WEDNESDAY PM: Climate Change

Climate Change: Past, Present, Future

- How is climate prediction different from weather prediction?

- Why it's simpler than you think

- Future climate predictions, uncertainties

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Weather ↔ Climate

"*Weather* tells you what to wear, *Climate* tells you what clothes to buy"

✗ Weather: the condition at a specific location at a specific time

✗ Climate: the average conditions and their variability (includes extremes); the statistics of weather

✗ Climate is an "envelope of possibilities" within which the weather bounces around

✗ Weather depends very sensitively on the evolution of the system from one moment to the next ("initial conditions")

✗ Climate is determined by the properties of the Earth system itself ("boundary conditions")

Weather Prediction and "Chaos"

- Weather prediction is a deterministic problem, yet 100% certainty is impossible

- this is because of the so-called "sensitivity to initial conditions": an ever so slight change/error in the initial conditions (e.g. the currently observed state of the atmosphere) can lead to completely different future states

- Often referred to as the "butterfly effect" (the flap of a butterfly's wings in Brazil setting off a tornado in Texas)

- Edward Lorenz (meteorologist, pioneer of chaos theory):

  - Chaos: When the present determines the future, but the approximate present does not approximately determine the future.

Henri Poincaré, the Three-Body Problem, and the Discovery of Chaos

- The "n-body problem": *given the quasi-steady orbital properties (instantaneous position, velocity, time) of a group of celestial bodies, predict their interactive forces; and consequently, predict their true orbital motions for all future times* [wikipedia]

- Oscar II, King of Sweden in 1887: prize for anyone who could solve this problem

- Henri Poincaré (famous French mathematician and physicist) could not completely solve the problem, but his work "is nevertheless of such importance that its publication will inaugurate a new era in the history of celestial mechanics" [Karl Weierstrass, one of the judges]

- Indeed, Poincaré's work led to the theory of chaos

- "It may happen that small differences in the initial positions may lead to enormous differences in the final phenomena. Prediction becomes impossible."

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Weather ↔ Climate

✗ Today's sunset: 8:28 pm

✗ Today's 5-day forecast: 95 / 61 F

✗ July Long-Term Climatology: 75 F / 54 F

✗ May 2014: average temperature 58 F (30th warmest in 126 year record), minimum: 29 F (on 13 May), maximum: 87 F (on 28 May)

✗ Weather: minutes to weeks, ~ the time scale to which a specific event may be forecast

✗ Climate: seasonal, annual, decadal, centurial, millennial, …

Factors in Climate Variability/Change

- External Factors (Astronomical)
  - Solar output
  - Orbital changes
  - Interplanetary dust
  - Collisions with other interplanetary bodies
- Comets
- Asteroids

- Internal Factors
  - Atmospheric transparency
  - Surface characteristics
  - Ocean currents, ocean chemistry
 - Volcanic activity
  - Continental drift

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Climate & Climate Change

- Climate is the accumulation of daily and seasonal weather events over a long period of time (climate is the statistics of weather)

- Climate can change on various time-scales: millions of years, thousands of years, hundreds of years, decades

- Climate can change in response to different factors:
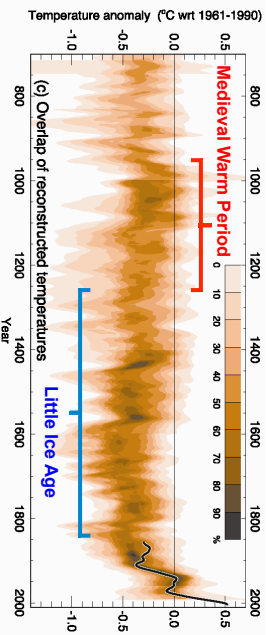
  - Natural
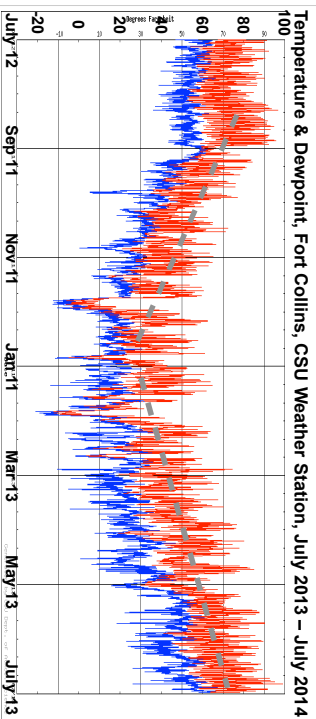 - Human-induced ("Anthropogenic")

