ATM 265, Spring 2019
Lecture 1
Overview / History
April 1, 2019

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ATM 265 Syllabus

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Course Structure:

- Two one-hour lectures per week
- Monday and Wednesday, 12pm – 1:30pm

Course Webpage on Canvas

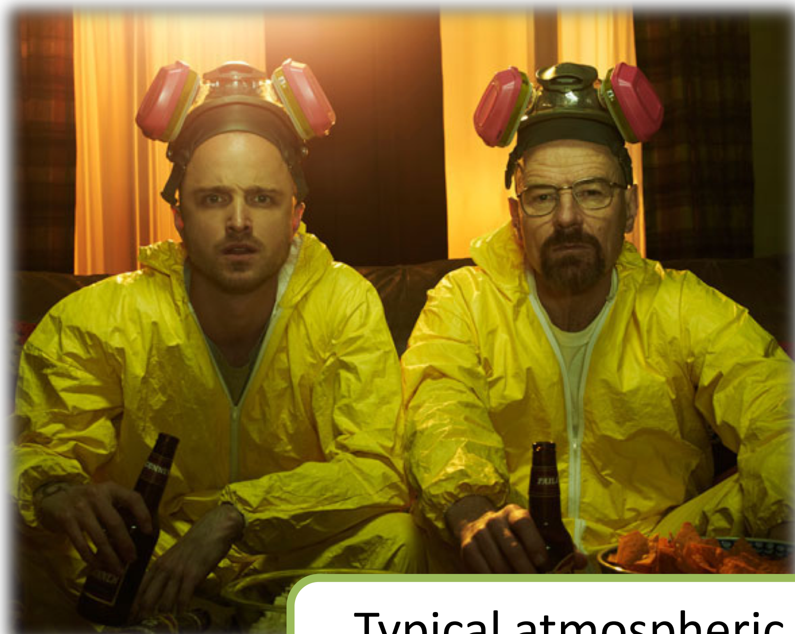
ATM 265 Syllabus

Evaluation:

- Reading assignments (20%)
- CESM Projects (2) (30%)
- Term Project (50%)

Who would be interested in this class?

ATM 265 targets anyone with an interest in model development, and understanding what goes on "under the hood" of atmospheric models. By the end of the class, atmospheric models should no longer be a black box.



Typical atmospheric model developers

Typical atmospheric model users

Reading Assignments

- A number of readings have been chosen, and the list will be periodically updated. This material is a combination of the defining literature of the field, technical reports and scientific editorials.
- A response piece (200 – 500 words) is required for six of the reading assignments.
- The response should not be a summary of the reading, but should provide your opinion or thoughts on the content.
- For example, if you were designing an atmospheric model, how would your decisions be affected by the content of the reading?
- Responses should be recorded on the course webpage. You are encouraged to read others' response pieces.

Some Readings (updated periodically)

Rood (2010) A perspective on the role of the dynamical core in the development of weather and climate models
Climate Models: An Assessment of Strengths and Limitations (Introduction through Chapter 2)
Thuburn (2008) Some conservation issues for dynamical cores of NWP and climate models
Held (2005) The gap between simulation and understanding in climate modeling
Lawrence et al. (2017) Crossing the chasm: How to develop weather and climate models for next generation computers?
Hurrell et al. (2010) A unified modeling approach to climate system prediction
Hamilton (2009) Research with fine-resolution global atmospheric models: A personal perspective
Jeevanjee et al. (2017) A perspective on climate model hierarchies
Climate Models: An Assessment of Strengths and Limitations (Chapter 5)
IPCC AR4 Working Group I: The Physical Basis Chapter 8

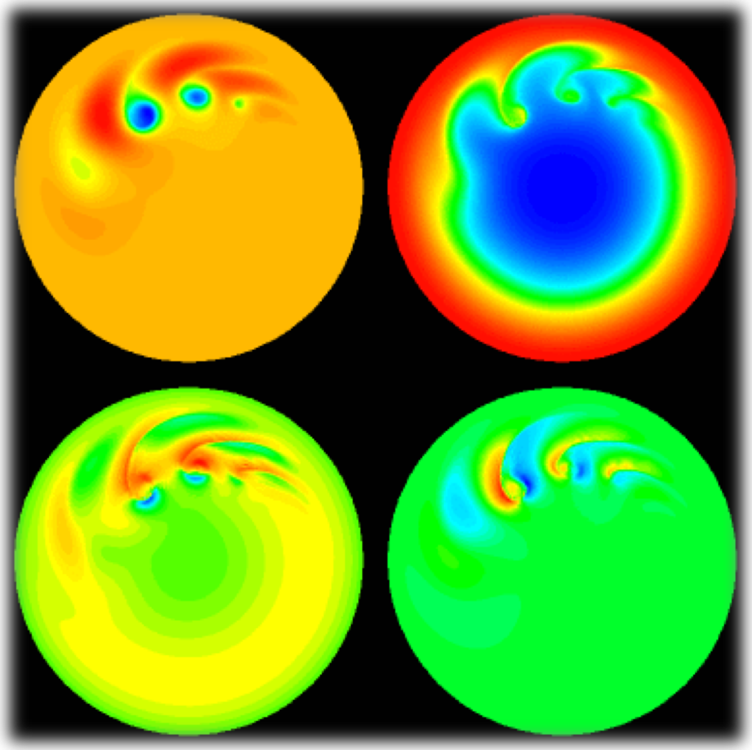
Cheyenne Supercomputer

- Student accounts will be created on the National Center for Atmospheric Research (NCAR) Cheyenne supercomputing cluster
- Login verification uses an encrypted RSA (physical) system via a personal Ubikey.
- A lost Ubikey costs $15, so protect it!
- Information on accessing the Cheyenne supercomputer will come in this week.

CESM Projects

- Two short introductory project on using the Community Atmosphere Model (CAM) to introduce the technicalities of using this modeling environment.

- The first project will investigate the use of CAM to run a baroclinic wave experiment. The goal is to familiarize the class with the use of an operational atmospheric modeling environment.



Course Projects

- Each student should choose one topic of interest / scientific question which is relevant to global or regional atmospheric modeling. Generally these topics should fit into one of three categories:

- Numerical: Studying a new numerical method, or some aspect of an existing numerical method relevant to atmospheric modeling.

- Theoretical: Using atmospheric models to better understand a topic of theoretical interest, such as atmospheric waves that emerge in an idealized atmosphere.

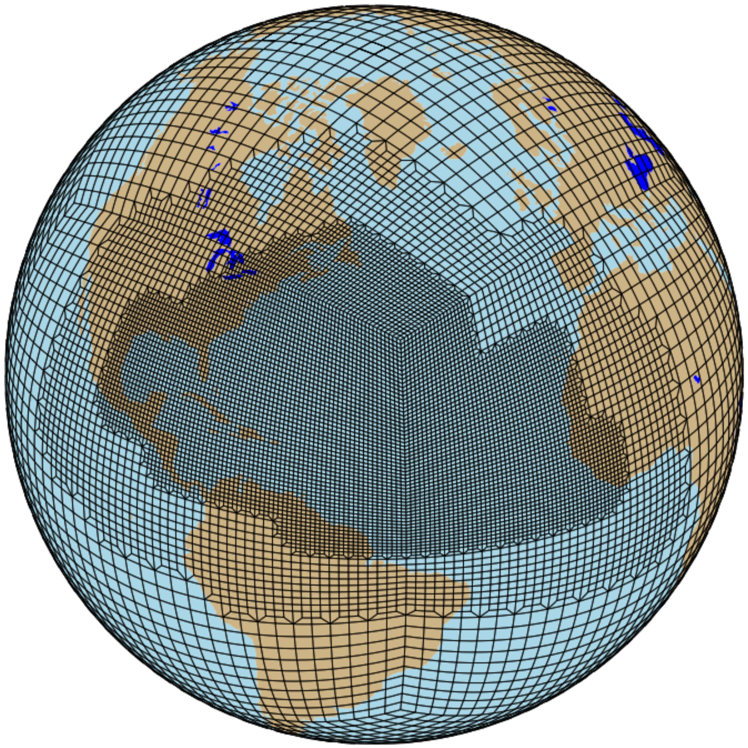
- Scientific: Using atmospheric models to answer a question of specific scientific interest.

Course Projects (Examples)

- The Community Atmosphere Model (CAM) Spectral Element (SE) method now has the capability of running on variable resolution atmospheric meshes.

- Which climatological features benefit the most from higher resolution?

- Does improving the resolution over topography improve the downstream climatology?



Course Projects (Examples)

- How well do current modeling systems at capturing the features of particular weather extremes?

- What are the large-scale drivers of a particular historical extreme?

Course Projects (Resources)

Software:

- Community Earth System Model (CESM)
- Energy Exascale Earth System Model (E3SM)
- HOMME (Spectral Element dynamical core) standalone model
- Weather Research and Forecasting (WRF) regional model
- Tempest Finite-Element dynamical core

Hardware:

- Cheyenne supercomputer course allocation
- Agri (Farm-II) local cluster

Course Projects

- Each student is required to provide a description of their research topic and results on the course webpage, plus a 10 minute presentation at the end of the quarter.

