MTMW14

The University of Reading

Numerical Modelling of Atmosphere and Oceans

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[High-Resolution global Climate Modelling](#)

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Aims of MTMW14 module

Bring you up to speed with the vital components of state-of-the-art numerical models for atmospheres and oceans and their use in predicting weather and climate.

Starting from fundamental properties of atmosphere and ocean:

- Learn how to design numerical schemes, preserving key properties.
- Perform simple prediction using models you will build.
- Critically evaluate and interrogate models.
- Prepare you for designing, implementing and testing your own components, to be inserted and used in complex models.

This competence is going to be very useful in your careers, even if you aim to analyse, albeit not develop models.

Course philosophy

attributed to Confucius, ~500 BC

我	聽	見	我	忘	記	**I hear I forget**
我	看	見	我	記	住	**I see I remember**
我	做	我	了	解		**I do I understand**

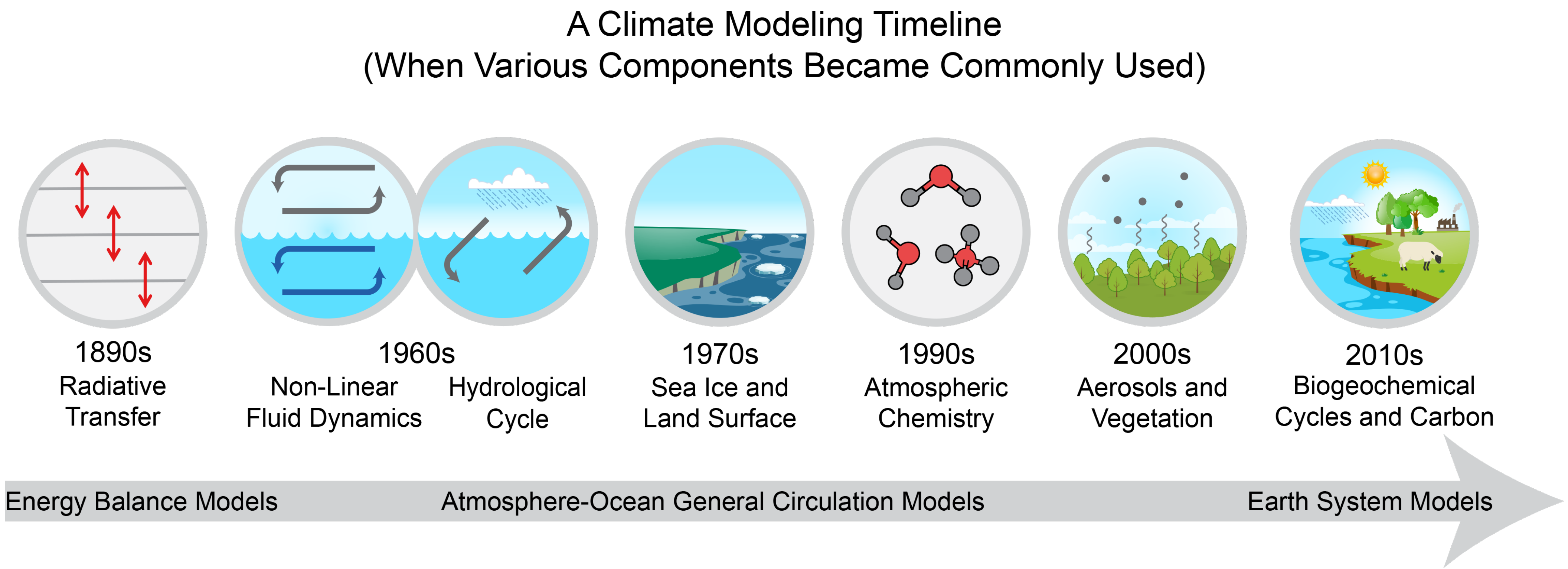
Probably the real quote is from Xunzi's *RuXiao*, and it goes:

Not hearing is not as good as hearing,
hearing is not as good as seeing,
seeing is not as good as knowing,
knowing is not as good as acting;
true learning continues until it is put into action**.**

"不聞不若聞之，聞之不若見之，見之不若知之
知之不若行之。學至於行之而止矣。"

This course is all yours: do and understand

Today's lecture



100 Years of Earth System Model Development

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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.

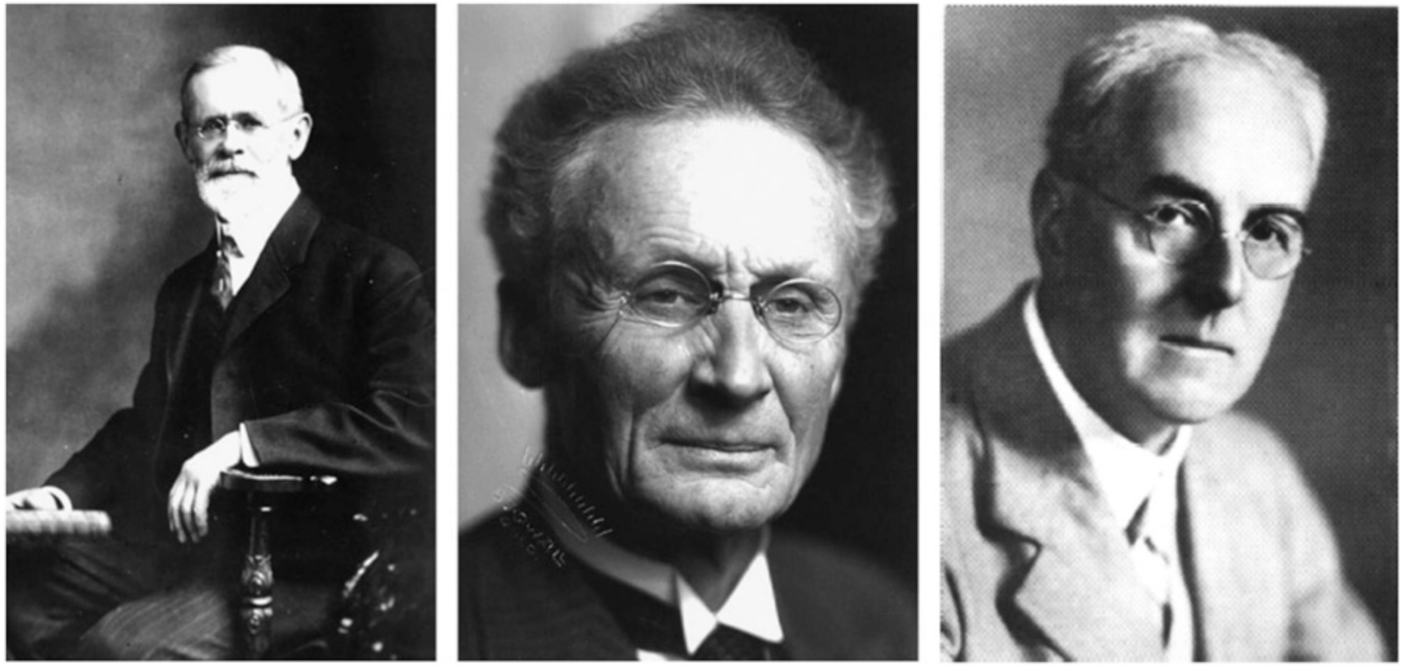
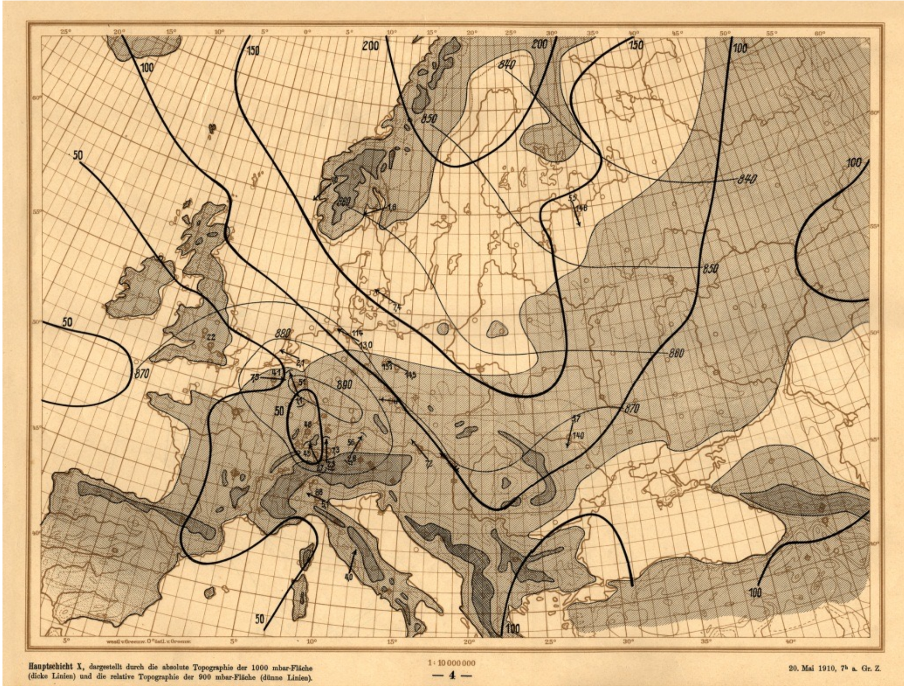


FIG. 12-1. (left) Cleveland Abbe (1838–1916). (middle) Vilhelm Bjerknes (1862–1951). (right) Lewis Fry Richardson (1881–1953).

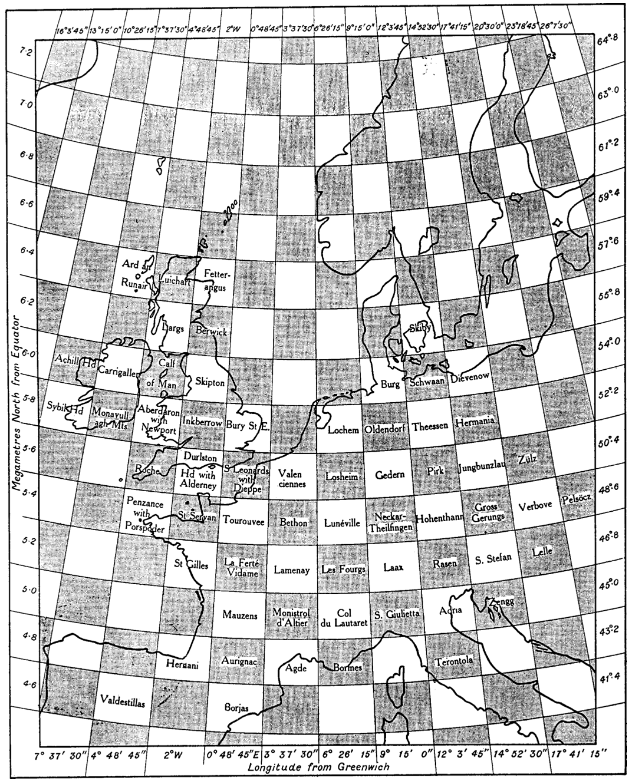
The great American meteorologist **Cleveland Abbe** recognized that meteorology is essentially the application of hydrodynamics and thermodynamics to the atmosphere (Abbe 1901), and he identified the system of mathematical equations that govern the evolution of the atmosphere (Willis and Hooke 2006).

The Norwegian scientist **Vilhelm Bjerknes** undertook a more explicit analysis of the weather prediction problem from a scientific perspective (Bjerknes 1904). His stated goal was to make meteorology an exact science, a true physics of the atmosphere. He argued that it should be possible to predict changes in the weather by solving systems of partial differential equations, which is exactly what we do today.

The English Quaker mathematician, **Lewis Fry Richardson**, went further. He wanted a worked example for his book ‘‘Weather Prediction by Numerical Processes’’ (Richardson 1922).



Although his results were not realistic, his achievement was heroic, and his book was remarkably prescient. His overall approach bears a striking resemblance to that used in modern weather and climate models, and he appreciated many of the issues that still preoccupy modelers today. In particular, he understood that the large-scale dynamics of the atmosphere would be resolved, while other processes, such as radiation, boundary layer turbulence, and cloud processes, would have to be parameterized.



