SAGES *Scottish Alliance for Geoscience, Environment & Society*

Observing, Modelling and Predicting Climate Change

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With thanks to Gabi Hegerl, Richard Essery, Kevin Trenberth and the "IPCC" for material.

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Outline

- Modelling the Climate System
- Predictions of the future.
- Observations of change.
- Possible causes of climate change.

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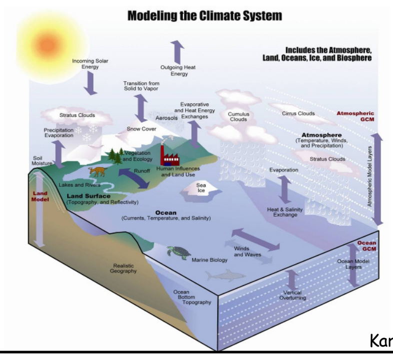
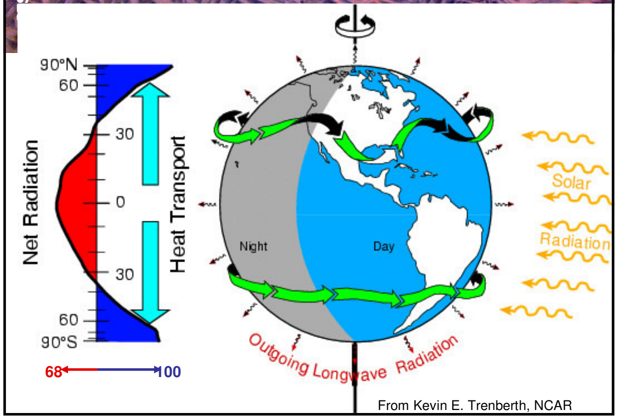
Modelling the Climate System



Main Message: Lots of things going on!

Karl and Trenberth 2003



The Components of the Climate System

- **Atmosphere:**
  - Volatile turbulent fluid, strong winds, Chaotic weather, clouds, water vapor feedback
  - Transports heat, moisture, materials etc.
  - Heat capacity equivalent to 3.2 m of ocean
- **Ocean:**
  - 70% of Earth, wet, fluid, high heat capacity
  - Stores, moves heat, fresh water, gases, chemicals
  - Adds delay of 10 to 100 years to response time

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The Components of the Climate System: Cont.

- **Land:**
  - Small heat capacity, small mass involved (conduction)
  - Water storage varies: affects sensible vs latent fluxes
  - Wide variety of features, slopes, vegetation, soils
  - Mixture of natural and managed
  - Vital in carbon and water cycles, ecosystems
- **Ice:**
  - Huge heat capacity, long time scales (conduction)
  - High albedo: ice-albedo feedback
  - Fresh water, changes sea level
  - Antarctica 65 m (WAIS 4-6m), Greenland 7m, other glaciers 0.35m

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Meteorology is (roughly) fluid dynamics on rotating sphere

$$\frac{D\mathbf{V}}{Dt} + 2\mathbf{\Omega} \wedge \mathbf{V} = -\frac{1}{\rho}\nabla p + \mathbf{g_a} + \mathbf{F_f}$$ Equations of motion

$$\frac{D}{Dt} = \frac{\partial}{\partial t} + \mathbf{V} \cdot \nabla$$

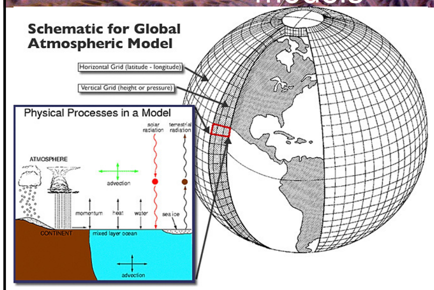
+ thermodynamics + moisture + radiation…

