Remembering Bertram Broberg

The ENIAC Forecasts: A Recreation

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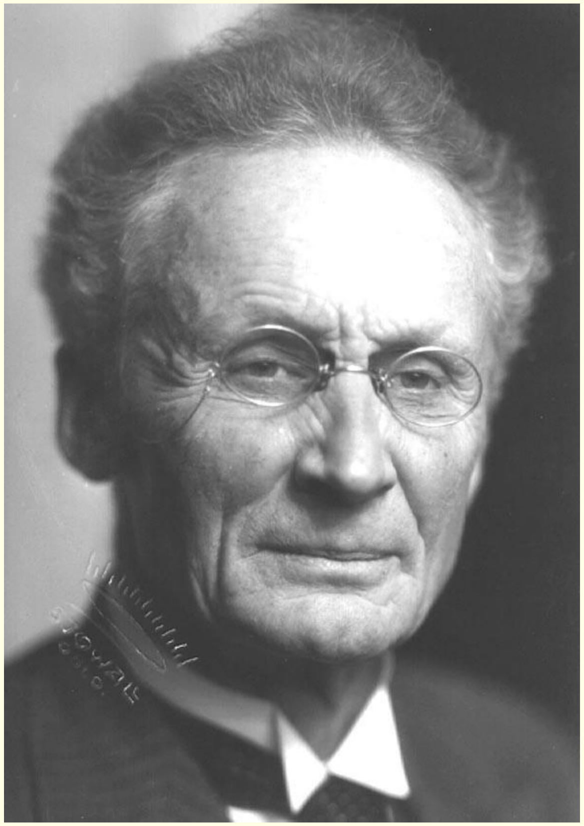
Swedish National Committee for Mechanics
Irish Society for Scientific & Engineering Mechanics

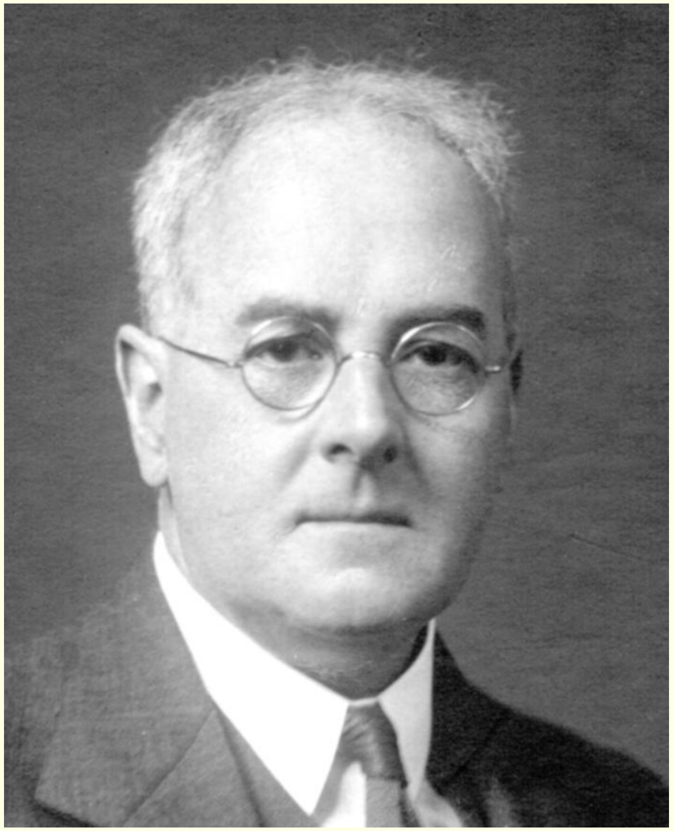
9–10 May, 2007.

Outline of the lecture

- Introduction
- Preparing the Ground
- The First Computer Forecast
- Into Operations
- Recreating the Forecasts

Pioneers of Scientific Forecasting





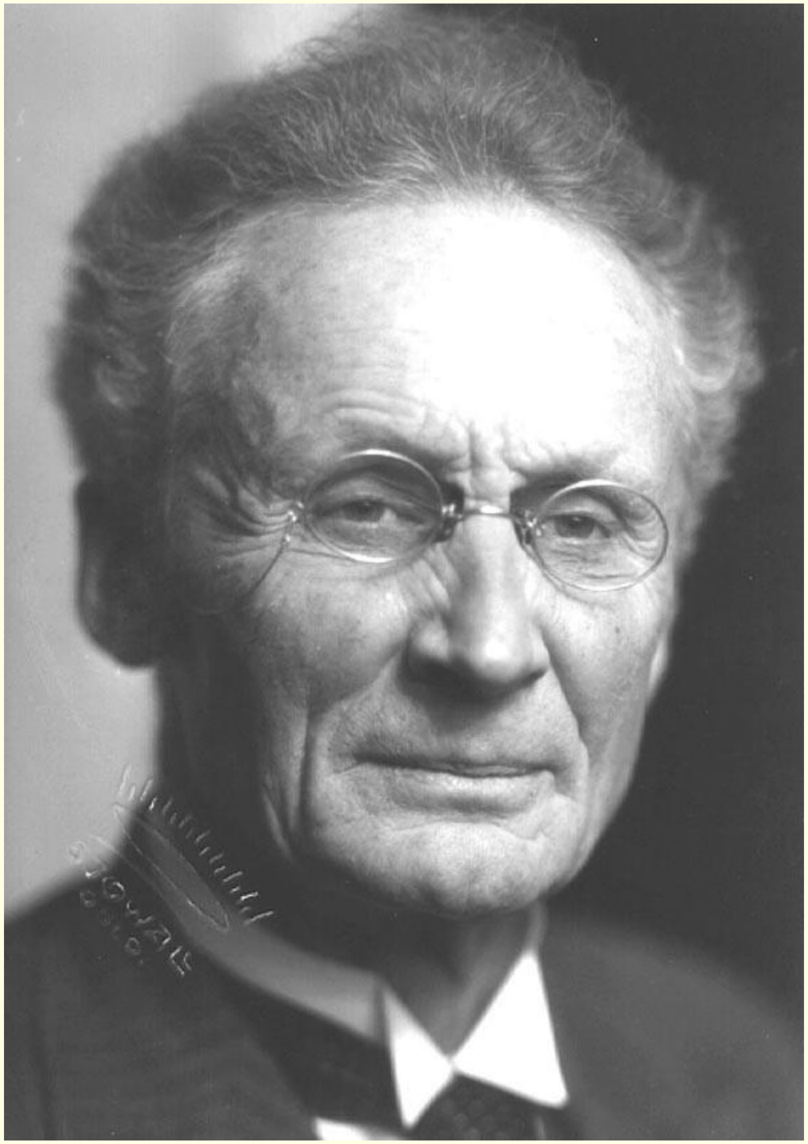
Cleveland Abbe, Vilhelm Bjerknes, Lewis Fry Richardson

