The Emergence of Numerical Weather Prediction: Richardson's Dream to the ENIAC

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Outline of the lecture

- *Pre-history of NWP*
- *Abbe, Bjerknes, Richardson*
- *Richardson's Forecast*
- *Developments, 1920–1950*
- *The ENIAC Integrations*
- *The Emergence of Operational NWP*

Newton's Law of Motion

The rate of change of momentum of a body is equal to the sum of the forces acting on the body.

$$\textbf{Force} = \textbf{Mass} \times \textbf{Acceleration}.$$

Edmund Halley (1656–1742)

Edmund Halley was a contemporary and friend of Isaac Newton; this was quite an achievement: Newton didn't have too many friends!

He was largely responsible for persuading Newton to publish his *Principia Mathematica*.

Halley and his Comet

Halley's analysis of a comet was an excellent example of the scientific method in action.

Observation:

The comets of 1456, 1531, 1607, and 1682 followed similar orbital paths around the Sun. Each appearance was separated from the previous one by about 76 years.

Hypothesis:

These events were due to the reappearance of one object on an orbit which brought it close to the Sun every 76 years.

Prediction:

In 1705, Halley forecast that the comet would return again in late 1758. Halley died in 1742.

Verification:

The comet was sighted, on schedule, on Christmas Day 1758 and has since borne Halley's name.

Further Confirmation:

Appearances of the comet have since been found in the historic record as far back as 2000 years.

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A Tricky Question

If the Astronomers can make accurate 76-year forecasts, why can't the Meteorologists do the same?

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- Size of the Problem

  Cometary motion is a relatively simple problem, with few degrees of freedom; Dynamics is enough.

  The atmosphere is a continuum with infinitely many variables; Thermodynamics is essential.

- Order versus Chaos

  The equations of the solar system are quasi-integrable and the motion is regular.

  The equations of the atmosphere are essentially nonlinear and the motion is chaotic.

The Navier-Stokes Equations

Euler's Equations:

$$\frac{\partial \mathbf{V}}{\partial t} + \mathbf{V} \cdot \nabla \mathbf{V} + \frac{1}{\rho} \nabla p = \mathbf{g} \,.$$

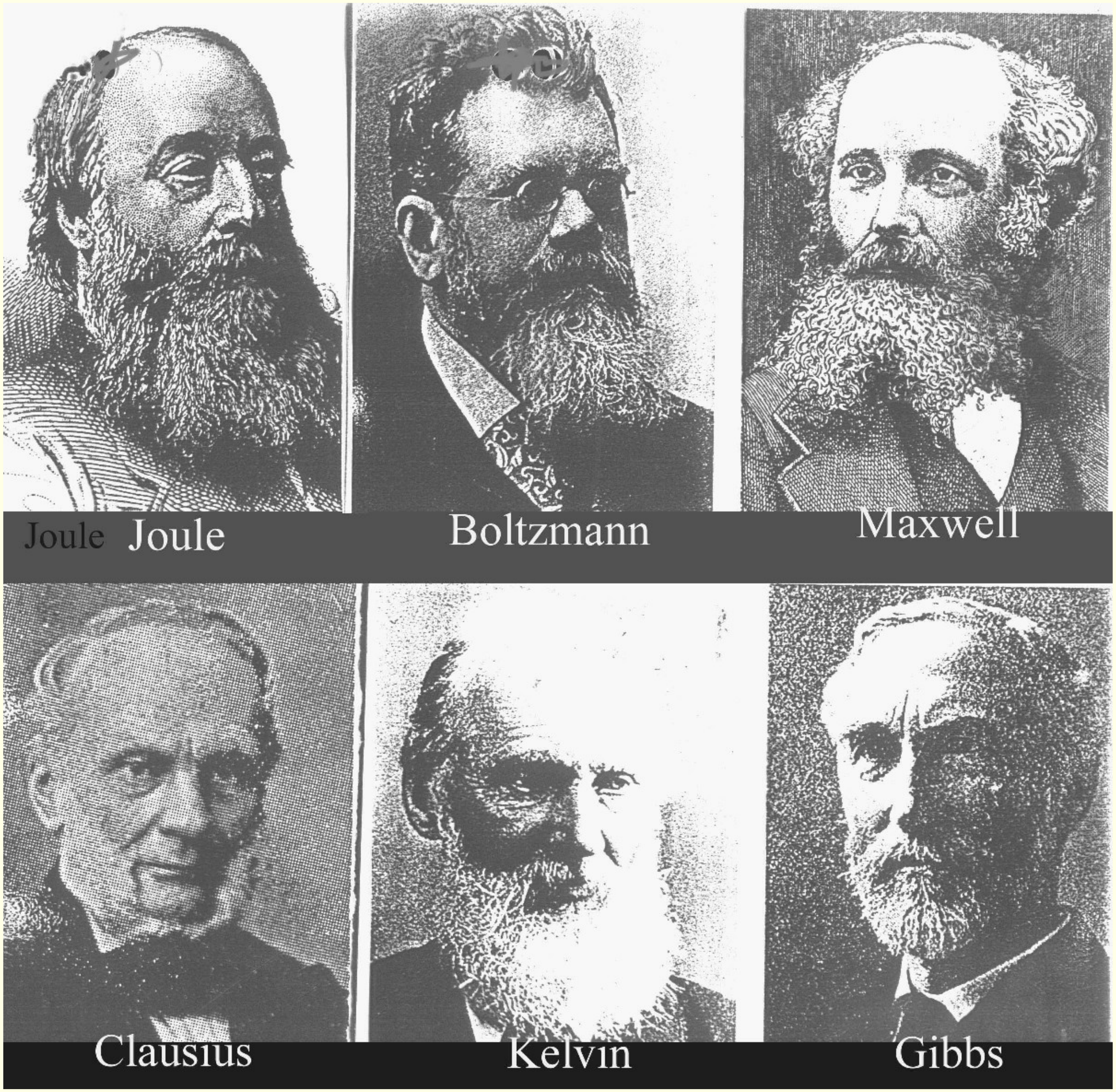
The Navier-Stokes Equations

$$\frac{\partial \mathbf{V}}{\partial t} + \mathbf{V} \cdot \nabla \mathbf{V} + \frac{1}{\rho} \nabla p = \nu \nabla^2 \mathbf{V} + \mathbf{g}^\star \,.$$

Motion on the rotating Earth:

$$\frac{\partial \mathbf{V}}{\partial t} + \mathbf{V} \cdot \nabla \mathbf{V} + 2\mathbf{\Omega} \times \mathbf{V} + \frac{1}{\rho} \nabla p = \nu \nabla^2 \mathbf{V} + \mathbf{g} \,.$$

The Inventors of Thermodynamics



The Equations of the Atmosphere

GAS LAW (Boyle's Law and Charles' Law.)
Relates the pressure, temperature and density

CONTINUITY EQUATION
Conservation of mass; air neither created nor distroyed

WATER CONTINUITY EQUATION
Conservation of water (liquid, solid and gas)

EQUATIONS OF MOTION: Navier-Stokes Equations
Describe how the change of velocity is determined by the pressure gradient, Coriolis force and friction

THERMODYNAMIC EQUATION
Determines changes of temperature due to heating or cooling, compression or rarifaction, etc.

Seven equations; seven variables (u, v, w, ρ, p, T, q).

