The Emergence of Numerical Weather Prediction: from Richardson to the ENIAC

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Outline

Prehistory

1890–1920

ENIAC

Recreating the ENIAC Forecast

PHONIAC

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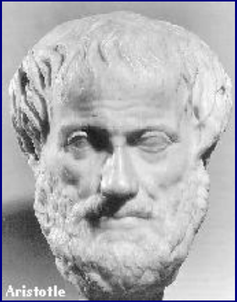
Aristotle's *Meteorologia*

Aristotle wrote the first book on Meteorology, the *Μετεωρολογια* (*μετεωρον*: Something in the air).

This work studied the causes of various weather phenomena.

Aristotle was a masterly speculator: for example, he believed that the lightning followed the thunder!



Aristotle (384-322 BC)

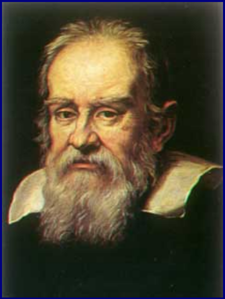
Money makes the world go round

Galileo Galilei (1564–1642)

Galileo formulated the basic law of falling bodies, which he verified by careful measurements.

He constructed a telescope, with which he studied lunar craters, and discovered four moons revolving around Jupiter.

Galileo is credited with the invention of the Thermometer.



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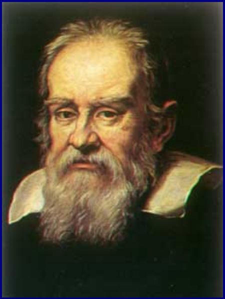

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Thus began quantitative meteorology.

Galileo's Thermometer

The **Galileo Thermometer** is a popular modern *collectable* and an attractive decoration.

As temperature rises, the fluid expands and its density decreases.

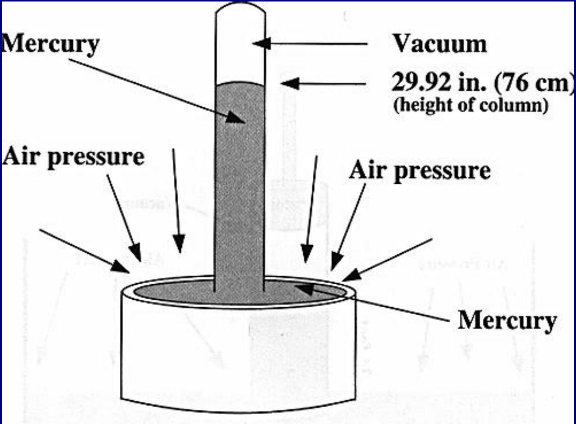
The reduced buoyancy causes the glass baubles to sink, indicating temperature changes.

Galileo's Ace Post-Doc.

Evangelista Torricelli (1608–1647), a student of Galileo, devised the first accurate barometer.

Torricelli inventing the barometer

Barometric Pressure



The relationship between the height of the mercury column and the character of the weather was soon noticed.

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:

Force $=$ Mass $\times$ 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!

Halley 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.

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

A Tricky Question

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If the Astronomers can make accurate 76-year forecasts ...

... why can't the Meteorologists do the same?

- **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.

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- 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.

Leonhard Euler (1707–1783)

- Born in Basel in 1707.
- Died 1783 in St Petersburg.
- Formulated the equations for incompressible, inviscid fluid flow:

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

$$\nabla \cdot \mathbf{V} = 0$$

Jean Le Rond d'Alembert

The Euler equations are **partial differential equations.**
D'Alembert introduced partial derivatives in studying the flow of wind in two dimensions.

George G Stokes, 1819–1903

George Gabriel Stokes, founder of modern hydrodynamics.

ASIDE: Stokes' Theorem

$$\oint_{\Gamma} \mathbf{V} \cdot d\mathbf{l} = \iint_{\Sigma} \nabla \times \mathbf{V} \cdot \mathbf{n} \, da \qquad \left[\text{Good for T-shirts}\right]$$

Stokes' Theorem was actually discovered by Kelvin in 1854. It is of central importance in fluid dynamics.

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This leads on to Bjerknes' Circulation Theorem:

$$\frac{dC}{dt} = -\iint_\Sigma \nabla\frac{1}{\rho} \times \nabla p\cdot d\mathbf{a} = -\oint_\Gamma \frac{dp}{\rho}\,,$$

which generalized Kelvin's Circulation Theorem to baroclinic fluids (ρ varying independently of p), and ushered in the study of Geophysical Fluid Dynamics.

Resolution of d'Alembert's Paradox

D'A, 1752: A body moving at constant speed through a gas or a fluid does not experience any resistance.