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Climate through the Ages

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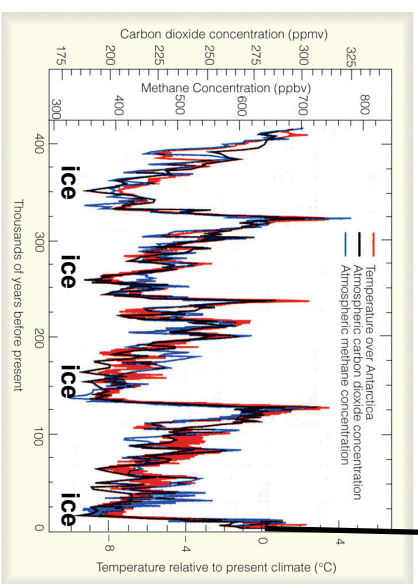
Reconstructed Temperature
(last 1,300 years), from IPCC 2007

Temperature anomaly (°C wrt 1961-1990)

(c) Overlap of reconstructed temperatures

Year

Medieval Warm Period

Little Ice Age

- Temperature relative to present, plotted as agreement between different reconstructions (e.g. from tree rings)
- Thermometer record available over past 150 years: solid line
- Relatively warm period 950–1250 (Medieval Warm Period)
- Relatively cold period 1250–1850 (Little Ice Age)

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Cautionary Note: Do Not Overinterpret every Wiggle in the Plot!

Temperature & Dewpoint, Fort Collins, CSU Weather Station, July 2013 – July 2014

Degrees Fahrenheit

- We are sure that July will be warmer than January due to increasing solar insolation, even though there's lots of natural variability along the way (mostly related to weather patterns)
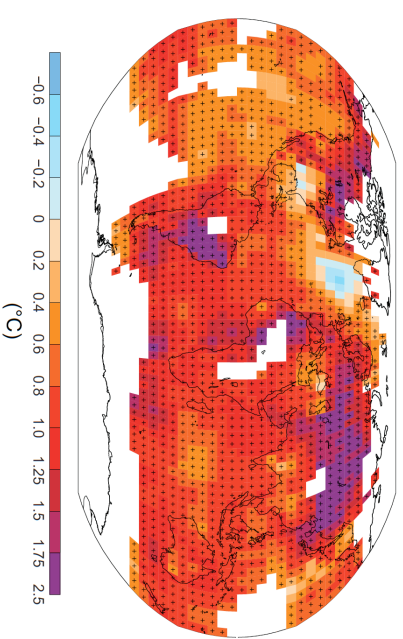- Individual warm or cold spells do not necessarily indicate a trend!

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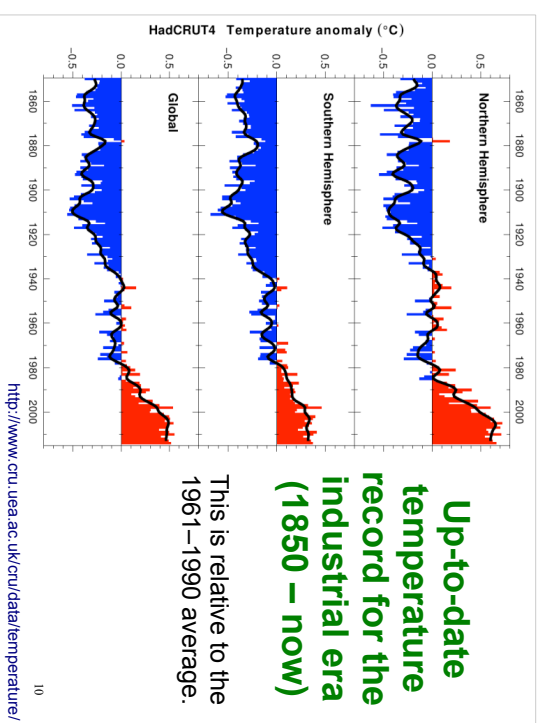
Up-to-date temperature record for the industrial era (1850 – now)

