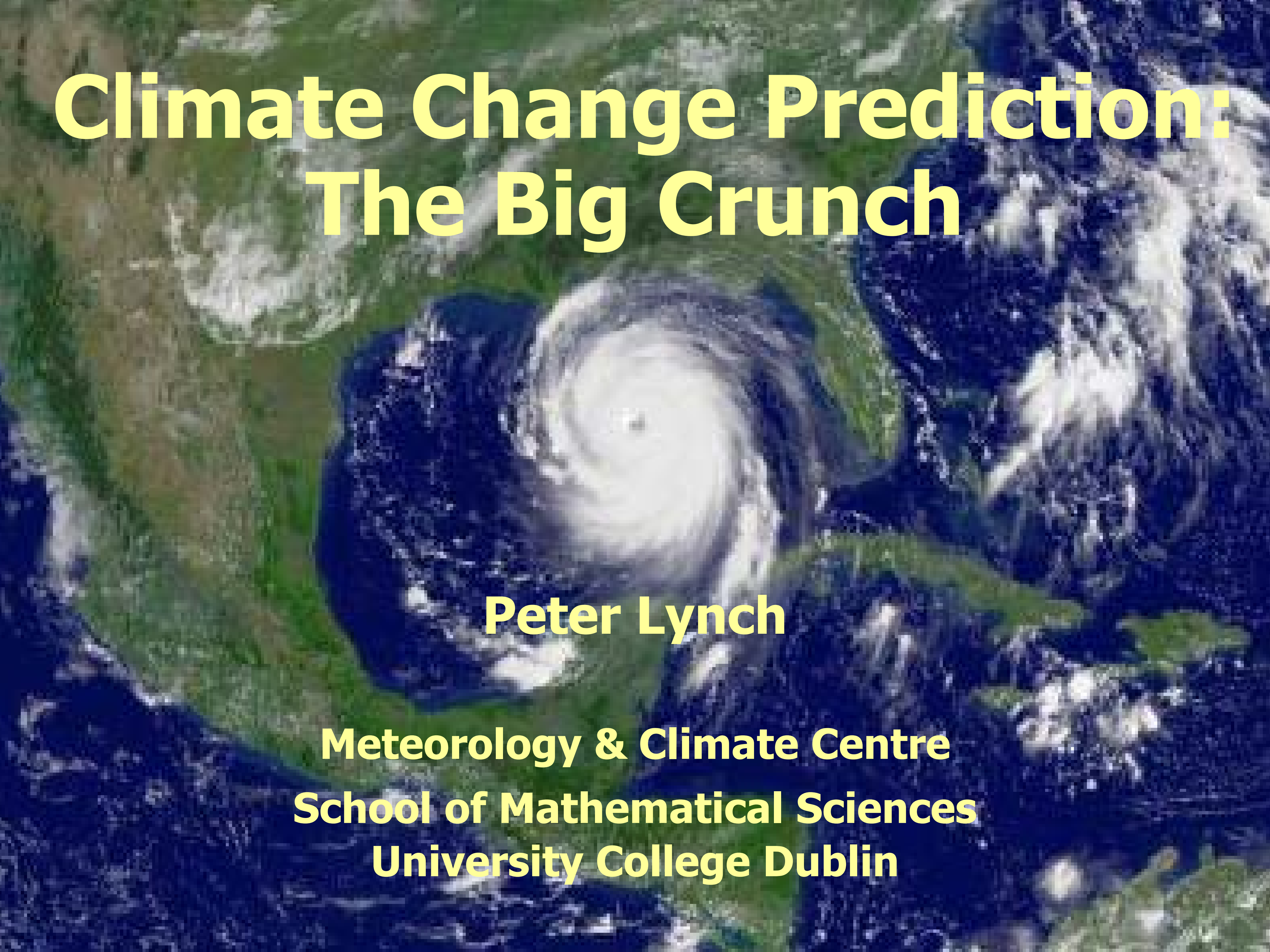

Climate Change Prediction: The Big Crunch

Peter Lynch

Meteorology & Climate Centre
School of Mathematical Sciences
University College Dublin

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Feature: February 2007

"A model approach to climate change"

Adam Scaife, Chris Folland and John Mitchell

"The Earth is warming up, with potentially disastrous consequences."

IPCC

The Intergovernmental Panel on Climate Change

Fourth Assessment Report

Climate Change 2007

Climate Change 2007:
The Physical Science Basis

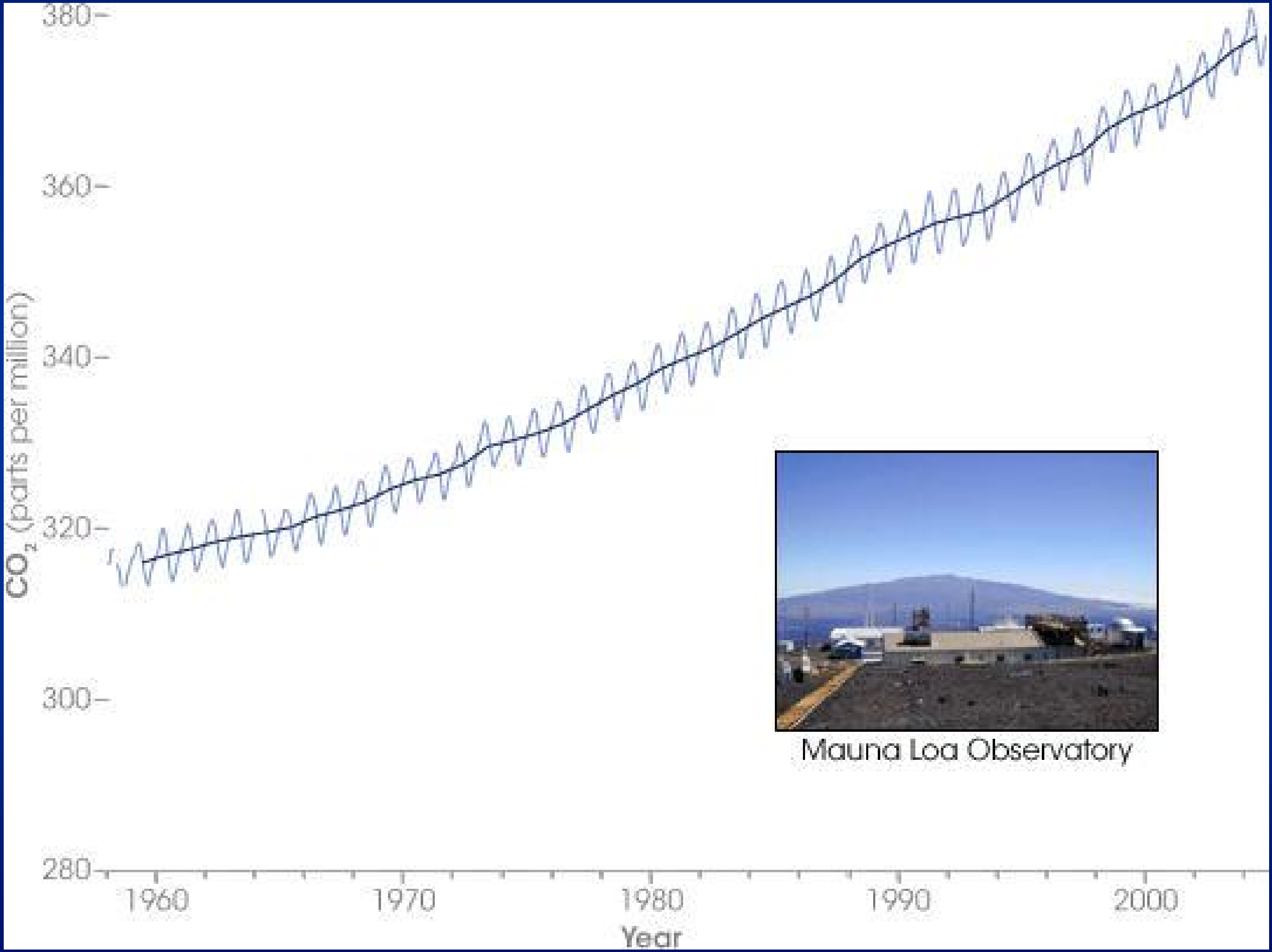
<u>Summary for Policymakers</u>

Warming of the climate system is <u>unequivocal</u> …

… there is very high confidence that the effect of human activities has been one of warming.

Concentration of CO_2

Mauna Loa, Hawaii, 1958–2004

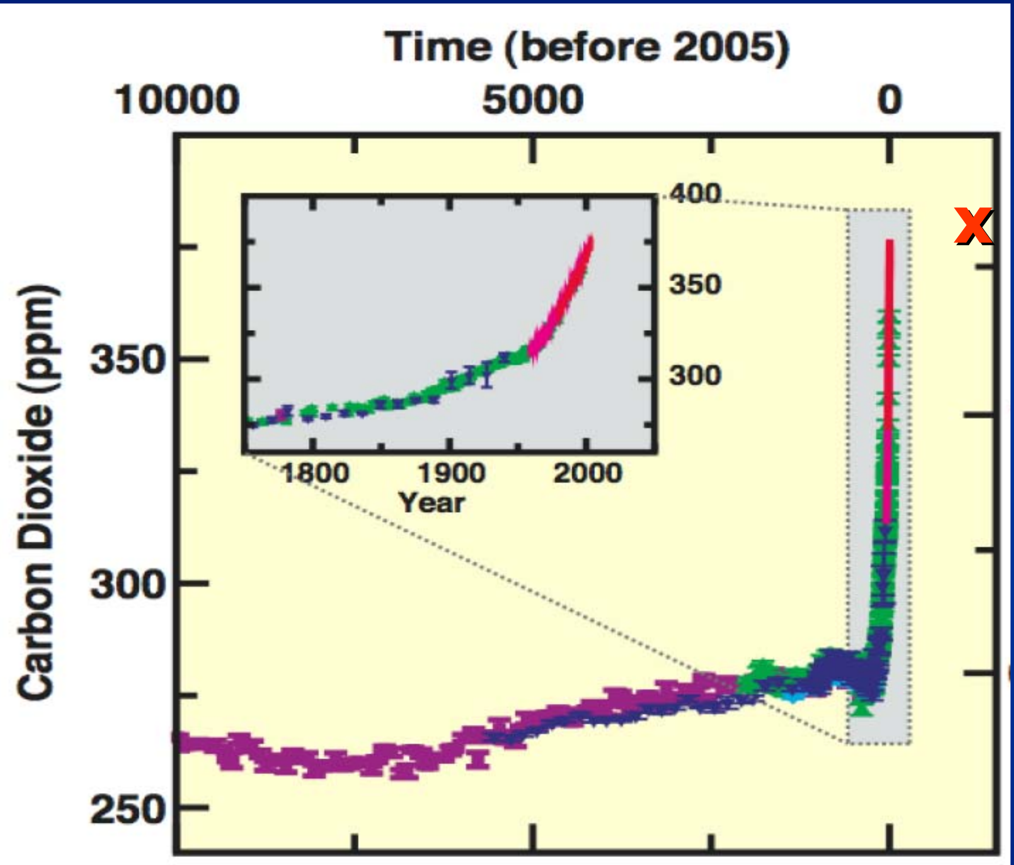


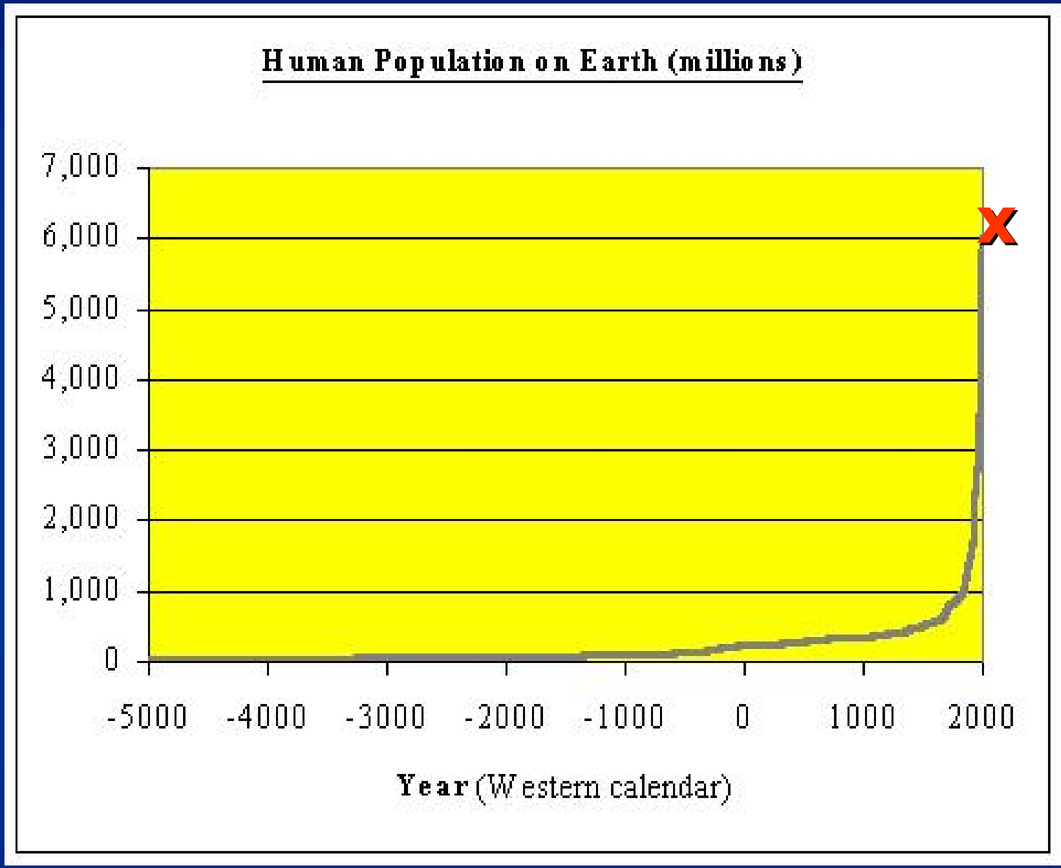
Climate Change 2007:
The Physical Science Basis