$$\frac{\partial \rho}{\partial t} + \nabla(\rho \mathbf{V}) = 0$$ Continuity

Numerical Solutions

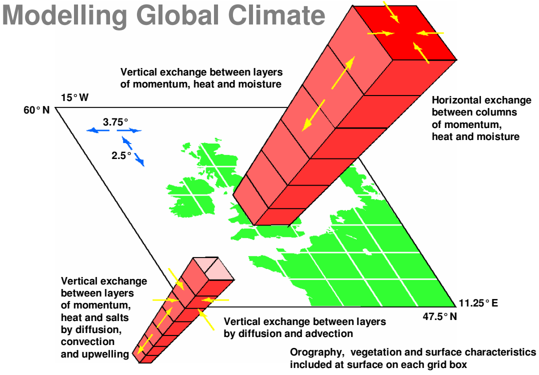
- No (known) analytical solutions to these equations.
  - Not surprising – think of range of phenomenon in weather.
- So discretise equations of motion on a grid. (Easy to say; hard to do!)
- Lots of ways of doing this but two major ones at the moment.
  - Represent as truncated sum of spherical harmonics
  - Or as values at points/averaged over regular grid.
  - New methods are being developed

Representing the fields: Gridpoint models



Represent space as a grid of regular (in long/latt co-ords)

Modelling Global Climate



Derivatives

$+X_{i-1,j+1}$	$+X_{i,j+1}$	$+X_{i+1,j+1}$
$+X_{i-1,j}$	$+X_{i,j}$	$+X_{i+1,j}$
$+X_{i-1,j-1}$	$+X_{i,j-1}$	$+X_{i+1,j-1}$

$$\frac{d}{dx} = \frac{X_{i+1,j} - X_{i-1,j}}{2\Delta x}$$

$$\frac{d}{dy} = \frac{X_{i,j+1} - X_{i,j-1}}{2\Delta y}$$

Representing the fields: Spectral Models

- Represent fields as truncated sum of spherical harmonics
- Derivatives easy to calculate (from analytical expression) and PDE's turn into ODE's
- Non-linear terms become computationally hard though.
- So do linear & diffusive terms in spectral space then transform to grid point space to compute advective terms.

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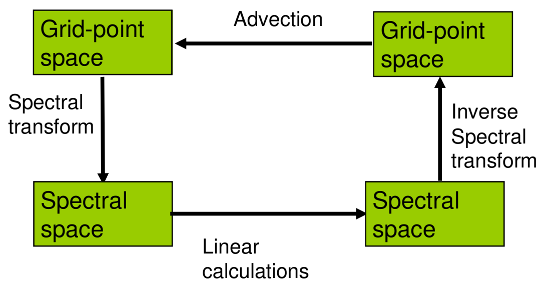
Schematic



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Computing advective terms

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Eulerian vs Lagragian view of a fluid

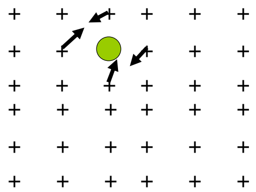
- Eulerian view. Sit at a point and watch the fluid move past.
- Lagrangian view. Sit on a parcel of fluid and watch the world move past.
- For pure advection in a Lagrangian view parcel properties stay constant.

$$\frac{DC}{Dt} = \frac{\partial C}{\partial t} + \mathbf{V} \cdot \nabla C = 0$$

Eulerian

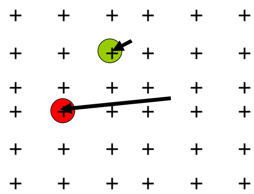
$$\frac{DC}{Dt} = \frac{\partial C}{\partial t} + \mathbf{V} \cdot \nabla C = 0$$

$$\frac{\partial C}{\partial t} = -\mathbf{V} \cdot \nabla C$$



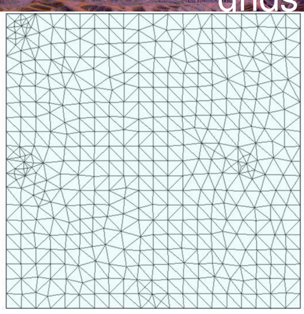
For each grid-point compute divergence and take dot-product with velocity field.