- Some course projects have the potential to lead to academic papers. Pursuing this course if strongly encouraged, and additional help will be available towards this goal.

Course Projects: Important Dates

- Immediately: Consult with me about possible project ideas.
- April 10, 2019: Brief description of project due in class.
- May 1, 2019: Send me a brief progress report.
- June 5, 2019: Student presentations (catered?)

Global Atmospheric Modeling

Global Atmospheric Modeling

- Global atmospheric models were originally constructed as a means of understanding the general circulation of the atmosphere.

- They have been used as predictive models on timescales of days to weeks (for numerical weather prediction) up to centuries (long-term climate forecasts).

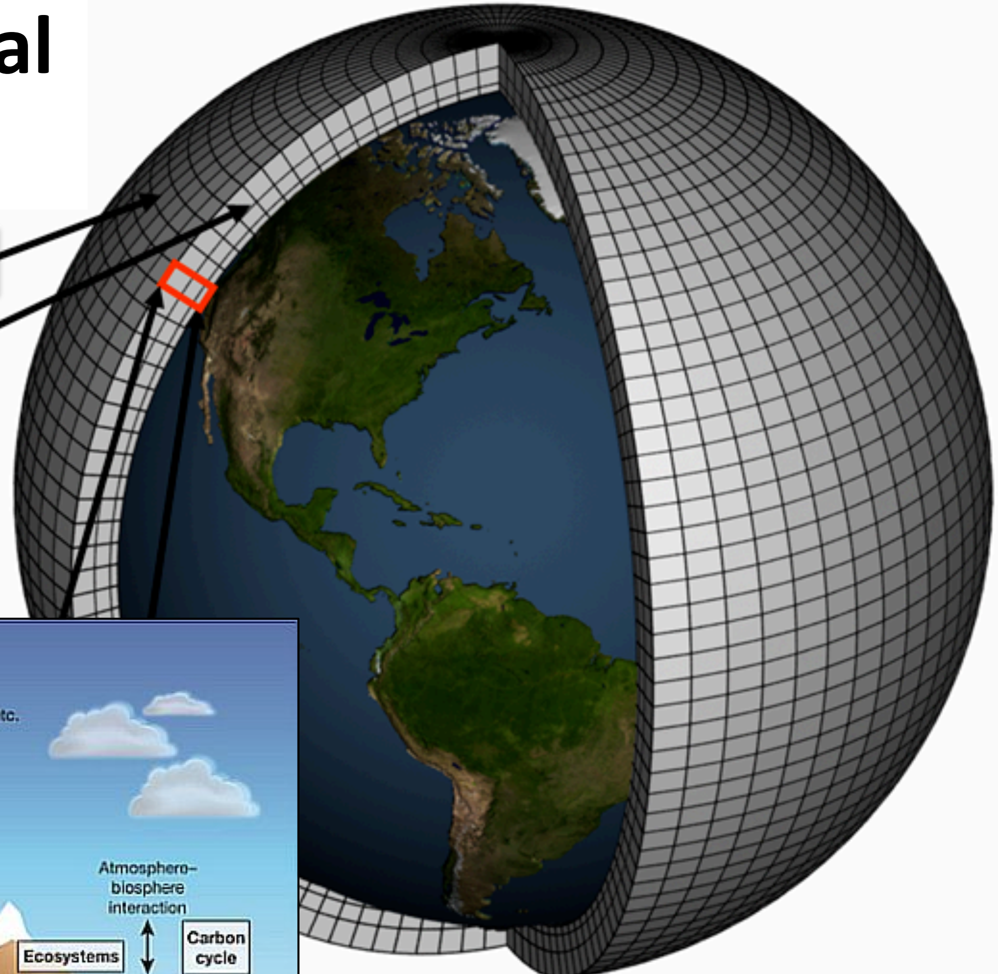
- Atmospheric models are also a tool which allow for experiments to be performed on the Earth system.

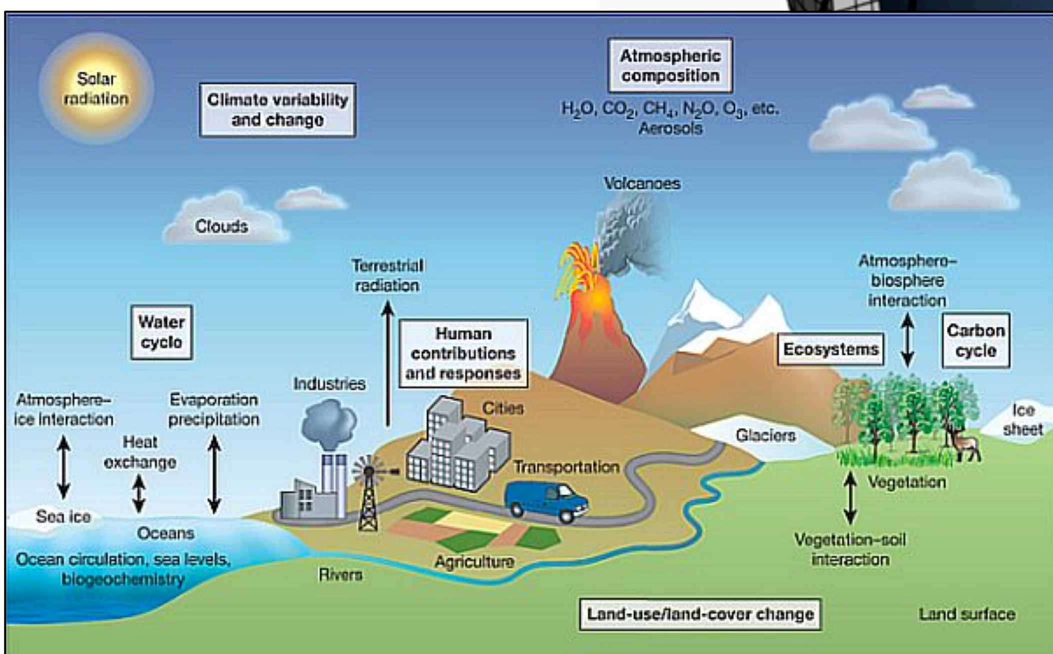
- They have been used as "laboratories" for studying paleoclimate, planetary atmospheres (Mars, Titan, Jupiter), and answering scientific questions regarding the drivers of weather and climate.