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.

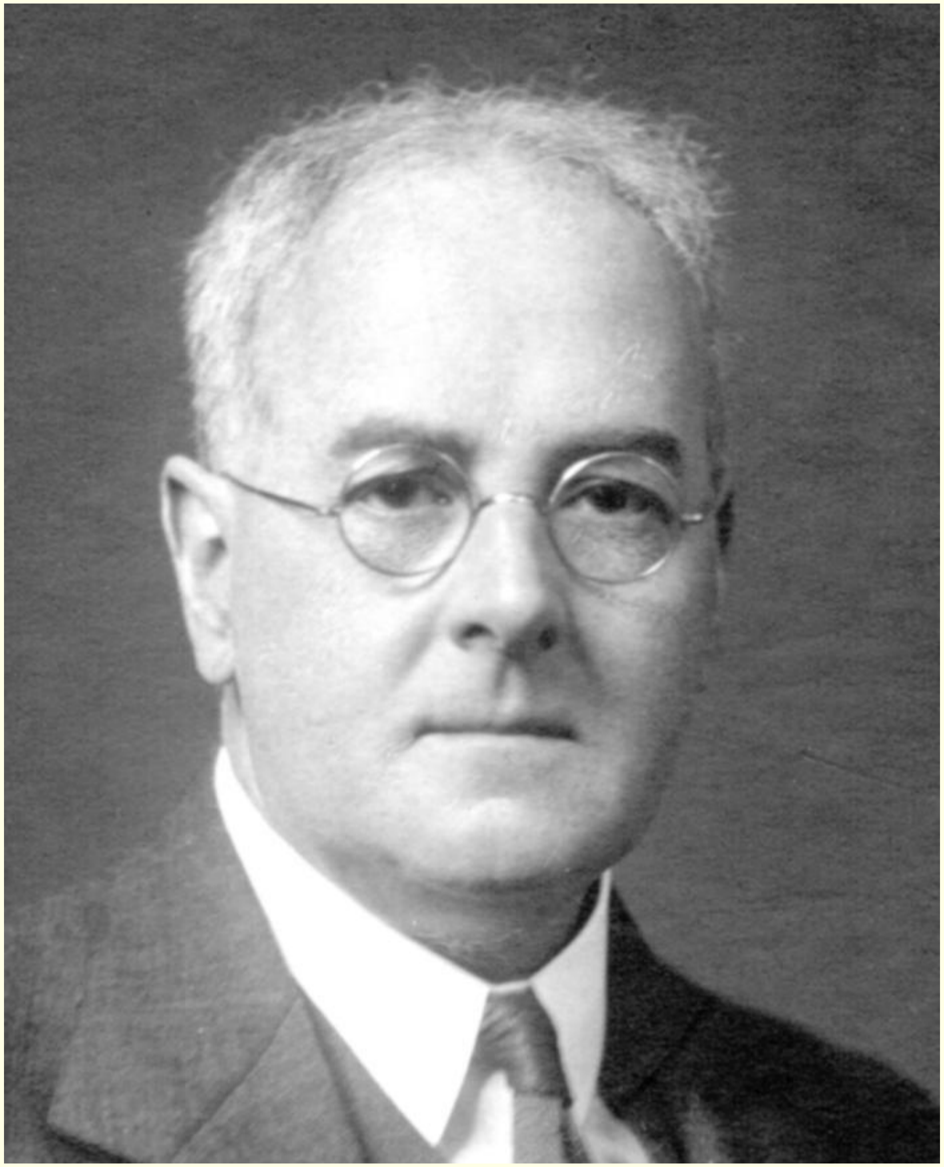


Vilhelm Bjerknes

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



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 practical reality.

Today, forecasts are prepared routinely using methods similar to Richardson's ...

... his dream has indeed come true.