Semi-Lagrangian -- now used by most atmospheric models

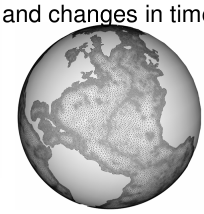


For each grid-point work out trajectory and where values came from. These places not on grid so need to interpolate values.

New approaches – adaptive grids



ICOM – Imperial College Ocean Model. Grid resolution varies and changes in time



Further Reading

ECMWF lecture notes:

http://www.ecmwf.int/newsevents/training/rcourse_notes/index.html

ICOM

http://amcg.ese.ic.ac.uk/index.php?title=ICOM

Sub-grid.

- Recall equations of motion
- Split into large scale average and residual.

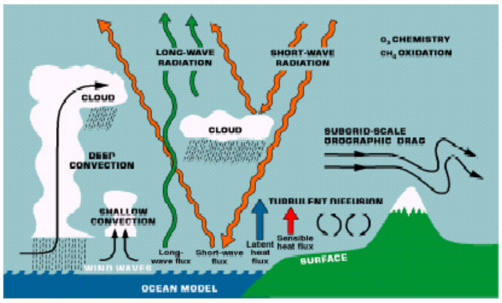
$$\overline{\mathbf{V}\nabla\cdot\mathbf{V}} = \overline{(\overline{\mathbf{V}}+\mathbf{V}')\nabla\cdot(\overline{\mathbf{V}}+\mathbf{V}')}$$
$$= \overline{\mathbf{V}}\nabla\cdot\overline{\mathbf{V}} + \overline{\mathbf{V}'\nabla\cdot\mathbf{V}'} + \left\{\overline{\mathbf{V}'\nabla\cdot\overline{\overline{\mathbf{V}}}} + \overline{\overline{\overline{\mathbf{V}}}\nabla\cdot\mathbf{V}'}\right\}$$
$$= \overline{\mathbf{V}}\nabla\cdot\overline{\mathbf{V}} + \overline{\mathbf{V}'\nabla\cdot\mathbf{V}'}$$

Get large-scale terms that result from sub-grid scale motions…

Parameterisation

- Like the closure problem for fluid dynamics.
- Key processes:
  - Convection (which involves latent heat release from water vapour condensing)
  - Clouds in general.
  - Boundary layers.
  - Need to simplify radiation calculations into relatively small number of broad bands and assume radiation only goes up and down. Can verify calculations through comparison with line-by-line calculations.
  - Friction…
- Many specialists work in each area. An atmospheric model (Weather) is a complex piece of software. Numerical methods for dynamics are complex as are parameterisations.

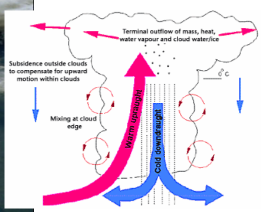
Parameterized Processes



Slingo

From Kevin E. Trenberth, NCAR

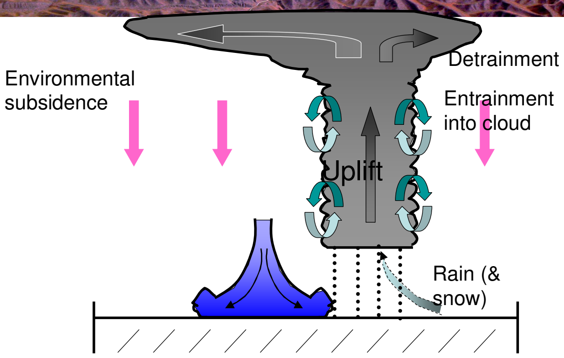
What are we trying to parameterize?



