The Origins of Computer Weather and Climate Prediction

Fulfilment of Richardson's Dream

Peter Lynch
School of Mathematics & Statistics
University College Dublin

★ ★ ★

Imperial College London, 30 May 2022

EPSRC Centre for Doctoral Training

Imperial College London

University of Reading

Outline

- Introduction
- Pioneers of NWP: The Dream
- Lewis Fry Richardson
- Max Margules
- Richardson's Peace Studies
- NWP Today
- Forecast Factory: The Fantasy

Outline

Introduction

Pioneers of NWP: The Dream

Lewis Fry Richardson

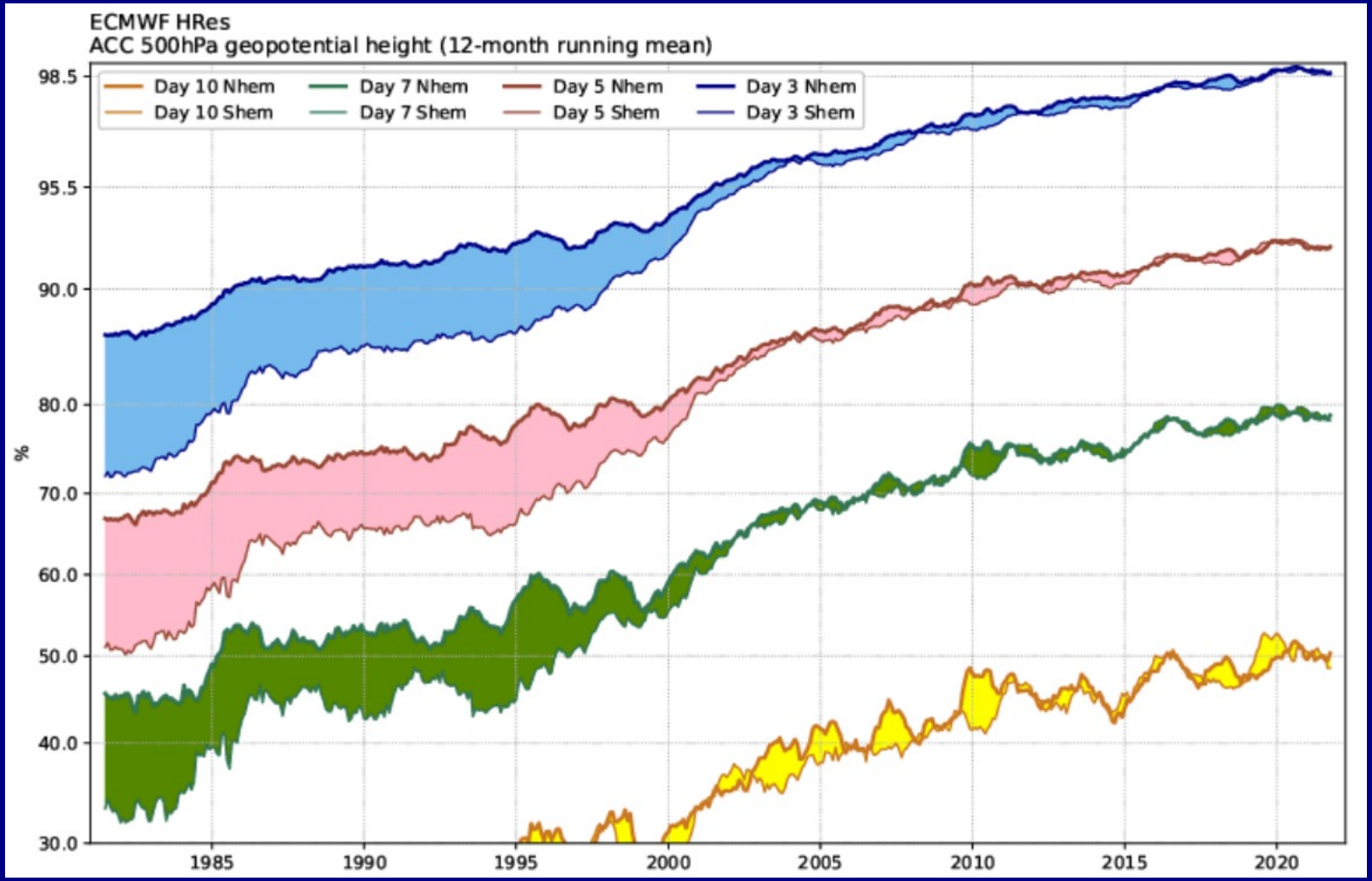
Max Margules

Richardson's Peace Studies

NWP Today

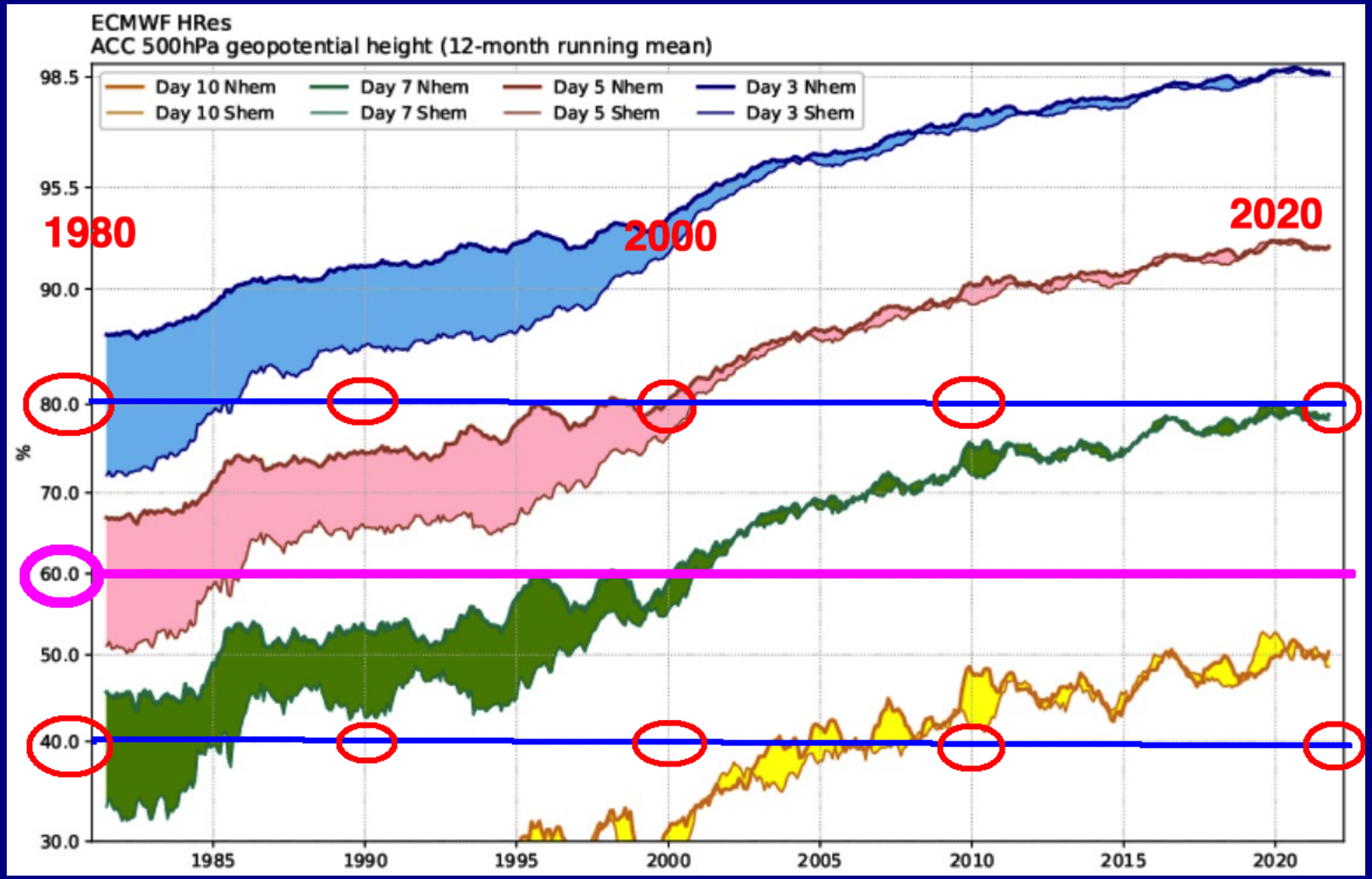
Forecast Factory: The Fantasy

Forecast Skill: Onward and Upward



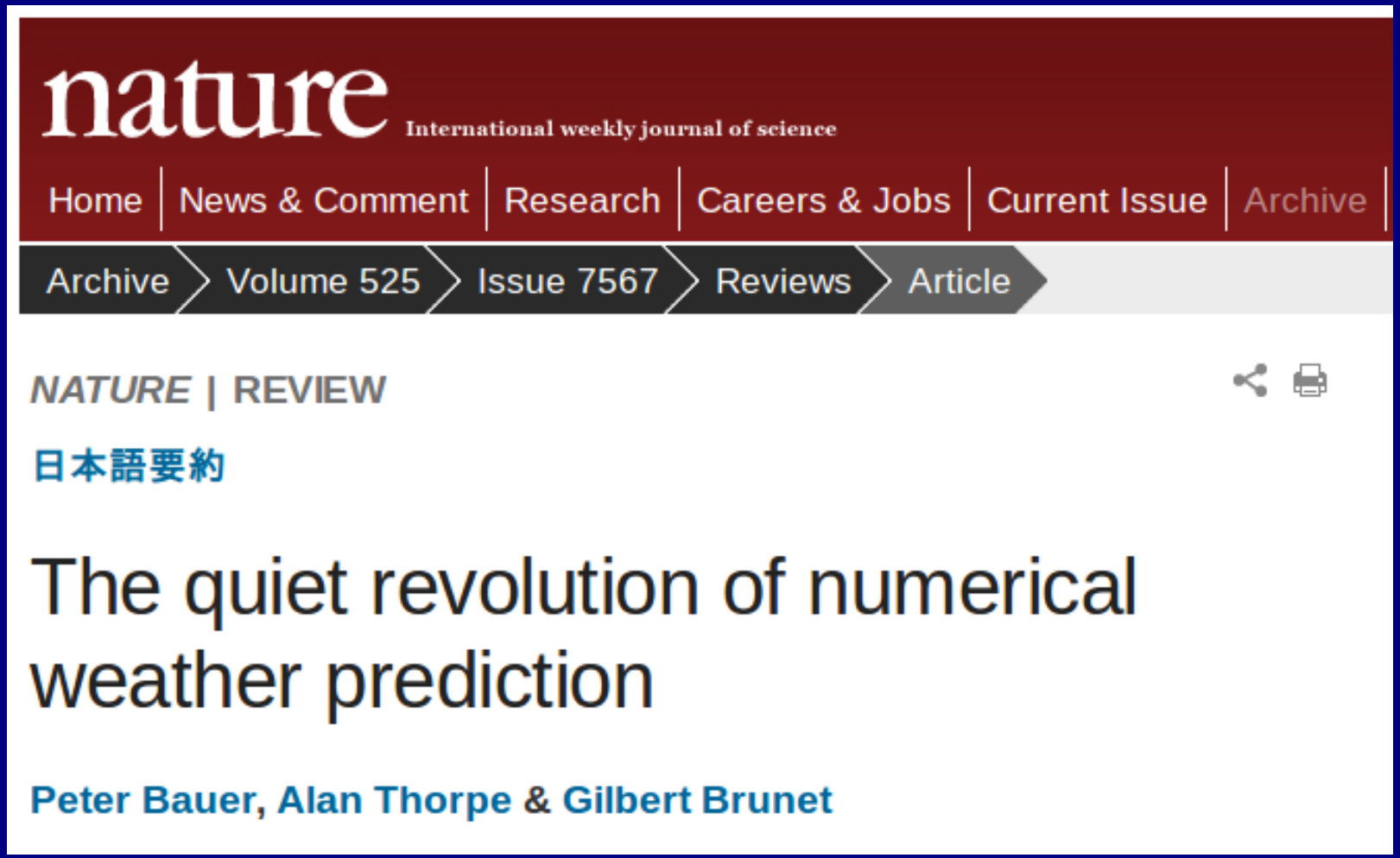
ECMWF Forecast Skill over 40 Years

Forecast Skill: Onward and Upward



ECMWF Forecast Skill over 40 Years

A Recent Review of NWP Progress



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Archive > Volume 525 > Issue 7567 > Reviews > Article

NATURE | REVIEW

日本語要約

The quiet revolution of numerical weather prediction

Peter Bauer, Alan Thorpe & Gilbert Brunet

Nature, 3 September 2015 Vol 525 p.47

The Quiet Revolution of NWP [Abstract]

- Steady accumulation of scientific knowledge.
- Steady accumulation of technological advances.

Advance in skill of NWP is among the greatest impacts of physical science in the 20th Century.

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- Steady accumulation of technological advances.

Advance in skill of NWP is among the greatest impacts of physical science in the 20th Century.

NWP is a computational problem comparable to:

- Modelling the behaviour of the human brain.
- Simulating the evolution of the early universe.

Performed every day at major operational centres.