The Primitive Equations

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

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

$$p = R\rho T$$

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

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

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

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

Seven equations; seven variables $(u, v, w, p, T, \rho, \rho_w)$**.**

Scientific Weather 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"**

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- **The equations are very complicated (non-linear) and a powerful computer is required to do the calculations**
- **The accuracy decreases as the range increases; there is an inherent limit of predictibility.**

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 (1862–1951)

Bjerknes' 1904 Manifesto

Objective:
To establish a science of meteorology

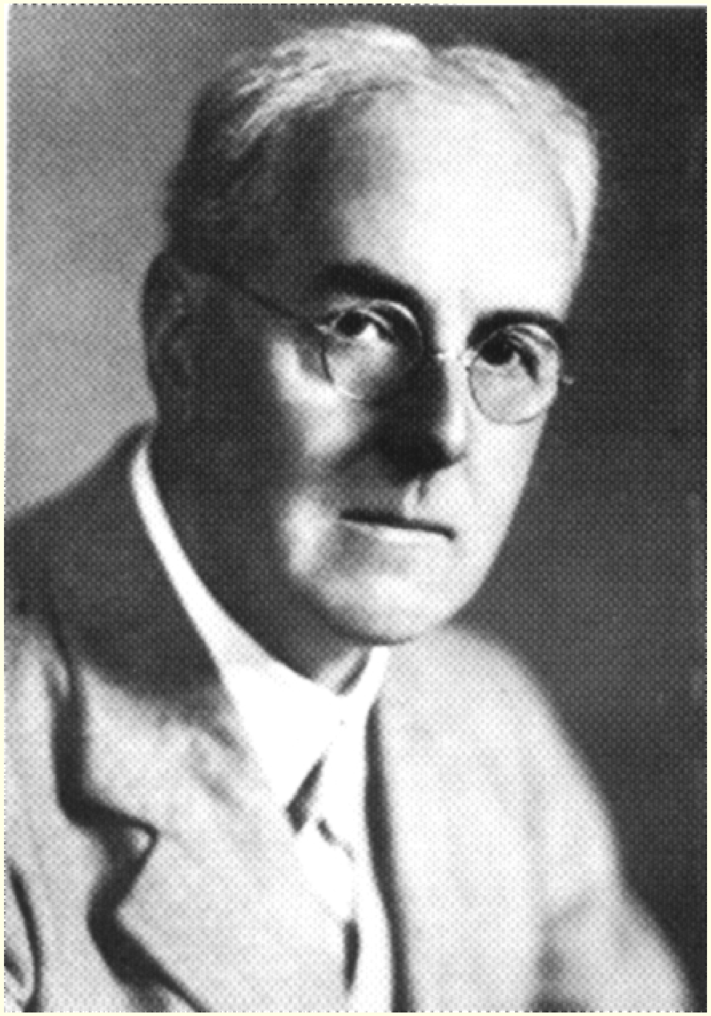
Purpose:
To predict future states of the atmosphere.

Necessary and sufficient conditions for the solution of the forecasting problem:

1. **A knowledge of the initial state**
2. **A knowledge of the physical laws**

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

Lewis Fry Richardson, 1881–1953.



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

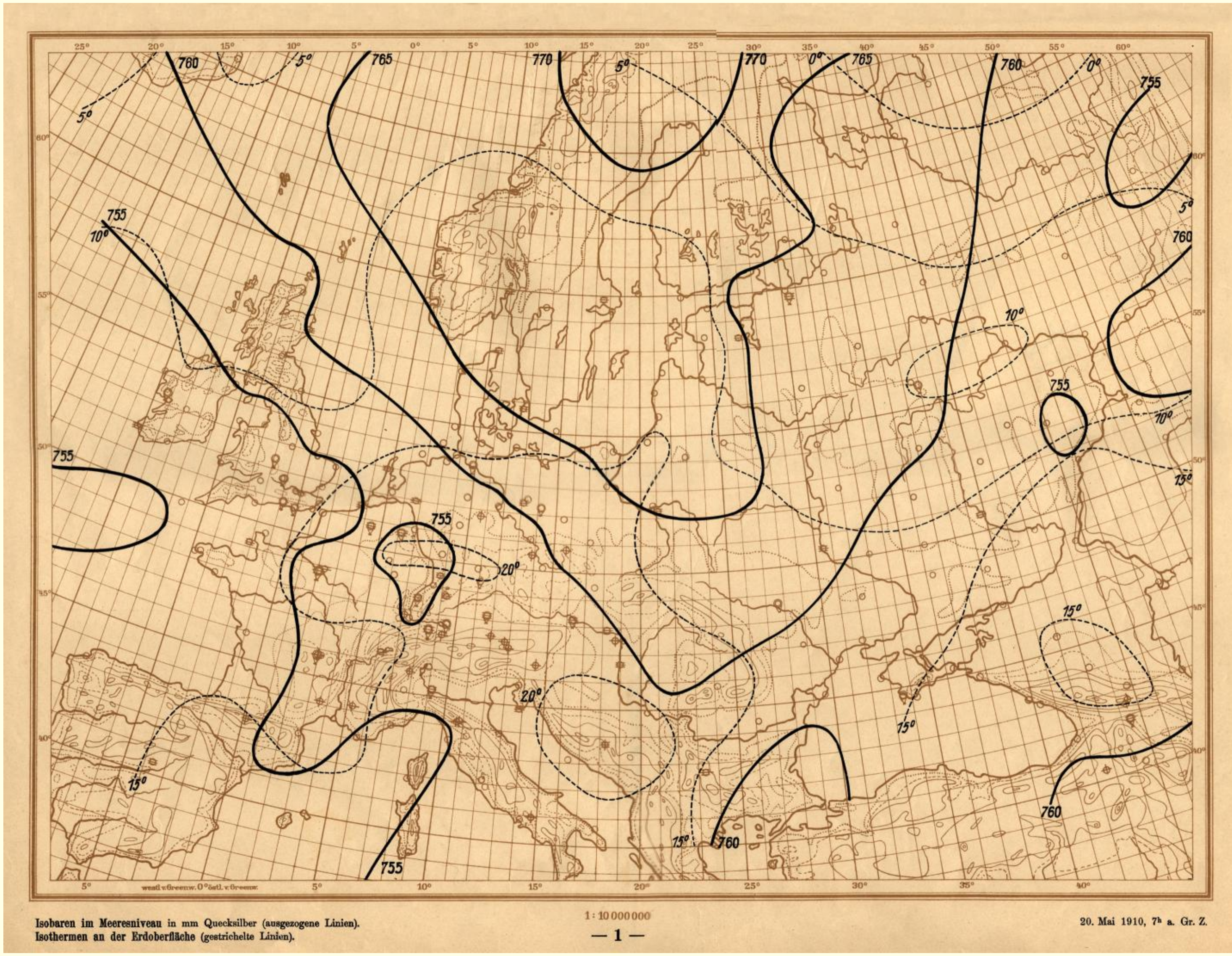
It took him two years !

His 'forecast' was a catastrophic failure:

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

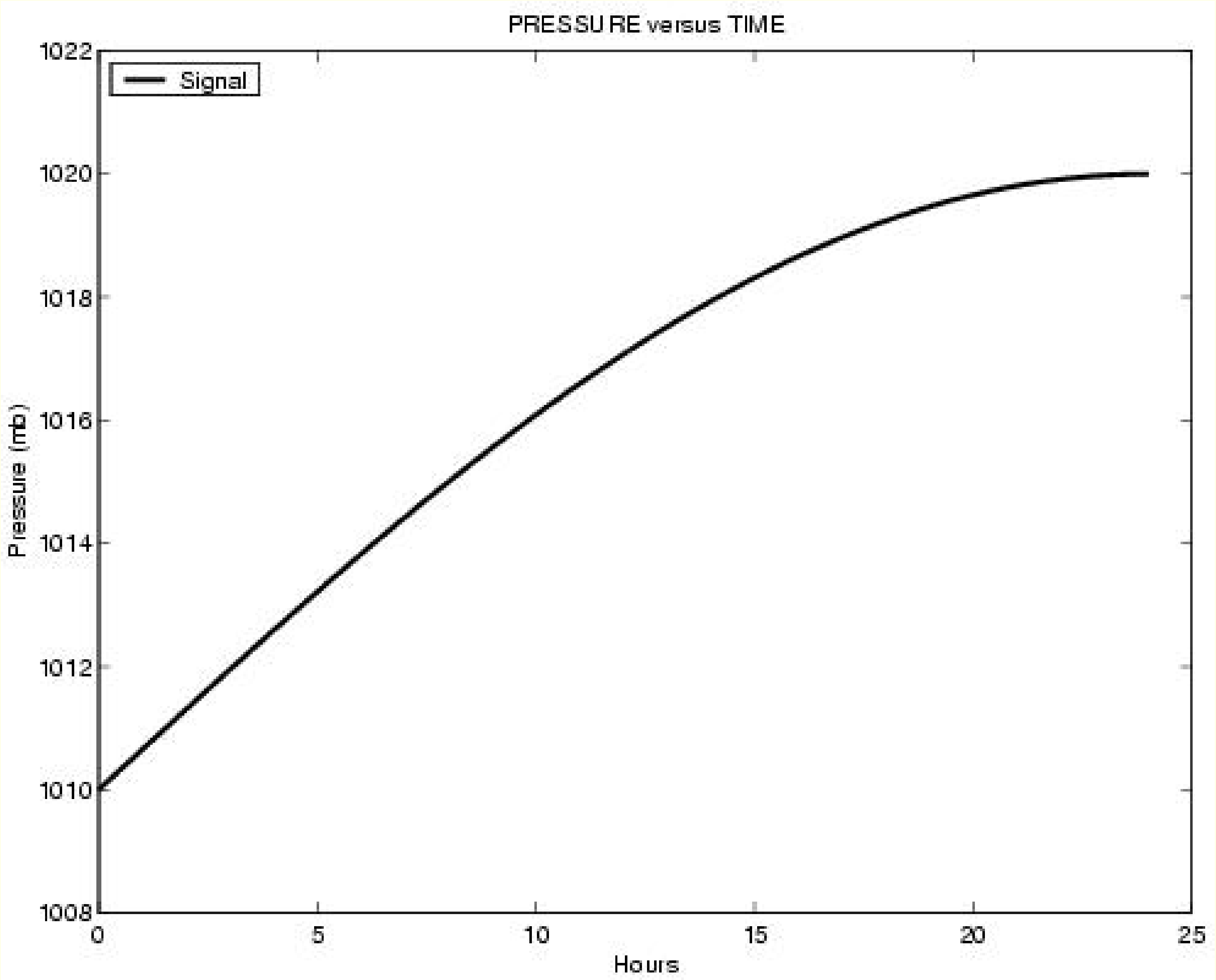
But Richardson's method was scientifically sound.