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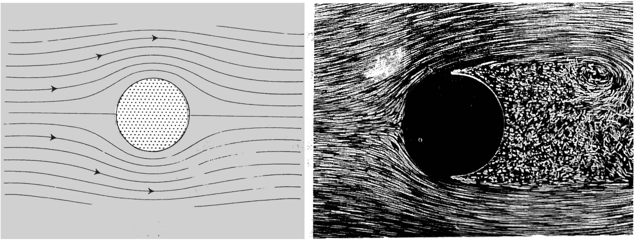

Fig. 9.1 Flow past a circular cylinder for (a) a hypothetical fluid with zero viscosity, (b) a real fluid with very small viscosity μ (from van Dyke 1982).

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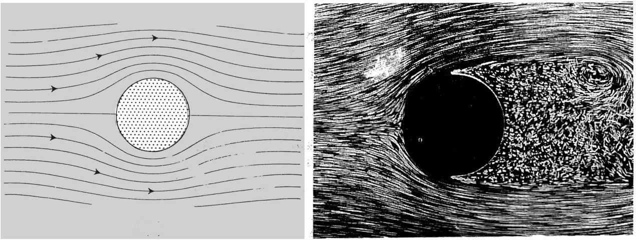

Fig. 9.1 Flow past a circular cylinder for (a) a hypothetical fluid with zero viscosity, (b) a real fluid with very small viscosity μ (from van Dyke 1982).

The minutest amount of viscosity has a profound qualitative impact on the character of the solution.

The Navier-Stokes equations include effect of viscosity.

The Navier-Stokes Equations

Euler's Equations:

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

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The Navier-Stokes Equations

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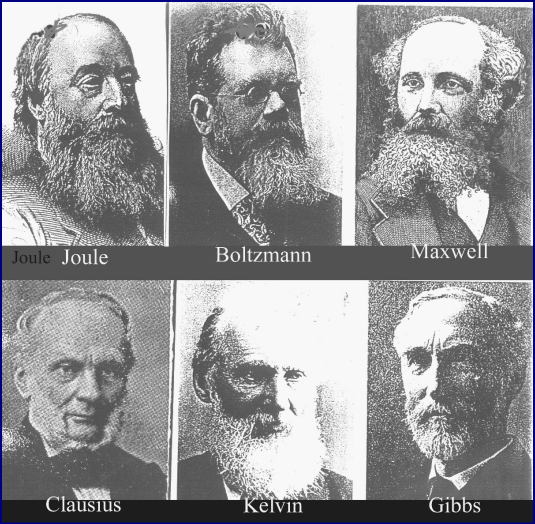
Motion on the rotating Earth:

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

The Inventors of Thermodynamics



It would appear from this sample that a fulsome beard may serve as a thermometer of proficiency in thermodynamics. More exhaustive research is required before a definitive conclusion can be reached.

The Equations of the Atmosphere

GAS LAW (Boyle's Law and Charles' Law.)

Relates the pressure, temperature and density

CONTINUITY EQUATION

Conservation of mass

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 rarefaction, etc.

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

The Primitive Equations

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

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

$$p = R\rho T$$

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

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

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

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

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:

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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.

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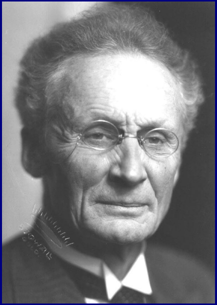
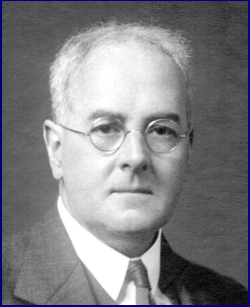
Pioneers of Scientific Forecasting

Cleveland Abbe, Vilhelm Bjerknes, Lewis Fry Richardson

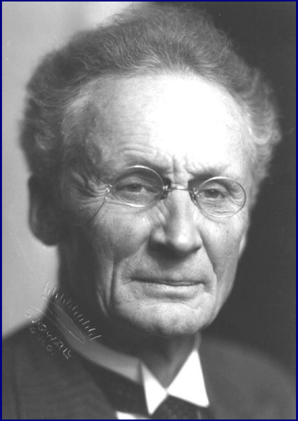
Cleveland Abbe

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

Vilhelm Bjerknes (1862–1951)

Bjerknes' 1904 Manifesto

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To establish a science of meteorology

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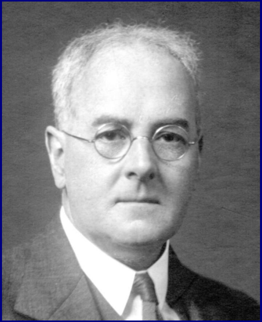
Step (1) is **Diagnostic.** Step (2) is **Prognostic.**

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 his methods . . .