HadCRUT4 Temperature anomaly (°C)

Northern Hemisphere

Southern Hemisphere

Global

This is relative to the 1961-1990 average.

http://www.cru.uea.ac.uk/cru/data/temperature/

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Observed change in surface temperature 1901-2012

IPCC 2013

(°C)

−0.6 −0.4 −0.2 0 0.2 0.4 0.6 0.8 1.0 1.25 1.5 1.75 2.5

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Climate Change is more than Surface Temperature Change!

Observed change in annual precipitation over land

1901–2010

1951–2010

−100 −50 −25 −10 −5 −2.5 0 2.5 5 10 25 50 100
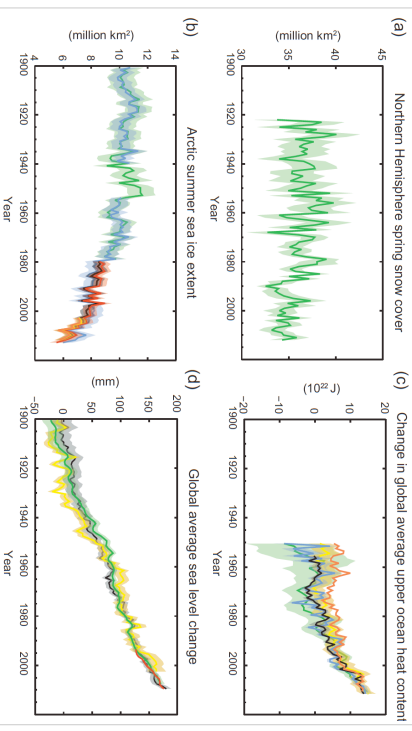
(mm yr⁻¹ per decade)

IPCC 2013
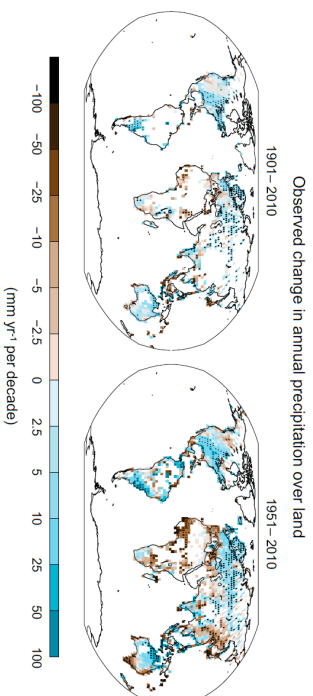
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Can we attribute the recent observed temperature changes to anthropogenic (human) forcing?

- To answer this scientists look at (amongst other things):

  - Basic physics

  - vertical/horizontal patterns of temperature changes

  - Oceanic temperature / heat content changes, sea level changes

  - Sea ice and glacier retreat

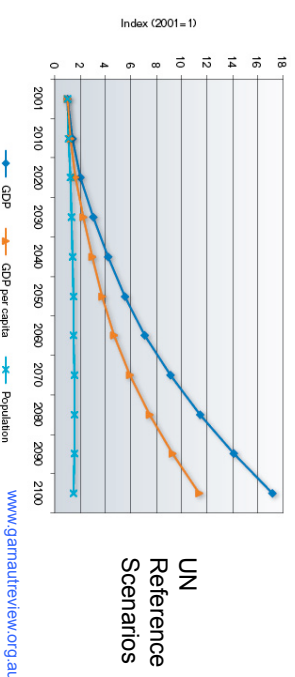 - Climate model response to imposed greenhouse gas forcing

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Climate Change is more than Surface Temperature Change!