The Leipzig Charts for 0700 UTC, May 20, 1910

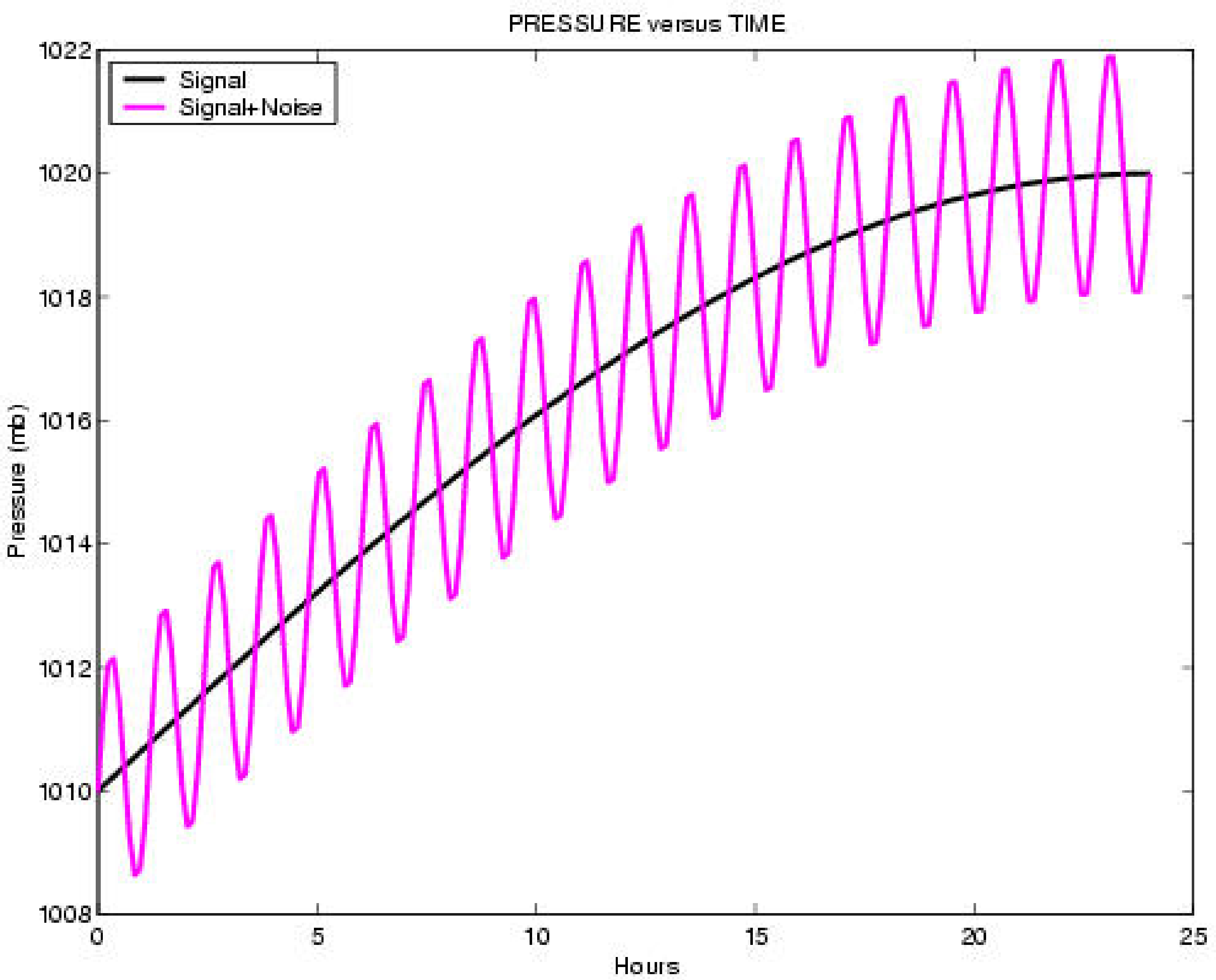


Bjerknes' sea level pressure analysis.

