

Global Warming 101 – or Everything you  
Wanted to Know About Our Changing Climate  
*(but were too afraid to ask)*

Michael Adler

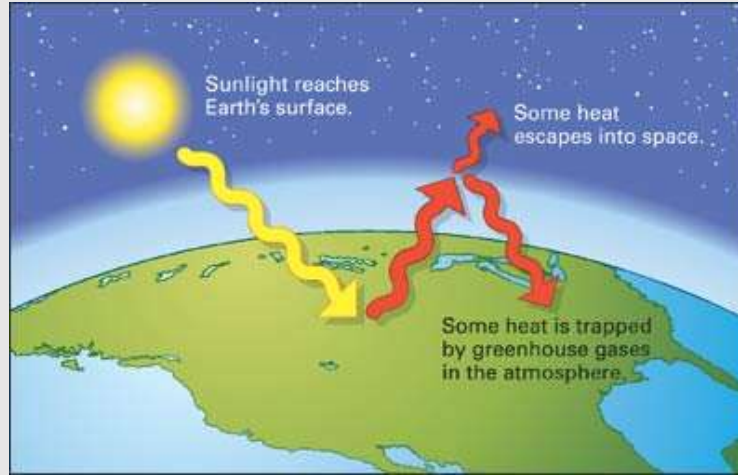
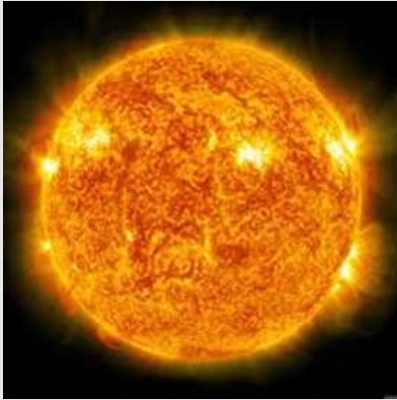
# Outline of Presentation

- Explanation of the greenhouse effect on Earth using simple models
- Applying the simple models to all of the terrestrial planets
- Measurements of climate related properties and comparison with complex Earth System Models(ESM)
- Projections of these models to 2100 and beyond
- Necessary changes to meet climate goals

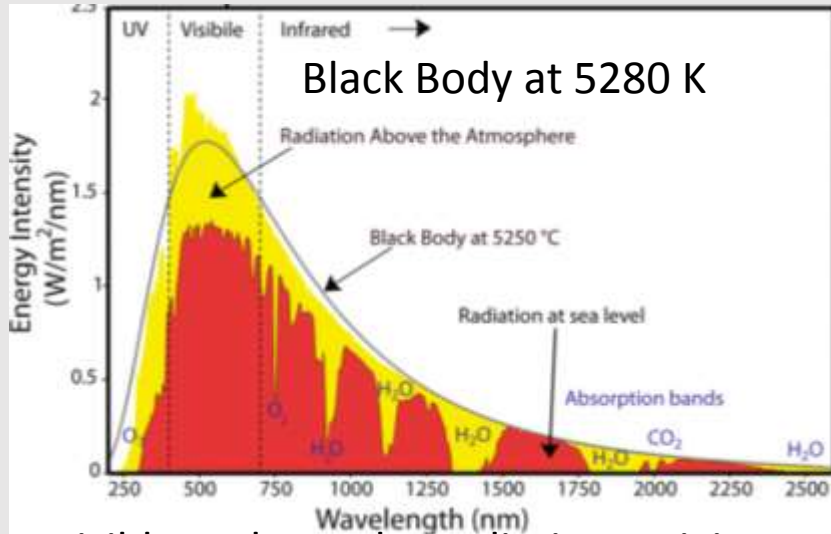
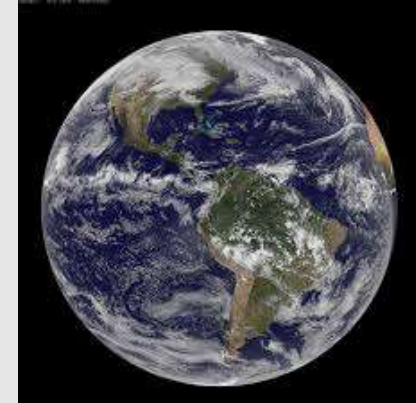
# The Greenhouse Effect

- The earth absorbs visible and ultraviolet light from the Sun. The Earth re-radiates infrared light up to the atmosphere and the atmosphere absorbs some of this radiation and re-radiates it back to the earth's surface
- The earth re-absorbs this energy with the result that it loses less heat than if there were no atmosphere

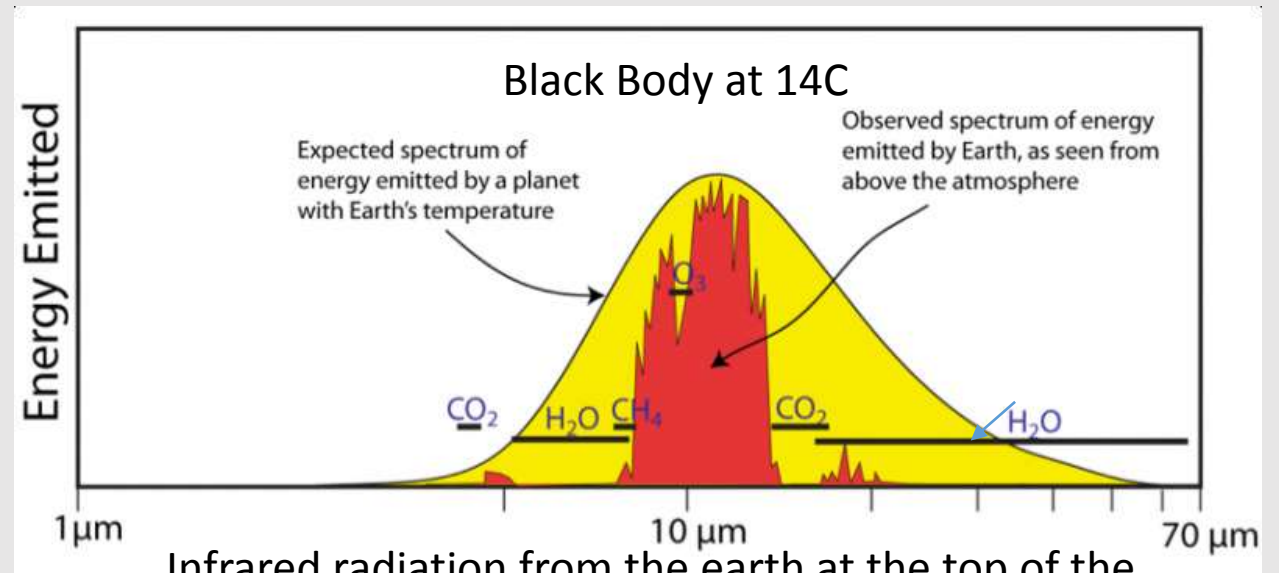
Sun surface  
5280 K



Earth surface  
287 K

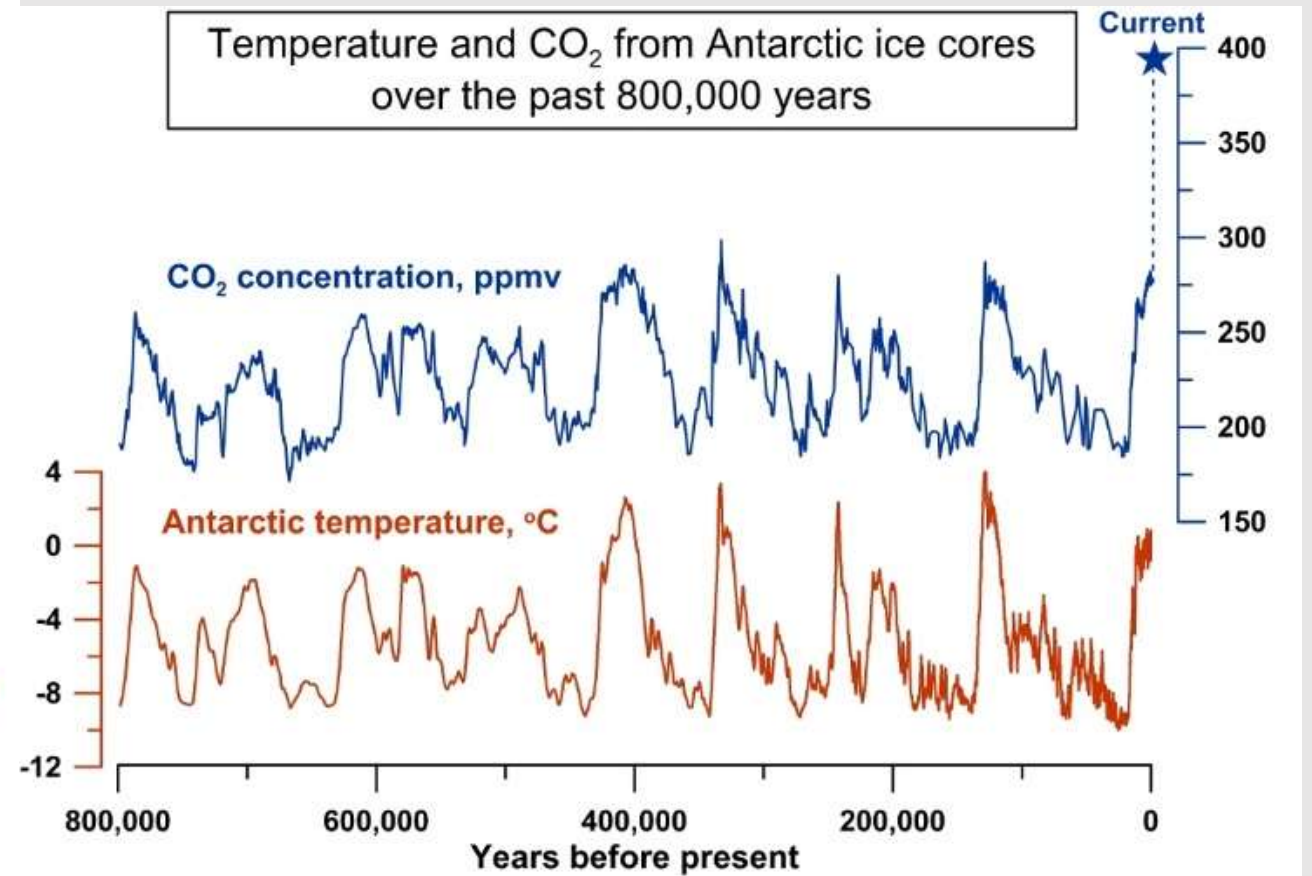
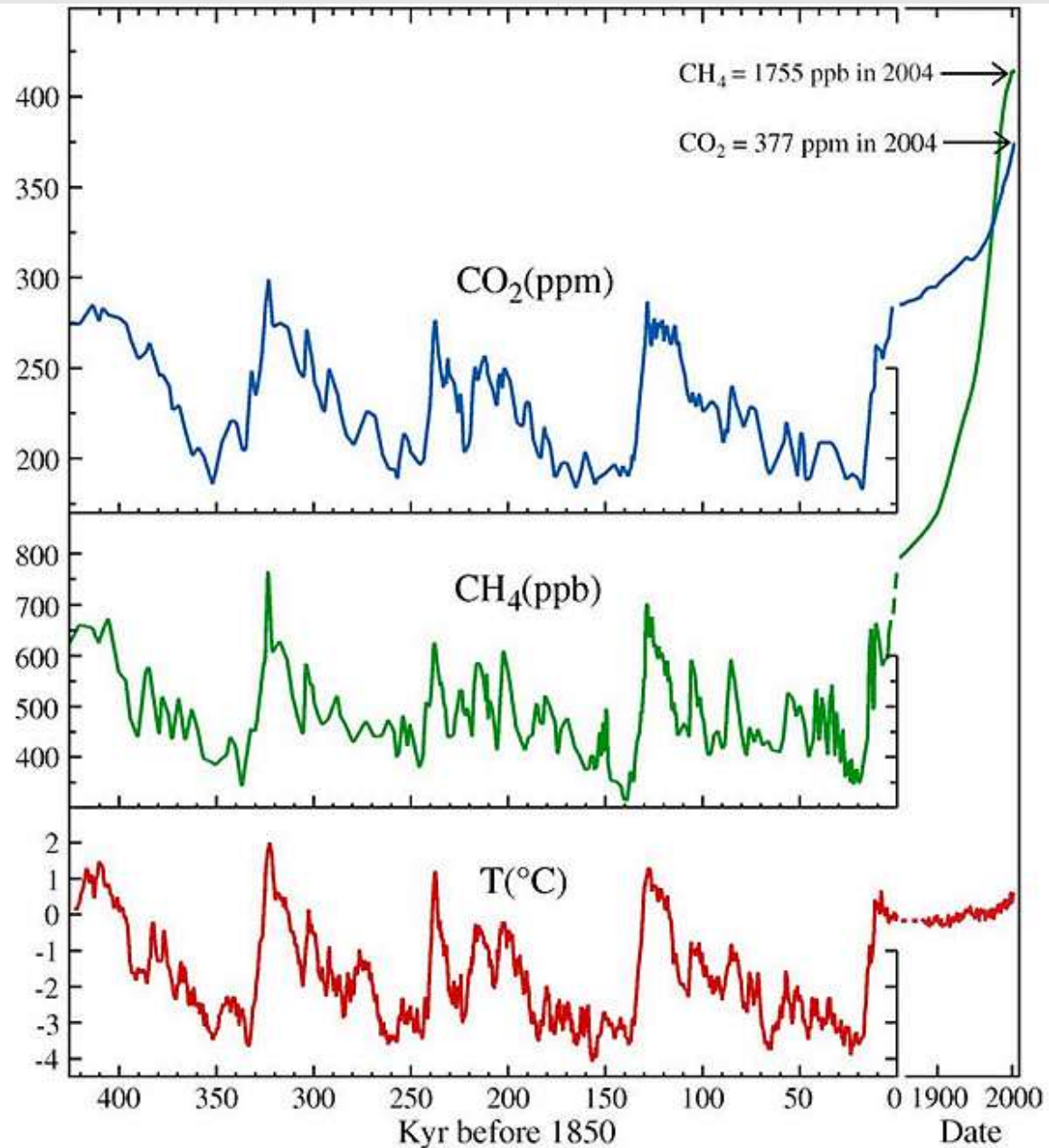


Visible and uv solar radiation arriving at the earth's surface



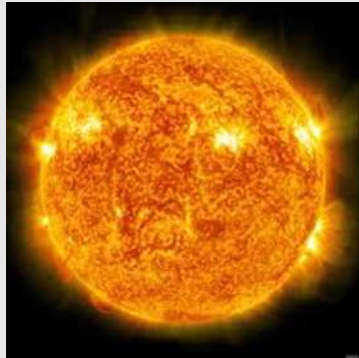
Infrared radiation from the earth at the top of the atmosphere

# Historical Correlation Between Greenhouse Gases and Temperature



# Calculating Earth's Temperature Assuming No Atmosphere

- The Stefan-Boltzmann law,  $S = \sigma T^4$ , is the sum of all of the power emitted by a black body at temperature  $T$  where  $\sigma$  is the Stefan-Boltzmann constant and is the integral of Planck's black body curve over the entire range of frequencies(1)
- Emitted solar radiation  $S_e = \sigma T_s^4$ , where  $\sigma = 5.67 \times 10^{-8}$ ,  $T = 5778\text{K}$ , is the surface temperature of the Sun and  $S_e = 6.32 \times 10^7 \text{W/m}^2$
- Radiation arriving at the earth is  $S_e$  times the Sun's surface area, divided by the area of the Sun's sphere at distance of earth  $S_{ar} = \sigma T_s^4 \cdot (4\pi R_s^2) / (4\pi D^2)$ , where  $R_s$  is the sun's radius, and  $D$  is the distance from the sun
- The earth's absorption area is its shadow disc area as shown in the diagram but its emission area is the entire spherical surface area



Radiation leaving the Sun per unit area of sun

$$S_e = \sigma T_{\text{sun}}^4$$

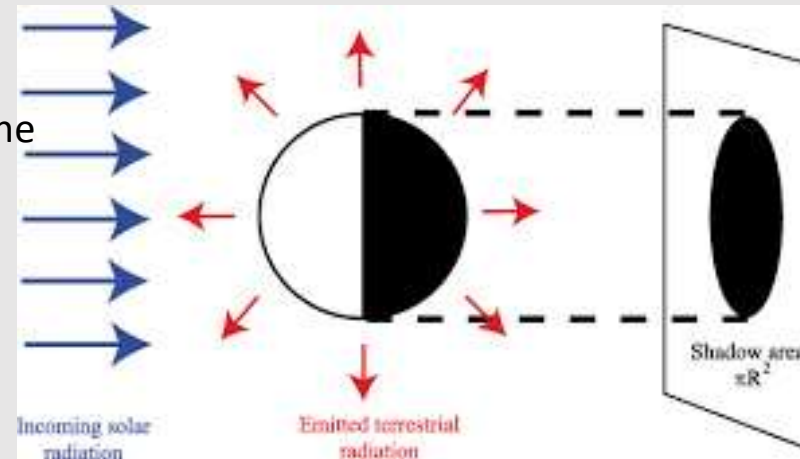
$$= 5.67 \times 10^{-8} (5778)^4$$

$$= 6.32 \times 10^7 \text{W/m}^2$$

Radiation arriving at the TOA of the Earth

$$S_{ar} = S_e \frac{4\pi R_s^2}{4\pi R_{se}^2}$$

$$S_{ar} = 1368 \text{ W/m}^2$$



Radiation that could be absorbed

$$S = S_{ar} \frac{(\pi R_e^2)}{(4\pi R_e^2)}$$

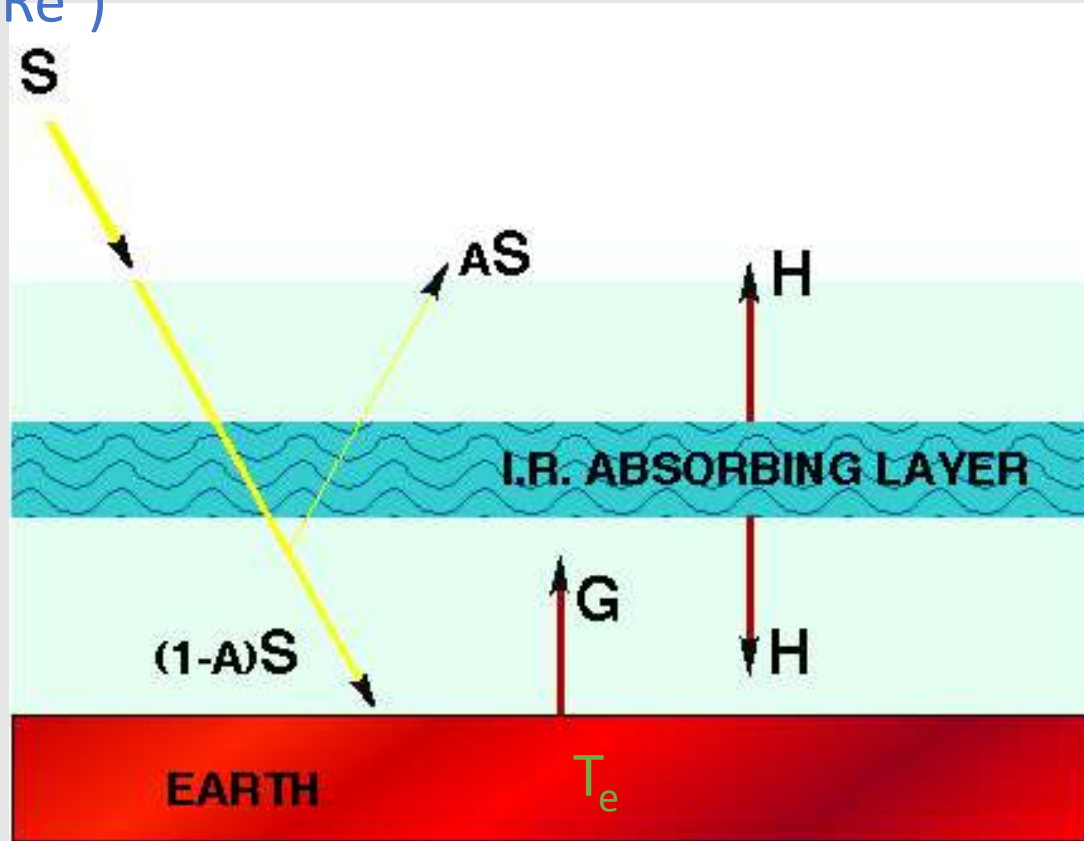
$$S = 342 \text{W/m}^2$$

Sun radius =  $6.96 \times 10^8 \text{m}$ , Sun distance =  $1.496 \times 10^{12} \text{m}$   
 Sun temperature =  $5778\text{K}$ , earth albedo =  $0.306$

# Calculating Earth's Temperature Assuming No Atmosphere

$$S = S_0 \left( \frac{\pi R_e^2}{4\pi R_e^2} \right)$$

$$S = 342 \text{ W/m}^2$$



- The power density being absorbed by the earth's surface is  $(1-A)S$  where  $A$  is the Earth's albedo, eg its reflectance
- If the earth is in thermal equilibrium it will emit all of the energy it is receiving from the sun
- Thus the power density of emitted radiation assuming no atmosphere is  $G = \sigma T_e^4$  where  $T_e$  is the temperature at the earth surface
- This works out to be  $T_e = 254.4 \text{ K}$  which is about  $-18^\circ \text{C}$  and it is not likely that life could exist in this environment
- Thus, the earth absorbs the solar short wave radiation in the visible and uv and re-emits at a much lower temperature in the long wave infrared

With  $A = 0.306$   
 $(1-A)S = 237 \text{ W/m}^2$

$$P_e = (1-A)S = 237 \text{ W/m}^2$$

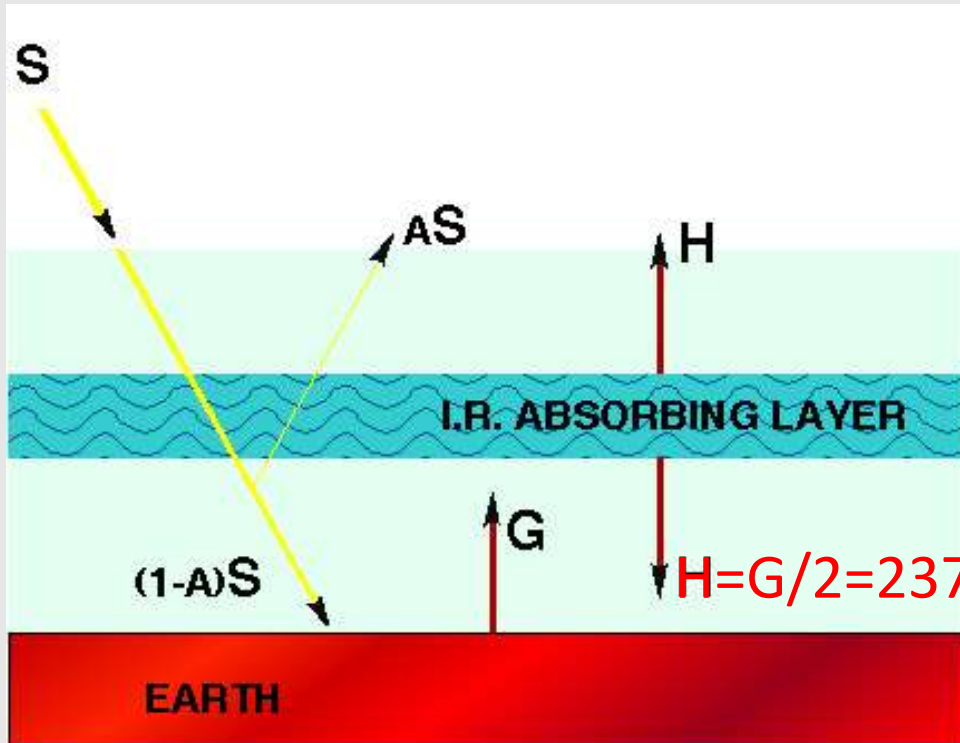
$$G = 237 \text{ W/m}^2$$

$$T_e = (G/\sigma)^{1/4} = 254 \text{ K} = -18^\circ \text{C} = -0.4^\circ \text{F}$$

Without an atmosphere Earth would not be inhabitable

# Calculating Earth's Temperature with a Perfectly Absorbing Atmosphere

$$S=342\text{W/m}^2$$



$$(1-A)S=237\text{W/m}^2$$

$$P_e=(1-A)S+G/2=474.65\text{W/m}^2$$

$$G=474\text{W/m}^2$$

$$T_e=(G/\sigma)^{1/4}=302.5\text{K}=29.5\text{C}=85.1\text{F}$$

- Assume that the earth has an atmosphere that absorbs all of the longwave IR radiation that the earth emits and back radiates all of it with half going into space and half to the earth's surface and the earth absorbed all of this
- Then the total absorbed power  $(1-A)S+H=474\text{W/m}^2$  which is  $237.33\text{W/m}^2$  from the Sun in shortwave (eg visible and some uv) radiation and  $237.33\text{W/m}^2$  in longwave IR radiation from the atmosphere

- The earth's temperature works out to be  $29.5\text{C}$  vs  $-18\text{C}$  with no atmosphere and this is the essence of the "greenhouse effect"
- If the atmosphere only absorbs 77% of the Earth's radiation the Earth's temperature is  $13\text{C}$  or  $55.4\text{F}$  which is about the actual average

