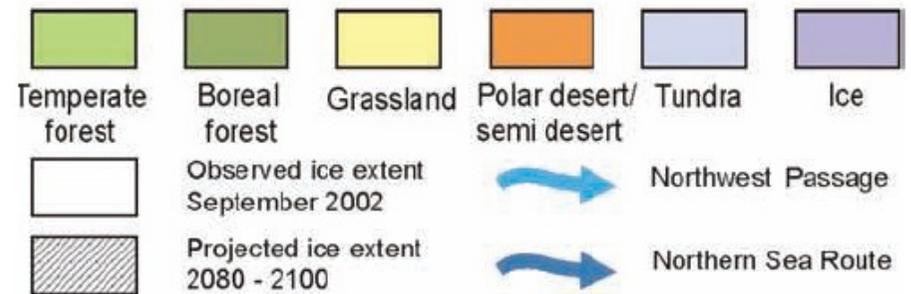
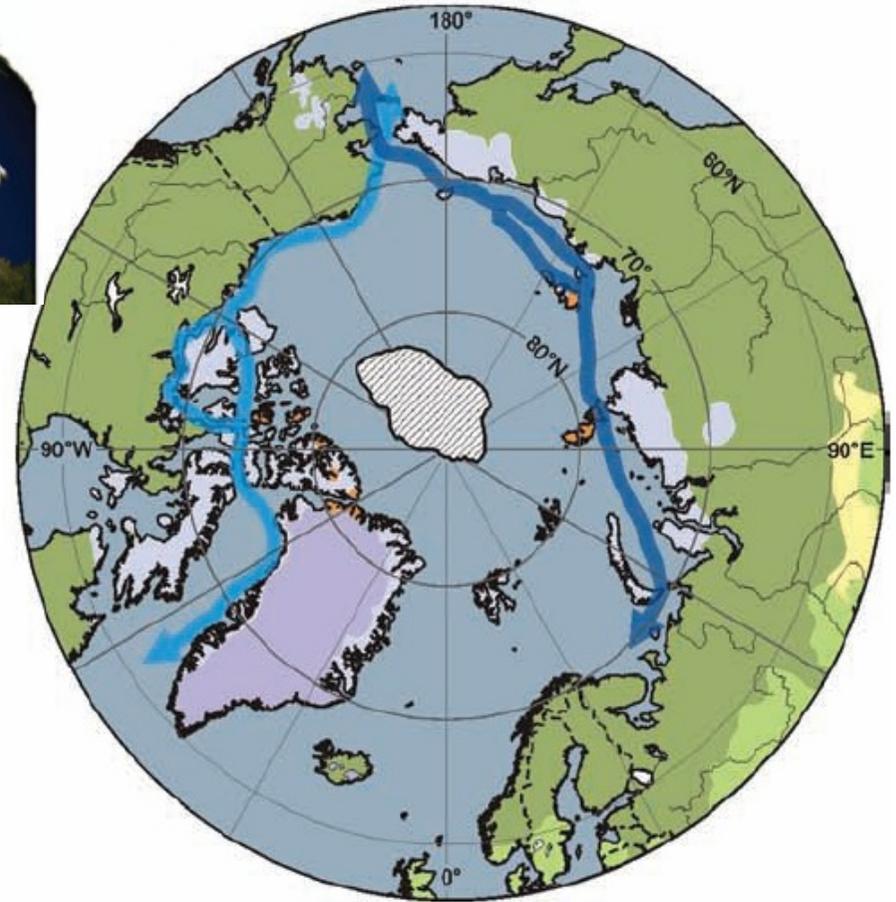
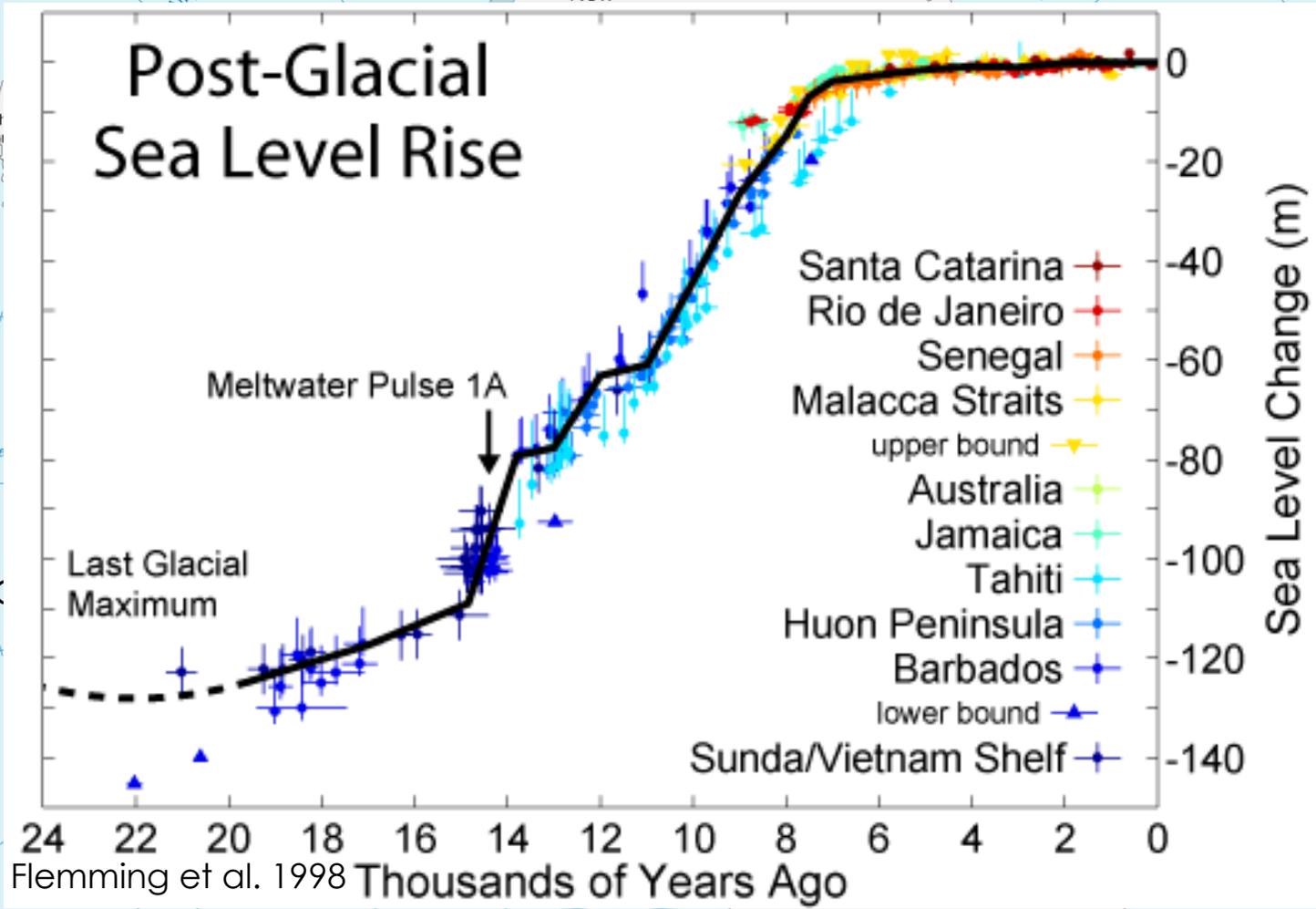
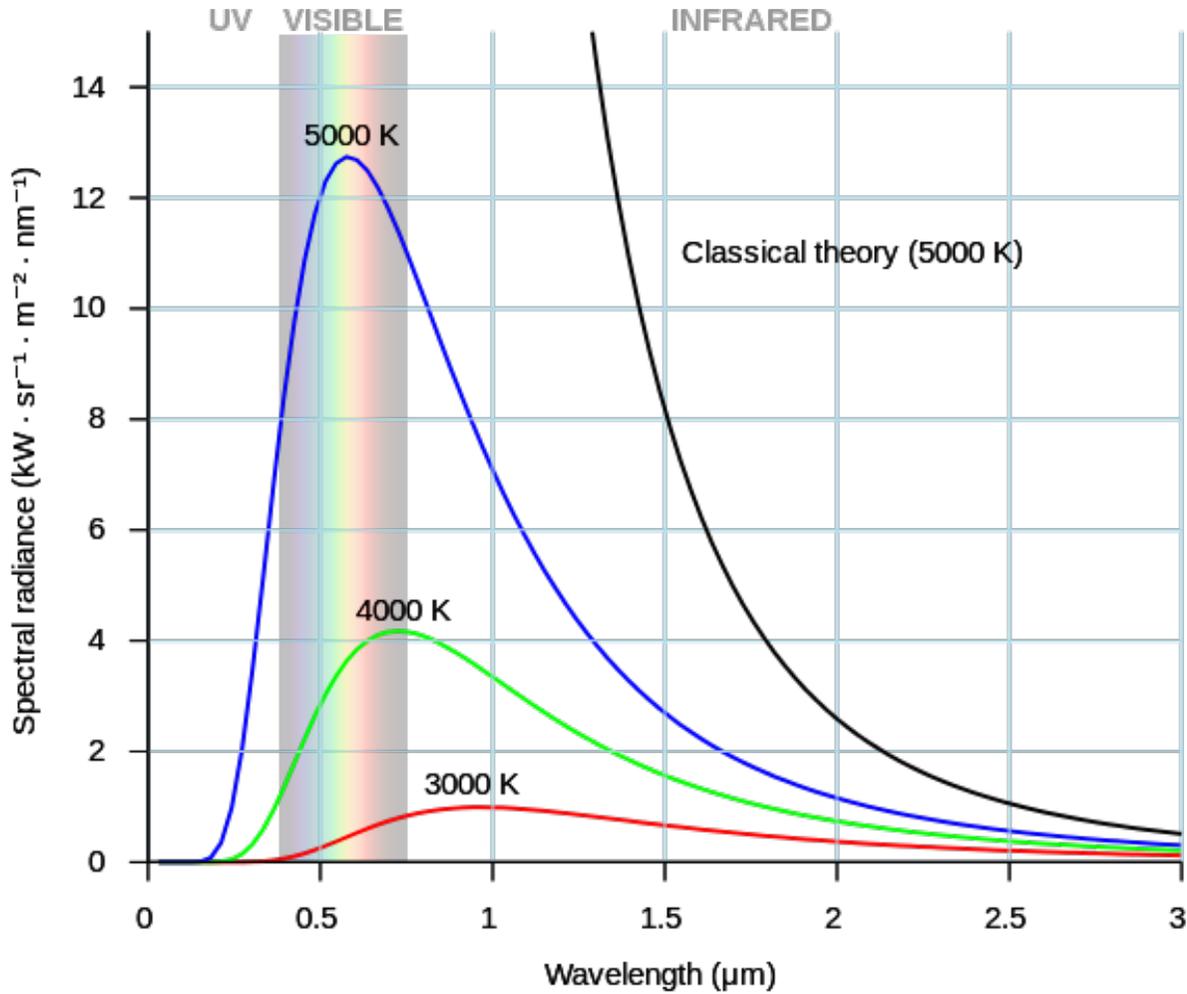
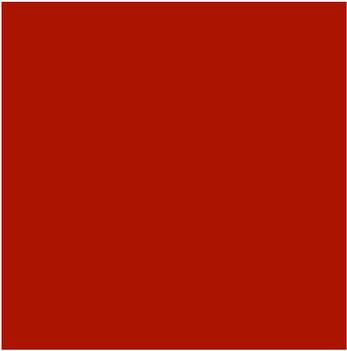


Figure TS.16. Vegetation of the Arctic and neighbouring regions. Top, present-day, based on floristic surveys. Bottom: modelled for 2090-2100 under the IS92a emissions scenario. IF15.21