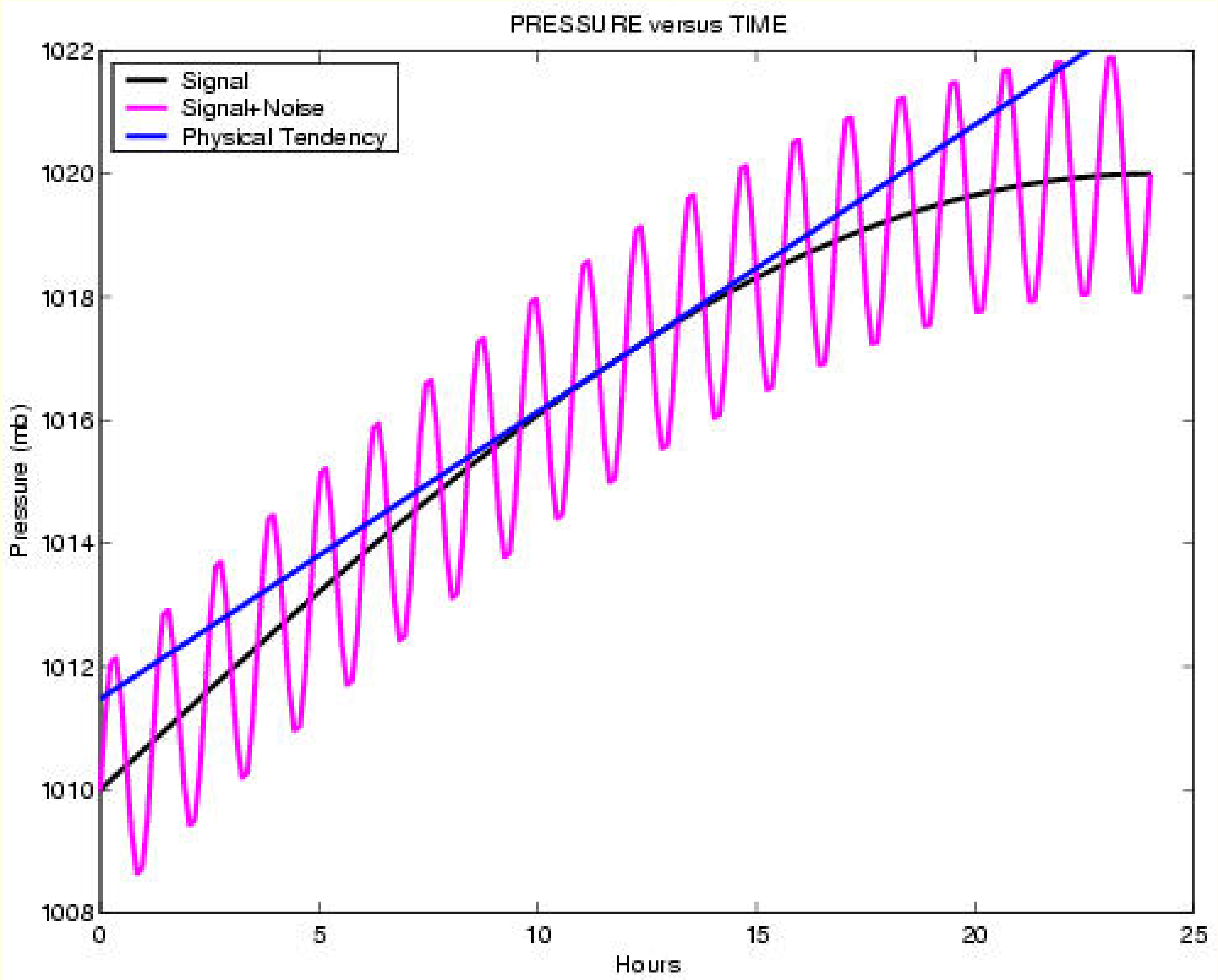
A Smooth Signal



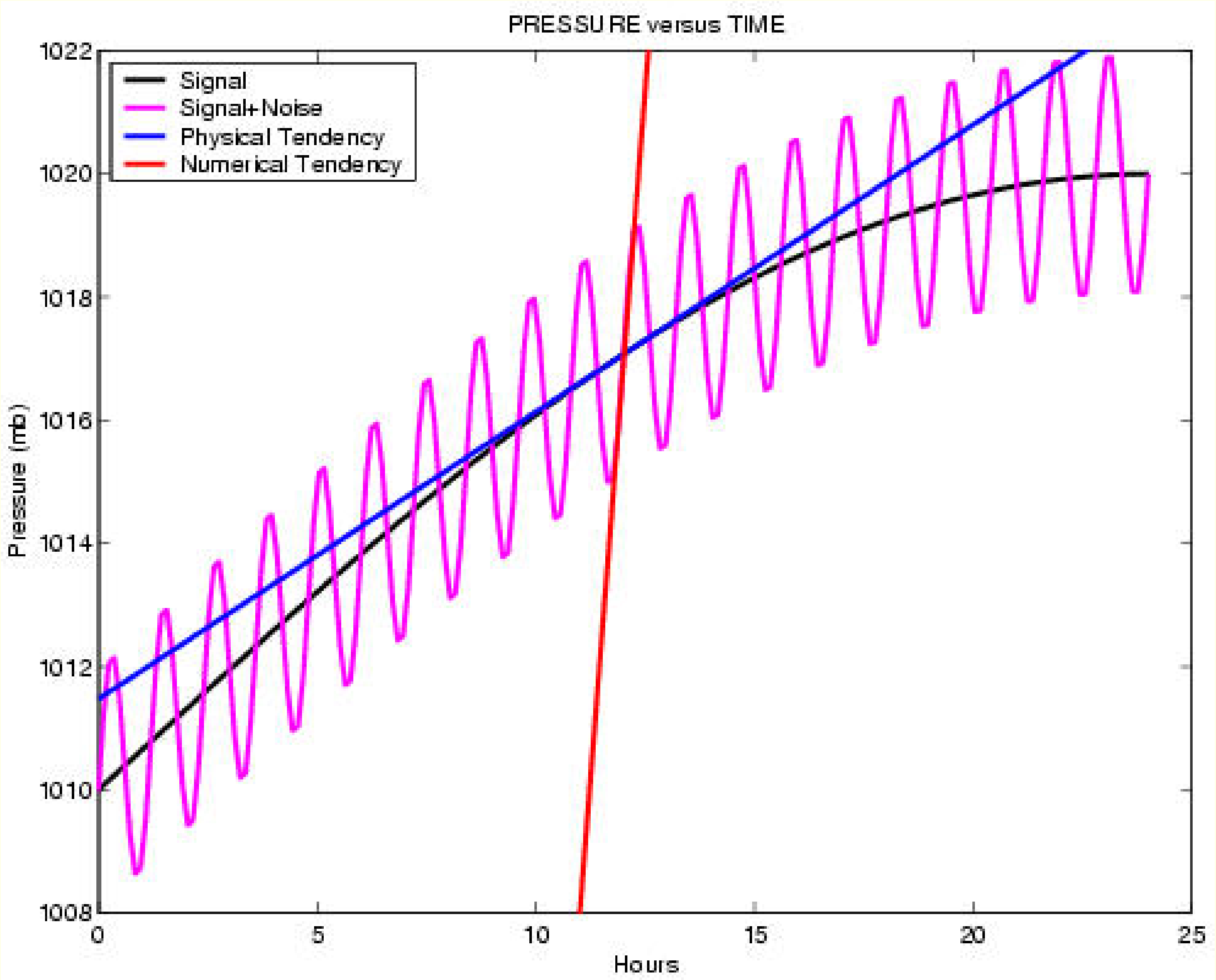
A Noisy Signal

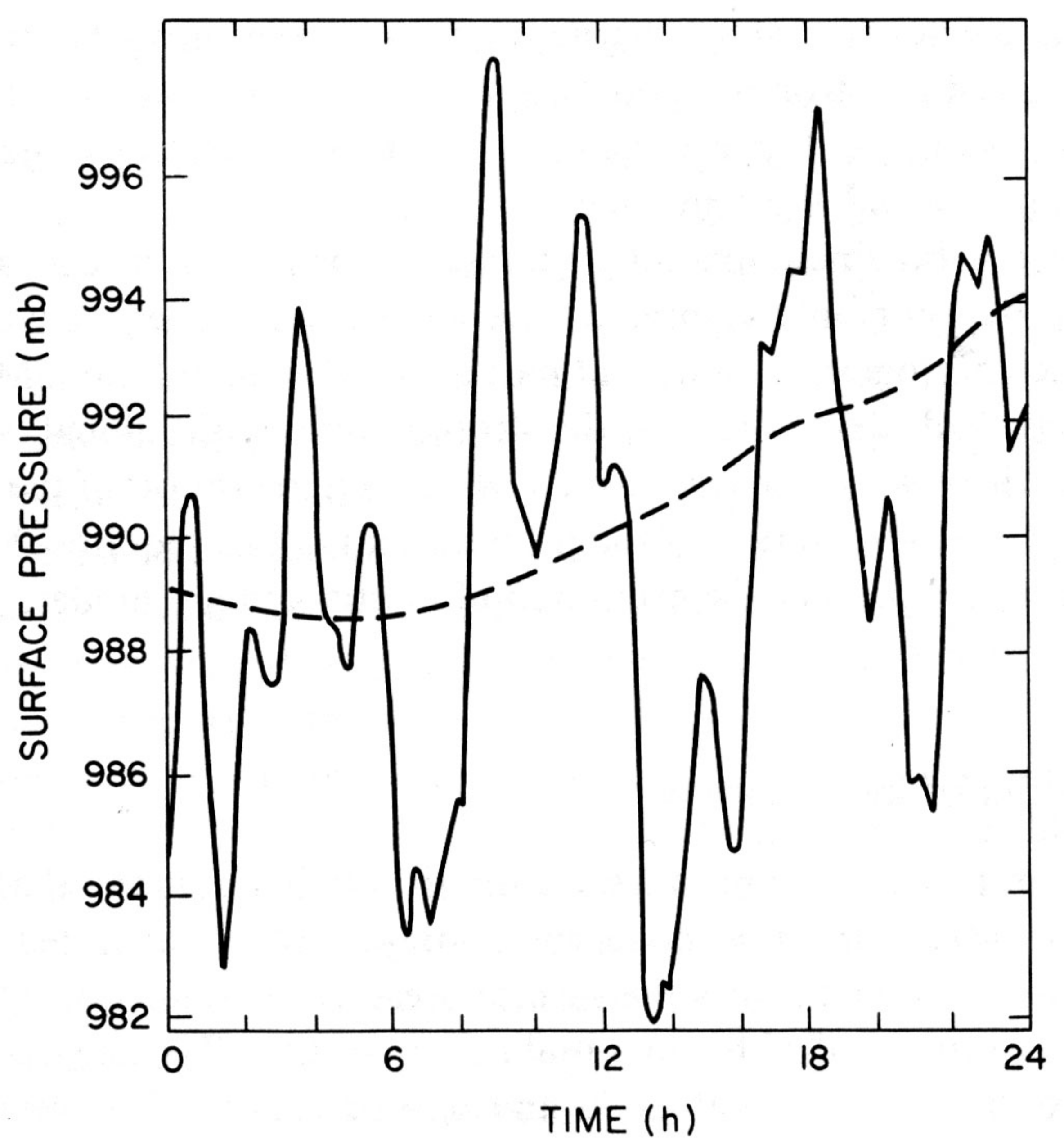


Tendency of a Smooth Signal



Tendency of a Noisy Signal





Evolution of surface pressure before and after NNMI.

