New Intro (Chapter 1)
(plus slides from Lynch)

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Numerical Weather Prediction

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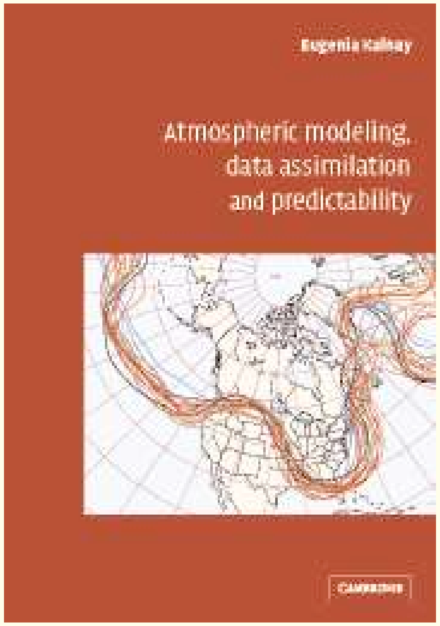
Text for the Course

The lectures will be based closely on the text

Atmospheric Modeling, Data Assimilation and Predictability
by
Eugenia Kalnay

published by Cambridge University Press (2002).



Introduction (Kalnay, Ch. 1)

- **Numerical weather prediction provides the basic guidance for operational weather forecasting beyond the first few hours.**
- **Numerical forecasts are generated by running computer models of the atmosphere that can simulate the evolution of the atmosphere over the next few days.**
- **NWP is an *initial-value problem*. The initial conditions are provided by analysis of weather observations.**
- **The skill of NWP forecasts depends on accuracy of both *the computer model* and *the initial conditions*.**

- Operational computer weather forecasts have been performed since about 1955.
- Since 1973, they have been global in extent.
- Over the years, the quality of the models and methods for using atmospheric observations has improved continuously, resulting in major forecast improvements.
- NCEP has the longest available record of the skill of numerical weather prediction.
- The "$S1$" score (Teweles and Wobus, 1954) measures the relative error in the horizontal gradient of the height of the 500 hPa pressure surface.
- A score of 70% or more corresponds to a useless forecast.
- A score of 20% or less corresponds to an essentially perfect forecast.

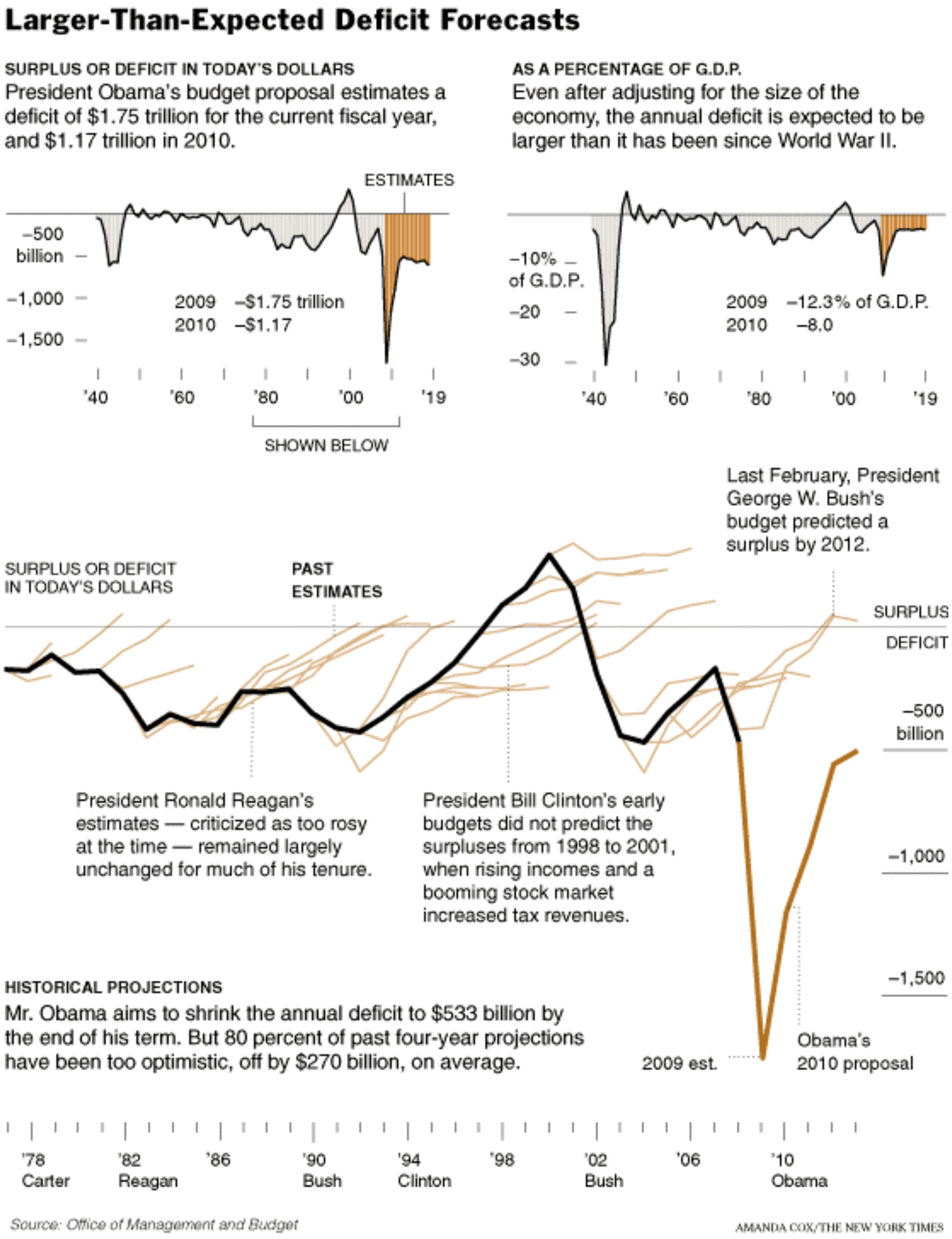
Economic Forecasts of the deficit (NYT July 28 2009)

Imagine if weather forecasts were like these economic forecasts!

Unlike economic forecasts, the skill of weather forecasts is measured and recorded.

NCEP has the longest record of numerical weather forecasts, starting in 1954.

Larger-Than-Expected Deficit Forecasts



SURPLUS OR DEFICIT IN TODAY'S DOLLARS
President Obama's budget proposal estimates a deficit of $1.75 trillion for the current fiscal year, and $1.17 trillion in 2010.

AS A PERCENTAGE OF G.D.P.
Even after adjusting for the size of the economy, the annual deficit is expected to be larger than it has been since World War II.

Last February, President George W. Bush's budget predicted a surplus by 2012.

President Ronald Reagan's estimates — criticized as too rosy at the time — remained largely unchanged for much of his tenure.

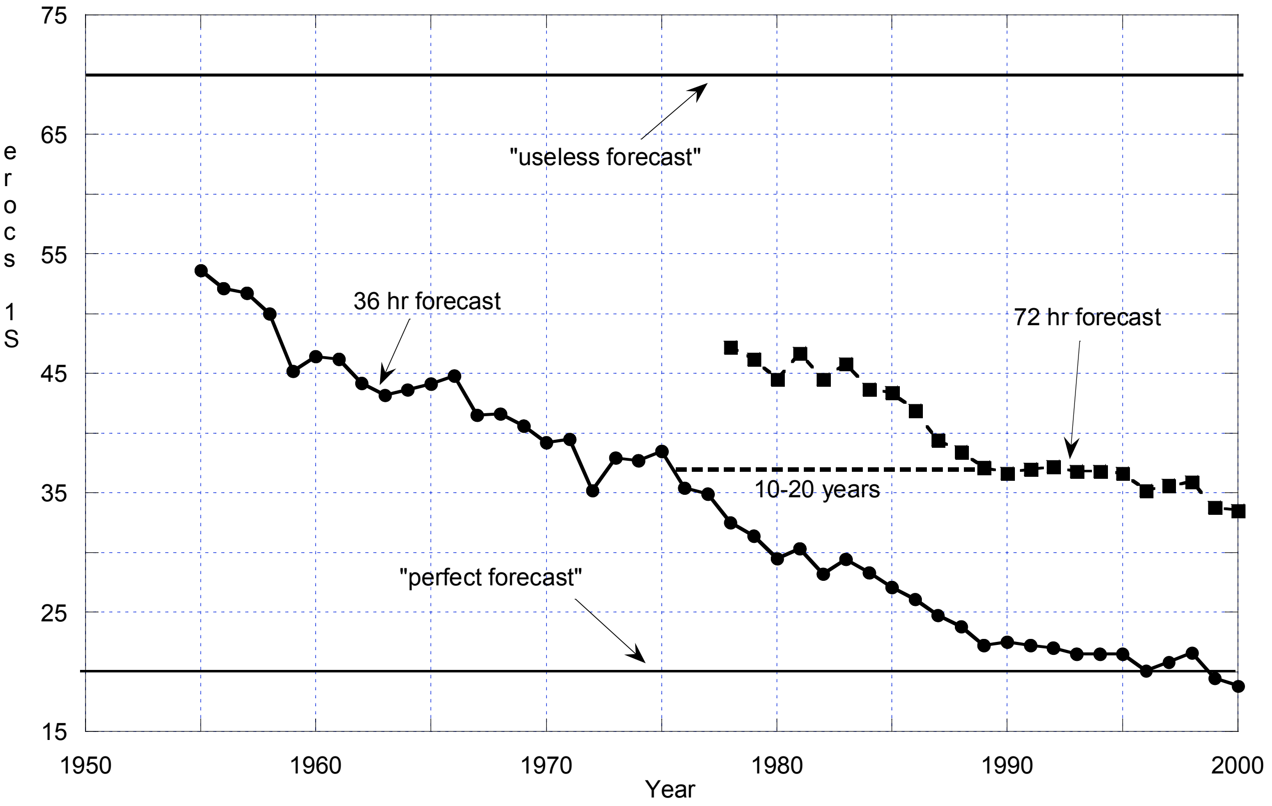
President Bill Clinton's early budgets did not predict the surpluses from 1998 to 2001, when rising incomes and a booming stock market increased tax revenues.

HISTORICAL PROJECTIONS
Mr. Obama aims to shrink the annual deficit to $533 billion by the end of his term. But 80 percent of past four-year projections have been too optimistic, off by $270 billion, on average.

Source: Office of Management and Budget

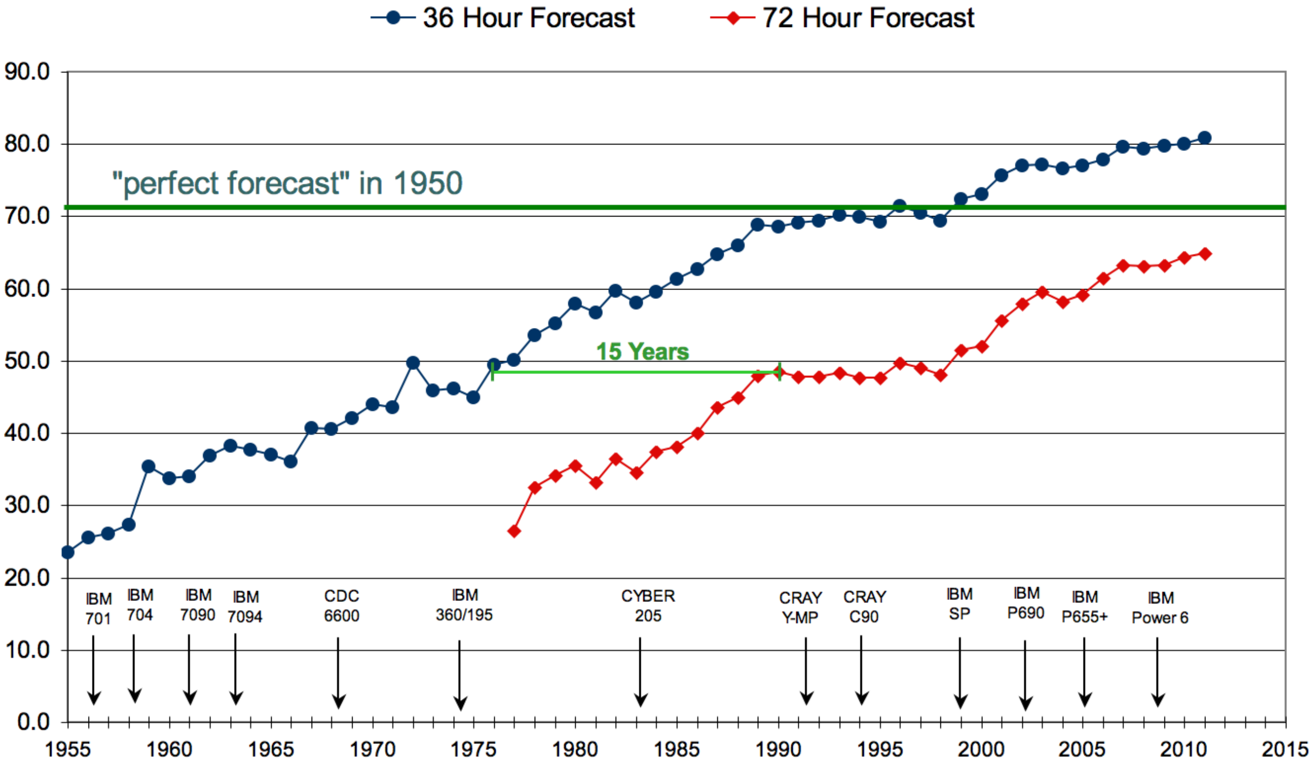
AMANDA COX/THE NEW YORK TIMES

NCEP operational S1 scores at 36 and 72 hr
over North America (500 hPa)



NCEP Operational Forecast Skill

36 and 72 Hour Forecasts @ 500 MB over North America
[100 * (1-S1/70) Method]



NCEP Central Operations January 2011

A “perfect forecast” was defined as the score obtained by comparing analyses hand-made by several experienced forecasters fitting the same observations over the data-rich North American region.
With this measure, the 36 hr forecasts are now better than perfect!

The accuracy of prediction is closely linked to the available computer power; the introduction of new machines is indicated in the figure.

Current 36-h 500-hPa forecasts over North America are close to what was considered essentially "perfect" 40 years ago.

The sea level pressure forecasts contain smaller-scale atmospheric structures, such as fronts, mesoscale convective systems that dominate summer precipitation, etc., and are still difficult to forecast in detail.

The 72-h forecasts of today are as accurate as the 36-h forecasts were 10–20 years ago.

The improvement in skill of numerical weather prediction over the last 50 years is due to four factors:

- Increased power of supercomputers, allowing much finer numerical resolution and fewer model approximations;
- 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)**
- **National Centers for Environmental Prediction (NCEP)**
- **National Oceanic and Atmospheric Administration (NOAA)**
- **National Center for Atmospheric Research (NCAR)**
- **National Meteorological Services (NMSs):**
  - **UK, France, Germany, Scandinavian and other European countries**
  - **Canada, Japan, Australia, and others.**
- **International Research Projects**
  - **HIRLAM, COSMO, ALADIN, HARMONIE, etc.**

In meteorology there has been a long tradition of sharing both data and research improvements.

All countries have benefited from this cooperation.

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)

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.

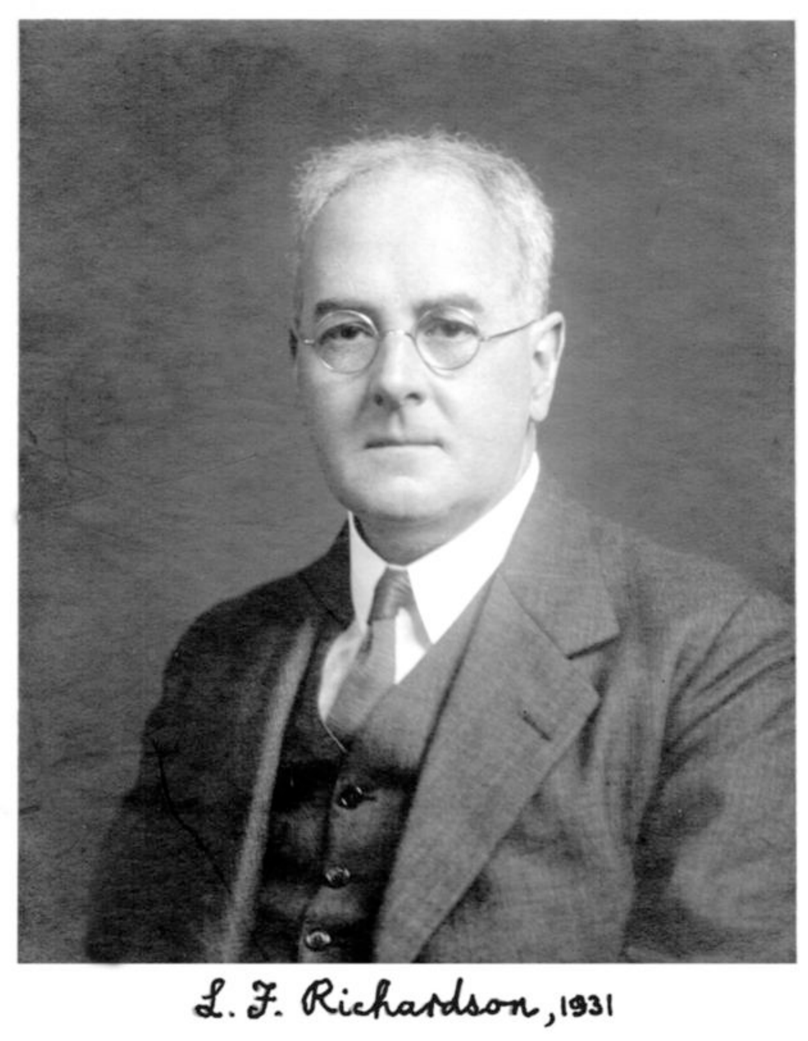
Scientific Weather Forecasting in a Nut-Shell

- 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"

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 predictibility.

