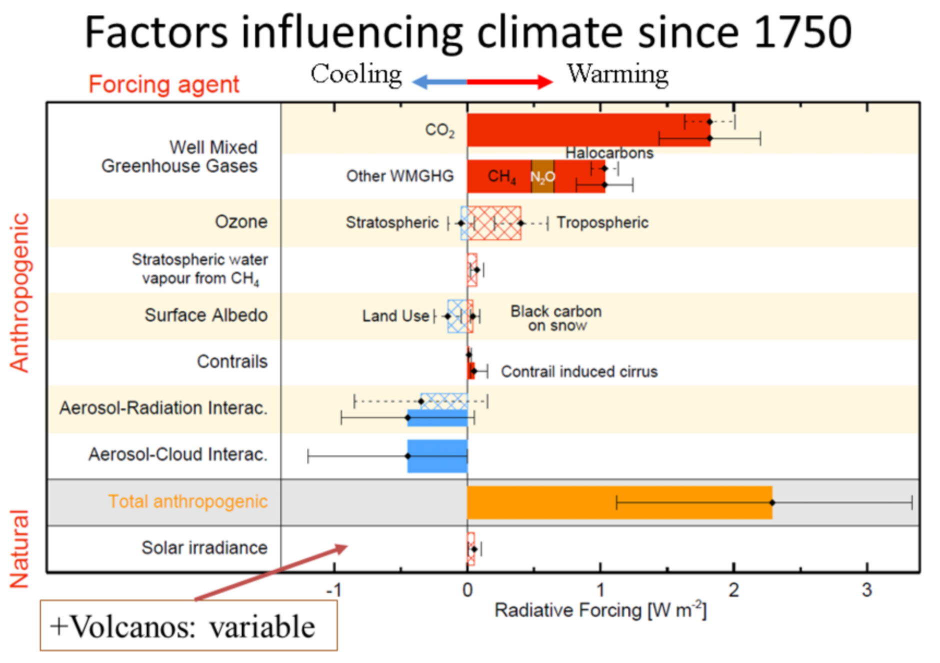
CLIMATE CHANGE:
Past, Present and Future

University of Reading

- Session 6: Predicting Climate Change
  - How can we predict climate change?
    - What determines climate?
    - What factors can cause climate change?
    - Why are super-computers invaluable in simulating the climate system?
    - Group Work
  - break
    - Climate models
    - Attribution of climate change



IPCC (2013) Figure 8.15; See also IPCC (2007) Fig. 2.20

The globally averaged net effect of human activities from 1750 to 2011 has been one of warming, with a radiative forcing of +2.29 [+1.13 to +3.33] W m^{-2} [IPCC 2013 SPM]. This includes the strong warming effect of greenhouse gases (CO_2, CH_4, N_2O, CFCs, HCFCs…), including low level ozone, and black carbon aerosols. The heating is partially offset by cooling, primarily from Sulphate aerosols, including their direct effect and indirect influence on clouds, but also including modified surface reflectance (albedo) from land use changes and a small net cooling effect from stratospheric ozone depletion. Changes in solar radiation have contributed only very slightly to this anthropogenic warming. The most uncertain radiative forcing agents are the cooling effect from Sulphate aerosols.

How do we predict climate change?

- Need to know what processes are important for determining the present day and past climate change
- What factors are potentially important for changing climate?
  - FORCINGS (e.g. solar output)
  - FEEDBACKS (e.g. ice-albedo)

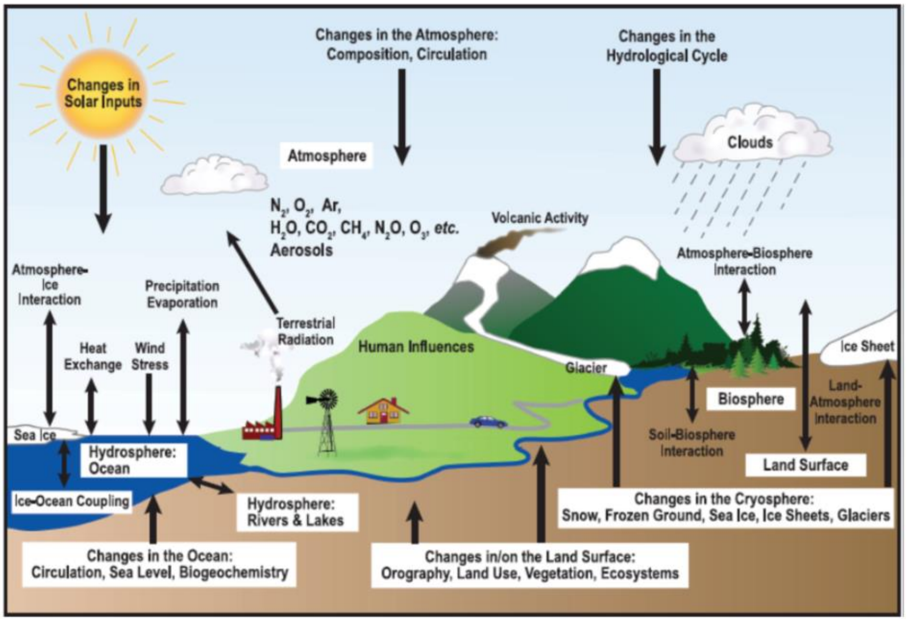
If one wishes to understand, detect and eventually predict the human influence on climate, one needs to understand the system that determines the climate of the Earth and of the processes that lead to climate change.

Clouds affect radiation fluxes

Radiation fluxes affect clouds

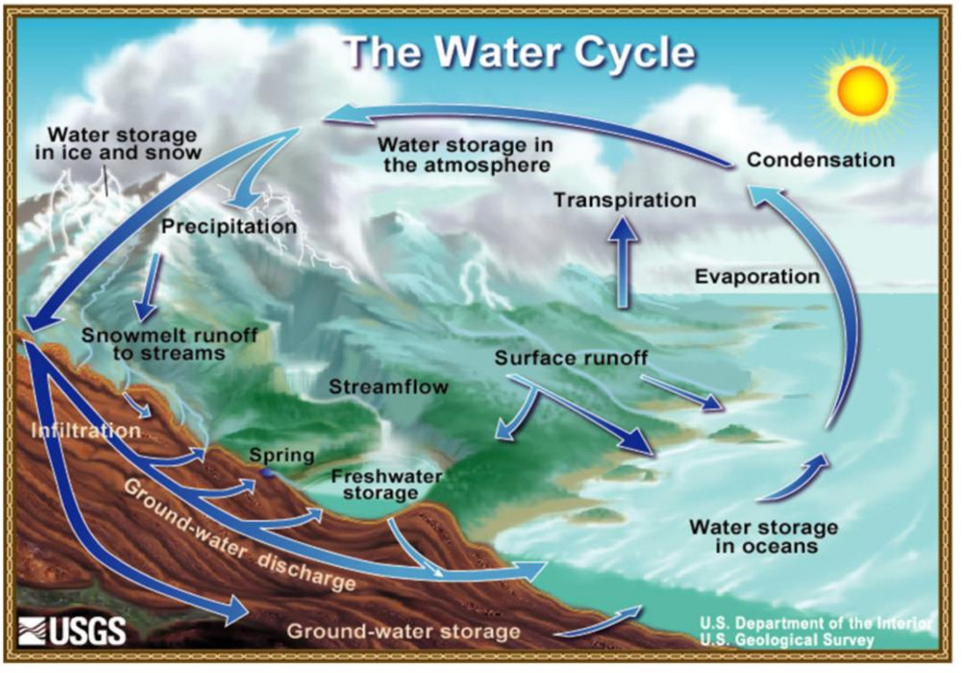
Clouds scatter sunlight and absorb and re-emit infra-red radiation so therefore can influence the surface temperature through heating or cooling effects. Surface temperature can also affect clouds through altering the stability of the atmosphere for example. This means that feedbacks are possible in which changes in surface temperature are either amplified dampened down by the effect of clouds. If clouds respond to a changes in surface temperature, they will alter the energy balance either to add to the temperature change or counteract it. This is an example of a feedback process (akin to the amplification of electronic signals such that you get feedback when the microphone is too close to the speakers).

