Weather and Climate:
Prediction from Days to Decades

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College of Engineering, Mathematics & Physical Sciences

Introductory Remarks.

- *Thank you for coming this evening*
- *The tradition of honouring ones predecessors*
- *Background to the establishment of the* UCD Meteorology & Climate Centre. *The* Memorandum of Understanding *between* ***UCD*** *and* ***Met Éireann***
- *A 200-year-old dream come true.*

The Dream:

On 4 May, 1801 the eminent physician William Patterson (*c.* 1750–1807) presented a paper on meteorology to the Royal Irish Academy.

In his concluding remarks, he suggested that *meteorology was of such national importance* that "the (Royal) Dublin Society should be encouraged to add to its establishment a professorship in the science".

Question: What happens when one Royal Institution passes the buck to another?

Answer: . . . nothing . . . !

⋆ ⋆ ⋆

The idea of a Chair of Meteorology was intermittently revived over the following two centuries, but to no effect.

Met Éireann came to the view, several years ago, that if anything was to happen, affirmative action was needed.

The result of consultations and discussion was that, in October 2003, a *Memorandum of Understanding* was signed by the Director of Met Éireann, Mr Declan Murphy, and the (then) President of UCD, Dr Art Cosgrove.

Some of the key players:

- **Mr Declan Murphy, Director, Met Éireann**
- **Mr Niall Callan, Sec. Gen., DoEHLG**
- **Prof Michael J Kennedy, Dean of Science, UCD**
- **Prof Adrian Ottewill, Head, Maths. Phys., UCD**
- **Dr Ted Cox, Maths. Phys., UCD**

Memorandum of Understanding
between
Met Éireann and UCD.

Signing of MoU by Declan Murphy and Art Cosgrove (2/10/03)
as Minister Pat The-Coop Gallagher looks on.

Thus was realized the idea first proposed more than two hundred years earlier by William Patterson.

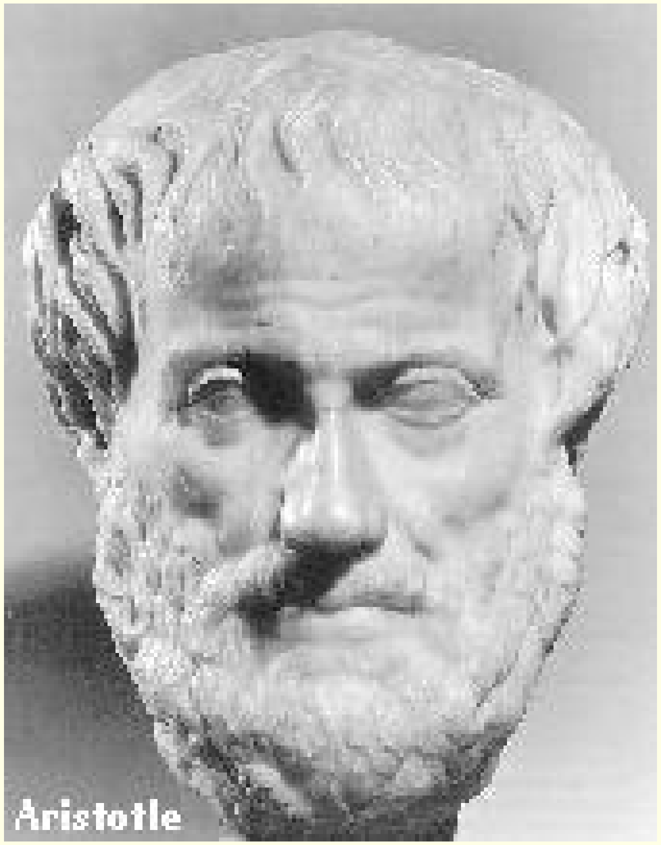
The curious object on the left above may be unknown to younger staff members.
It is the old crest of UCD, which appeared on the MoU but is now considered to be heterodox.

