An Introduction to Earth System Models

AT745 Earth System Models 2024

Dave Randall and the Earth System All Stars

Total of 28 classes, each 75 minutes long

We will schedule make-ups for three missed classes.

https://hogback.atmos.colostate.edu/group/dave/at745/

This fall AT745 will deal with "Earth System Models" (ESMs), which include representations of the atmosphere, the ocean, the land surface, sea ice, and in some cases continental ice sheets. The nature, scope and history and formulation of ESMs will be covered in general terms..

Each student will "adopt" and make two presentations about a current ESM. The first presentation will discuss the history and formulation of the model in general terms. The second presentation will zoom in on one particular aspect of the model. Both presentations will include a discussion of results produced by the model.

We will of course also compare the models with each other.

Guest lecturers will cover subjects that are far from my expertise. That's where the *Earth System All Stars* come in. The table below lists who will present what. The order of the presentations will be close to what is shown in the table, but not exactly the same.

Feel free to contact me if you have questions or suggestions.

What is a model?

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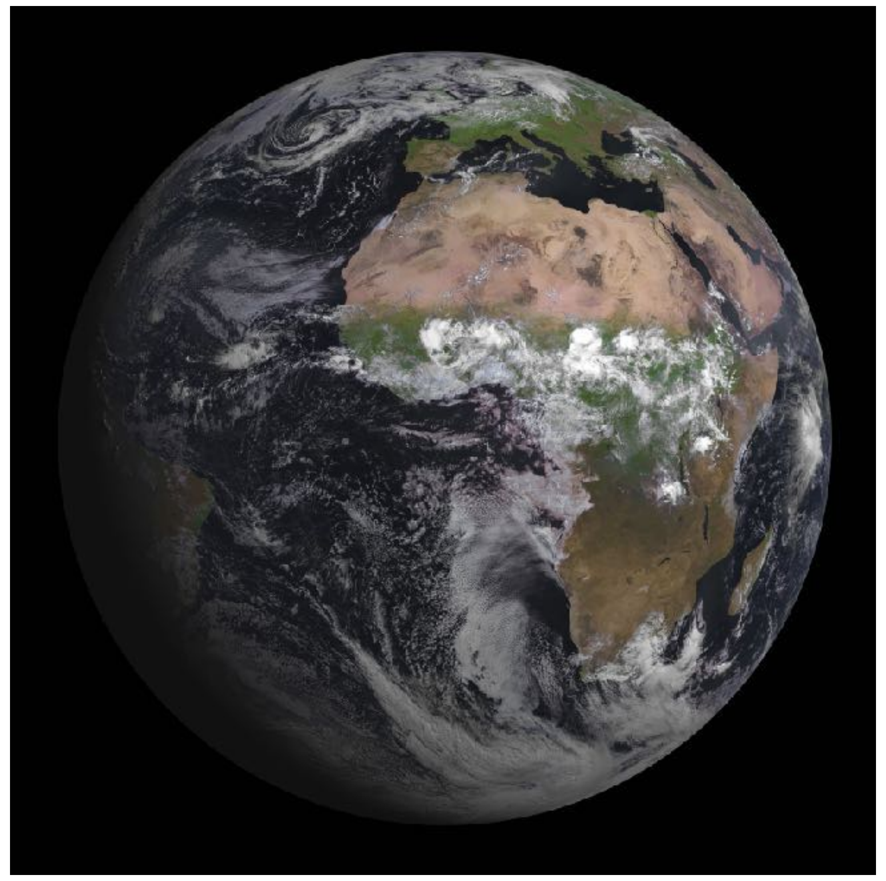
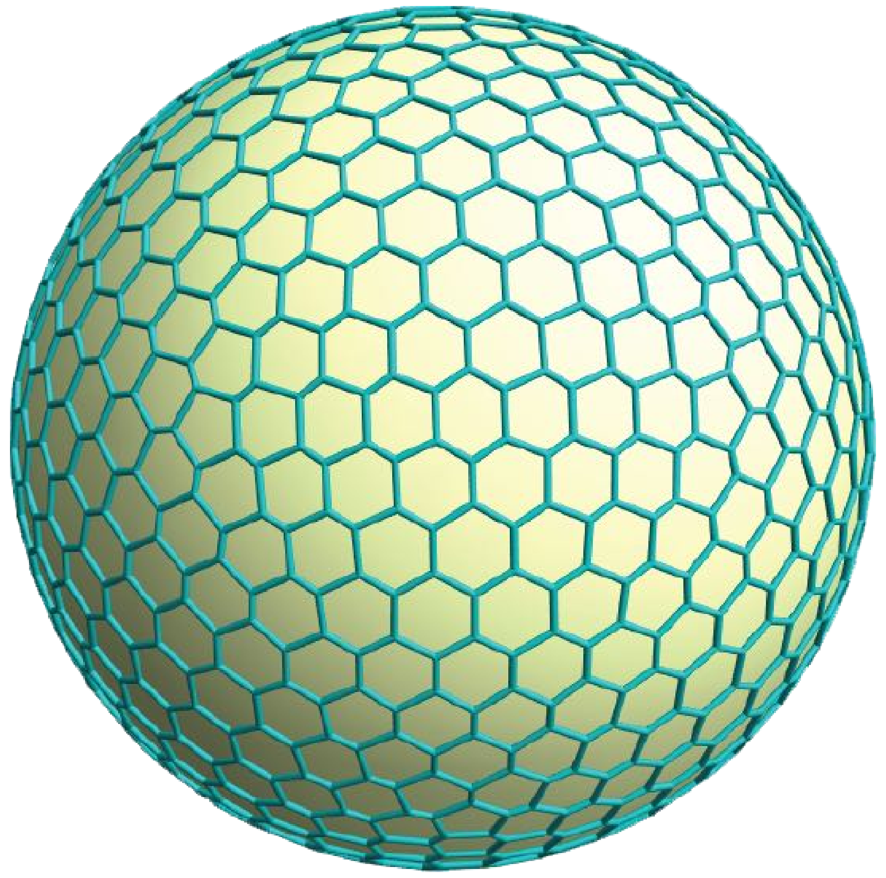
The models by themselves are just "stories" about the atmosphere. But the stories must be true, as far as we can tell.

Stories

What are models used for?

- Understanding — *models as collections of ideas*
  - Tools for organizing and interpreting measurements
  - Tools for performing numerical experiments
- Simulation — *models as software tools*
  - Quantitative accuracy
  - Practical applications including forecasting





Global forecast models

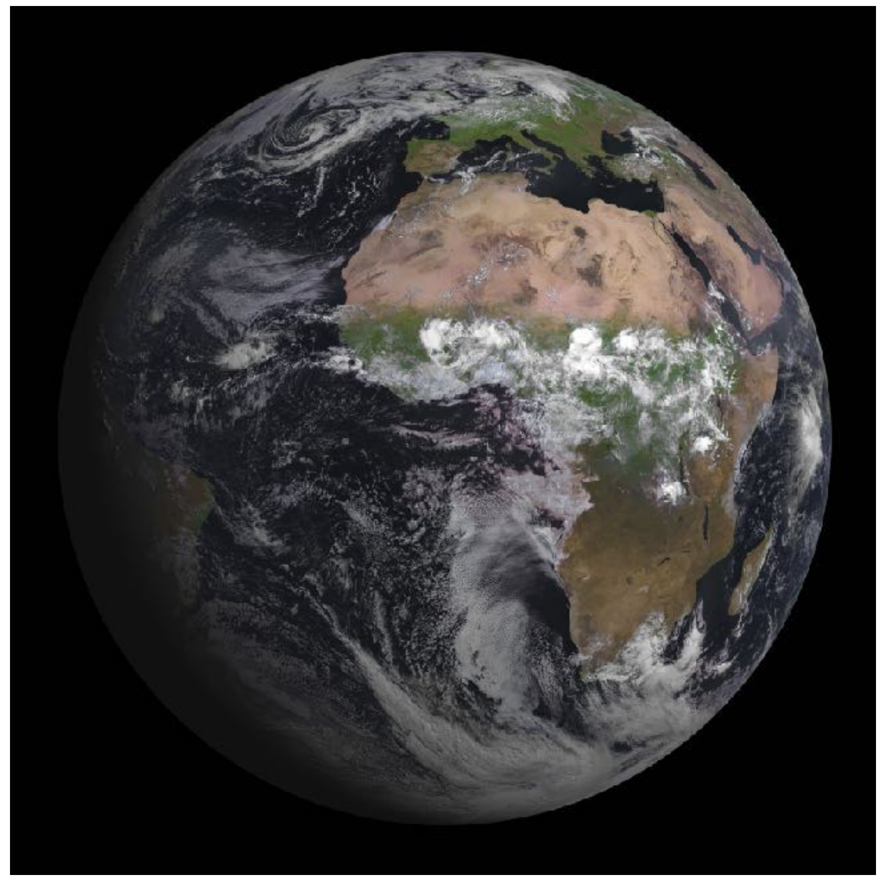
- Produce a product for a customer
- Operate on a fixed schedule
- Need modeling "technology"
- Need measurements as input
- Produce analyses and reanalyses
- Sometimes achieve important scientific advances

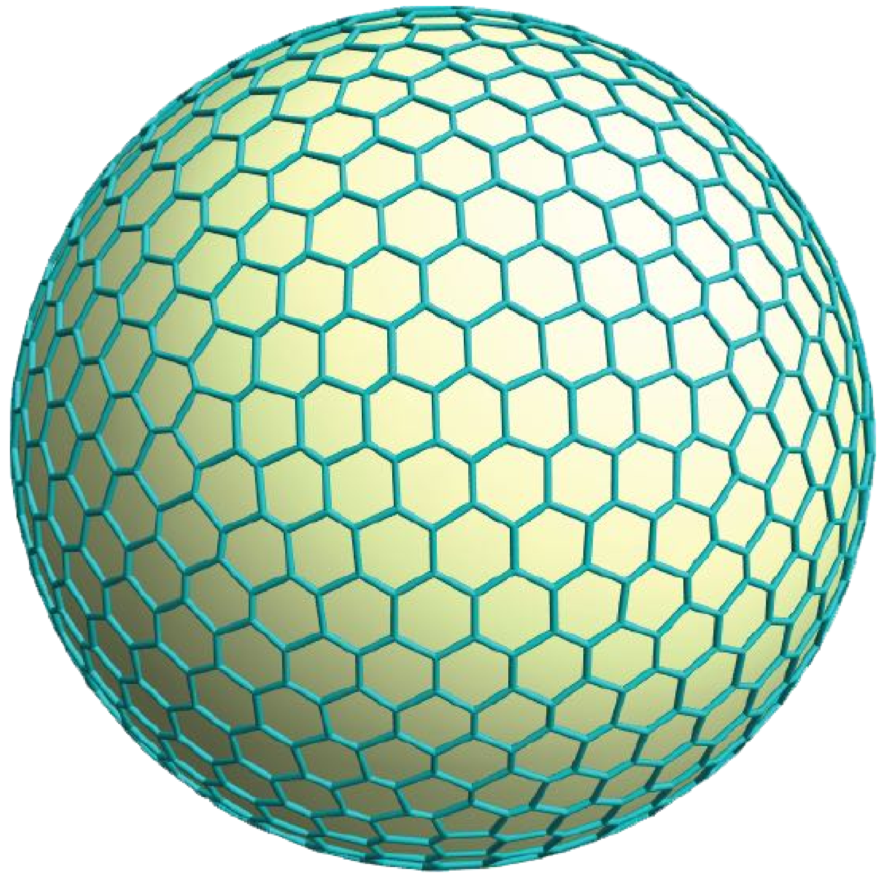
What does it mean to understand something?

We say that we understand something when we can connect it with a larger set of ideas, with at least semi-quantitative accuracy.

Sometimes we can simulate something without understanding it.

Sometimes we think we understand something but lack the ability to simulate it.





What is a climate model?

At a minimum, a climate model contains representations of the atmosphere, ocean, sea ice, and land surface.

Some climate models are highly simplified so that they can run fast on computers.

Other climate models are much more detailed, and run more slowly.

And then there are models of "intermediate complexity".

All three types are needed; they form a hierarchy of models.

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- Global Climate Model
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  - The name excludes NWP.

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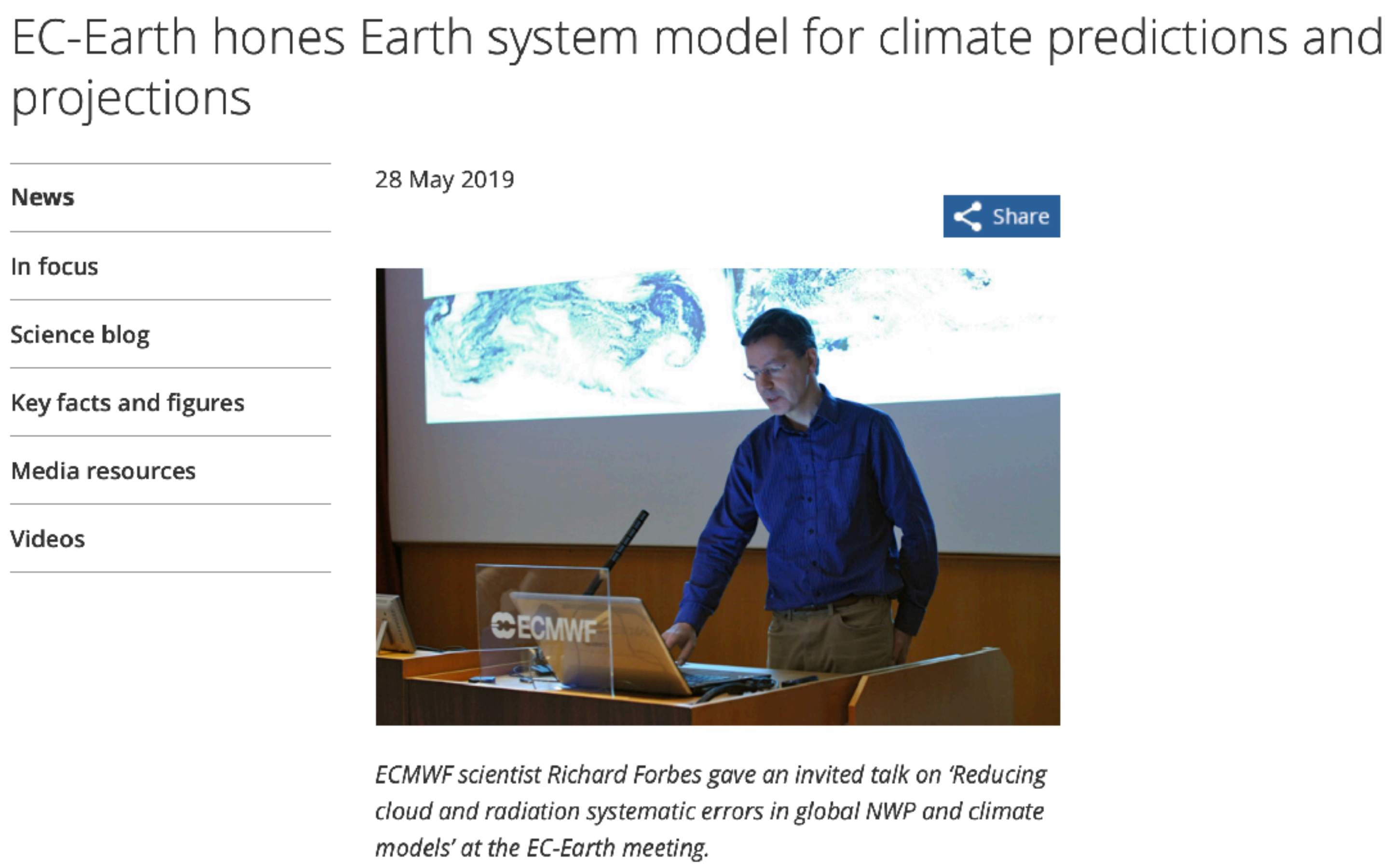
- Global Circulation Model
  - Accurate and flexible.
  - In my opinion the best use of the acronym.

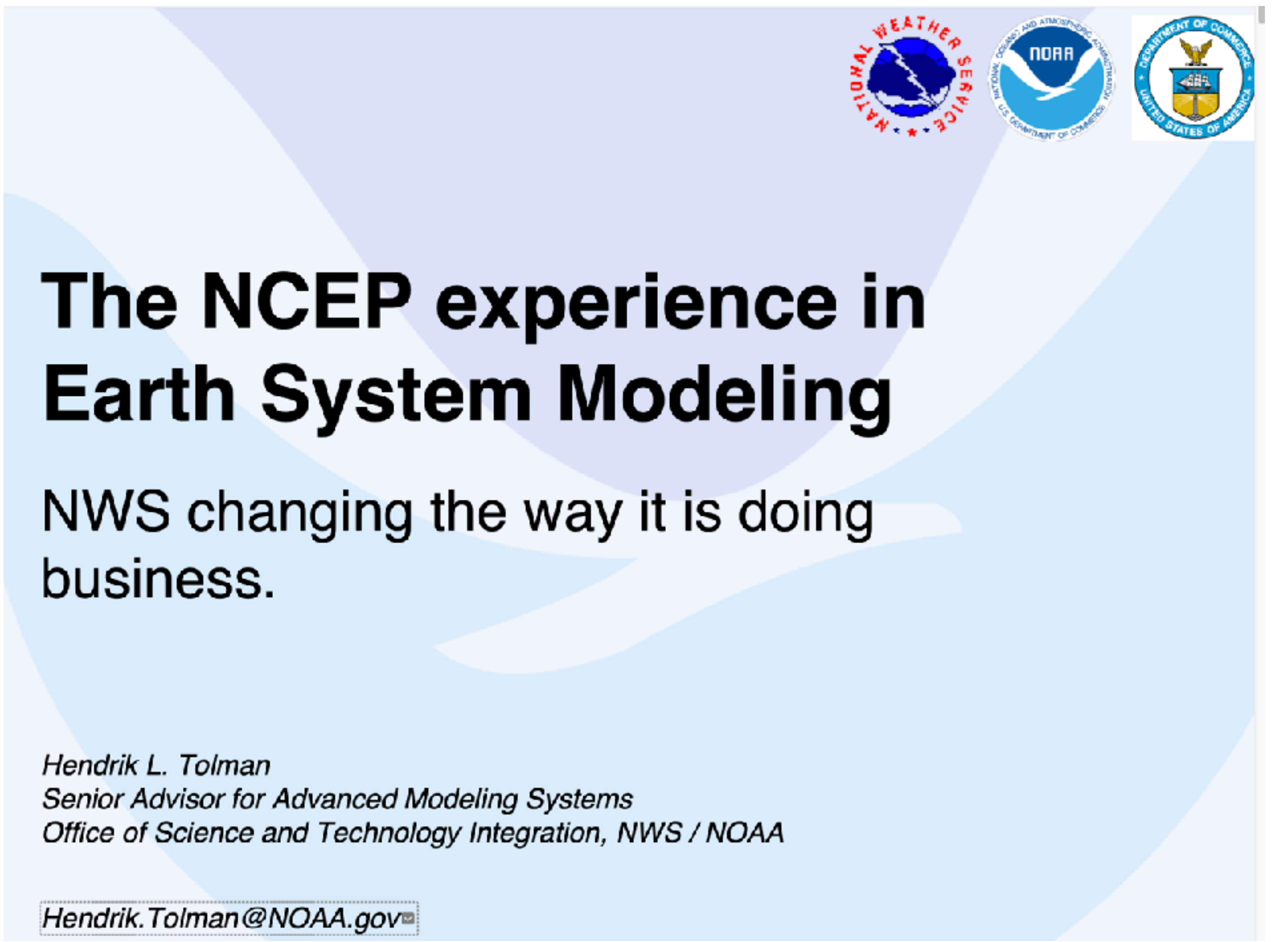
Is an Earth System Model the same as a climate model?

Initially no. An ESM was a climate model plus a closed carbon budget.

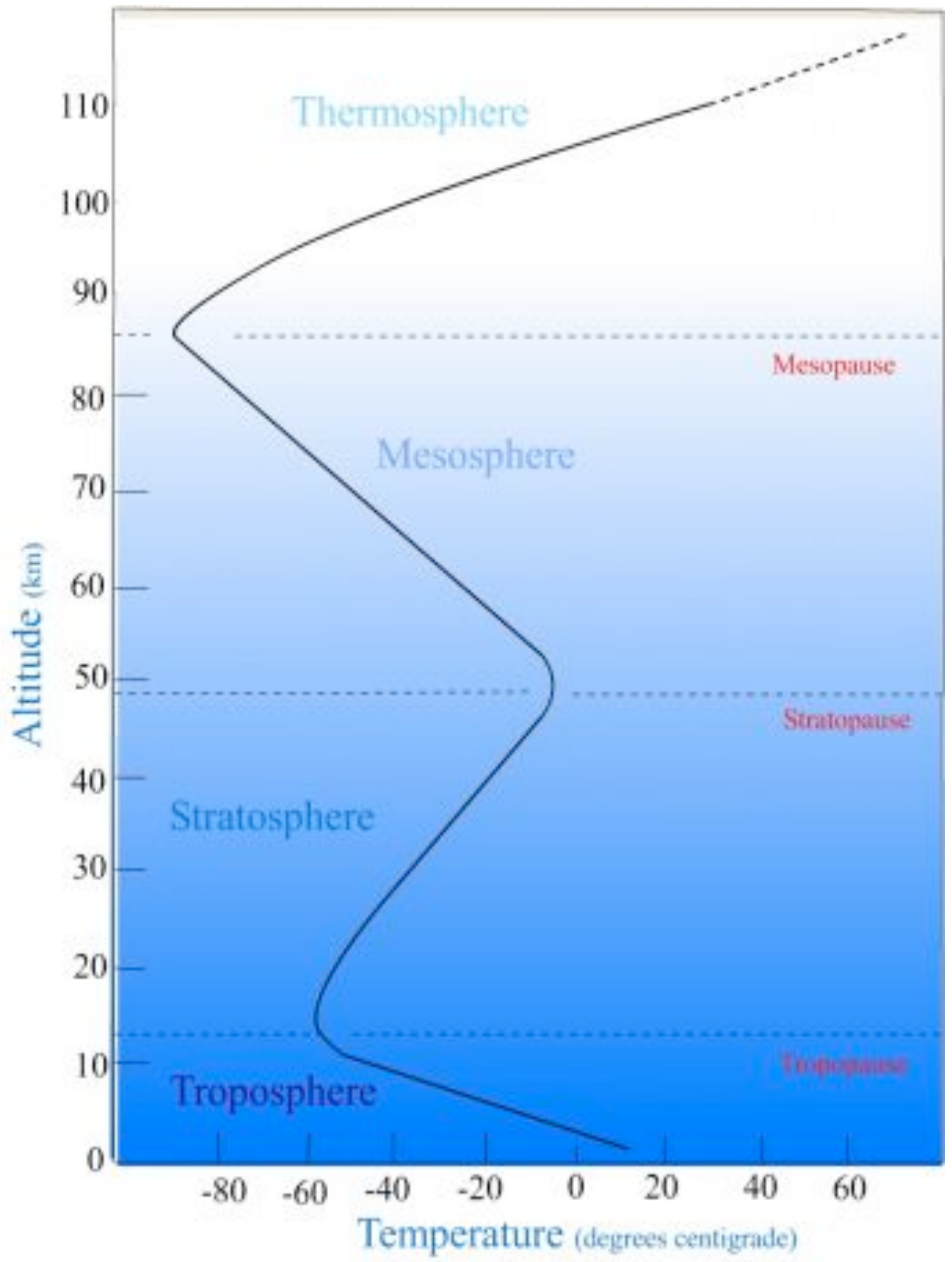
As time has passed, the term ESM is becoming more synonymous with "climate model."

There is a trend towards calling coupled forecast models ESMs.



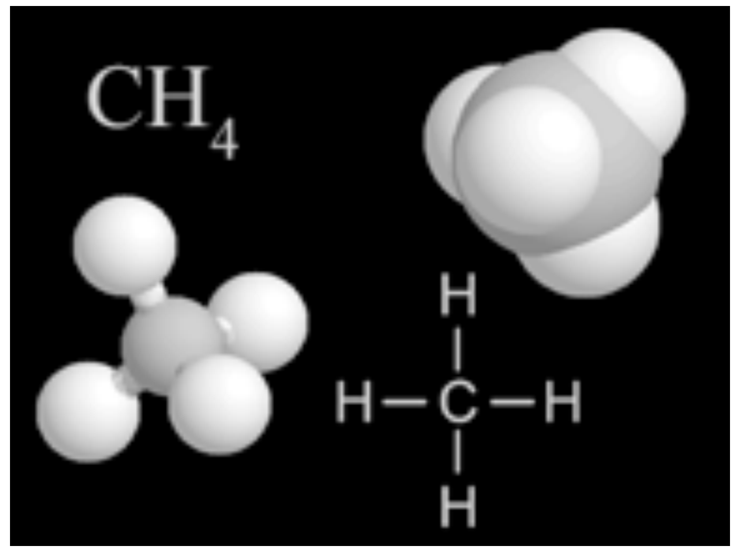


The scope of a model



Vertical extent?

Range of scales?



Chemistry?

Biology?