Lewis Fry Richardson, 1881–1953.



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

It took him two years !

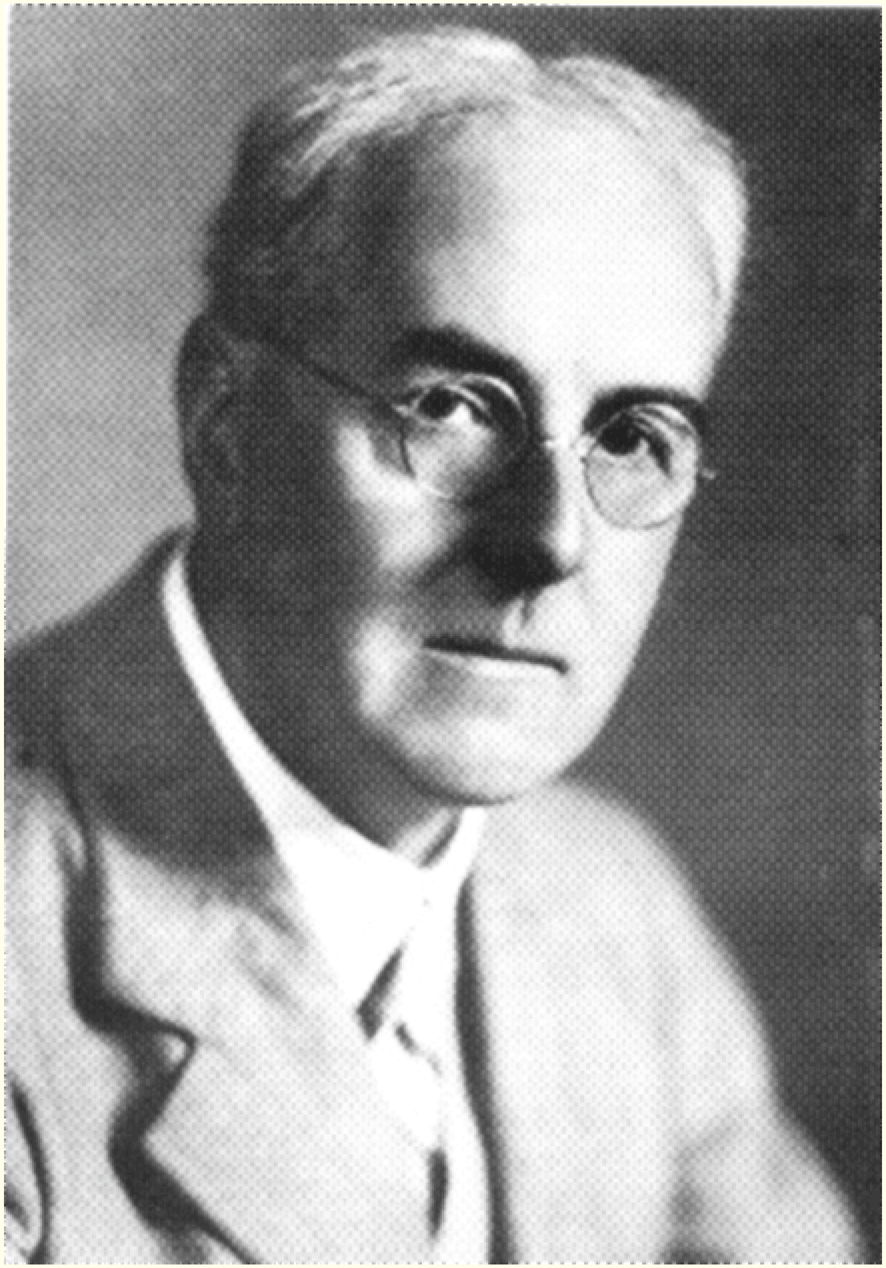
His ‘forecast’ was a catastrophic failure:

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

His method was unimpeachable.

So, *what went wrong?*

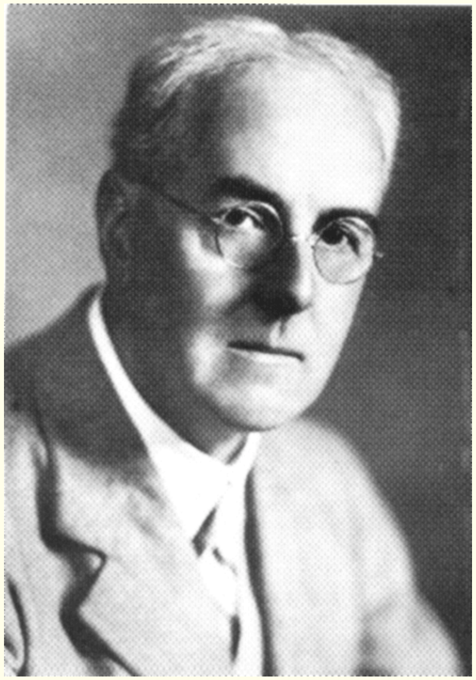
Lewis Fry Richardson, 1881–1953.



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
- 1913–1916: Met. Office. Superintendent, Eskdalemuir Observatory
- Resigned from Met Office in May, 1916. Joined Friends' Ambulance Unit.
- 1919: Re-employed by Met. Office
- 1920: M.O. linked to the Air Ministry. LFR 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.

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

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

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

$$p = R\rho T$$

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

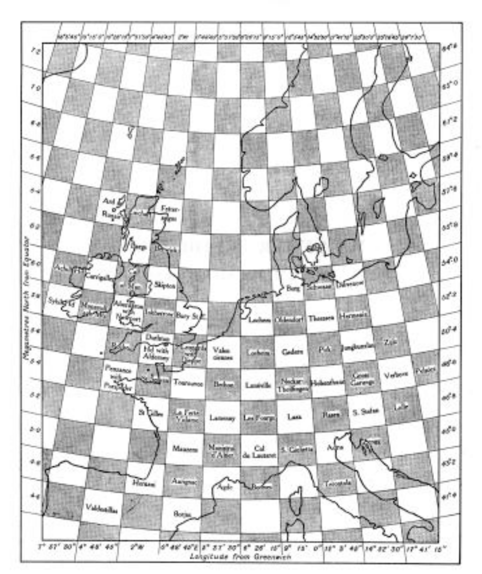
$$\frac{dT}{dt} + (\gamma - 1)T\nabla\cdot\mathbf{V} = \frac{Q}{c_p}$$

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

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

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

The Finite Difference Scheme



The globe is divided into cells, like the checkers of a chess-board.

Spatial derivatives are replaced by finite differences:

$$\frac{df}{dx} \to \frac{f(x+\Delta x) - f(x-\Delta x)}{2\Delta x} .$$

Similarly for time derivatives:

$$\frac{dQ}{dt} \to \frac{Q^{n+1} - Q^{n-1}}{2\Delta t} = F^n$$

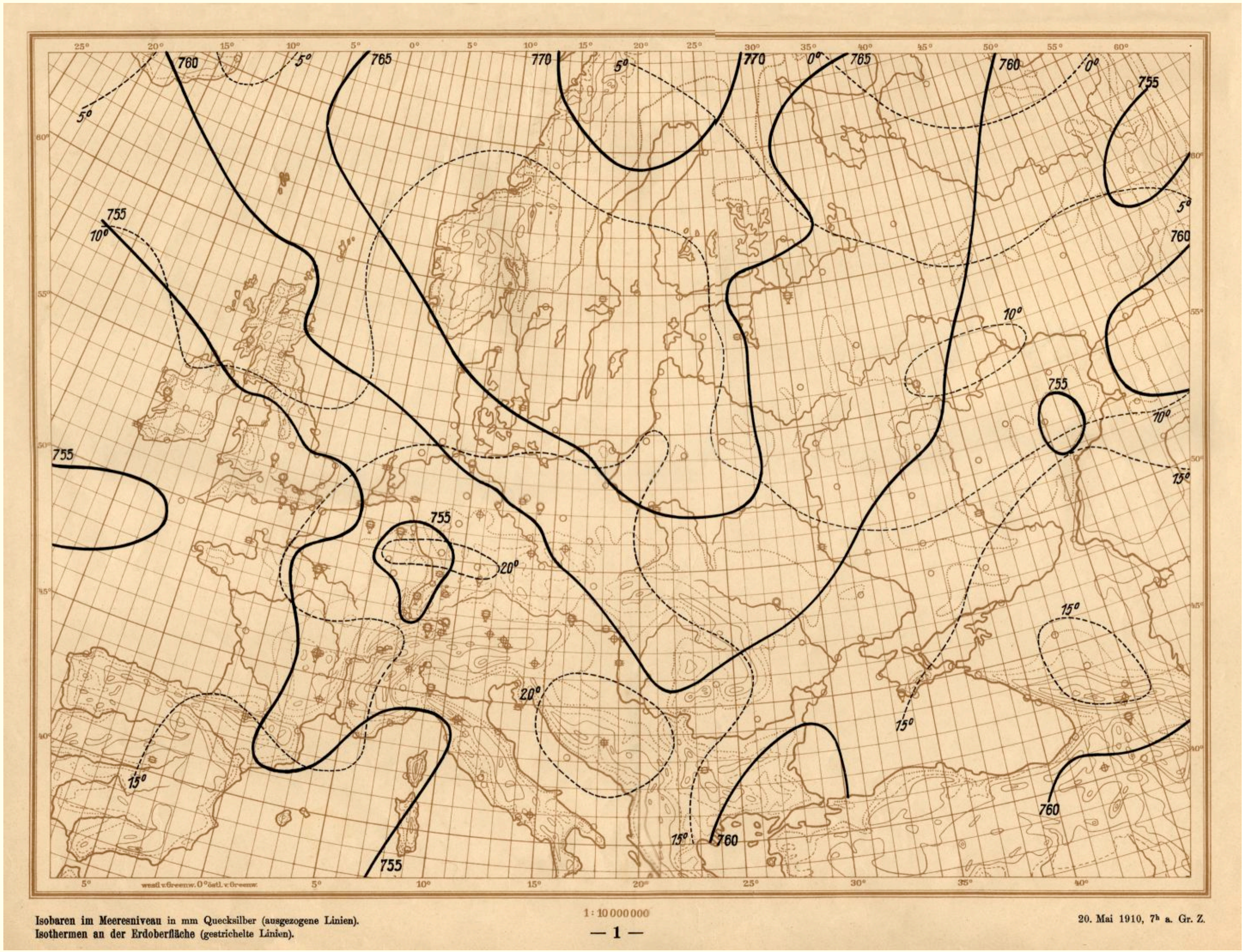
This can immediately be solved for Q^{n+1}:

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

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

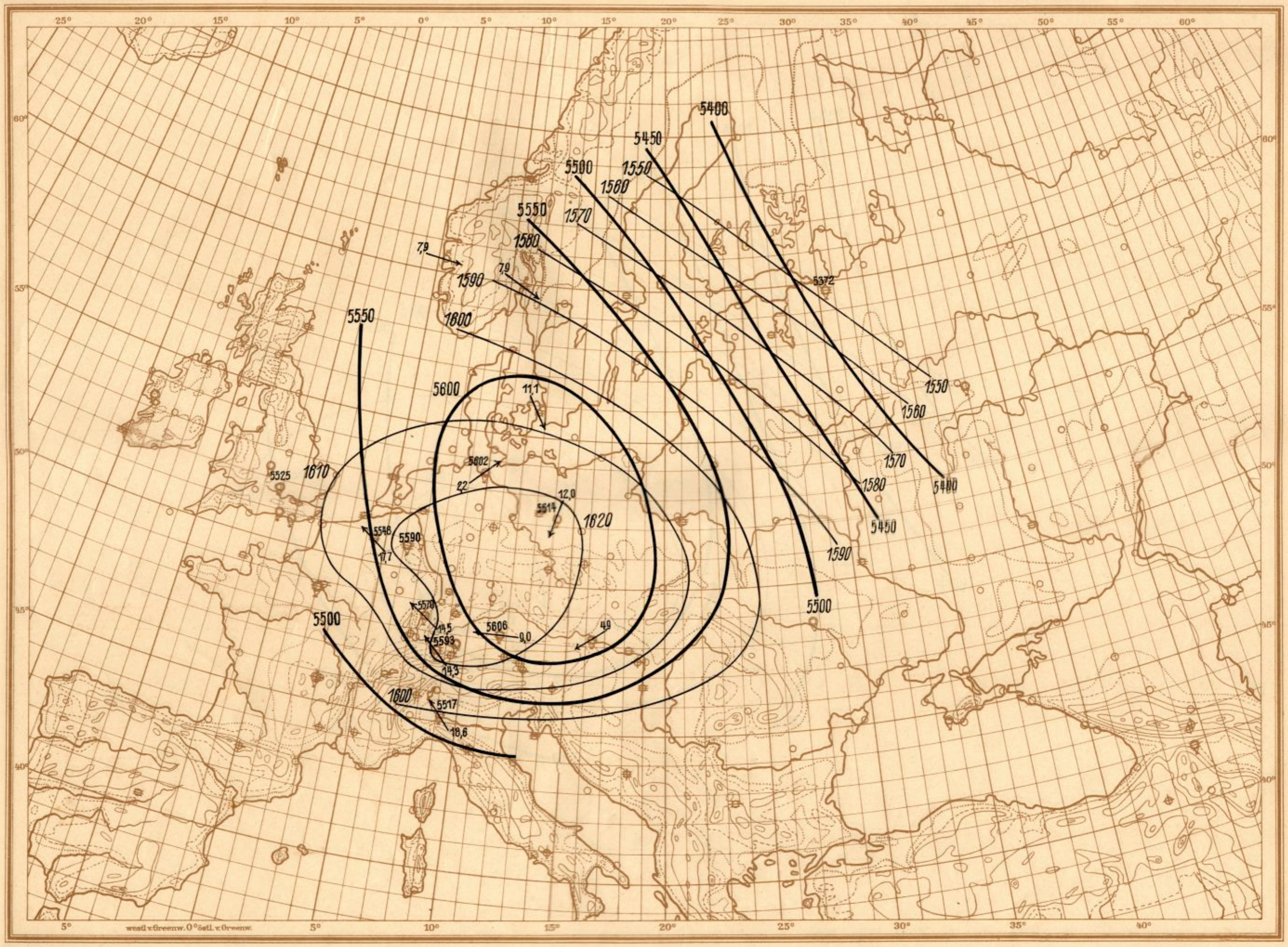
Richardson calculated only the initial rates of change.

The Leipzig Charts for 0700 UTC, May 20, 1910



Bjerknes' sea level pressure analysis.

The Leipzig Charts for 0700 UTC, May 20, 1910



Hauptschicht V, dargestellt durch die absolute Topographie der 500 mbar-Fläche (dicke Linien) und die relative Topographie der 400 mbar-Fläche (dünne Linien).

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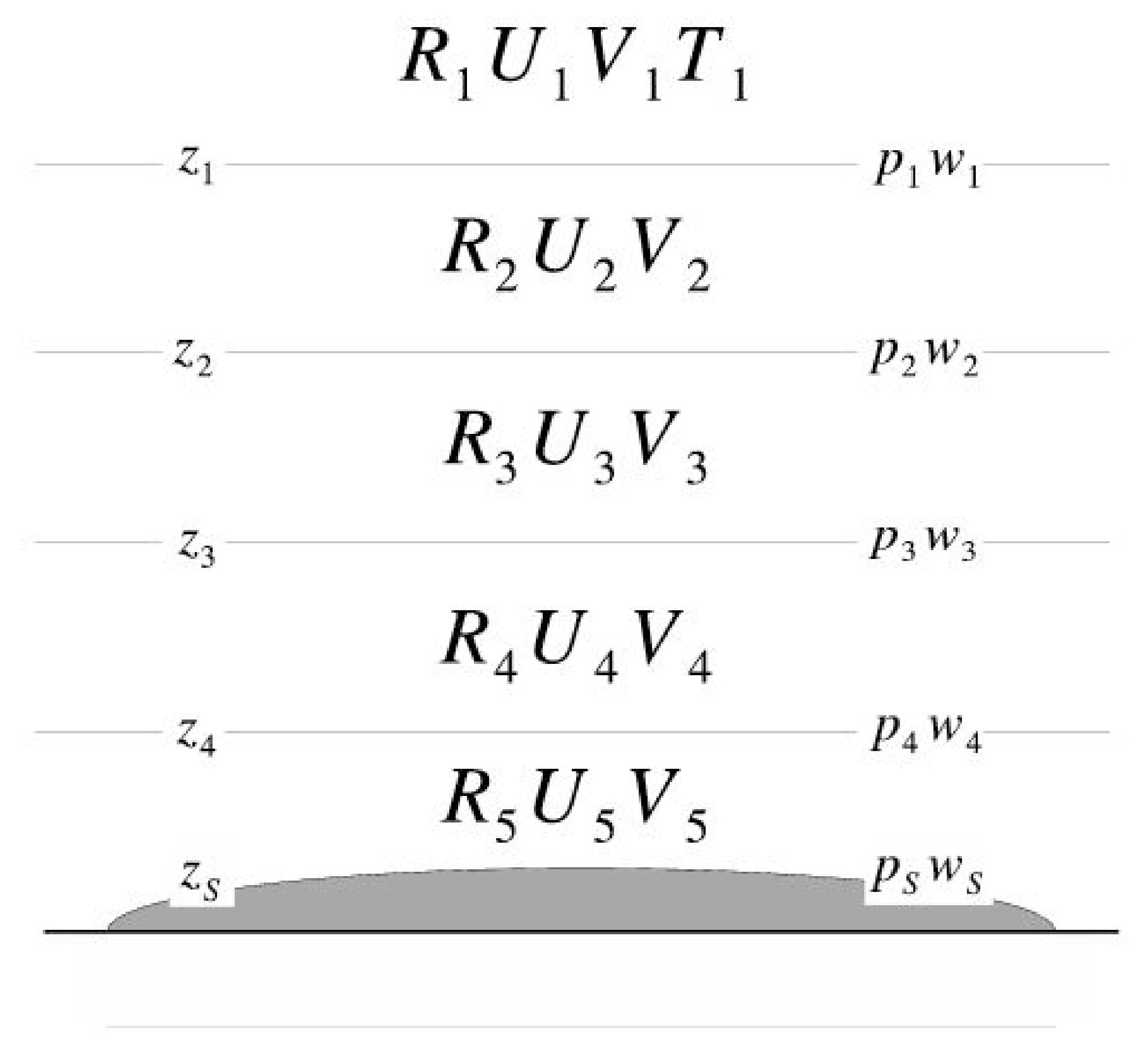
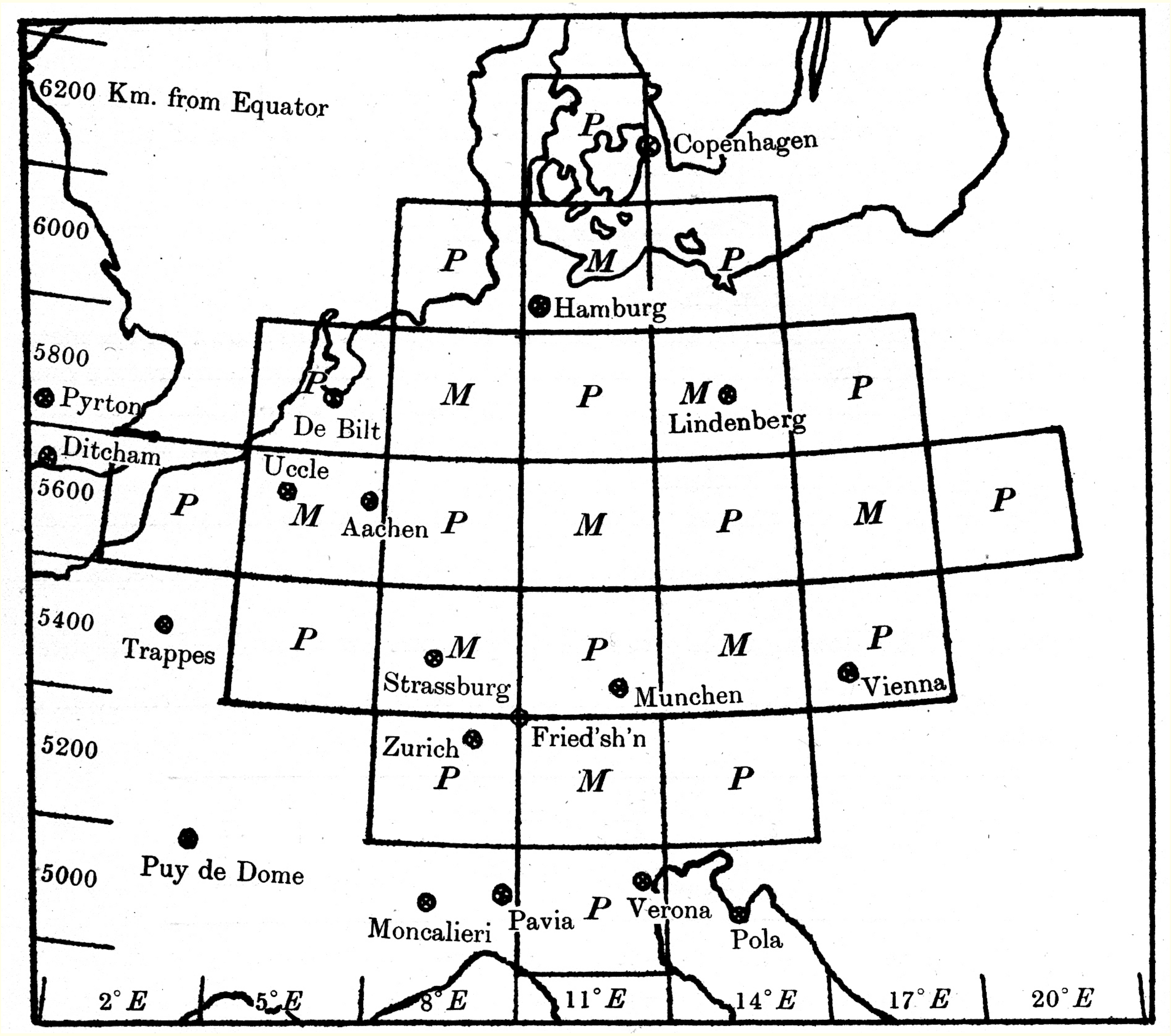
20. Mai 1910, 7^h a. Gr. Z.

Bjerknes' 500 hPa height analysis.

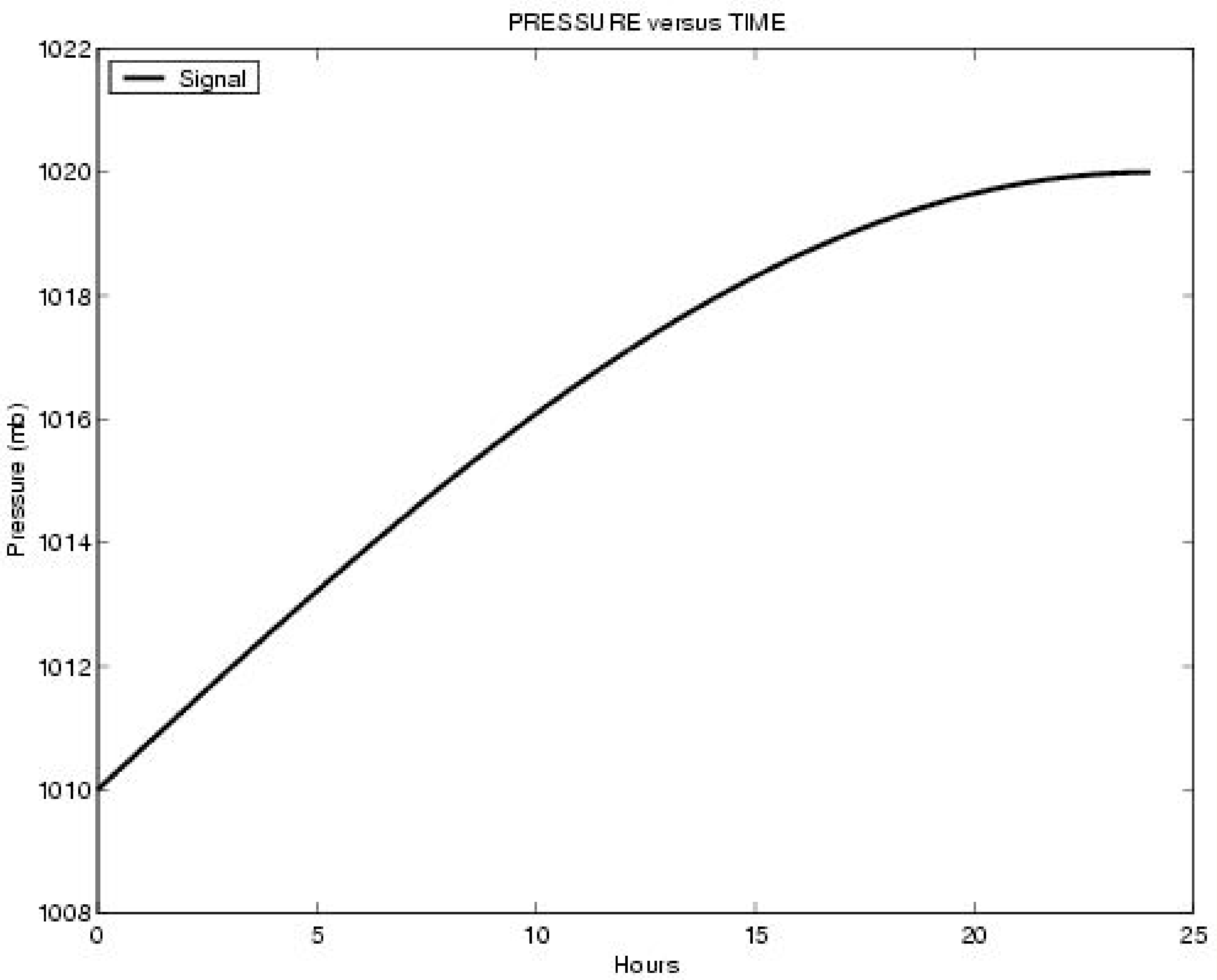
Richardson’s vertical stratification



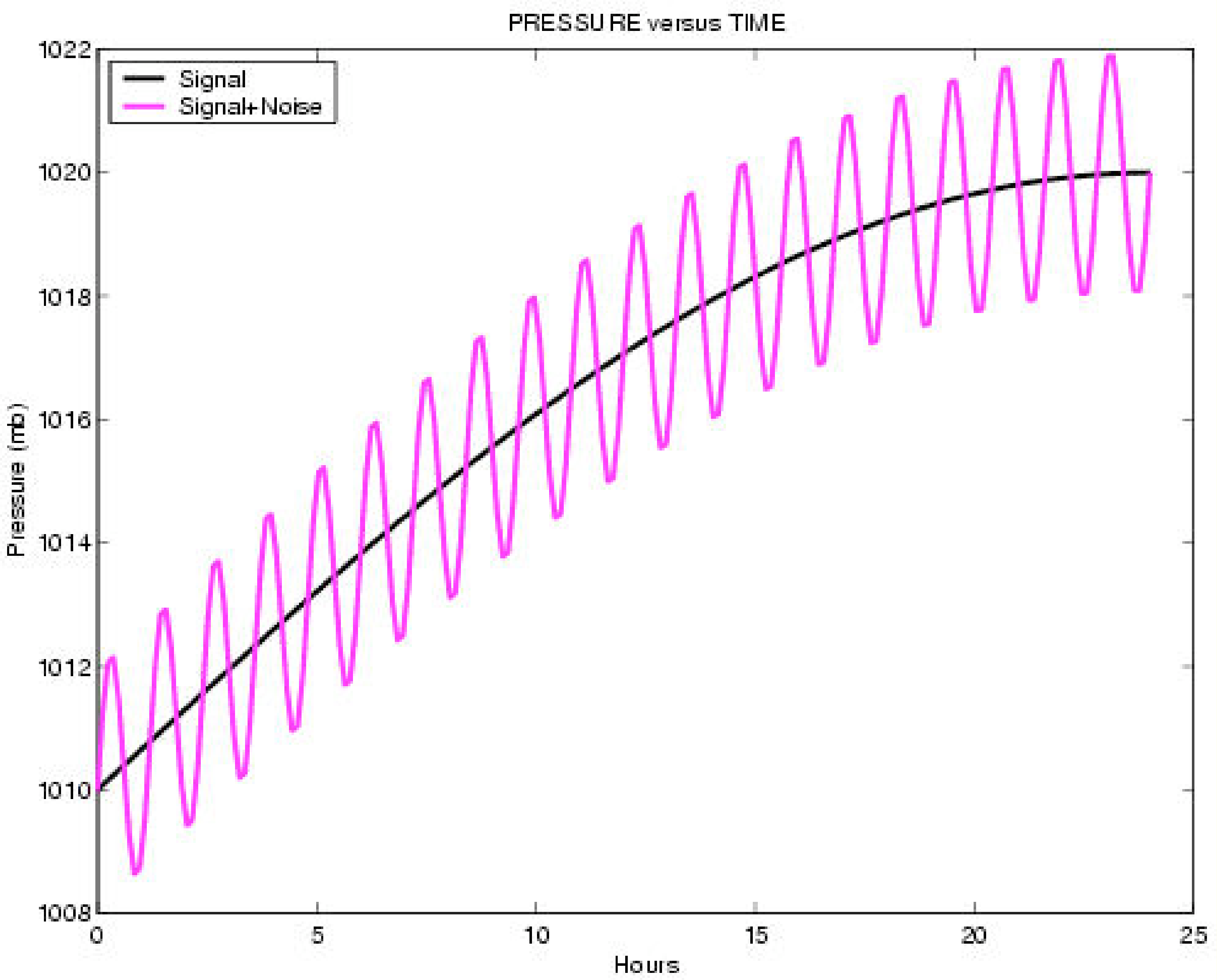


Grid used by Richardson for his forecast.

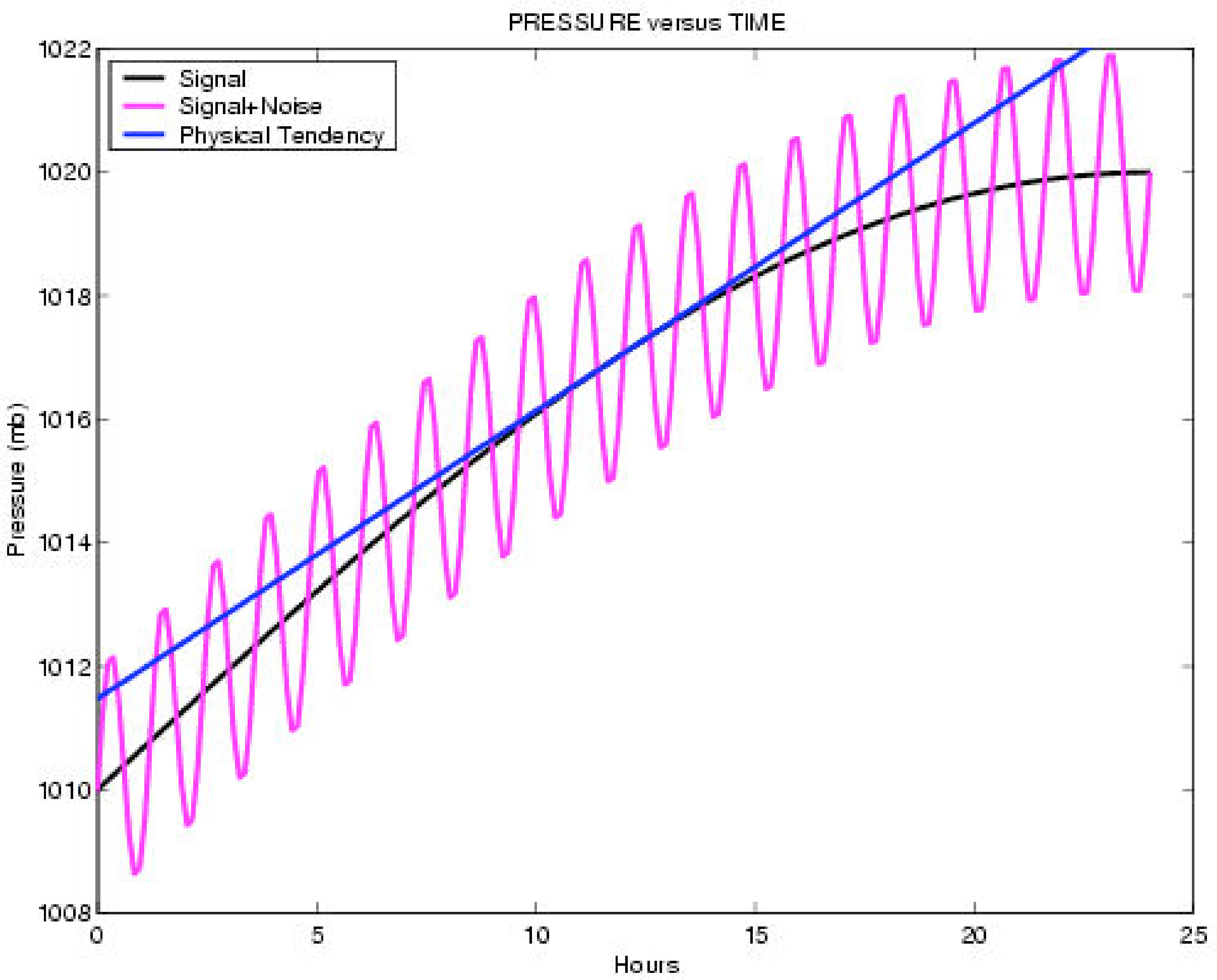
Smooth Evolution of Pressure



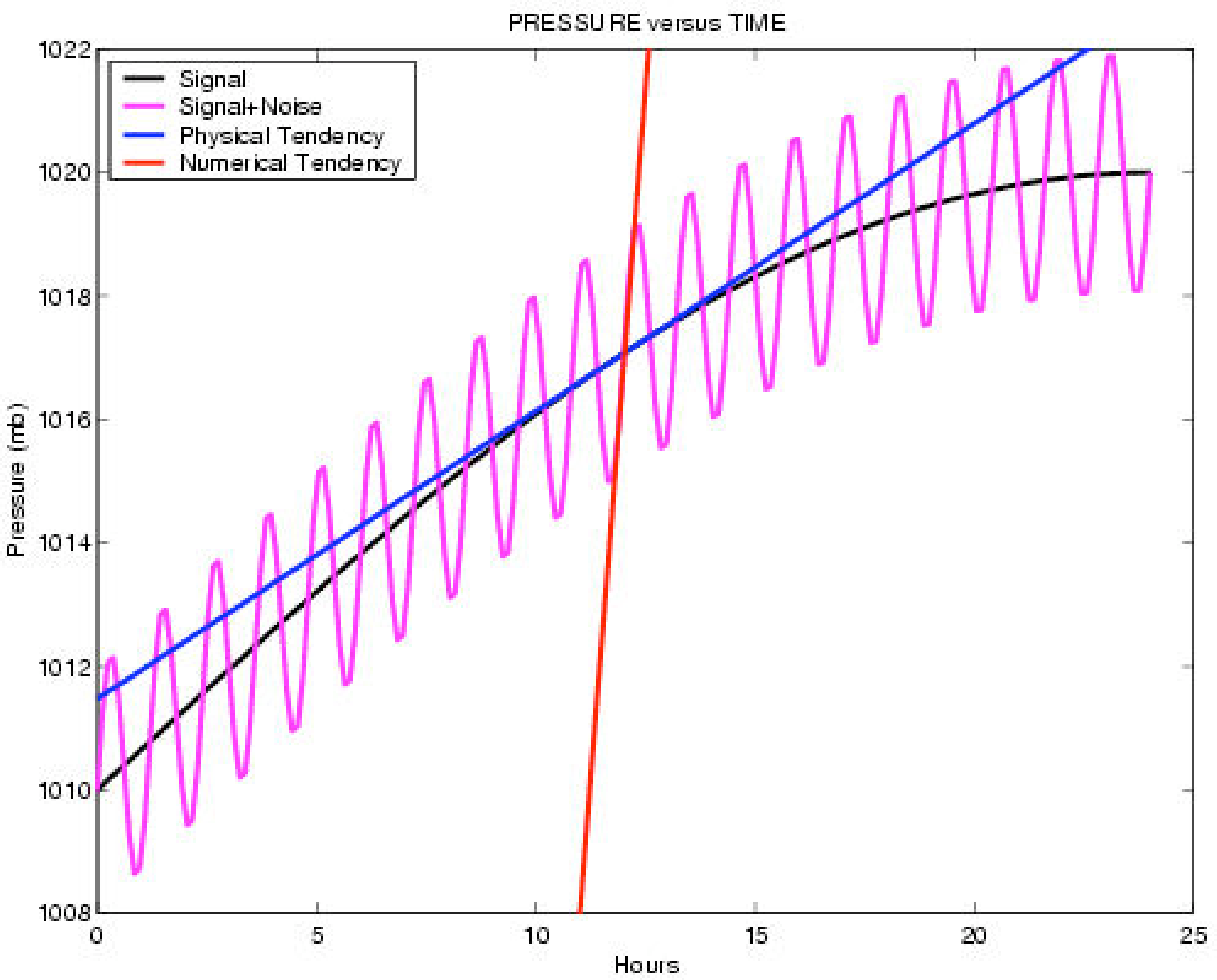
Noisy Evolution of Pressure

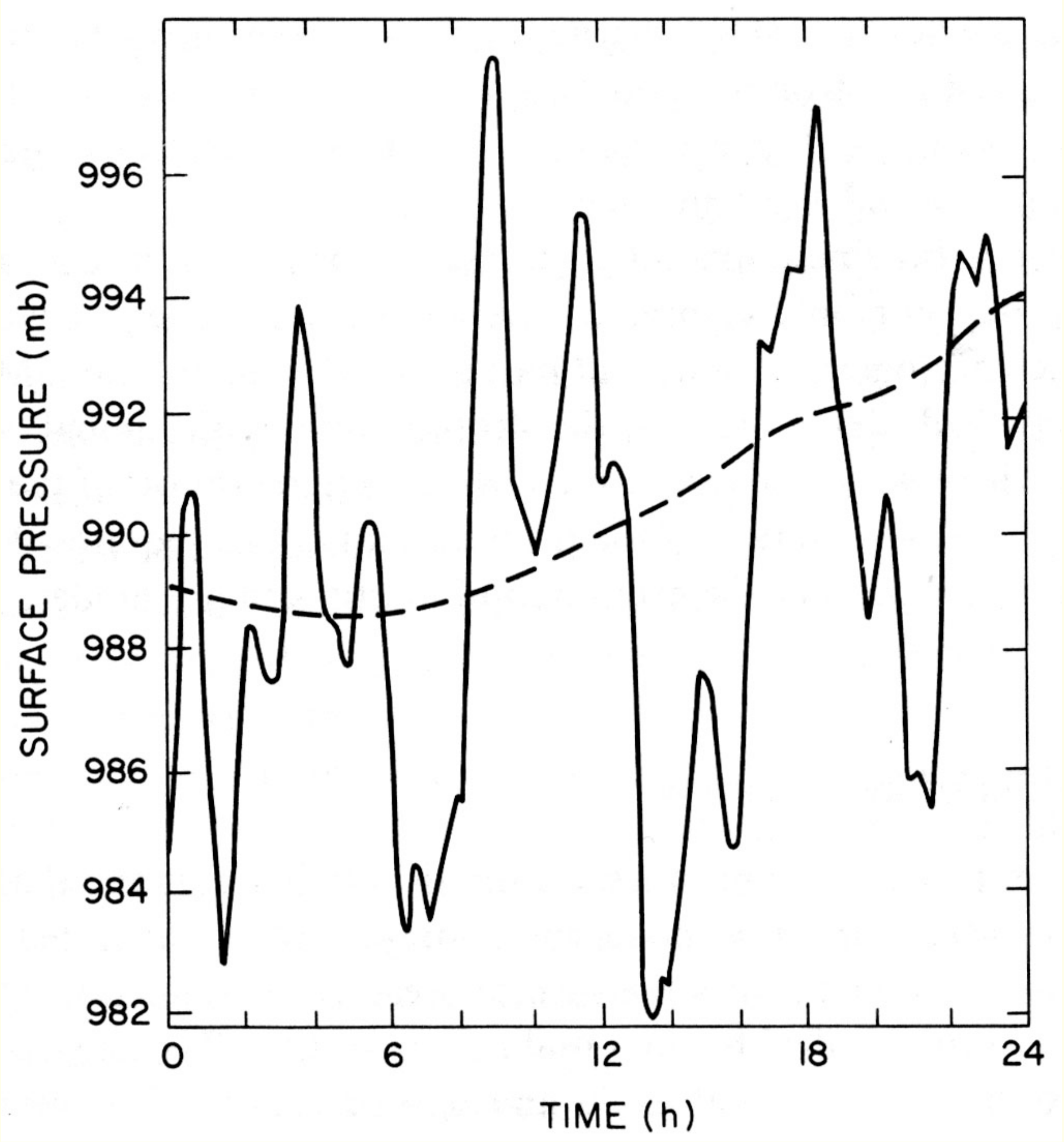


Tendency of a Smooth Signal



Tendency of a Noisy Signal





Evolution of surface pressure before and after NNMI.

(Williamson and Temperton, 1981)

Crucial Advances, 1920–1950

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

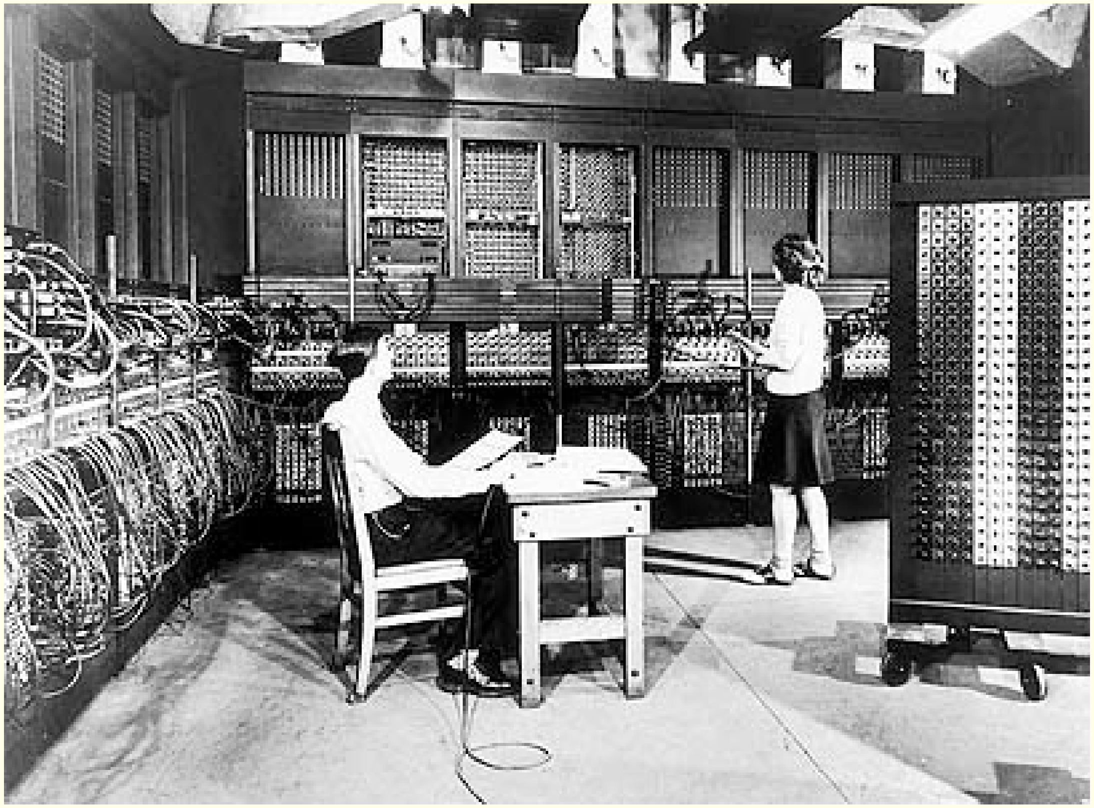
Electronic Computer Project

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



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

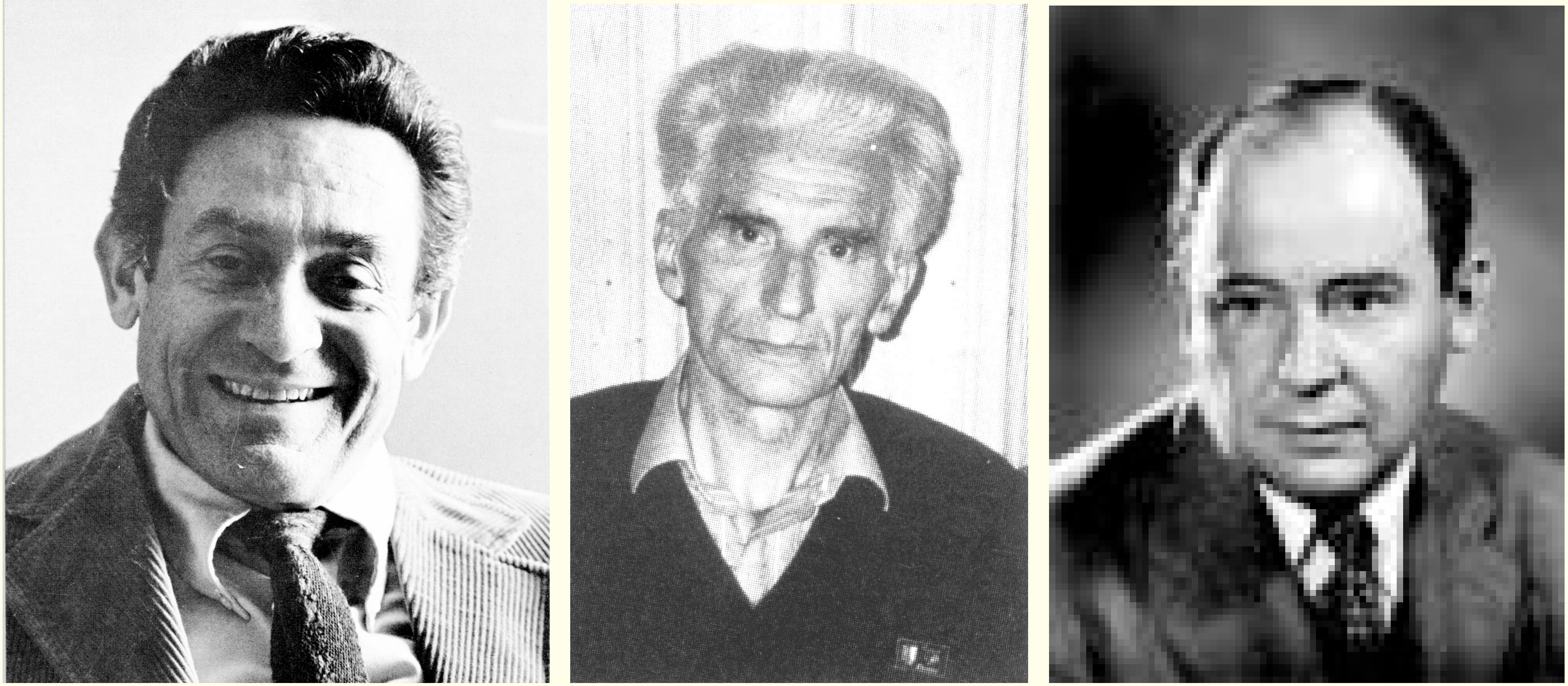
- **18,000 vacuum tubes**
- **70,000 resistors**
- **10,000 capacitors**
- **6,000 switches**
- **Power: 140 kWatts**

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

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

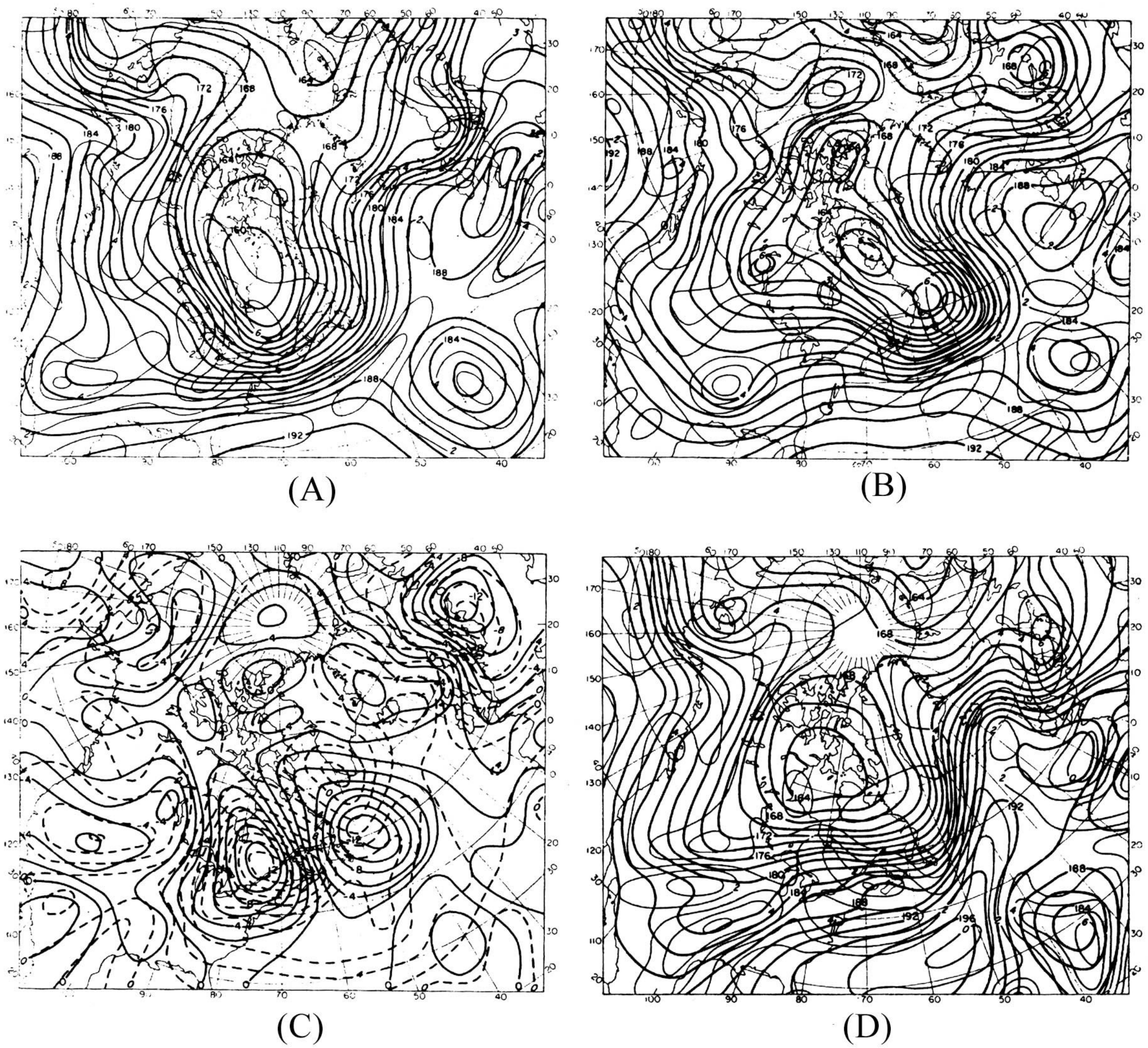
Charney, Fjørtoft, von Neumann



Charney, J.G., R. Fjørtoft and J. von Neumann, 1950:

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

ENIAC: First Computer Forecast



(A) (B)

(C) (D)

Richardson's reaction

- ***"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)."***

Jule G. Charney (1917-1981) was one of the giants in the history of numerical weather prediction. In his 1951 paper "Dynamical Forecasting by Numerical Process", he introduced the subject of this book as well as it could be introduced today. We reproduce here parts of the paper (emphasis added):

"As meteorologists have long known, ***the atmosphere exhibits no periodicities of the kind that enable one to predict the weather in the same way one predicts the tides***. No simple set of causal relationships can be found which relate the state of the atmosphere at one instant of time to its state at another.

It was this realization that *led V. Bjerknes (1904)* ***to define the problem of prognosis as nothing less than the integration of the equations of motion of the atmosphere***.

But it remained for *Richardson (1922)* to suggest the practical means for the solution of this problem. *He proposed to integrate the equations of motion numerically and showed exactly how this might be done*. *That the actual forecast used to test his method was unsuccessful was in no way a measure of the value of his work*.

From Charney, 1951:

“For a long time no one ventured to follow in Richardson's footsteps. The paucity of the observational network and the enormity of the computational task stood as apparently insurmountable barriers to the realization of his dream that one day it might be possible to advance the computation faster than the weather. But with the increase in the density and extent of the surface and upper-air observational network on the one hand, and the development of large-capacity high-speed computing machines on the other, interest has revived in Richardson's problem, and attempts have been made to attack it anew.

“These efforts have been characterized by a devotion to objectives more limited than Richardson's. Instead of attempting to deal with the atmosphere in all its complexity, one tries to be satisfied with *simplified models* approximating the actual motions a greater or lesser degree. By *starting with models incorporating only what it is thought to be the most important of the atmospheric influences*, and by gradually bringing in others, one is able to proceed inductively and thereby to avoid the pitfalls inevitably encountered when a great many poorly understood factors are introduced all at once.

“A necessary condition for the success of this stepwise method is, of course, that the first approximations bear a recognizable resemblance to the actual motions. Fortunately, the science of meteorology has progressed to the point where one feels that at east the main factors governing the large-scale atmospheric motions are well known. *Thus integrations of even the linearized barotropic and thermally inactive baroclinic equations have yielded solutions bearing a marked resemblance to reality*.

Recall that Richardson failed spectacularly: he predicted a change of 146hPa in 6 hours, whereas the change was essentially zero. The failure was due to the lack of balance in the initial conditions: fast gravity waves give large time derivatives.

Moreover, if Richardson had continued beyond computing the first derivative, the system would have “blown up” because of computational instability

$c\,\Delta t < \Delta x$ and for Gravity Waves *c*~300m/sec

Charney et al (1948, 1949) and Eliassen (1949) solved both of these problems by deriving "filtered" equations of motion, based on quasi-geostrophic (slowly varying) balance, which filtered out (i.e., did not include) gravity and sound waves, and were based on pressure fields alone. In the last two sentences of the introduction, Charney (1951) points out that this approach was justified by the fact that forecasters' experience was that they were able to predict tomorrow's weather from pressure charts alone:

"In the selection of a suitable first approximation, Richardson's discovery that the horizontal divergence was an unmeasurable quantity had to be taken into account. Here a consideration of forecasting practice gave rise to the belief that this difficulty could be surmounted: forecasts were made by means of geostrophic reasoning from the pressure field alone--forecasts in which the concept of horizontal divergence played no role.

In order to understand better Charney’s comment, we quote an anecdote from Lorenz (1990) on his interactions with Jule Charney:

"On another occasion when our conversations had turned closer to scientific matters, Jule was talking again about the early days of NWP. For a proper perspective, we should recall that at the time when Charney was a student, pressure was king. The centers of weather activity were acknowledged to be the highs and lows. A good prognostic chart was one that had the isobars in the right locations. Naturally, then, the thing that was responsible for the weather changes was the thing that made the pressure change. This was readily shown to be the divergence of the wind field. The divergence could not be very accurately measured, and a corollary deduced by some meteorologists, including some of Charney’s advisors, was that the dynamic equations could not be used to forecast the weather.

Such reasoning simply did not make sense to Jule. The idea that the wind field might serve instead of the pressure field as a basis for dynamical forecasting, proposed by Rossby, gave Jule a route to follow. He told us, however, that what really inspired him to develop the equations that later became the basis for NWP was a determination to prove, to those who had assured him that the task was impossible, that they were wrong.

Lorenz (1990) on his interactions with Jule Charney:

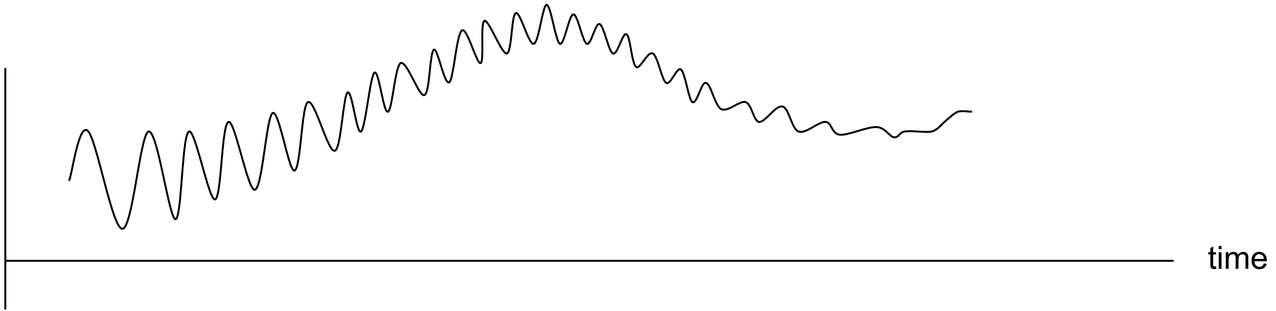
"On another occasion when our conversations had turned closer to scientific matters, Jule was talking again about the early days of NWP.

The previous occasion was a story about an invitation Charney received to appear on the Today show, to talk about how computers were going to forecast the weather. Since the show was at 7am, Charney, a late riser, had never watched it. He told us that he felt that he ought to see the show at least once before agreeing to appear on it, and so, one morning, he managed to pull himself out of bed and turn on the TV set, and the first person he saw was a chimpanzee. He decided he could never compete with a chimpanzee for the public’s favor, and so he gracefully declined to appear, much to the dismay of the computer company that had engineered the invitation in the first place.

It is remarkable that in his 1951 paper, just after the triumph of performing the first successful forecasts with filtered models, Charney already saw that much more progress would come from the use of the primitive (unfiltered) equations of motion as Richardson had originally attempted:

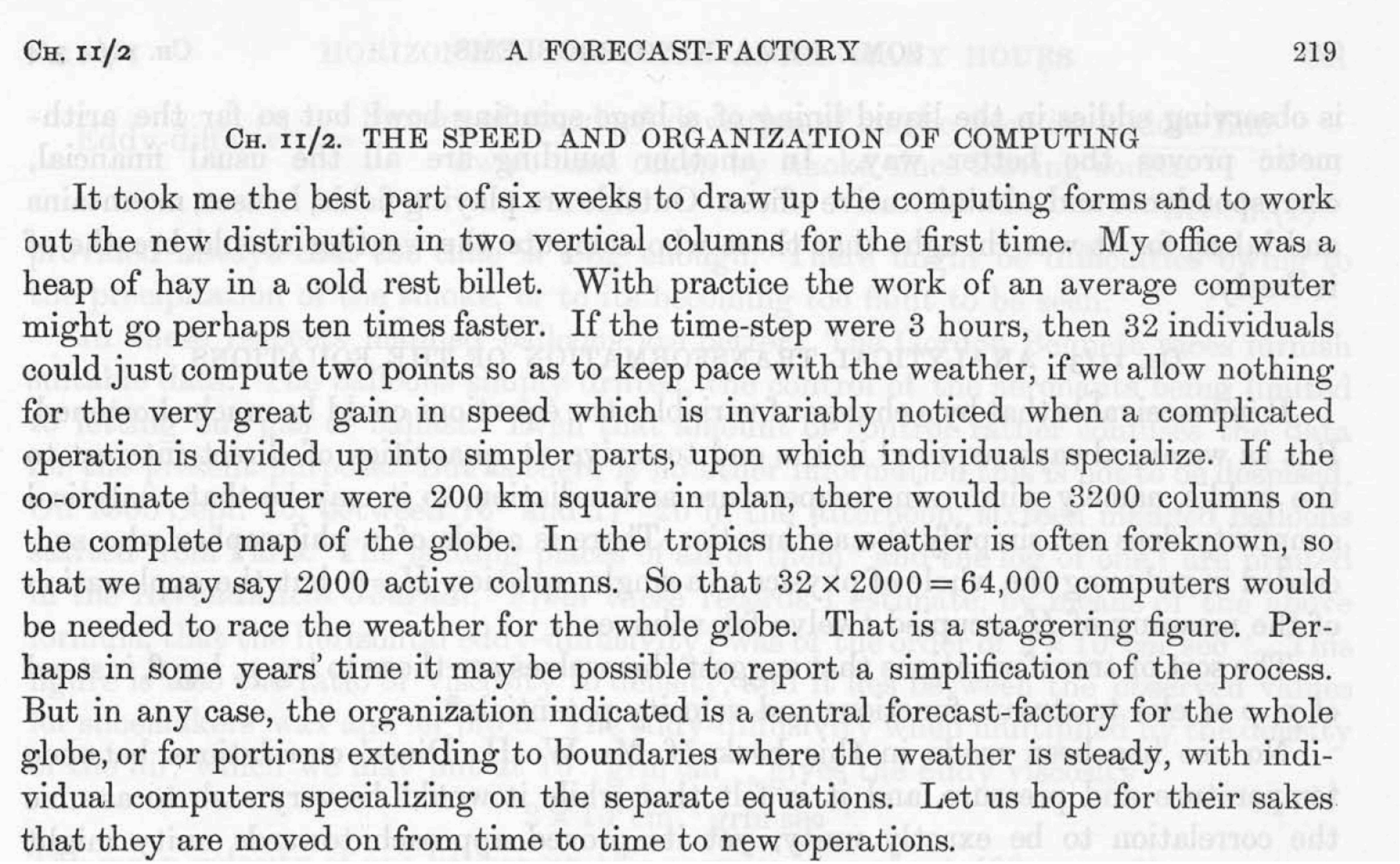
"The discussion so far has dealt exclusively with the quasi-geostrophic equations as the basis for numerical forecasting. Yet there has been no intention to exclude the possibility that the primitive Eulerian equations can also be used for this purpose. The outlook for numerical forecasting would be 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. We have merely indicated two obstacles that stand in the way of the applications of the primitive equations: First, there is the difficulty raised by Richardson that the horizontal divergence cannot be measured with sufficient accuracy. Moreover, the horizontal divergence is only one of a class of meteorological unobservables which also includes the horizontal acceleration. And second, if the primitive Eulerian equations are employed, a stringent and seemingly artificial bound is imposed on the size of the time interval for the finite difference equations. The first obstacle is the most formidable, for the second only means that the integration must proceed in steps of the order of fifteen minutes rather than two hours. Yet the first does not seem insurmountable, as the following considerations will indicate."

He described an unpublished study by Charney and J.C. Freeman, in which they integrated barotropic primitive equations (i.e., shallow water equations, chapter 2) which include not only the slowly varying quasi-geostrophic solution, but also fast gravity waves. They initialized the forecast assuming zero initial divergence, and compared the result to a barotropic forecast (with gravity waves filtered out). The results were similar to those shown schematically in Fig. 1.2: they observed that over a day or so the gravity waves subsided (through a process that we call geostrophic adjustment) and did not otherwise affect the forecast of the slow waves. From this result Charney concluded that numerical forecasting could indeed use the full primitive equations (as eventually happened in operational practice). He listed in the paper the complete primitive equations in pressure coordinates, essentially as they are used in current operational weather prediction, but without heating (diabatic) and frictional terms, which he expected to have minor effects in one or two day forecasts.



