# Introduction to Climate Modelling

## Meet 1 - What, When, How ?

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# What, When, How ?

Climate modelling has been the cradle of recent environmental mitigative steps and how we perceive the environment we live in.

There are many notions of climate models, and how mathematical and statistical models are implemented for the same. We try to answer some of those questions in this introductory presentation on CM.

## References

The lecture notes of the course 'Introduction to Climate Modelling' by Prof. T Stocker, Physikalisches Institut, Universität Bern have been a remarkable guidance and inspiration for this summary on CM.

# The Components of Climate System

The climate system is analysed in 6 different 'spheres', which correspond to varying techniques, time scales and inferences. The components, alongwith their determining processes are-

- **Atmosphere** - Weather, radiation balance, cloud formation, atmospheric flow, trace gases, tranport of heat, dust and aerosols
- **Hydrosphere** - Ocean basins, deep water turnover, carbon turnover, water currents, pressure systems, underwater springs, marine methanogens
- **Cryosphere** - All forms of ice systems like glaciers, permafrost and icebergs, albedo and radiation balance, salinity in ciritical regions
- **Lithosphere** - Positioning of continents, reflectivity of earth's surface, dust reservior, tranfer of momentum and energy
- **Biosphere** - Dynamic vegetation, $CO_2$ cycle, local gas balance, water vapour regulation
- **Anthroposhpere** - This abstraction of a climate component models the human actions that directly or indirectly affect the climate, both immediately and over the long term. Such processes can be modelled as non zero overall diffusion of gases(external forcings) in the environment

# Visualising the Components

Here is a very good pictorial representation of the various interactions between the components of the climate system.

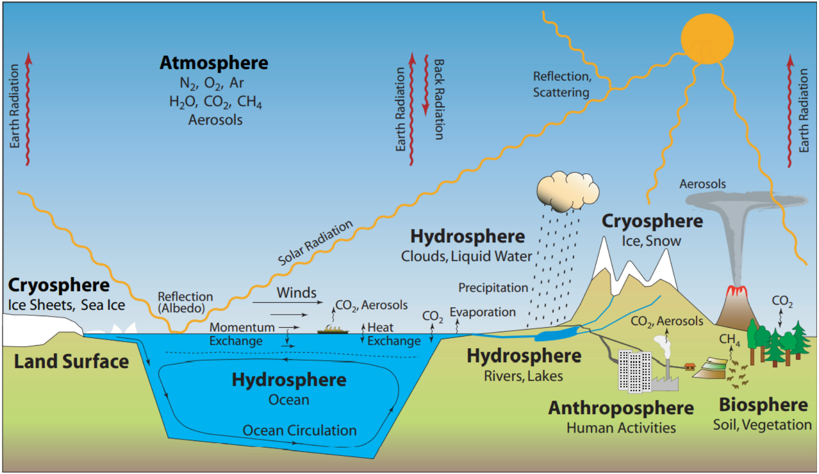


Figure: Components of the Climate

# Global Radiation Balance Model

The global radiation balance model is one of the most primitive models which tries to answer the dependence of temperature of earth from the concentrations of greehouse gases, reflectivity of earth and the assumption of Sun being the sole energy source. Some inferences-

- 341 W/m$^2$ reaches the upper atmosphere of earth (which is about a quarter of the Solar Constant $S_0$=1367 W/m$^2$
- Major parts of the shortwave spectrum is reflected back by clouds and earth's surface
- Earth emits longwave radiation due to it's own temperature, which is explained by the Stefan-Boltzmann's Law, $Q = \sigma A T^4$
- Failure to account for the greenhouse gases gives a mismatch of negative net 100 W/m$^2$
- The total net absorbed radiation after accounting for all processes is 0.9 W/m$^2$ - earth is getting warmer !!

