The Abdus Salam International Centre for Theoretical Physics

Workshop on the Science of Climate Change: a focus on Central America and the Caribbean Islands

The experience of developing an Earth System Modeling in Brazil

Paulo Nobre

paulo.nobre@inpe.br

Center for Weather Forecasting and Climate Studies – CPTEC

National Institute for Space Research – INPE

Brazil

14 - 16 March 2017 Centro Cultural Tomas de Aquino
Universidad San Carlos, Antigua, Guatemala

ICTP Workshop on the Science of Climate Change, Antigua, 15 March 2017

Earth System Models

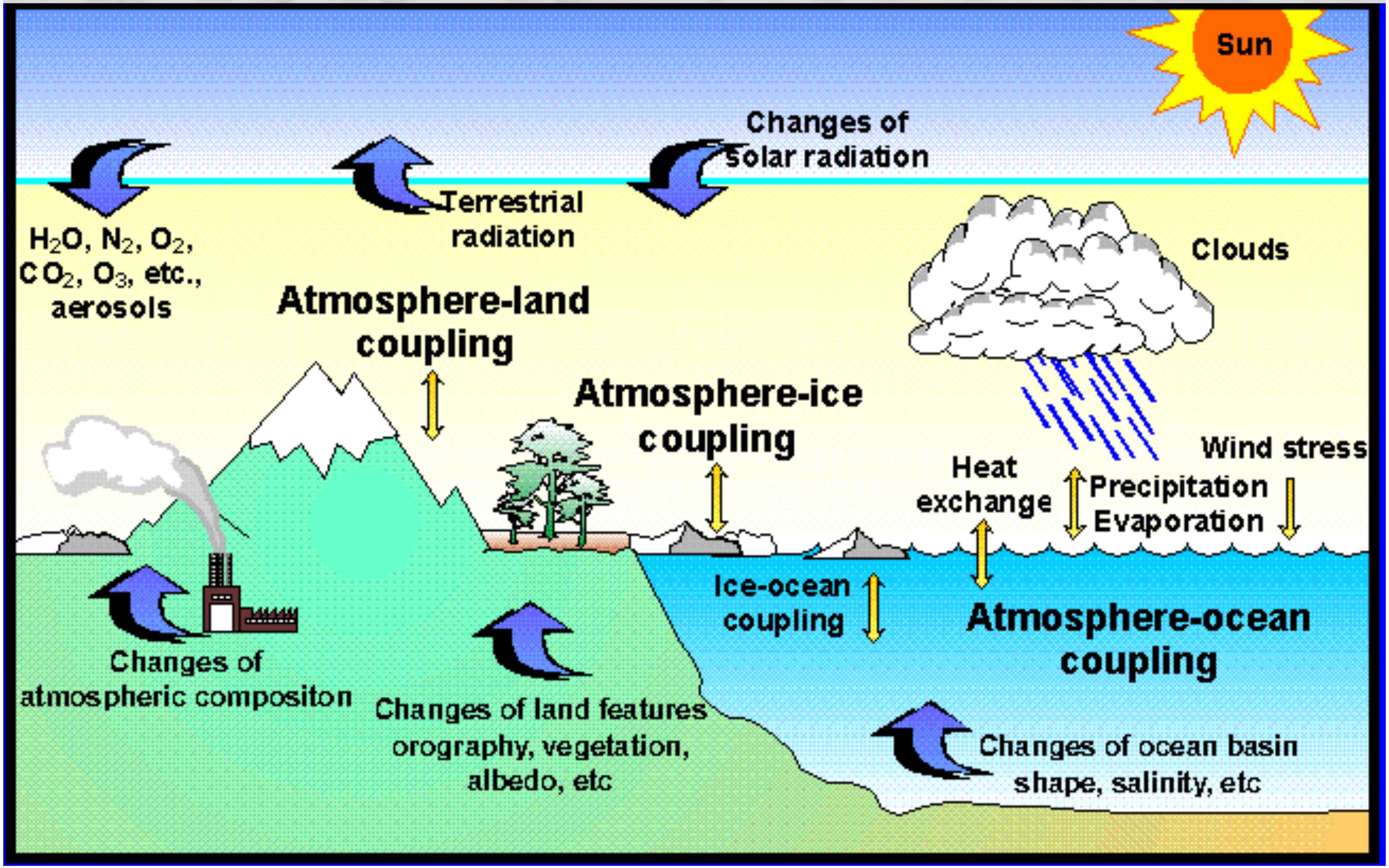
- **A climate model is a mathematical representation of the observed real world**

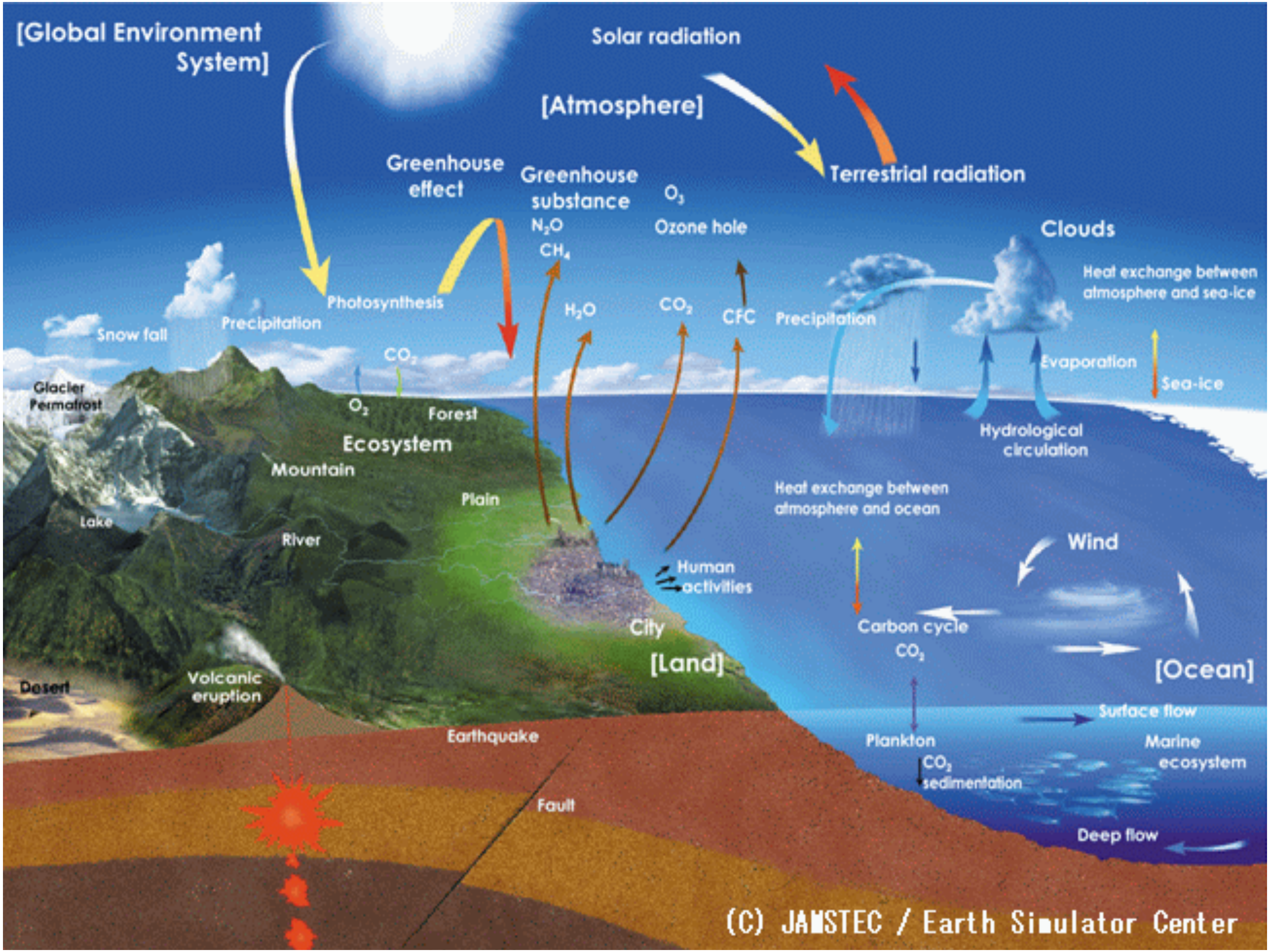
- **Purpose:** To obtain a theoretically or practically manageable representation of the Earth system by reducing its complexity and removing details that are not relevant for specific consideration.

- **Climate models** use quantitative methods to **simulate** the interactions of the atmosphere, oceans, land surface, and ice

Courtesy: Prof. Guy Brasseur (2011)

Modeling the Earth System





[Global Environment System]
Solar radiation
[Atmosphere]
Terrestrial radiation
Greenhouse effect
Greenhouse substance
N2O
CH4
O3
Ozone hole
Clouds
Heat exchange between atmosphere and sea-ice
Photosynthesis
H2O
CO2
CFC
Precipitation
Snow fall
Precipitation
CO2
Evaporation
Sea-ice
Glacier
Permafrost
O2
Forest
Ecosystem
Mountain
Hydrological circulation
Plain
Heat exchange between atmosphere and ocean
Lake
River
Wind
Human activities
City
Carbon cycle
CO2
[Land]
[Ocean]
Desert
Volcanic eruption
Surface flow
Earthquake
Plankton
Marine ecosystem
CO2 sedimentation
Fault
Deep flow
(C) JAMSTEC / Earth Simulator Center

Earth System Modeling: Some concrete Objectives

- Provide a **predictive capability** for the Earth System on time scales from days to seasons to decades
- Go **beyond the physical climate system** to include a predictive capability for marine and terrestrial ecosystems
- Require development of an **assimilative approach** to the coupled Earth System.
- Include an assessment of today's suite of Earth System **observations** within a predictive context and those observations needed to be sustained routinely
- Identify new **observations and algorithms** needed to advance prediction skill

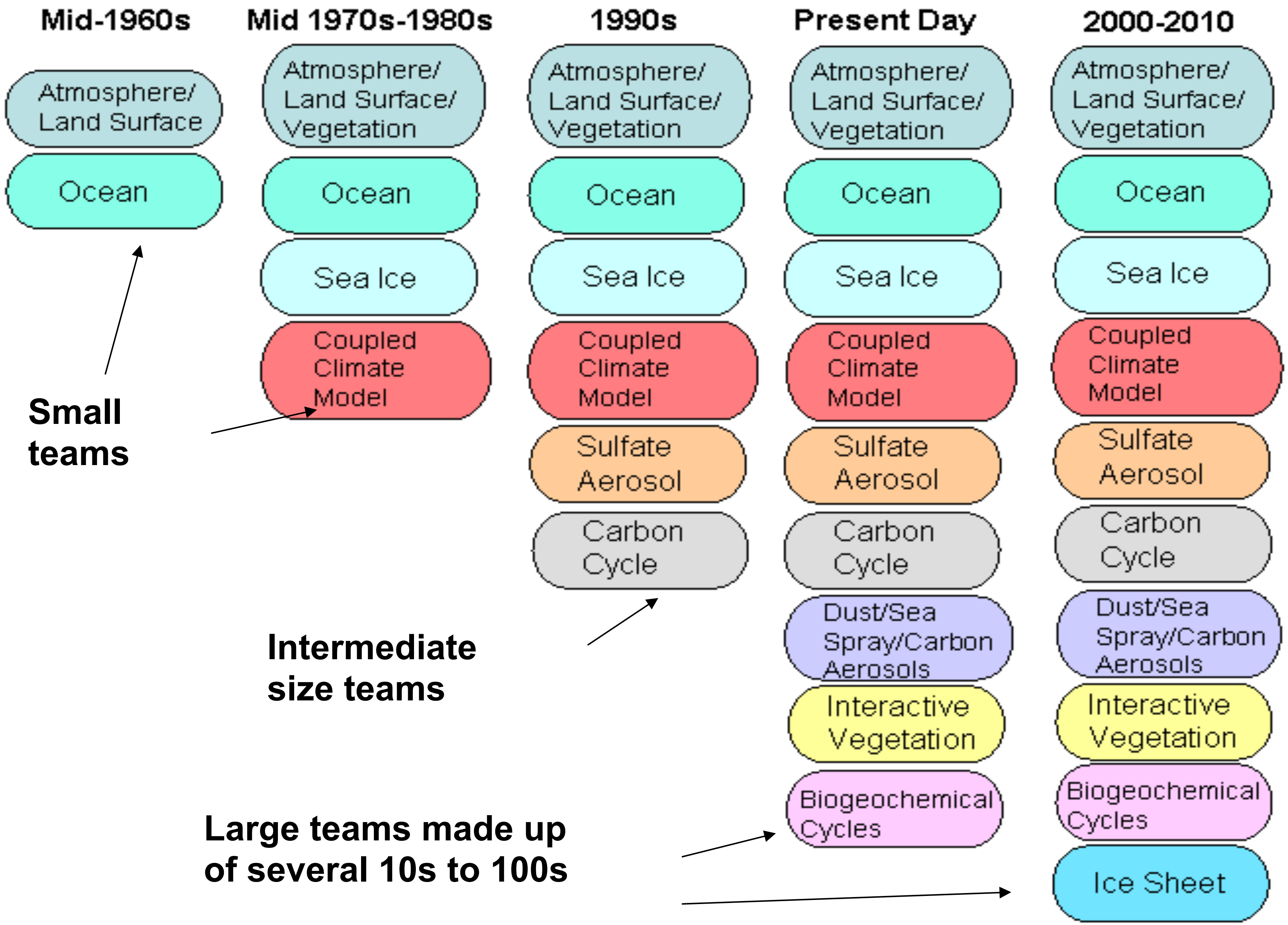
Courtesy: Prof. Guy Brasseur (2011)

Earth System Modeling:
Some concrete Objectives

- Include a predictive capability for **disease vectors**
- Focus on **regional aspects** (coastal region, megacities, tropical forest, Arctic, et and link with integrated field studies).
- Include **agricultural forecasts**
- **Education and training** in the development and use of such component
- Develop an advanced **forecasting capability** indicating aspects of the Earth system particularly vulnerable and prone to disruption on lead times of weeks to seasons to decades
- Provide **policy neutral** information on the implications and ramifications of environmental prediction.