Ca 6m/sec



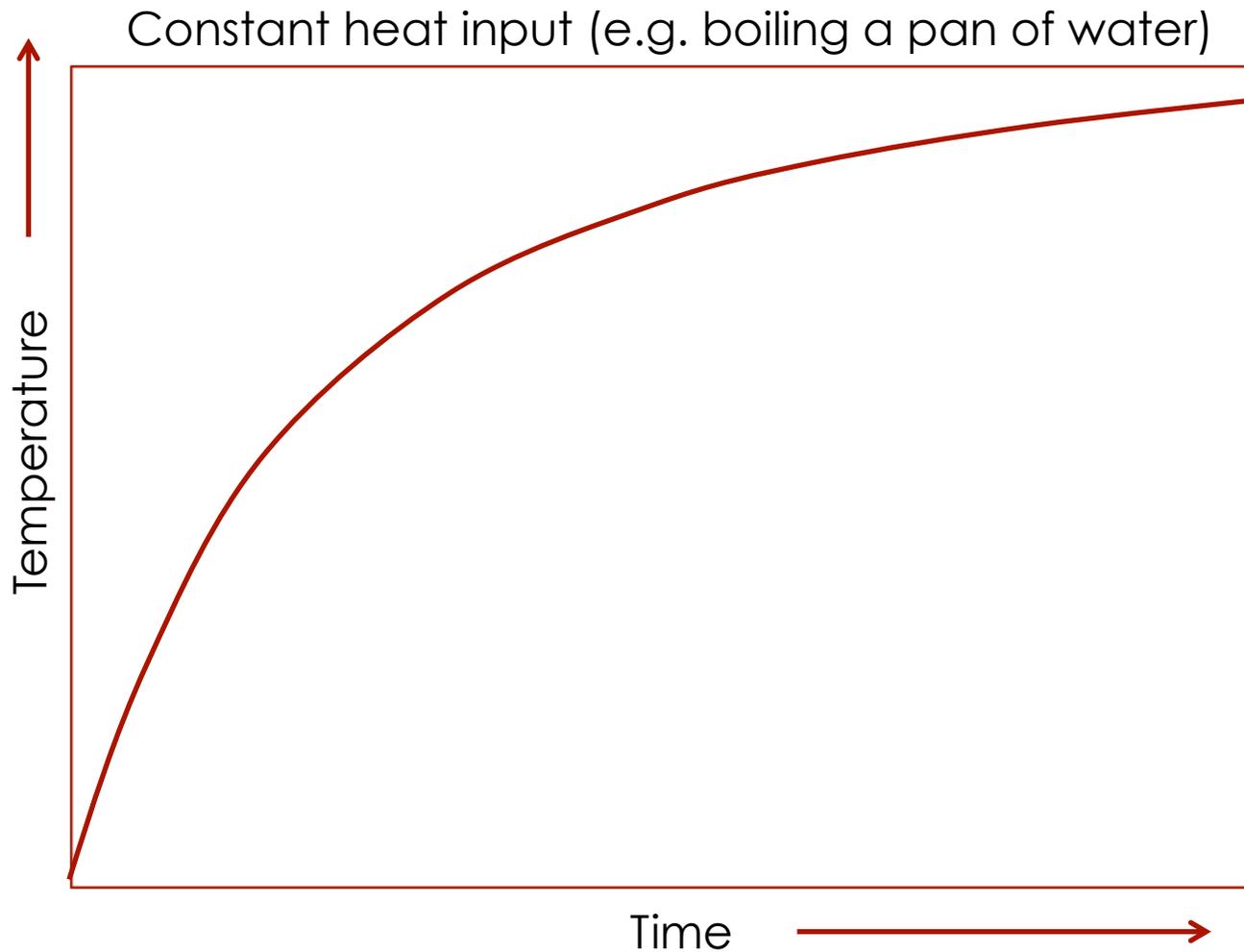
Blackbody feedback



Peak proportional to Temperature

Energy out proportional to T⁴
Note: T in Kelvin

Blackbody feedback



Negative feedback

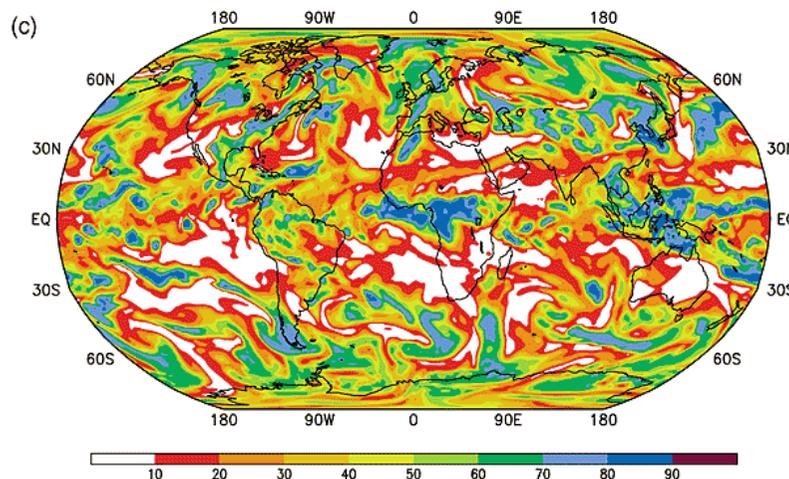
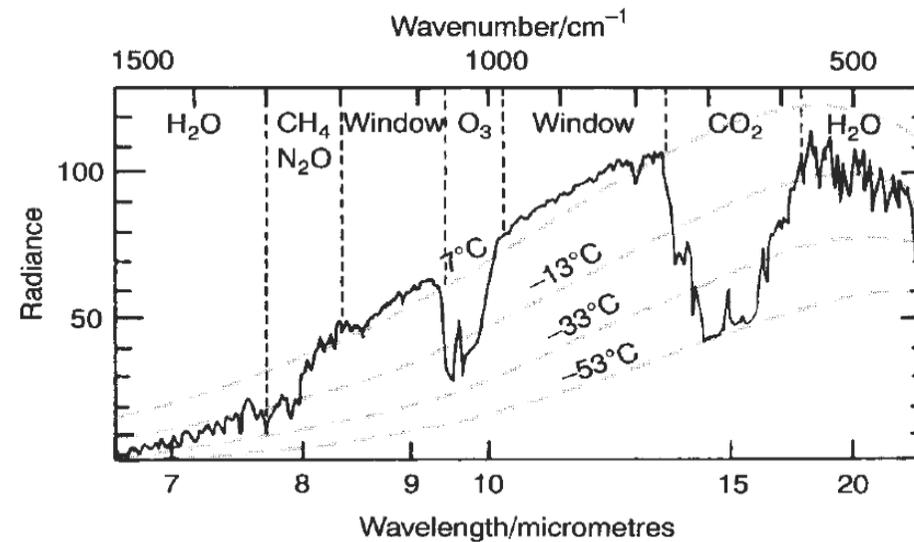
Higher temperatures => Greater energy loss (T^4)

Water Vapour Feedback

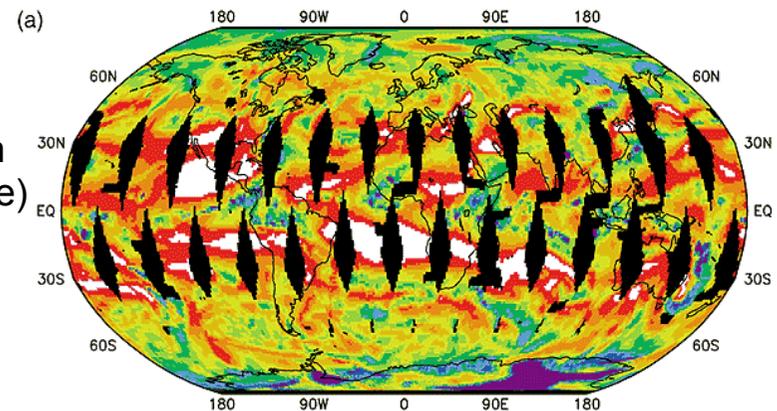
Water vapour is dominant greenhouse gas

Increased water vapour increases absorption in IR

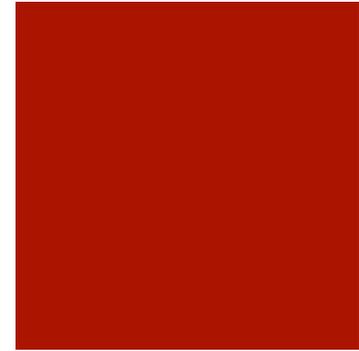
Causes additional increases in temperature



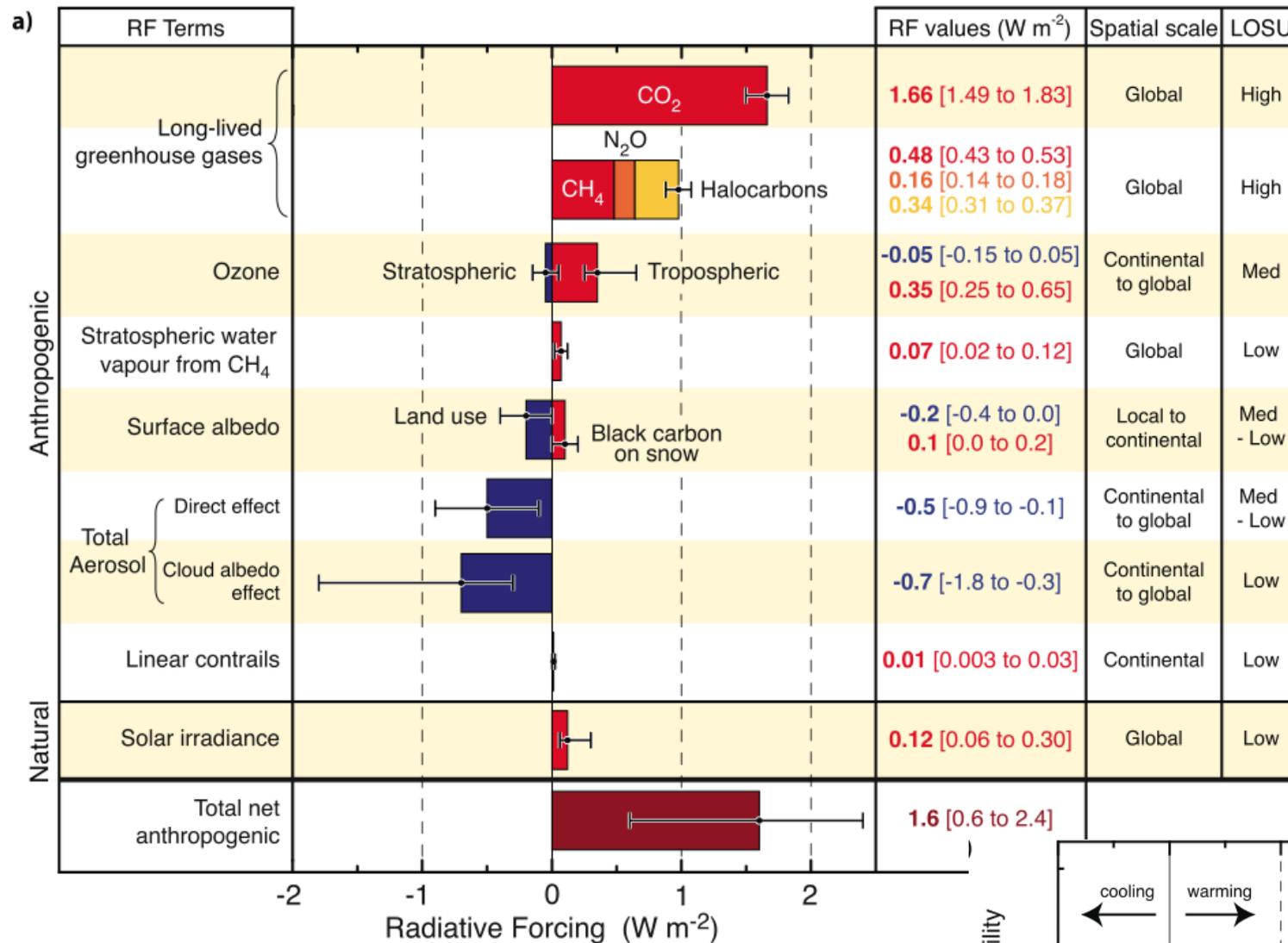
Water saturation
(mid troposphere)
<-Simulation
Observed->



Clouds?

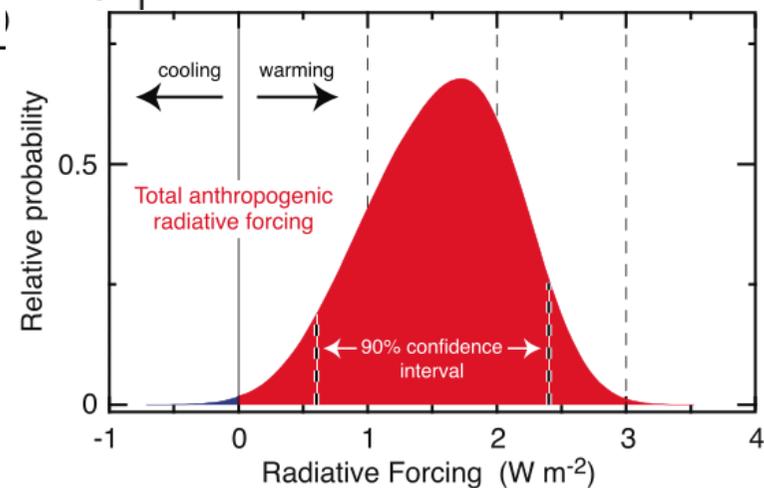


- Complex and controversial
 - Clouds are white, they reflect sunlight (negative feedback)
 - Clouds have high humidity, so lots of water vapour (positive feedback)
- Probably a negative feedback, but level of scientific understanding still poor (but improving, see IPCC AR5).