Charney concluded this remarkable paper with a discussion that includes a list of the physical processes that take place at scales too small to be resolved, and are incorporated in present models through "parameterizations of the subgrid-scale physics" (condensation, radiation, and turbulent fluxes of heat, momentum and moisture)

Richardson: Invention of the parallel computer



Ch. II/2 A FORECAST-FACTORY 219

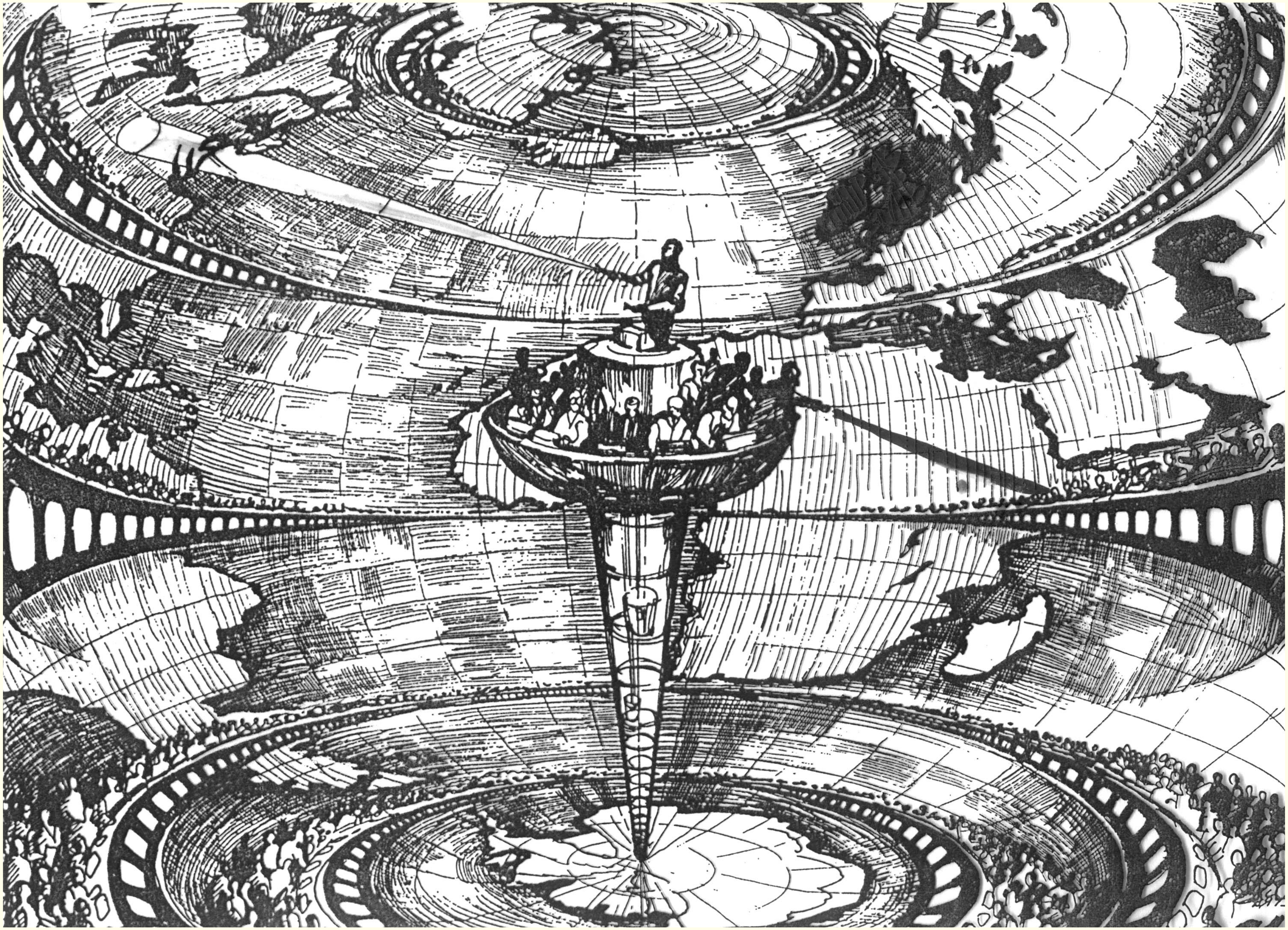
Ch. II/2. THE SPEED AND ORGANIZATION OF COMPUTING

It took me the best part of six weeks to draw up the computing forms and to work out the new distribution in two vertical columns for the first time. My office was a heap of hay in a cold rest billet. With practice the work of an average computer might go perhaps ten times faster. If the time-step were 3 hours, then 32 individuals could just compute two points so as to keep pace with the weather, if we allow nothing for the very great gain in speed which is invariably noticed when a complicated operation is divided up into simpler parts, upon which individuals specialize. If the co-ordinate chequer were 200 km square in plan, there would be 3200 columns on the complete map of the globe. In the tropics the weather is often foreknown, so that we may say 2000 active columns. So that $32 \times 2000 = 64{,}000$ computers would be needed to race the weather for the whole globe. That is a staggering figure. Perhaps in some years' time it may be possible to report a simplification of the process. But in any case, the organization indicated is a central forecast-factory for the whole globe, or for portions extending to boundaries where the weather is steady, with individual computers specializing on the separate equations. Let us hope for their sakes that they are moved on from time to time to new operations.

After so much hard reasoning, may one play with a fantasy? Imagine a large hall like a theatre, except that the circles and galleries go right round through the space usually occupied by the stage. The walls of this chamber are painted to form a map of the globe. The ceiling represents the north polar regions, England is in the gallery, the tropics in the upper circle, Australia on the dress circle and the antarctic in the pit. A myriad computers are at work upon the weather of the part of the map where each sits, but each computer attends only to one equation or part of an equation. The work of each region is coordinated by an official of higher rank. Numerous little "night signs" display the instantaneous values so that neighbouring computers can read them. Each number is thus displayed in three adjacent zones so as to maintain communication to the North and South on the map. From the floor of the pit a tall pillar rises to half the height of the hall. It carries a large pulpit on its top. In this sits the man in charge of the whole theatre; he is surrounded by several assistants and messengers. One of his duties is to maintain a uniform speed of progress in all parts of the globe. In this respect he is like the conductor of an orchestra in which the instruments are slide-rules and calculating machines. But instead of waving a baton he turns a beam of rosy light upon any region that is running ahead of the rest, and a beam of blue light upon those who are behindhand.

Four senior clerks in the central pulpit are collecting the future weather as fast as it is being computed, and despatching it by pneumatic carrier to a quiet room. There it will be coded and telephoned to the radio transmitting station.

Messengers carry piles of used computing forms down to a storehouse in the cellar.



Richardson's Forecast Factory (A. Lannerback).

Dagens Nyheter, Stockholm. Reproduced from L. Bengtsson, *ECMWF*, 1984

64,000 Computers: The first Massively Parallel Processor

In a neighbouring building there is a research department, where they invent improvements. But there is much experimenting on a small scale before any change is made in the complex routine of the computing theatre. In a basement an enthusiast is observing eddies in the liquid lining of a huge spinning bowl, but so far the arithmetic proves the better way. In another building are all the usual financial, correspondence and administrative offices. Outside are playing fields, houses, mountains and lakes, for it was thought that those who compute the weather should breathe of it freely.

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 forecasting began in May, 1955, with a three-level quasi-geostrophic model.

Move to Primitive Equations

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.

All modern NWP centres have abandoned the QG equations for operational forecasting. (However, they are invaluable for theoretical studies).

Parameterization

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.

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

Data Assimilation

NWP is an initial-value problem.

The model integrates the equations forward in time, starting from the initial conditions.

In the early NWP experiments, hand interpolations of the observations to grid points were performed.

These fields of initial conditions were manually digitized.

The need for an automatic "objective analysis" quickly became apparent.

There is another important issue: the data available are not enough to initialize current models.

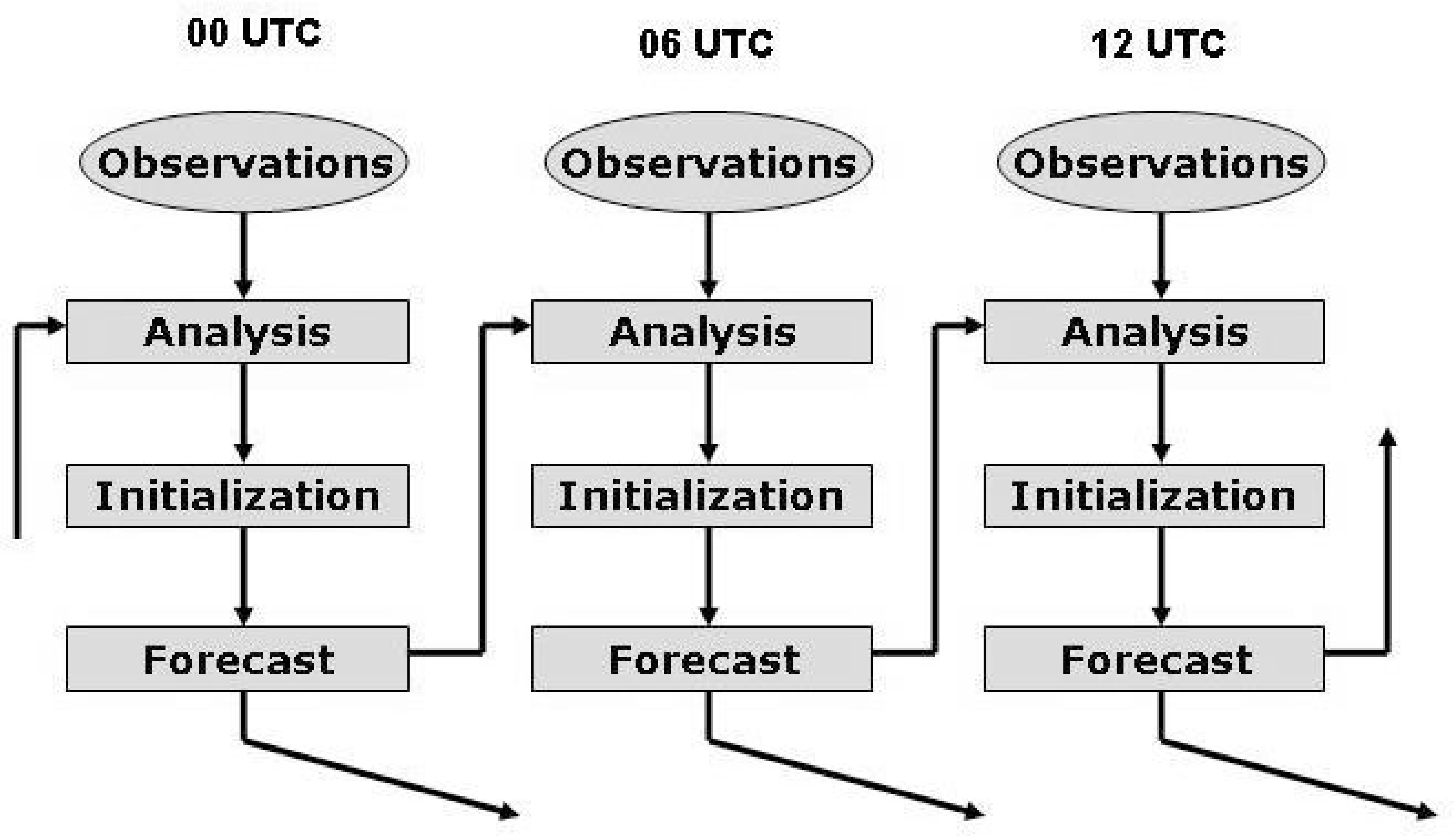
Modern primitive equations models have a number of degrees of freedom of the order of 10^7.

For a time window of ± 3 hours, there are typically 10 to 100 thousand observations of the atmosphere, two orders of magnitude less than the number of degrees of freedom of the model.

Moreover, their distribution in space and time is very nonuniform in space.

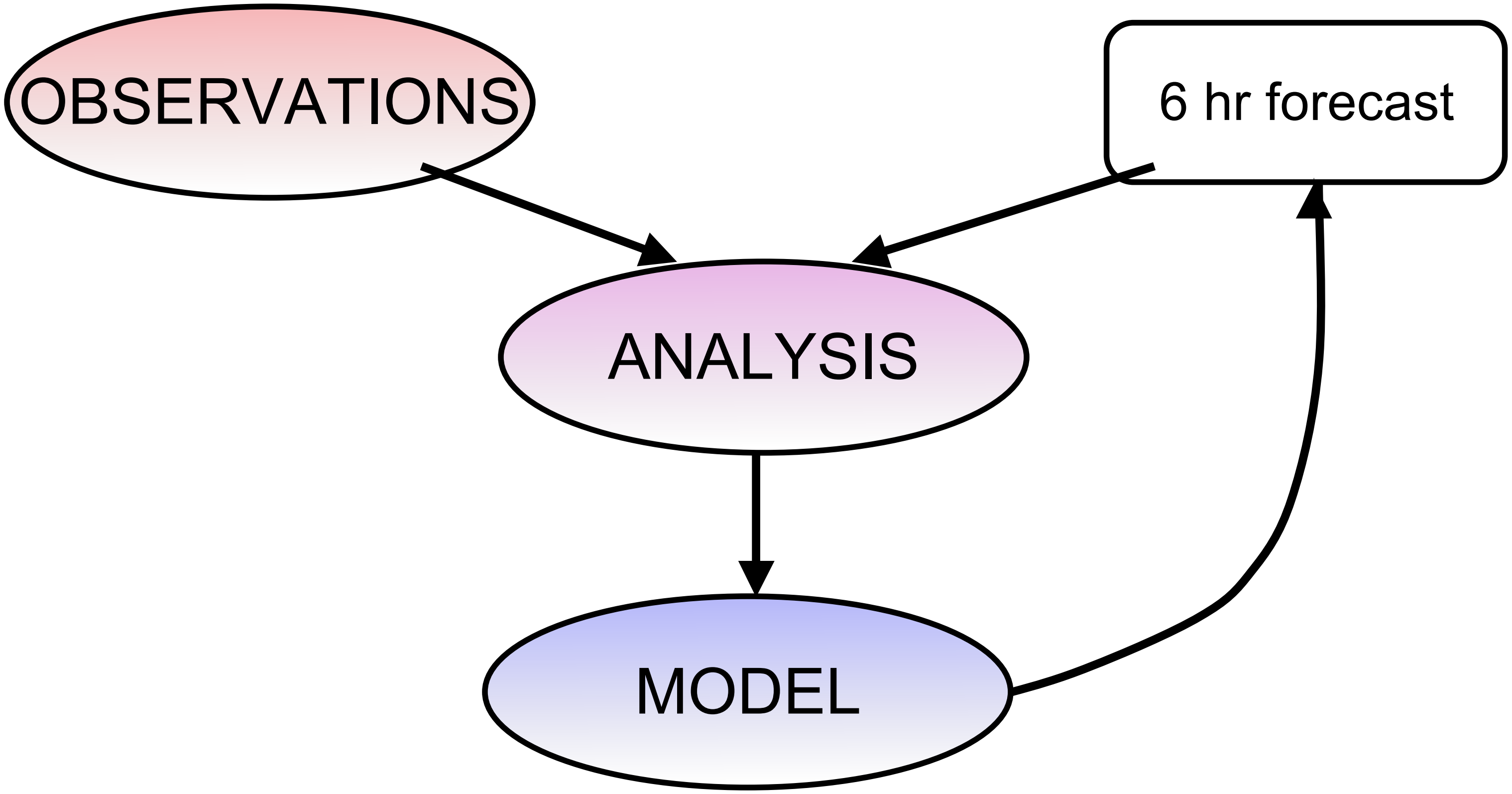
It is necessary to use additional information (denoted *background, first guess* or *prior information*).

A short-range forecast is used as the first guess in operational data assimilation systems.



Typical 6-hour analysis cycle.