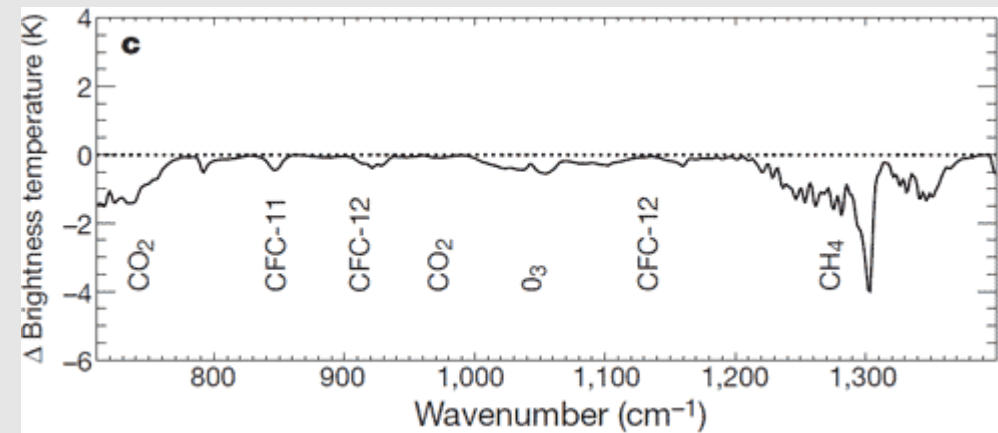
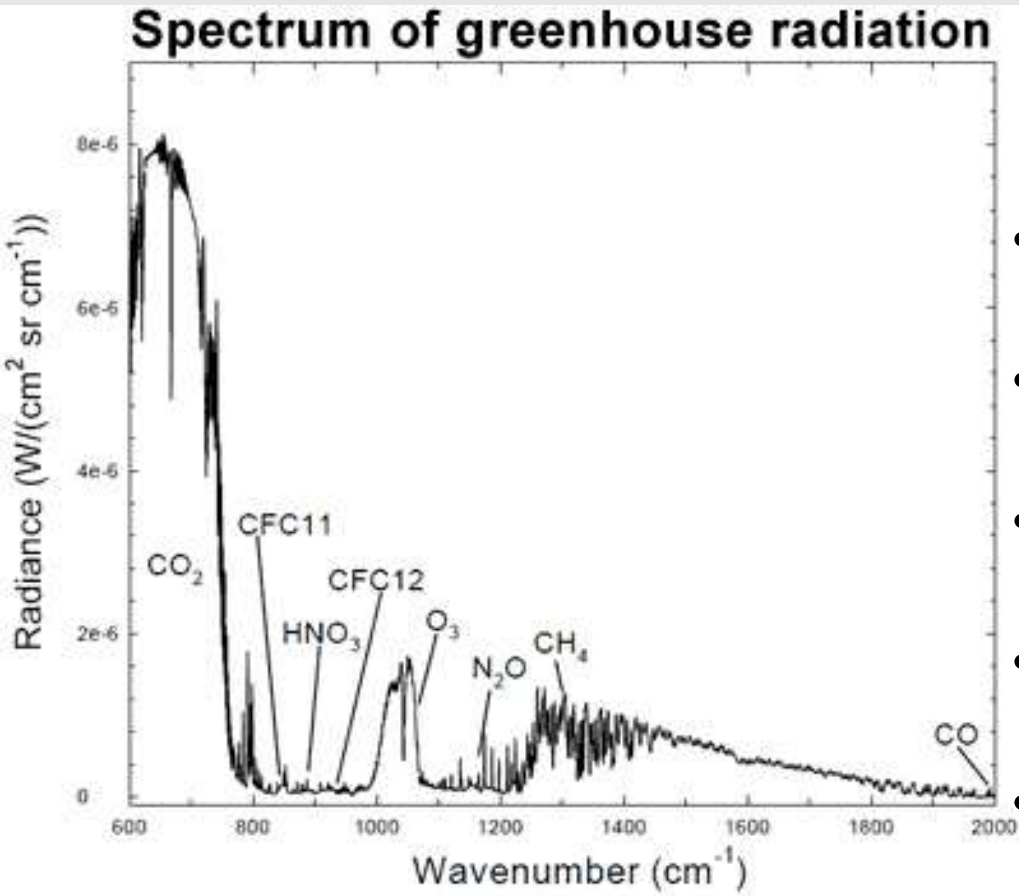
# Does the Greenhouse Effect Violate the 2<sup>nd</sup> Law of Thermodynamics

- A simplified version of the 2<sup>nd</sup> law says a colder body cannot warm a warmer body and the atmosphere is colder than the Earth(1)
- However, the Sun warms the Earth and the Earth is the source of the heat that heats the atmosphere so the net heat is flowing from the earth
- The atmosphere acts like the Earth's "blanket" causing some of the heat to be retained due to the back radiation from the atmosphere
- This is analogous to a person using a blanket in a cold room to loose less heat
- If the Earth was not producing heat, the atmosphere would have no effect just as a blanket on a cold stove does not cause the stove to get warmer
- Heat must be produced by the Earth or the stove for there to be an effect
- Similiarly, a person coming in to a house at 72F from outdoors at 20F feels warmer even though the house at 72F is cooler than the person at 98.6F because less heat is lost

*In summary, the Greenhouse Effect is critical to life on Earth and at the same time a too large Greenhouse effect leads to Global Warming*



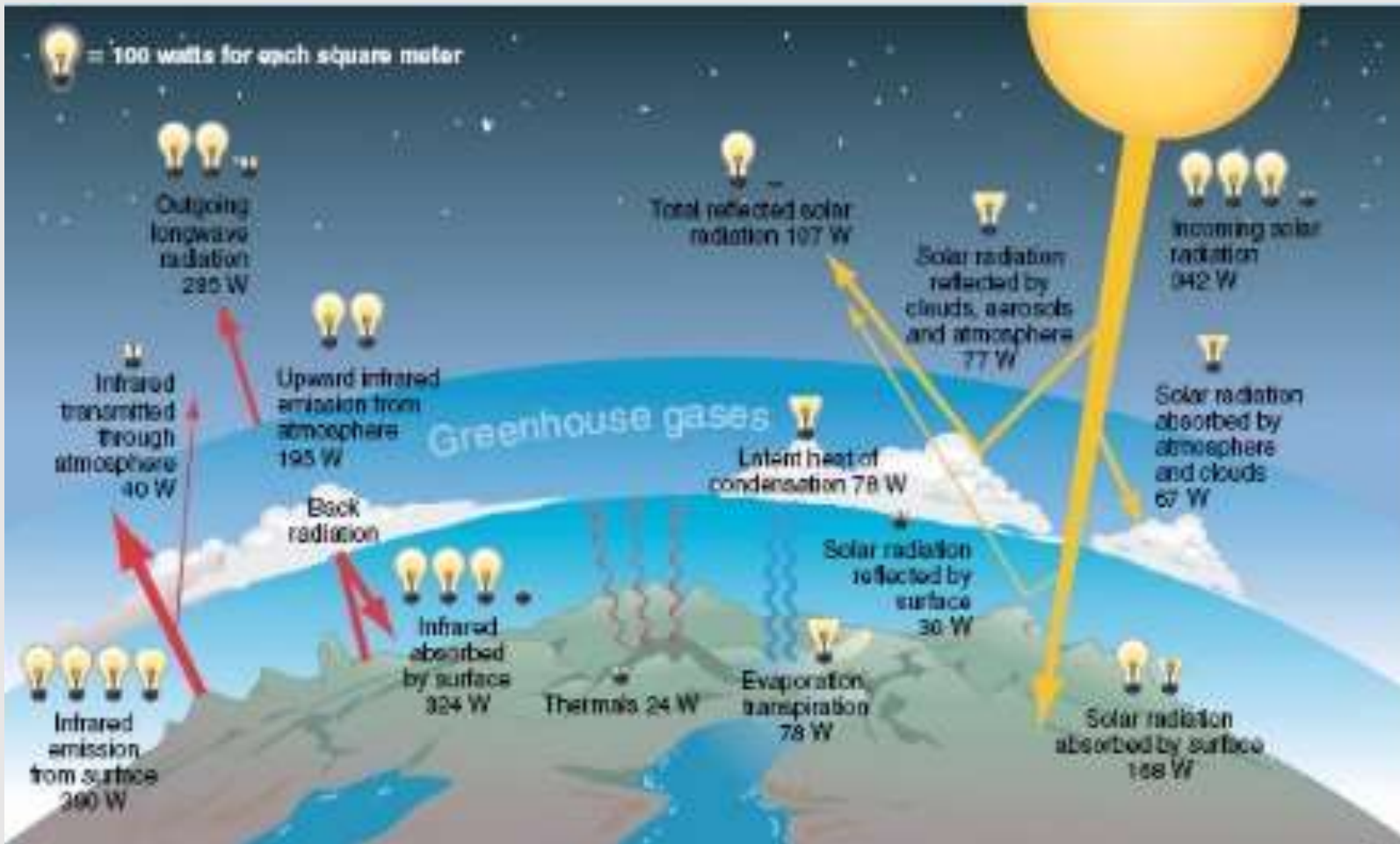
# The Measured Greenhouse Effect



- As an answer to the skepticism about the greenhouse effect, actual measurements have been made
- The upper graph is the measured back long wave radiation from the atmosphere reaching the earth's surface(1),(2)
- The absorption of this back radiation from the atmosphere accounts for the observed Greenhouse effect
- The lower graph are measurements of the change in the outgoing spectrum from 1970 to 1996 due to trace gases. (3)
- The measurements were done by the IRIS NASA satellite and by the Japanese IMG satellite
- This difference is a measurement of the increase in the Greenhouse effect
- When analyzed, this results in a 1.0-2.2 C increase in the surface temperature(1) which is in the actual range





# The Actual Greenhouse Effect

- The diagram (1) shows the actual results of detailed calculations and includes many more effects than the simple model
- The first difference is that  $67\text{W}/\text{m}^2$  of the solar radiation is absorbed by the atmosphere and clouds
- Thus only  $168\text{W}/\text{m}^2$  reaches the surface vs  $237\text{W}/\text{m}^2$  in the simple model
- Because of the increased absorption in the atmosphere and clouds  $324\text{W}/\text{m}^2$  is back radiated to the earth vs  $148\text{W}/\text{m}^2$  in the simple model
- The third difference is that in the complete model  $104\text{W}/\text{m}^2$  is lost from the surface because of thermal radiation from volcanos and evaporative processes



- The net infrared emission from the earth for the complete model  $G = 388\text{W}/\text{m}^2$  compared with  $G = 385\text{W}/\text{m}^2$  in the simple model
- That they are virtually the same is not an accident as the total emission from the earth is what determines the earth's temperature of  $14\text{C}$  via the Stefan Boltzmann law where  $T_e = (G/\sigma)^{1/4} = 287\text{K}$  or  $14\text{C}$

# Planetary Surface Temperatures Provides More Information About the Greenhouse Effect

Planet	 Mercury	 Venus	 Earth	 Mars
$T_p, K (^{\circ}C)$	437 (163)	232 (-41)	255 (-18)	209 (-64)
$T_{obs}, K (^{\circ}C)$	~440 (167)	735 (462)	288 (15)	215 (-58)
Atmosphere: Pressure, kPa composition [trace gases]	none	9300 CO <sub>2</sub> (0.965), N <sub>2</sub> (0.035), [SO <sub>2</sub> , Ar]	101 N <sub>2</sub> (0.78), O <sub>2</sub> (0.21), Ar(0.009), [CO <sub>2</sub> , H <sub>2</sub> O]	0.64 CO <sub>2</sub> (0.95), N <sub>2</sub> (0.03), Ar(0.02), [O <sub>2</sub> , CO]

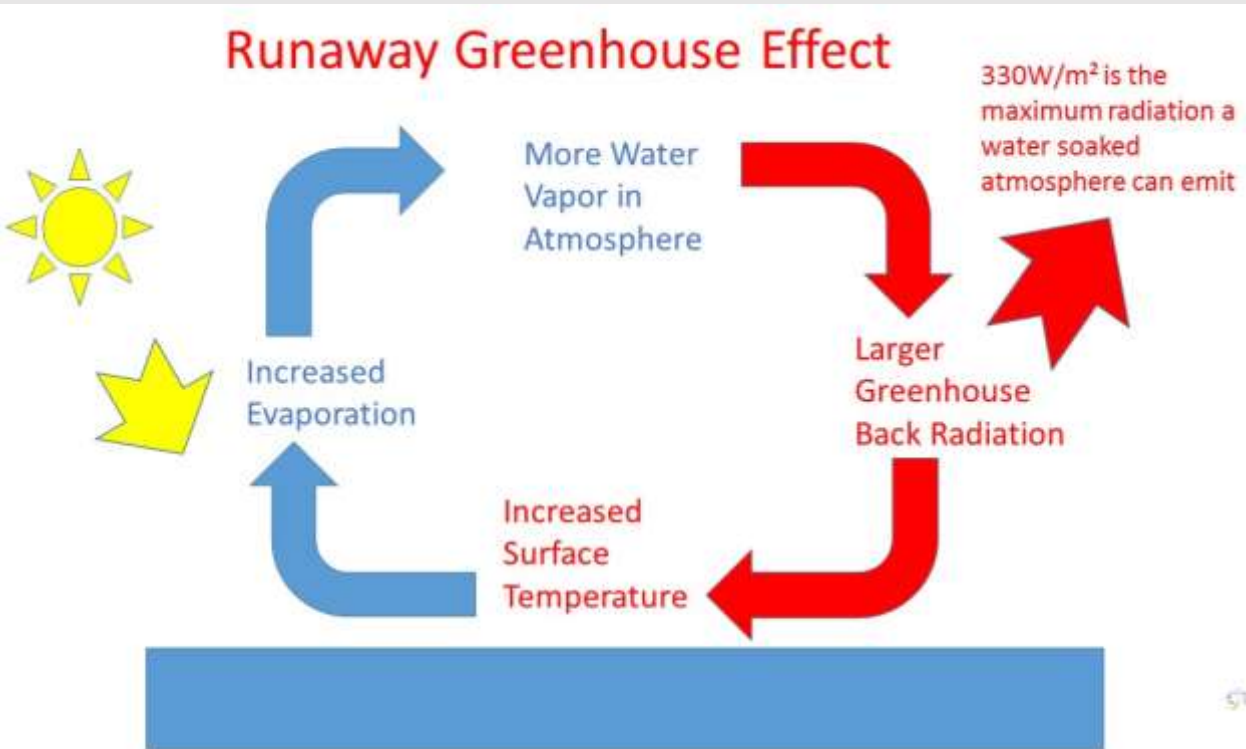
- The table gives a summary of the surface temperatures both calculated and measured (1) for the terrestrial planets
- The top row gives the temperature for the planet assuming it does not have an atmosphere based on using the black body calculation shown earlier for earth
- The second row gives the measured surface temperature and the agreement for Mercury and Mars is very good
- Earth gives reasonable agreement with the one layer model

- Venus with its dense atmosphere gives poor agreement with the no atmosphere assumption
- The incident power from the sun for Venus is  $2643W/m^2$
- The power absorbed at the surface is  $132W/m^2$  for an albedo of 0.8
- The one layer model gives a surface temperature of 260K which is much too low and even with a zero albedo the result is 390K which is also too low

# Venus's Surface Temperature

- However, Venus has such a dense atmosphere that the underlying assumption that the short wavelength solar radiation reaches the surface is a very bad approximation
- In fact a better assumption may be that the solar radiation is fully absorbed at the top of the atmosphere
- Then using the no atmosphere model for the top of Venus's atmosphere(TOA)  $P=\sigma T_{\text{top}}^4$  gives a temperature of 210K using  $132\text{W}/\text{m}^2$  for the solar radiation
- The measured top of the atmosphere from the Magellen satellite is 220K in good agreement with the above(1)
- The key question is how the 730K surface temperature can be reconciled and the conventional answer found throughout the literature is that Venus has a “runaway” Greenhouse Effect

# The Runaway Greenhouse Effect

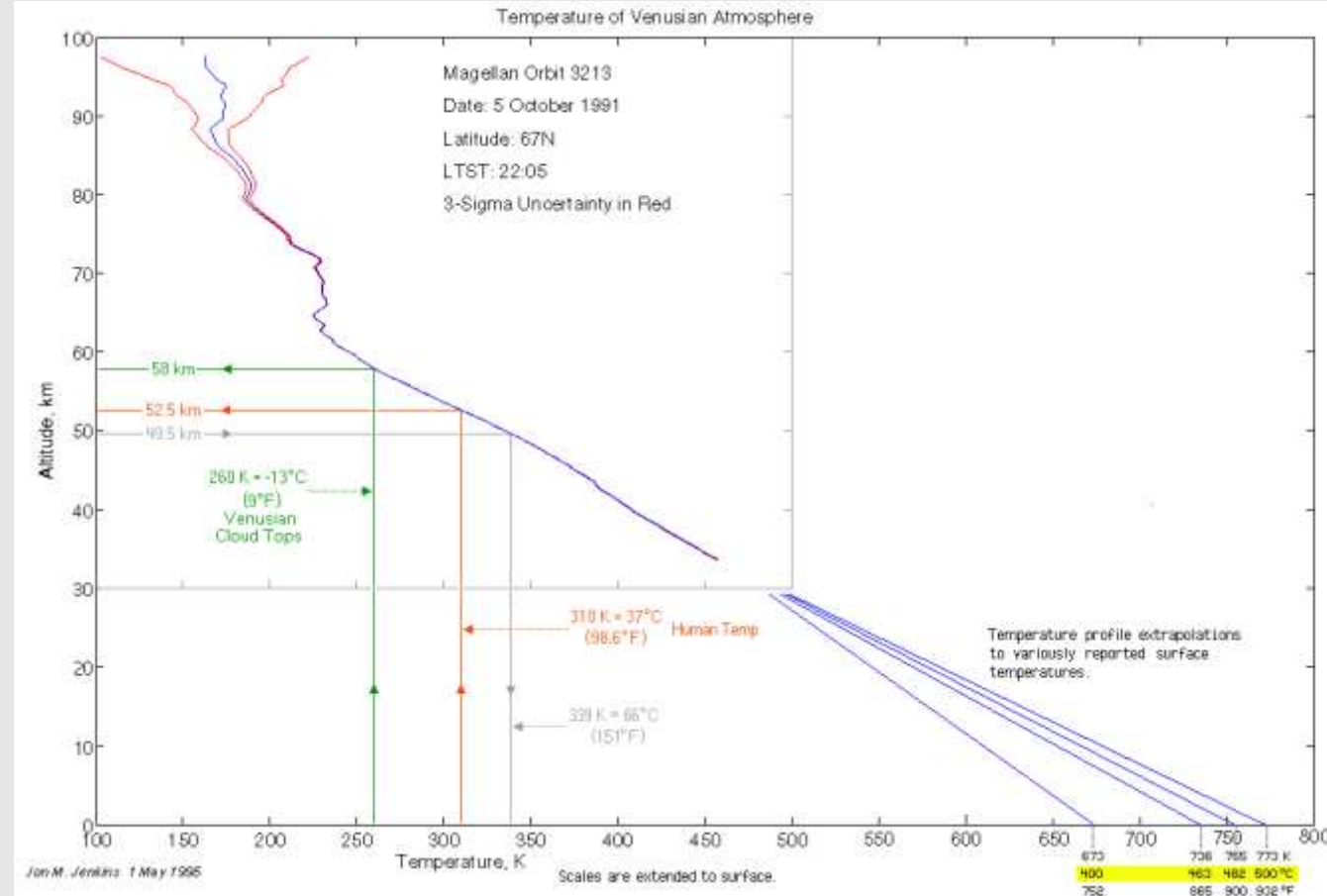


- In a situation where the surface of a planet has a large source of water a positive feedback effect can occur where the surface temperature can increase dramatically(1)(2)
- There is a limit to the power that a water saturated atmosphere can emit and is about 330W/m<sup>2</sup> (3)
- If a steady state situation demands more heat emission than this the surface temperature can rise to over 1000K and a runaway situation can exist until all of the water is evaporated
- This almost certainly happened on Venus in its past and there is a key clue here

- Venus has a hydrogen/deuterium ratio of 100 compared to 10,000 on earth(4)
- This can be explained if Venus started out with similar water content as earth but lost 99.9% of its water due to a runaway greenhouse effect and because of a lack of magnetic field solar wind particles disassociated the water into hydrogen, deuterium, and oxygen with the lighter hydrogen atoms escaping preferentially
- Because of a lack of water Venus has no plate tectonics and there is no sequestration for CO<sub>2</sub> so all of it is in the atmosphere making up 96% of the total and resulting in a very dense atmosphere

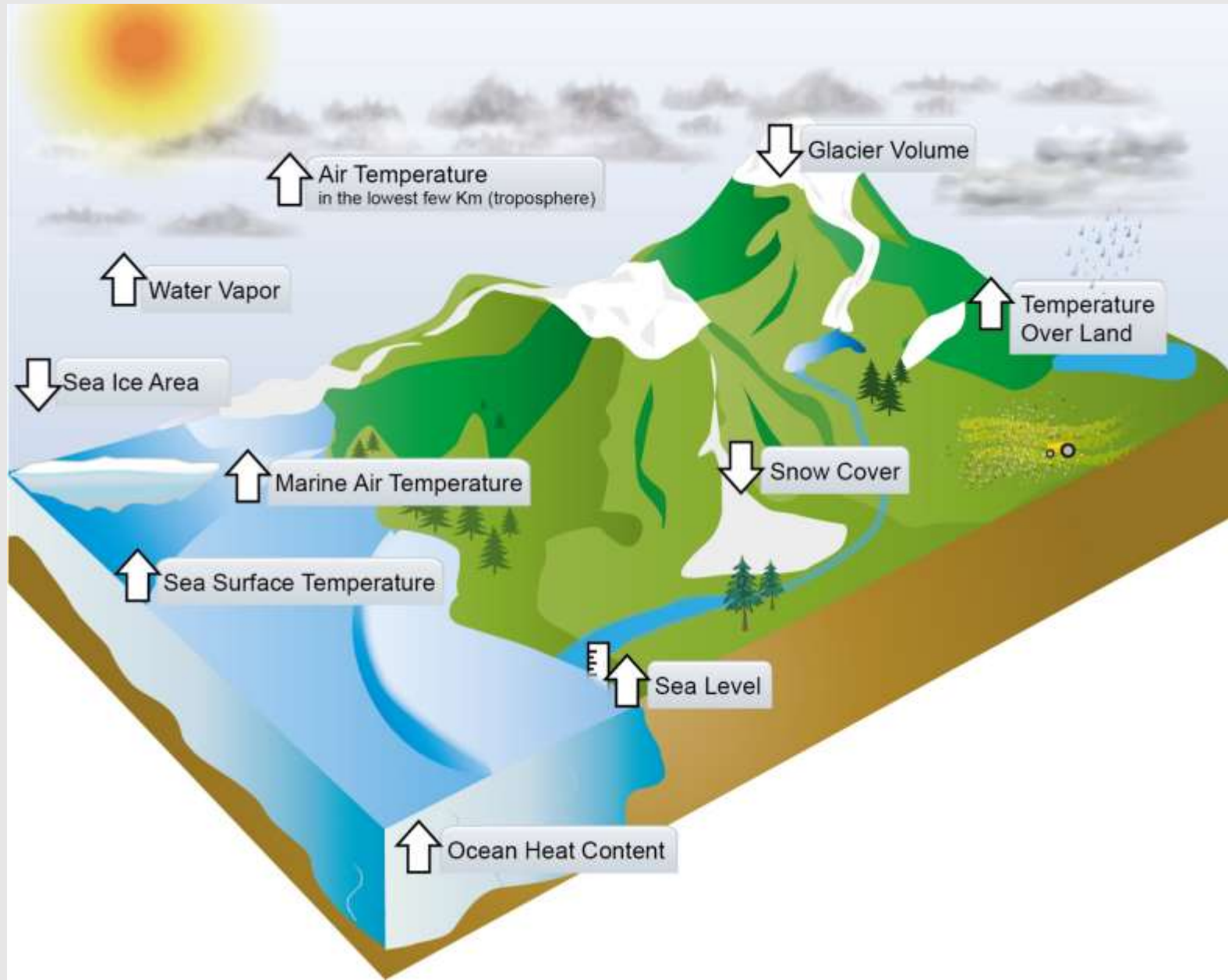
- The runaway greenhouse effect may have resulted in a very high surface temperatures at one time but it does not explain why the surface is at 730K today(1,2,3)
- The answer is that Venus's atmosphere is largely a closed system receiving little heat in or out and thus is adiabatic
- The lapse rate (temperature change with altitude) for a dry adiabatic system is 7.8K/km(4) for CO2
- Taking this lapse rate and an atmosphere of 65km(5)(6) with the temperature there at 220K, the surface temperature is 727K which is very close to the measured value of 730K
- This results in a surface pressure of 92 times that on earth(2)(3)

# Venus's High Surface Temperature

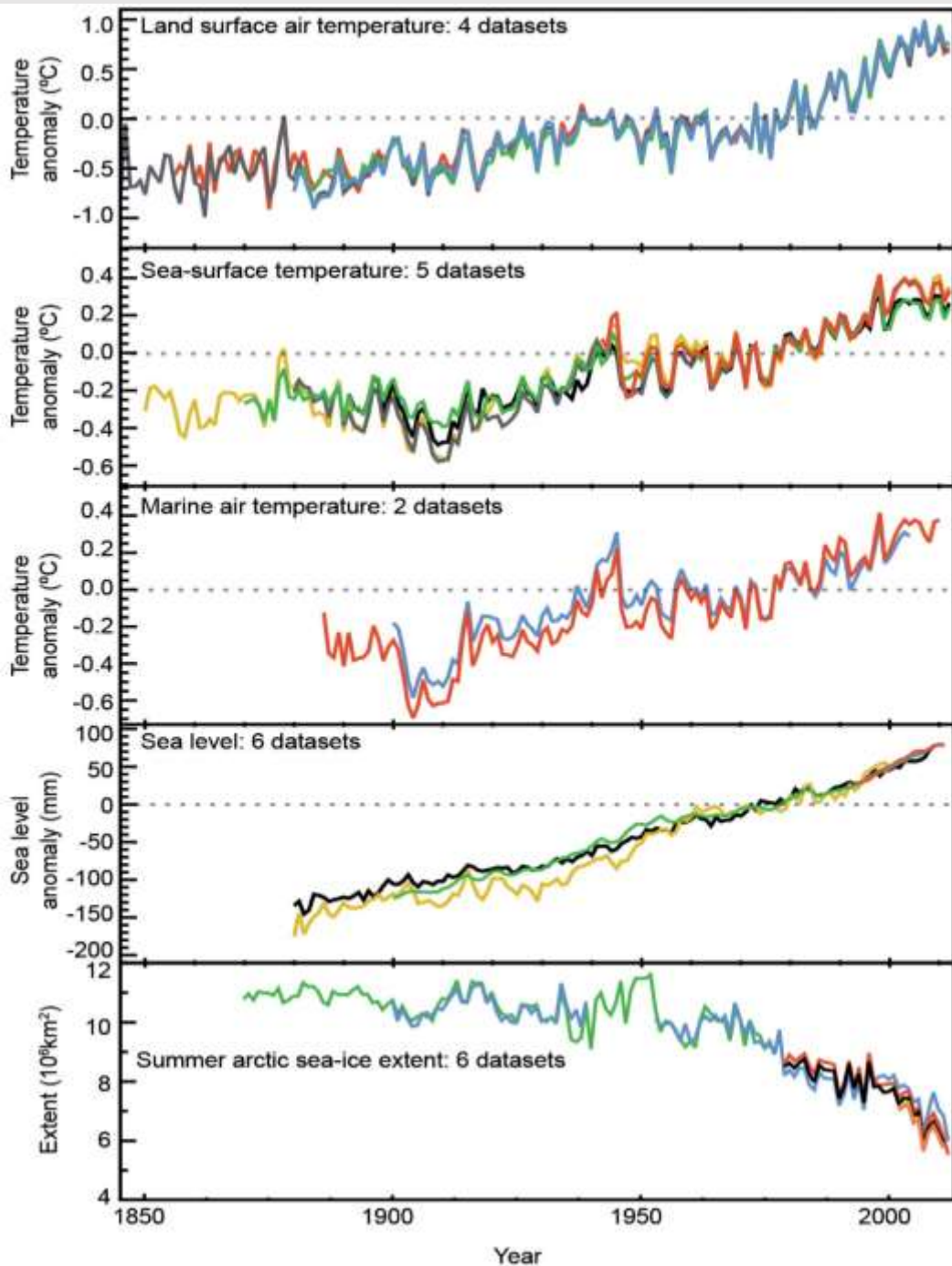


If earth had a similar atmosphere it would also have a very high surface temperature and pressure, thank goodness for plate tectonics