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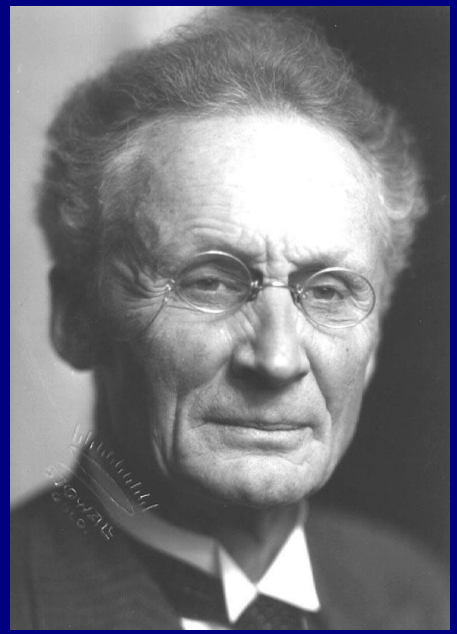
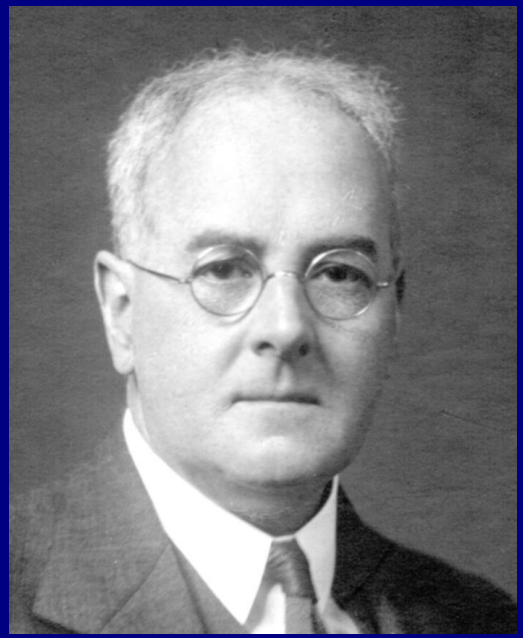
Pioneers of Scientific Forecasting

Cleveland Abbe, Vilhelm Bjerknes, Lewis Fry Richardson

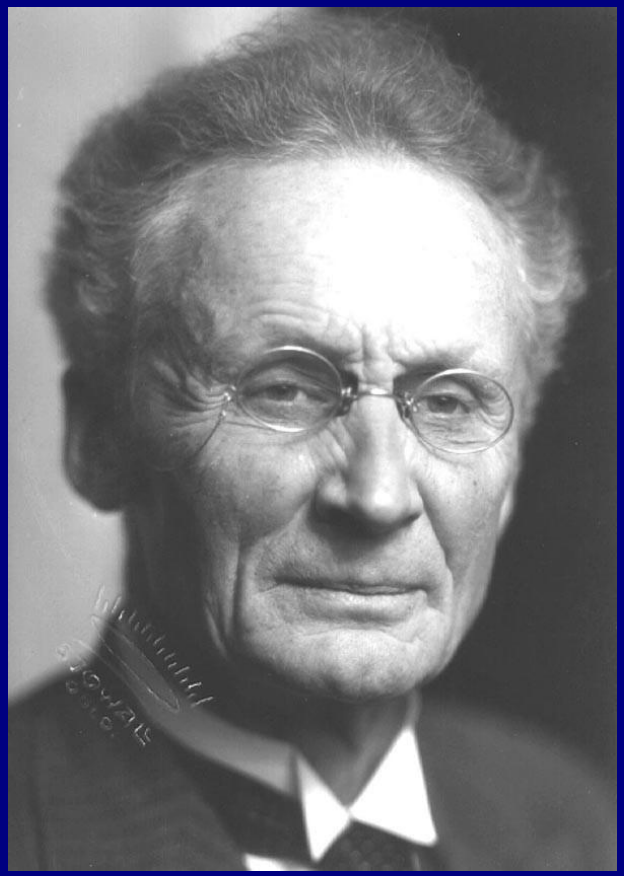
Cleveland Abbe

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

Bjerknes' 1904 Manifesto

To establish a science of meteorology, with the aim of predicting future states of the atmosphere.

"If it is true, as every scientist believes, that subsequent atmospheric states develop from the preceeding ones according to physical law, then it is apparent that the necessary and sufficient conditions for the rational solution of forecasting problems are the following:

1. A sufficiently accurate knowledge of the *state* of the atmosphere at the initial time.

2. A sufficiently accurate knowledge of the *laws* according to which one state of the atmosphere develops from another."

- Step (1) is Diagnostic.
- Step (2) is Prognostic.

Vilhelm Bjerknes (1862–1951)

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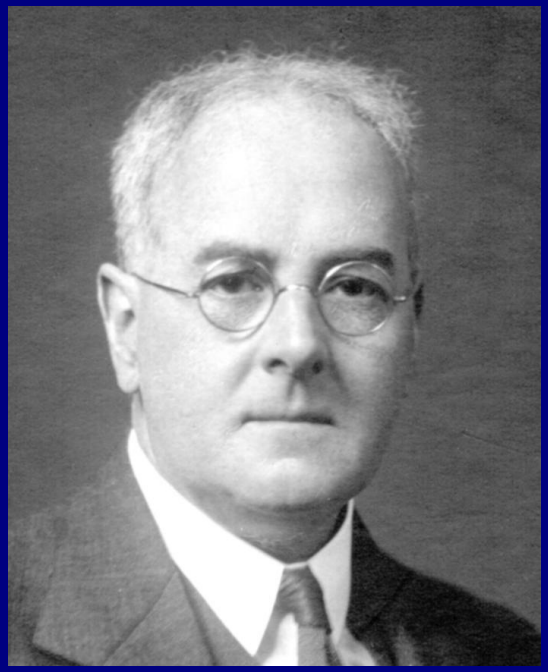
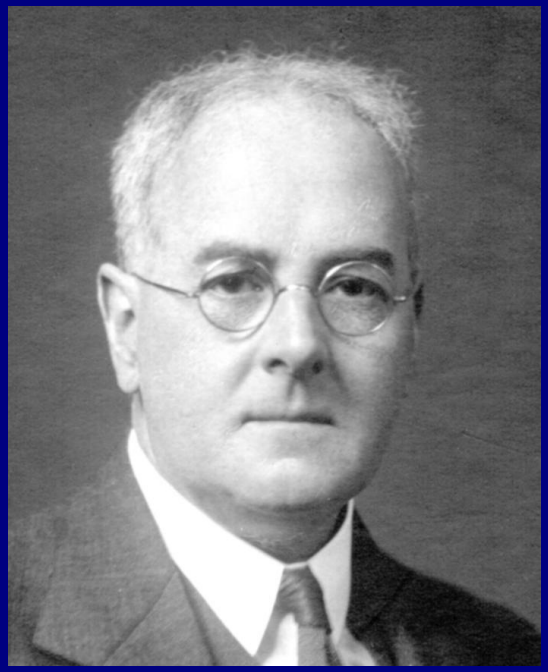


The English Quaker scientist Lewis Fry Richardson attempted a direct solution of the equations of motion.

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.

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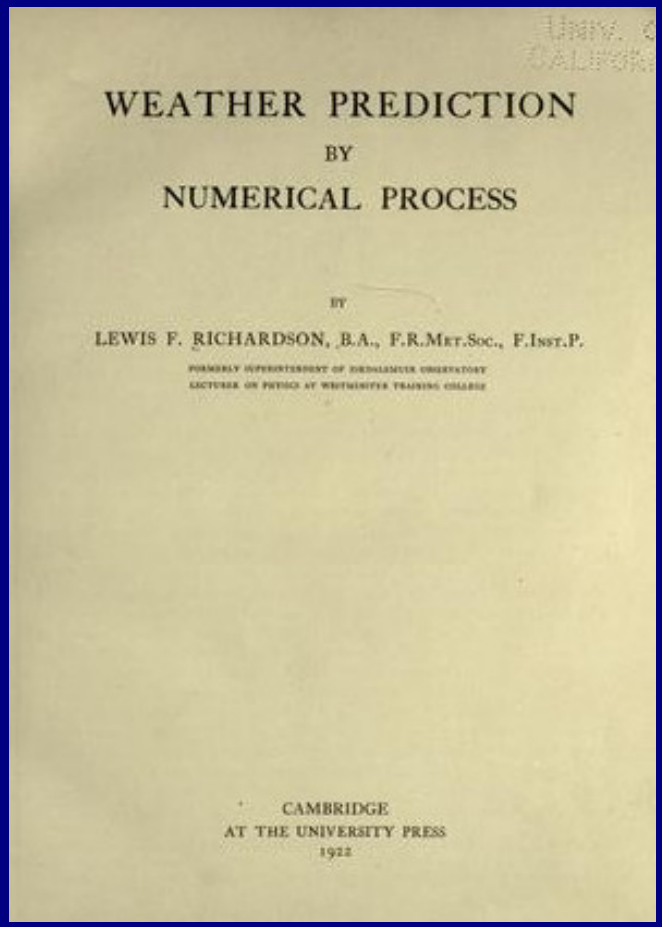
Today, forecasts are prepared routinely using his method . . . his dream has indeed come true.

Richardson's Dream

In *Weather Prediction by Numerical Process* (1922), Richardson wrote the following:

> ***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.***

Weather Prediction by Numerical Process



WEATHER PREDICTION

BY

NUMERICAL PROCESS

BY

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

CAMBRIDGE
AT THE UNIVERSITY PRESS
1922

WPNP published by Cambridge University Press in 1922 . . .

. . . just one hundred years ago!

Weather Prediction by Numerical Process

- Mathematical method for predicting the weather.
- Richardson's ideas were fundamentally sound.
- His methodology is essentially that used today.
- But, his method was utterly impractical.
- His trial forecast was little short of outlandish.

Richardson's ideas were eclipsed for decades and his wonderful opus gathered dust and was forgotten.

The Origin of Richardson's Method

LFR first applied his approximate method for the solution of differential equations to investigate the stresses in masonry dams.

But the method was completely general and he realized that it had potential for use in a wide range of problems governed by PDEs.

In a letter to Karl Pearson (c. 1910), he wrote that 'there should be applications to meteorology'. This is the first inkling of his interest in weather prediction.

LFR began serious work on the problem in 1913, when LFR was S'visor at Eskdalemuir Observatory.

Eskdalemuir Office & Computing Room (1911)

The Method described in WPNP

Initial state specified by pressure, temperature, density, humidity and wind fields.

Changes described by seven differential equations.

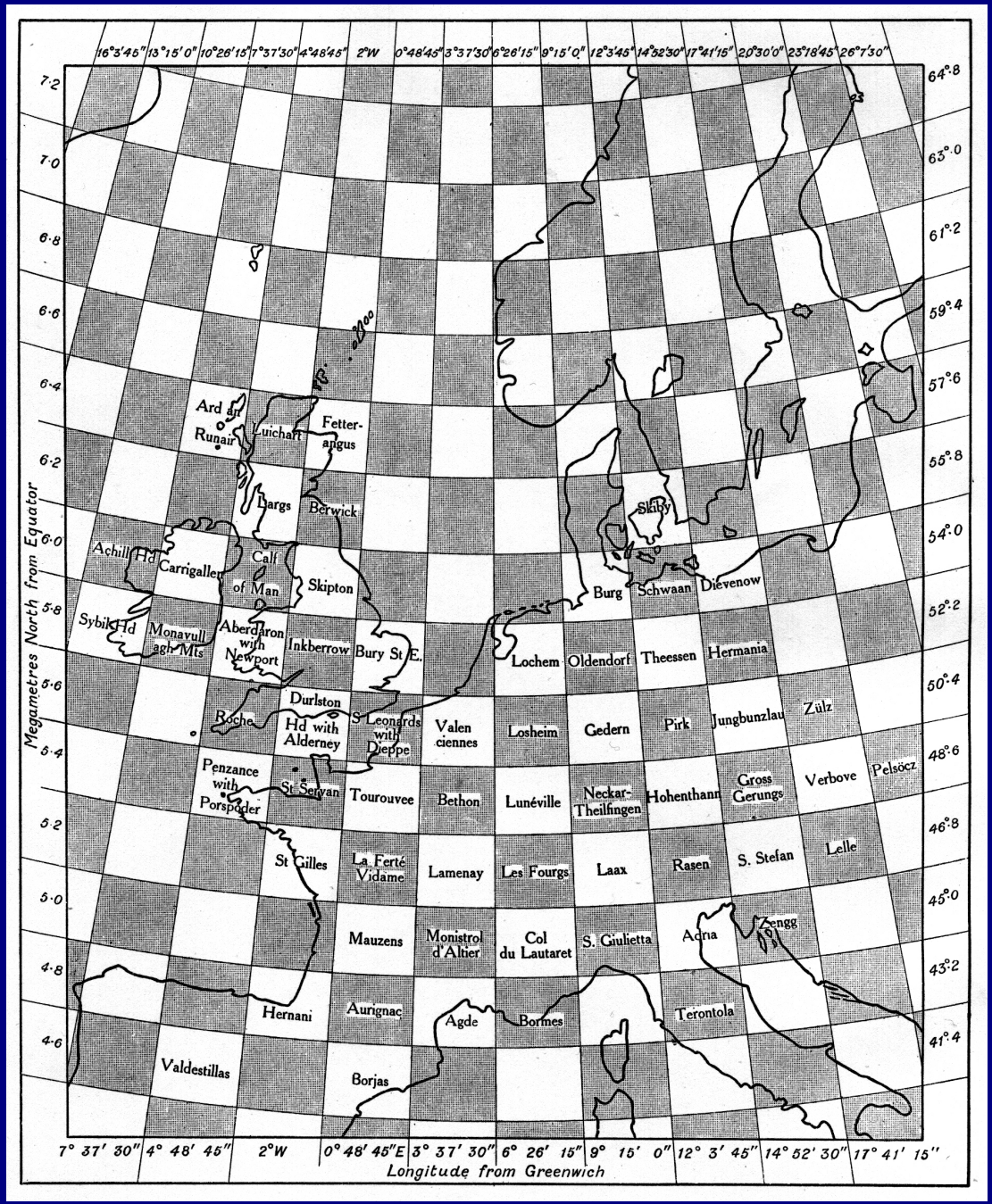
Atmosphere divided into discrete columns of extent 3° east-west and 200 km north-south.

12,000 columns covered the globe.

Each column divided vertically into five cells.

Equations expressed in finite difference form.

Changes calculated by arithmetical means.