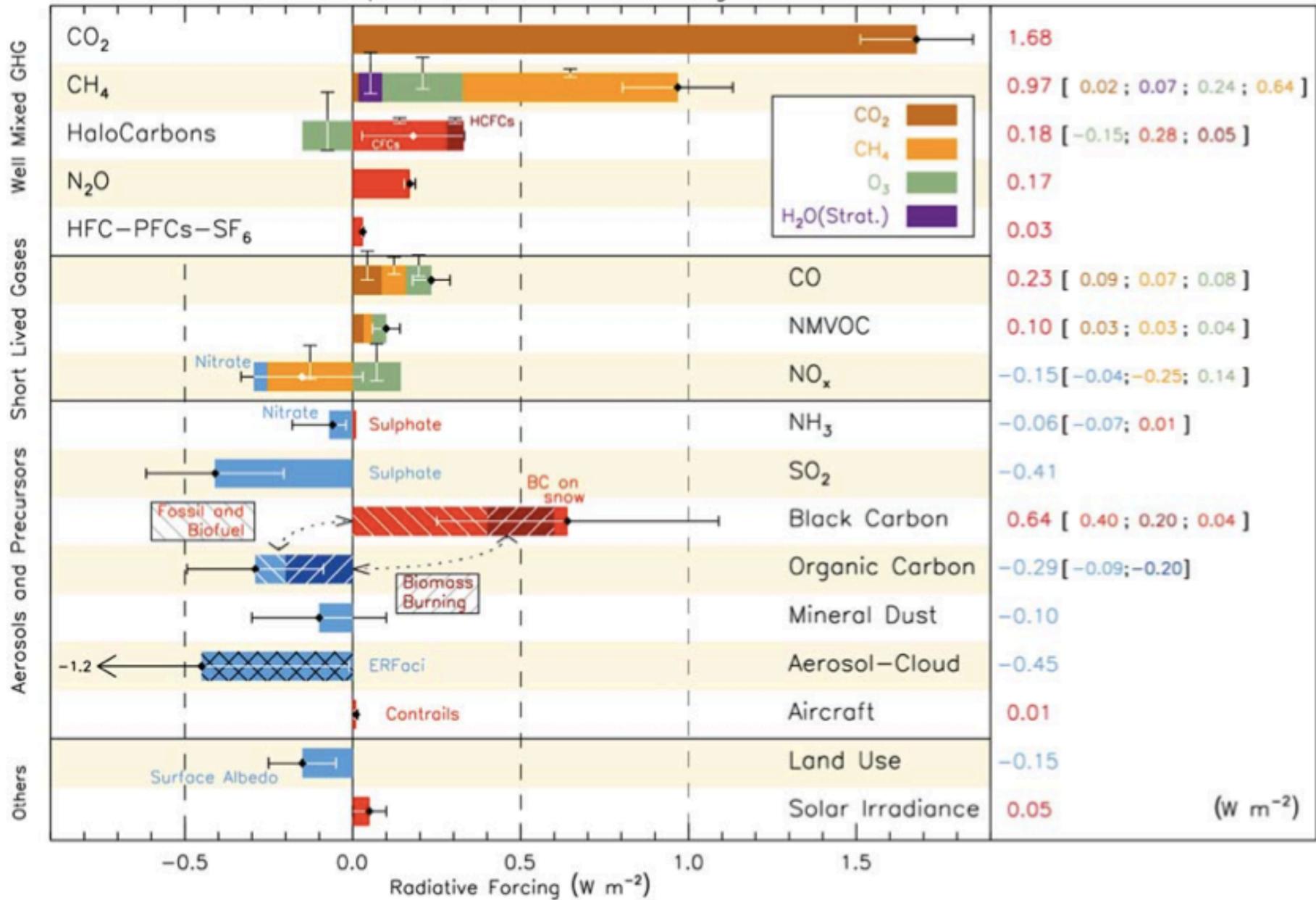
©IPCC 2007: WG1-AR4

Radiative Forcings IPCC AR4 2007

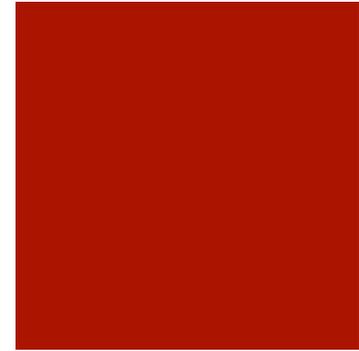


©IPCC 2007: WG1-AR4

Components of Radiative Forcing



“Real” Climate Sensitivity



$$G_0 = \frac{\delta T}{\delta F} = 0.27^\circ \text{ C W}^{-1} \text{ m}^2$$

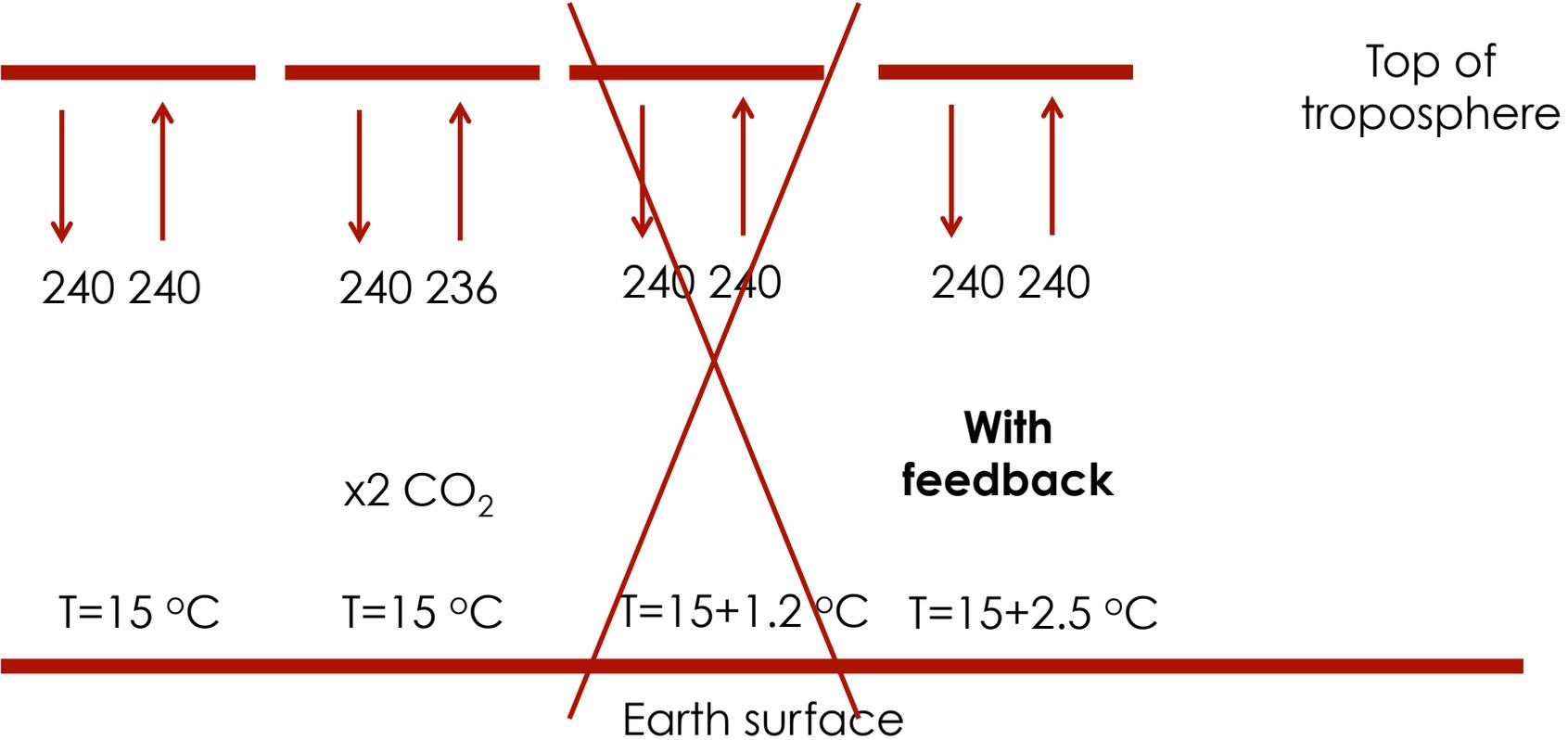
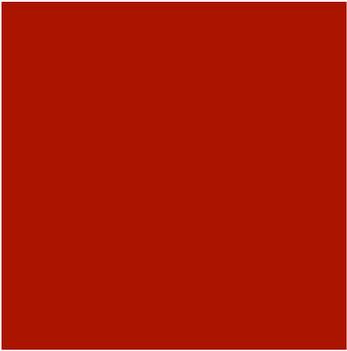
No feedback

$$G_0 = \frac{\delta T}{\delta F} = 0.60^\circ \text{ C W}^{-1} \text{ m}^2$$

With feedback

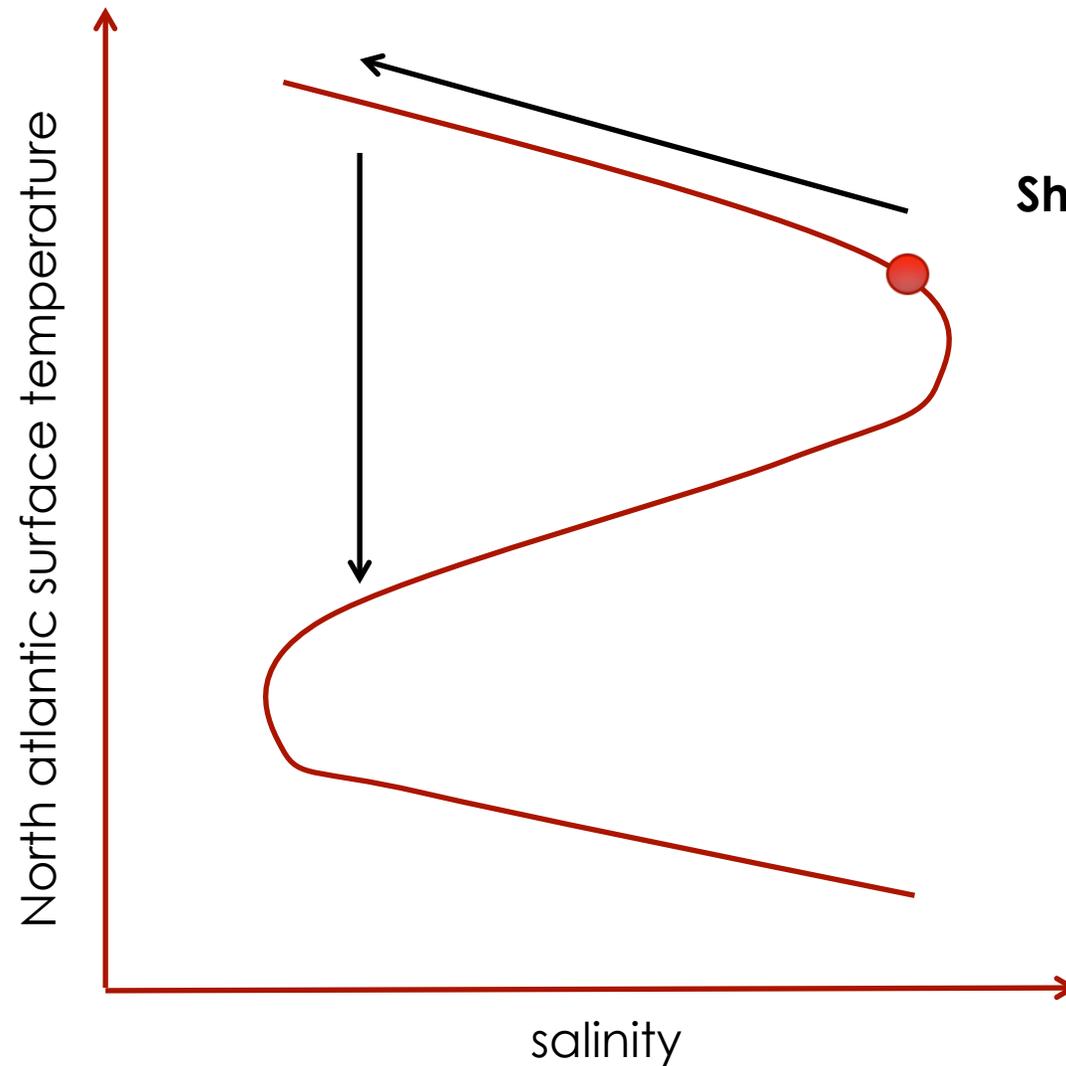
Radiative forcing

- Imbalance in incoming and outgoing radiation



**Pre-industrial CO₂ = 280 ppm,
now = 400 ppm**

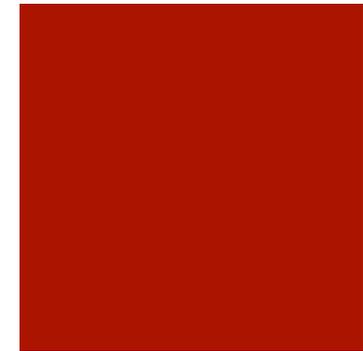
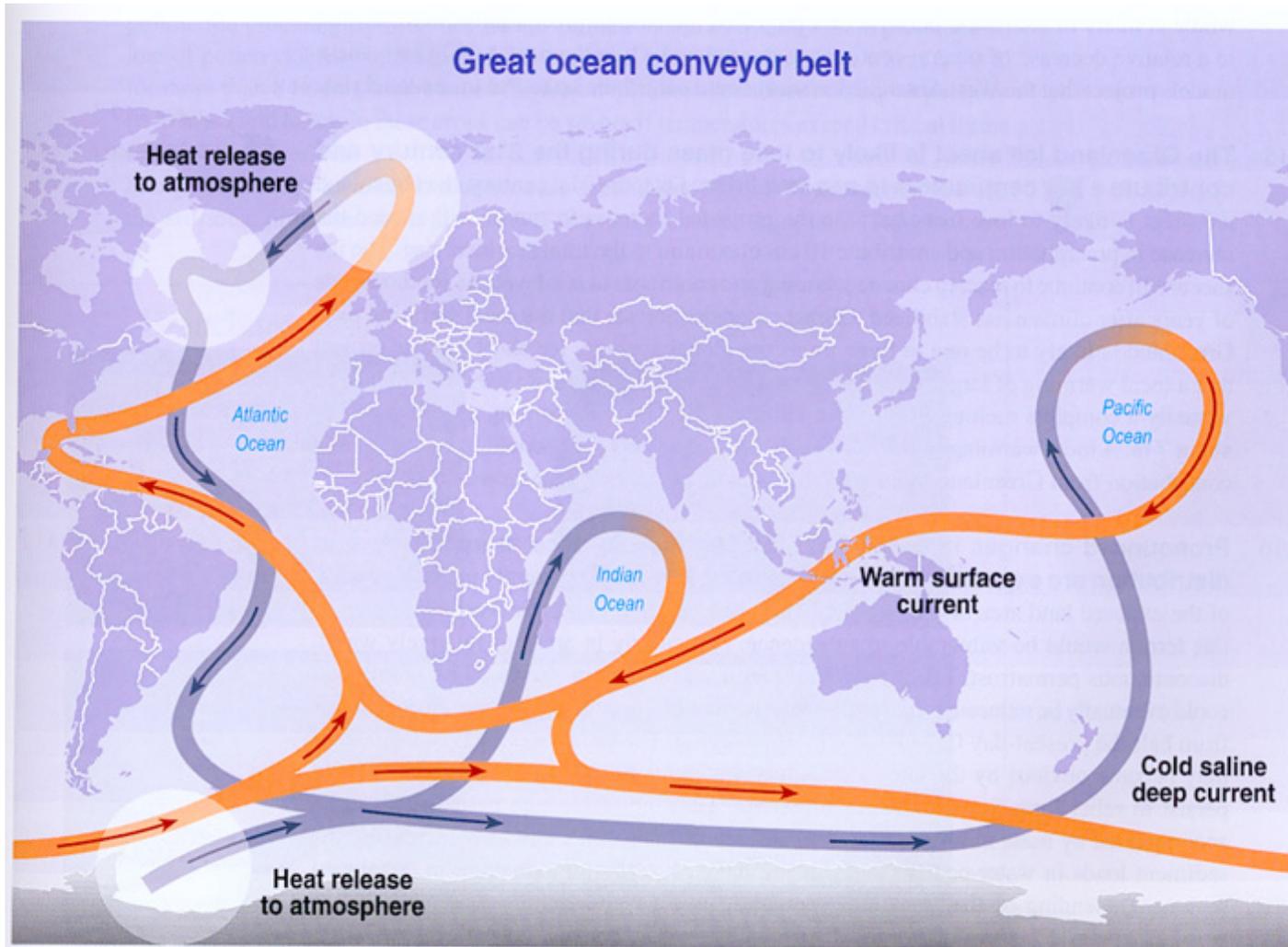
The scary stuff – non-linear feedback



