# Módulo 1

# Introducción al modelado del sistema climático

¿Qué es un modelo climático? (global, regional)

¿Cómo se usa?

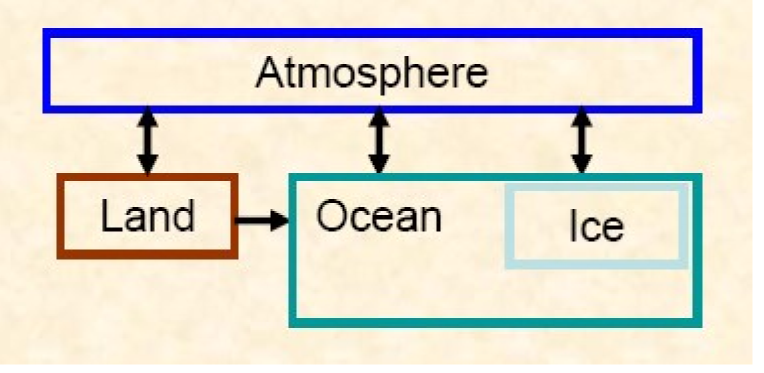
¿Podemos confiar en sus resultados?

¿Cuáles son las fuentes de incertidumbre?

¿Cómo evolucionan los modelos?

¿Qué es un modelo climático global acoplado?

Un GCM es una representación matemática de las principales componentes del sistema climático y de sus interacciones. Las ecuaciones de un GCM se resuelven en un retículo global tridimensional y se resuelven en un ordenador.

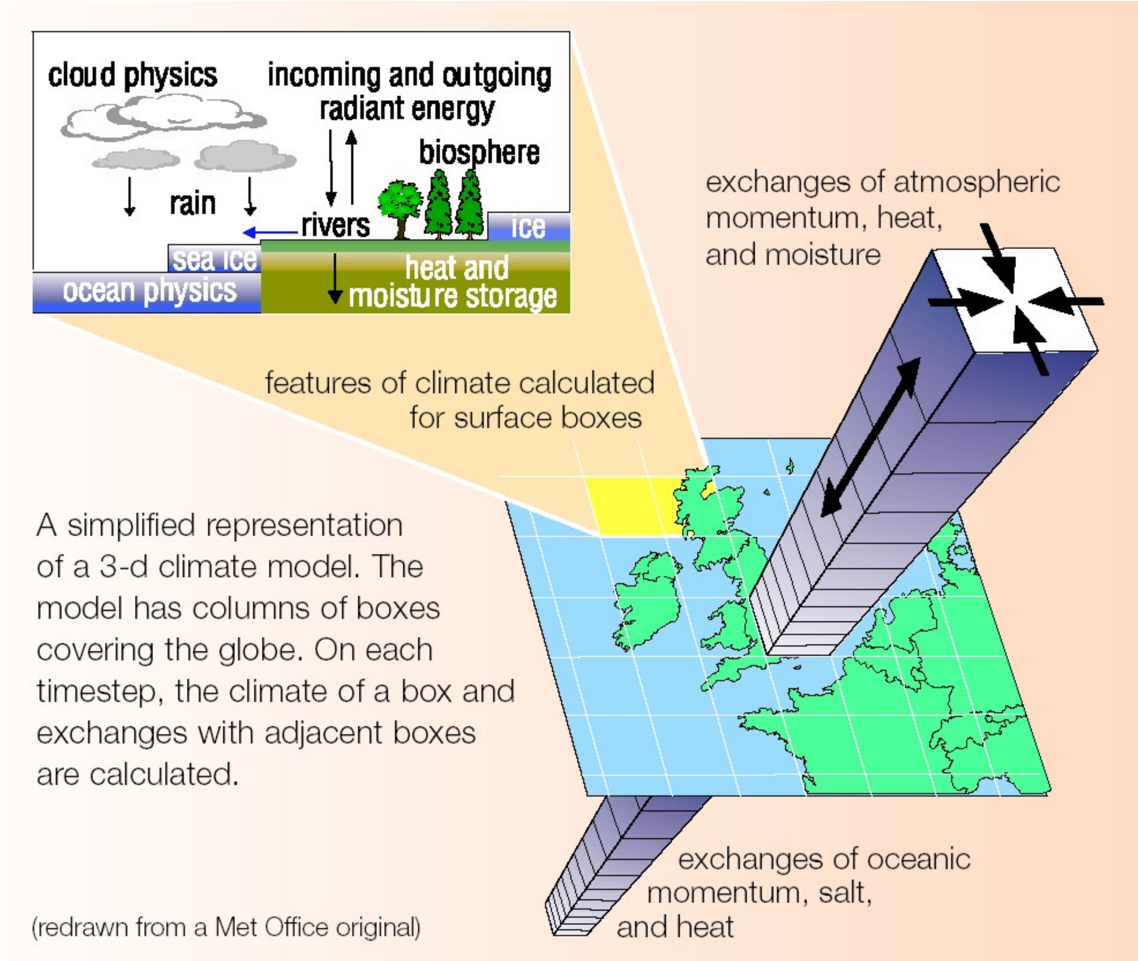


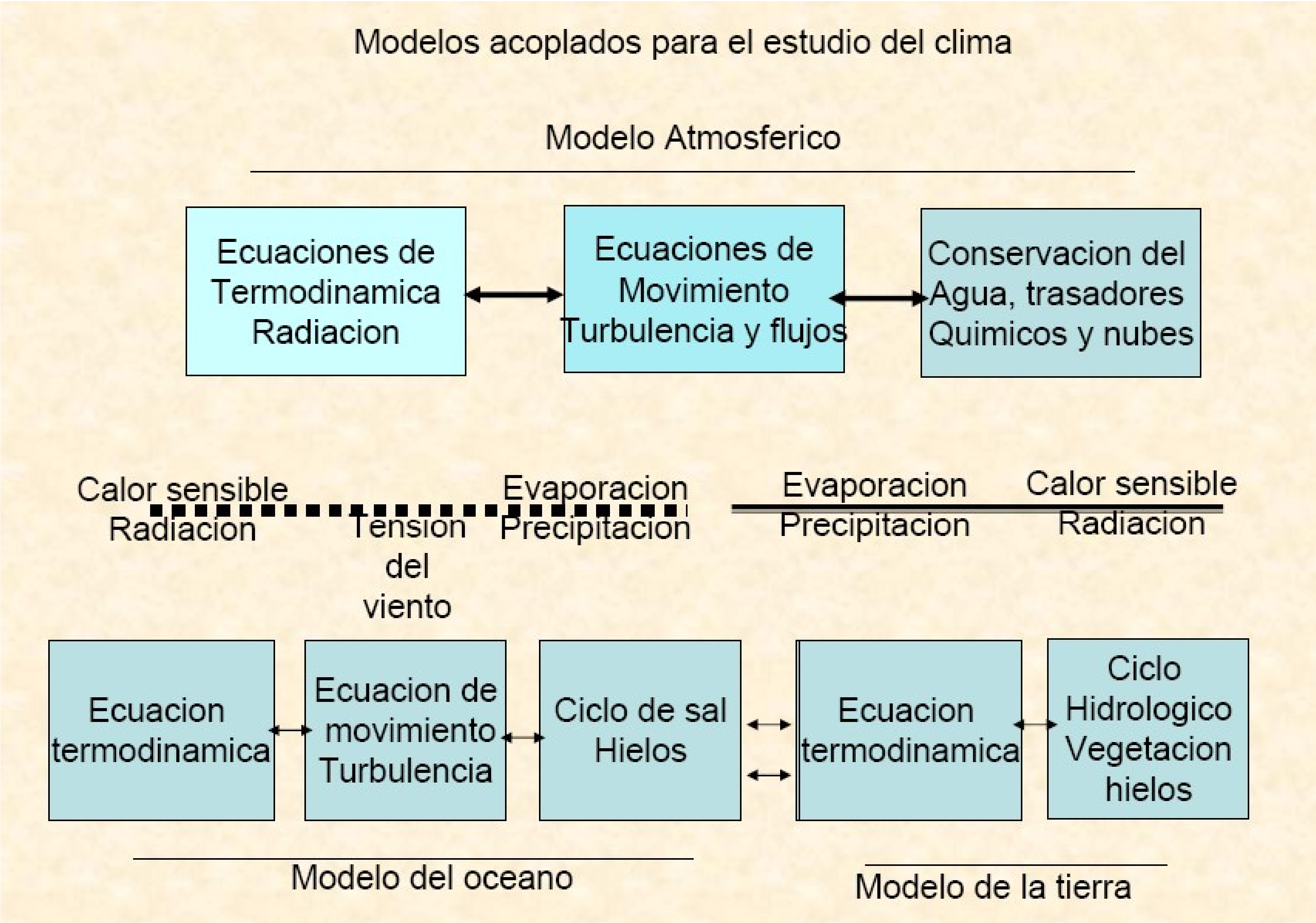
# General Circulation Model or Global Climate Model (GCM): Computer models of the Earth-atmosphere system

**A numerical model solving the Navier-Stokes equations (+ some more) using a collection of boxes in the horizontal and in the vertical covering the whole earth**

- **100-300 km wide**
- **about 30-100 on top of each other**

**The time step is around 30 min**





Modelos acoplados para el estudio del clima
Modelo Atmosferico
Ecuaciones de Termodinamica Radiacion
Ecuaciones de Movimiento Turbulencia y flujos
Conservacion del Agua, trasadores Quimicos y nubes
Calor sensible Radiacion
Tension del viento
Evaporacion Precipitacion
Evaporacion Precipitacion
Calor sensible Radiacion
Ecuacion termodinamica
Ecuacion de movimiento Turbulencia
Ciclo de sal Hielos
Ecuacion termodinamica
Ciclo Hidrologico Vegetacion hielos
Modelo del oceano
Modelo de la tierra


(I. Orlanski)

Simulación explícita vs parametrización

. Procesos simulados explícitamente: escala mayor que la escala del retículo, simulación basada en el conocimiento científico teórico (principios de conservación de energía, masa y momento). Ejemplo: circulación de gran escala.

. Procesos parametrizados: escala menor que la escala del retículo, las formulaciones están guiadas por principios físicos, pero también hacen uso de información estadística obtenida de datos observacionales. Ejemplo: nubes.

The information needed to run a GCM (atmosphere and ocean) is:

Initial state of all the variables in all boxes.

A description of the land surface (topography and land use)

Solar radiation

Gas and aerosol composition of the atmosphere

# 3D Computer Models of the Earth-Atmosphere System

►Resources needed to run a coupled GCM (atmosphere and ocean)

• Climate models are run on computers in the 10-teraflop range (1 teraflop = $10^{12}$ flops)

• Despite this speed, models on these computers are still coarse-grained, (horizontal resolution coarser than 100 kilometres) and takes several weeks to perform a typical climate change simulation

• Super computer (many processors & many TB disk)

• Takes ~2 weeks for 100 years simulation

(→ ~5-6 weeks for a 250 years climate change simulation)

• Each doubling of a model's horizontal resolution requires a factor of 8x increase in computational power

¿Cómo/para qué se usan los GCMs?