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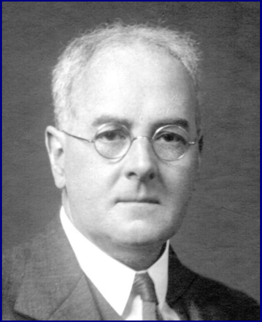

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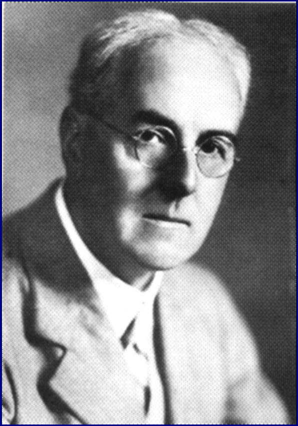
. . . his dream has indeed come true.

Lewis Fry Richardson, 1881–1953.



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

It took him two years !

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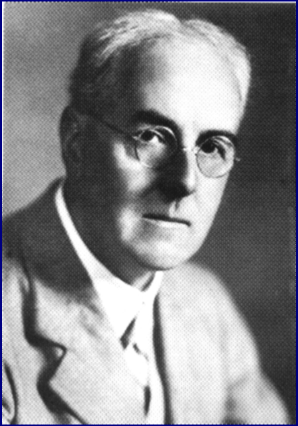

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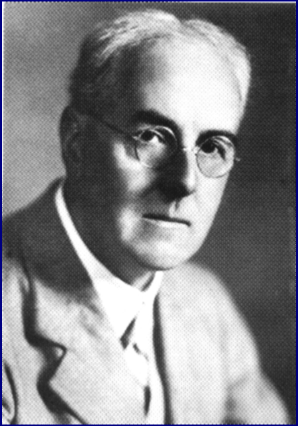

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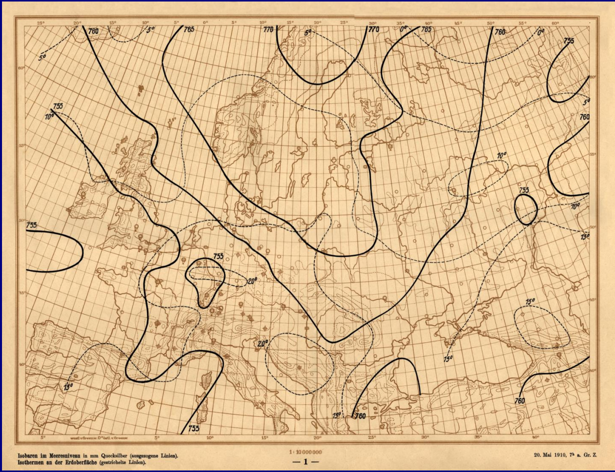
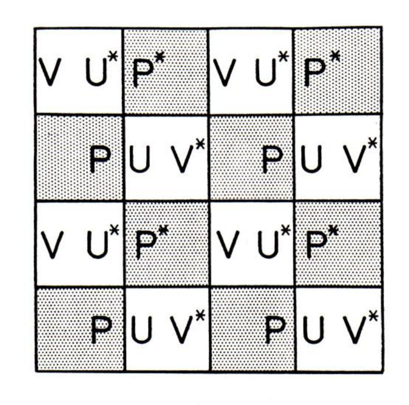
But Richardson’s method was scientifically sound.

The Leipzig Charts for 0700 UTC, May 20, 1910

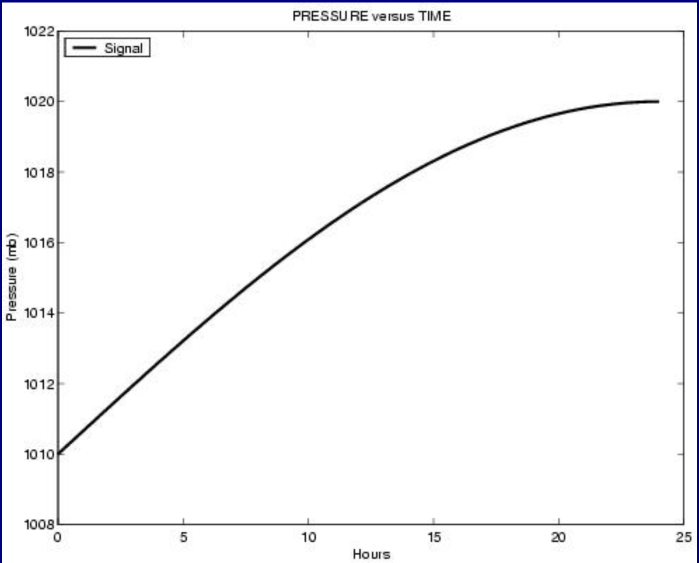


Bjerknes' sea level pressure analysis.