The Climate System



The Earth's climate is an interactive system consisting of five major components: the atmosphere, the hydrosphere (liquid water), the cryosphere (ice/snow), the land surface and the biosphere. These are all forced or influenced by various external forcing mechanisms, the most important of which is the Sun.

Many physical, chemical and biological interaction processes occur among the various components of the climate system on a wide range of space and time scales, making the system extremely complex. Although the components of the climate system are very different in their composition, physical and chemical properties, structure and behaviour, they are all linked by fluxes of mass, heat and momentum: all subsystems are open and interrelated.



The balance between the solar heating and longwave radiative cooling across the planet lead to a circulation of the atmosphere and ocean which further modify the radiation balance. These two factors, combined with the distribution of land and oceans and the rotation of the Earth, generate our weather patterns, the characteristics of which when sampled over many years describe the climate zones on Earth. Understanding how our weather patterns are caused involves detailed representation of all the component parts of the climate system and how they interact with one another; this understanding is crucial in being able to predict climate change. One of the most important involves the global cycle of water, from evaporation over the ocean, transport in the gaseous phase of water vapour through the atmosphere, condensation as water droplets (or ice formation) and precipitation (including rain, snow, hail, etc) to the surface and transport across the surface through rivers or glaciers eventually back to the oceans.

What determines climate change?

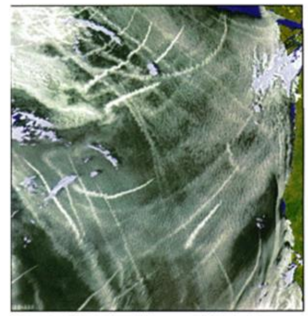


Figure 1: Ship tracks off the coast of Washington

- **Radiative Energy Balance**
  - Natural factors:
    - sun, volcanic eruptions,
  - Anthropogenic (man-made) impacts:
    - Greenhouse gas emission, land use change,
- Indirect effects
  - e.g. emission of smoke from ships produce condensation nuclei that change the impact of clouds
- Internal (random) variations
  - Changes in ocean circulation that are not caused by any external forcing (e.g. changes in the sun)

Any change, whether natural or anthropogenic, in the components of the climate system and their interactions, or in the external forcing, may result in climate variations.

How do we predict climate change using models?

- What is a model?
  - "A representation of a system that allows for investigation of the properties of the system and prediction of future outcomes."
  - "**Model**, **models**, or **modelling** may refer to: a pattern, plan, representation, or description designed to show the structure or workings of an object, system, or concept" (Wikipedia).
- What is a prediction?

Models can be statistical or physical or a combination. e.g. estimate temperature based on past statistics **OR** Estimate temperature based upon physics or atmosphere and some starting observations

- e.g. weather forecasts; other examples: business model, economic model, engineering

A climate model is a simplified representation of the Earth and all its component parts. The strengths of using a computer model are the relative speed of computation and the ability to deconstruct the workings of the system into its component parts, thereby aiding understanding. Although these models are based on physics combined with observations of the real world, they are only approximations and constantly require checking to see that their predictions are physically sensible. A climate model can range from a simple "zero dimensional" energy balance model (e.g. Arrhenius) up to a fully coupled atmosphere-ocean-biosphere model (e.g. Hadley Centre models).

Simple models?

$$\Delta F = \alpha \ln(C/C_0)$$

- Svente **Arrhenius** estimated the effect of changes in "carbonic acid" (CO_2) on the ground temperature
- **Milankovitch**: estimated surface temperature based on calculated solar radiation changes
- Simple models good for simple systems; many aspects of the Earth's climate system are not simple….

- How can we represent all the components of the climate system?

In 1895, Arrhenius presented a paper to the Stockholm Physical Society titled, "On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground." This article described an energy budget model that considered the radiative effects of carbon dioxide (carbonic acid) and water vapour on the surface temperature of the Earth, and variations in atmospheric carbon dioxide concentrations. These are still used today but contrasting types and complexities of models are used to tackle different questions.

The beginnings of Numerical Weather Prediction (NWP)

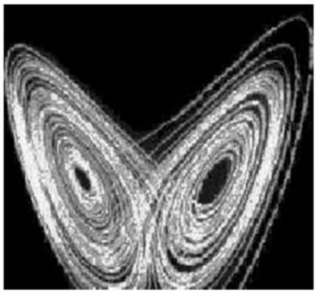
- L.F. **Richardson** (1881-1953)
  - Proposed scheme for weather forecasting based on solving theoretical equations (1922)
  - Envisaged room full of people (who he termed “computers” or “calculators”!) all calculating and passing their results to neighbouring “computers”
  - This was before the invention of the calculators and computers we know today
- Computer models (*simulators*) of weather and climate use these basic equations to move air around the planet in response to the radiative energy balance
  - In addition to simulating weather patterns, the entire environment must also be encapsulated including the ocean, land surface, ice sheets, global water cycle, etc

Weather Prediction by Numerical Process: In 1922, suitable fast computing was unavailable. Richardson described his ideas thus :-

“After so much hard reasoning, may one play with a fantasy? Imagine a large hall like a theatre, except that the circles and galleries go right round through the space usually occupied by the stage. The walls of this chamber are painted to form a map of the globe. The ceiling represents the north polar regions, England is in the gallery, the tropics in the upper circle, Australia on the dress circle and the antarctic in the pit.

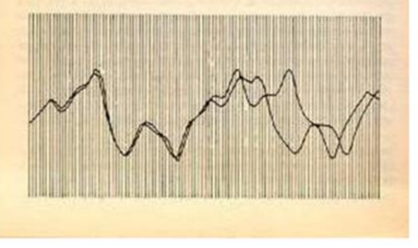
A myriad computers are at work upon the weather of the part of the map where each sits, but each computer attends only to one equation or part of an equation. The work of each region is coordinated by an official of higher rank. Numerous little "night signs" display the instantaneous values so that neighbouring computers can read them. Each number is thus displayed in three adjacent zones so as to maintain communication to the North and South on the map…..” (Richardson 1922)

The butterfly effect



e.g. *Chaos – James Gleick*

- Edward Lorenz
  - Mathematician with keen interest in weather
  - 1961: Developed primitive computer weather model



From Lorenz's 1961 printouts

Edward Lorenz pioneered chaos theory (although did not coin the phrase). He used a primitive computer model to simulate wave like patterns in the atmosphere, corresponding to our weather and found that minute variations in the initial values of variables in his three variable computer weather model (c. 1960) would result in grossly divergent weather patterns. This sensitive dependence on initial conditions came to be known as the butterfly effect. While chaotic weather patterns are difficult to predict beyond 10 days, changes in mean conditions are potentially more predictable since they depend not so much on the initial conditions but more on the physical processes, such as cloud physics.