Courtesy: Prof. Guy Brasseur (2011)

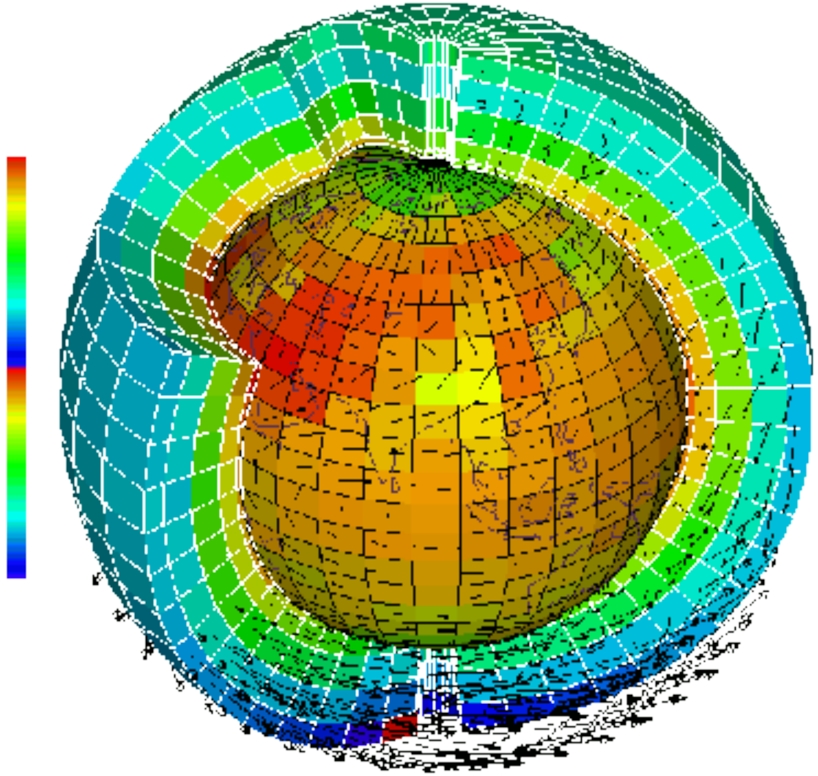
Timeline of Climate Model Development



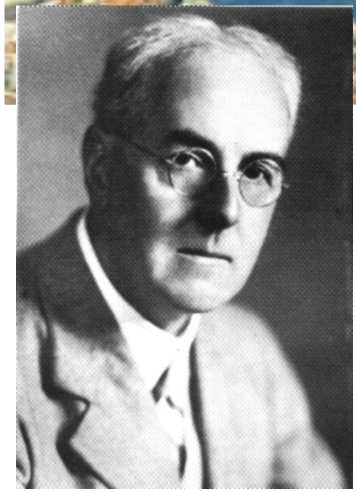
From Weather Modeling to Climate Modeling

Richardson (1922)

The weather machine

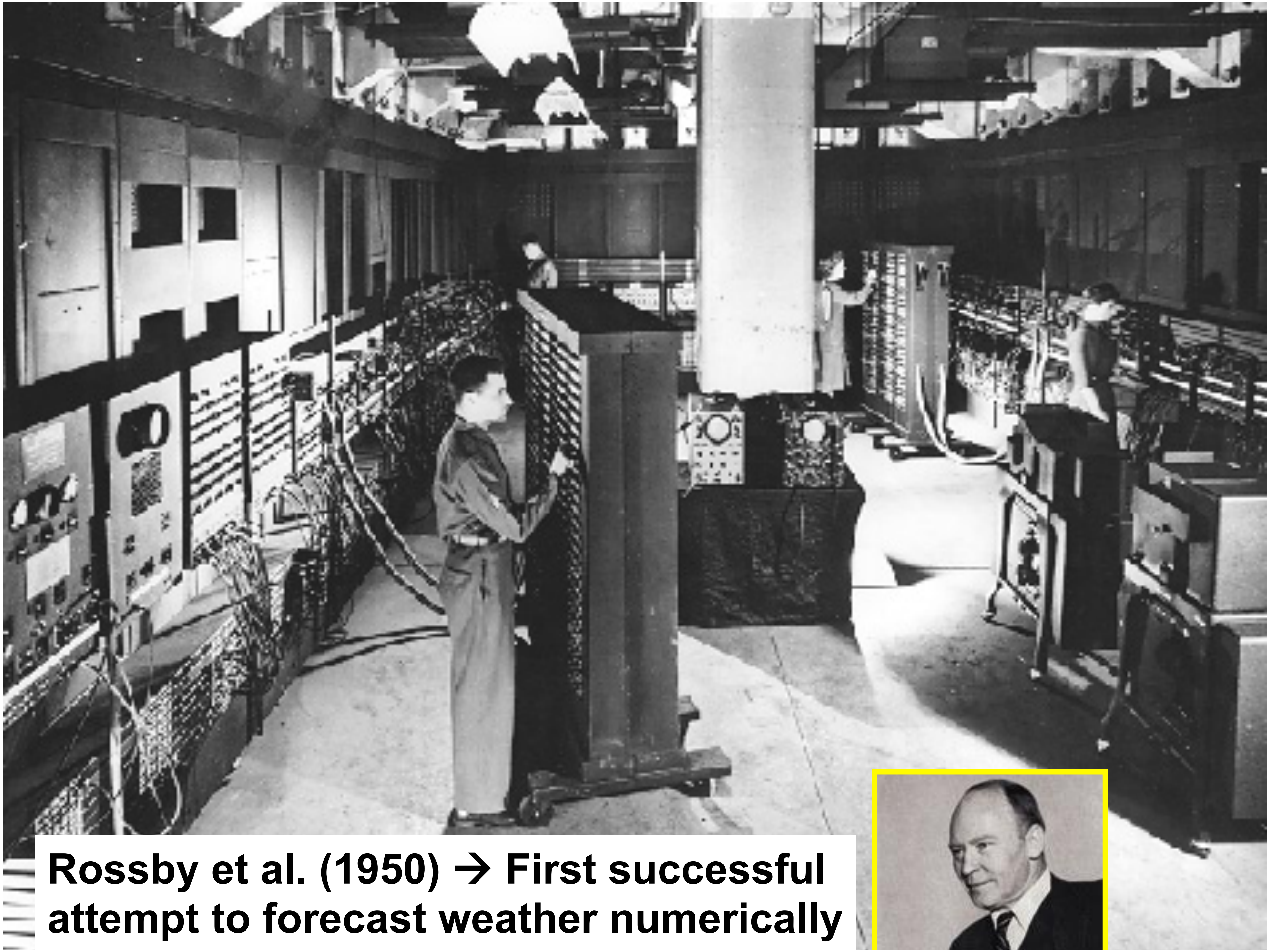


An artist view of recent climate models
(L. Fairhead /LMD-CNRS)



Before the Age of Computing

In 1922, Lewis Fry Richardson, a British mathematician and meteorologist, proposed an immersive giant globe to numerically forecast weather. This “factory” would employ 64,000 human computers to sit in tiers around the interior circumference of a giant globe.



Rossby et al. (1950) → First successful attempt to forecast weather numerically

93 PETAFLOP
Sunway TaihuLigh

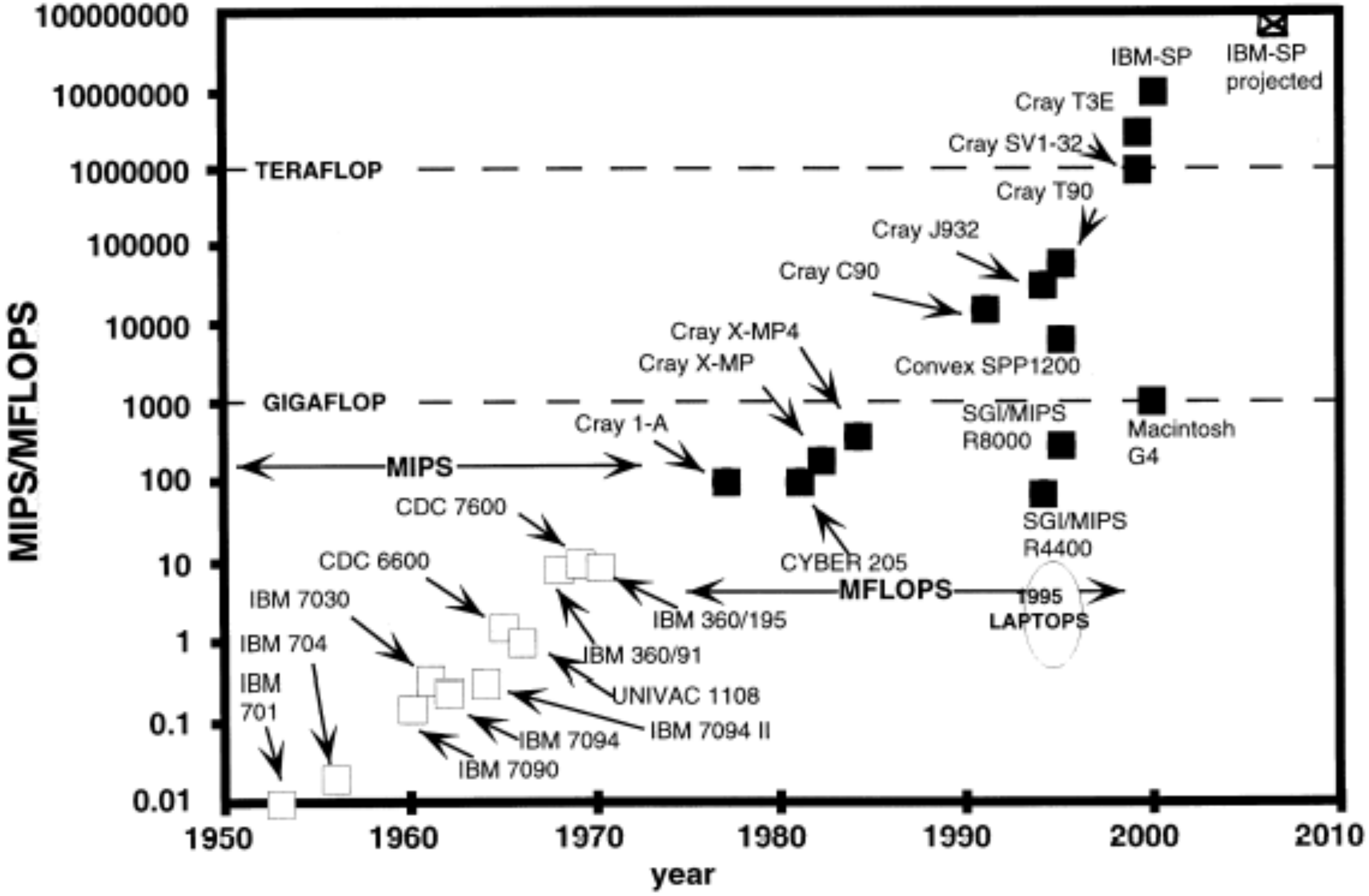
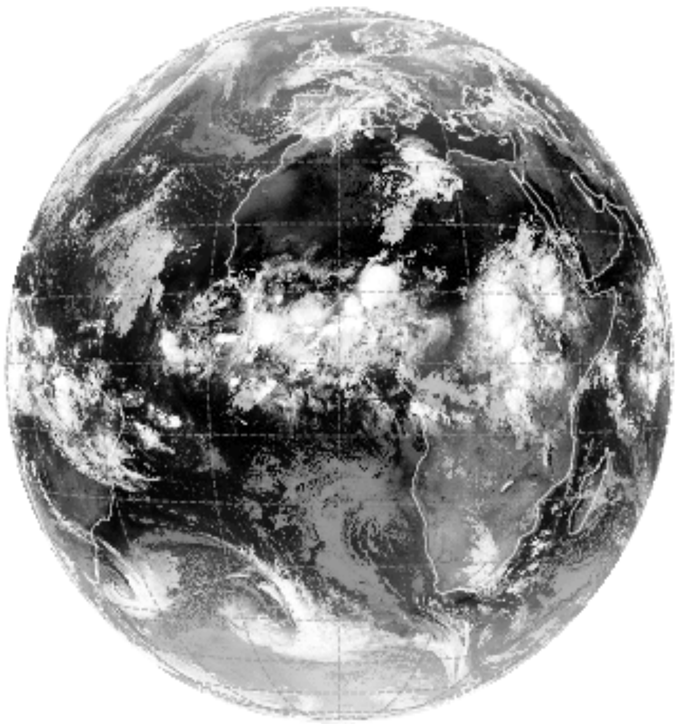


Figure 5. Development of computer power since 1950. Speeds are shown in millions of instructions per second (MIPS) up to 1974 and in millions of floating point operations per second (MFLOPS) from 1975 onwards. The rate of increase is exponential and shows no signs of tailing off (modified from *A Climate Modelling Primer*, by K McGuffie and A Henderson-Sellers, 1997, reproduced by permission of John Wiley & Sons, Ltd)