Outline of this Inaugural Lecture

- **The Emergence of the Science of Meteorology**
- **The Development of Numerical Weather Prediction**
- **Modern Computer Weather Forecasting**
- **Climate Change and its Prediction**

The central theme of the lecture will be the remarkable progress which has been made in our ability to predict the behaviour of the atmosphere over a wide range of time-scales, *from days to decades.*

Aristotle's *Meteorologia*



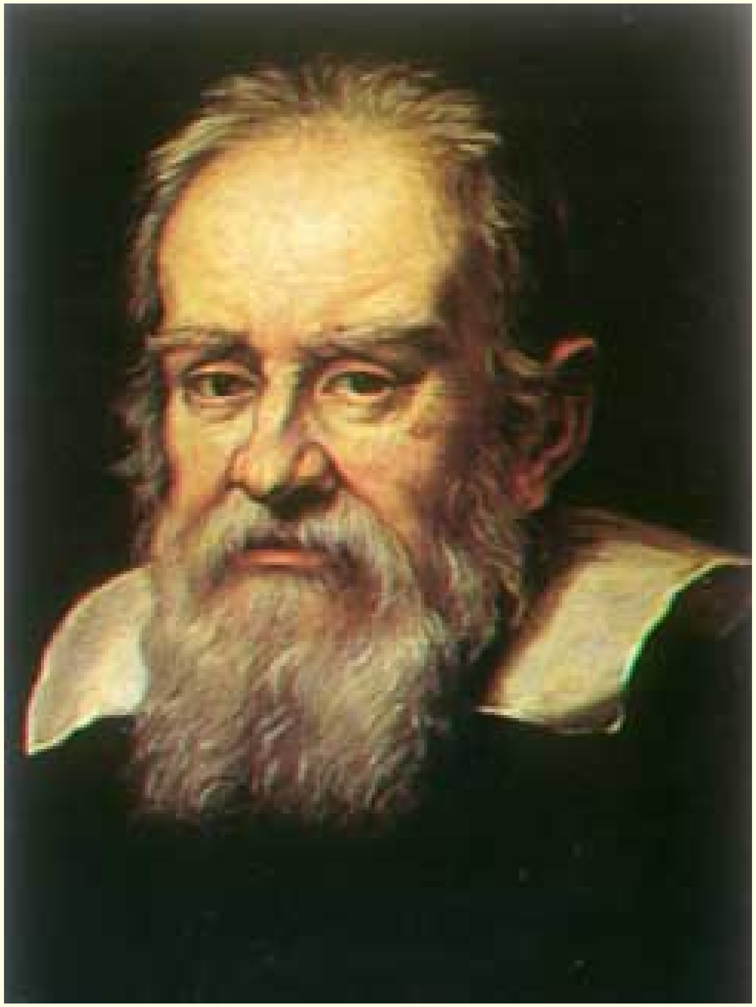
Aristotle (384-322 BC) was a past master at asking questions.

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

This work dealt with the causes of various weather phenomena and with the origin of comets.

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

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.