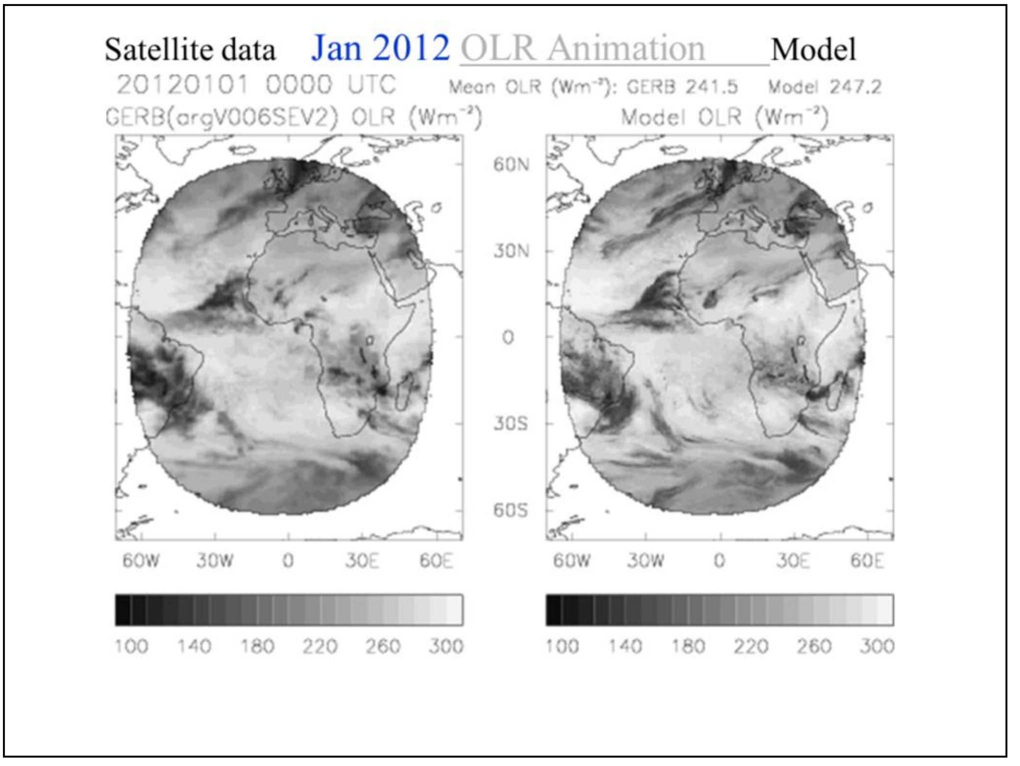
Numerical Weather prediction models

- Based on physical laws + approximations
  - Run forecasts from initial conditions (observations)
  - Represent components of the Earth's environment using a series of mathematical equations, loops and logical operators (if X then Y)
  - Millions of lines of computer code (language)!
- Must build these processes into complex simulators of the climate system
  - Climate models similar to weather forecast computer models but with more components of climate system
- Models are developed, evaluated and improved by comparing with observations

Approximating the basic equations of the atmosphere in computer code allows the huge amount of computational power to calculate the motions of the atmosphere and approximate the (known) important processes of the Earth-atmosphere system.

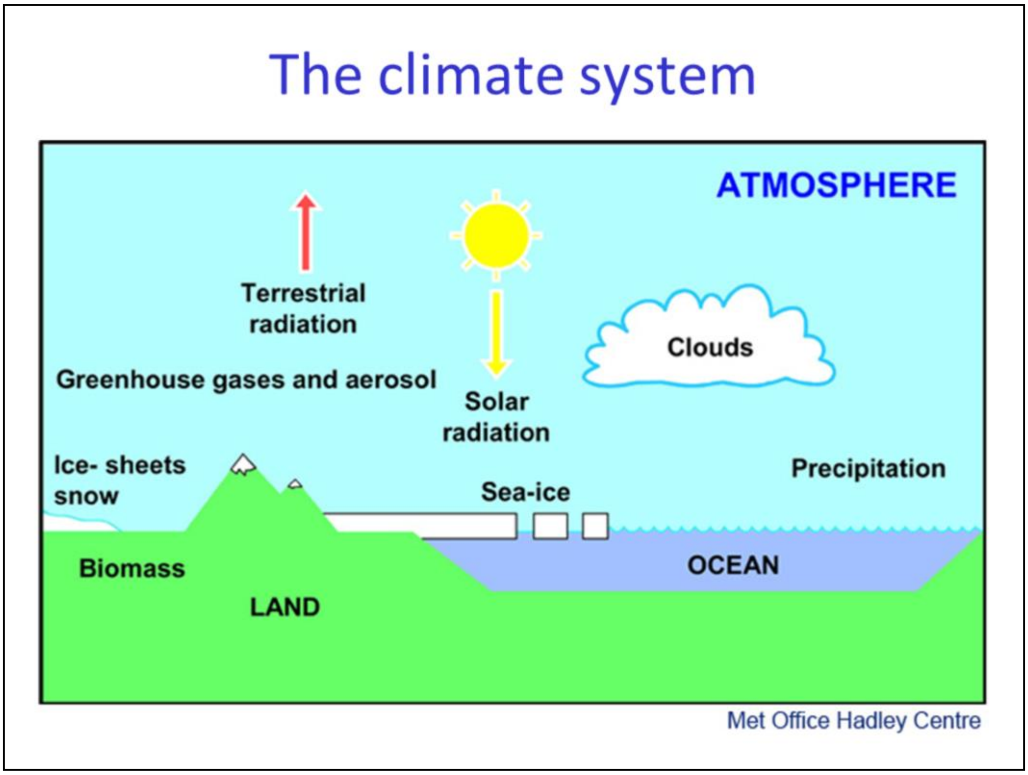
In Numerical Weather Prediction, a key to achieving accurate predictions is, in addition to resolving as many of the important processes as practicable, to prescribe accurate initial conditions. This is achieved by assimilating all the best observational data in near-real time.

In other words, if you start your forecast off with inaccurate weather patterns, the forecast will be poor. Combining the model global coverage with observations to create an accurate start point ensures the best possible forecasts. If the model is poor, the forecasts will quickly become poor.

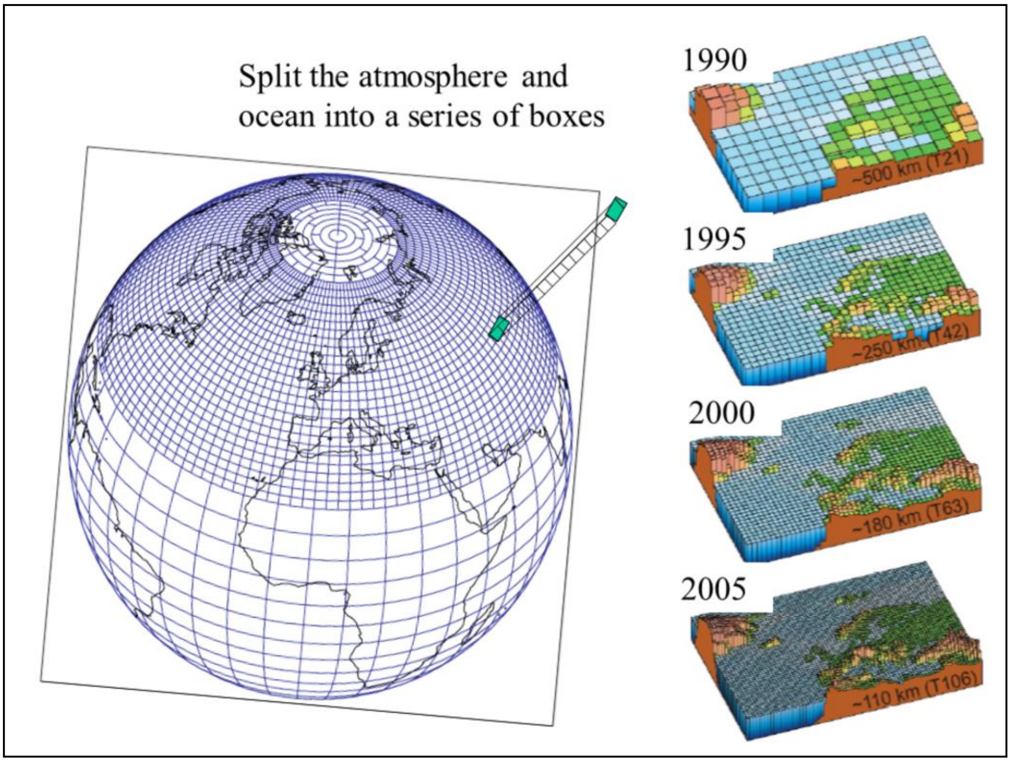


Sophisticated computer models have been developed by thousands of scientists over periods of decades that approximate the important components of the Earth's environment. These models are used to forecast weather evolution and predict how changes in natural and man-made influences on the environment alter future climate.