# GRB model

The Global Radiation balance model is quantitatively summarised in the chart below -

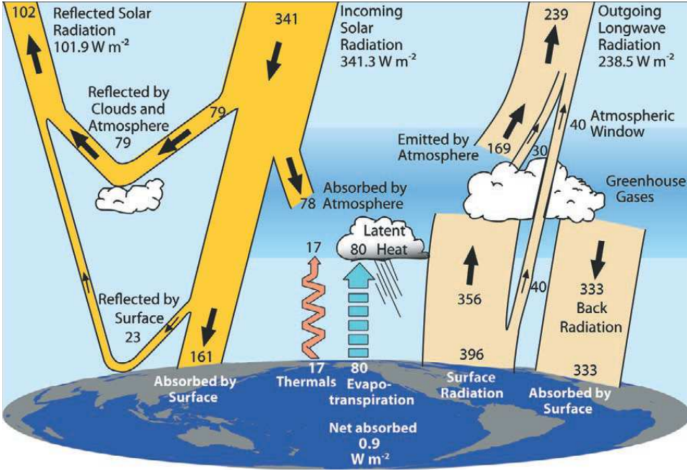


Figure: GRB Model

Climate modelling is heavily dependent on data to determine the accuracy, efficacy and judge the complexity of our model by backtesting. Observational data is available only since the last few centuries, which is not enough for modelling highly complicated algorithms with a respectable coefficient of confidence. To overcome this, experimental physicists came up with a novel technique to estimate these parameters like temperature, gas concentrations etc. by exploring the Arctic and Greenland ice reserves.

- **Paleo-Thermometer** - Scientists use this technique to analyse the temperature in historical time scales, by judging the stable isotopes trapped in stationary and isolated water bodies like ice sheets in the Arctic and Greenland.
- **Paleo-gas enclosures** - Gas voids between sheets of ice or closed ice caves give an excellent source of finding the gas concentrations, as the air in such enclosures has remained completely unaffected by the outside world, since thousands of years.
- Other sources of paleo-climatic archives are lake and ocean sediments, ice cores, tree rings, speleotherms (in calcareous caves)

The above methods of obtaining historical data for climate modelling are accurate, but they do not show the entire picture. For example, the data obtained from temperature measurement from Paleo-Thermometer indicates a temperature spike in the 10-11$^{th}$ centuries. This variability is not explained by climate models, as it was actually caused by solar flares, volcanic eruptions and dynamic vegetation changes in that time rather than

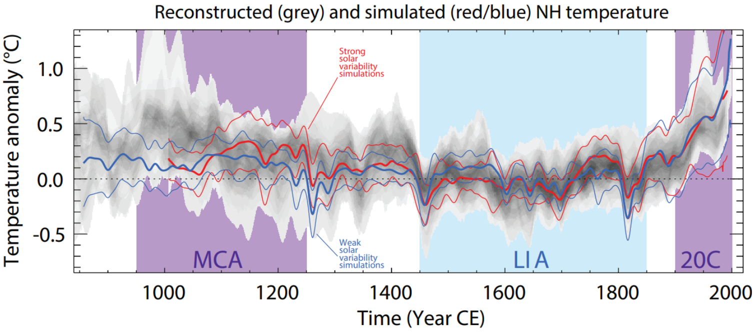


Figure: Predicted vs Observed Temperature Difference

1. **Wilhelm Bjernkes** - He realised that climate modelling and analysis is a mathematical and physical problem, and that it can be completely represented by a set of mathematical equations, and the climatic conditions can be predicted to almost sure accuracy using those conditions. He adopted the *theory of determinism* from Laplace, but was eventually proven wrong by Lorenz.
2. **Lewis Fry Richardson** - The first mathematical model for numerical analysis based pr edition of weather. He primitive mathematical formulations like the conservation of horizontal momentum, continuity equations and the ideal gas equation. This formulation was susceptible to large errors due to inaccurate initialisation of the differential equations, which eventually led to growing errors, and the often called 'Butterfly Effect'.
3. **Carl Gustav Rossby** - He introduced the idea of *conservation of vorticity*, which is a much more stringent condition than the conservation of momentum equations. The rotation of earth and the related Coriolis Forces are accounted for by this interpretation. The conservation of vorticity laws have led to prediction of hurricanes in US.