**Shutting down of the
North Atlantic
Thermohaline
circulation**



Ocean Circulations



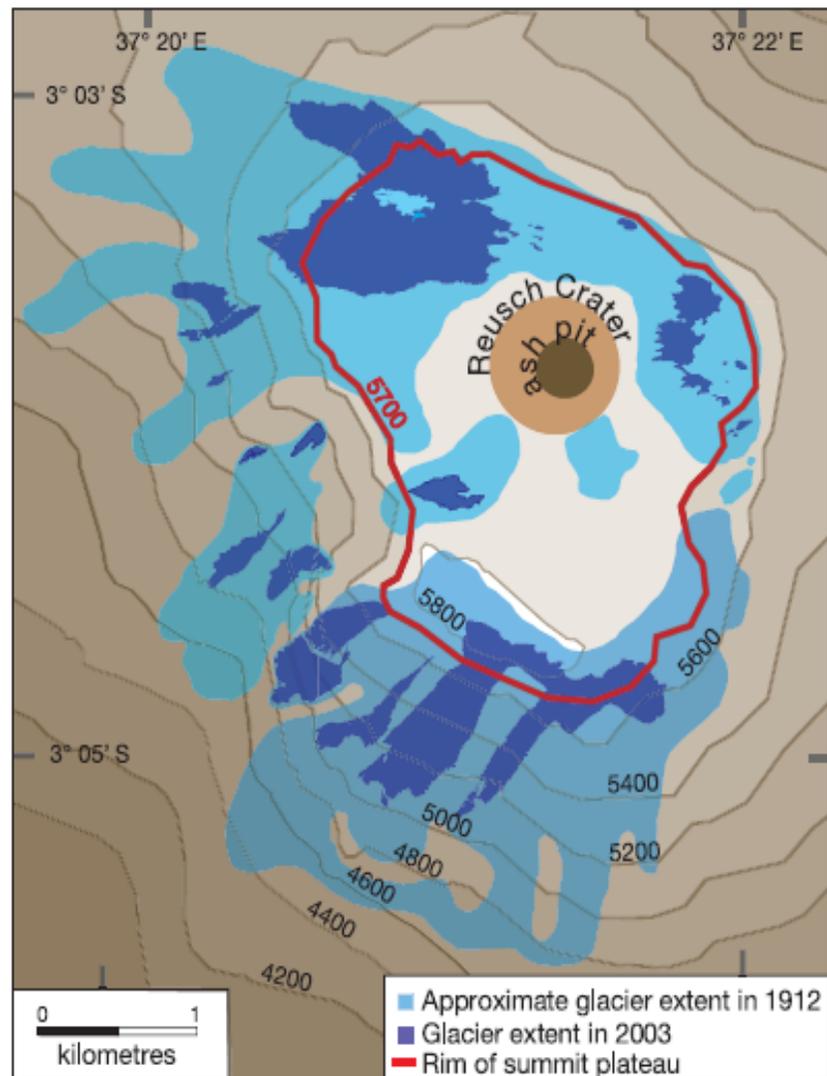


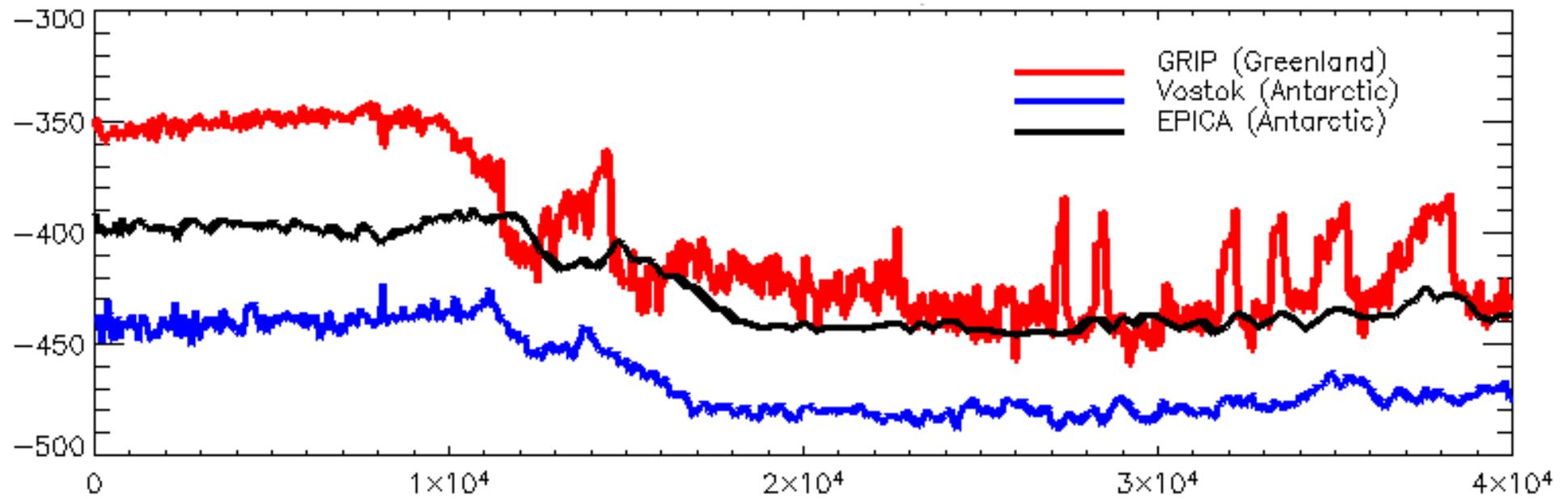
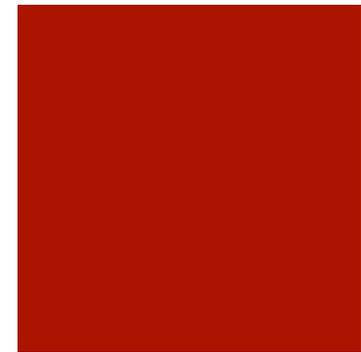
Figure TS.10. Changes in the Mt. Kilimanjaro ice cap and snow cover over time. Decrease in surface area of Kilimanjaro glaciers from 1912 to 2003. [F9.2]



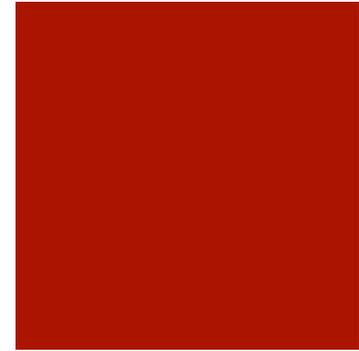
- Modern southern permafrost boundary
- Permafrost area likely to thaw by 2100
- Permafrost area projected to be under different stages of degradation

Figure TS.11. Projected future changes in the northern Asia permafrost boundary under the SRES A2 scenario for 2100. [F10.5]

The younger dryas



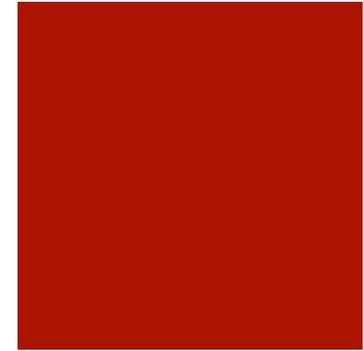
Avoiding “non-linear” events



- The risk of irreversible change increases with temperature rises
 - Vulnerability of ice sheets increases
 - Larger degree of permafrost melting
 - Breakdown of biomass in rainforests
- Smaller rises minimize this risk, 2 degrees is thought to be reasonable (450 ppm CO₂) but there is still much uncertainty (week 4).

Conclusions

- Detailed measurements enable the degree of imbalance between incoming and outgoing radiation from various physical processes to be calculated as a **radiative forcing**
- Anthropogenic changes are amplified by feedbacks, which makes climate **twice as sensitive** to changes as might otherwise be expected.
- Potential for major, and **irreversible** (on the short term) changes exist.

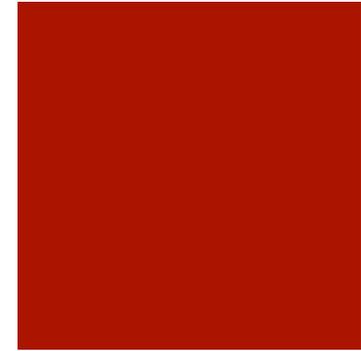




The challenges of climate change

Lecture 4 – Modeling the Climate

Weather is not climate



Daily Express 2013

Worst winter for decades: Record-breaking snow predicted for November

BRITAIN is braced for the "worst winter in decades" with the first major snowfall expected in weeks.

By: [Nathan Rao](#)

Published: Sat, October 12, 2013

 Recommend 475k

 Tweet 4,773

 Share 332

Daily Express (yesterday)

Winter 2014 set to be 'coldest for century' Britain faces ARCTIC FREEZE in just weeks

WINTER 2014 is on track to be the coldest for a century as Britain is just WEEKS AWAY from a crippling ARCTIC FREEZE.

By: [Nathan Rao](#)

Published: Thu, October 9, 2014

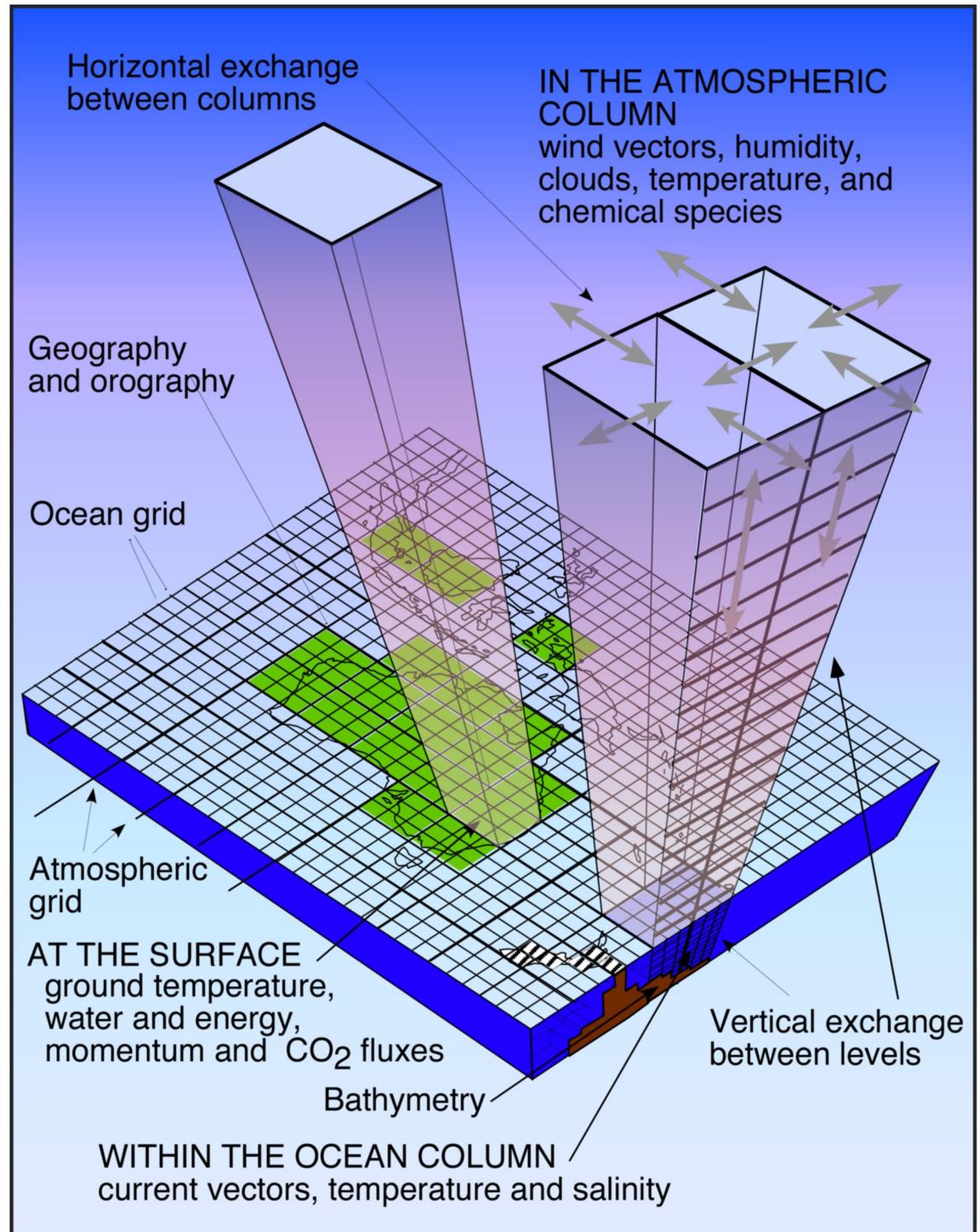
 Recommend 34k

 Tweet 429

 Share 51

Ocean
Atmosphere
General
Circulation
Models
(OAGCM)

AIM: To enable
projections of future
climate



What's in a model

- Basic physics
- Conservation laws
- Equations of state

- Transport of energy via convection/radiation
- Moist processes (evaporation/condensation etc)