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*
  - **Quasi-geostrophic Theory**
- *Numerical Analysis*
  - **CFL Criterion**
- *Atmopsheric Observations*
  - **Radiosonde**
- *Electronic Computing*
  - **ENIAC**

The Meteorology Project

Project estblished by John von Neumann in <u>1946.</u>

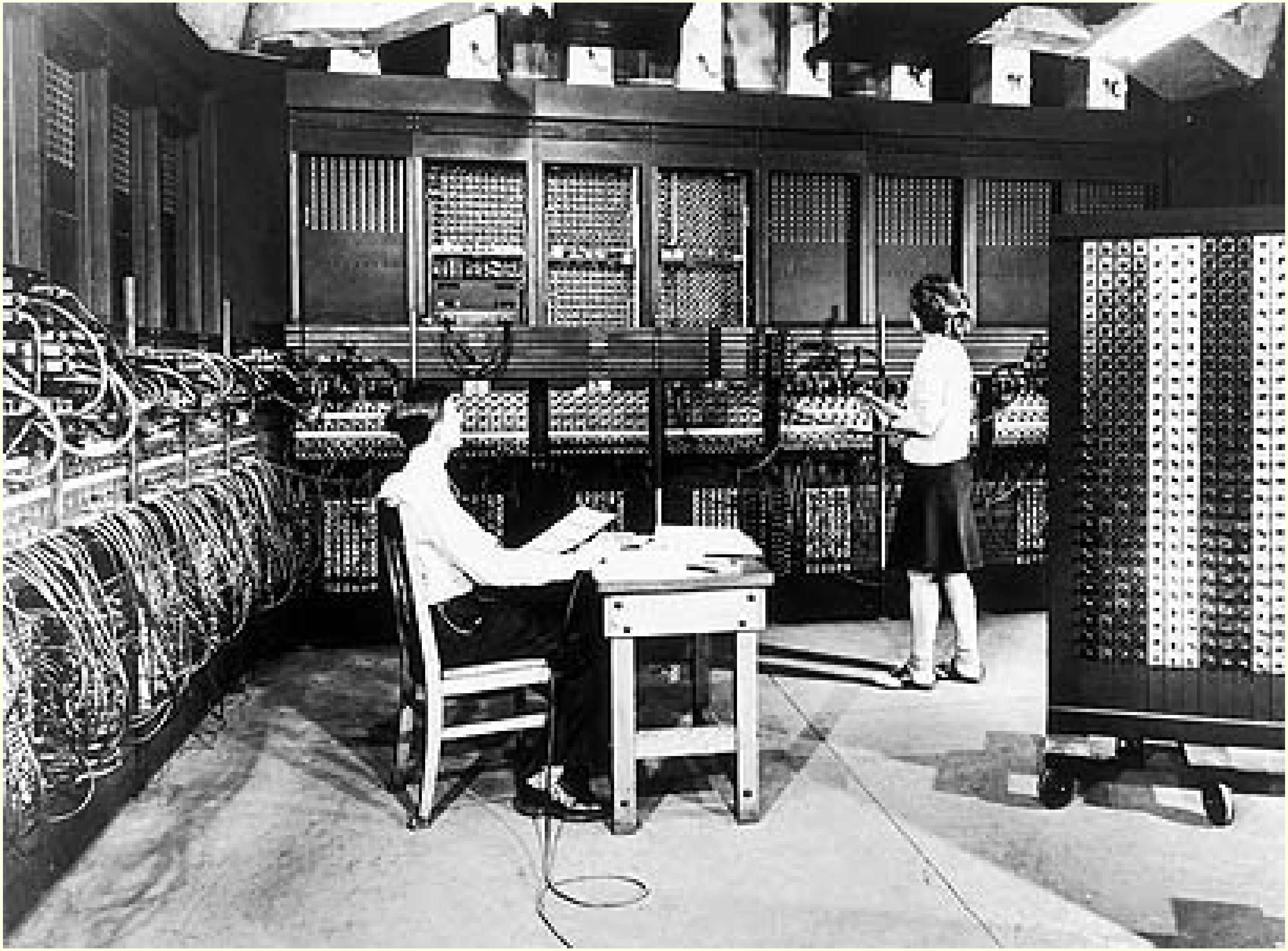
Objective of the project:

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

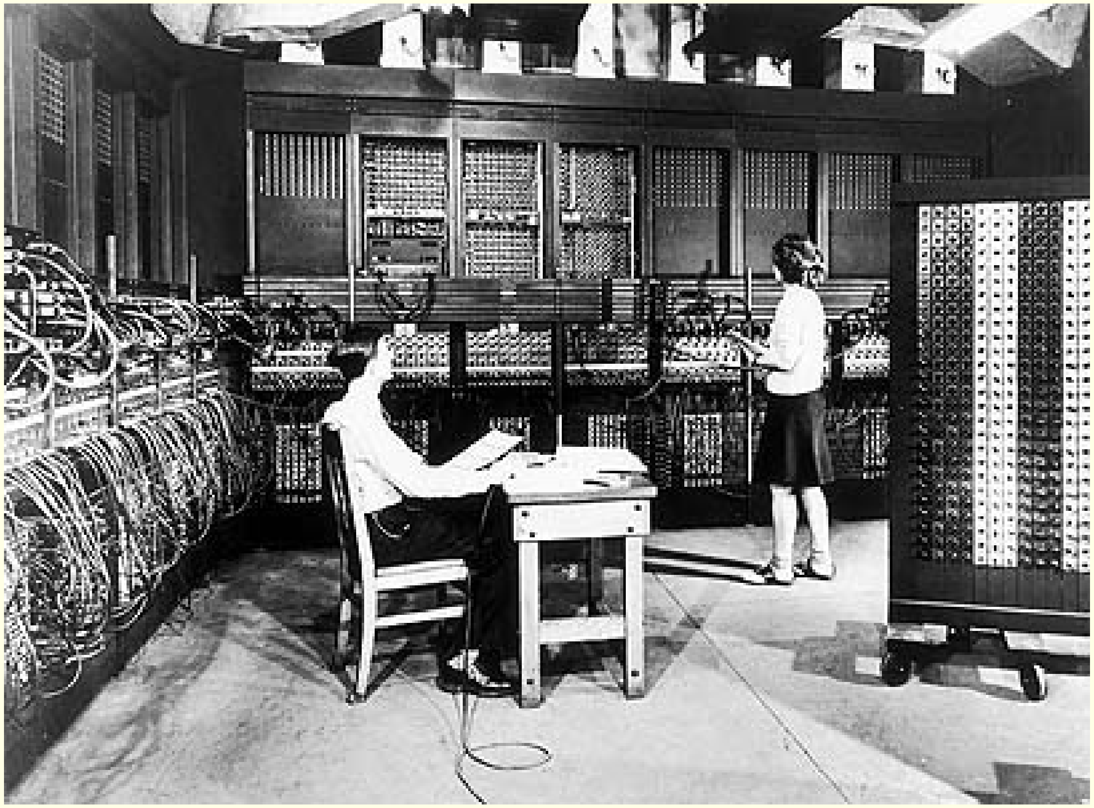
A Proposal for Funding listed three "possibilities":