Diagnóstico: e.g. clima actual, último máximo glacial

Detección y atribución: rol del forzante antropogénico en las variaciones climáticas del siglo 20

Pronóstico:
Escenarios del siglo 21
Predicción decadal
Predicción estacional / interanual

# Limitations of a GCM

- To run a coupled GCM takes ~ 5-7 weeks for 250 years simulation in a super computer

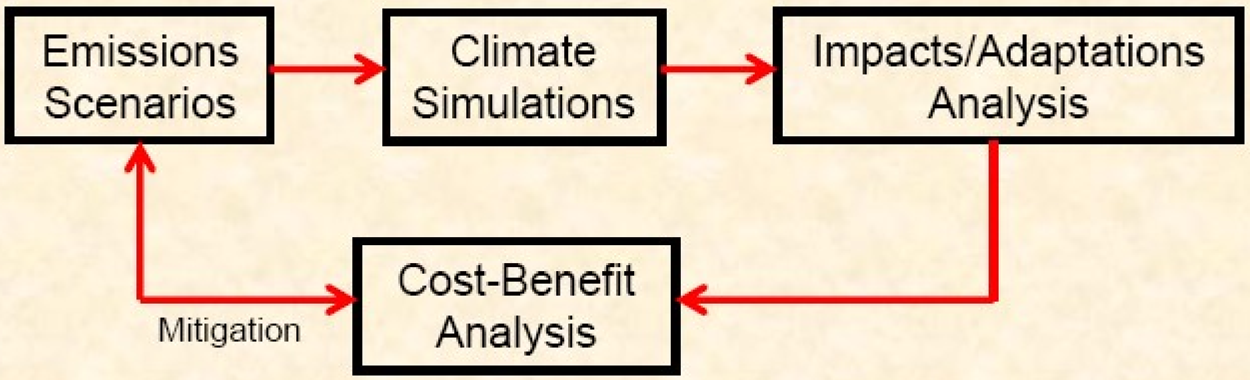
- Inside each box many processes must be described in an approximate way (e.g. clouds)

- High resolution (ie very small boxes) would give us less approximations BUT a very time consuming and slow model.

- Thus, a GCM is a compromise between details in physics and numerical speed of the model (how long simulations we need)!

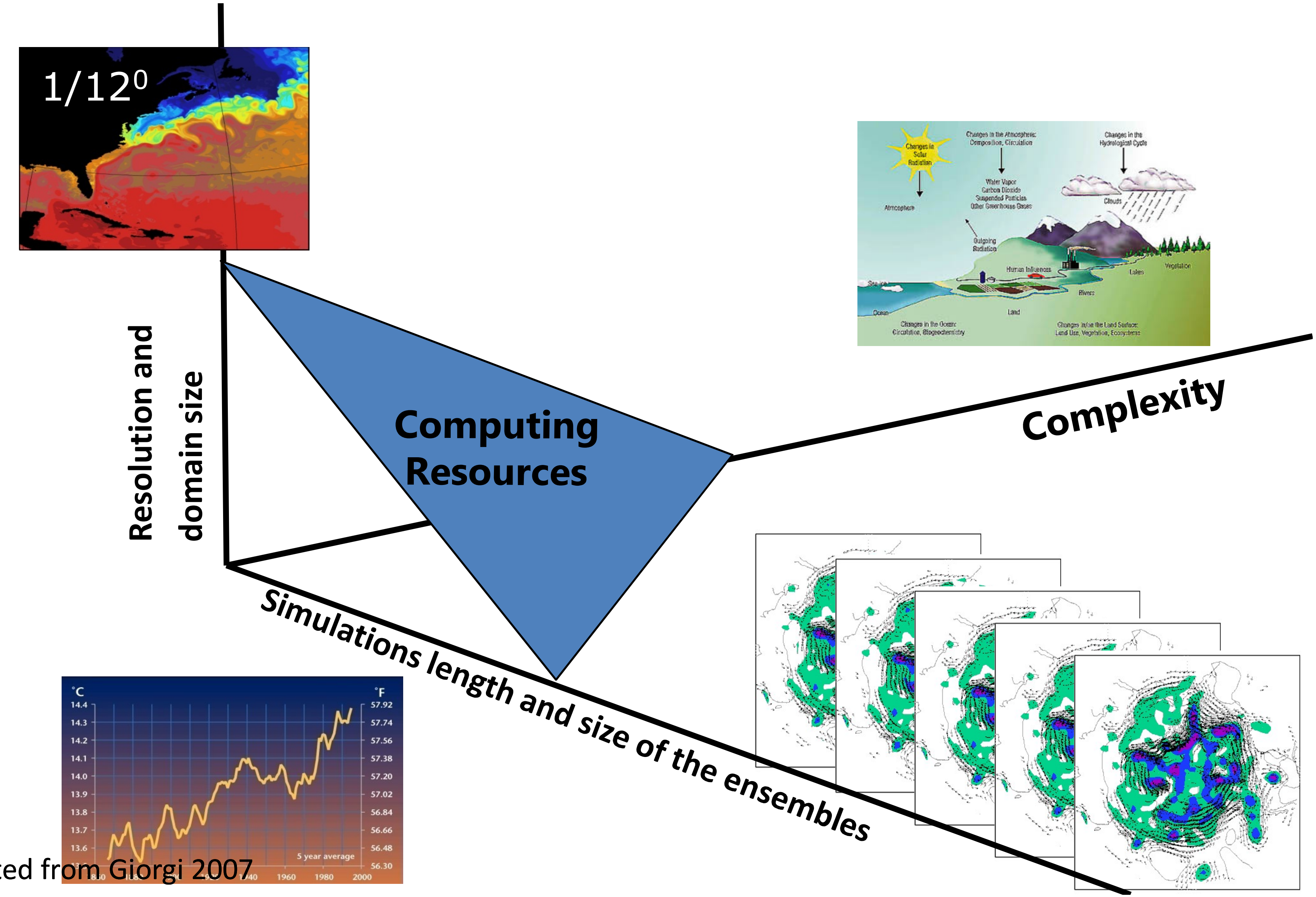
¿Cómo/para qué se usan los GCMs?

# Guia para regulaciones




- Climate modeling is essential for optimal decision-making
- Climate model disagreement is responsible for *part* of the uncertainty
- Climate modeling informs but does not prescribe policy

# Competing demands to improve climate simulations




Adapted from Giorgi 2007

¿Cómo se podrían mejorar los GCMs?

. Improve completeness: addition of new processes, more comprehensive forcing

. Improve correctness: compare to observations, better theory.

. Improve resolution: climate simulation advances as increased computing power allows better resolution .

(I. Orlanski)

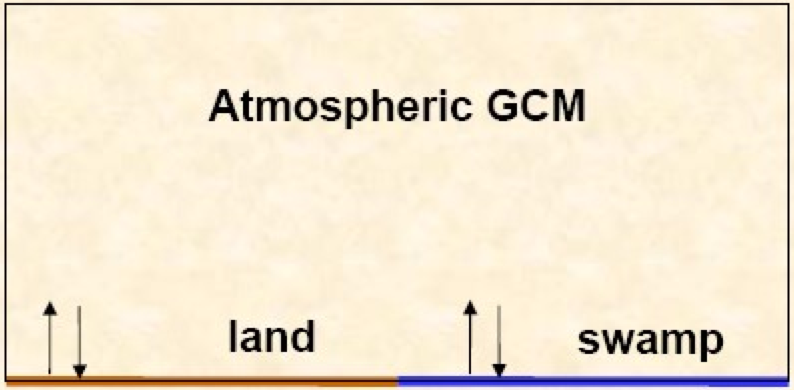
# Tipos de Modelos acoplados

- Atmosphere-swamp ocean
- Atmosphere-mixed layer ocean
- Atmosphere-ocean GCM
- Earth system models of intermediate complexity (EMICs)

# Atmósfera-pantano (océano)

- Ocean is represented as a wet surface with zero heat capacity.
- Surface temperature is interactively determined.
- Albedo of swamp surface increases when temperature falls below freezing.

# Atmósfera-pantano



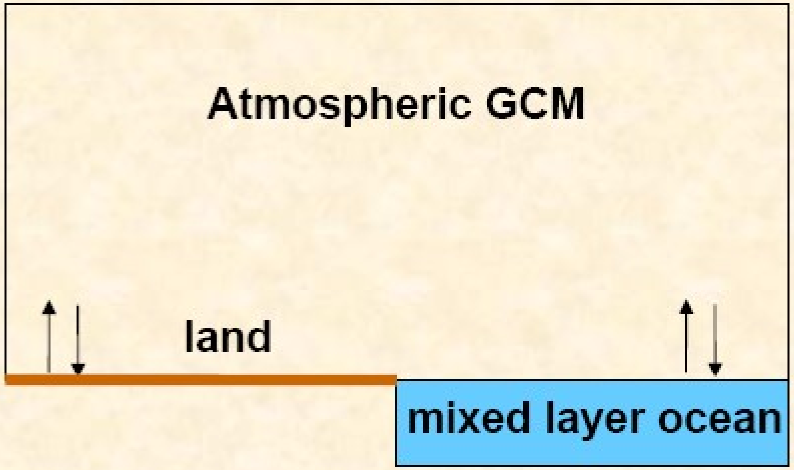

$$S_{\downarrow}(1-\alpha)+F_{\downarrow}-F_{\uparrow}-SH-LH=0$$

# Atmosfera-una capa de oceano

- Ocean is represented as a shallow, motionless slab of water.
- Mixed layer depth is chosen to represent seasonal heat storage in upper ocean.
- Ocean temperature is interactively determined.
- Sea ice thermodynamics are included.

# Atmosfera-una capa de oceano

Mixed layer ocean

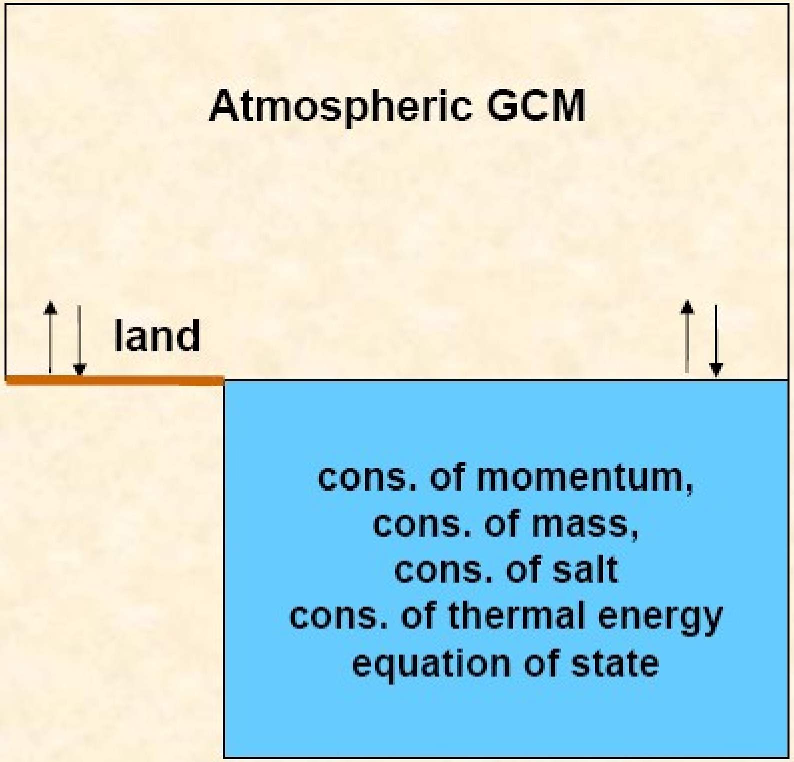



$$\rho c_p h \frac{\partial T}{\partial t} = S_{\downarrow}(1-\alpha) + F_{\downarrow} - F_{\uparrow} - SH - LH$$

# Atmósfera-océano GCM

- Ocean component is a full dynamical ocean model, including advection, diffusion, heat storage.
- Relatively complete representation of physical and dynamical feedbacks between atmosphere and ocean.