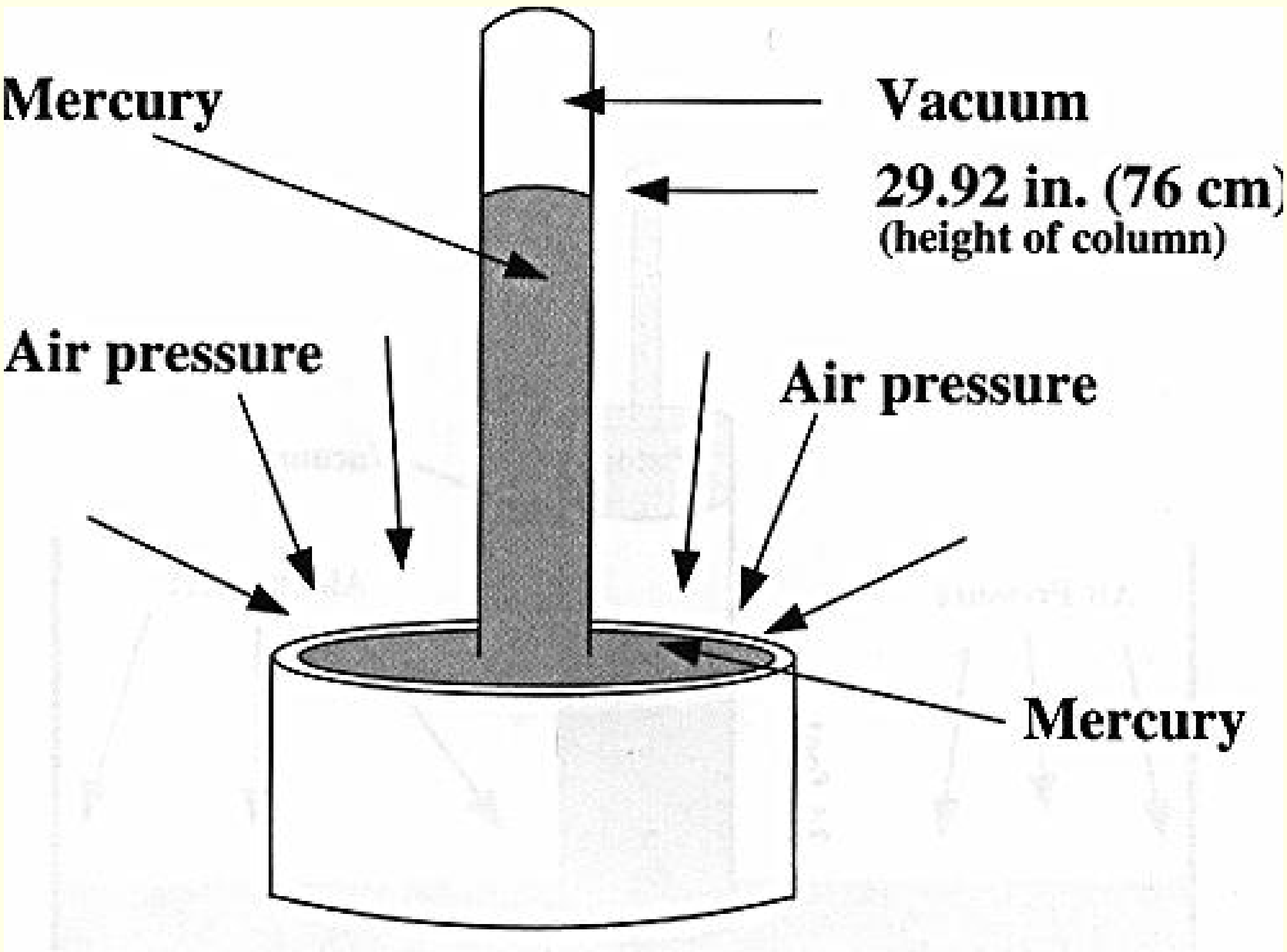
Galileo is credited with the invention of the Thermometer.

Galileo's Star Pupil

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.

Isaac Newton (1642-1727)

Sir Isaac Newton
(1642-1727)

Newton established the fundamental principles of Dynamics.

He formulated the basic law of Gravitation.

He produced monumental results in Celestial Mechanics.

He laid the foundation for differential and integral Calculus.

He made fundamental contributions to Optics.

Arguably the greatest scientist the world has ever known.

Newton: the Inventor of Science

John Banville, in his work ***The Newton Letters*****, goes so far as to write that** <u>**'Newton invented science'**</u>**.**

This is a provocative and thought-provoking claim.

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.

If $\mathbf{F}$ is the total applied force, Newton's Second Law gives

$$\frac{d\mathbf{p}}{dt} = \mathbf{F}\,.$$

The acceleration $\mathbf{a}$ is the rate of change of velocity, that is, $\mathbf{a} = d\mathbf{V}/dt$. If the mass m is constant, we have

$$\mathbf{F} = m\mathbf{a}\,.$$

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

Edmund Halley (1656–1742)

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

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

Halley and his Comet

Halley's analysis of what is now called Halley's comet is an excellent example of the scientific method in action.

Observation:

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

Hypothesis:

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

Prediction:

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

Verification:

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

Further Confirmation:

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

A Tricky Question

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 (effectively) infinitely many variables; Thermodynamics is essential.