(Williamson and Temperton, 1981)

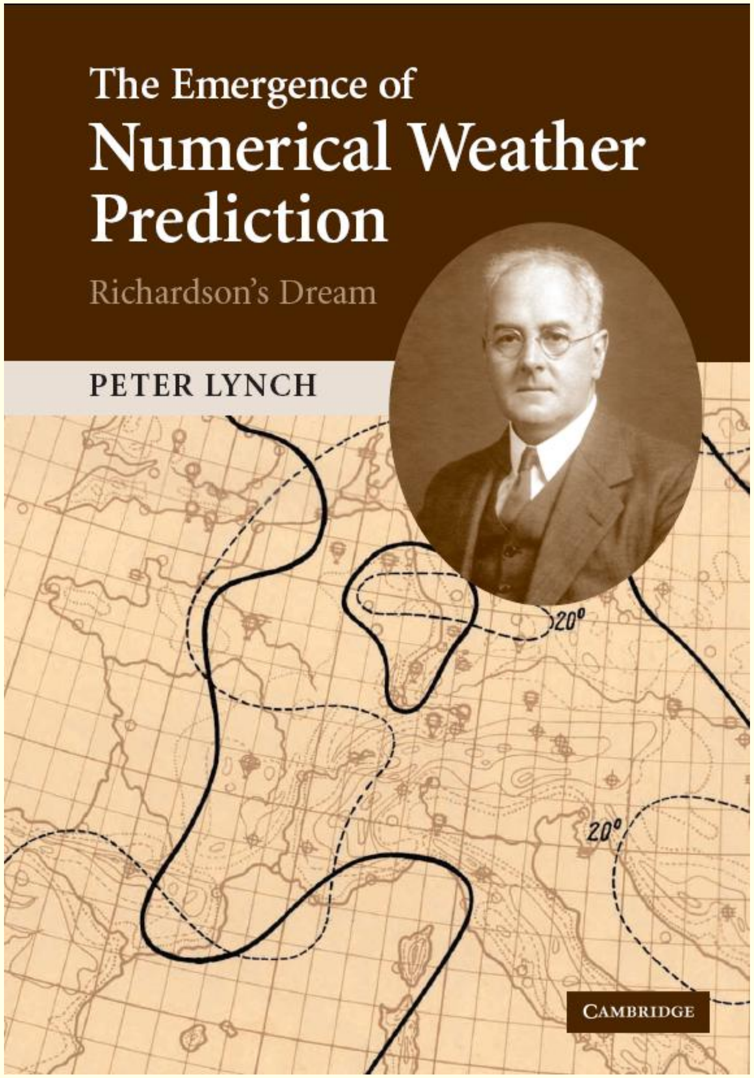
Initialization of Richardson's Forecast

Richardson's Forecast has been repeated on a computer.

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

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

Observations: The barometer was steady!



Richardson's Forecast and the emergence of NWP are described in a recent book.

Richardson's Forecast Factory

©François Schuiten

Richardson's Forecast Factory

©François Schuiten

64,000 Computers: The first Massively Parallel Processor

Crucial Advances, 1920–1950

- *Dynamic Meteorology*
  - Rossby Waves
  - Quasi-geostrophic Theory
  - Baroclinic Instability
- *Numerical Analysis*
  - CFL Criterion
- *Atmopsheric Observations*
  - Radiosonde
- *Electronic Computing*
  - ENIAC

The Meteorology Project

Project estblished by John von Neumann in 1946.

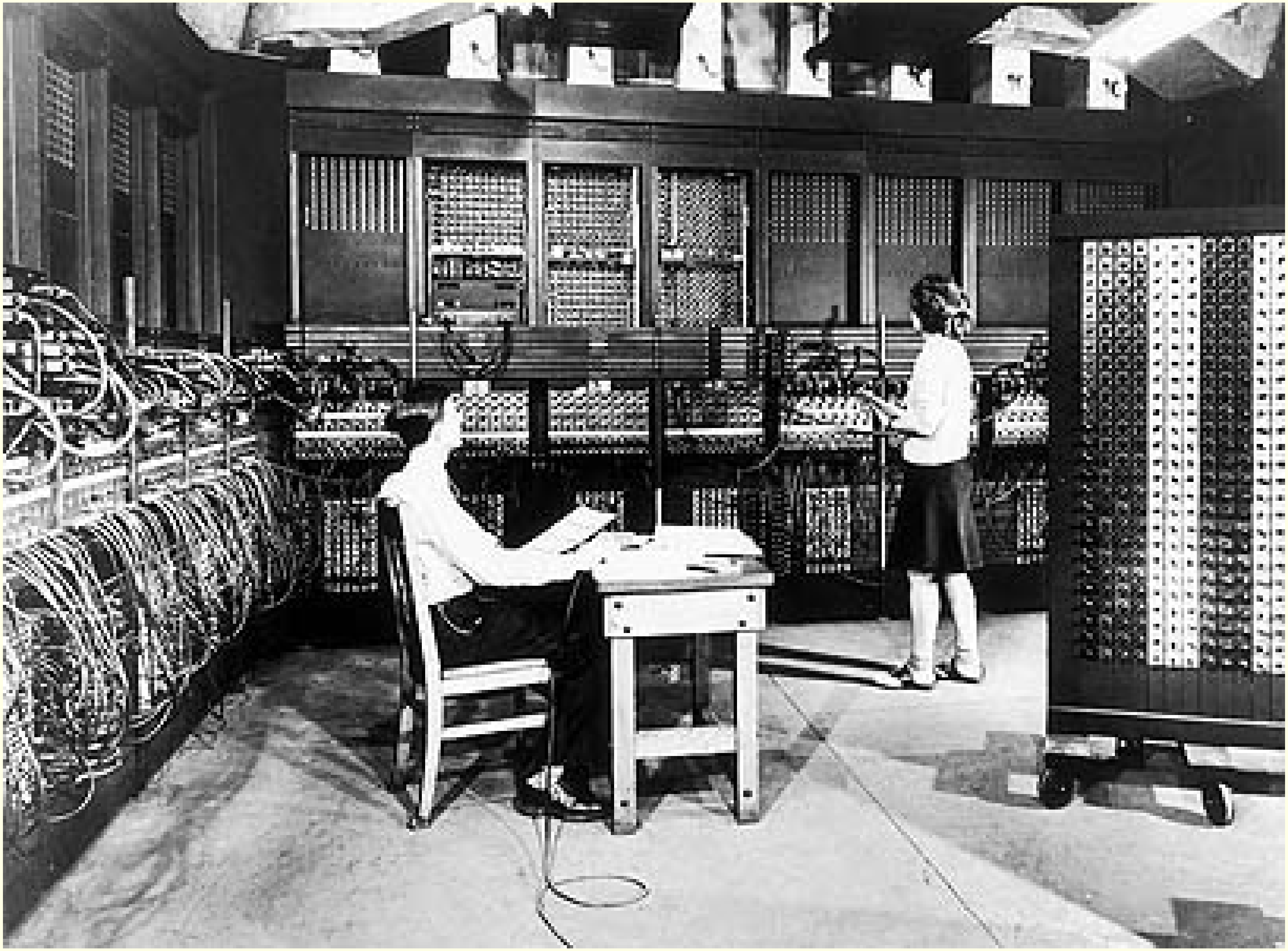
Objective of the project:

To study the problem of predicting the weather using a digital electronic computer.