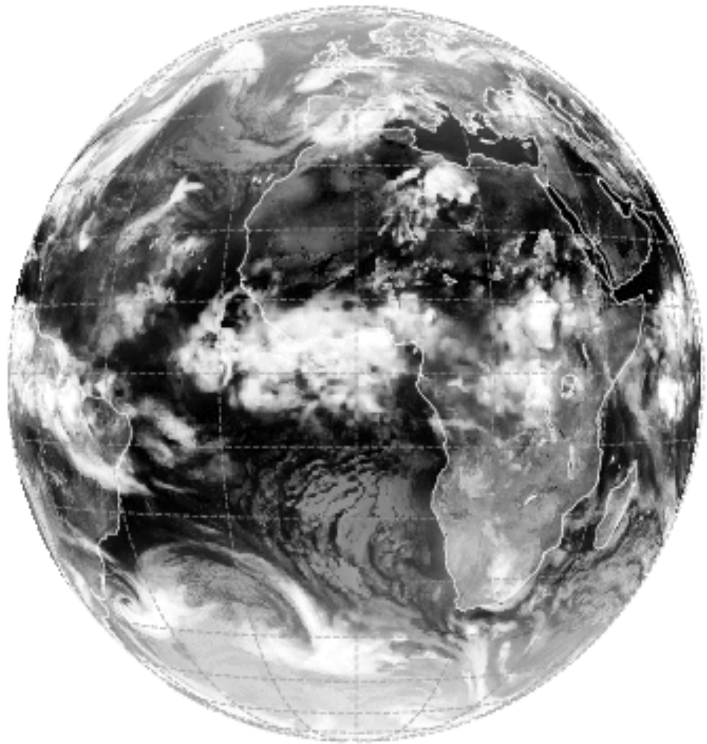
Weather Prediction compared with Satellite Observations

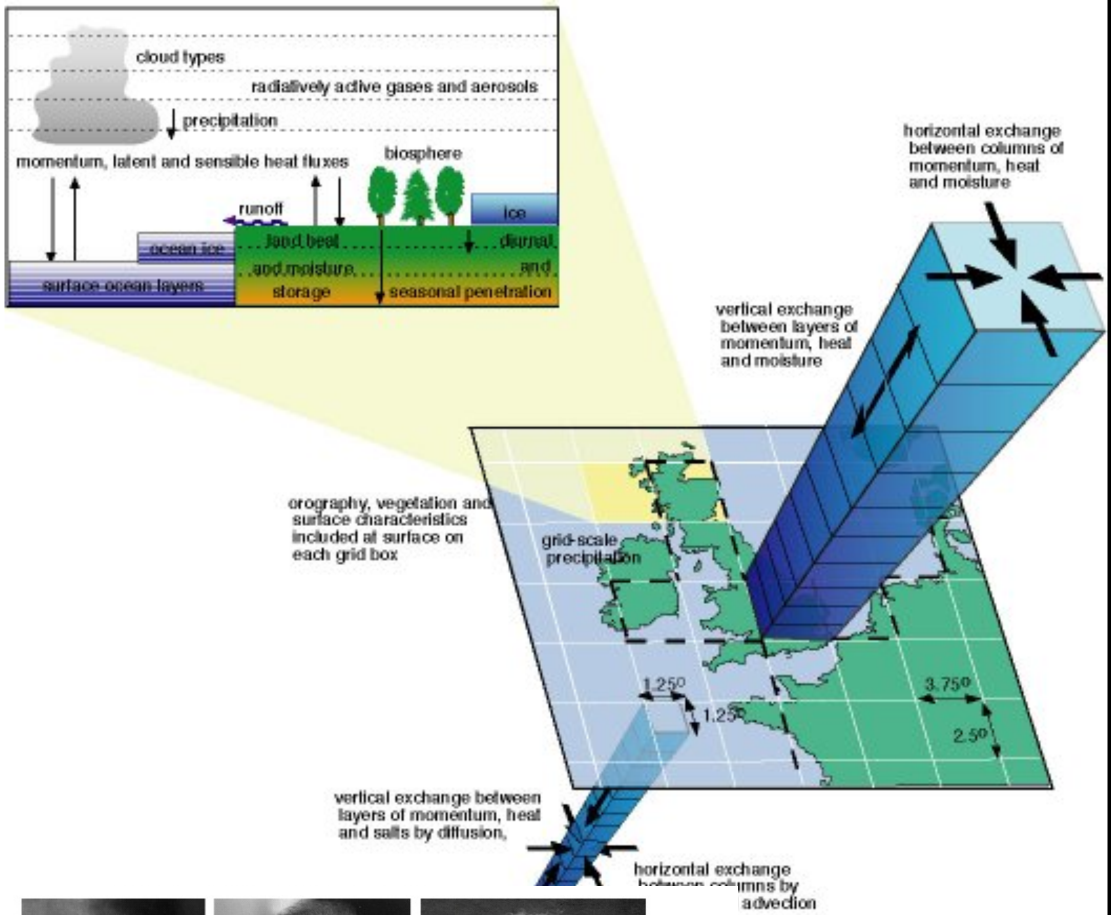
ECMWF predictions and Meteosat observations

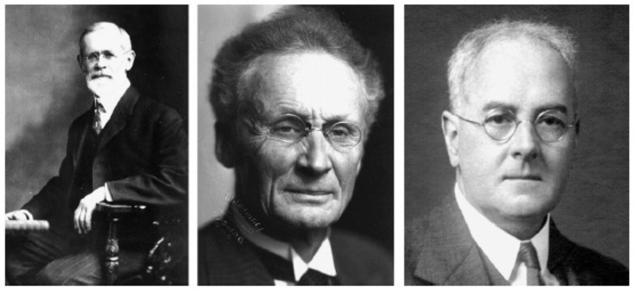
Meteosat 9 IR10.8 20080525 0 UTC



ECMWF Fc 20080525 00 UTC+0h:







Left: Cleveland Abbe (1838–1916). Centre: Vilhelm Bjerknes (1862–1951). Right: Lewis Fry Richardson (1881–1953).

(Lynch, 2007)

Atmospheric Models

Atmospheric dynamics (+chemistry)

Ocean dynamics (+salinity)

Sea ice

Land surface

+vegetation (+CO2)

Simplified representations based on **physical laws**

Courtesy: Prof. Guy Brasseur (2011)

Numerical Weather Prediction: Atmospheric Primitive Equations

$$\frac{du}{dt} = -\frac{1}{\rho a \cos\varphi}\frac{\partial p}{\partial \lambda} + fv + uv\frac{\tan\varphi}{a} + F_\lambda$$

$$\frac{dv}{dt} - \frac{1}{\rho a}\frac{\partial p}{\partial \varphi} - fu - u^2\frac{\tan\varphi}{a} + F_\varphi$$

$$\frac{\partial p}{\partial z} = -\rho g$$

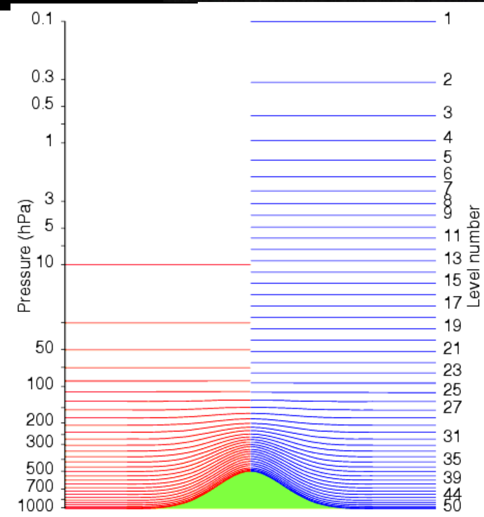
$$\frac{\partial \rho}{\partial t} = -\nabla \cdot \rho \mathbf{V}$$

$$p = R\rho T$$

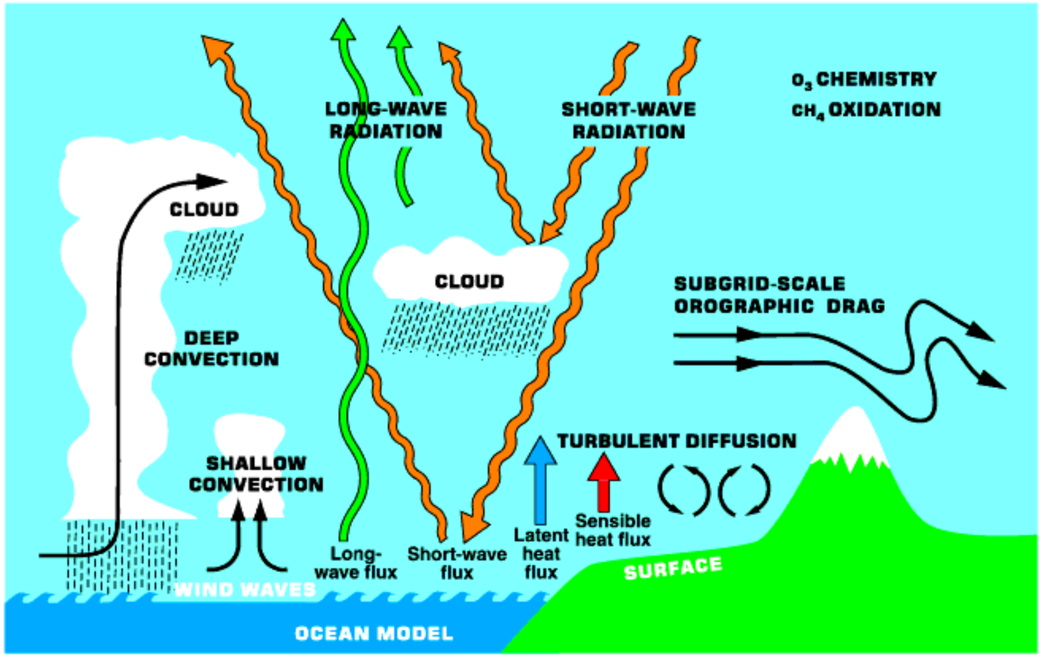
$$C_p\frac{d\Theta}{dt} = \frac{\Theta}{T}Q$$

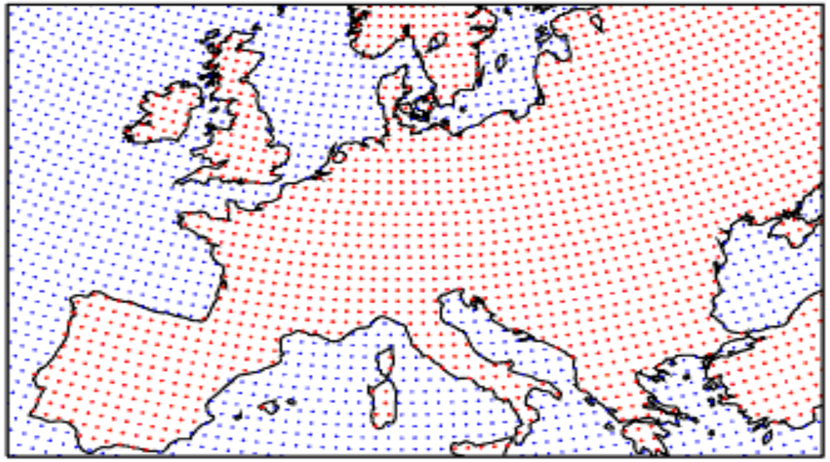
u, v, w, p, ρ, T

Primitive equations



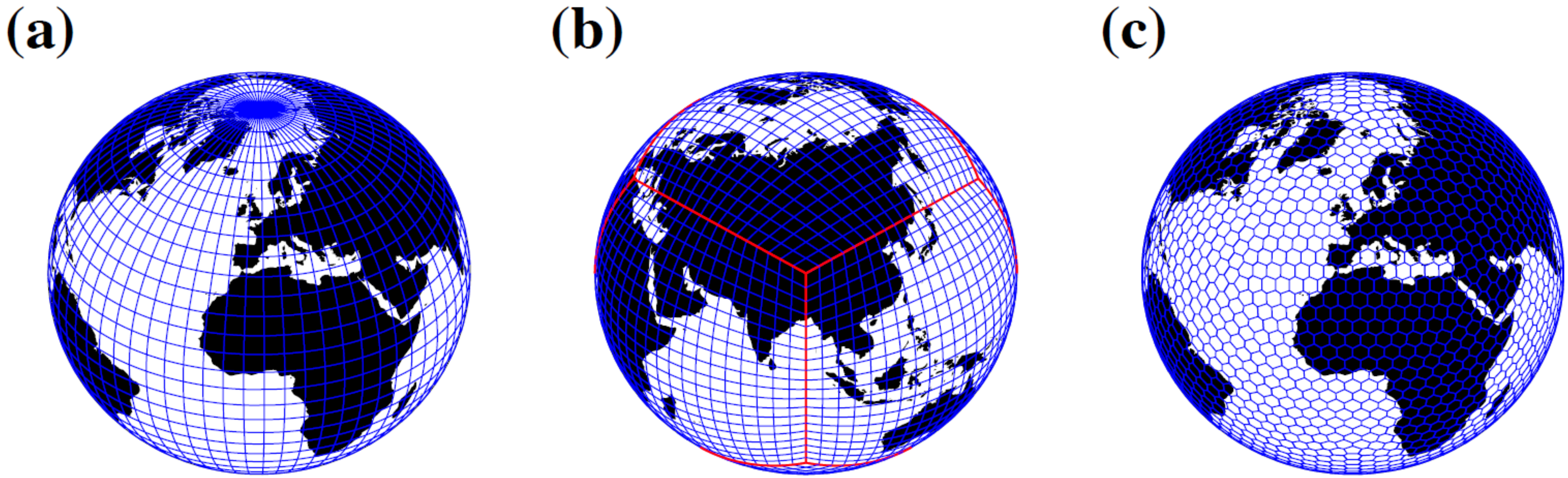
Discretization



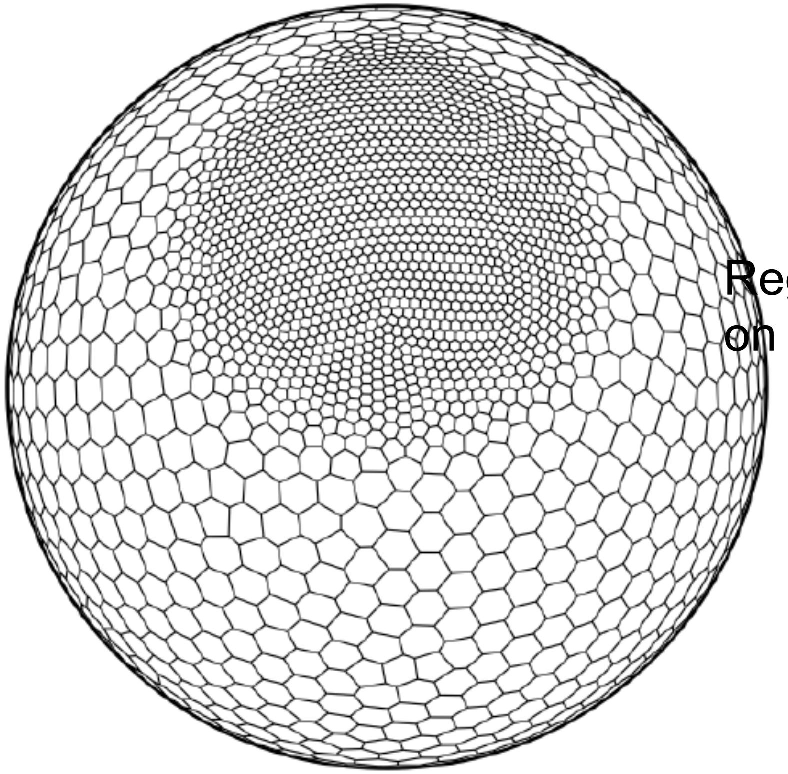


ICTP Workshop on the Science of Climate Change, Antigua, 15 March 2017

Grids: Lat-long, Cubed-Sphere,icosahedral (hexagons and pentagons)

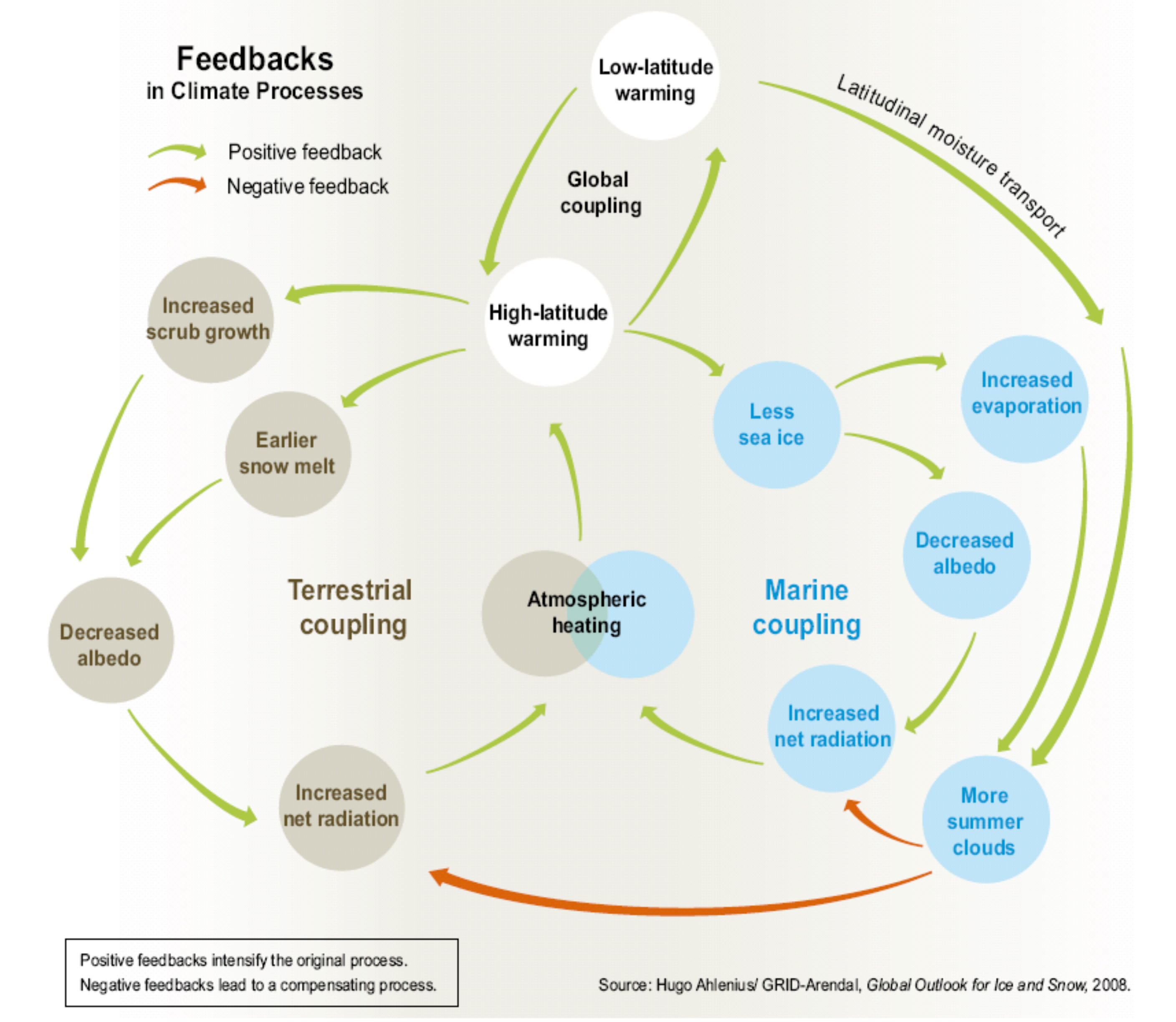


Adaptive Grid to highlight processes in a given region (From T. Ringler, LANL)



Regional focus
on a global grid system

Figure V.1. A variable resolution grid based on a Spherical Centroidal Voronoi Tesselation.

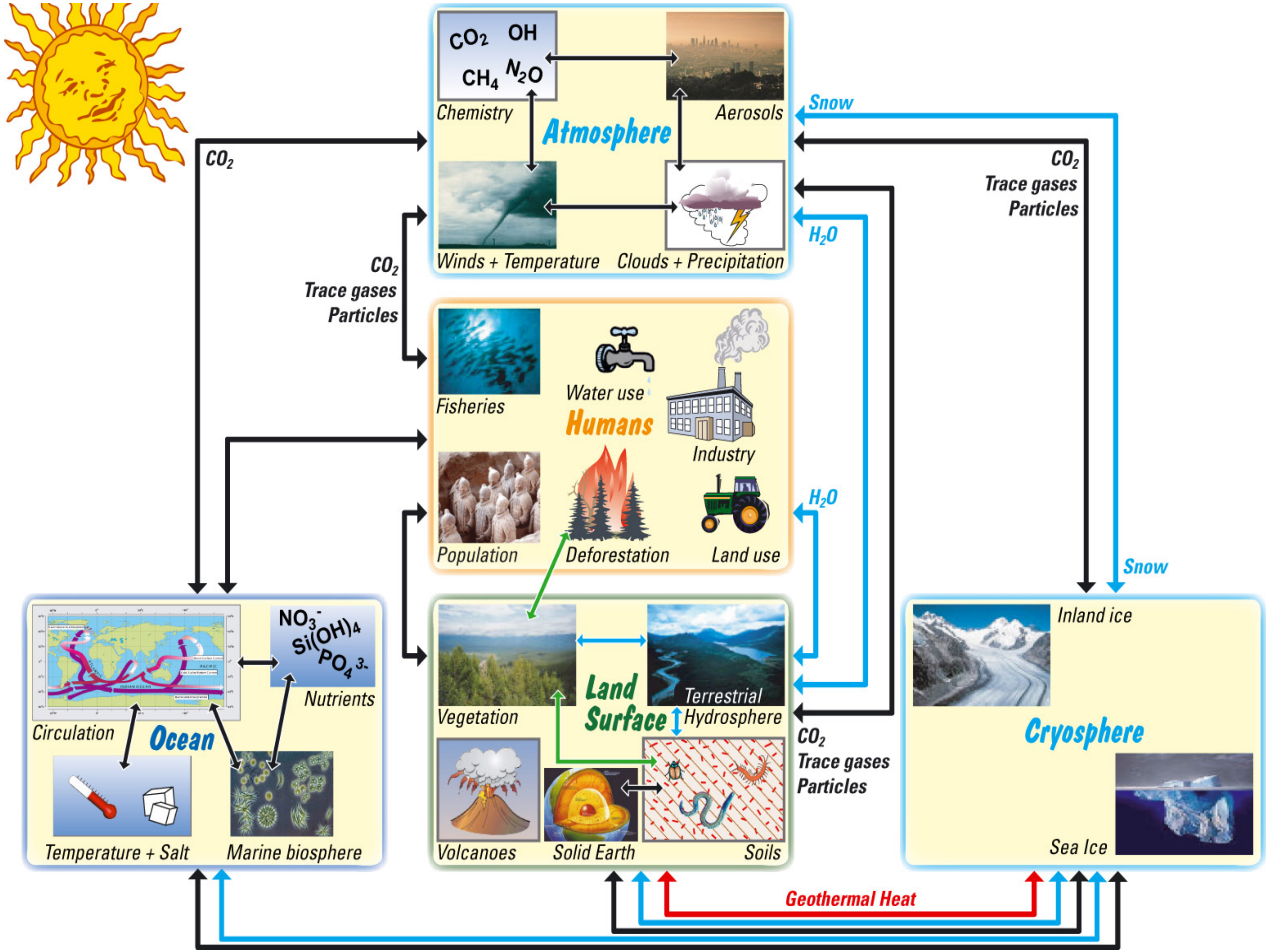


Climate system is highly nonlinear

Strong coupling among subsystems with different time scales

→Models needed!

Courtesy: Prof. Guy Brasseur (2011)



CO_2 OH
CH_4 N_2O
Chemistry
Aerosols
Atmosphere
Winds + Temperature
Clouds + Precipitation
Snow
CO_2
CO_2
Trace gases
Particles
H_2O
CO_2
Trace gases
Particles
Fisheries
Water use
Humans
Industry
Population
Deforestation
Land use
H_2O
Snow
NO_3^-
$Si(OH)_4$
PO_4^{3-}
Nutrients
Circulation
Ocean
Temperature + Salt
Marine biosphere
Vegetation
Land
Surface
Terrestrial
Hydrosphere
Volcanoes
Solid Earth
Soils
CO_2
Trace gases
Particles
Inland ice
Cryosphere
Sea Ice
Geothermal Heat

Introducing Life into Earth System Models

Theoretical bases for modelling the physical system are much firmer than for natural ecosystems.

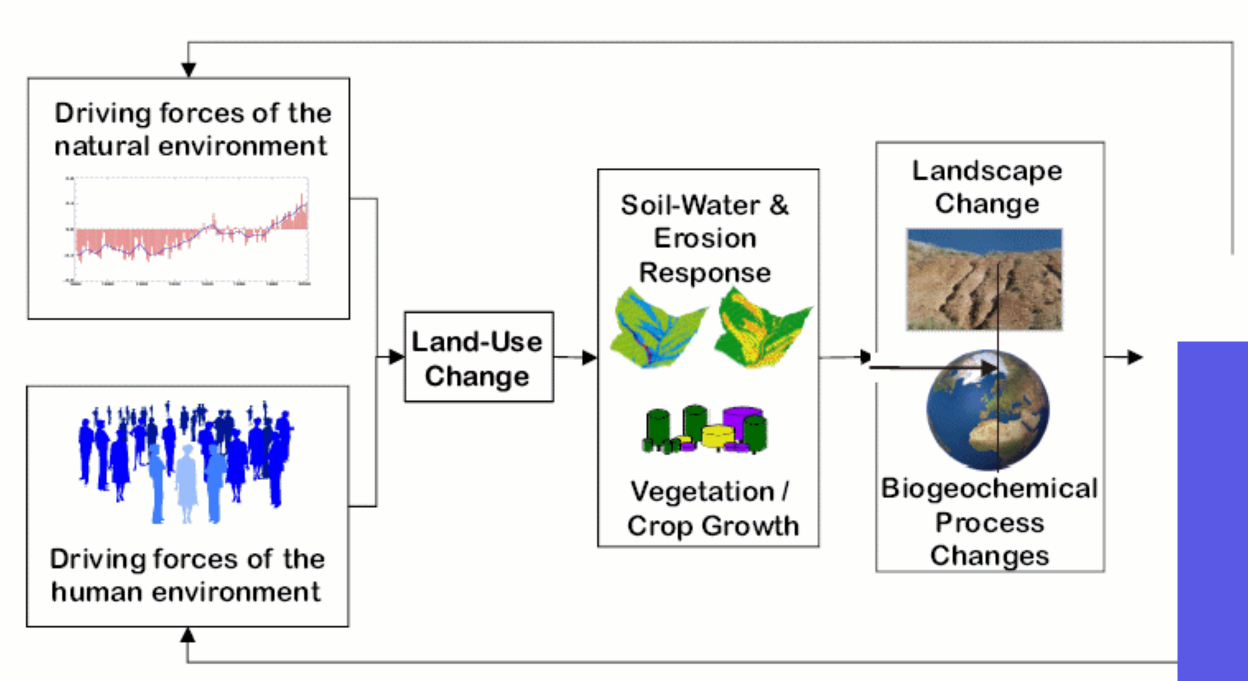
The challenge is:

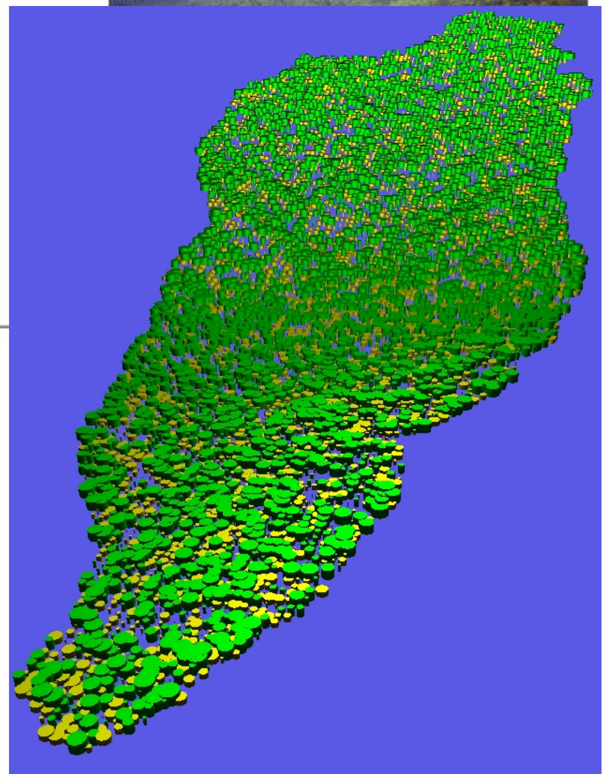
- To develop a modelling system for the biosphere broadest terms, which can represent in functional form how it is influenced by, and itself influences, human activities and the climate system
- To establish a modelling framework that allows such a modelling system to be fully coupled with the physical system.