(a) Northern Hemisphere spring snow cover
(million km²)
45 40 35 30
1900 1920 1940 1960 1980 2000
Year

(b) Arctic summer sea ice extent
(million km²)
14 12 10 8 6
1900 1920 1940 1960 1980 2000
Year

(c) Change in global average upper ocean heat content
(10²² J)
20 10 0 −10 −20
1900 1920 1940 1960 1980 2000
Year

(d) Global average sea level change
(mm)
200 150 100 50 0 −50
1900 1920 1940 1960 1980 2000
Year

IPCC 2013

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Population growth is not the driver of future climate!

Index (2001 = 1)

18 16 14 12 10 8 6 4 2 0
2001 2010 2020 2030 2040 2050 2060 2070 2080 2090 2100

— GDP
— GDP per capita
— Population

UN Reference Scenarios

www.garnautreview.org.au

- Population to grow by 40% in 100 years
- Global economy to grow by 1600%
  (assumes 2.8% annual GDP growth)

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Shanghai, China 1990

CO$_2$ emissions by country

CO$_2$ emissions per capita

Shanghai, China 2012

Where is it 10°F Warmer

"on average?"

Denver ➜ Amarillo

Grand Junction ➜ Tucson

Illinois ➜ Mississippi

Water? Crops?
Real Estate? Health?

ANNUAL
MEAN DAILY MAXIMUM TEMPERATURE

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Concentrations of most GHGs have been increasing in the modern age

IPCC, 2007
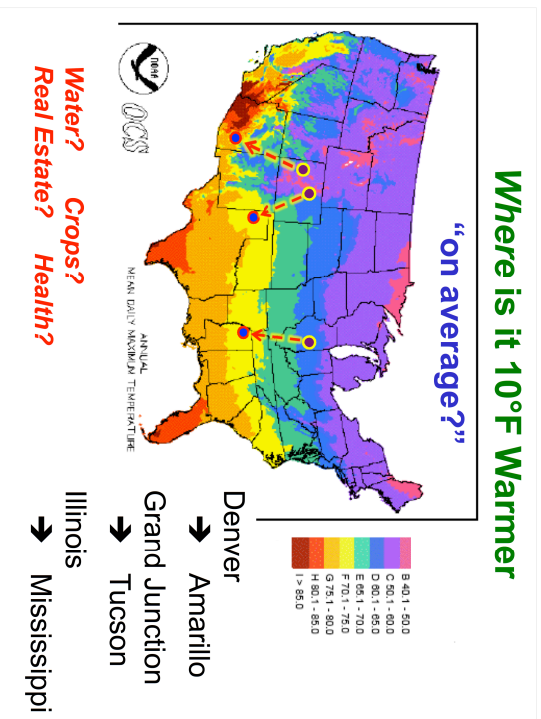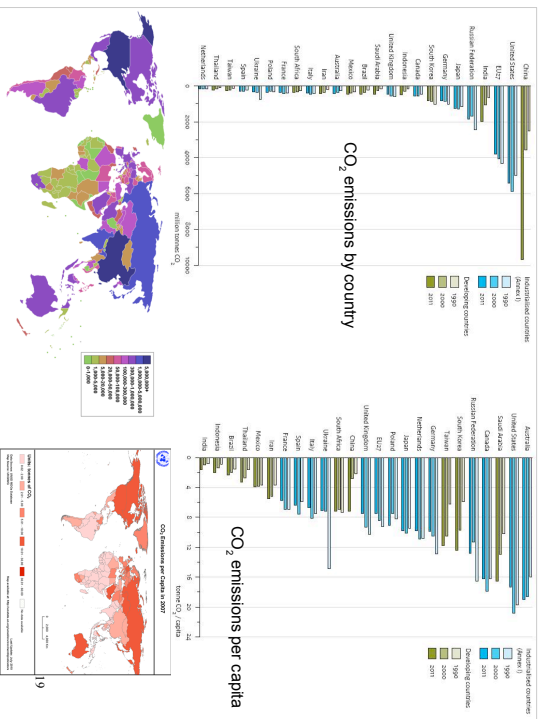
A Region On the Edge