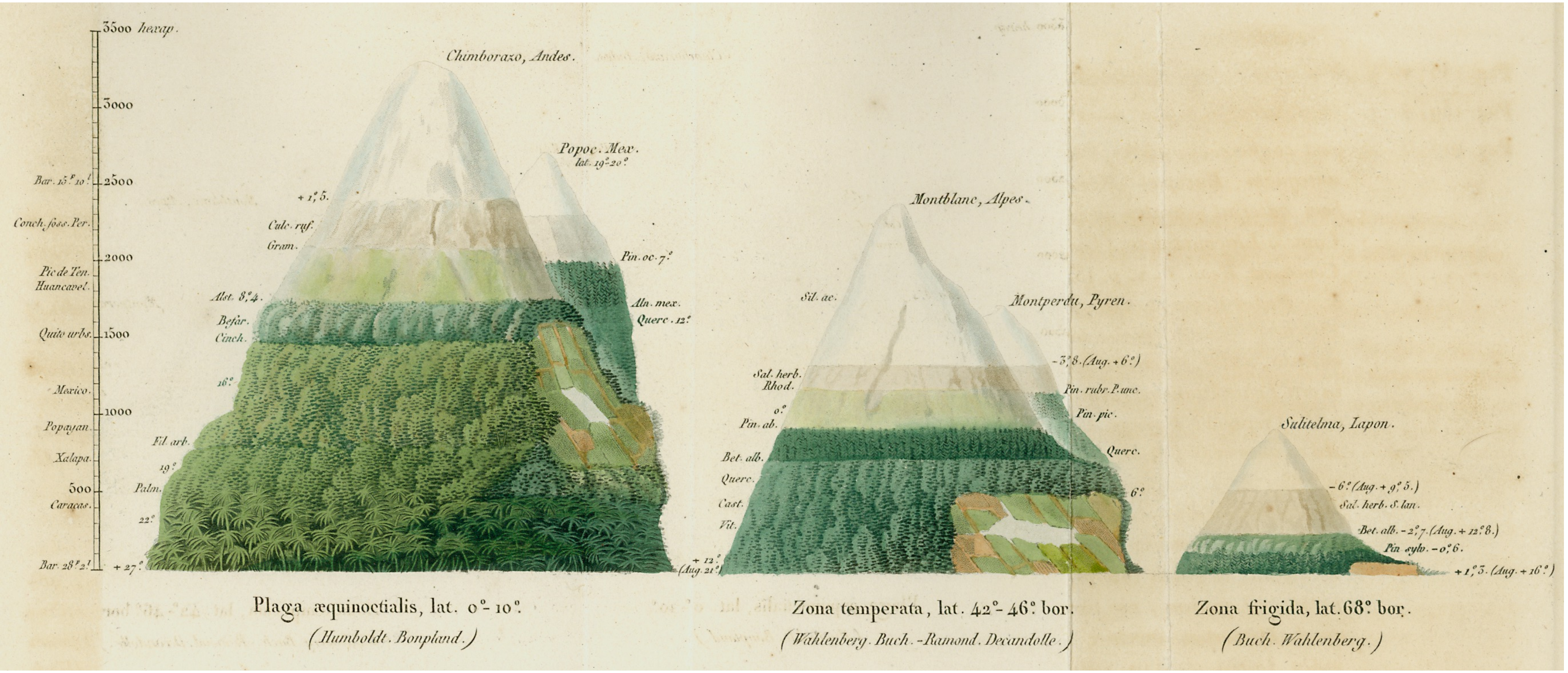
The English Quaker mathematician, **Lewis Fry Richardson**, went further. He wanted a worked example for his book ''Weather Prediction by Numerical Processes'' (Richardson 1922). Partly to create such an example, he attempted what is now called numerical weather prediction (NWP): a direct (but approximate) solution of the equations of motion. The result was his famous ''failed'' numerical forecast (actually a hindcast) for 20 May 1910. He carried out the calculations by hand, in the intervals between driving for the Friends Ambulance Unit during the war in France (Ashford 1985; Lynch 2006).

He used what we now call the quasi-static approximation. To obtain approximate solutions of the differential equations of the model, he proposed a method based on finite differences, a technique that he had devised and previously applied to stresses in a masonry dam (Richardson 1911). He discretized his domain on a longitude–latitude grid or ''lattice'' that covered part of western Europe, with five layers to represent the atmosphere's vertical structure.

Early ESM thinking

Von Humboldt's ideas were the foundations of today's Earth System Models

*Even if nature does not produce the same species in similar climates, nevertheless vegetation exhibits the most striking visual similarities in **habit** even in the most distant regions. This phenomenon is one of the most remarkable in the history of organic creations ...*



Alexander Von Humboldt: De Distributione Geographica Plantanum, 1817

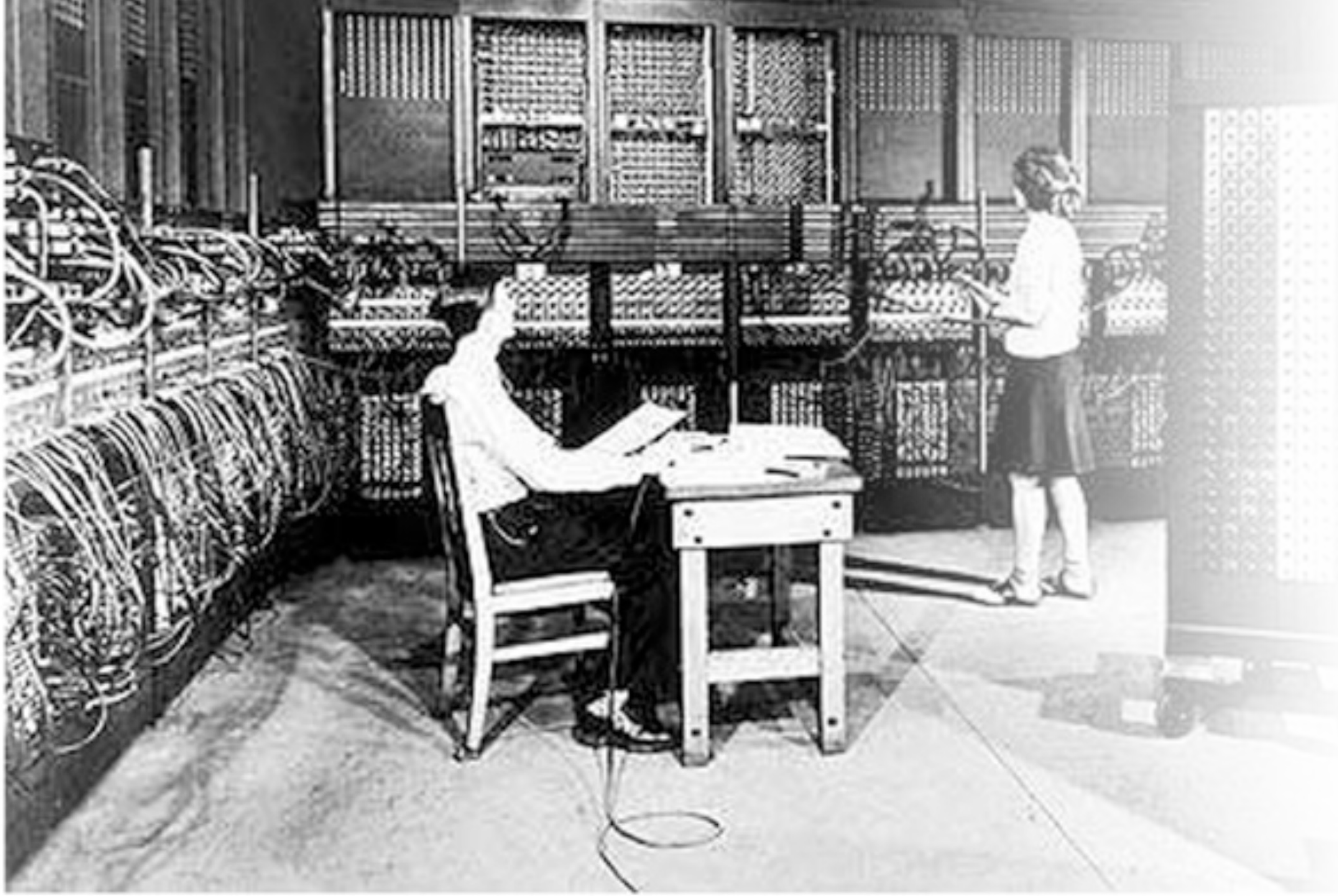


FIG. 12-2. The Electronic Numerical Integrator and Comp
(ENIAC). [Courtesy of International Business Machines Co
ration. ©1946 International Business Machines Corporation.]

The Electronic Numerical Integrator and Computer (ENIAC), an electronic computer commissioned by the U.S. Army for calculating the paths of projectiles, was completed in 1945. It was the first programmable electronic digital computer ever built. The gigantic machine used 18000 thermionic tubes, filled a large room, and consumed 140 kW of power (Fig. 12-2). Both input and output were by means of punched cards. McCartney (1999) provides an absorbing account of the origins, design, development, and legacy of ENIAC.

In the late 1940s, the mathematician John von Neumann recognized that weather forecasting, a problem of both great economic and military importance, and strong intrinsic scientific interest, is an ideal application for a digital computer. He established a Meteorology Project at the Institute for Advanced Study in Princeton, and recruited meteorologist Jule Charney to lead it.

Charney et al. (1950) noted that the computation time for a 24-h forecast was about 24 h. In other words, the team could just keep pace with the weather, provided that the ENIAC did not fail. The computation time included offline operations, such as the reading, punching, and interfiling of punch cards. Lynch and Lynch (2008) recreated the ENIAC integrations using a programmable cell phone, which they called the Portable Hand-Operated Numerical Integrator and Computer (PHONIAC). In this recreation, PHONIAC executed the main loop of the 24-h forecast in less than one second.

3. The 1950s

The 1950s saw some major advances in our understanding of the global circulation. For example, **Edward Lorenz (1955)** of MIT published the first of his most influential papers, which defined and analyzed available potential energy, and provided important insights into the atmospheric energy cycle. At the University of Chicago, David Fultz carried out rotating annulus experiments that reproduced some of the observed characteristics of the global circulation of the atmosphere (Fultz et al. 1959). Both of these studies (and many others) influenced the development of atmospheric numerical models during the 1950s.

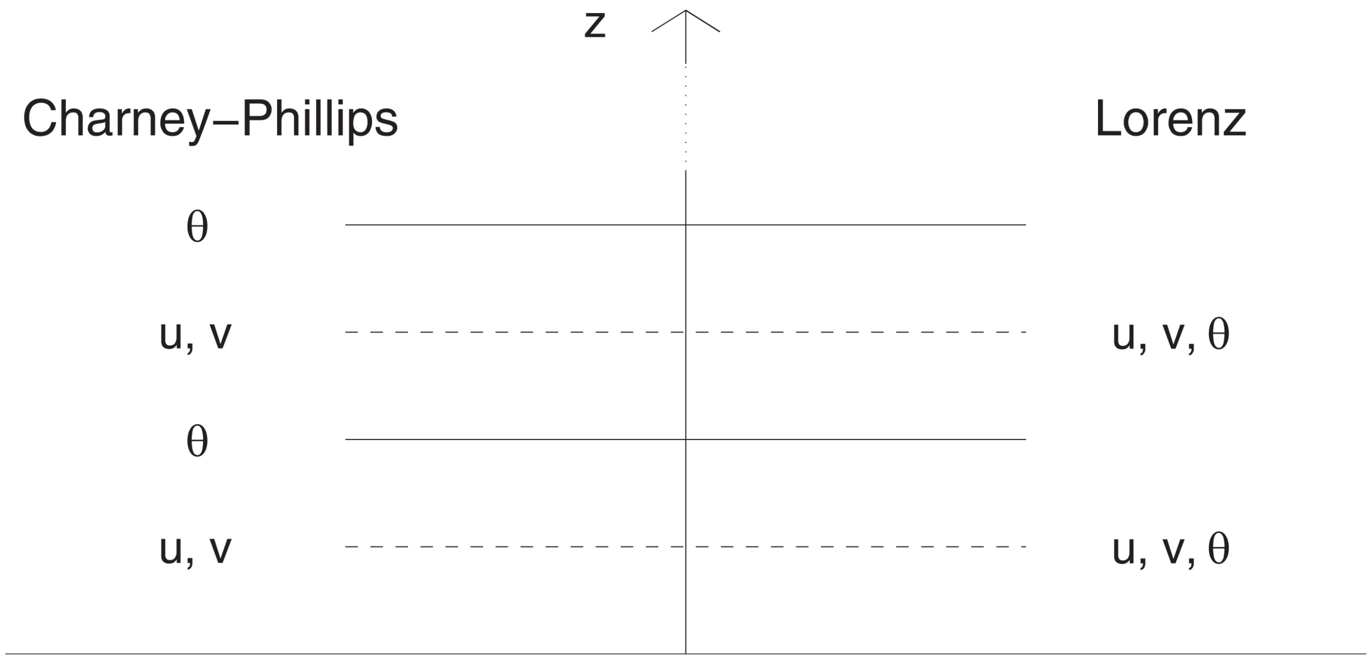


FIG. 12-3. Schematic showing the vertical placement of the horizontal velocity components u and v and potential temperature θ on the Charney–Phillips and Lorenz grids.

Early Dynamical Cores

Early model builders had to make some very basic choices that are still under discussion today. An example is the choice of how the different variables in the model should be arranged in the vertical. Charney and Phillips (1953) offset the thermodynamic variable, potential temperature u, relative to the horizontal wind components u and y, because this arrangement is natural to capture hydrostatic and thermal wind balance. Lorenz (1960), on the other hand, placed u at the same levels as u and y (Fig. 12-3), because that arrangement is advantageous for conservation of total energy.

4. 1960s: Model development in the Age of Aquarius

Creation of several now-legendary ‘‘ancestral’’ models, which were aimed mainly at climate simulation rather than weather prediction. In many cases, the earliest versions of the ancestral models were not truly global, and used simplified geography. They incorporated simple parameterizations of surface fluxes, radiation, cumulus convection, and stratiform or ‘‘large-scale’’ clouds, and they were coupled to very simple land surface models. With one important exception they used prescribed sea surface temperatures (SSTs), rather than coupling with an ocean model.

The GFDL model

GFDL’s atmosphere model was developed by Smagorinsky, Syukuro Manabe, and collaborators (Smagorinsky et al. 1965; Manabe and Smagorinsky 1967). Early versions covered only the Northern Hemisphere, with a stereographic map projection, and used idealized geography.

By 1965, the GFDL model had relatively high vertical resolution for the time, with nine glorious layers.

During the 1960s, the GFDL modeling team achieved many important firsts, including a very influential parameterization for the horizontal diffusion of momentum (Smagorinsky 1963), the first radiation parameterization (Manabe and Möller 1961; Manabe and Strickler 1964), the first cumulus parameterization (Smagorinsky 1963; Smagorinsky et al. 1965; Manabe et al. 1965), and the first land surface model (Budyko and Zubenok 1961; Manabe 1969a).