Schematic of a Global Climate Model

Horizontal Grid

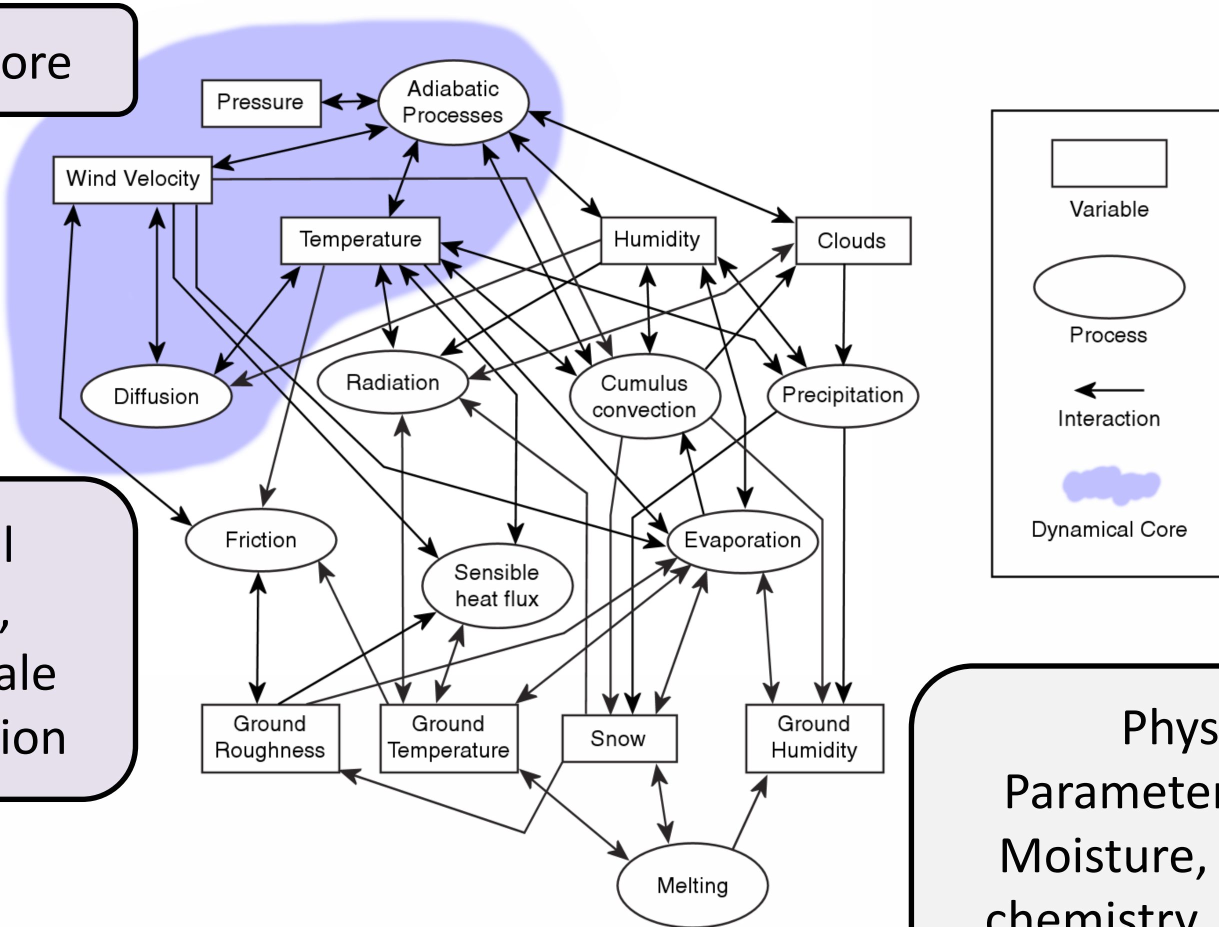
Vertical Grid





Anatomy of an Atmospheric Model

Dynamical Core



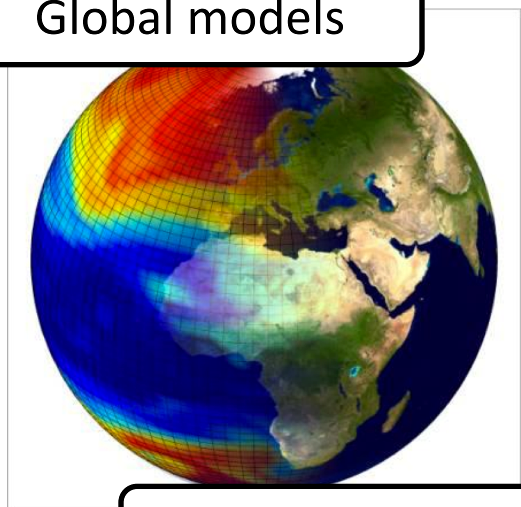
Horizontal transport, resolved-scale vertical motion

Physical Parameterizations: Moisture, ice, land, chemistry, radiation, etc.

Climate vs. NWP

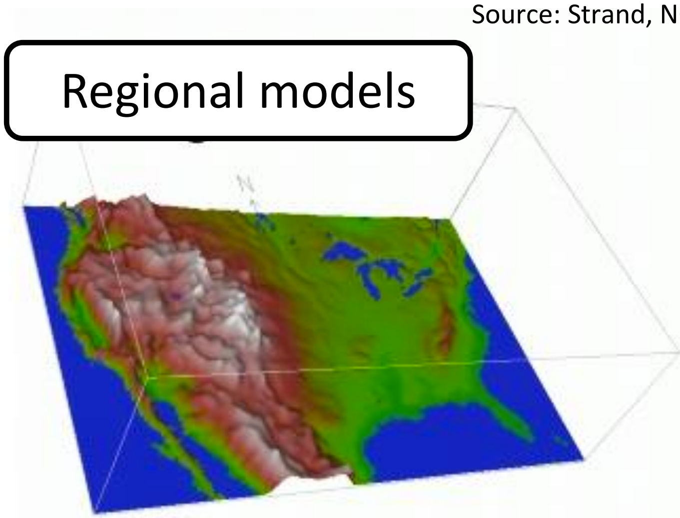
- Climate models and numerical weather prediction (NWP) models used to be very different.
- The former requires coarse global grid spacing (typically 100km) and a different set of physical parameterizations that were relevant on long time scales.
- The latter require maximal performance and high spatial resolution (10km plus), so that forecasts can be computed quickly and accurately. The physical parameterizations for NWP were generally minimal.
- In the past decade, the line between climate models and NWP models has been blurred, and now these models are often used interchangeably.

Global vs. Regional Modeling



No explicitly driven boundary conditions except at the surface and the top-of-the-atmosphere.

Source: Strand, NCAR



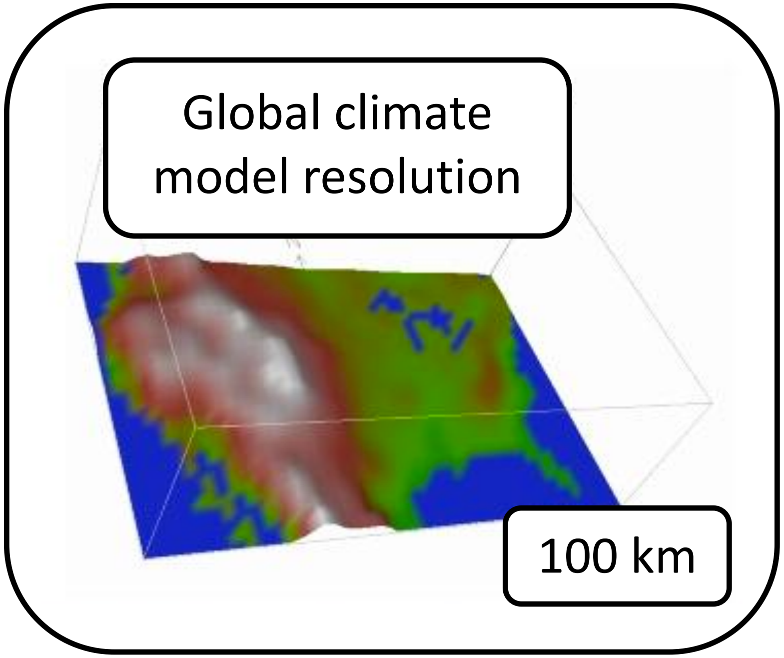
Lateral boundary conditions must be specified by a global model or reanalysis data.

Time Scales vs. Spatial Resolution

- Global climate models (multi-decadal simulations) are typically run at coarse resolutions (i.e., around 100 km) since

  (1) computational resources are not available / too expensive

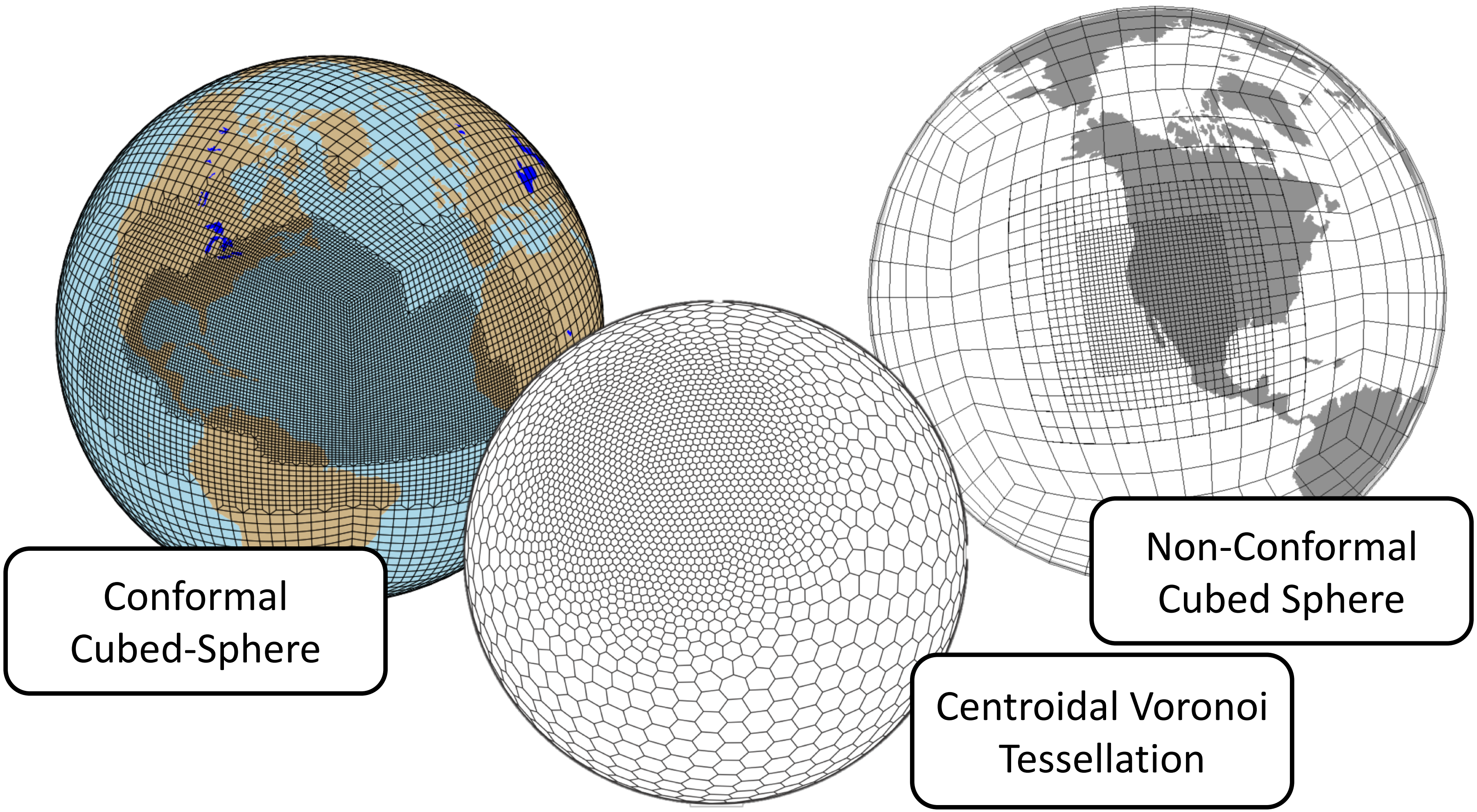
  (2) current modeling systems are not well designed to operate at finer scales (i.e., there's little to gain by running at high resolution except the glory).