The scope of this class

Date	Who	What
8/20	David Randall, CSU	Historical overview 1
8/22	David Randall, CSU	Historical overview 2
8/26	David Randall, CSU	Dynamical cores 1
8/27	David Randall, CSU	Dynamical cores 2
8/29	David Randall, CSU	Boundary layer parameterization 1
9/3	David Randall, CSU	Boundary layer parameterization 2
9/5	Missed class	
9/10	Andrew Gettelman, Pacific Northwest National Laboratory	Microphysics parameterizations
9/12	Robert Pincus, Lamont-Doherty Earth Observatory|(virtual)	Radiation parameterizations
9/17	Nicholas Pedatella, NCAR/HAO	Modeling the high atmosphere
9/19	Alice DuVivier, NCAR/CGD	Sea ice models
9/24	David Randall, CSU	Cumulus parameterization 1
9/26	David Randall, CSU	Cumulus parameterization 2
10/1	Missed class	
10/3	Scott Denning, CSU	Land surface and carbon cycle modeling
10/8	Student presentations	Model overview
10/10	Student presentations	Model overview
10/14	TBD	TBD
10/15	Gokhan Danagasoglu, NCAR/CGD	Ocean models 1
10/17	Gokhan Danagasoglu, NCAR/CGD	Ocean models 2

Date	Who	What
10/22	Jadwiga Richter, NCAR/CGD	Gravity wave drag parameterizations
10/24	Missed class	
10/29	Rich Loft, AreandDee LLC	High-performance computing for ESMs
10/31	Rebecca Buchholz, NCAR/ACOM	Chemistry parameterizations
11/4	Dmitrii Kochkov, Google	Neural GCMs
11/5		
11/7		
11/12	Peter Jan van Leeuwen, CSU	Data assimilation
11/14	Jon Petch, NCAR/CGD	Operational NWP
11/19	Pat Keys, CSU	People parameterizations
11/21	David Randall, CSU	A look ahead
12/3	Student presentations	Model focused
12/5	Student presentations	Model focused
TBD	Gunter LeGuy, NCAR/CGD	Ice sheet models
TBD	Brian Dobbins, NCAR/CGD	Software infrastructure for ESMs
TBD	David Randall, CSU	Tuning
TBD	David Randall, CSU	Open source and Intercomparisons including CMIP and IPCC

Now we continue with Chapter 1.

Earth System Models

Atmosphere

- Mass
- Momentum
- Energy
- Moisture
- Various chemical species

Ocean

- Mass
- Momentum
- Energy
- Salt
- Sea ice
- Various chemical species
- Marine biology

Land Surface

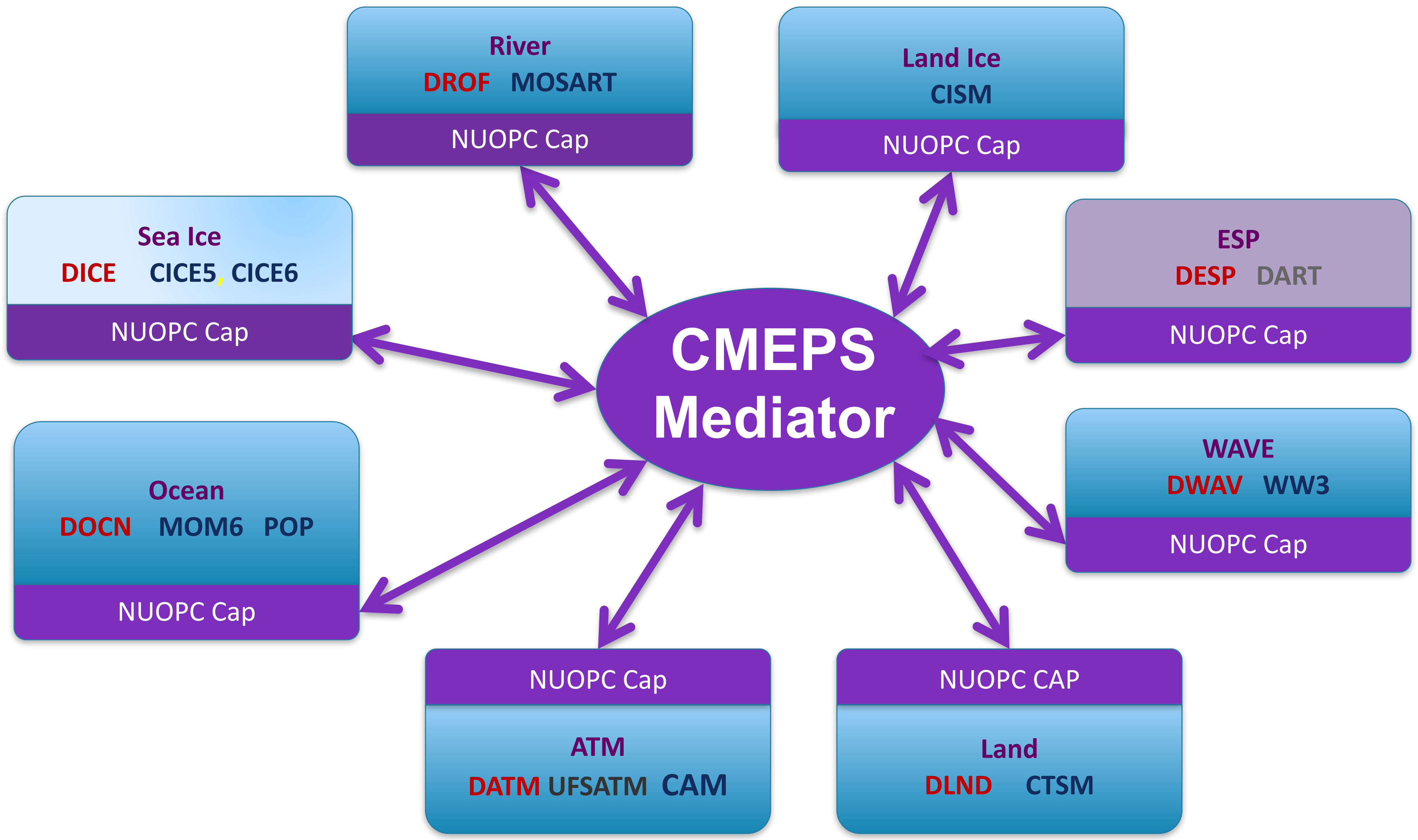
- Soil
- Terrestrial biology
- Energy
- Water
- Snow, etc.
- Carbon

Ice sheets

- Rheology
- Bottom friction

Couplers/Mediators

- Communicate fluxes between components
- Account for differences in grids
- Maintain conservation of water and energy



Aspirations

Create a realistic and flexible simulation tool.

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In the process of designing the model, learn about how the real world works.

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Use numerical experiments to learn even more about how the real world works.

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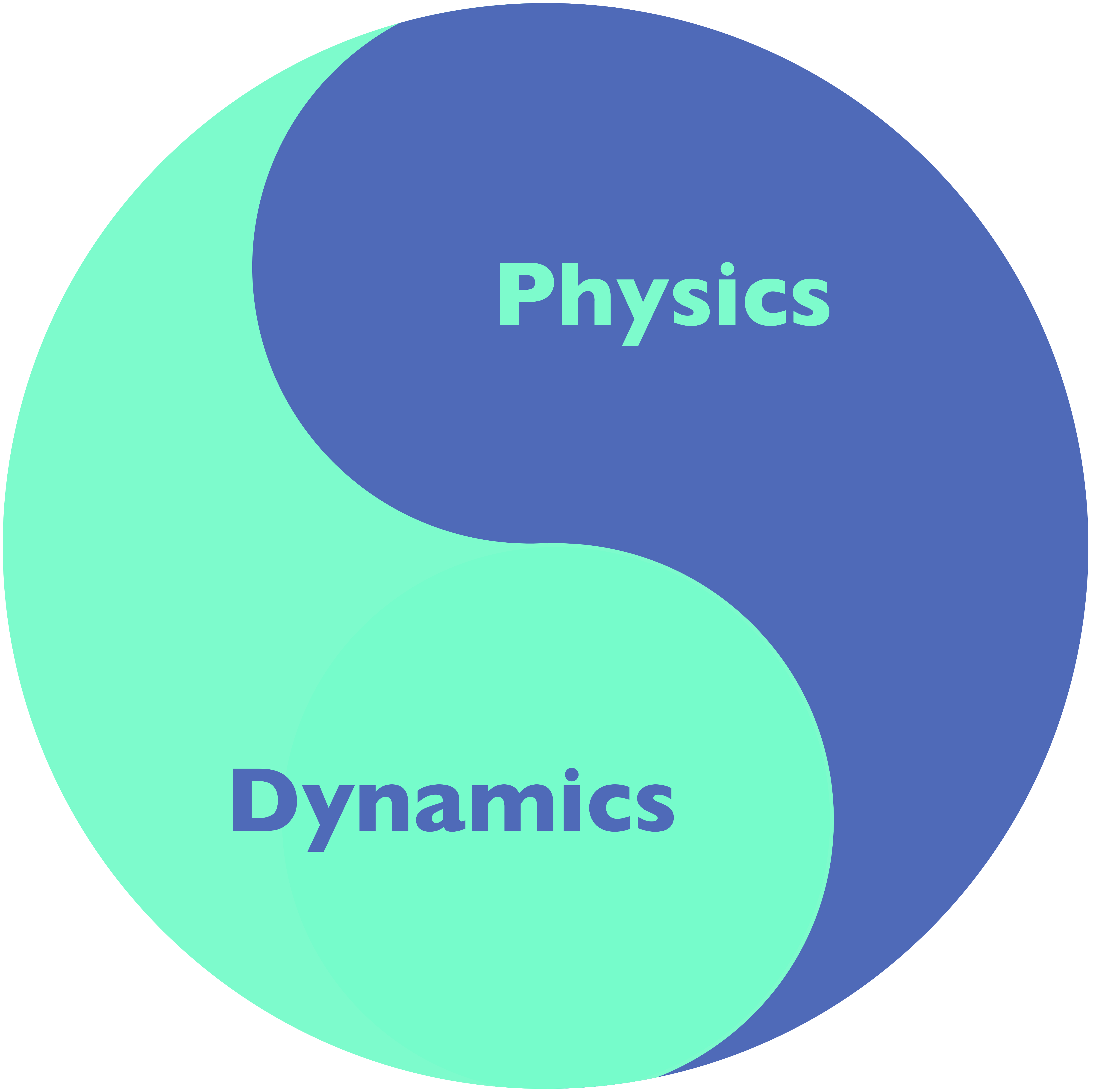
Simulation

Understanding

“Physics” refers to parameterized processes.

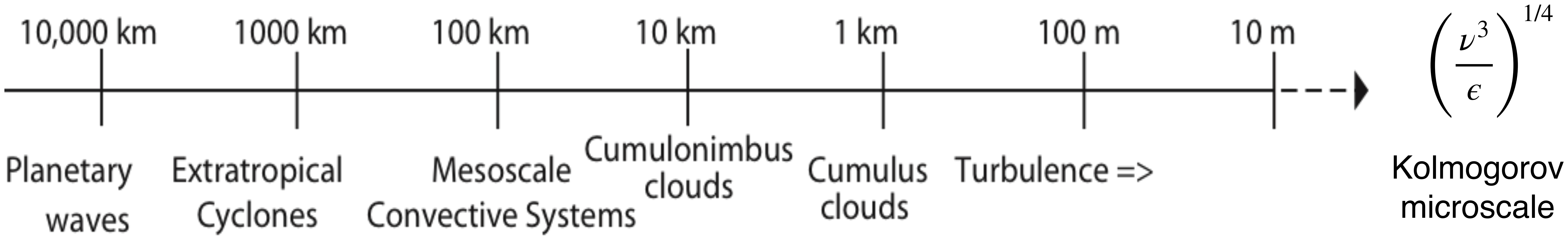
“Dynamics” refers to everything else.



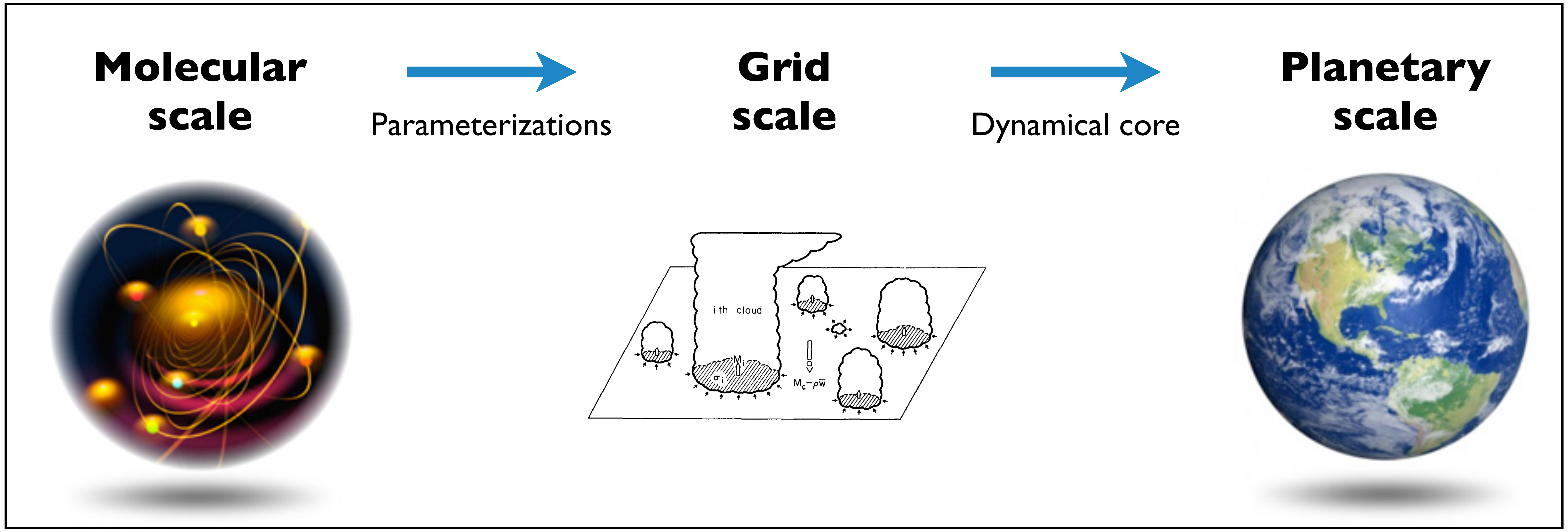
The many *emergent phenomena* of the global atmosphere originate with fundamental physical principles that apply on small scales.

The climate system starts at the molecular scale and works up.

Scales of motion

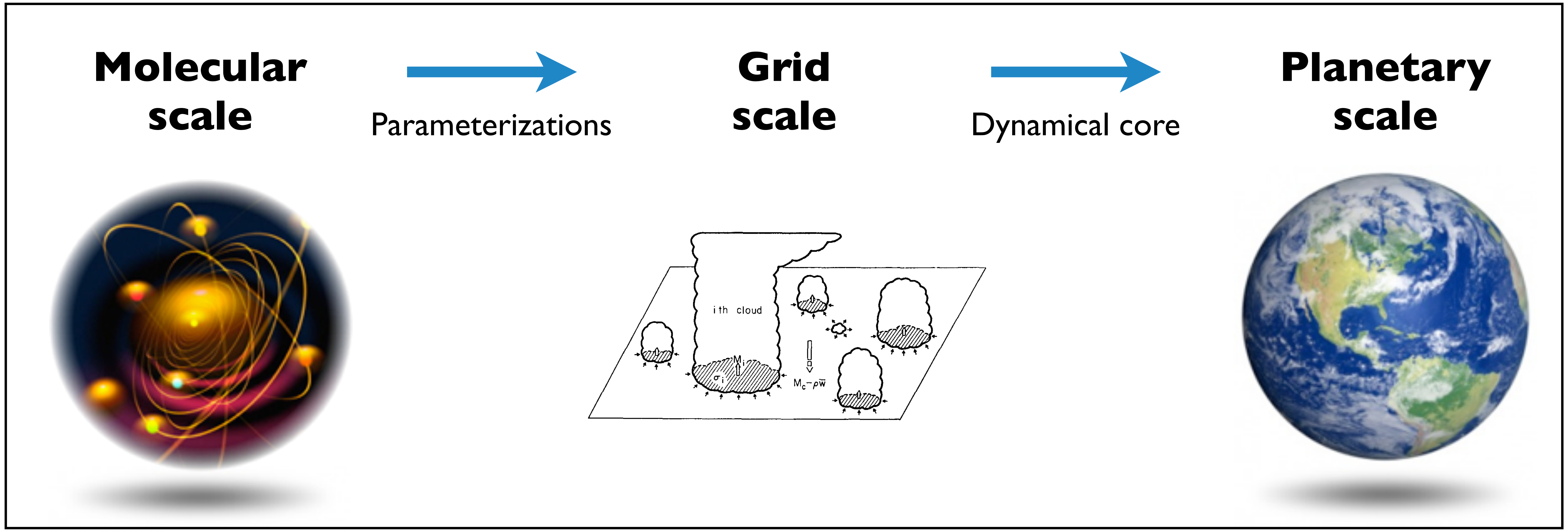


The many *emergent phenomena* of the global atmosphere originate with fundamental physical principles that apply on small scales.



Modelers build parameterizations that connect the molecular scale to the grid scale.

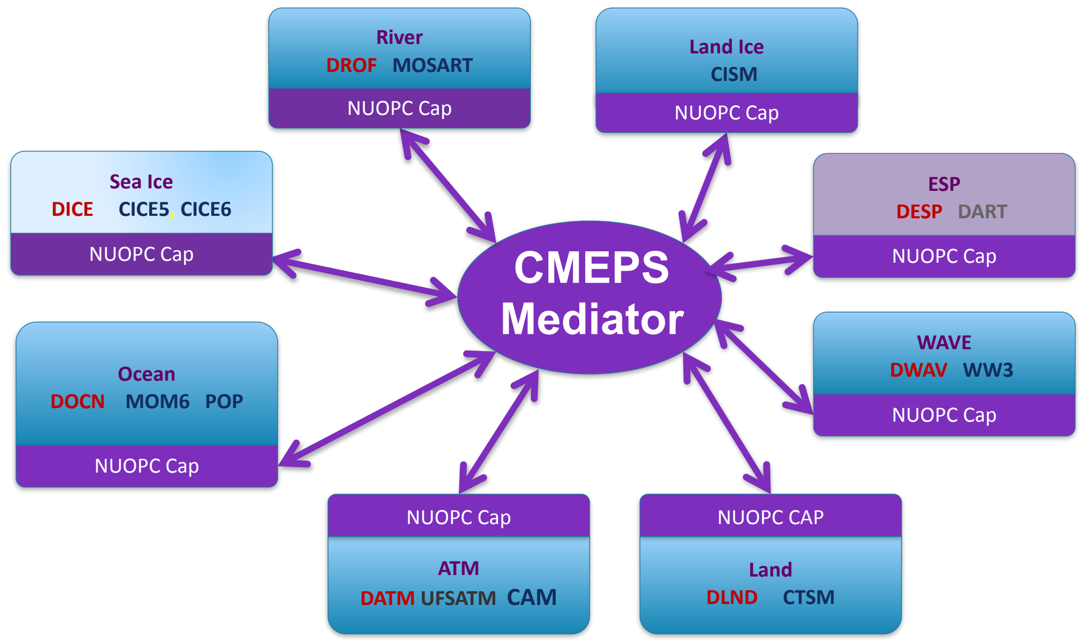
We also build dynamical cores that connect the grid scale to the planetary scale.



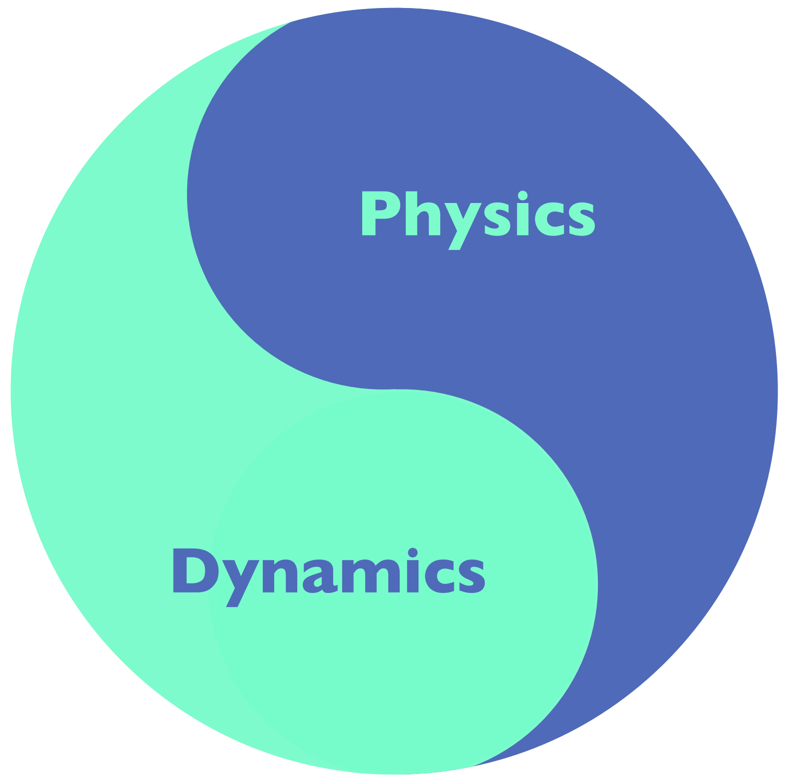
Near the grid scale, the motions are "represented" but not resolved.

Coupling is actually a more general issue.

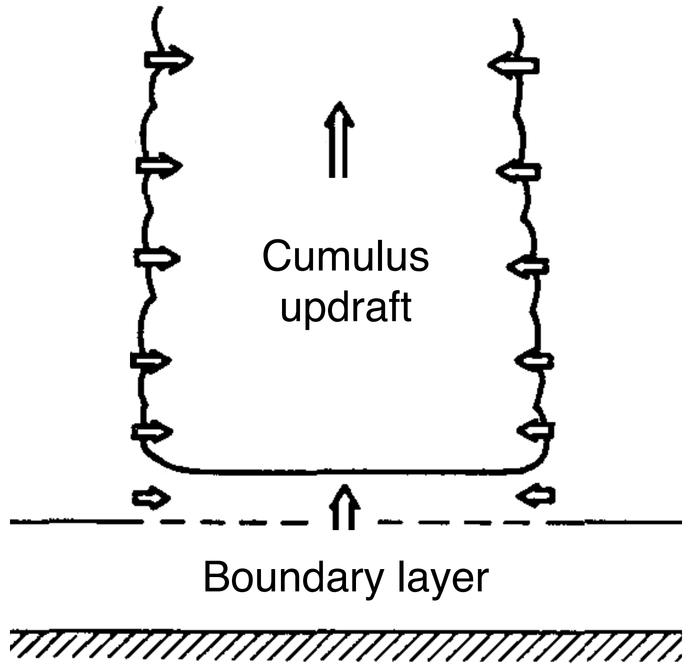
- Coupling components



- Coupling physics and dynamics



- Coupling different parts of the physics



Synergy with high-performance computing

Global models have always used the fastest computers available.

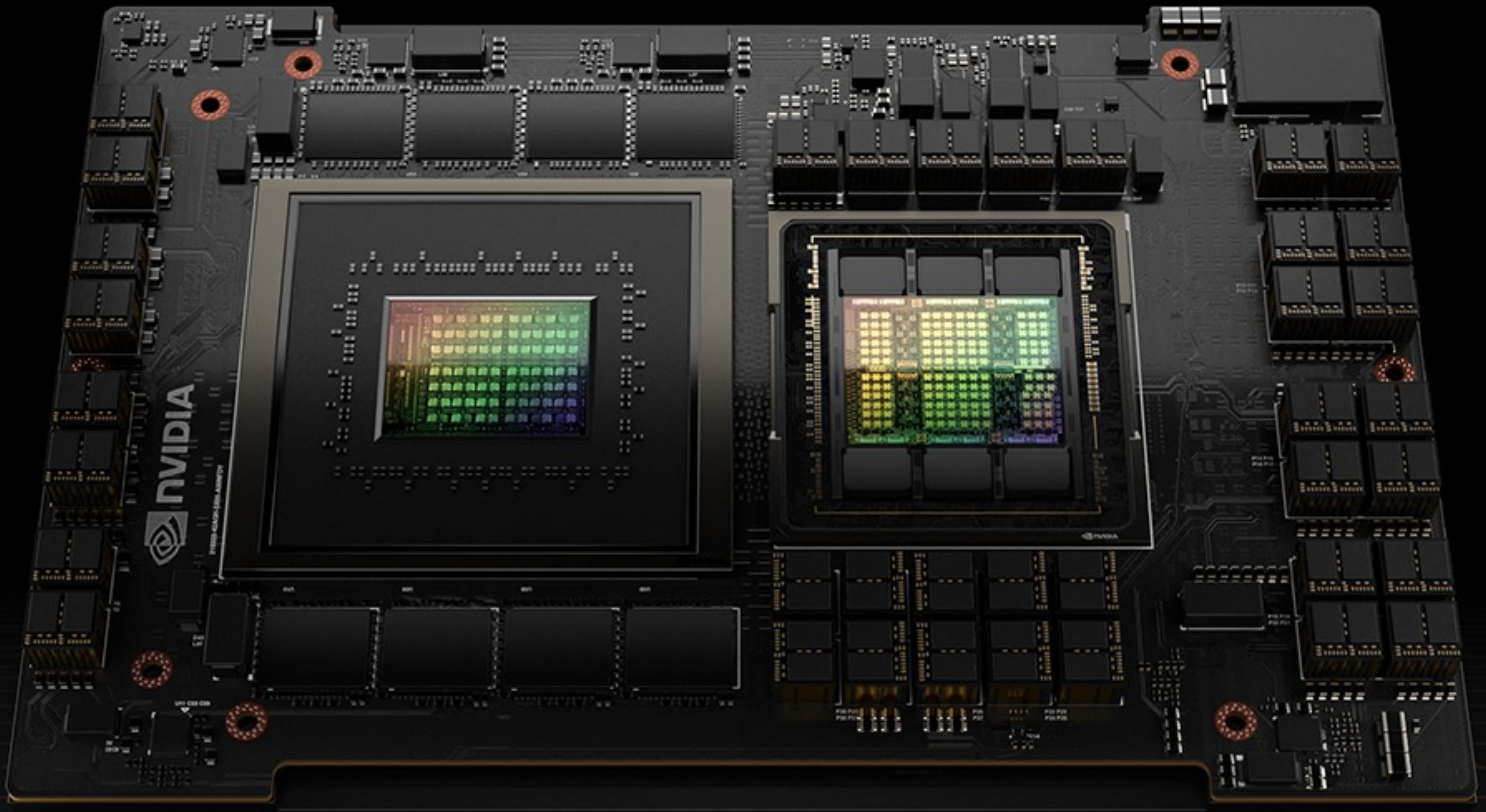
Model design is influenced by computer hardware.