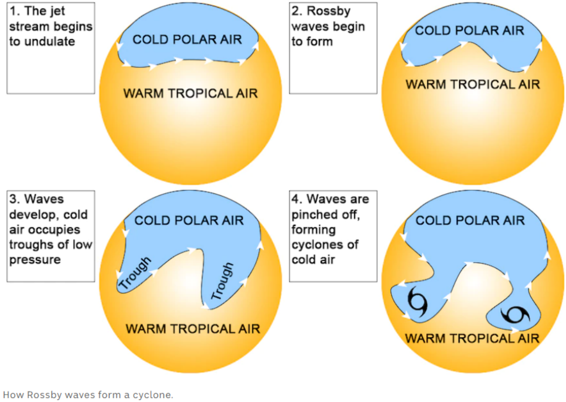


Figure: Hurricane Prediction Using Rossby Waves

- **Norman Phillips** - His remarkable research formed the way for *generalised circulation models*, which would completely solve the equations of atmospheric flow. He inculcated the idea of advection for modelling the transport of pollutants suspended in the air with the flow of winds. The operator of advection transport is- $u \cdot \nabla = u_x \frac{\partial}{\partial x} + u_y \frac{\partial}{\partial y} + u_z \frac{\partial}{\partial z}$
- **Edward Lorenz** - He advocated for the Chaos Theory, where he proposed his findings that even a small change in the initial conditions can propagate the errors over simulation time, and cause a significant error, often referred to as the *'Butterfly Effect'*. This eventually and inevitably led to the development of ensemble methods for climate modelling, which is the canon of modern research.
- **Syukuru Manake** - Found out that the oceanic and atmospheric models are inseparable for climate research. One difficulty in doing so was the different time scales of atmospheric and oceanic processes that were involved. This was overcome by incorporating a *non physical flux correction*, which has been in use for the past 30 years.

# Evolution of Climate Models

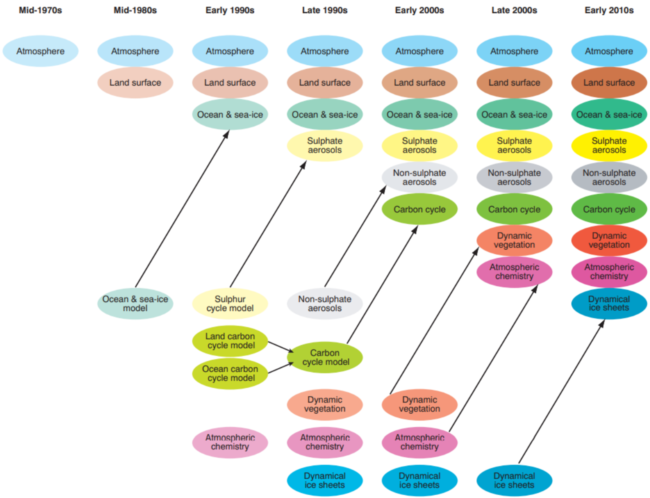


Figure: Development of Climate Models and their Complexities

# Some Further Reading on Recent Research

- Simulation of the 20th century to quantify the link between increases in atmospheric CO2 concentrations and changes in temperature
- Decrease in Arctic sea ice cover since around 1960
- Summer temperatures in Europe towards the end of the 21st century
- CO2 emissions permitted for prescribed atmospheric concentration paths
- Prediction of the weak El Niño of 2002/2003

# Conclusions and Further Goals

Research developing and using climate models has become interdisciplinary and comprises domains of physics (thermodynamics, fluid dynamics, atmospheric physics, oceanography), chemistry (organic, inorganic and surface chemistry, reaction kinetics, geochemistry, cycles of carbon, nitrogen, etc.) and biology (vegetation dynamics, ecology).

## UNFCCC Goals

Article 2: The ultimate objective of this Convention and any related legal instruments that the Conference of the Parties may adopt is to achieve, in accordance with the relevant provisions of the Convention, stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner.