Numerical Weather Prediction
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Meteorology & Climate Cenhre
School of Mathematical Sciences
University College Dublin
Text for the Course

The lectures will be based closely on the text

Atmospheric Modeling, Data Assimilation and Predictability

by

Eugenia Kalnay

• Numerical weather prediction provides the basic guidance for operational weather forecasting beyond the first few hours.
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The skill of NWP forecasts depends on accuracy of both the computer model and the initial conditions.
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A score of 20% or less corresponds to an essentially perfect forecast.
Definition of S1 Score

S1 Skill Score is the sum of the absolute horizontal gradients of the differences between the forecast and analysis values, normalised by the sum of the maximum absolute gradients of a forecast or analysis value.
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It measures the model ability to forecast correctly the horizontal gradients of scalar variables such as MSLP. The full range of the S1 score is from 0 to 200, with a low score being better than a high score.

A perfect score of 0 occurs when the forecast and analysis gradients are the same, even though the values may be different.

Typically a score of about 70 represents the limit of usefulness and 20 is excellent.
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The 72-h forecasts of today are as accurate as the 36-h forecasts were 10–20 years ago.

Similarly, 5-day forecasts, which had no useful skill 15 years ago, are now moderately skilful.
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- Improved representation of small-scale **physical processes** (clouds, precipitation, turbulent transfers of heat, moisture, momentum, and radiation) within the models;
- Increased availability of **data**, especially satellite and aircraft data over the oceans and the Southern Hemisphere.
- More accurate methods of **data assimilation**, which result in **improved initial conditions** for the models;
Major NWP research takes place in large national and international operational weather centres and in universities.

- European Center for Medium Range Weather Forecasts (ECMWF)
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- International Research Projects
  - HIRLAM, COSMO, ALADIN, HARMONIE, etc.
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In this lecture, we give an overview of the major components and milestones in numerical forecasting. They will be discussed in detail in the following lectures.
Vilhelm Bjerknes (1862–1951)
Objective: To establish a science of meteorology

Acid test: To predict future states of the atmosphere.
Bjerknes’ 1904 Manifesto

Objective:
To establish a science of meteorology

Acid test:
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** of the atmosphere
2. A knowledge of the **physical laws** which determine the evolution of the atmosphere.

Step (1) is **Diagnostic**. Step (2) is **Prognostic**.
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 as **mathematical equations**
- Using **observations**, we determine the atmospheric state at a given initial time: “Today’s Weather”
- Using **the equations**, we calculate how this state changes over time: “Tomorrow’s Weather”
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**BUT:**

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

It took him two years!

His ‘forecast’ was a catastrophic failure:

\[ \Delta p = 145 \text{ hPa in 6 hours} \]

His method was unimpeachable.

So, what went wrong?
In 1904, Margules published a paper in the *Festschrift* marking the sixtieth birthday of his teacher Ludwig Boltzmann: Õber die Beziehung zwischen Barometerschwankungen und Kontinuitätsgleichung. “On the Relationship between Barometric Variations and the Continuity Equation.”
Margules examined pressure changes predicted using the continuity equation.

He found that, to obtain a realistic pressure tendency, the winds must be known to an unrealistic precision.

He showed that synoptic forecasting by this means was doomed to failure.
Margules examined pressure changes predicted using the **continuity equation**.

He found that, to obtain a realistic pressure tendency, the winds must be known to an **unrealistic precision**.

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According to Fortak (2001), Margules was convinced that weather forecasting was:

“**immoral and damaging to the character of a meteorologist.**”
Tendency \textit{via} Continuity Equation

The environs of Dublin:

\begin{itemize}
  \item A square of side \(\sim 15\)km.
  \item Analogous to a cell of a finite difference model of the atmosphere.
\end{itemize}
A Box of Air over Dublin

Influx equals Outflow: Pressure remains unchanged.

Influx exceeds Outflow: Pressure will rise.
Pressure Tendency

Assume a westerly wind over Dublin

\[ u > 0, \quad v = 0. \]

Assume also that the surface pressure is initially 1000 hPa.
Pressure Tendency

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Using Conservation of Mass, a simple *back-of-the-envelope* calculation yields the following *amazing result*:

- If the speed on the western side *exceeds* that on the east by *just* 1 m/s, the pressure tendency is about 7 Pa/s.
- If this influx continues, the pressure will *double* in about 4 hours.
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Conclusion:
We must apply the Continuity Equation with great care.
A first attempt at calculating synoptic changes using physical principles was made by Felix Exner, working in Vienna. Exner followed a radically different line from Bjerknes. He did not make direct use of the continuity equation. His method was based on a system reduced to the essentials.
Exner’s Method

- Exner assumed **geostrophic balance and thermal forcing constant in time**.
- He deduced a **mean zonal wind from temperature observations**.
- He derived a prediction equation for **advection of the pressure pattern with constant speed, modified by heating**.
- His method yielded a **realistic forecast in the case illustrated in his paper**.
Exner’s Forecast

Calculated Pressure Change
between 8pm and 12pm on 3 January, 1895
Hundreths of an inch. [*Steigt*=rises; *Fällt*=falls].
Observed Pressure Change
between 8pm and 12pm on 3 January, 1895
Hundredths of an inch. [Steigt=rises; Fällt=falls].
Richardson’s Reaction

Exner’s work deserves attention as a first attempt at systematic, scientific weather forecasting.

The only reference by Richardson to the method was a single sentence in his book *Weather Prediction by Numerical Process* (p. 43):

“F. M. Exner has published a prognostic method based on the source of air supply.”

It would appear from this that Richardson was not particularly impressed by it!

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* * *

It is noteworthy that

- Exner’s forecast was *unspectacular but reasonable*.
- Richardson’s forecast was *spectacularly unreasonable*. 
Bjerknes proposed graphical methods for the solution of the forecasting problem.

Richardson was bolder — or perhaps more foolhardy — than Bjerknes.

He attempted a bulldozer approach, calculating changes from the full PDEs.
- Born, 11 October, 1881, Newcastle-upon-Tyne
- Family background: well-known Quaker family
- 1900–1904: Kings College, Cambridge
- 1919: Re-employed by Met. Office
- 1920: M.O. linked to the Air Ministry. Resigned, on grounds of conscience
- **1922:** *Weather Prediction by Numerical Process*
- 1926: Break with Meteorology. Worked on Psychometric Studies. Later on mathematical causes of Warfare
- 1940: Resigned to pursue “peace studies”
- Died, September, 1953.

Richardson contributed to **Meteorology, Numerical Analysis, Fractals, Psychology** and **Conflict Resolution.**
Eskdalemuir Observatory in 1911

(where Richardson’s dream began to take shape)
Table 1.1. *Chapter titles of Weather Prediction by Numerical Process.*

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chapter 1</td>
<td>Summary</td>
</tr>
<tr>
<td>Chapter 2</td>
<td>Introductory Example</td>
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<td>Chapter 3</td>
<td>The Choice of Coordinate Differences</td>
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<td>Chapter 4</td>
<td>The Fundamental Equations</td>
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<td>Chapter 5</td>
<td>Finding The Vertical Velocity</td>
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<td>Chapter 6</td>
<td>Special Treatment For The Stratosphere</td>
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<tr>
<td>Chapter 7</td>
<td>The Arrangement of Points and Instants</td>
</tr>
<tr>
<td>Chapter 8</td>
<td>Review of Operations in Sequence</td>
</tr>
<tr>
<td>Chapter 9</td>
<td>An Example Worked on Computing Forms</td>
</tr>
<tr>
<td>Chapter 10</td>
<td>Smoothing The Initial Data</td>
</tr>
<tr>
<td>Chapter 11</td>
<td>Some Remaining Problems</td>
</tr>
<tr>
<td>Chapter 12</td>
<td>Units and Notation</td>
</tr>
</tbody>
</table>
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 destroyed

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 rarification, etc.

Seven equations; seven variables \((u, v, w, \rho, p, T, q)\).
The Primitive Equations

\[
\begin{align*}
\frac{du}{dt} - \left( f + \frac{u \tan \phi}{a} \right) v + \frac{1}{\rho} \frac{\partial p}{\partial x} + F_x &= 0 \\
\frac{dv}{dt} + \left( f + \frac{u \tan \phi}{a} \right) u + \frac{1}{\rho} \frac{\partial p}{\partial y} + F_y &= 0 \\
p &= R\rho T \\
\frac{\partial p}{\partial y} + g\rho &= 0 \\
\frac{dT}{dt} + (\gamma - 1)T \nabla \cdot \mathbf{V} &= \frac{Q}{c_p} \\
\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \mathbf{V} &= 0 \\
\frac{\partial \rho_w}{\partial t} + \nabla \cdot \rho_w \mathbf{V} &= \text{[Sources – Sinks]}
\end{align*}
\]

Seven equations; seven variables \((u, v, w, p, T, \rho, \rho_w)\).
The globe is divided into cells, like the checkers of a chess-board. Spatial derivatives are replaced by finite differences:

\[
\frac{df}{dx} \rightarrow \frac{f(x + \Delta x) - f(x - \Delta x)}{2\Delta x}.
\]

Similarly for time derivatives:

\[
\frac{dQ}{dt} \rightarrow \frac{Q^{n+1} - Q^{n-1}}{2\Delta t} = F^n
\]

This can immediately be solved for \( Q^{n+1} \):

\[
Q^{n+1} = Q^{n-1} + 2\Delta t F^n.
\]

By repeating the calculations for many time steps, we can get a forecast of any length.

Richardson calculated only the initial rates of change.
Bjerknes’ sea level pressure analysis.
Bjerknes’ 500 hPa height analysis.
Richardson’s vertical stratification

\[ R_1 U_1 V_1 T_1 \]

\[ z_1 \quad p_1 w_1 \]

\[ R_2 U_2 V_2 \]

\[ z_2 \quad p_2 w_2 \]

\[ R_3 U_3 V_3 \]

\[ z_3 \quad p_3 w_3 \]

\[ R_4 U_4 V_4 \]

\[ z_4 \quad p_4 w_4 \]

\[ R_5 U_5 V_5 \]

\[ z_S \quad p_S w_S \]
Grid used by Richardson for his forecast.
Richardson Grid (also called an Arakawa E-grid)
Richardson’s Spread-sheet

The figure in the bottom right corner is the forecast change in surface pressure: 145 mb in six hours!
Smooth Evolution of Pressure
Noisy Evolution of Pressure
Tendency of a Smooth Signal

![Graph showing pressure versus time with different lines representing signal, signal+noise, and physical tendency.](image)
Tendency of a Noisy Signal
Richardson’s Forecast Factory (A. Lannerback).
Dagens Nyheter, Stockholm. Reproduced from L. Bengtsson, _ECMWF_, 1984
Richardson’s Forecast Factory (A. Lannerback).
Dagens Nyheter, Stockholm. Reproduced from L. Bengtsson, ECMWF, 1984

64,000 Computers: The first Massively Parallel Processor
What went wrong?

- Richardson extrapolated *instantaneous* pressure change, assuming it to remain constant over a long time period.
- This ignores the propensity of the atmosphere to respond rapidly to changes.
- An increase of pressure causes an immediate pressure gradient which acts to resist further change.
- The resulting *gravity wave oscillations* act in such a way as to restore balance.
- They result in pressure changes which may be large but which oscillate rapidly in time.

(Margules, 1893, was the first comprehensive study of gravity wave dynamics)
The ineluctable conclusion is that . . .

the instantaneous rate of change is not a reliable indicator of the long-term variation in pressure.
To obtain an accurate prediction, the **time step has to be short enough to allow the adjustment to take place.**

Gravity-wave oscillations **need not spoil the forecast.**

They may be regarded as **noise superimposed on the synoptic evolution.**

They may also be effectively removed by an adjustment of the data, known as **initialization.**
Evolution of surface pressure before and after NNMI.  
(Williamson and Temperton, 1981)
“The scheme of numerical forecasting has been developed so far that it is reasonable to expect that when the smoothing ... has been arranged, it may give forecasts agreeing with the actual smoothed weather.”
Richardson devoted a short chapter of his book to smoothing.

He outlined five smoothing methods:

- A. Space Means.
- B. Time Means.
- C. Potential Function.
- D. Stream Function.
- E. Smoothing during the Forecast.

Richardson’s *Method B* is a close cousin of Digital Filtering Initialization, which has some current popularity.
Grid for extending Richardson’s forecast
Digital Filter Response

Frequency Response of Dolph-Chebyshev Filter

Response $H$

Frequency $\theta$

0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1

0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1

1 0.9 0.8 0.7 0.6 0.5 0.4 0.3 0.2 0.1 0
1000 hPa height and surface pressure before initialization
1000 hPa height and surface pressure after initialization
Forecast without Filtering