Average Annual Precipitation
Colorado
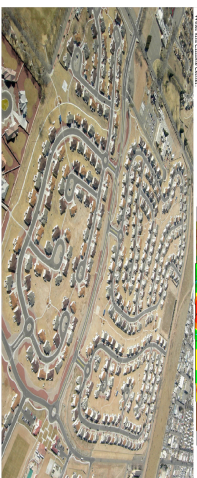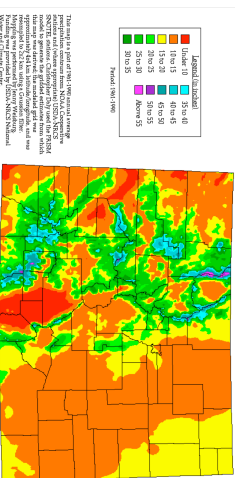
Much of the region already receives only marginal precipitation

Just enough snow to support forests and reservoirs

Just enough irrigation water to support farming
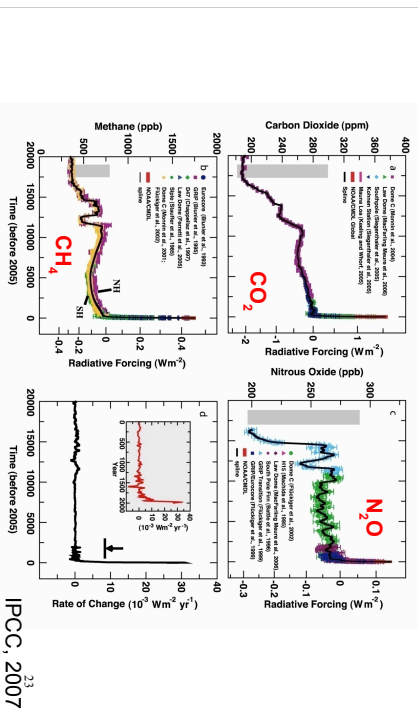
Just enough water to support 5.1 million people
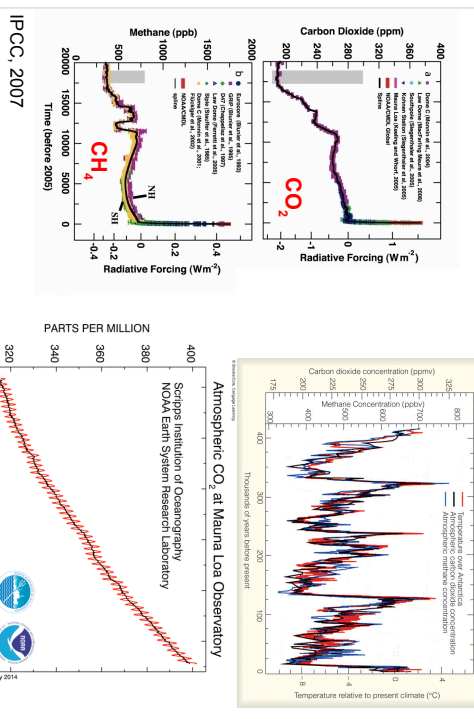
Anthropogenic Climate Variability and Change