- Clock speed
- Memory capacity
- Parallelism

Computers have evolved in several different directions over the years.

- Scalar machines
- Vector machines
- Massively parallel machines
- Machines based on GPUs (graphical processing units, a.k.a. game chips)

Grace Hopper



A “Grace-Hopper” super-chip

Chapter 12

100 Years of Earth System Model Development

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PETER R. GENT,[c] ANDREW GETTELMAN,[c] STEPHEN M. GRIFFIES,[d] PETER LYNCH,[e] HUGH MORRISON,[c]
ROBERT PINCUS,[f] AND JOHN THUBURN[g]

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[b] *Department of Atmospheric Sciences, University of Washington, Seattle, Washington*
[c] *National Center for Atmospheric Research, Boulder, Colorado*
[d] *Geophysical Fluid Dynamics Laboratory, Princeton, New Jersey*
[e] *University College Dublin, Dublin, Ireland*
[f] *CIRES, University of Colorado Boulder, Boulder, Colorado*
[g] *University of Exeter, Exeter, United Kingdom*

ABSTRACT

Today's global Earth system models began as simple regional models of tropospheric weather systems. Over the past century, the physical realism of the models has steadily increased, while the scope of the models has broadened to include the global troposphere and stratosphere, the ocean, the vegetated land surface, and terrestrial ice sheets. This chapter gives an approximately chronological account of the many and profound conceptual and technological advances that made today's models possible. For brevity, we omit any discussion of the roles of chemistry and biogeochemistry, and terrestrial ice sheets.

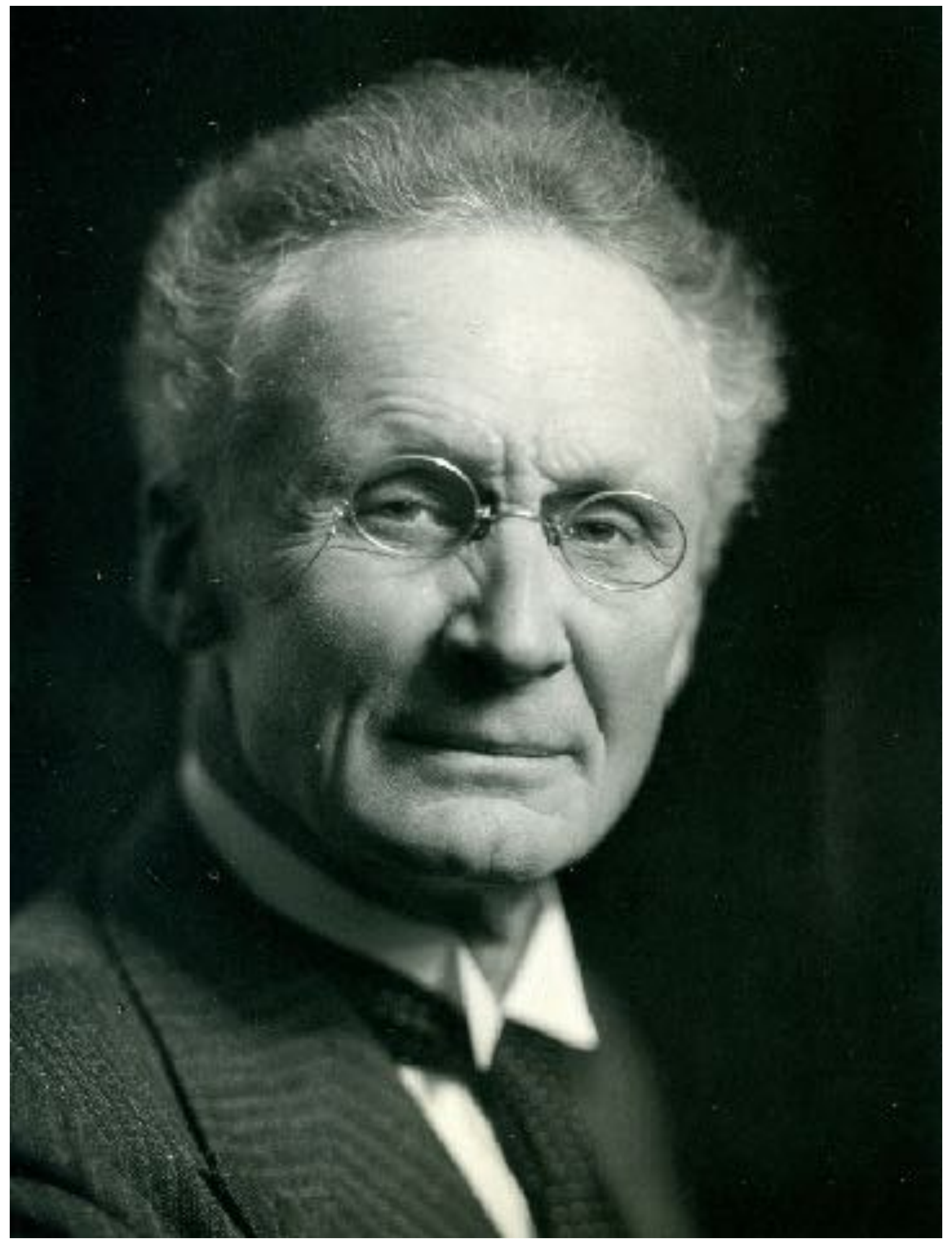
Assignment:

Read the 100 years paper.

The Dawn of Earth System Modeling

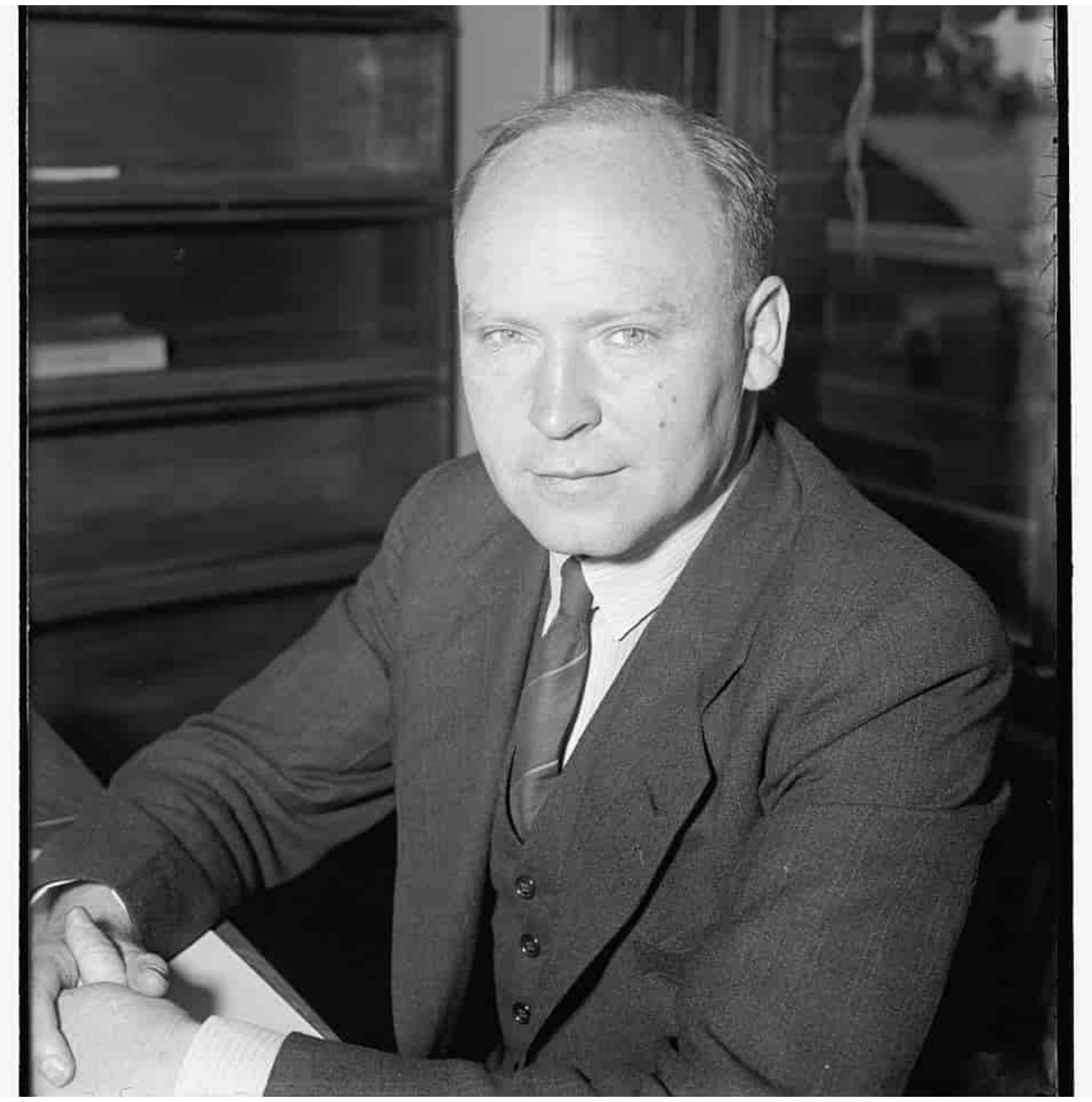
How did we get here?

The conceptual groundwork for today's weather and climate models was laid in Europe.



V. Bjerknes

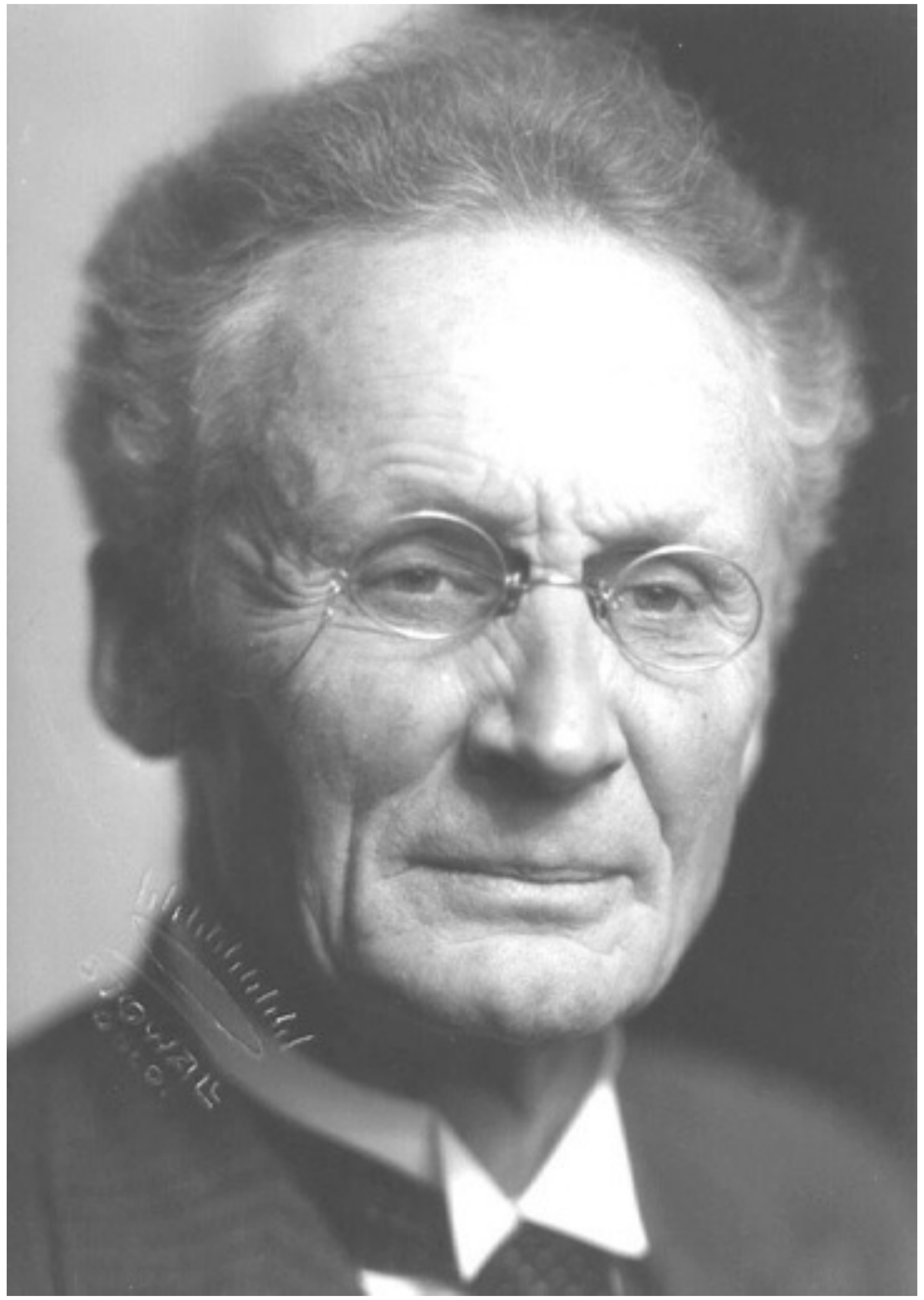
L. F. Richardson



C. G. Rossby

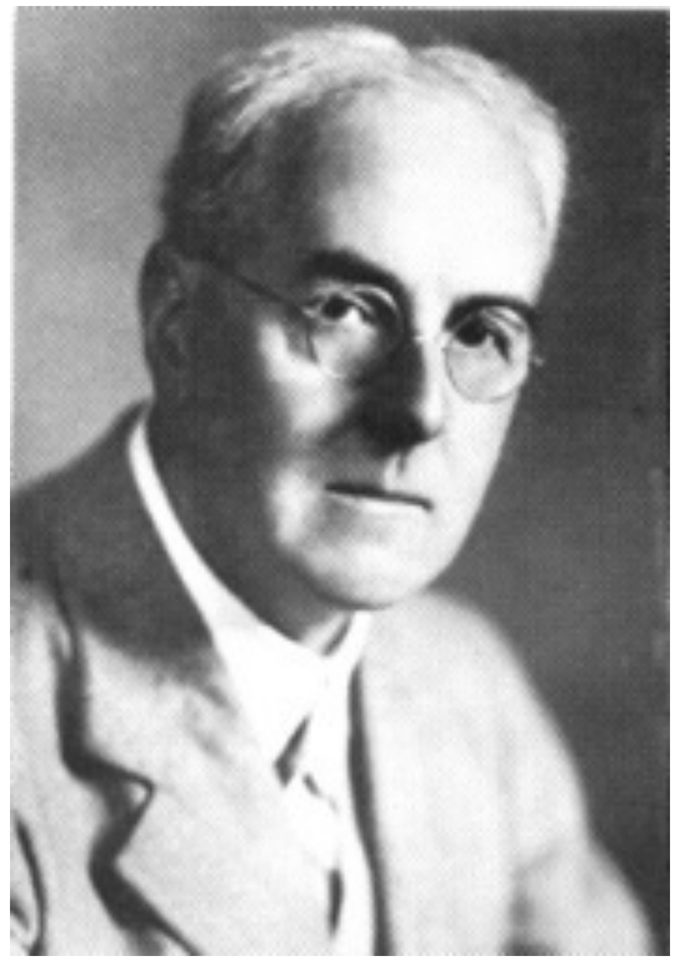
~1900

At the beginning of the 20th century, 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.... 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...”



Lewis F. Richardson

Richardson's Model

Governing equations

- Finite-difference in spherical horizontal coordinates with height as the vertical coordinate

Horizontal grid spacing:

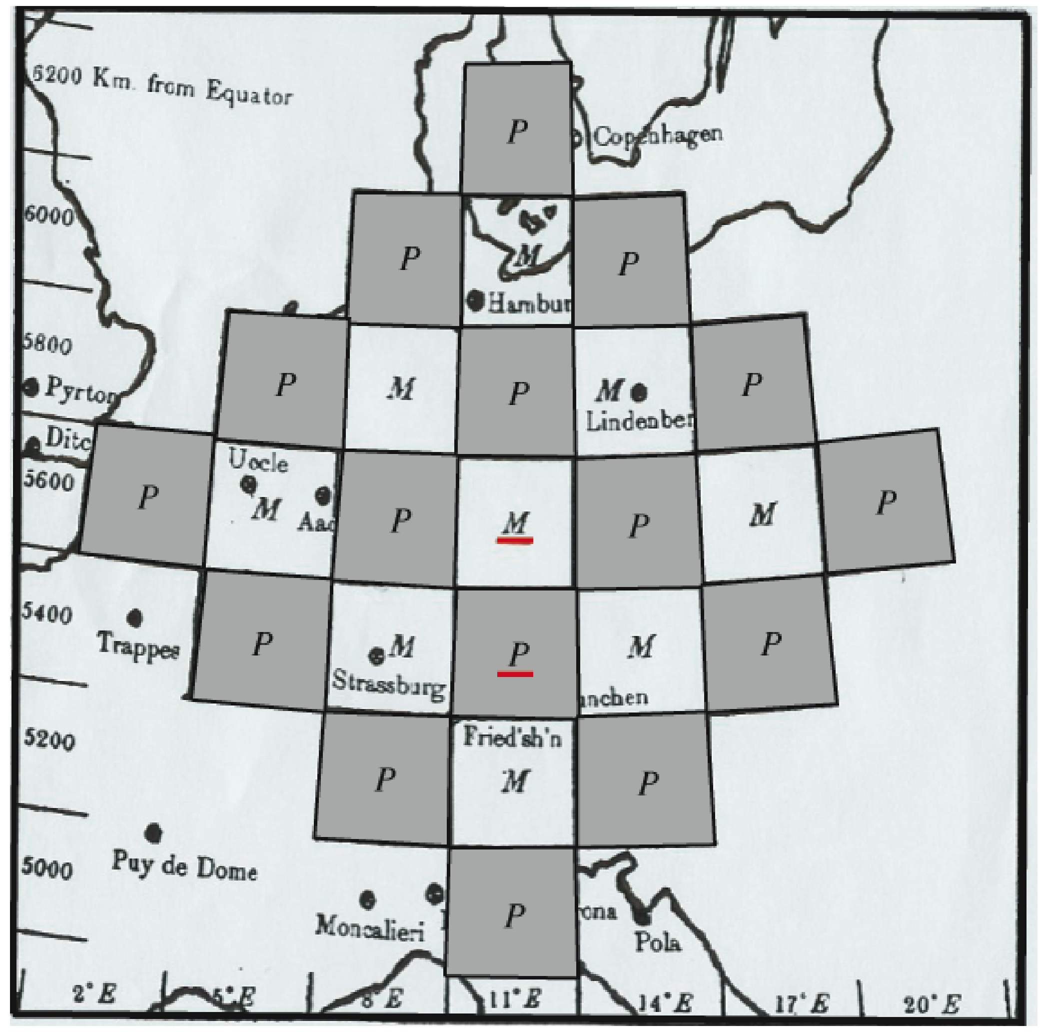
- About 200 km

Horizontal staggering:

- E grid

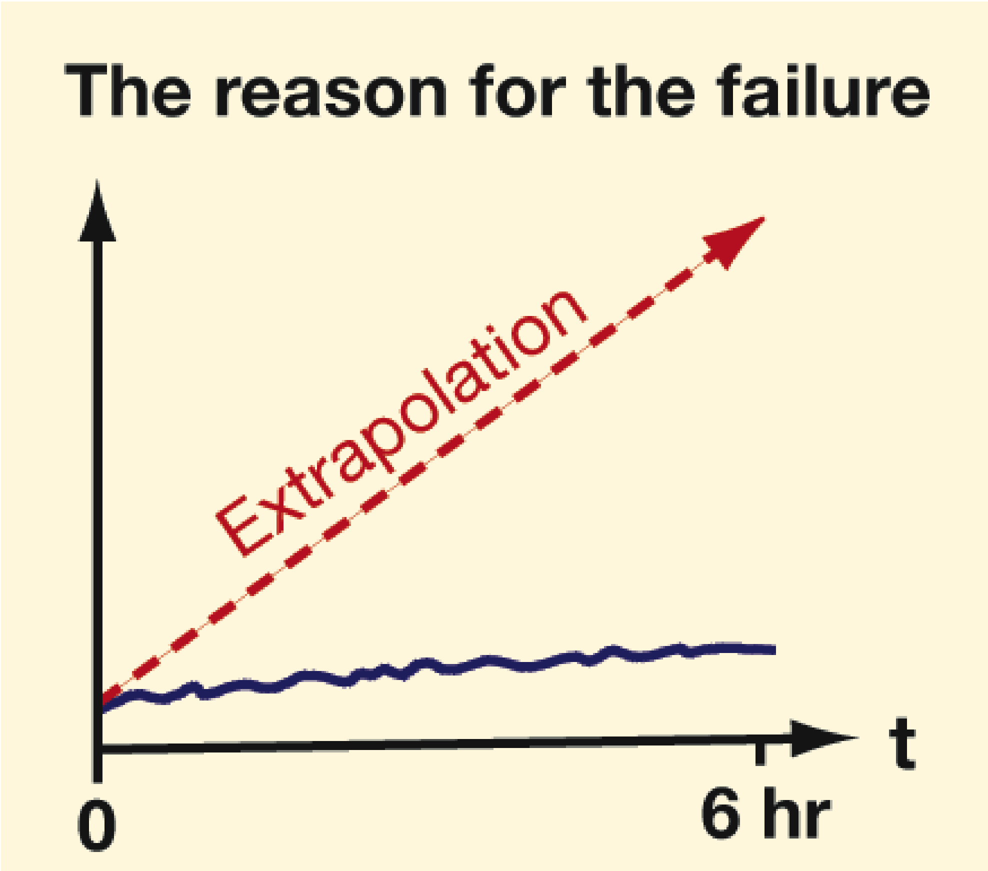
Vertical staggering:

- L grid



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."

1939

Rossby publishes his famous paper on the Rossby wave, but without detailed justification.

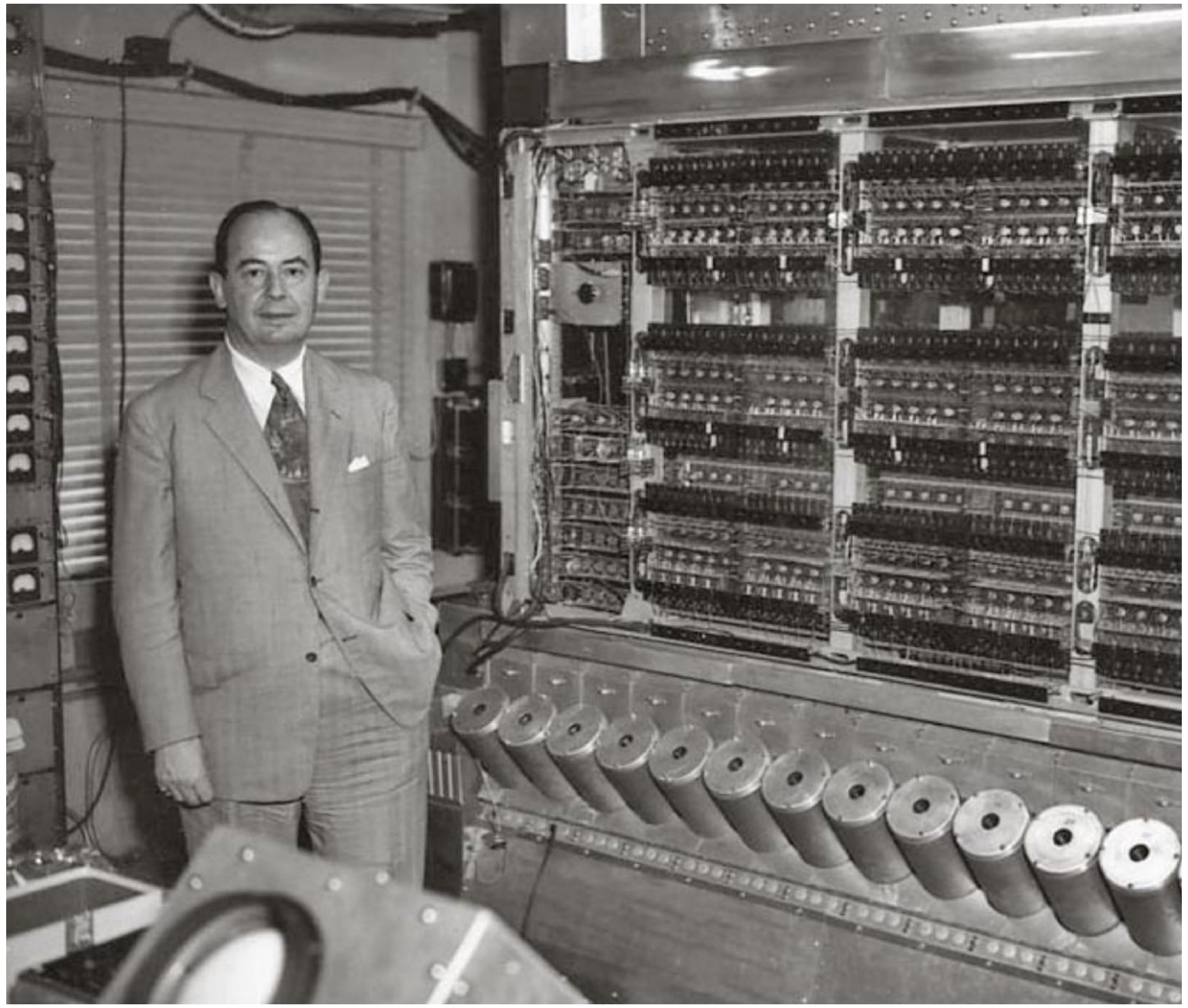
1947

Charney's paper
on baroclinic
instability.