Summary for Policymakers

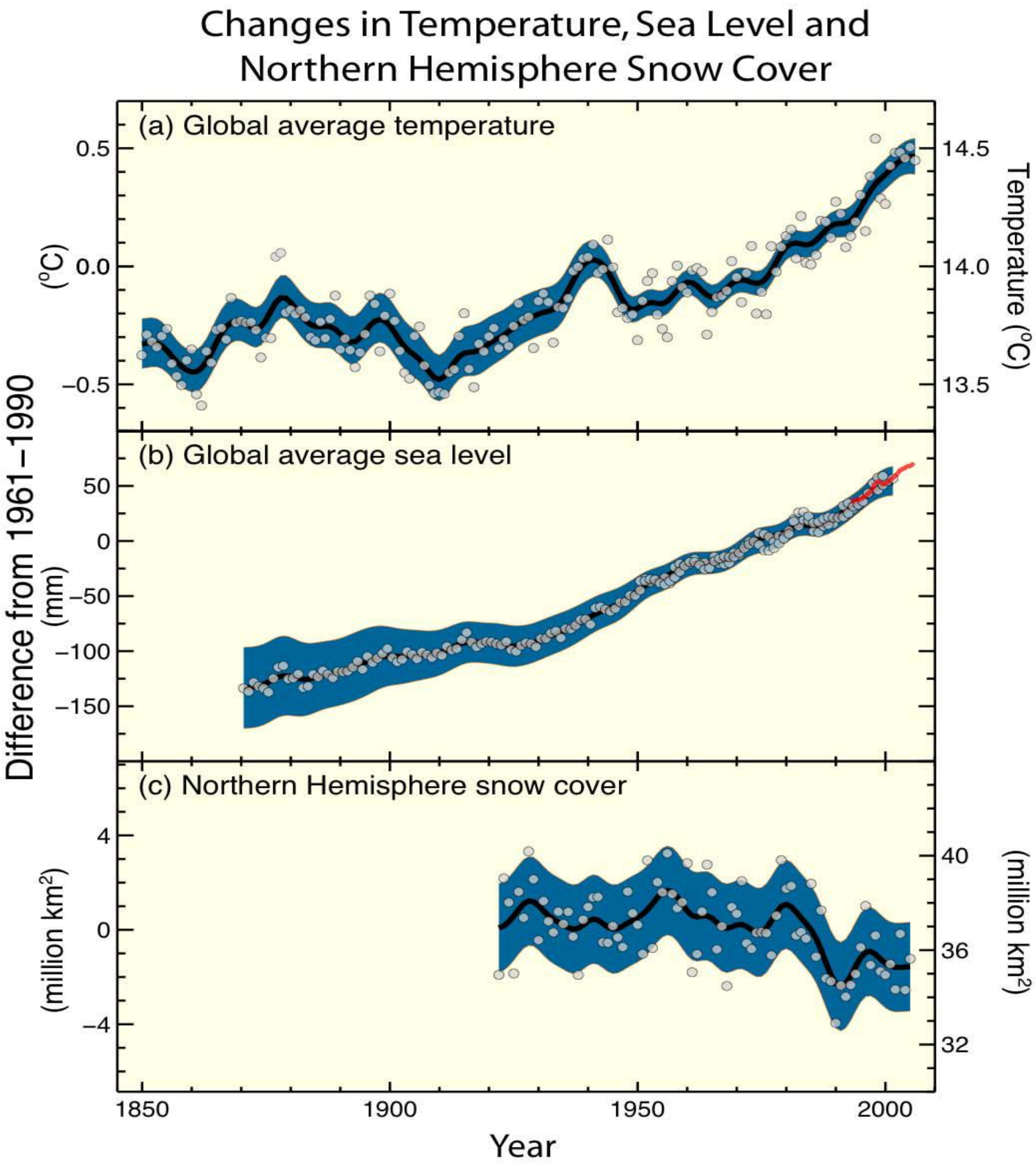
The atmospheric concentration of carbon dioxide in 2005 exceeds by far the natural range over the last 650,000 years.

CO2 Concentration, last 10,000 years





Human population, last 7,000 years



Changes in Temperature, Sea Level and Northern Hemisphere Snow Cover
(a) Global average temperature
(b) Global average sea level
(c) Northern Hemisphere snow cover
Difference from 1961–1990
(°C)
(mm)
(million km²)
Temperature (°C)
(million km²)
0.5
0.0
−0.5
14.5
14.0
13.5
50
0
−50
−100
−150
4
0
−4
40
36
32
1850
1900
1950
2000
Year

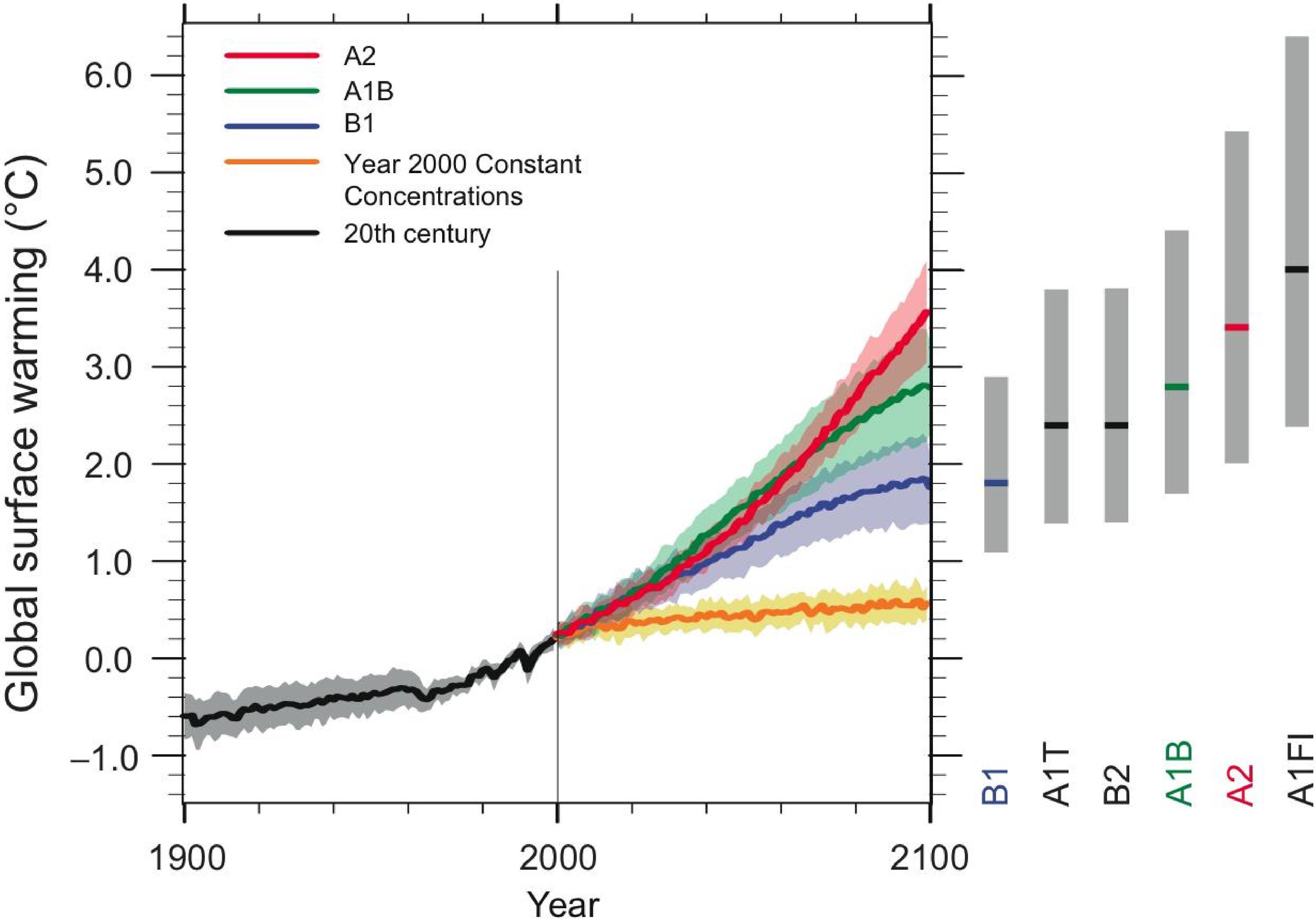
IoP, Birr,

Climate Change 2007:
The Physical Science Basis

Summary for Policymakers

For the next two decades a warming of about 0.2°C per decade is projected …

Multi-model Averages and Assessed Ranges for Surface Warming



How do they do that?

How does the IPCC know what is going to happen?

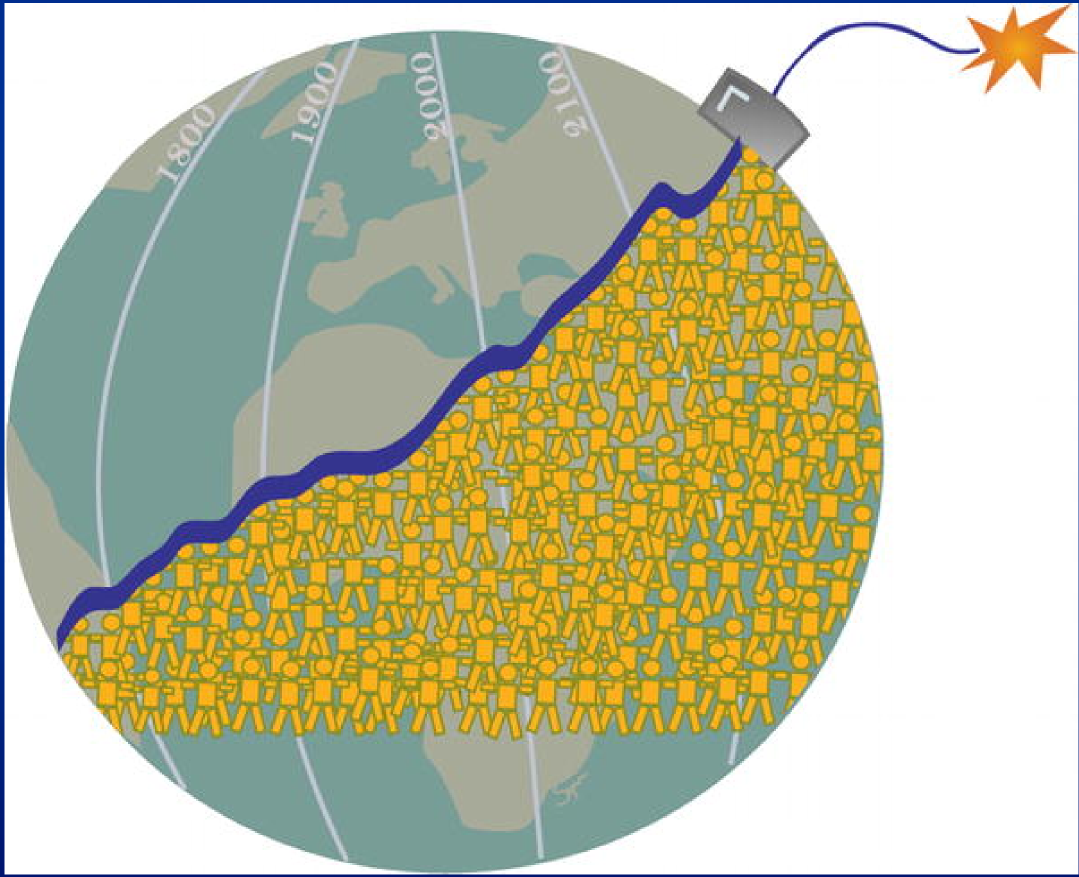
Our best means of anticipating climate change is by means of ***computer climate models*****.**

