The Emergence of NWP

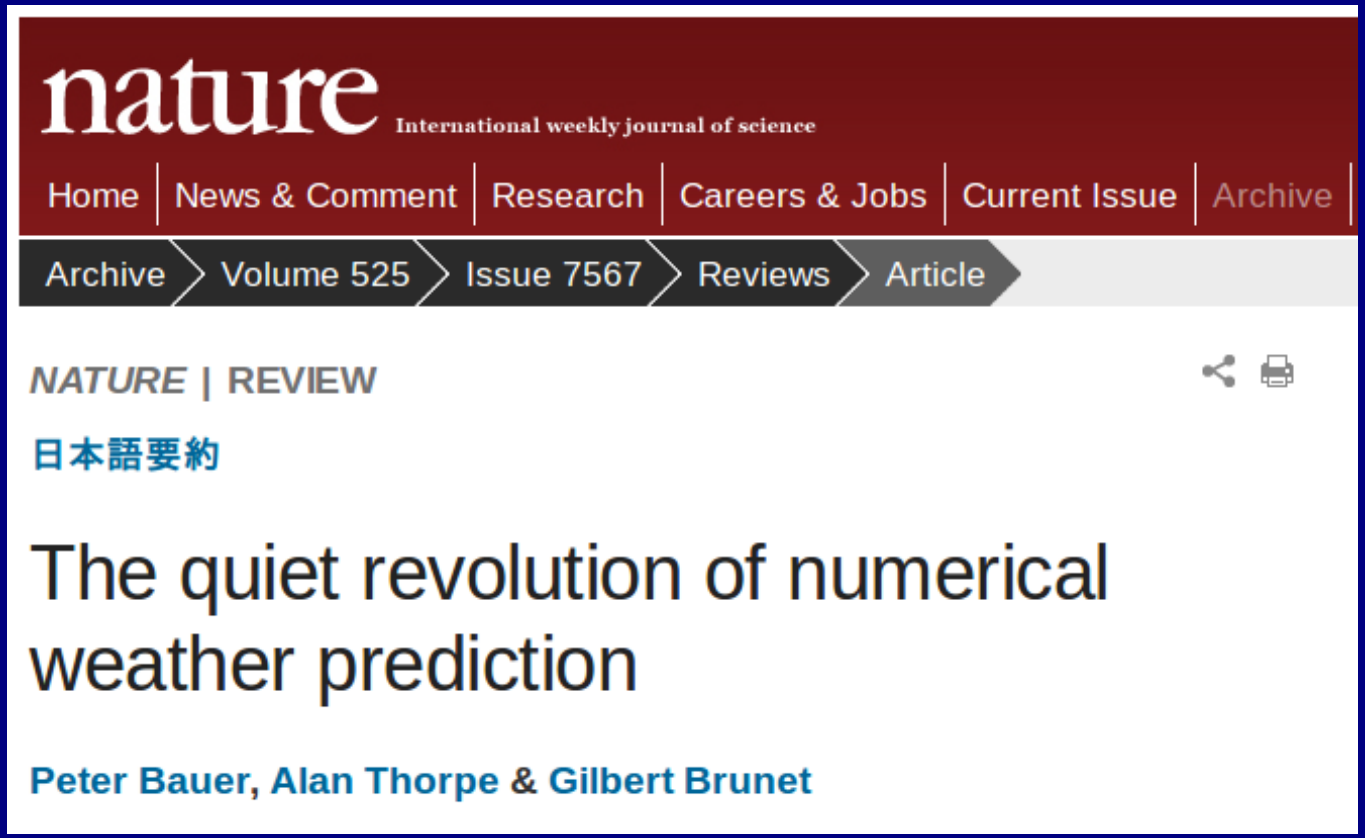
Fulfilment of a Dream
&
Realization of a Fantasy

Peter Lynch
School of Mathematics & Statistics
University College Dublin

IoP, London, 23 January 2020

Outline

A Recent Paper in Nature



The Origins of Numerical Weather Prediction

Nature, 3 September 2015 Vol 525 pg. 47

The Quiet Revolution of NWP [Abstract]

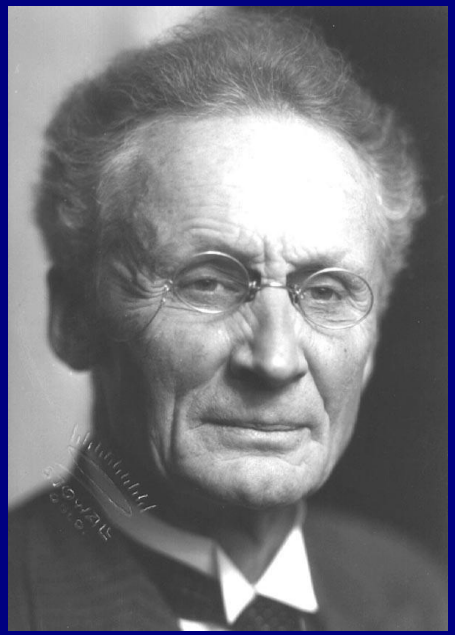
- Advances in NWP represent a quiet revolution.
- Steady accumulation of technological advances.
- Among the greatest impacts of physical science.
- NWP is a computational problem comparable to:
  - Modelling the behaviour of the human brain.
  - Simulating the evolution of the early universe.

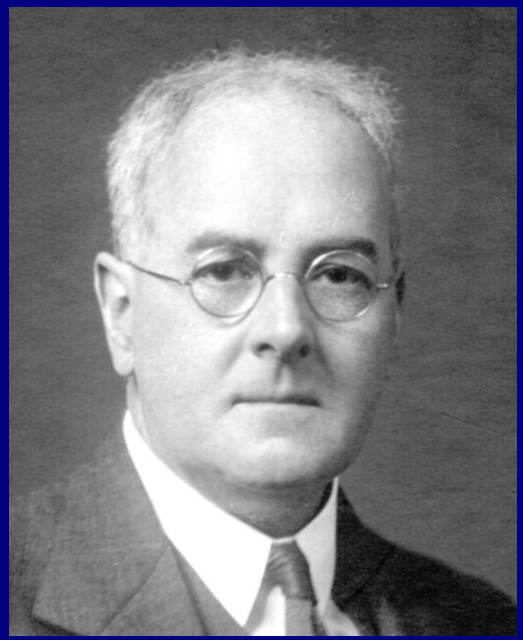
The Quiet Revolution of NWP [Abstract]

- Advances in NWP represent a quiet revolution.
- Steady accumulation of technological advances.
- Among the greatest impacts of physical science.
- NWP is a computational problem comparable to:
  - Modelling the behaviour of the human brain.
  - Simulating the evolution of the early universe.
- Performed daily at operational weather centres.

Outline

Pioneers of Scientific Forecasting





Abbe **Bjerknes** **Richardson**

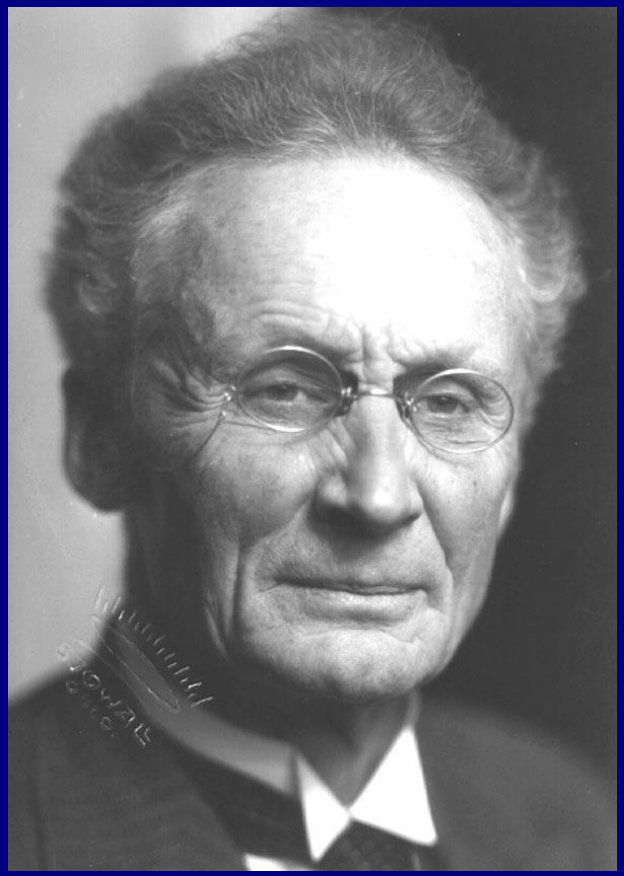
Cleveland Abbe

By 1890, the American meteorologist Cleveland Abbe had recognized that:

Meteorology is essentially the application of hydrodynamics and thermodynamics to the atmosphere.

Abbe proposed a mathematical approach to forecasting.