Various resources at the Intergovernmental Panel on Climate Change (IPCC) Website:

http://www.ipcc.ch/report/ar5/index.shtml

IPCC, 2007

Atmospheric CO_2 at Mauna Loa Observatory

Scripps Institution of Oceanography
NOAA Earth System Research Laboratory
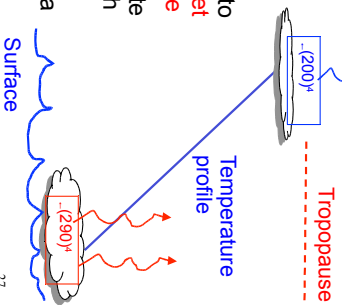
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Feedbacks

- *A process that changes the sensitivity of the climate response to an external forcing*

- **Positive feedback:** increase the magnitude of the response to the forcing
  - Ice/albedo feedback
  - Water vapor feedback
  - Ocean carbon cycle feedbacks
- **Negative feedback:** decrease the magnitude of the response to the forcing
  - Stefan-Boltzmann feedback (i.e. warmer Earth emits more radiation out to space)
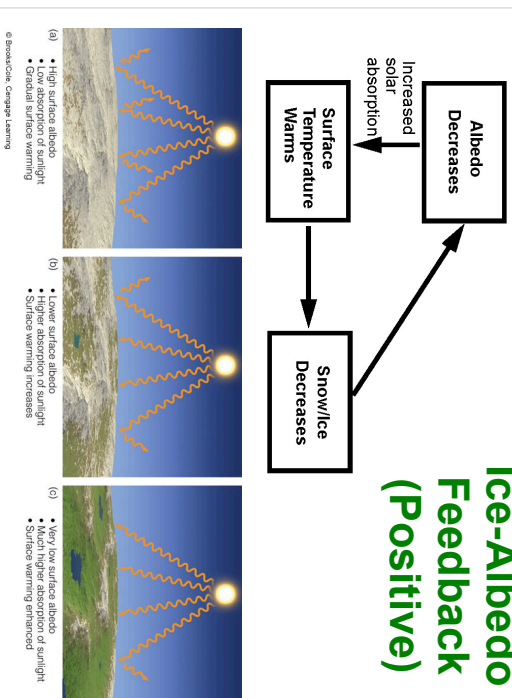
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Cloud Feedback

- Effect of clouds on climate: thick vs thin, high vs low

- High, very thin clouds warm the climate (let most sunlight through, emit at low temperature)

- Low, thick clouds cool the climate (emit a lot of terrestrial radiation, reflect a lot of solar radiation)

- Recall: in the net clouds contribute to Earth's albedo, i.e. **clouds have a net cooling influence on average climate**

- Cloud *feedback* in a warming climate depends on relative changes of high vs low clouds

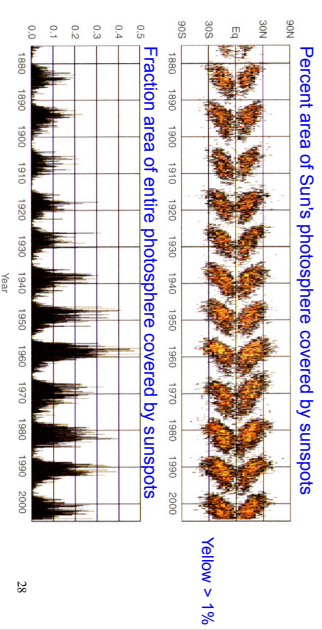- Currently, clouds are thought to be a slight positive feedback, but big uncertainties

Temperature profile

Tropopause

-(200)⁴

-(290)⁴

Surface

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Ice-Albedo Feedback (Positive)

Increased solar absorption

Surface Temperature Warms

Albedo Decreases

Snow/Ice Decreases

(a)
- High surface albedo
- Low absorption of sunlight
- Gradual surface warming

(b)
- Lower surface albedo
- Higher absorption of sunlight
- Surface warming increases

(c)
- Very low surface albedo
- Much higher absorption of sunlight
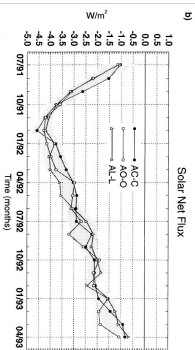- Surface warming enhanced