- Order versus Chaos

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

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

Euler's Equations for Fluid Flow

Leonhard Euler

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

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

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

The Navier-Stokes Equations

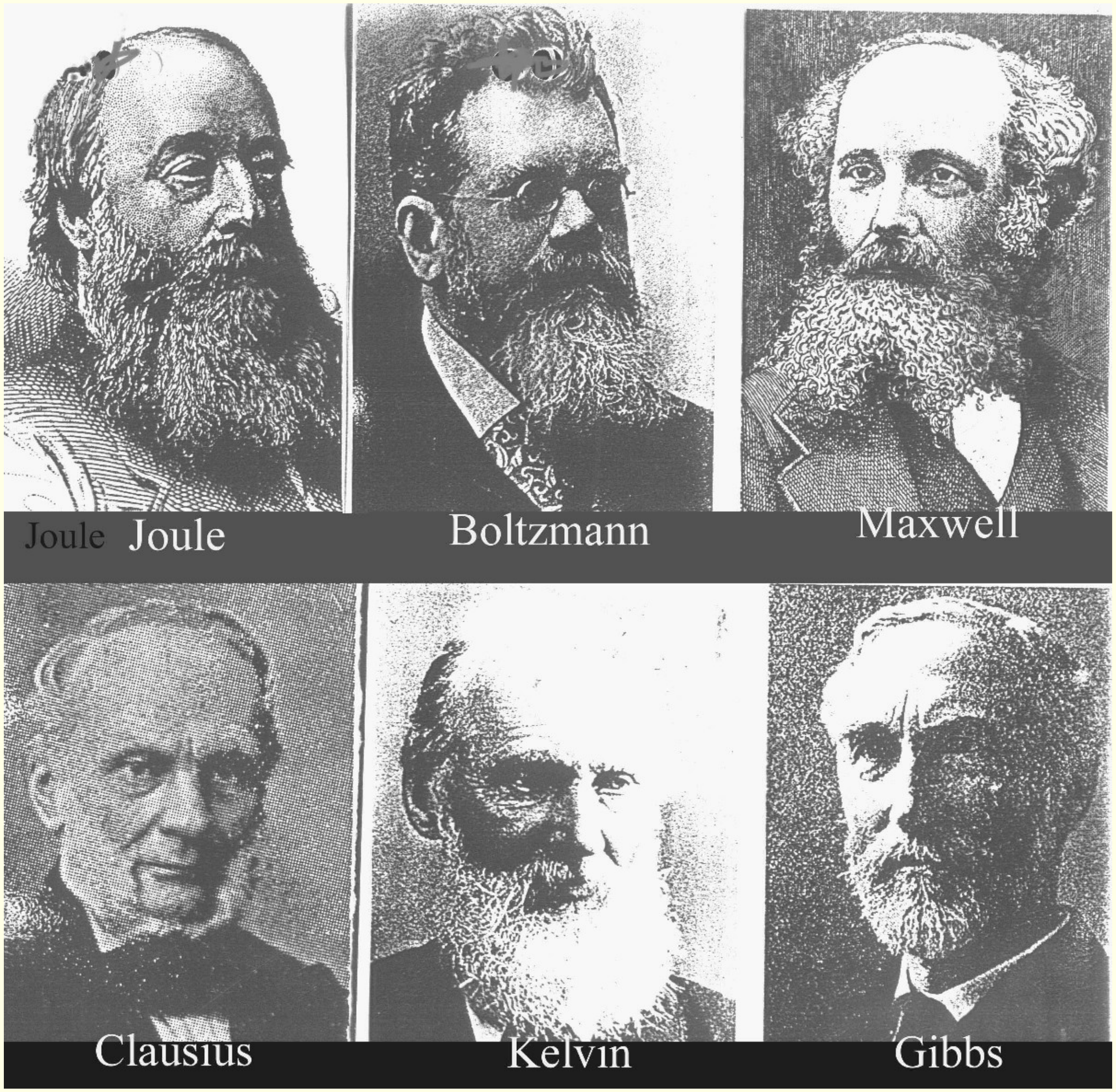
$$\frac{\partial \mathbf{V}}{\partial t} + \mathbf{V} \cdot \nabla \mathbf{V} + \frac{1}{\rho} \nabla p = \nu \nabla^2 \mathbf{V} + \mathbf{g}^\star \,.$$

The Navier-Stokes Equations describe how the change of velocity, the acceleration of the fluid, is determined by the pressure gradient force, the gravitational force and the frictional force.

For motion relative to the rotating earth, we must include the Coriolis force:

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

The Hairy Men of Thermo-D



It would appear from this sample that a fulsome beard may serve as a thermometer of proficiency in thermodynamics.

However, 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; 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 $(u, v, w, p, T, \rho, \rho_w)$**.**