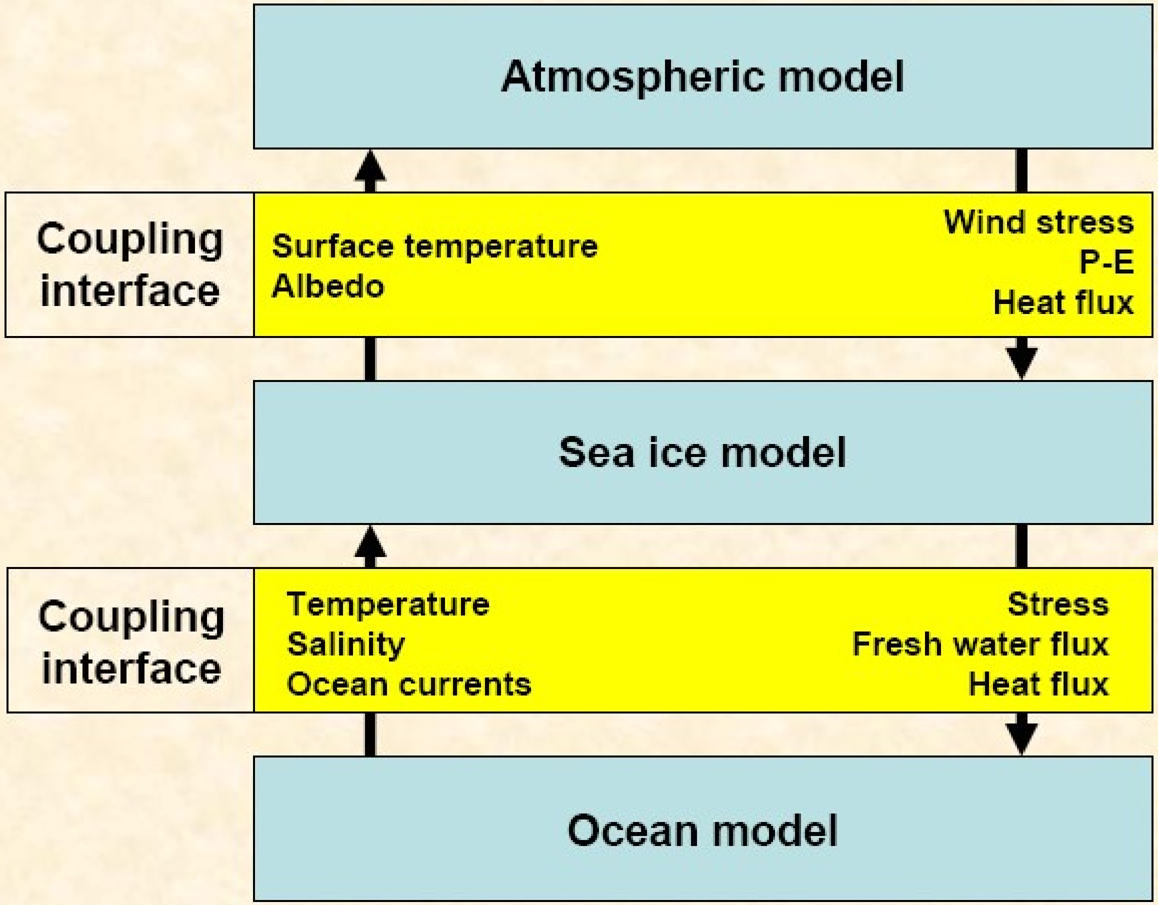
# Atmósfera-Océano GCM



# Métodos de acoplamiento

- Communication between components is an essential element of coupled models.
- Model component codes are often developed separately, so grids can be different, making regridding necessary.
- Frequency of communication must be managed, particularly given the difference in response times of atmosphere and ocean.

# Métodos de acoplamiento: Ejemplo

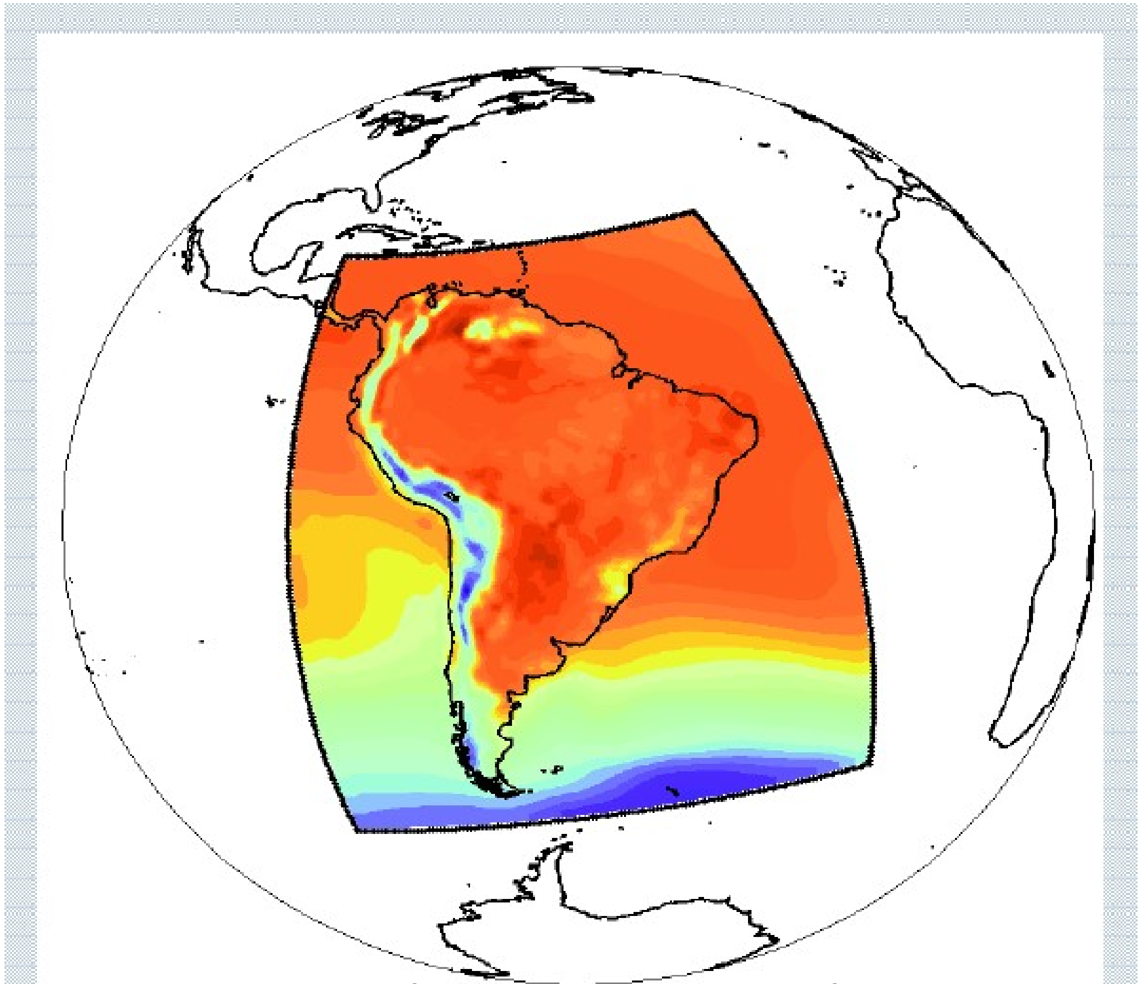


**¿Cómo se obtiene información climática a mayor resolución para una dada región? "Anidando" un modelo climático de área limitada de alta resolución (10 a 50 km) en un modelo global (técnica llamada *dynamical downscaling*)**

# Regional climate modeling

RCA domain

Resolution:
50km



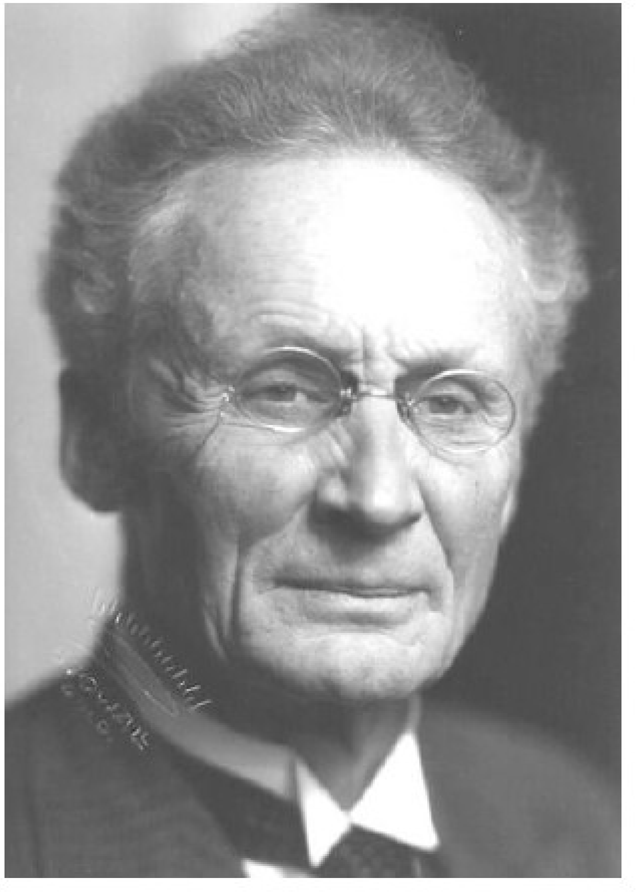
**Collaboration Rossby Centre/SMHI (Sweden) - CIMA/CONICET-UBA (Argentina)**

P.Samuelsson, SMHI

# Un poco de historia…

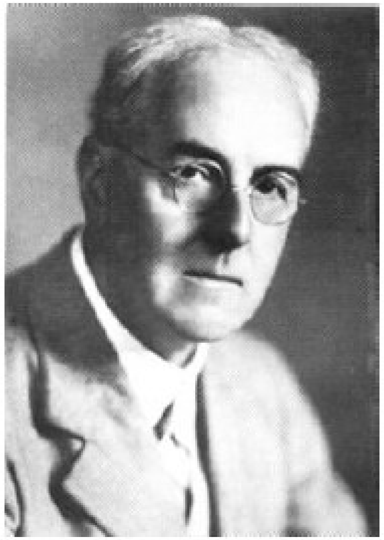
# ~1900

**100 years ago, Vilhem Bjerknes (1862-1951) understood that it is possible to predict the weather by solving differential equations.**



# 1922

"The scheme is complicated because the atmosphere is complicated, but it has been reduced to a set of computing forms. These are ready to assist anyone who wishes to make partial experimental forecasts from such incomplete observational data as are now available. In such a way it is thought that our knowledge of meteorology might be tested and widened, and concurrently the set of forms might be revised and simplified. Perhaps some day in the dim future it will be possible to advance the computations faster than the weather advances and at a cost less than the saving to mankind due to the information gained. But that is a dream..."



**L. F. Richardson**


**Richardson's Forecast Factory**

# WEATHER PREDICTION

BY

# NUMERICAL PROCESS

BY

LEWIS F. RICHARDSON, B.A., F.R.MET.SOC., F.INST.P.

FORMERLY SUPERINTENDENT OF ESKDALEMUIR OBSERVATORY

LECTURER ON PHYSICS AT WESTMINSTER TRAINING COLLEGE

CAMBRIDGE

AT THE UNIVERSITY PRESS

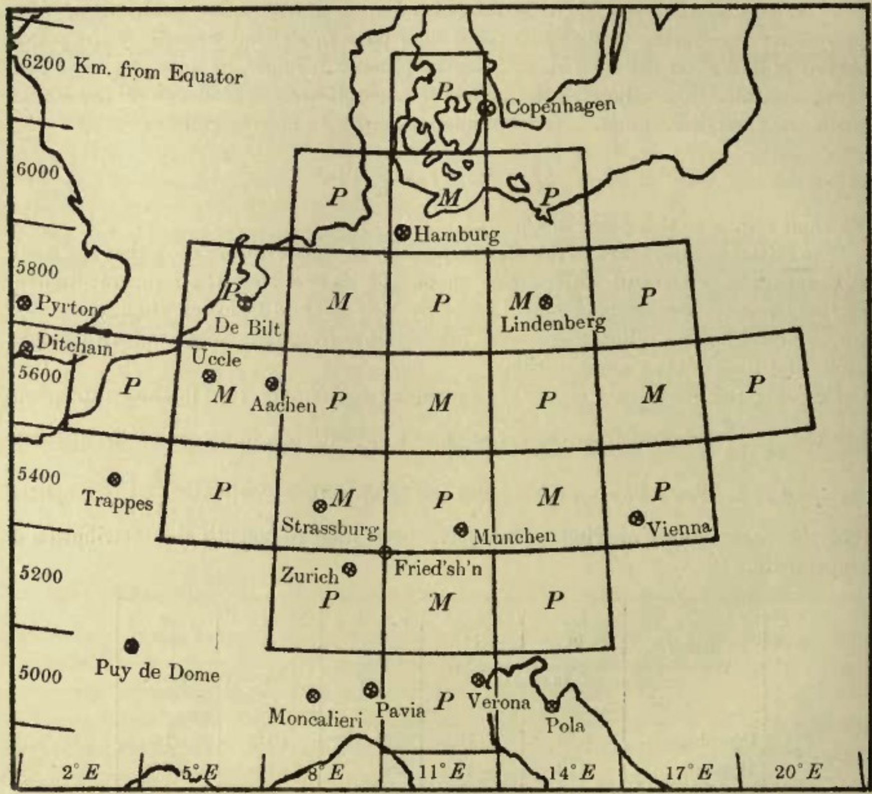
1922



**The temperature of the soil** is required at a series of depths. The depths proposed in Ch. 4/10/0 appear to be unnecessarily thin when their thermal conductance is compared with that of the atmospheric strata, and so the alternate divisions are here omitted, leaving those at $z_{12}=6\cdot39$, $z_{14}=53\cdot6$ cm etc. The temperature is required at intermediate depths which, by following the process of gradation proposed in Ch. 4/10/0, are taken to be $z_{11}=1\cdot72$, $z_{13}=19\cdot1$ cm.

In default of direct observations the temperature at $z_{11}$ may be estimated from the statistics of E. Ebermayer*, for these refer to Bavaria in which the $P$ point to be treated is situated. The mean of six stations for May 1868 shows that the air at a

[*continued on p.* 186]



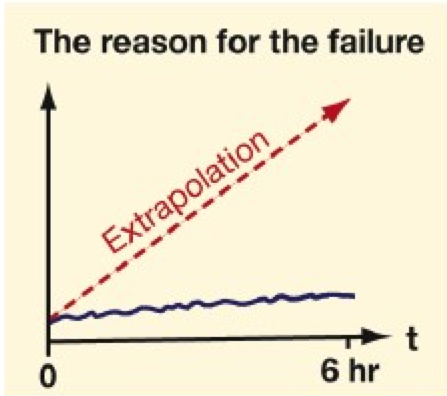

MAP OF POINTS FOR PRESSURE ($P$) AND MOMENTUM ($M$) USED IN THE EXAMPLE of Ch. 9.

NOTE: These points are placed at the centres of the chequers, and to the centres also the latitude and longitude refer. Each chequer measures 3° from west to east and 200 km from south to north.

* *Die physikalischen Einwirkungen des Waldes*, Berlin, Verlag von Wiegandt, Hempel und Parey, 1873.

# Disastrous results

**The surface pressure tendency at a grid point was 145 mb over 6 hours, while the observations showed practically no change.**

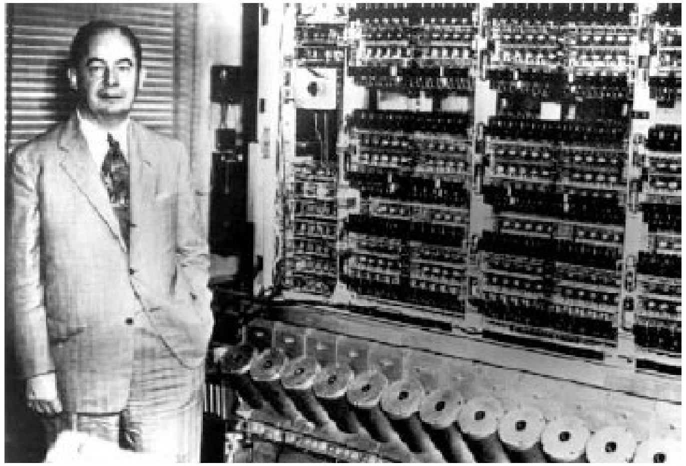



**Charney (1951):**

***"That the actual forecast ... was unsuccessful was in no way a measure of the value of his work... The real value ... lay in the fact that it crystallized once and for all the essential problems that would have to be faced by future workers in the field."***