© Brooks/Cole, Cengage Learning

Solar Variability

- The Sun's output is not exactly constant at 1366 W/m² – it does show some modest variation in time

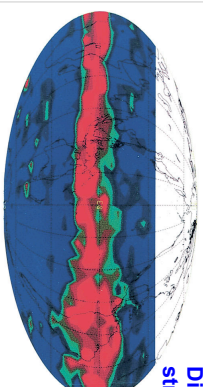- 11-year cycle in output, corresponding to variations in sunspots (large number of spots = high output)

Percent area of Sun's photosphere covered by sunspots

Fraction area of entire photosphere covered by sunspots

Yellow > 1%
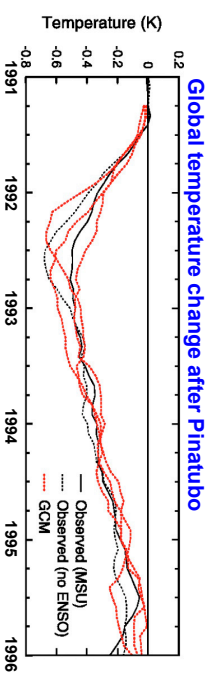
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Volcanoes

- Volcanoes emit sulfur dioxide that become aerosols (airborne solids) in the stratosphere → reflect sunlight, increase earth's albedo reducing the solar radiation absorbed by the climate system
- For example, lower-left: globally-averaged reduction in absorbed solar radiation after Mt. Pinatubo eruption in summer 1991
- Some are advocating man-made stratospheric injections of aerosols to mitigate anthropogenic climate warming

- Greenhouse Gases
- Volcanoes
- Solar variations
- Land use changes
- Aerosols
- Ozone changes

Force "full-blown" climate model with past radiative perturbations → what is the response?

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Volcanoes

Distribution of Mt. Pinatubo stratospheric forcing

Global temperature change after Pinatubo

- Reduction in solar radiation due to Mt. Pinatubo led to a cooling of the globally-averaged temperature ~ 0.5-0.7 C

Past Radiative Forcing
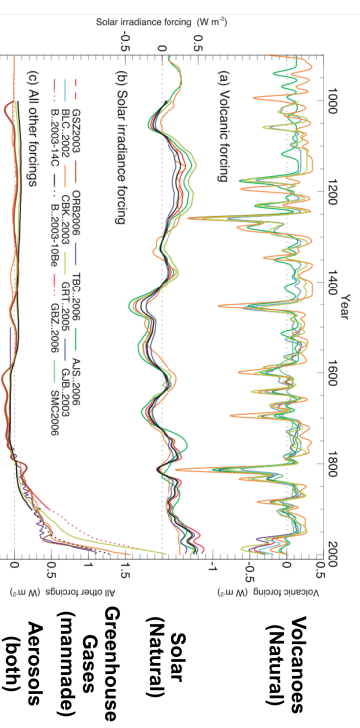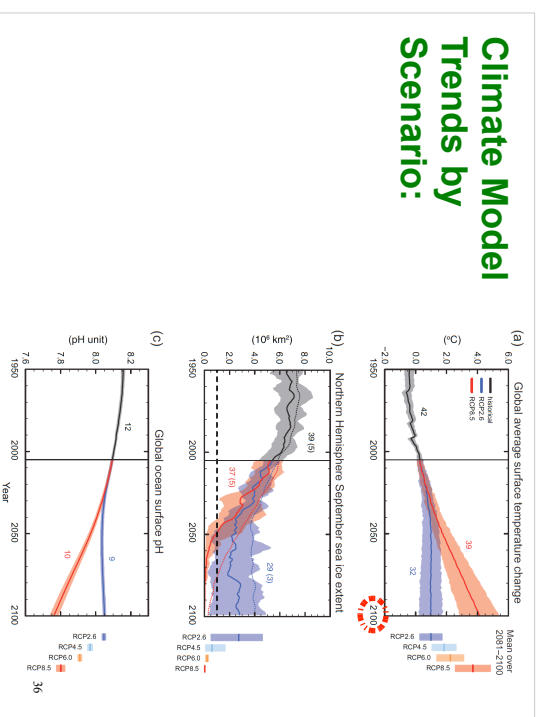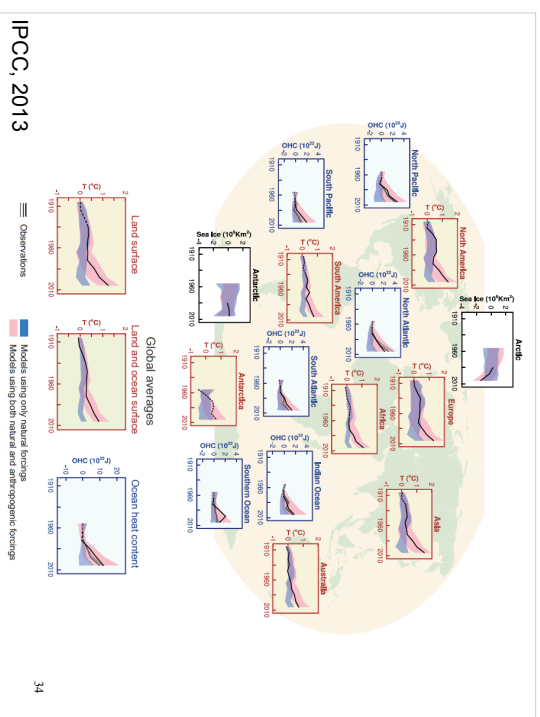
IPCC, 2007

