# La modelización del sistema climático: realidades y perspectivas

**Maria Noguer**

Cambio Climático en la Europa Mediterránea
(Barcelona 8-9 Noviembre 2007)

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## Or….

Retos científicos y computacionales en el entendimiento y predicción de la vida futura de la tierra


Nuevo enfoque en la modelización climática

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## New era in climate system modelling

**IPCC AR4**

before

- Reproduce historical trends
- Prove climate change is occurring
- SRES scenarios – predictions

after

- Asses impacts
- Mitigations options
- Test adaptation strategies
- Look at regional detail
- Earth System Models

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## Outline

- State of the art – 2 results from IPCC AR4
- What is a climate model?
- Developing climate models
- Predicting climate – Uncertainties
- Competing demands – complexity, resolution, ensembles
- Earth observations
- Future research challenges

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Key results from IPCC AR4 – where we are now

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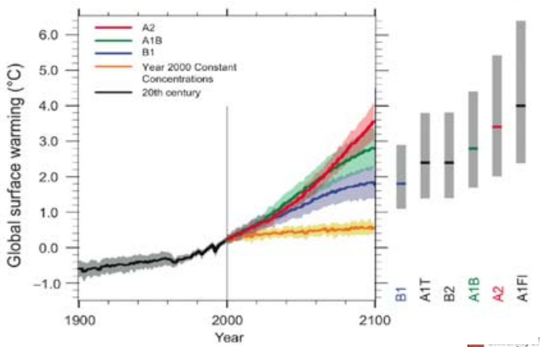
## Projections of 21st century climate

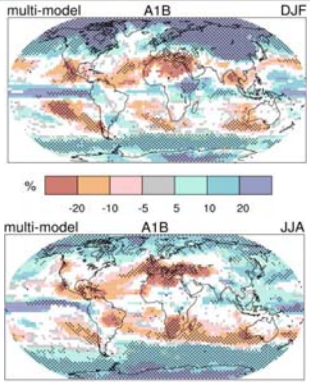



IPCC AR4

## Global warming perturbs the water cycle very profoundly

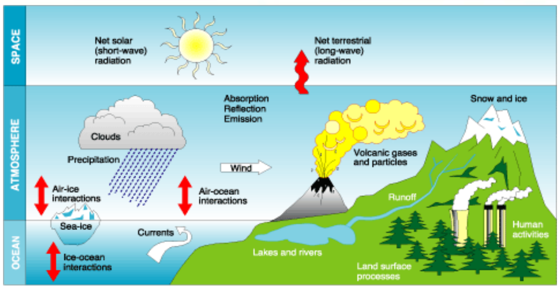
**IPCC 4th Assessment Report: Projections of likely shifts in rainfall patterns**

- % change in rainfall by end of 21st century, where more than 2/3 of the models agree on the sign of the change.
- White areas denote regions where no consistent signal is predicted e.g. Africa.




## What is a climate model?

## Models contain all the components of the climate system




They consider all the possible influences on climate including human behaviour and our response to climate change.

## Fundamentals of climate modelling

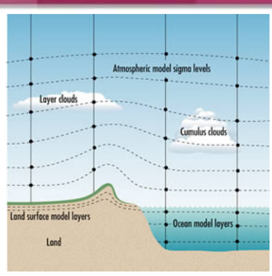
**Climate Models** are huge computer codes based on **fundamental** mathematical equations of motion, thermodynamics and radiative transfer

*These govern:*

- Flow of air and water - winds in the atmosphere, currents in the ocean.
- Exchange of heat between the atmosphere and the earth's surface
- Release of latent heat by condensation during the formation of clouds and raindrops
- Absorption of sunshine and emission of thermal (infra-red) radiation

**Climate models are extensions of weather forecast models**

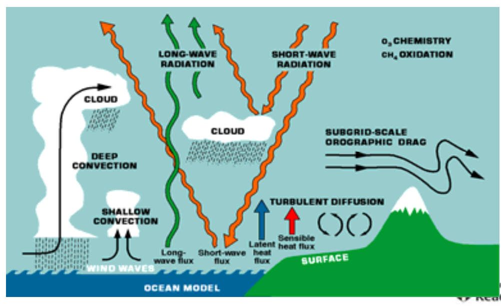
## Fundamentals of climate modelling




- To solve these equations we represent the earth by a grid of squares, typically of length 150 km or smaller.
- The atmosphere and oceans are divided into vertical slices of varying depths.
- This gives us a 3-dimensional picture of the circulation of the atmosphere and oceans.

## Physical parametrizations in atmospheric models

Processes that are not explicitly represented by the basic dynamical and thermodynamic variables in the basic equations (dynamics, continuity, thermodynamic, equation of state) on the grid of the model need to be included by *parametrizations*.



## Developing climate models

## Richardson's forecast factory

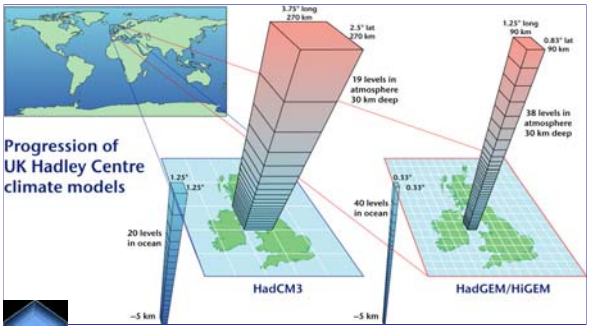
©Francois Schuiten

64,000 computers –The first Massively Parallel Processor

## Progression of UK Climate Models

| | HadCM2 1994 | HadCM3 1998 | HadGEM1 2004 | HiGEM 2005 | NUGAM 2006 |
|---|---|---|---|---|---|
| **Atmosphere** | ~300km<br>19 levels | ~300km<br>19 levels | ~150km<br>38 levels | ~90km<br>38 levels | ~60km<br>L38 |
| **Ocean** | $2.5^0 \times 3.75^0$<br>20 levels | $1.25^0 \times 1.25^0$<br>20 levels | $1^0 \times 1^0$ $(1/3^0)$<br>40 levels | $1/3^0 \times 1/3^0$<br>40 levels | -<br>$(1/6^0 \times 1/6^0)$ |
| **Flux Adjustment?** | Yes | No | No | No | (No) |
| **Computing** | 1 | 4 | 40<br>Met Office<br>NEC<br>(1Tflops) | 400<br>RCUK HPCx<br>(10Tflops) | Earth<br>Simulator<br>(35Tflops) |