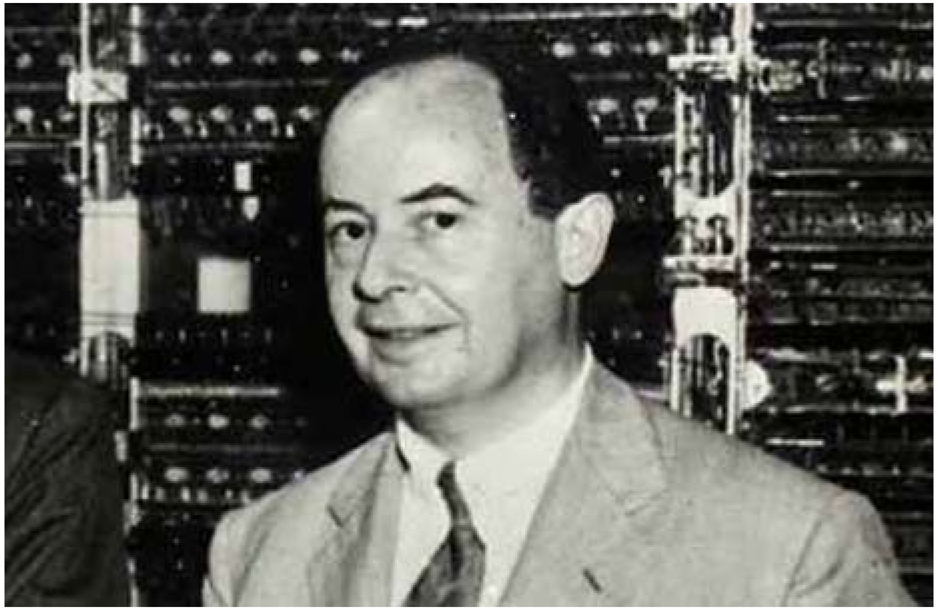
# 1946

**Von Neumann recognizes meteorology as a perfect application for the electronic computer.**

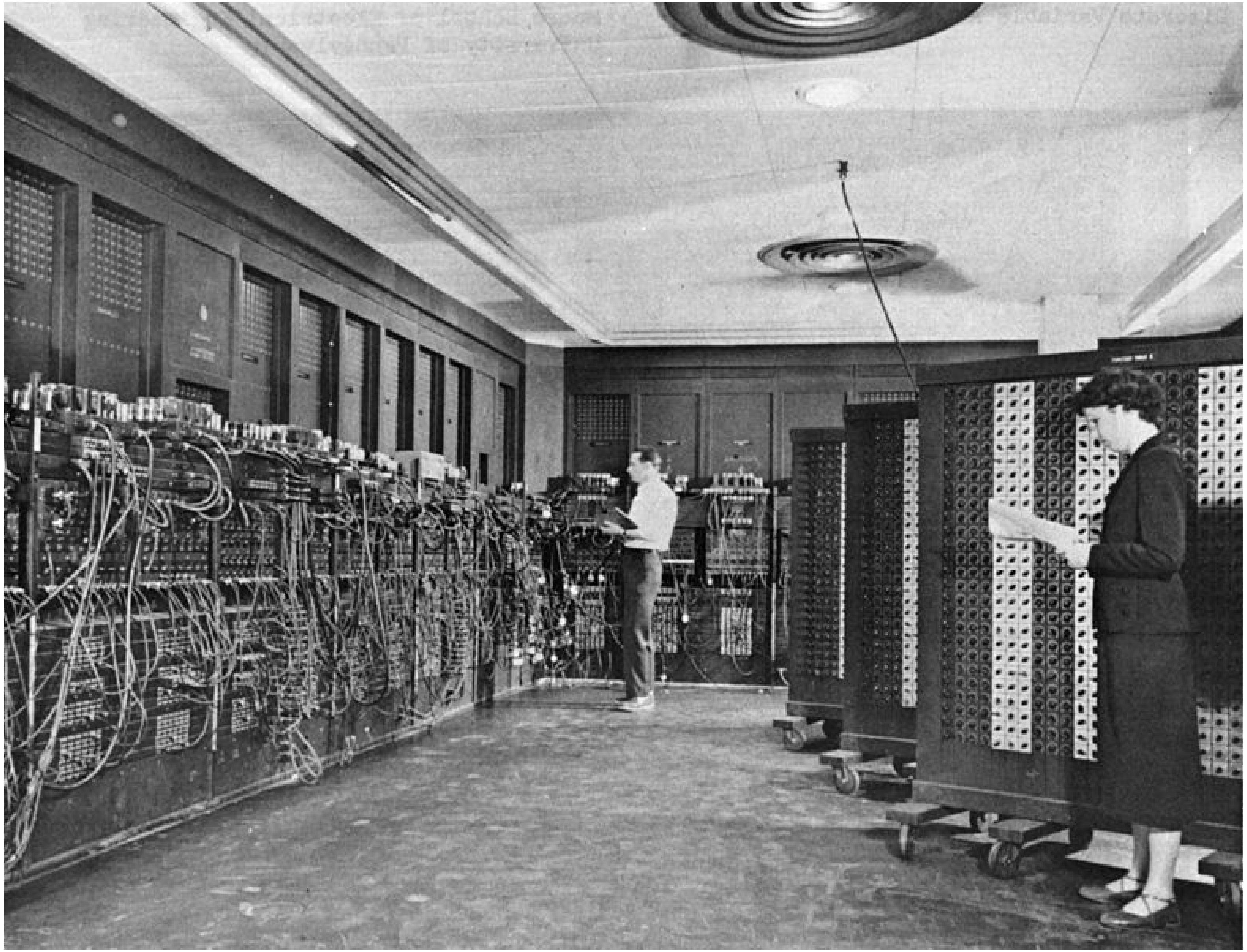


John von Neumann
and ENIAC

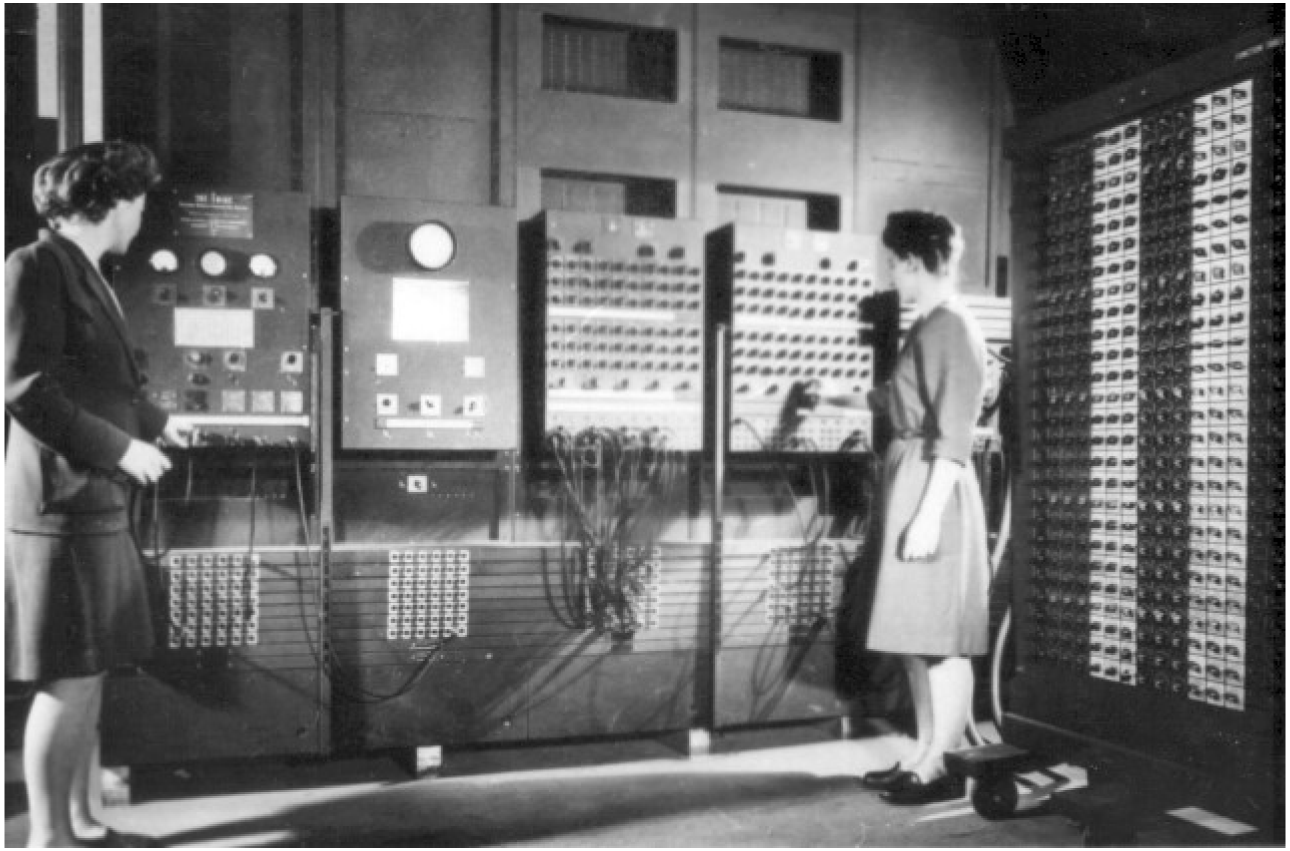
*Numerical Integration of the Barotropic Vorticity Equation (1950)*



Von Neumann's team performed the world's first numerical weather forecasts on the ENIAC computer; von Neumann published the paper *Numerical Integration of the Barotropic Vorticity Equation* in 1950



**ENIAC** (**Electronic Numerical Integrator And Computer**) was the first electronic *general-purpose* computer. It was Turing-complete, digital, and capable of being reprogrammed to solve a full range of computing problems.



Programmers Betty Jean Jennings (left) and Fran Bilas (right) operate ENIAC's main control panel at the Moore School of Electrical Engineering. (U.S. Army photo from the archives of the ARL Technical Library

# 1948

**Charney's paper on midlatitude scale analysis. Charney joins Von Neumann's group at the Institute for Advanced Study.**

**Jule Charney, Norman Phillips, Glenn Lewis, Norma Gilbarg, George Platzman**

***It took them 24 hours to do a one-day simulation.***

# 1950

**First successful numerical forecast, using the nondivergent barotropic vorticity equation.**

**Grid spacing: 736 km**

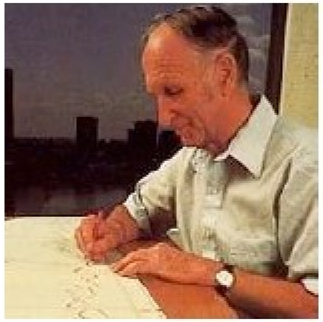
# 1950-55

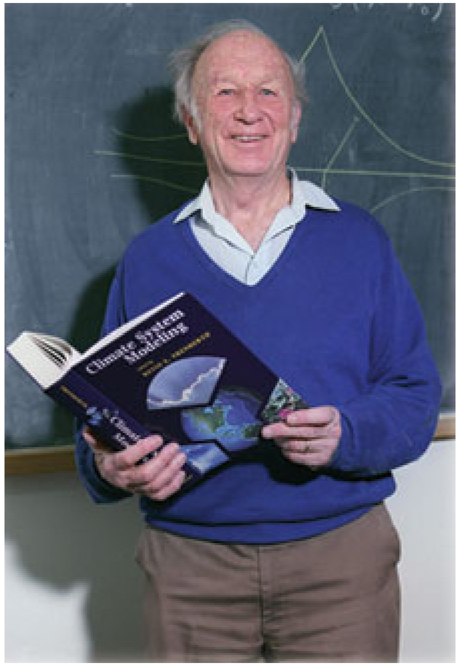
First baroclinic numerical models (Charney and Phillips).
Observational studies of the general circulation by V. Starr's group at MIT.

Rotating annulus experiments at the University of Chicago (D. Fultz).

1955 Operational NWP begins in the U.S., Sweden, Japan, etc.

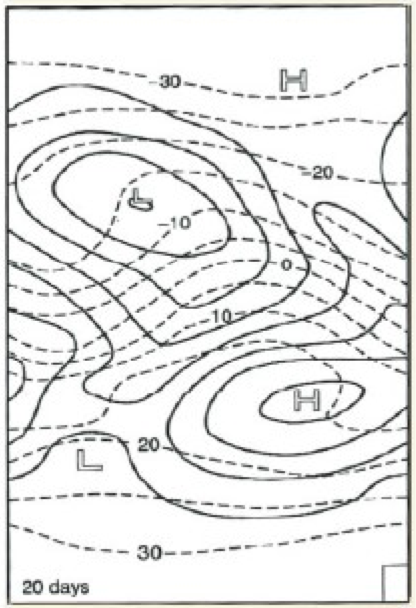
Lorenz publishes his paper on available potential energy.

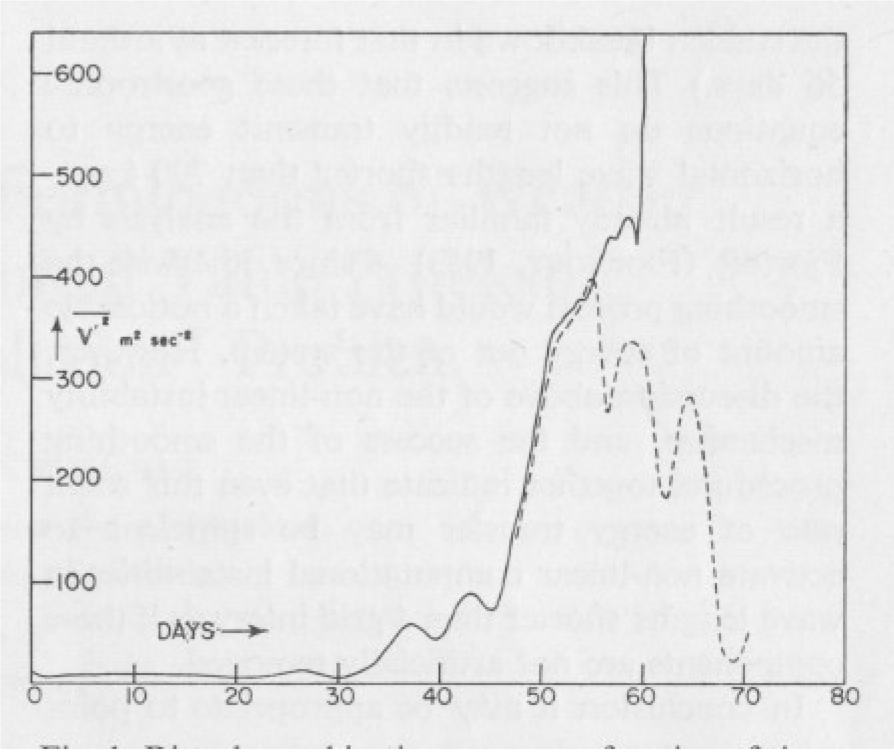




# 1956

**First general circulation model is constructed by N. Phillips, who promptly discovers nonlinear computational instability.**






Phillips had created an experimental general circulation model, one of the first, and it appeared to work, but when the computation was extended beyond a certain time the computed values simply exploded to astronomical values.

-The instability was unaffected by a reduction in the time step.

-The magnitude of the solution values did not simply grow exponentially but remained relatively small and nearly constant before exploding into astronomical values.

# Late 50s

1955-60 Experimental forecasts with the primitive equations (Hinkelman, Germany).

1958 Smagorinsky builds a two-level general circulation model (zonal channel on a sphere).

1959 Phillips publishes an interpretation of nonlinear computational instability.

# The First GCM Results

1963 Smagorinsky publishes his results.

1964 Leith publishes his results.

1965 Mintz publishes results from UCLA.

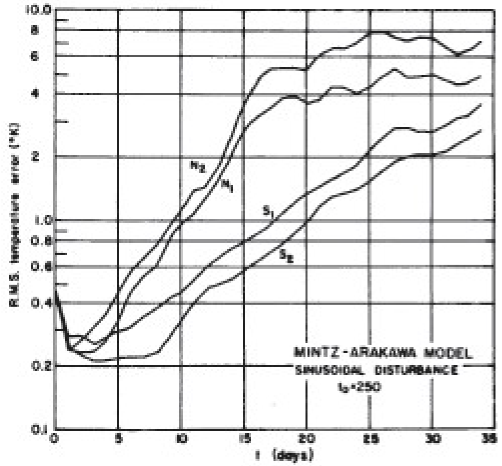
1965 9-level GFDL results are published by Smagorinsky, Manabe, and Holloway.

1967 The NCAR 2-level model is published by Kasahara and Washington.

1969 First ocean GCM results are published by Bryan.

# Mid-60s

1966 Charney makes predictability experiments with the three GCMs.




1966 The “Arakawa Jacobian” is published.

IBM 360/91
2 MFlops

Manabe and colleagues explore the effects of increased $CO_2$.

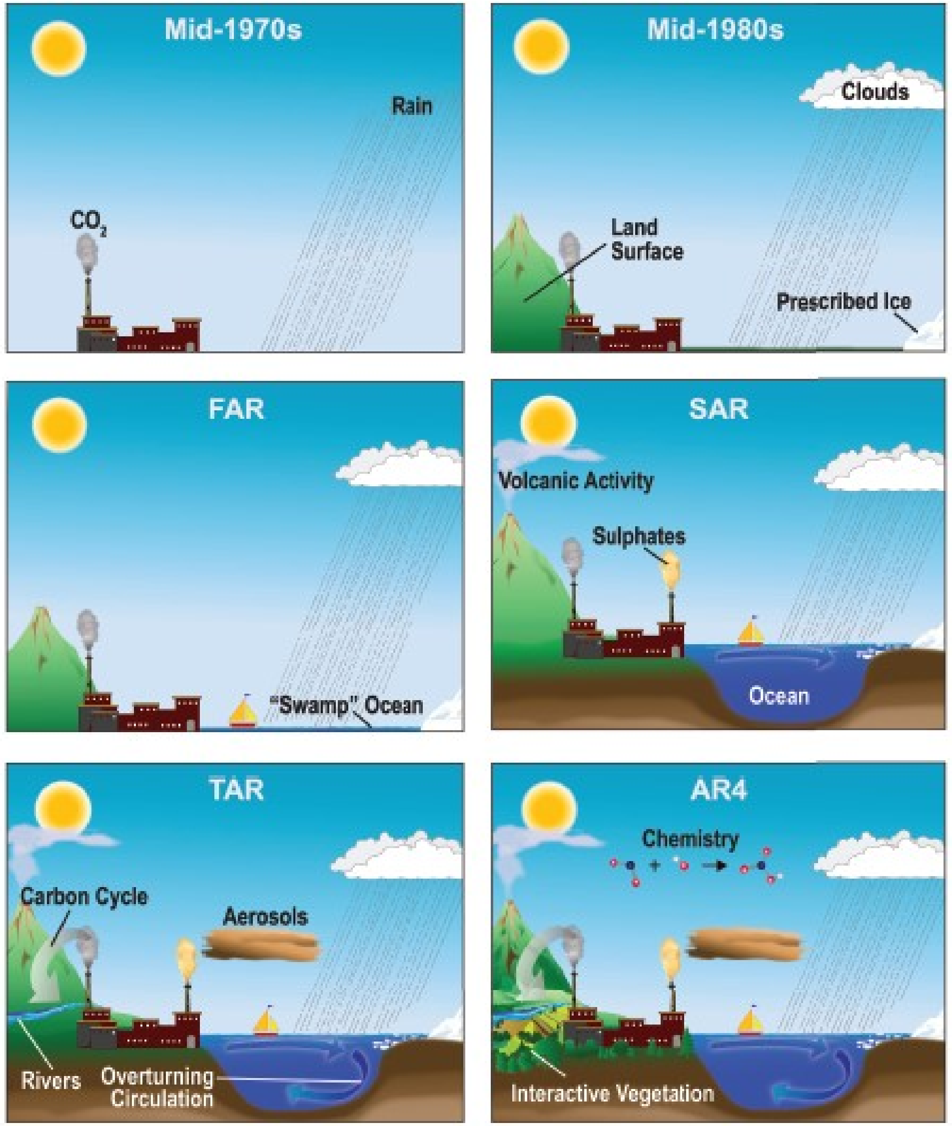



**Figure 1.2.** *The complexity of climate models has increased over the last few decades. The additional physics incorporated in the models are shown pictorially by the different features of the modelled world.*