Vilhelm Bjerknes

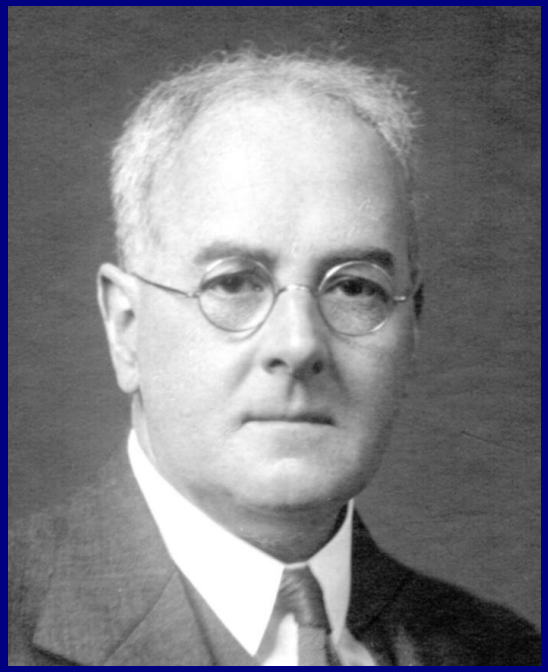


A more explicit analysis of weather prediction was undertaken by the Norwegian scientist Vilhelm Bjerknes

He identified the two crucial components of a scientific forecasting system:

- Analysis
- Integration

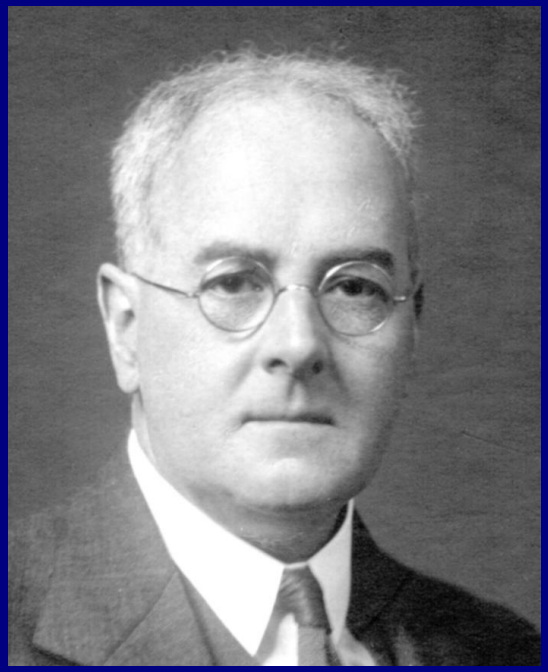
Lewis Fry Richardson



The English Quaker scientist Lewis Fry Richardson attempted a direct solution of the equations of motion.

He dreamed that numerical forecasting would become a reality 'one day in the distant future'.

Lewis Fry Richardson

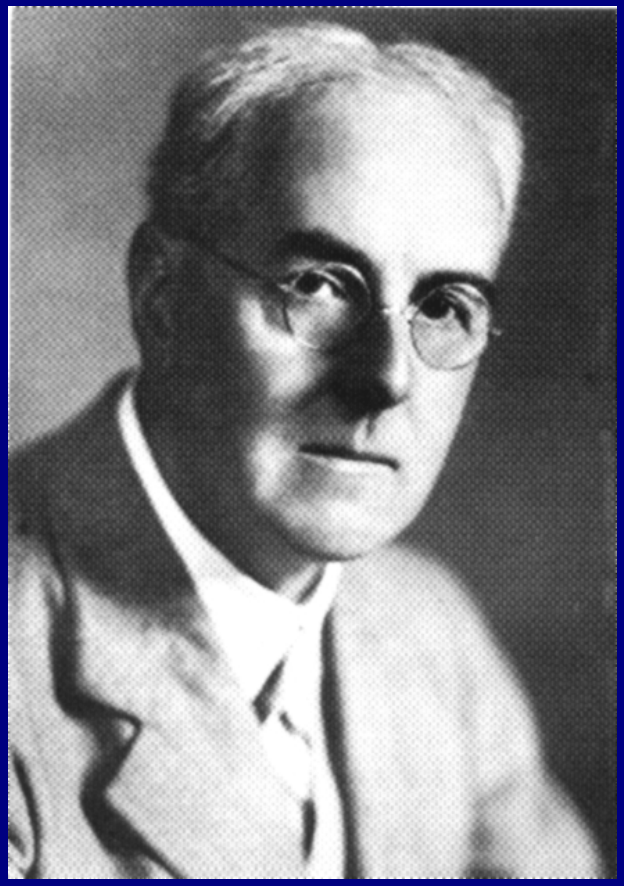


The English Quaker scientist Lewis Fry Richardson attempted a direct solution of the equations of motion.

He dreamed that numerical forecasting would become a reality 'one day in the distant future'.

Today, forecasts are prepared routinely using his method . . . his dream has indeed come true.

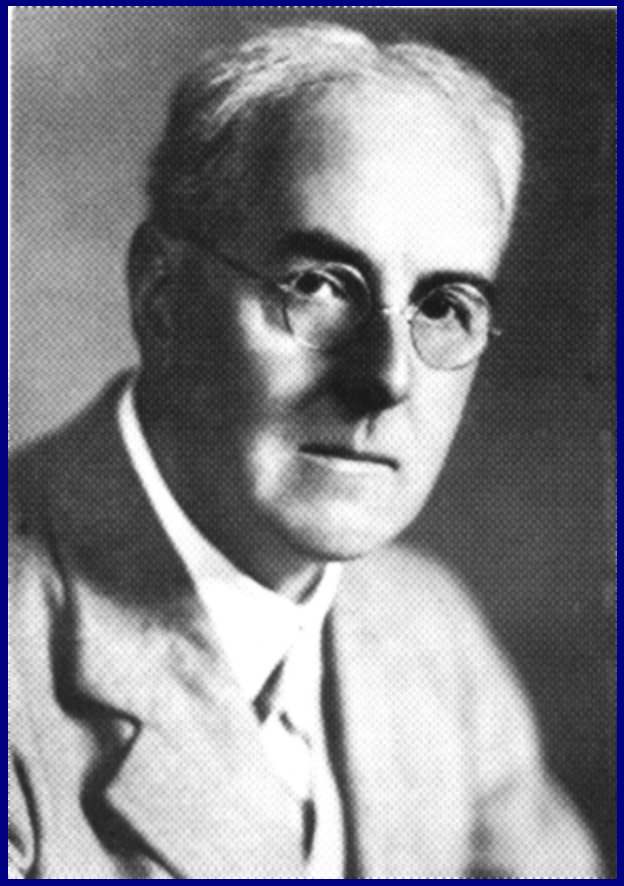
Lewis Fry Richardson, 1881–1953.



During WW I, Richardson computed by hand the pressure change at a single point.

It took him two years !

Lewis Fry Richardson, 1881–1953.



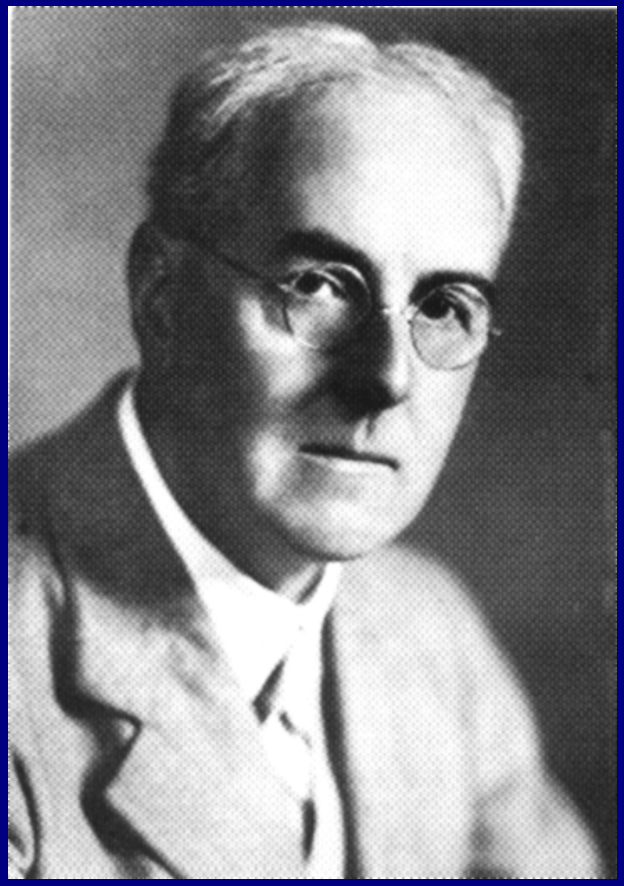
During WW I, Richardson computed by hand the pressure change at a single point.

It took him two years !

His 'forecast' was a catastrophic failure:

$\Delta p =$ 145 hPa in 6 hrs

Lewis Fry Richardson, 1881–1953.



During WW I, Richardson computed by hand the pressure change at a single point.

It took him two years !