16°3'45" 13°15'0" 10°26'15" 7°37'30" 4°48'45" 2°W 0°48'45" 3°37'30" 6°26'15" 9°15'0" 12°3'45" 14°52'30" 17°41'15" 20°30'0" 23°18'45" 26°7'30"
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52°2
50°4
48°6
46°8
45°0
43°2
41°4
Megametres North from Equator
Ard an Runair
Luichart
Fetter-angus
Largs
Berwick
Skiby
Achill Hd
Carrigaller
Calf of Man
Skipton
Burg
Schwaan
Dievenow
Sybil Hd
Monavull agh Mts
Aberdaron with Newport
Inkberrow
Bury St E.
Lochem
Oldendorf
Theessen
Hermania
Durlston Hd with Alderney
St Leonards with Dieppe
Valenciennes
Losheim
Gedern
Pirk
Jungbunzlau
Zülz
Roche
Penzance with Porspoder
St Senyan
Tourouvee
Bethon
Lunéville
Neckar-Theilfingen
Hohenthann
Gross Gerungs
Verbove
Pelsöcz
St Gilles
La Ferté Vidame
Lamenay
Les Fourgs
Laax
Rasen
S. Stefan
Lelle
Mauzens
Monistrol d'Altier
Col du Lautaret
S. Giulietta
Adria
Zengg
Hernani
Aurignac
Agde
Bormes
Terontola
Valdestillas
Borjas
7° 37' 30" 4° 48' 45" 2°W 0° 48' 45"E 3° 37' 30" 6° 26' 15" 9° 15' 0" 12° 3' 45" 14° 52' 30" 17° 41' 15"
Longitude from Greenwich

The Sample Forecast

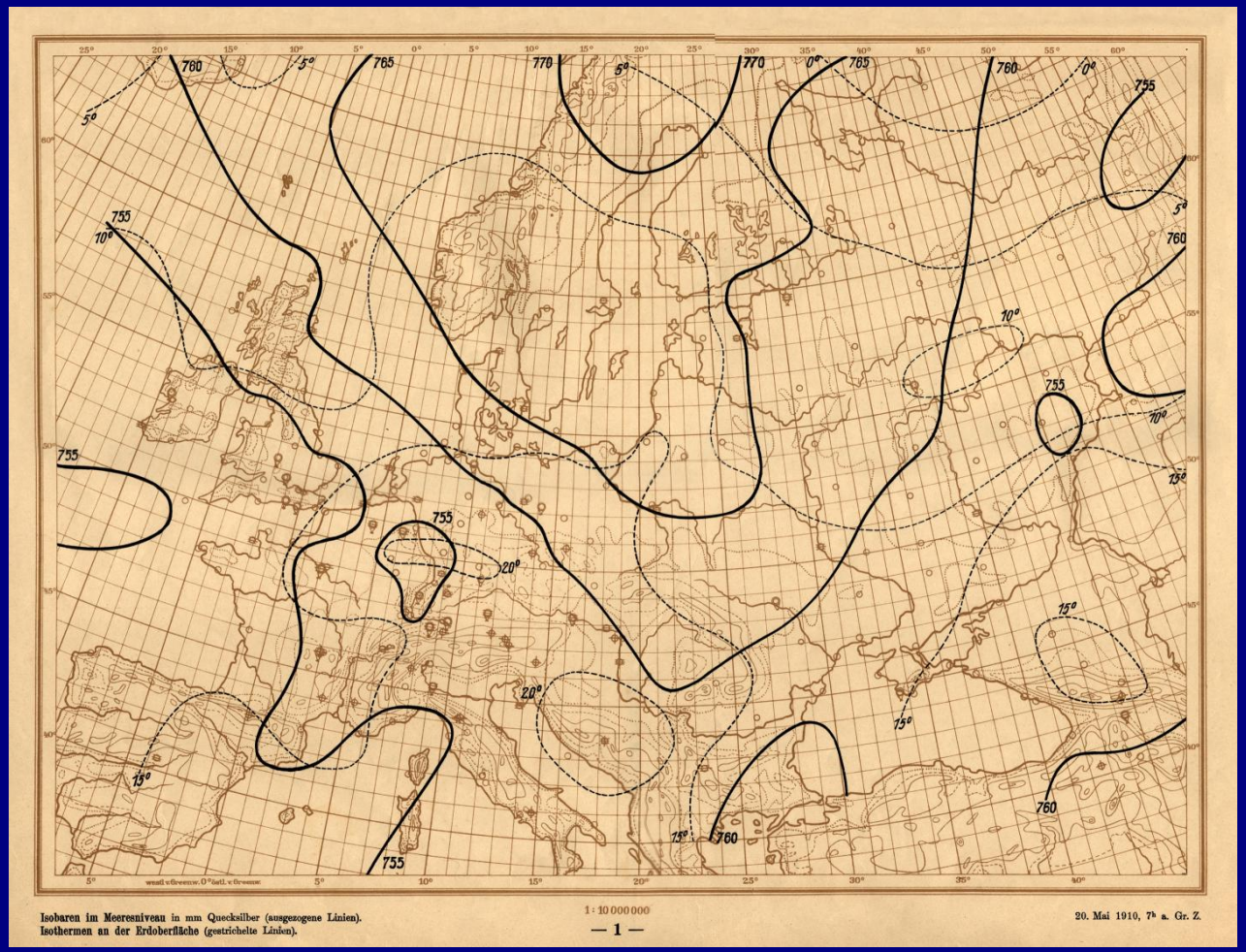
Forecast was worked out in France in rest periods between transporting wounded soldiers in WW I.

Richardson calculated the *initial changes in two columns* over central Europe.

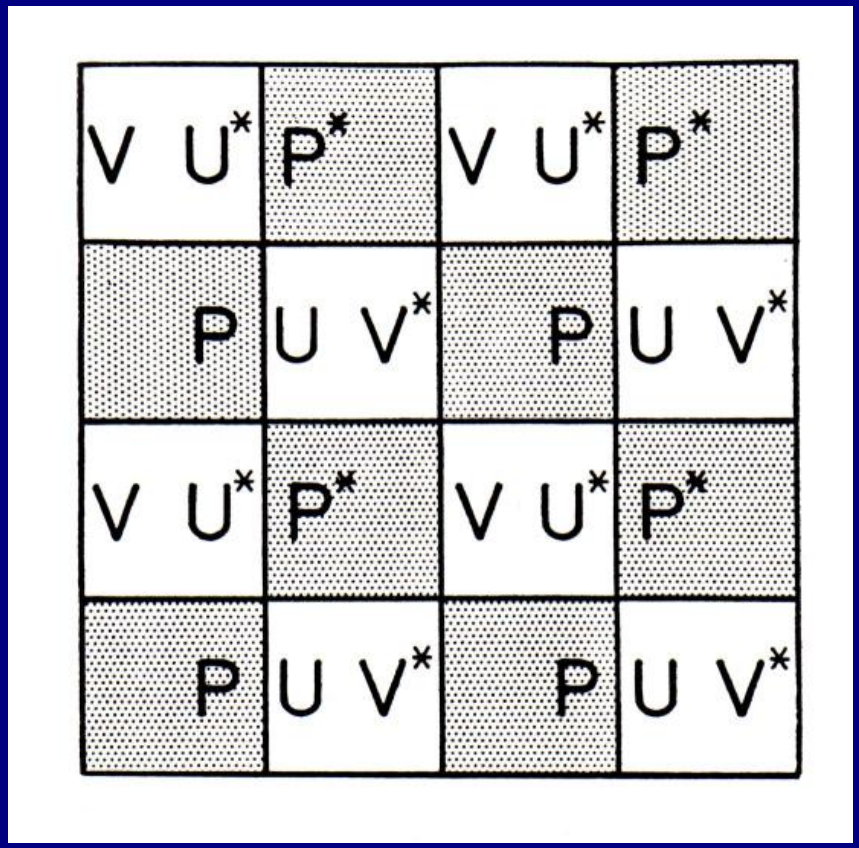
The extent of his 'forecast': 20 numbers.

If Richardson spent ten hours per week at his chore it must have occupied him for about two years.

The Leipzig Charts for 0700 UTC, May 20, 1910

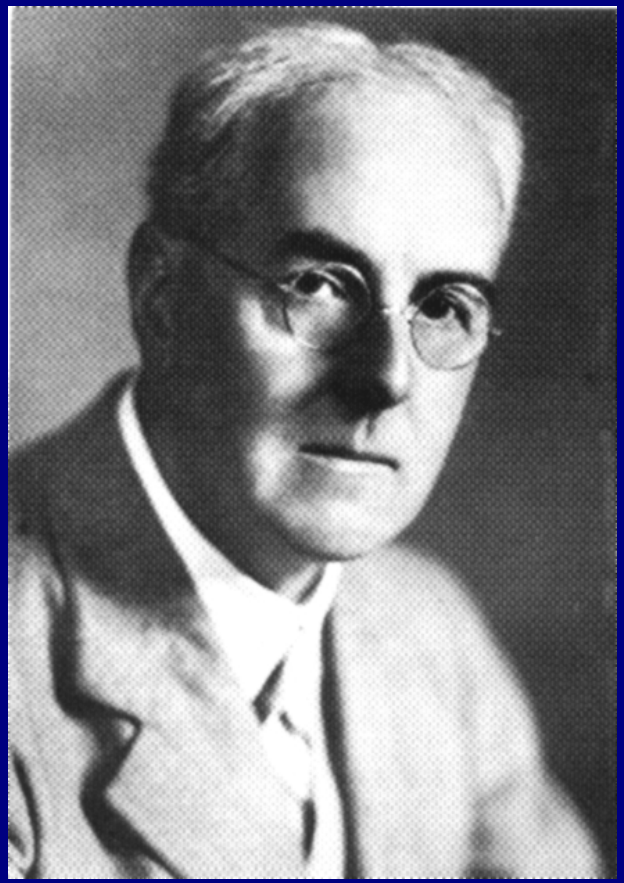


Bjerknes' sea level pressure analysis.



Richardson Grid (also called an Arakawa E-grid)

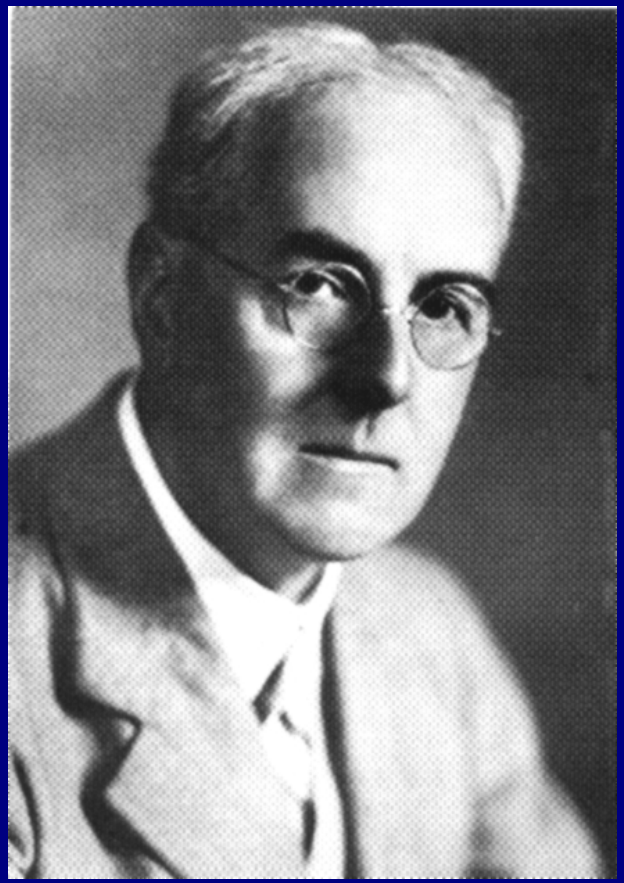
Lewis Fry Richardson, 1881–1953.



Richardson computed by hand the pressure change at a single point.

It took him two years !

Lewis Fry Richardson, 1881–1953.



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

But Richardson’s method was scientifically sound.

The problem

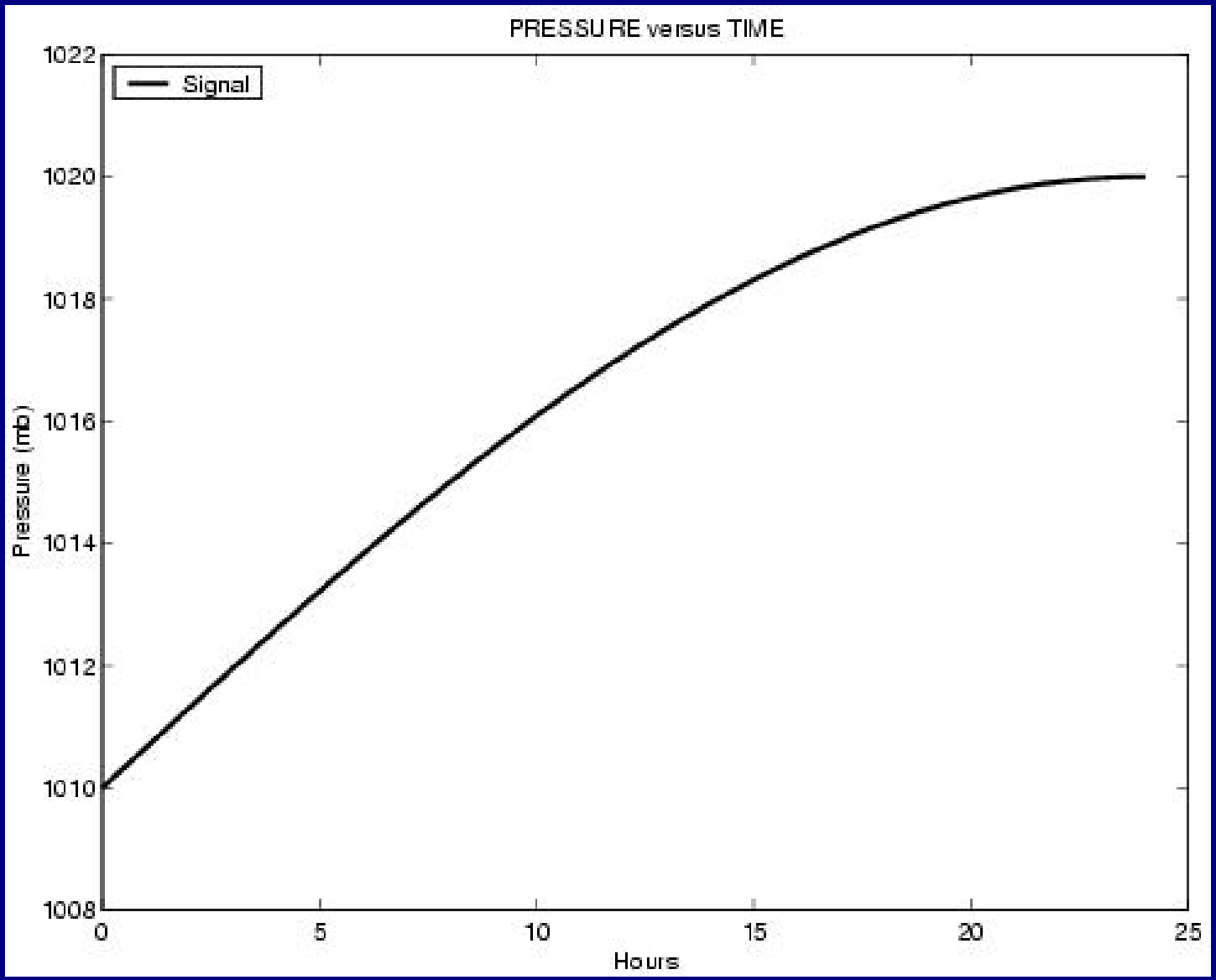
Richardson used computed tendencies to deduce the long-term change.