## UK in typical climate models

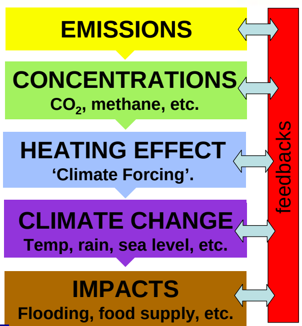



## Predicting climate

» Uncertainties

» Competing demands

## Steps in predicting future climate




**Scenarios from population, energy, economics models**

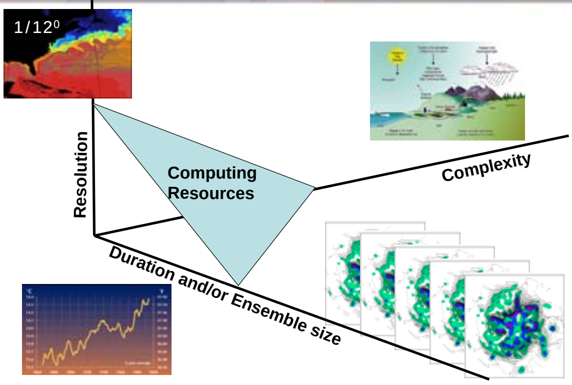
**Carbon cycle and chemistry models**

**Gas properties**

**Coupled climate models**

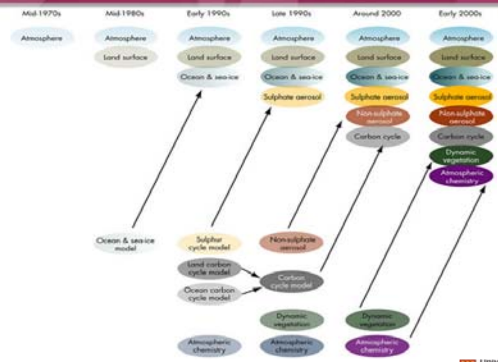
**Impacts models**

## Competing demands of resolution, complexity and uncertainty in Climate System Modelling

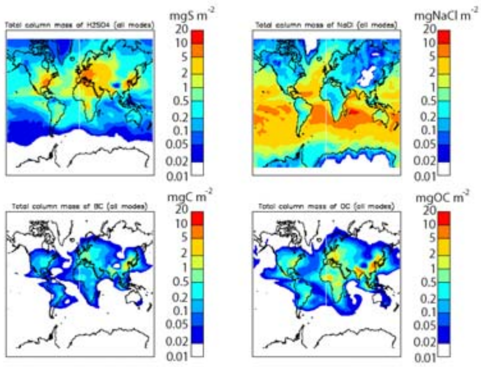



## Adding complexity

## Development of climate models over the last 30 years



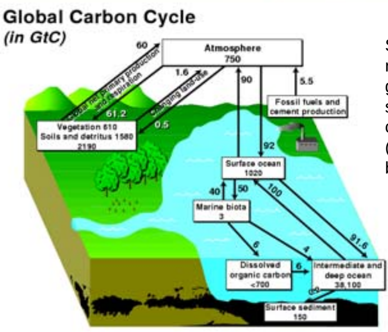

## Atmospheric chemistry





Graham Mann, University of Leeds

## Carbon cycle modelling




Schematic representation of the global carbon cycle, showing the stores of carbon and the fluxes (exchanges) of carbon between them.

Source: Mac Post (Oak Ridge National Laboratory)

## Increasing resolution

## Climate consists of a continuum of time and space scales

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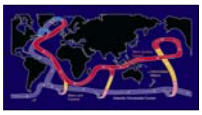
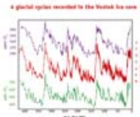
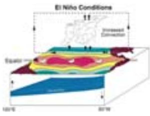
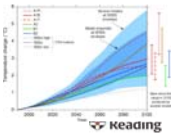
from days to months, years, decades and millennia



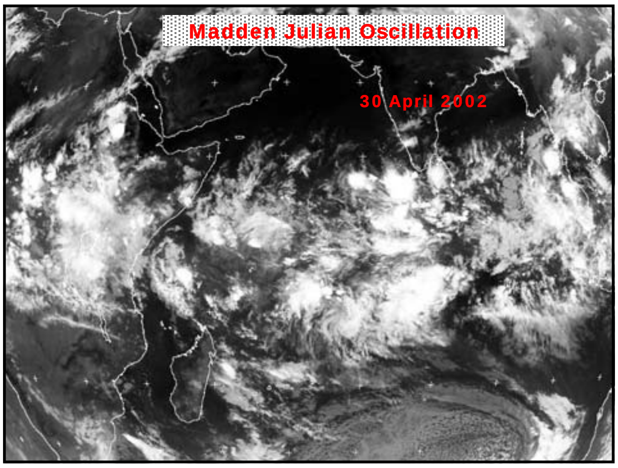


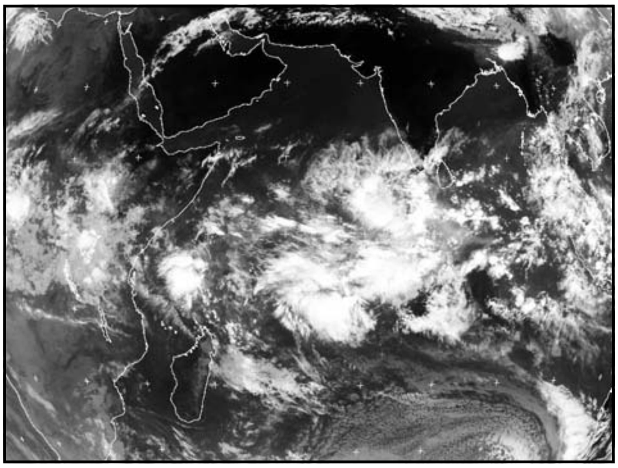
from local to regional, continental and global