A Physical Model: Spitfire

The "real thing"

Airfix Model

A Mathematical Model: The Population Explosion



Observation

$$P(t) = P(0)\exp(\alpha t)$$

Prediction Model

$$\frac{dP}{dt} = \alpha P$$

Climate Models

- The climate system is **enormously complex**
- Climate models are amongst the most complex models in all of science
- Climate models are based on **fluid mechanics and thermodynamics**

The Basis of Climate Modelling

Newton's Law of Motion

$$F = ma$$

The Navier-Stokes Equations

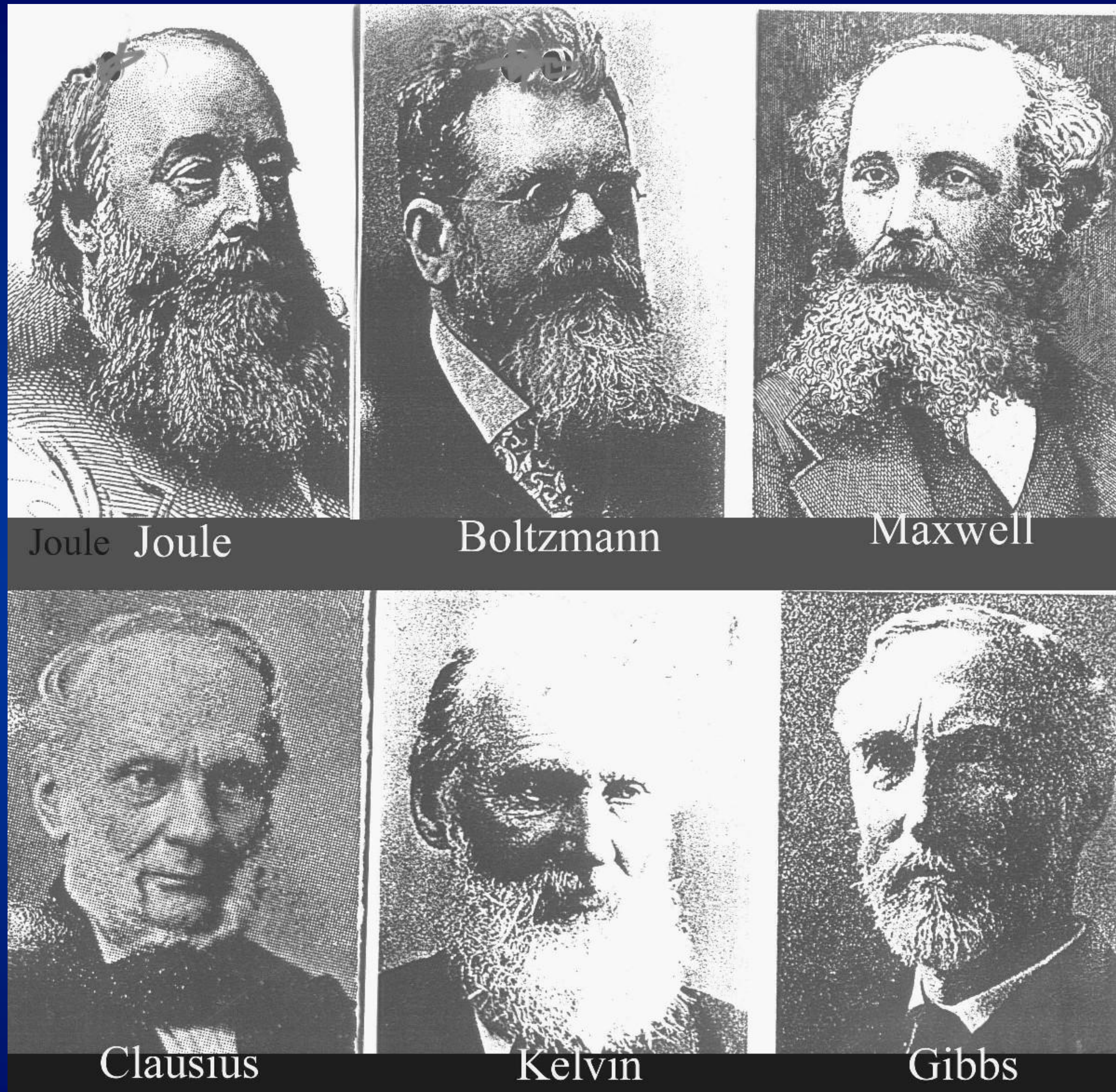
$$\frac{\partial \mathbf{V}}{\partial t} + \mathbf{V} \cdot \nabla \mathbf{V} + \frac{1}{\rho} \nabla p = \nu \nabla^2 \mathbf{V} + \mathbf{g}^\star .$$

The Navier-Stokes Equations describe how the change of velocity, the acceleration of the fluid, is determined by the pressure gradient force, the gravitational force and the frictional force.

For motion relative to the rotating earth, we must include the Coriolis force:

$$\frac{\partial \mathbf{V}}{\partial t} + \mathbf{V} \cdot \nabla \mathbf{V} + 2\boldsymbol{\Omega} \times \mathbf{V} + \frac{1}{\rho} \nabla p = \nu \nabla^2 \mathbf{V} + \mathbf{g} .$$

Thermodynamics



The Atmospheric Equations

- The Navier-Stokes Equations
- The Continuity Equation
- Continuity Equation for Water
- The Thermodynamic Equation
- The Equation of State (Boyle/Charles)

Newton's second law

$$\frac{D_r u}{Dt} - \frac{uv\tan\phi}{r} - 2\Omega\sin\phi v + \frac{c_{pd}\theta}{r\cos\phi}\frac{\partial\Pi}{\partial\lambda} = -\left(\frac{uw}{r} + 2\Omega\cos\phi w\right) + S^u$$

$$\frac{D_r v}{Dt} + \frac{u^2\tan\phi}{r} + 2\Omega\sin\phi u + \frac{c_{pd}\theta}{r}\frac{\partial\Pi}{\partial\phi} = -\left(\frac{vw}{r}\right) + S^v$$

$$\frac{D_r w}{Dt} + c_{pd}\theta\frac{\partial\Pi}{\partial r} + \frac{\partial\Pi}{\partial r} = \left(\frac{u^2 + v^2}{r}\right) + 2\Omega\cos\phi u + S^w$$

mass continuity

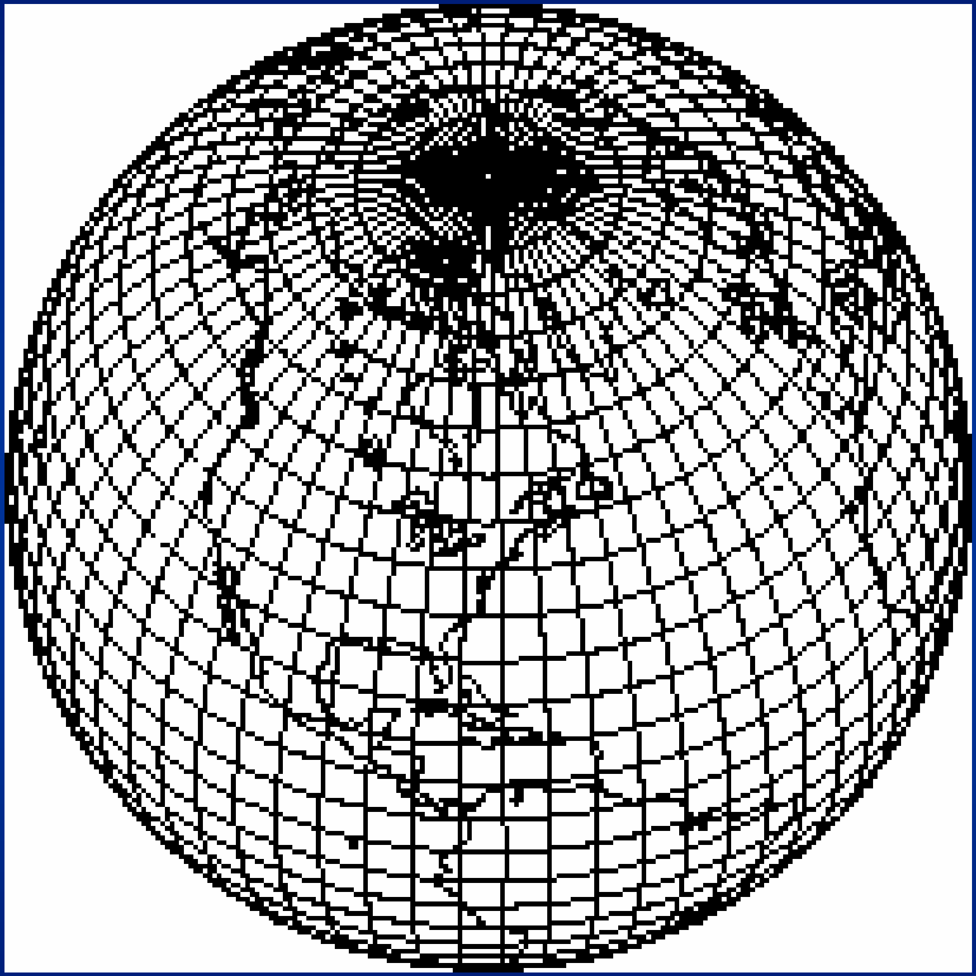
$$\frac{D_r}{Dt}\left(\rho_d r^2\cos\phi\right) + \rho_d r^2\cos\phi\left[\frac{\partial}{\partial\lambda}\left(\frac{u}{r\cos\phi}\right) + \frac{\partial}{\partial\phi}\left(\frac{v}{r}\right) + \frac{\partial w}{\partial r}\right] = 0$$

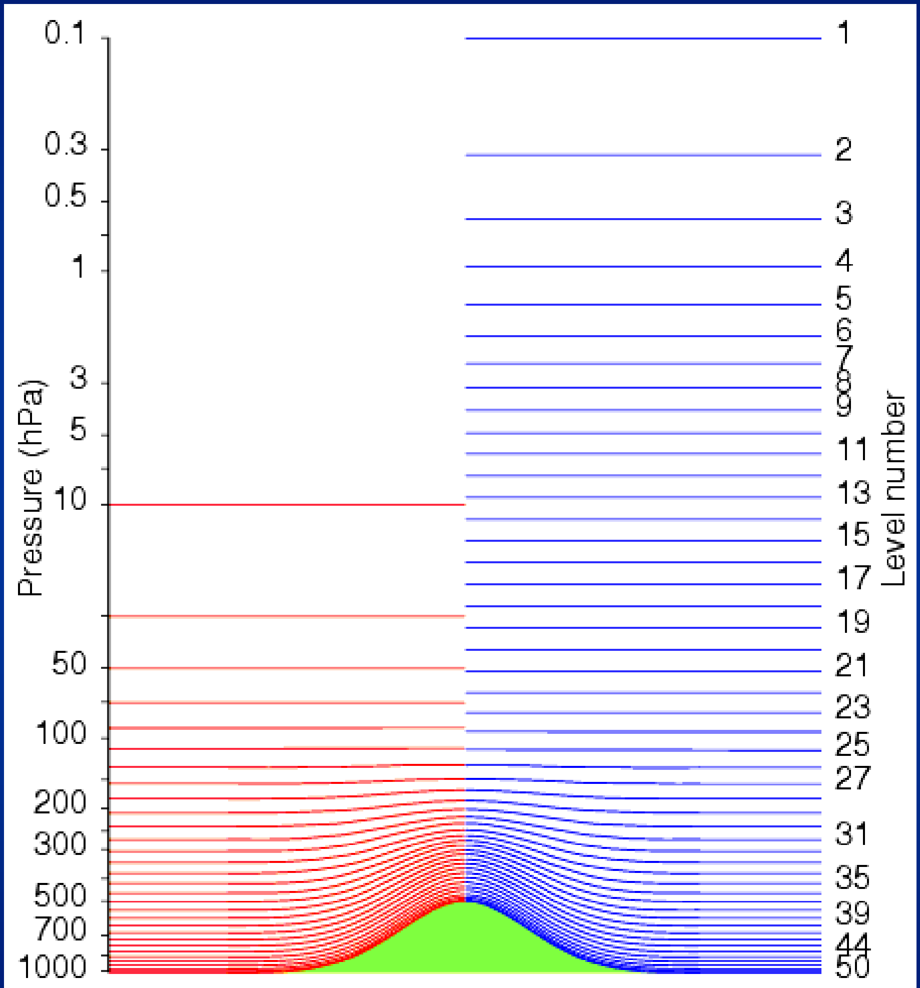
thermodynamics

$$\frac{D_r\theta}{Dt} = S^\theta$$

↖ Source term

Computational Grid





Vilhelm Bjerknes (1862–1951)