His 'forecast' was a catastrophic failure:

$\Delta p =$ 145 hPa in 6 hrs

Yet, Richardson's method was scientifically sound.

Initialization of Richardson's Forecast

Richardson's Forecast has been re-run on a computer.

The atmospheric observations for 20 May 1910 *were recovered from original sources.*

- **ORIGINAL:** $\frac{\partial p_s}{\partial t} = +\mathbf{145}\,\mathrm{hPa}/6\,\mathrm{h}$

Initialization of Richardson's Forecast

Richardson's Forecast has been re-run on a computer.

The atmospheric observations for 20 May 1910 *were recovered from original sources.*

- **ORIGINAL:** $\frac{\partial p_s}{\partial t} = +\mathbf{145}\,\mathrm{hPa}/6\,\mathrm{h}$
- **INITIALIZED:** $\frac{\partial p_s}{\partial t} = -\mathbf{0.9}\,\mathrm{hPa}/6\,\mathrm{h}$

Observations: The barometer was steady!

Outline

Weather and Climate Models

Computer models for simulating weather and climate are known as **Earth System Models.**

They are of great complexity.

At the heart of every model is a **Dynamical Core.**

At the kernel of the core lie the **Navier-Stokes Equations.**

George Gabriel Stokes

G. G. Stokes was born in Skreen, Co. Sligo, just 200 years ago.

His equations for fluid flow underlie all atmospheric and ocean models.

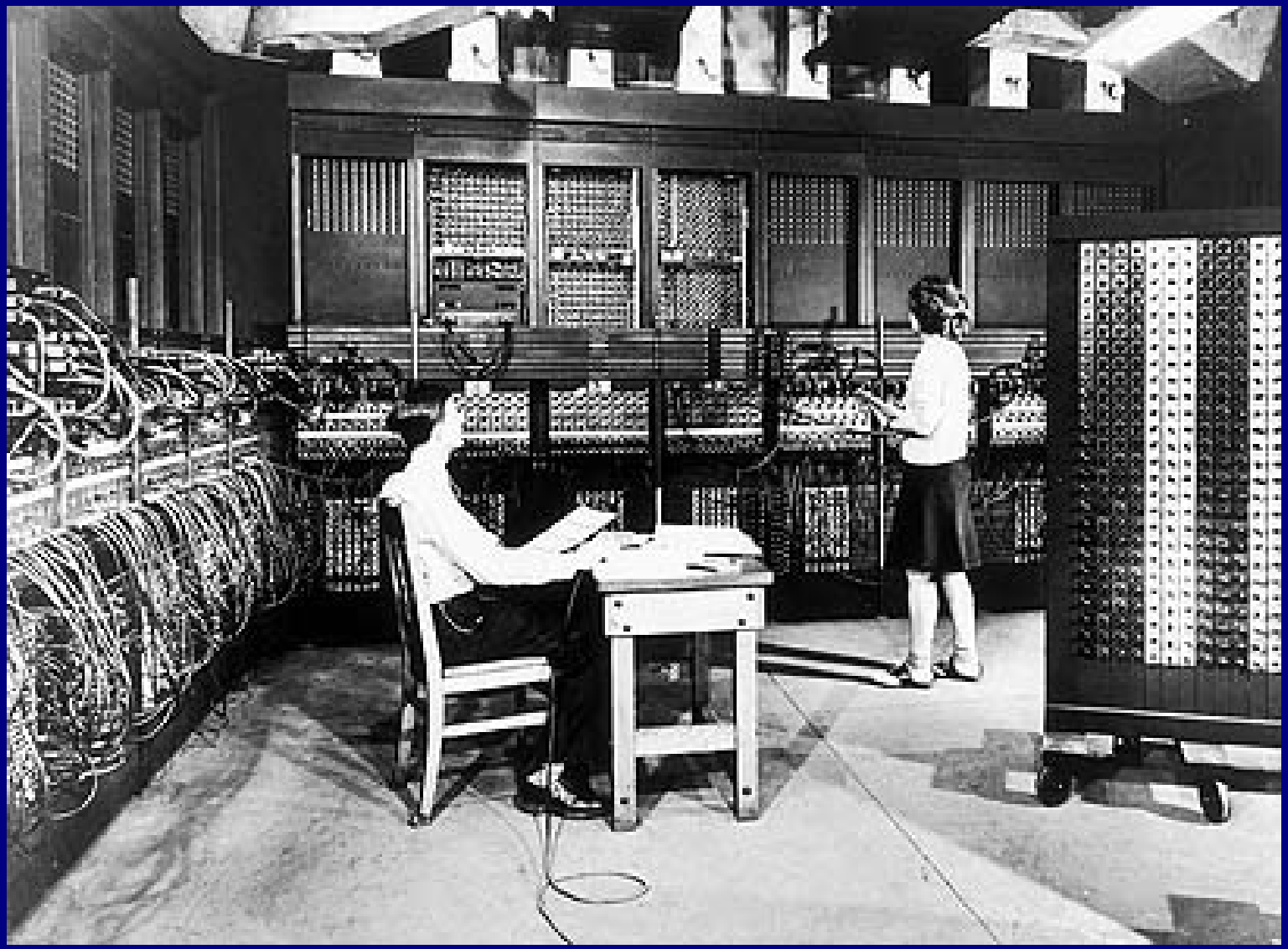
$$\frac{\partial \boldsymbol{V}}{\partial t} + \boldsymbol{V} \cdot \nabla \boldsymbol{V} = -\frac{1}{\rho} \nabla p + \nu \nabla^2 \boldsymbol{V} - \boldsymbol{g}$$

Outline

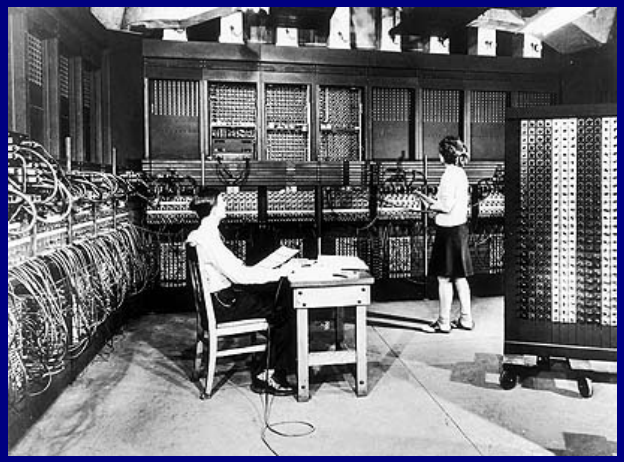
Crucial Advances, 1920–1950

- **Dynamic Meteorology**
  - Quasi-geostrophic Theory
- **Numerical Analysis**
  - CFL Criterion
- **Atmopsheric Observations**
  - Radiosondes
- **Electronic Computing**
  - ENIAC

The ENIAC



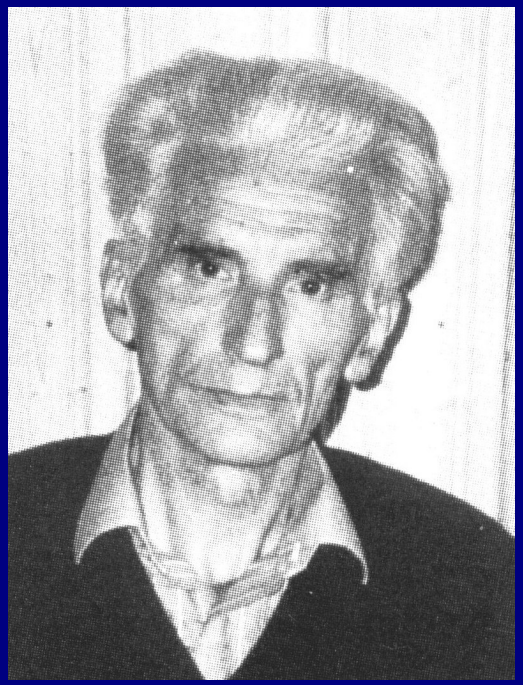
The ENIAC



The **ENIAC** was the first multi-purpose programmable electronic digital computer:

- 18,000 vacuum tubes
- 70,000 resistors
- 10,000 capacitors
- 6,000 switches
- Power: 140 kWatts