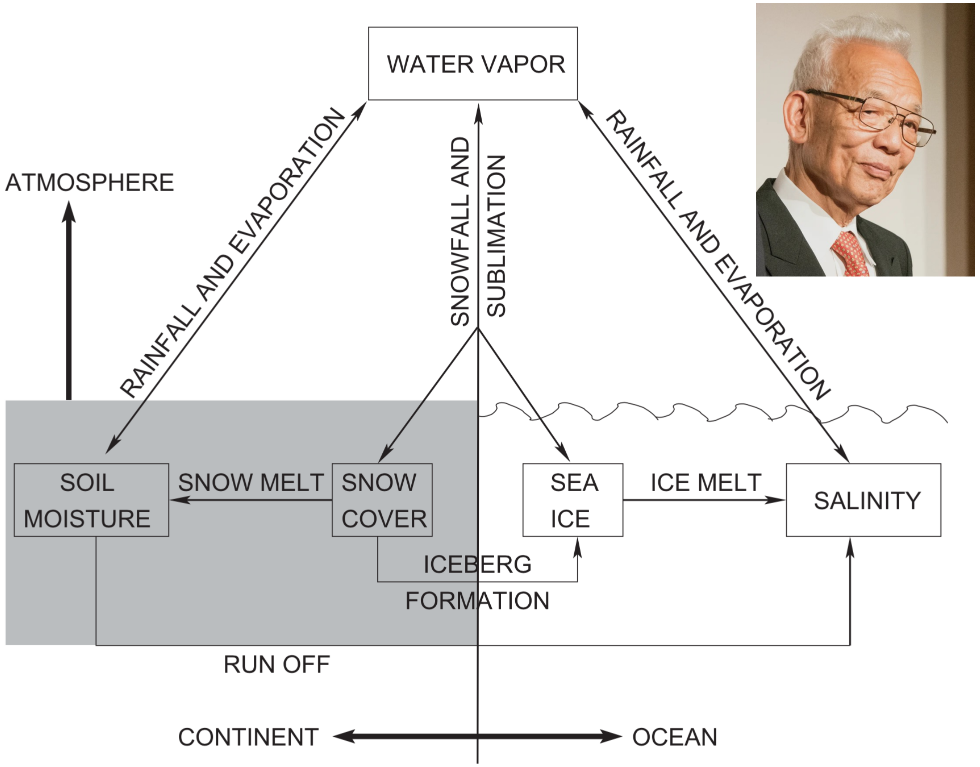


FIG. 12-4. A schematic of the early GFDL model [from Manabe (1969b)].

GFDL atmosphere model produced unrealistic results in humid regions with steep lapse rates. Manabe et al. (1965, p. 770) wrote that

because of convective instability, intense grid-scale convection develops exponentially in the area where the lapse rate is unstable. . . . Therefore, it is desirable to design a scheme of convection such that the grid-scale convection does not develop. . . . We used a very simple scheme of convective adjustment depending upon both relative humidity and the lapse rate and successfully avoided the abnormal growth of grid-scale convection.

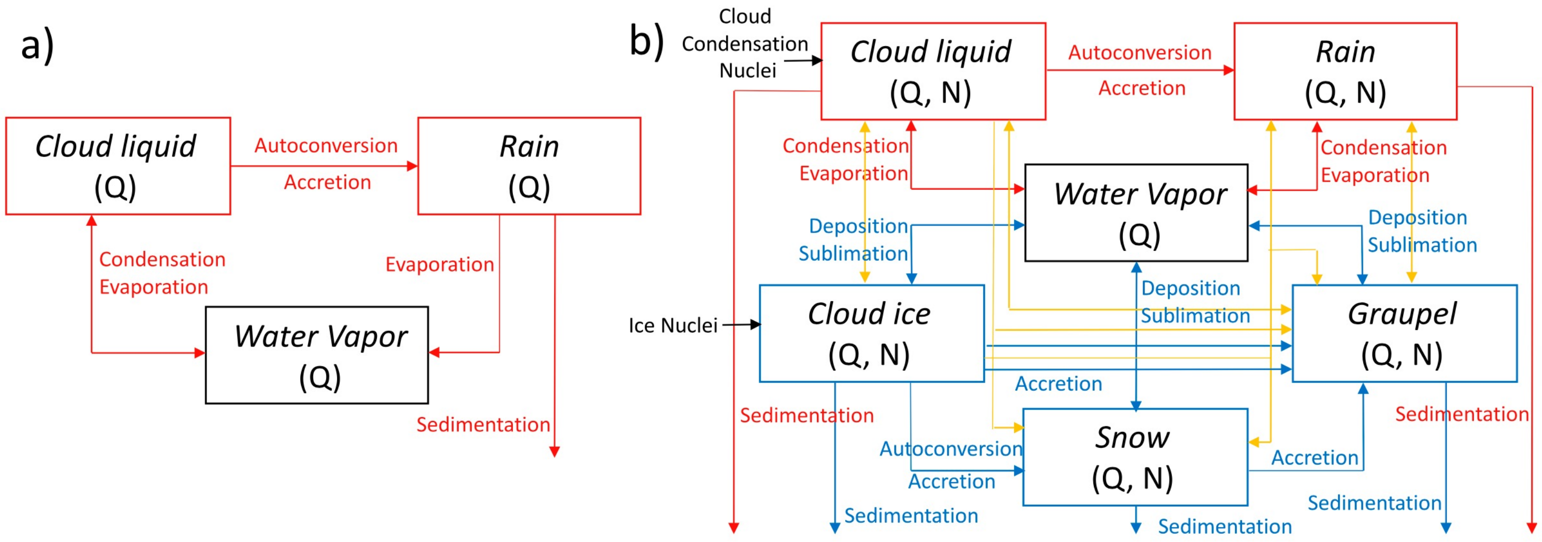


FIG. 12-5. (a) Diagram of the Kessler microphysics parameterization. (b) Diagram of a typical two-moment parameterization with multiple ice classes.

Examples of 1960s "physics"

Much work happened in the area of land surface modelling, but aspects of physics is the so-called (bulk) microphysics.

Kessler recognized the utility of analyzing data using simplified water mass continuity equations. As he wrote (Kessler 1995, p. 121):

I worked with a strong sense for interactions among processes as discussed here, and in expectation that their study would be facilitated by simple means to portray microphysical processes. The first process to be considered was conversion of cloud to precipitation. How to portray it? I did little more than observe in the literature and with my own eyes that thin water clouds seem to be persistent, and that rain falls from dense clouds.

This behavior was captured by continuity equations for cloud water and rain mass that were developed and initially applied in a kinematic flow model (Kessler 1969). Conversion processes between cloud and rain were represented by ‘‘autoconversion’’ using a threshold cloud mass mixing ratio above which conversion occurred, and ‘‘accretion,’’ which represented the growth of existing raindrops by collection of cloud. Rain was allowed to evaporate and sediment and the precipitation rate was calculated explicitly from the predicted rain field.

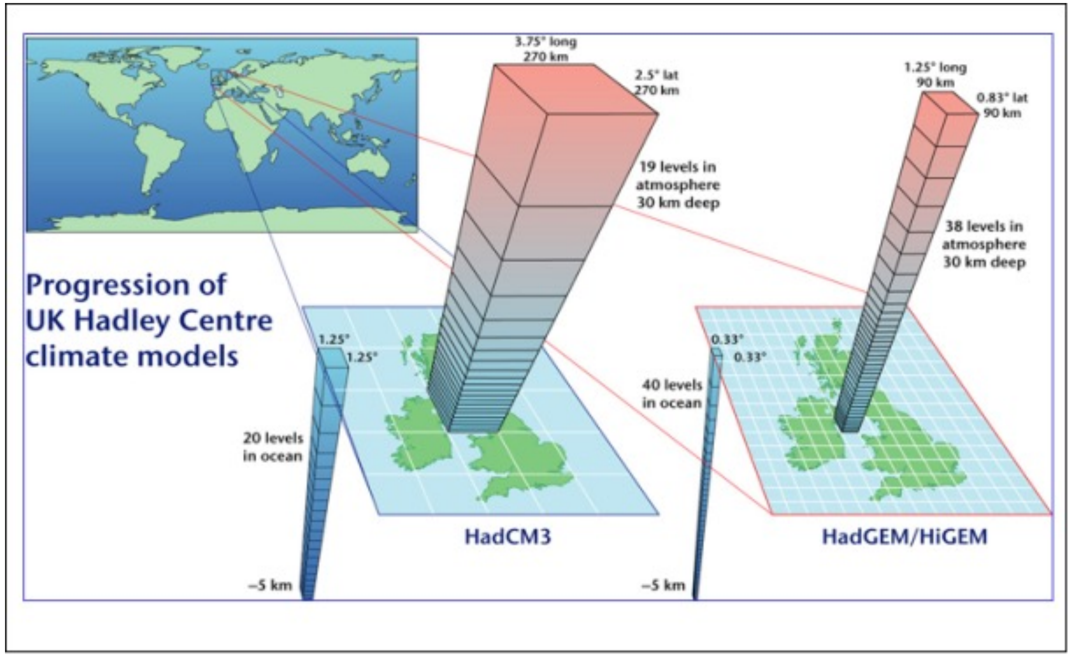
Simulations of global warming in column mode

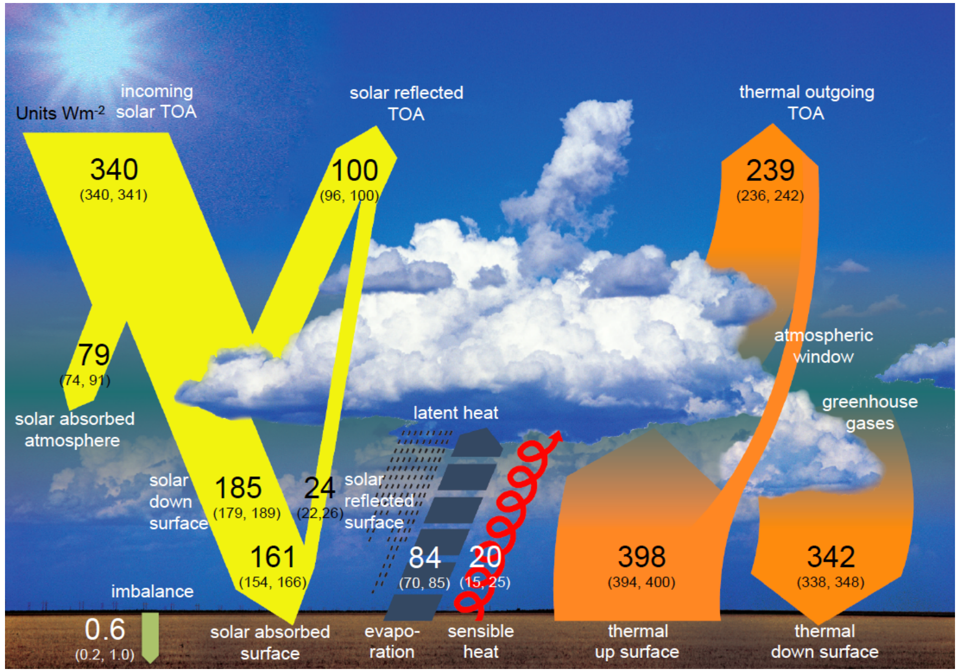
Fundamentally the reason for the 2021 Nobel Prize to Manabe-sensei

Manabe and Möller (1961) demonstrated that radiation is roughly balanced by convection (Manabe and Strickler 1964).10 The GFDL team performed pioneering one-dimensional simulations of ‘‘radiative-convective equilibrium’’ (RCE; Manabe and Strickler 1964; Manabe and Wetherald 1967), an idealization that continues to be useful today (e.g., Wing et al. 2018).

To mention one very important example, the study of Manabe and Wetherald (1967) pointed to the importance of the water vapor feedback for climate change. As noted by Manabe and Strickler (1964) in a paper describing single-column modeling of RCE, ‘‘one of the major purposes of our study is the construction of a model of radiative transfer simple enough to be incorporated into a general circulation model of the atmosphere.’’

During the 1960s, Manabe and Wetherald (1967) had already studied the effects of increasing atmospheric carbon dioxide concentrations on the ‘‘climate’’ of a one-dimensional RCE model, and this work pointed to the importance of the water-vapor feedback on climate change.



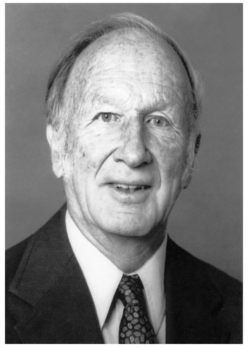


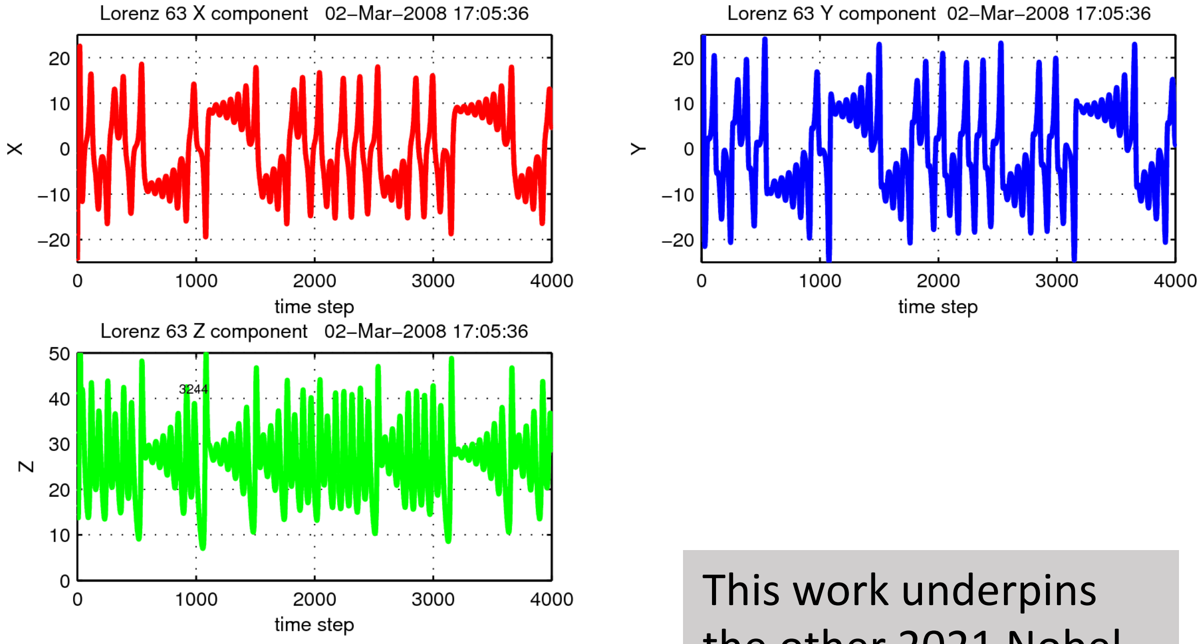
Seeds of chaos

Lorenz's revolutionary paper on deterministic non-periodic flow (**Lorenz 1963**) transformed our understanding of the limits of deterministic weather prediction, and eventually led to ensemble forecasting (Lewis 2005).