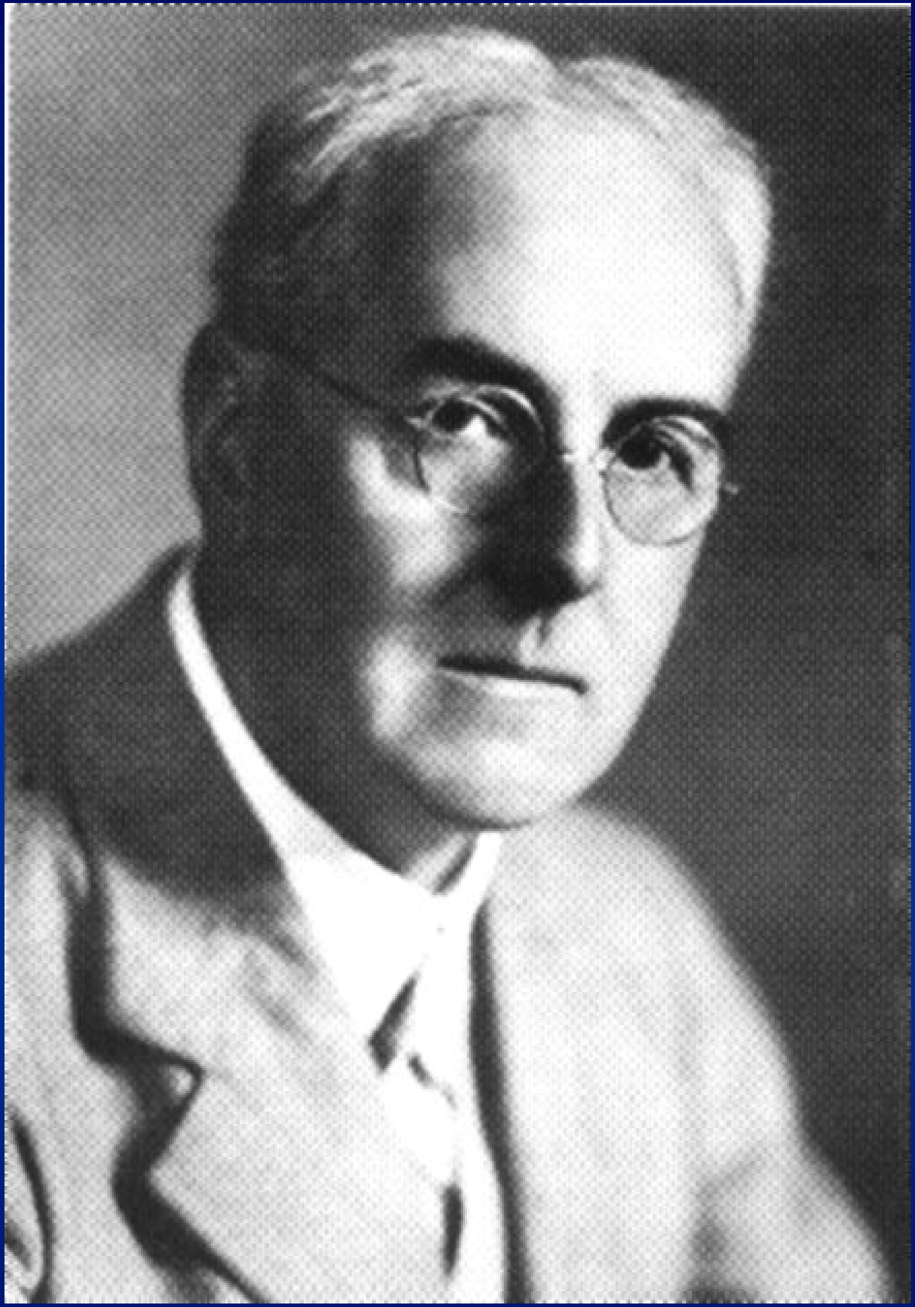
Bjerknes' 1904 Manifesto

To predict future states of the atmosphere.

We need:

1. **A sufficiently accurate knowledge of the initial state of the atmosphere**

2. **A sufficiently accurate knowledge of the laws of physics governing its behaviour.**



Lewis Fry Richardson (1881–1953)

Richardson computed by hand the pressure change at a single point.

It took him two years !

His ‘forecast’ was a catastrophic failure:

Δp = 145 hPa in 6 hours

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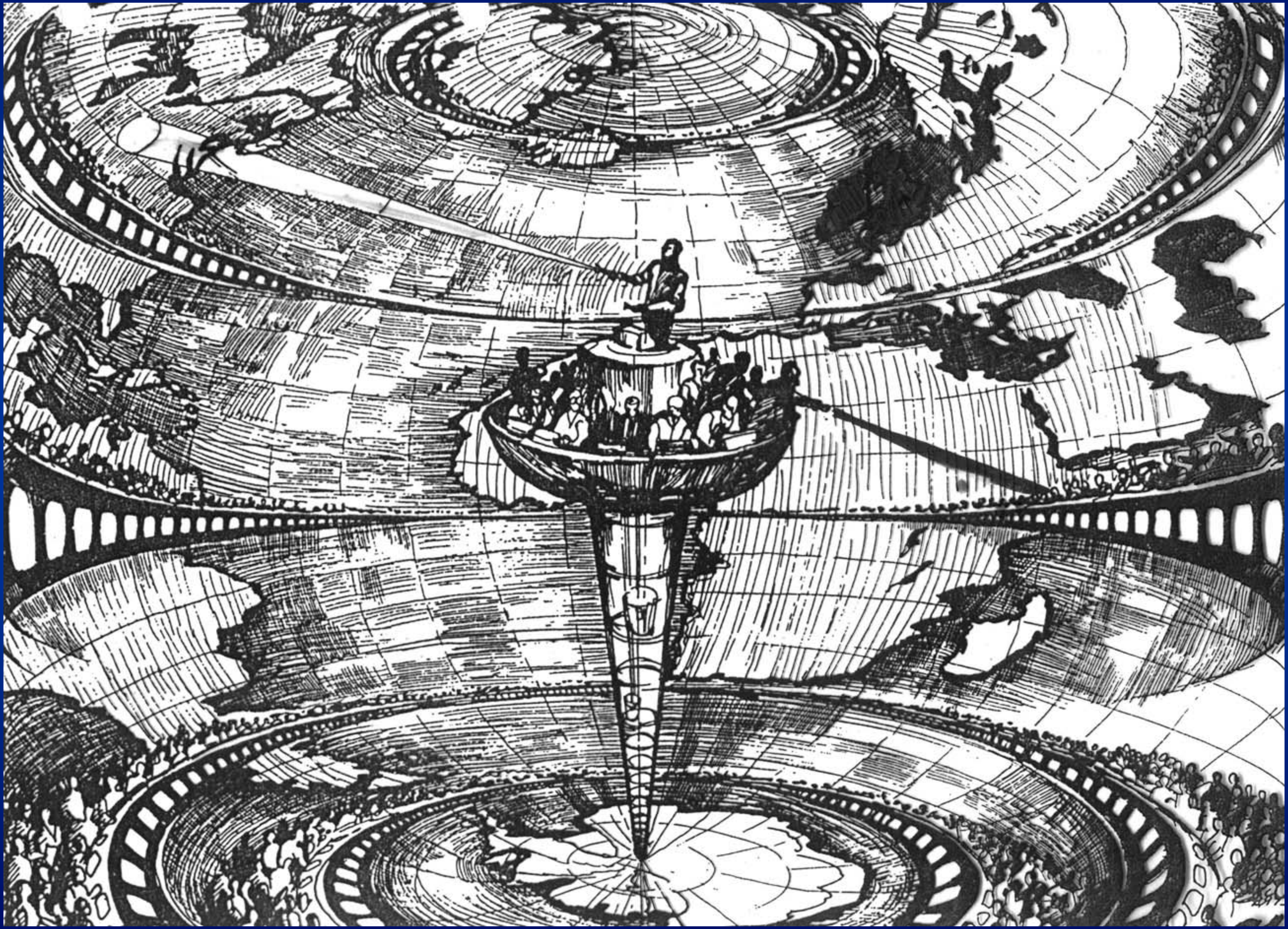
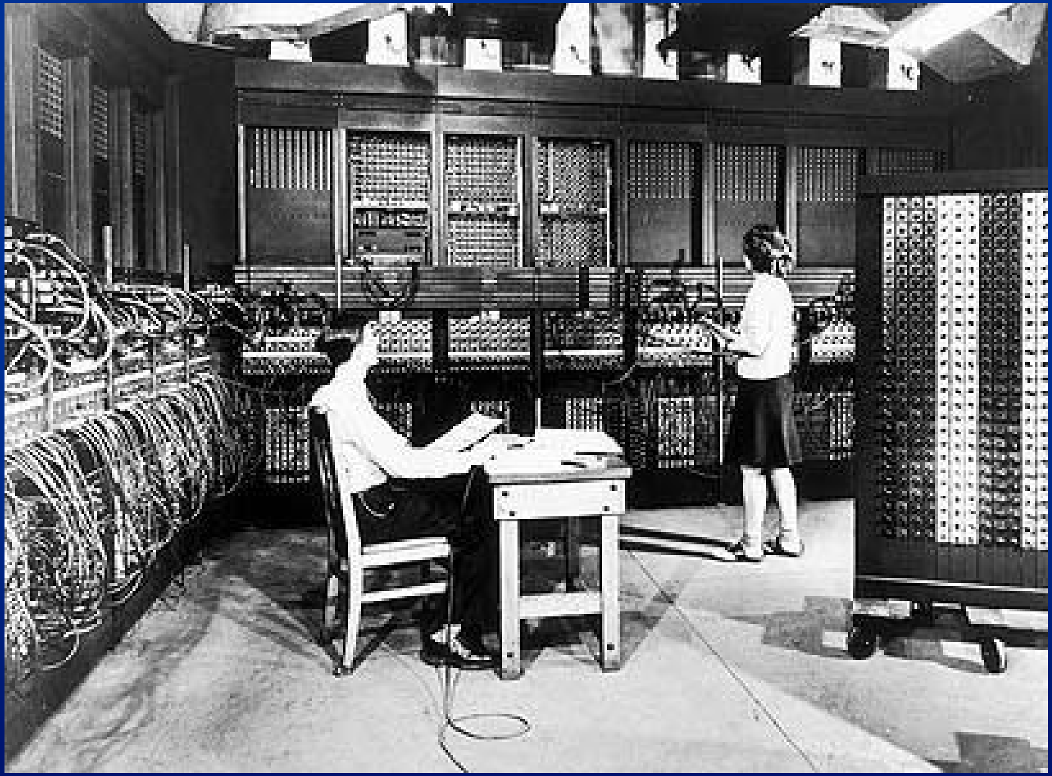
Richardson's Forecast Factory (…the start of *The Big Crunch…*)