Charney Fjørtoft von Neumann

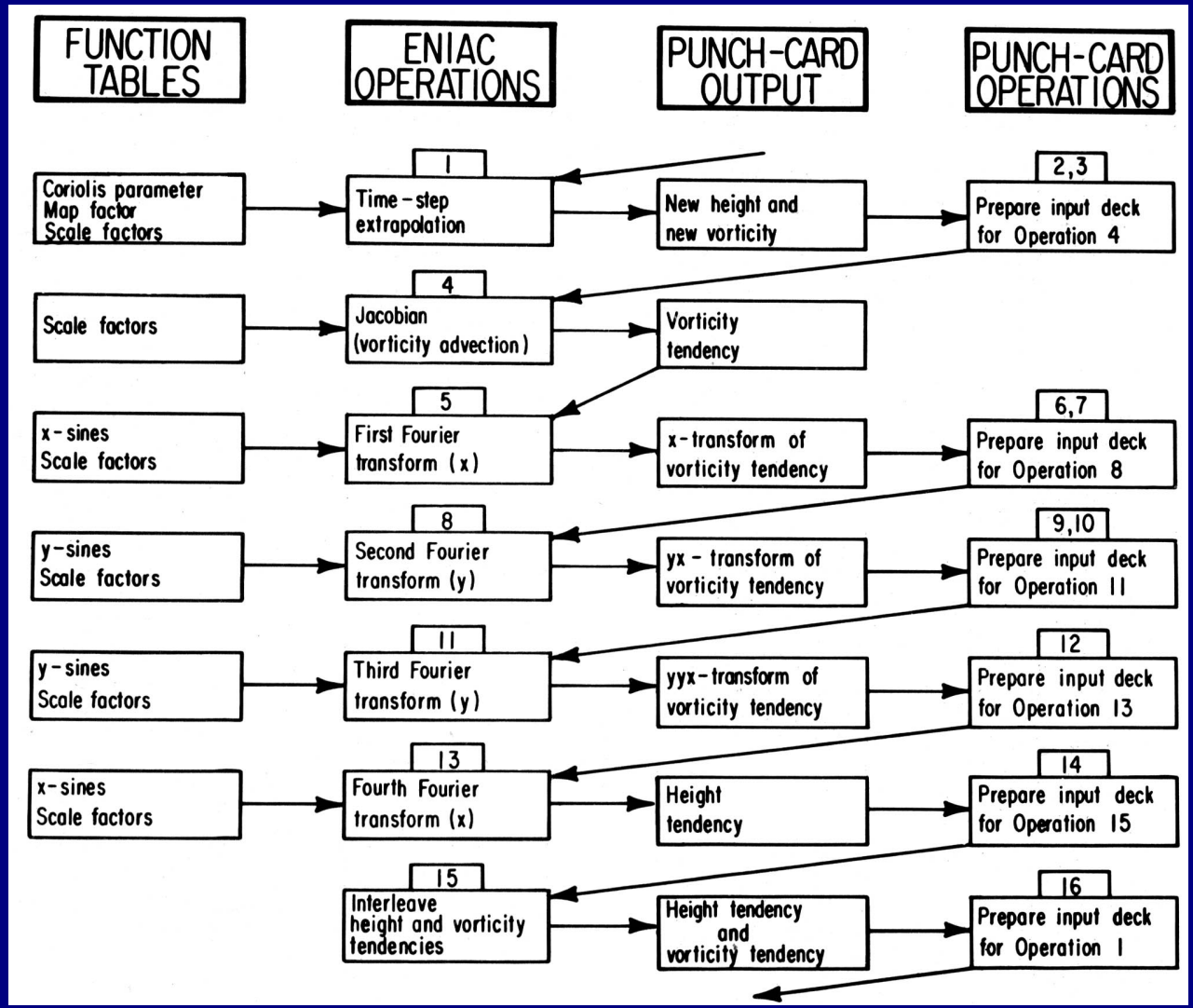

Numerical integration of the barotropic vorticity equation
***Tellus*, 2, 237–254 (1950).**

Charney, et al., *Tellus*, 1950.

- The atmosphere is treated as a single layer.
- The flow is assumed to be nondivergent.
- Absolute vorticity $\zeta + f$ is conserved.

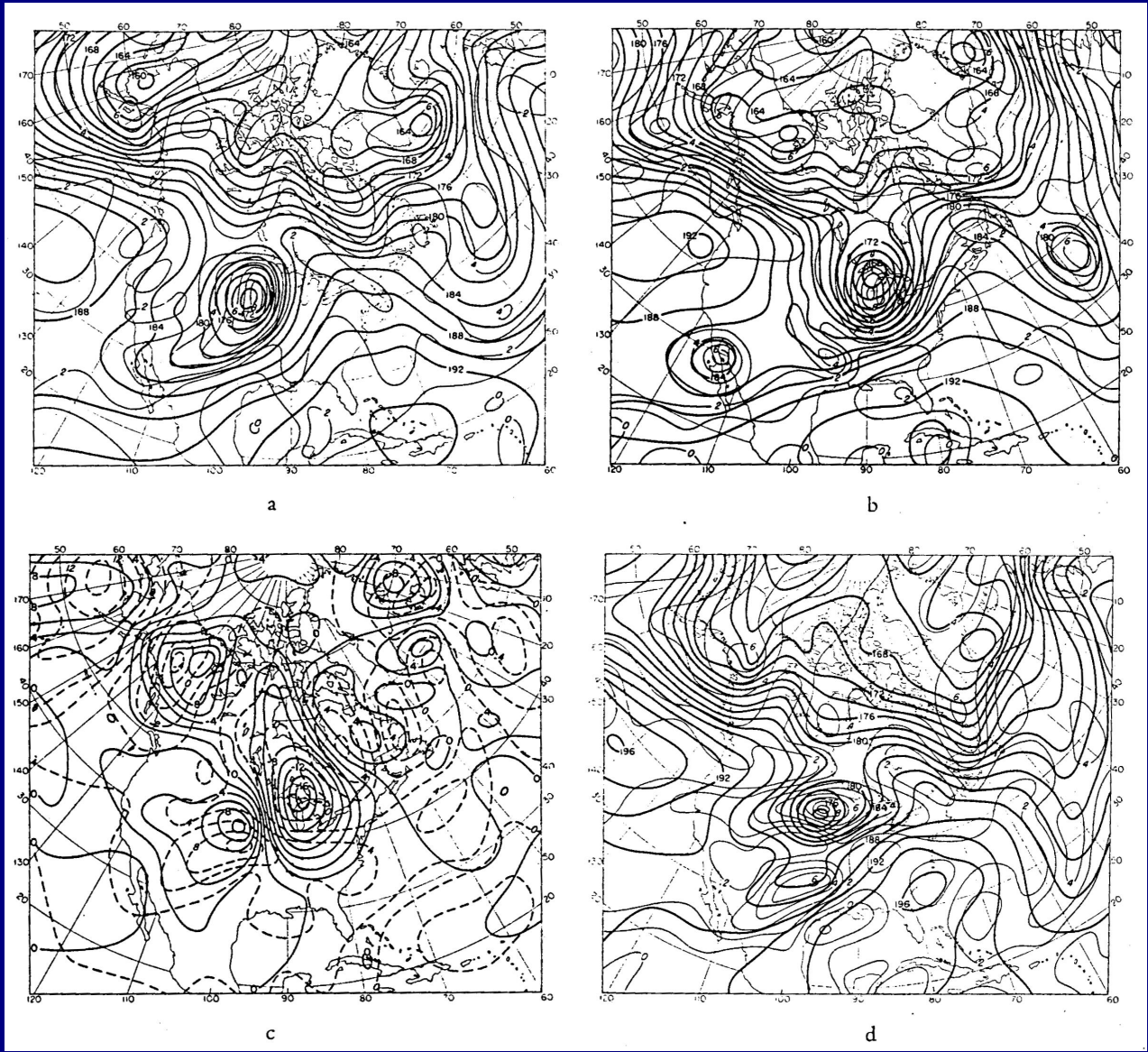
$$\frac{d(\zeta + f)}{dt} = 0.$$

The ENIAC Algorithm: Flow-chart



G. W. Platzman: The ENIAC Computations of 1950 — Gateway to Numerical Weather Prediction (BAMS, April, 1979).

ENIAC Forecast for Jan 5, 1949



NWP Operations

The Joint Numerical Weather Prediction Unit was established on July 1, 1954:

- **Air Weather Service of US Air Force**
- **The US Weather Bureau**
- **The Naval Weather Service.**

$\star$ $\star$ $\star$

May 1955:

Operational numerical weather forecasting using a 3-level quasi-geostrophic model.