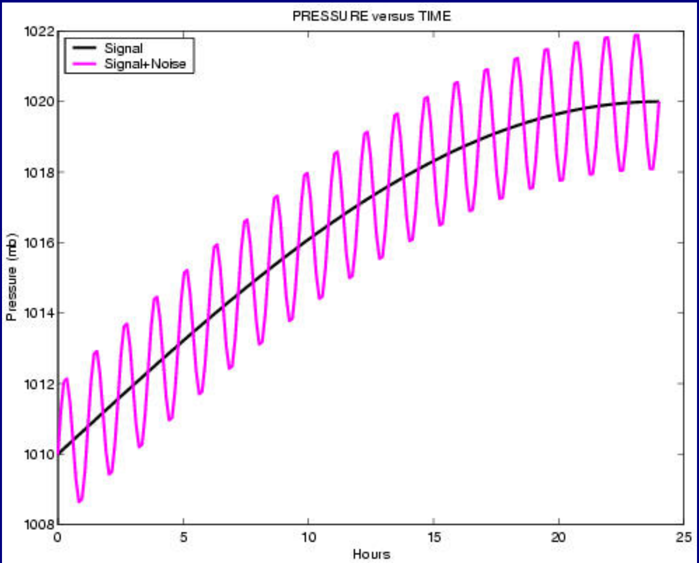


Richardson Grid (also called an Arakawa E-grid)

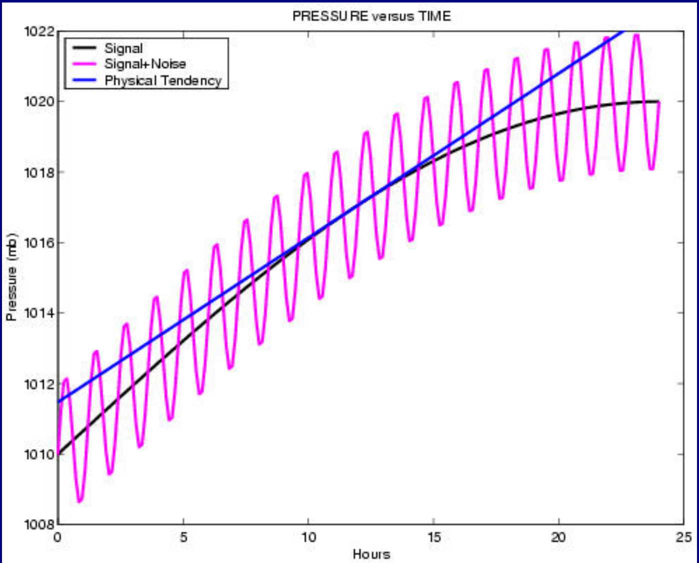
A Smooth Signal



A Noisy Signal



Tendency of a Smooth Signal



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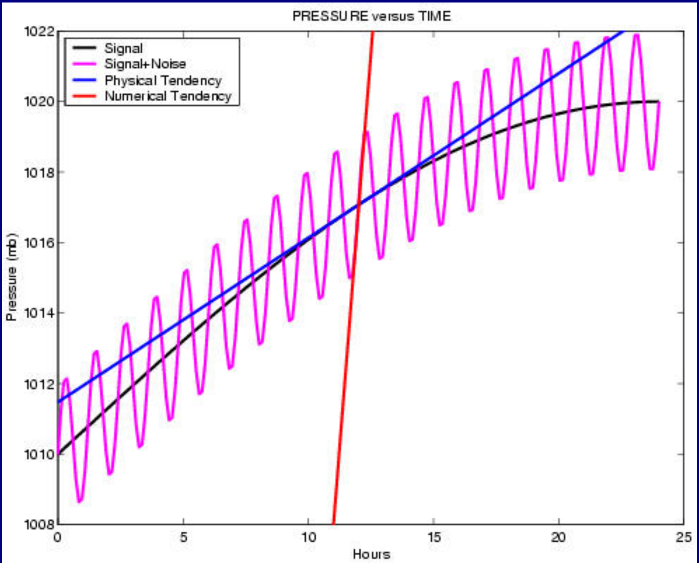

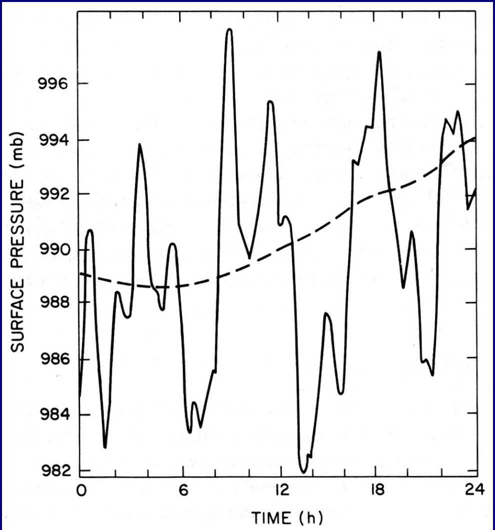

Evolution of surface pressure before and after NNMI.
(Williamson and Temperton, 1981)

Initialization of Richardson's Forecast

Richardson's Forecast was repeated on a computer.