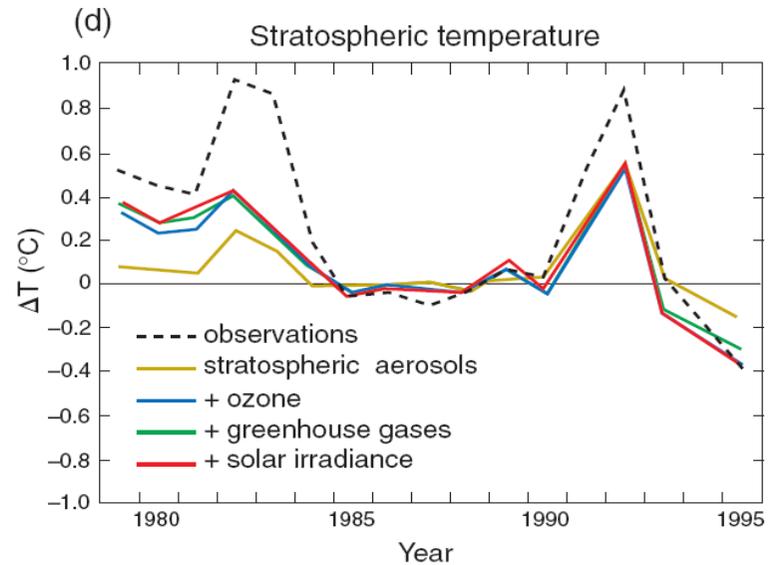
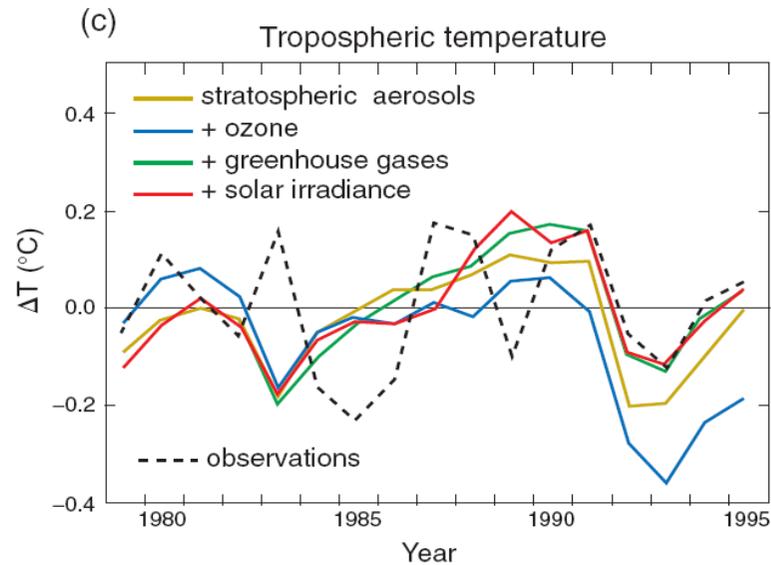
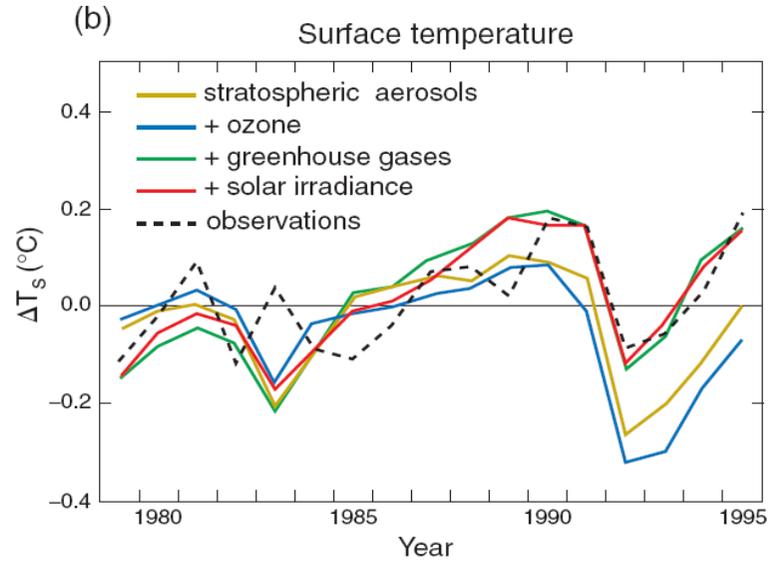
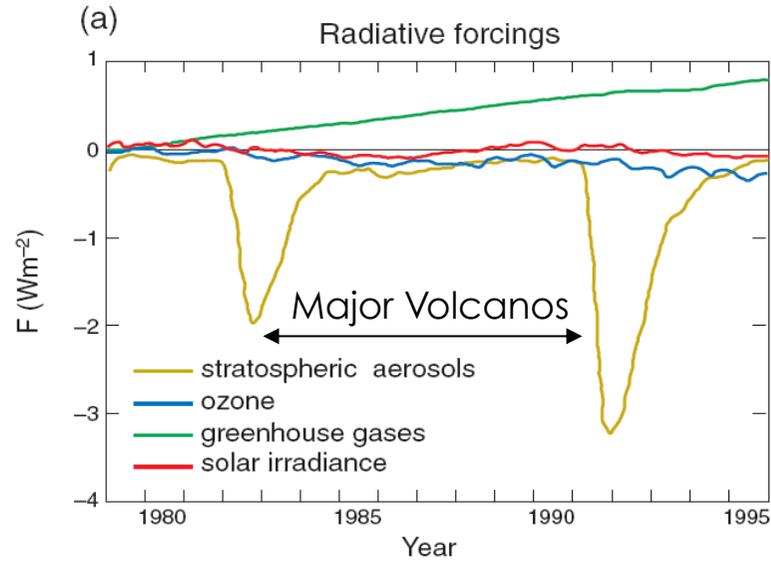
- Geography/resolution



Ab initio

Parameterization

State of art ca 1997



-> Major volcanic eruptions are a visible and predictable perturbation on the climate.

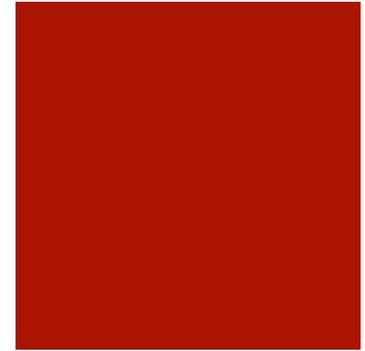
Climate
Weather



Model	Grid length in mid-latitudes	Grid points	Vertical levels	Forecast length	Run times (UTC)	Initial conditions
Global	25 km	1024 x 769	70 (lid ~80 km)	144 hrs (for 00z and 12z)	00, 06, 12, 18	Incremental 4D-Var
North Atlantic European (NAE)	12 km	600 x 360	70 (lid ~80 km)	48 hrs	00, 06, 12, 18	Incremental 4D-Var
UK4	4 km	288 x 360	70 (lid ~40 km)	36 hrs	03, 09, 15, 21	Incremental 3D-Var
UKV	1.5 km inner 4 km outer	744x928	70 (lid ~40 km)	36 hrs	03, 09, 15, 21	Incremental 3D-Var
MOGREPS Global ensemble	60 km	432 x 325	70 (lid ~80 km)	72 hrs	00, 12	Global analysis + 24 member ETKF perturbations
MOGREPS Regional ensemble	18km	400 x 240	70 (lid ~80km)	54 hrs	06, 18	NAE analysis + 24 member perturbations interpolated from global ensemble

Seasonal and climate configurations of the Unified Modelling system				
Configuration	Atmosphere Resolution	Ocean Resolution	Initial Conditions	Typical Run Length
Seasonal	38 levels to 40 km 1.875° x 1.25° ~140 km at mid-latitudes	42 levels 1.0° x 1.0°	Atmos: Met Office global analyses Ocean: data assimilation based on FOAM Sea ice: present-day conditions taken from previous climate model 20th century simulation	40-member ensembles of ~7 month runs, updated monthly
Decadal	19 levels to 40 km 3.75° x 2.5° ~280 km at mid-latitudes	20 levels 1.25° x 1.25°	Atmos: ECMWF global analyses Ocean: data assimilation of observed anomalies	10-member ensembles of ~10 year runs, updated annually
Centennial	38 levels to 40 km 1.875° x 1.25° ~140 km at mid-latitudes	40 levels 1.0° x (1.0° increasing smoothly from 30°N/S to 0.33° at equator)	Atmos: Met Office global analyses representative of current climate Ocean: Levitus present-day observed ocean conditions Sea ice: present-day conditions taken from previous climate model 20th century simulation	~100s years
Earth System	38 levels to 40 km 1.875° x 1.25° ~140 km at mid-latitudes	40 levels 1.0° x (1.0° increasing smoothly from 30°N/S to 0.33° at equator)	Atmos: Met Office global analyses representative of current climate Ocean: Levitus present-day observed ocean conditions Sea ice: present-day conditions taken from previous climate model 20th century simulation	~100s years
Regional climate	19 levels 0.22° x 0.22° (~24km) to 0.44° x 0.44° (~50km) limited area	-	Met Office global analyses; ECMWF reanalyses used at lateral boundaries	~10 years, or up to 150 years for climate change runs

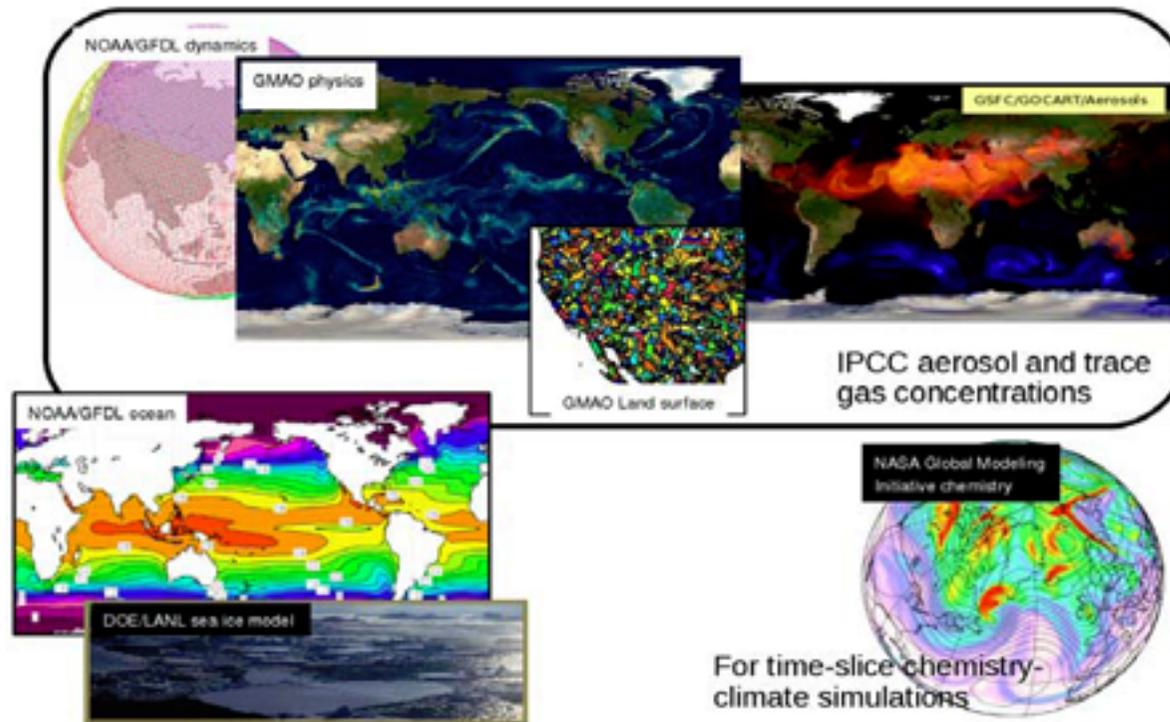
State of the art ~today



State of the art ~today

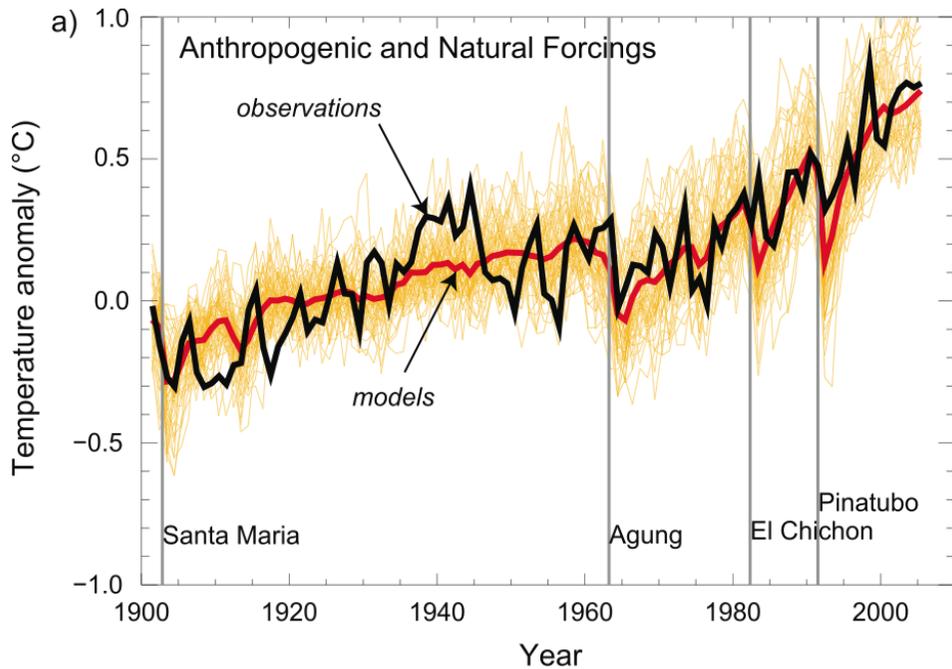
Models are highly advanced (e.g. GEOS-5) BUT still fail to match some detailed measurements