Outline

European Centre for Medium-Range Weather Forecasts (ECMWF, Reading, UK)

Forecast of Hurricane Sandy

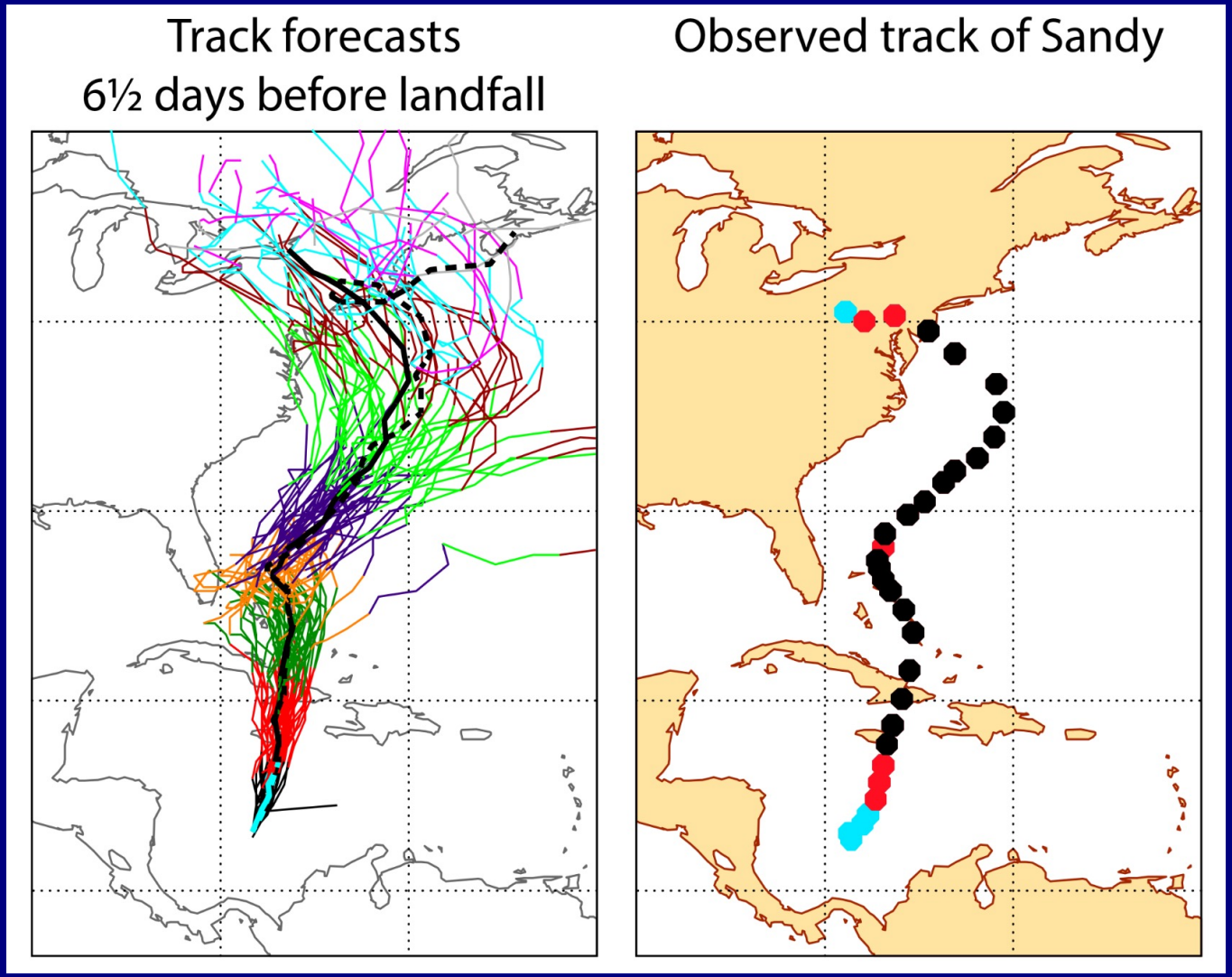
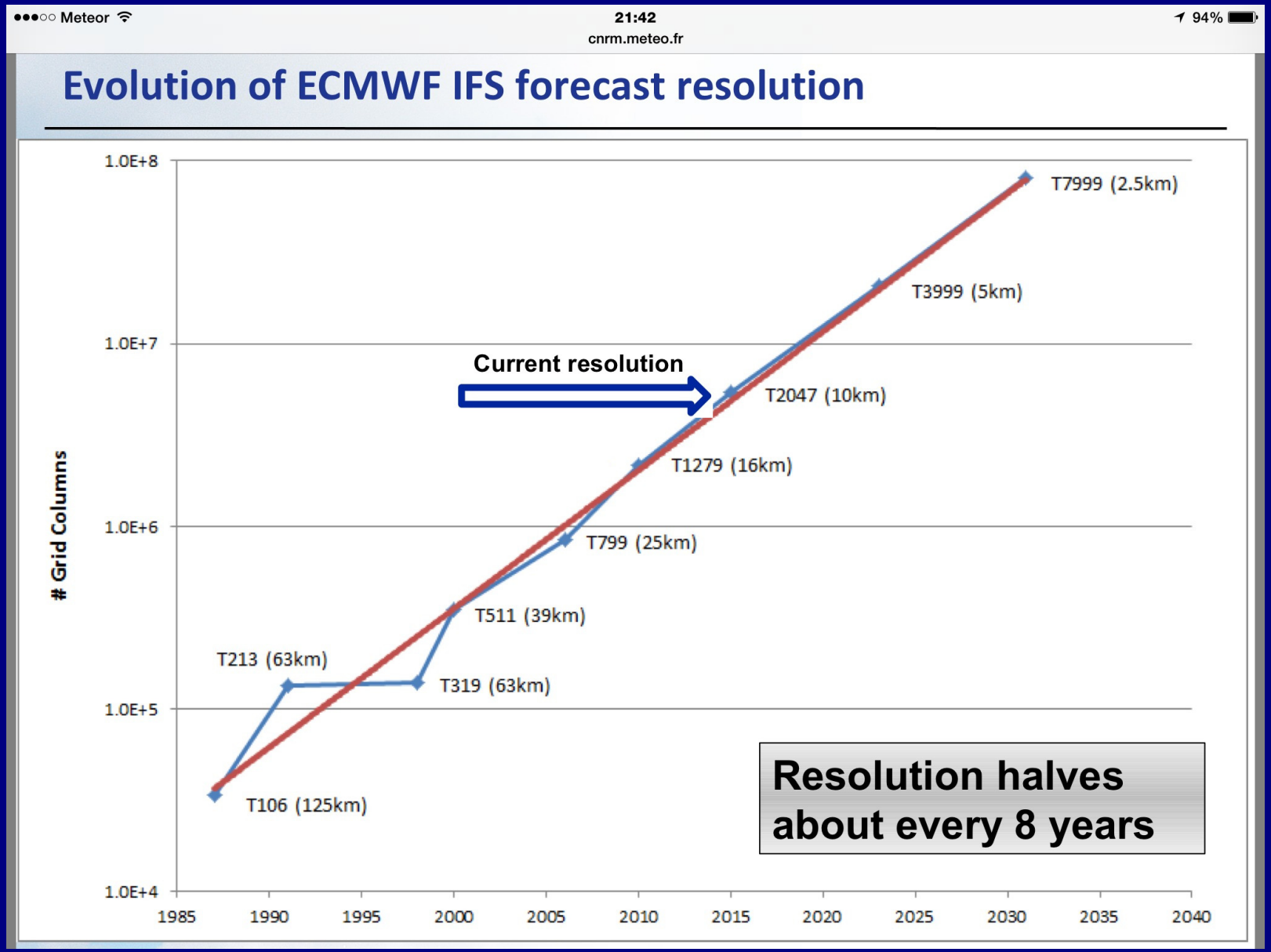