How we parameterise

What is there…

"Mass-flux" parameterization



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(Atmospheric) Modelling over-view

- Dynamical core – solve large scale flow.
  - Linear terms
  - Advection
- Parameterisations.
  - Act on columns so each column can be treated independently.
  - Key for climate
- Codes run on parallel computers but don't scale well to hundreds of CPU's
- Climate problem doesn't have very high resolution as need to run ensembles and for decades to centuries.

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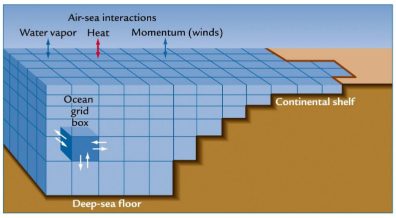
Ocean Models

Modelled Ocean circulations driven by:

- Wind stress
- Density variations (colder and saltier water is more dense)

Thermohaline circulation driven by sinking of cold, salty water



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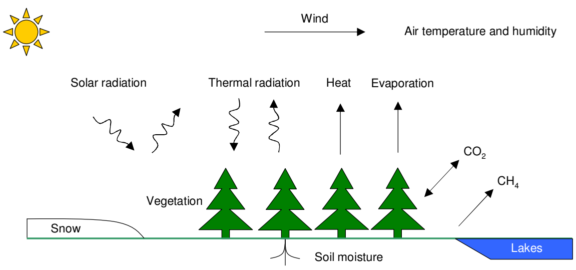
Land Surface Models



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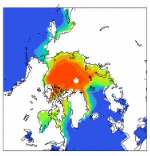
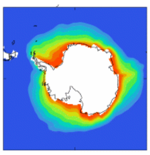
Sea Ice Models

Sea ice rejects brine when freezing, transports and releases fresh water on melt, reduces heat exchange with the atmosphere

Thermodynamics: melting and freezing, conduction of heat
Dynamics: ice motion driven by wind and ocean circulations





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Model resolution increasing with time.

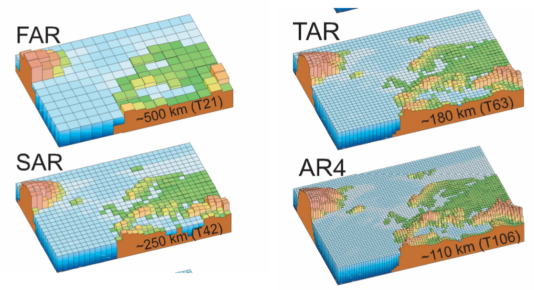

Figure 1.4. *Geographic resolution characteristic of the generations of climate models used in the IPCC Assessment Reports: FAR (IPCC, 1990), SAR (IPCC, 1996), TAR (IPCC, 2001a), and AR4 (2007). The figures above show how successive genera-*

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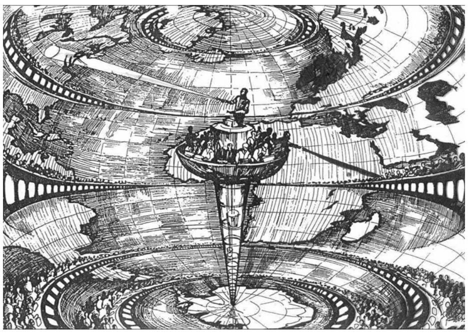
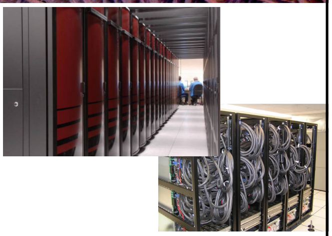
Early Visions



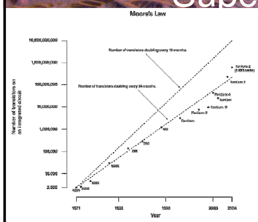
More recent visions

Cray Y-MP ~ 1990



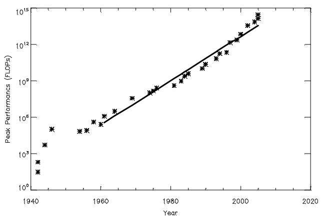
HECToR – Edinburgh 2007

Moore's Law and Supercomputers



Number of transistors doubles every 2 years. But as they get smaller they go faster.