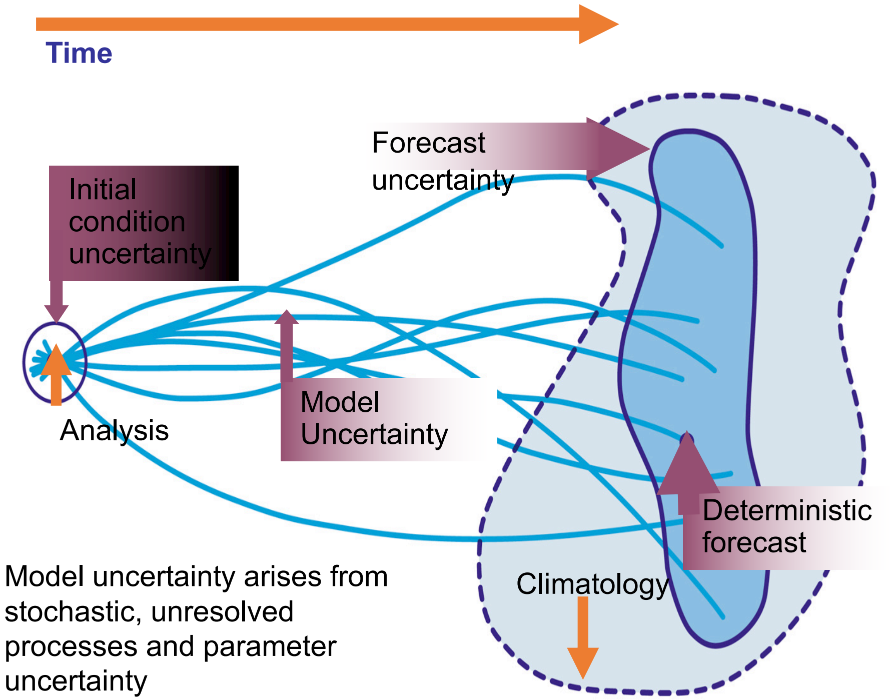
Motivated by Lorenz's discovery, Charney (1966) used early versions of the Livermore, UCLA, and GFDL models to investigate the sensitivity of the atmospheric circulation to small perturbations.

This work by Charney and colleagues could perhaps be viewed as the **first model intercomparison study.**

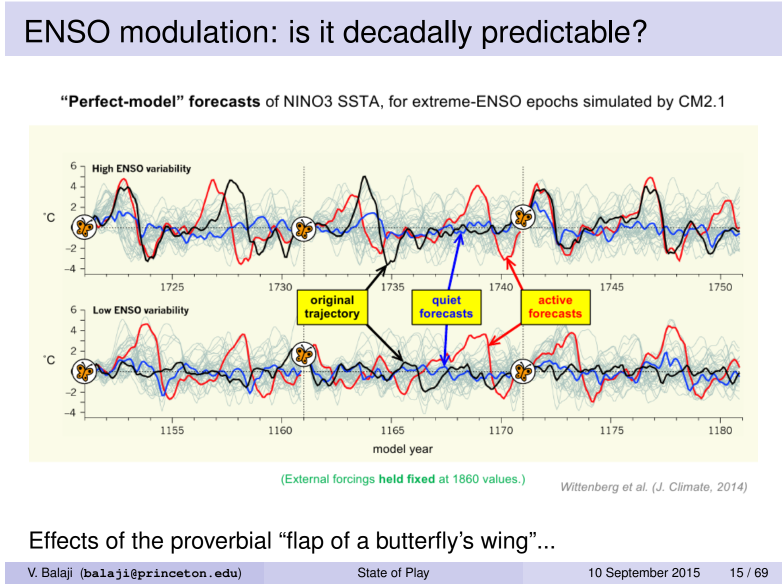




This work underpins the other 2021 Nobel prize, to Hasselmann



Model uncertainty arises from stochastic, unresolved processes and parameter uncertainty



The 1970s: more modelling groups and much more coupled climate system.

But also, **THE SPECTRAL METHOD BECOMES POPULAR**
During the 1970s and early 1980s, the global spectral6 method (Silberman 1954; Robert 1966; Baer 1972; Bourke 1974) became widely used in the dynamical cores of atmospheric models. In this approach, the horizontal distribution of model fields is represented by an expansion in spherical harmonics (Fig. 12-6). The spectral representation allows horizontal derivatives to be calculated very accurately and, with a triangular truncation of the expansion, gives homogeneous and isotropic resolution. Moreover, a spectral dynamical core that solves the barotropic vorticity equation conserves energy and enstrophy, as in the continuous system.

The calculation of quadratic nonlinear terms directly from the spectral representation using interaction coefficients was prohibitively expensive, and for other types of nonlinearity even more so. This barrier to the use of the spectral method was removed with the introduction of the spectral transform method by Eliassen et al. (1970) and Orszag (1970). In the spectral transform method, the nonlinear advection terms, along with any terms based on physical parameterizations, are computed in grid space, and efficient transforms are used to go back and forth between grid space and the spectral representation (Jarraud and Simmons 1983). As a result of these strengths of the spectral method, it was soon adopted by GFDL, NCAR, and ECMWF, and it dominated atmospheric modeling efforts around the world for the next two decades (see the review by Williamson 2007). It is still used today at several major modeling centers.

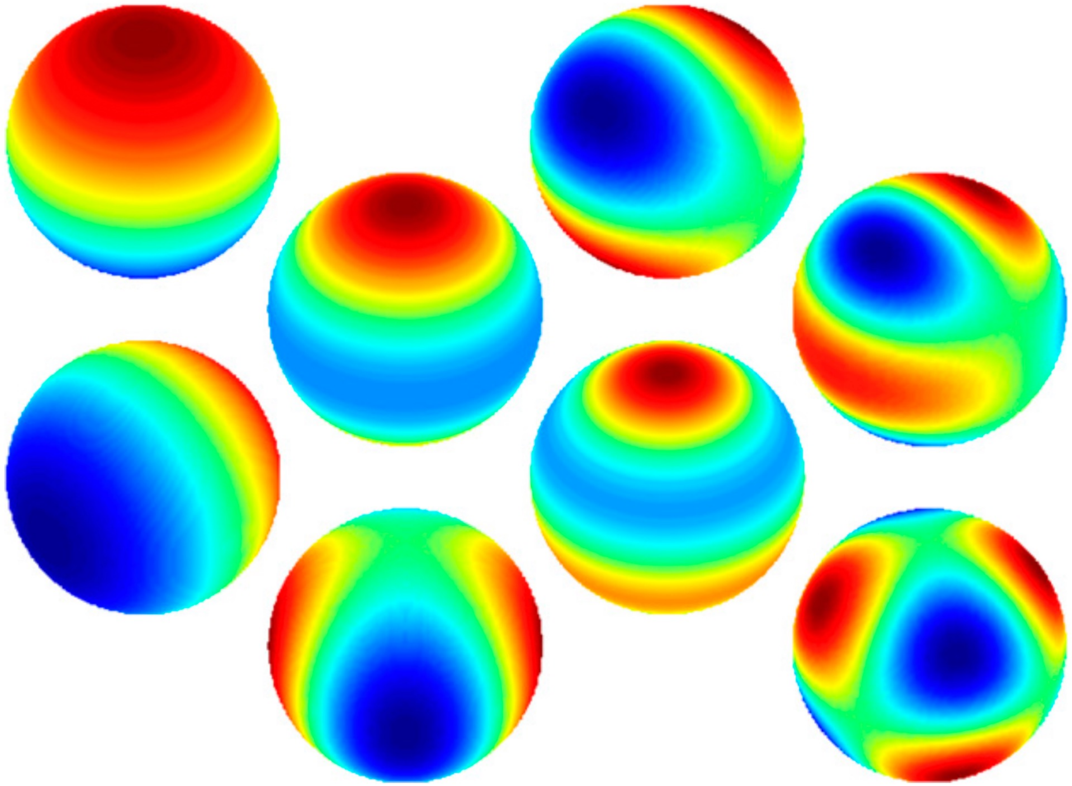


FIG. 12-6. Some examples of spherical harmonics. Spherical harmonics are wave-like functions defined on the surface of a sphere. They are spherical analogs of the sines and cosines that provide a basis for Fourier series in one dimension.

Improvements to grid-point models in the 1970s

For the modeling centers that persevered with gridpoint methods, important progress was made along two lines. One was the understanding that, in order to adequately capture geostrophic balance, it is necessary to adequately simulate the adjustment toward balance that occurs through the radiation of gravity waves. Ideally, non propagating computational modes should be avoided and the entire wave spectrum should have group velocities of the correct sign. These properties depend crucially on the staggering of variables on the grid, and systematic study (Winninghoff 1968; Arakawa and Lamb 1977; Randall 1994) concluded that the B grid (for large Dx/LR), C grid (for small Dx/LR), and Z grid (for all Dx/LR) horizontal staggerings perform best (Fig. 12-7). Here Dx is the grid spacing and LR is a key dynamical length scale called the Rossby radius of deformation.

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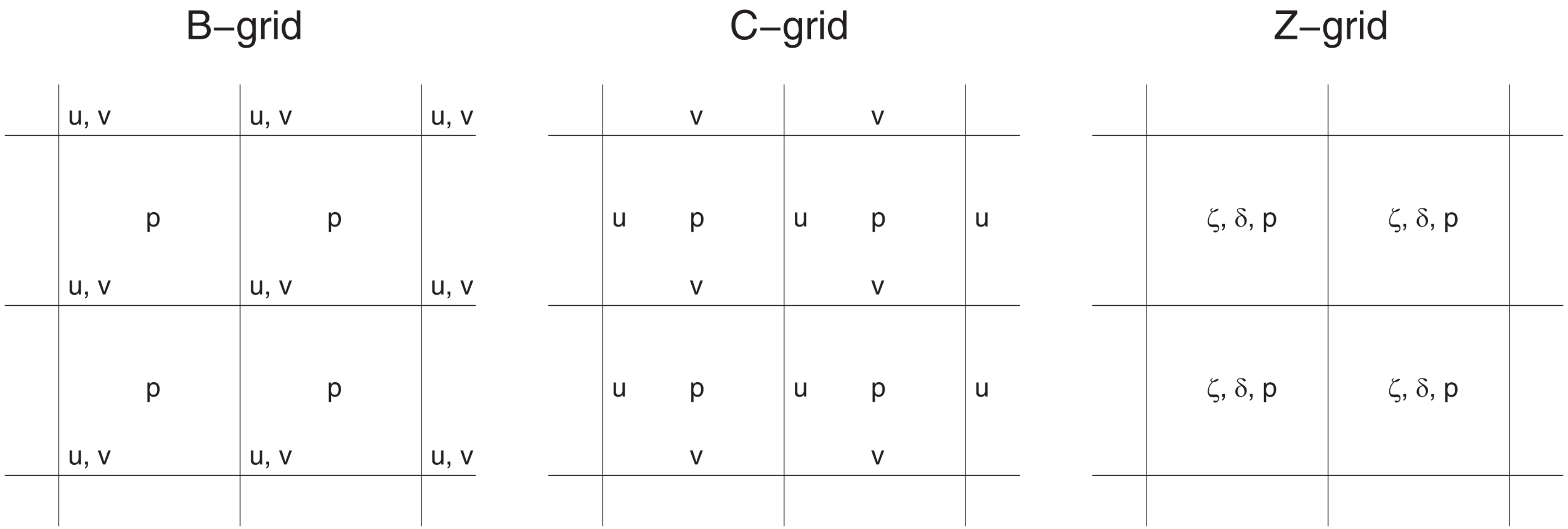


FIG. 12-7. Schematic showing the horizontal distribution of variables on the (left) B grid, (middle) C grid, and (right) Z grid. Here, u is the eastward velocity component, v is the northward velocity component, p is the pressure, ζ is the vertical component of vorticity, and δ is the horizontal velocity divergence.

The 1970s saw also

1. **Addition of a stratosphere**
2. **Introduction of key parametrizations: Boundary Layer Parametrization and Convective Parametrization**
3. **Introduction of ocean and sea ice models**
4. **Early examples of support for community models**
5. **First "modern" examples of simulation of global warming**

The first simulation of global warming with a true climate model was reported by **Manabe and Wetherald (1975).** Their model was idealized through the use of a limited computational domain, simplified topography, no energy transport by the oceans, no seasonal or diurnal cycles, and fixed cloudiness. It is remarkable that this first simulation with a simplified model, more than 40 years ago, predicted many changes that have now been observed in the real atmosphere, including a warming troposphere with greater warming near the pole, a cooling stratosphere, stronger precipitation, and increased atmospheric water vapor. The successful strategy of Manabe and Wetherald (1975), Manabe and Stouffer (1980), and Manabe and Wetherald (1980) was to explore the possibility of anthropogenic climate change using the relatively simple models available at the time, rather than waiting for the more complete models of the future.