1949

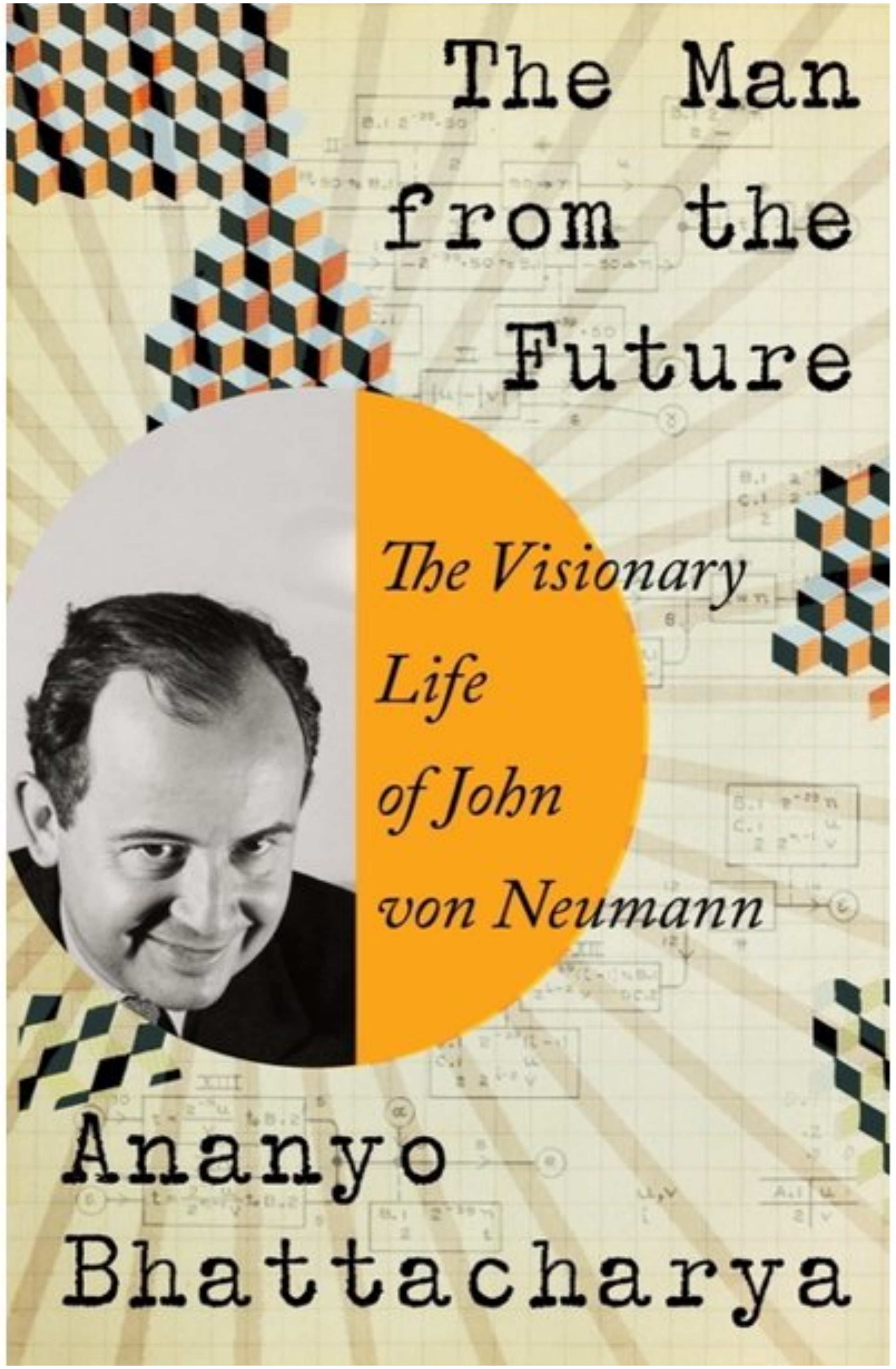
Charney publishes papers laying the foundation for numerical weather prediction, and explaining why Rossby's model worked so well.

Late 1940s



John von Neumann and ENIAC

Jule Charney, Norman Phillips, Glenn Lewis, Norma Gilbarg, George Platzman.
The computer in the background of this picture was called the MANIAC I.

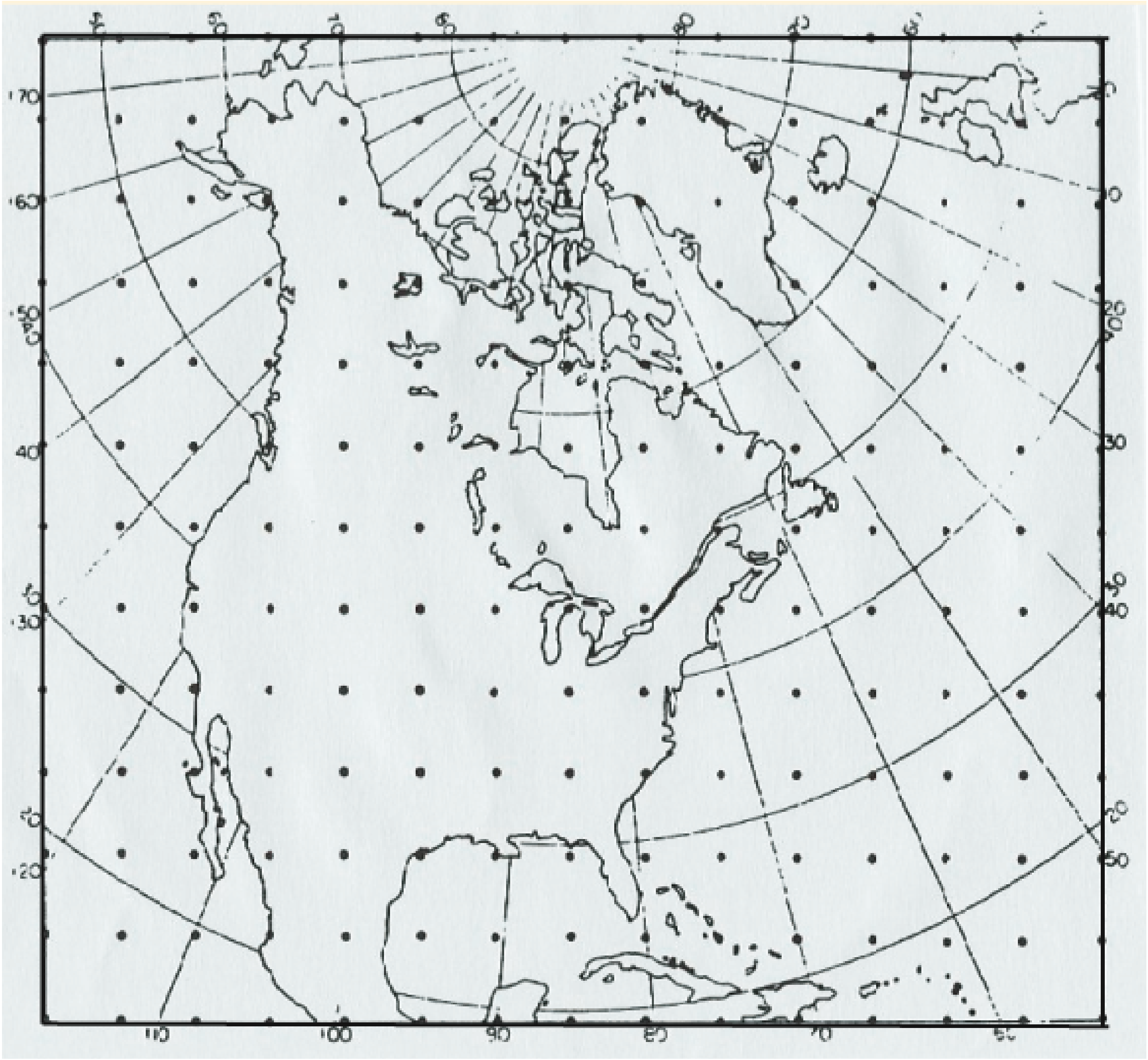

The Man from the Future
The Visionary Life of John von Neumann
Ananyo Bhattacharya

Staff members of the Electronic Computer Project, 1952, including Lambert Rockefellow, Elizabeth C. Wooden, Norma Gilbarg, Hedvig Selberg, Frank E. Fell, Hewitt Crane, Richard W. Melville, Ephraim H. Frei, Margaret Lambe, Peter Panagos, Gordon Kent, Norman Phillips, Herman Goldstine, James Pomerene, Julian Bigelow, and Gerald Estrin.

https://albert.ias.edu/entities/archivalmaterial/df460224-03e8-47b4-8941-e9878b49c113

1950

The first successful numerical forecast, using the nondivergent barotropic vorticity equation.



Grid spacing: 736 km

1950-55

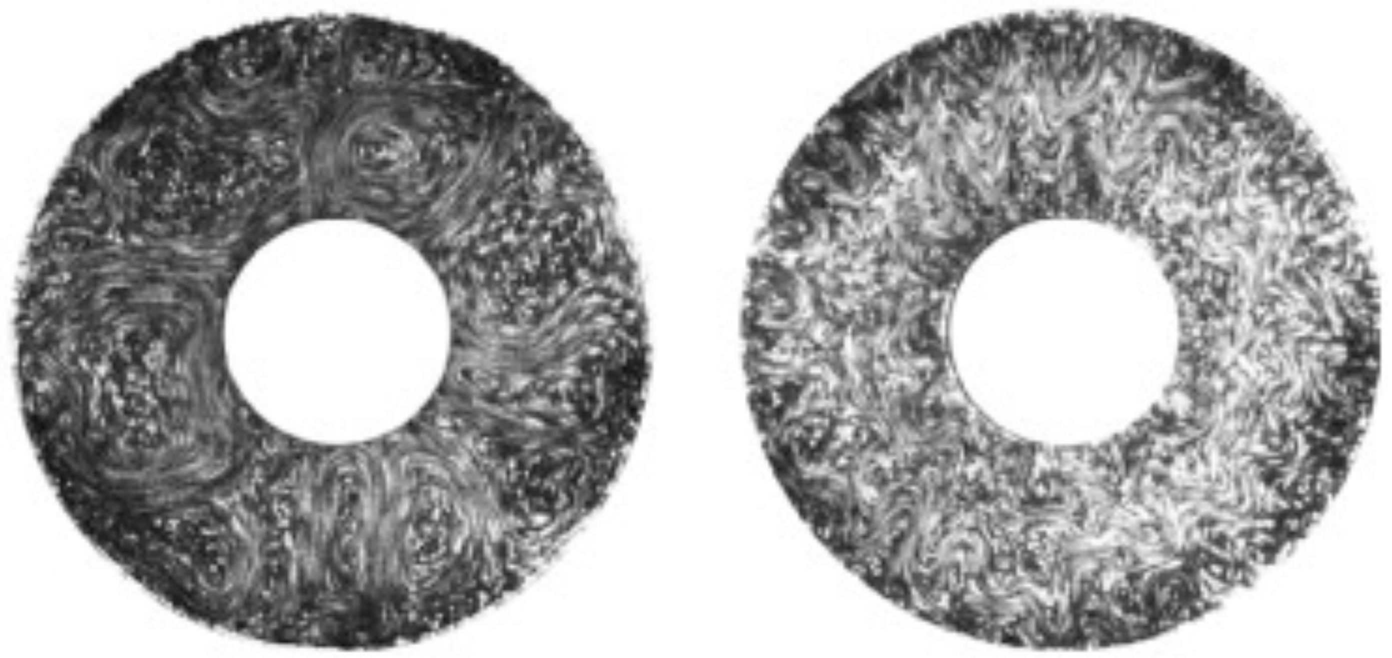
First *baroclinic* numerical models (Charney and Phillips).

Observational studies of the general circulation by Victor Starr's group at MIT.

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

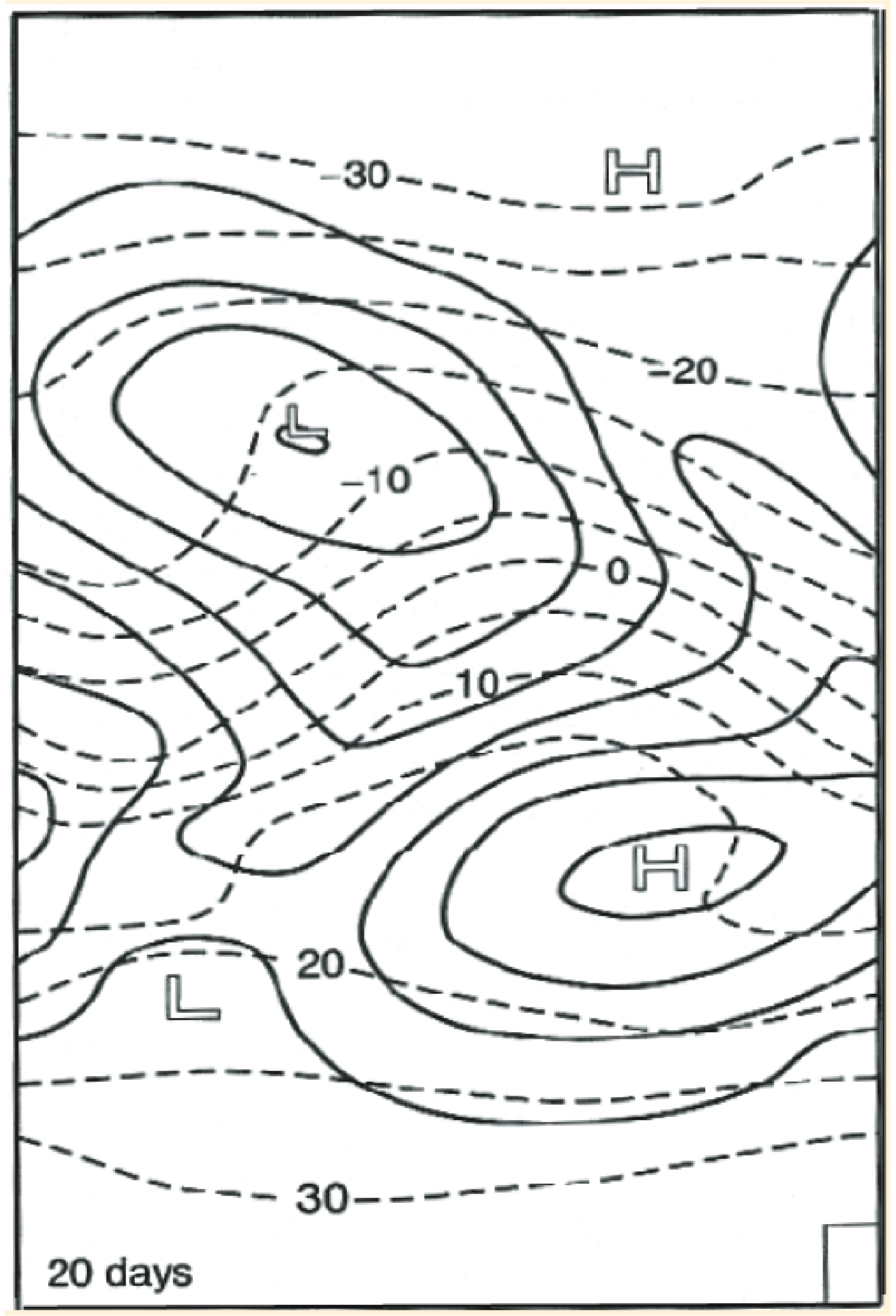
Operational NWP begins in the U.S., Sweden, & Japan.

Lorenz publishes his paper on available potential energy.



1956

The first general circulation model is constructed by Norman Phillips, who promptly discovers nonlinear computational instability.



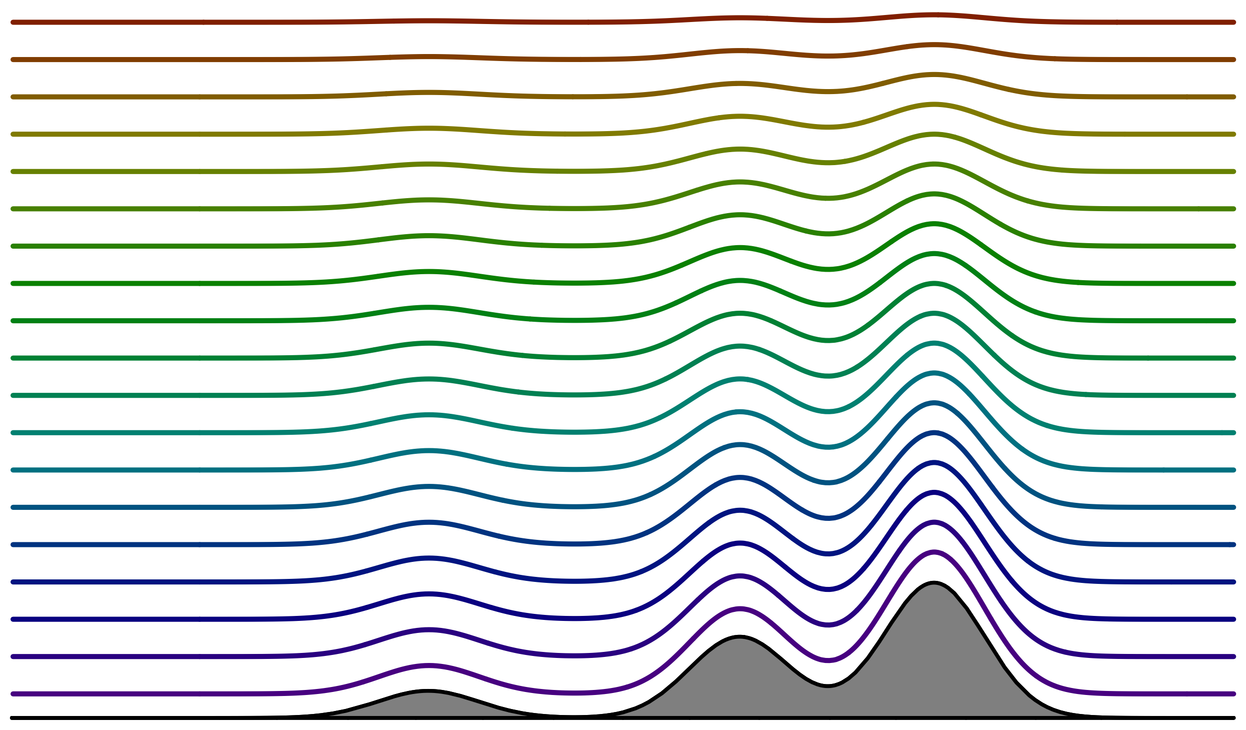
Late 50s

1955-60: The first experimental forecasts with the primitive equations (Hinkelman, Germany).

1957: Phillips proposes the terrain-following sigma coordinate.

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

1959: Phillips publishes an interpretation of nonlinear computational instability.



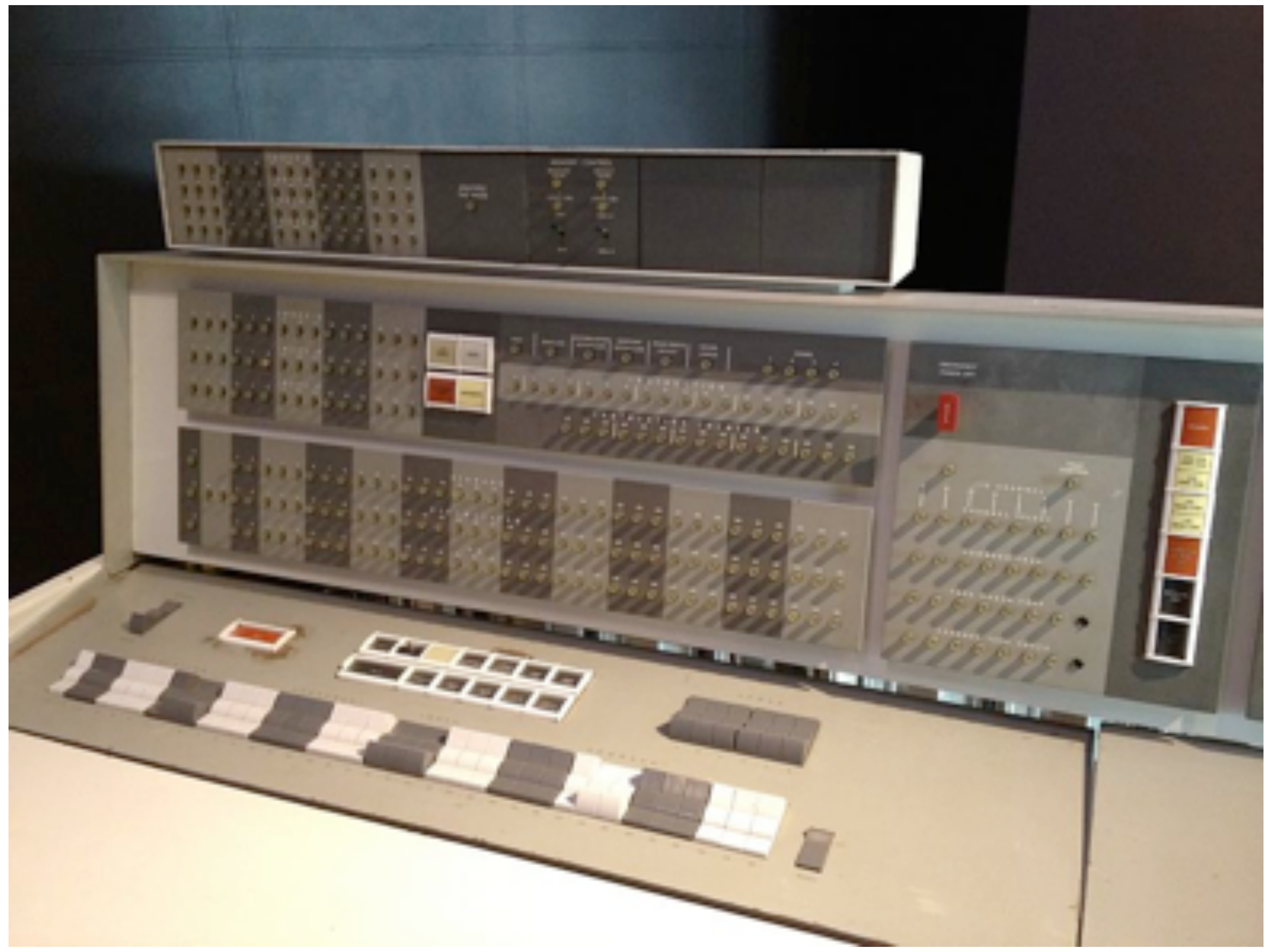
Early 60s

1960: Lorenz publishes "Energy and NWP."

1960: A climate modeling project is started at the Lawrence Radiation Laboratory by Chuck Leith.

1961: A climate modeling project is started at UCLA by Yale Mintz and Akio Arakawa.

1962: Charney experiments with the primitive and balance equations.