Data Assimilation: We need to improve observations, analysis scheme and model



OBSERVATIONS

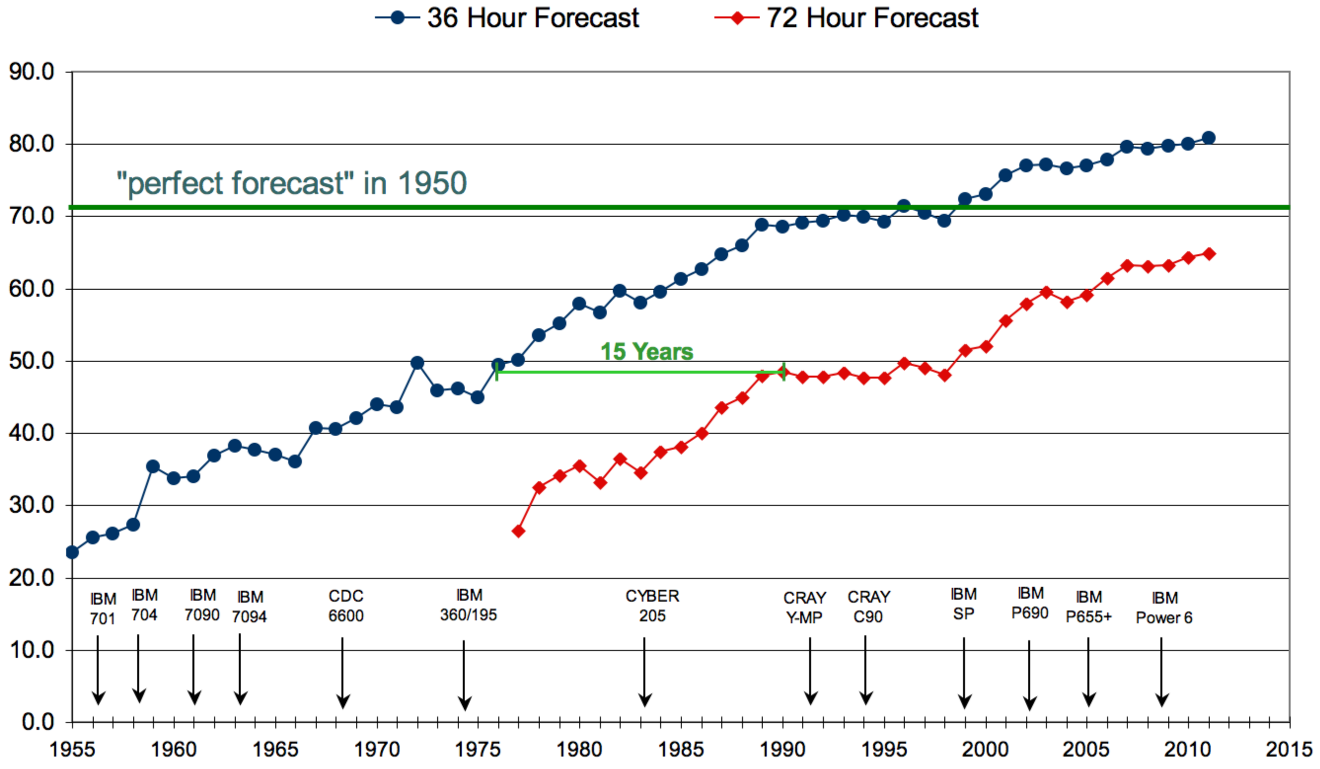
6 hr forecast

ANALYSIS

MODEL

NCEP Operational Forecast Skill

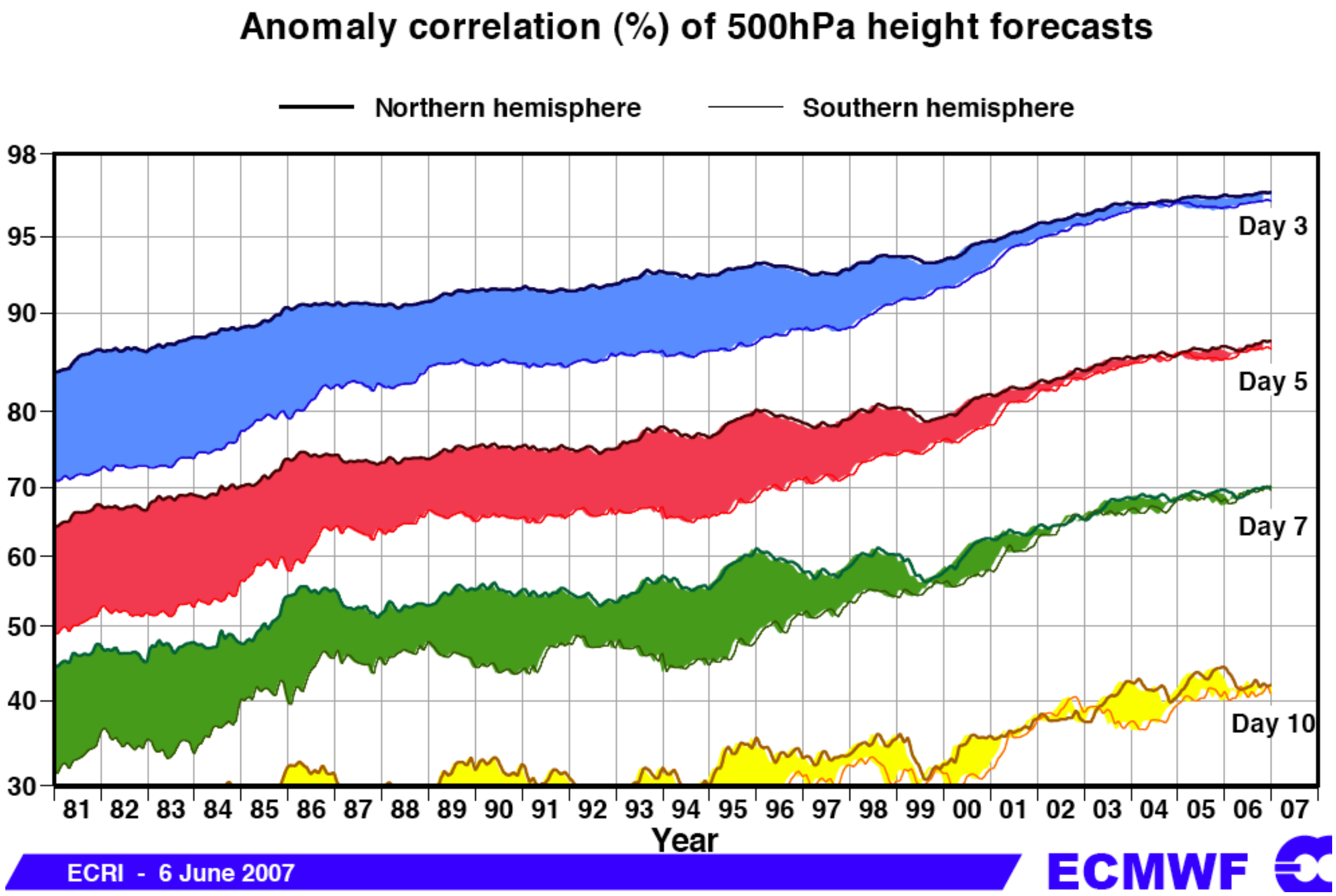
36 and 72 Hour Forecasts @ 500 MB over North America
[100 * (1-S1/70) Method]



NCEP Central Operations January 2011

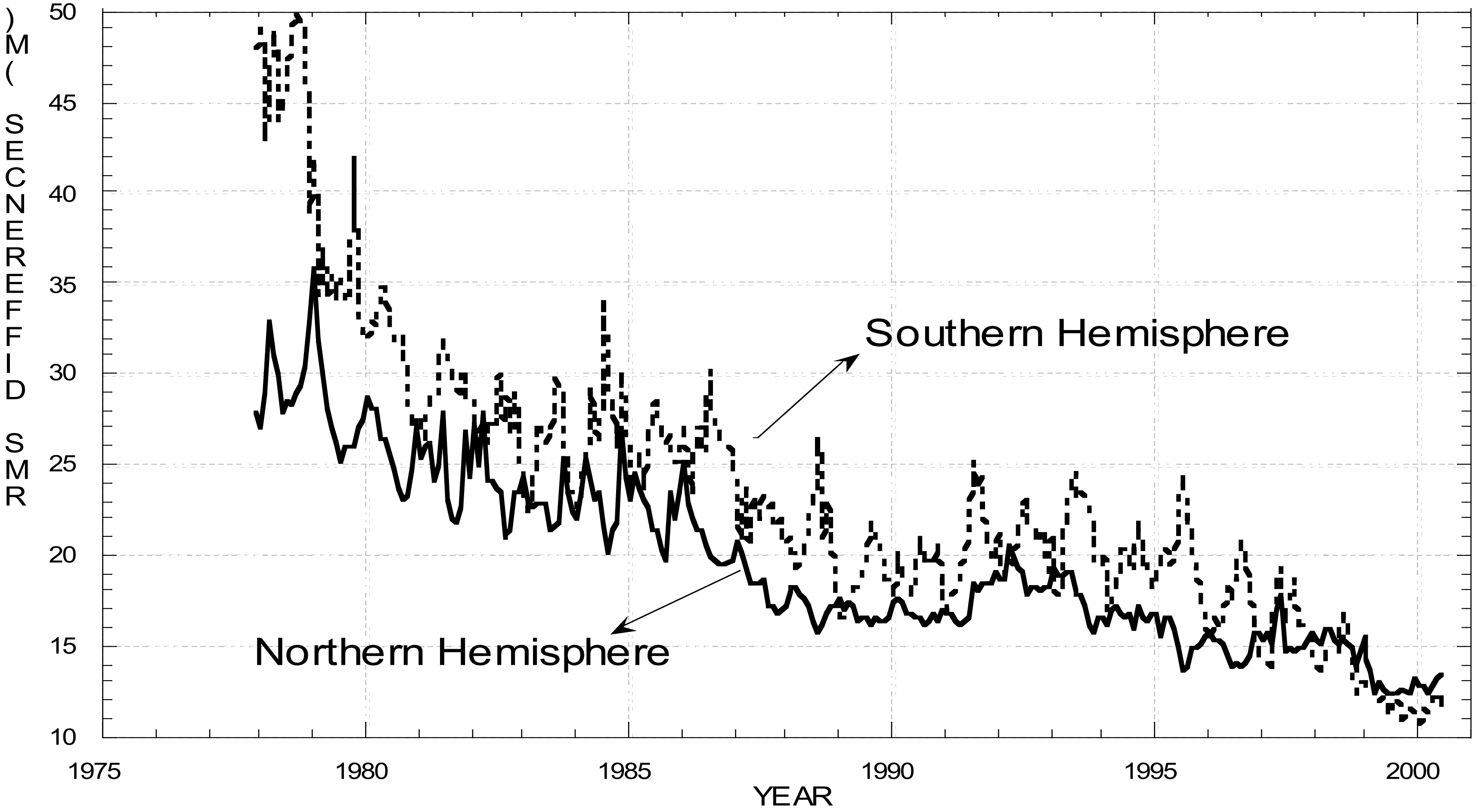
A “perfect forecast” was defined as the score obtained by comparing analyses hand-made by several experienced forecasters fitting the same observations over the data-rich North American region.
With this measure, the 36 hr forecasts are now better than perfect!

Comparisons of Northern and Southern Hemispheres



Thanks to satellite data the SH has improved even faster than the NH!

We are getting better… (NCEP observational increments)



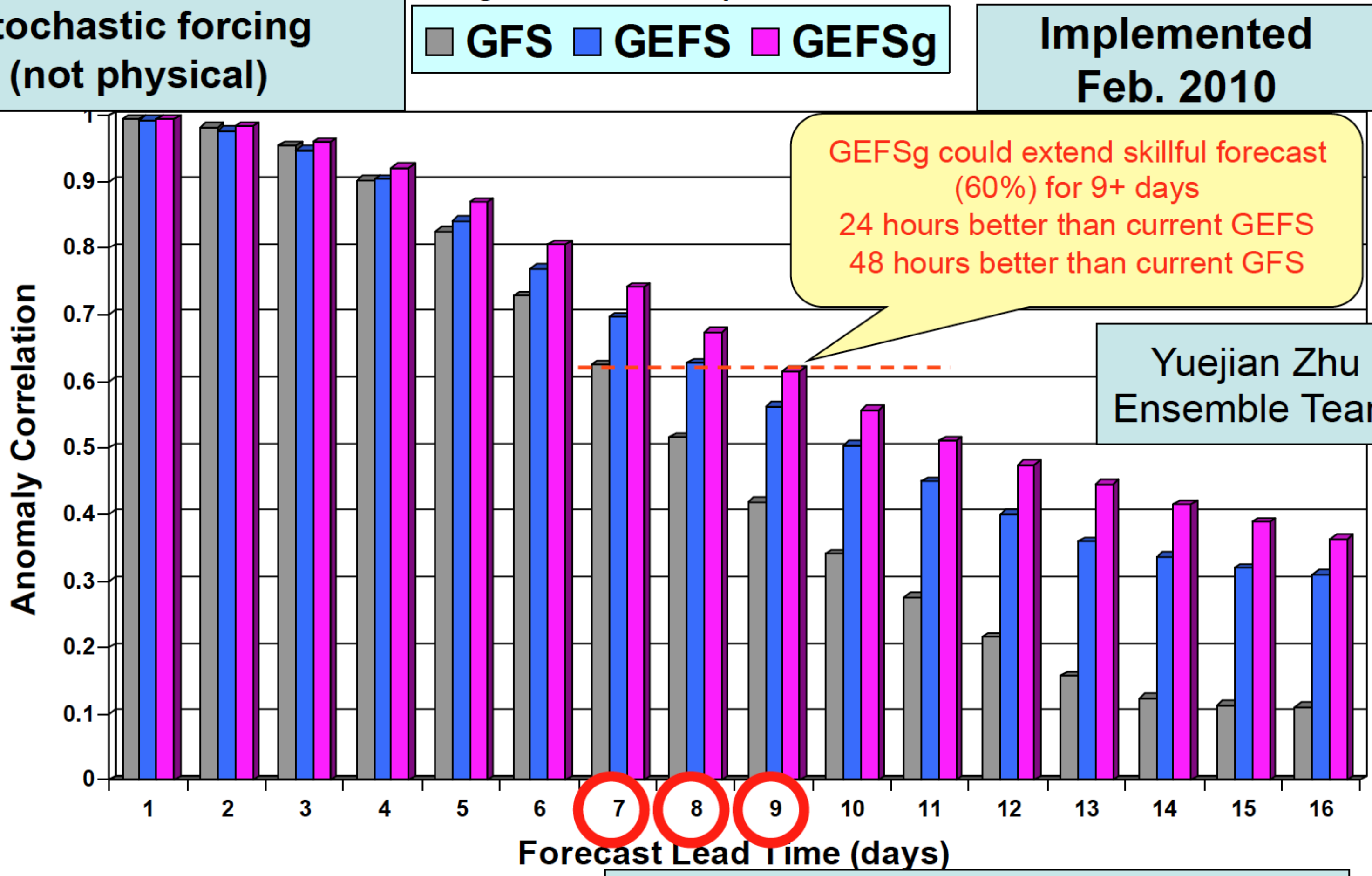
500MB RMS FITS TO RAWINSONDES
6 HR FORECASTS

NCEP Global Ensemble Upgrade

100 → 70 km Res
Stochastic forcing
(not physical)

August 1st – September 30th 2007

Implemented
Feb. 2010



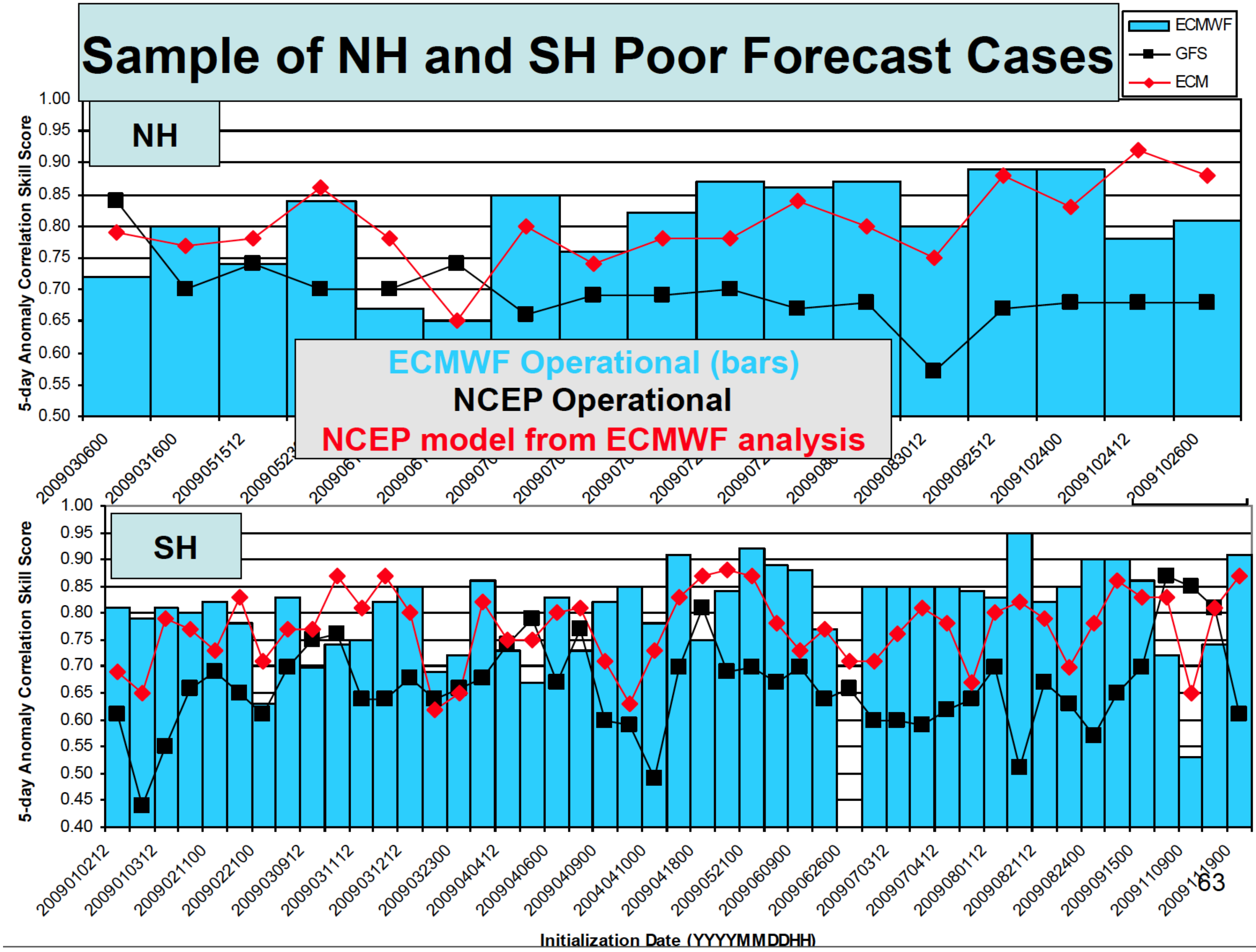
GEFSg could extend skillful forecast (60%) for 9+ days
24 hours better than current GEFS
48 hours better than current GFS

Yuejian Zhu
Ensemble Team

Q4FY11: T254/L42
Future:
GEFS initialization merged with Hybrid GDAS

North American Ens. Fcst. System (NAEFS)
With Canada, Mexico
National Unified Operational Prediction Capabilty (NUOPC)
With Navy, USAF