GEOS-5 Model



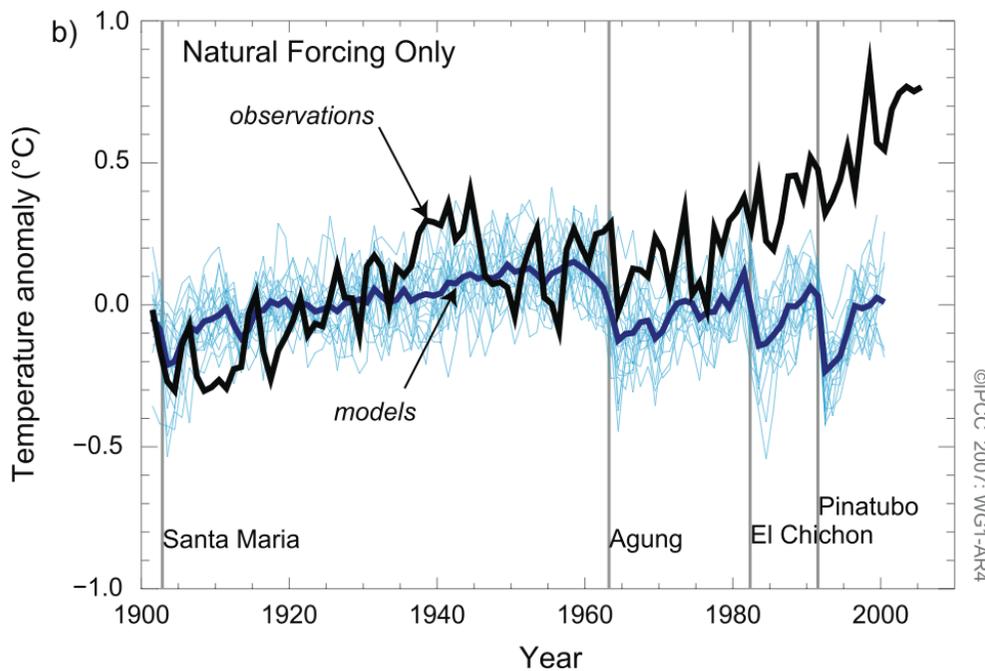
.....These errors include: too strong surface wind stress in high latitudes; too strong cloud radiative forcing in low latitudes, and too weak cloud radiative forcing in high latitudes; errors in precipitation typical of most state-of-the-art climate models, e.g., a strong double Inter-Tropical Convergence Zone (ITCZ). (Vikhliav et al. GEOS-5)

http://gmao.gsfc.nasa.gov/GEOS/geos5/geos5_research/CTB_seminar_11_2010.php



“Warming of the climate is unequivocal”, “It is extremely likely that human influence has been the dominant cause of the observed warming”

IPCC 2013



“Greenhouse gas forcing has very likely [90%] caused most of the observed global warming over the last 50 years.”

IPCC 2007

*....likely [67%]..
IPCC 2001*

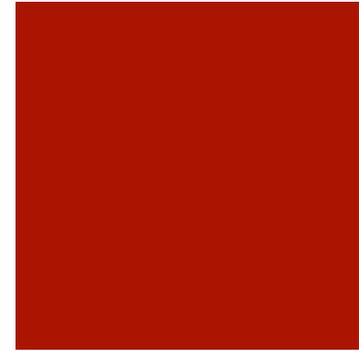
IPC 2007

©IPCC 2007: WG1-AR4

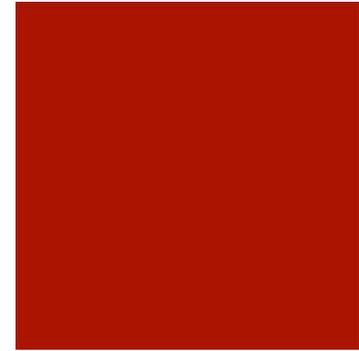
Inevitable Problems of projection

- Even with a perfect model:
 - Anthropogenic changes in future climate depend on human activity – need different scenarios (SRES)

- Some natural variations (e.g. volcanoes) are unpredictable, so can't be easily folded in.

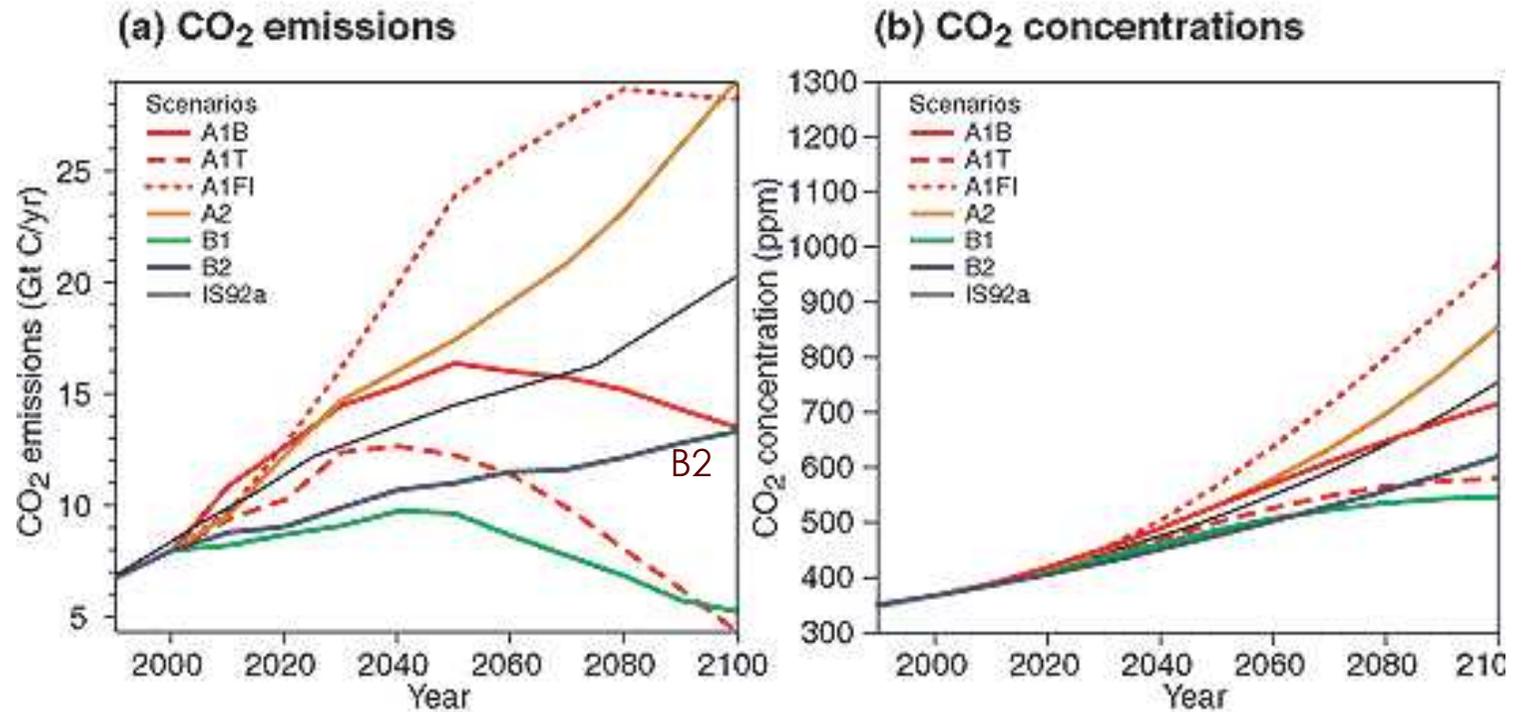


Potentially soluble problems with projection



- Garbage in = Garbage out (GIGO)
- Real world is complex
 - Geography
 - Ocean cycles (El Nino etc)
- Real physics is complicated and not all well understood.
 - Water
 - Radiative transfer

Special Report on Emissions Scenarios



1. Population peaks mid century.

A1: technology-led economy,
F fossil fuels vs (B “balanced”) vs T non-fossil fuelled.

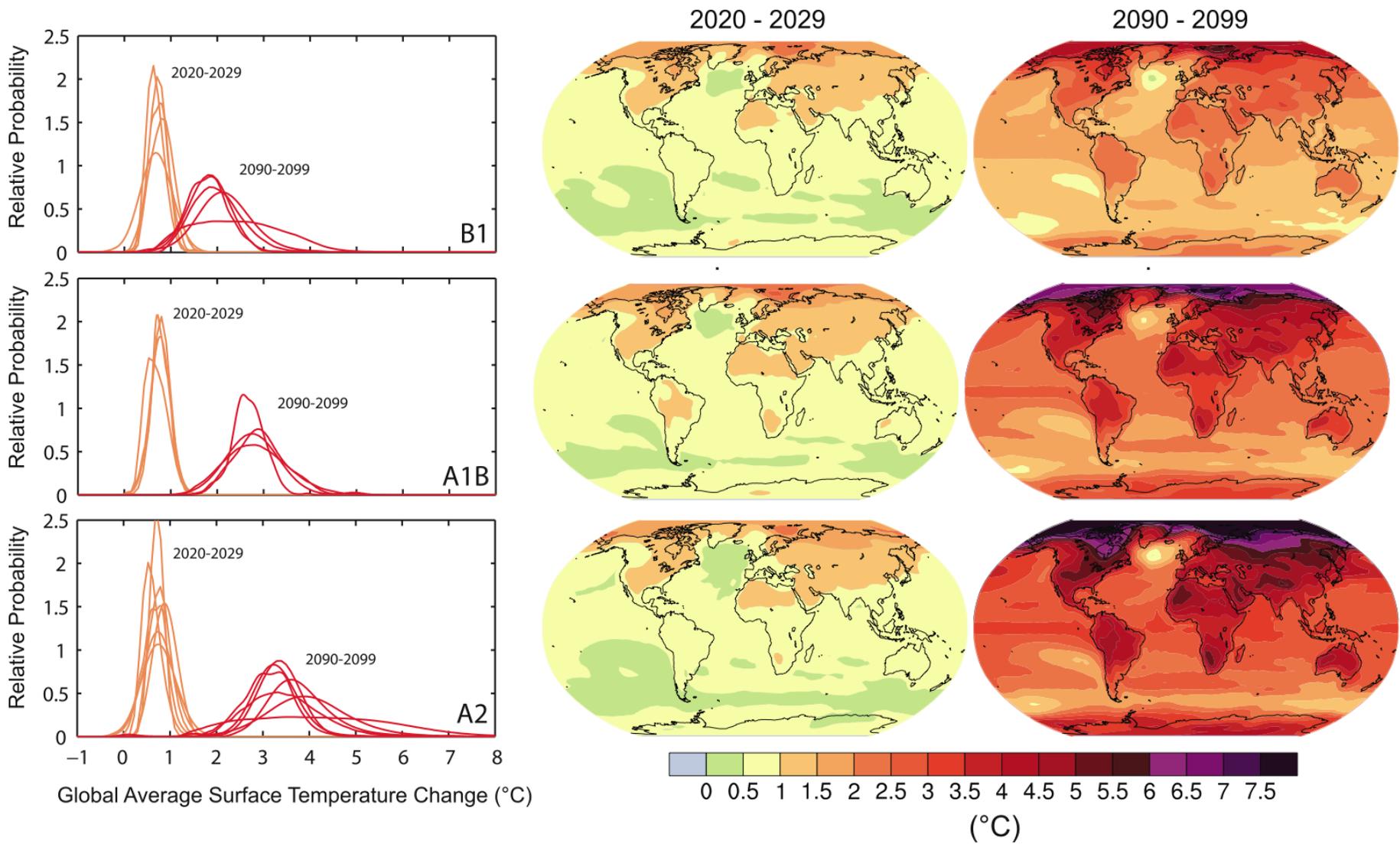
B1: info & service economy; sustainability & global sol’ns.

2. Population continues to increase.

A2: very heterogeneous world (“business as usual”)

B2: lower growth rate; emphasis on local solutions (smart but *laissez-faire*)

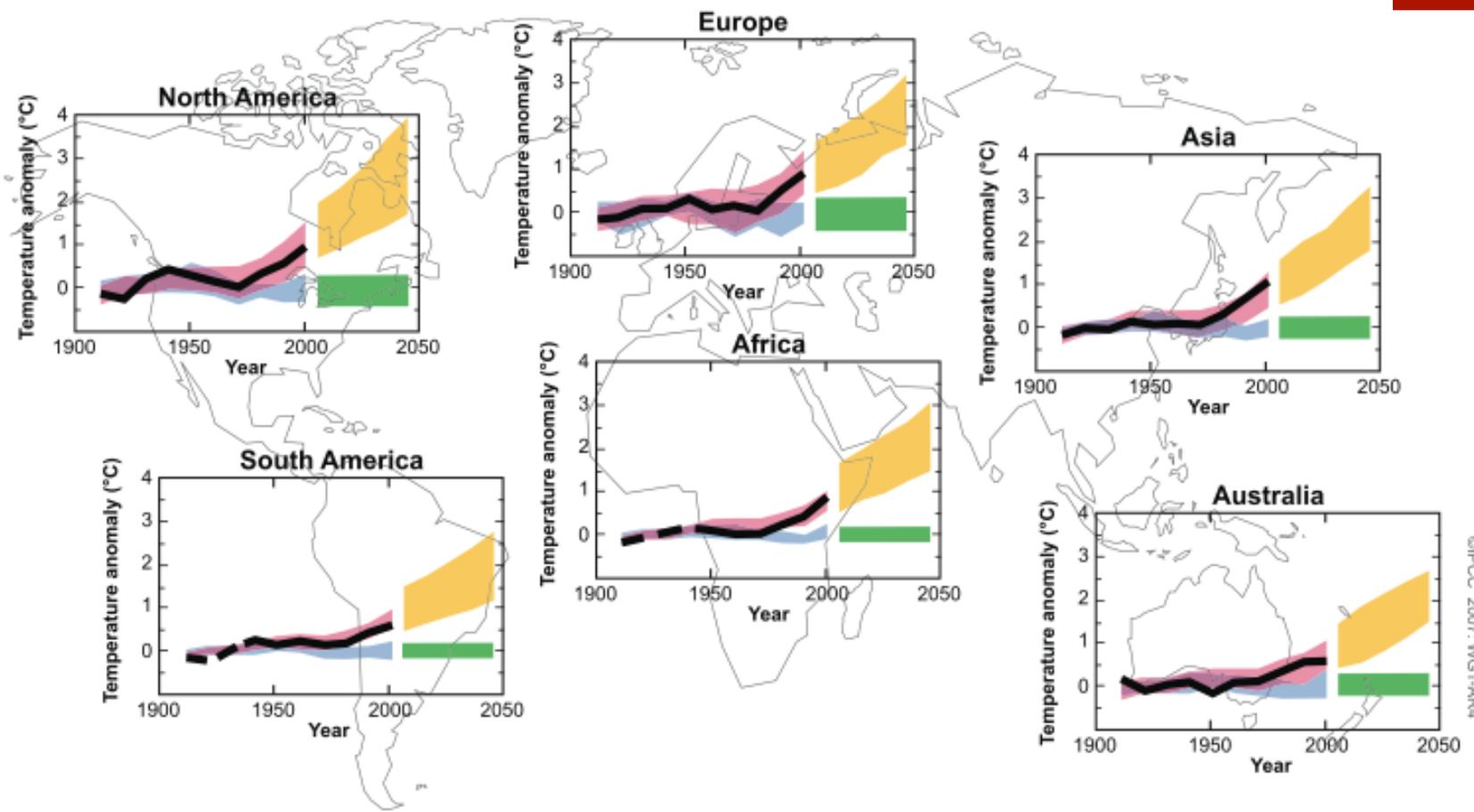
not predictions, but a range of plausible assumptions