- ***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.

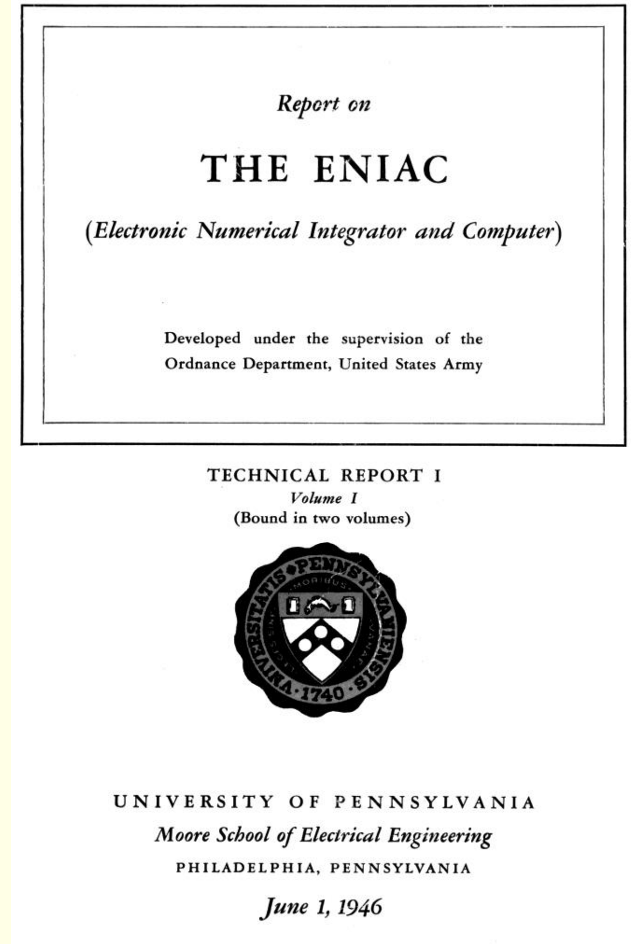
It had:

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

The ENIAC: Technical Details.

ENIAC was a decimal machine. No high-level language. Assembly language. Fixed-point arithmetic: $-1 < x < +1$.

10 registers, that is,
Ten words of high-speed memory.
Function Tables:
624 6-digit words of "ROM", set on ten-pole rotary switches.
"Peripheral Memory":
Punch-cards.
Speed: FP multiply: 2ms
(say, 500 Flops).
Access to Function Tables: 1ms.
Access to Punch-card equipment:
You can imagine!


Report on

THE ENIAC

(*Electronic Numerical Integrator and Computer*)

Developed under the supervision of the
Ordnance Department, United States Army

TECHNICAL REPORT I
Volume I
(Bound in two volumes)

UNIVERSITY OF PENNSYLVANIA
Moore School of Electrical Engineering
PHILADELPHIA, PENNSYLVANIA
June 1, 1946

Evolution of the Project

- **Plan A: Integrate the Primitive Equations**
  Problems similar to Richardson's would arise

- **Plan B: Integrate baroclinic Q-G System**
  Too computationally demanding

- **Plan C: Solve barotropic vorticity equation**
  Very satisfactory initial results

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

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

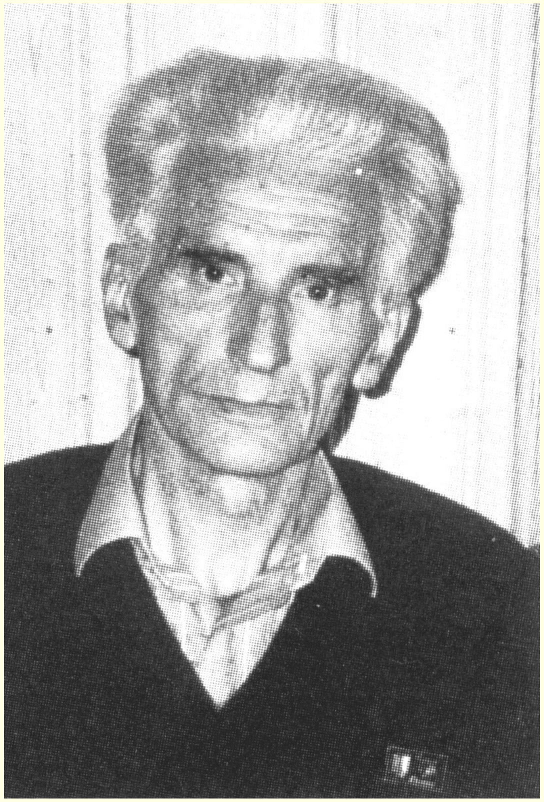
- **The atmosphere is treated as a single layer.**
- **The flow is assumed to be nondivergent.**
- **Absolute vorticity is conserved.**