- For the purposes of numerical weather prediction (multi-day simulations), high-resolution global atmospheric models (10km resolution and finer) can be used.
- For the purposes of practical regional planning, global climate models are too coarse. Dynamical or statistical downscaling techniques can be applied in this context to extract higher resolution information.

Variable Resolution Models

However, global atmospheric models with enhanced resolution where needed are growing increasingly popular.



A History of Atmospheric Modeling

Ancient Times

Before the invention of modern meteorological devices, weather prediction techniques were limited to sky observations.

> “When evening comes, you say,
> 'It will be fair weather: for the sky is red.'
> And in the morning,
> 'Today it will be stormy, for the sky is red and overcast.’ ”
>
> *Matthew 16:2-3*

Other weather “lore” was discovered, of course.

> *Seagull, seagull sit on the sand.*
> *It's never good weather when you're on the land.*

The 1600s

1643 Evangelista Torricelli invents the barometer, able to measure the pressure of the air.

He observed that the pressure of the air is highly correlated with the weather.

For example, he observed that a drop in air pressure often signalled a coming storm.

Evangelista Torricelli

1664 Francesco Folli invents the first "practical" hygrometer, capable of determining the humidity of the air.

The 1700s

1709 German physicist and engineer Daniel Gabriel Fahrenheit develops the alcohol thermometer, and later the mercury thermometer.

(Surprise!) He's also responsible for the Farenheit scale, which he proposed in 1724.

Daniel Gabriel Farenheit

1765 French chemist Antoine-Laurent de Lavoisier begins making daily measurements of air pressure, moisture content, wind speed and direction.

> "It is almost possible to predict one or two days in advance, within a rather broad range of probability, what the weather is going to be; it is even thought that it will not be impossible to publish daily forecasts, which would be very useful to society."
>
> *- Antoine-Laurent de Lavoisier*

The 1700s

Antoine-Laurent de Lavoisier was also responsible for several other notable discoveries:

- He stated the first version of the law of conservation of mass.
- He was involved with the invention of the metric system.
- He wrote the first exhaustive list of chemical elements and was involved heavily in discoveries that led to the development of modern chemistry.

Antoine-Laurent de Lavoisier: "The father of modern chemistry."

The 1800s

1837

With the invention of the electric telegraph at last there was a mechanism for communicating weather conditions over a vast geographical area.

1849

Under the leadership of Joseph Henry, the Smithsonian began to establish an observation network across the US.

However, the idea of a national system for predicting the weather was slow to take off in both Europe and America

Joseph Henry

The 1800s

1854

The advent of modern meteorology started with a disaster…

In 1854, a French warship and 38 merchant vessels sank in a violent storm in the northwest of the Black Sea.

The director of the Paris Observatory, Urbain Le Verrier, was directed to investigate…

He discovered that the storm had formed two days earlier in the southeast. If a tracking system had been in place, it could have given prior warning to the ships.

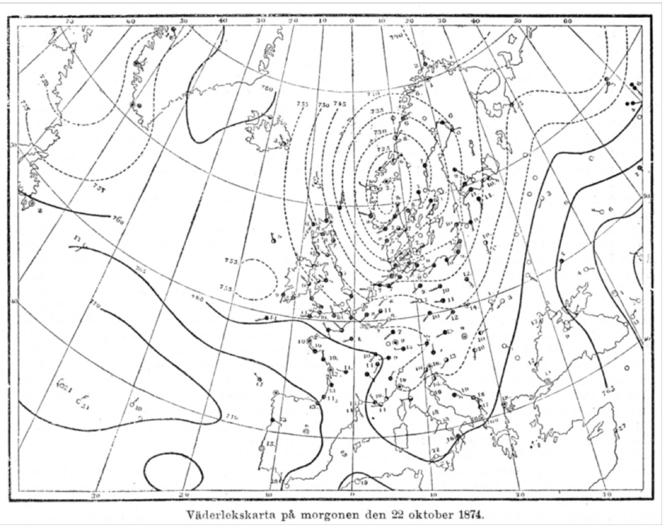
Urbain Le Verrier

The 1800s

1855 A year later, a national storm warning service was established in France.

1860 Robert FitzRoy uses the new telegraph system to produce the first synoptic charts in England. He coins the term "weather forecast" and publishes the first ever forecasts of this type.

1873 The International Meteorological Organization is formed in Vienna.



Early synoptic chart.

The US Army Signal Corp, forerunner to the National Weather Service, issues its first hurrican warning.

Early 1900s

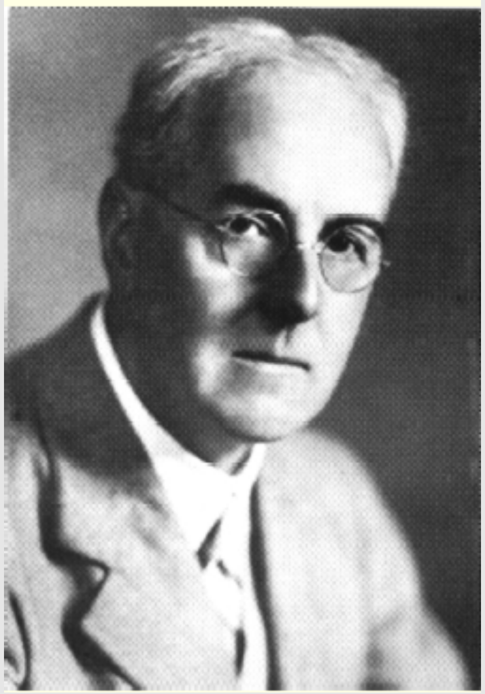
Well into the 1900s meteorologists constructed their forecasts exclusively via historical weather patterns.

1916

Norwegian meteorologist Vilhelm Bjerknes introduces the first set of equations of motion for the atmosphere using the theory of fluids.

1922

Enter: British meteorologist Lewis Fry Richardson. His work *Weather Prediction by Numerical Process* was published in 1922, proposing a mathematical technique for systematic forecasting.

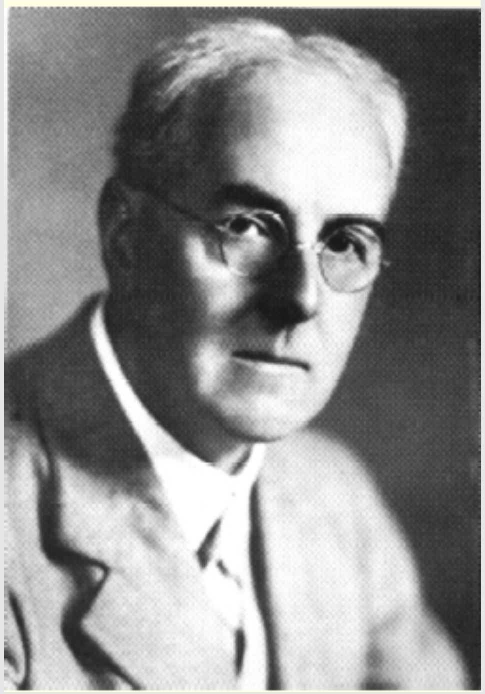


Lewis Fry Richardson

Early 1900s: Lewis Fry Richardson

Richardson made the first attempt at mathematically (using primitive numerical methods) to forecast the weather during a single day – 20 May 1910, using initial data at 7am to predict the next six hours.