Courtesy: Prof. Guy Brasseur (2011)

Example of **Individual Based Models** for representing ecosystems and **Agent Based Models** for representing human behaviour

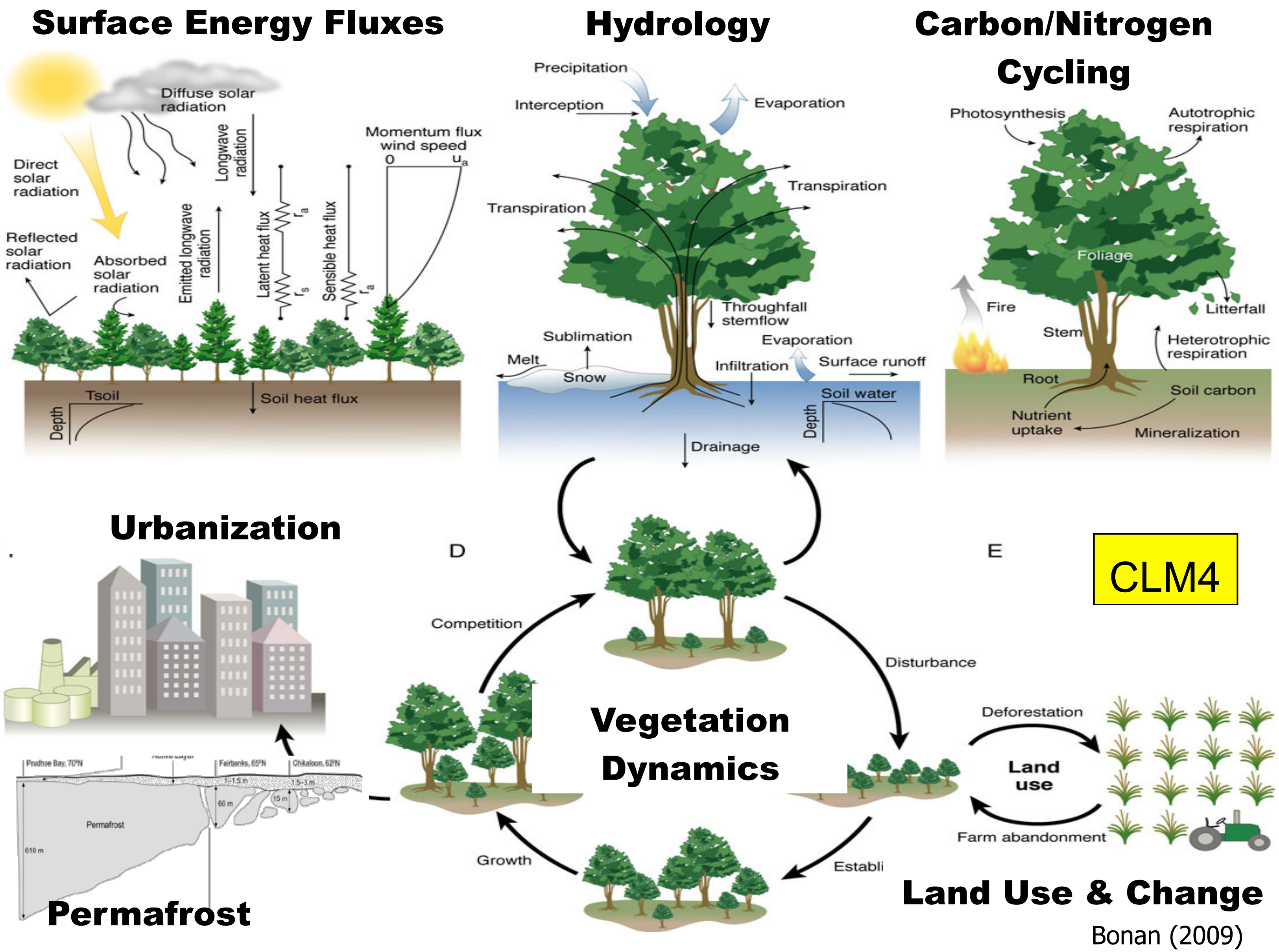
UNIVERSITY OF CAMBRIDGE
Department of Geography





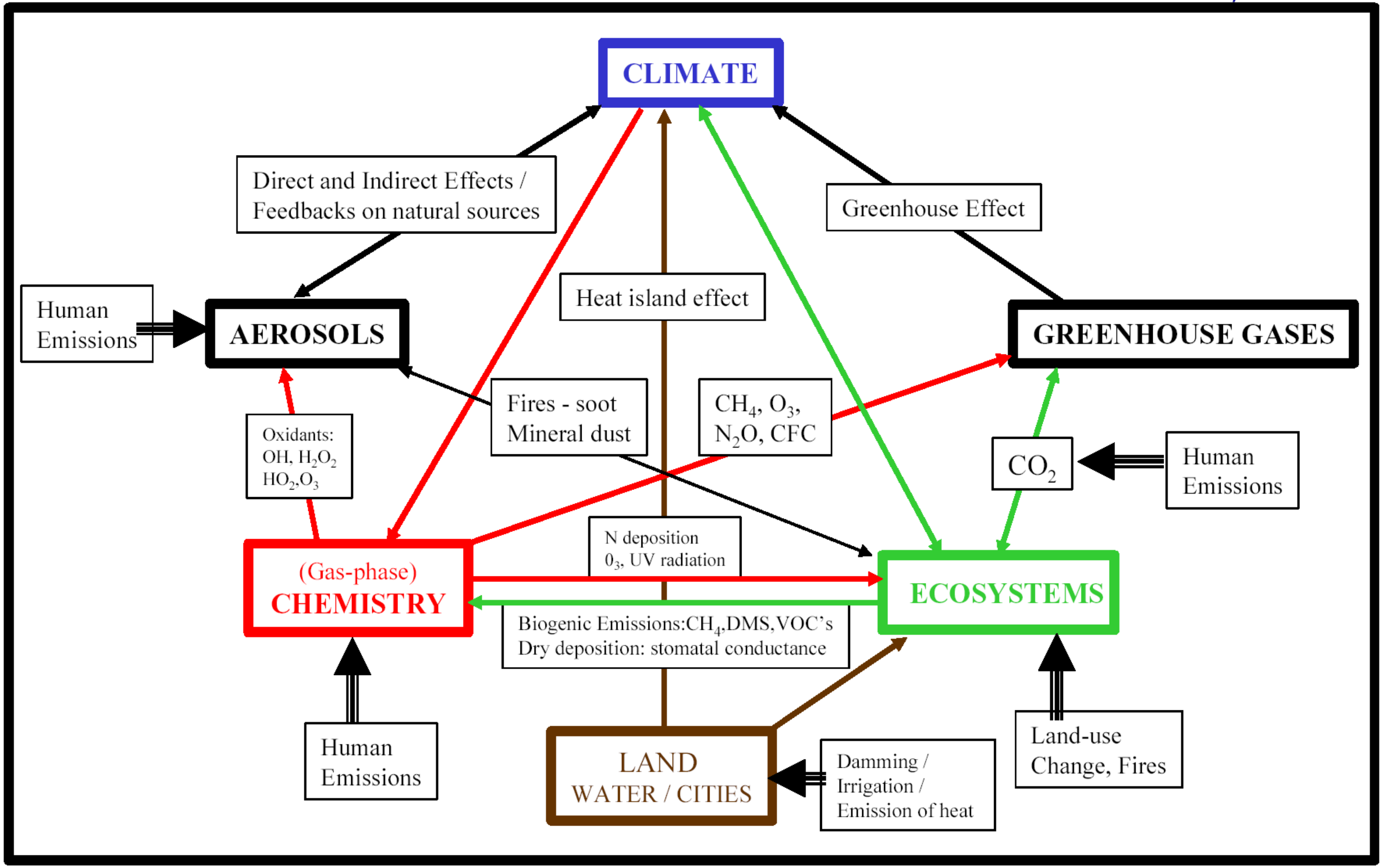
Trees are represented by an individual based model that represents all trees over 5 years in age over the study region. Over time the trees grow, and are cut down by people, represented as individual agents, each with their own unique behavior.

Community Land Model 4



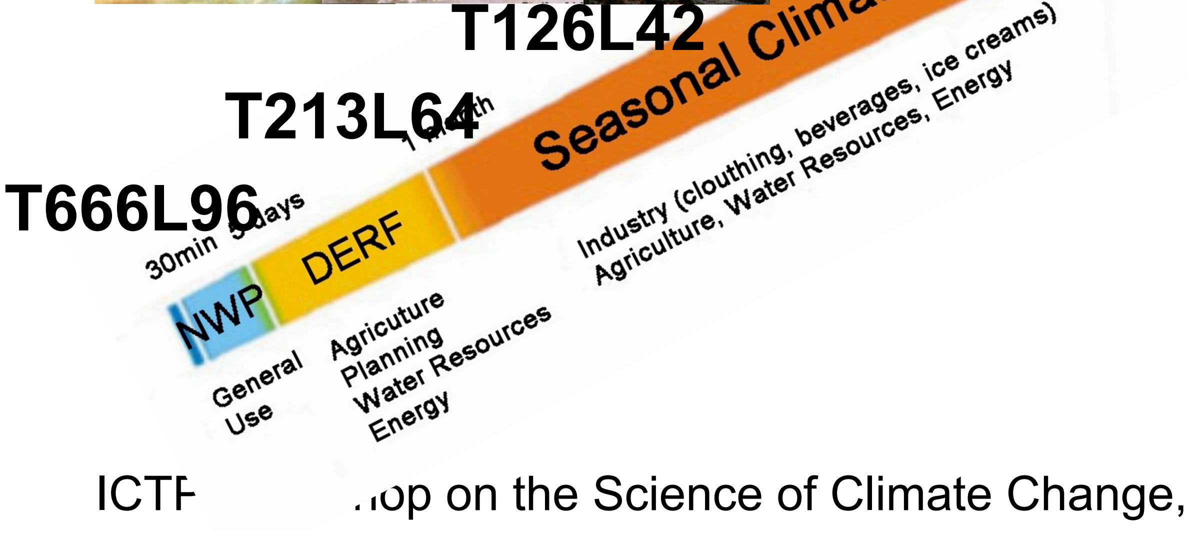
Climate/Chemistry/Ecology/Hydrology

Based on P. Cox, 2004

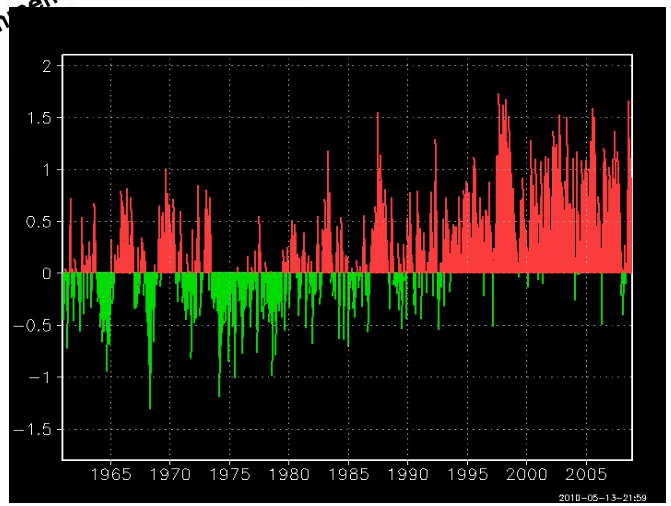


The Brazilian ESM - BESM development strategy:
One-Model: From Weather Forecasting to Global Climate Change Scenarios