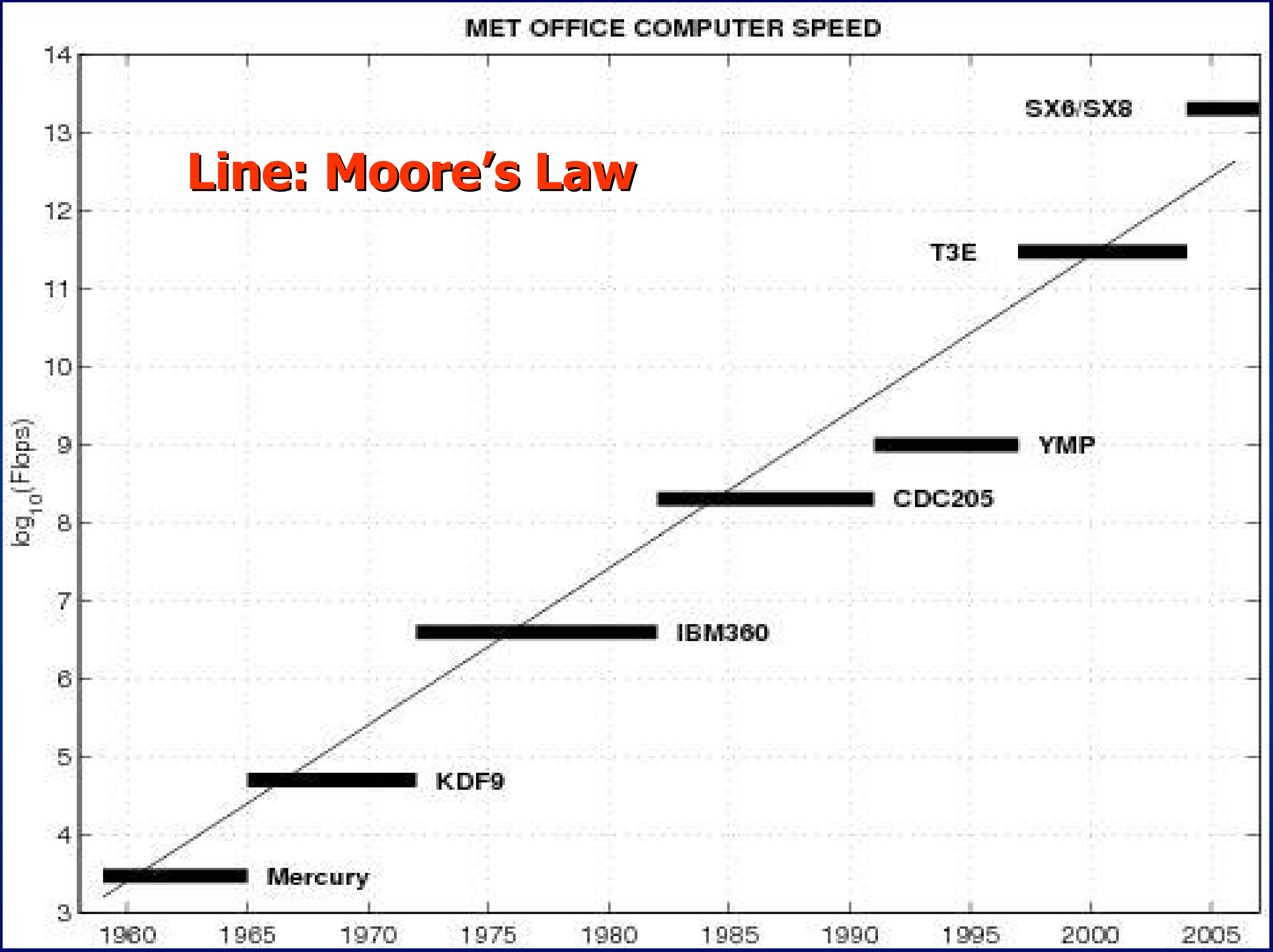
ENIAC

Electronic Numerical Integrator and Computer

The first multipurpose programmable electronic digital computer

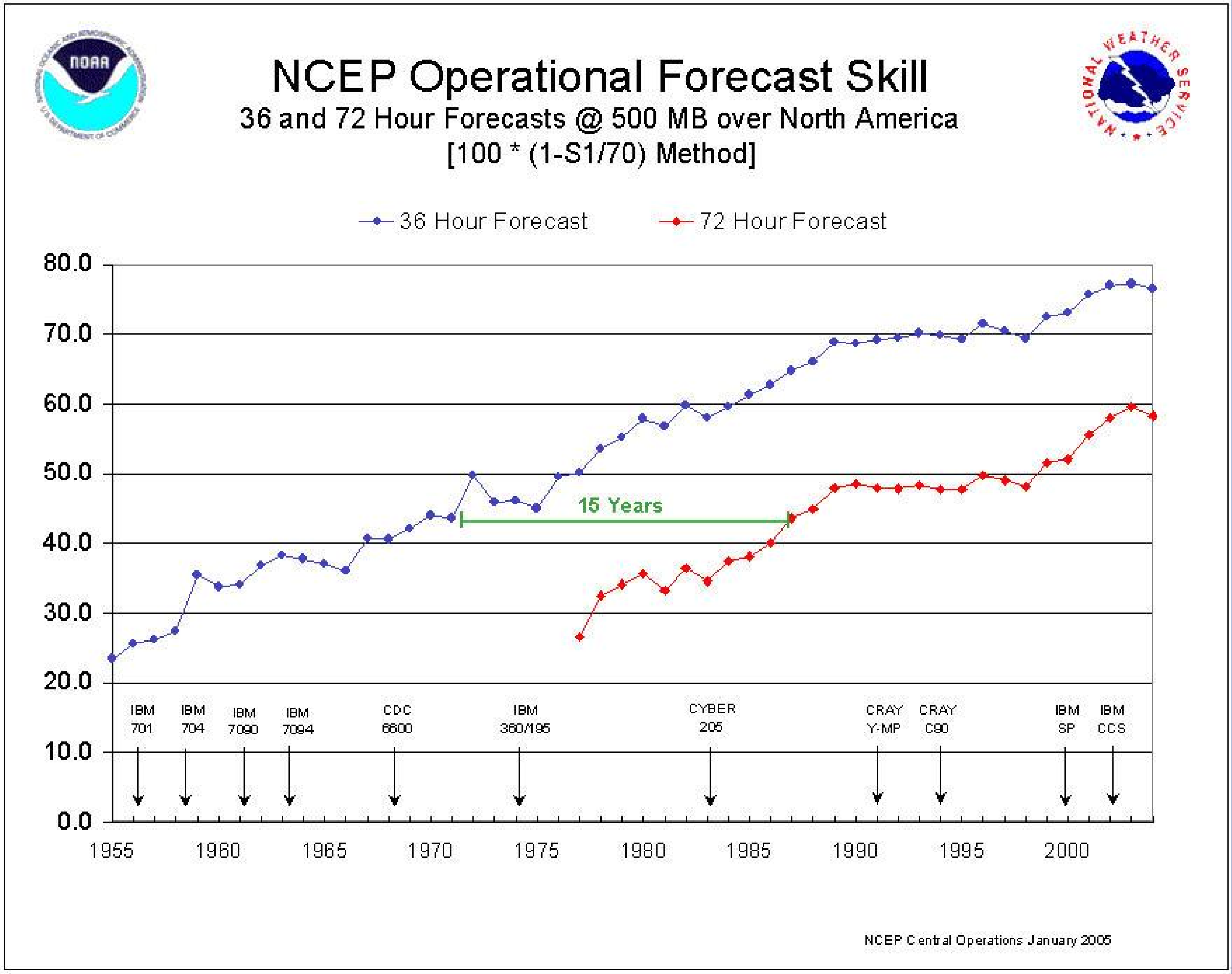


- 18,000 valves
- 70,000 resistors
- 10,000 capacitors
- 6,000 switches
- 140 kWatts power


MET OFFICE COMPUTER SPEED
Line: Moore's Law
log10(Flops)
14
13
12
11
10
9
8
7
6
5
4
3
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
SX6/SX8
T3E
YMP
CDC205
IBM360
KDF9
Mercury

Computer Forecasting Skill

[The longest verification series in existence]



Elements of the Climate System

- The atmosphere
- The ocean
- The cryosphere
- The geosphere
- The biosphere

There are interactions between these sub-systems

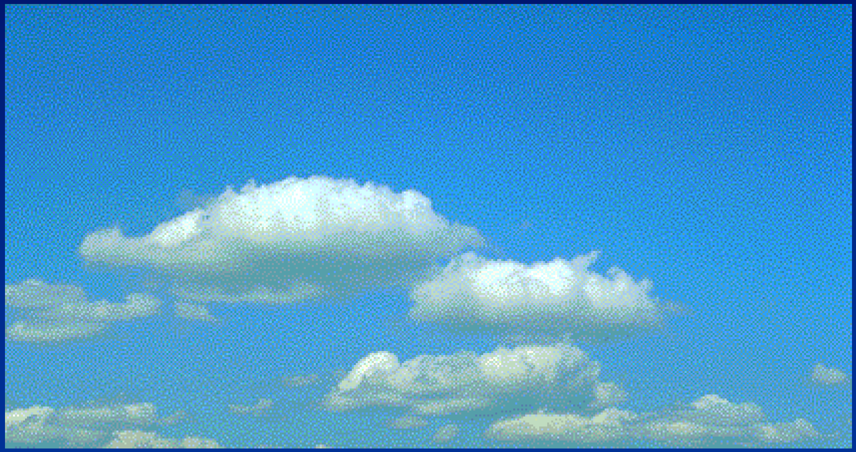
All these sub-systems are represented in modern Earth System Models

Parameterisation

We have to represent a wide range of processes occurring on scales smaller than the resolution of the models.

- **Convective and stratiform clouds**
- **Infrared and visible radiation**
- **The topography of the Earth's surface**
- **Atmospheric turbulence on many scales.**

CLOUDS AND CLIMATE



Low clouds reflect sunlight but trap little infra-red radiation;

They act to cool climate

High clouds reflect sulight but also trap infra-red radiation;

They act to warm climate

Global warming may change the characteristics of clouds, thus altering their effect on climate

UNCERTAINTIES IN CLIMATE CHANGE PREDICTIONS

- **Projections of future emissions**
- **Initial climate conditions**
- **Natural and human climate factors**
- **Realism of the climate model**
  - **feedbacks**
  - **resolution**
  - **extremes of climate**
- **Surprises ! ! !**

Some Irish Contributors to Met. & Climate Science

- Robert Boyle (1627-1691)
- Richard Kirwan (1733–1812)
- Francis Beaufort (1774–1857)
- John Tyndall (1820–1893)
- George G Stokes (1819–1903)
- William Thompson (1824–1907)
- Osborne Reynolds (1842–1912)

John Tyndall (1820–1893)

- Born at Leighlinbridge Co Carlow
- Studied with Bunsen in Marburg
- Associated with Royal Institution
- Assistant to Michael Faraday
- Wrote 16 books and 145 papers.