IBM 7094

The Ancestral Models

GFDL

UCLA

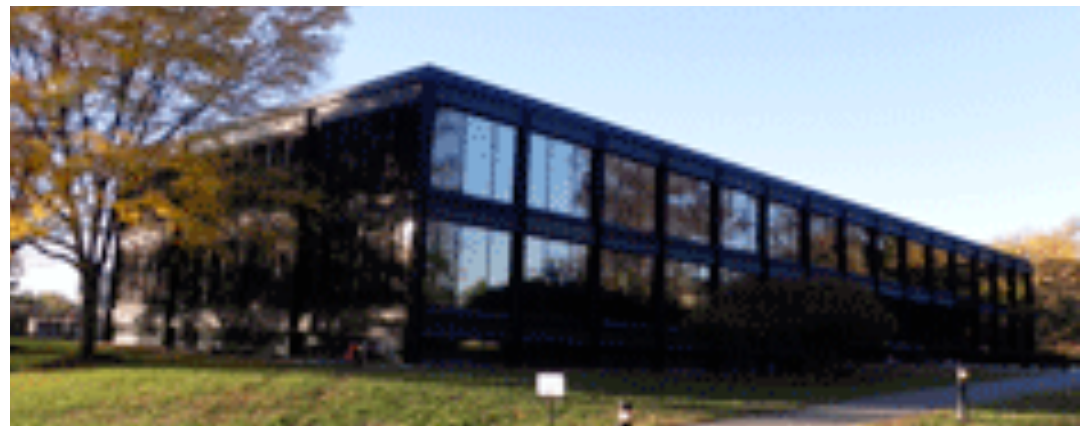
Lawrence Radiation Laboratory

National Center for Atmospheric Research

The Ancestral Models

USA only

- The GFDL model
  - First radiation parameterization
  - First cumulus parameterization
  - “Bucket” land surface model
  - Relatively high vertical resolution



- The UCLA model
  - Conservative numerical methods
  - Mass-flux convection
  - Radiatively interactive clouds

- The Livermore model
  - Short lifetime
  - Pressure as the vertical coordinate
  - Strong smoothing needed

- The NCAR model
  - Height as the vertical coordinate

The pioneers

Joseph Smagorinisky

Syukuro Manabe

Yale Mintz & Akio Arakawa

Chuck Leith

Akira Kasahara & Warren Washington

Kirk Bryan

Bill Hibler

Bert Semtner

Piers Sellers & Robert Dickinson

The pioneers shown on the previous slide were all men.

They all did their work in the United States, although three of them had grown up in Japan.

Among the first women to work with global models, starting in the 1970s, were Eugenia Kalnay and Claire Parkinson.

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.

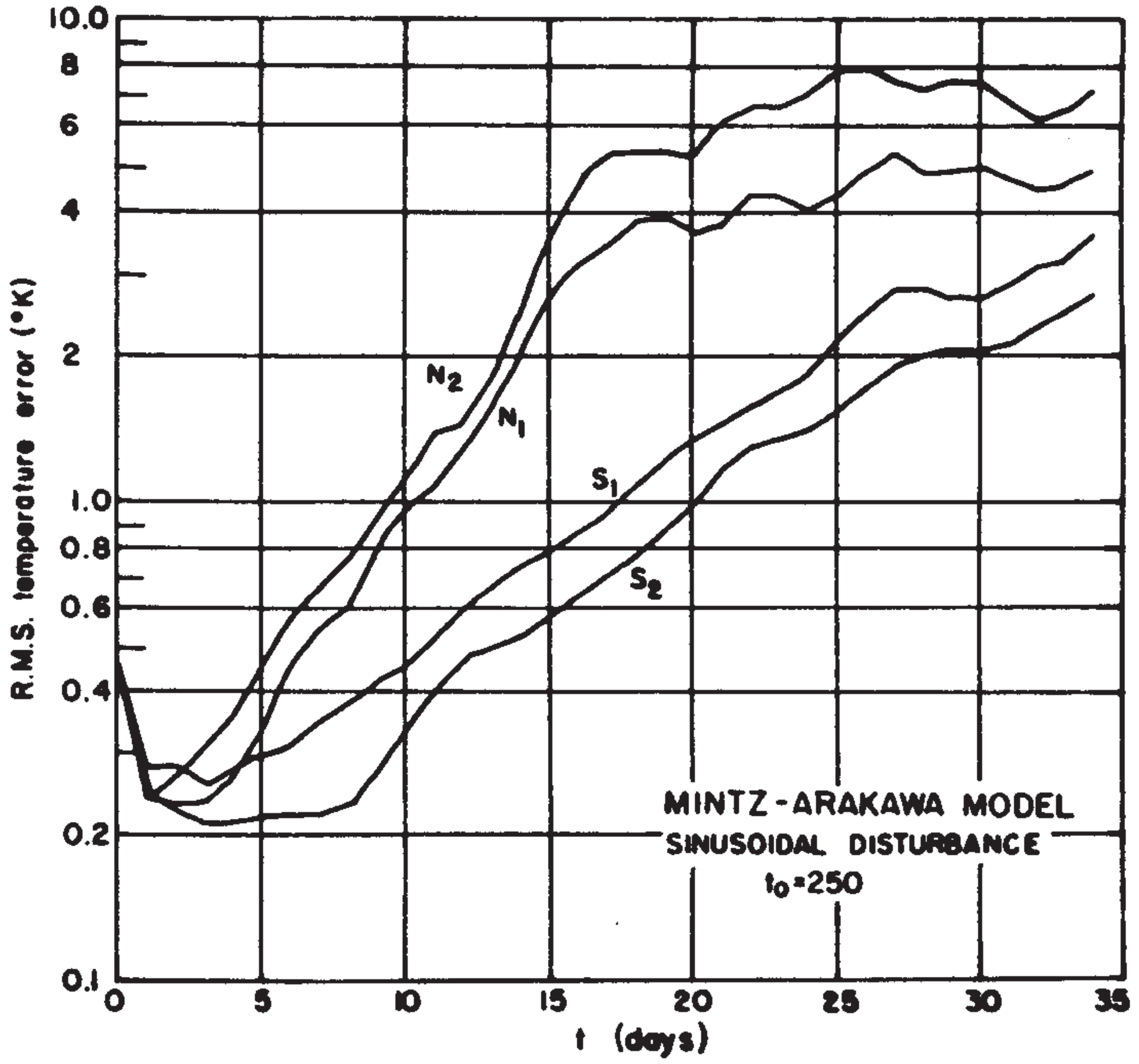
1967: The NCAR 2-level model is published by Kasahara and Washington.

1969: First ocean GCM results are published by Bryan.

NCAR's CDC 3600, circa 1963

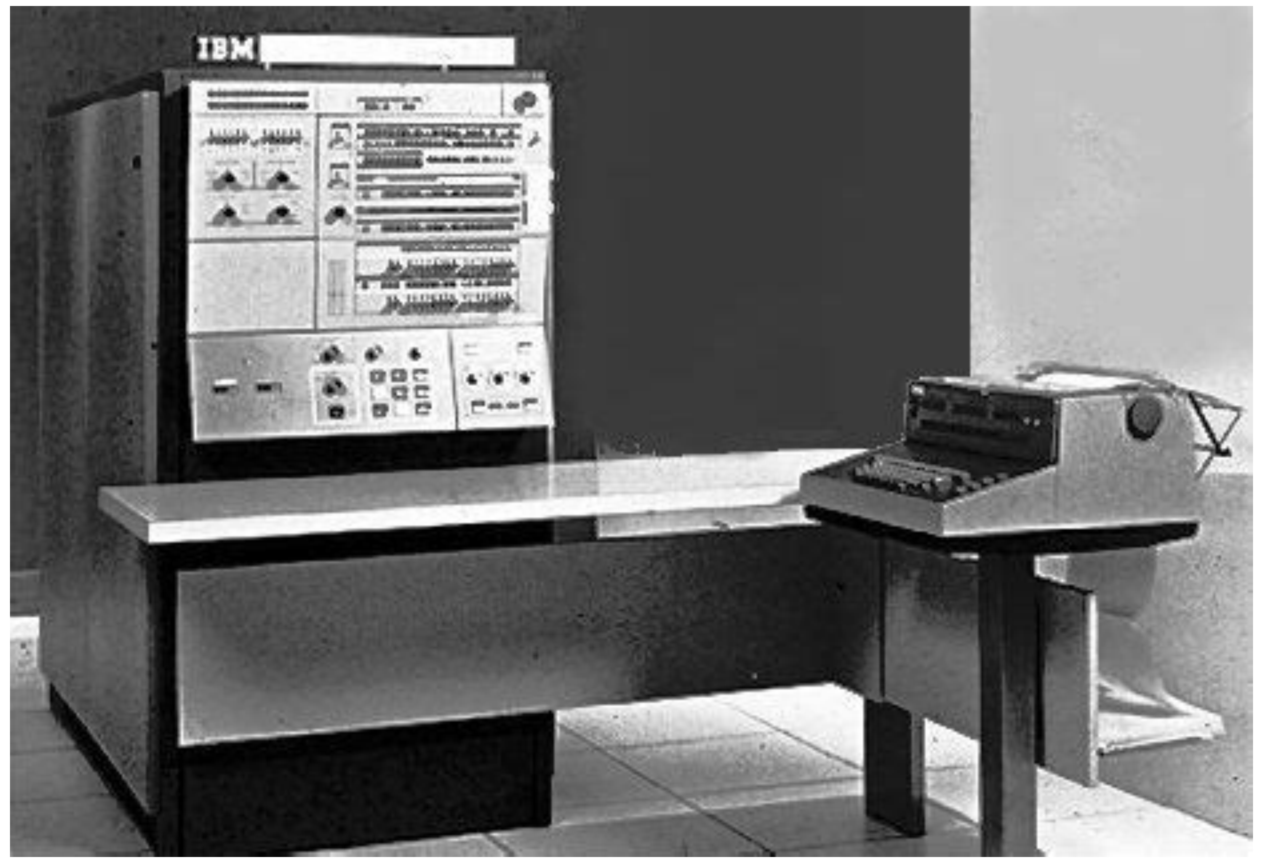
Mid-60s

1966: Charney makes predictability experiments with the three GCMs.



1966: The "Arakawa Jacobian" is published.

1967: Manabe and colleagues begin to explore the effects of increased CO_2, using simplified models.



First Ocean GCM

JOURNAL OF COMPUTATIONAL PHYSICS 4, 347–376 (1969)

A Numerical Method for the Study of the Circulation of the World Ocean

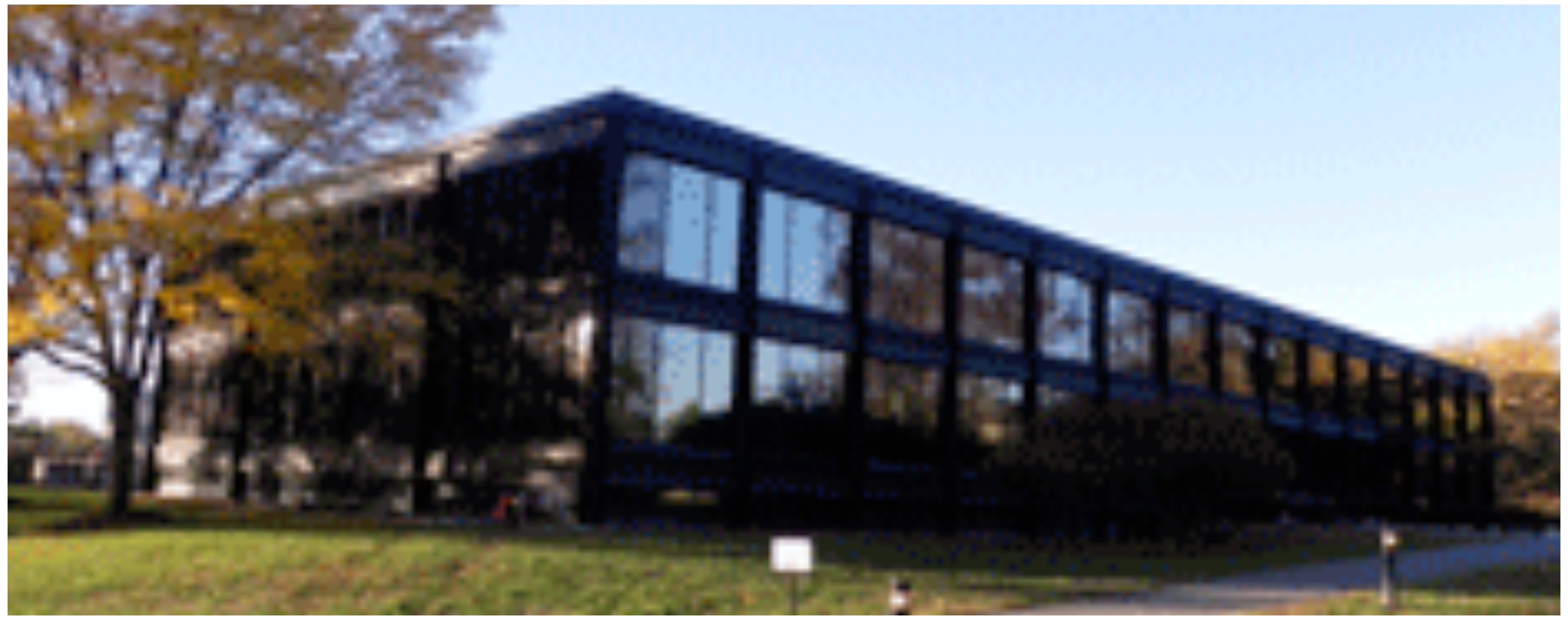
KIRK BRYAN

Geophysical Fluid Dynamics Laboratory, ESSA,
Princeton, New Jersey 08540

Received December 26, 1968

ABSTRACT

A model is presented for studying ocean circulation problems taking into account the complicated outline and bottom topography of the World Ocean. To obtain an efficient scheme for the study of low-frequency, large-scale current systems, surface gravity-inertial waves are filtered out by the "rigid-lid" approximation. To resolve special features of the ocean circulation, such as the Equatorial Undercurrent, the numerical model allows for a variable spacing in either the zonal or meridional direction. The model is designed to be as consistent as possible with the continuous equations with respect to energy. It is demonstrated that no fictitious energy generation or decay is associated with the nonlinear terms in the finite difference form of the momentum equations. The energy generation by buoyancy forces for the numerical model is also designed in such a way that no energy "leak" occurs in the transformation from potential to kinetic energy.



Kirk Bryan

Early Sea Ice Models

A Model for the Thermodynamic Growth of Sea Ice in Numerical Investigations of Climate

ALBERT J. SEMTNER, JR.[1]

Climate Dynamics Program, Rand Corporation, Santa Monica, Calif. 90406

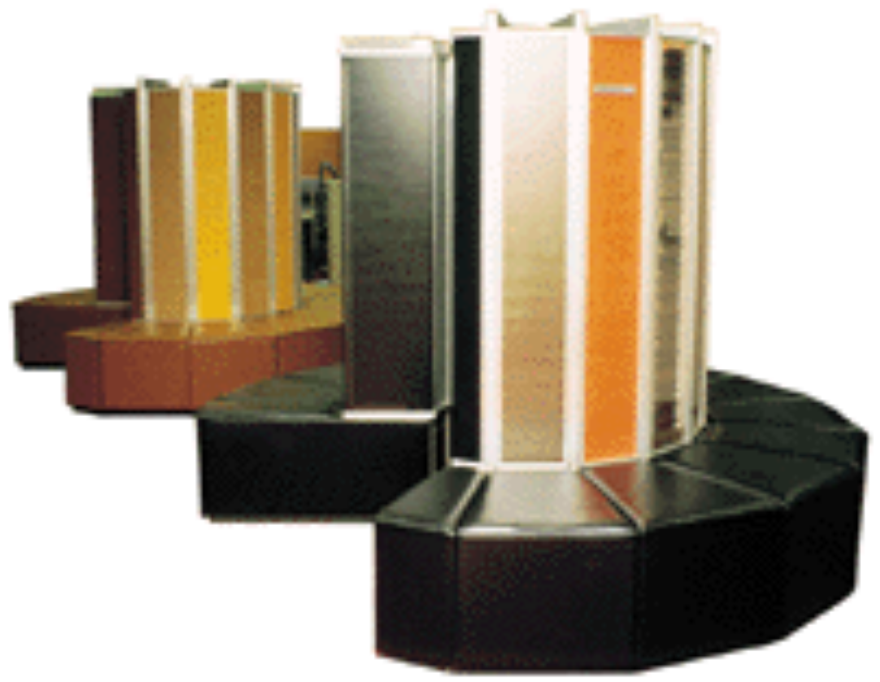
(Manuscript received 11 July 1975, in revised form 27 December 1975)

ABSTRACT

A model is presented whereby the thickness and extent of sea ice may be predicted in climate simulations. A basic one-dimensional diffusion process is taken to act in the ice, with modifications due to penetration of solar radiation, melting of internal brine pockets, and accumulation of an insulating snow cover. This formulation is similar to that of a previous study by Maykut and Untersteiner, but the introduction of a streamlined numerical method makes the model more suitable for use at each grid point of a coupled atmosphere-ocean model. In spite of its simplicity, the ice model accurately reproduces the results of Maykut and Untersteiner for a wide variety of environmental conditions. In 25 paired experiments, annual average equilibrium thicknesses of ice agree within 24 cm for 75% of the cases; and the average absolute error for all cases is 22 cm. The new model has fewer computational requirements than one layer of ocean in the polar regions, and it can be further simplified if additional savings of computer time are desired.

Global modeling in the 70s

- More global modeling centers are set up, some outside the U.S.
- Annual cycles are simulated.
- Arakawa & Schubert, 1974.
- "Climate simulation" usually means a perpetual January with prescribed SSTs.
- Vector computing arrives.
- Global numerical weather prediction begins, and ECMWF is created.
- First simulation of global warming.
- Models are used to simulate the effects of supersonic airliners on the stratosphere
  -- a loss of innocence.
- Cloud feedbacks hit prime time.
- Satellite data becomes more useful.



Cray 1-A

ECMWF

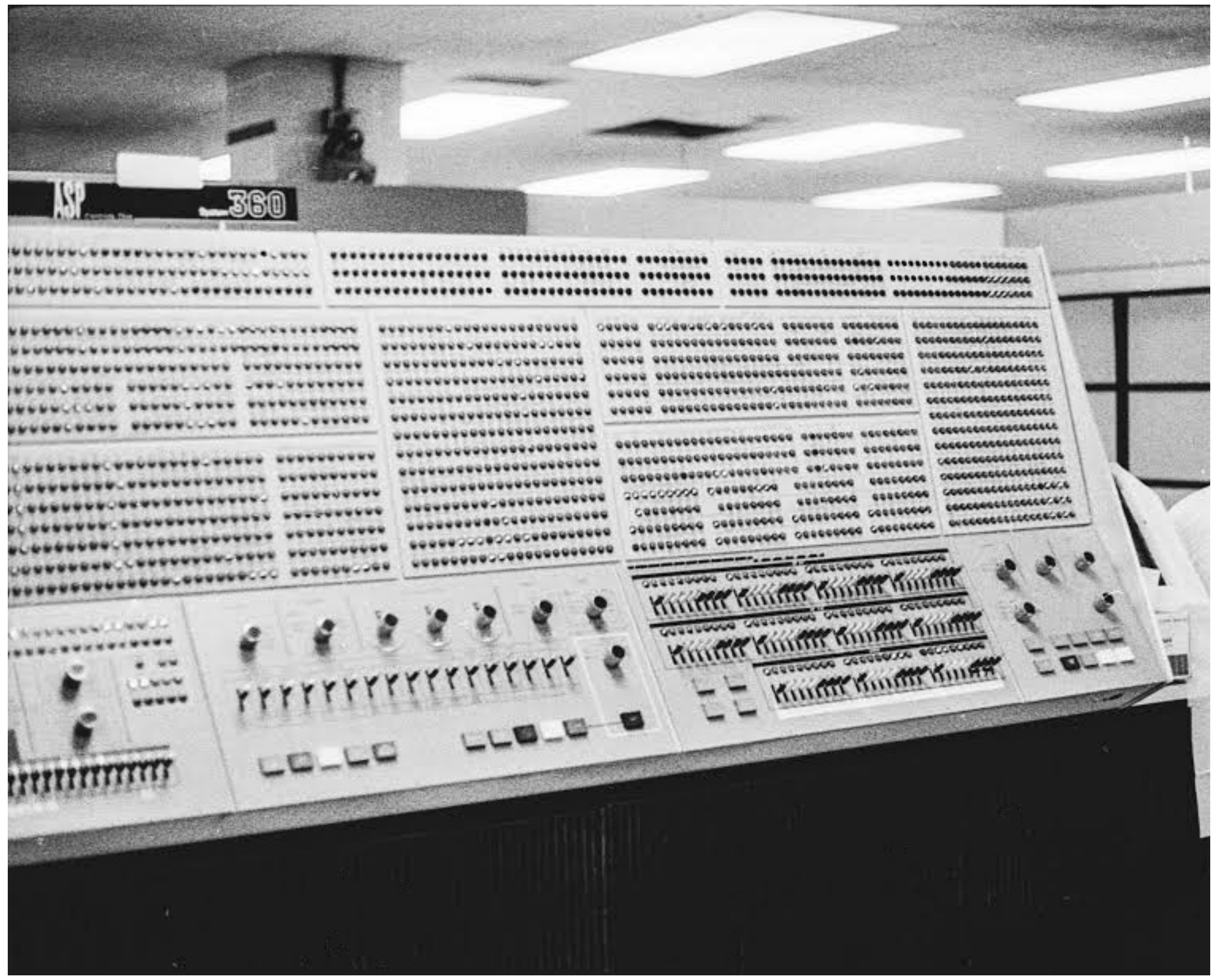
A loss of innocence

During the 1970s, with support from the Climate Impact Assessment Program (CIAP) of the U. S. Department of Transportation, some global atmospheric models were extended upward to include the stratosphere with interactive ozone chemistry, and used to simulate the effects of supersonic airliners on stratospheric ozone.

This was the first time that agency funding was made available specifically for the application of global atmospheric models to investigate anthropogenic effects on the climate system.

IBM 360/91

- The machine had 4 MB of solid-state "main" memory.
- The CPU could do 5.5 million floating-point multiplies per second.
- Disk drives held 2 MB and were the size of clothes washers.
- Input was via a card reader.
- Printers did 600 *lines* per minute



Computer "console"

Disk drive

Card reader

"Line printer"

NCAR's Cray-1

Delivered in 1977

80 Mflops
8 MB of main memory

Users had to be there in the building with it.

The Effects of Doubling the CO_2 Concentration on the Climate of a General Circulation Model[1]

SYUKURO MANABE AND RICHARD T. WETHERALD

Geophysical Fluid Dynamics Laboratory/NOAA, Princeton University, Princeton, N.J. 08540

(Manuscript received 6 June 1974, in revised form 8 August 1974)

ABSTRACT

An attempt is made to estimate the temperature changes resulting from doubling the present CO_2 concentration by the use of a simplified three-dimensional general circulation model. This model contains the following simplifications: a limited computational domain, an idealized topography, no heat transport by ocean currents, and fixed cloudiness. Despite these limitations, the results from this computation yield some indication of how the increase of CO_2 concentration may affect the distribution of temperature in the atmosphere. It is shown that the CO_2 increase raises the temperature of the model troposphere, whereas it lowers that of the model stratosphere. The tropospheric warming is somewhat larger than that expected from a radiative-convective equilibrium model. In particular, the increase of surface temperature in higher latitudes is magnified due to the recession of the snow boundary and the thermal stability of the lower troposphere which limits convective heating to the lowest layer. It is also shown that the doubling of carbon dioxide significantly increases the intensity of the hydrologic cycle of the model.

In 1975, Manabe & Wetherald predicted:

- Warming troposphere
- Greater warming near the poles
- Cooling stratosphere
- More rain and higher humidity

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- Warming troposphere
- Greater warming near the poles
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- More rain and higher humidity

All of these things have now happened.

1978: Global numerical weather prediction began in the U.S.

U.S. DEPARTMENT OF COMMERCE
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
NATIONAL WEATHER SERVICE
NATIONAL METEOROLOGICAL CENTER

OFFICE NOTE 178

The NMC 9-Layer Global Primitive Equation
Model on a Latitude-Longitude Grid

John D. Stackpole
Development Division

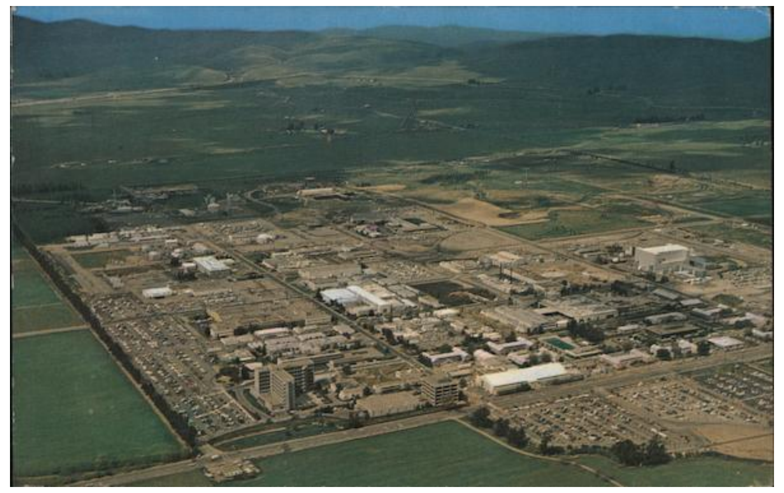
MAY 1978

John Stackpole

At the end of the 1970s, the U.S. was firmly at the forefront of global modeling.