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IPCC 2007: Scenario -> OAGCM -> Climate prediction

Phenomenon ^a and direction of trend	Likelihood that trend occurred in late 20th century (typically post-1960)	Likelihood of a human contribution to observed trend	D	Likelihood of future trend based on projections for 21st century using SRES ^b scenarios
Warmer and fewer cold days and nights over most land areas	<i>Very likely^c</i>	<i>Likely^e</i>	★	<i>Virtually certain^e</i>
Warmer and more frequent hot days and nights over most land areas	<i>Very likely^d</i>	<i>Likely (nights)^e</i>	★	<i>Virtually certain^e</i>
Warm spells / heat waves: Frequency increases over most land areas	<i>Likely</i>	<i>More likely than not</i>		<i>Very likely</i>
Heavy precipitation events. Frequency (or proportion of total rainfall from heavy falls) increases over most areas	<i>Likely</i>	<i>More likely than not</i>		<i>Very likely</i>
Area affected by droughts increases	<i>Likely in many regions since 1970s</i>	<i>More likely than not</i>	★	<i>Likely</i>
Intense tropical cyclone activity increases	<i>Likely in some regions since 1970</i>	<i>More likely than not</i>		<i>Likely</i>
Increased incidence of extreme high sea level (excludes tsunamis) ^f	<i>Likely</i>	<i>More likely than not^g</i>		<i>Likely^h</i>



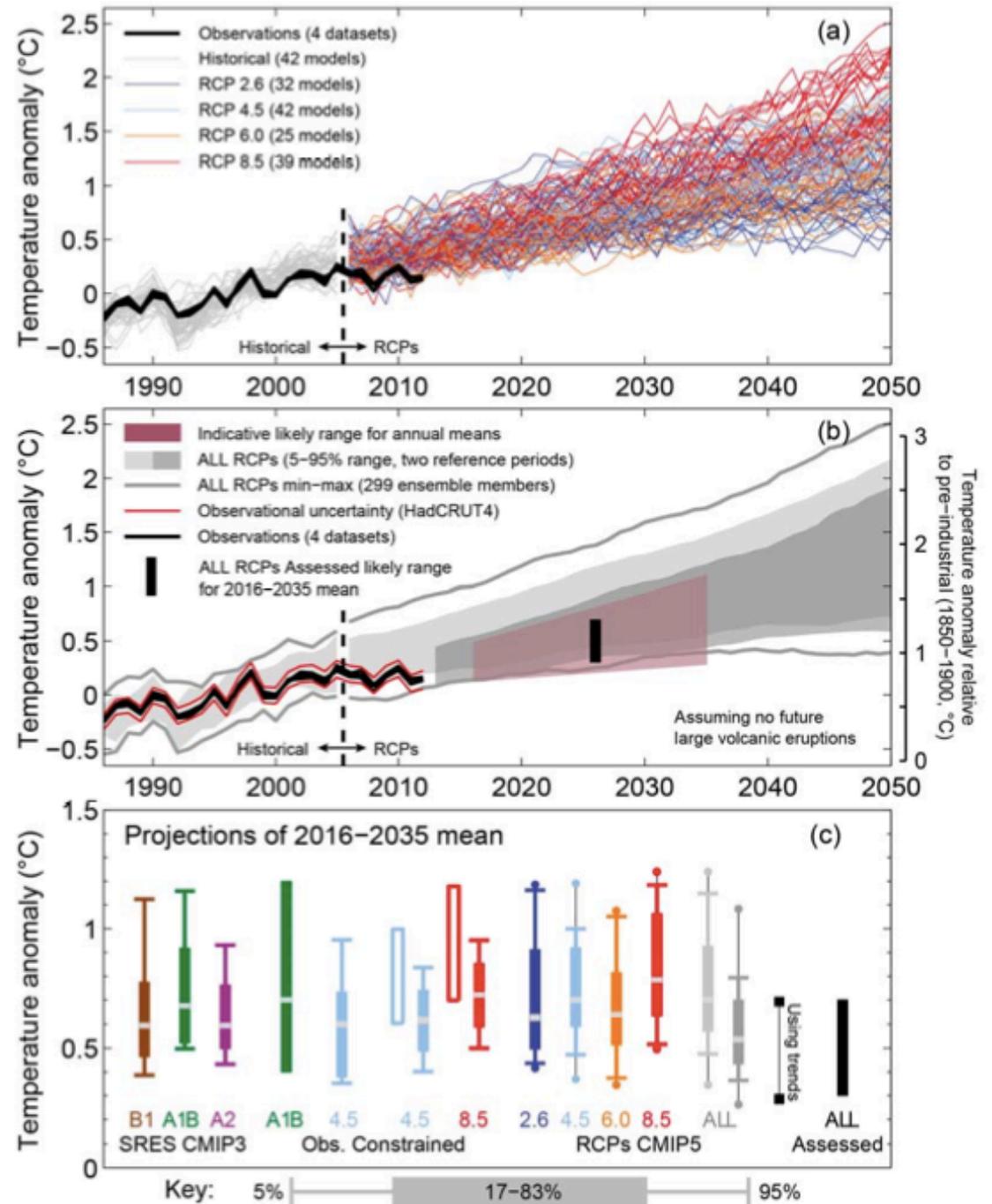
models using natural forcing only
 projected changes (A1B scenario)
 observations

models using both anthropogenic and natural forcings
 range of anomalies with natural forcing only in 20th century simulations

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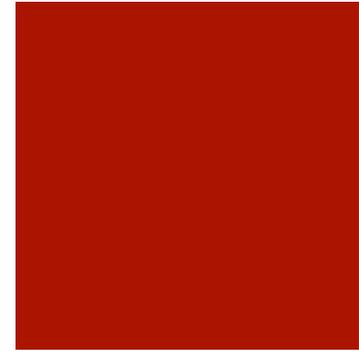
The last 20 years

Global mean temperature near-term projections relative to 1986–2005



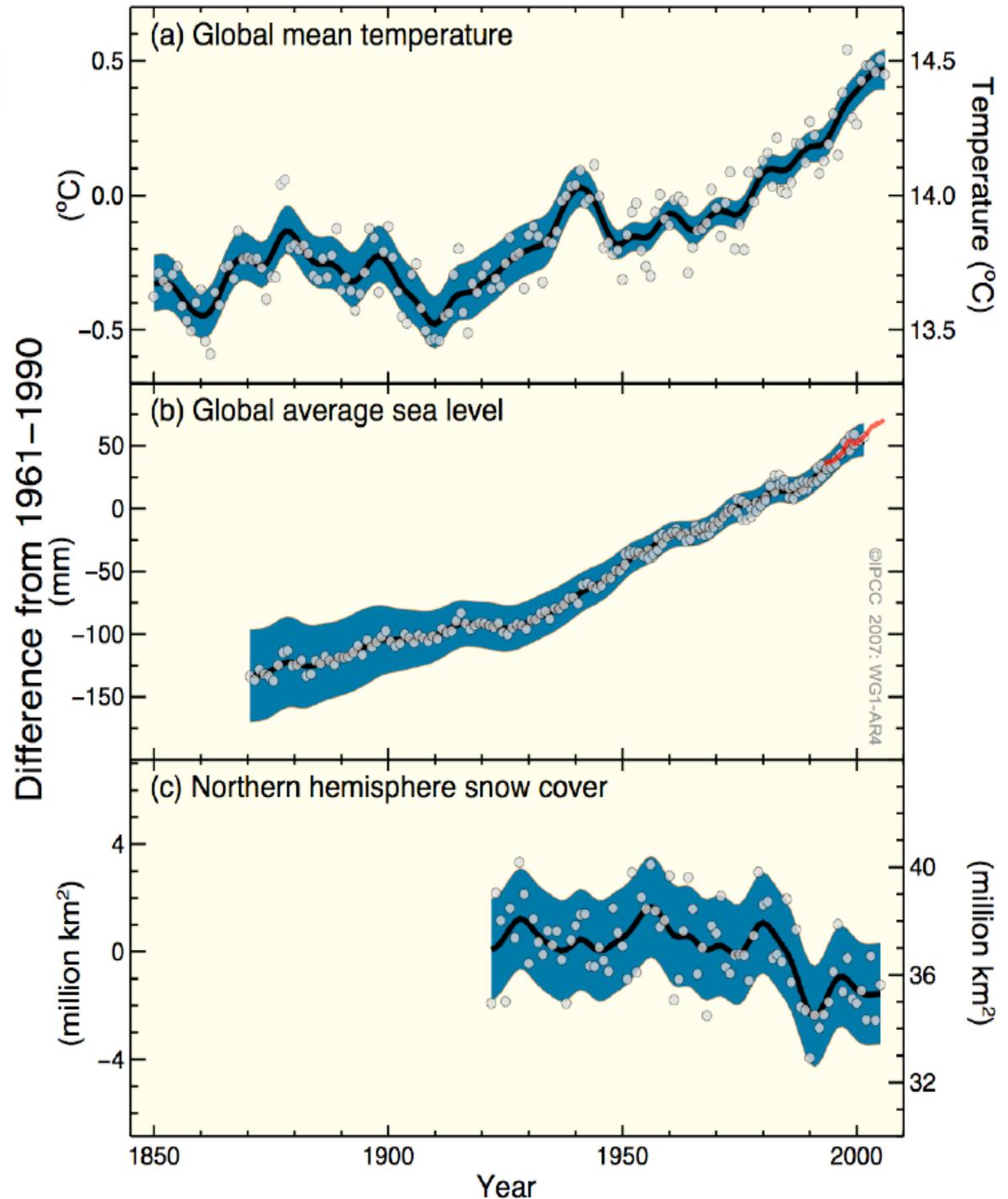
Hallmarks of real warming

- Carbon dioxide and other greenhouse gases can have their radiative forcing directly measured.
- Stratospheric cooling, more heat is being returned to Earth than escapes.
- The re-radiated IR emission has been directly observed.
- Models only re-create recent past temperature trends with the addition of anthropogenic forcing
- Nights are warming faster than days
- The ocean is warming from the top down



Not only global warming

- Sea level rises – loss of habitat, fish spawning grounds etc.
- CO₂ absorbed in the ocean causes acidification
- More on implications next lecture.

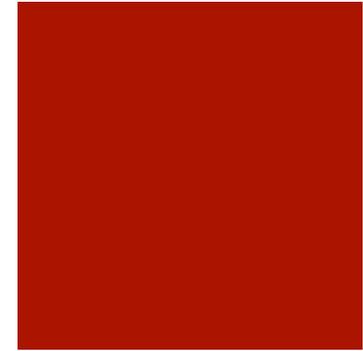


Doubting voices

- Massive, non-anthropogenic climate change has occurred in the past, and will happen in the

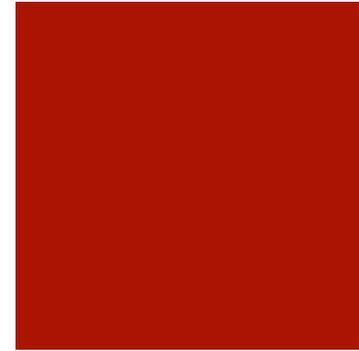
■ **Think about how you might now answer these critics**

- Evidence for recent warming depends critically on the data and time range chosen.
- There is insufficient evidence to conclude that anthropogenic global warming is occurring.



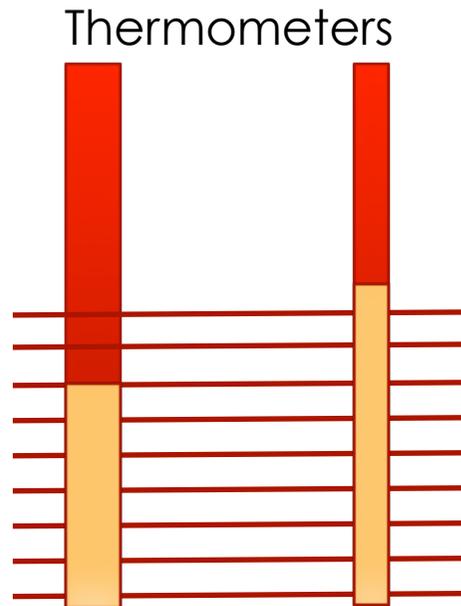
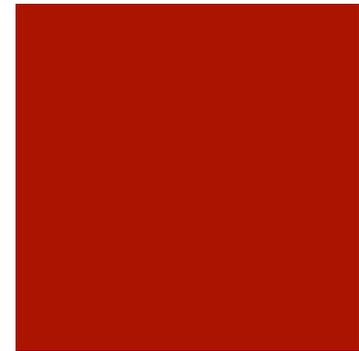
Justifiable concerns?