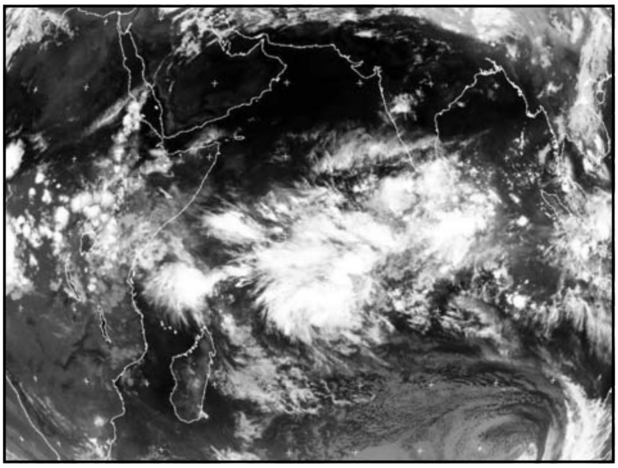


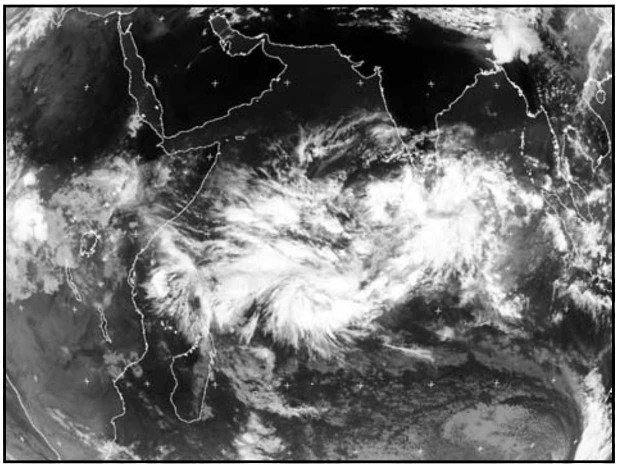



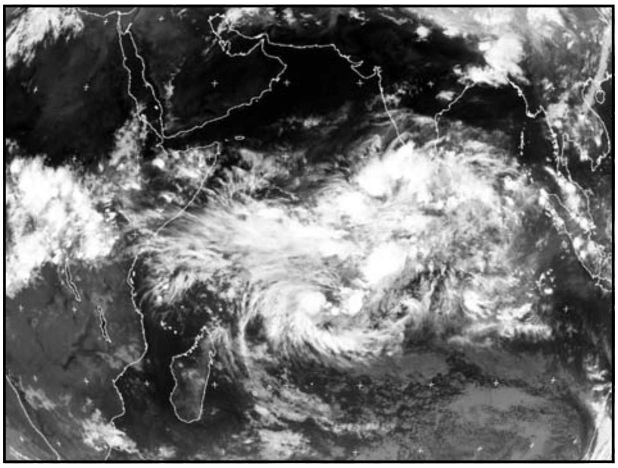
Reading

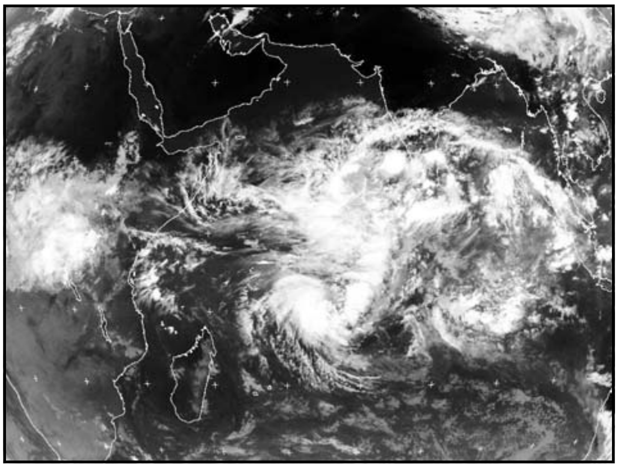