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

This equation looks deceptively simple. But it is nonlinear:

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

Charney, Fjørtoft, von Neumann



Charney **Fjørtoft** **von Neumann**

Numerical integration of the barotropic vorticity equation

***Tellus*, 2, 237–254 (1950).**

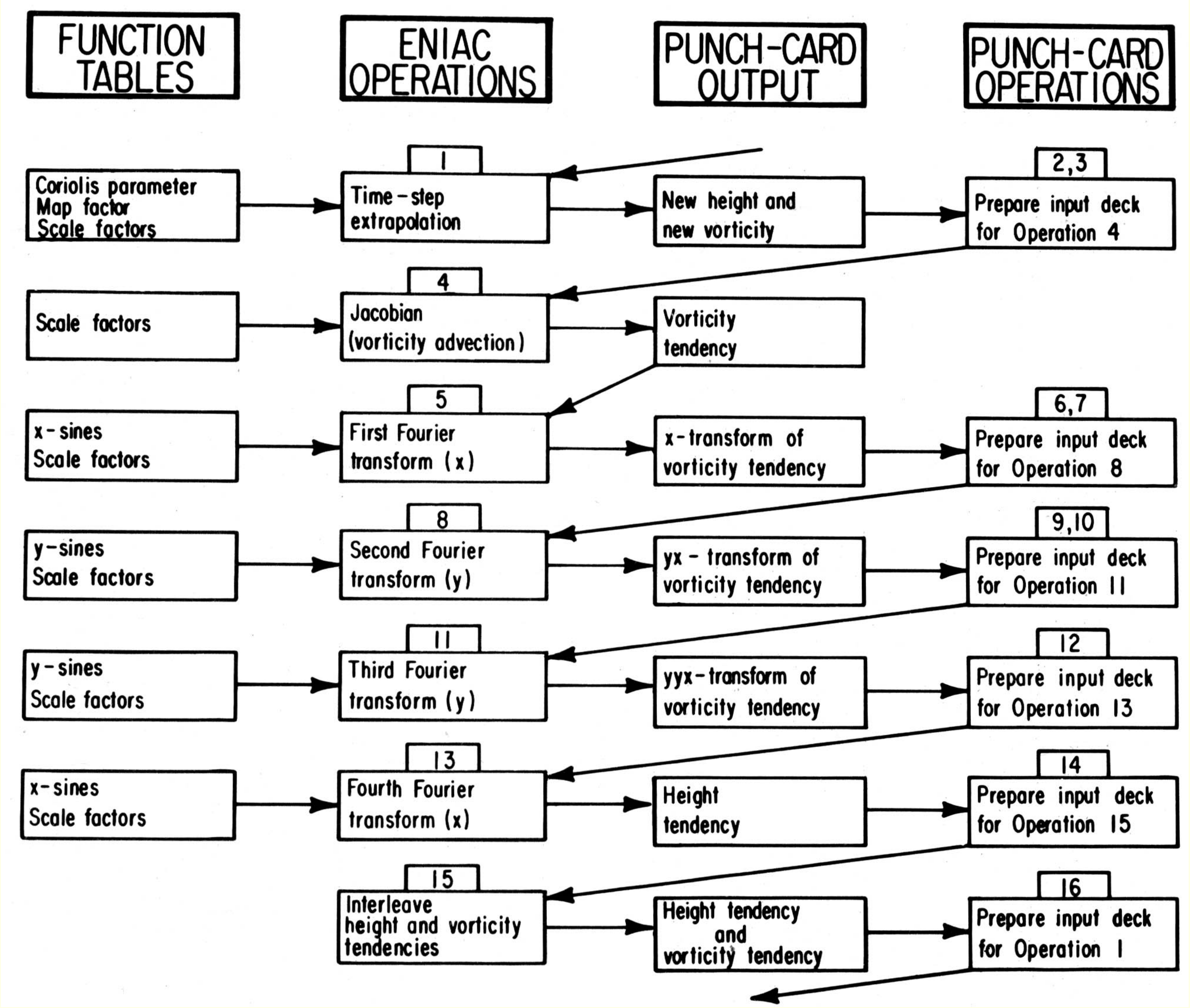
Solution method for BPVE

$$\frac{\partial \zeta}{\partial t} = \mathbf{J}(\psi, \zeta + f)$$

1. **Compute the Jacobian**
2. **Step forward (Leapfrog scheme)**
3. **Solve Poisson equation $\nabla^2\psi = \zeta$ (Fourier expansion)**
4. **Go to (1).**

- **Timestep : Δt = 1 hour**
- **Gridstep : Δx = 750 km (at North Pole)**
- **Gridsize : 19 $\times$ 16 $\approx$ 300 points**
- **Elapsed time for 24 hour forecast: About 24 hours.**