Figure 1.4. The models used to evaluate future ges have therefore evolved over time. Most of the ork on $CO_2$-induced climate change was based on general circulation models coupled to simple 'slab' s (i.e., models omitting ocean dynamics), from the f Manabe and Wetherald (1975) to the review of ınd Mitchell (1987). At the same time the physical ıe models has become more comprehensive (see 5.2 the example of clouds). Similarly, most of the nted in the FAR were from atmospheric models, om models of the coupled climate system, and were yse changes in the equilibrium climate resulting ing of the atmospheric $CO_2$ concentration. Current ctions can investigate time-dependent scenarios of ution and can make use of much more complex ın-atmosphere models, sometimes even including ıemical or biochemical components.

:l evolution toward increased complexity and ıs occurred in the domain of numerical weather ıd has resulted in a large and verifiable improvement al weather forecast quality. This example alone esent models are more realistic than were those of ı. There is also, however, a continuing awareness do not provide a perfect simulation of reality, lving all important spatial or time scales remains ırrent capabilities, and also because the behaviour nplex nonlinear system may in general be chaotic. ı known since the work of Lorenz (1963) that even ls may display intricate behaviour because of their s. The inherent nonlinear behaviour of the climate ırs in climate simulations at all time scales (Ghil, :t, the study of nonlinear dynamical systems has ɔrtant for a wide range of scientific disciplines, and ıding mathematical developments are essential to ıary studies. Simple models of ocean-atmosphere climate-biosphere interactions or climate-economy may exhibit a similar behaviour, characterised by dictability, bifurcations and transition to chaos.

n, many of the key processes that control climate abrupt climate changes (e.g., clouds, vegetation, ection) depend on very small spatial scales. They presented in full detail in the context of global scientific understanding of them is still notably Consequently, there is a continuing need to assist l interpretation of complex models through models r conceptually simpler, or limited to a number of to a specific region, therefore enabling a deeper g of the processes at work or a more relevant with observations. With the development of ɔacities, simpler models have not disappeared; on a stronger emphasis has been given to the concept ıy of models' as the only way to provide a linkage oretical understanding and the complexity of els (Held, 2005).

The list of these 'simpler' models is very long. Simplicity may lie in the reduced number of equations (e.g., a single

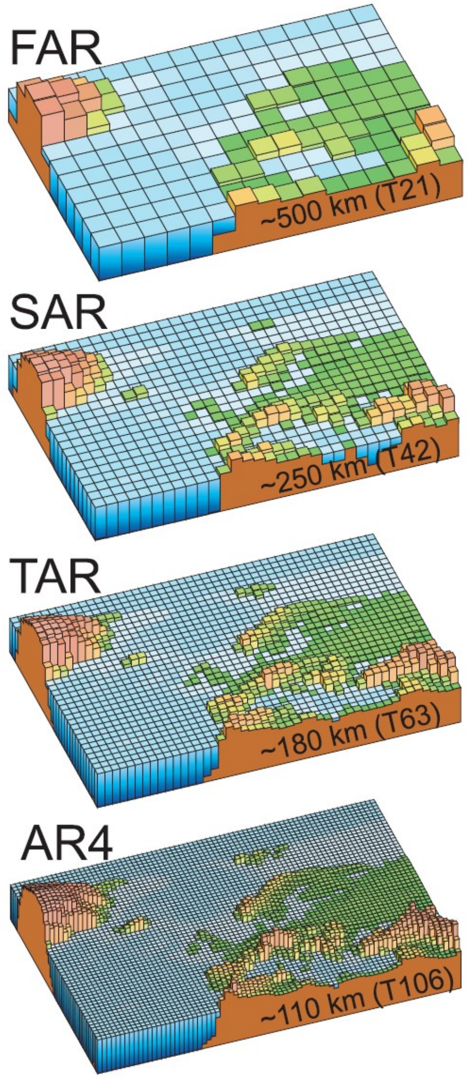



**Figure 1.4.** *Geographic resolution characteristic of the generations of climate models used in the IPCC Assessment Reports: FAR (IPCC, 1990), SAR (IPCC, 1996), TAR (IPCC, 2001a), and AR4 (2007). The figures above show how successive generations of these global models increasingly resolved northern Europe. These illustrations are representative of the most detailed horizontal resolution used for short-term climate simulations. The century-long simulations cited in IPCC Assessment Reports after the FAR were typically run with the previous generation's resolution. Vertical resolution in both atmosphere and ocean models is not shown, but it has increased comparably with the horizontal resolution, beginning typically with a single-layer slab ocean and ten atmospheric layers in the FAR and progressing to about thirty levels in both atmosphere and ocean.*

IPCC AR4 2007

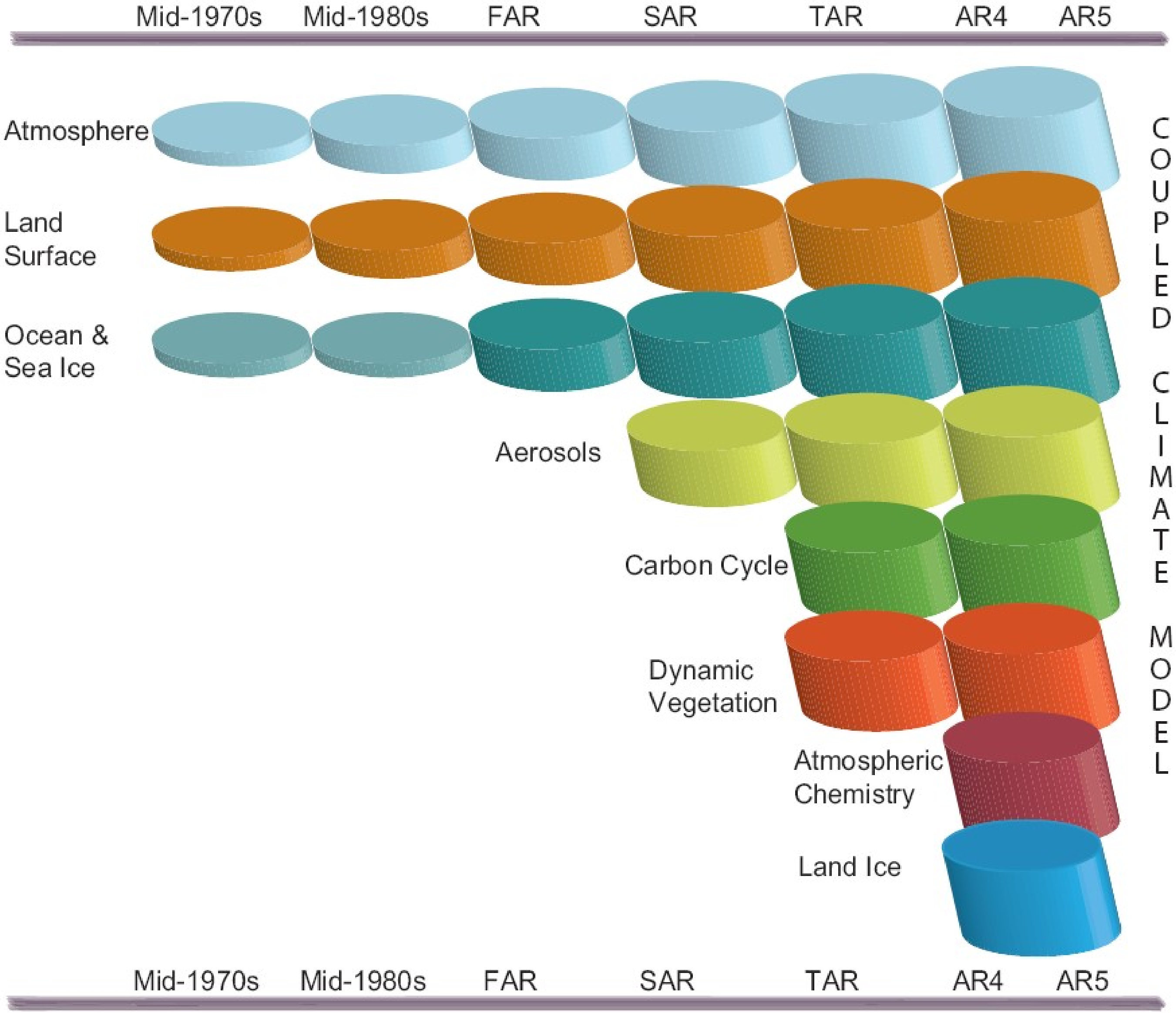
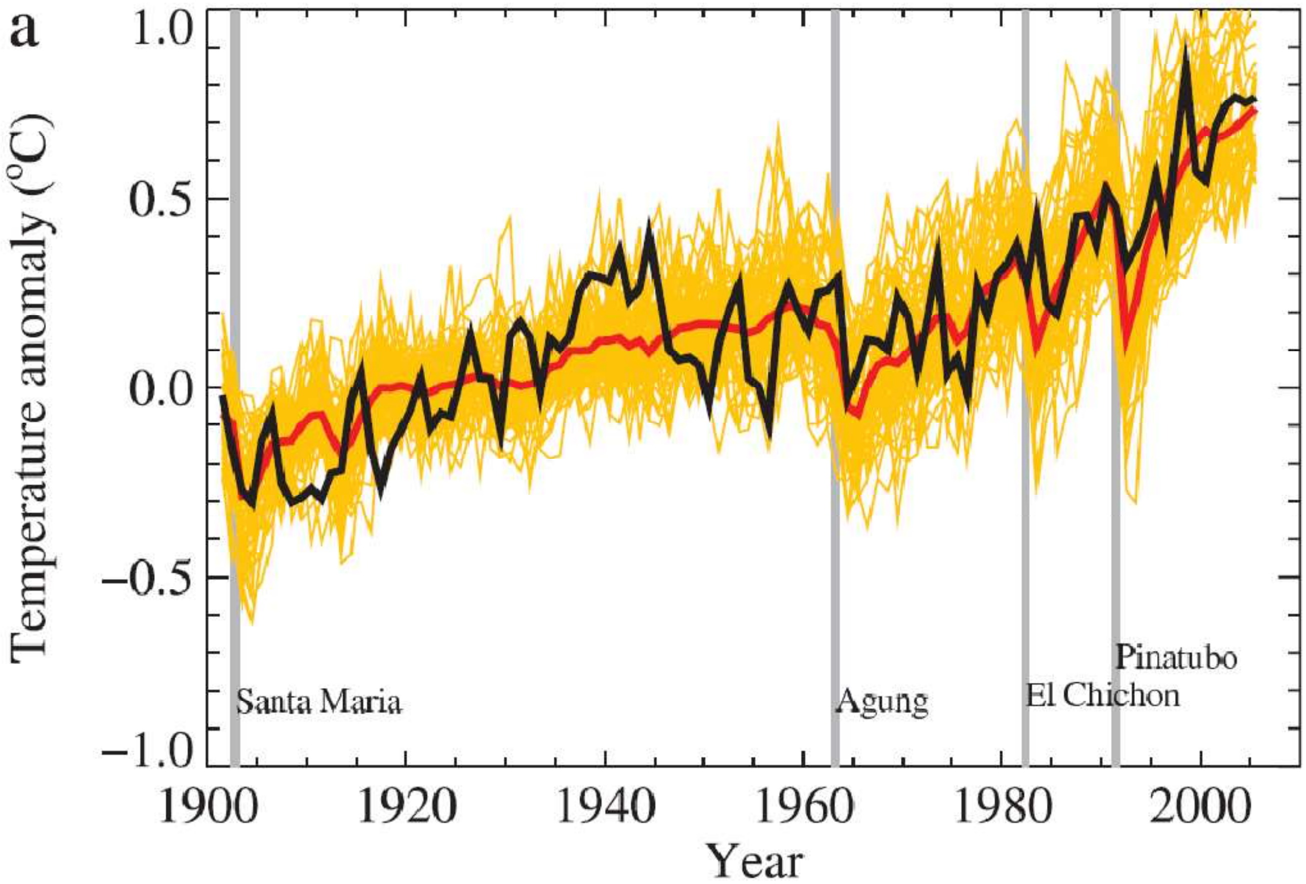