The animation (click on "OLR Animation") showed that weather forecast models are good at representing the large weather systems at middle latitudes but are not so good at resolving the convective processes in the tropics which are acting at smaller spatial scales than can easily be resolved in global models.

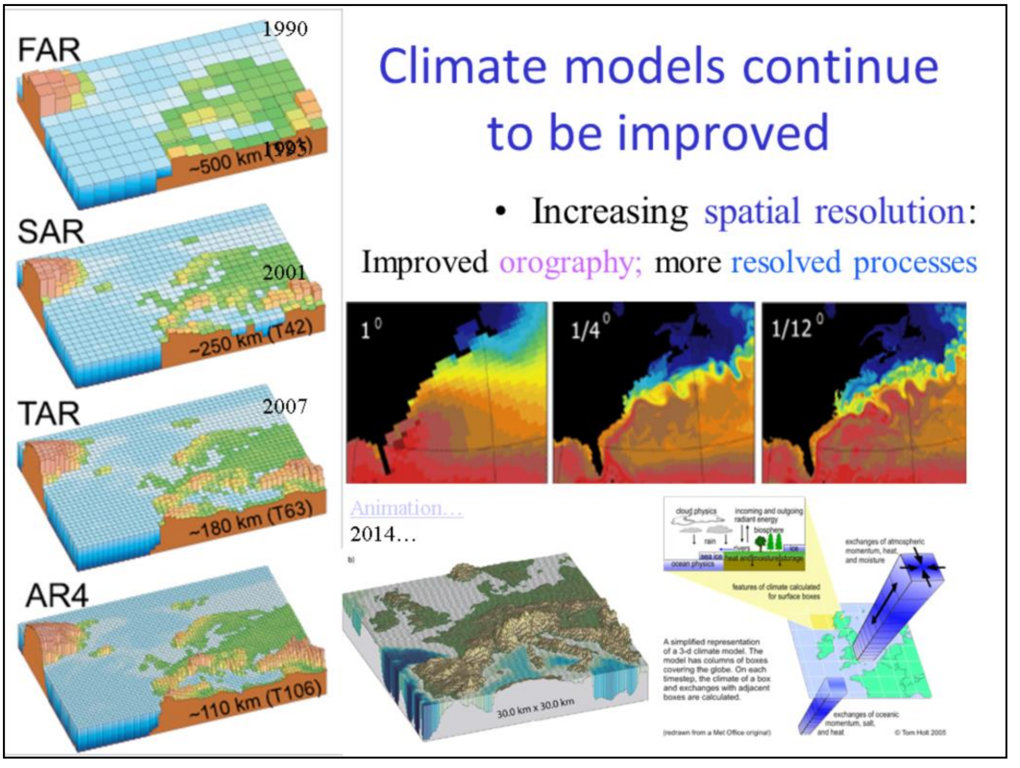


In order to estimate climate change, we have to build a mathematical model of the complete climate system. Firstly, the atmosphere; the way it circulates, the processes that go on in it, such as the formation of clouds and the passage of terrestrial and solar radiation through it. Secondly, the ocean, because there is a constant exchange of heat, momentum and water vapour between the ocean and atmosphere and because in the ocean there are very large currents which act to transport heat and salt. In fact, the ocean does about half the work of the climate system in transporting heat between the equator and the poles. Thirdly, the land, because it affects the flow of air over it, and is important in the hydrological (water) cycle. In addition, we model the cryosphere; ice on land and sea. All of these components of the climate system interact to produce the feedbacks which determine how climate will change in the future.

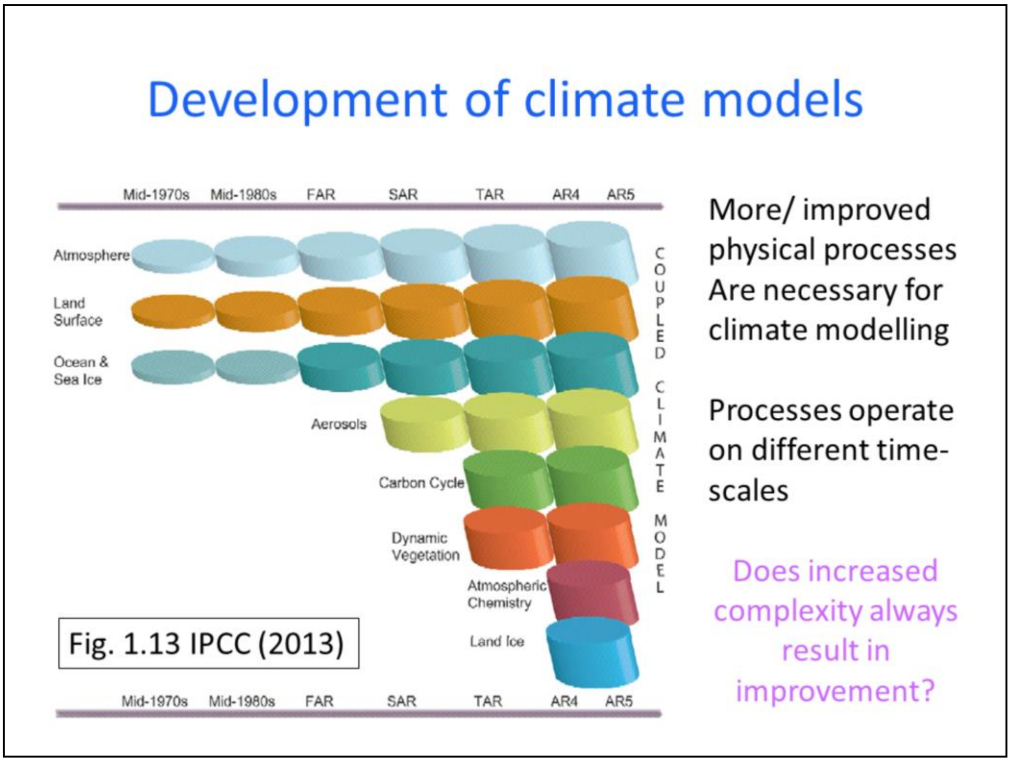


The climate model is a mathematical description of the Earth's climate system, broken into a number of grid boxes and levels in the atmosphere, ocean and land, as shown above. At each of these grid points in the atmosphere (for example) equations are solved which describe the large-scale balances of momentum, heat and moisture. Similar equations are solved for the ocean.

Processes such as convective storms are smaller than the model grid boxes and so must be approximated using "parametrizations". These parametrizations are developed and tested using observations and also finer scale models such as cloud resolving models.