# How Do We Know that the Climate is Warming



# Historical Climate Change

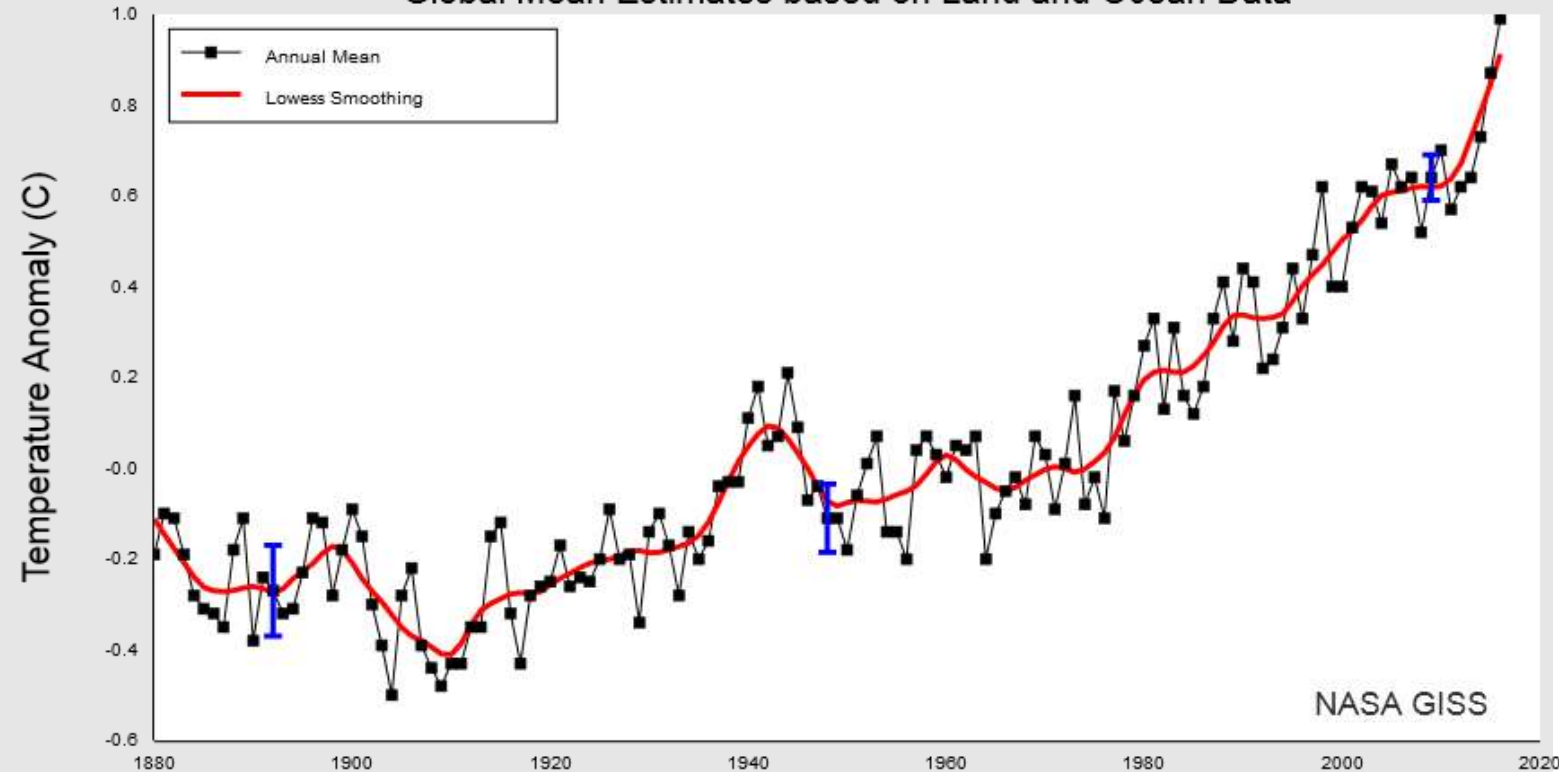


- The land surface temperature since the late 19<sup>th</sup> century has increased by 0.85C and the last three decades have been successively warmer than any in the past with the 2000 decade being the warmest
- The warming trend has increased since 1950 with a 0.72C increase based on 7 data sets
- Significant increases are also seen for sea surface temperature(0.8mm/year) and marine air temperature
- One of the biggest concerns is the rise in sea level driven by a reduction in global glaciation
- Both Greenland and Antarctic have contributed 0.25-0.99mm/year increase in sea level from 1971 to 2010(1)
- Land storage of water does not seem to have changed
- The Arctic sea ice extent has decreased 3.5% to 4.1% per decade with a range of 0.45 to 0.51 million km<sup>2</sup> loss per decade(2)
- The total since 1950 the total loss is 4 million km<sup>2</sup>

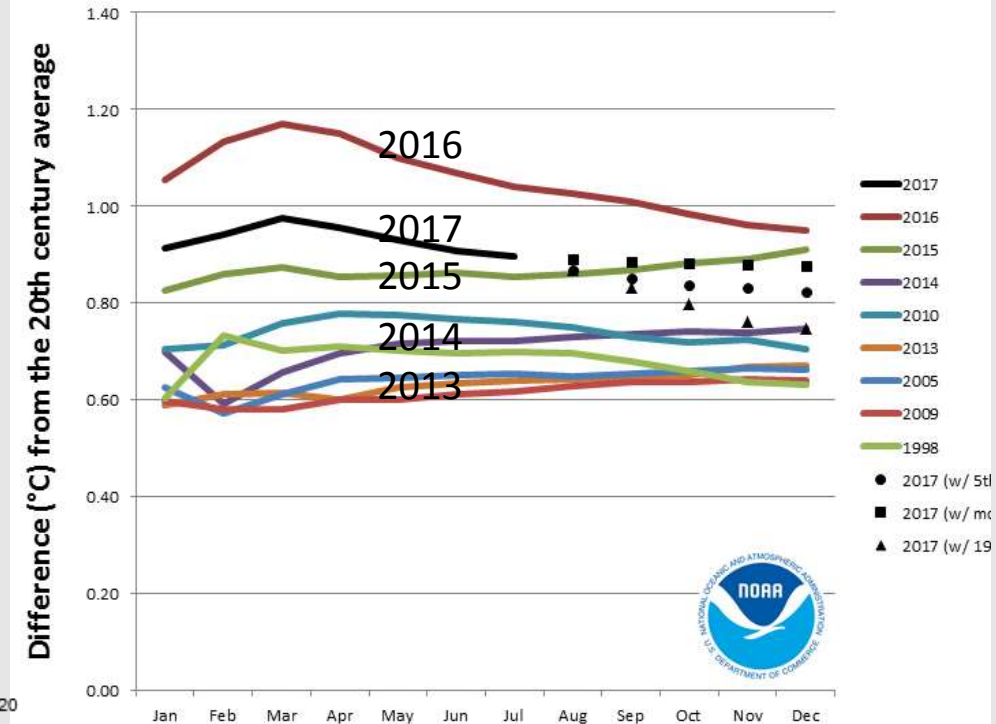


# Latest Data on Global Temperatures

Global Mean Estimates based on Land and Ocean Data



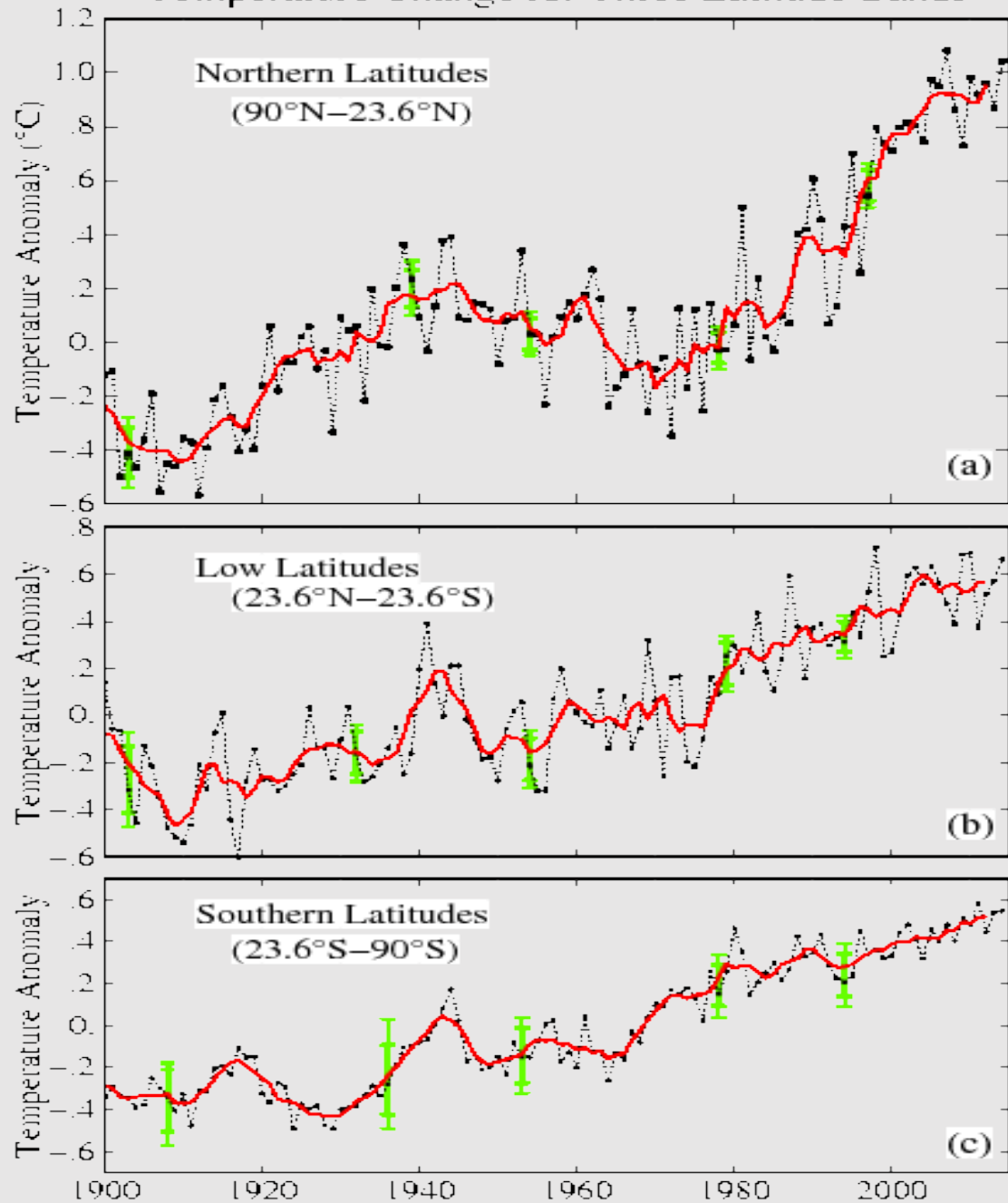
Year-to-Date Global Temperatures for 2017 and the other eight warmest years on record



- The previous temperature profile was seen by some to show a roll-off in the 15 years previous to 2013 when the previous data was compiled
- However, when more recent data was added as seen above the curve has made a noticeable uptick resuming its rapid temperature rise since 1980(1)

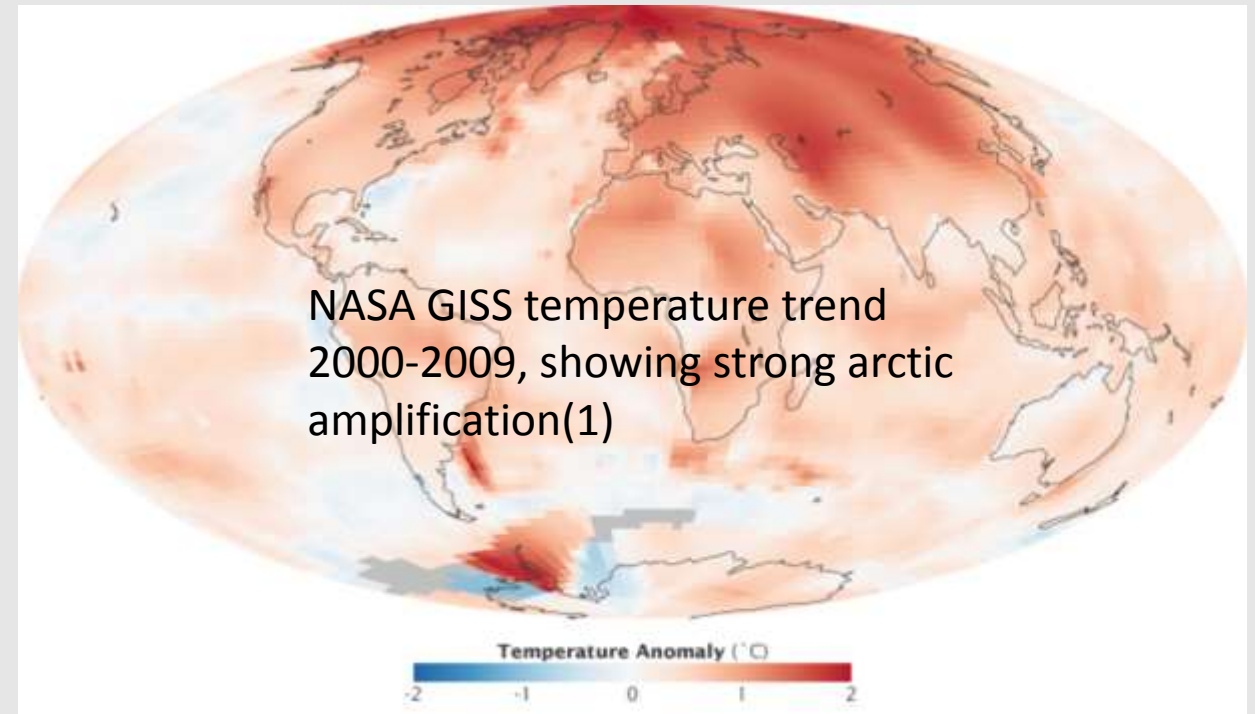
- Looking at the last 5 years, there has been a significant and continuous rise in global temperatures(2)
- Before 2013 the temperatures had rolled off but now it is seen as a normal fluctuation that has been seen many times before

Temperature Change for Three Latitude Bands

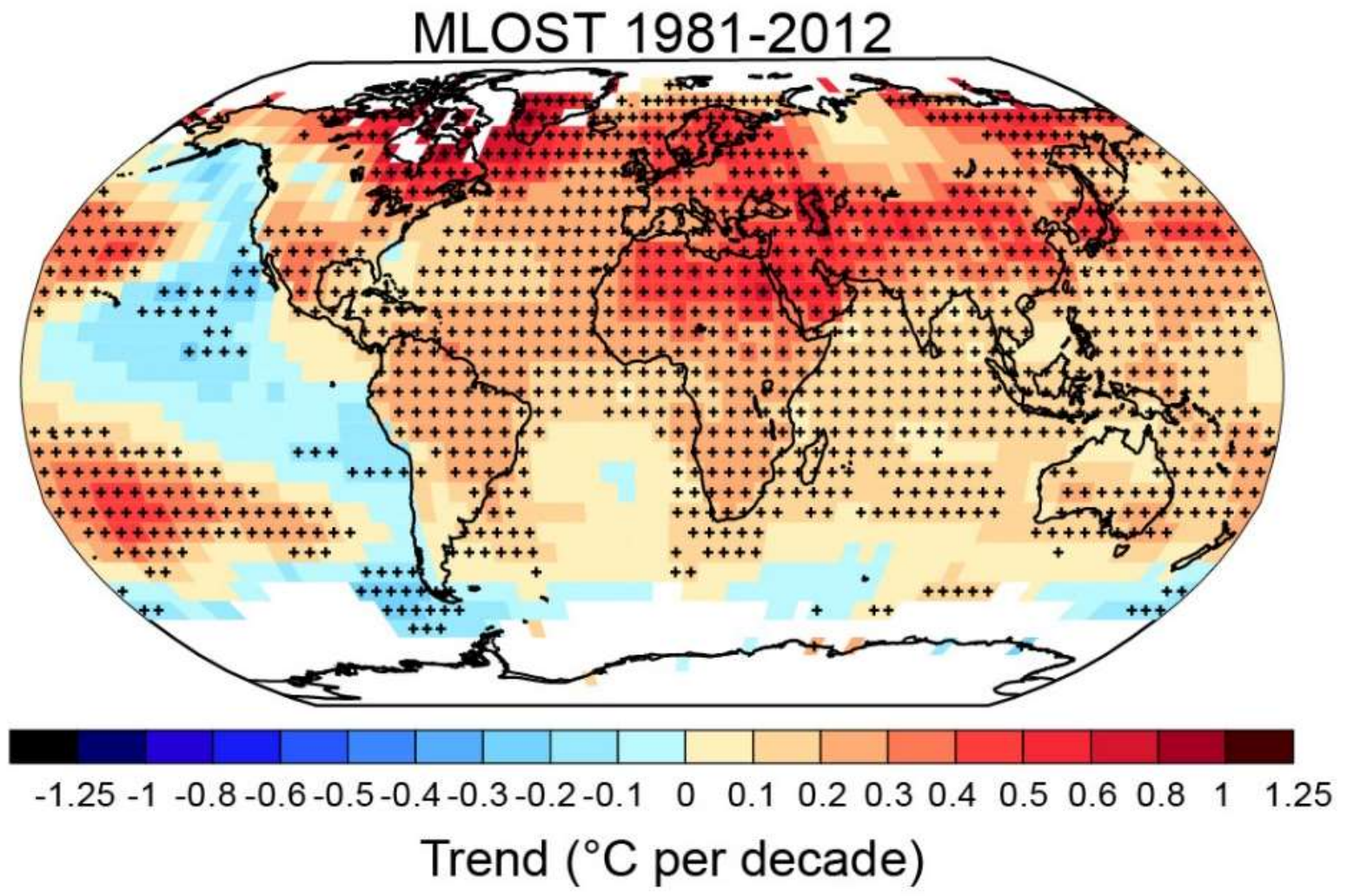
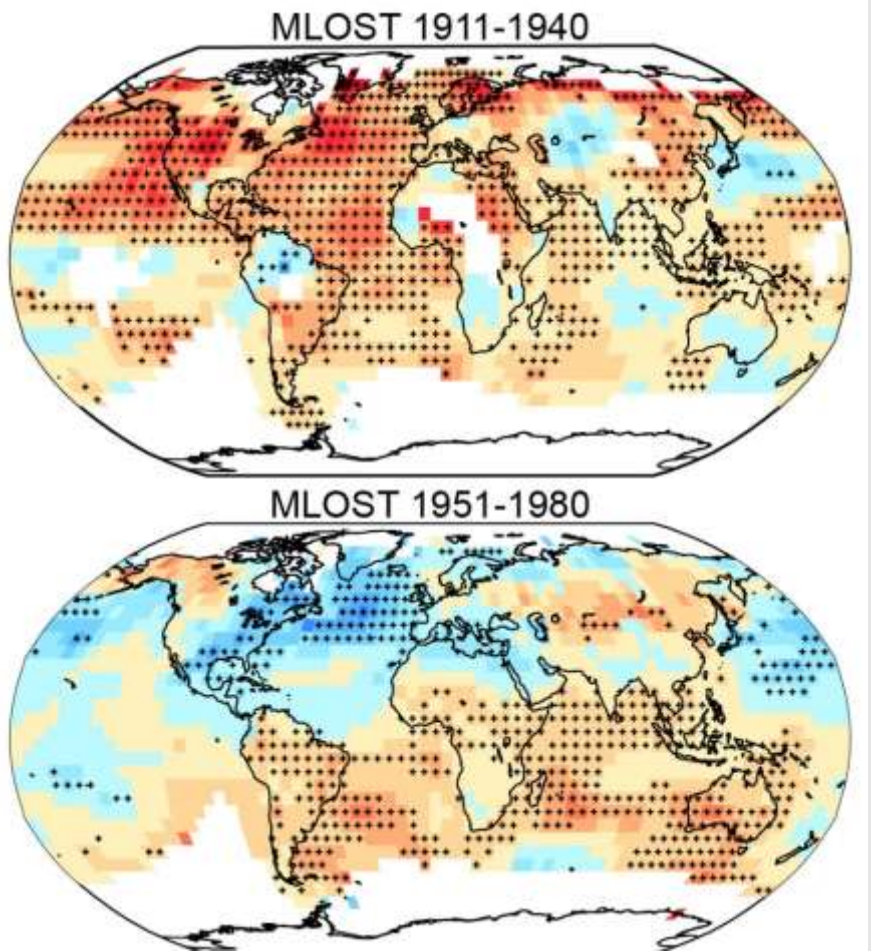


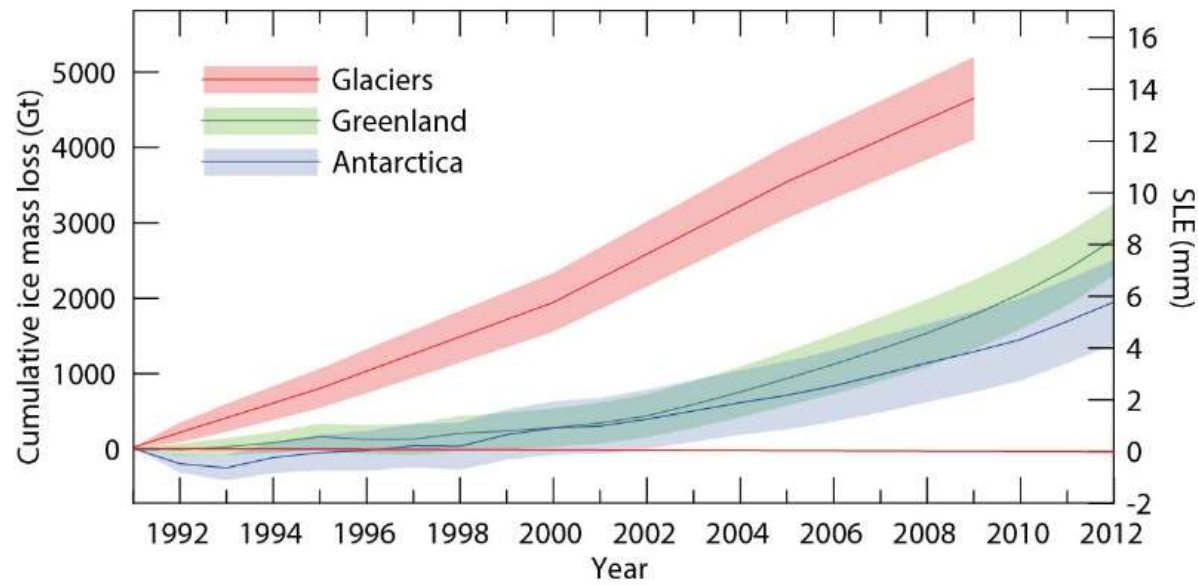
## Polar Amplification

- Climate system feedbacks that contribute to recent polar amplification include the(1)
  - reduction of snow cover and sea ice
  - changes in atmospheric and ocean circulation
  - the presence of anthropogenic soot in the Arctic environment,
  - increases in cloud cover and water vapor
- Overall, sea ice changes are thought to be the major source of polar amplification



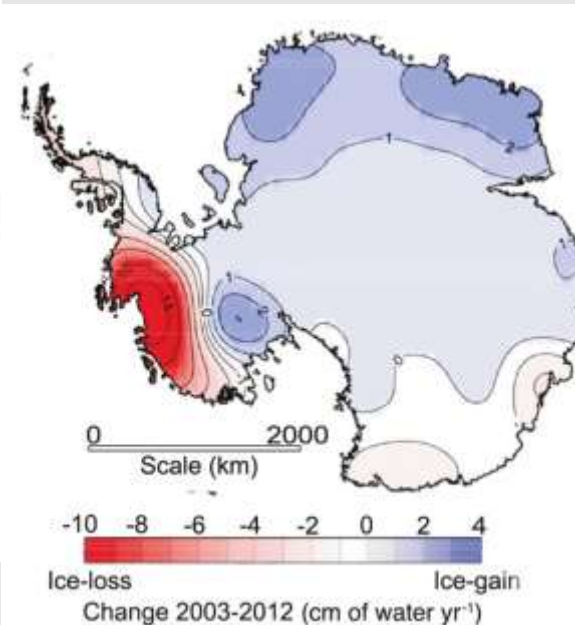
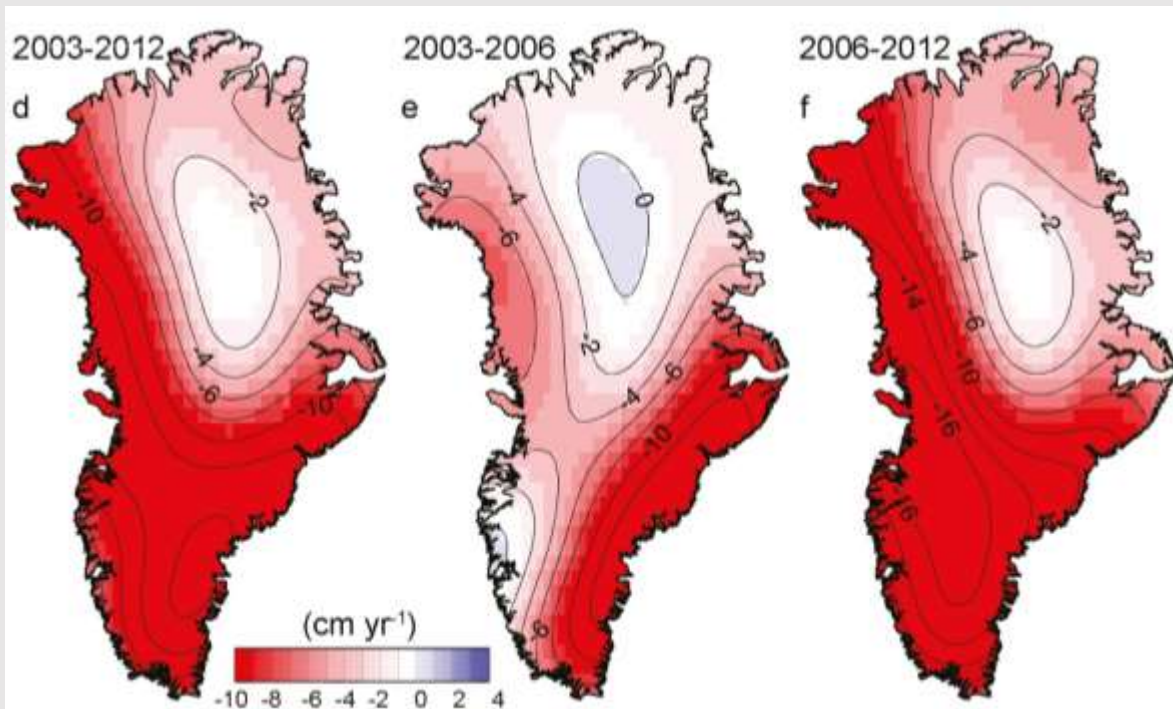
# Rate of Change in Temperature Across the Globe