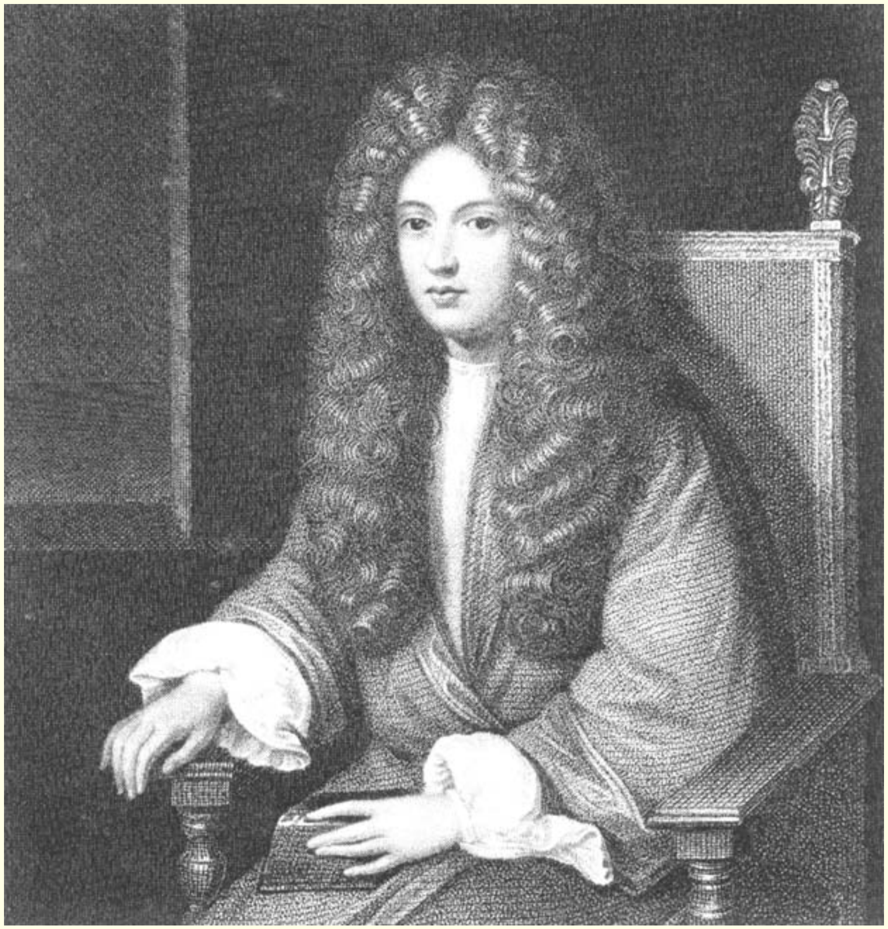
Scientific Weather Forecasting in a Nut-Shell

- **The atmosphere is a physical system**
- **Its behaviour is governed by the laws of physics**
- **These laws are expressed quantitatively in the form of mathematical equations**
- **Using observations, we can specify the atmospheric state at a given initial time: "Today's Weather"**
- **Using the equations, we can calculate how this state will change over time: "Tomorrow's Weather"**

- **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.**

Irish Scientists who have made Contributions to Meteorology

Robert Boyle (1627-1691)



Robert Boyle was born in Lismore, Co. Waterford.

He was a founding fellow of the Royal Society.

Boyle formulated the relationship between pressure and volume of a fixed mass of gas at fixed temperature.

$$p \propto 1/V$$

Richard Kirwan (1733–1812)

Richard Kirwan was born in Co. Galway. He grew up at Cregg Castle, which was built in 1648 by the Kirwan family.

He was a noted Chemist, Mineralogist, Meteorologist and Geologist

He was an early President of the Royal Irish Academy

He anticipated the concept of air-masses

He believed that the Aurora Borealis resulted from combustion of equatorial air.

Francis Beaufort (1774–1857)

Born near Navan in Co. Meath.

Served in the Royal Navy in the Napoleonic wars.

Helped to establish a telegraph line from Dublin to Galway.

Appointed Hydrographer to the Royal Navy in 1829, a post he held until the age of 81.

Promoted Rear Admiral in 1846.

Knight Commander of the Bath two years later.

Best remembered for his scale for estimating the force of the winds at sea — the Beaufort scale.

John Tyndall (1820–1893)

Born in 1820 at Leighlinbridge, Carlow.

Studied with Robert Bunsen in Marburg, 1848.

Associated with the Royal Institution from 1853. Assistant to Michael Faraday.

Published more than 16 books and 145 papers.

Tyndall and the Greenhouse Effect

Tyndall wrote that, without water vapour, the Earth's surface would be *held fast in the iron grip of frost*.

He showed that water vapour, carbon dioxide and ozone are strong absorbers of heat radiation.

This is what we now call the Greenhouse Effect.

Tyndall speculated how changes in water vapour and carbon dioxide could be related to climate change.