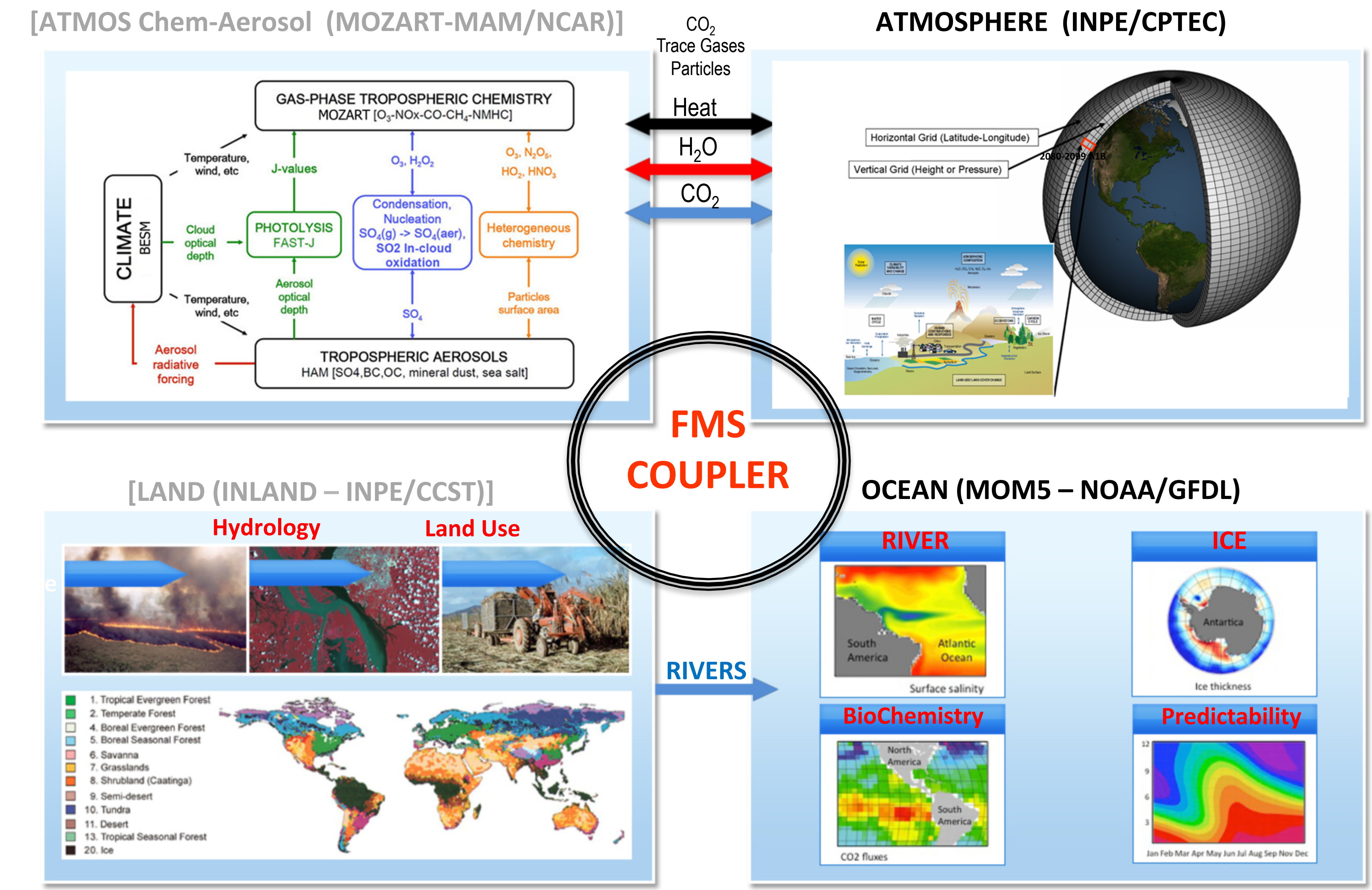
Extreme Events Hit Brazil



Surface Temperature Trend in Brazil



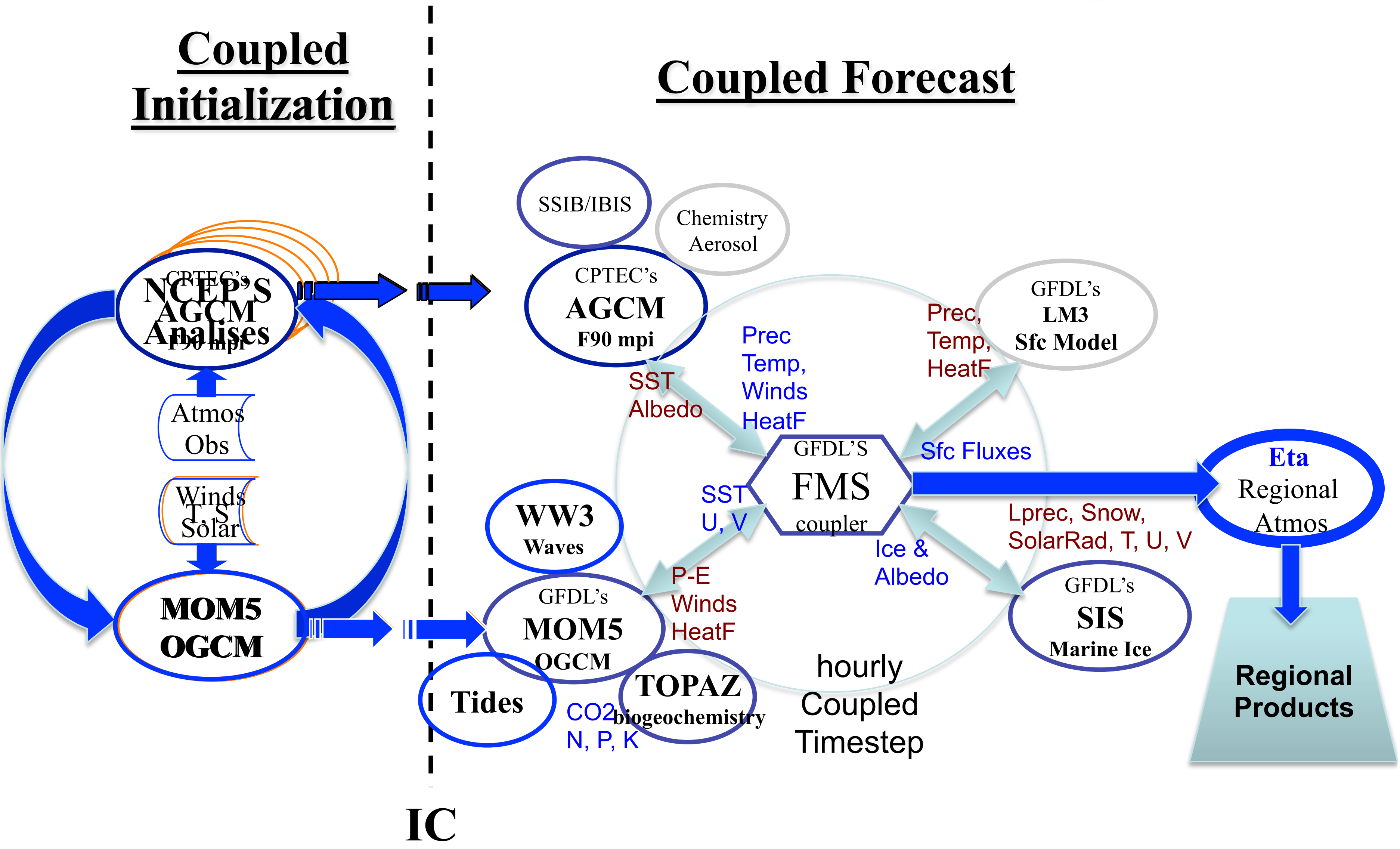
BESM Component Models



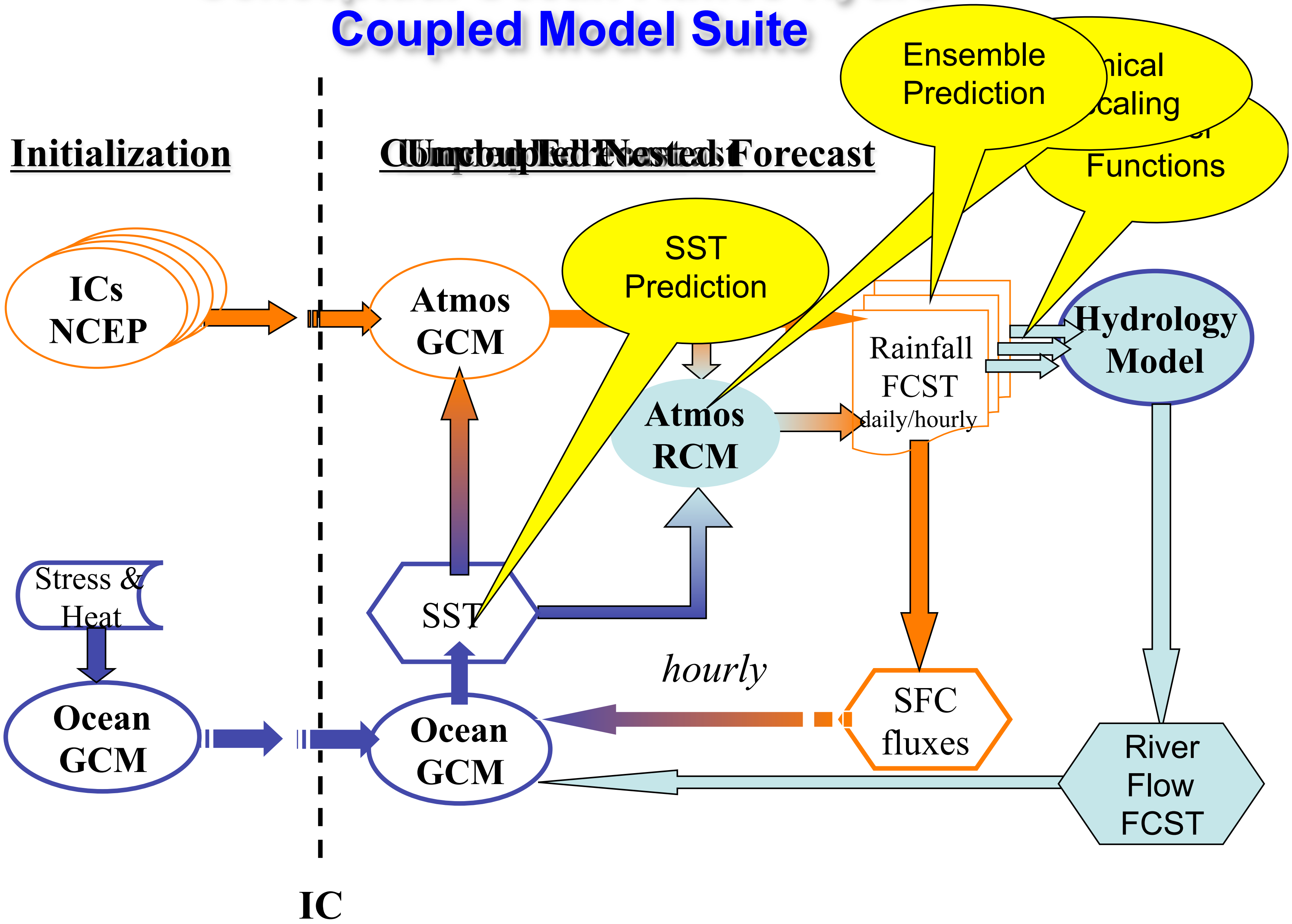
Courtesy: Paulo Nobre

ICTP Workshop on the Science of Climate Change, Antigua, 15 March 2017

BESM
Climate Forecast System



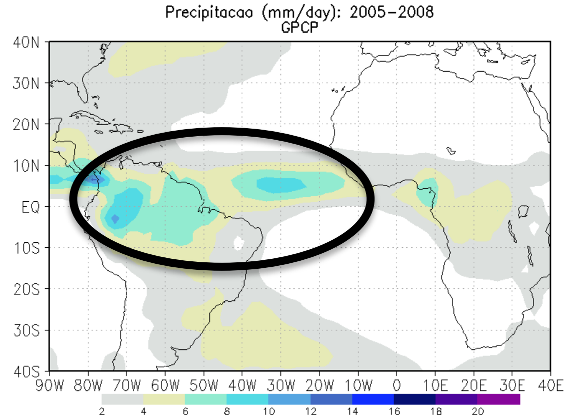
Conceptual Ocean-Atmos-Hydro Coupled Model Suite



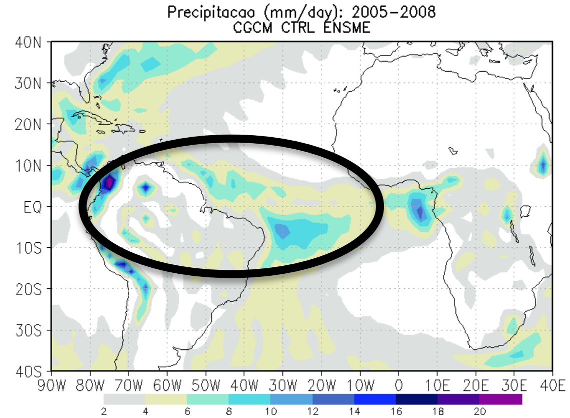
ICTP Workshop on the Science of Climate Change, Antigua, 15 March 2017