Tyndall and the Greenhouse Effect

"without water vapour, the Earth's surface would be held fast in the iron grip of frost"

Tyndall showed that water vapour, CO2 and ozone are strong absorbers of heat radiation

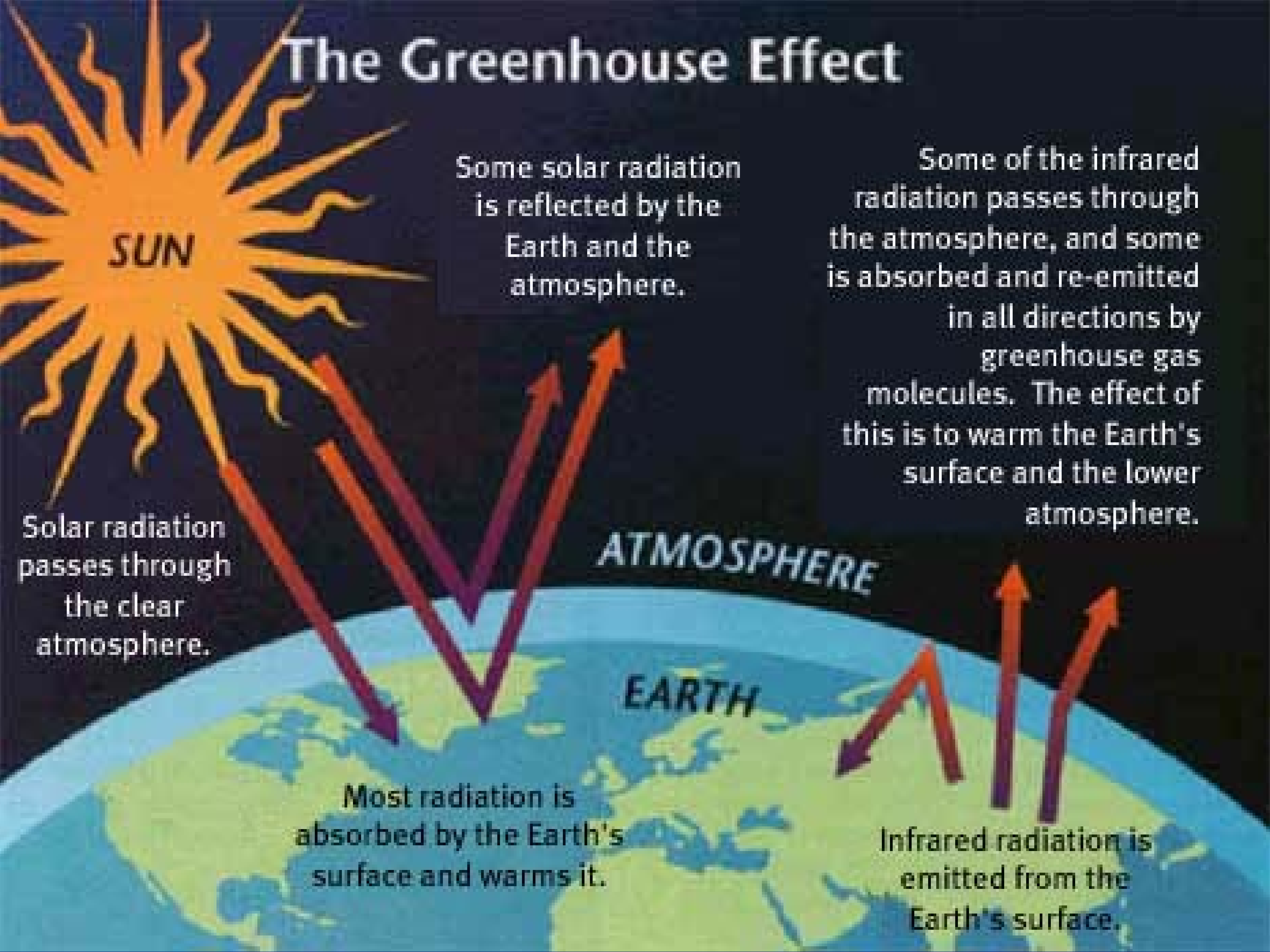
Tyndall speculated how changes in water vapour and CO2 are related to climate change

This is what we call the Greenhouse Effect.

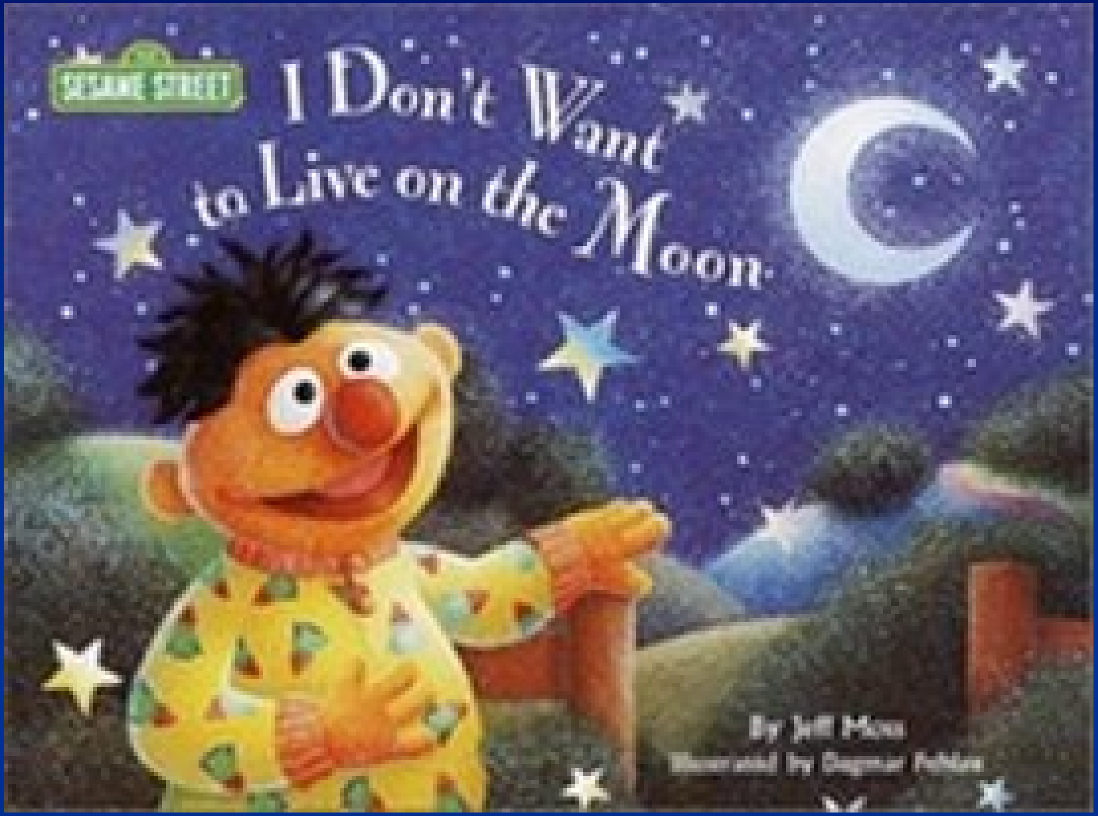
THE GREENHOUSE EFFECT

Visible energy from the sun passes through the glass and heats the ground

Infra-red heat energy from the ground is partly reflected by the glass, and some is trapped inside the greenhouse

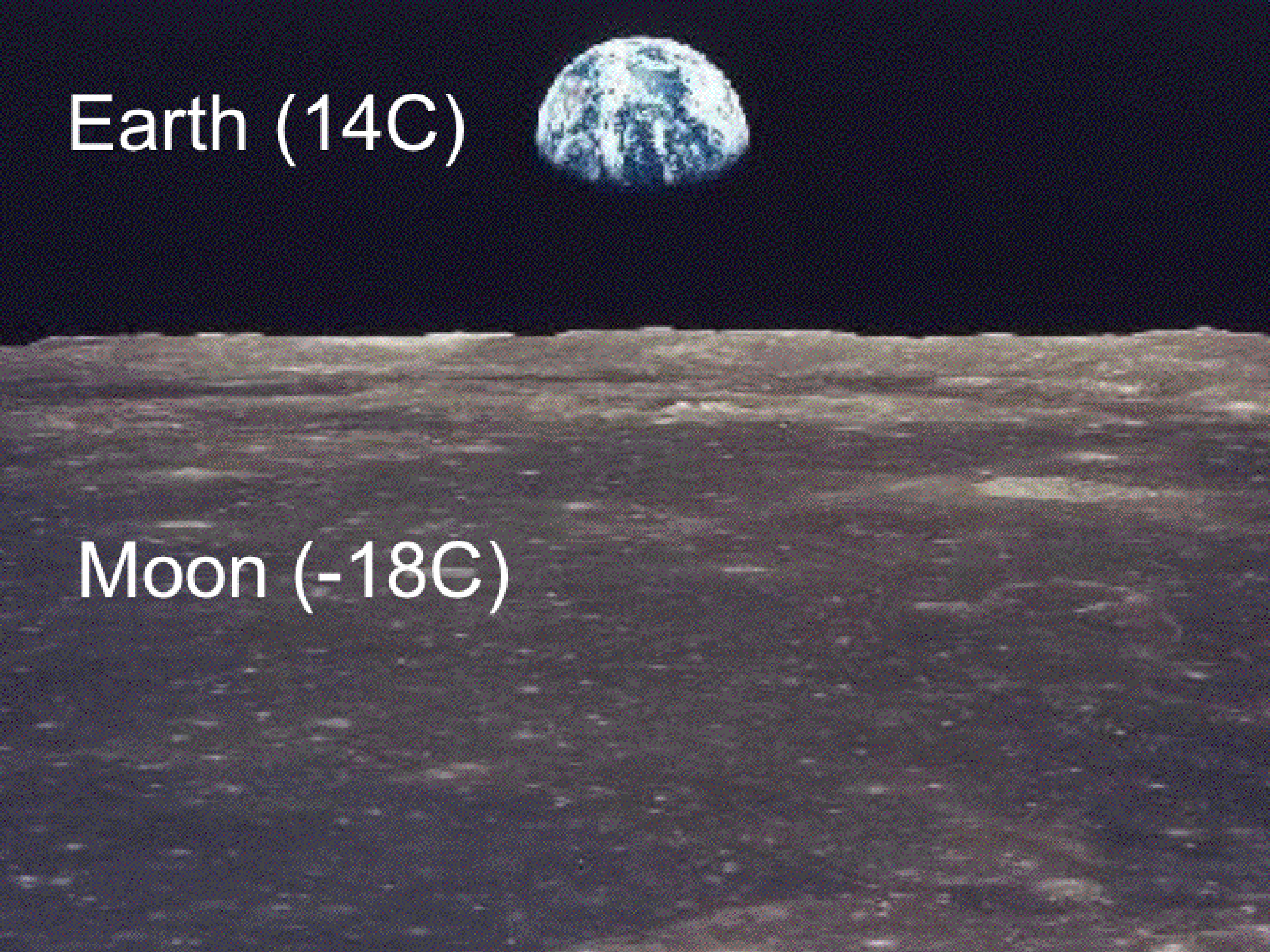

The Greenhouse Effect
SUN
Some solar radiation is reflected by the Earth and the atmosphere.
Some of the infrared radiation passes through the atmosphere, and some is absorbed and re-emitted in all directions by greenhouse gas molecules. The effect of this is to warm the Earth's surface and the lower atmosphere.
Solar radiation passes through the clear atmosphere.
ATMOSPHERE
EARTH
Most radiation is absorbed by the Earth's surface and warms it.
Infrared radiation is emitted from the Earth's surface.

I don't want to live on the moon

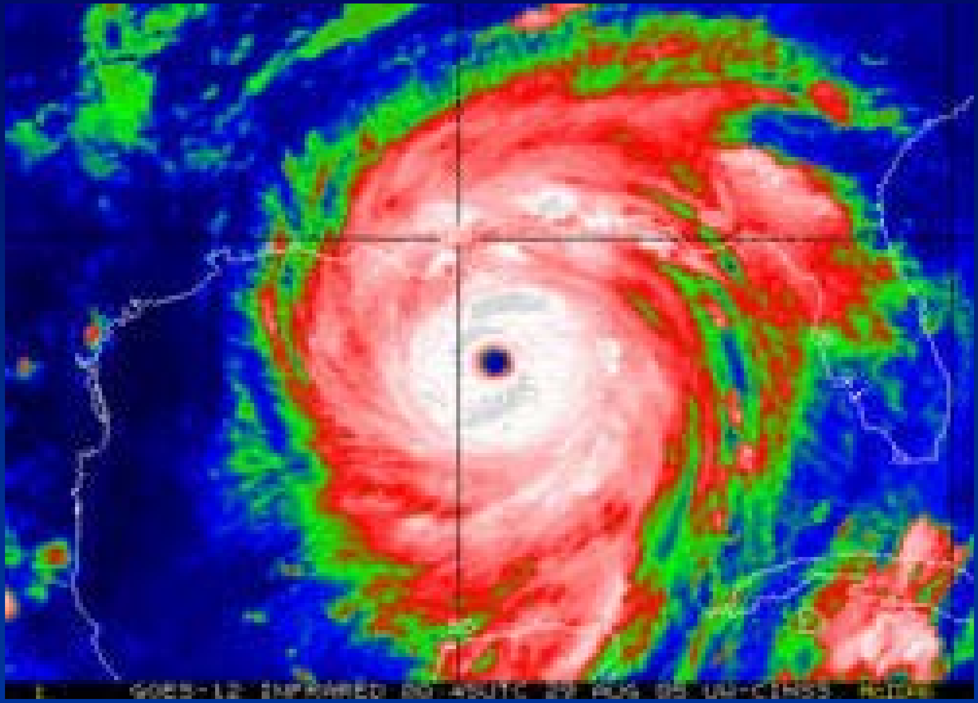


Ernie

Well, I'd like to visit the moon
On a rocket ship high in the air
Yes, I'd like to visit the moon
But I don't think I'd like to live there


Earth (14C)
Moon (-18C)

Hurricane Katrina



- Sustained winds 175 mph
- Category 5 storm at maximum
- Category 4 on landfall
- 150 miles wide: as big as Ireland
- 10 metre storm surge
- Torrential rainfall.