Sample of NH and SH Poor Forecast Cases

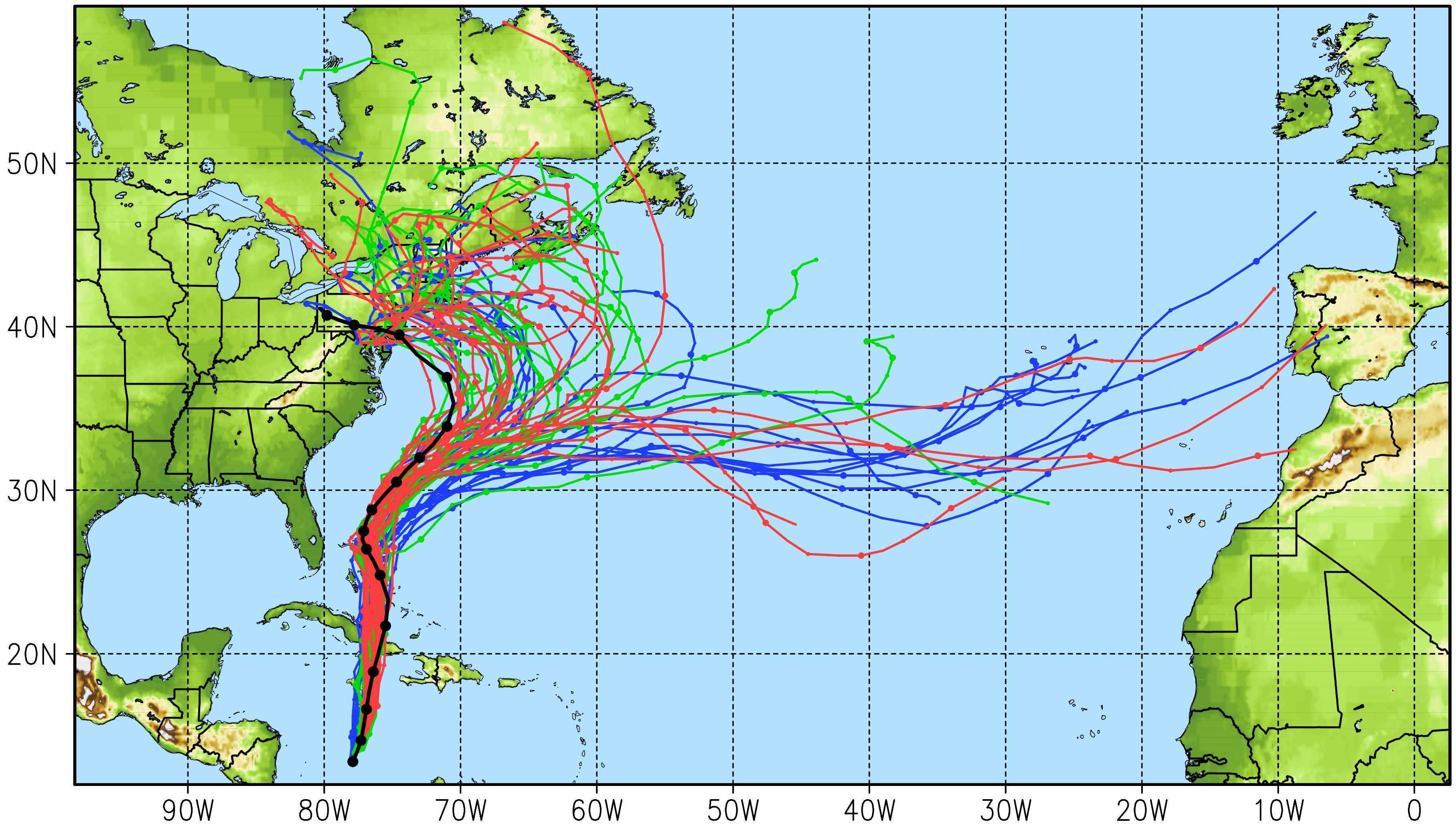


ECMWF Operational (bars)

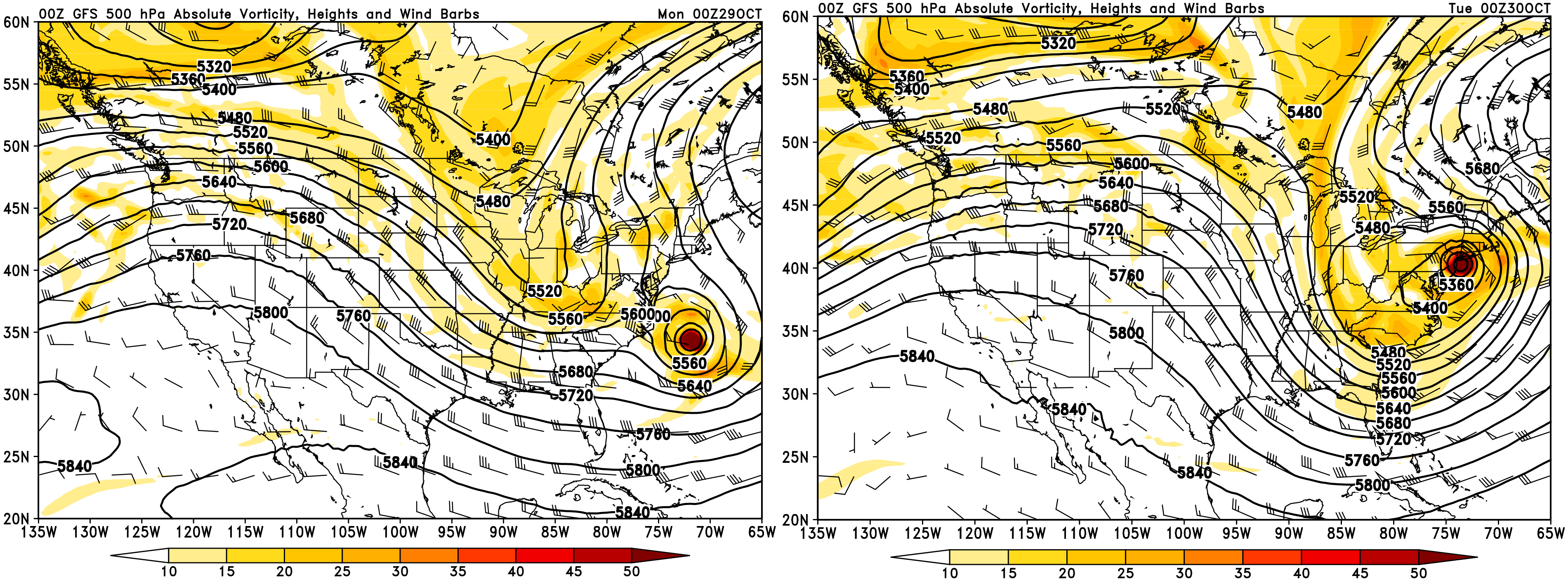
NCEP Operational

NCEP model from ECMWF analysis

Sandy’s GFS ensemble forecast, started on 12Z23/10 (blue), 18Z/23/10 (green) and 00Z/24/10/2012 (red)



Why did Sandy turn west around 00Z/29/10/2012?
It was captured by a deep trough!

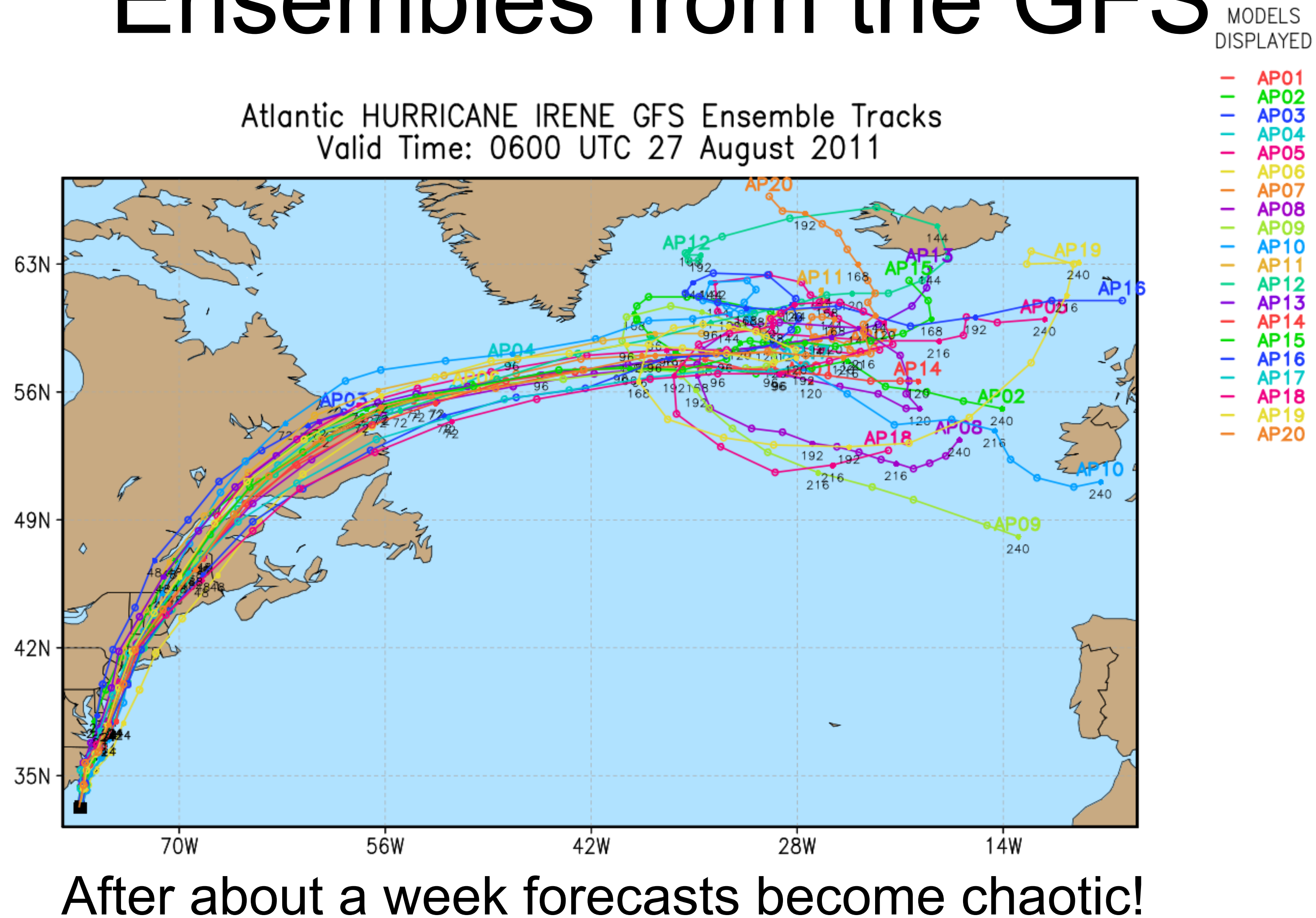


Monday, 00Z/29/10/2012

Tuesday, 00Z/30/10/2012
Landfall

500 hPa NCEP analysis of absolute vorticity, winds and heights

Ensembles from the GFS

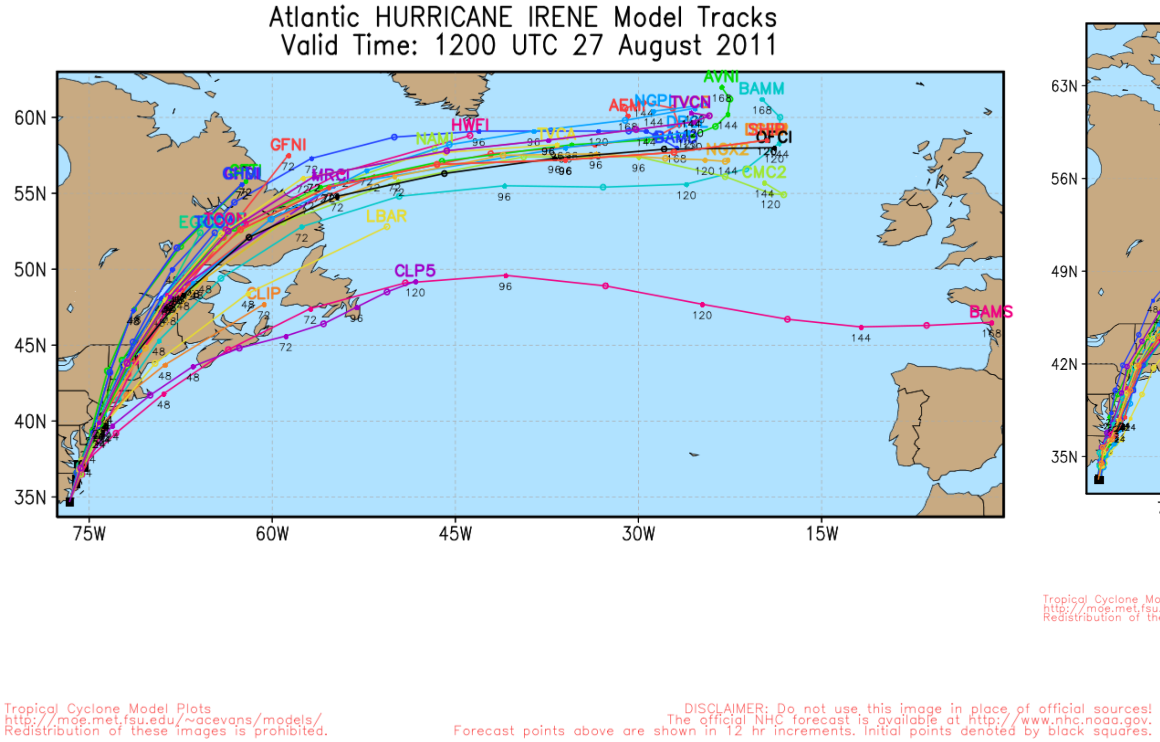


After about a week forecasts become chaotic!

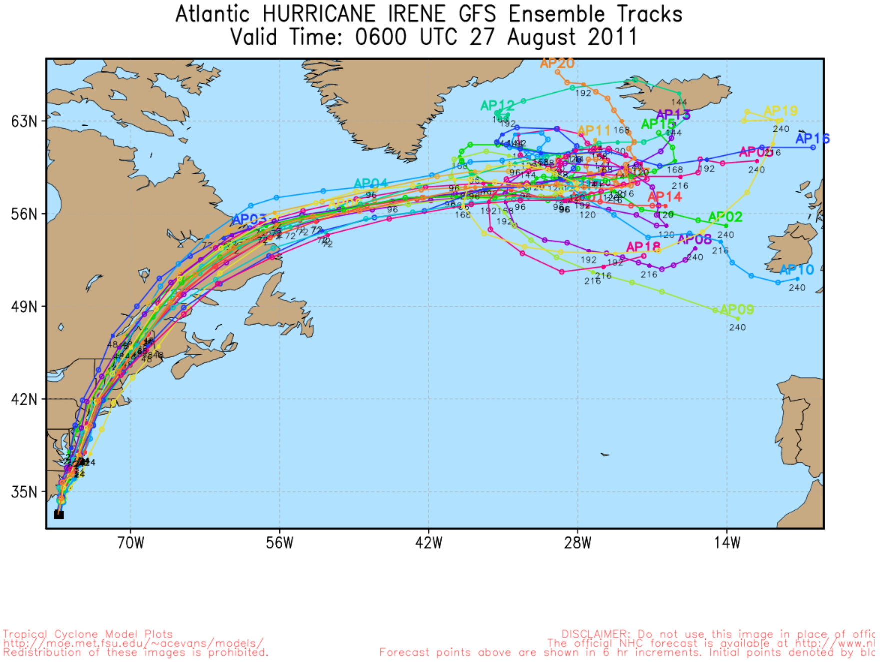
Tropical Cyclone Model Plots
http://moe.met.fsu.edu/~acevans/models/
Redistribution of these images is prohibited.

DISCLAIMER: Do not use this image in place of official sources!
The official NHC forecast is available at http://www.nhc.noaa.gov.
Forecast points above are shown in 6 hr increments. Initial points denoted by black squares.

Ensemble from different models



6 days



10 days

The Future

- Detailed short-range forecasts, using storm-scale models able to provide skilful predictions of severe weather;
- More sophisticated methods of data assimilation, capable of extracting the maximum possible information from observing systems, especially remote sensors such as satellites and radars;
- Development of adaptive observing systems, in which additional observations are placed where ensembles indicate that there is rapid error growth (low predictability);
- Improvement in the usefulness of medium-range forecasts, especially through the use of ensemble forecasting;
- Fully coupled atmospheric–hydrological systems, where the atmospheric model precipitation is down-scaled and used to extend the length of river flow prediction;

- More use of detailed atmosphere–ocean–land coupled models, in which long-lasting coupled anomalies such as SST and soil moisture anomalies lead to more skilful predictions of anomalies in weather patterns beyond the limit of weather predictability;
- More guidance to governments and the public on subjects such as air pollution, ultraviolet radiation and transport of contaminants, which affect health;
- 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.