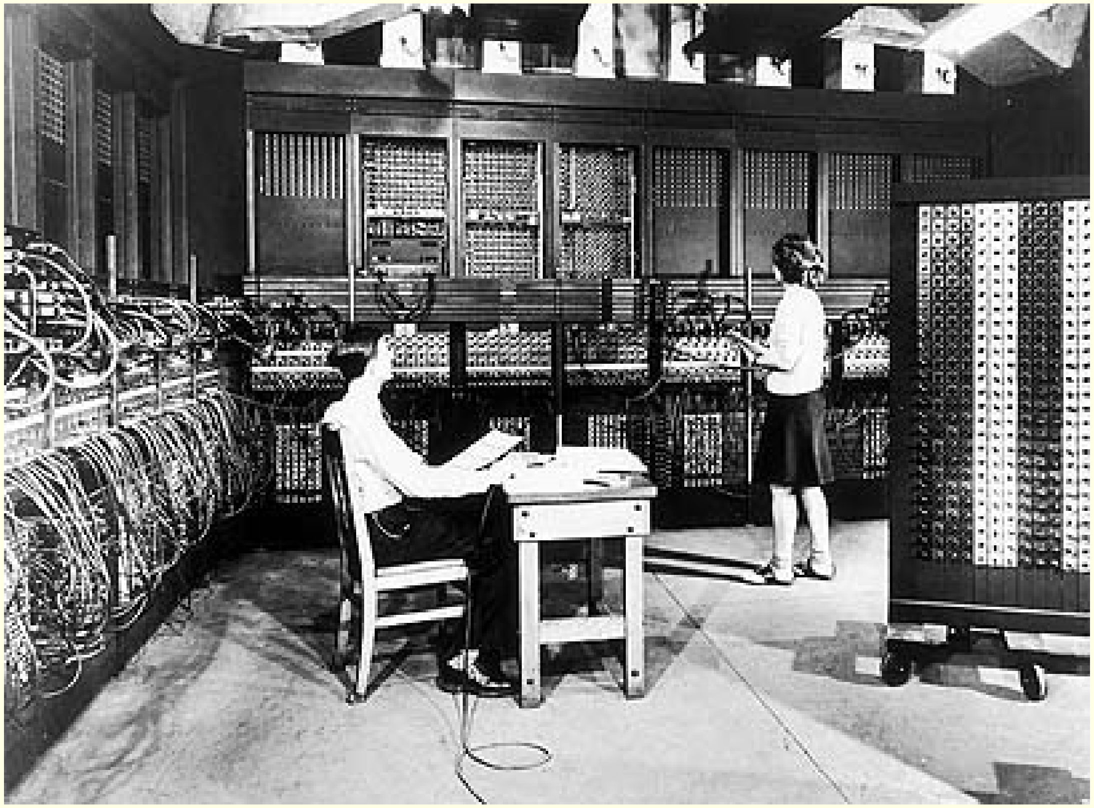
A Proposal for Funding listed three “possibilities”:

- ***New methods of weather prediction***
- ***Rational basis for planning observations***
- ***Step towards influencing the weather!***

The ENIAC



The ENIAC

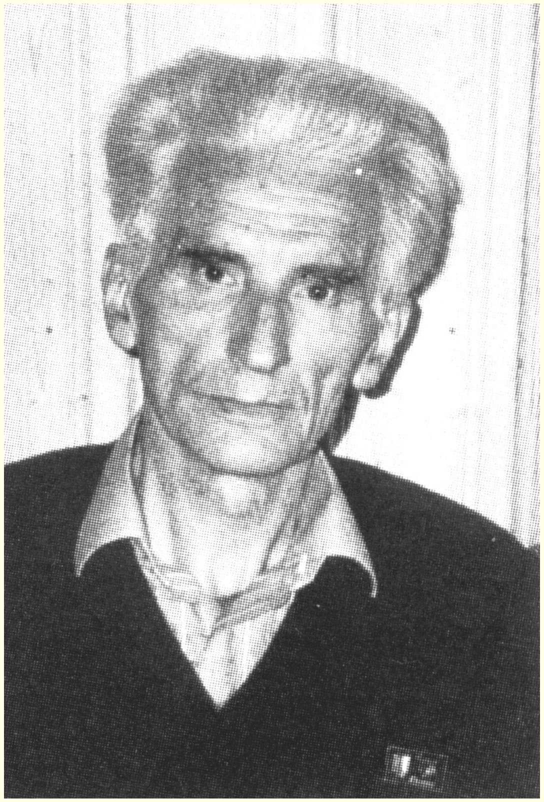


The **ENIAC** was the first multi-purpose programmable electronic digital computer.

It had:

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

Charney, Fjørtoft, von Neumann


Charney **Fjørtoft** **von Neumann**

Numerical integration of the barotropic vorticity equation

***Tellus*, 2, 237–254 (1950).**

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

$$\begin{bmatrix}\textbf{Absolute}\\ \textbf{Vorticity}\end{bmatrix} = \begin{bmatrix}\textbf{Relative}\\ \textbf{Vorticity}\end{bmatrix} + \begin{bmatrix}\textbf{Planetary}\\ \textbf{Vorticity}\end{bmatrix} \qquad \eta = \zeta + f\,.$$

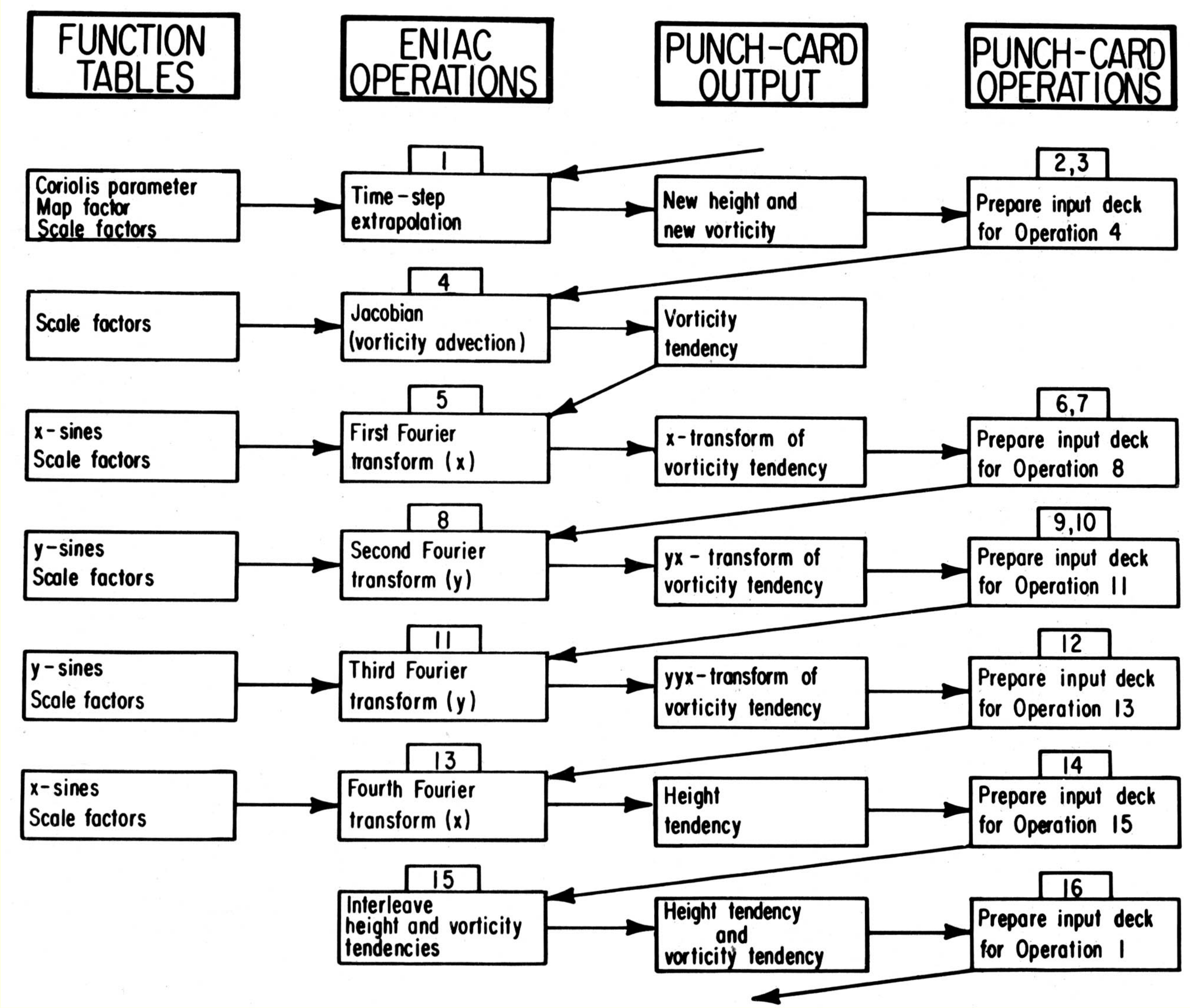
- **The atmosphere is treated as a single layer.**
- **The flow is assumed to be nondivergent.**
- **Absolute vorticity is conserved.**