**Figure 1.13 |** The development of climate models over the last 35 years showing how the different components were coupled into comprehensive climate models over time each aspect (e.g., the atmosphere, which comprises a wide range of atmospheric processes) the complexity and range of processes has increased over time (illustrated by grow cylinders). Note that during the same time the horizontal and vertical resolution has increased considerably e.g., for spectral models from T21L9 (roughly 500 km horizontal resc tion and 9 vertical levels) in the 1970s to T95L95 (roughly 100 km horizontal resolution and 95 vertical levels) at present, and that now ensembles with at least three independ experiments can be considered as standard.

IPCC AR5 2013

# Bonus:
# Ejemplo de aplicación de un ensemble de modelos globales acoplados

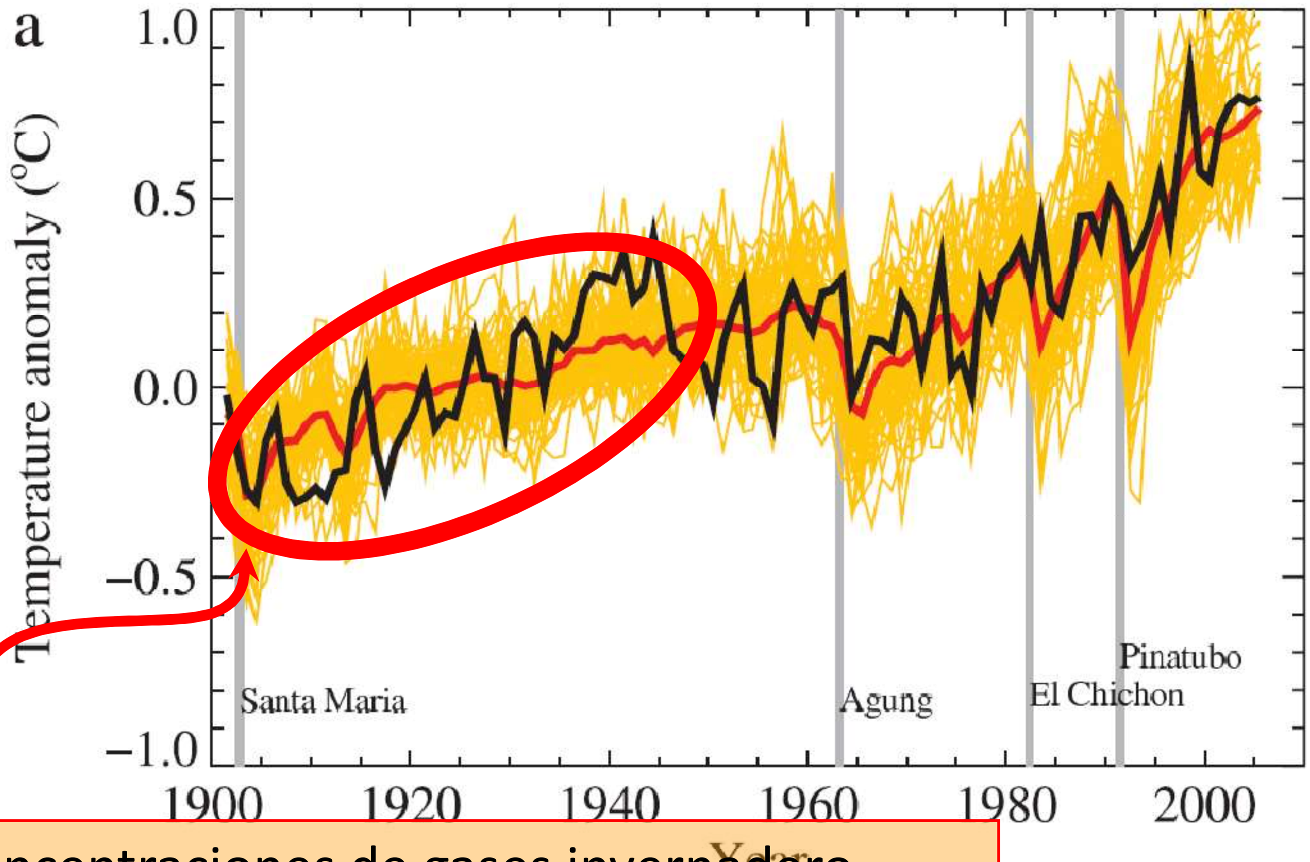
## Anomalías de la temperatura de superficie media global: observaciones y modelos climáticos




Amarillo: modelos individuales,
Negro: ensemble de modelos (promedio de los modelos individuales)
Rojo: observaciones

IPCC AR4, 2007

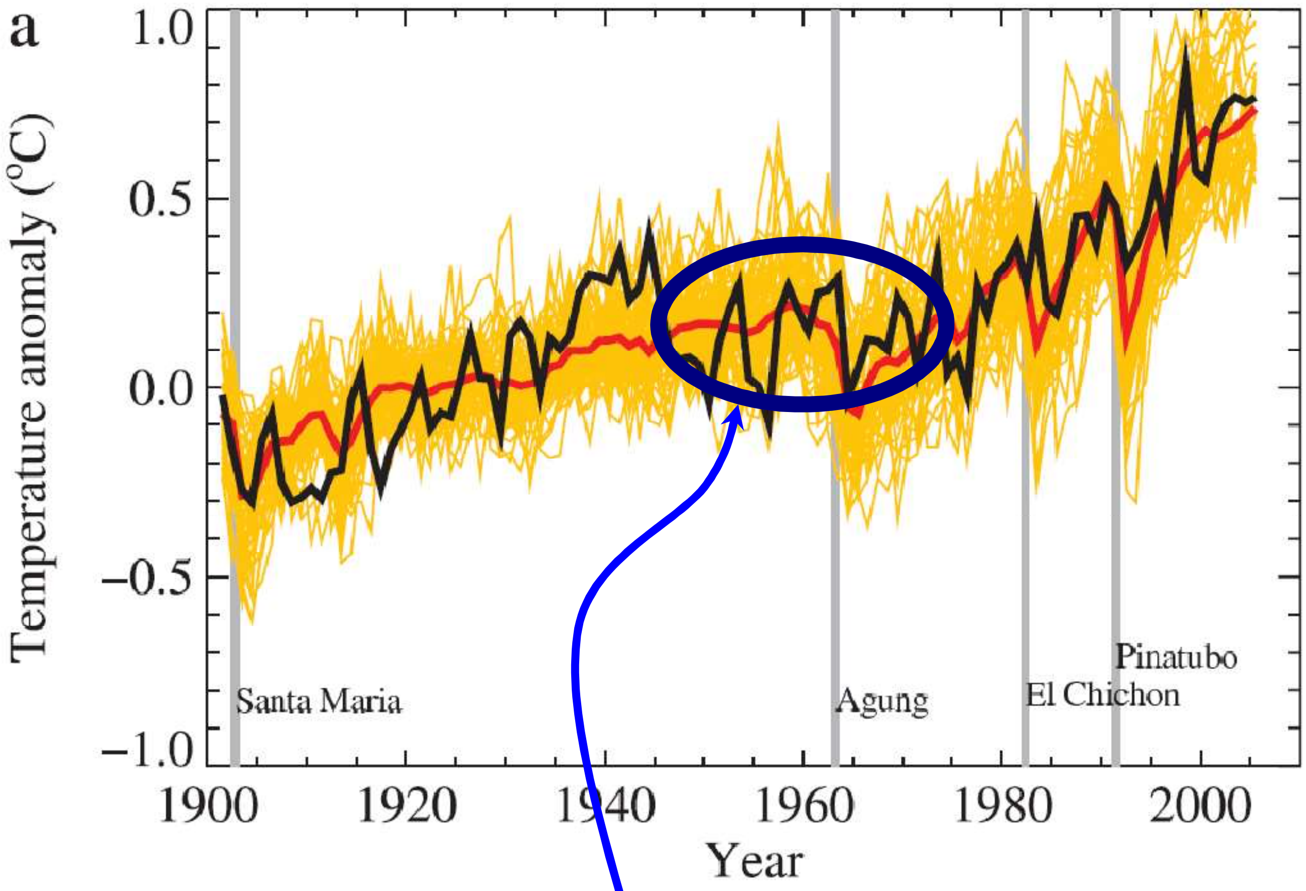
## Anomalías de la temperatura de superficie media global: observaciones y modelos climáticos




•Concentraciones de gases invernadero comenzaron a crecer;
•Actividad solar probablemente se incrementó;
•Poca actividad volcánica