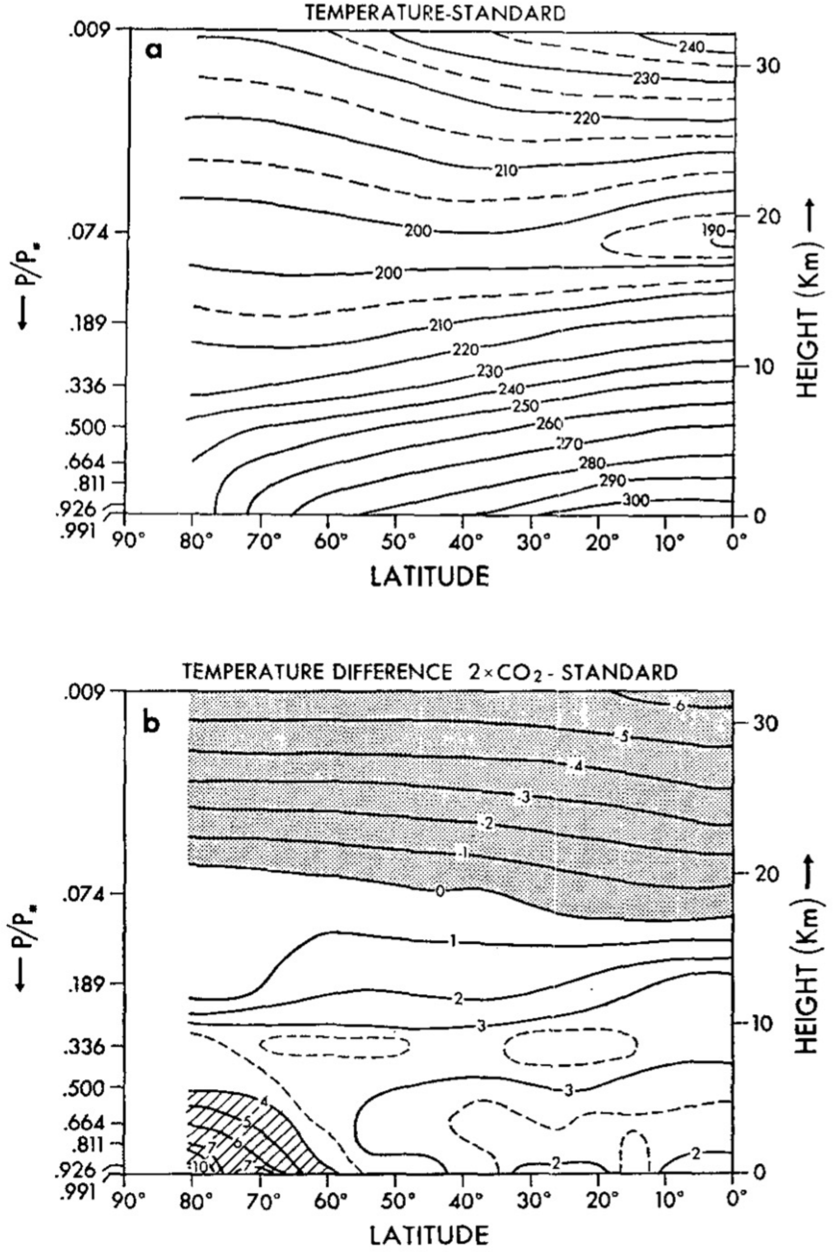


FIG. 4. Latitude-height distribution of the zonal mean temperature (K) for the standard case (a) and of the increase in zonal mean temperature (K) resulting from the doubling of CO_2 concentration (b). Stippling indicates a decrease in temperature.

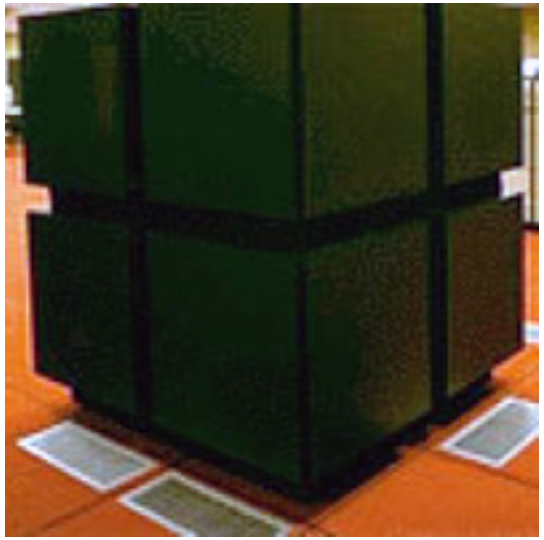
The 1980s and the birth of community modelling

In 1983, NCAR released the Community Climate Model (CCM) (Pitcher et al. 1983; Williamson 1983; Williamson et al. 1983; Kiehl et al. 1998). Initially, the CCM was essentially an atmosphere model coupled to a simple land surface model. It lacked a coupled ocean model, so calling it a ‘‘climate model’’ was a bit of an exaggeration. The CCM was widely used because it was freely available and fully documented.

During the 1980s, Washington and Meehl (1983), Washington and Meehl (1984) and Washington and Meehl (1989) used versions of the CCM to perform increasingly detailed simulations of anthropogenic greenhouse warming. In the late 1990s, Washington et al. (2000) developed the Parallel Climate Model (PCM). The atmosphere component was the CCM3 at T42 resolution, and the ocean component was the POP model at about 0.58 resolution.

The PCM was one of the first models designed to run very efficiently on the parallel computers that were emerging at that time. The PCM was subsequently used to run ensembles of twentieth-century simulations forced by the individual climate forcings, such as greenhouse gases, aerosols and solar variability, rather than their combined effects. The interesting results are presented in Meehl et al. (2003).

C1 (CRAY-1A, Cray Computer)
NCAR becomes Cray Computer's first customer for this vector-processing system



Capitol (Connection Machine 2, Thinking Machines)
With over 8,000 processors, this machine enabled the NCAR-University of Colorado Center for Applied Parallel Processing

More modelling milestones in the 1980s

- Radiative transfer (Stephens et al. 1984 still a great overview), particularly radiation and clouds
- Boundary layer, particularly BL and clouds
- Much more work on convective parametrization
- Cloud microphysics
- Land surface modelling
- Re-analysis

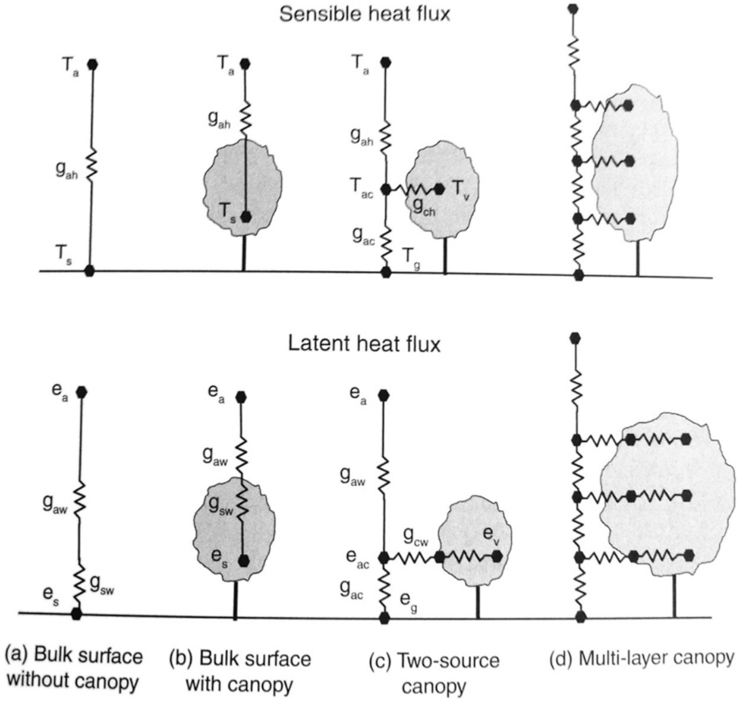


FIG. 12-10. Equivalent resistor networks used to represent surface energy flux in land surface models of several levels of complexity, where T is temperature, e is vapor pressure, and g is conductance (transfer coefficient). Subscripts a, s, c, v, and g refer to lowest atmospheric layer, surface, canopy air space, vegetation, and ground surface respectively. Subscripts h and w refer to sensible and latent heat, respectively. [Redrawn from Bonan (2015); Ecological climatology: concepts and applications. © Gordan Bonan 2016. Reproduced with permission of The Licensor through PLSclear.]

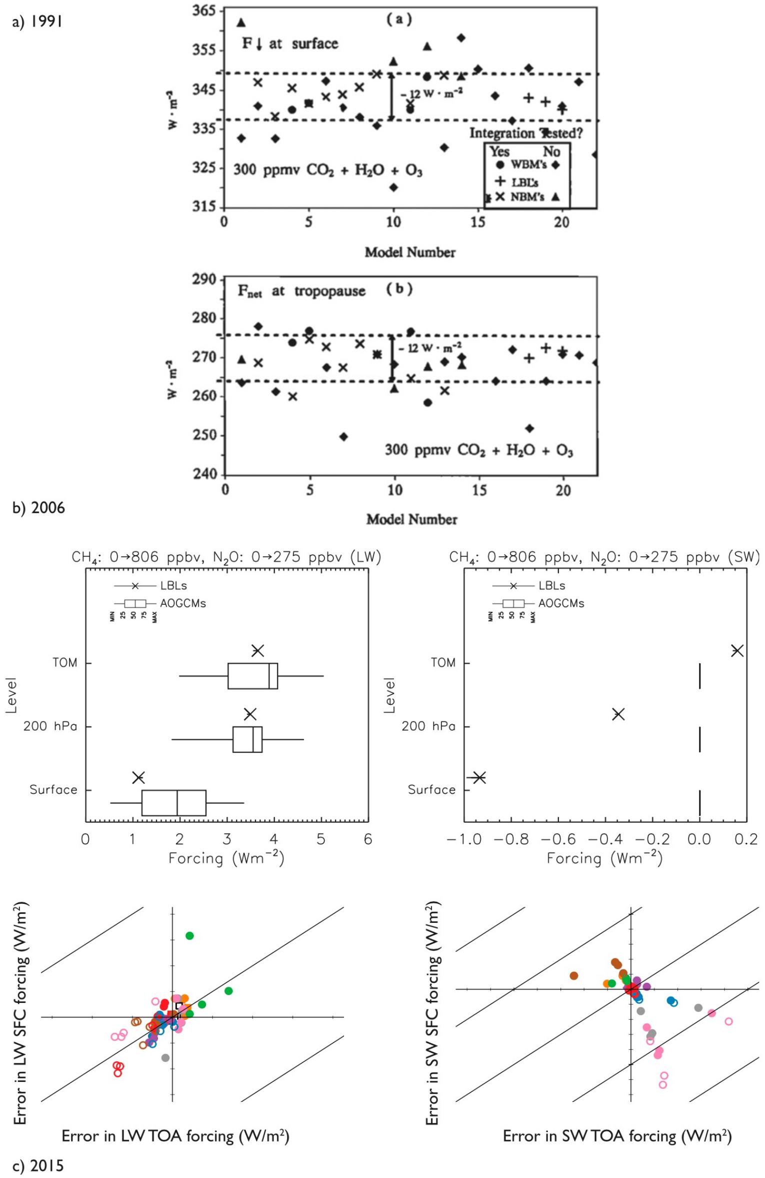


FIG. 12-9. The treatments of radiation in global models have been compared to benchmark "line-by-line" calculations for many decades. (a) Results for longwave fluxes at the surface and the tropopause in a single idealized but quasi-realistic atmosphere. The line-by-line models, shown as plus signs, agree with each other quite well, partly because they share the same spectroscopic data; by comparison both narrow- and wide-band models ("NBMs" and "WBMs" respectively) show signifcantly more variation. (b) Published 15 years later, focuses on forcing (i.e., the change in flux caused by a change in composition) here the impacts of methane and nitrous oxide. Line-by-line calculations are indistinguishable from one another while the GCMs show variation of 25% or more of the signal in the longwave while entirely ignoring the impact in the shortwave. (c) Appearing almost a decade later still, shows that errors in GCM parameterizations (circles) still swamp those from line-by-line models (squares) in calculations of the forcing by quadrupled carbon dioxide concentrations. Panel (a) is Fig. 15 of Ellingson et al. (1991); (b) is Fig. 6 of Collins et al. (2006b); (c) is redrawn from Fig. 3 and supplemental material in Pincus et al. (2015).

The 1990s: Hadley Centre and other initiatives designed to respond to societal concern, alongside CMIP and IPCC

In 1990 the **Met Office Hadley Centre** was opened (Folland et al. 2004), creating a dedicated center for research on Earth's climate (e.g., Senior and Mitchell 2000; Mitchell et al. 1995b). The Hadley Centre's Unified Model (Cullen 1993; Cullen et al. 1997; Davies et al. 1998) is designed for use in both operational NWP and climate simulation. This has the advantage that operational NWP is an excellent way to test a climate model (e.g., Palmer et al. 2008; Senior et al. 2010).
A version of the ECMWF forecast model was modified to create ECHAM (Roeckner et al. 1989; Simmons et al. 1989; Stevens et al. 2013), a climate model in use at the Max Planck Institute for Meteorology in Hamburg.

As mentioned in section 6d, Cess et al. (1989) organized an **intercomparison of results from many modeling groups.** Additional intercomparisons proliferated during the 1990s. An important example is the Atmospheric Model Intercomparison Project (AMIP; Gates 1992). AMIP was presaged by the study of Lau (1985), who showed that the atmosphere responds strongly and predictably to prescribed observed interannual changes in sea surface temperatures. An AMIP simulation uses an atmospheric model (coupled to a land surface model) with prescribed observed sea surface temperatures for a sequence of real years. An AMIP simulation can be used to test the ability of a global atmospheric model to respond realistically to interannual variability of sea surface temperatures such as that associated with El Niño. The experimental design is similar to that developed by Lau (1985), but follows a formal protocol. AMIP simulations continue to be a valuable and widely used method to test global atmospheric models (e.g., Eyring et al. 2016).