# Sea Ice and Glacier Changes

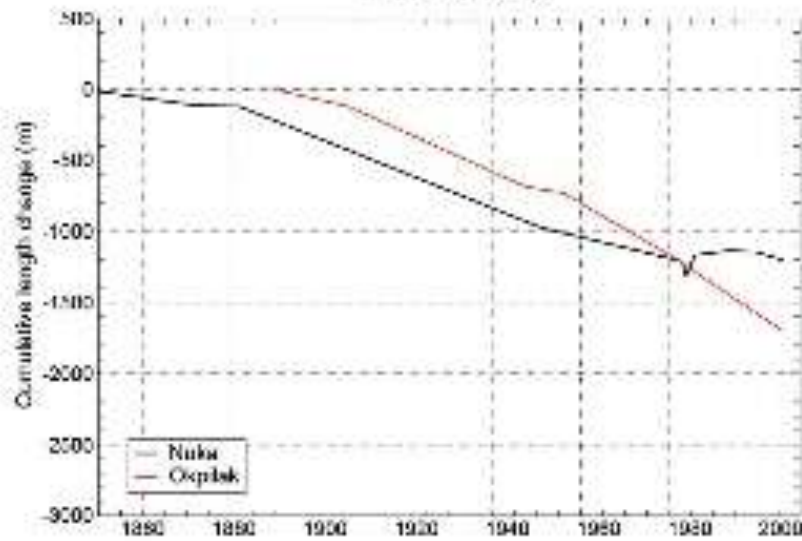
- There has been continued ice mass loss in both the arctic and the Antarctic and this has come from glaciers and ice sheets
- This has resulted in 28mm in sea level rise and represents 10,000 Gt of ice in the last 20 years
- The Glaciers in Antarctica are increasing except in the Weddell sea
- However, in Greenland the ice loss went from 34 Gt/yr in 1992-2001 to 215 Gt/yr in 2002-2012(1)
- This came from surface melt and runoff and accounted for 0.09 to 0.59mm/year sea level increase



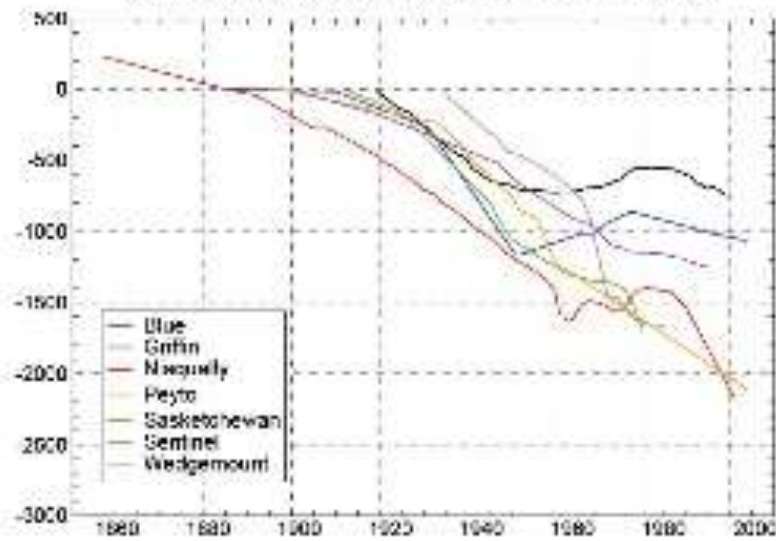
- In the last decade the largest contributions to global glacier loss were from Alaska, the Canadian arctic, and the periphery of the Greenland ice sheet, and the Andes and Asian mountains
- These accounted for 80% of the total ice loss

# Glacier Terminus Shrinkage (scale is 1000's meters)

## 1 Alaska



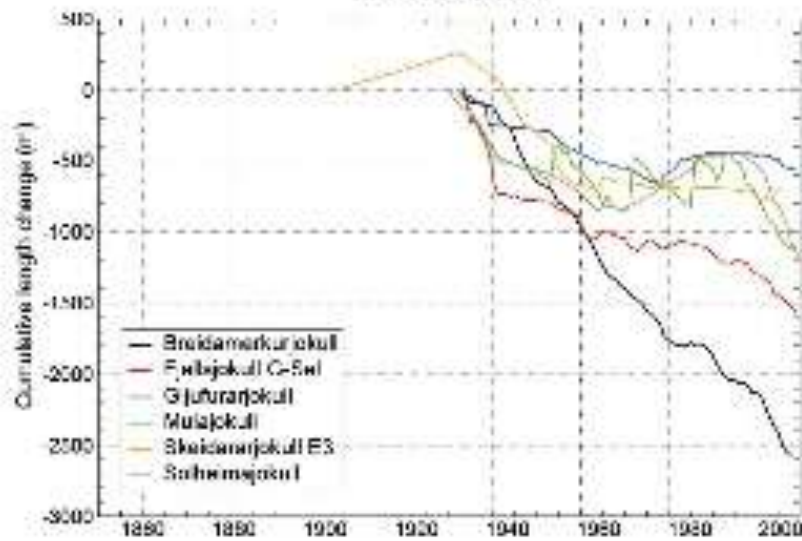
## 2 Western Canada and US



## 5 Greenland



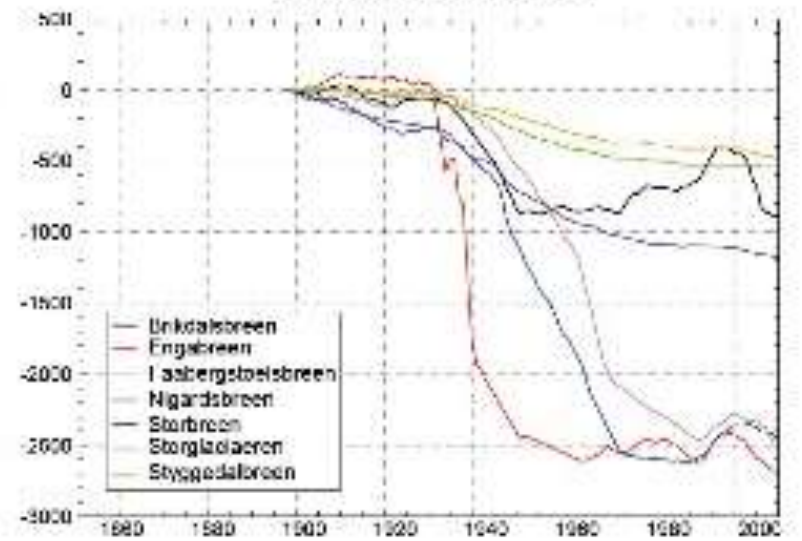
## 6 Iceland



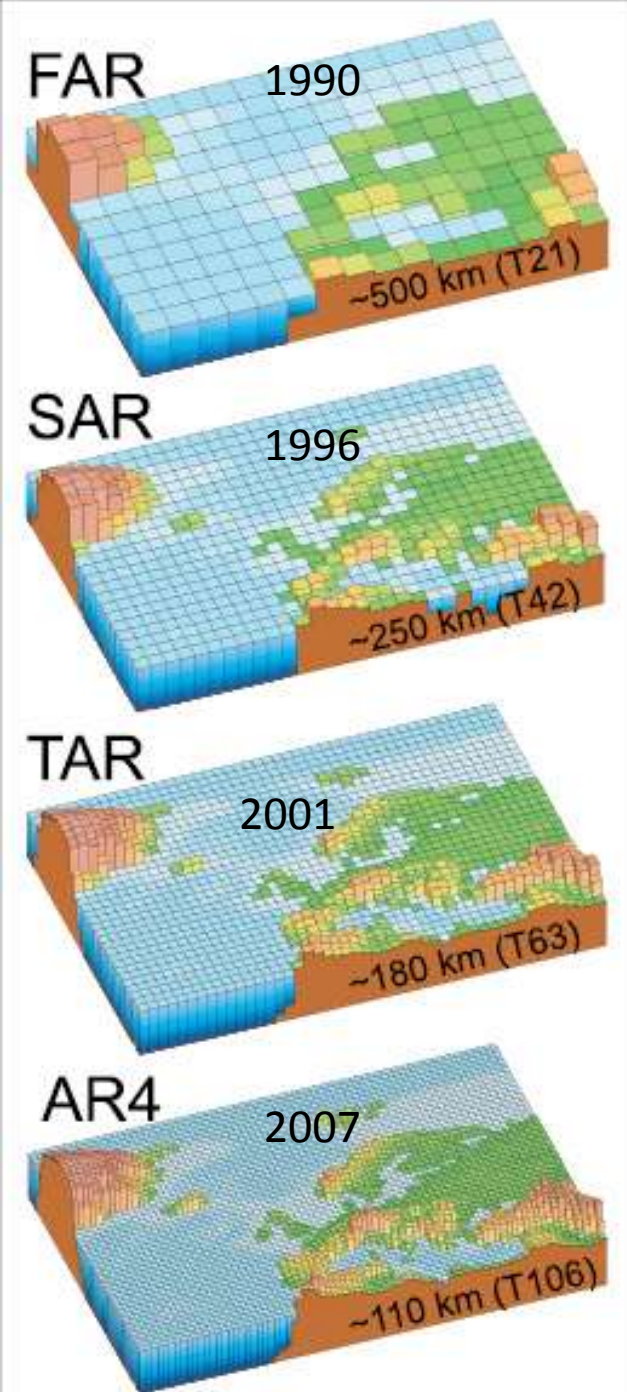
## 7 Svalbard



## 8 Scandinavia



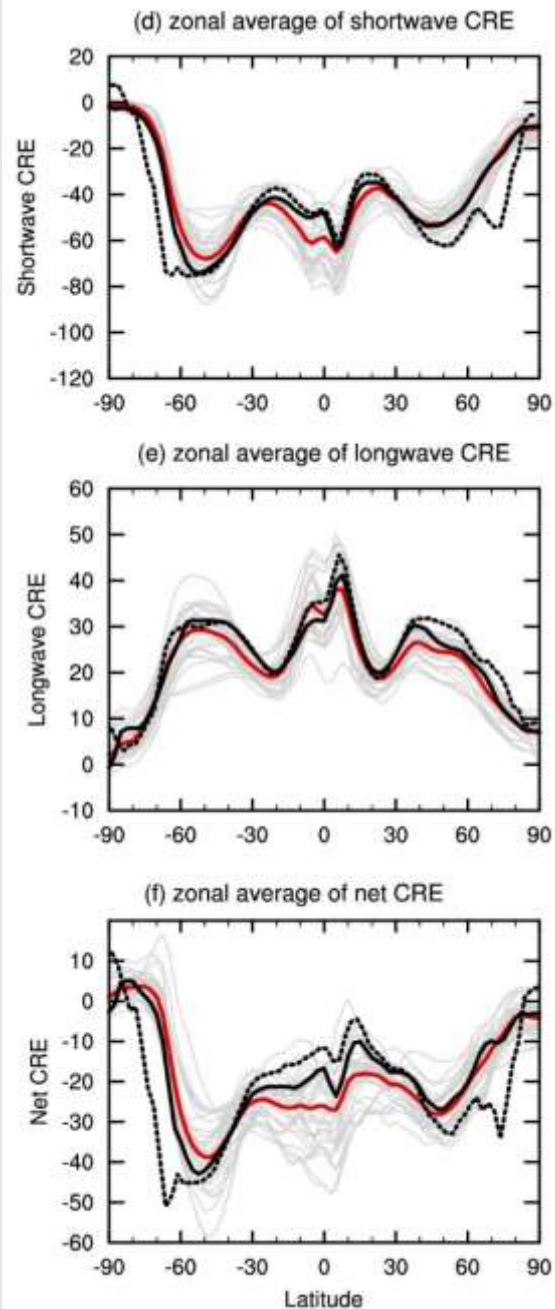
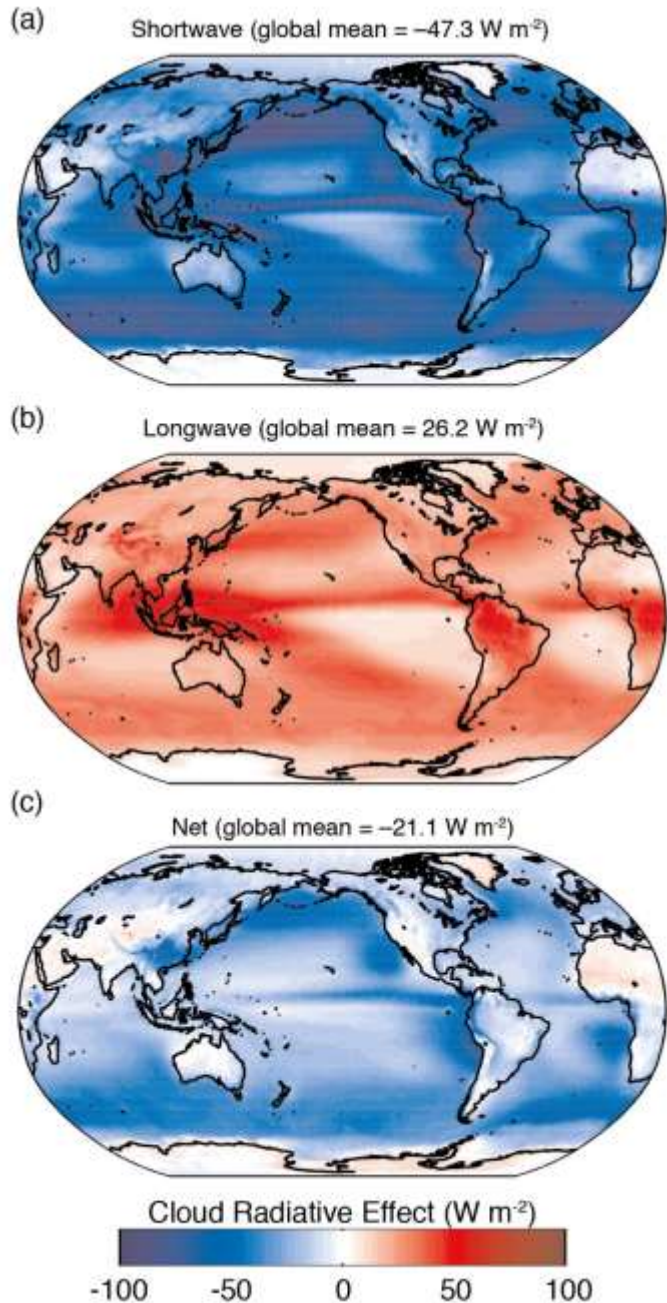
# Earth System Climate Models



- The figure shows the increase in resolution of climate modeling in four generations of IPCC reports spanning 1990-2007
- The 4<sup>th</sup> generation Atmosphere Ocean General Circulation models(AOGCM) which were used in the 2007 report include an incredible array of complex process including
  - Atmosphere effects of convection, clouds, aerosol and boundary layer effects, radiation
  - Land effects of vegetation & soil type, moisture, snow, temperature feedback
  - Sea ice effects of different albedos for bare ice, melting ice, snow covered ice, open water
- The 5<sup>th</sup> generation Earth System Models(ESM)(2) include all of the 4<sup>th</sup> generation processes but add feedbacks among physical, chemical and biogeochemical processes
  - Climate influences on sources and sinks of CO<sub>2</sub> and CH<sub>4</sub>, eg the carbon and methane cycles
  - Aerosol particles and their interaction with clouds and radiative transfer and the sulfur cyc
  - Interactive time varying stratospheric ozone concentrations and chemistry

*Many of the effects of the greenhouse gases and other factors such as clouds and aerosols are expressed in terms the change in energy density in the atmosphere*

*This is called Radiative Forcing and is expressed in  $W/m^2$*

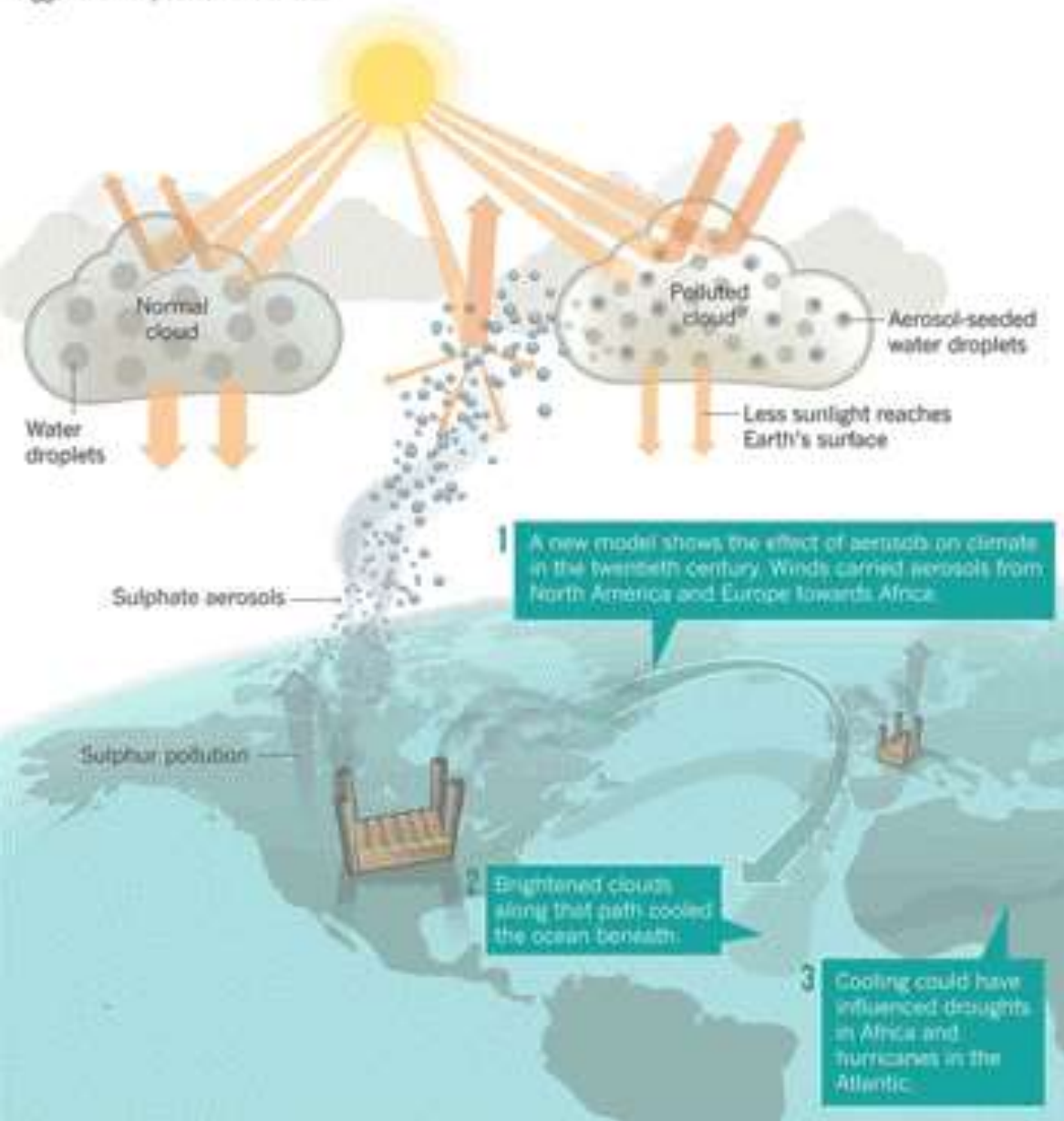


# Cloud Radiative Effect

- One of the major issues influencing radiative fluxes in the atmosphere are the effect of clouds in absorbing or emitting radiation
- The plots on the left are the measured CRE from the for (a) shortwave (from the Sun), (b) longwave radiative (from the atmosphere), and (c) the net radiative effect
- The plots on the right show the zonal averages for the CRE for two different measurements in black, the CMIP5 model mean in red, and individual models in gray
- There is also a wide variation between individual models seen in the zonal comparison and the CRE shows up as the biggest cause of differing climate projections from the various models
- Improvements are being sought in the areas of fractional coverage of clouds, their vertical distribution, as well as their ice and water content

# THE POWER OF POLLUTION

Aerosols — tiny particles from pollution, volcanoes, dust and other sources — can reflect or absorb sunlight directly, or seed cloud droplets and brighten clouds. New climate models suggest that aerosols and clouds can have bigger than expected influences.

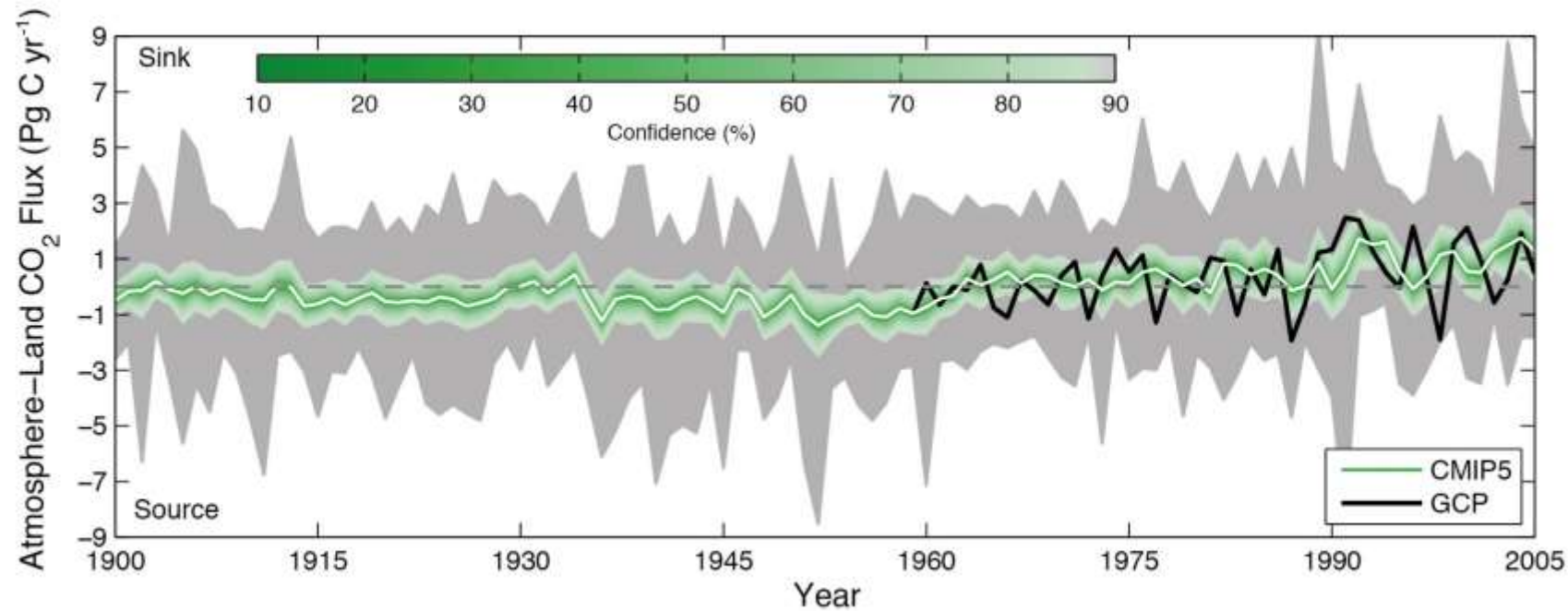
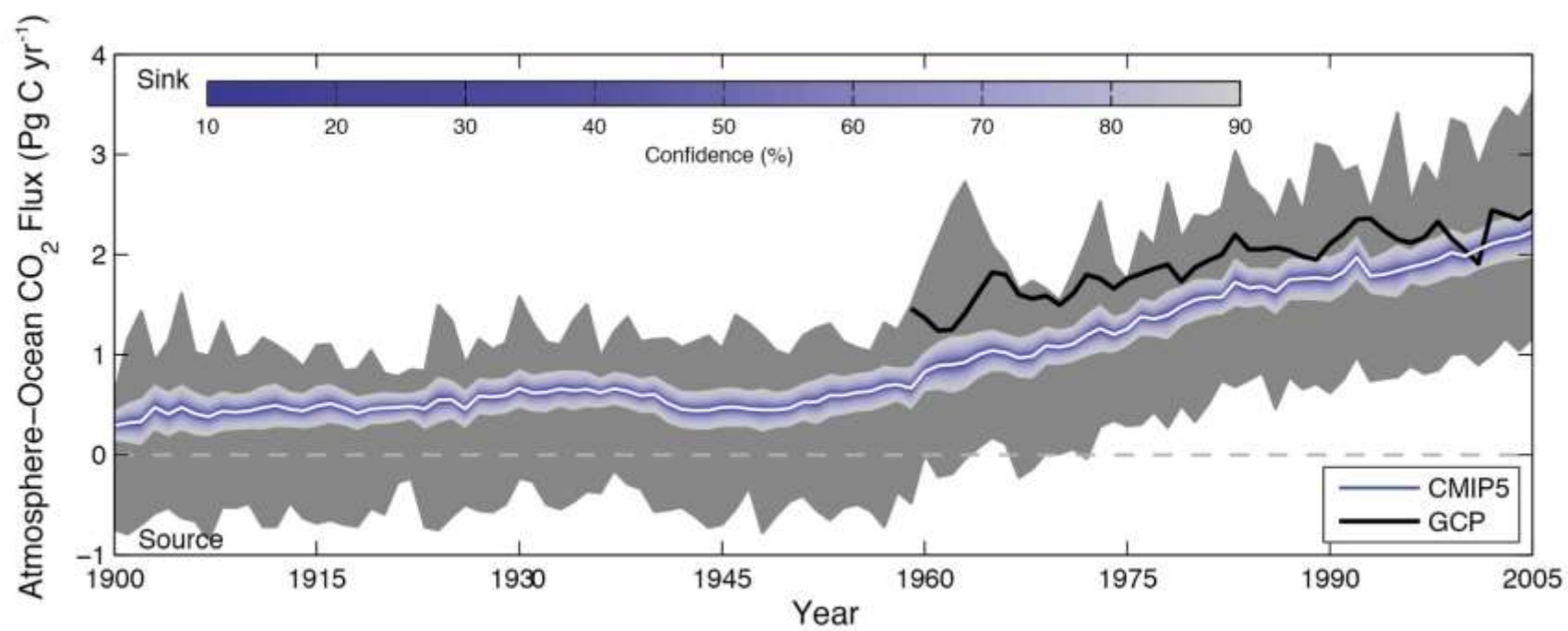