With a time step of six hours, he obtained the unacceptable value

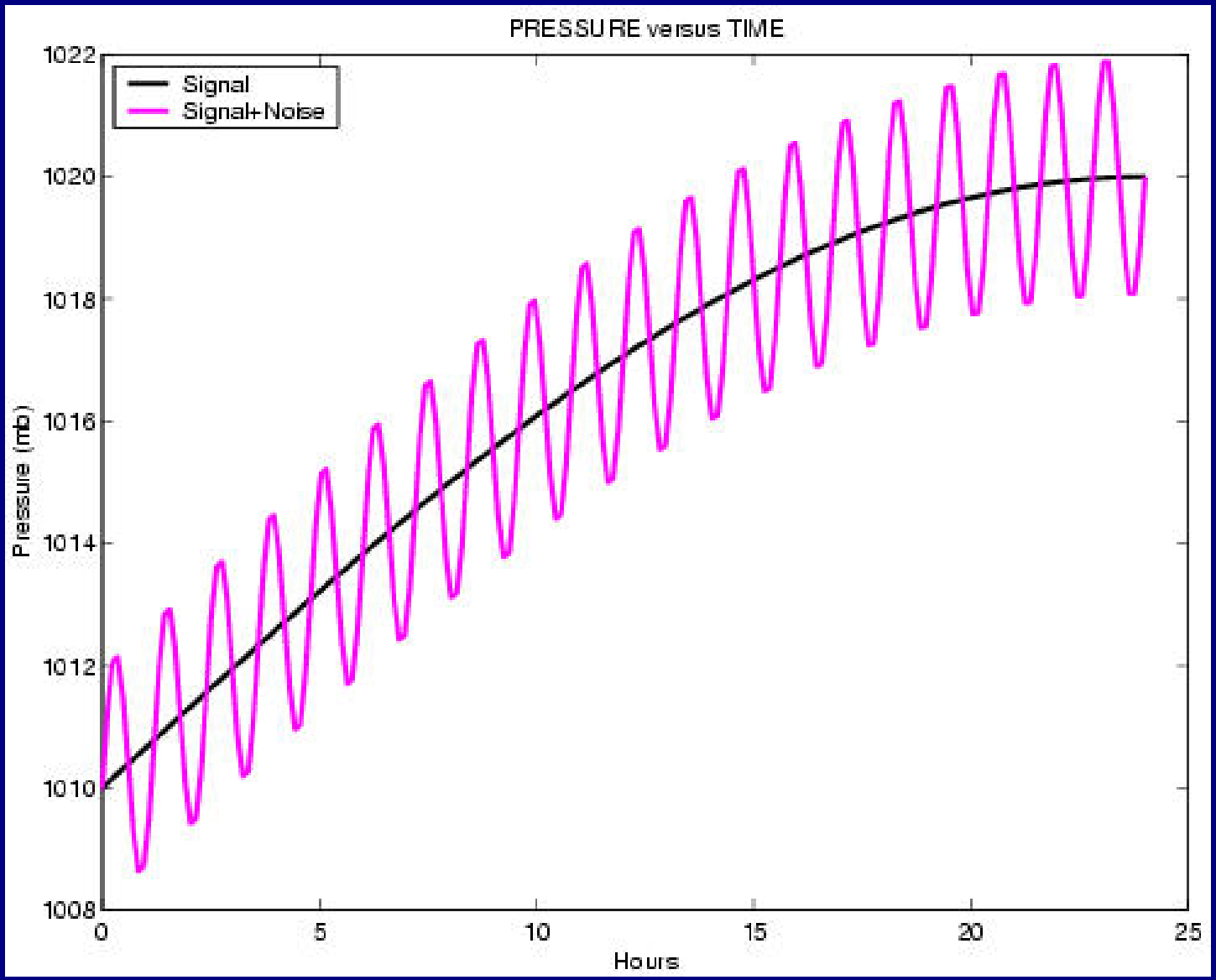
$$\Delta p = \textbf{145 hPa in 6 hrs}$$

Problem:
the instantaneous pressure tendency does not reflect the long-term change.

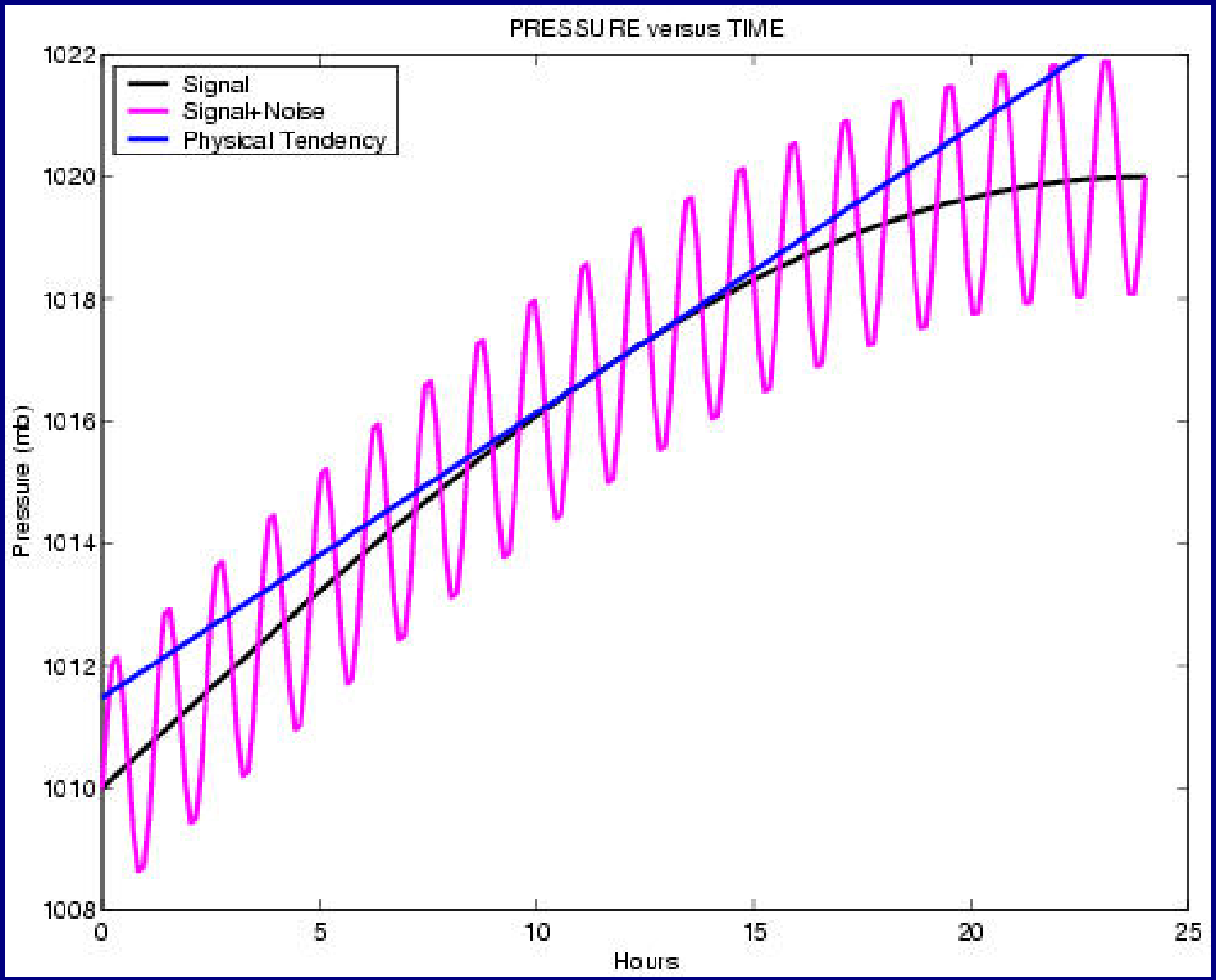
A Smooth Signal



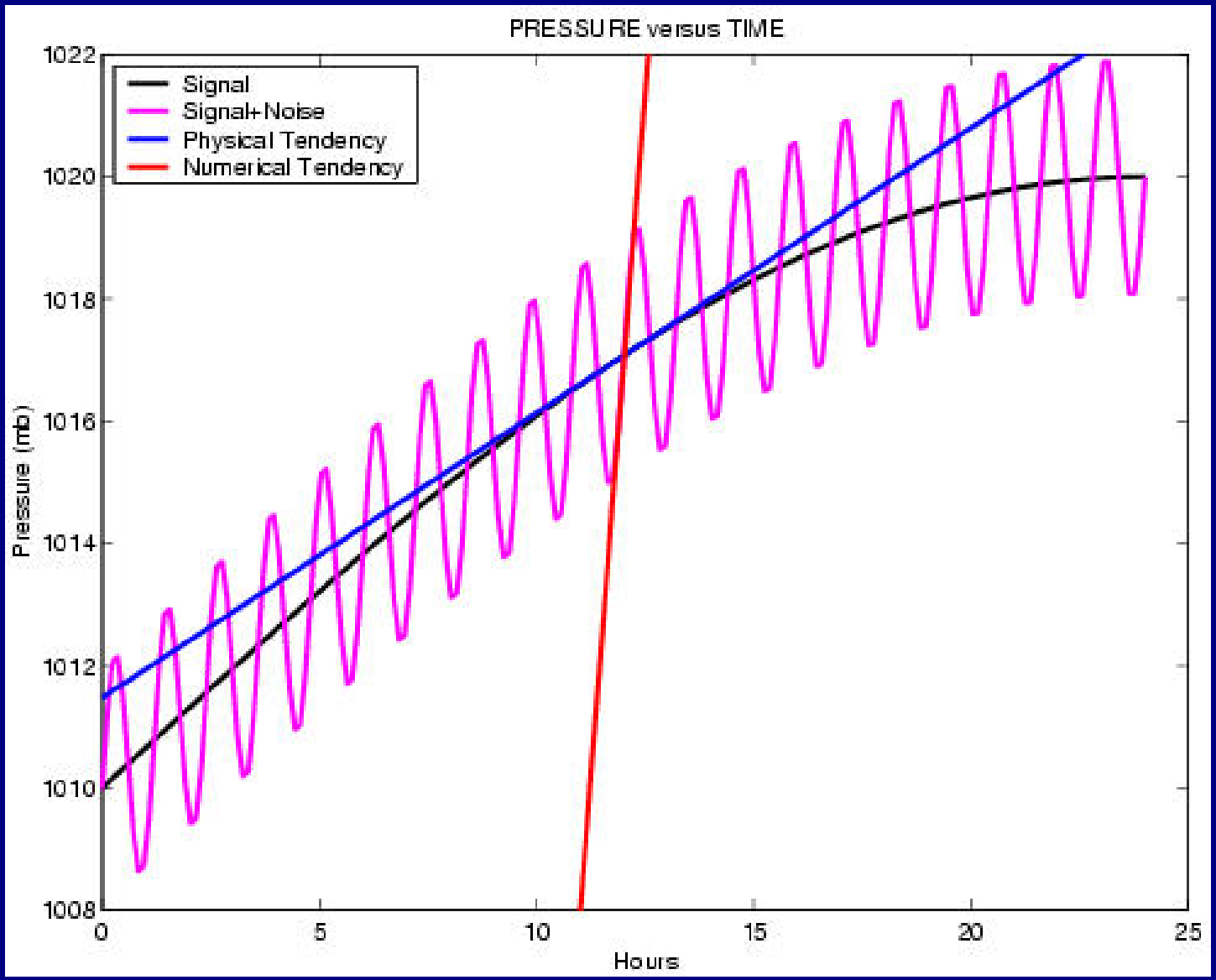
A Noisy Signal



Tendency of a Smooth Signal



Tendency of a Noisy Signal



Possible Solutions

Small time steps are required to represent rapid variations:

- **Combine many time steps short enough to simulate high frequency variations accurately.**

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Equations include high-frequency oscillations:

- **Filter HF Solutions from the Equations.**

Possible Solutions

Small time steps are required
to represent rapid variations:

- Combine many time steps short enough to simulate high frequency variations accurately.