Cloud Cover Parameterization in BESM & Amazon Rainfall-Circulation

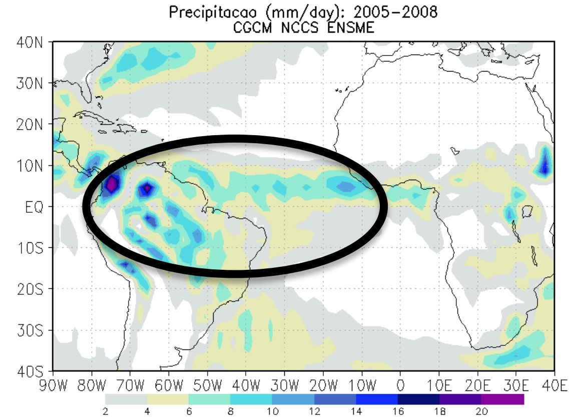
GPCP



BESM 2.3

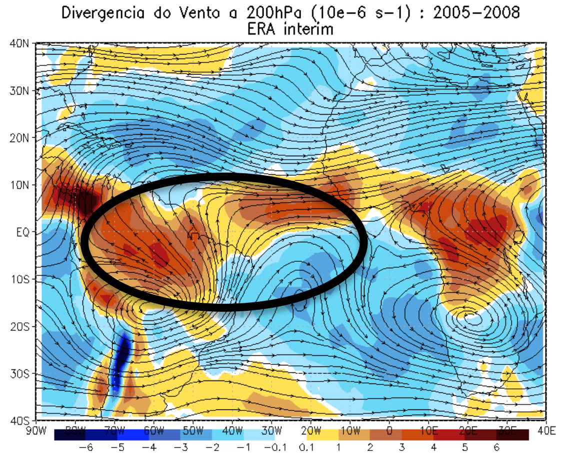


BESM 2.3.1

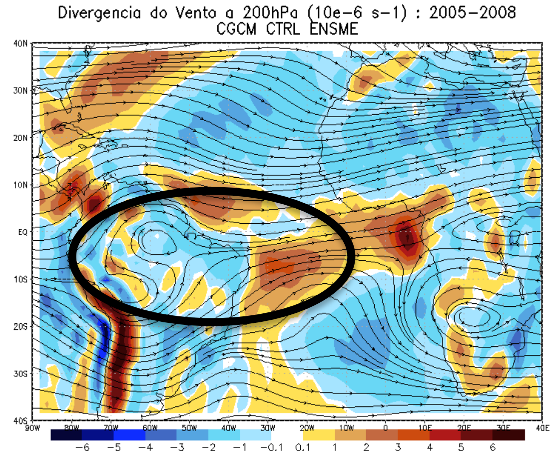


BESM UPPER LEVEL FLOW

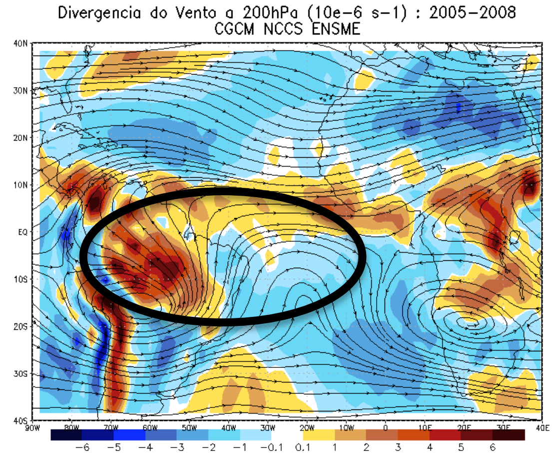
ERA interim REANALISYS



BESM 2.3



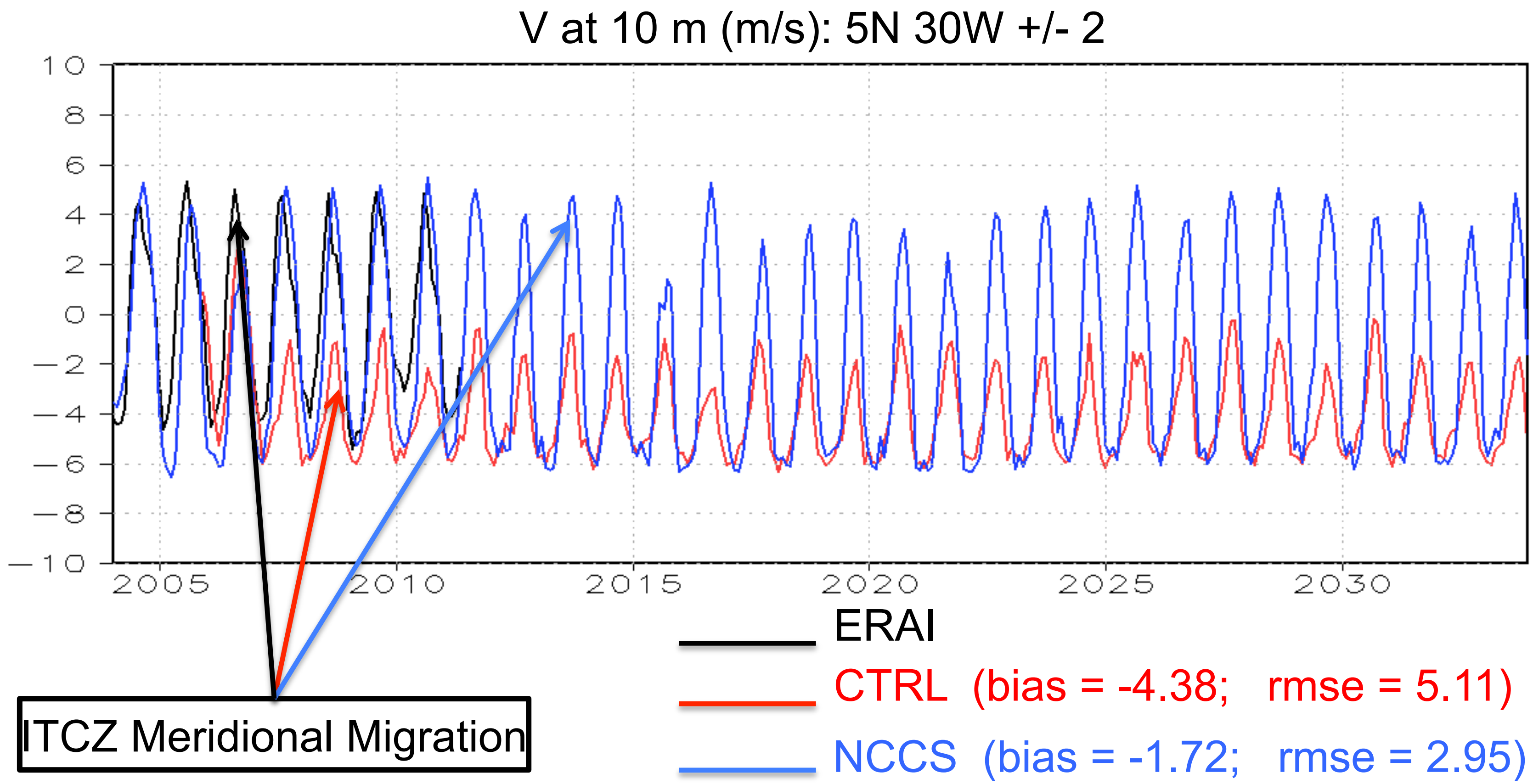
BESM 2.3.1



Bottino and Nobre (2017), Submitted

ICTP Workshop on the Science of Climate Change, Antigua, 15 March 2017

BESM Atlantic ITCZ simulations



Bottino and Nobre (2017), Submitted

ICTP Workshop on the Science of Climate Change, Antigua, 15 March 2017

BESM version 2.7 – under construction

SPECTRAL DYNAMICS: Semi_Lagrangian (<=25km) Eulerian (>25km)

S-L **RADIATION**: RRTMG

PBL: dry MY2.0; moist Park

Deep **CONVECTION** Grell

Cloud MICROPHYSICS: Ferreir-1M

CHEMIMSTRY: <MOZART>

AEROSSOLS: <MAM>

ATMOSPHERE

FMS COUPLER

LAND

VEGETATION: SSiB, LM3

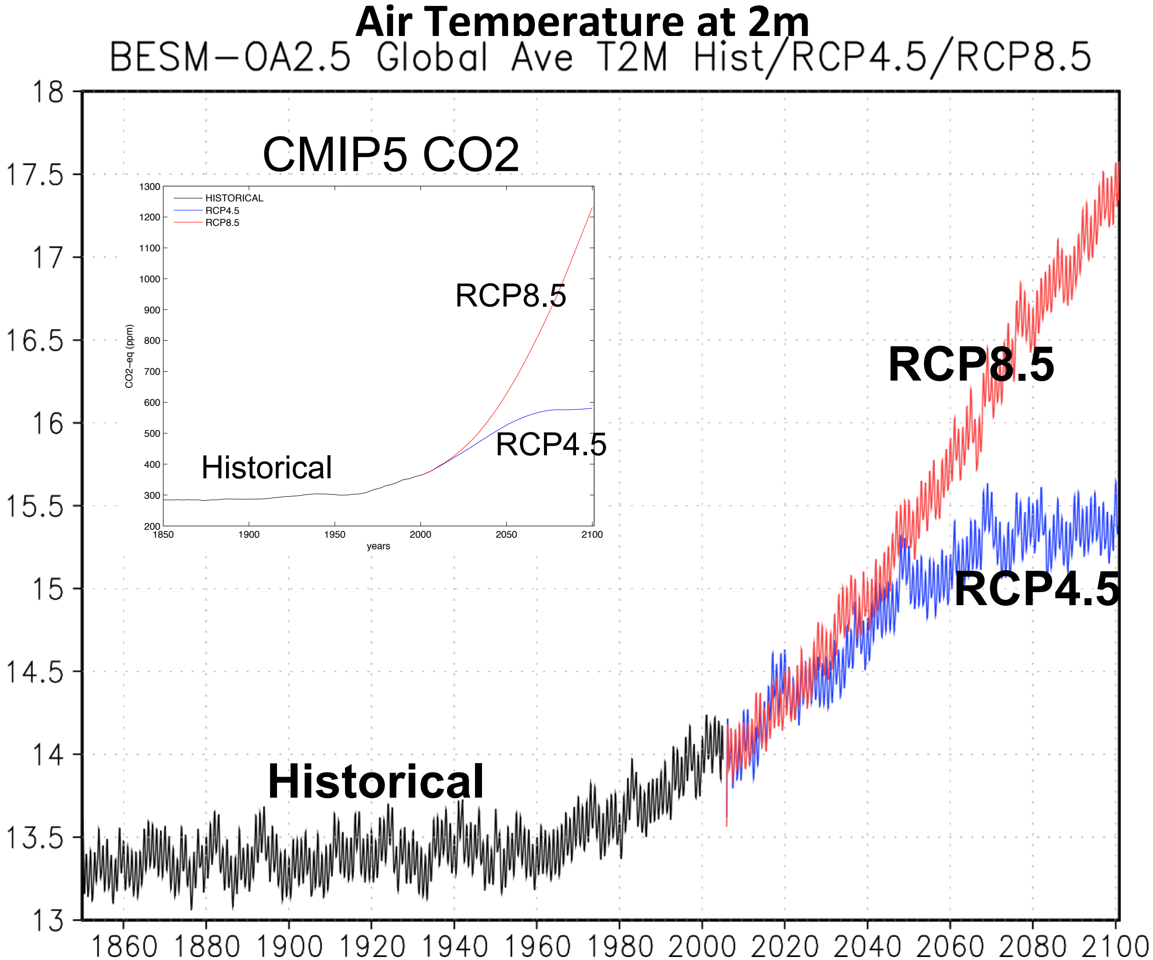
HIDROLOGY: THMB <HAND>

OCEAN

MOM5: KPP <GISSVM>

MOM5: TOPAZ, SIS

BESM2.5 CMIP5 Runs 1850-2100



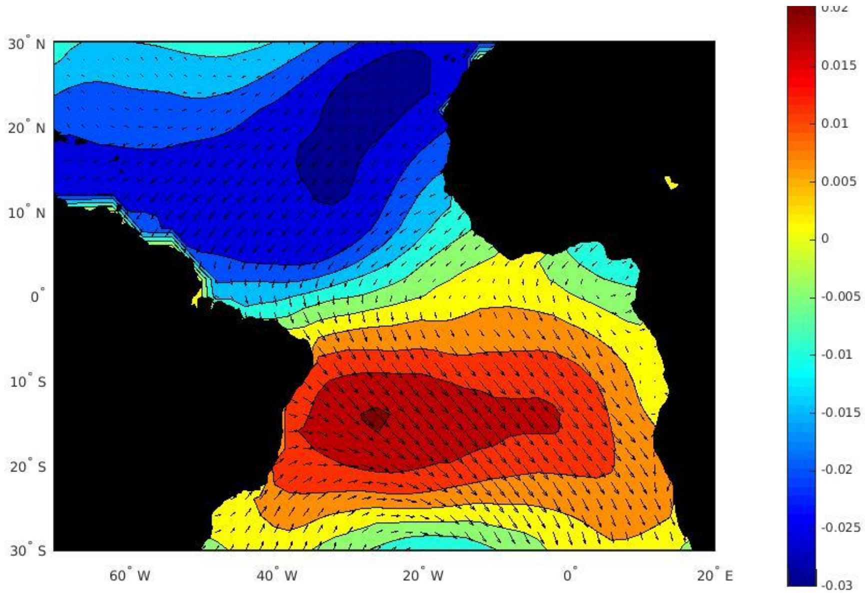
Courtesy: V. Capistrano, INPE

ICTP Workshop on the Science of Climate Change, Antigua, 15 March 2017

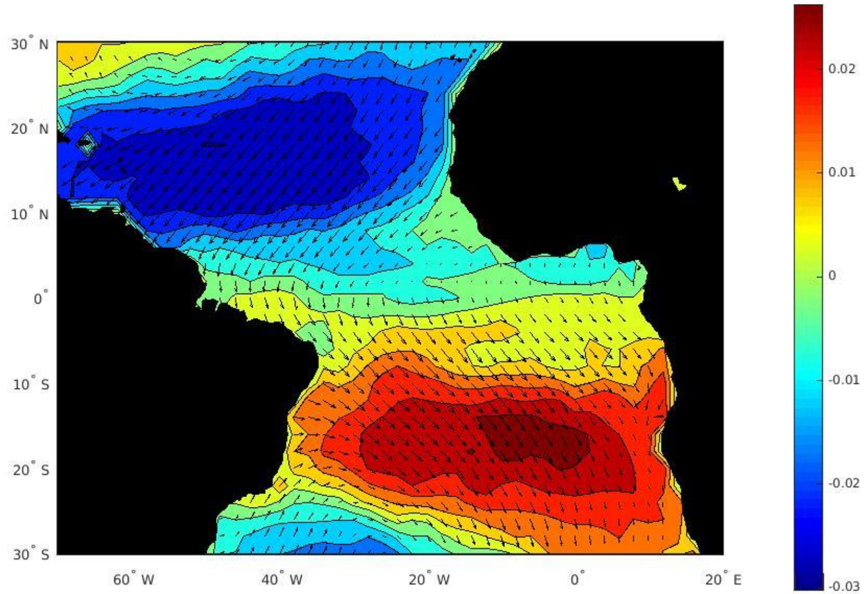
Atlantic Meridional Mode

SST, Taux, Tauy Joint EOF1

ERSSTv4 (9.3%)