## Aerosol Caused Climate Effects

- Atmospheric aerosols come from natural and anthropogenic sources such as volcano's, air pollution (SO<sub>2</sub>), smoke and airplane contrails
- Aerosols scatter and absorb light and **also serve as** condensation and ice nucleation sites, on which cloud droplets and ice particles can form
- Aerosol particles can also affect clouds making them brighter so they reflect more light
- Climate models account for these indirect effects separately as radiation interactions and cloud interactions(1) and are quantified as Effective Radiative Forcing(ERF)



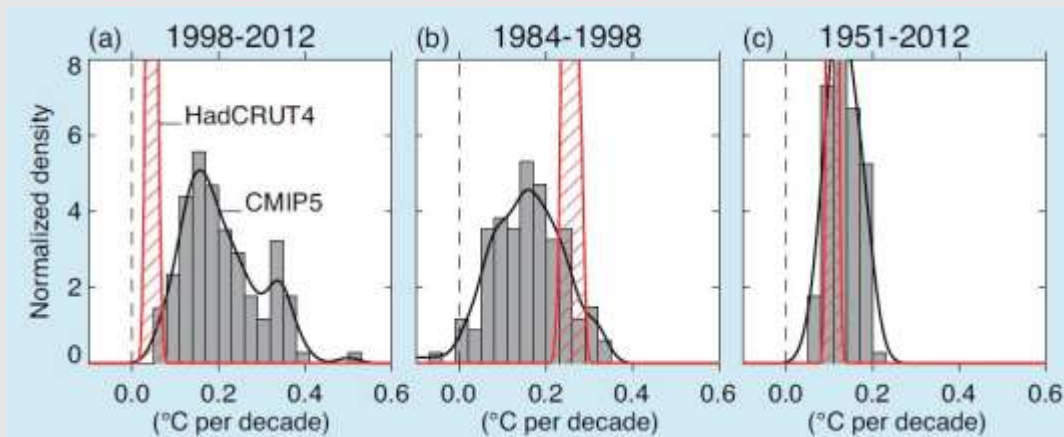
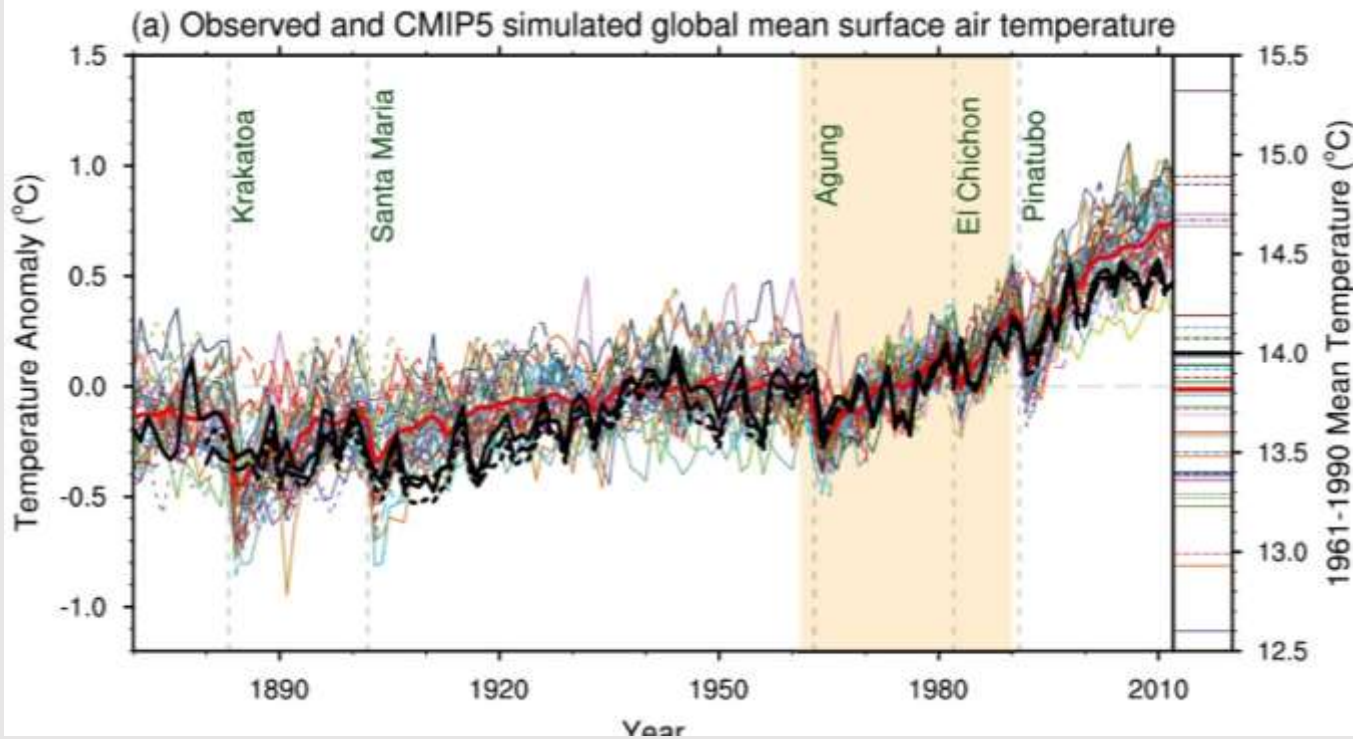
# Carbon Cycle Modeling in IPCC5



- One of the improvements in IPCC5 modeling over IPCC4 is inclusion of the carbon cycle
- The graphs(1) show the amount of  $\text{CO}_2$  either stored(sinked) in the ocean(top) or the land(bottom) or emitted(sourced) in giga tons/year
- The solid line are estimates from the Global Carbon Project(2)

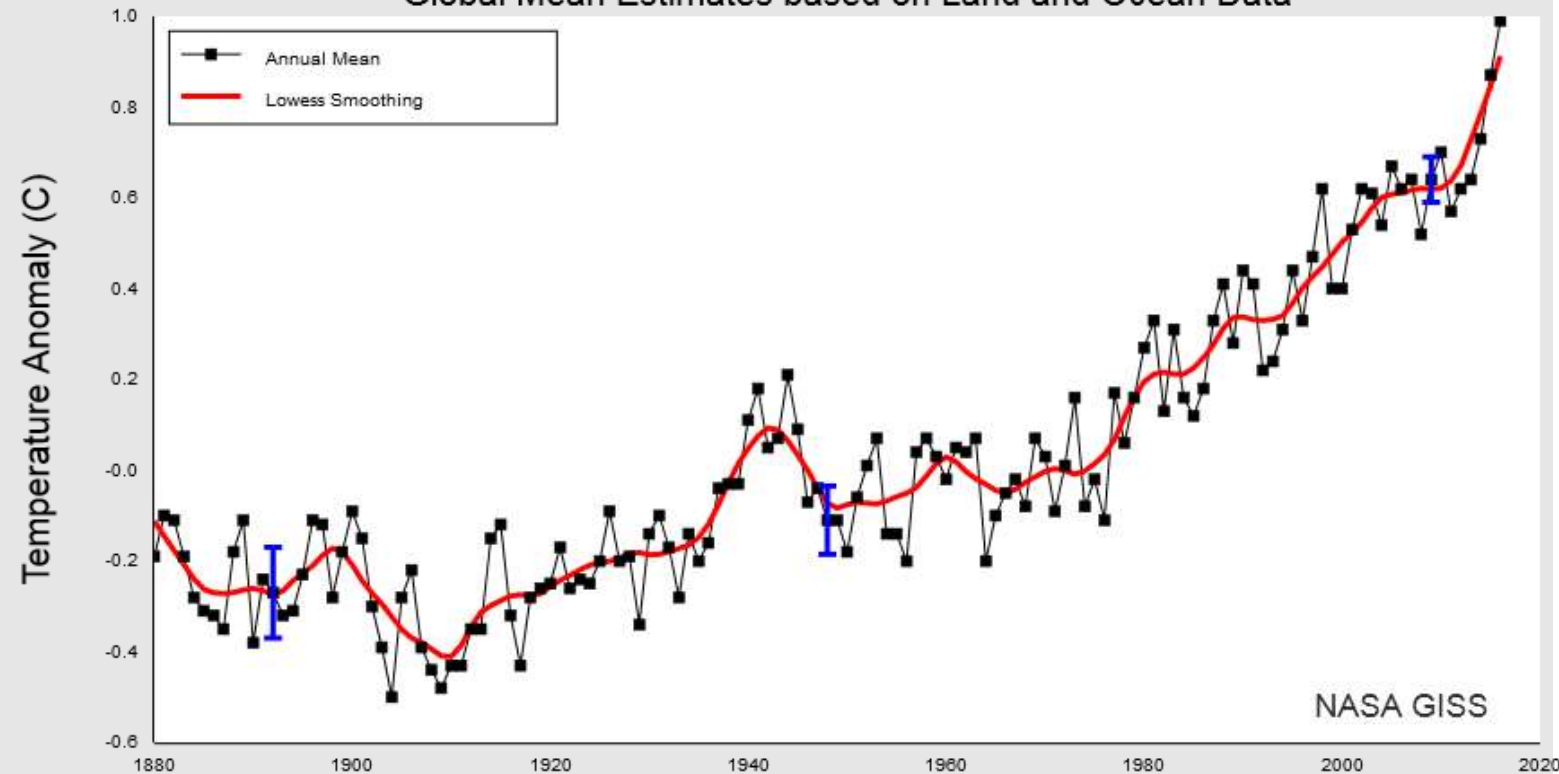
# IPCC5 ESM Model Results

- Figure shows the observed and simulated mean surface temperature changes where the black line is the observed data(referenced for 1961-1990)
- The top graph is for the ESM models with each model shown separately and the red line being the CMIP5 mean(Coupled Model Intercomparison Project)
- While the overall fit is very good most of the models over estimated the temperature rise in the last 15 years
- The lower graph shows the distributions of observed versus model results over different periods
- As can be seen the overall accuracy from 1951-2012 is very good
- The models under predicted the temperature over the 1984-1998 period while they over predicted in 1998-2012

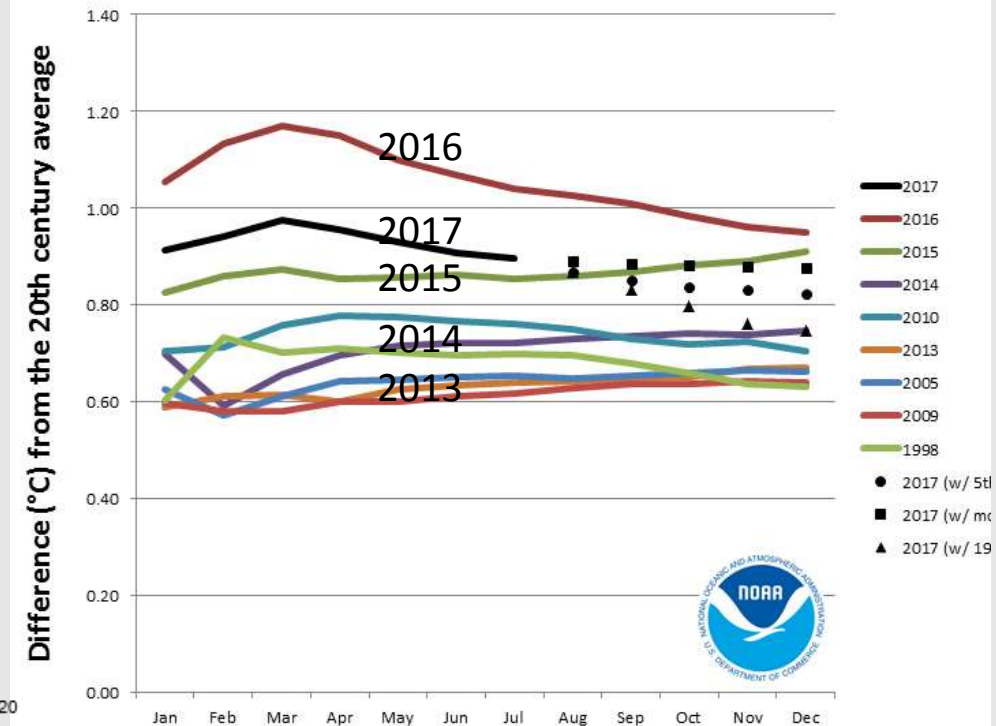


# Latest Data on Global Temperatures

Global Mean Estimates based on Land and Ocean Data



Year-to-Date Global Temperatures for 2017 and the other eight warmest years on record

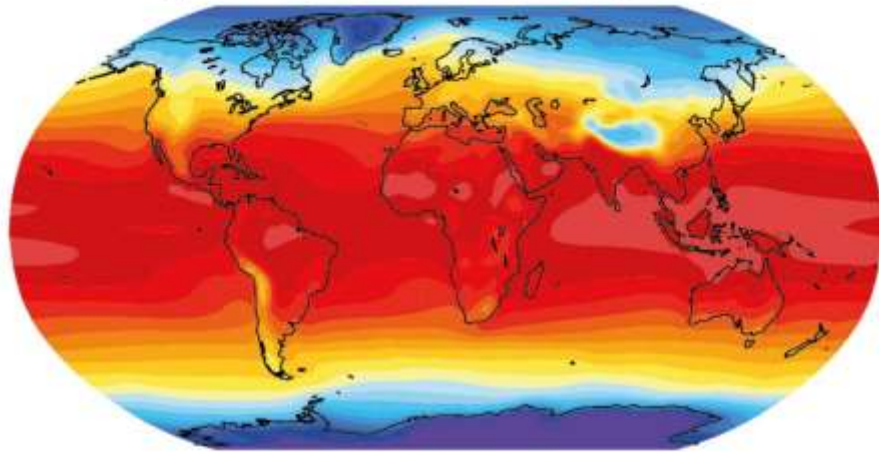


- The previous temperature profile shows a roll-off in the 15 years previous to 2013 when the previous data was compiled
- However, when more recent data was added as seen above the curve has made a noticeable uptick resuming its rapid temperature rise since 1980(1)

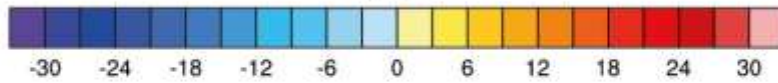
- Looking at the last 5 years, there has been a significant and continuous rise in global temperatures(2)
- Before 2013 the temperatures had rolled off but now it is seen as a normal fluctuation that has been seen many times before

# Calculations and Errors for Mean Temperature and Mean Precipitation

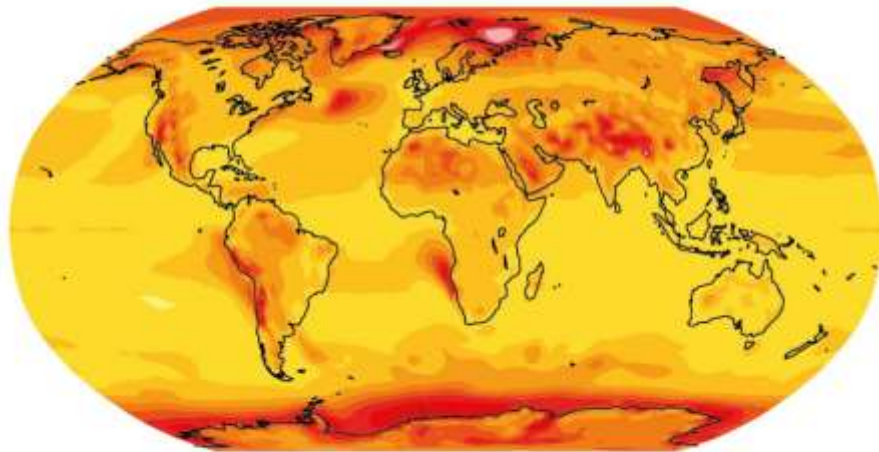
(a) Multi Model Mean Surface Temperature



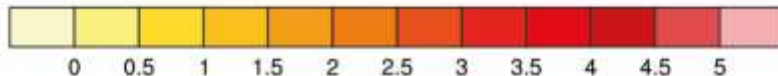
(°C)



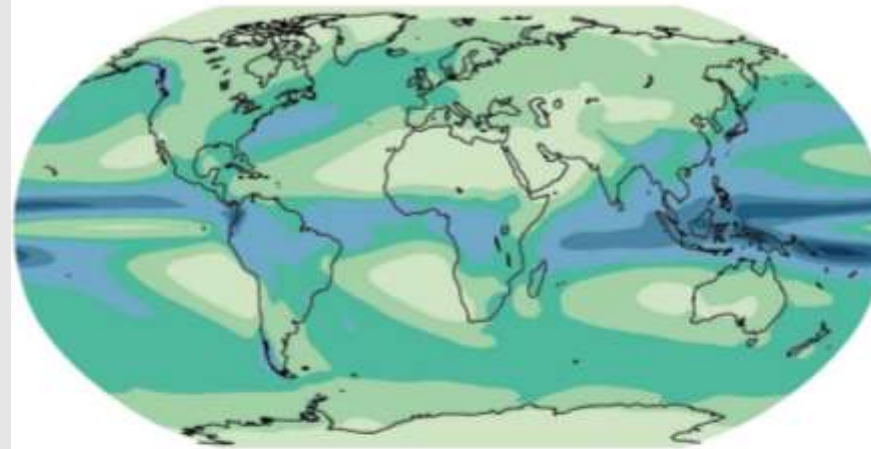
(c) Multi Model Mean of Absolute Error



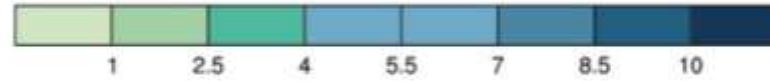
(°C)



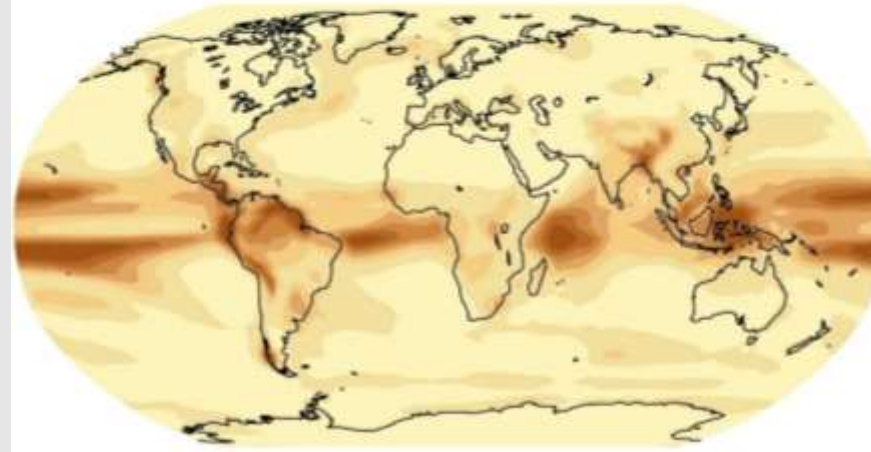
(a) Multi Model Mean Precipitation



(mm day<sup>-1</sup>)



(c) Multi Model Mean of Absolute Error

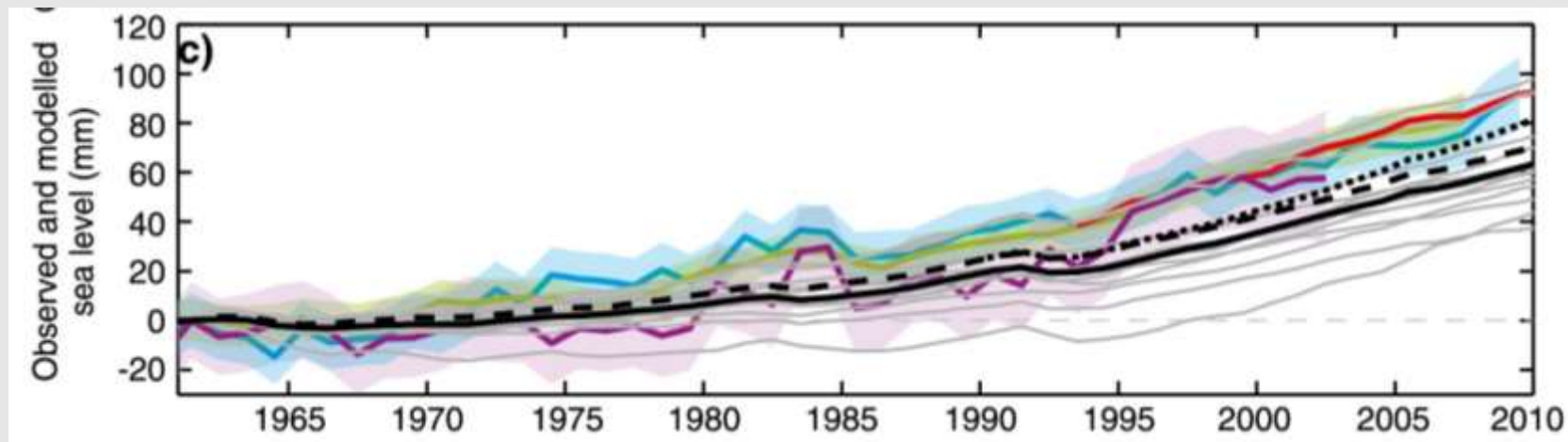
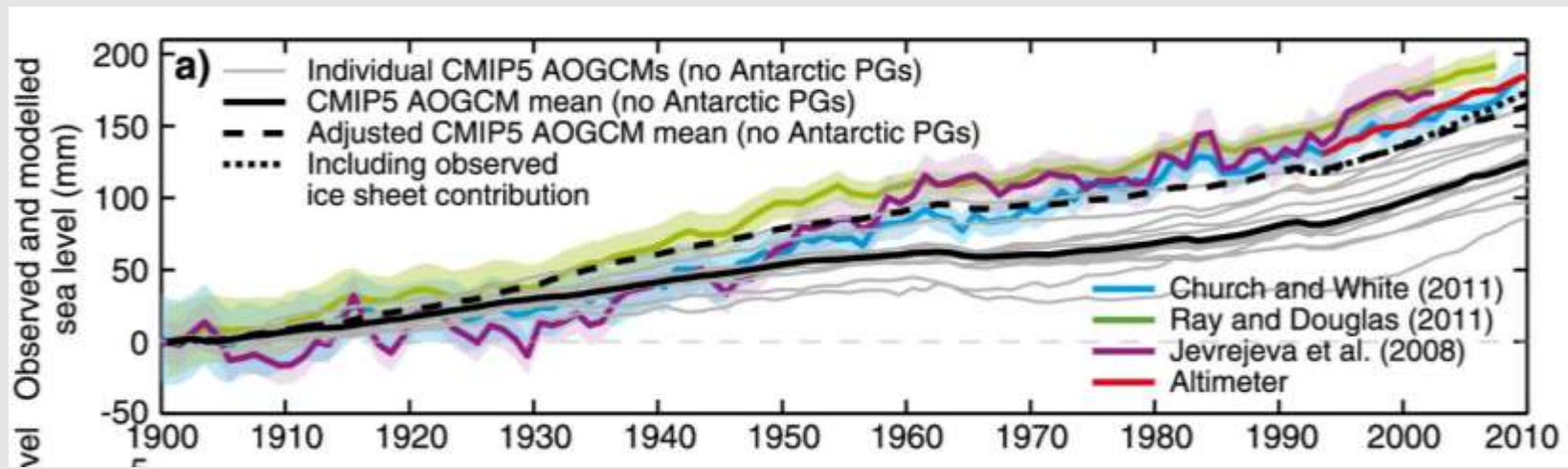


(mm day<sup>-1</sup>)



- Top left plot is the mean surface temperature at 2 meters between 1980 and 2005 calculated as the mean of all ESM models
- Top right plot is the mean precipitation between 1980 and 2005 calculated as the mean of all ESM models
- The bottom plots are the error of the model from observations
- There is “high confidence” that the large scale patterns of surface temperature are well simulated except over the Himalaya’s, Andes, and the polar regions where the errors in measurement are the largest(1)
- The precipitation the broad scale precipitation patterns are in “modest” agreement(1) except for the tropics