This calculation took roughly 3 months to complete, and predicted a huge rise in pressure (145 mbars)…



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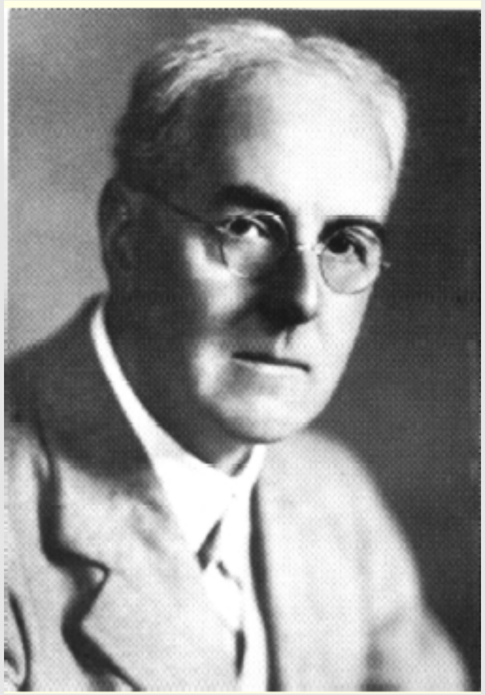
However, observations showed that pressure remained more or less static…



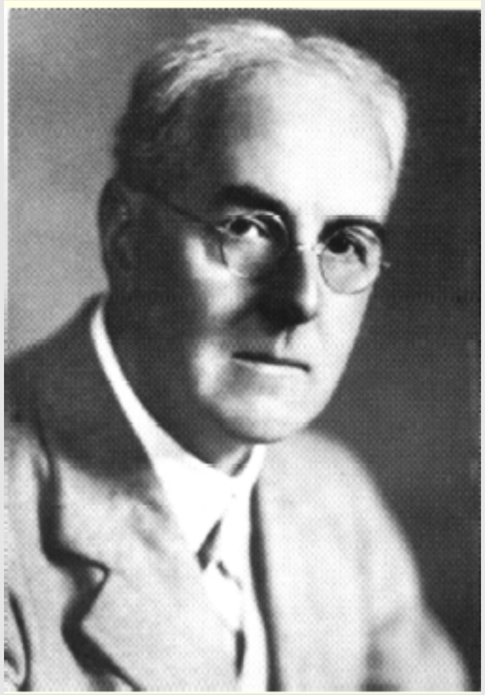
Lewis Fry Richardson

Early 1900s: Lewis Fry Richardson

Consequently, his calculation was considered a "dramatic failure."

A detailed analysis tracked the problem to a failure to use smoothing (essentially he was using an unstable numerical technique that seemed reasonable at the time).

…After making appropriate corrections, his forecast was essentially accurate!



Lewis Fry Richardson

Early 1900s: Lewis Fry Richardson

"After so much hard reasoning, may one play with a fantasy? Imagine a large hall like a theatre, except that the circles and galleries go right round through the space usually occupied by the stage. The walls of this chamber are painted to form a map of the globe. The ceiling represents the north polar regions, England is in the gallery, the tropics in the upper circle, Australia on the dress circle and the Antarctic in the pit.

A myriad computers are at work upon the weather of the part of the map where each sits, but each computer attends only to one equation or part of an equation."

Keep in mind that when Richardson described "computers" he referred to actual people performing computations by hand.

Mid 1900s: Advent of Computation

Richardson's formulas were so complicated that, on working them out by hand, nobody could predict the weather in time.

1940s

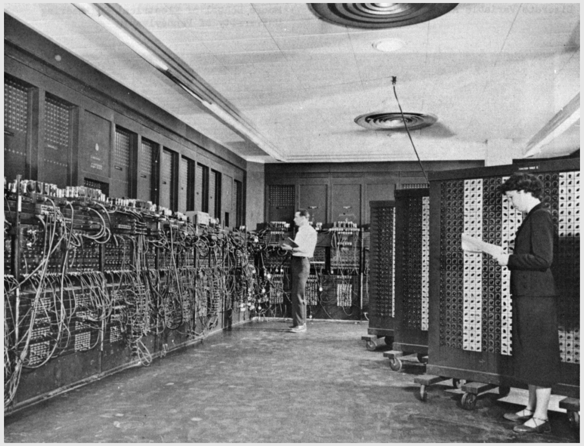
John von Neumann is successful in computing the behavior of explosions using numerical methods. Seeing the parallels with numerical weather prediction, he advocates for using computers to model the atmosphere.

John von Neumann

Mid 1900s: Advent of Computation

1950

Von Neumann recruits Jule Gregory Charney (from Carl-Gustaf Rossby's lab at the University of Chicago) to develop a numerical framework for weather prediction. The first successful experiment finally came about in 1950 (at Princeton, on the ENIAC computer).



ENIAC

1954

The first real-time numerical weather prediction experiments are performed by the Royal Swedish Air Force Weather Service.

Mid 1900s: The First Global Models

1955

The first atmospheric general circulation model (GCM) is developed by Norman Phillips, Princeton University. His computer held 5 kilobytes of memory plus 10 kilobytes of data storage, and successfully modeled a two-layer atmosphere on a cylinder 17 cells high and 16 cells in circumference.

1958 → 1965

Joseph Smagorinsky (US Weather Bureau) and Syukuro Manabe develop the first three-dimensional atmosphere model built from the primitive equations. This led to the Geophysical Fluid Dynamical Laboratory (GFDL, Princeton) family of GCMs.

1956 → 1964

Motivated by Phillips' paper, Yale Mintz recruited Akio Arakawa to develop a two-layer model with realistic topography. This led to the UCLA family of models, and this work was incorporated into later work by the European Center for Medium Range Weather Forecasting (ECMWF)

The 1900s

GFDL: Geophysical Fluid Dynamics Laboratory (Manabe)

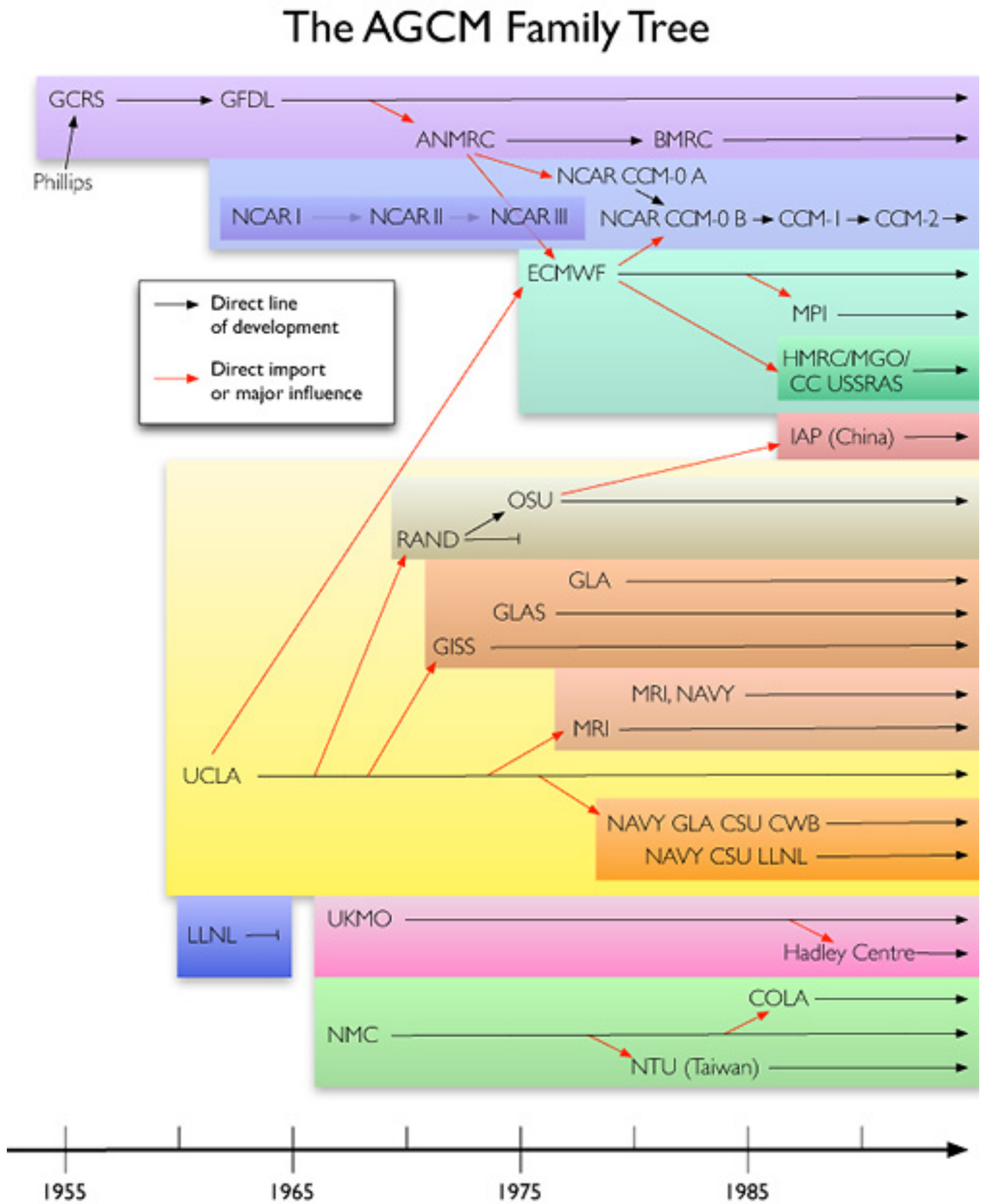
NCAR: National Center for Atmospheric Research

CCM: NCAR's Community Climate Model

ECMWF: European Centre for Medium-Range Weather Forecasts

GISS: Goddard Institute for Space Sciences (Hansen)

UCLA: University of California, Los Angeles (Mintz, Arakawa).



Late 1900s: Algorithmic Development

1965

A panel of the US National Academic of Sciences reported that: "Although global models were largely successful at reproducing gross features of the atmosphere, there were significant shortfalls in these models that could only be addressed by substantially increased computational power."

1970s → Today

Algorithmic developments from computational fluid dynamics (generally Aerospace) have led to dramatic advancements in the quality of GCMs.