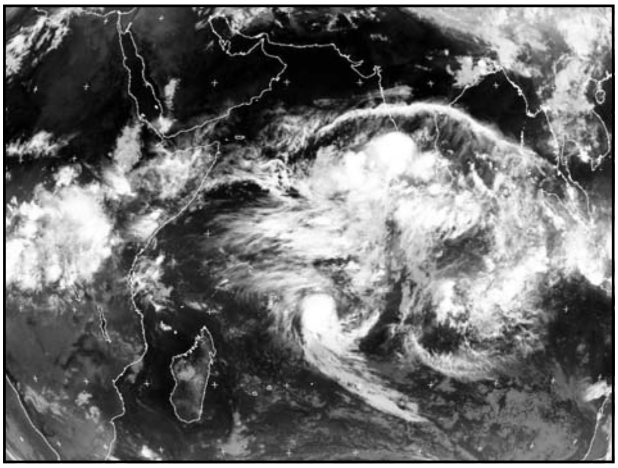
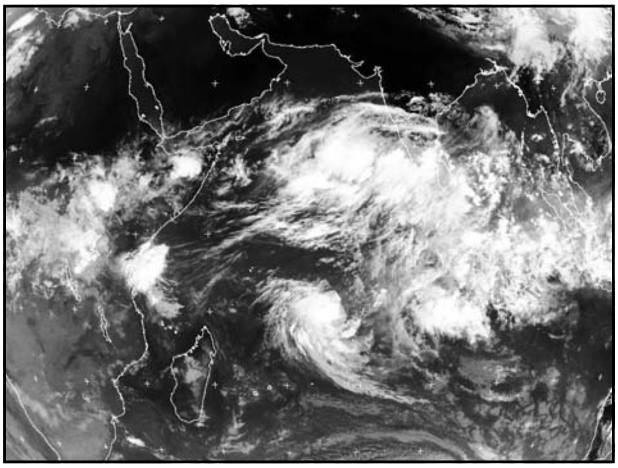
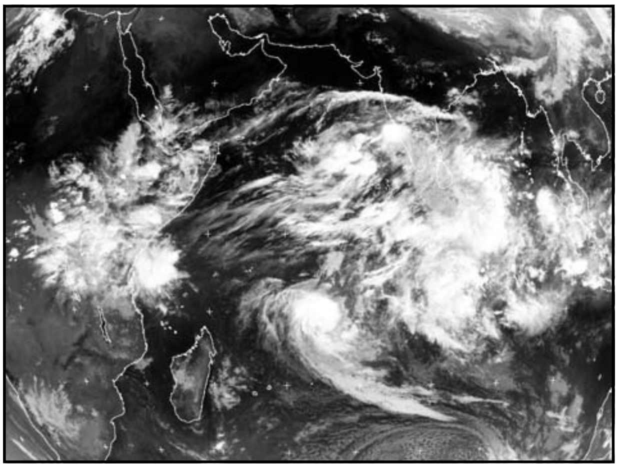
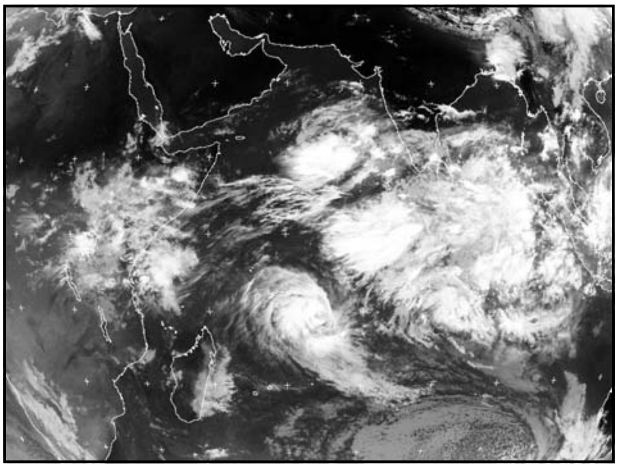
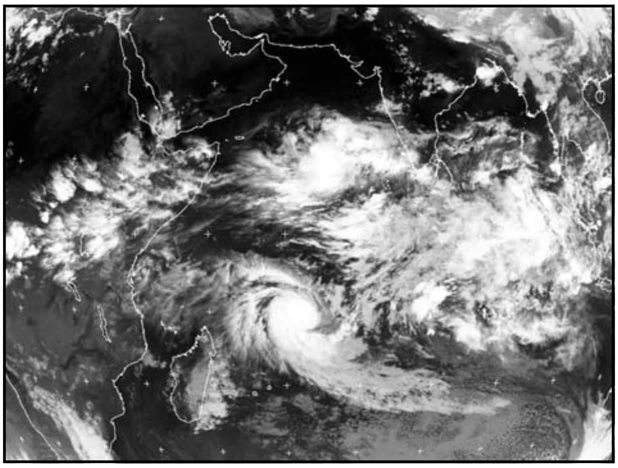