IPCC AR4, 2007

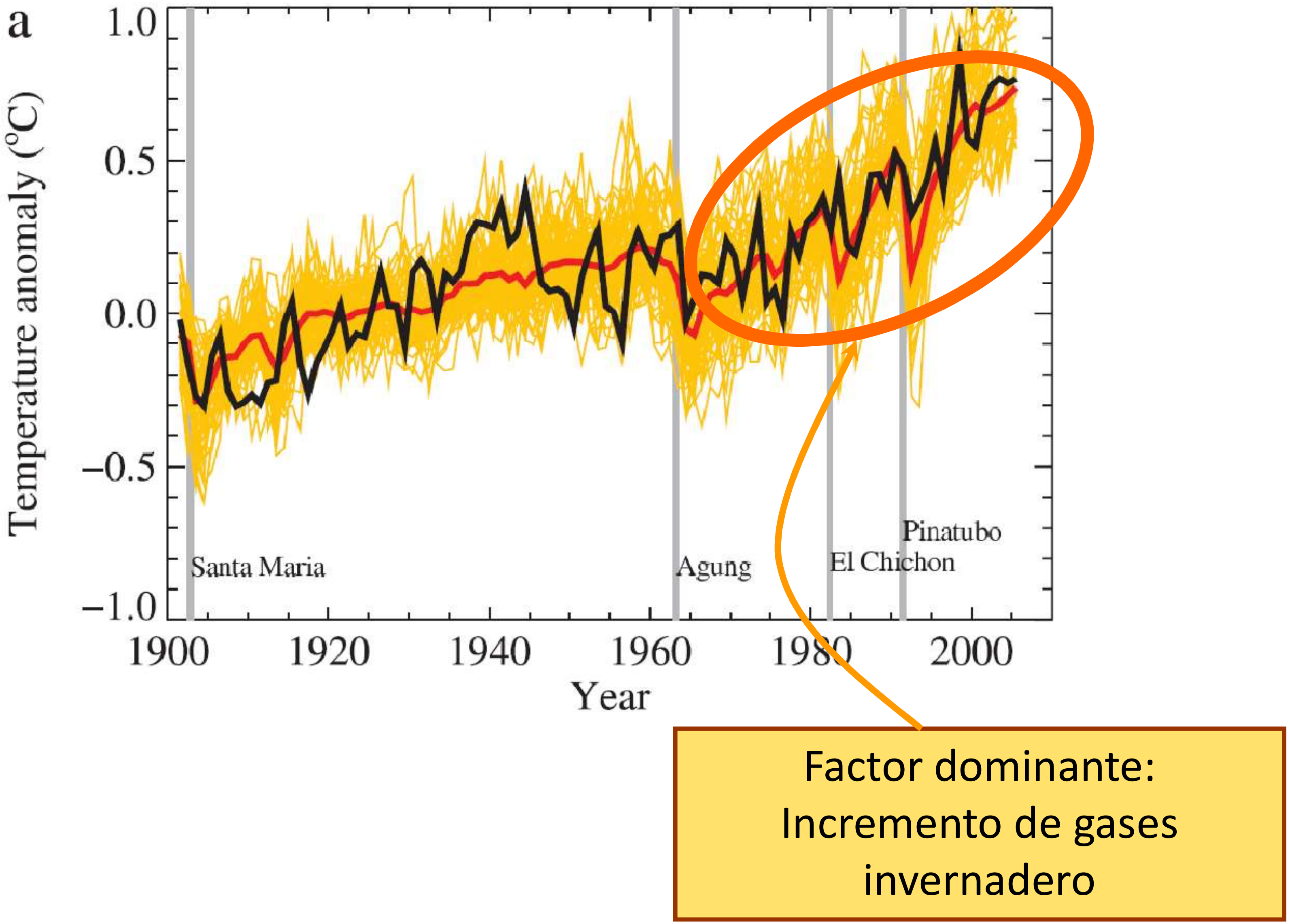
## Anomalías de la temperatura de superficie media global: observaciones y modelos climáticos




•Emisión de aerosoles (antropogénicos);
•Erupción del Monte Agung (1963)

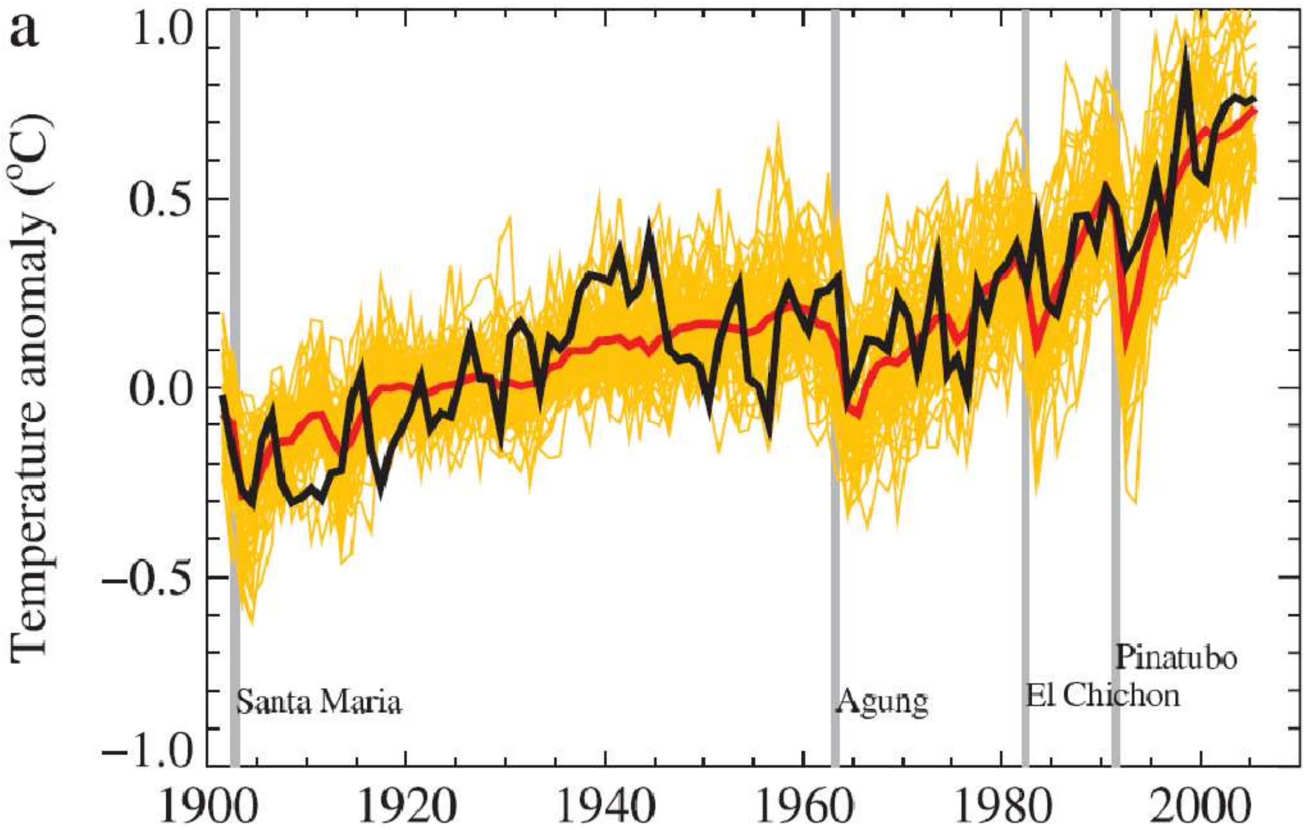
IPCC AR4, 2007

**Anomalías de la temperatura de superficie media global: observaciones y modelos climáticos**




IPCC AR4, 2007

## Anomalías de la temperatura de superficie media global: observaciones y modelos climáticos

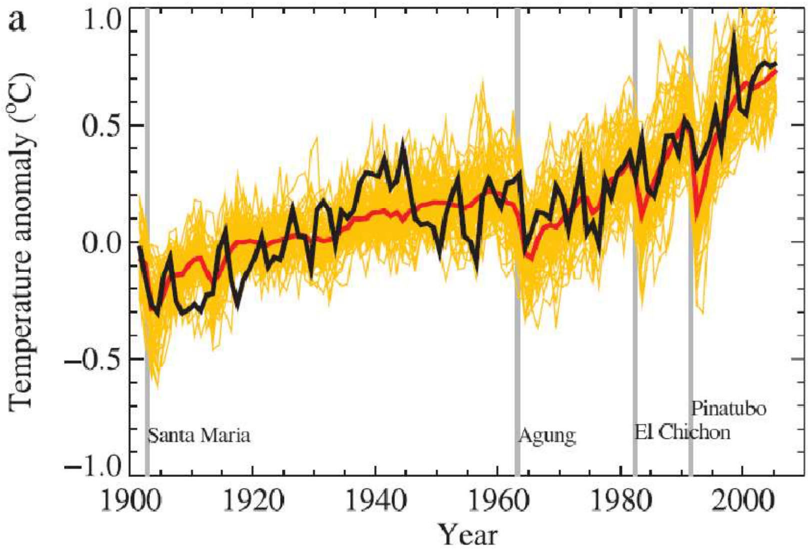



**Conclusión: Los modelos pueden simular los cambios observados en la temperatura media global cuando incluyen los principales factores externos (naturales y antropogénicos)**

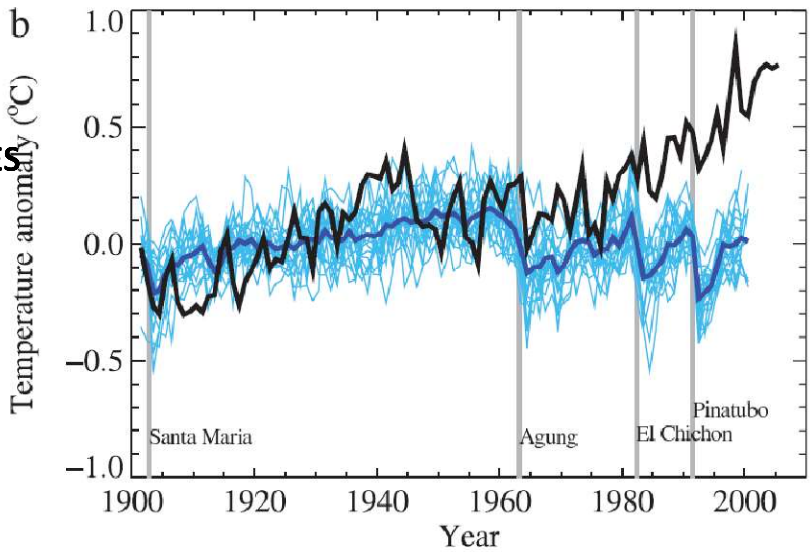
IPCC AR4, 2007

# Anomalías de la temperatura de superficie media global: observaciones y modelos climáticos

**SIMULACIONES CON FORZANTES ANTROPOGENICOS Y NATURALES**



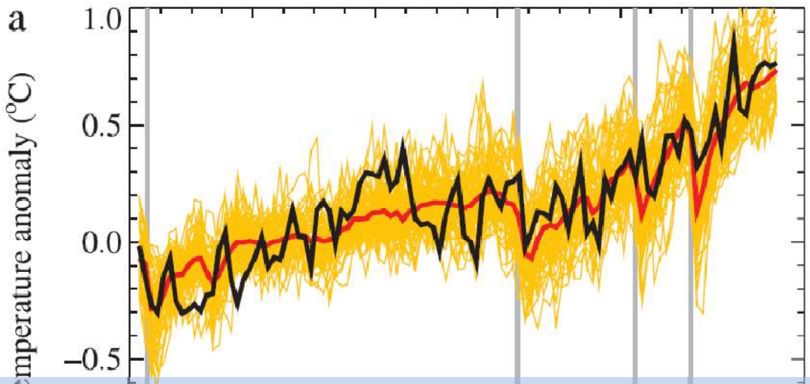

**SIMULACIONES SOLO CON FORZANTES NATURALES**




IPCC AR4, 2007

## Anomalías de la temperatura de superficie media global: observaciones y modelos climáticos

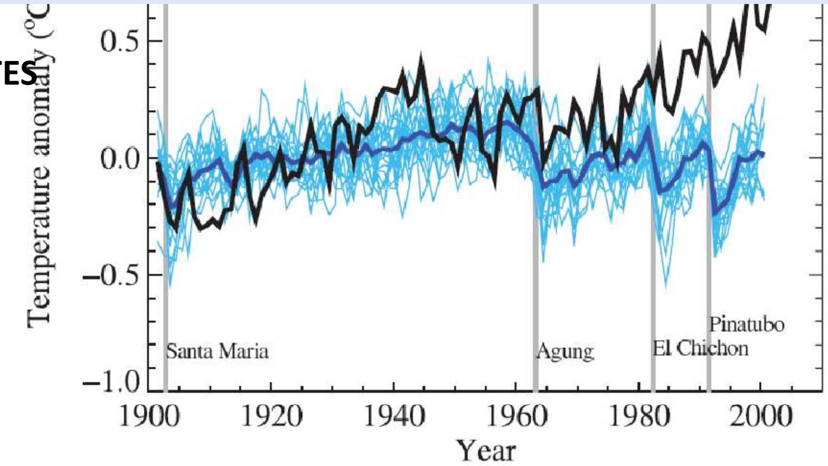
**SIMULACIONES CON FORZANTES ANTROPOGENICOS Y NATURALES**




CONCLUSION DE IPCC WG1 AR4 (2007):

Es muy improbable que el calentamiento durante el s.20 pueda ser explicado por causas naturales

**SIMULACIONES SOLO CON FORZANTES NATURALES**




IPCC AR4, 2007