# Observed & Modeled Sea Level Change

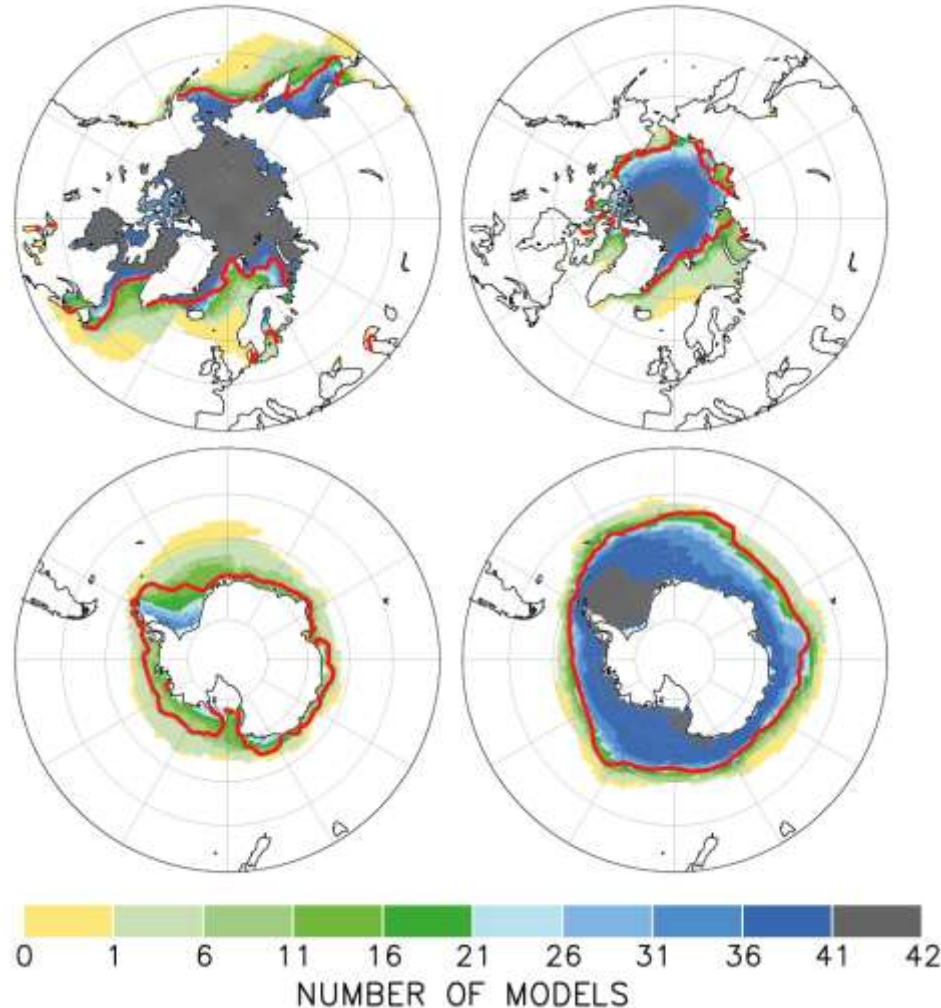
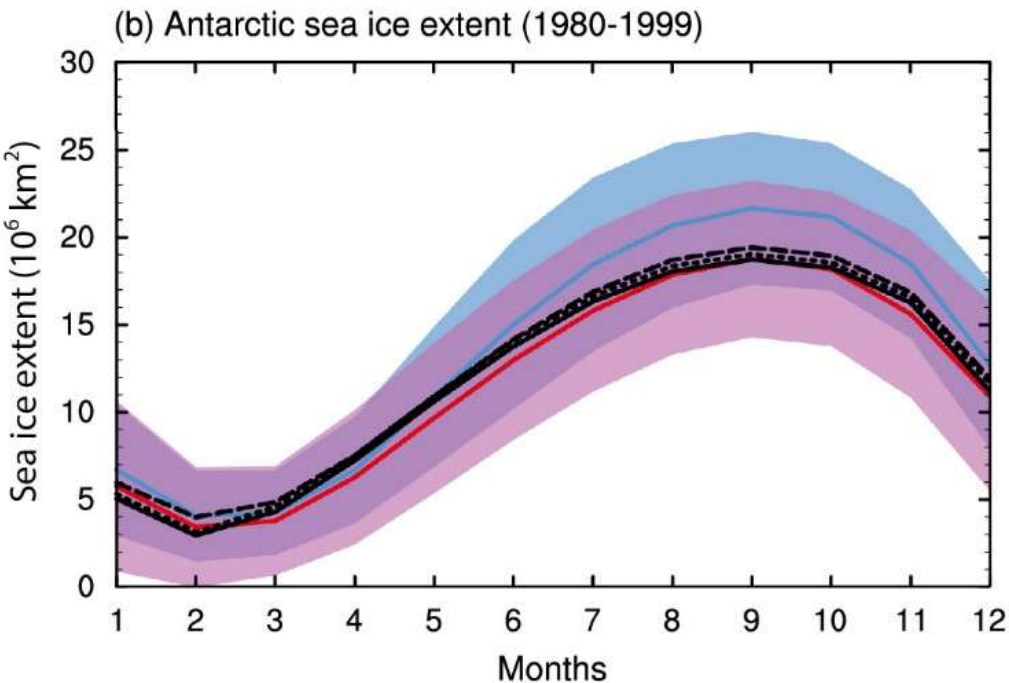
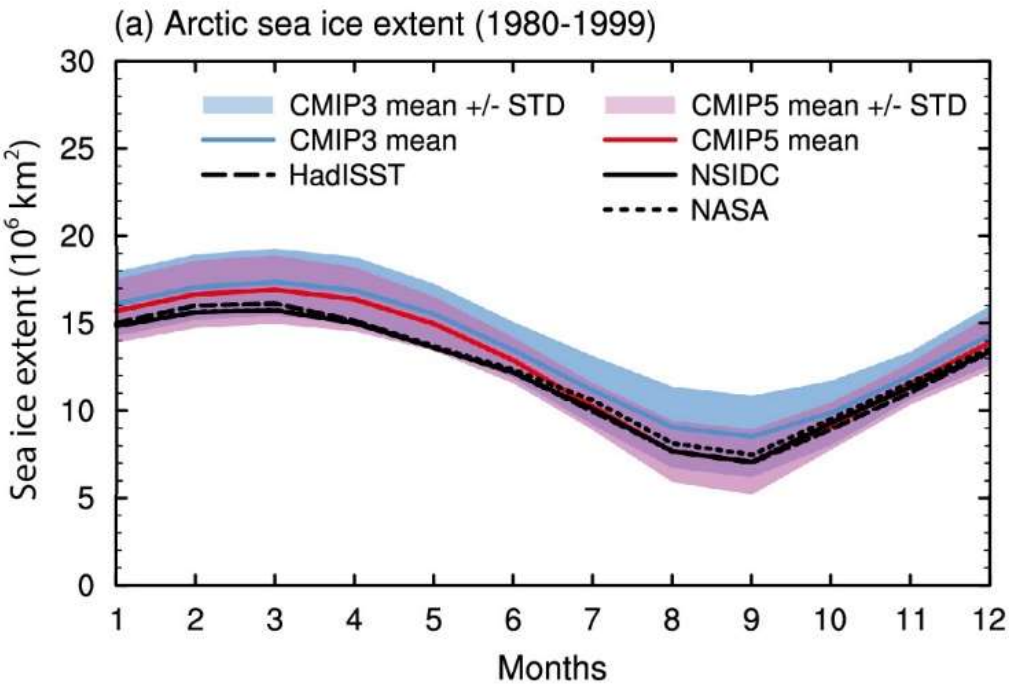


- The first graph shows the observed from 4 data sets (colored lines) and modeled changes in sea level from 1900 and 2010 and the solid red line is from satellite altimeter data which began in 1993
- The solid line is CMIP5 model average for the sea level rise due to thermal expansion of the ocean due to increases of sea heat content
- The dashed line includes the thermal expansion model plus the observed contribution from glaciers and the black dotted line includes the observed ice sheet contributions which began in 1993

- It is interesting to note that the bulk of the rise has been thermal expansion which is 0.8mm/yr and comes from the upper 700m of the sea(1)
- Together with the glacier contribution this explains 60% of the rise for 1901-1990 but 90% of the observed rise since 1990(1)
- The ice sheet contributions have the potential to increase substantially but they are relatively small now so do not test the models going forward(2)

# Sea Ice Extent Observed and Modeled

- Mean sea ice extent is shown for 1980-1999 comparing models from 2007(CMIP3) and 2013(CMIP5) with observations
- Definite improvement is seen in predicting summer sea ice in the Arctic and winter in the Antarctic

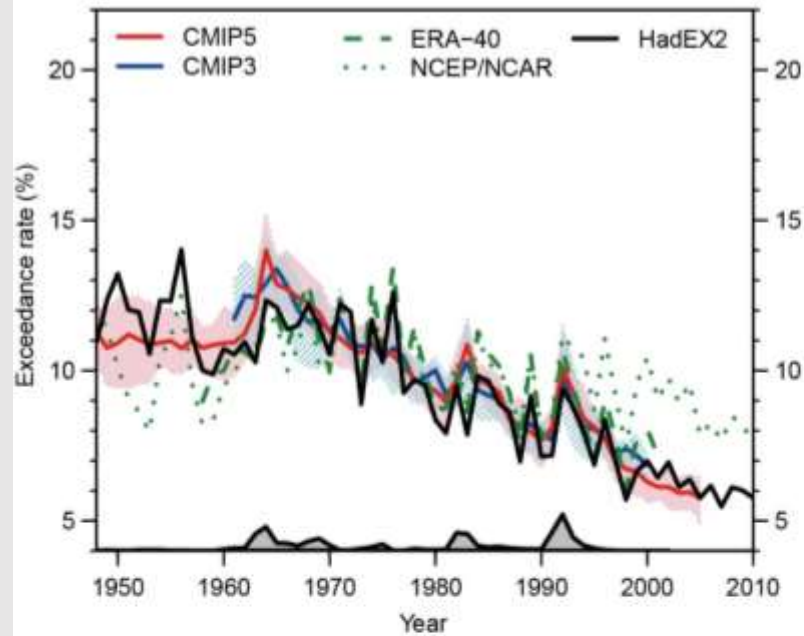


- Sea ice distribution in the Arctic and Antarctic in both March(left) and September(right)
- The color is a measure of how many models correctly predicted the extent of 15% or more ice coverage
- Red lines are the observed distribution with good agreement except summer ice extent in the Antarctic

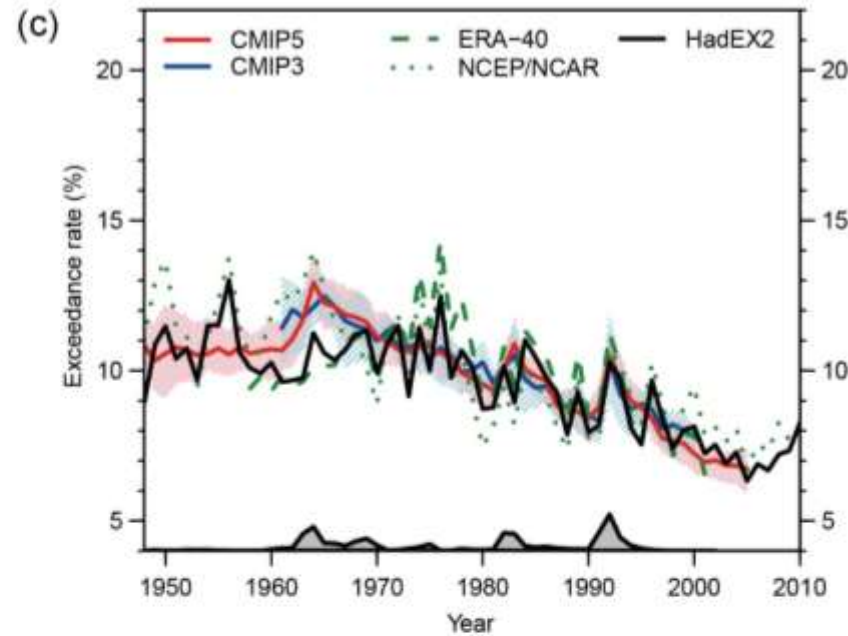
# Changes in Temperature Extremes

- In addition to a global warming in the average temperatures there is a significant trend in the warming of the extremes in day and night time temperatures
- The red and blue lines are the model averages for the 2013 and the 2007 models
- As can be seen there is good agreement with the data
- In addition to the temperature extremes there will be more adverse weather extremes
- In 2017 there were 16 events costing over \$1 B each for a total of \$360 B.
- The past average was 5 such events

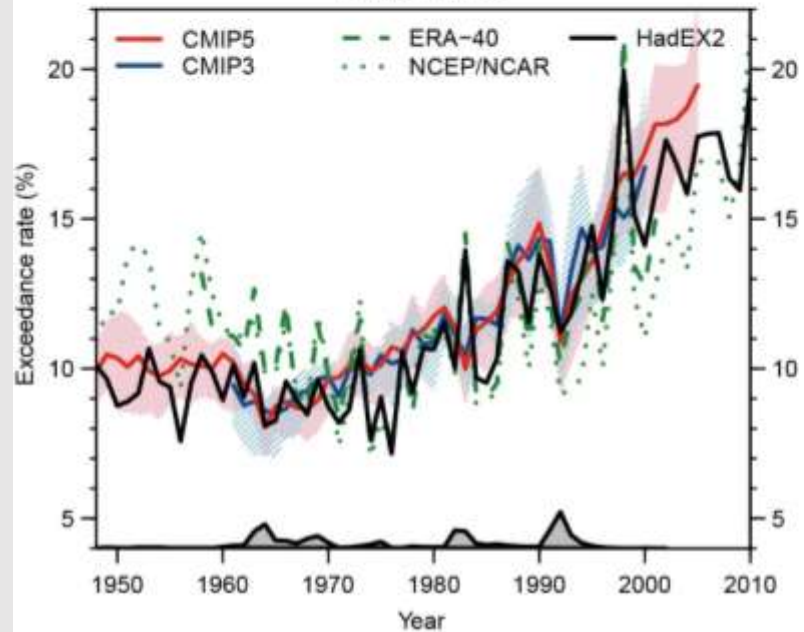
Cold nights



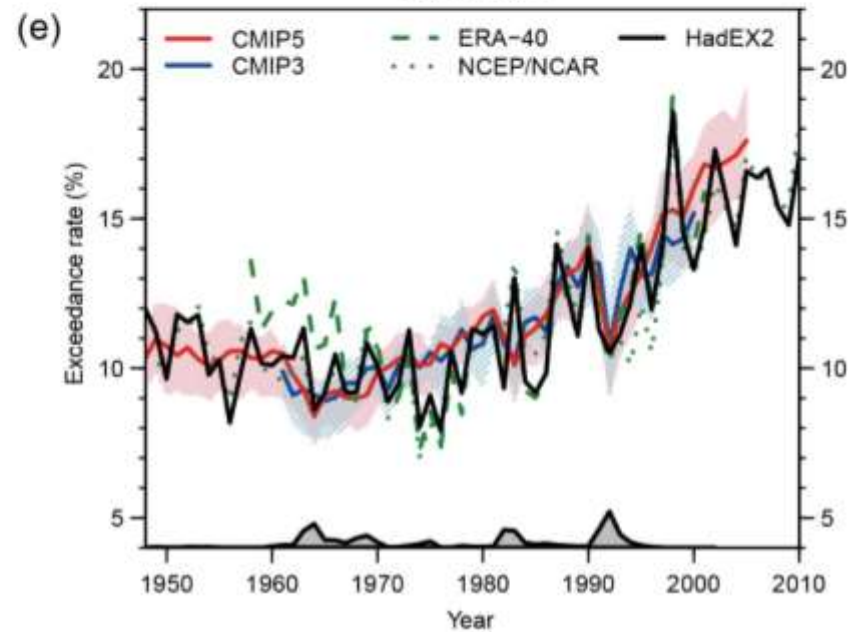
Cold days



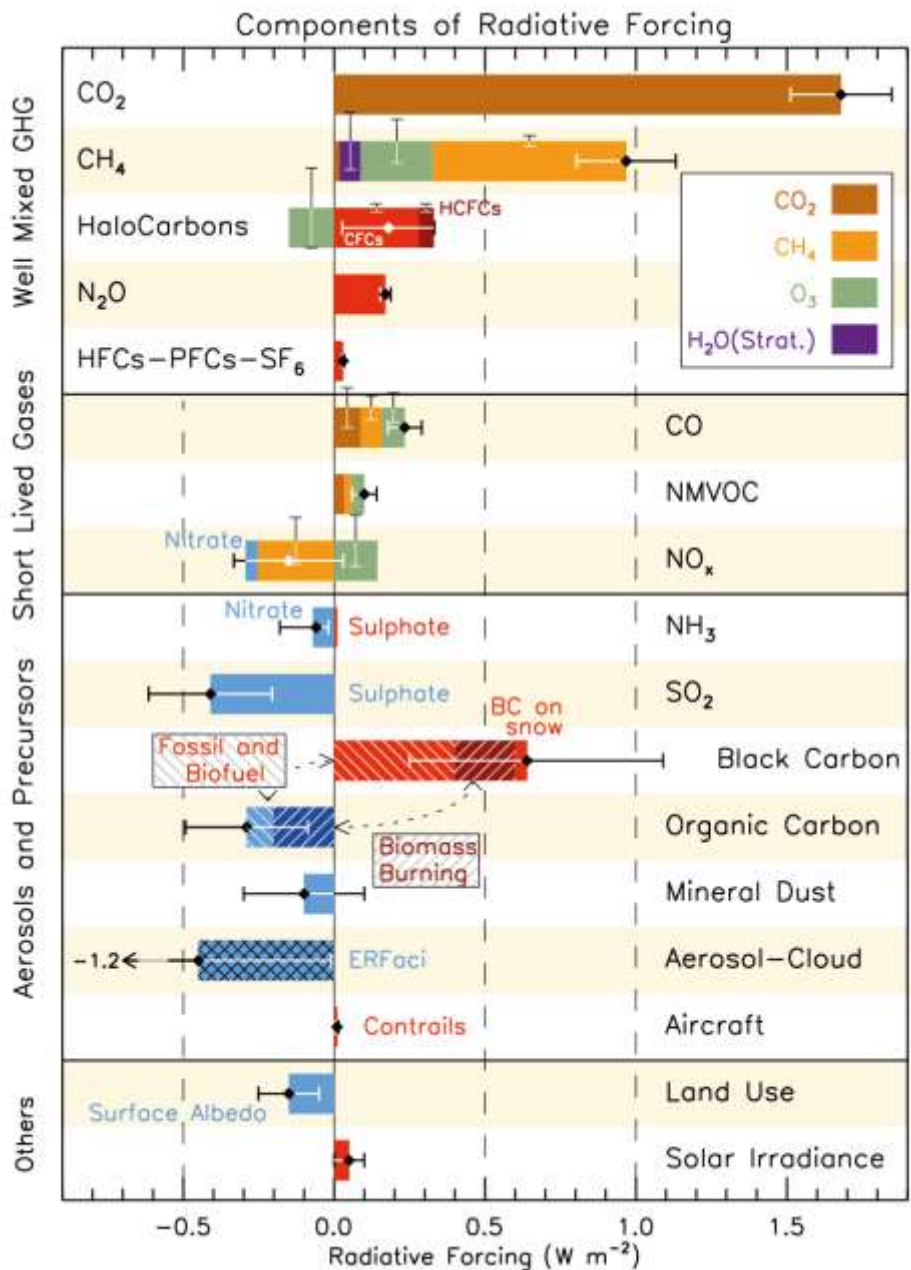
Warm nights



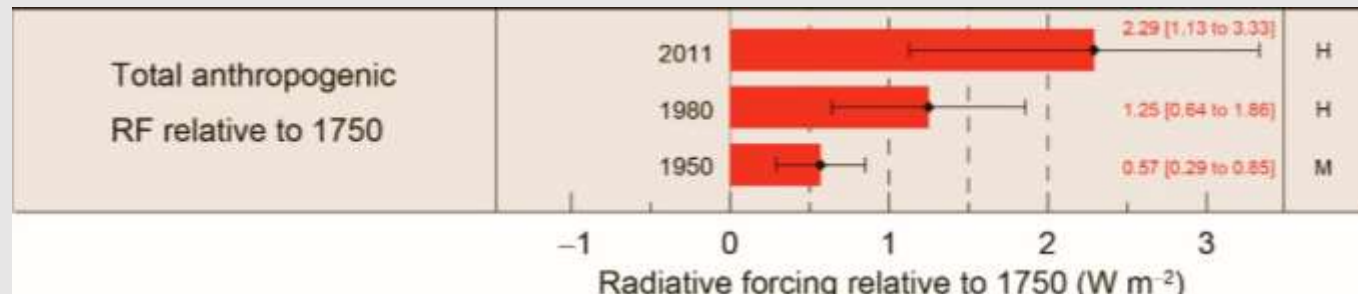
Warm days



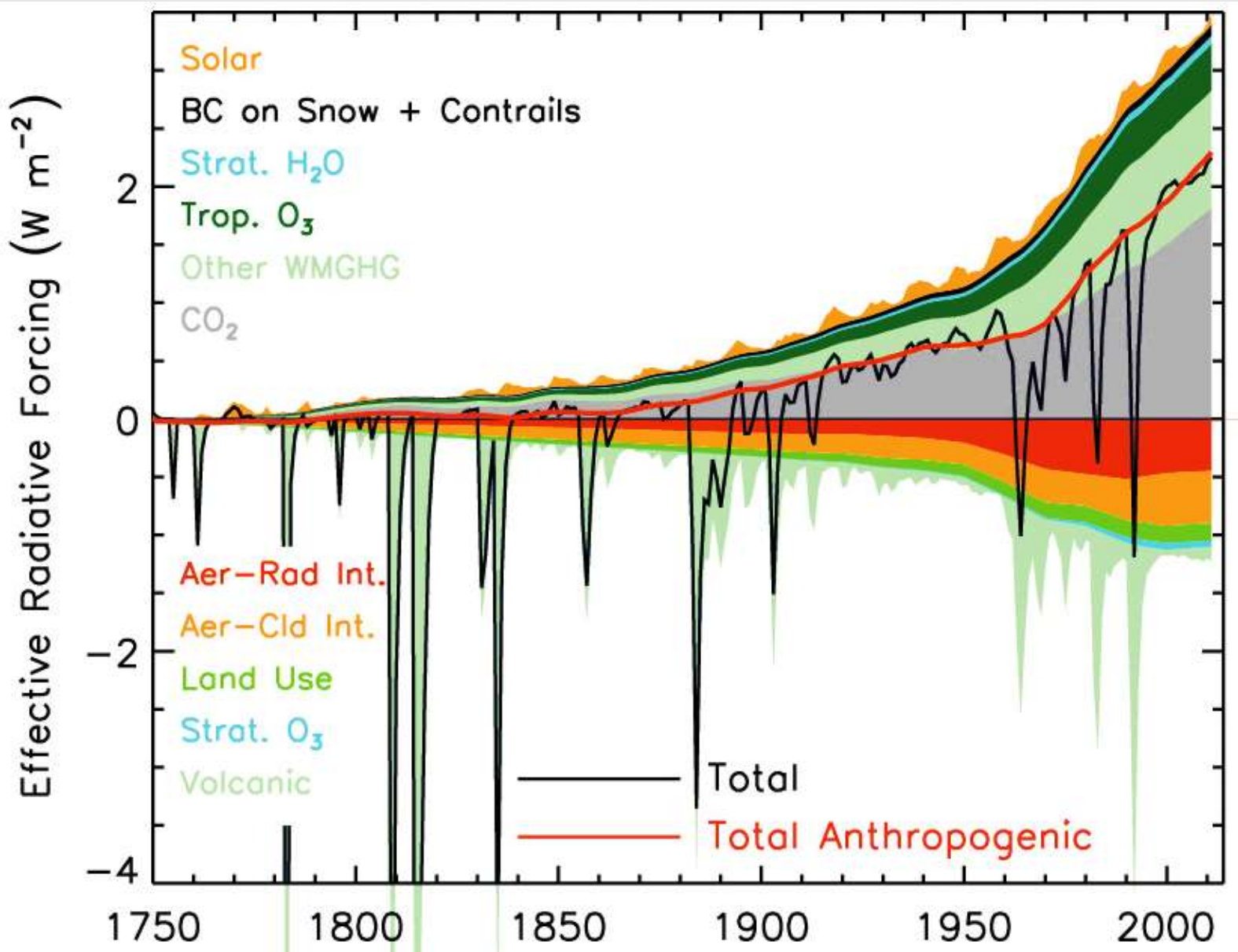
# Radiative Forcing Changes from 1750 to 2011



- This chart(1) is the change in anthropogenic forcing during the Industrial Revolution
- It lists all of the greenhouse gases by the size of their net radiation in  $W/m^2$  and the error bars associated with each specie
- The effects are grouped into categories, well mixed long lived greenhouse gases, short term GH gases, and aerosols which have a cooling effect
- Ozone is treated in two different ways with the first as a gas in the stratosphere which largely absorbs uv radiation and has a cooling effect
- It also is shown with methane and with gases from air pollution precursor sources where it is created by the chemistry in the troposphere when exposed to sunlight(2) and acts as a greenhouse gas
- The error bars show the uncertainty with the main issue coming from the aerosols because of their complex interactions with the solar radiation and clouds