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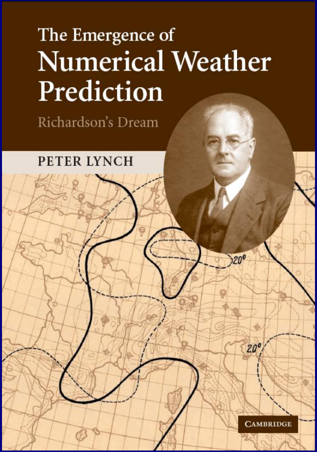
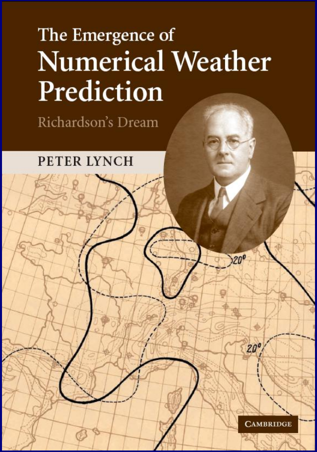
Observations:

The barometer was steady!



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



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Competition for a copy of the book ? ? ?

Richardson’s Forecast Factory

ⓒFrançois Schuiten

Richardson’s Forecast Factory

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64,000 Computers: the first Massively Parallel Processor

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Crucial Advances, 1920–1950

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

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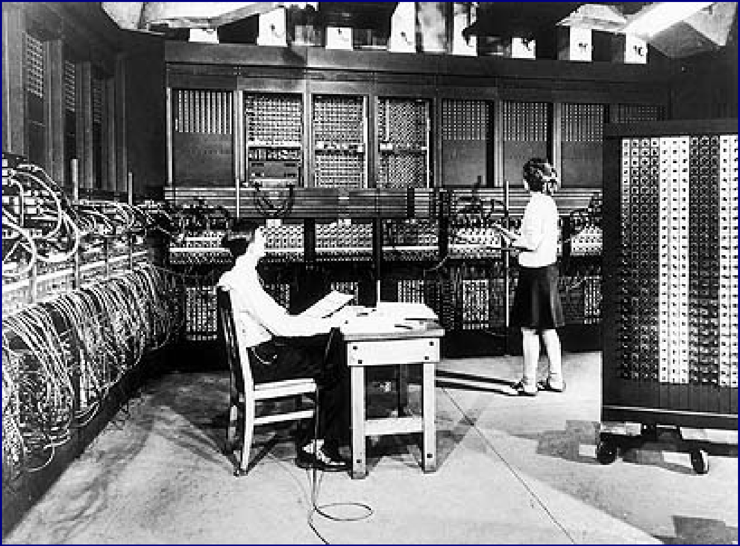
A Proposal for Funding listed three “possibilities":

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

The ENIAC



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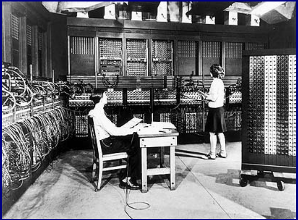

The **ENIAC** was the first multi-purpose programmable electronic digital computer.
It had:

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

The ENIAC: Technical Details.

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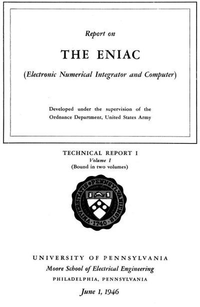
Report on

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

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

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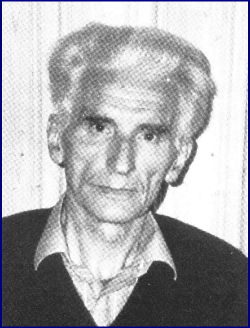
- **Plan B: Integrate baroclinic Q-G System**
  Too computationally demanding for ENIAC

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

Charney Fjørtoft von Neumann



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

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

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

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

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

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

This equation looks simple. But it is nonlinear:

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

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

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

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

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

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

The barotropic vorticity equation

Solution method

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

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4. Go to (1).