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

This equation looks deceptively simple. But it is nonlinear:

$$\frac{\partial}{\partial t}[\nabla^2\psi] + \left\{\frac{\partial\psi}{\partial x}\frac{\partial\nabla^2\psi}{\partial y} - \frac{\partial\psi}{\partial y}\frac{\partial\nabla^2\psi}{\partial x}\right\} + \beta\frac{\partial\psi}{\partial x} = 0\,,$$

ENIAC Algorithm



Flow-chart for the computations.

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

$$\frac{d}{dt}(\zeta + f) = \frac{\partial\zeta}{\partial t} + \mathbf{V}\cdot\nabla(\zeta + f) = 0$$

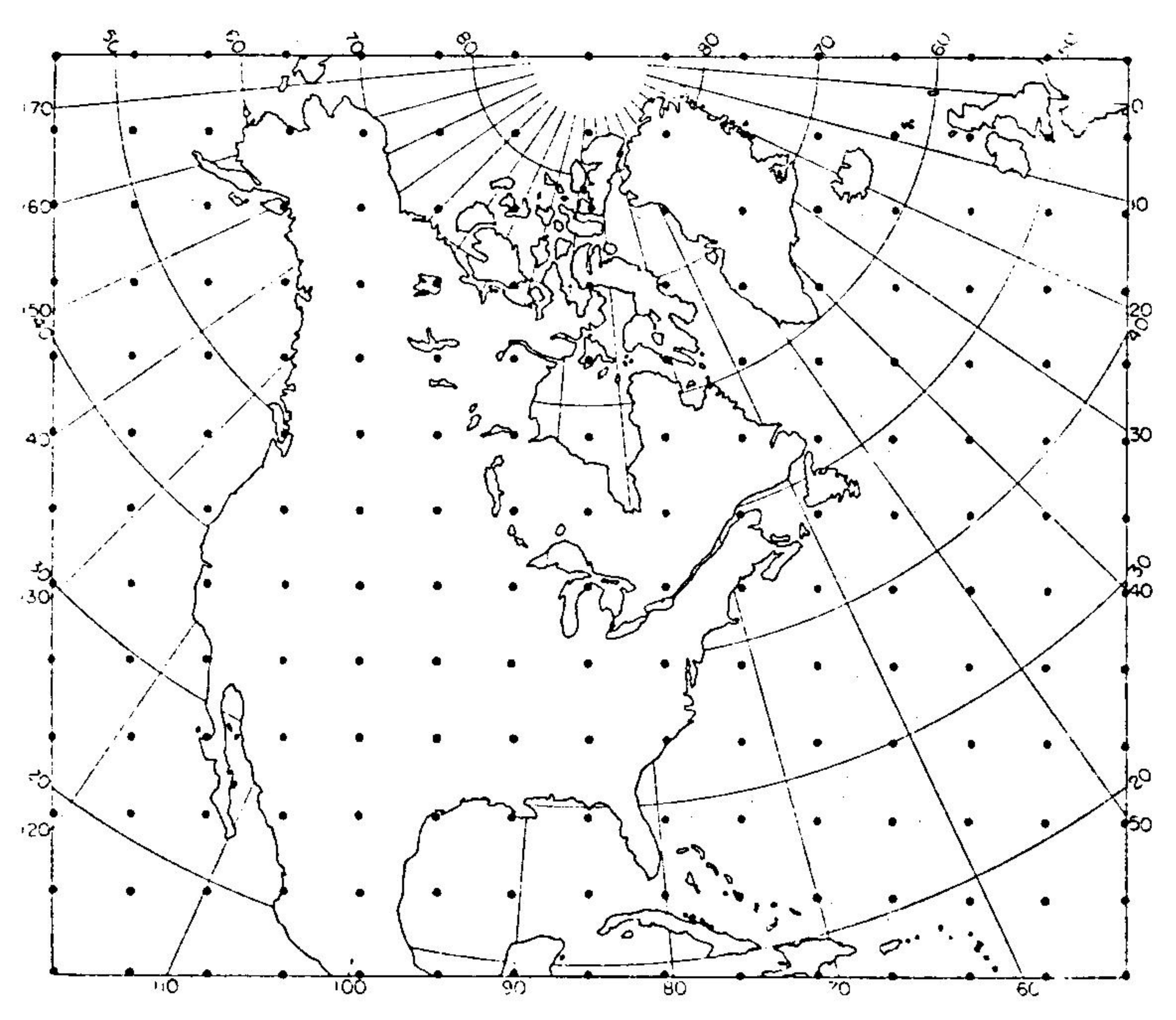
$$\mathbf{V} = (g/f)\mathbf{k}\times\nabla z\,; \qquad \mathbf{V} = \mathbf{k}\times\nabla\psi\,.$$

$$\zeta = g\boldsymbol{\nabla}\cdot(1/f)\boldsymbol{\nabla}z = (g/f)\boldsymbol{\nabla}^2 z + \beta u/f$$

$$\mathbf{V}\cdot\nabla\alpha = -\frac{g}{f}\frac{\partial z}{\partial y}\frac{\partial\alpha}{\partial x} + \frac{g}{f}\frac{\partial z}{\partial x}\frac{\partial\alpha}{\partial y} = -\frac{g}{f}J(\alpha, z)\,.$$

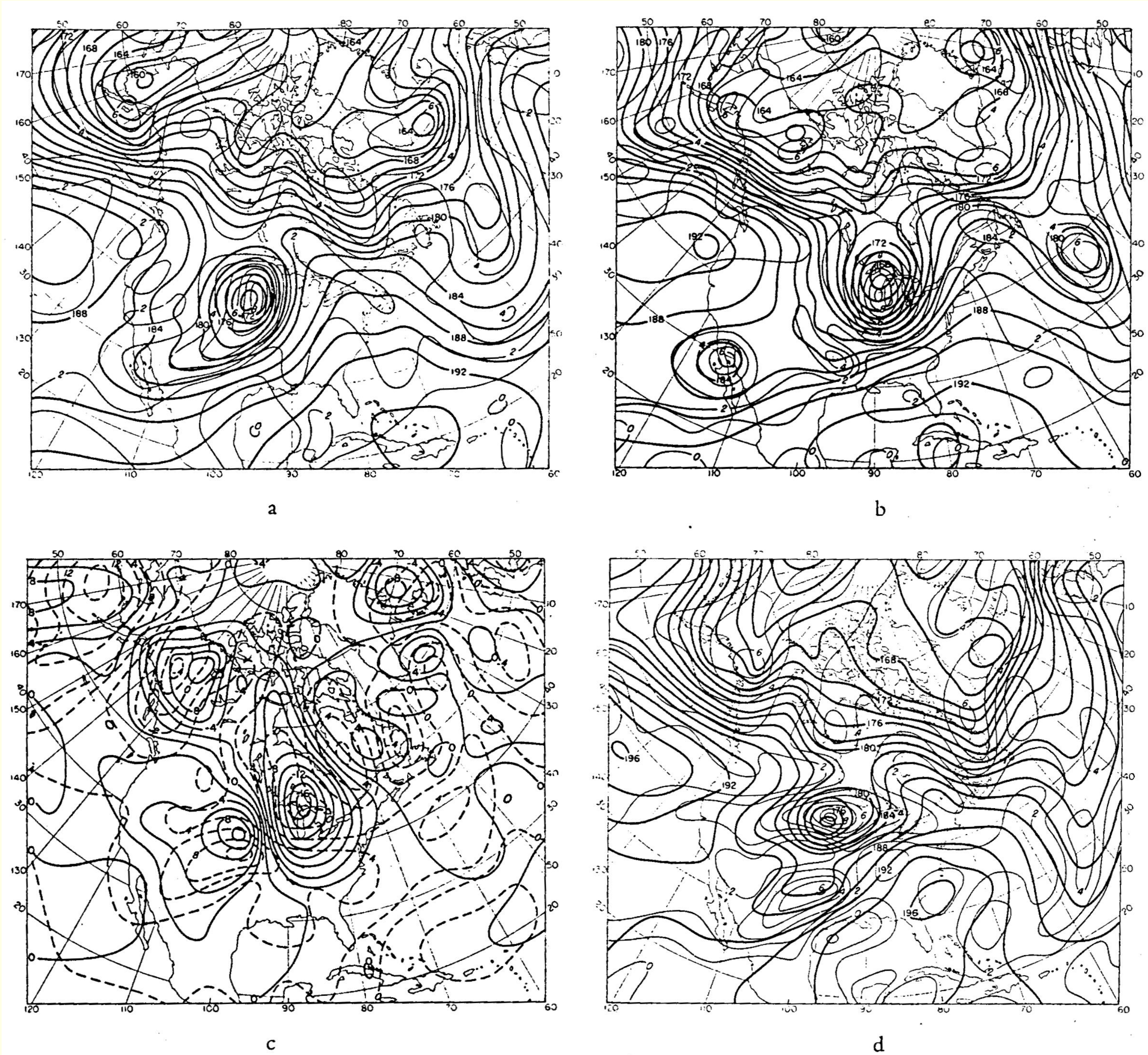
$$\frac{\partial}{\partial t}(\nabla^2 z) = J\left(\frac{g}{f}\nabla^2 z + f, z\right)$$