Doubling time of peak supercomputer performance is about 18 months.



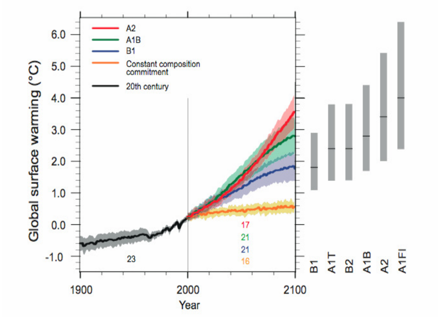
Computational requirements

Computational requirements scale as $(1/\text{resolution})^4$. Decrease resolution means increasing the number of gridboxes in east/west, North/south and vertically as well as reducing the time-step proportionally. Improved algorithms can change the constant of proportionality.

So doubling the resolution increases the computational requirement by 16. Given increase in super-computer performance could do the same kind of simulations as today at ½ the resolution in 10 years time…

CESD Projections of Future Changes in Climate

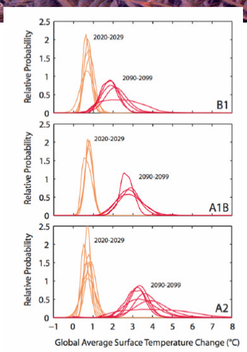
Best estimate for low scenario (B1) is 1.8°C (*likely* range is 1.1°C to 2.9°C), and for high scenario (A1FI) is 4.0°C (*likely* range is 2.4°C to 6.4°C).



CESD Projections of Future Changes in Climate

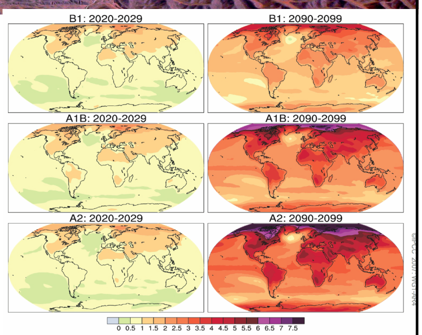
Near term projections insensitive to choice of scenario

Longer term projections depend on scenario and climate model sensitivities

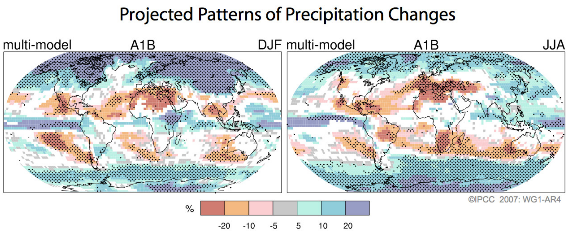


CESD Projections of Future Changes in Climate

Projected warming in 21st century expected to be greatest over land and at most high northern latitudes and least over the Southern Ocean and parts of the North Atlantic Ocean



Projections of Future Changes in Climate

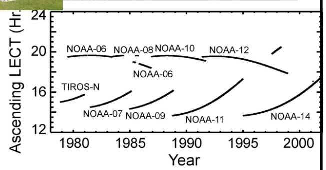


Precipitation increases *very likely* in high latitudes

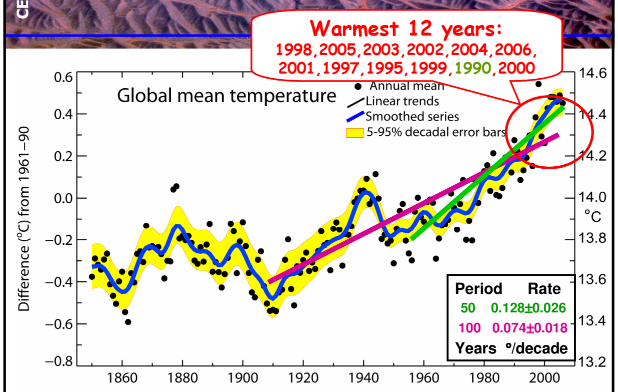
Decreases *likely* in most subtropical land regions

What is the problem with Observations?