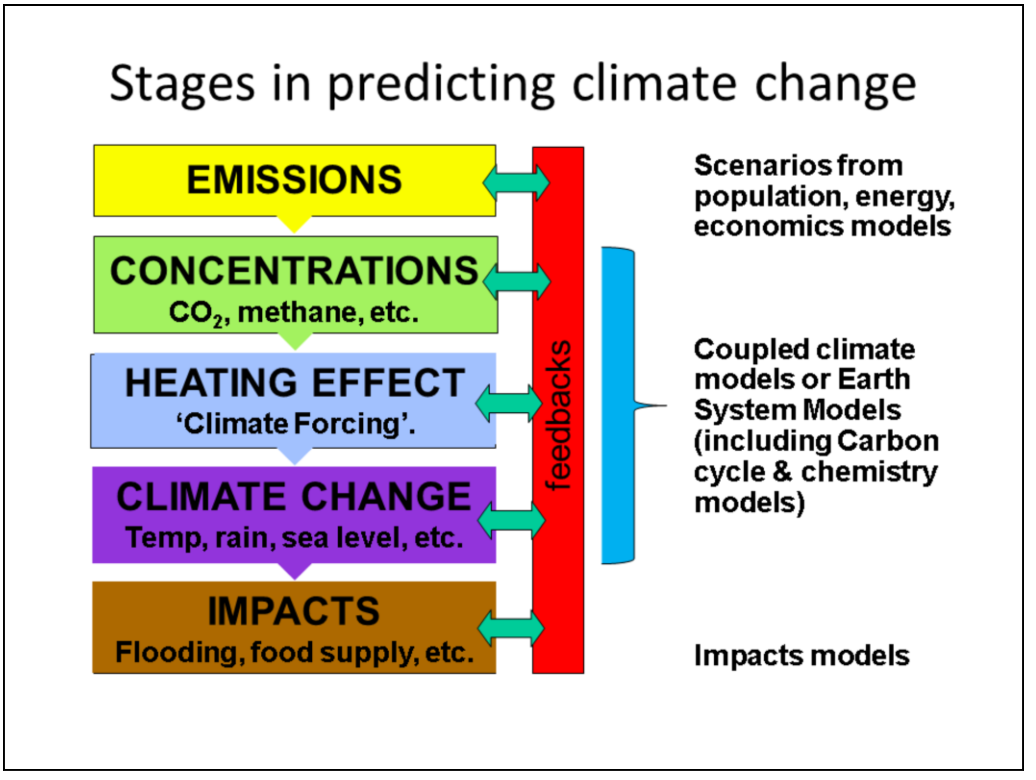


The atmospheric part of the third Met Office Hadley Centre coupled ocean-atmosphere climate model, HadGEM2 has a grid of 1.25° latitude x 1.875° longitude, and has 60 vertical levels in the atmosphere. The ocean model has 40 vertical levels and a grid size of 1° latitude x longitude up to 1/3°. In all, there are over ten million grid points in the model (atmosphere and ocean with more in the soil and ice sheets). At each of these grid points equations are solved every model time step (about 15 minutes) throughout a model experiment which may last 250 or, in some cases, 1000 years. The latest version (HadGEM3) is run at a higher resolution. It isn't necessarily better though! Regional models run at much higher space resolution but due to the computational cost, it is difficult to run these globally at present.

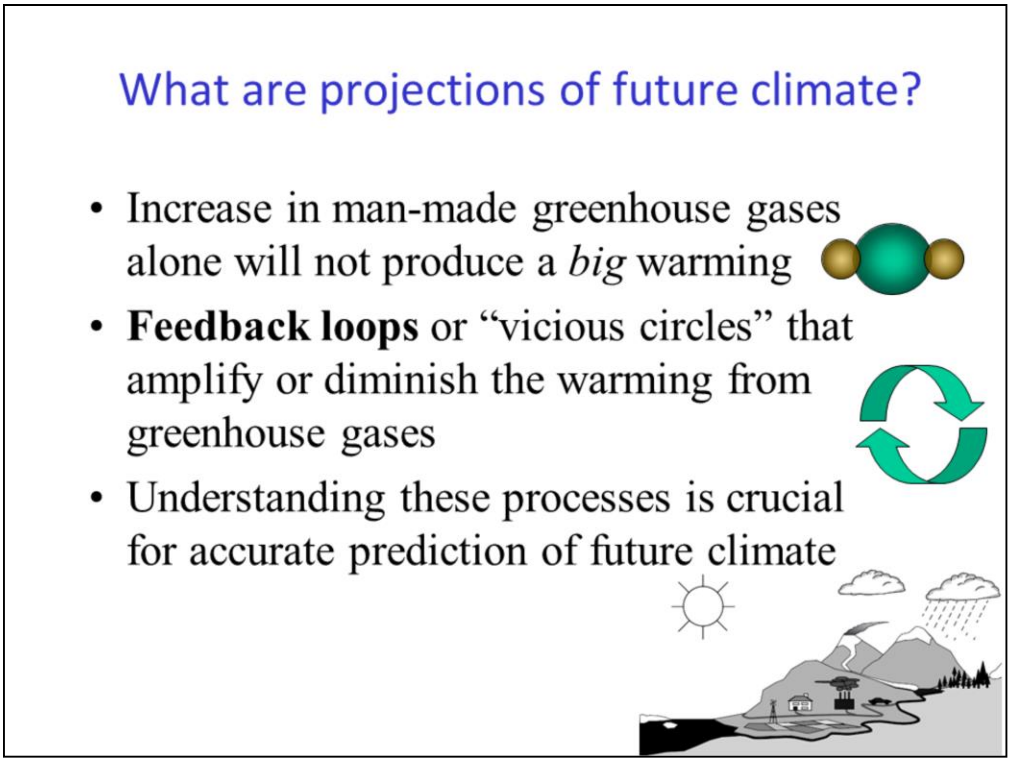


Comprehensive climate models are based on physical laws represented by mathematical equations that are solved using a three-dimensional grid over the globe. For climate simulation, the major components of the climate system must be represented in sub-models (atmosphere, ocean, land surface, cryosphere and biosphere), along with the processes that go on within and between them.

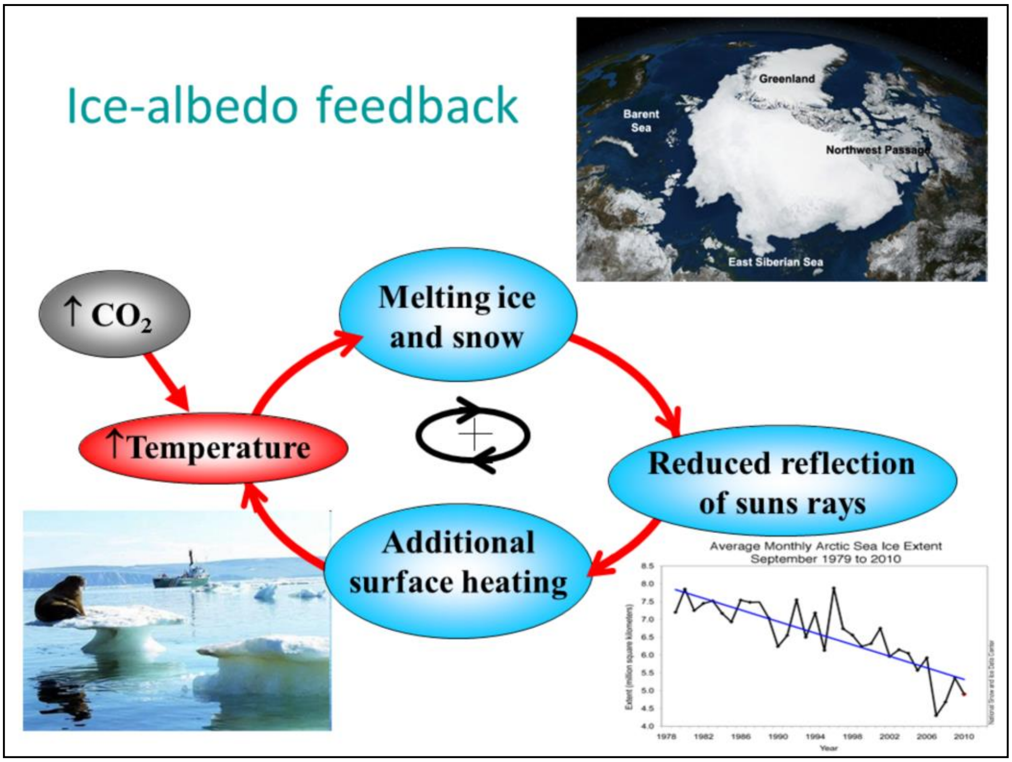
The ultimate aim is to model as much as possible of the whole of the Earth's climate system so that all the components can interact and, thus, the predictions of climate change will continuously take into account the effect of feedbacks among components. The Figure above shows the past, present and possible future evolution of climate models.