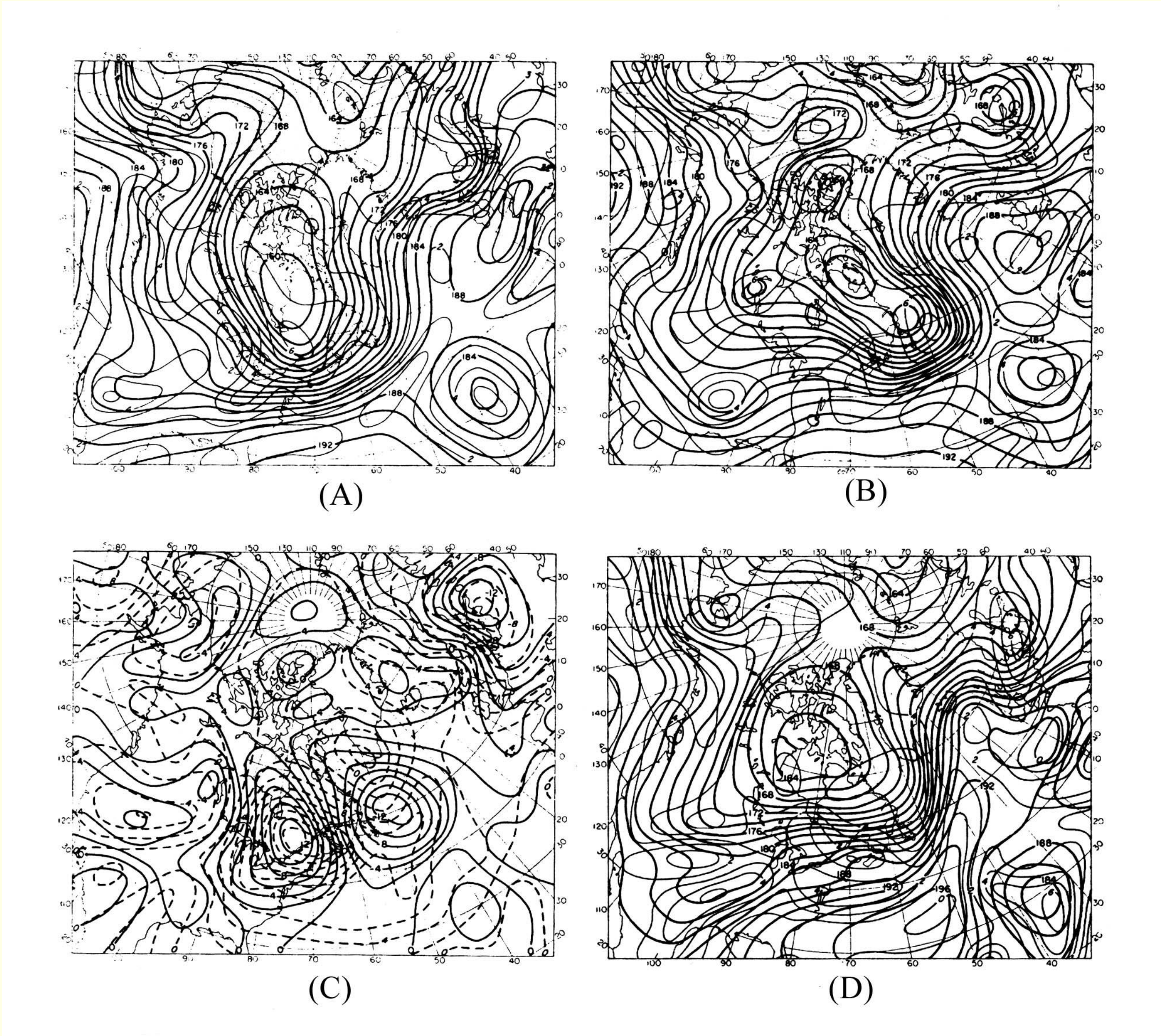
Each forecast involved punching about 25,000 cards.
Most of the time was spent handling card-decks.



Flow-chart for the computations.

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

ENIAC: First Computer Forecast



Key people in the ENIAC endeavour

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.

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

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

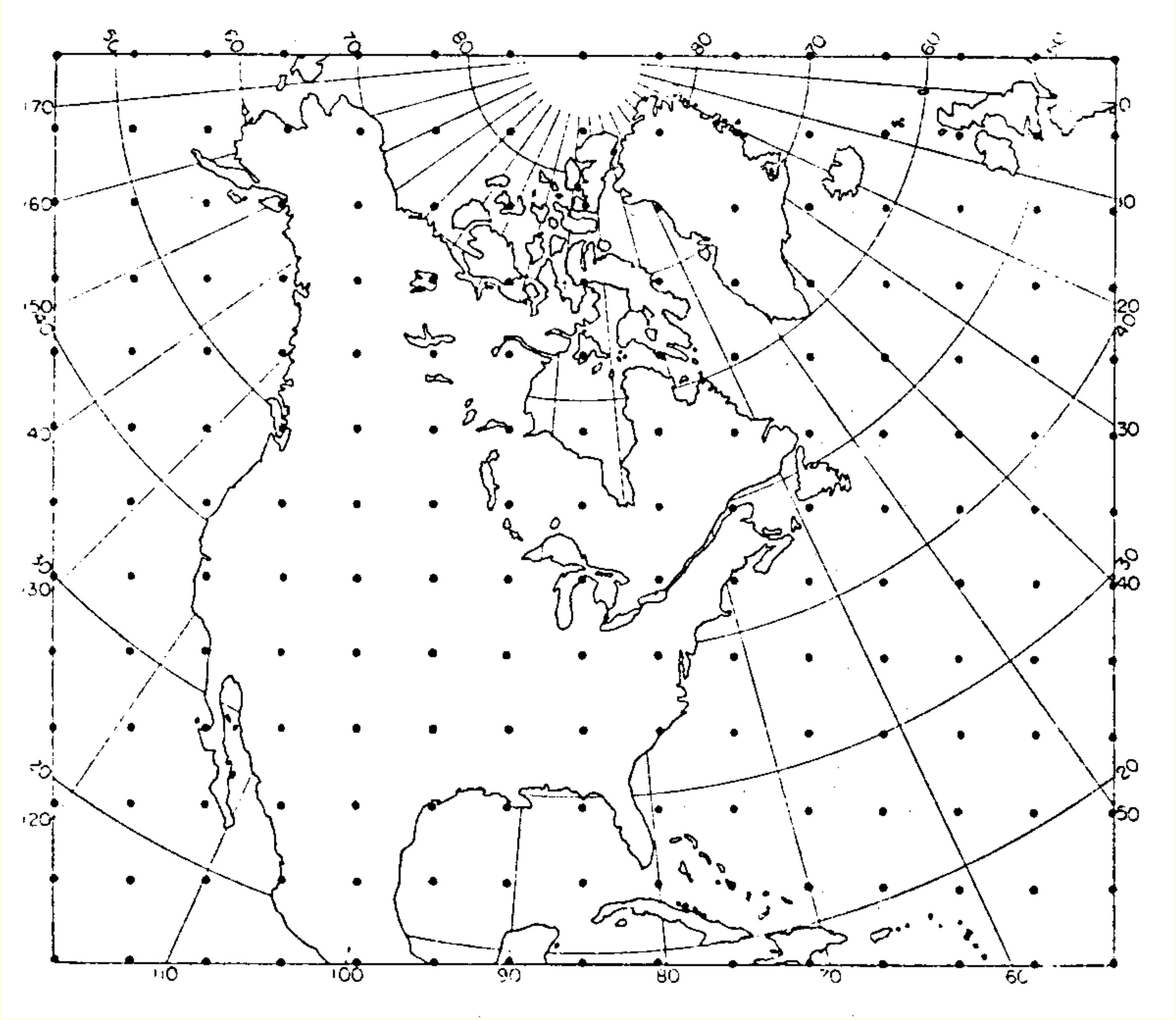
$$\mathbf{V} = (g/f)\mathbf{k} \times \nabla z \,; \qquad \mathbf{V} = \mathbf{k} \times \nabla \psi \,.$$