- Observing system not stable
- Climate changes slowly compared to obs. system.
- Examples:



Global mean temperatures are rising



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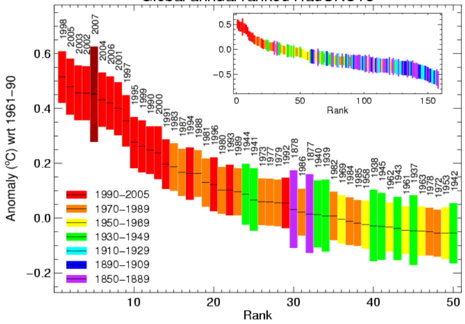
Communicating Uncertainties

Global annual ranked HadCRUT3



John Kennedy, Met Office Hadley Centre

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Extreme events have consequences

Tewkesbury 2007Photograph: Daniel Berehulak/GettyImages

Met Office provisional figures show that May to July in the England and Wales Precipitation is the wettest in a record that began in 1766.

We must learn from the events of recent days. These rains were unprecedented, but it would be wrong to suppose that such an event could never happen again…. (Hazel Blears, House of Commons, July 2007)

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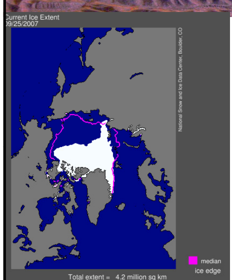
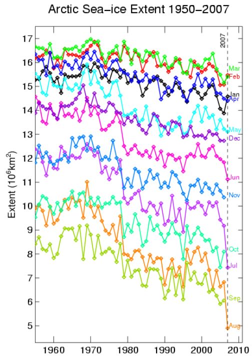
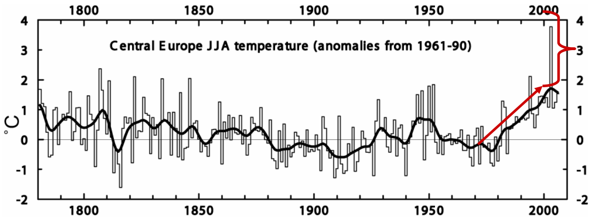
Sea-ice (its ½ what is should be)





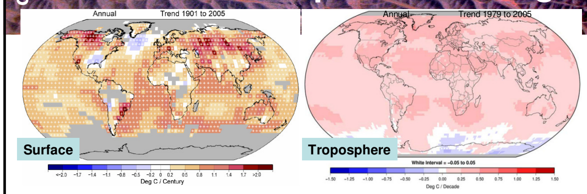
Is this unexpected? Are we missing something fundamental in our understanding of the Earth system?

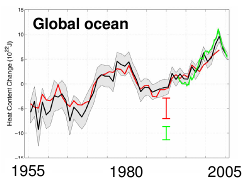
Heat waves are increasing: an example



Extreme Heat Wave
Summer 2003
Europe

Observed widespread warming

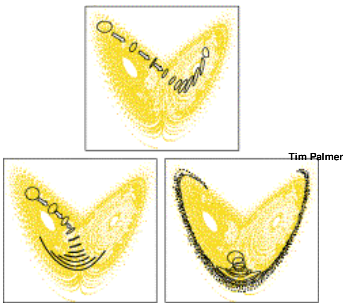


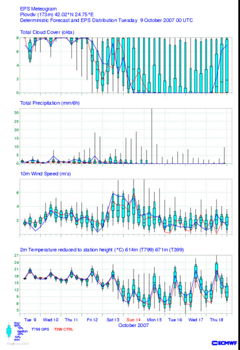


- extremely unlikely without external forcing
- very unlikely due to known natural causes

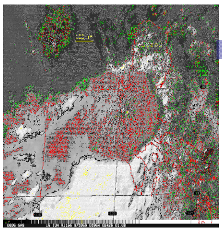
What might cause observed change?