How much the climate will change in the future depends upon two factors: how much greenhouse gas emissions grow, and how sensitive the climate system is to these emissions. The rate of climate change is also determined by these factors and how rapidly heat is up-taken by the deep oceans. We predict future climate change in a number of stages, shown above. Projections of future emissions are deduced from separate models which take into account population growth, energy use, economics, technological developments, and so forth. Having obtained projections of how emissions will change these emissions are applied to climate models which through physical and chemical interactions leads to a simulated 3-dimensional structure of atmospheric concentrations. The resulting heating and cooling effects will be calculated and the circulation of the atmosphere and ocean and its thermal and physical properties will respond to the heating and cooling effects. Following on from the climate change prediction, the impacts of climate change, on socio-economic sectors such as water resources, food supply and flooding, can be calculated.

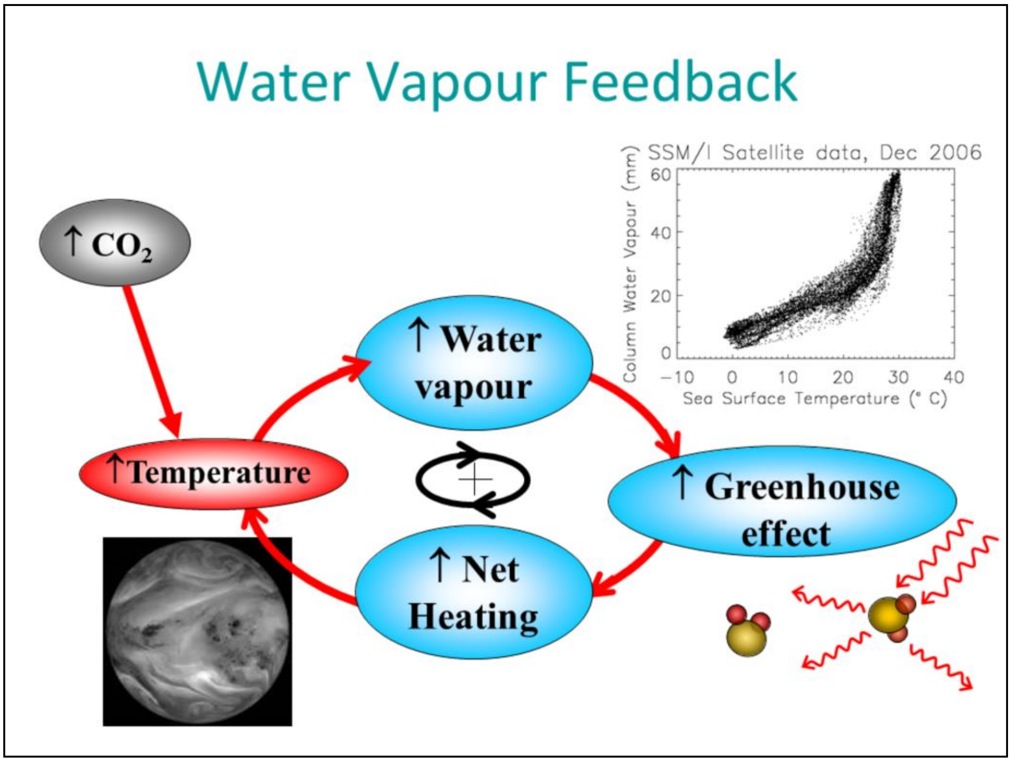


The additional heating of the climate system which would occur if the concentration of CO_2 in the atmosphere was doubled, is about 3.7 Wm^{-2} (so 3.7 additional Joules of energy for each of the 510 trillion square metres that cover the globe). In a simple world this would ultimately warm the surface by about 1 °C. The prediction of climate change is complicated by the fact that, once climate change starts, there will be consequences (vicious cycles or feedbacks) in the climate system which can act to either enhance or reduce the size of the warming.



For example, as the atmosphere and surface warms sea ice begins to melt. Some of the solar radiation which would otherwise be reflected from the sea ice is absorbed by the ocean, and heats it further. This is an example of an amplifying (or positive) feedback. It causes temperature changes (cooling or warming) to be amplified.

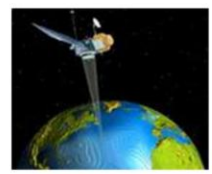
On the other hand, when carbon dioxide concentrations increase in the atmosphere then it acts to speed up the growth of plants and trees (the fertilisation effect) which in turn absorb more of the carbon dioxide; this acts as a negative feedback (it impedes the increases in atmospheric carbon dioxide).



The strongest positive (amplifying) feedback that is known to operate involves the invisible gaseous water vapour which fills the atmosphere. As the atmosphere warms it will also be able to ‘hold’ more water vapour. Water vapour itself is a very powerful greenhouse gas, and the water vapour feedback is one of the better understood and most powerful positive feedbacks which roughly doubles the amount of warming or cooling caused by a radiative forcing compared to the case in which no water vapour feedback operated.

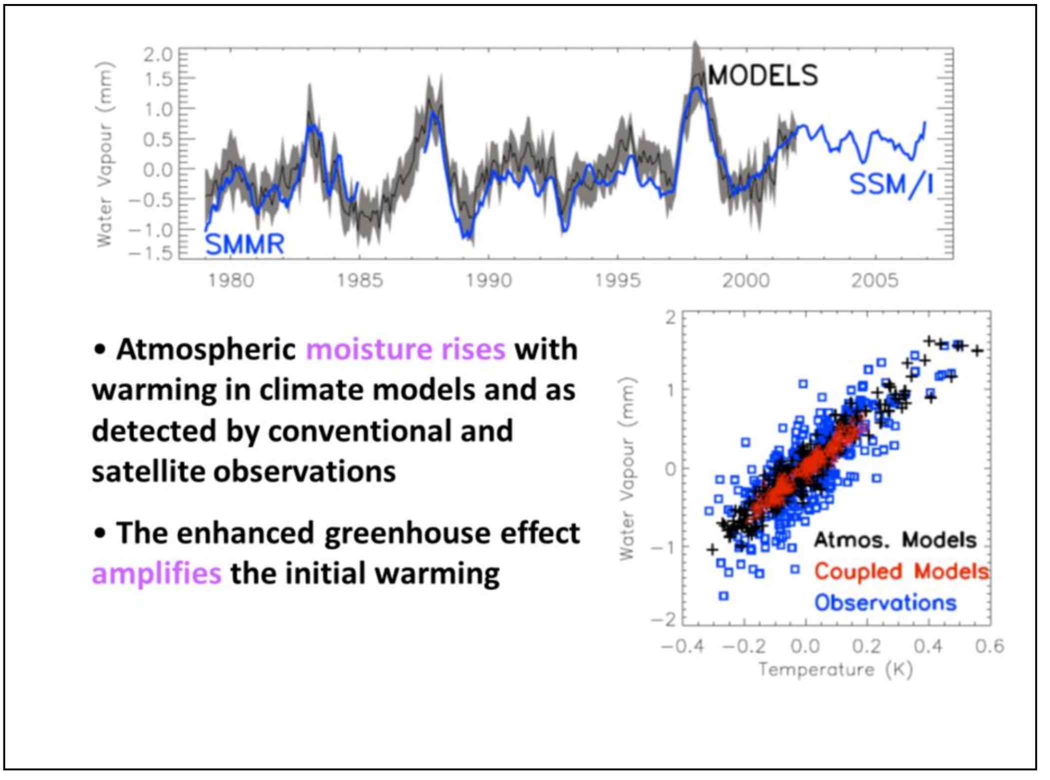
Climate models (simulators)