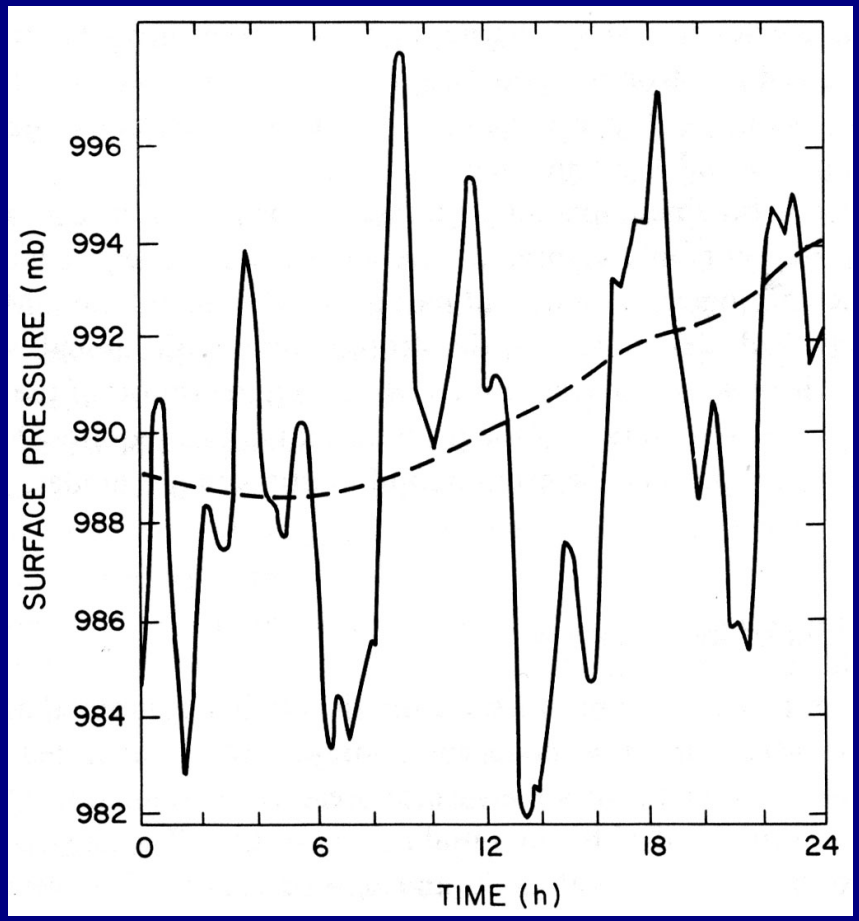
Equations include high-frequency oscillations:

- Filter HF Solutions from the Equations.

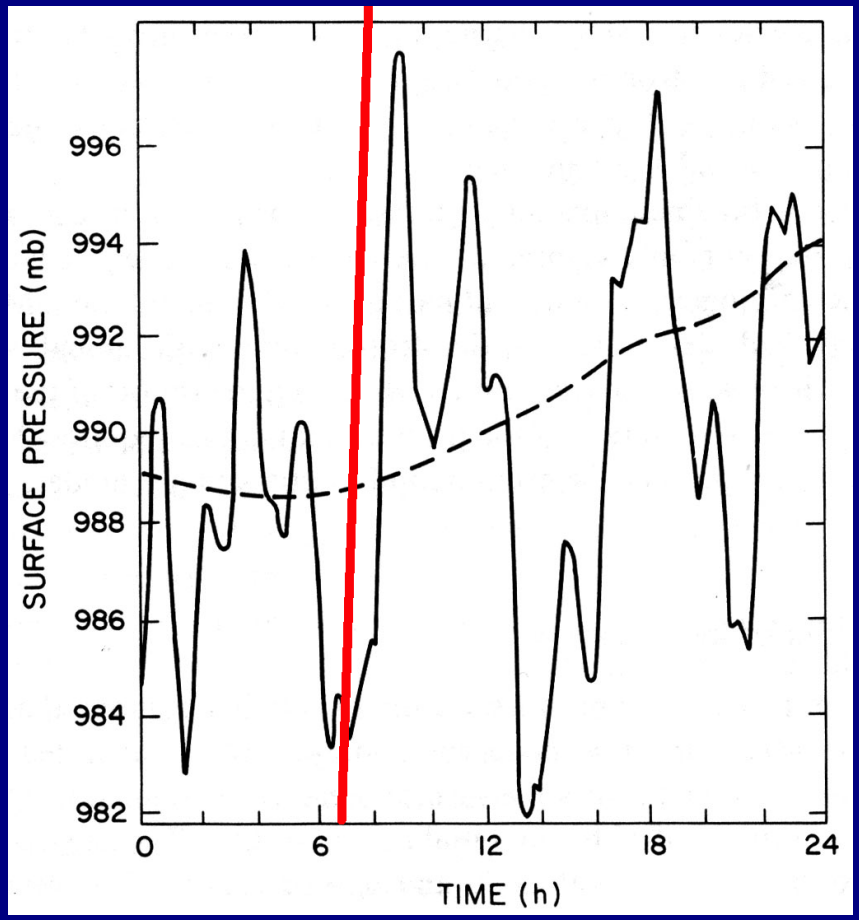
Data errors induce spurious HF components:

- Adjust the initial data to eliminate the HF waves.

Richardson devoted a chapter of WPNP to smoothing!



Evolution of surface pressure before and after initialiation. (Williamson and Temperton, 1981)



Evolution of surface pressure before and after initialiation.
Red line: 24 hPa/hr or 144 hPa/6 hr.

Initialization of Richardson's Forecast

Richardson's Forecast was repeated on a computer.

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

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

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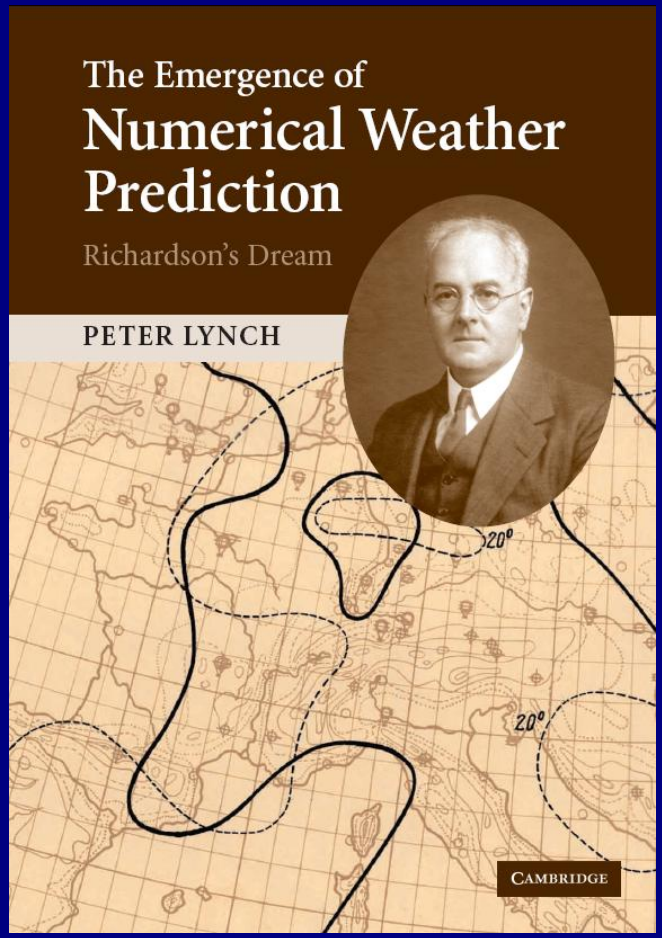
- **ORIGINAL:** $\frac{\partial p_s}{\partial t} = +\mathbf{145}\,\mathrm{hPa}/6\,\mathrm{h}$
- **INITIALIZED:** $\frac{\partial p_s}{\partial t} = -\mathbf{0.9}\,\mathrm{hPa}/6\,\mathrm{h}$

Observations: The barometer was steady!

Full Account of the Forecast



Richardson's Forecast and the Emergence of NWP are described in this book.

Cambridge Univ. Press, 2006

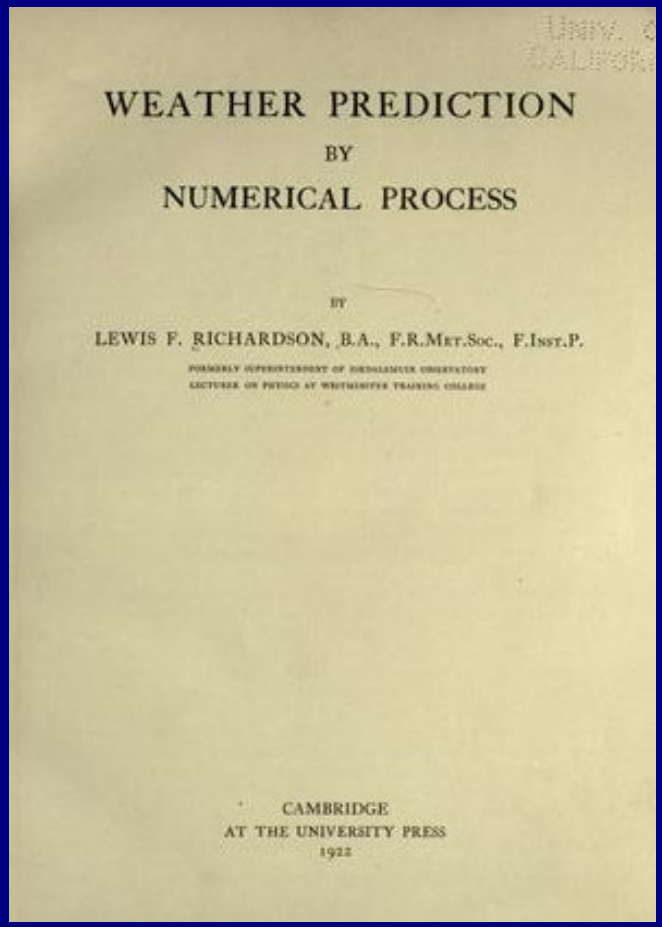
[Available in paperback form]

Richardson's Forecast Factory

©François Schuiten

64,000 Computers: the first Massively Parallel Processor

Weather Prediction by Numerical Process



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CAMBRIDGE
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1922

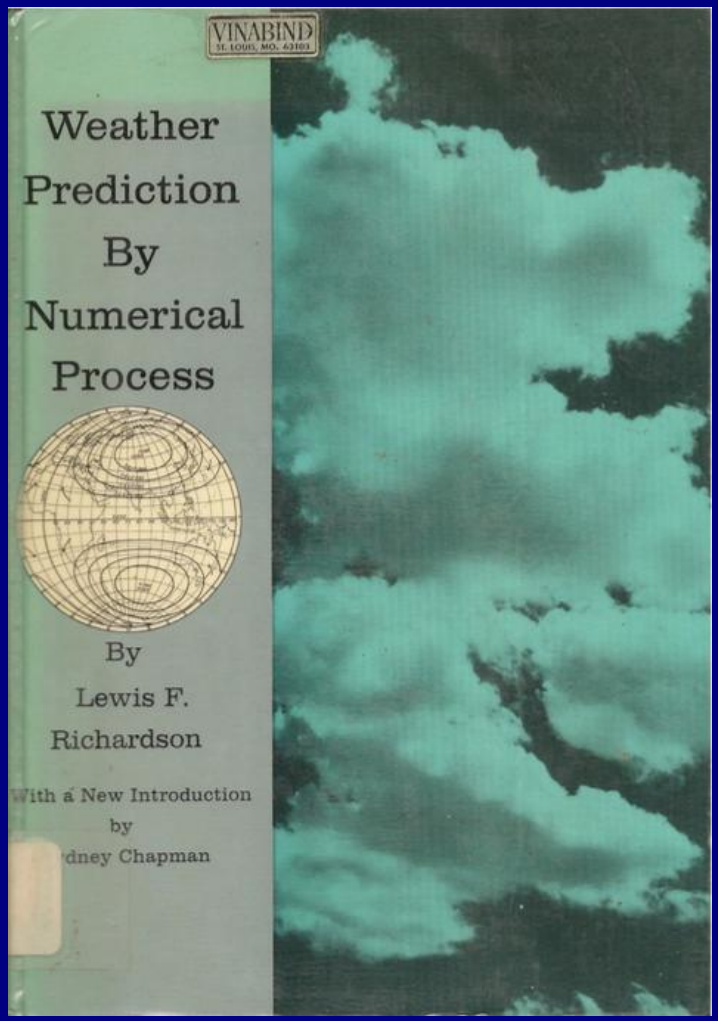
WPNP published by Cambridge University Press in 1922 . . .

. . . just one hundred years ago!

Weather Prediction by Numerical Process

- Published by Cambridge University Press, one hundred years ago, in 1922.
- The price was 30 shillings (£1.50)
- The print run was 750 copies.
- Akira Kasahara bought a copy in 1955, more than thirty years after publication.
- Re-issued in 1965 as a Dover paperback and the 3,000 copies (price $2) sold out within a decade.
- CUP published "Second Edition" in 2007.