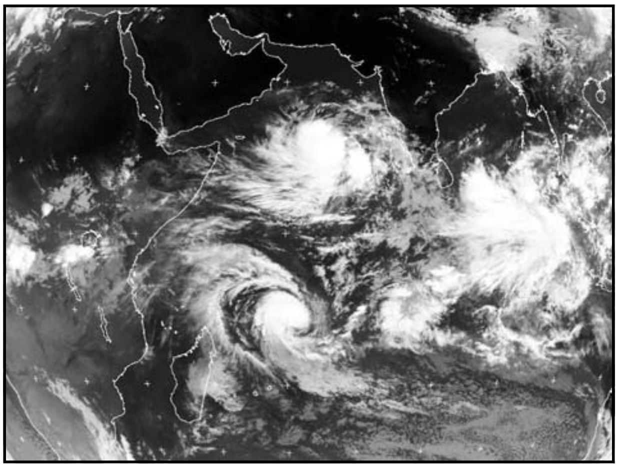



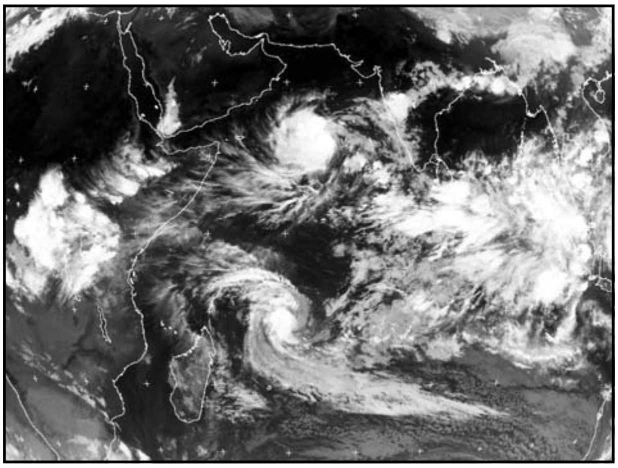


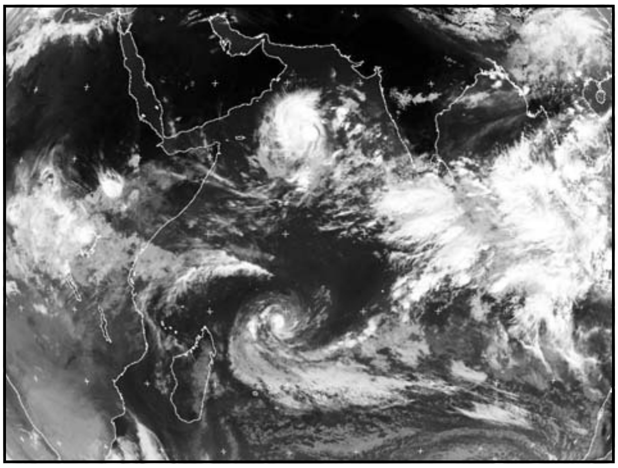


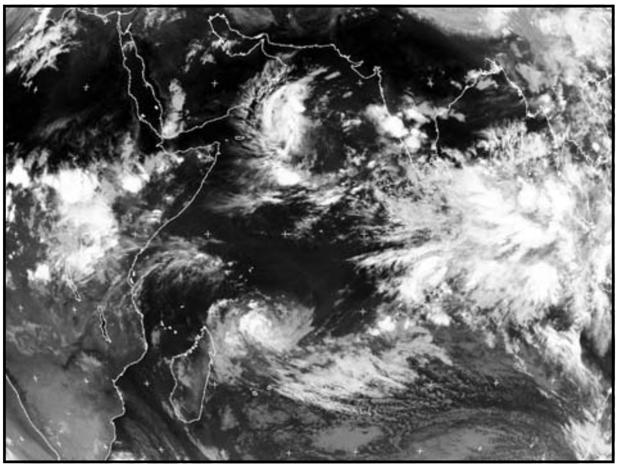


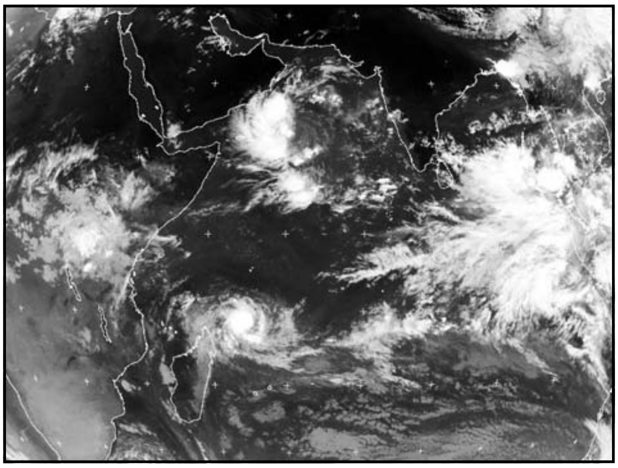







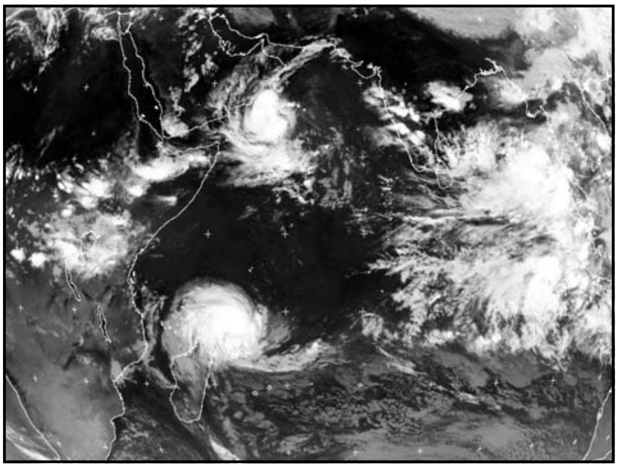


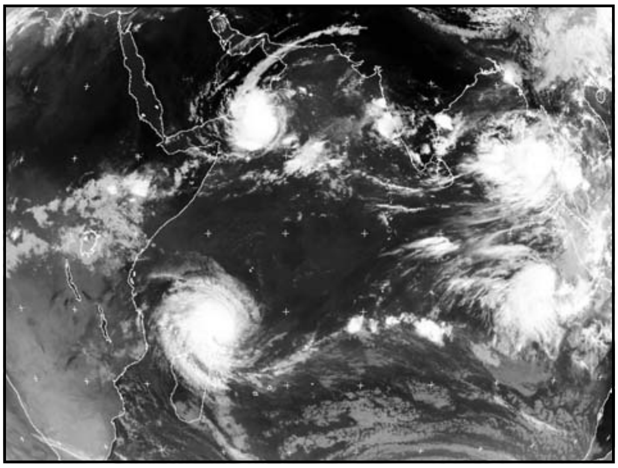


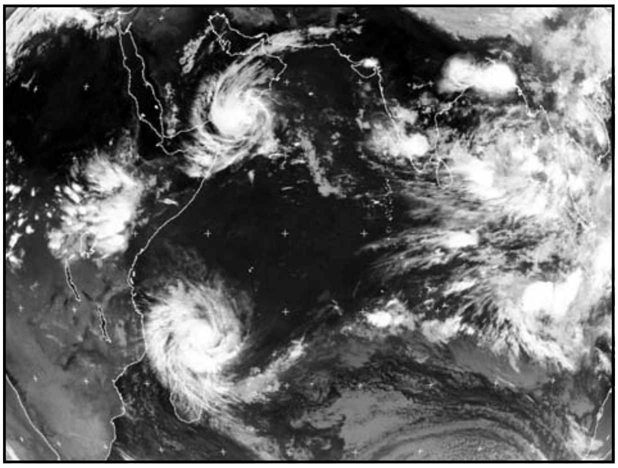


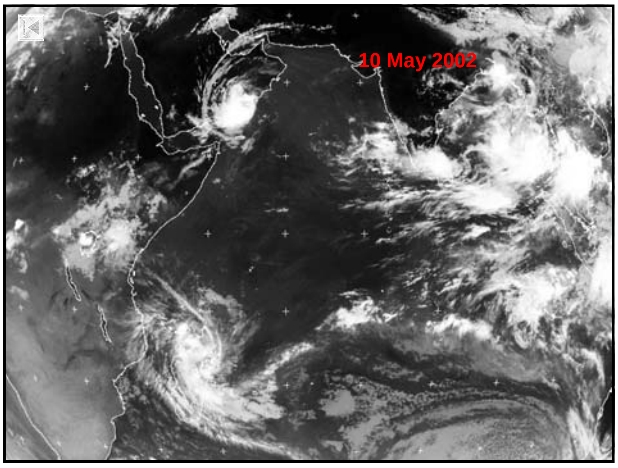












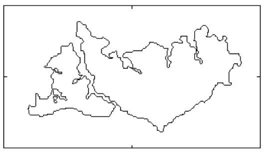

## Weather and climate

- Climate is fundamentally the statistics of weather – weather provides the building blocks of the climate system.
- Extreme weather may present some of the most severe impacts of climate variability and change.
- Climate models **must** be able to simulate the weather and must therefore adequately resolve it.

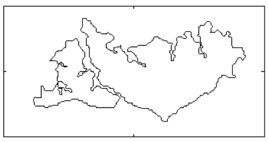
## Moving to higher resolution
## I: Complexity in the atmosphere

Simulations of the diurnal cycle and land-sea breezes over the Tiwi Islands in the Timor Sea