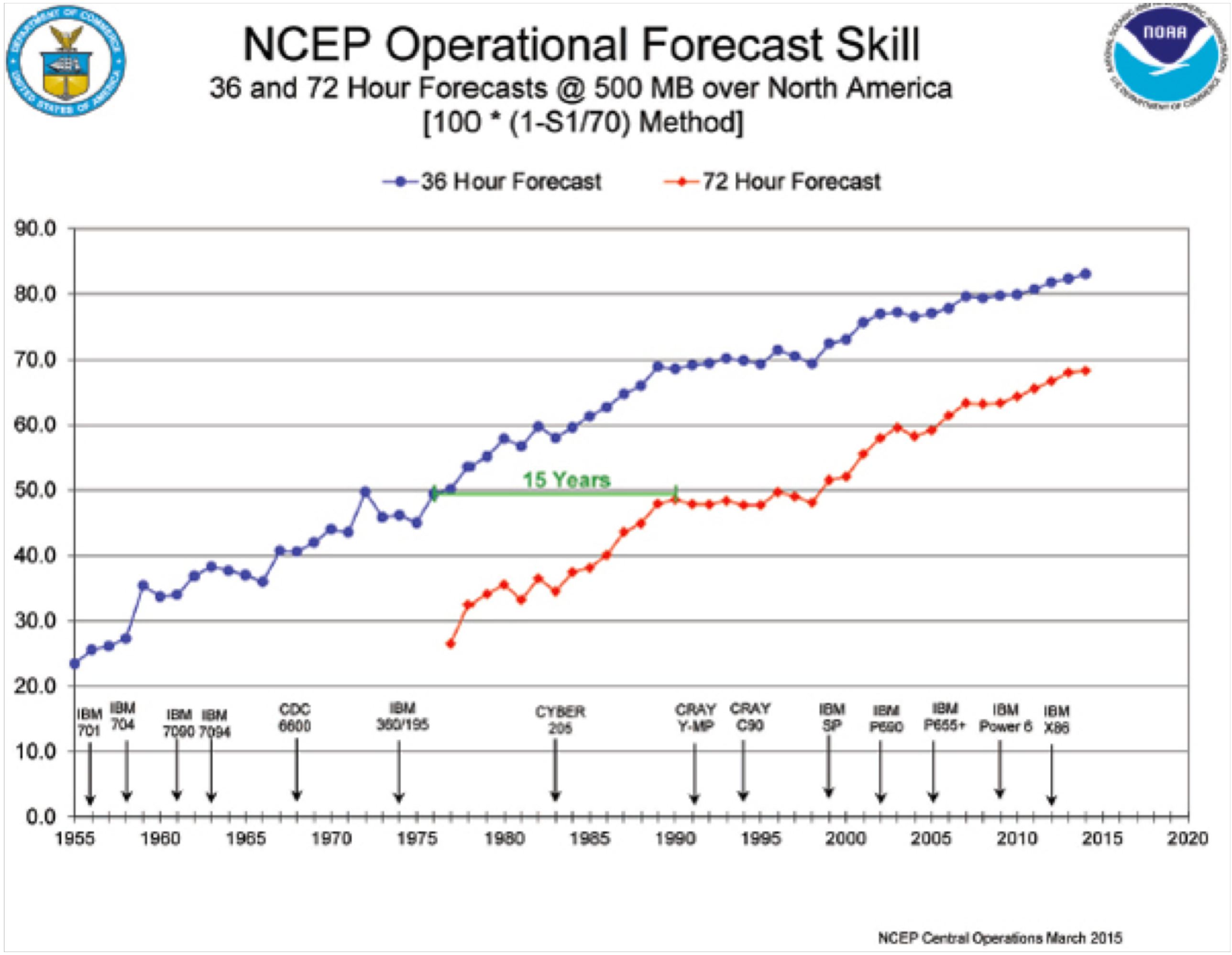
The number of general circulation models has exploded: There are 17 operational hydrostatic GCMs today being maintained by atmospheric modeling centers around the world.

Global model resolution has reached as low as 3km globally (NICAM model on the Earth Simulator, Japan)

Ongoing Algorithmic Development

Computer power and time versus model accuracy as defined by the S1 score (a measure of the skill of the forecast) of 36- and 72-hour NCEP 500-millibar forecasts.

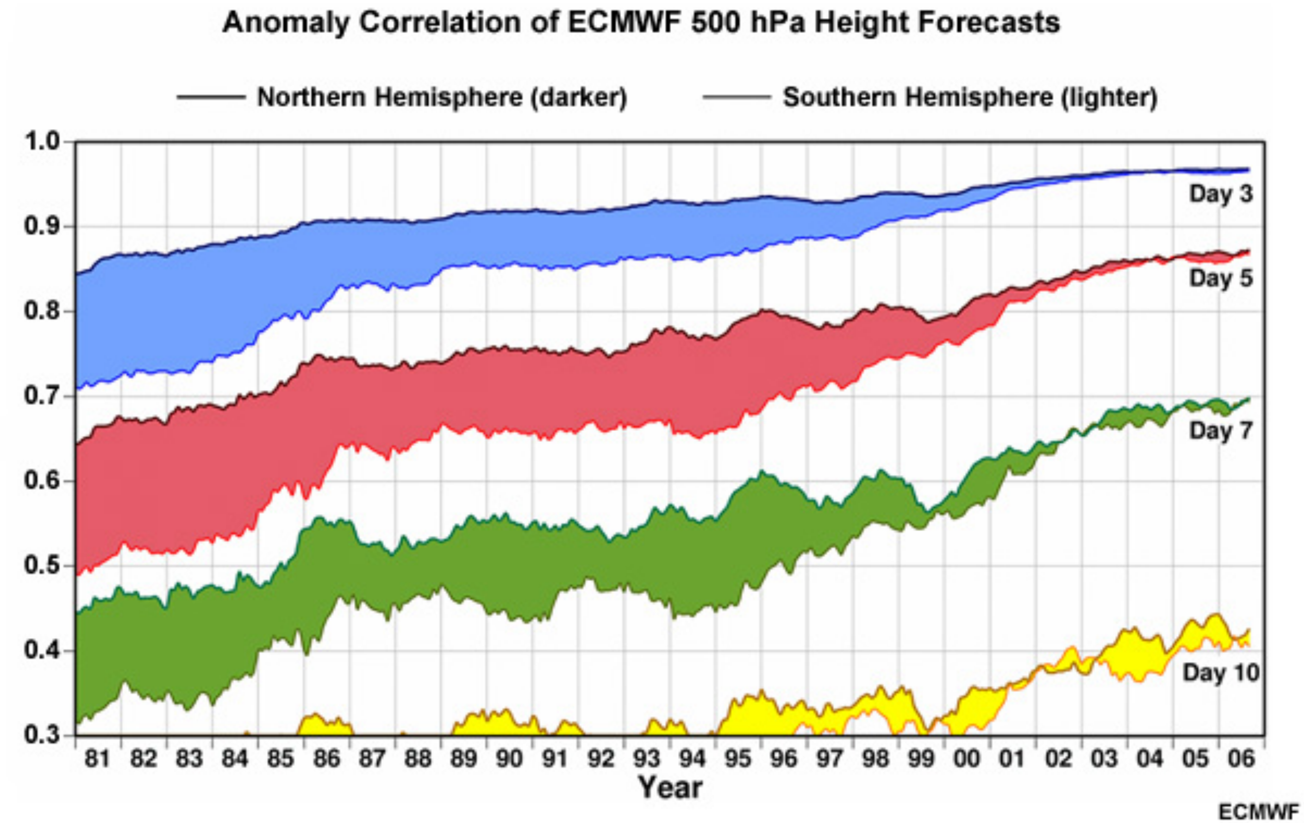
(Source: NOAA)



Ongoing Algorithmic Development

Forecast skill (measured by the anomaly correlation) for 500 hPa height forecasts using the ECMWF short-term forecasting model.