WPNP Dover and Second Editions



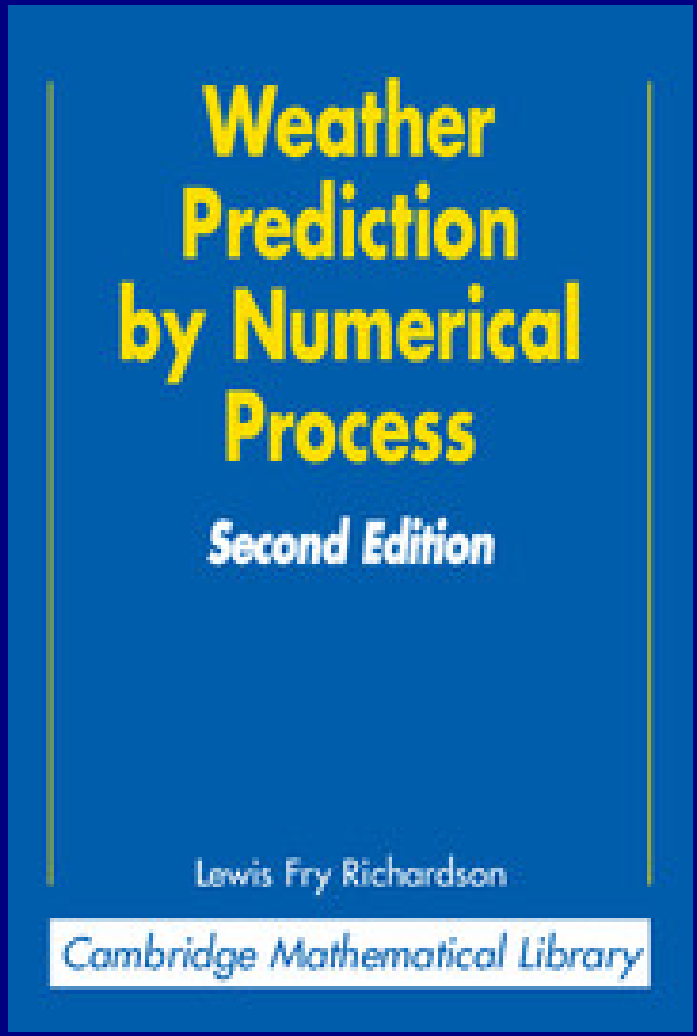


Table 1.1 *Chapter titles of* Weather Prediction by Numerical Process.

Chapter 1	Summary
Chapter 2	Introductory Example
Chapter 3	The Choice of Coordinate Differences
Chapter 4	The Fundamental Equations
Chapter 5	Finding the Vertical Velocity
Chapter 6	Special Treatment for the Stratosphere
Chapter 7	The Arrangement of Points and Instants
Chapter 8	Review of Operations in Sequence
Chapter 9	An Example Worked on Computing Forms
Chapter 10	Smoothing the Initial Data
Chapter 11	Some Remaining Problems
Chapter 12	Units and Notation

Table 1.2 *Page-count of* Weather Prediction by Numerical Process.

Dynamics	Momentum Equations	11		
	Vertical Velocity	10		
	The Stratosphere	24		
	Total Dynamics		45	
Numerics	Finite Differences	12		
	Numerical Algorithm	25		
	Total Numerics		37	
	Dynamics + Numerics			82
Physics	Clouds and Water	12		
	Energy and Entropy	8		
	Radiation	19		
	Turbulence	36		
	Surface, Soil, Sea	23		
	Total Physics			98
Miscellaneous	Summary	3		
	Initial Data	7		
	Analysis of Results	5		
	Smoothing	3		
	Forecast Factory	1		
	Computing Forms	23		
	Notation and Index	14		
	Total Miscellaneous			56
Total Pages				236

The Initial Response

Reviews were generally favourable:

- **"A strikingly original scientific work"**
- **"One of the most remarkable books on meteorology ever written."**
- **Sydney Chapman: "the enterprise contemplated in this book is of almost quixotic boldness".**
- **Edgar W. Woolard, U.S. Weather Bureau: "It is to be hoped that the author will continue his excellent work along these lines . . . and that others will follow."**

The Initial Response

However, not all reviews were so positive:

- **Napier Shaw:** **“the wildest guess at the pressure change would not have been wider of the mark.”**
- **Alexander McAdie, Harvard:** **The book “will probably be quickly placed on a library shelf . . . to rest undisturbed.”**

Whipple's Review

A perceptive review by F. J. W. Whipple, Met Office came closest to explaining Richardson's unrealistic forecast, postulating that rapidly-travelling waves contributed to its failure.

"The trouble that he meets is that quite small discrepancies in the estimate of the strengths of the winds may lead to comparatively large errors in the computed changes of pressure."

Whipple appears to have had a clear understanding of the causes of Richardson's forecast catastrophe.

Aftermath

Richardson's work was not taken seriously

His book failed to have any significant impact on the practice of meteorology for decades

Aftermath

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His book failed to have any significant impact on the practice of meteorology for decades

But finally . . .

. . . Richardson's brilliant and prescient ideas are now universally recognised and his work is the foundation upon which modern forecasting is built.

Met Office Website

1915 Nov 24 LFR

An early version of Richardson's gridded map

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Introduction

Pioneers of NWP: The Dream

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Max Margules

Richardson's Peace Studies

NWP Today

Forecast Factory: The Fantasy

1904: A Fateful Year

The year 1904 was pivotal for NWP:

- **Vilhelm Bjerknes'** announced his program for rational weather forecasting.
- **Felix Exner** attempted an actual calculation of the atmospheric changes.
- **Max Margules** demonstrated that weather prediction was fraught with danger.

Max Margules (1856–1920)

In 1904, Margules published a paper in the *Festschrift* marking the sixtieth birthday of his former teacher, the renowned physicist Ludwig Boltzmann:

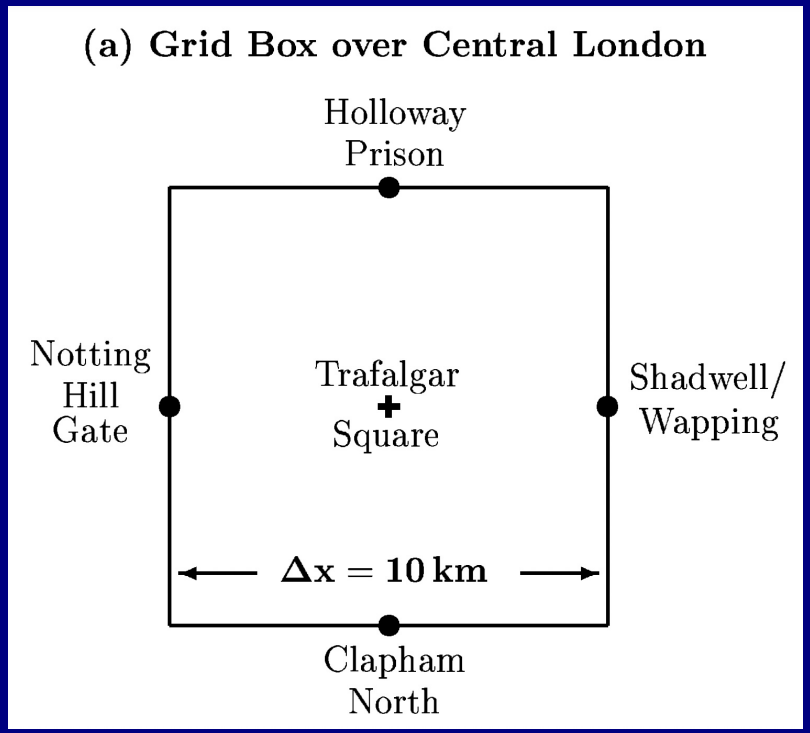
Über die Beziehung zwischen Barometerschwankungen und Kontinuitätsgleichung.

Margules' Approach

- Margules considered the possibility of predicting pressure changes using the continuity equation.
- He showed that, to obtain an accurate estimate of the pressure tendency, the winds would have to be known to an impractically high accuracy.
- So forecasting synoptic changes by this means was doomed to failure.

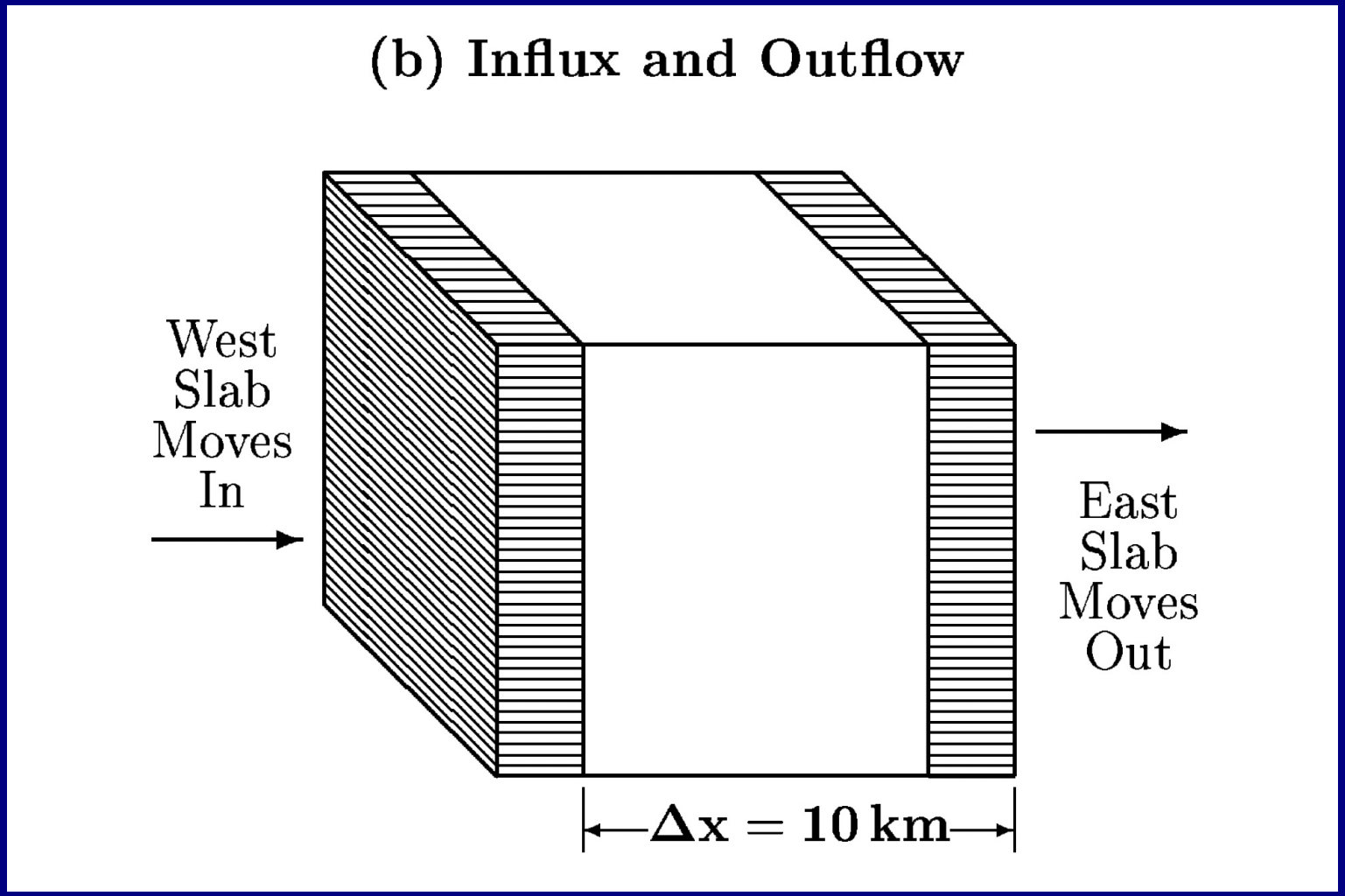
Margules conclusion:
Weather forecasting is *"immoral and damaging* to the character of a meteorologist" (Quote: Fortak, 2001).

Tendency from Continuity Equation

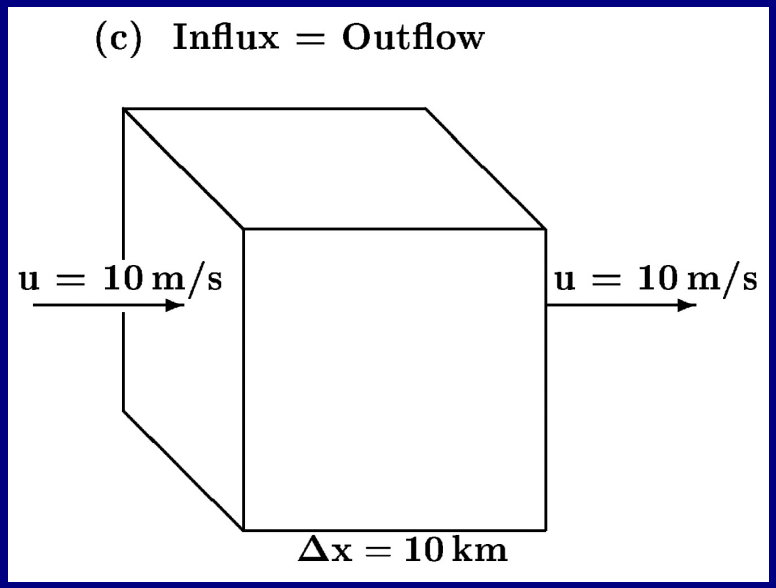


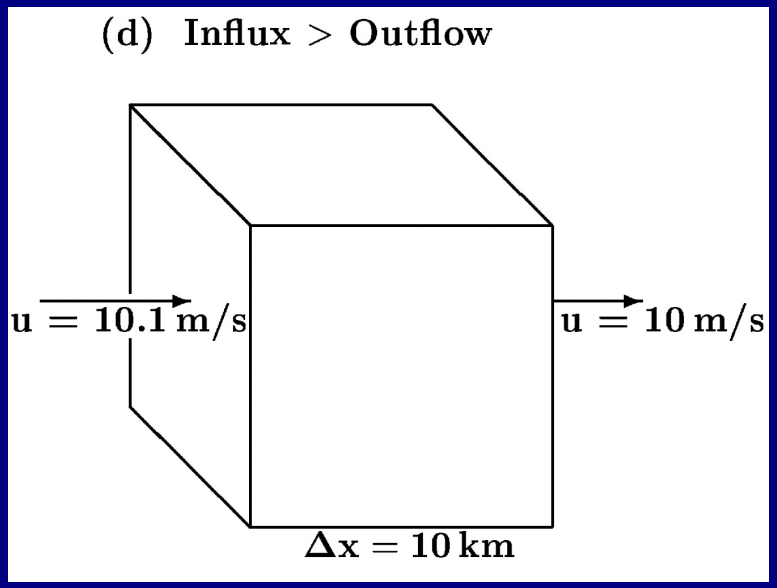
- Square of side 10 km over Central London.
- Like a cell of an atmospheric model.

“What Flows In Must Flow Out?”



A Box of Air over London





Influx equals Outflow:
Pressure unchanged.