GFDL

UCLA



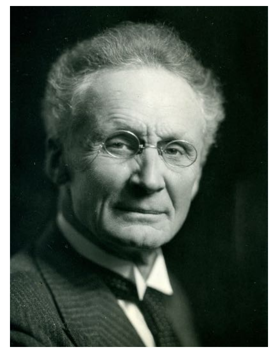
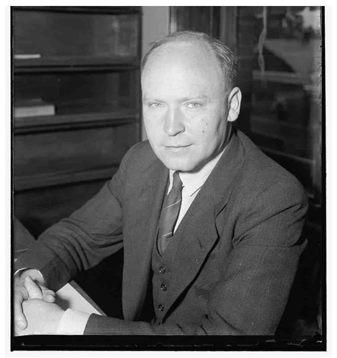
Lawrence Radiation Laboratory

NCAR

1979: ECMWF begins operations

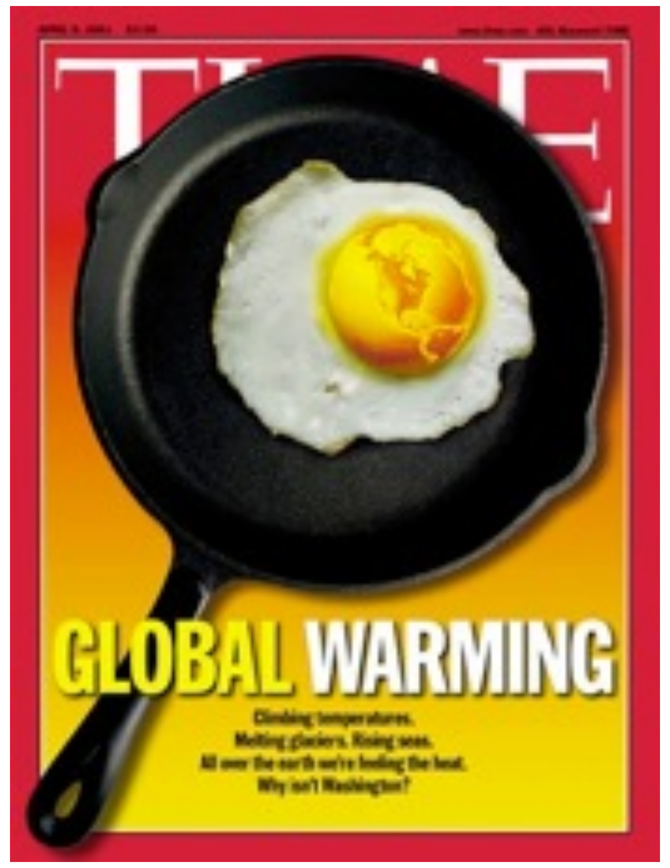
The creation of ECMWF heralded a European renaissance in weather and climate modeling.

ECMWF's universally recognized scientific excellence, strong academic connections, and robust funding model produced the world's most skillful global weather forecasts and also exerted, through collaborations and publications, a major influence on all of the world's climate models.

During the 1980s

- Hilding Sundqvist argues for predicting cloud water.
- The CCM is born.
- Land-surface modeling gets a higher profile.
- Spectral models become popular.
- The Earth's radiation budget gets more attention.
- Global warming becomes a political issue.



Dickinson and Sellers begin work on land-surface process parameterizations.

Climate modeling in the 90s

- The Age of Intercomparison begins.
- Parameterization testing becomes organized.
- Reanalysis gets under way.
- The spectral method starts to die, as semi-Lagrangian advection becomes popular.
- The carbon cycle gets attention.
- Aerosols become widely appreciated.
- The IPCC begins its work.
- Operational seasonal prediction with coupled models begins.
- Creation of the CCSM→CESM.

Cray C90

CCSM

Ice sheet models

The Glimmer community ice sheet model

I. C. Rutt,[1] M. Hagdorn,[2] N. R. J. Hulton,[2] and A. J. Payne[3]

Received 18 March 2008; revised 23 November 2008; accepted 26 January 2009; published 10 April 2009.

[1] We present a detailed description of the Glimmer ice sheet model, comprising the physics represented in the model and the numerical techniques used. Established methods are combined with good software design to yield an adaptable and widely applicable model. A flexible framework for coupling Glimmer to global climate forcing is also described. Testing and benchmarking is of crucial importance if the outputs of numerical models are to be regarded as credible; we demonstrate that Glimmer performs very well against the well-known EISMINT benchmarks and against other analytical solutions for ice flow. Glimmer therefore represents a well-founded and flexible framework for the open-source development of ice sheet modeling.

Citation: Rutt, I. C., M. Hagdorn, N. R. J. Hulton, and A. J. Payne (2009), The Glimmer community ice sheet model, *J. Geophys. Res.*, *114*, F02004, doi:10.1029/2008JF001015.

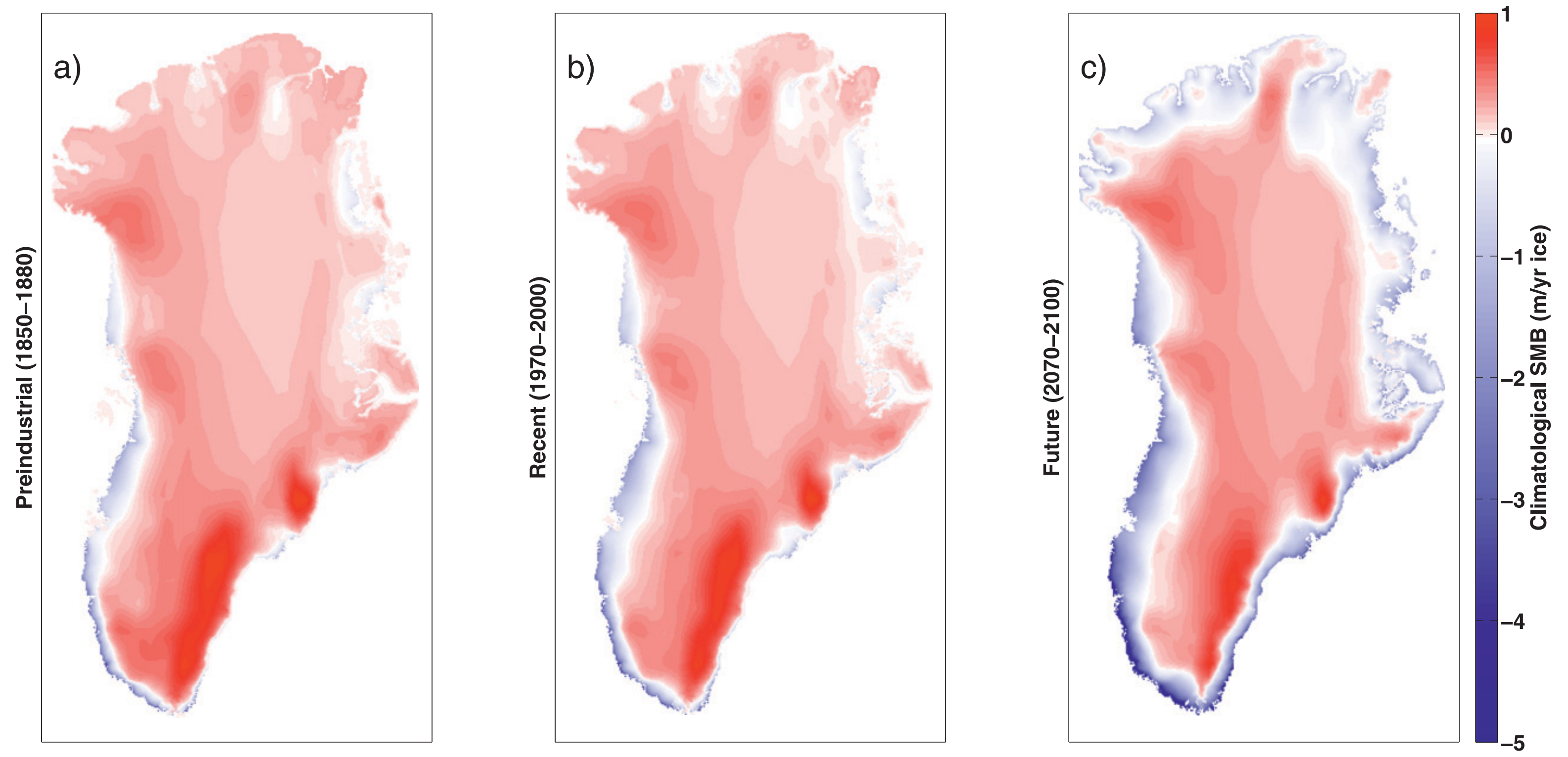
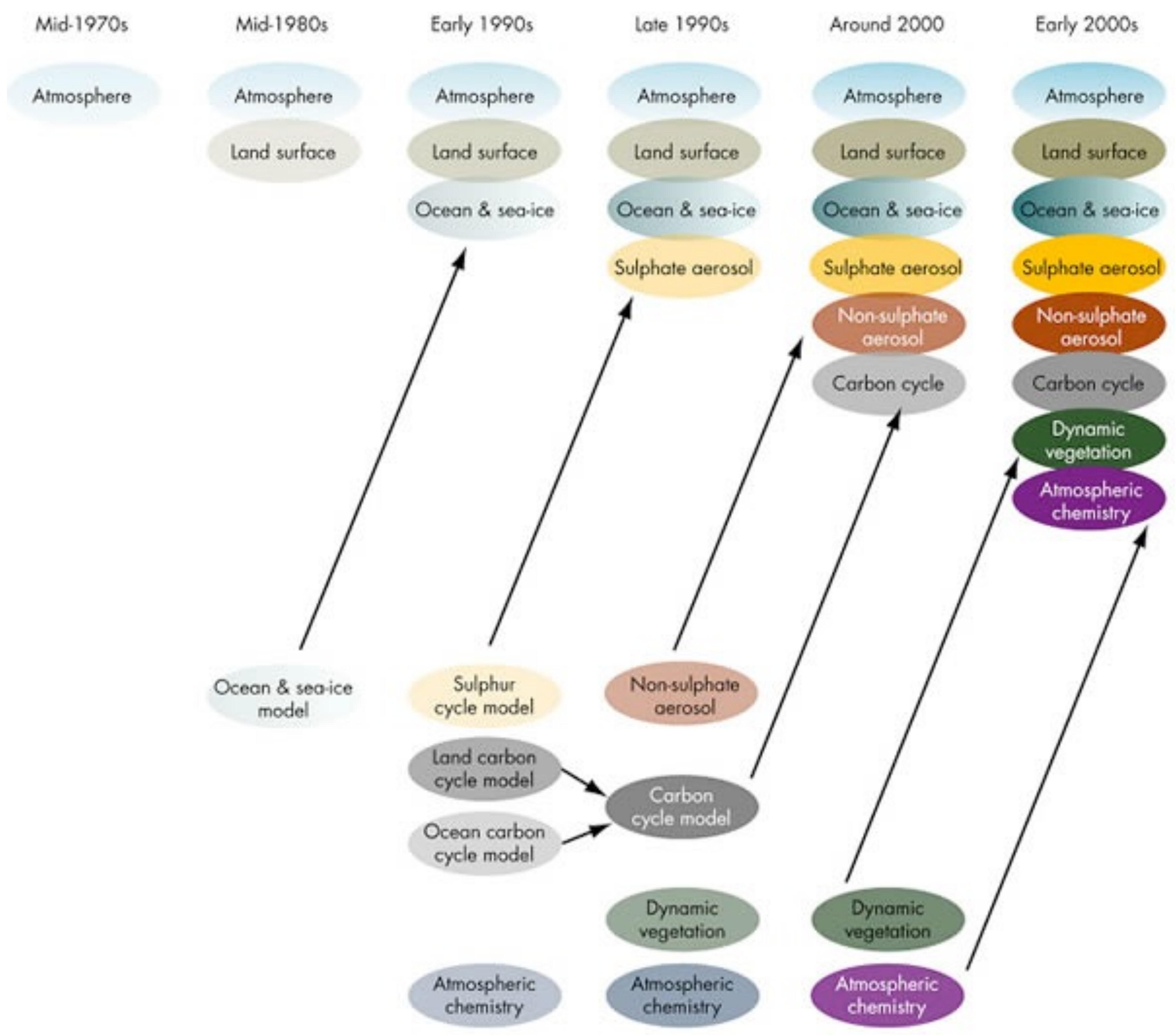


Fig. 10. Climatological SMB of the simulated GIS for the (a) preindustrial (1850–80), (b) modern (1970–2000), and (c) future (2070–2100) periods averaged over the five top-ranking ensemble members.

therefore it is important to choose model parameters that give an accurate spun-up geometry.

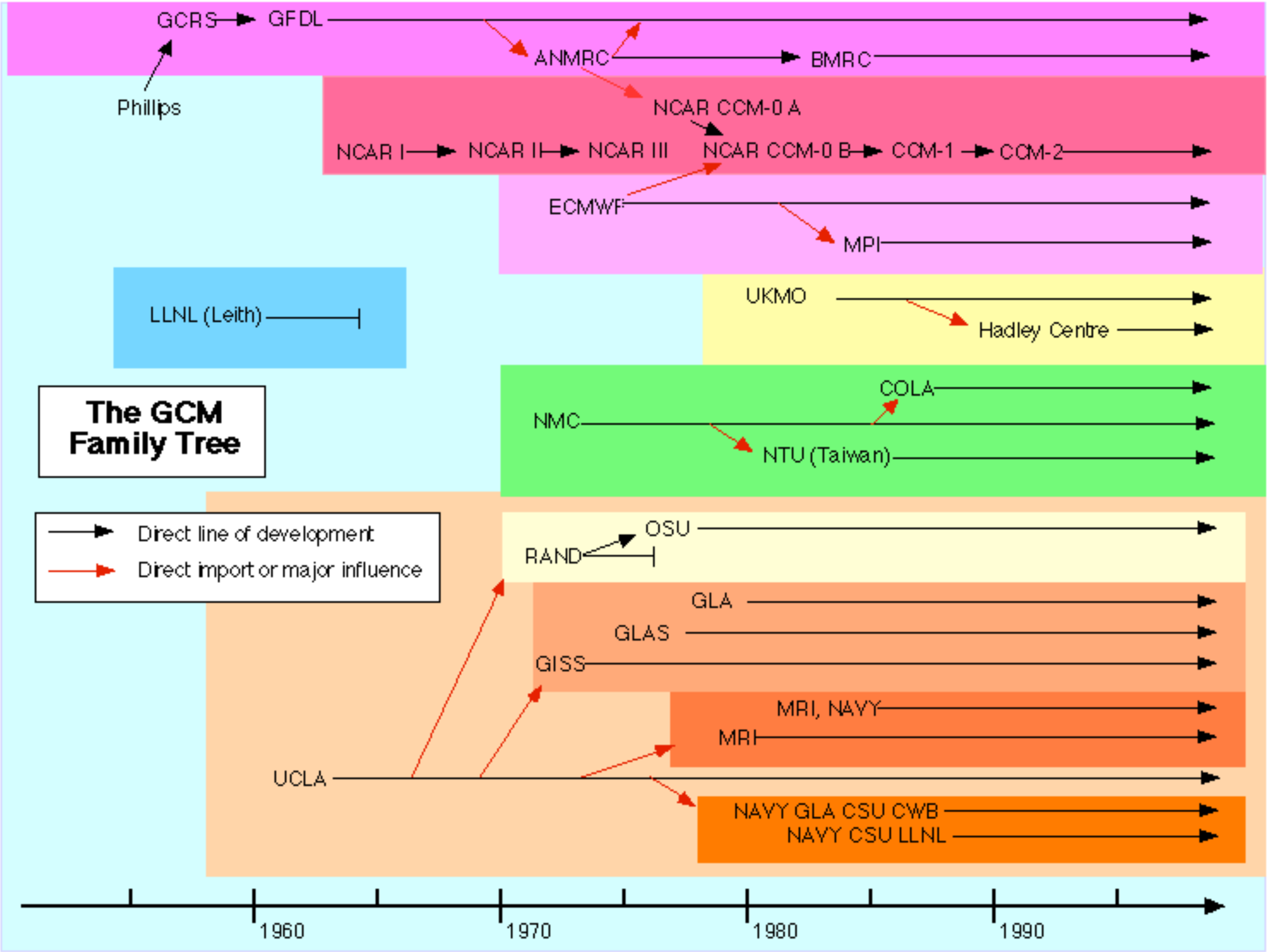
The coupled CESM1(CISM) model requires further development to reduce biases and increase realism. Desired model improvements can be divided into four categories: 1) a more sophisticated dynamic ice sheet model, 2) more accurate downscaling of atmospheric fields to the land surface, 3) more realistic treatment of

Broader and Deeper



The models are not all independent.

GCM Family Tree Circa 2000



ESMs are proliferating.

- CESM
- GFDL
- E3SM
- GISS
- MPI
- MIROC
- ECMWF
- UFS

And quite a few more…

List of CMIP6 models

Model
BCC-ESM1
BCCCSM2MR
CESM2
CESM2-WACCM
CNRM-ESM2-1
CNRMCM61
CanESM5
E3SM-1-0
EC-EARTH3-VEG
GFDL-CM4
GFDL-ESM4
GISSE2-1-G
GISSE2-1-H
HADGEM3-GC31-LL
INM-CM4-8
IPSL-CM6A-LR
MIROC-ES2L
MIROC6
MPI-ESM1-2-HR
MRI-ESM2
NESM3
NORCPM1
NORESM2-LM
SAM0UNICON
UKESM1-0-LL

CMIP

The World Climate Research Programme's
Coupled Model Intercomparison Project


CMIP6/ESGF contributors
This map was made with Google My Maps. Create your own.
Finland
Iceland
Russia
Canada
Ukraine
Kazakhstan
Mongolia
North Atlantic Ocean
China
Iraq
Iran
Afghanistan
Pakistan
Algeria
Libya
Egypt
Arabia
Mexico
Mali
Niger
Sudan
Chad
Thailand
Nigeria
Ethiopia
Venezuela
Colombia
Kenya
DRC
Indonesia
Tanzania
Papua New Guinea
Brazil
Peru
Angola
Bolivia
Namibia
Madagascar
Indian Ocean
South Pacific Ocean
South Atlantic Ocean
Chile
Australia
South Africa
New Zealand
Argentina
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Weather & climate with the same global model

In ~1990, the UK Met Office created the Unified Model, which is used for both weather and climate.

About 10 years later, Deutsche Wetterdienst and MPI Meteorology teamed up to create the model that is now called ICON. It is used for both operational forecasting and climate research.

Met Office 1999 Bracknell

Deutsche Wetterdienst Offenbach

MPI Meteorology Hamburg

ECMWF has broadened its scope.

Today, ECMWF is directly involved in climate science through:

- the EC-Earth project,
- the Copernicus Climate Change Service, and
- the Destination Earth initiative.

EC EARTH

Climate
Change Service
climate.copernicus.eu

DESTINATION EARTH

European Ascendance

The Unified Model, ICON, and ECMWF's Integrated Forecasting System are among the most advanced global models in the world today.

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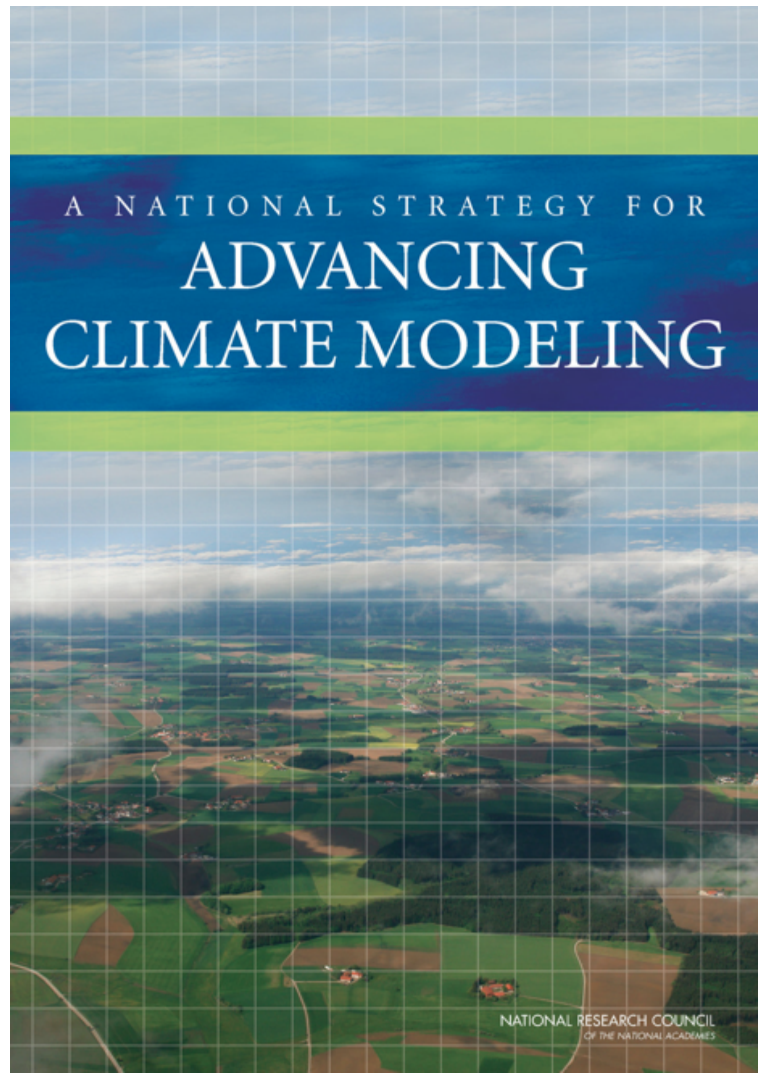
In retrospect, Europe took the lead in global modeling decades ago, *due in part to their visionary unification of weather and climate modeling*.

European Ascendance

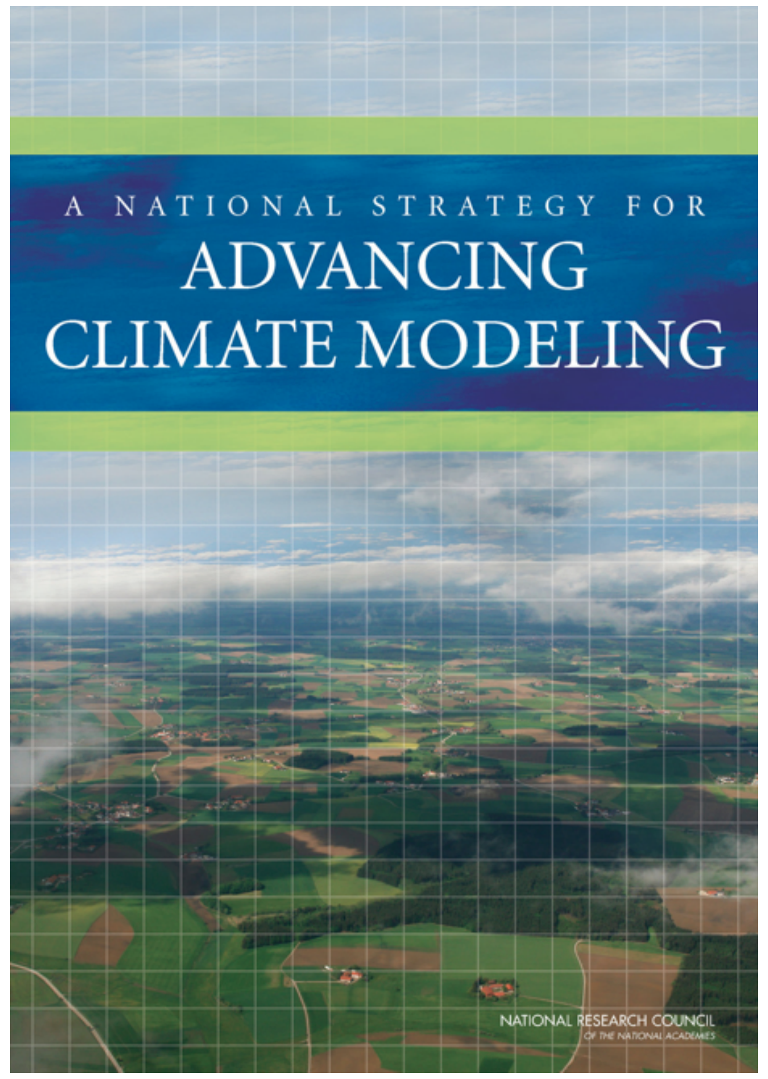
The Unified Model, ICON, and ECMWF's Integrated Forecasting System are among the most advanced global models in the world today.

In retrospect, Europe took the lead in global modeling decades ago, *due in part to their visionary unification of weather and climate modeling*.

The U.S. has fallen behind.



Bretherton, C., and Coauthors, 2012: *A National Strategy for Advancing Climate Modeling*. The National Academies Press, 294 pp.