1 km Model Rainfall



12km Model Rainfall

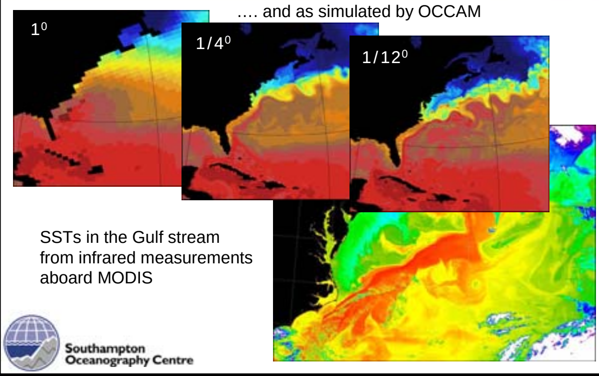


Local time: 09:50 am

Evidence that 1km resolution is needed:
12 km version of the Unified Model fails to capture diurnal cycle and convective organisation

## Moving to higher resolution
## II: Complexity in the ocean

…. and as simulated by OCCAM

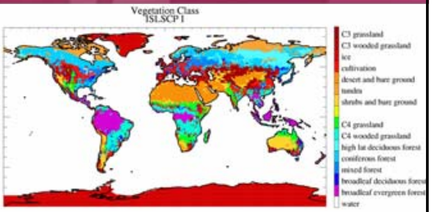


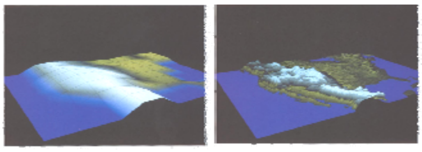

SSTs in the Gulf stream from infrared measurements aboard MODIS

Southampton Oceanography Centre

## Moving to higher resolution
## III: Complexity in the land surface

Large variations in vegetation are not resolved but have impacts on local climate

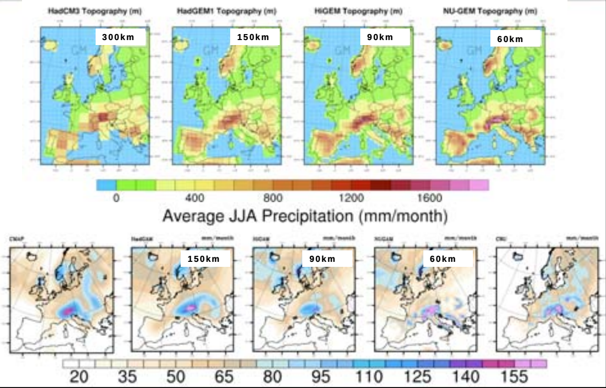


How the Rockies appear in a standard resolution (~300km) model

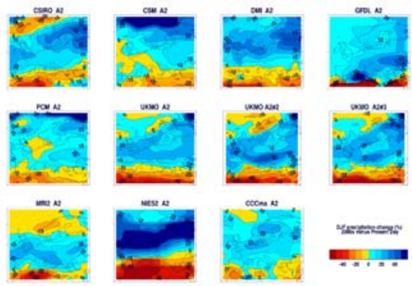
…….. and in a high resolution (~60km) model.