- Other feedbacks include
  - Ice/albedo, cloud, etc
  - Tipping points?
- Must build processes that may produce feedbacks into complex models of the climate system
- Models are developed, evaluated and improved by comparing with **observations**



There are many of these feedbacks, both positive and negative, which we do not fully understand. This lack of understanding is the main cause of the uncertainty in climate response to a particular emissions scenario of the future; this applies in particular to changes in clouds which we will return to later.

To assess the accuracy of model predictions, the realism of these feedback processes must be evaluated using observations. For example, the water vapour feedback is relatively well understood because it has been demonstrated that water vapour near the surface in the atmosphere increases by around 7% for every degrees C rise in temperatures, in line with theoretical considerations and with model projections.



Atmosphere-only and fully coupled climate models are able to reproduce the observed variations in column integrated water vapour and its dependence on surface temperature over the oceans. Integrated water vapour is a key variable since it affects:

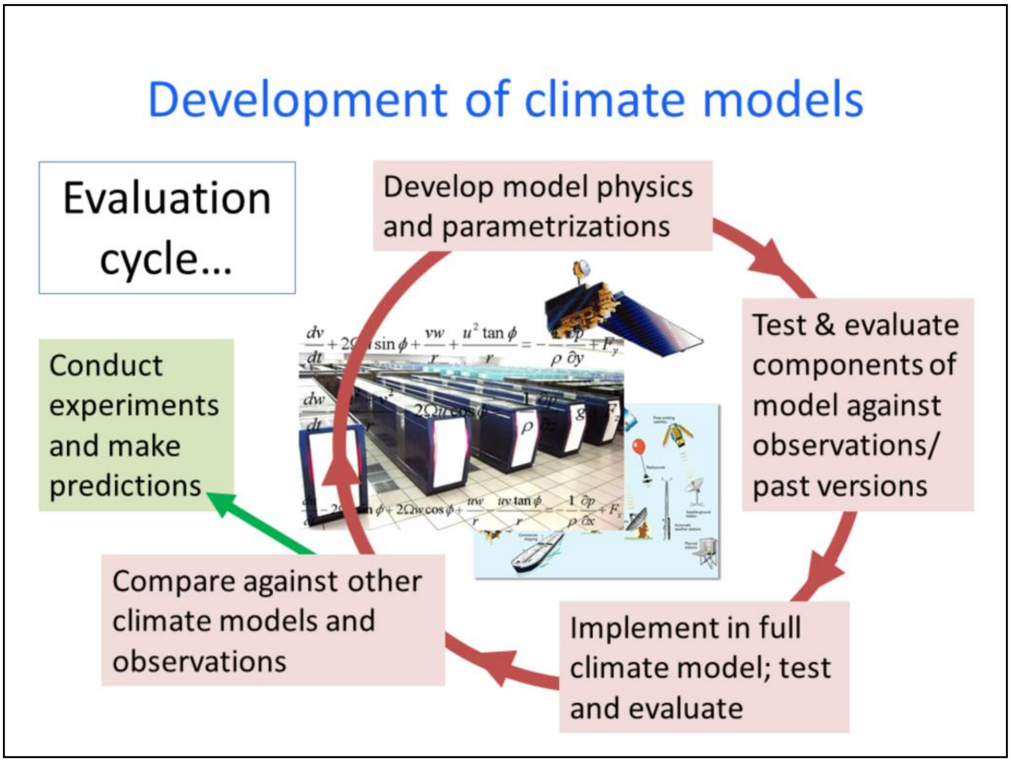
- Precipitation over convective regions

- Radiative cooling of the atmosphere to the surface

- Global precipitation through a combination of the above

- Strongly positive water vapour feedback

Column integrated water vapour is mostly determined by moisture in the lower troposphere while changes in moisture throughout the middle and upper troposphere are more important for water vapour feedback so it is important to ensure that models accurately capture changes in water vapour at these levels too.

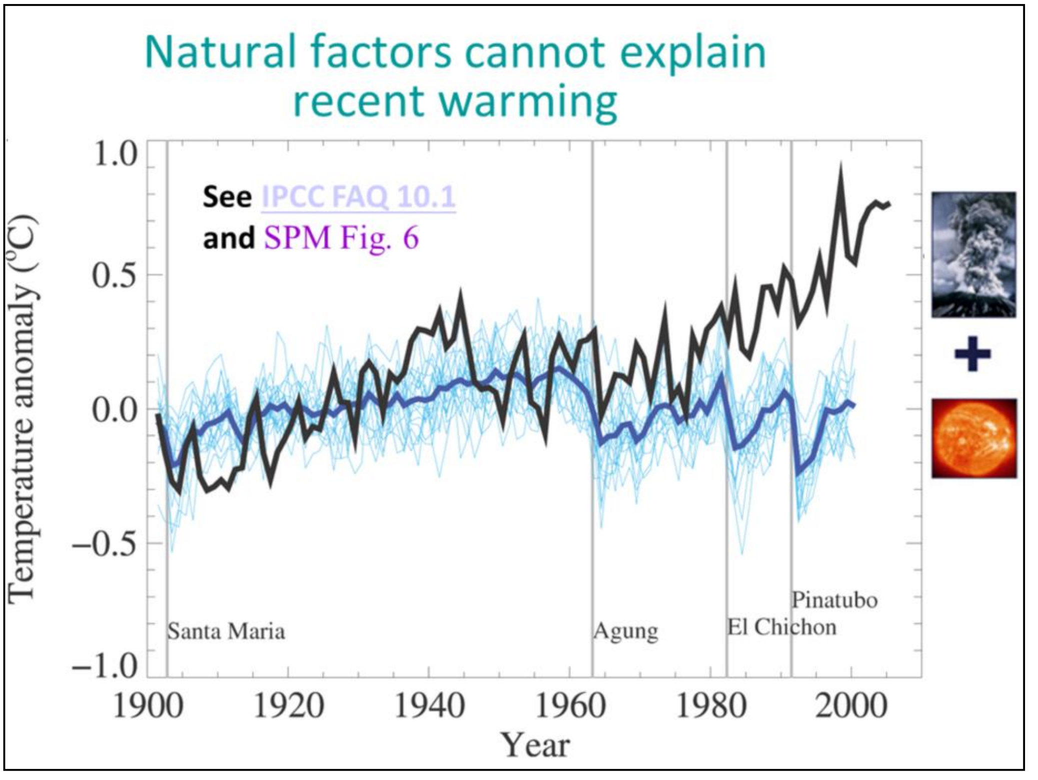


Climate models (and weather forecast models) are continually being evaluated and improved through comparisons with observations and other types of models.