BESM2.5 historical run (11.4%)

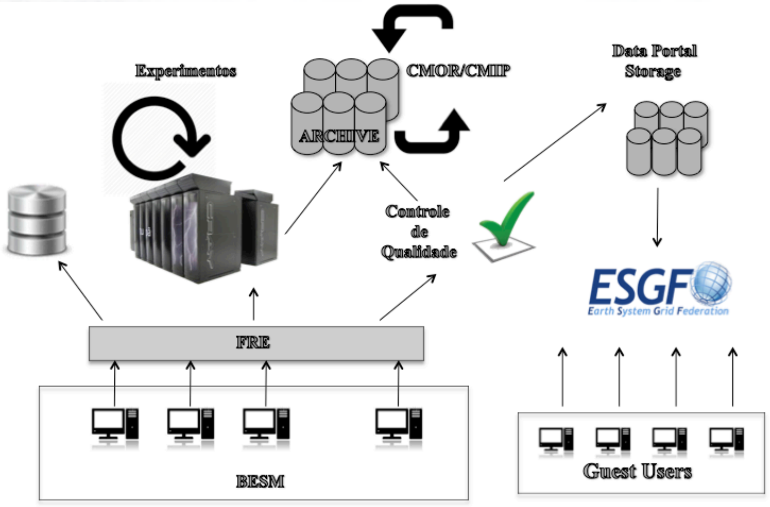


S. Veiga et al (2017) in preparation

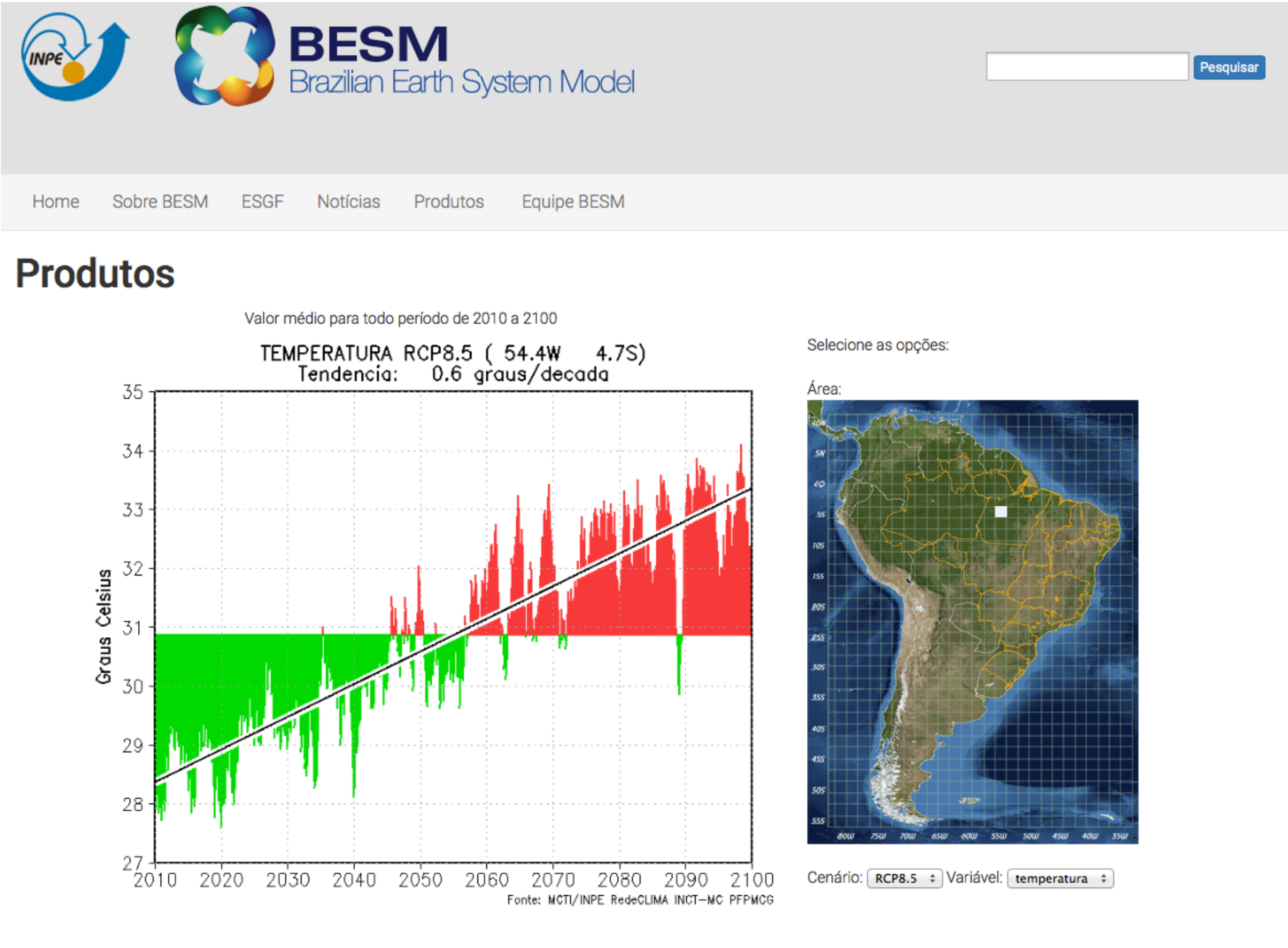
BESM CMIP5 scenarios

available through ESGF at:

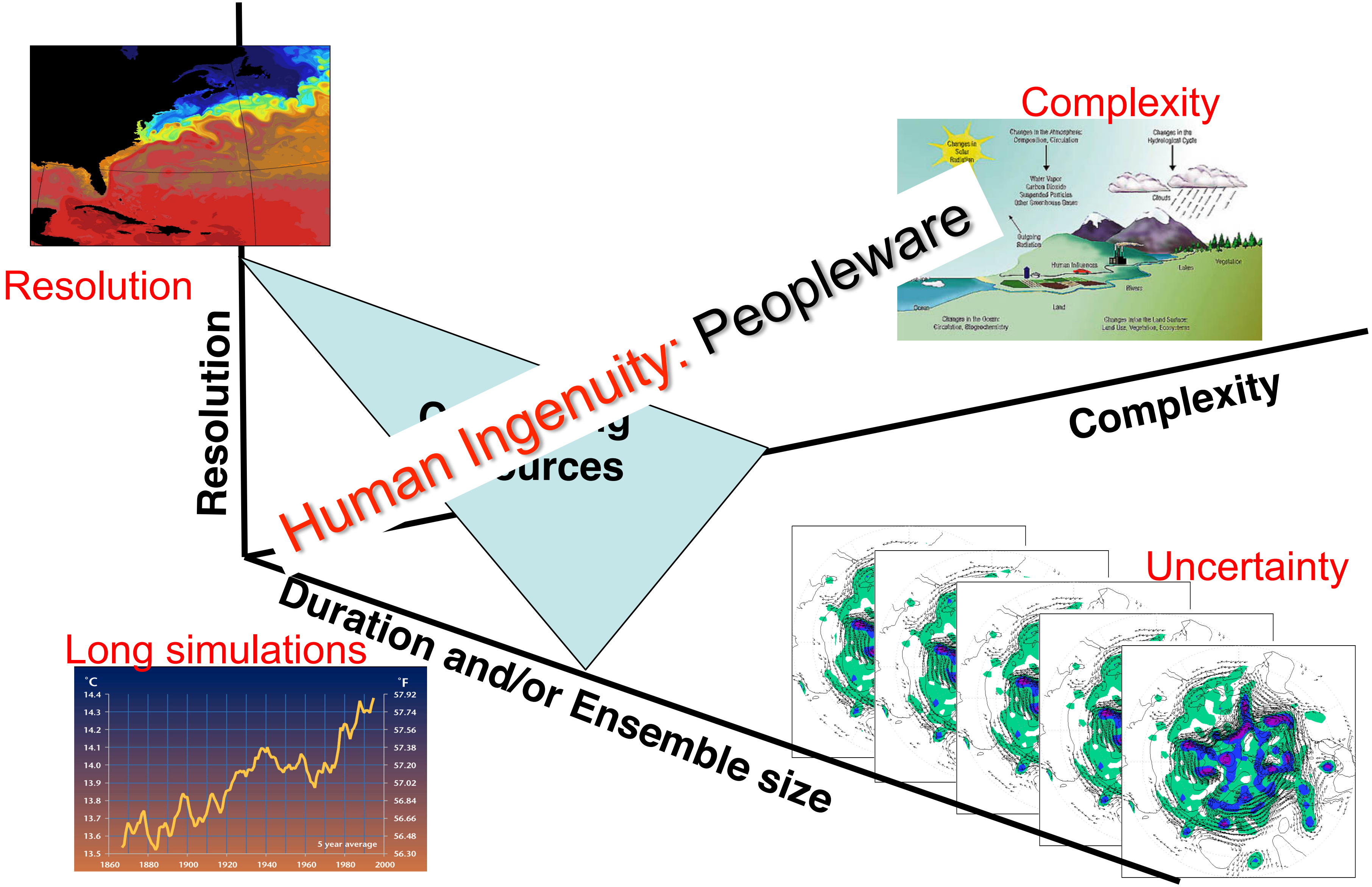
https://dm2.cptec.inpe.br/projects/esgf-inpe/



http://besm.ccst.inpe.br/produtos/



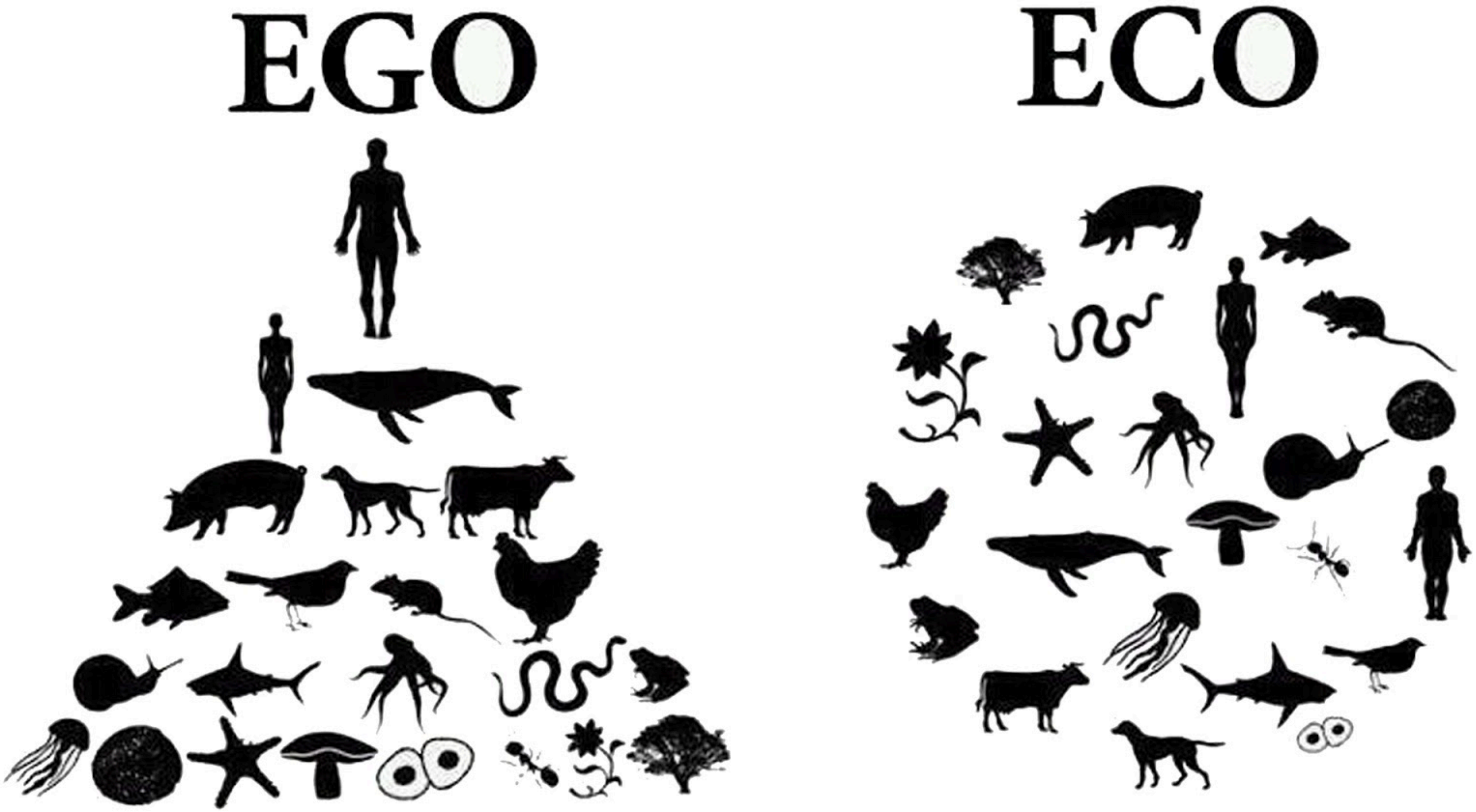
Competing demands of resolution, complexity, uncertainty, and long integrations in Climate System Modelling:



Courtesy: Prof. J. Shukla

ICTP Workshop on the Science of Climate Change, Antigua, 15 March 2017

Cooperation:
a superior form of evolution.



Source: Scharmer and Senge, Theory U

Thank you for your attention

paulo.nobre@inpe.br