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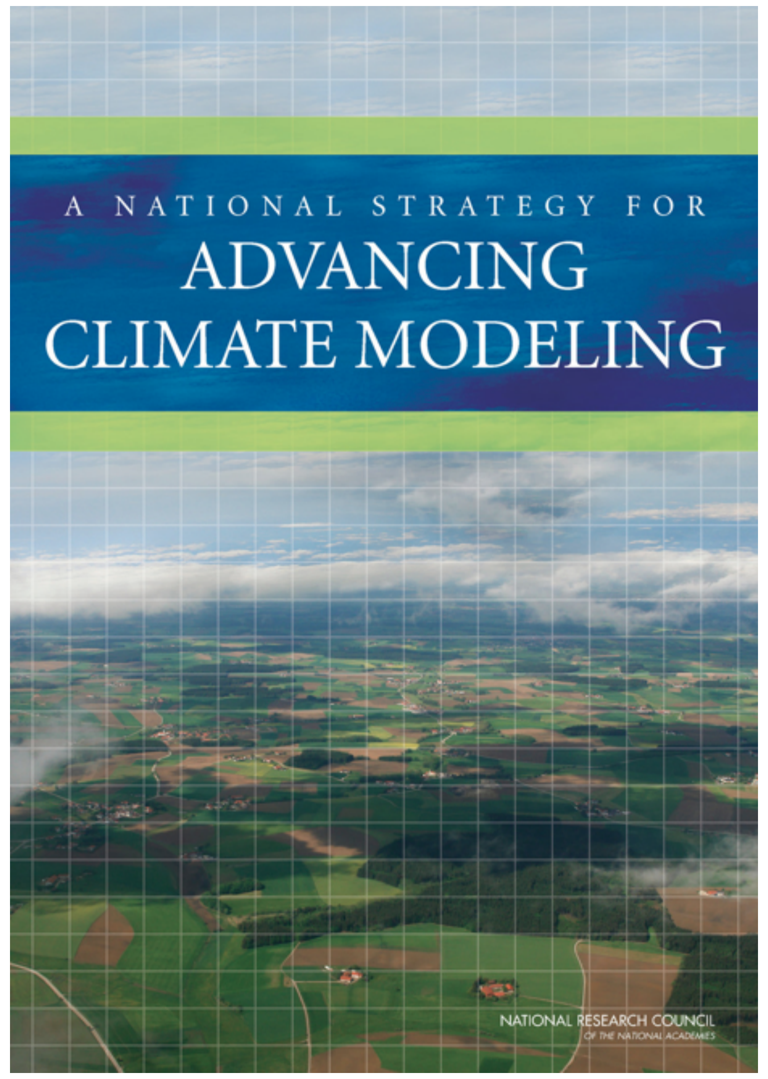
Recommendation:

"Nurture a unified weather-climate modeling effort that better exploits the synergies between weather forecasting, data assimilation, and climate modeling."



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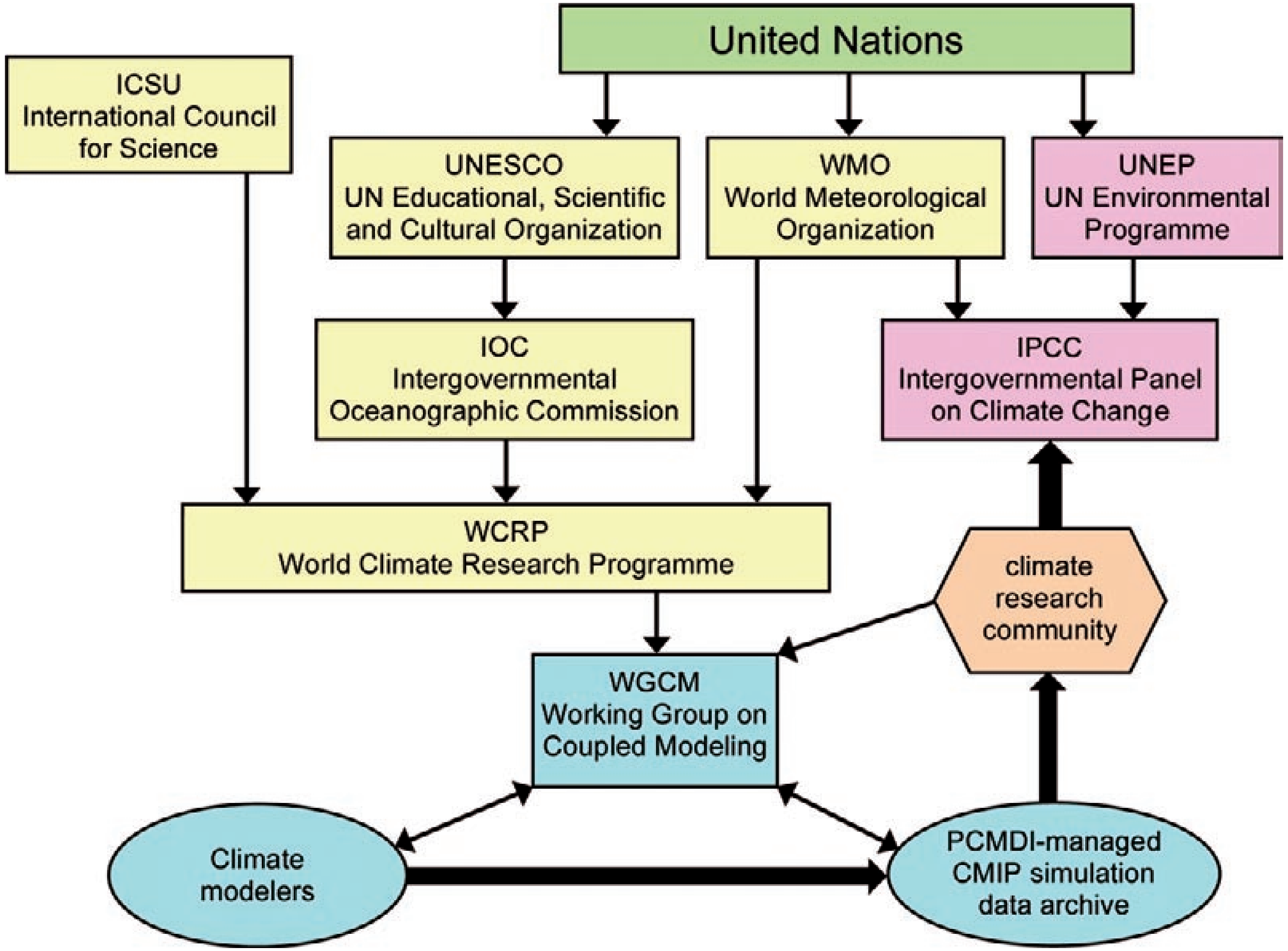
Progress towards this goal has been modest at best.


COSTA RICA
ESTONIE
DOMINICAN REPUBLIC
MALI

Bureaucracy

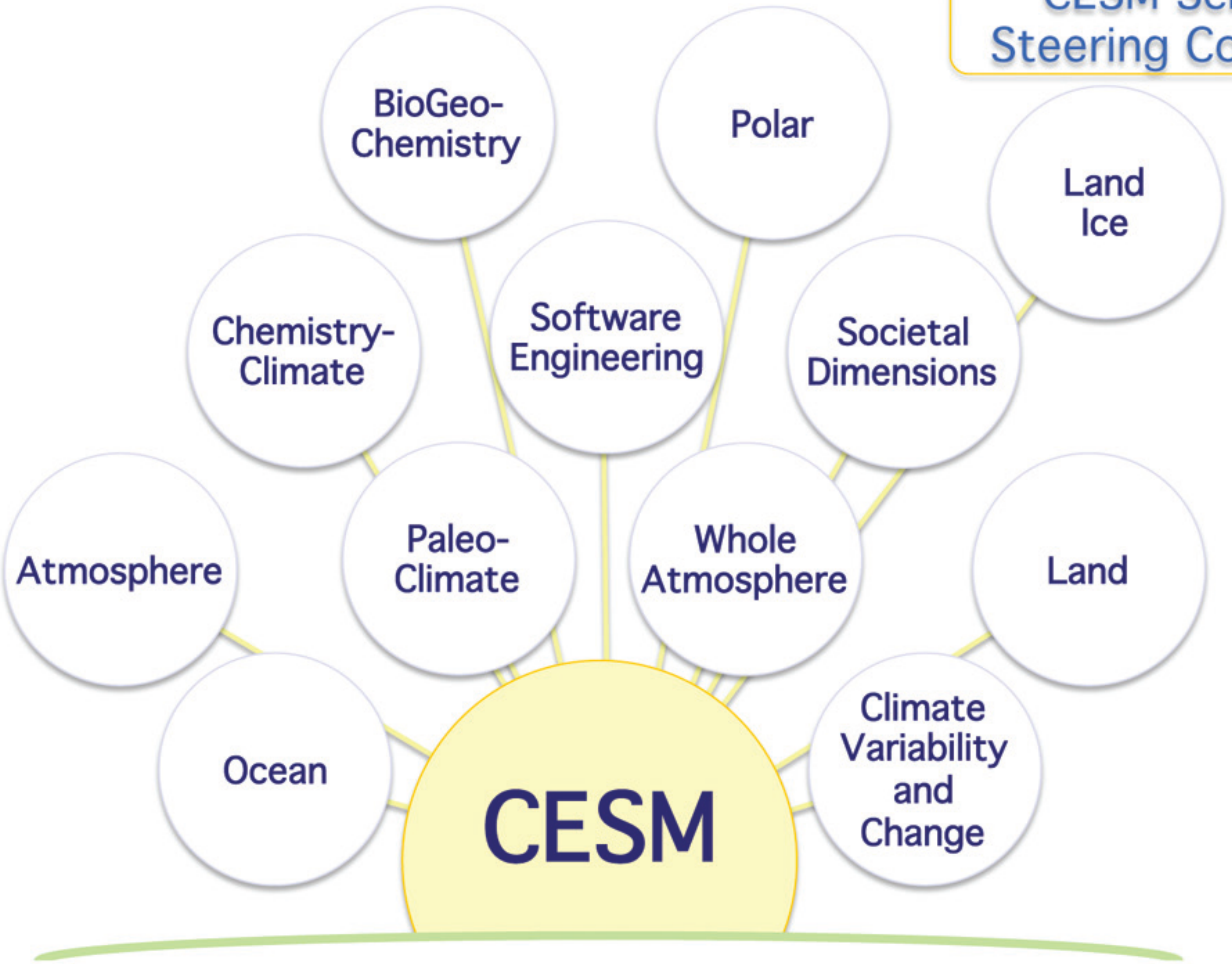


Taylor et al., 2012

CESM Management

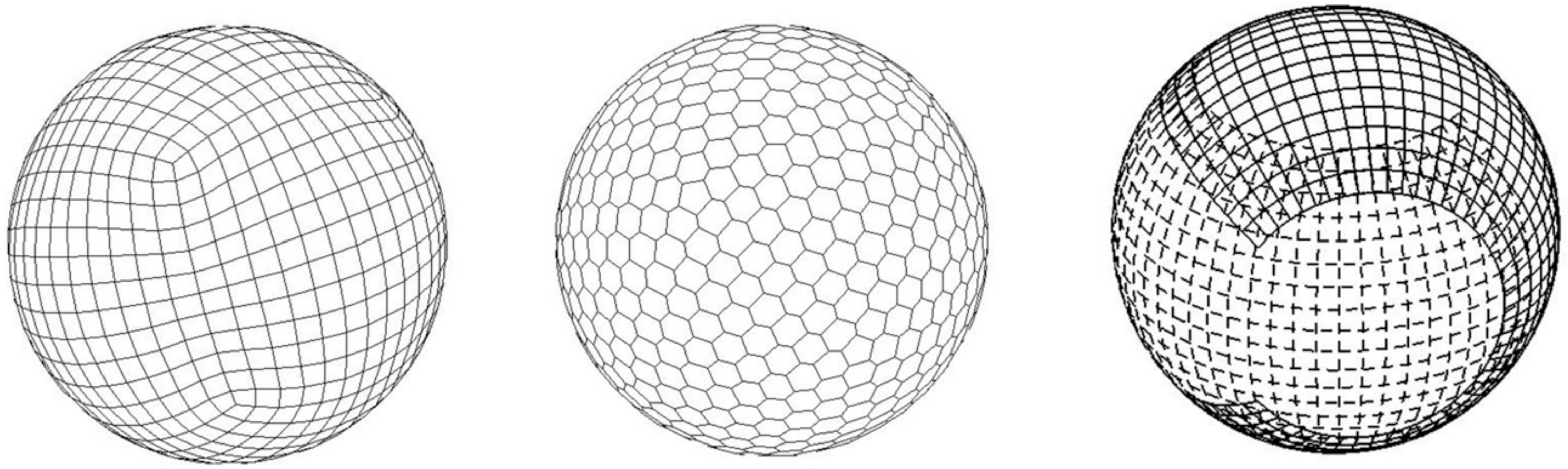
CESM Advisory Board

CESM Scientific Steering Committee



Into the 21st Century

- Massively parallel computing
- Semi-Lagrangian advection
- Unstructured grids
- Eddy-resolving ocean models
- Sea ice thickness distributions
- Parameterized phenology



An appetite for flops

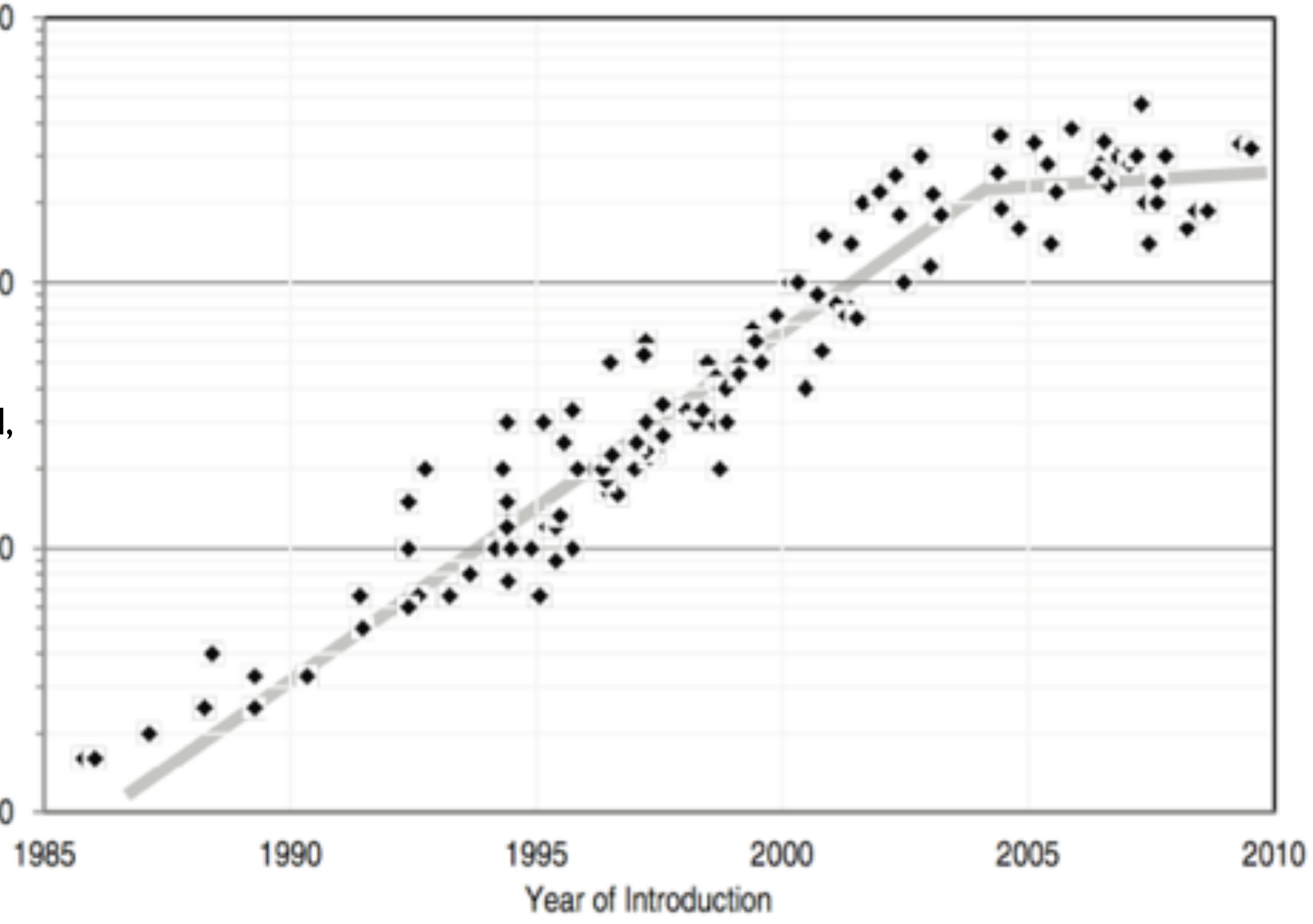
It takes about a *million million* floating-point operations to simulate one day, with modest resolution.

Computer power has increased by about a factor of one hundred *billion* (10^{11})since I was in graduate school.

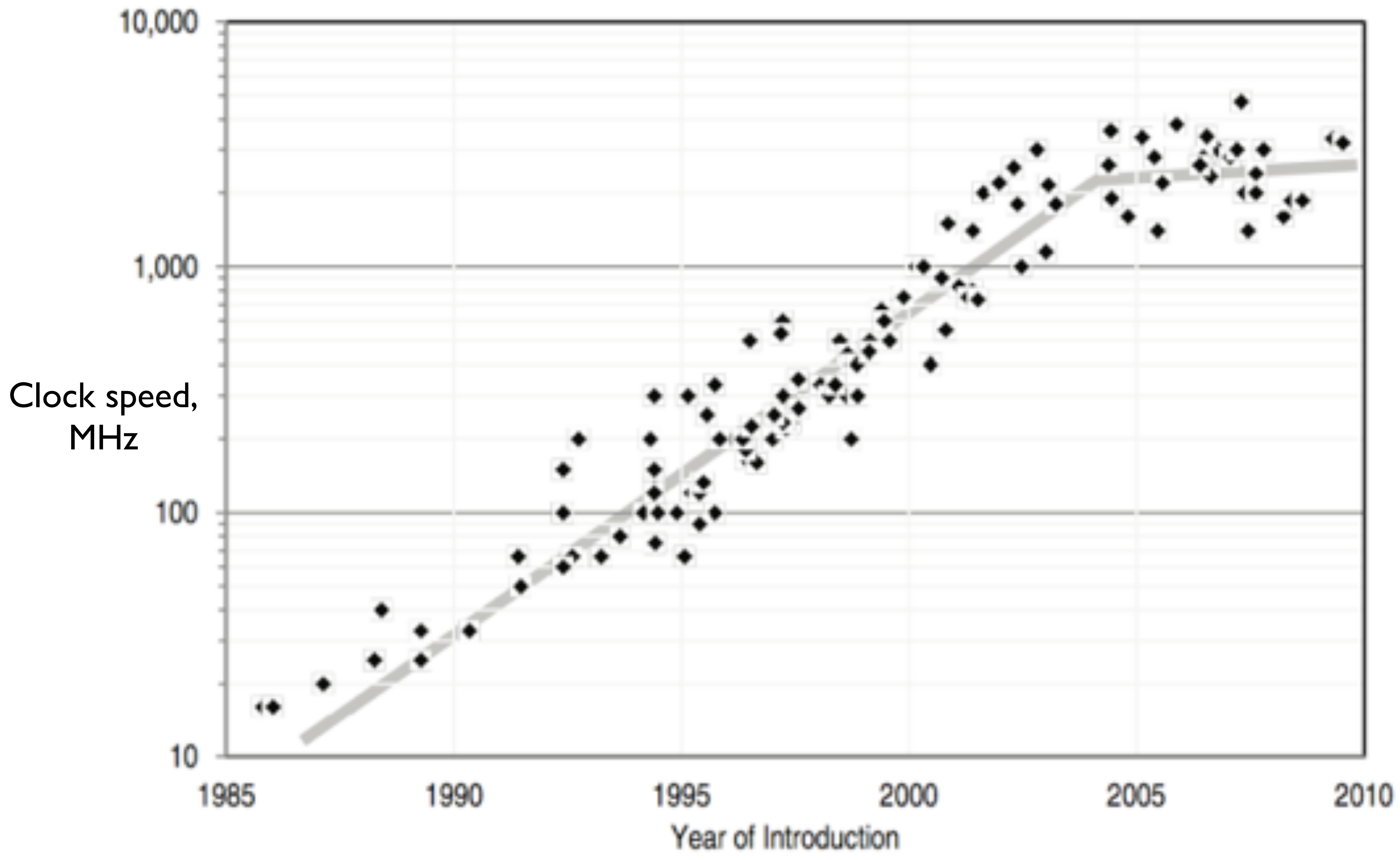
The machines are getting harder to program.

Where technology is leading us

Clock speed, MHz

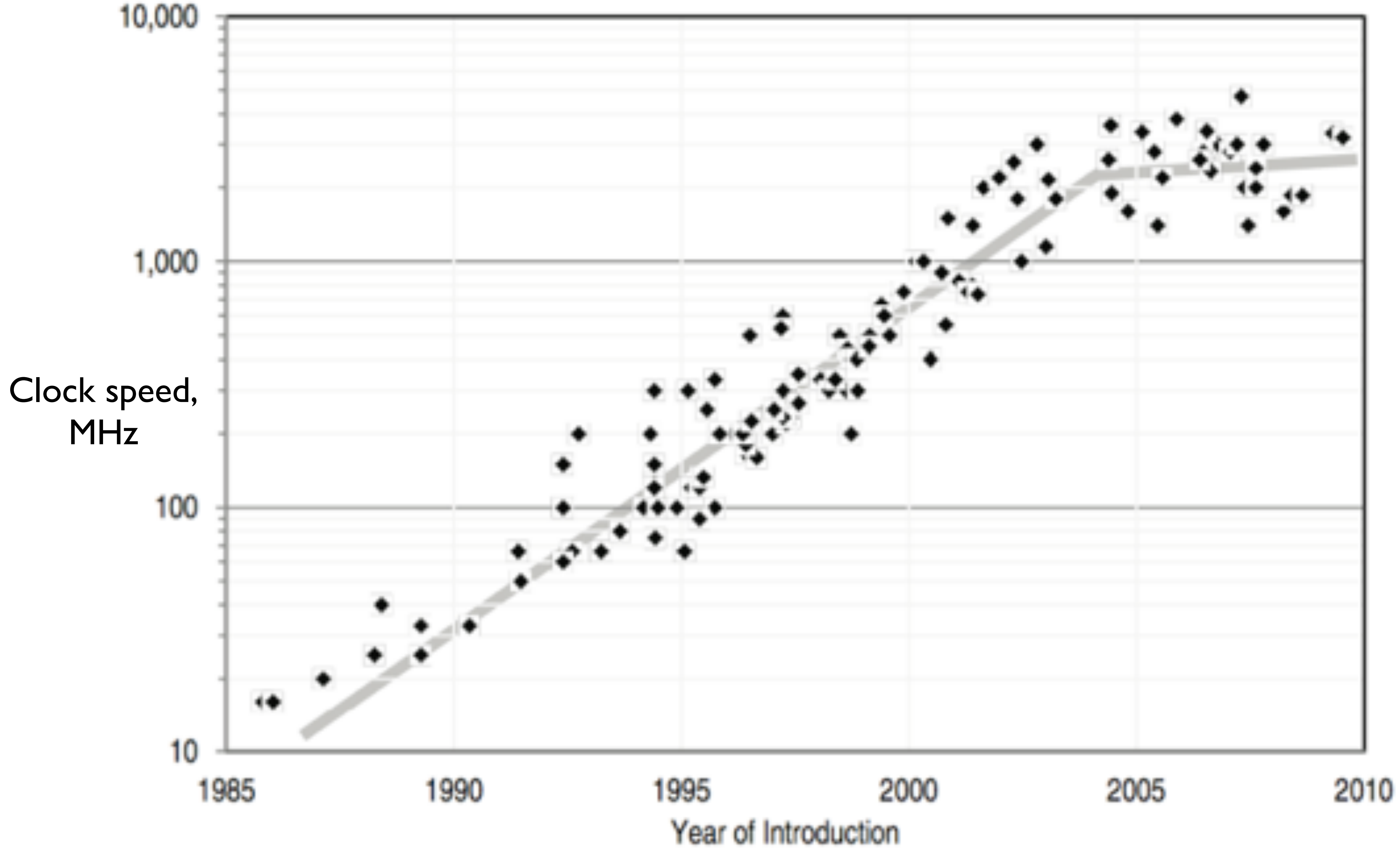


Where technology is leading us



It used to be true that as computers got faster, the additional speed could be used either to refine the grid or to make longer runs on the same grid.