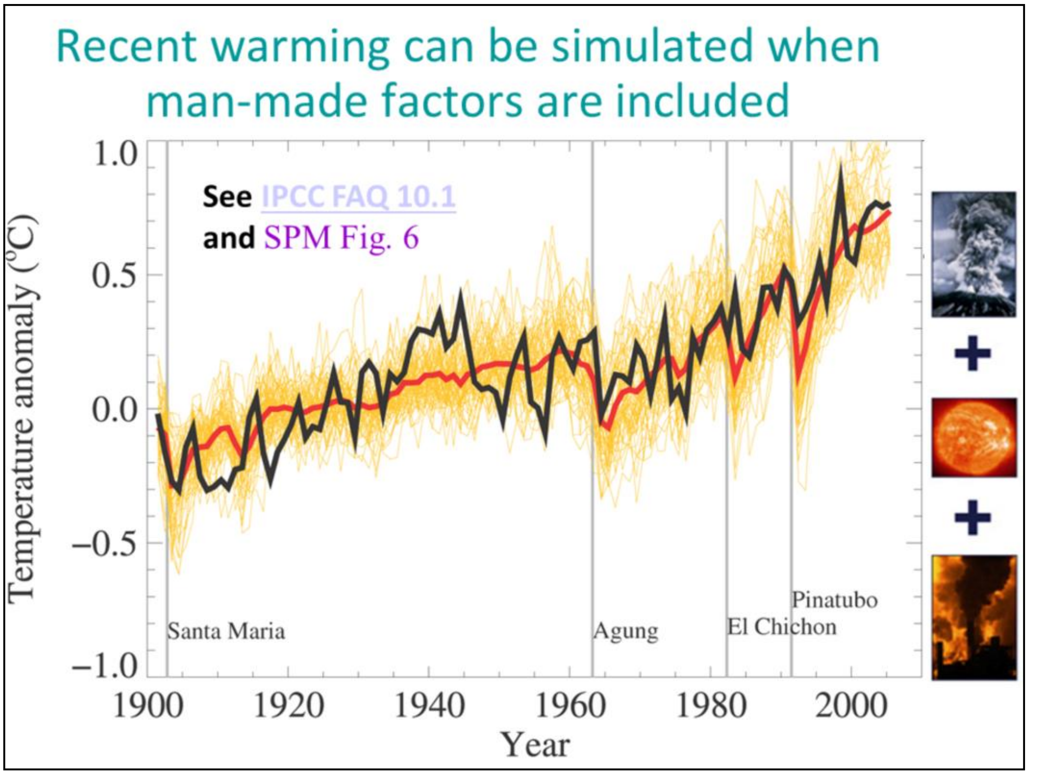
Experiments with climate models

- How much of the recent warming can be explained by natural effects?
- To answer such questions, experiments can be performed with climate simulations
- When changes in the sun and volcanic eruptions are incorporated, the climate model provides simulations of recent climate change
- What about when increased greenhouse gases are included? And sulphate aerosols?

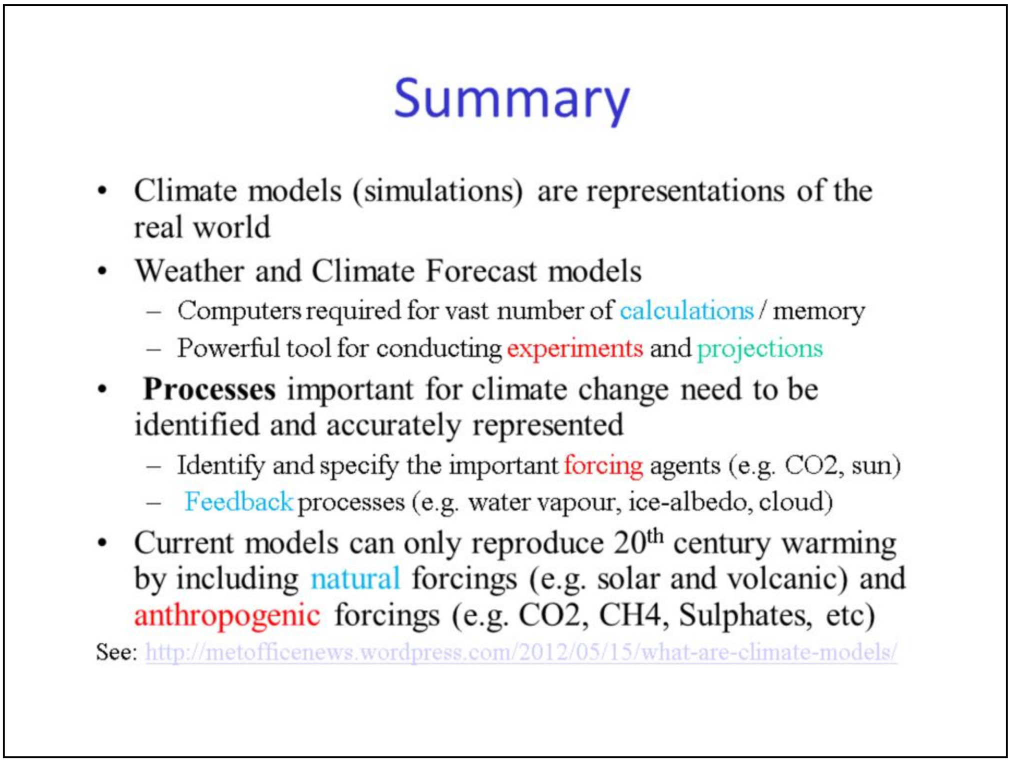
By prescribing scenarios in which atmospheric constituents change in response to human-related emissions and changes in natural forcing agents such as the sun or volcanos, experiments can be made with climate models to see how well they reproduce the past climate and then what they project for future climate.



As we have already outlined, natural factors include a chaotic variability of climate due largely to interactions between atmosphere and ocean, changes in the output of the Sun and changes in the optical depth of the atmosphere from volcanic emissions. Climate models have been driven by changes in all these natural factors, and it simulates changes in global temperature shown by the blue band in the slide above. This clearly does not agree with observations, particularly in the period since about 1970 when observed temperatures have risen by about 0.5 °C, but those simulated from natural factors have hardly changed at all.



If the climate model is now driven by changes in human-made factors — changes in greenhouse gas concentrations and sulphate particles — in addition to natural factors, observations (black) and model simulation (red/orange) are in much better agreement. In particular, the warming since about 1970 is captured. Of course, this agreement may, to some extent, be fortuitous, for example, if the heating effect of man-made greenhouse gases and the cooling effect of man-made aerosols have been overestimated. Nevertheless, the ability to simulate recent warming only when human activities are taken into account is a powerful argument for the influence of man on climate. In addition to simulating the global mean temperature, the model also simulates the pattern of changes in temperature, across the surface of the Earth and through the depth of the atmosphere. These 'fingerprints of man-made warming' have been compared to observations, providing even stronger evidence for the majority of the long-term trend over the last 50 years having been due to human activity.



Additional Material

Like weather forecast models, the “chaotic” parts of the climate system (weather, El Nino timings, ocean circulations) are sensitive to the initial conditions that are fed as input to the model. Therefore it is common, like in weather forecasting, to run lots of identical experiments with slightly different starting conditions: an ensemble. This allows the noisy parts of climate to be represented in the resulting output.

Recently another type of ensemble has become popular: Perturbed Physics Ensembles. In these ensembles, rather than starting with different initial conditions, identical models are run with slightly different physics parameters (for example how much a cloud rains for a given amount of cloud water, etc). An example of this is climateprediction.net .

Finally, a grand ensemble of completely different models are used by the IPCC to provide predictions of future climate and its likely uncertainty range.