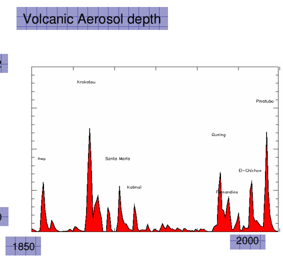
Chaos – Model evolution is uncertain





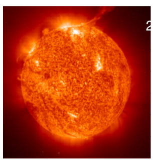
Natural Factors that *might* effect climate: Volcanoes

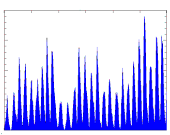




Large tropical volcanoes inject SO2 into the Stratosphere where it stays for 2-3 years. Effect is to make an aerosol that scatters light increasing the earth's albedo.

Natural Factors that *might* effect climate: Solar Irradiance





Solar activity (sunspots etc) & irradiance changes with 11-year solar cycle. There are long term changes in solar activity – the Maunder Minimum being one example. Converting this to changes in solar irradiance can be done though very uncertain. "Sun-like" starts which show activity variations have been used to estimate irradiance changes. Recent work (astronomical) and modelling (Lean et al) suggests there may be no significant long term variation in solar irradiance.

Human Factors: Greenhouse gases

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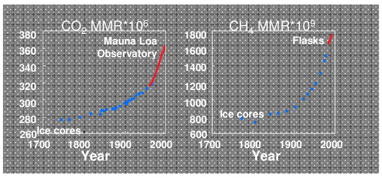
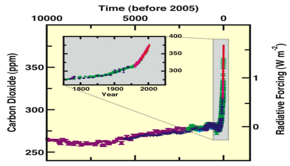


Greenhouse gas concentrations have changed over the last century. Their effect is to decrease IR transmission by the atmosphere



Human Factors: Aerosols

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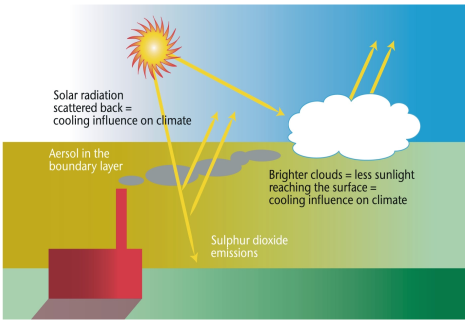

Thanks to Met Office

Attribution

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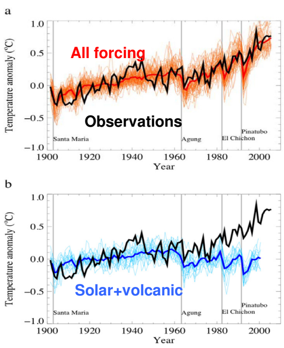
- are observed changes consistent with

☑expected responses to forcings

☒inconsistent with alternative explanations



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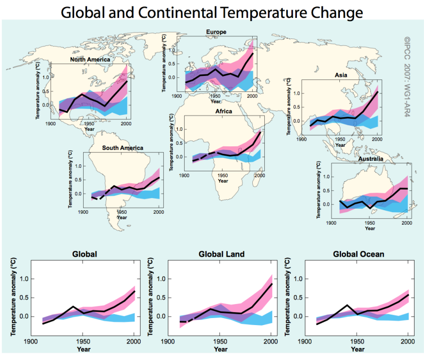
Understanding and Attributing Climate Change

Continental warming *likely* shows a significant anthropogenic contribution over the past 50 years



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Summary

- General Circulation models are build bottom up and encapsulate our knowledge of the processes and physics that drive the Earth System but are uncertain.
  - Basic equations are well known but large scale modelling of various processes such as convection is uncertain.
  - Predicted changes are large
- Observations show clear evidence of change with change largely caused by human emissions of greenhouse gases.