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- Gridstep: Δx = 750 km (at North Pole)
- Gridsize: $19 \times 16 \approx 300$ points
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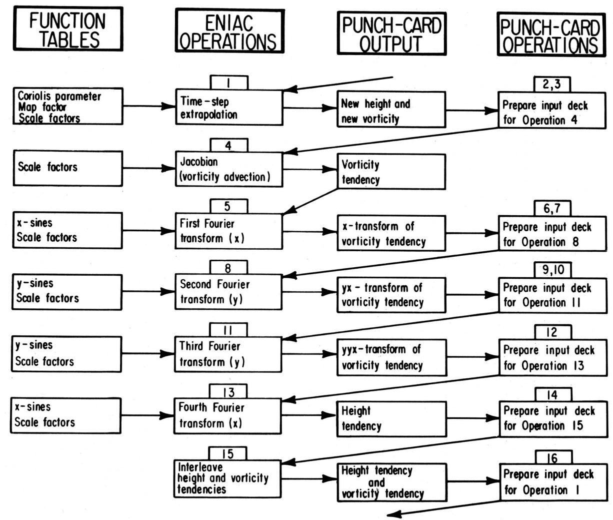
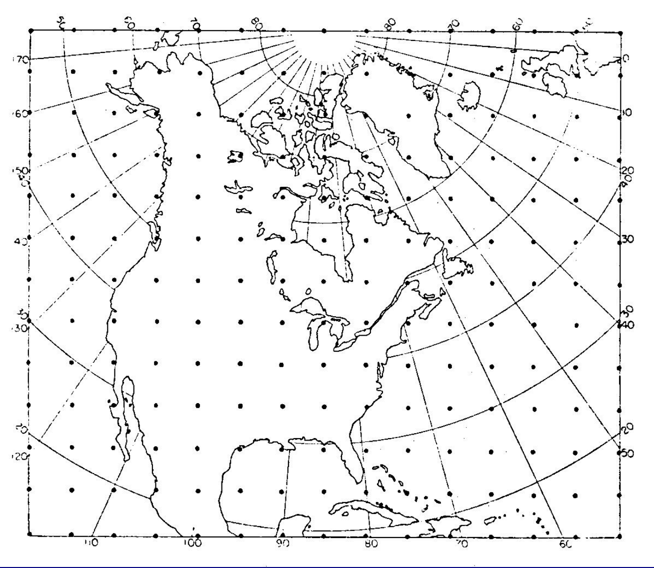
Each forecast involved punching about 25,000 cards.
Most of the time was spent handling card-decks.

The ENIAC Algorithm: Flow-chart

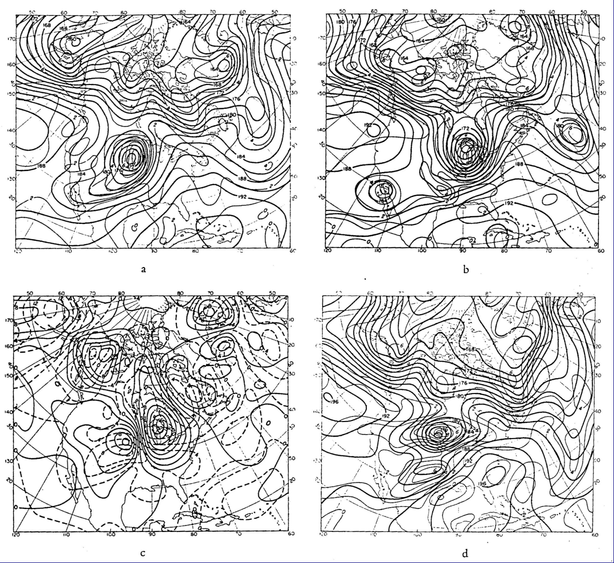


G. W. Platzman: The ENIAC Computations of 1950 — Gateway to Numerical Weather Prediction (BAMS, April, 1979).

Computational grid for the integrations



ENIAC Forecast for Jan 5, 1949



Key people in the ENIAC endeavour

Richardson's reaction

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- "This is . . . an enormous scientific advance on the single . . . result in which Richardson (1922) ended."

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.

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Operational numerical weather forecasting began in **May 1955**, using a 3-level quasi-geostrophic model.

Outline

Recreating the ENIAC Forecasts

The ENIAC integrations have been repeated using:

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

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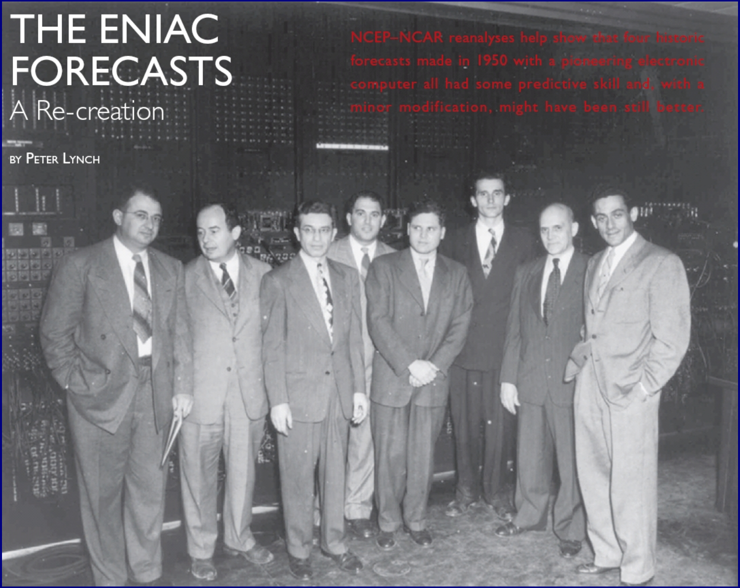
The matlab code is available on the website
http://maths.ucd.ie/∼plynch/eniac