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

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

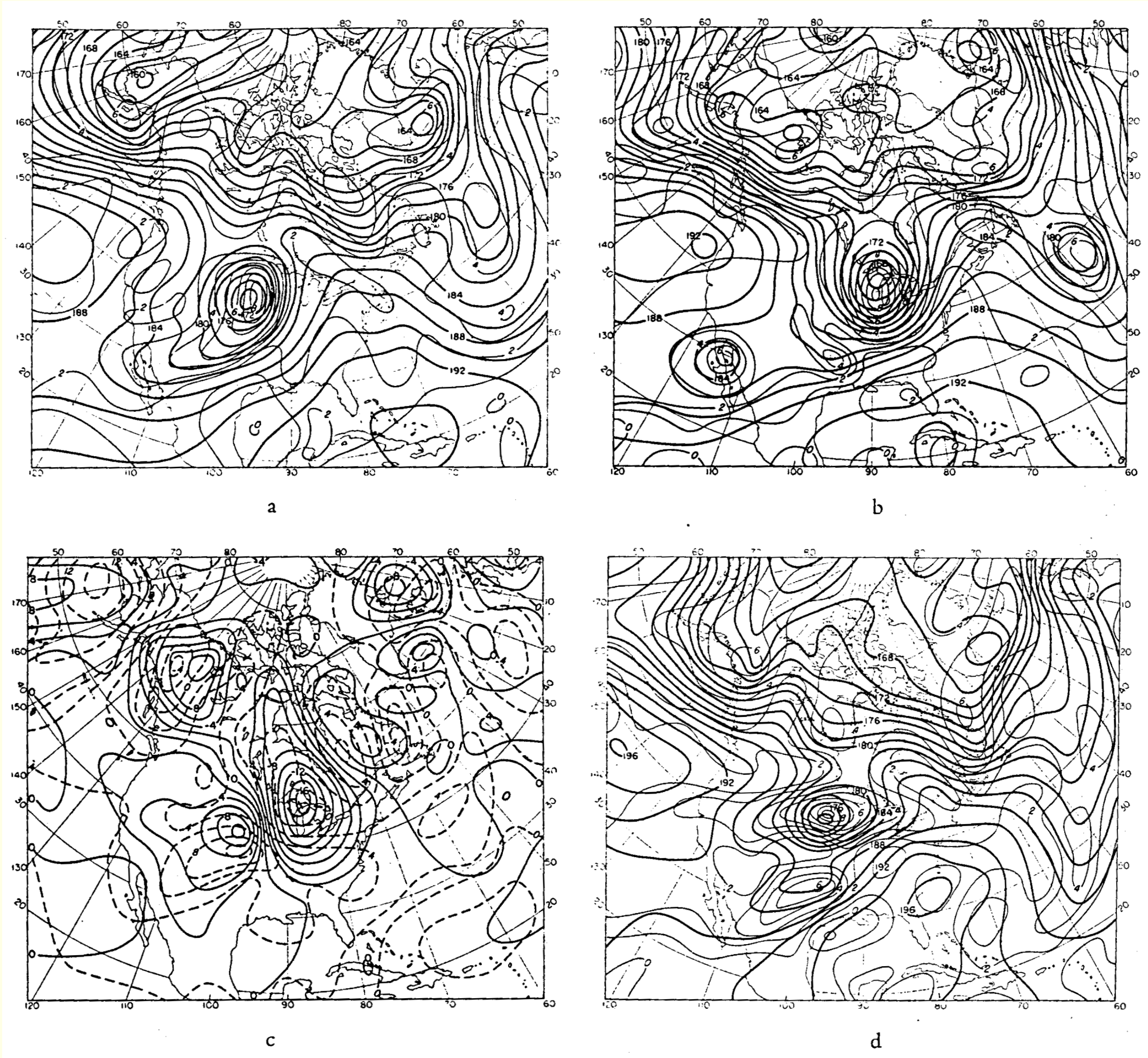
$$\frac{\partial}{\partial t}(\nabla^2 z) = J\left(\frac{g}{f}\nabla^2 z + f, z\right)$$