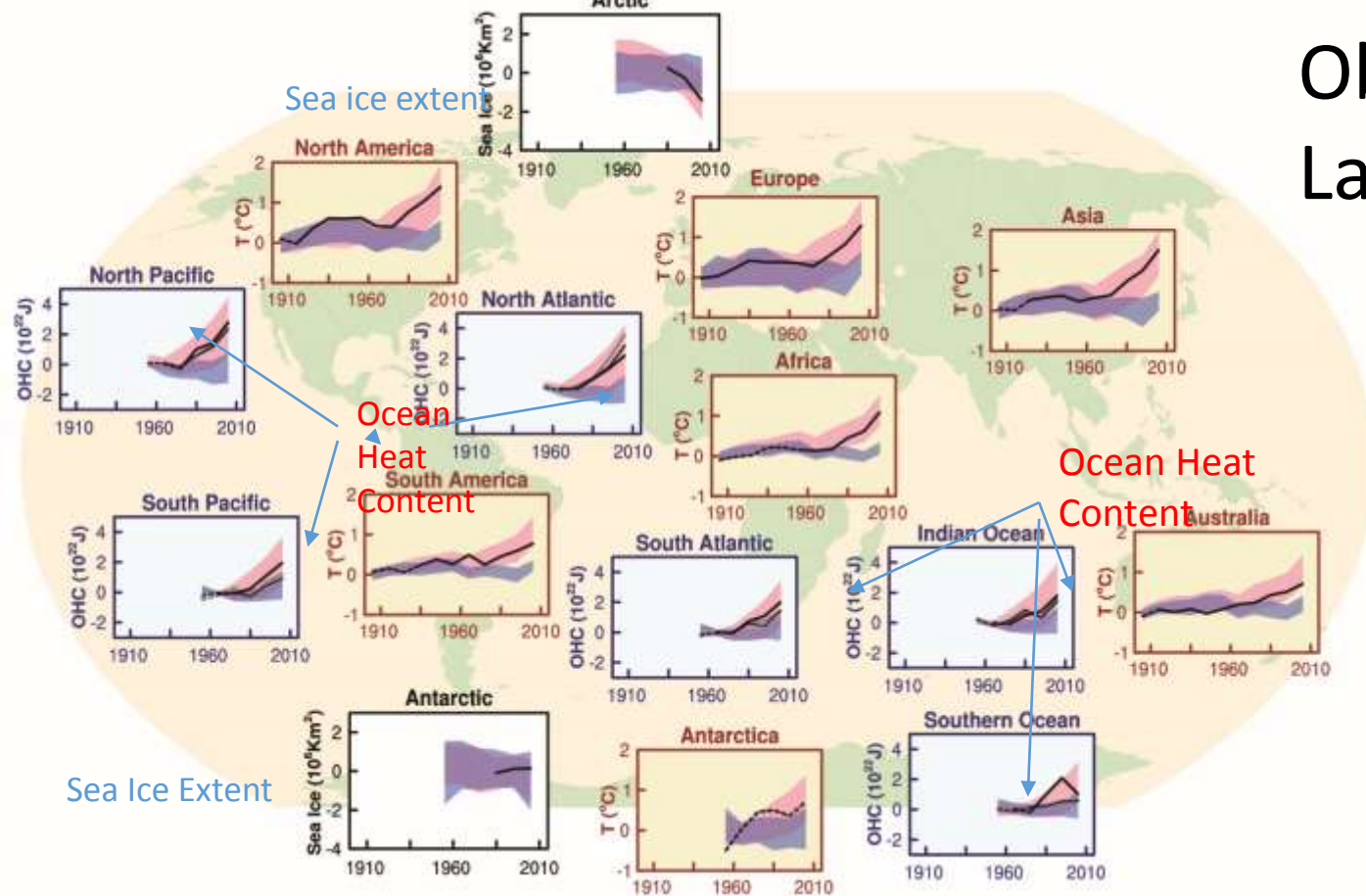




## Anthropogenic and Natural Radiative Forcing

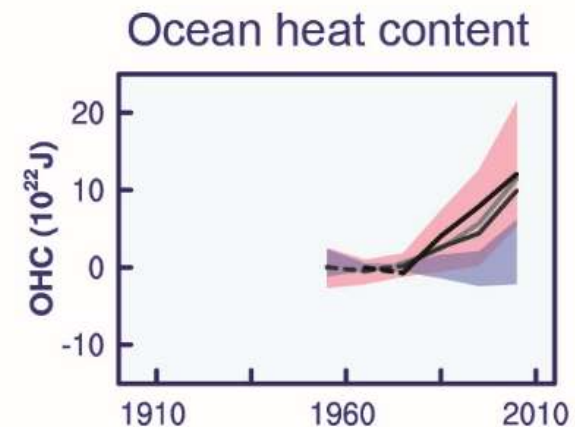
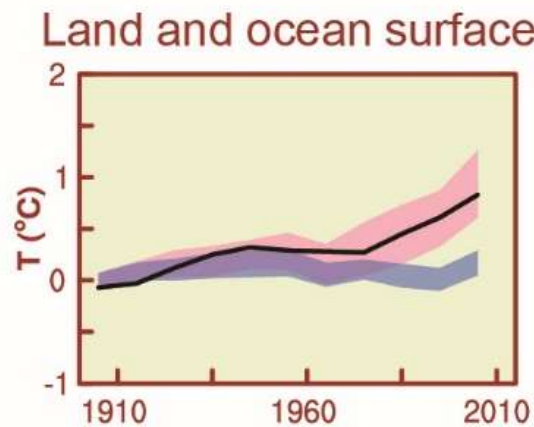
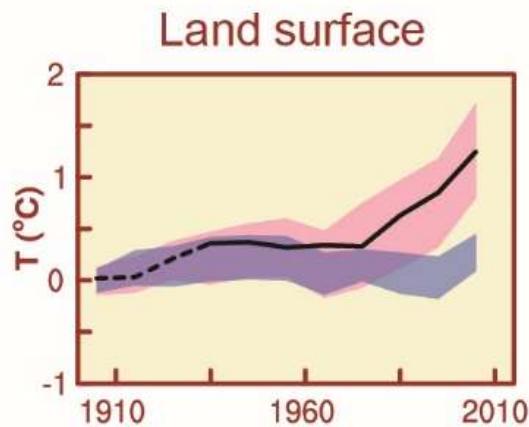
- Figure shows the natural and anthropogenic radiative forcings from 1750 to 2011
- Effects not addressed such as volcanic eruptions and solar variations are shown
- The solar irradiance variations follow the sunspot cycle (1)
- There is a small warming effect of black carbon on snow(0.04W/m<sup>2</sup>), airplane contrails(0.01W/m<sup>2</sup>), and stratospheric H<sub>2</sub>O(0.7W/m<sup>2</sup>) (2)
- The relative sizes of the ozone tropospheric ozone warming effect and the stratospheric cooling are shown showing a net warming effect
- There is also a cooling effect due to increases in the earth's surface albedo from changes in land use
- Effects of the aerosol radiative and cloud interactions are shown and are a strong cooling effect partially offsetting the greenhouse warmings effects(3)

# Observed and Simulated Global Large Scale Climate Changes(1)

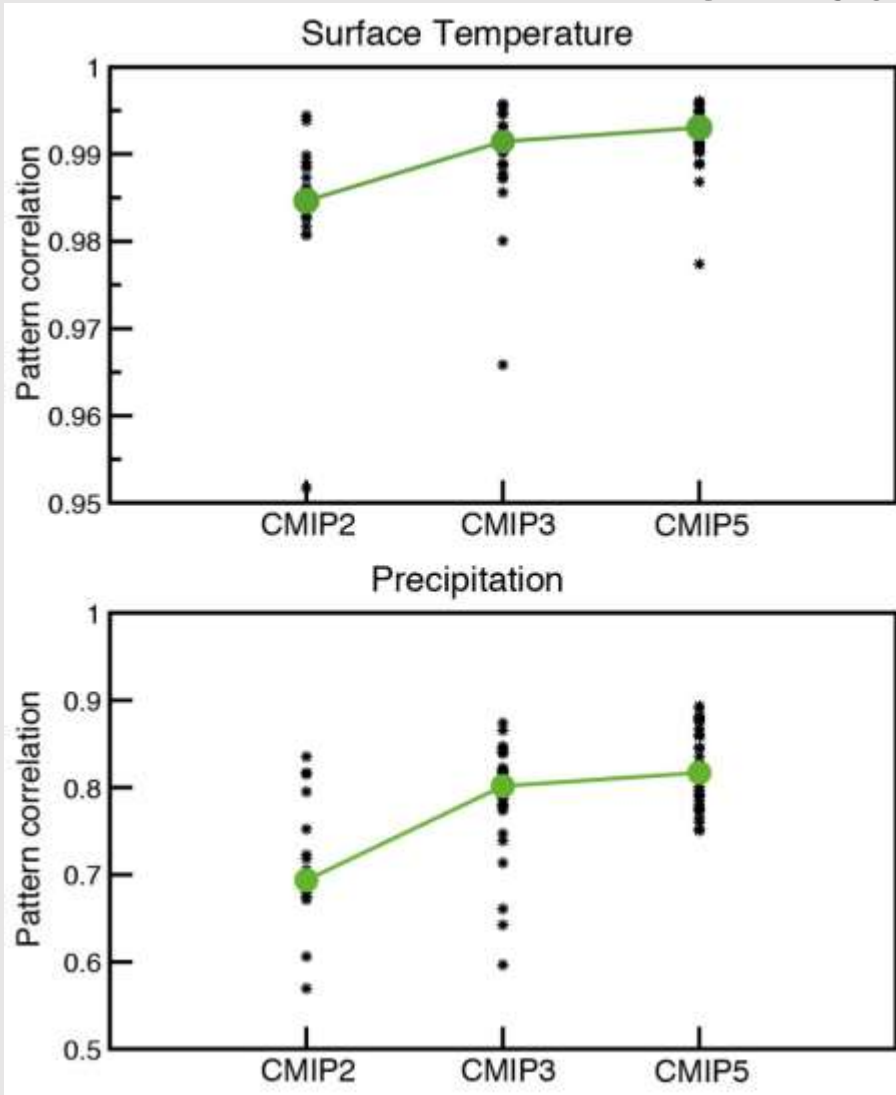


- Arctic and Antarctic September sea ice extent
- Ocean heat content
- Continent temperature rise
- Modeled with natural forcings alone(blue)and then total forcings(pink) including anthropogenic forcings

## Global averages



# Climate Models Summary

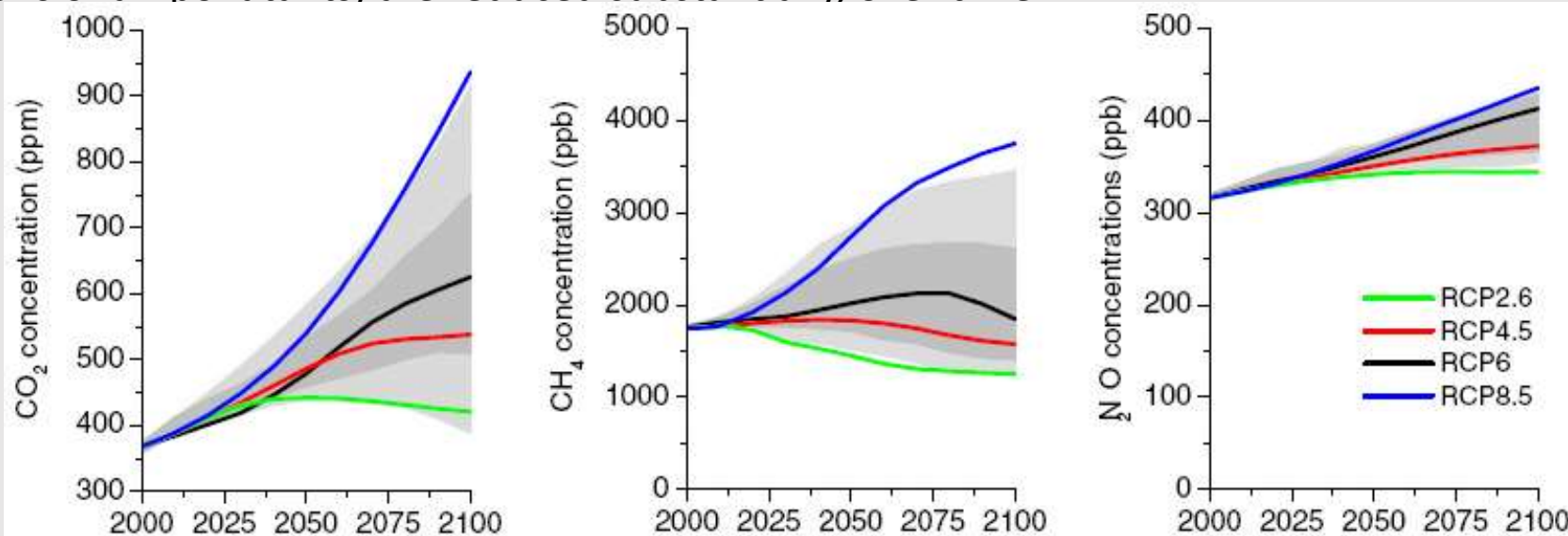


- The figure shows the correlation (a measure of pattern similarity) between observed and modelled temperature and precipitation for three generations of models.
- The figure illustrates the ongoing, albeit modest, improvement. It is interesting to note that both the poorest and best performing models demonstrate improvement
- From this and the previous slides it can be seen that the models are doing an amazing job in modeling all matter of climate processes
  - Average surface temperature on land and water and combined
  - Actual temperatures patterns across the globe
  - Actual precipitation patterns across the globe
  - Changes in the number of coldest and warmest days and nights
  - Ice sheet and glacier growth and loss as well as the details of ice extent throughout the seasons
  - Sea level changes, sea temperature, and sea heat content
  - Detailed cloud effects and aerosol effects and interactions

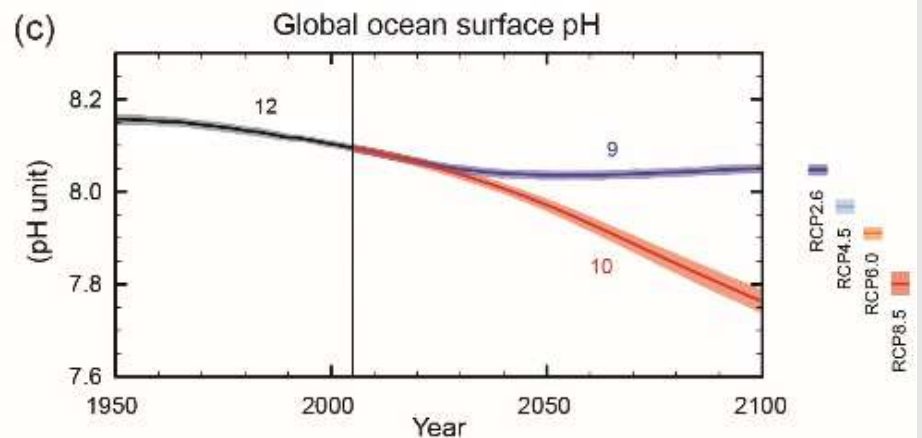
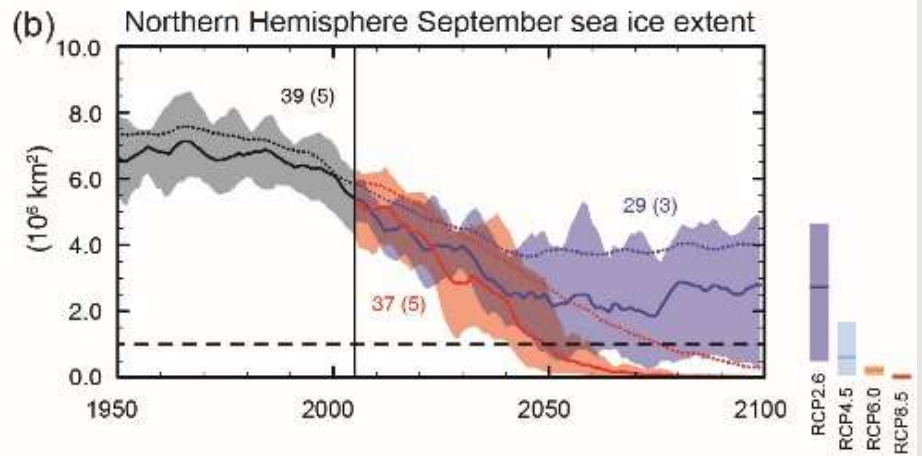
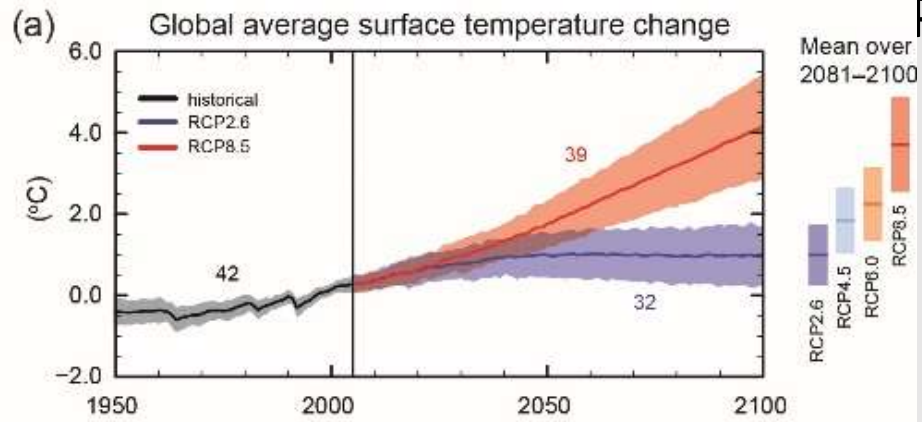
The figures show a summary of results from the last three CMIP (Coupled Model Intercomparison Project) models done in 2000, 2007, and 2013

# Future Climate Change Projections

- Four climate forcing scenarios have been developed called Representative Concentration Pathways(RCP's) where emissions and socio economic scenarios are developed in parallel, building on different trajectories of radiative forcing over time(1)(2)
- RCP8.5:This RCP is characterized by increasing greenhouse gas emissions over time hitting 8.5 W/m<sup>2</sup> in 2100, representative of scenarios in the literature that lead to high greenhouse gas concentration levels
- RCP6:It is a stabilization scenario in which total radiative forcing is stabilized shortly after 2100 at 6 W/m<sup>2</sup>, without overshooting the long-run radiative forcing target level
- RCP4.5:It is a stabilization scenario in which total radiative forcing is stabilized shortly after 2100 at 4.5 W/m<sup>2</sup>, without overshooting the long-run radiative forcing target level
- RCP2.6: It is a “peak-and-decline” scenario; its radiative forcing level first reaches a value of around 3.1 W/m<sup>2</sup> by mid-century, and returns to 2.6 W/m<sup>2</sup> by2100. In order to reach such radiative forcing levels, greenhouse gas emissions (and indirectly emissions of air pollutants) are reduced substantially, over time

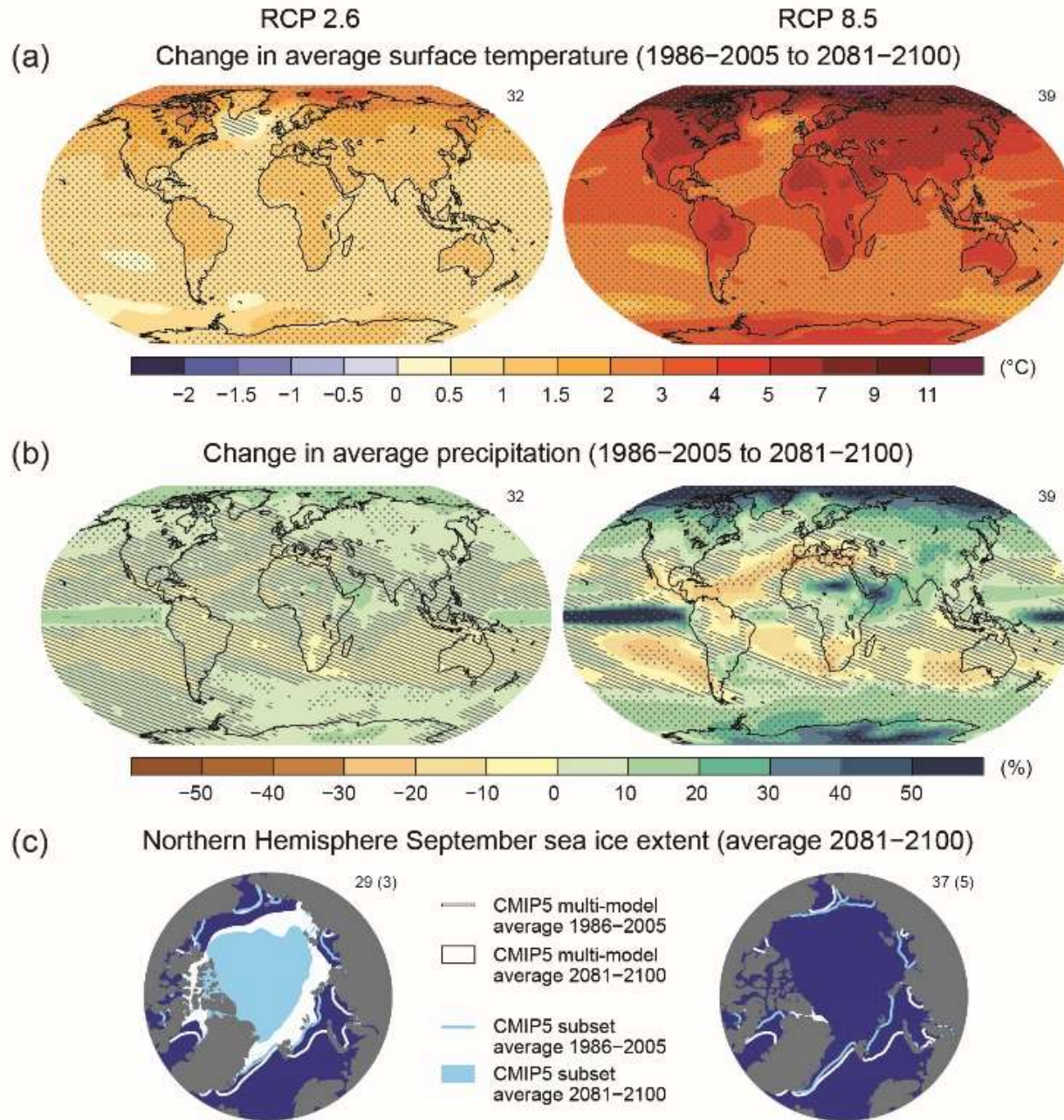


# Projections of Temperature, Northern Sea Ice Extent, and pH



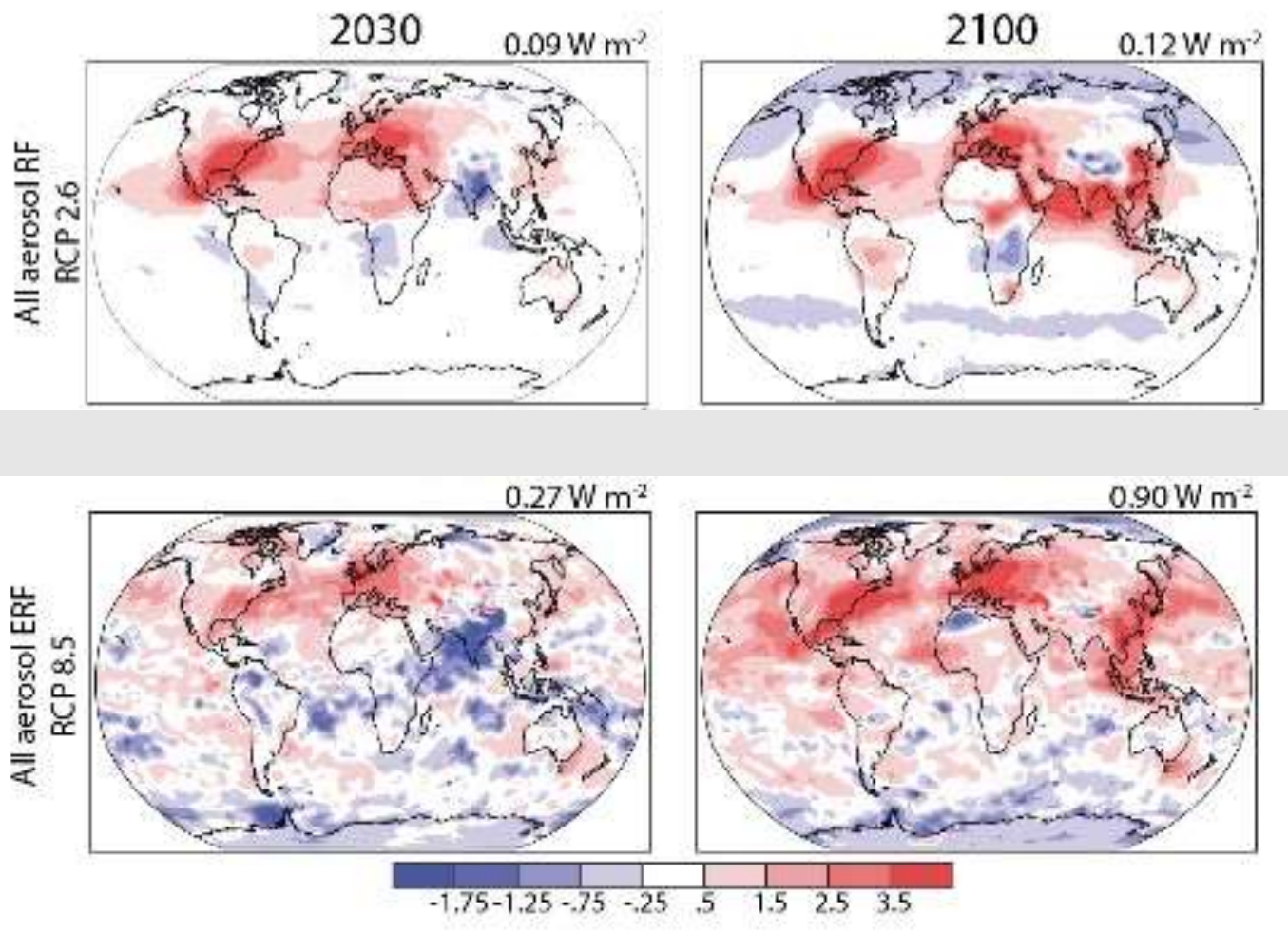
- The plots are the projected mean global temperature and northern sea ice extent for scenarios RCP 2.6 and RCP8.5
- For the temperature graph the change is relative to the mean from 1986-2005
- The number of models used are shown and the colored area reflect the range of models used
- The global mean temperature for the period 2016-2035 will likely be in the range of 0.3C to 0.7C(1)
- For the period of 2081-2100 it is likely that for RCP2.6 the increase will be 0.3C to 1.7C, for RCP4.5 between 1.1C to 2.6C, for RCP6.9 between 1.4C to 3.1C and for RCP8.5 between 2.6C to 4.8C
- It is virtually certain that heat waves will occur with more frequency and duration
- Except for RCP2.6 warming will continue beyond 2100
- The dashed line in the sea ice represents nearly ice free conditions
- As can be seen the RCP8.5 scenario the arctic will be become ice free in September by 2050
- The oceans are becoming more acidic due to increased dissolved CO<sub>2</sub>
- The ocean's surface layer (the top 100 yards or so) could lose 50 percent of its carbonate ion by the end of this century unless we reduce emissions dramatically.(2)
- Marine animals will find it harder to build skeletons, construct reefs, or simply to grow and breathe.