Figure : Landfall, New Jersey, 30 October 2012

Resolution of the IFS System



Growth in Forecast Skill

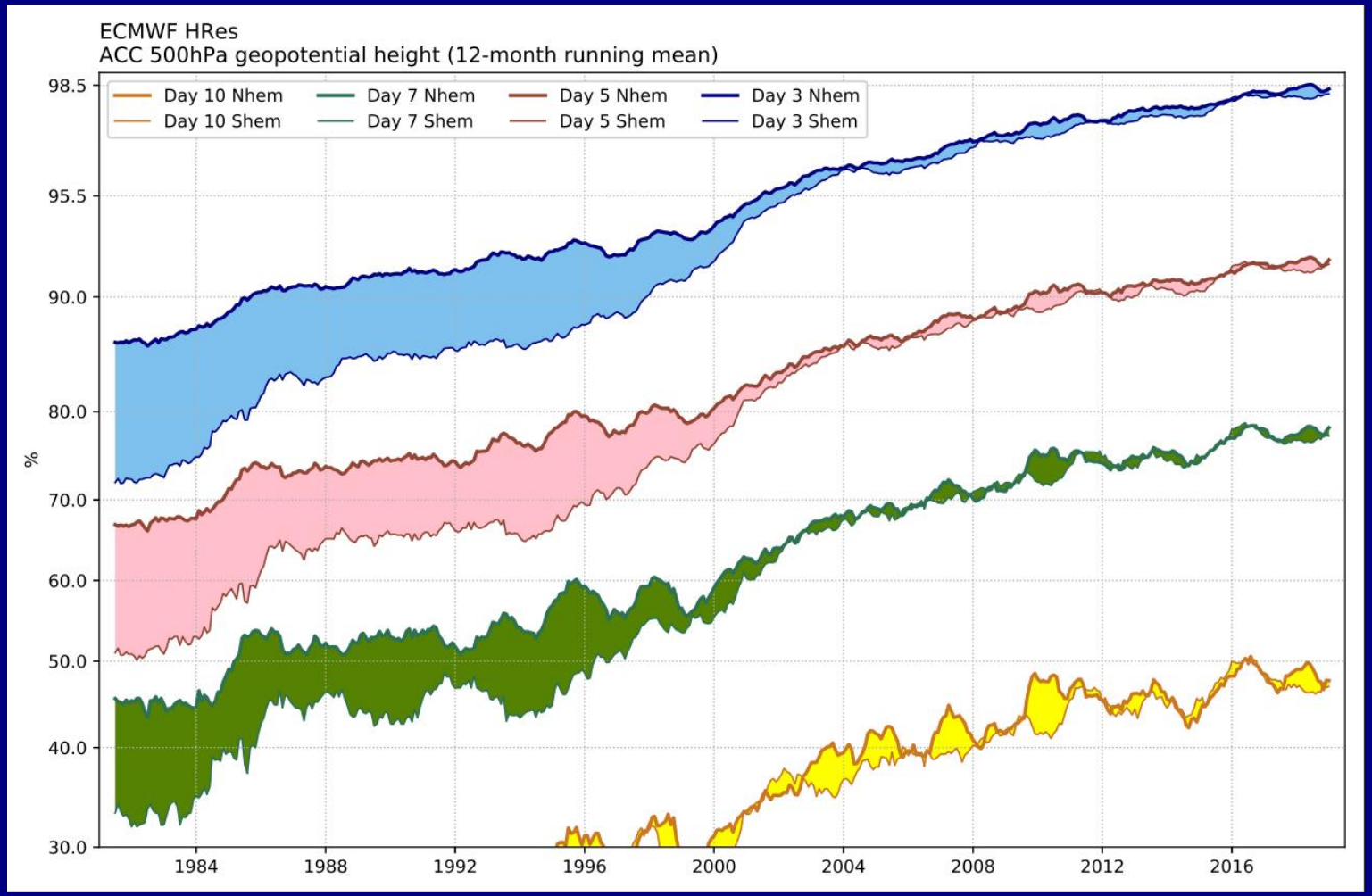


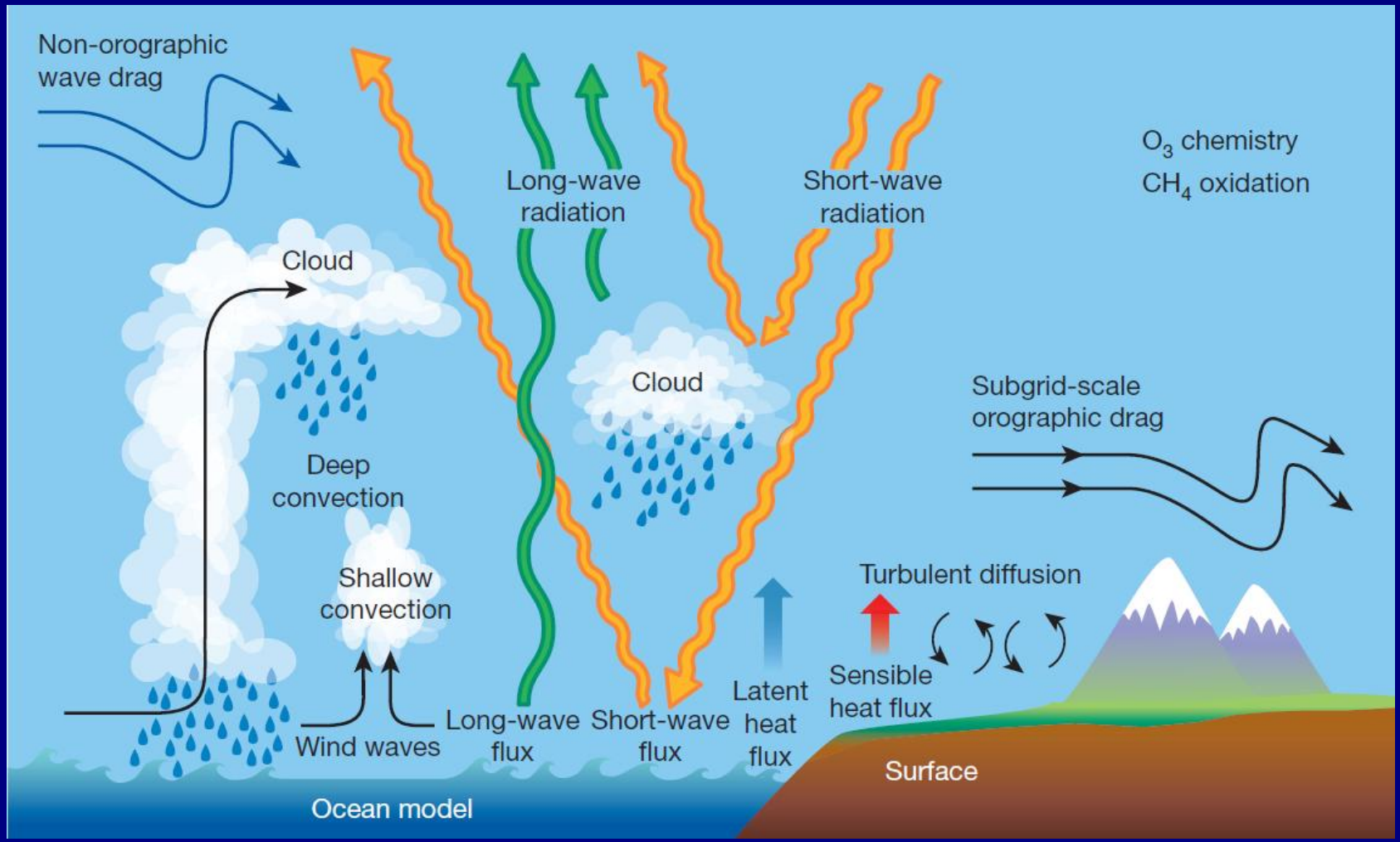
Figure : Anomaly correlation of 500 hPa geopotential height

Outline

Reasons for Progress in Weather Forecasting

- Faster computers;
- Better numerical schemes;
- Enhancements in model resolution;
- New observational data from satellites;
- More comprehensive physical processes;
- Paradigm shift to probabilistic forecasting;
- More sophisticated methods of data assimilation.

Physical Processes in the Atmosphere



The Equations of the Atmosphere

GAS LAWS

THERMODYNAMIC EQUATION

EQUATIONS OF MOTION: Navier-Stokes Equations

CONTINUITY EQUATION

WATER SUBSTANCE EQUATION

The Primitive Equations

$$\frac{du}{dt} - \left(f + \frac{u \tan\phi}{a}\right) v + \frac{1}{\rho}\frac{\partial p}{\partial x} + F_x = 0$$

$$\frac{dv}{dt} + \left(f + \frac{u \tan\phi}{a}\right) u + \frac{1}{\rho}\frac{\partial p}{\partial y} + F_y = 0$$

$$\frac{\partial p}{\partial z} + g\rho = 0$$

$$p = R\rho T$$

$$\frac{dT}{dt} + (\gamma - 1) T \nabla \cdot \mathbf{V} = \frac{Q}{c_p}$$

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \mathbf{V} = 0$$

$$\frac{\partial \rho_w}{\partial t} + \nabla \cdot \rho_w \mathbf{V} = [\textbf{Sources} - \textbf{Sinks}]$$

Scientific Forecasting in a Nut-Shell

- The atmosphere is a physical system
- Its behaviour is governed by the laws of physics
- These laws are expressed quantitatively in the form of mathematical equations
- Using observations, we can specify the atmospheric state at a given initial time:
  "Today's Weather"
- Using the equations, we can calculate how this state will change over time:
  "Tomorrow's Weather"

Scientific Forecasting in a Nut-Shell

Problems:

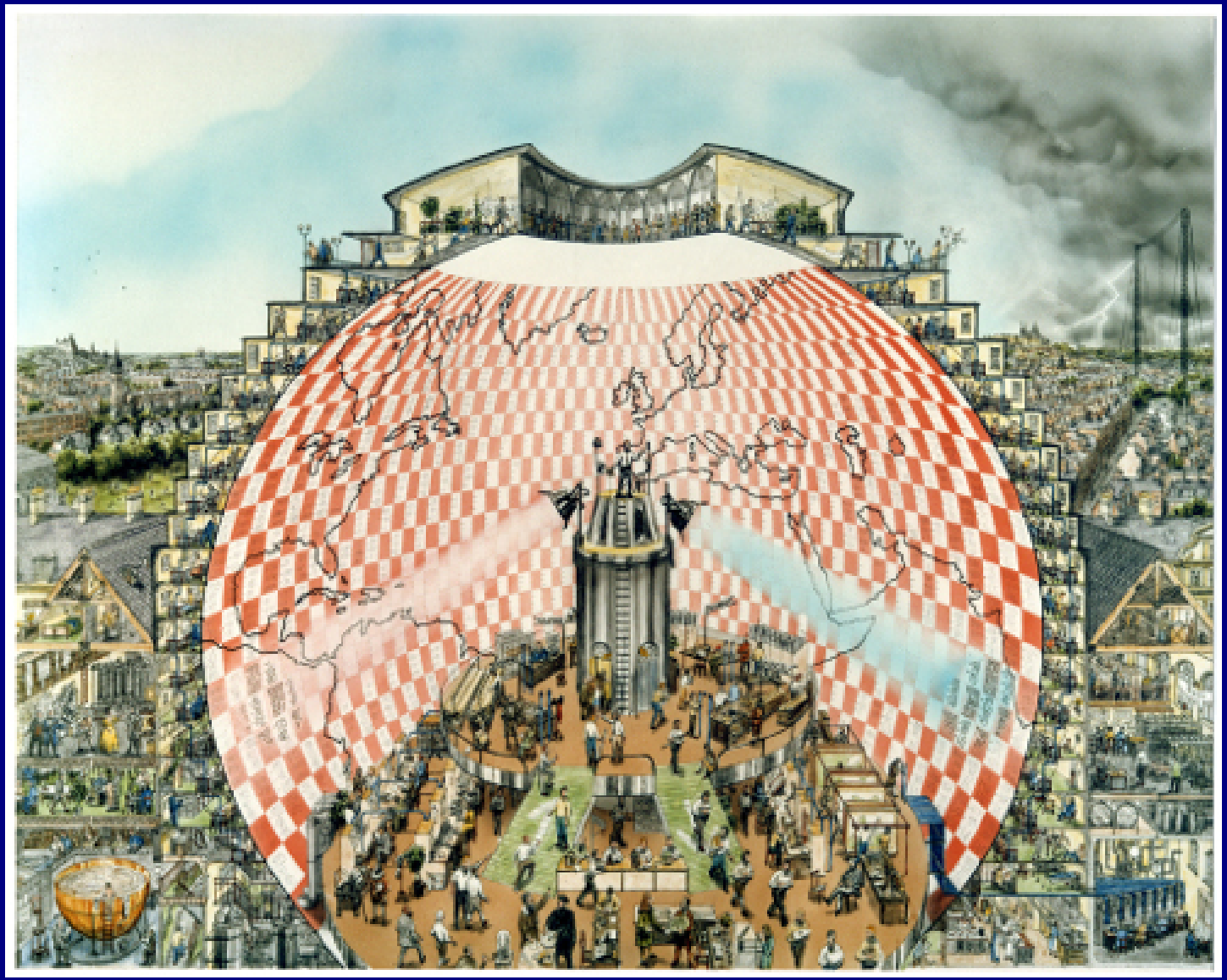
- **The equations are very complicated (non-linear): Powerful computer required to solve them.**
- **The accuracy decreases as the range increases; There is an inherent limit of predictibility.**

Future Progress

- Faster computers $\Longrightarrow$
  Increased model resolution.
- More complex computer architecture $\Longrightarrow$
  Smarter parallelisation algorithms.
- New observational data from satellites $\Longrightarrow$
  More advanced methods of data assimilation.
- More comprehensive physical processes.
- More comprehensive chemical processes.
- Greater emphasis on probabilistic forecasting.