Where technology is leading us



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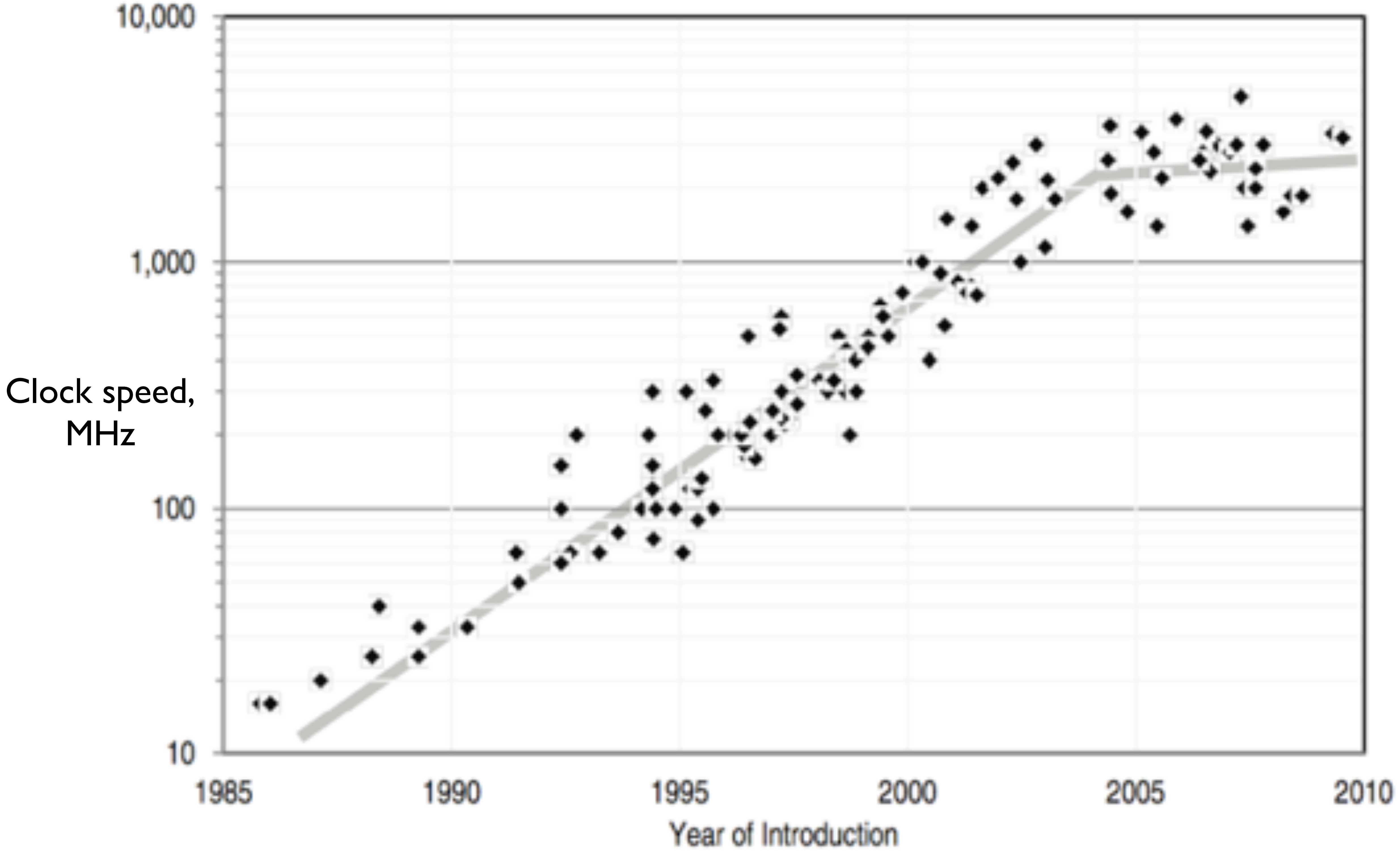
No more.

Where technology is leading us



It used to be true that as computers got faster, the additional speed could be used either to refine the grid or to make longer runs on the same grid.

No more.

Technology trends now encourage us to drastically refine our grids, but are less compatible with dramatically longer runs on the existing grids.

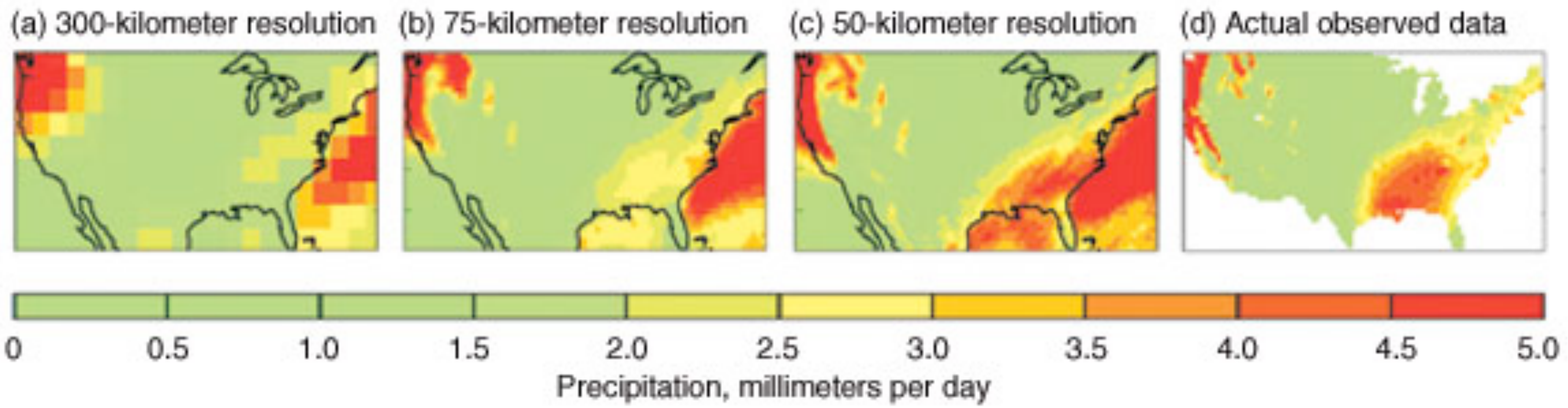
Increasing resolution

Incremental improvements

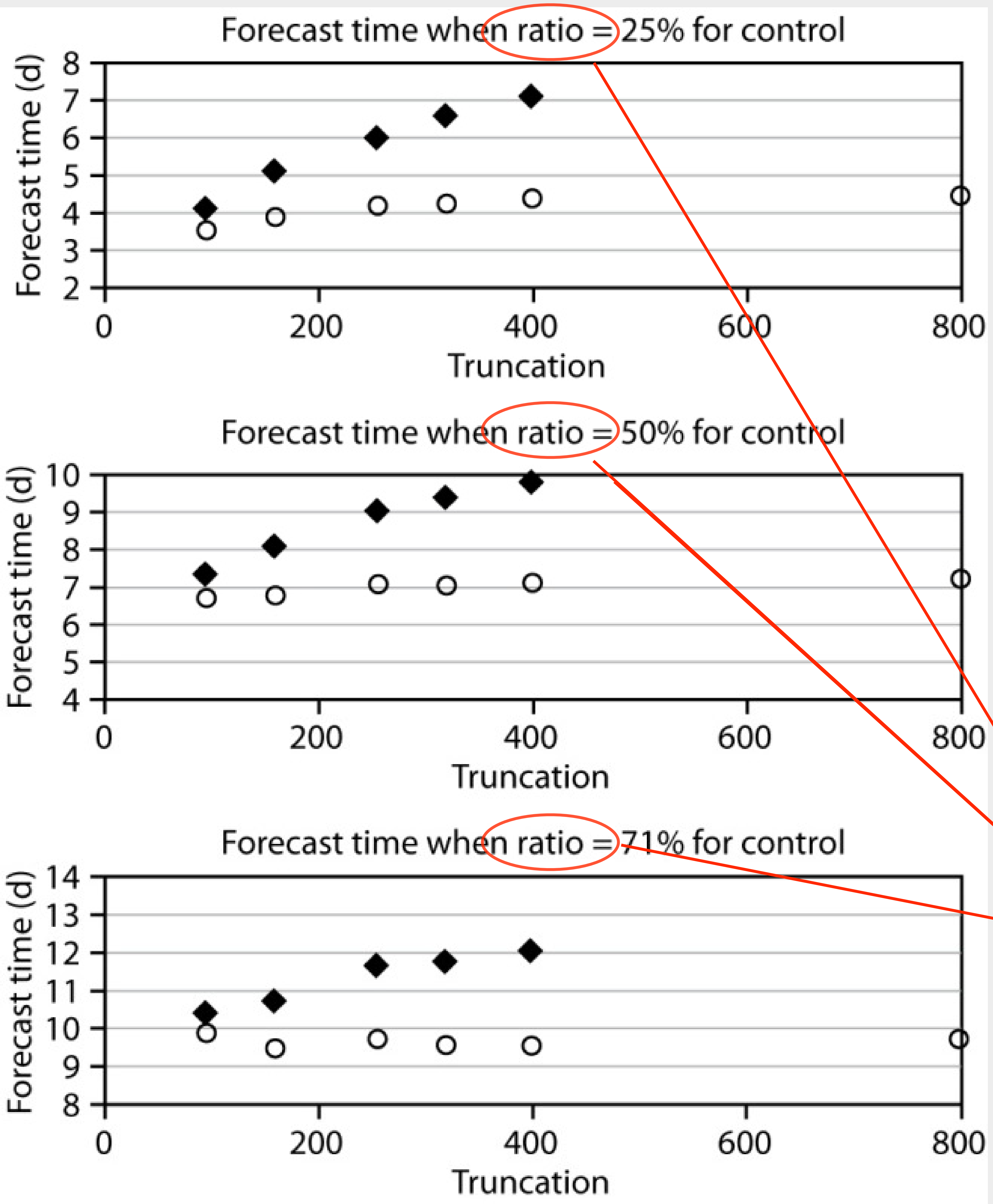
- Mountains
- Tropical cyclones
- Ocean basins

Qualitative changes

- Eddy-permitting ocean models
- Convection-permitting atmosphere models



Error growth as a function of resolution



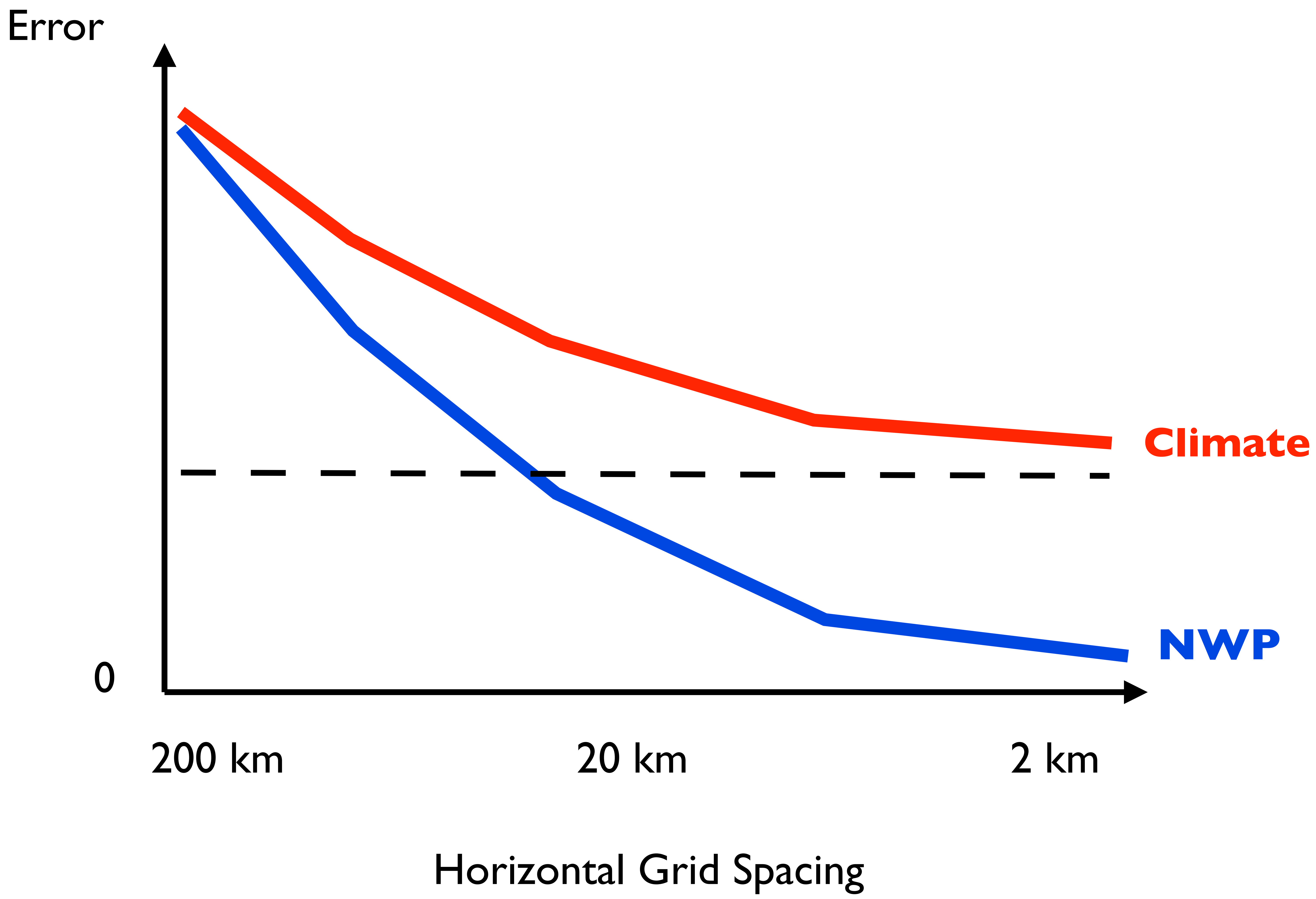
Buizza 2010:

"...although further increases in resolution are expected to improve the forecast skill in the short and medium forecast range, simple resolution increases without model improvements would bring only very limited improvements in the long forecast range."

"Ratio" refers to the ratio of forecast error to its saturation value. Black symbols for the T799 "perfect model," grey symbols for real forecasts.

Error versus resolution

without changing the parameterizations



The trend to non-hydrostatic models

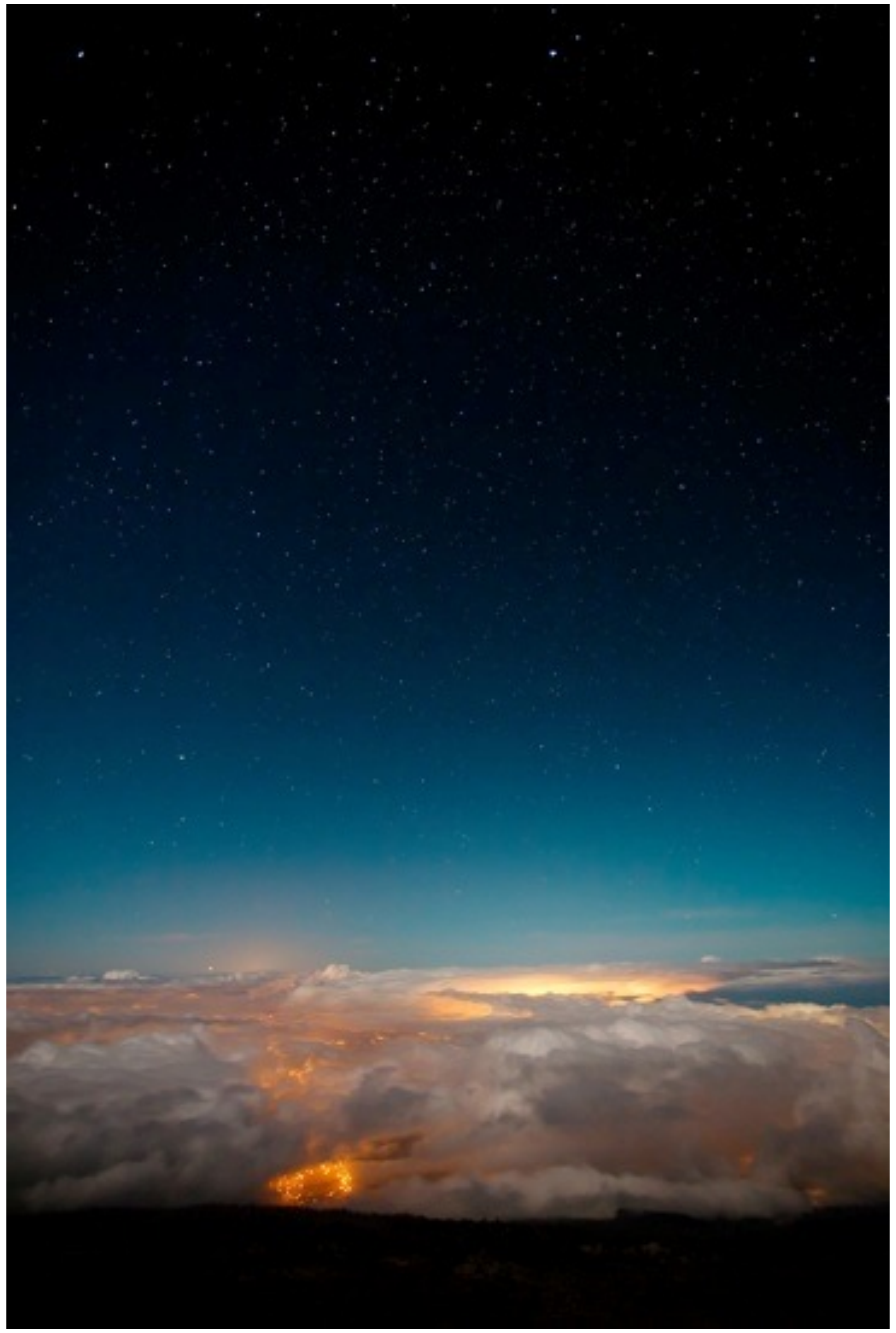
Faster, massively parallel computers are allowing us to use finer grids.

Finer grids can resolve weather systems, e.g., thunderstorms, that are not quasi-static.

For this reason, we are now building GCMs that do not use the quasi-static approximation.

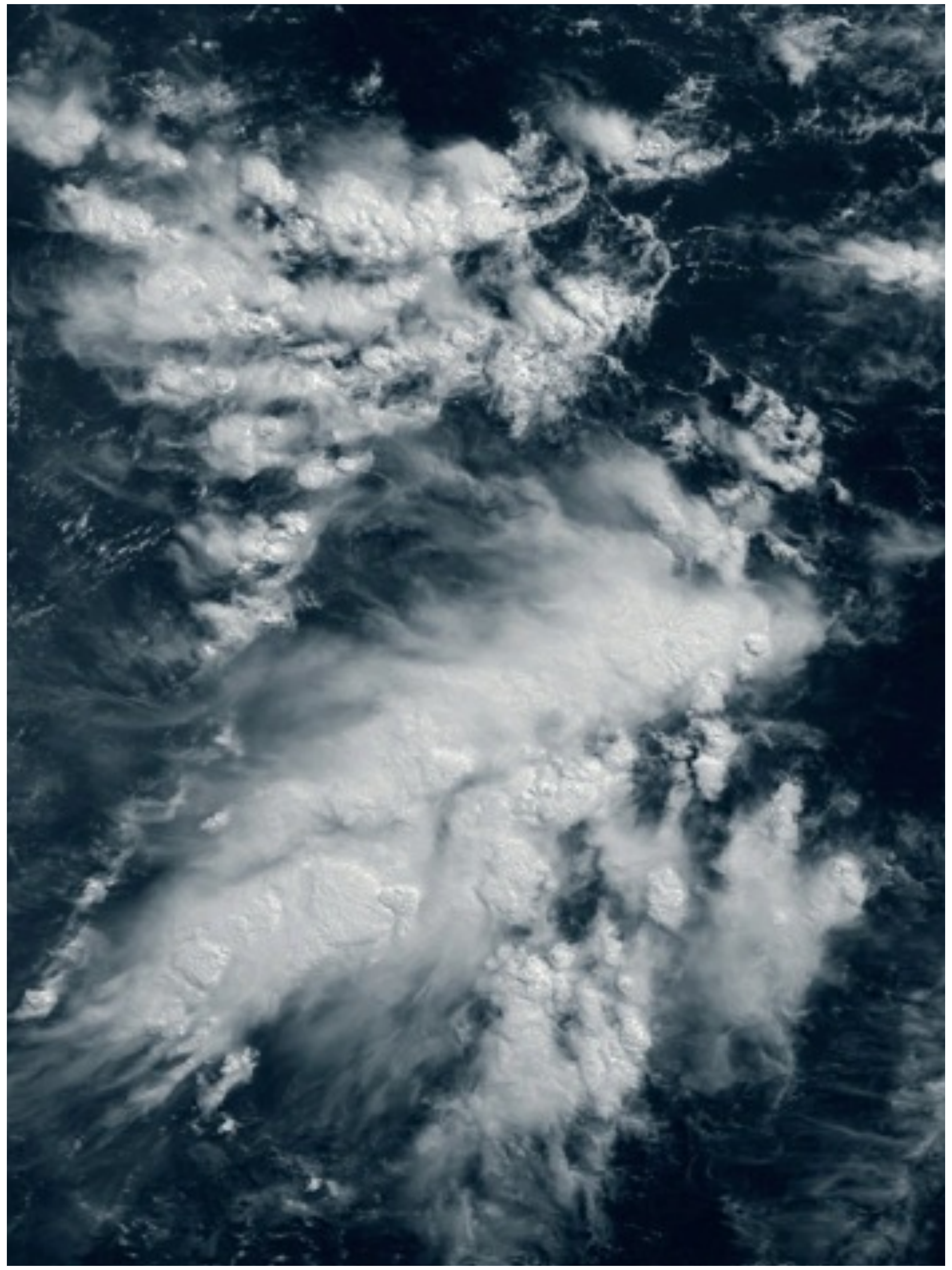
These new high-resolution GCMs can borrow ideas from the well established mesoscale modeling community.

In non-hydrostatic models, vertically propagating sound waves must be controlled or filtered.



High-resolution physics

- The nature of the "sub-grid" physical processes depends on the grid size.
- Parameterizations that are appropriate for low-resolution models are not appropriate for high-resolution models, and vice-versa.
- Can we design general or "unified" physical parameterizations that can be applied to a wide range of grid spacings?



Parameterize less.

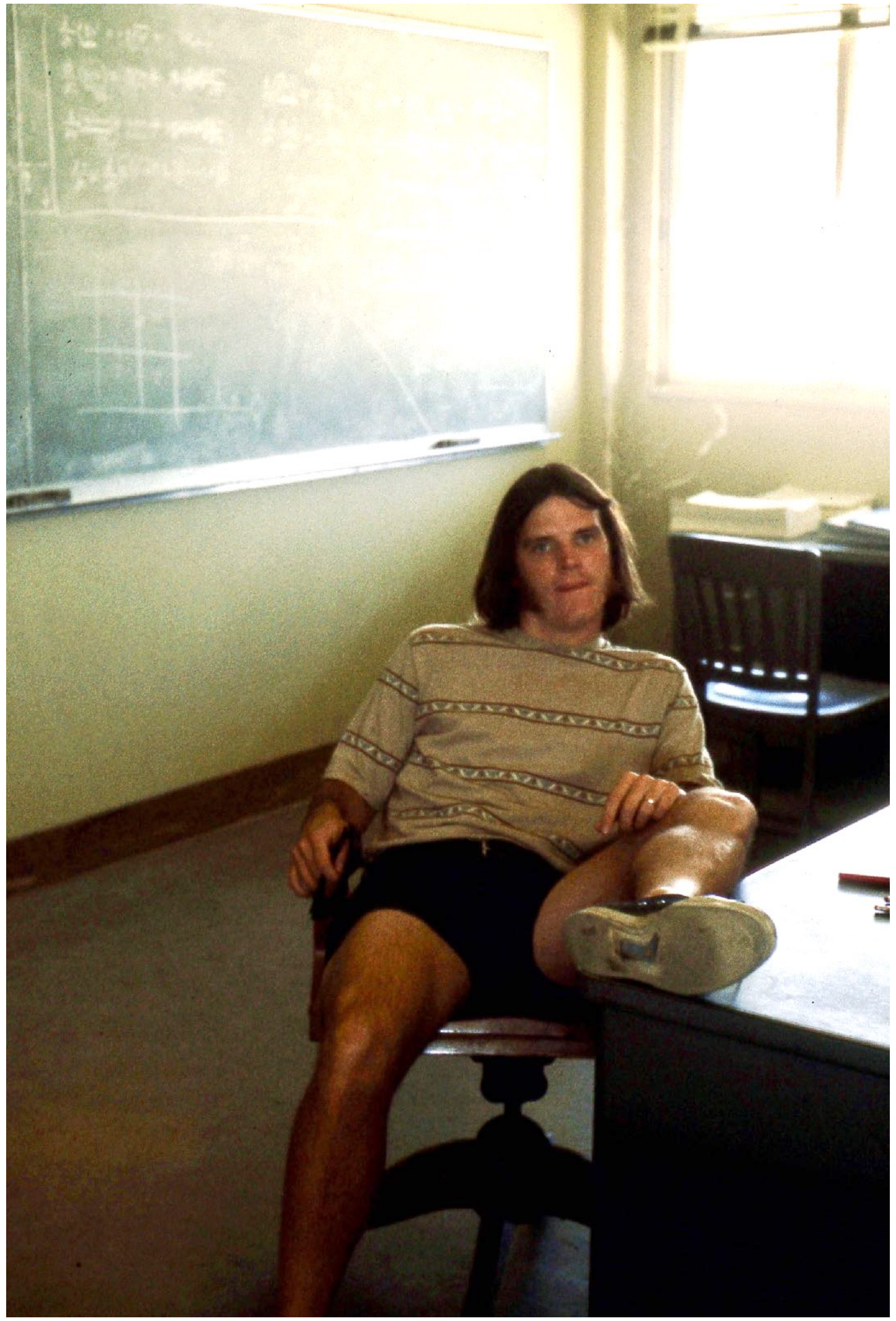
Global circulation

Cloud-scale
&mesoscale
processes

Radiation,
Microphysics,
Turbulence

When I was in grad school...

- All global circulation models were made in the USA.
- The work was purely academic — real-world applications we not being implemented yet.
- Funding was modest.
- The model users were the model developers.
- It took about two hours on a "fast" computer to simulate one day with a grid spacing of 400 km.



1970s	Now

1970s	Now
Troposphere	Troposphere & stratosphere, ocean with sea ice, land surface, lots of biology and chemistry, terrestrial ice sheets

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Model as a tool to achieve understanding	Model as a tool for performing simulations

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Closed modeling shops	Open modeling shops, with lots of international intercomparison projects

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All men	All people