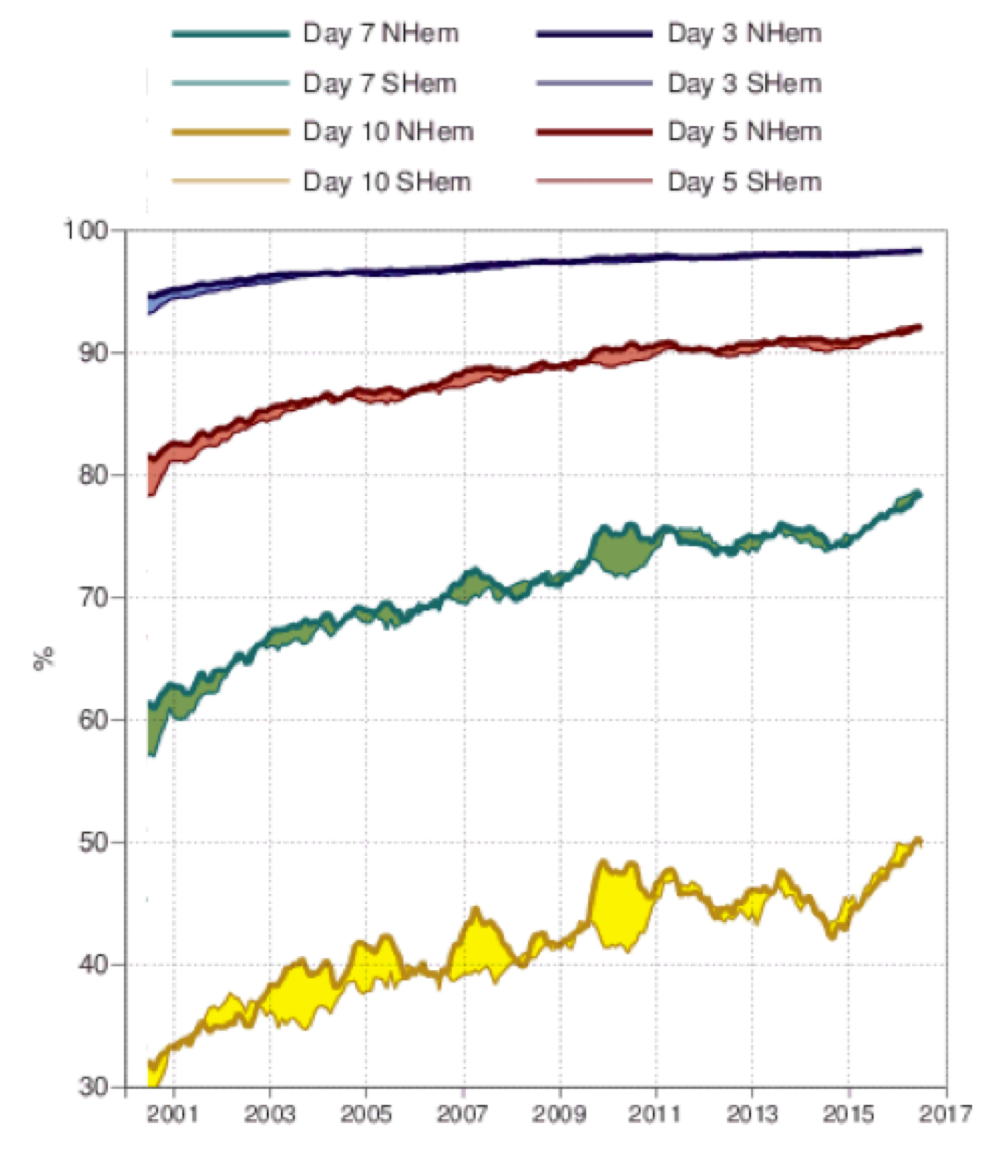
(Source: ECMWF)



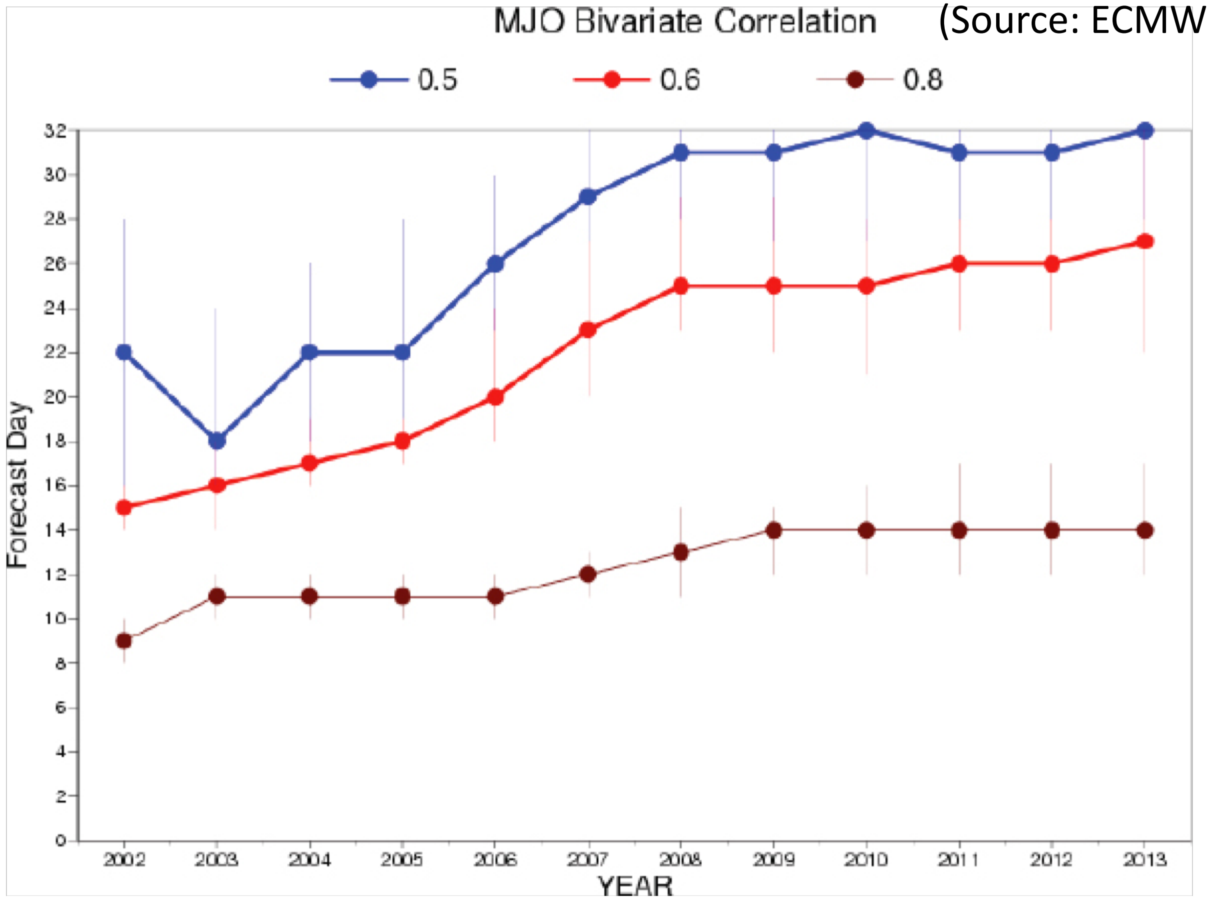
Ongoing Algorithmic Development

Forecast skill (measured by the anomaly correlation) for 500 hPa height forecasts using the ECMWF short-term forecasting model (2001 to 2017).

(Source: ECMWF)



Ongoing Algorithmic Development



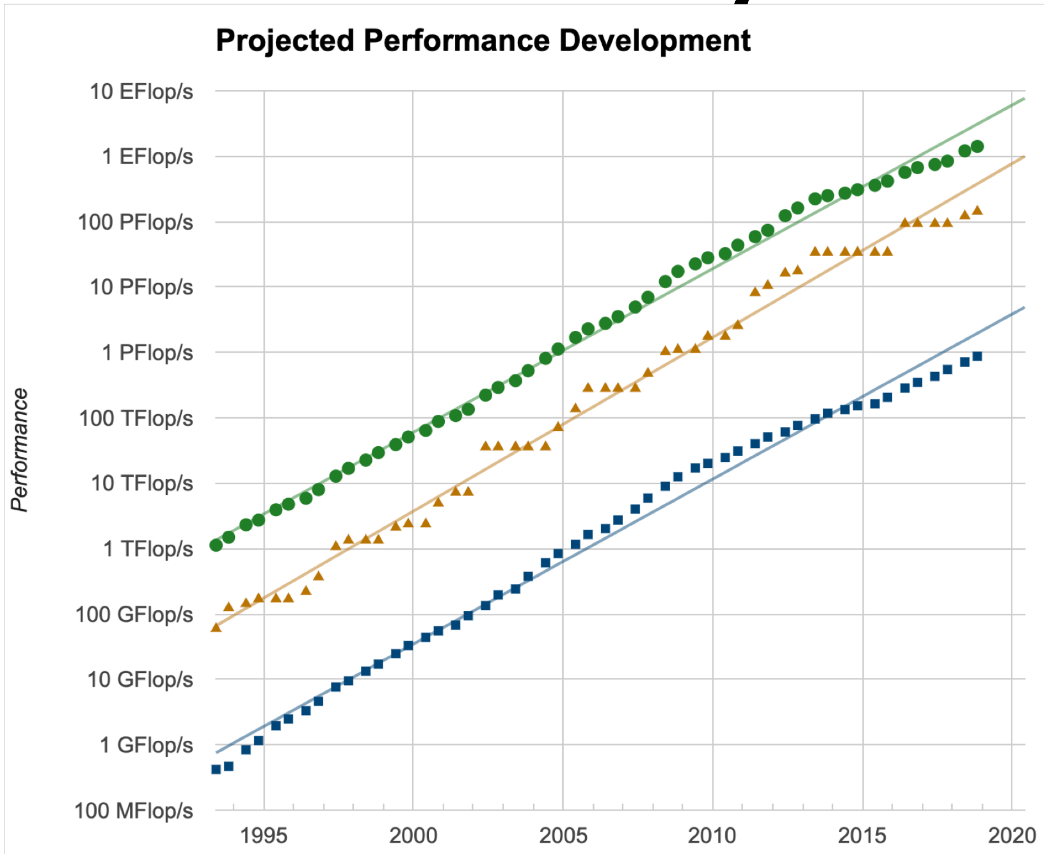
(Source: ECMWF)

Subseasonal to seasonal forecasting of key low-frequency atmospheric features (i.e. Madden Julian Oscillation) allows for longer time forecasting.