Influx exceeds Outflow:
Pressure will rise.

Pressure Tendency

Assume a westerly wind over London

$$u > 0\,, \qquad v = 0\,.$$

Assume the surface pressure is initially 1000 hPa.

Using Conservation of Mass, a simple calculation yields the following amazing result:

- **If the speed on the western side *exceeds* that on the east by 0.1 m/s, then $\partial p_s/\partial t \approx 1$ Pa/s.**
- **If this influx continues, the pressure will *double* in a day.**

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We must use the continuity equation with great care!

Richardson and Margules

Margules sent a copy of his 1904 paper to the Met Office. His results showed that LFR's approach was doomed from the outset.

Richardson ascribed the difficulties with his predicted tendency to spurious divergence values.

It seems that Richardson was unaware of Margules' paper. He makes no reference to it.

Had Richardson been aware Margules' results, he might have decided not to proceed with his forecast.

Later, LFR proposed using the vertical component of vorticity as a primary variable.

Outline

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Pioneers of NWP: The Dream

Lewis Fry Richardson

Max Margules

Richardson's Peace Studies

NWP Today

Forecast Factory: The Fantasy

Digression: Peace Studies

- Richardson retired early to devote all his energies to peace studies.
- His mathematical analysis of the causes of war were ahead of their time.
- His seminal work was Arms and Insecurity.
- In a letter to *Nature* he posed the question: "Must an arms race necessarily lead to warfare?"
- In 1985, Oliver Ashford wrote: "Let us hope that before long history will show that an arms race can indeed end without fighting."

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- In 1985, Oliver Ashford wrote: "Let us hope that before long history will show that an arms race can indeed end without fighting."
- Four years later the collapse of the Soviet Union brought the nuclear arms race to an abrupt end.

Observation of Henry Stommel (1985)

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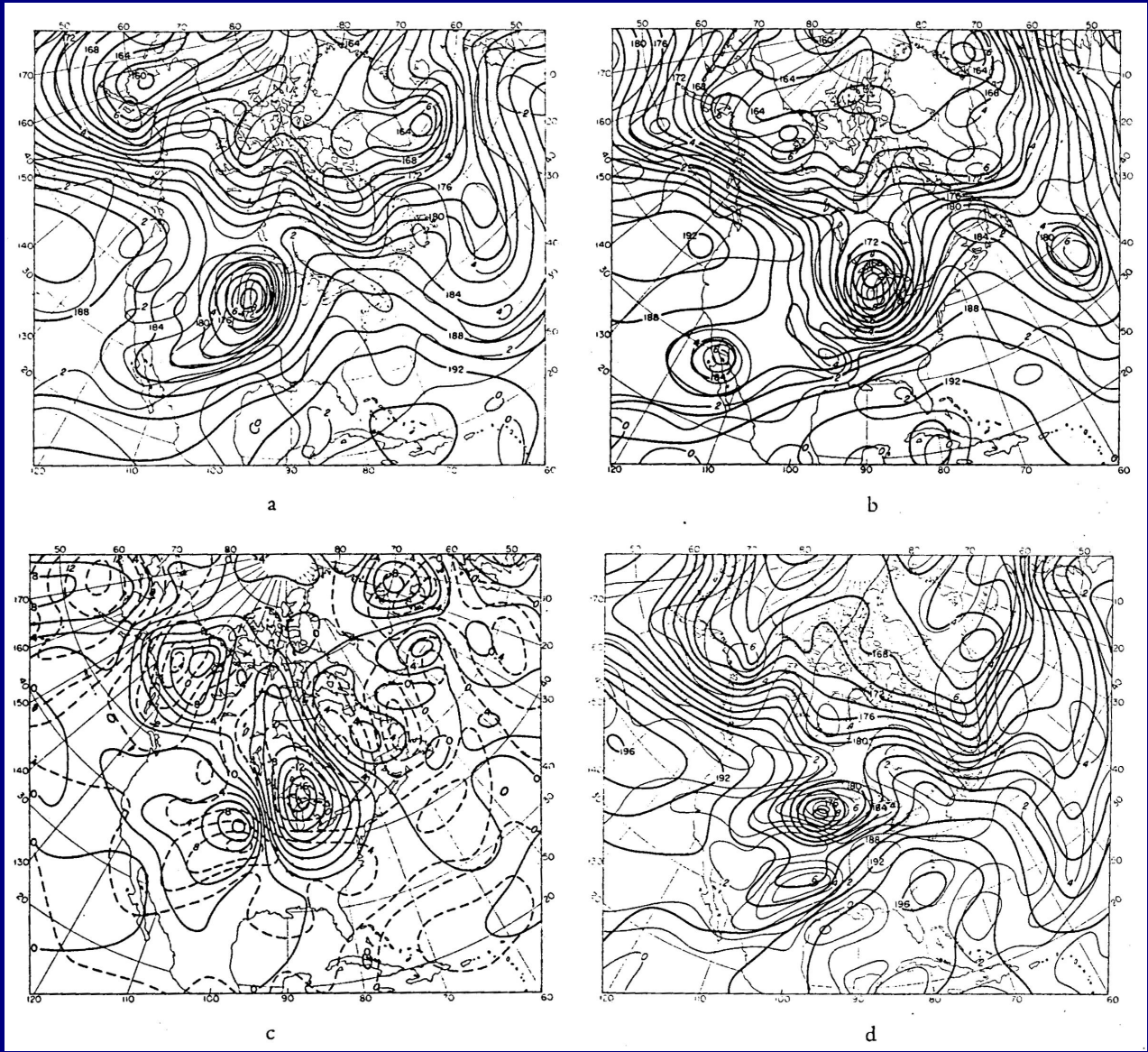
Crucial Advances, 1920–1950

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

ENIAC Forecast for Jan 5, 1949



Weather and Climate Models

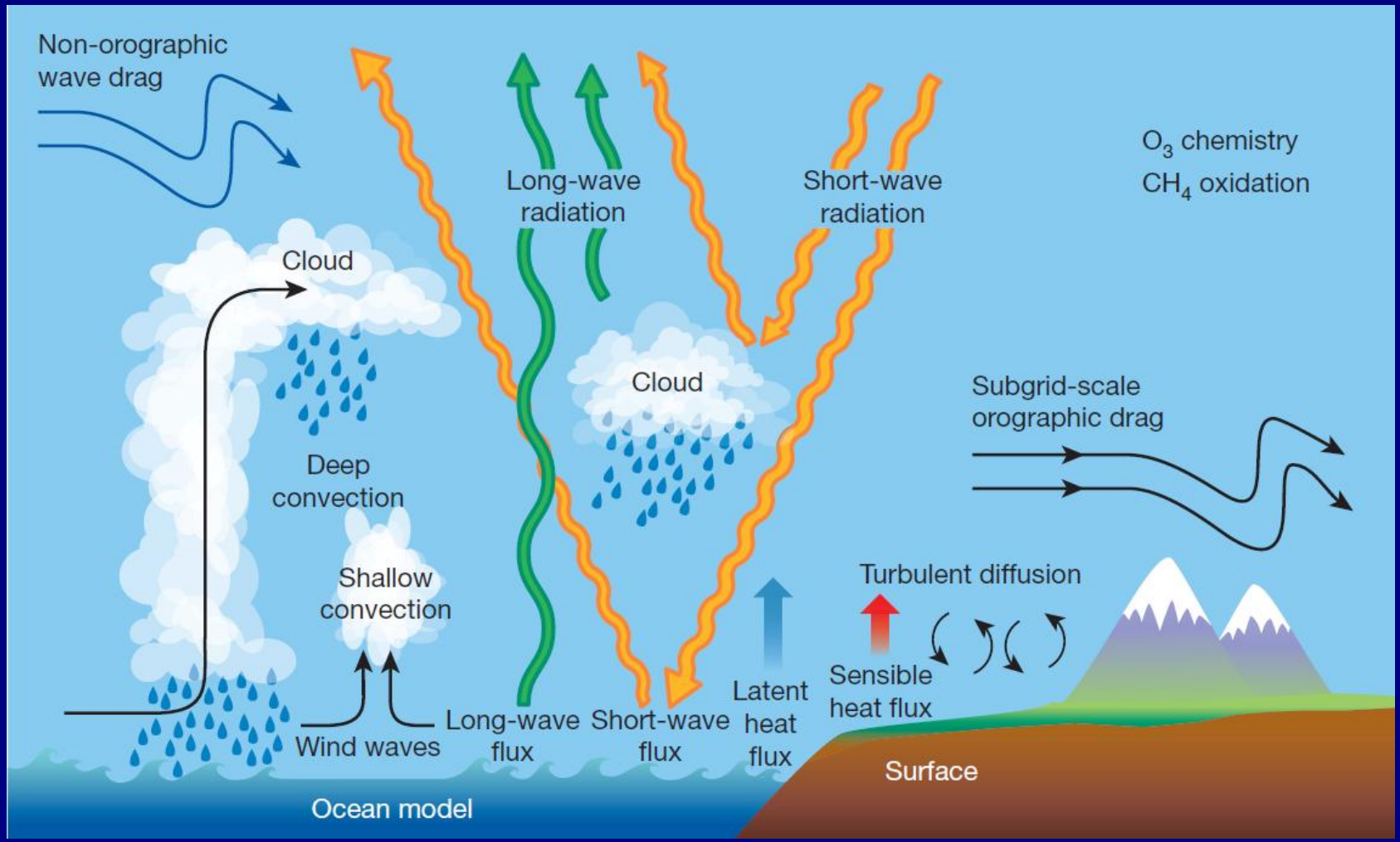
Computer models for simulating weather and climate are known as **Earth System Models.**

They are of great complexity.

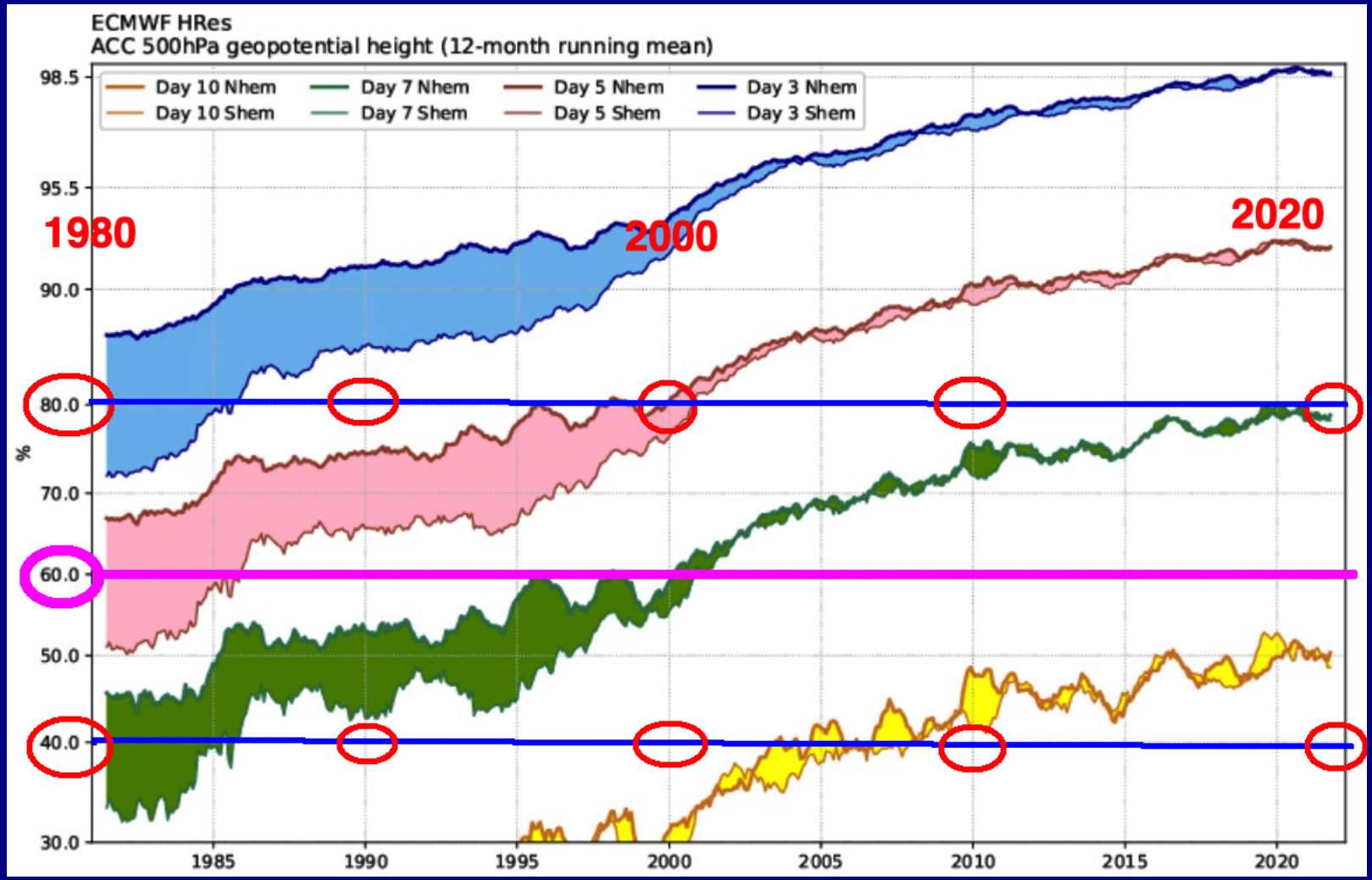
At the heart of every model is a **Dynamical Core.**

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

Physical Processes in the Atmosphere



Forecast Skill: Onward and Upward



ECMWF Forecast Skill over 40 Years

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.