# Worldwide Change in Temperature, Precipitation, and Sea Ice,



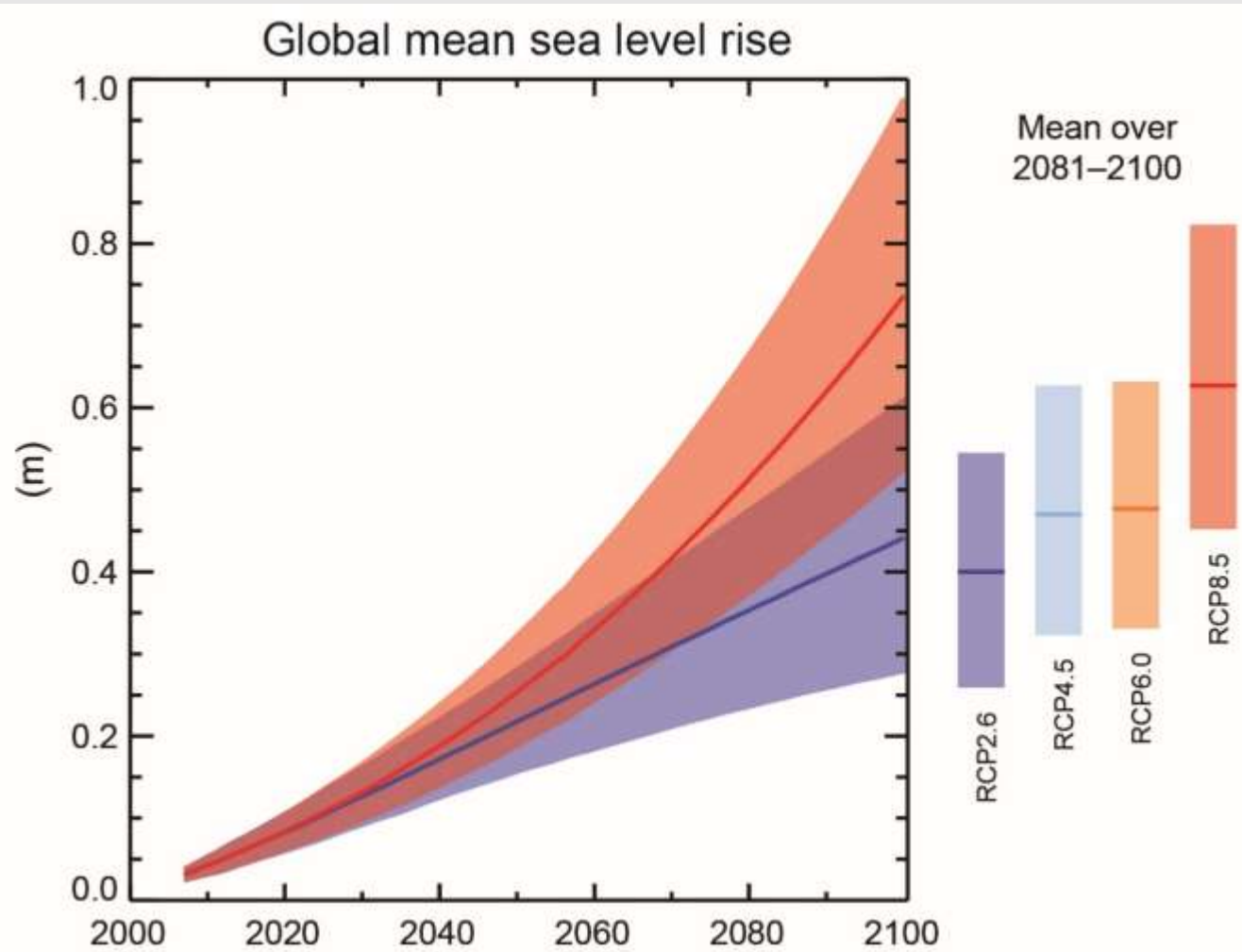
- The effects shown are for the period of 2081-2100 for the scenarios RCP2.6 and RCP8.5 relative to the period 1986-2005
- High latitudes and the equatorial Pacific will likely see an increase in precipitation for RCP8.5 while in many mid-latitude and sun-tropical dry regions precipitation will likely decrease(1)
- Extreme precipitation events over most mid latitude areas will become more intense and be more frequent
- Areas encompassed by monsoon's will likely increase and monsoons will likely intensify due to an increase in atmospheric moisture
- In the Antarctic, a decrease in sea ice extent and volume is projected with low confidence for the end of the 21st century as global mean surface temperature rises.
- By 2100 the global glacier volume, excluding glaciers on the periphery of Antarctica, is projected to decrease by 15 to 55% for RCP2.6, and by 35 to 85% for RCP8.5 (medium confidence)

# Reducing Pollution Increases Radiative Forcing Due to Aerosols 2030, 2100



- The figures show the aerosol projections for 2030 and 2100 for scenarios RCP2.6 and RCP8.5 relative to 2000
- Most components of aerosols and ozone precursors are estimated to decrease toward the end of this century in the RCPs except methane in RCP8.5(1)
- Early in the century, on the other hand, both scenarios indicate increased negative aerosol forcing over South Asia, with reversal between 2030 and 2100.
- The ERF in 2100 shows positive values relative to 2000 in North America, Europe and Asia even with RCP8.5, which indicates the aerosol forcing is projected to approach to the pre-industrial level.
- This is in marked contrast to 2000 seen earlier for which there was a large negative forcing of  $-1.17 W/m^2$  so with less aerosols there will be less offsetting of the global warming as exists now

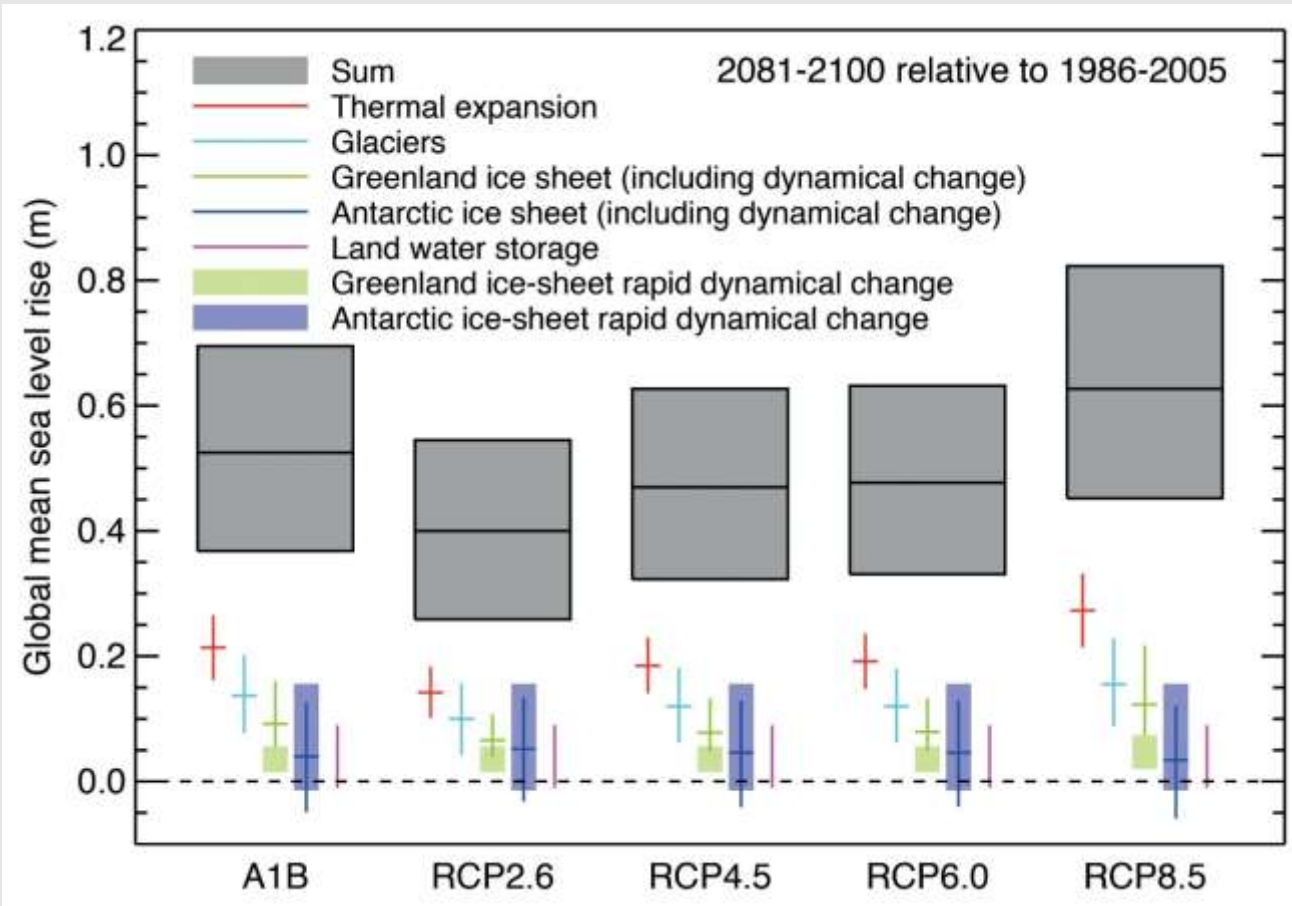
# Global Sea Level Rise



- Under all RCP scenarios, the rate of sea level rise will very likely exceed that observed during 1971 to 2010 due to increased ocean warming and increased loss of mass from glaciers and ice sheets.(1)
- Global mean sea level rise for 2081–2100 relative to 1986–2005 will likely be in the ranges of 0.26 to 0.55 m for RCP2.6, 0.32 to 0.63 m for RCP4.5, 0.33 to 0.63 m for RCP6.0, and 0.45 to 0.82 m for RCP8.5 (medium confidence)
- In the RCP projections, thermal expansion accounts for 30 to 55% of 21st century global mean sea level rise, and glaciers for 15 to 35%.
- While surface melting will remain small, an increase in snowfall on the Antarctic ice sheet is expected (medium confidence), resulting in a negative contribution to future sea level
- Changes in outflow from both ice sheets combined will likely make a contribution in the range of 0.03 to 0.20 m by 2081–2100 (medium confidence).

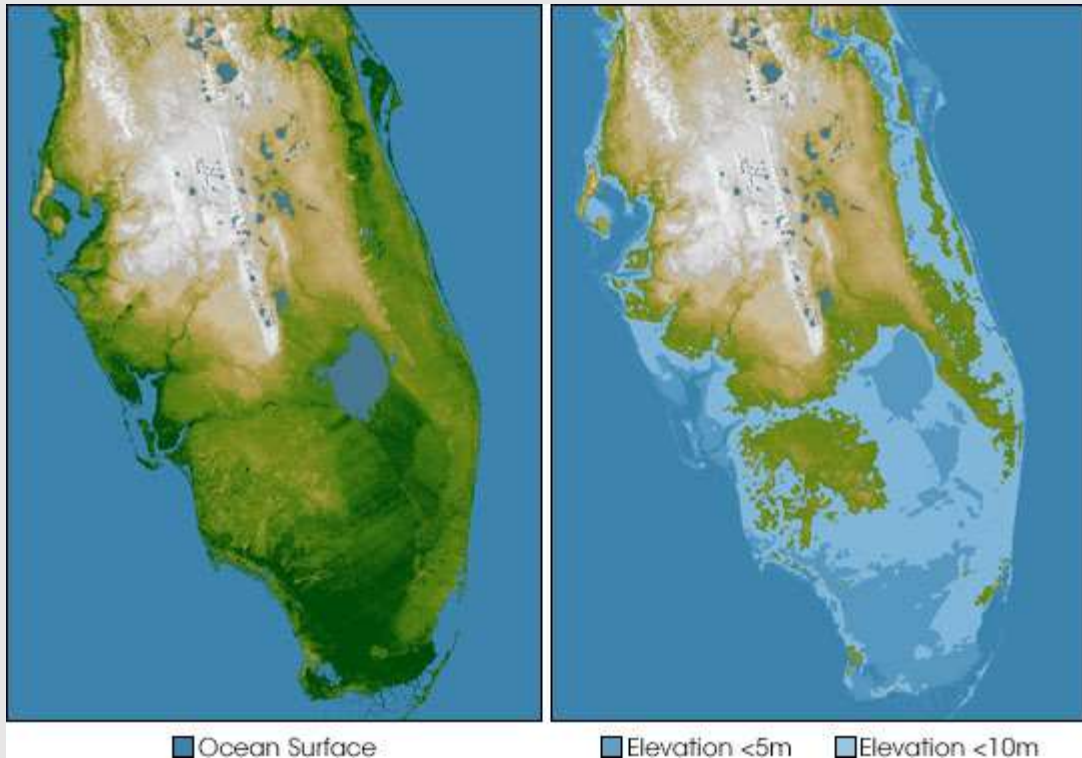


# Sea Level Rise



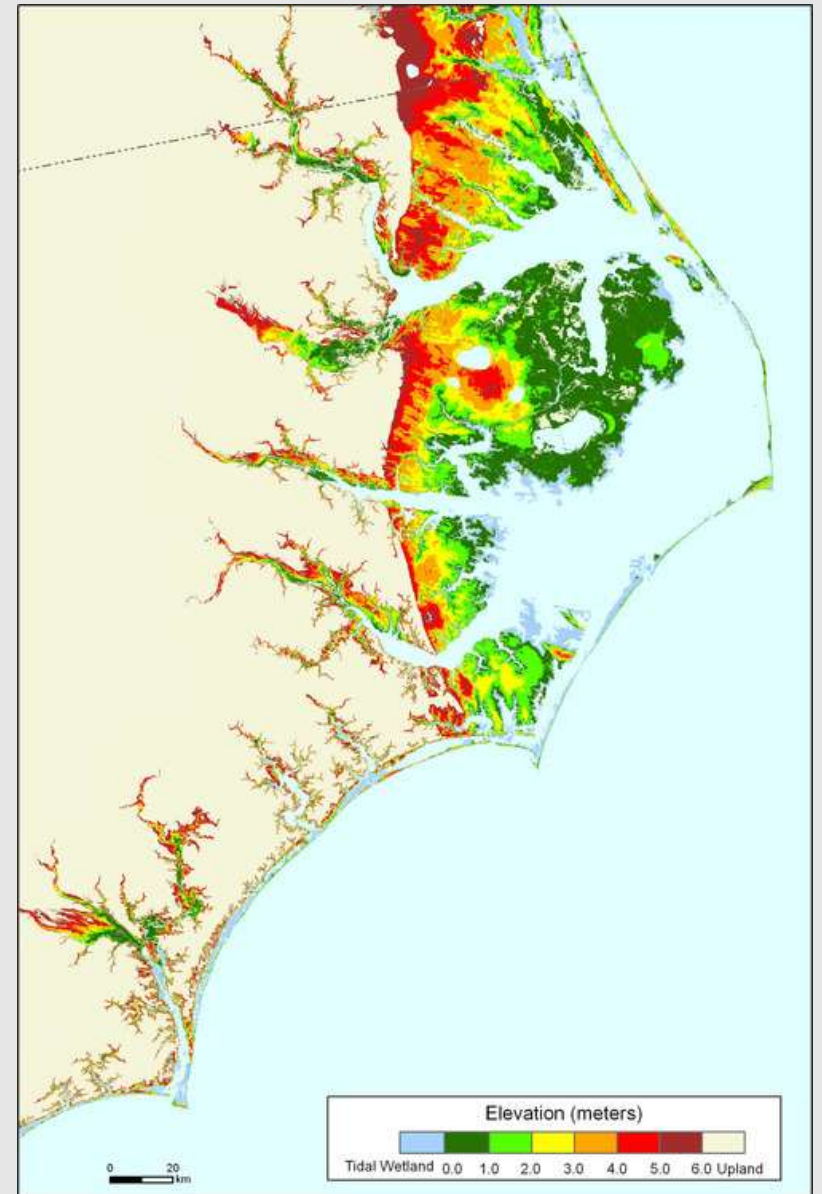
- The figure shows the various components of the sea level rise with the last component after thermal expansion, glaciers, and ice sheets being loss of land water storage
- It is virtually certain that mean sea rise will continue beyond 2100 (1)
- For a radiative forcing that corresponds to a CO<sub>2</sub> concentration that is above 700 ppm but below 1500 ppm, as in the scenario RCP8.5, the projected rise is 1 m to more than 3 m (medium confidence)
- Sea level rise due to ocean thermal expansion will continue for centuries to millennia. The amount of ocean thermal expansion increases with global warming (models give a range of 0.2 to 0.6 m /°C).

- Studies (2) show that a mean temperature rise between 2C and 4C would result in a near-complete loss of the Greenland ice sheet over a millennium or more, causing a sea level rise of about 7 m.
- About 3.3 m of equivalent global sea level of the West Antarctic ice sheet is grounded on areas with downward sloping bedrock, which may be subject to potential ice loss via the marine ice sheet instability.

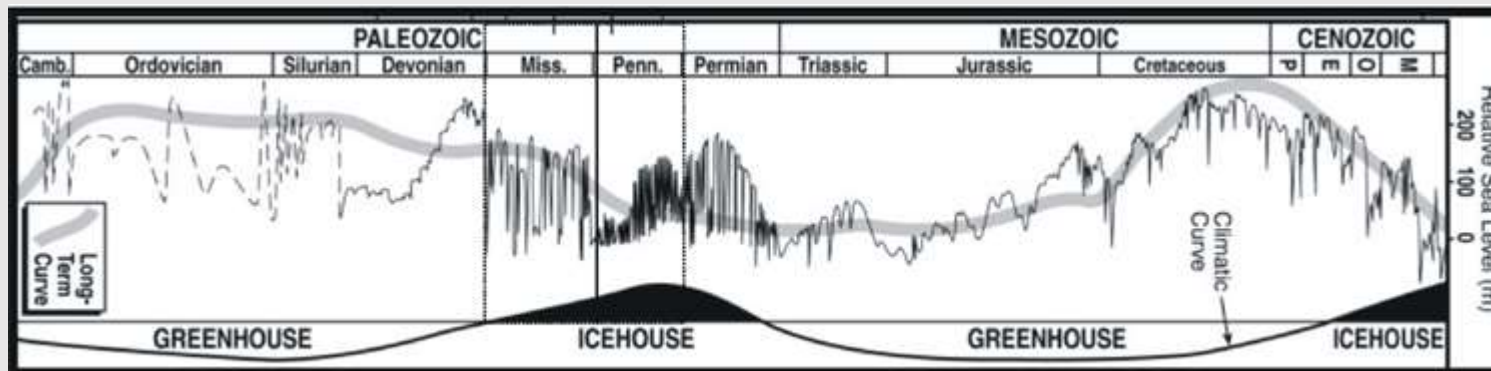


NASA

NRDC map



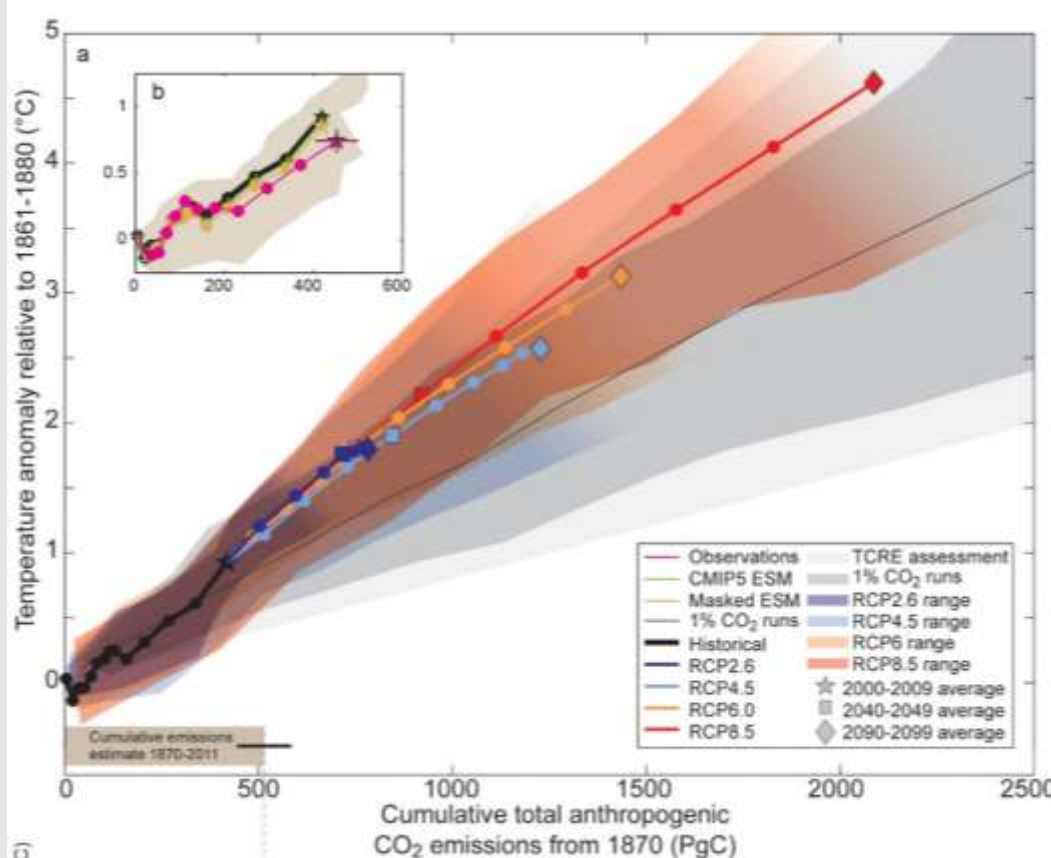
### Phanerozoic Sea Level Curve



After Longman, M. W., and M. D. Sonnenfeld, (1996)

**Elevations of Land Close to Sea Level**  
 Elevations are above spring high water, which is the average high tide during new and full moons, and approximately the inland boundary of tidal wetlands. This map is a general graphical representation of elevations in the area depicted, not designed to estimate the precise elevations at specific locations. Actual elevations at specific locations may be 30 cm above or below the elevation shown.  
 Source: J.G. Titus and J Wang, 2008. "Maps of Lands Close to Sea Level along the Mid-Atlantic Coast". US Environmental Protection Agency.

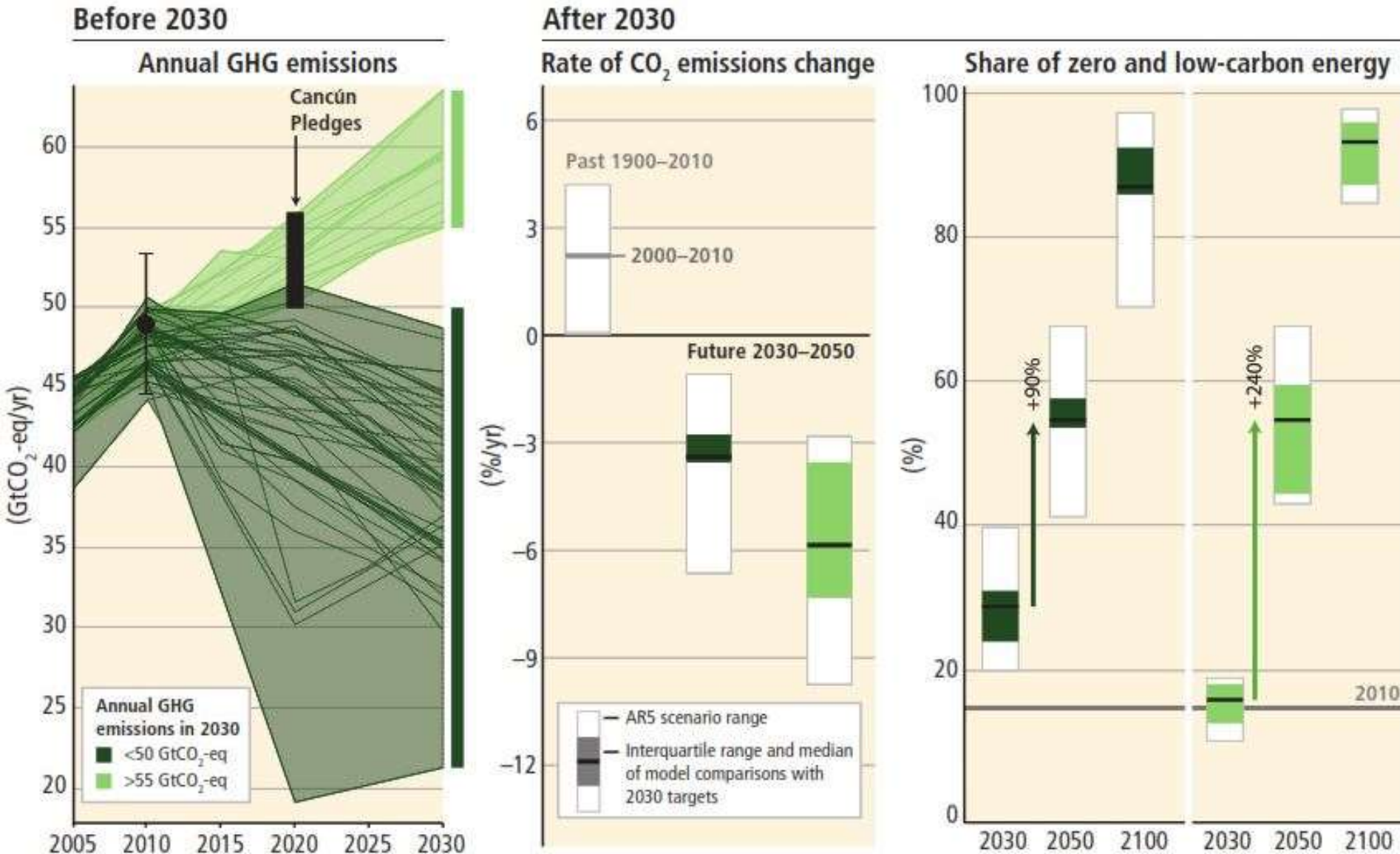
# Climate Change Beyond 2100



- The most widely discussed climate target is to limit the surface temperature rise to under 2°C from pre industrial levels
- The figure shows an almost linear increase of surface temperature with cumulative CO<sub>2</sub> emissions from 1870 where the unit PgC is petagrams of carbon and 1 PgC is 1000 mega tons of CO<sub>2</sub> or 1Giga ton
- The four RCP scenarios are shown with 2040-2049(square symbol) and the 2100(diamond symbol) milestones
- To make the 2°C goal with a probability of >33%, >50%, and >66%, carbon emissions since 1870 must be held to about 900 PgC, 820 PgC and 790 PgC, respectively(1)
- At present 500PgC of CO<sub>2</sub> emissions have occurred since 1870
- There are very long time scales in achieving stabilization even if emissions were to cease due to long time scales in the deep ocean
- This will result in a persistent warming for hundreds of years, continuing at about the level of warming that had been realized from a time when emissions were ceased

- Stabilization of global temperature does not imply stabilization for all aspects of the climate system.
- It is **virtually certain** that global mean sea level rise will continue beyond 2100, with sea level rise due to thermal expansion to continue for centuries to millennia. (2)
- Global mean sea level rise depends on the pathway of CO<sub>2</sub> emissions, not only on the cumulative total; reducing emissions earlier rather than later, for the same cumulative total, leads to a larger mitigation of sea level rise.

# Requirements to Maintain 2 Degree C Temp Rise



- Depending on actions between now and 2030 to reduce CO<sub>2</sub>, future reductions to maintain 2 C max temperature rise can vary significantly
- The black data bars apply to keeping CO<sub>2</sub> emissions under 50 Giga tons by 2030 and the green data is if the emissions are greater
- The yearly required decrease in CO<sub>2</sub> emissions beyond 2030 vary from 3 to 6 percent per year
- Also, by 2100 virtually all emissions of CO<sub>2</sub> must be eliminated

END