Intercomparisons have also been crucial for the work of the **Intergovernmental Panel on Climate Change (IPCC)**, which issued **its first assessment report in 1990 (IPCC 1990)** and continues its work today (e.g., Stocker et al. 2013). The IPCC is a truly historic enterprise that is strongly reliant on results from ESMs. The Coupled Model Intercomparison Project (CMIP) has been particularly central to the work of the IPCC (Meehl et al. 2000; Covey et al. 2003; Eyring et al. 2016).

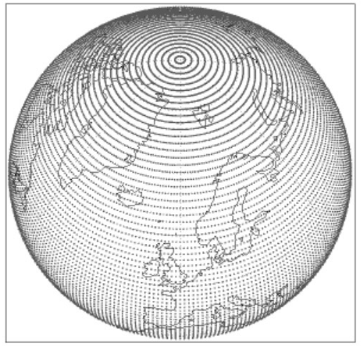
1990s dynamical cores

- The emergence of Semi-Lagrangian – Semi-Implicit (SISL), which was wonderful for vector supercomputers
- Emergence of reduced grids near the poles (best in spectral models)
- Emergence of non-hydrostatic models
- New vertical coordinates and split schemes in horizontal and vertical
- Unification of modelling systems for weather and climate modelling

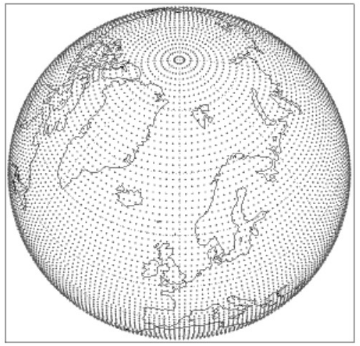
But also:

- Introduction of photosynthesis in land surface models, as part of the “carbonisation” of weather and climate models
- More advances in unified radiation
- Advances in modelling of sea ice.

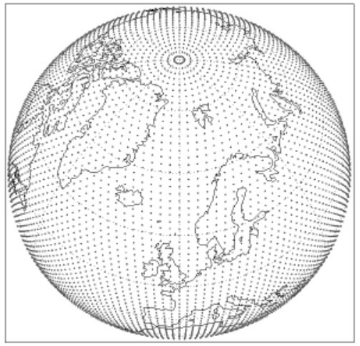
F80 regular Gaussian grid



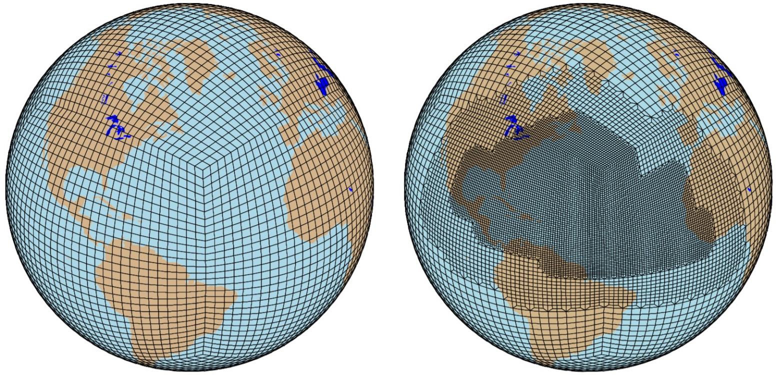
N80 original reduced Gaussian grid



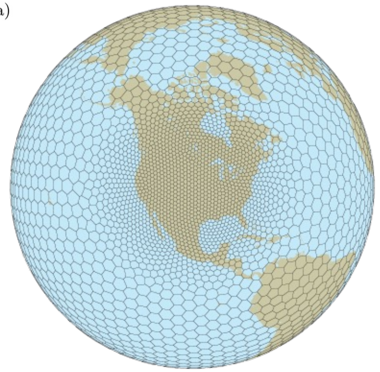
O80 octahedral reduced Gaussian grid



Looking towards the 21st century



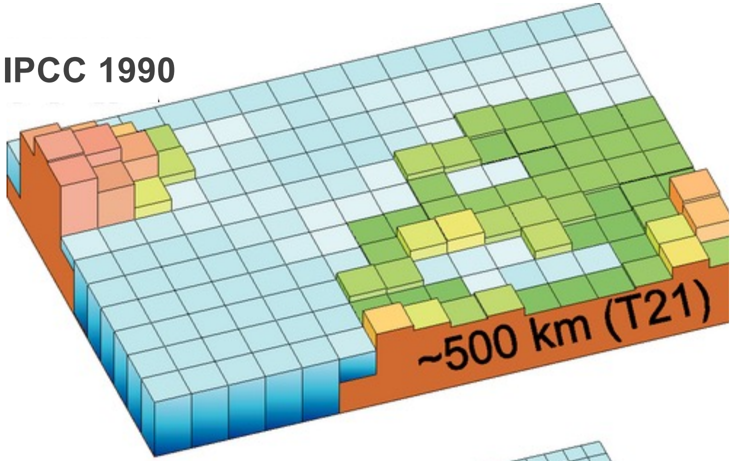
(a) (b)



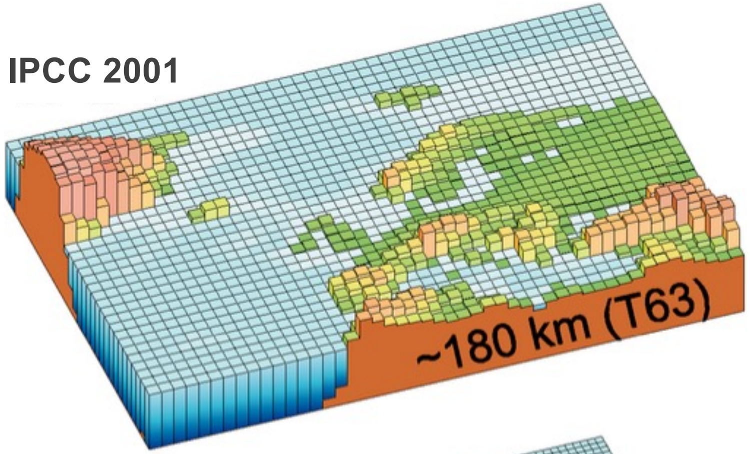
What can be done to improve models?

Increase spatial resolution

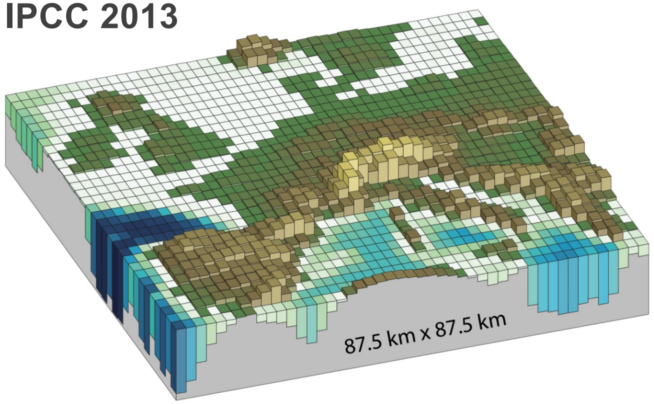
IPCC 1990



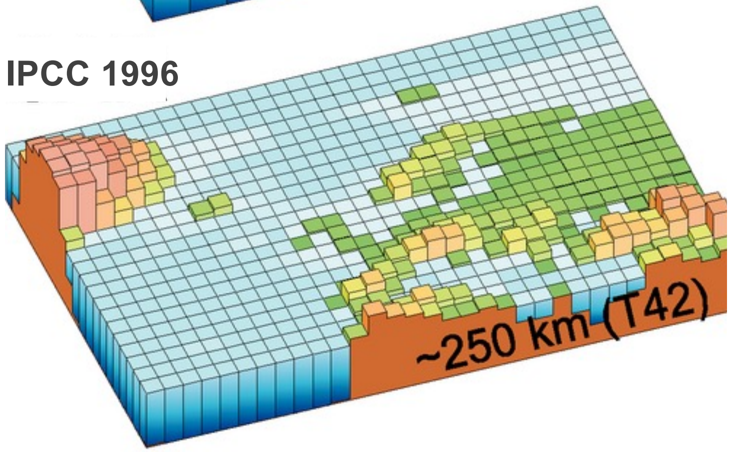
IPCC 2001



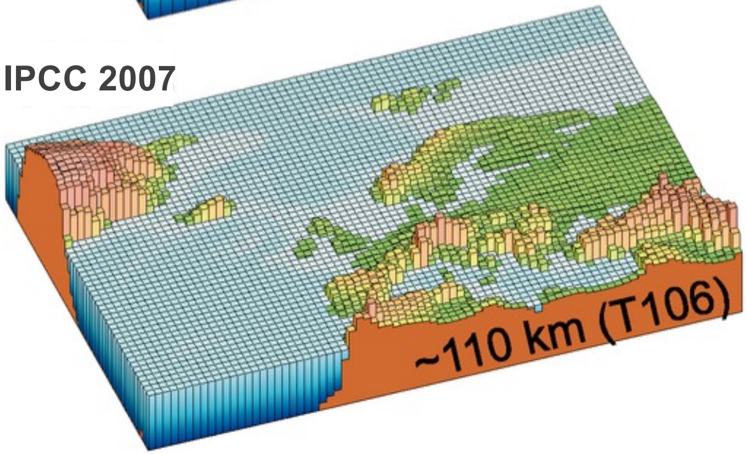
IPCC 2013



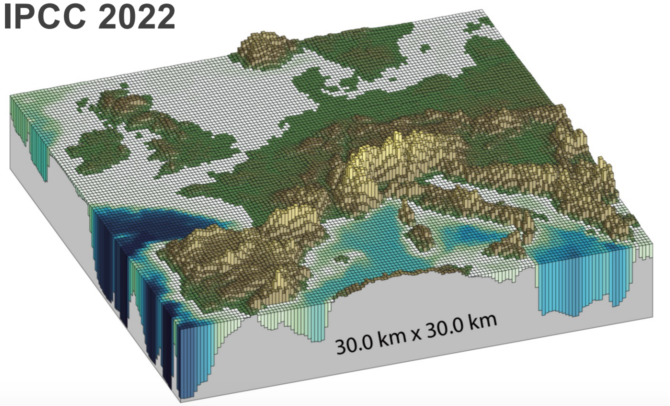
IPCC 1996



IPCC 2007

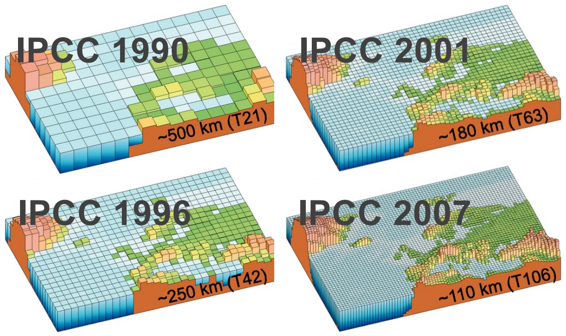


IPCC 2022

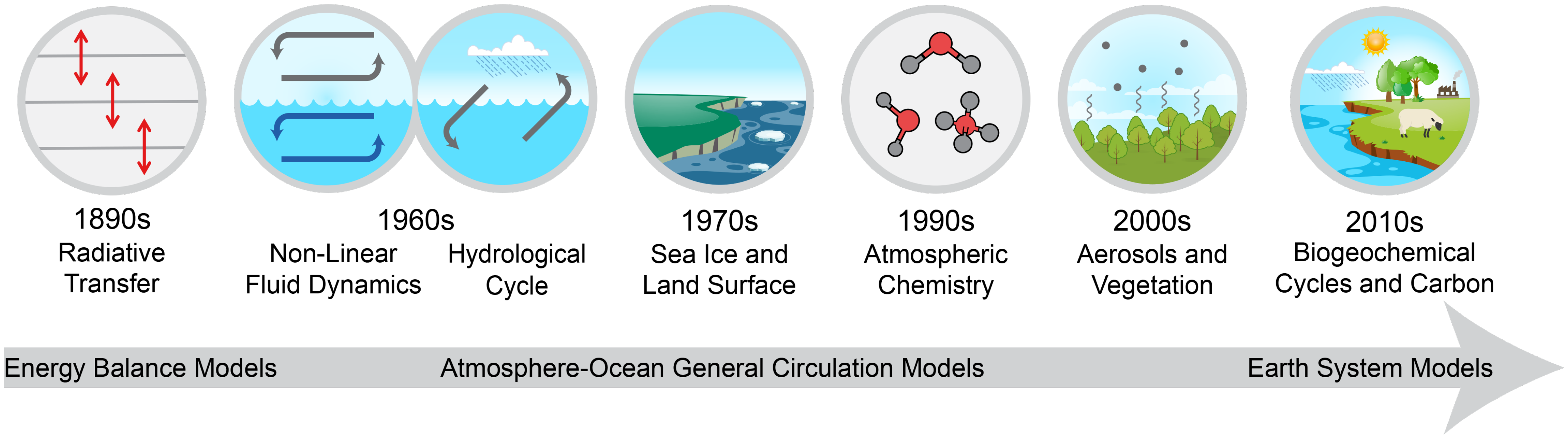


What can be done to improve models?