The barotropic vorticity equation



The computational grid for the integrations

ENIAC Forecast for Jan 5, 1949



Recreating the ENIAC Forecasts

The ENIAC integrations have been recreated using:

- **A `MATLAB` program to solve the BVE**
- **Data from the NCEP/NCAR reanalysis**

The matlab code is available on the author's website

`http://maths.ucd.ie/~plynch/eniac`

NCEP/NCAR Reanalysis

The initial dates for the four forecasts were:

- **January 5, 1949**
- **January 30, 1949**
- **January 31, 1949**
- **February 13, 1949**

When a reconstruction was first conceived, a laborious digitization of hand-drawn charts appeared necessary.

The NCEP/NCAR 40-Year Reanalysis Project

E. Kalnay,[*] M. Kanamitsu,[*] R. Kistler,[*] W. Collins,[*] D. Deaven,[*] L. Gandin,[*] M. Iredell,[*] S. Saha,[*] G. White,[*] J. Woollen,[*] Y. Zhu,[*] M. Chelliah,[+] W. Ebisuzaki,[+] W. Higgins,[+] J. Janowiak,[+] K. C. Mo,[+] C. Ropelewski,[+] J. Wang,[+] A. Leetmaa,[*] R. Reynolds,[*] Roy Jenne,[#] and Dennis Joseph[#]

Bulletin of the American Meteorological Society, March, 1996

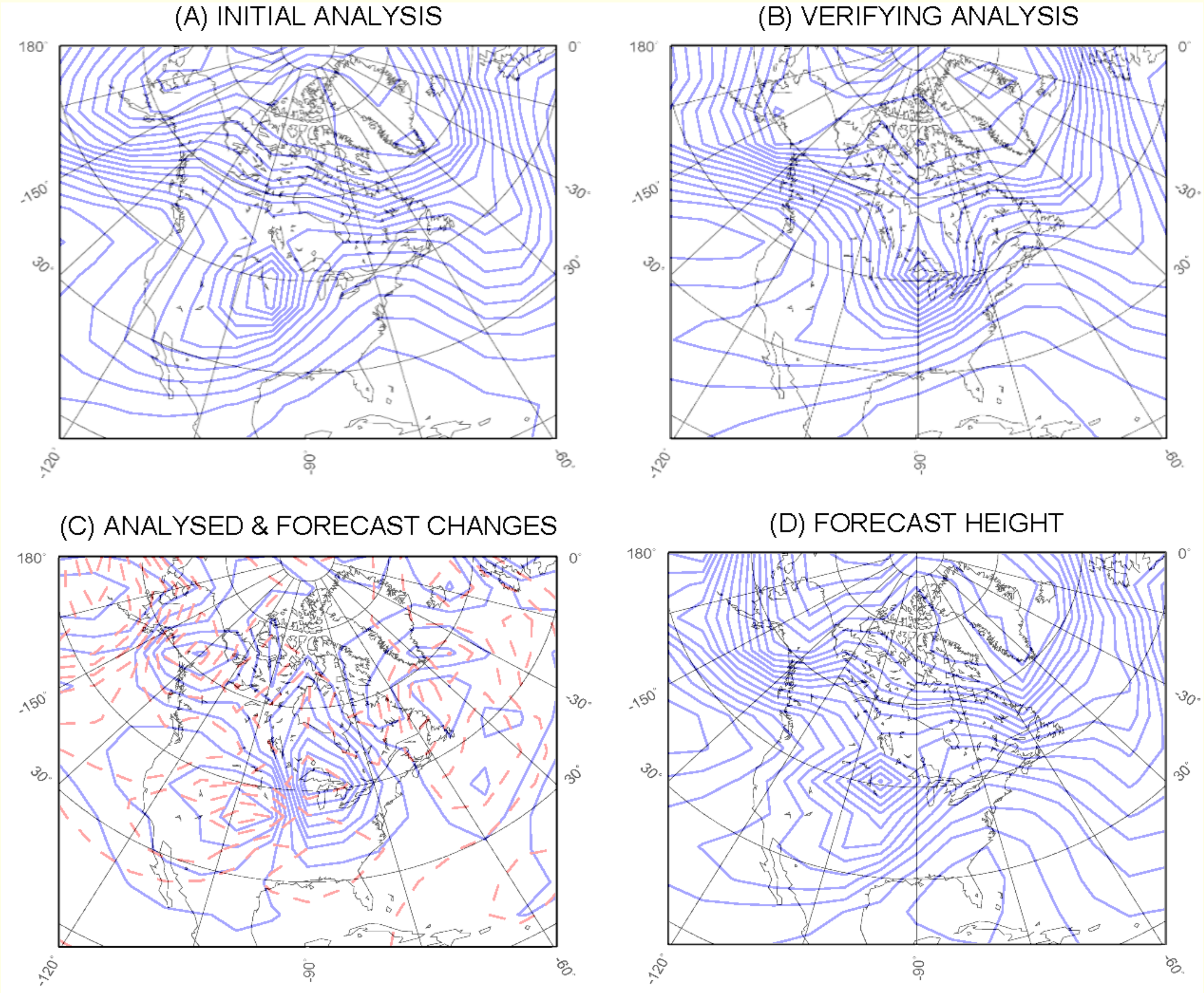
The NCEP–NCAR 50-Year Reanalysis: Monthly Means CD-ROM and Documentation

Robert Kistler,* Eugenia Kalnay,+ William Collins,* Suranjana Saha,* Glenn White,* John Woollen,* Muthuvel Chelliah,# Wesley Ebisuzaki,# Masao Kanamitsu,# Vernon Kousky,# Huug van den Dool,# Roy Jenne,@ and Michael Fiorino&

Editor's note: This article is accompanied by a CD-ROM that contains the complete documentation of the NCEP–NCAR Reanalysis and all of the data analyses and forecasts. It is provided to members through the sponsorship of SAIC and GSC.

Bulletin of the American Meteorological Society, February, 2001

Recreation of the Forecast



Computing Time for ENIAC Runs

- *George Platzman, during his* **Starr Lecture,** *re-ran an ENIAC forecast*
- *The algorithm was coded on an IBM 5110, a desk-top machine*
- *The program execution was completed during the lecture (**about one hour**)*
- *The program* `eniac.m` *was run on a Sony Vaio (model VGN-TX2XP)*
- *The main loop of the 24-hour forecast ran in **about 30 ms**.*

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.***

Operational numerical weather forecasting began in May, 1955, using a three-level quasi-geostrophic model.

See article by Harper, et al. in BAMS, May, 2007.

The End

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