- Statistical and systematic errors on direct measurement
- Baselines for temperature proxies
- Attribution
- Past performance is not a good guide to future return



Real data

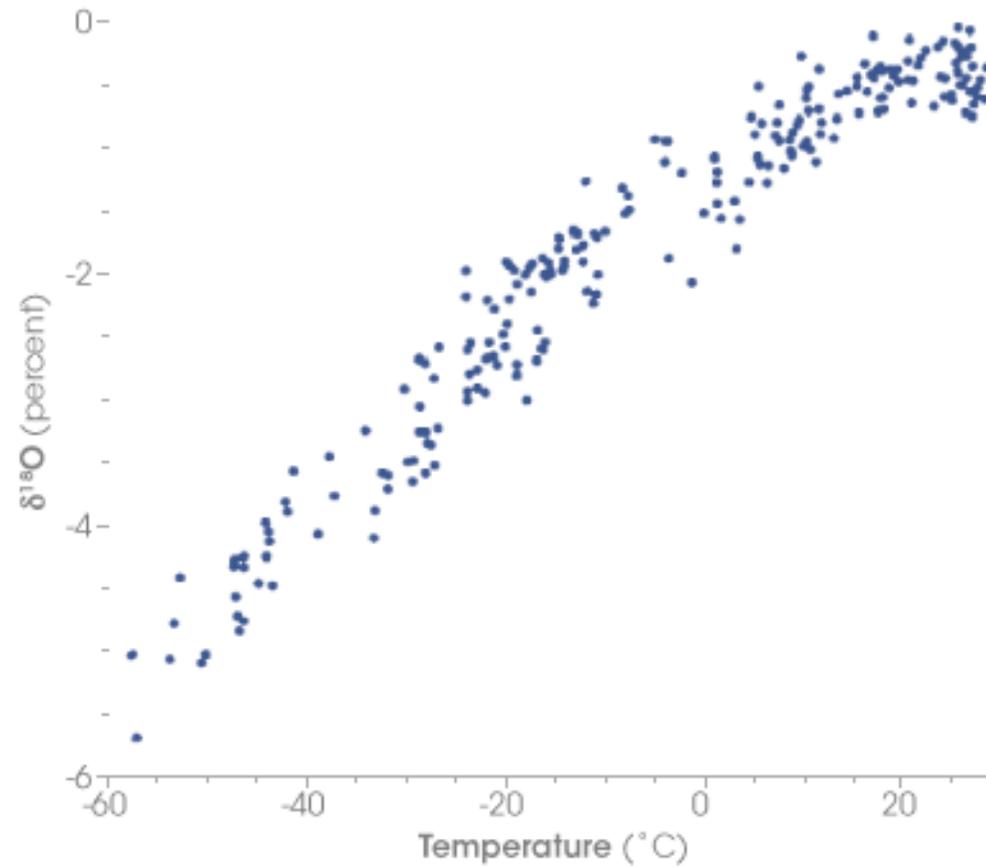
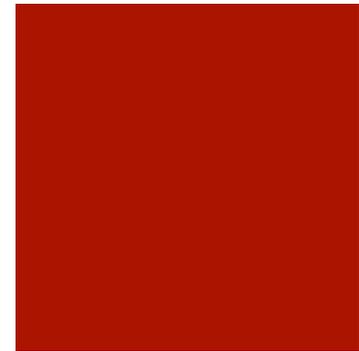
- Measurements aren't perfect.....



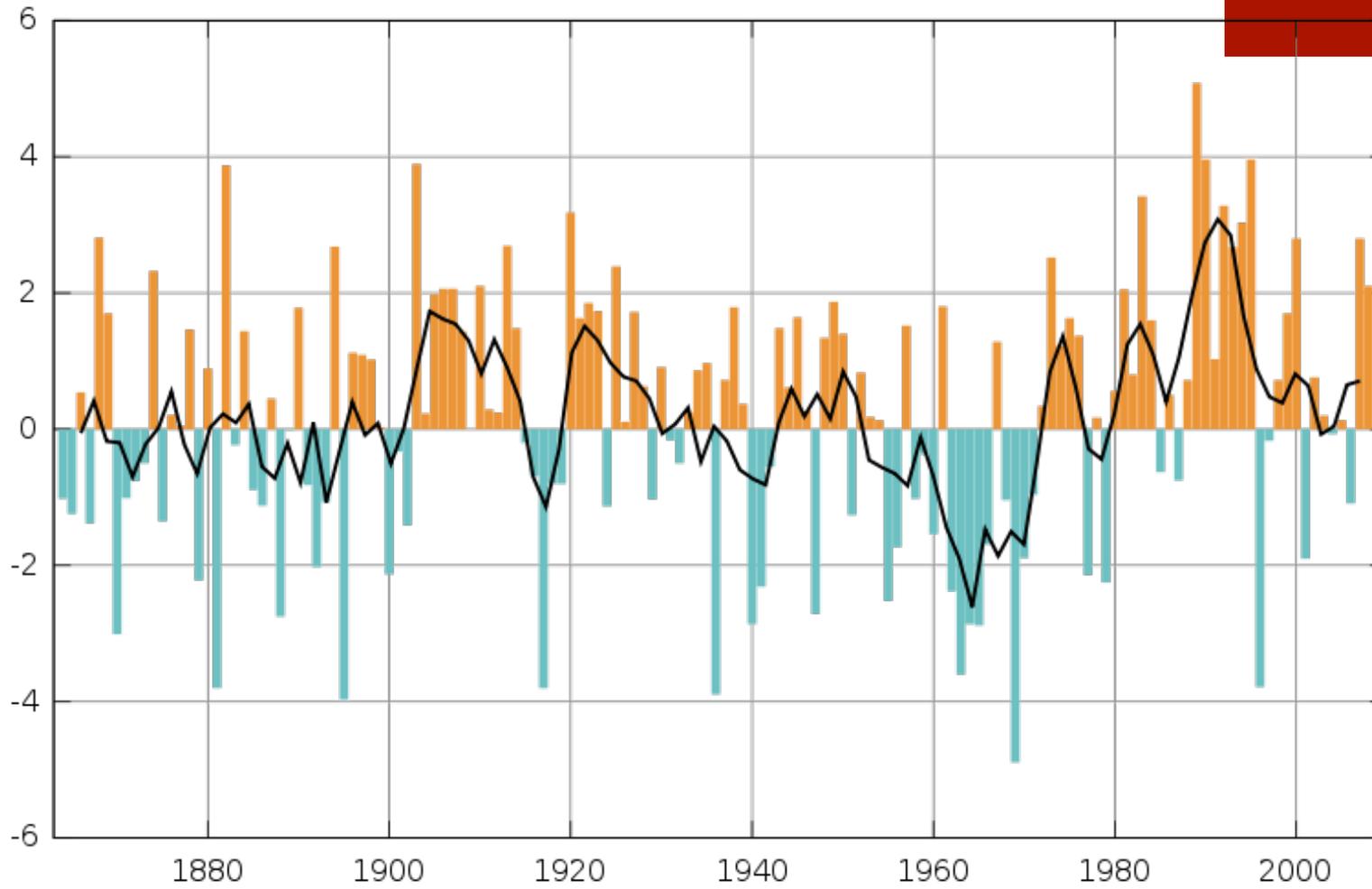
Statistical errors affect the accuracy to which the thermometer can be read – inevitable, and act in both directions.

Systematic errors reflect additional sources of uncertainty, and often act in a single direction

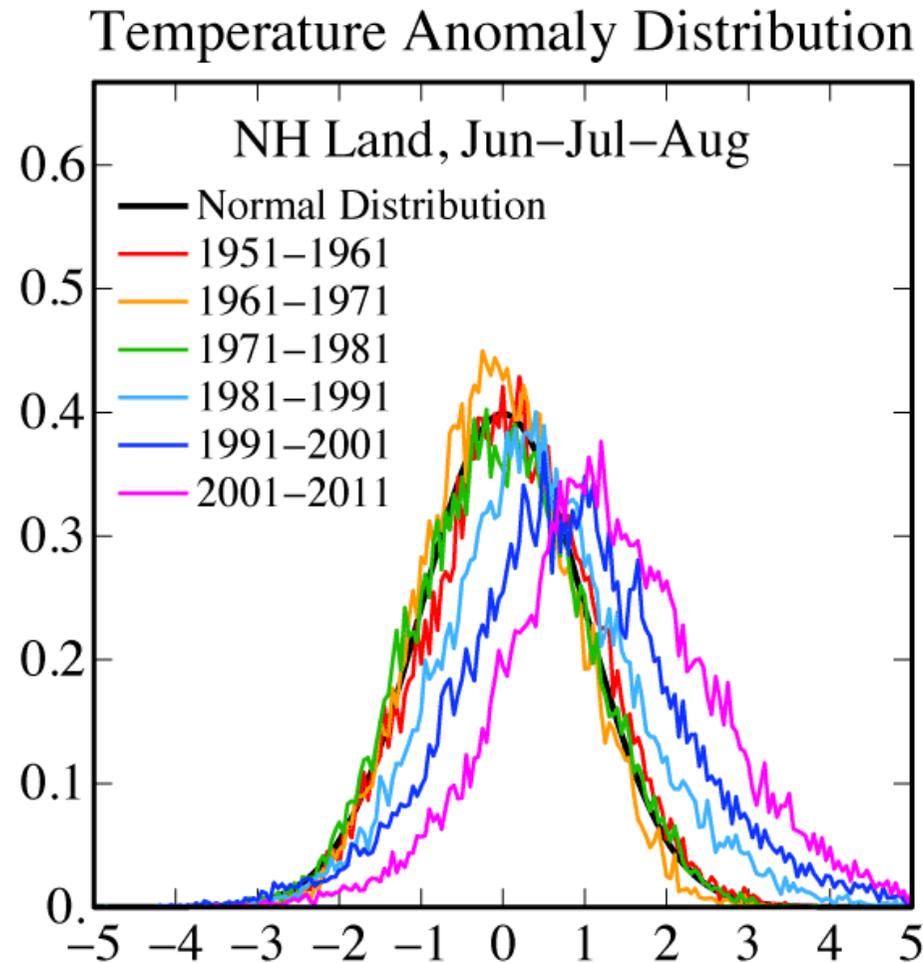
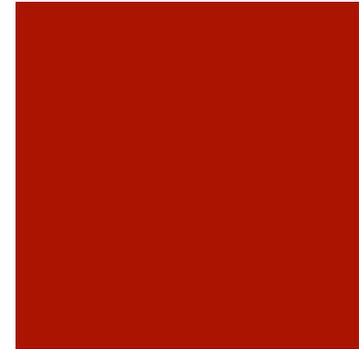
Temperature proxies



Natural variability



Simple temperature records



- Strongly dependent on quality of data, and local effects (note the units of the x-axis are standard deviations, not degrees)

IPCC approach

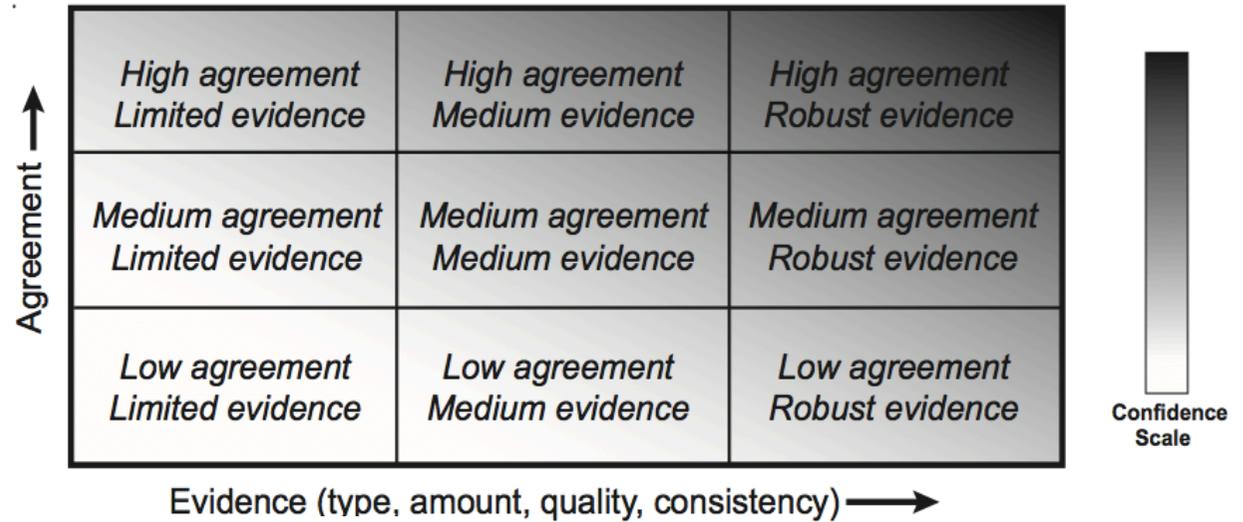


Table 1. Likelihood Scale	
Term*	Likelihood of the Outcome
<i>Virtually certain</i>	99-100% probability
<i>Very likely</i>	90-100% probability
<i>Likely</i>	66-100% probability
<i>About as likely as not</i>	33 to 66% probability
<i>Unlikely</i>	0-33% probability
<i>Very unlikely</i>	0-10% probability
<i>Exceptionally unlikely</i>	0-1% probability

Note that improved treatment of uncertainty is a “key goal” of AR5

Attribution

- A warming record does not attribute the cause