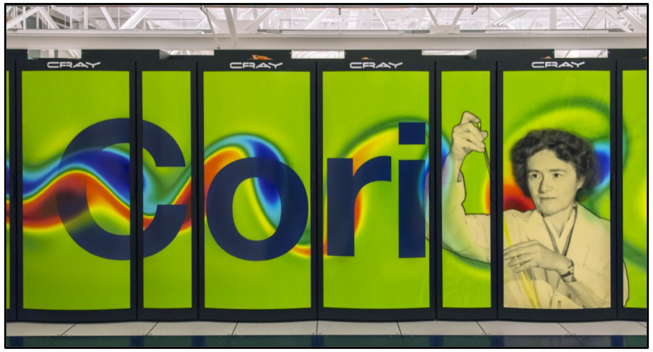
Ensemble modeling is now being used to produce probabilistic forecasts up to 12 months in advance, i.e. the North American Multi-Model Ensemble (NMME).

More information about NMME: https://www.ncdc.noaa.gov/data-access/model-data/model-datasets/north-american-multi-model-ensemble

The 21st Century: A New Era for GCMs



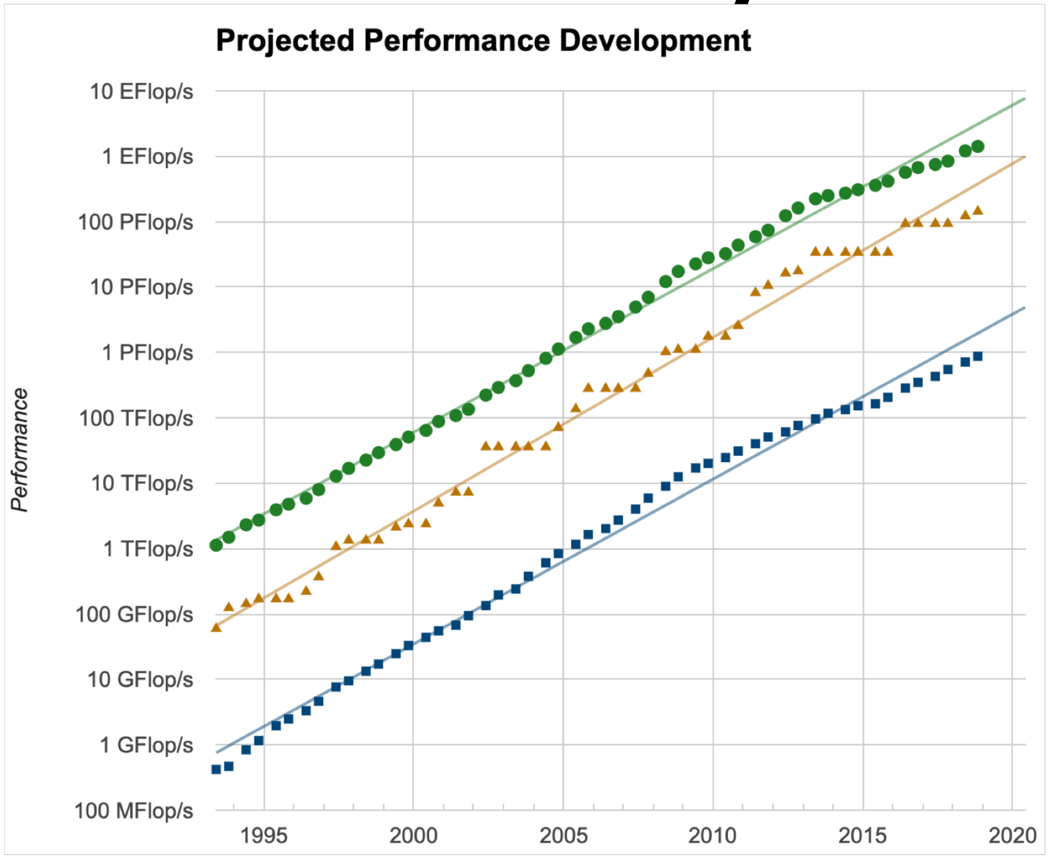
NCAR Cheyenne supercomputer
(5.34-petaflops in 145,152 cores)



NERSC (DOE) Cori Supercomputer
(14.01-petaflops in 622,336 cores)

The power of supercomputing systems continues to grow at an exponential pace.

The 21st Century: A New Era for GCMs



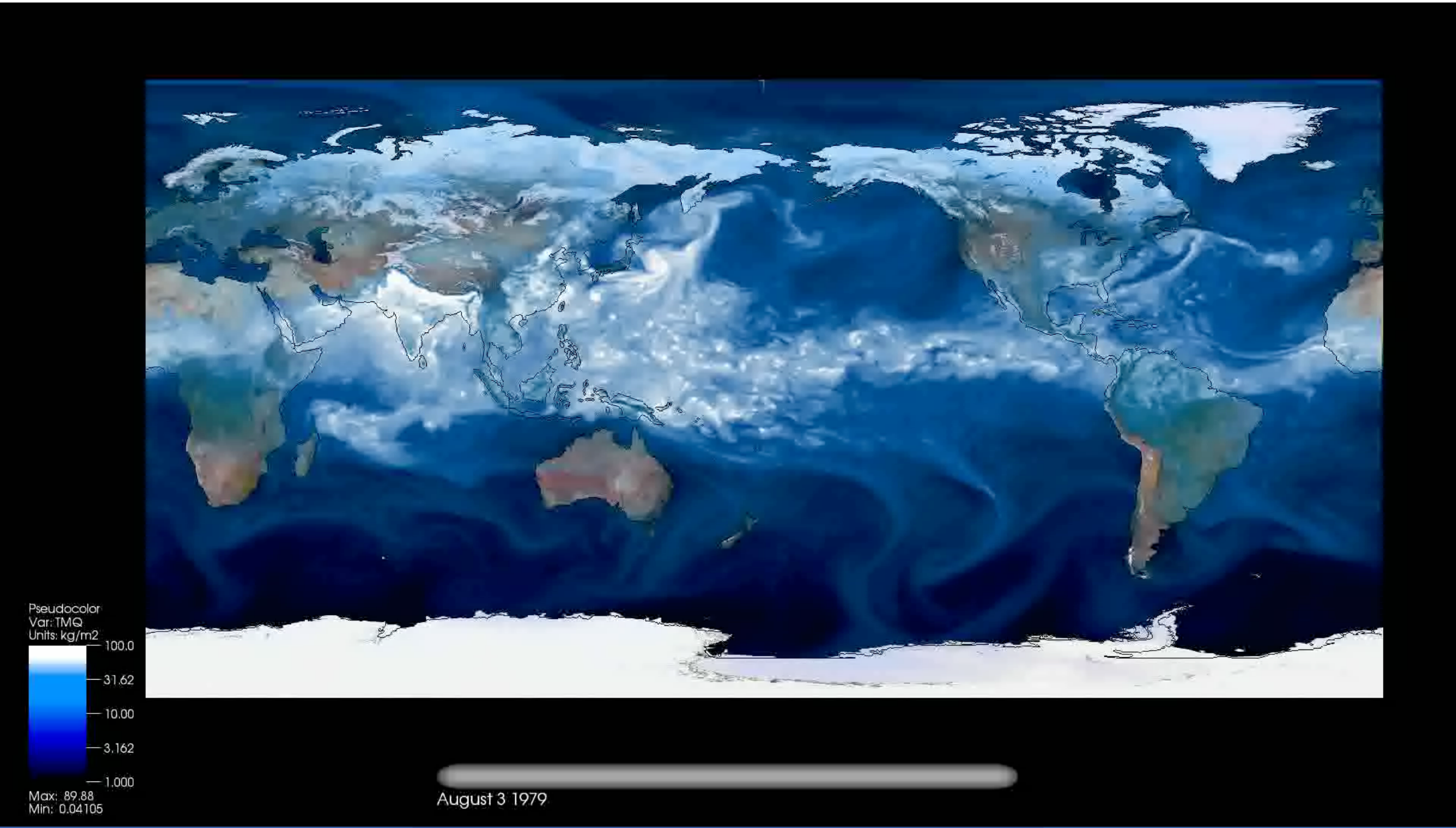
NERSC (DOE) Summit Supercomputer
143.5-petaflops in 2,397,824 cores

#1 Supercomputer on the top500 ranking for November 2018

(featuring a move to GPU architectures)

The power of supercomputing systems continues to grow at an exponential pace.

The 21st Century: A New Era for GCMs



The 21st Century: A New Era for GCMs

Forecast of Hurricane Sandy, initialized on Oct 25, 2012. Sandy made landfall in the continental US on Oct 29, 2012. The uncharacteristic westward recurving is captured nicely in this simulation (even though the model is not really a NWP model).

(Source: Colin Zarzycki, University of Michigan)