## Moving to higher resolutions:
## IV: Representing topographical influences




## Duration and/or Ensemble size

## State of climate change regional prediction



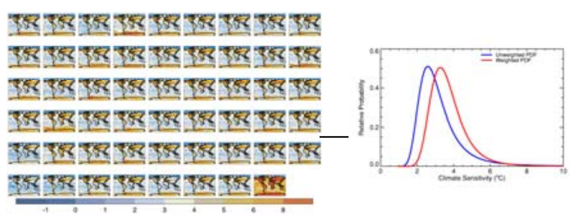

We can produce a small number of different predictions with little idea of how reliable they might be

## ENSEMBLES project

- Quantify the uncertainty in long-term predictions of climate change
- Funded by EU
- Develop an ensemble prediction system for Europe
- Quantify and reduce uncertainty
- Linking results to agriculture, health, food security, water, etc.

http://www.ensembles-eu.org/

## Climate Prediction Modelling



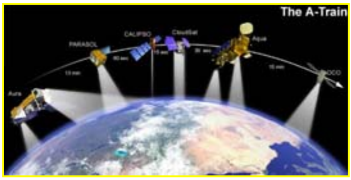
From Murphy *et al*, Nature 2004

## Exploiting Earth Observations

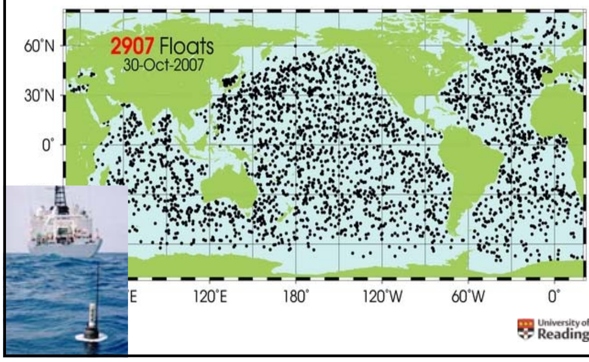
## Earth Observations

Using ultra-high resolution modelling as pseudo-observations for exploring processes – exploiting tera/petaflop computing

Using remote sensing (e.g. CloudSat) to describe vertical structure of clouds and precipitation




## Example: Argo dataset




## Future research challenge

## Future research challenges

Some aspects of climate change which remain uncertain:

- Regional and local changes in rainfall and its characteristics in space and time
- Changes in the frequency and intensity of extreme weather events
- Effects of global warming on e.g. El Niño, monsoons
- Potential ‘tipping points’ in the climate system

## Fresh approach to earth system models

## Building a house upon the sand?

By trying to extend traditional methods of building earth system models are we storing up problems for the future?

Is the past approach of incremental development by adding complexity the best way forward?

Are there new ways of approaching the problem that draw upon developments in other fields?

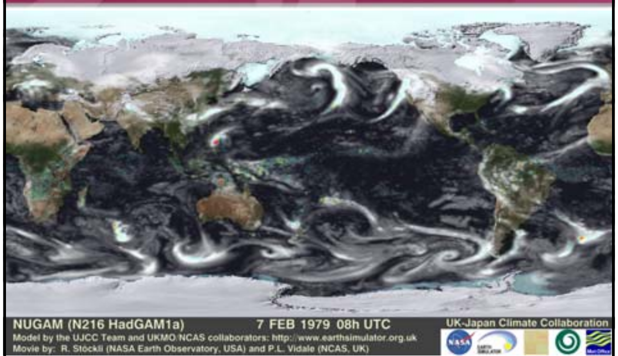
## Why it is timely to tackle this problem

Access to tera/petascale computing facilities


Developing links with other disciples


New Earth Observations datasets, both remotely-sensed and surface based are coming available

## Climate modelling at weather resolution on the Earth Simulator



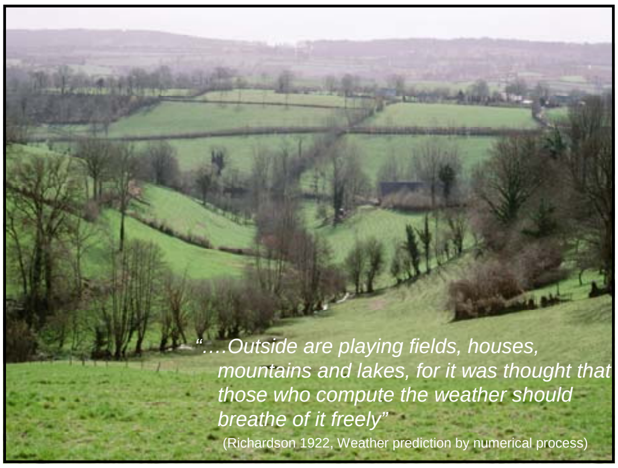

## Four big challenges ……. and an exciting time ahead

I: How to represent the multi-scale nature of the climate system.

II: How to develop model codes that will exploit future peta-scale computing architectures.

III: How to represent living organisms and human responses in earth system models.

IV: How to exploit Earth Observations data.




## Thanks for your time

Visit www.walker-institute.ac.uk

## Time for a fresh approach to modelling the Earth System

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- Objective 1: Build a dynamical core for a global model which can represent the multi-scale nature of the earth system and which is computationally efficient on future hardware architectures
- Five key aspects need to be considered:
  - Choice of basic grid that avoids singularities
  - Accurate representation of orography (computational mesh generation)
  - Efficient down- (or up-) scaling within the same model (mesh adaptation)
  - Formulation of the governing equation to be valid at all scales
  - Solution of these equations on the discrete space defined by the generated meshes (equation discretisation
- Each aspect should take advantage of the latest development of the sub-disciplines related to it. It is worth exploring methodologies used by other disciplines which make extensive us of Computational Fluid Dynamics.
- The design needs to be flexible to allow for future upgrades and for ease of maintenance

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## Time for a fresh approach to modelling the Earth System

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- Objective 2: Represent the interaction of life with the physical system. All aspects of the modelling (physical, chemical and biological) are brought together right at the very beginning.
- Objective 3: Design appropriate methods for introducing human responses into the system.

- Foster the approach in which we attack the problem from the top-down, using knowledge of processes and phenomena gained from the top-end models to guide their representation in the full ESM.
- Capability to use a range of computing platforms from desktops to clusters to distributing computing to pet flop supercomputers. Thus the system must be flexible and portable; it will be essential to maintain a strong engagement with the hardware industry.