Katrina and Global Warming

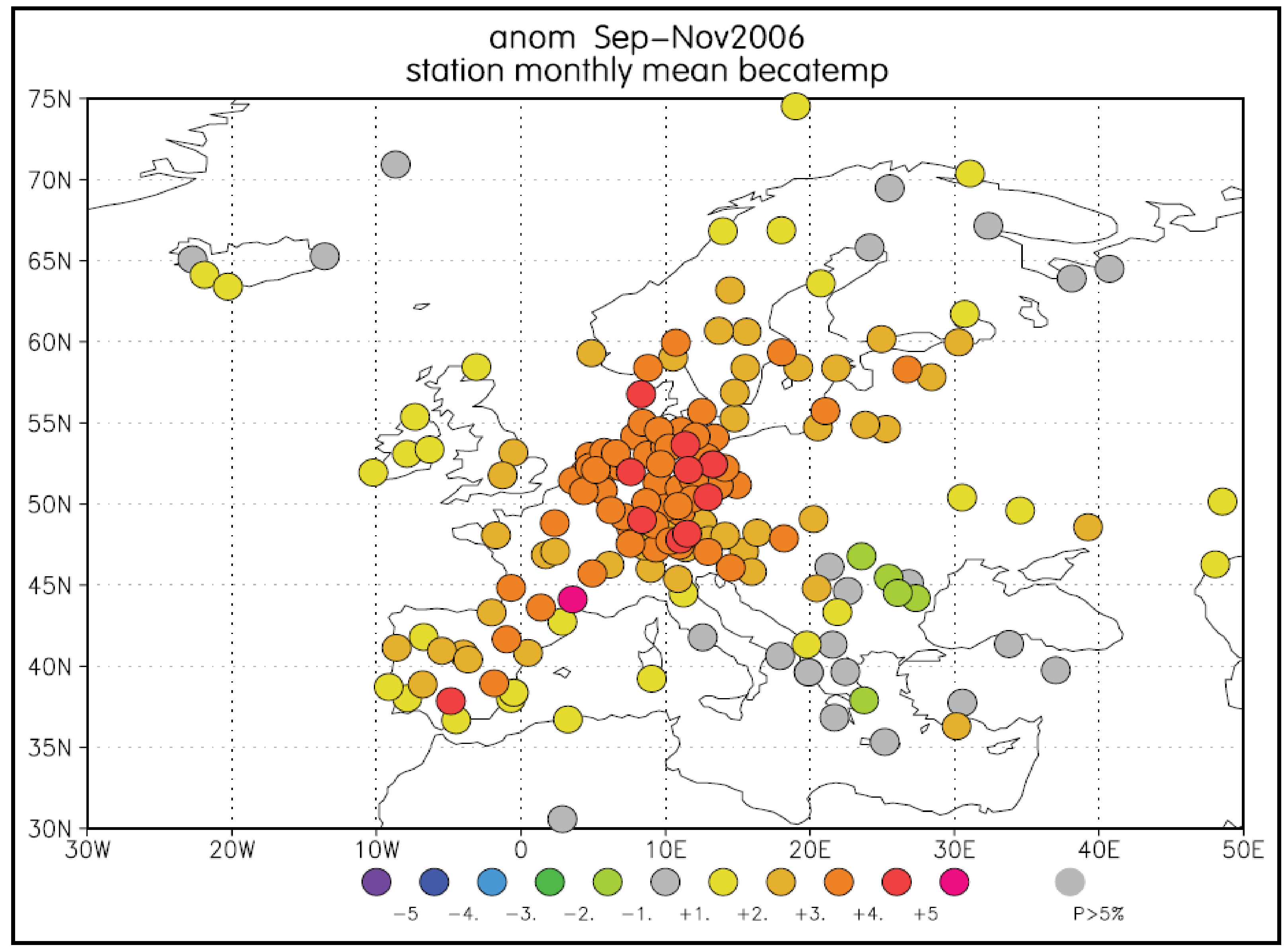
Was Hurricane Katrina due to climate change?

We cannot be sure. Storms like this have occurred before.

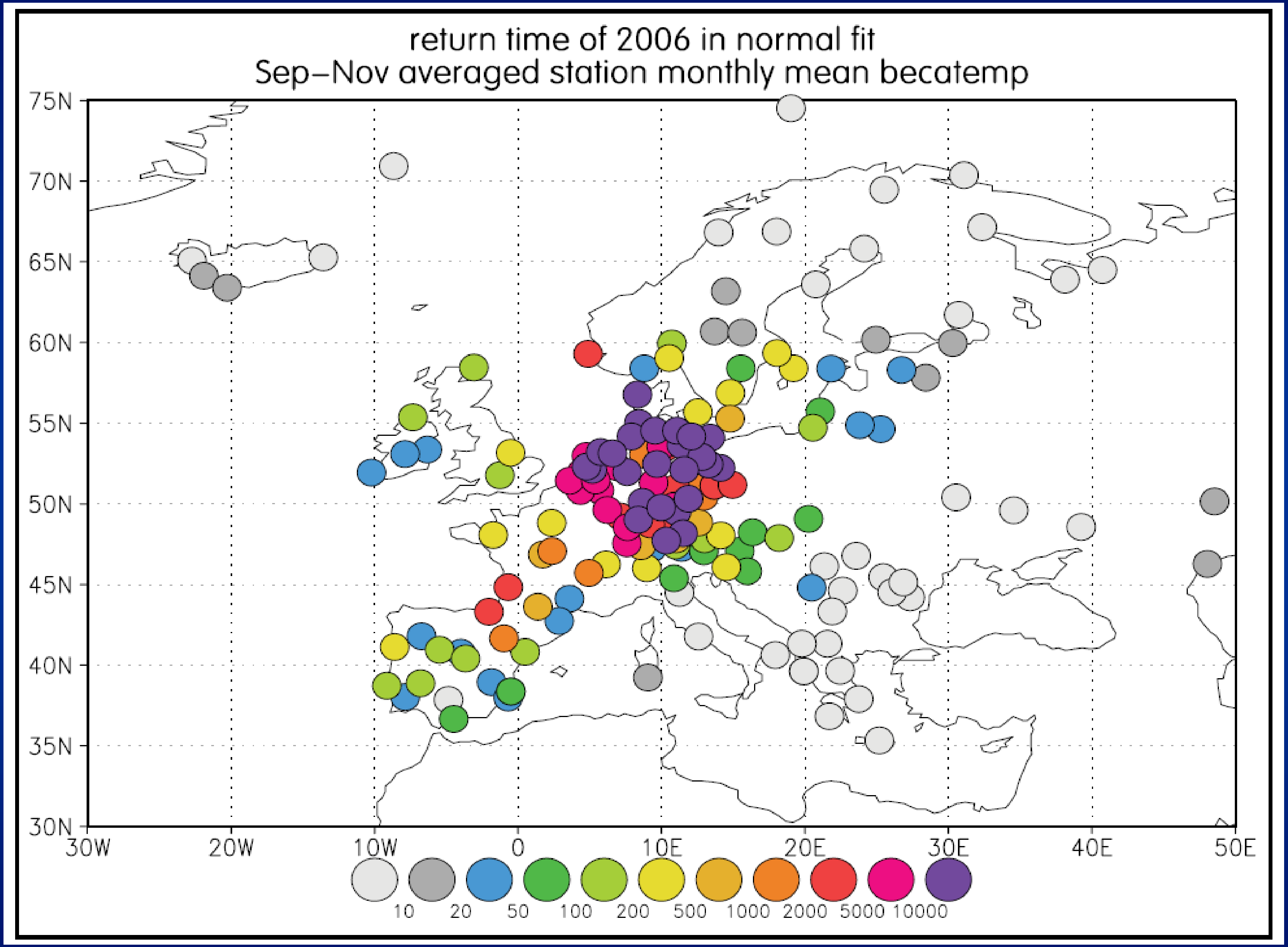
However, violent hurricanes will become more common in a warmer world:

Higher temperatures =>
Warmer oceans =>
More moisture and energy =>
Larger, fiercer storms.

Extraordinarily Mild Autumn, 2006



Return time for Normal fit



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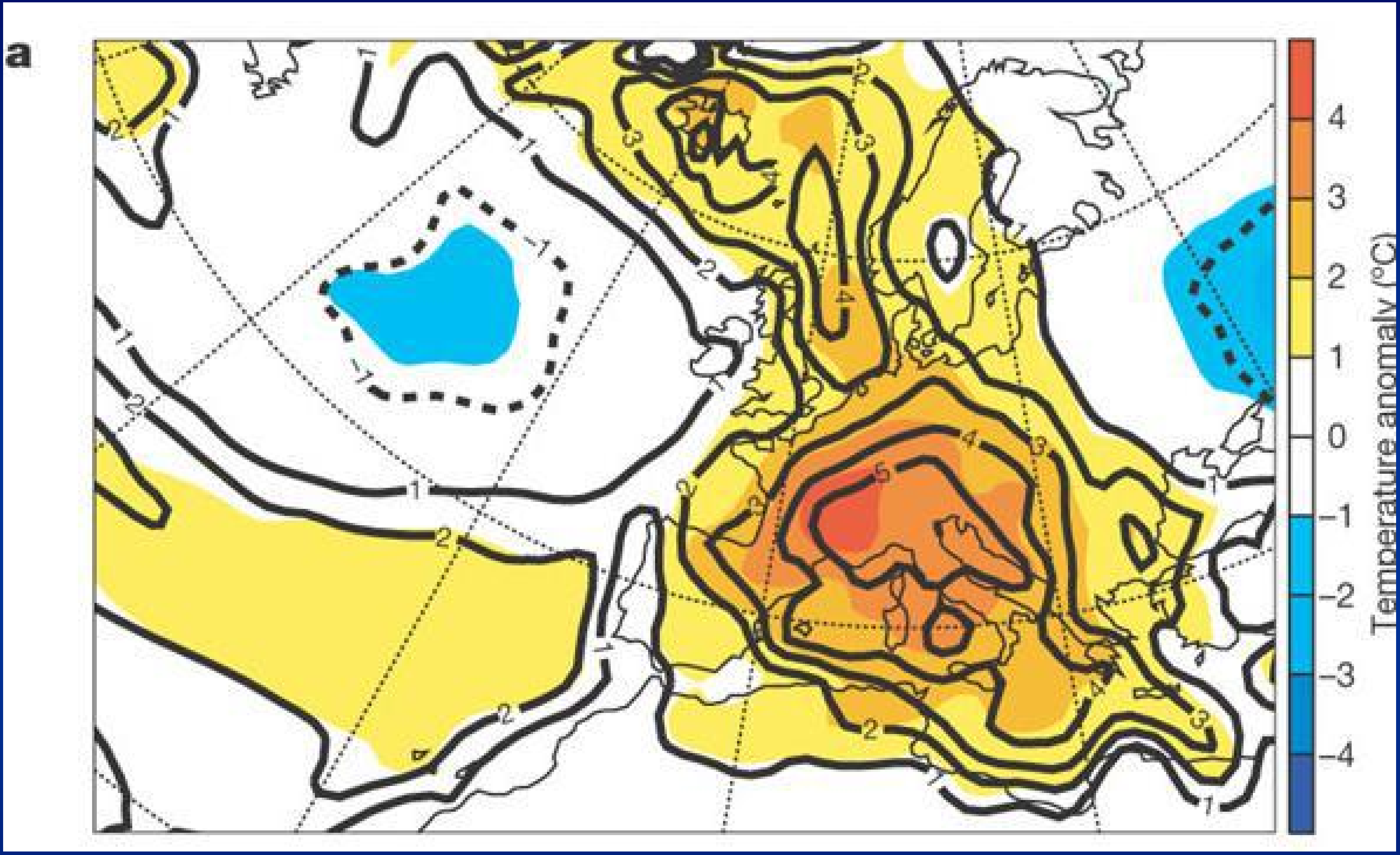
European Heatwave, Summer 2003

- The hottest Summer in 500 years.
- There were more than 27,000 excess deaths due to the heat.

Was this merely a rare meteorological event or a first glimpse of things to come? **Probably both!**

Temperature Anomaly, June–August, 2003



Colour: Deviation from 1961–1990 mean.
Contours: ΔT normalized by standard deviation.