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Future trends from Climate Models

IPCC, 2013

Depending on the scenario, anywhere from 1–5 C for globally averaged warming in the year 2100. This warming is not uniformly distributed.

Climate Model Trends by Scenario:

IPCC, 2007

Observed temperatures

Climate model prediction using human AND natural factors

Climate model prediction using natural factors ONLY

IPCC, 2013

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Climate Model Trends by Scenario

NH September sea-ice extent

2081–2100

RCP2.6   RCP4.5

RCP6.0   RCP8.5

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Climate Model Trends by Scenario

Global mean sea level rise

Mean over
2081–2100

RCP2.6
RCP4.5
RCP6.0
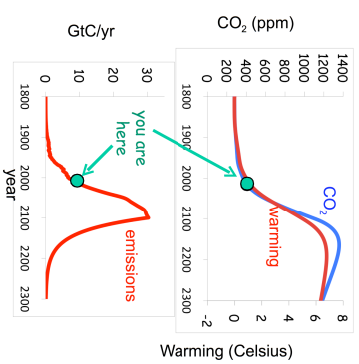RCP8.5

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The Long Tail

- If China and India industrialize with coal ...

- CO_2 will rise to **4 times** **preindustrial**

- Extra CO_2 will remain for **millennia** after coal is **gone**

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We Know for Sure

- CO_2 molecules absorb & re-emit thermal radiation (John Tyndall, 1859)
- Doubling the number of CO_2 molecules would add 4 W m^{-2} to the Earth 24/7 (Svante Arrhenius, 1896)
- If China and India industrialize with coal, CO_2 will approach ~400% of its preindustrial level by 2100
- Additional CO_2 will continue adding heat to Earth for thousands of years

What We're Not So Sure About

- **By precisely how much** the climate will change, especially locally
- How climate varies on **relatively short time-scales** (years to a couple of decades)
- The economic, political, and social **consequences** of these changes
- **What to do** about all of this

Solutions

- To provide a decent standard of living for billions of people on Earth …
- … we must generate huge amounts of energy without releasing CO_2.
- This is definitely possible (as an engineering task) …
- … but currently expensive and politically difficult.
- Can't do it by "tinkering around the edges."
- Requires profound changes to energy and economics