Short-range forecast of sea-level pressure, from *uninitialized data*. The contour interval is 4 hPa. Single forward time step of size $\Delta t = 3600 \text{ s}$. 
Short-range forecast of sea-level pressure, from filtered data. The contour interval is 4 hPa. Single forward time step of size $\Delta t = 3600\, \text{s}$. 
Table 1: Analysis of the pressure changes (hPa) across each layer, and the pressure change at the base of each layer.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Level</th>
<th>Total Divergence $\nabla \cdot \mathbf{U} + [\rho w]$</th>
<th>Change in Pressure Thickness $\frac{\partial[p]}{\partial t} \Delta t$</th>
<th>Change in Base Pressure $\frac{\partial p}{\partial t} \Delta t$</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>1</td>
<td>$-0.0229$</td>
<td>$+48.3$</td>
<td>$+48.3$</td>
</tr>
<tr>
<td>II</td>
<td>2</td>
<td>$-0.0136$</td>
<td>$+28.7$</td>
<td>$+77.1$</td>
</tr>
<tr>
<td>III</td>
<td>3</td>
<td>$-0.0124$</td>
<td>$+26.2$</td>
<td>$+103.2$</td>
</tr>
<tr>
<td>IV</td>
<td>4</td>
<td>$-0.0110$</td>
<td>$+23.3$</td>
<td>$+126.5$</td>
</tr>
<tr>
<td>V</td>
<td>S</td>
<td>$-0.0088$</td>
<td>$+18.6$</td>
<td><strong>$+145.1$</strong></td>
</tr>
</tbody>
</table>
Table 2: Analysis of the pressure changes (hPa) for the forecast from data after Digital Filtering.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Level</th>
<th>Total Divergence</th>
<th>Change in Pressure Thickness</th>
<th>Change in Base Pressure</th>
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<tbody>
<tr>
<td>I</td>
<td>1</td>
<td>$\nabla \cdot \mathbf{U} + [\rho w]$</td>
<td>$-0.2$</td>
<td>$-0.2$</td>
</tr>
<tr>
<td>II</td>
<td>2</td>
<td>$+0.0011$</td>
<td>$-2.4$</td>
<td>$-2.6$</td>
</tr>
<tr>
<td>III</td>
<td>3</td>
<td>$+0.0002$</td>
<td>$-0.4$</td>
<td>$-3.0$</td>
</tr>
<tr>
<td>IV</td>
<td>4</td>
<td>$+0.0000$</td>
<td>$-0.1$</td>
<td>$-3.1$</td>
</tr>
<tr>
<td>V</td>
<td>5</td>
<td>$-0.0010$</td>
<td>$+2.1$</td>
<td>$-0.9$</td>
</tr>
</tbody>
</table>
Surface pressure at Bayreuth for a week in May, 1910
Crucial Advances, 1920–1950

- Dynamic Meteorology
  - Rossby Waves
  - Quasi-geostrophic Theory
  - Baroclinic Instability

- Numerical Analysis
  - CFL Criterion

- Atmospheric Observations
  - Radiosonde

- Electronic Computing
  - ENIAC
Von Neumann’s idea (1946):

Weather forecasting was, *par excellence*, a scientific problem suitable for solution using a large computer.

**Objective:**
To predict the weather by simulating the dynamics of the atmosphere using a digital electronic computer.
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
Evolution of the Meteorology 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

\[
\frac{d}{dt}(\zeta + f) = 0
\]
Charney, J.G., R. Fjørtoft and J. von Neumann, 1950:
ENIAC: First Computer Forecast
“Allow me to congratulate you ... on the remarkable progress which has been made.

“This is ... an enormous scientific advance on the ... result in Richardson (1922).”
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 forecasting began in May, 1955, with a three-level quasi-geostrophic model.
In 1951, Jule Charney wrote:

**The outlook for numerical forecasting would be indeed dismal if the quasi-geostrophic approximation represented the upper limit of attainable accuracy, for it is known that it applies only indifferently, if at all, to many of the small-scale but meteorologically significant motions.**
In 1951, Jule Charney wrote:

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All modern NWP centres have abandoned the QG equations for operational forecasting. (However, they are invaluable for theoretical studies).
Small-scale physical processes cannot be represented explicitly in computer models. They must be represented by bulk formulae. This is called *parameterization of the subgrid-scale physics*. 
Parameterization

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- Condensation phenomena
- Solar radiation
- Long-wave radiation
- Orographic effects
- Land-atmosphere interactions
- Ocean-atmosphere interactions
- Turbulent transfer of momentum and heat.
Data Assimilation

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Present-day operational systems typically use a 6-h cycle performed four times a day.
Typical 6-hour analysis cycle.
For an introduction to Operational NWP and the evolution of forecast skill read Kalnay, §1.5.
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The Future

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• Fully coupled atmospheric–hydrological systems, where the atmospheric model precipitation is down-scaled and used to extend the length of river flow prediction;
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• An explosive growth of systems with emphasis on commercial applications of NWP, from guidance on the state of highways to air pollution, flood prediction, guidance to agriculture, construction, etc.