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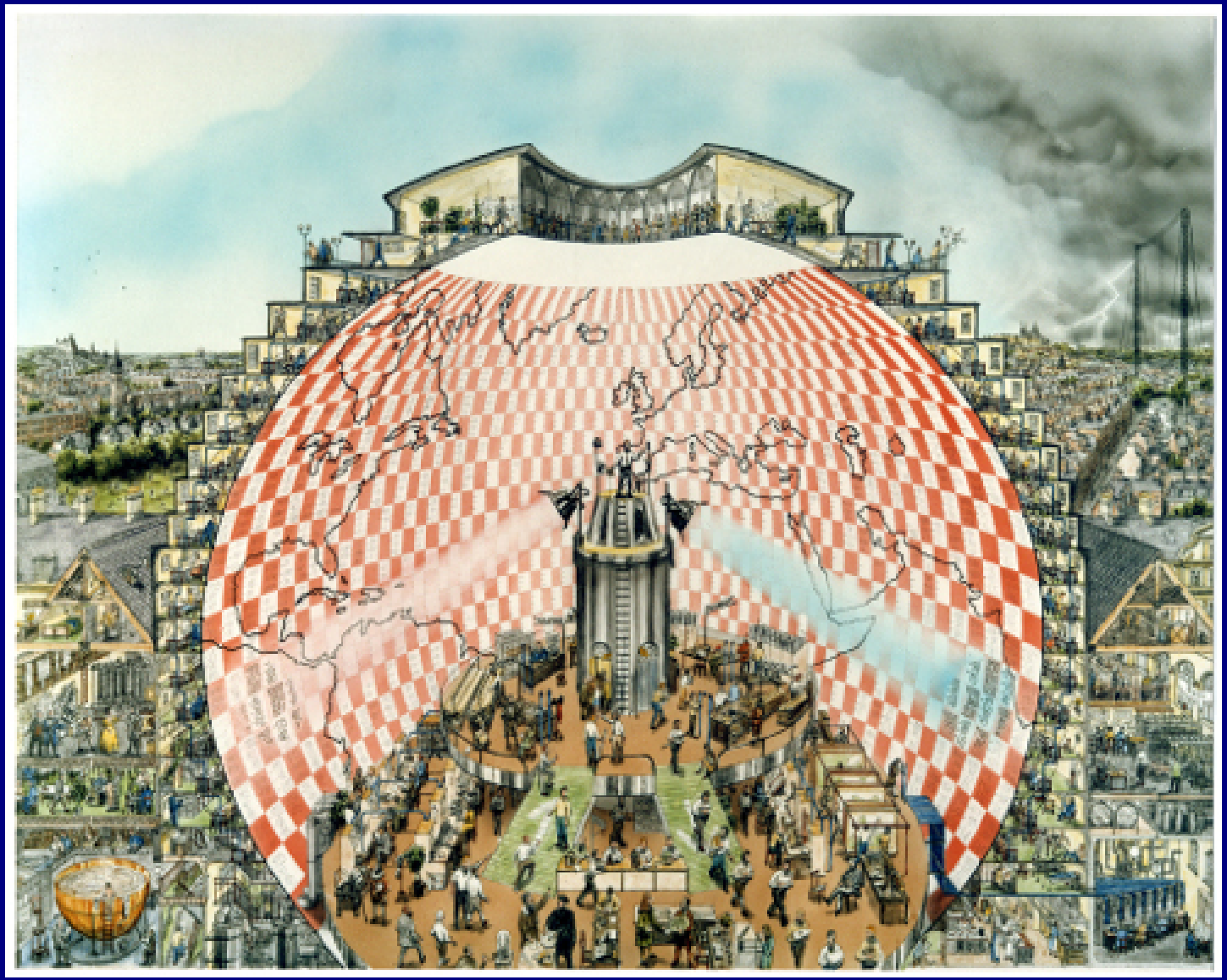
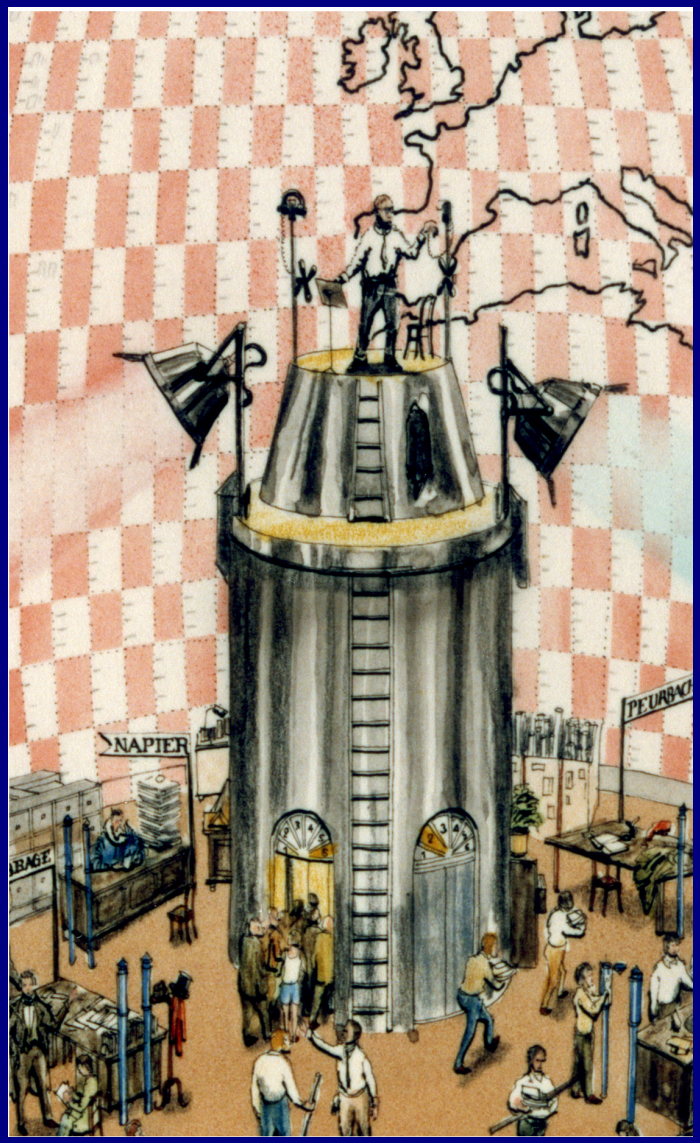


©Stephen Conlin, 1986

Zoom: Richardson Directing the Forecast



Lewis Fry Richardson conducting the forecast

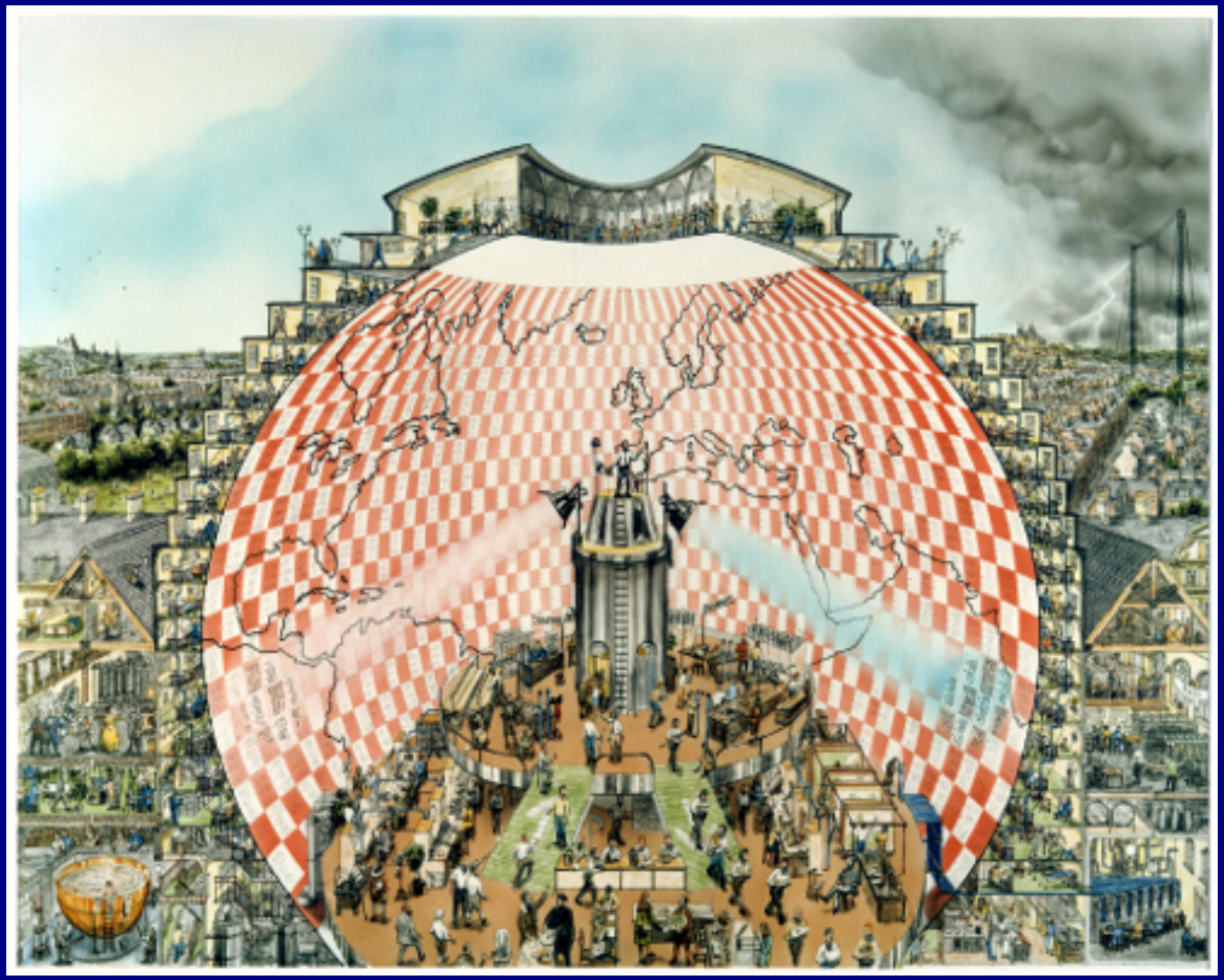
Zoom: Historical Figures in Computing

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.**

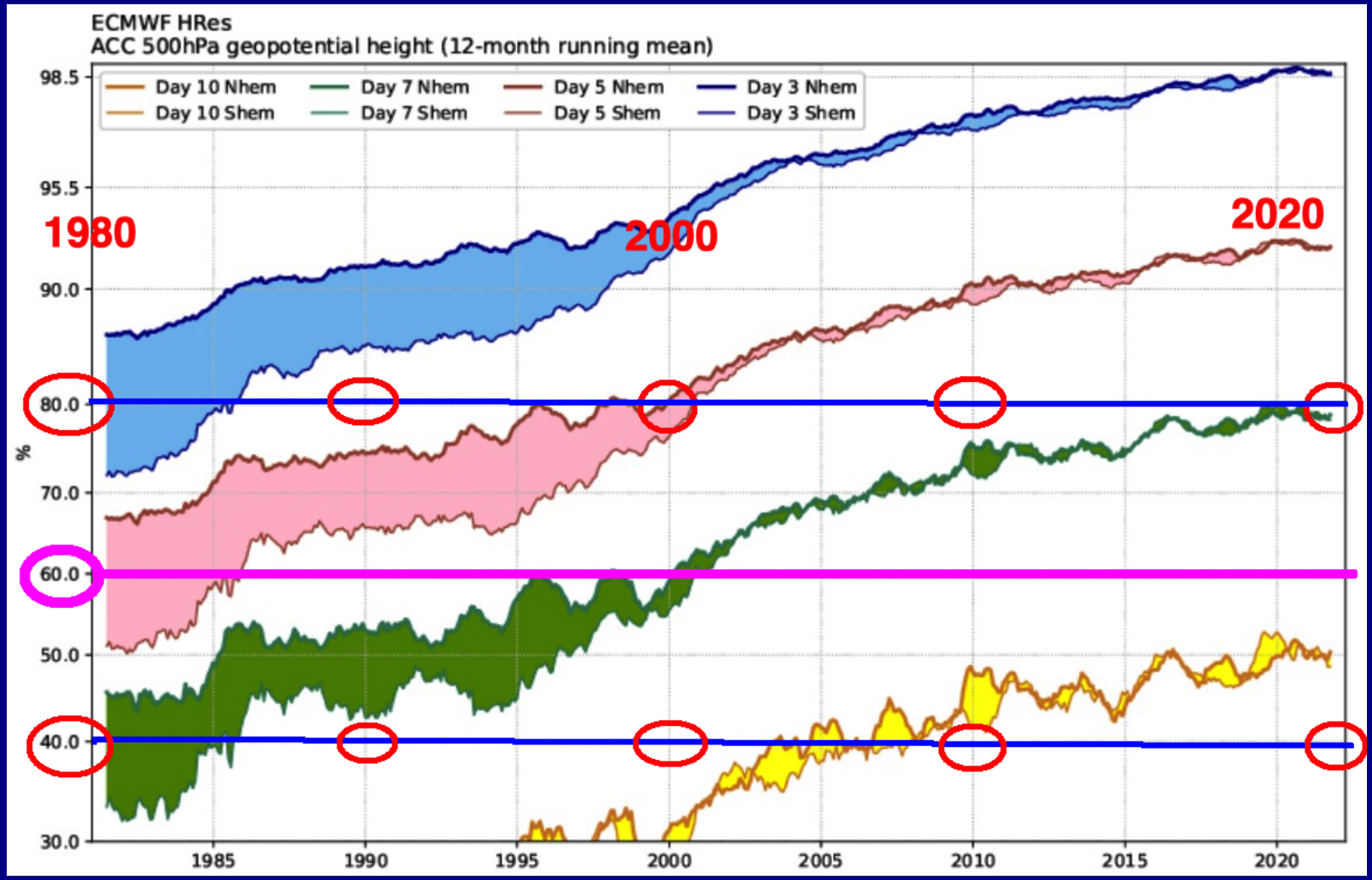
[Reprint on my website]

High-res Image with Zoom on website of European Meteorological Society:

http://www.emetsoc.org/

Thank you

Forecast Skill: Onward and Upward



Anomaly correlation of 500 hPa geopotential height