Increase complexity

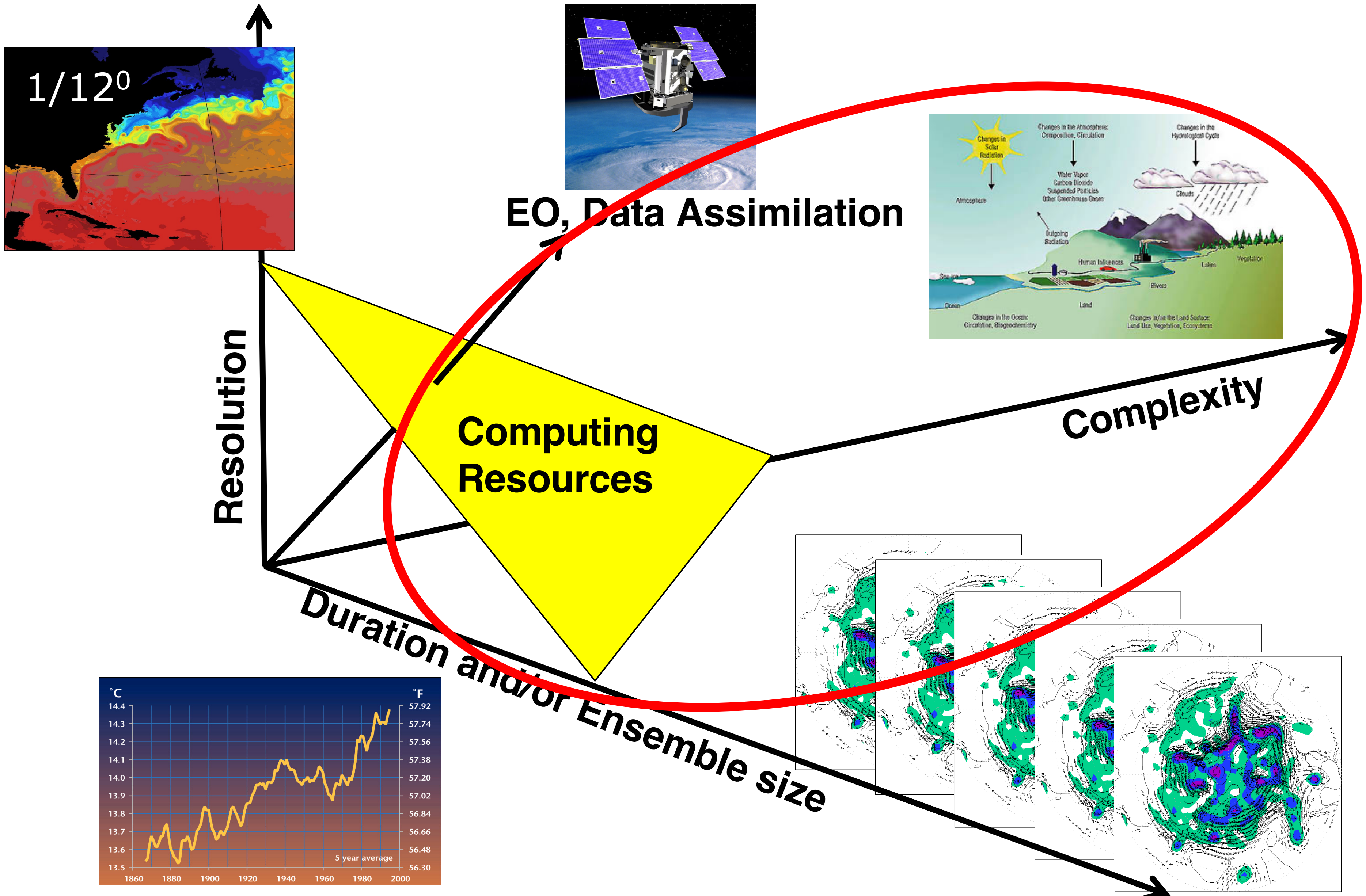


A Climate Modeling Timeline
(When Various Components Became Commonly Used)



HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

Computing resources are finite: a number of compromises



Into the 21st century

- New dynamical cores suitable for massively parallel computers, including adaptive mesh refinement

- Couplers capable of dealing with ESM complexity and parallelism

- Far more radiation and clouds, radiation and aerosols, cloud microphysics and aerosols, etc.

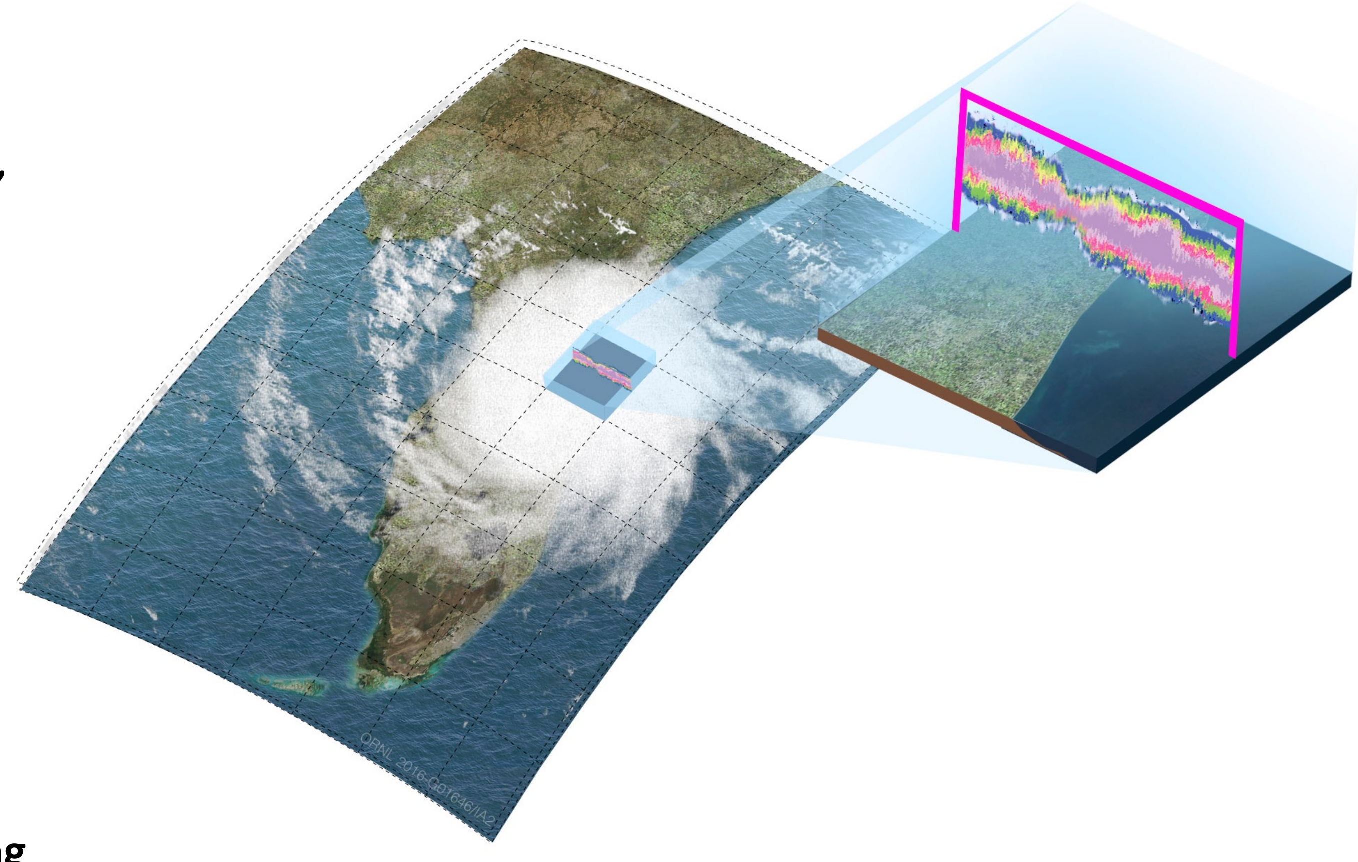
- Far more land surface and hydrology
- More complex sea ice models

The birth of Global Cloud-Resolving Models (GCRMs)

- Superparametrization

Ocean models moving to mesoscale parametrization

Earth System Modelling: couple everything to everything else



… we know what needs to be done

TOWARD A NEW GENERATION OF WORLD CLIMATE RESEARCH AND COMPUTING FACILITIES

BY J. SHUKLA, T. N. PALMER, R. HAGEDORN, B. HOSKINS, J. KINTER, J. MAROTZKE, M. MILLER, AND J. SLINGO

To accelerate progress in understanding and
national climate research facilities must

Ambitious partnership neede climate prediction

Current global climate models struggle to represent precipitation a
implications for the physical evidence base to support climate acti
overcome this shortcoming but requires collaboration on an unprecedented scale.

Julia Slingo, Paul Bates, Peter Bauer, Stephen Belcher, Tim Palmer, Graeme Stephens, Bjorn Stevens, Thomas Stocker and Georg Teutsch

OPINION VIEWPOINT

'A CERN for climate chang

Local effects such as thunderstorms, crucial for predicting global warming, could be simulated by fine-scale global climate models.

PERSPECTIVE

The scientific challenge of understanding and estimating climate change

Tim Palmer[a,1] and Bjorn Stevens[b,1]

Edited by Jagadish Shukla, George Mason University, Fairfax, VA, and accepted by Editorial Board Member Robert E. Dickinson October 21, 2019 (received for review May 21, 2019)

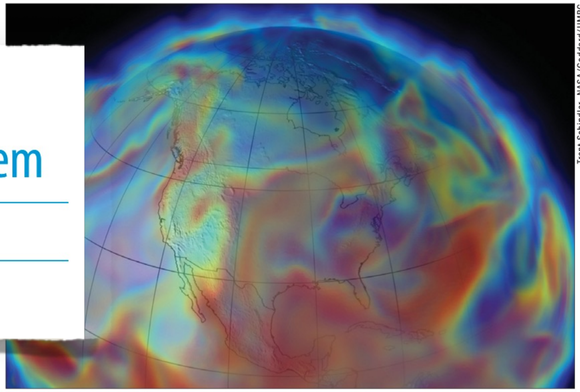
Build high-resolution global climate models

International supercomputing centres dedicated to climate prediction are needed to reduce uncertainties in global warming, says Tim Palmer.

Comment: Forum physicsworld.com

A CERN for climate change

Providing reliable predictions of the climate requires substantial



Trent Schindler, NASA/Goddard/UMBC

A global approach to a global problem Modelling the climate may require a unified strategy for computing.

of weather will become more likely under climate change? Good question, but the trouble is we do not know the answer with any great confidence.

PROCEEDINGS A

rspa.royalsocietypublishing.org

Research

CrossMark

A personal perspective on modelling the climate system

T. N. Palmer

Department of Physics, University of Oxford, Oxford, UK

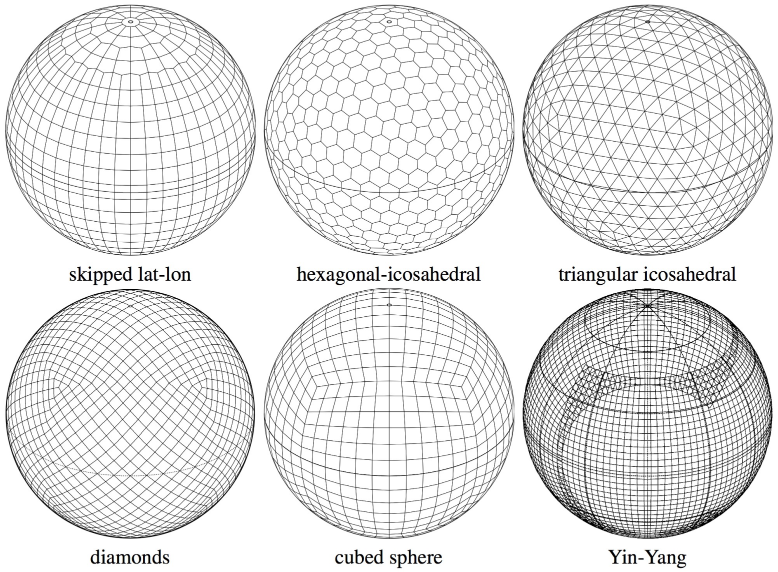
THE ROYAL SOCIETY

CLIMATE CHANGE : SCIENCE AND SOLUTIONS | BRIEFING 1

Next generation climate models: a step change for net zero and climate adaptation

Current Modelling Trends:

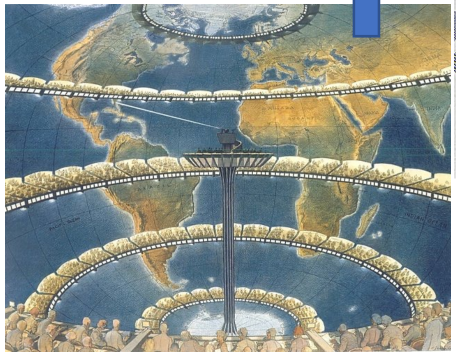
Resolution towards 1km → Digital Twins
Need for uniform grids and codes **scalable** on HPCs with millions of cores



Removal of physical parametrizations, e.g. removal of convective parametrization and of ocean mesoscale parametrizations