The barotropic vorticity equation

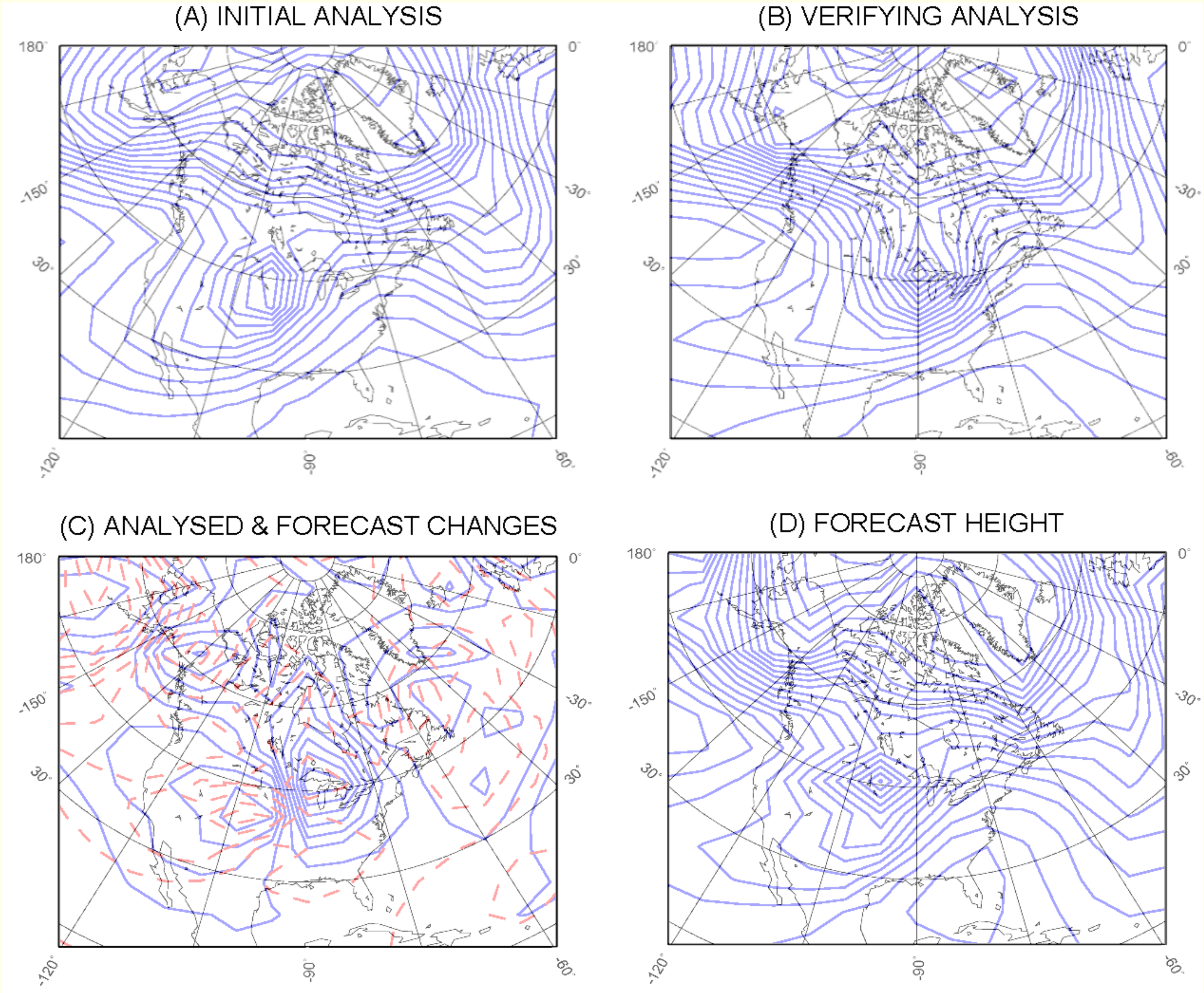


The computational grid for the integrations

ENIAC Forecast for Jan 5, 1949



Recreation of the Forecast



	Mean error		RMS error		S1 Score	
Case	FCST.	PERS.	FCST.	PERS.	FCST.	PERS.
1	56.4	**−9.2**	113.4	**94.6**	**61.0**	62.2
2	31.1	**6.3**	**99.2**	114.6	**45.6**	62.9
3	−35.2	**20.4**	92.7	**89.2**	**46.4**	58.4
4	39.4	**1.1**	81.9	**80.7**	**39.5**	50.1

Mean error (bias), RMS error and S1 scores

Charney et al used the equation in the height form

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

They could have used the streamfunction form

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

They would then not have to have ignored the beta-term

	Mean error		RMS error		S1 Score	
Case	z-EQN	ψ-EQN	z-EQN	ψ-EQN	z-EQN	ψ-EQN
1	56.4	**44.4**	113.4	**106.7**	**61.0**	61.4
2	31.1	**23.2**	99.2	**88.6**	45.6	**44.1**
3	**−35.2**	−39.6	92.7	**88.2**	46.4	**45.4**
4	39.4	**19.9**	81.9	**72.1**	39.5	**36.9**

Scores for height equation and streamfunction equation

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 15 ms**.*

Thank You