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## Time for a fresh approach to modelling the Earth System

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- It has to be an *end-to-end system (not just a model) in which the scientists poses a question, designs and implements an "experiment", perform simulations and then uses a whole suite of tools to extract knowledge from the results.*
- It should allow the scientists to have as simple or as complex a system as needed for the problem to be tackled, and it should be based around a common set of user interfaces and knowledge discovery tools that are portable across computer architectures, computational and data grids.
- The model itself should be built using a flexible framework which allows different components to be coupled together or for single modules to be run stand alone in forced mode to enable basic understanding of processes.

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## Ensembles

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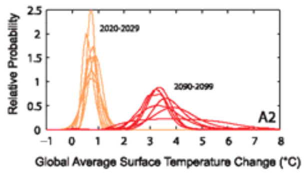


Run multiple scenarios
Produce frequency distributions of outcome

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## The earth system is also very complex...

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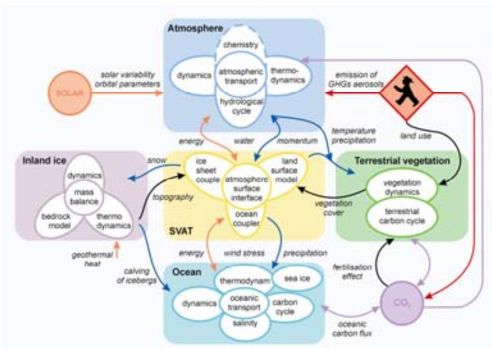


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## Fundamentals of climate modelling

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**Climate Models** are huge computer codes based on **fundamental** mathematical equations of motion, thermodynamics and radiative transfer

*These govern:*

- Flow of air and water - winds in the atmosphere, currents in the ocean.
- Exchange of heat between the atmosphere and the earth's surface
- Release of latent heat by condensation during the formation of clouds and raindrops
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**Climate models are extensions of weather forecast models**

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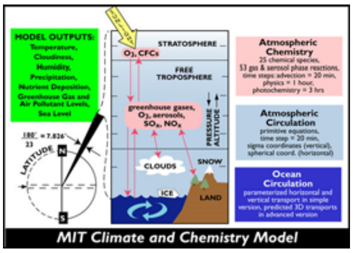
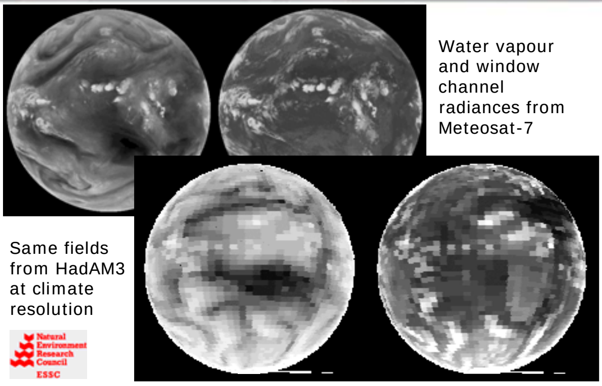
## Atmospheric chemistry

- Atmospheric chemistry (aerosol, ozone, methane - interactions



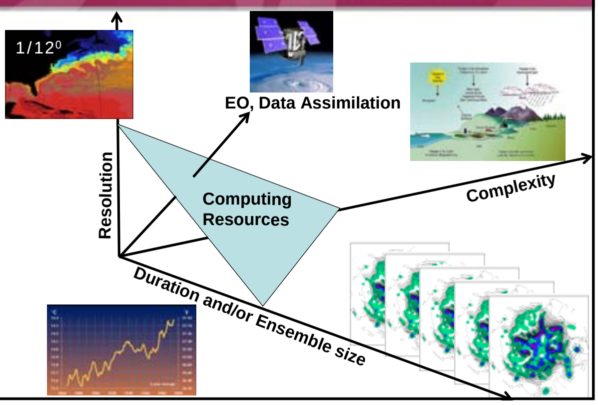

## Why a move to higher resolution is necessary
## I: Complexity in the atmosphere



Water vapour and window channel radiances from Meteosat-7

Same fields from HadAM3 at climate resolution

## Balancing future demands




## Brief history of climate modelling (I)

- **1922**: Lewis Fry Richardson
  - basic equations and methodology of numerical weather prediction
- **1950**: Charney, Fjørtoft and von Neumann (1950)
  - first numerical weather forecast (barotropic vorticity equation model)
- **1956**: Norman Phillips
  - first general circulation experiment (two-layer, quasi-geostrophic hemispheric model)
- **1963**: Smagorinsky, Manabe and collaborators at GFDL, USA
  - 9 level primitive equation model
- **1960s and 1970s**: Other groups and their offshoots began work
  - University of California Los Angeles (UCLA), National Center for Atmospheric Research (NCAR, Boulder, Colorado) and UK Meteorological Office

## Brief history of climate modelling (II)

- **1980s**: First coupled model simulation
- **1990s** onwards: Era of model intercomparisons
  - AMIP, CMIP, SMIP, ENSIP, PMIP……
- **2000** onwards: Multi-model ensemble seasonal forecasting systems
  - DEMETER
- **2004**: EU ENSEMBLES Project – combined seasonal-to-decadal and climate change multi-model ensembles
- **2007**: IPCC Fourth Assessment Report
  - climate projections to 2100 from 18 coupled ocean-atmosphere-cryosphere models.

## Setting up a climate simulation

- Defining the initial conditions especially for the ocean and land surface – critical for seasonal to decadal predictions.
- Defining the external forcings e.g. solar constant, GHG/aerosol concentrations or emissions.
- Defining the surface boundary conditions and characteristics