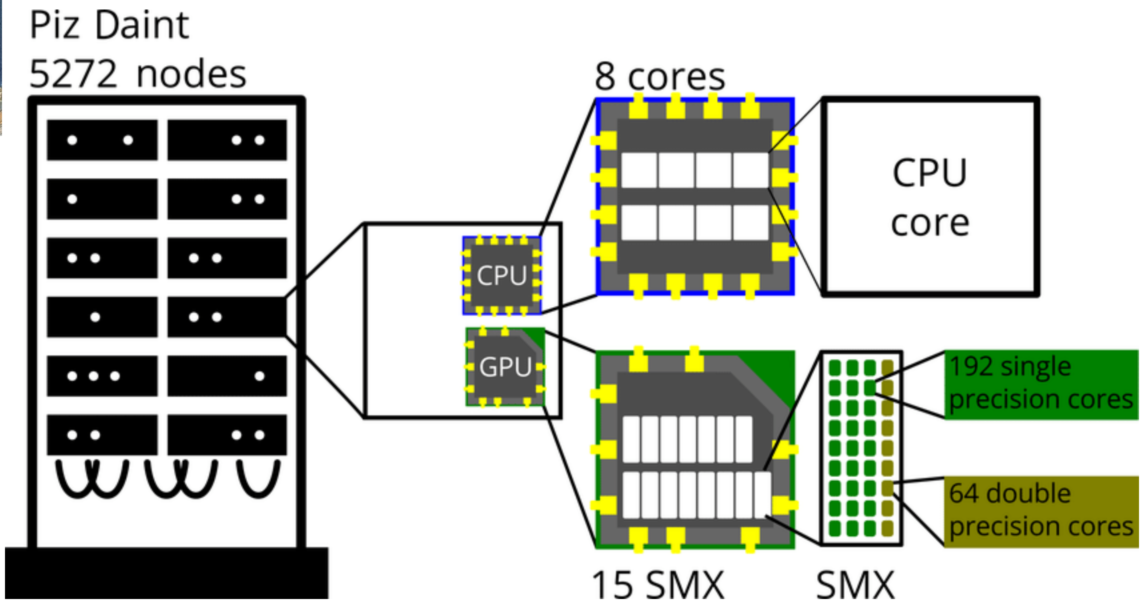
Large Ensembles (order of 100 members)

More and more ESM processes



Richardson's factory still a valid concept

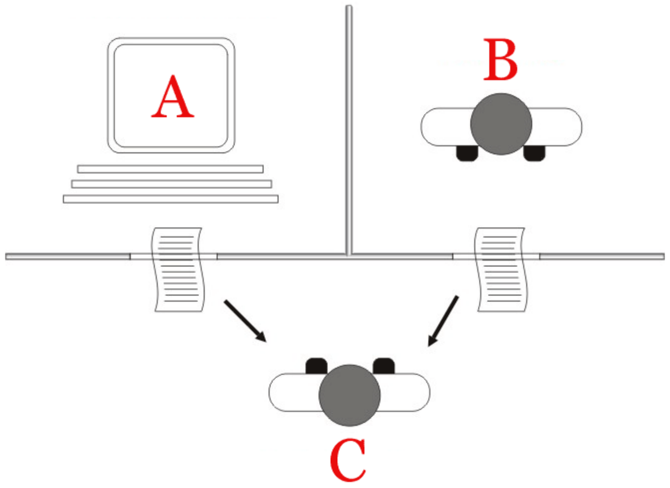
Piz Daint currently at 5MW
Top US supercomputer (Frontier) at 25-30MW



Pushing the frontiers of understanding

Challenge researchers to be adventurous and ambitious in environmental science, exploiting new technologies and approaches.

A Turing test for climate in DYAMOND



In keeping with the spirit of Bletchley Park

See also: Palmer TN. 2016 A personal perspective on modelling the climate system. *Proc. R. Soc. A* **472**: 20150772.

Thanks to R. Schiemann, NCAS-Climate, Reading, for the history reminder

One of these is our "good old" Unified Model at 5km; another is a satellite image…

… (Matsuno 2016): his idea was to provide a <u>tropical analogue to the mid-latitude numerical experiments of Phillips (1956) and Smagorinsky (1963)</u>— one that could resolve the transient dynamics of tropical deep convection, and its various forms of organization…

… NICAM demonstrated the ability of a model to use unfiltered equations of atmospheric motion, on a global domain, to <u>represent convective storms in the tropics as a component of the general circulation</u>.

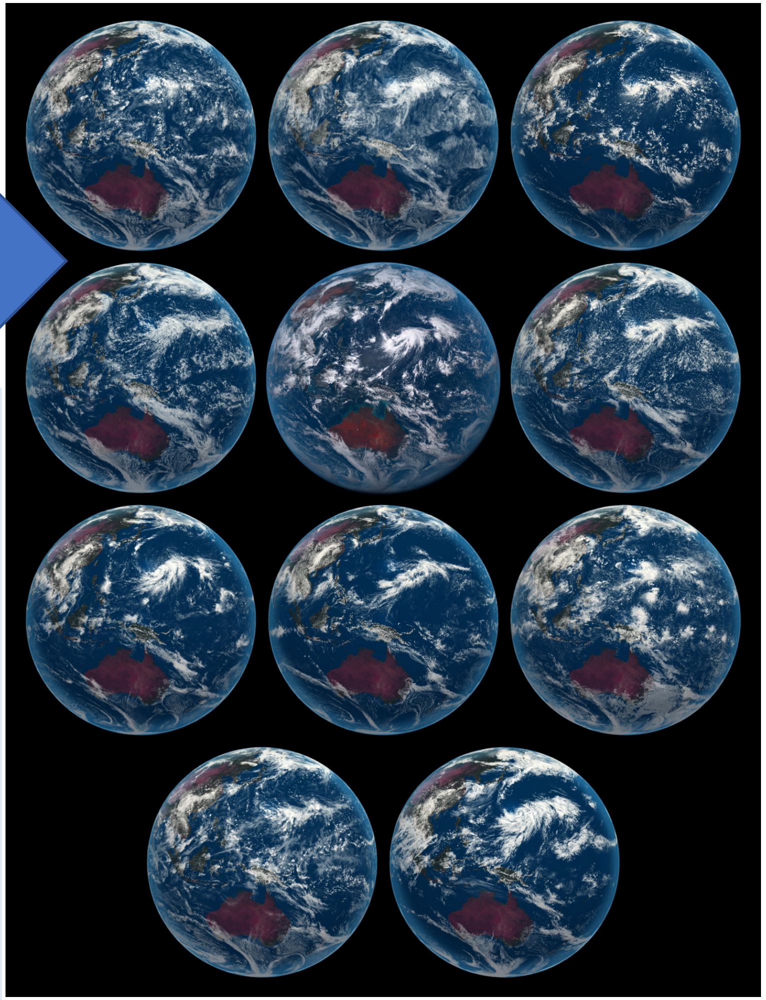


Image created by MPI-Meteorology, Hamburg, in:

Stevens, B., et al. (2019) [DYAMOND: the DYnamics of the Atmospheric general circulation Modeled On Non-hydrostatic Domains.](https://doi.org/10.1186/s40645-019-0304-z) Progress in Earth and Planetary Science. doi: https://doi.org/10.1186/s40645-019-0304-z

WARM WORLD

BETTER (M1)

FASTER (M2)

EASIER (M3)

SMARTER (M4)

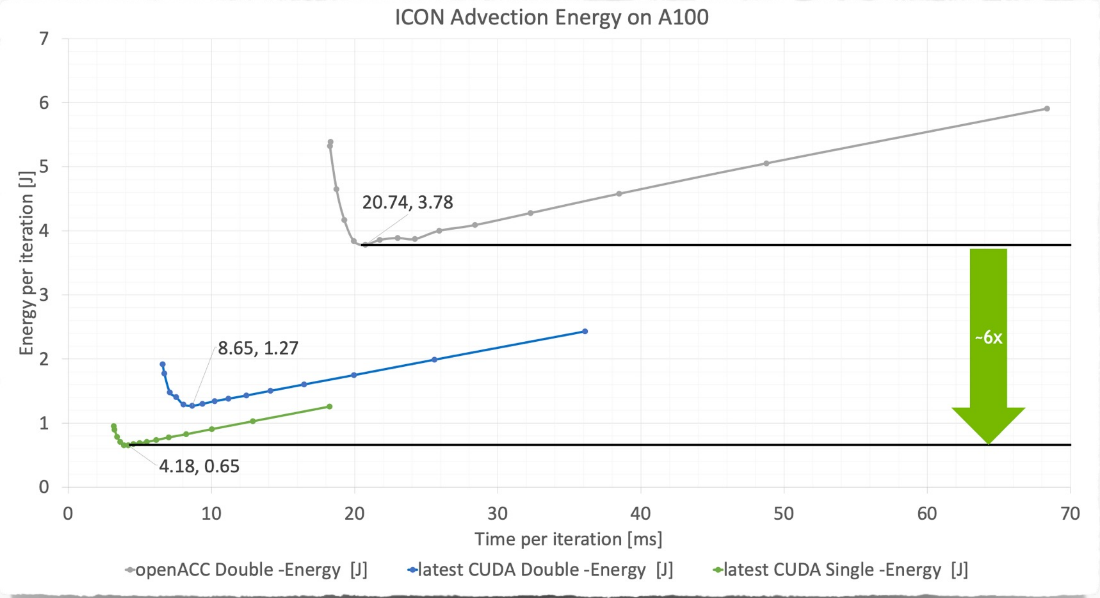
Gefördert vom
Bundesministerium
für Bildung
und Forschung

Link to animation

... but

FASTER (M2)

1. Refactor code for scalable development — ICON-C
2. Initiate target performance ports to meet throughput goals



… less code more developers

Opportunities/Challenges

- New generation of dynamical cores
  - New numerical methods
    - Unstructured meshes
    - New parallelism paradigms
    - Domain languages
  - GPUs
  - Reduced precision (all the way to 16bit)
    - «Faulty» chips and reduced power usage
  - Stochastic Physics
- High-resolution models as development labs for parameterisation
  - SCMs and observational emulators
  - Machine Learning: best suited for GPUs?
  - A new generation of super-parameterisation?
- Reduced communications: back to Eulerian
- Reduced writing of data: if we were to write all data from DYAMOND, we would generate 2PB per day!
  - Internalised process analysis
  - Ensemble techniques

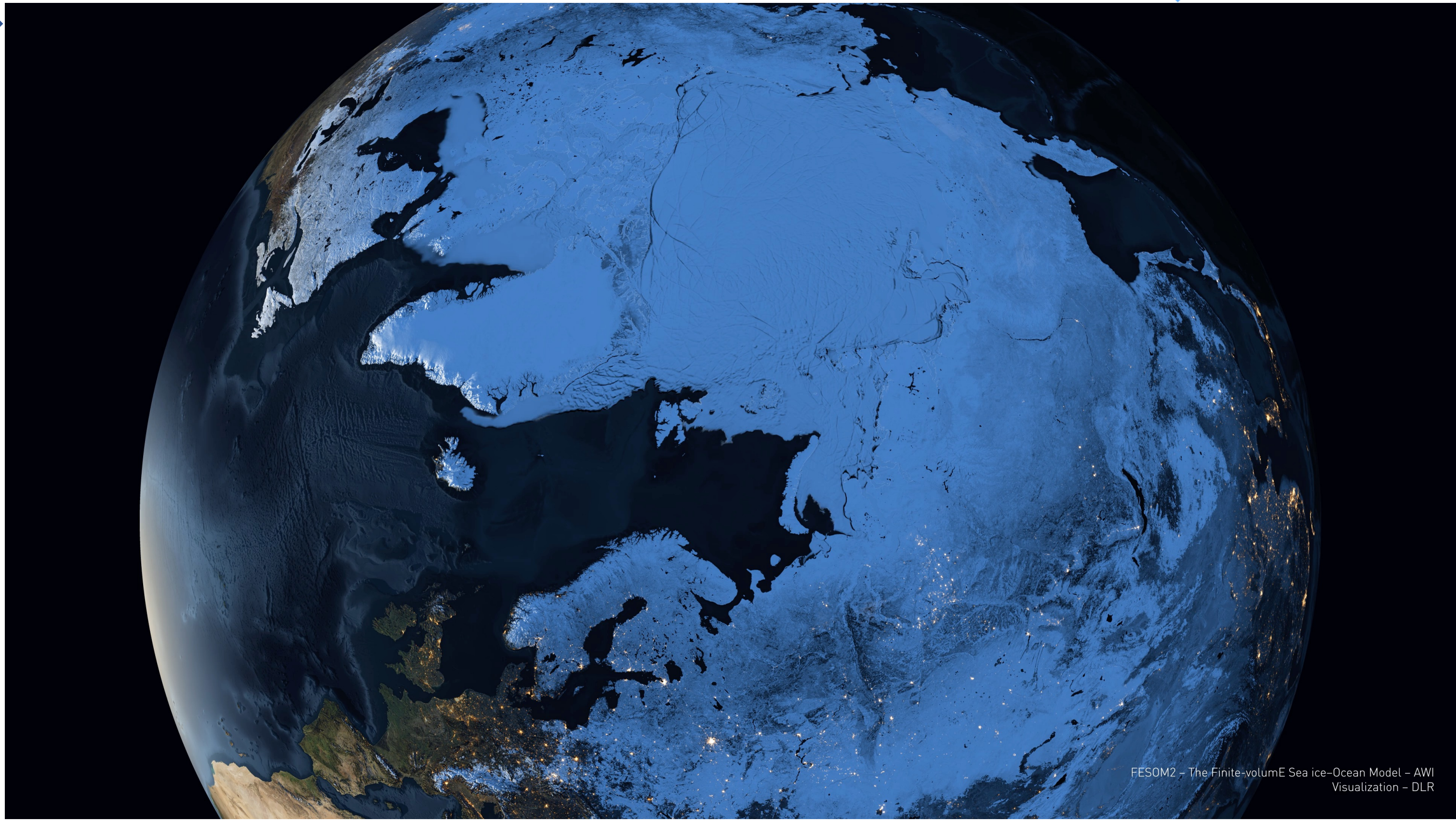
We shall experiment with many of these in EERIE

PRIMAVERA

NextGEMS started in 2021: target 3km global coupled

next GEMS

AWI sea ice simulation with unstructured mesh
Δx = 1.0km, by Nikolay Koldunov



HELMHOLTZ ASSOCIATION

AWI

This afternoon

- Mark will introduce you to Project 1, and you will start working on it right away
- Please arrive on time, so that Mark can start his introduction and still have time to sit with you and help you make a good start