Bull. Amer. Met. Soc., 89, 45–55 (Jan 2008)



NCEP/NCAR Reanalysis

The initial dates for the four forecasts were:

- January 5, 1949
- January 30, 1949
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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

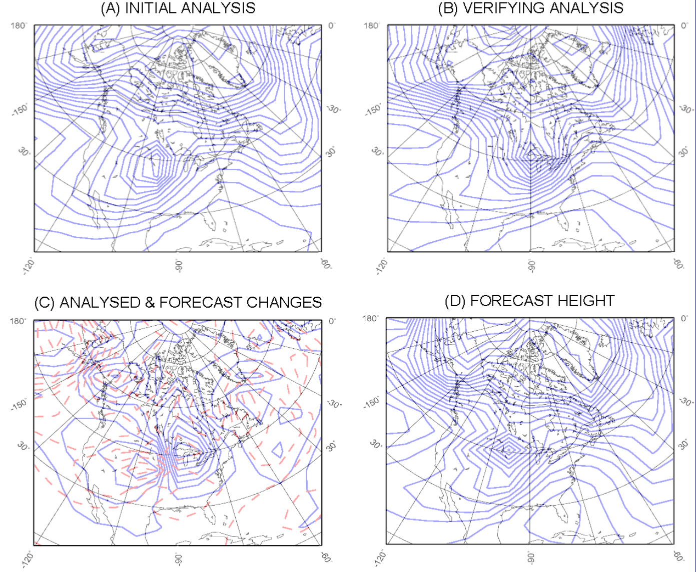
The NCEP–NCAR 50-Year Reanalysis: Monthly Means CD-ROM and Documentation

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



	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*, (1979) re-ran an ENIAC forecast
- The algorithm was coded on an IBM 5110, a desk-top machine
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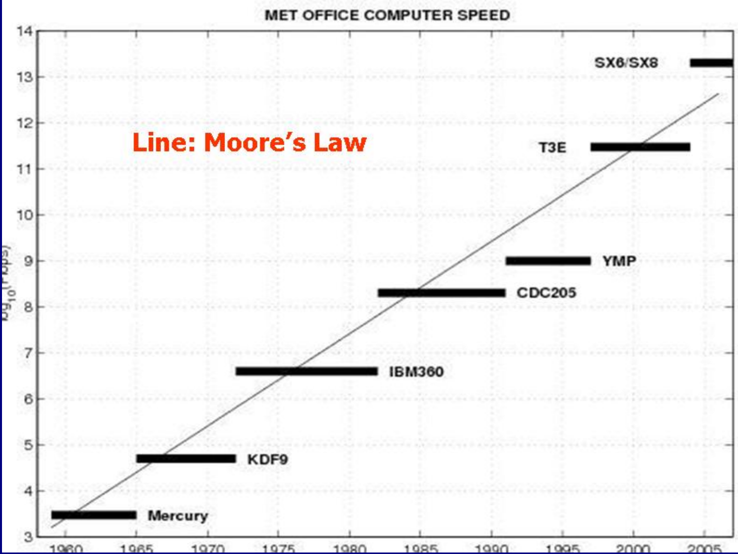
- The algorithm was coded on an IBM 5110, a desk-top machine
- The program execution was completed during the lecture (about one hour)
- The program ENIAC.M was run on a Sony Vaio (model VGN-TX2XP)
- The main loop of the 24-hour forecast ran in about 30 ms.

Outline


MET OFFICE COMPUTER SPEED
Line: Moore's Law
SX6/SX8
T3E
YMP
CDC205
IBM360
KDF9
Mercury
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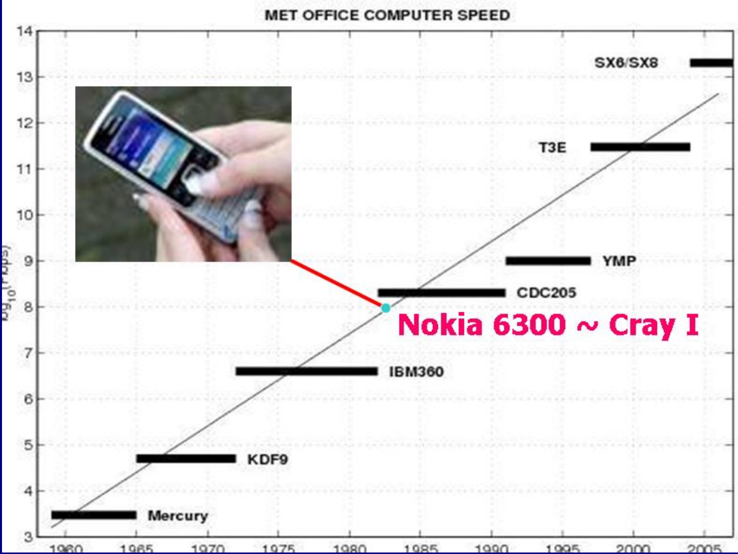
MET OFFICE COMPUTER SPEED
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T3E
YMP
CDC205
Nokia 6300 ~ Cray I
IBM360
KDF9
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Forecasts by PHONIAC

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A modern hand-held mobile phone has far greater power than the ENIAC had.