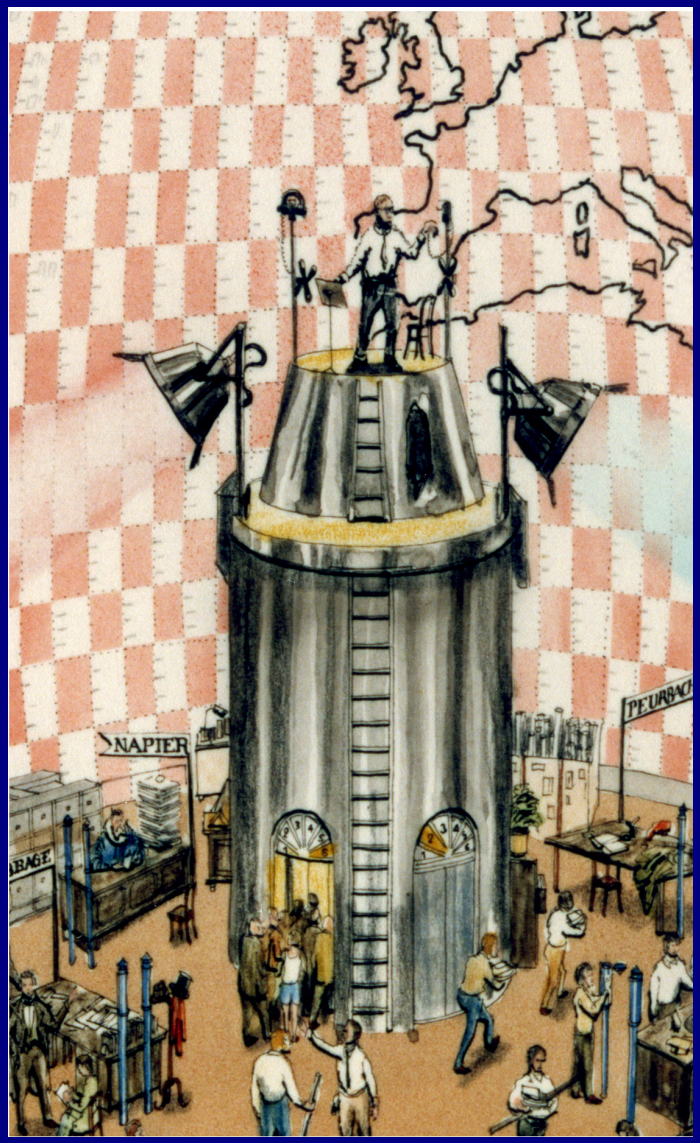
Outline

Richardson's Forecast Factory



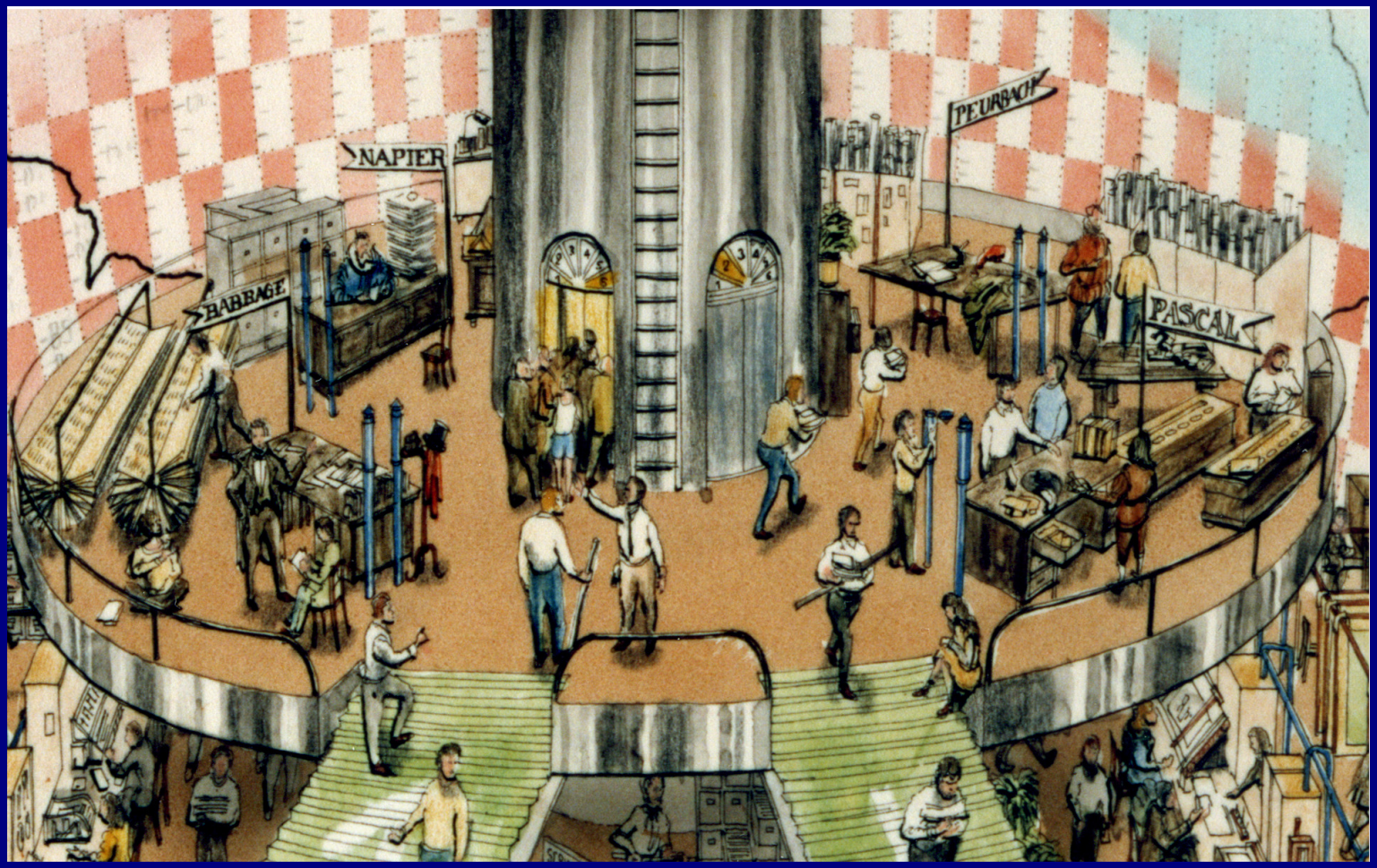
©Stephen Conlin, 1986

Zoom: Richardson Directing the Forecast



Lewis Fry Richardson conducting the forecast

Zoom: Historical Figures in Computing

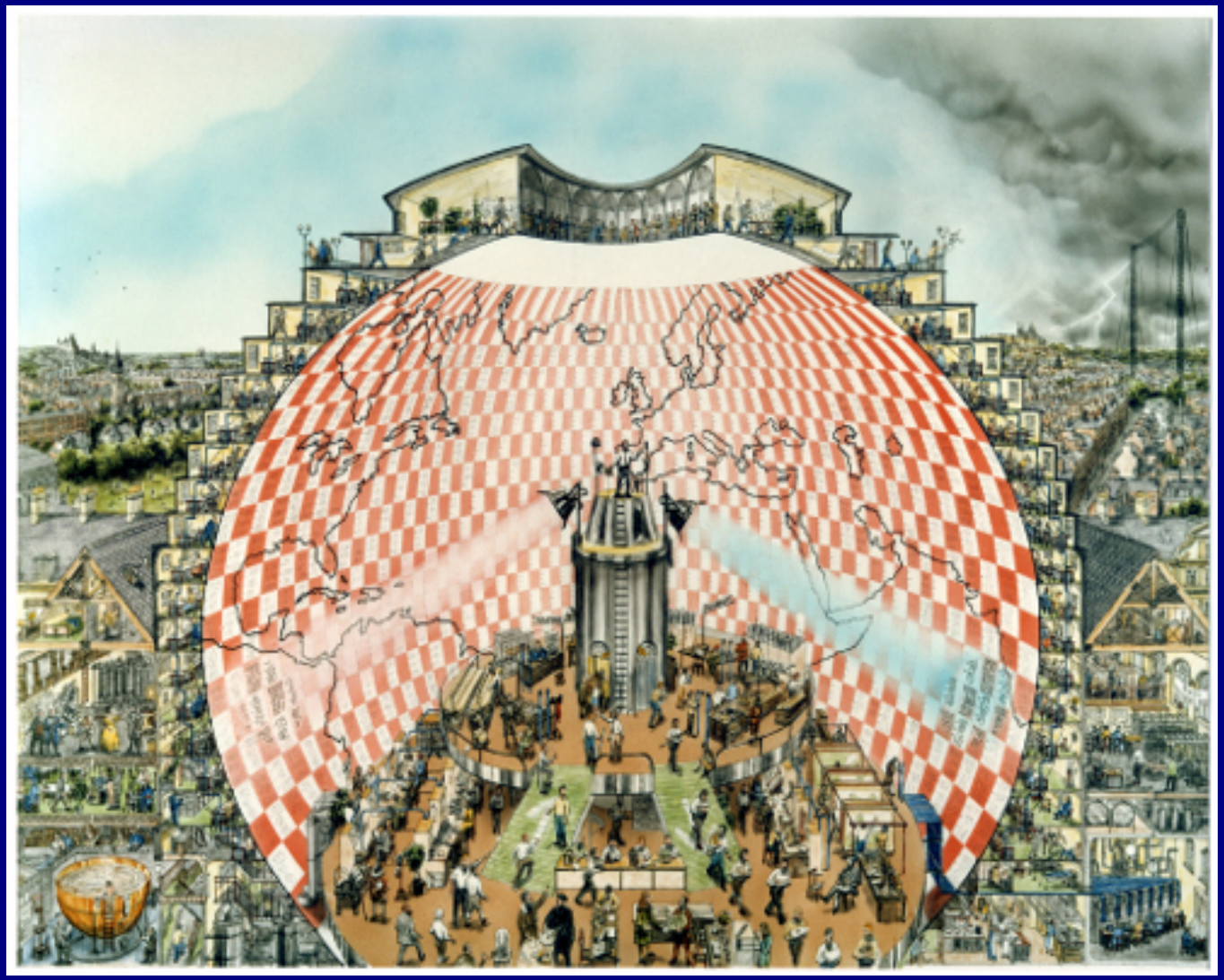


Napier / Babbage / Pascal / Peurbach

Zoom: Experimentation & Research

Babbage's Analytical Engine
Kelvin on left. Boole on right.

Richardson's Forecast Factory



64,000 Computers: the first Massively Parallel Processor

The Fantastic Forecast Factory

An Artist's Impression of Richardson's Fantastic Forecast Factory.
***Weather*, 71, 14–18.**

[Reprint on my website]

High-res Image on my website.

[http://maths.ucd.ie/∼plynch]

Thank you

Growth in Forecast Skill

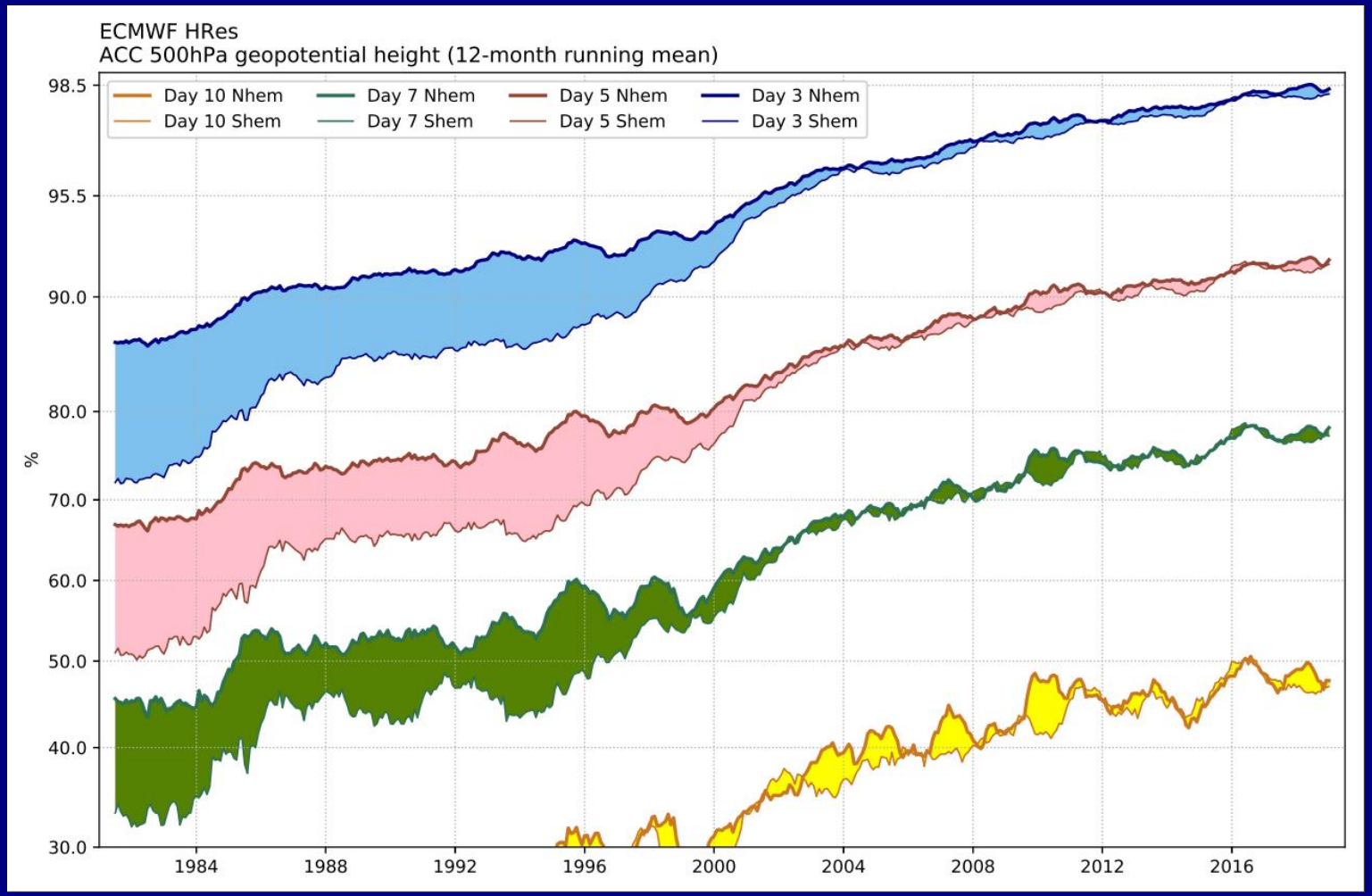


Figure : Anomaly correlation of 500 hPa geopotential height