Summer 2007 has been simulated with and without the effect of mankind's activities

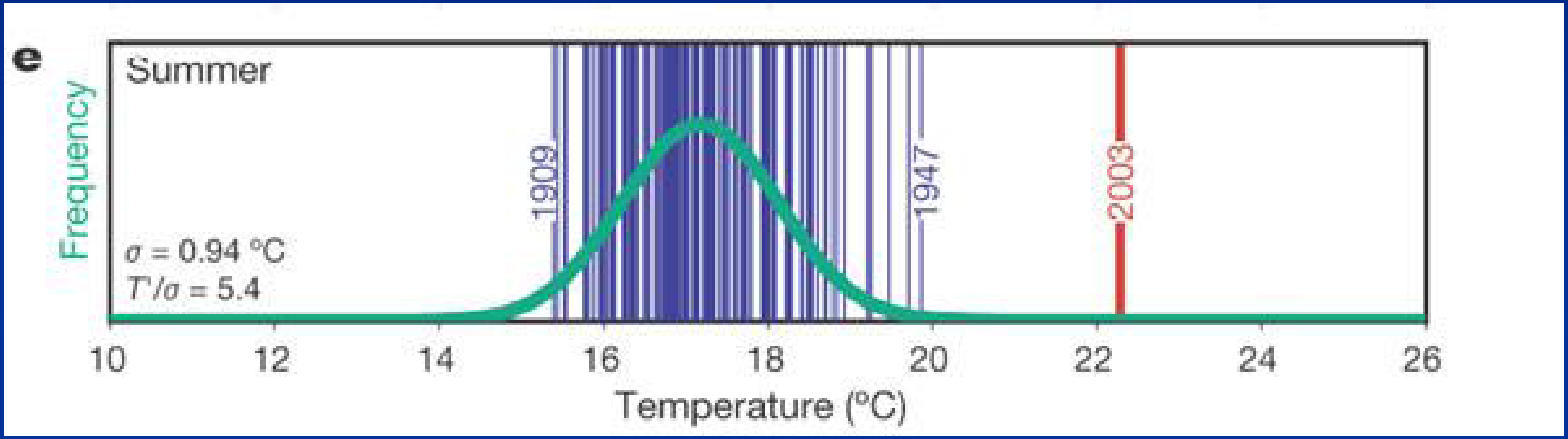
[Schär, et al., *Nature*, 427, Jan 22, 2004]

Conclusion:

Such heatwaves are now four times more likely, due to human influence on climate.

Distribution of Temperatures

Swiss temperature series, 1864–2003



The 2003 heatwave was far outside the expected range. It was an extremely rare event:

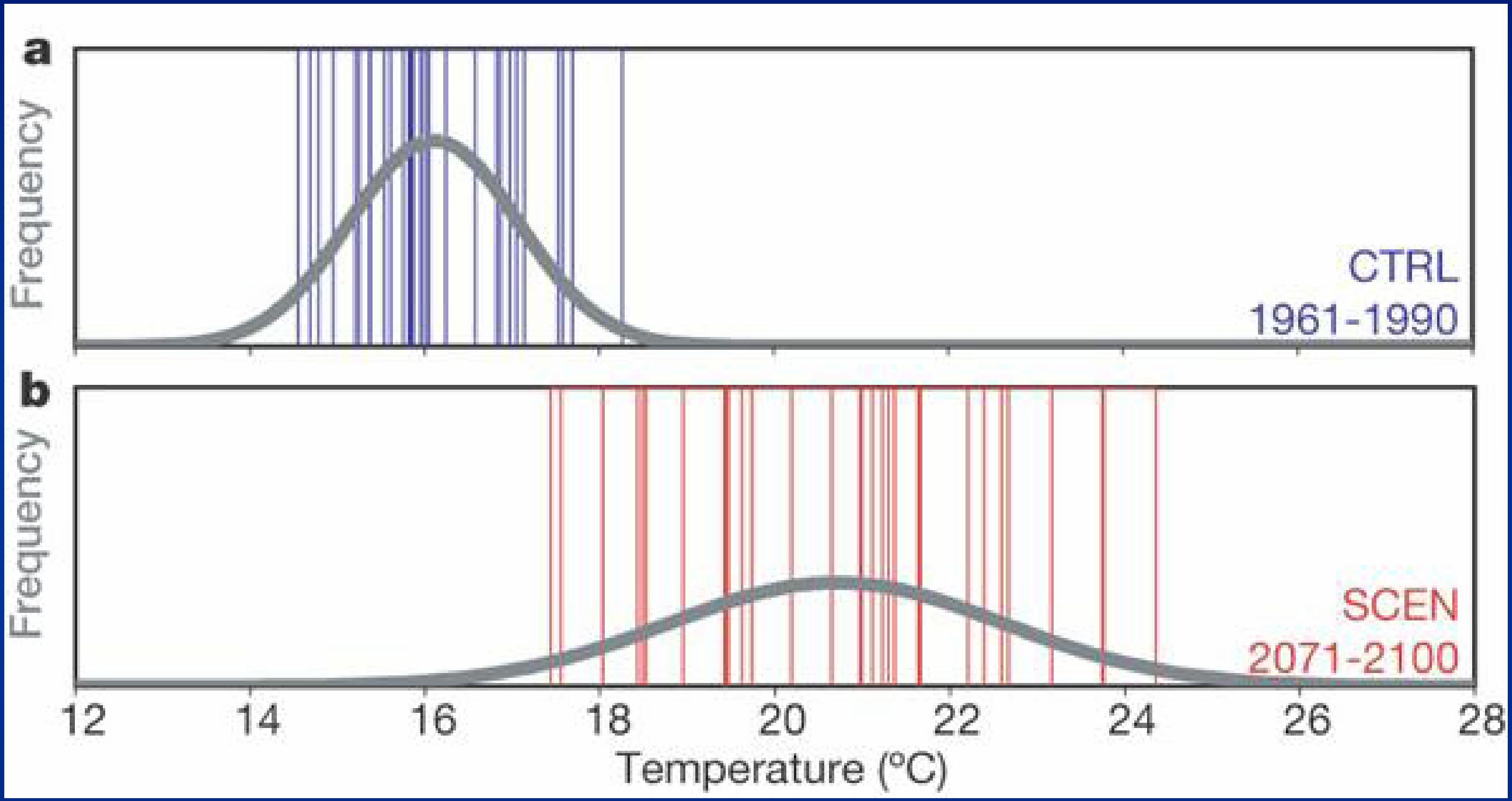
$\sigma = 0.94K$

$\Delta T = 5.4\ \sigma$

UCD DUBLIN

Predicted Change in Distribution

Both mean and standard deviation will change.



Top: Distribution in past: T = 16.1°C, σ = 0.97°C

Bottom: Distribution in future: T = 20.7°C, σ = 1.84°C

Consequences of global warming

Increased frequency of floods and droughts

Water supplies and ecosystems under threat

Agricultural practices will have to change

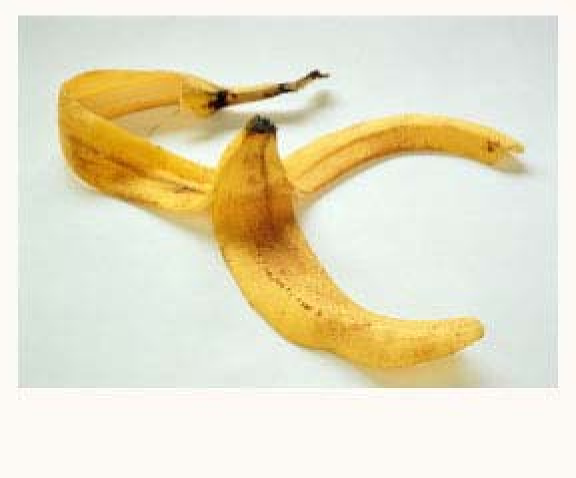
Millions of people displaced as the sea rises

Global economy severely affected.

Why trust climate models?

- Based on established laws of physics
- Embody our best knowledge about the interactions and feedback mechanisms
- Forecast weather skilfully over days ahead
- Reproduce the current worldwide climate
- Simulate ice ages & Holocene warm period.

Surprises



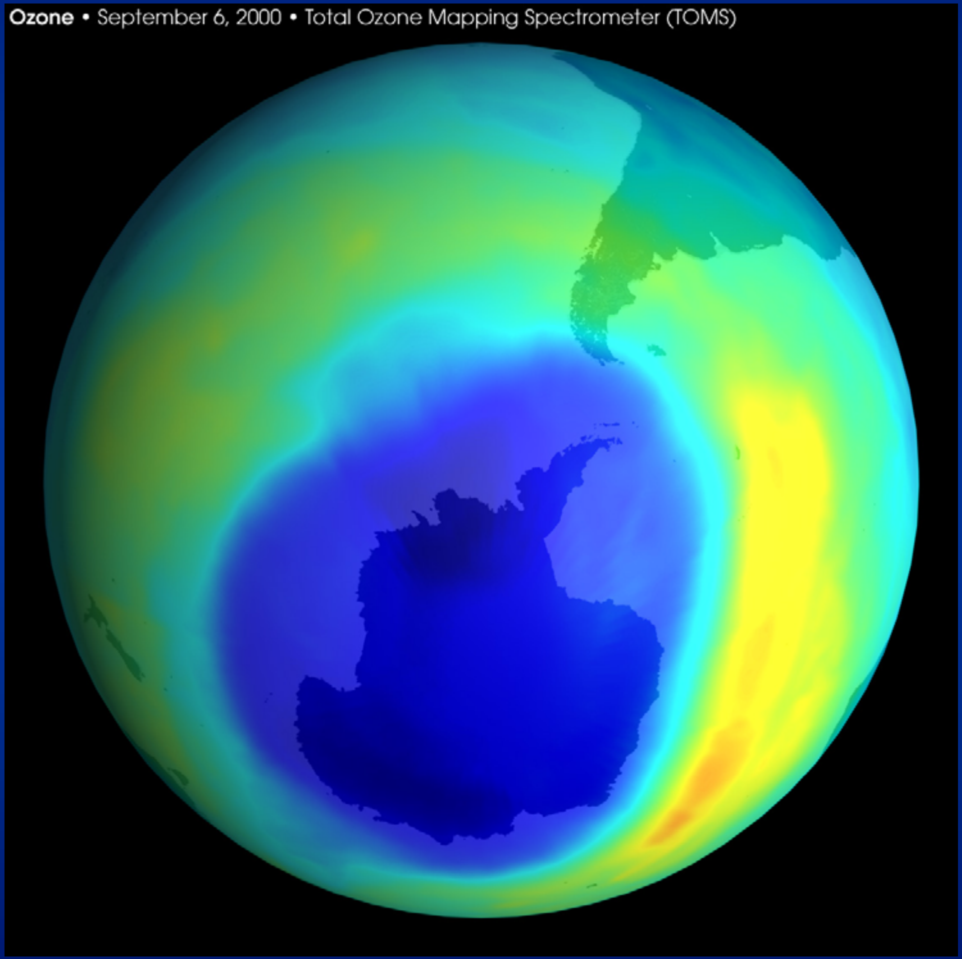
It is very likely that we will be unpleasantly surprised by factors unforeseen.

Let us call such events
<u>Unanticipated Emergent Phenomena</u>

"UEPs"

The term "Banana Skins" does not have sufficient academic gravitas.

A UEP: The Ozone Hole



The Ozone Hole was **not Anticipated**

Initial response was **disbelief**

It was explained **after the event !**

Nonlinear systems: bifurcations.

Example:
Hurricanes require
SST > 26˚C

If SST were everywhere below 26˚C,
we would not know about hurricanes

Atmospheric systems we have yet to dream of may be possible

Positive Feedbacks

- Water vapour
- Clouds (sign uncertain !)
- Ice-albedo effect
- Carbon cycle: Death of rainforests
- CO_2 and Methane from thawing permafrost
- Methane hydrates from beneath ocean floor.

Climate out of control

If a positive feedback is not controlled, it could trigger further run-away effects

A qualitative change of climate regime cannot be ruled out.

There is an unquantifiable risk of catastrophic climate change

We face a clear challenge

- To avoid drastic changes by **minimizing production of greenhouse gases**
- To develop responsible **mitigation** and **adaptation** policies
- To avoid reaching a "tipping-point" where a **UEP** will get us.

Thank you

We have nowhere else to go!

Venus: Hot and sticky

Mars: Leaves you breathless

Jupiter: We can’t stand !