We therefore decided to repeat the ENIAC integrations using a programmable mobile phone.

Forecasts by PHONIAC

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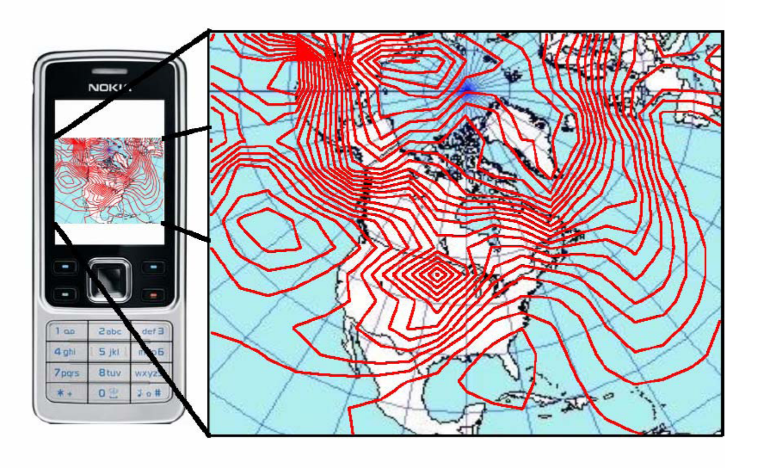
A modern hand-held mobile phone has far greater power than the ENIAC had.

We therefore decided to repeat the ENIAC integrations using a programmable mobile phone.

We converted the program ENIAC.M **to** PHONIAC.JAR**, a J2ME application, and implemented it on a mobile phone.**

This technology has great potential for generation and delivery of operational weather forecast products.

PHONIAC: Portable Hand Operated Numerical Integrator and Computer



Weather, November 2008

Forecasts by PHONIAC

Weather – November 2008, Vol. 63, No. 11

Peter Lynch[1]
and Owen Lynch[2]

[1]*University College Dublin, Meteorology and Climate Centre, Dublin*
[2]*Dublin Software Laboratory, IBM Ireland*

The first computer weather forecasts were made in 1950, using the ENIAC (Electronic Numerical Integrator and Computer). The ENIAC forecasts led to operational numerical weather prediction within five years, and paved the way for the remarkable advances in weather prediction and climate modelling that have been made over the past half century. The basis for the forecasts was the barotropic vorticity equation (BVE). In the present study, we describe the solution of the BVE on a mobile phone (cell-phone), and repeat one of the ENIAC forecasts. We speculate on the possible applications of mobile phones for micro-scale numerical weather prediction.

The ENIAC Integrations

and John von Neumann (1950; cited below as CFvN). The story of this work was recounted by George Platzman in his Victor P. Starr Memorial Lecture (Platzman, 1979). The atmosphere was treated as a single layer, represented by conditions at the 500 hPa level, modelled by the BVE. This equation, expressing the conservation of absolute vorticity following the flow, gives the rate of change of the Laplacian of height in terms of the advection. The tendency of the height field is obtained by solving a Poisson equation with homogeneous boundary conditions. The height field may then be advanced to the next time level. With a one hour time-step, this cycle is repeated 24 times for a one-day forecast.

The initial data for the forecasts were prepared manually from standard operational 500 hPa analysis charts of the U.S. Weather Bureau, discretised to a grid of 19 by 16 points, with grid interval of 736 km. Centred spatial finite differences and a leapfrog time-scheme were used. The boundary conditions for height were held constant throughout each 24-hour integration. The forecast starting at 0300 UTC, January 5, 1949 is shown in

vorticity. The forecast height and vorticity are shown in the right panel. The feature of primary interest was an intense depression over the United States. This deepened, moving NE to the 90 °W meridian in 24 hours. A discussion of this forecast, which underestimated the development of the depression, may be found in CFvN and in Lynch (2008).

Dramatic growth in computing power

The oft-cited paper in *Tellus* (CFvN) gives a complete account of the computational algorithm and discusses four forecast cases. The ENIAC, which had been completed in 1945, was the first programmable electronic digital computer ever built. It was a gigantic machine, with 18,000 thermionic valves, filling a large room and consuming 140 kW of power. Input and output was by means of punch-cards. McCartney (1999) provides an absorbing account of the origins, design, development and destiny of ENIAC.

Advances in computer technology over the past half-century have been spectacular. The increase in computing power is encap-

A Challenge to you all . . .

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Run a system to acquire and assimilate observations

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There are many more possibilities for these devices.

Thank you