George G Stokes, 1819–1903

- Founder of modern hydrodynamics
- Stokes' Theorem
- Stokes Drag and Stokes' Law
- Fluorescence
- Stokes Drift
- Stokes Waves
- Campbell-Stokes Sunshine Recorder
- Navier-Stokes Equations

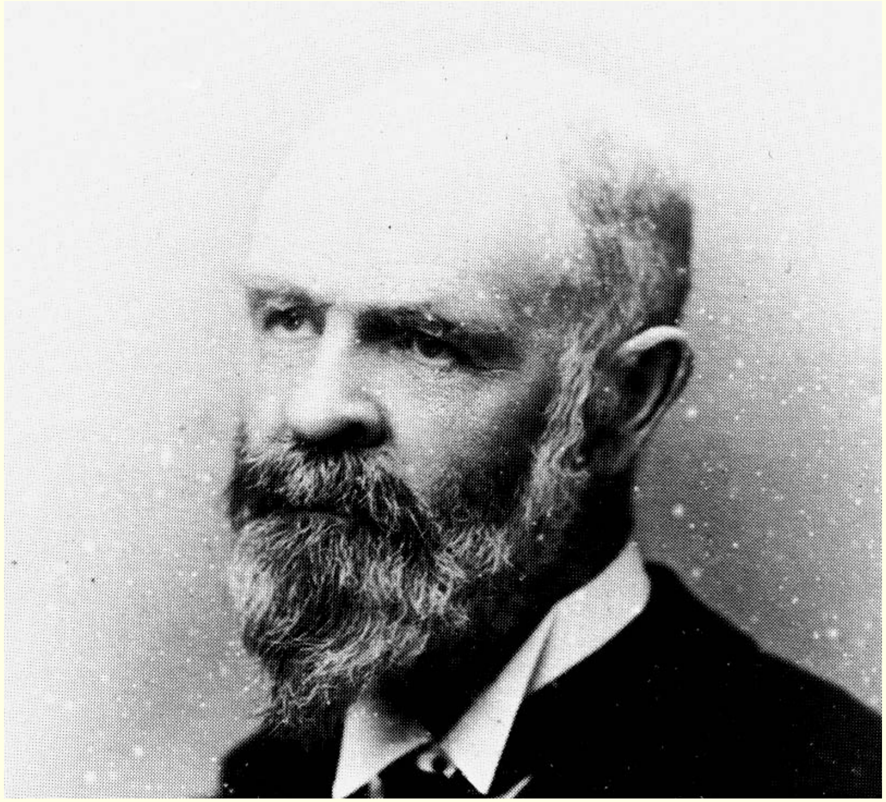
William Thompson (1824–1907)

Sir William Thompson, 1st Baron Kelvin of Largs, born in Belfast. His family moved to Glasgow in 1832.

Kelvin was one of the most brilliant scientists of the 19th century.

- Professor of Natural Philosophy in Glasgow at age 22
- Pioneering research into electrodynamic and thermoelectric properties of matter.
- Developed the foundations of thermodynamics.
- Introduced the absolute scale of temperature; zero at -273°.
- Knighted 1866, after completion of the Atlantic Telegraph cable.
- Invented a tide machine, which predicted the water levels for a year in advance.

Robert Henry Scott (1833–1916)



Robert Scott, born in Dublin, 1833.

Founder of Valentia Observatory

First Director of the British Meteorological Office.

Osborne Reynolds, 1842–1912

- **Born in Belfast, 1842**
- **Graduated from Queens College, Cambridge in 1867**
- **First Professor of Engineering at Owens College, Manchester, in 1868**
- **Work in heat transfer led to major developments in boiler and condenser design**
- **The Reynolds Number provides a criterion for turbulence.**

$$\mathrm{Re} \equiv \frac{VL}{\nu}$$

With the exception of Kirwan, all these scientists, though born in Ireland, made their names abroad.

All that has now changed!!!

Met Éireann-UCD Link

In October 2003, Met Éireann and UCD signed an agreement to establish a Meteorology & Climatology Centre.

- **The Centre is based in the School of Mathematical Sciences, here in Belfield**
- **A Professor, an Adjunct Professor and a Lecturer have been appointed**
- **A post-graduate course commenced in September, 2004. The first group of students will be conferred with Master of Science degrees in December**
- **A programme of research in meteorology is under way. Currently, we have two doctoral students**
- **Undergraduate meteorology modules are being designed.**

In future, our Stokeses and Kelvins will not have to leave Ireland to make their marks on meteorology.

A Brief History of

Numerical Weather Prediction

Vilhelm Bjerknes (1862–1951)

Bjerknes' 1904 Manifesto

Objective:
To establish a science of meteorology

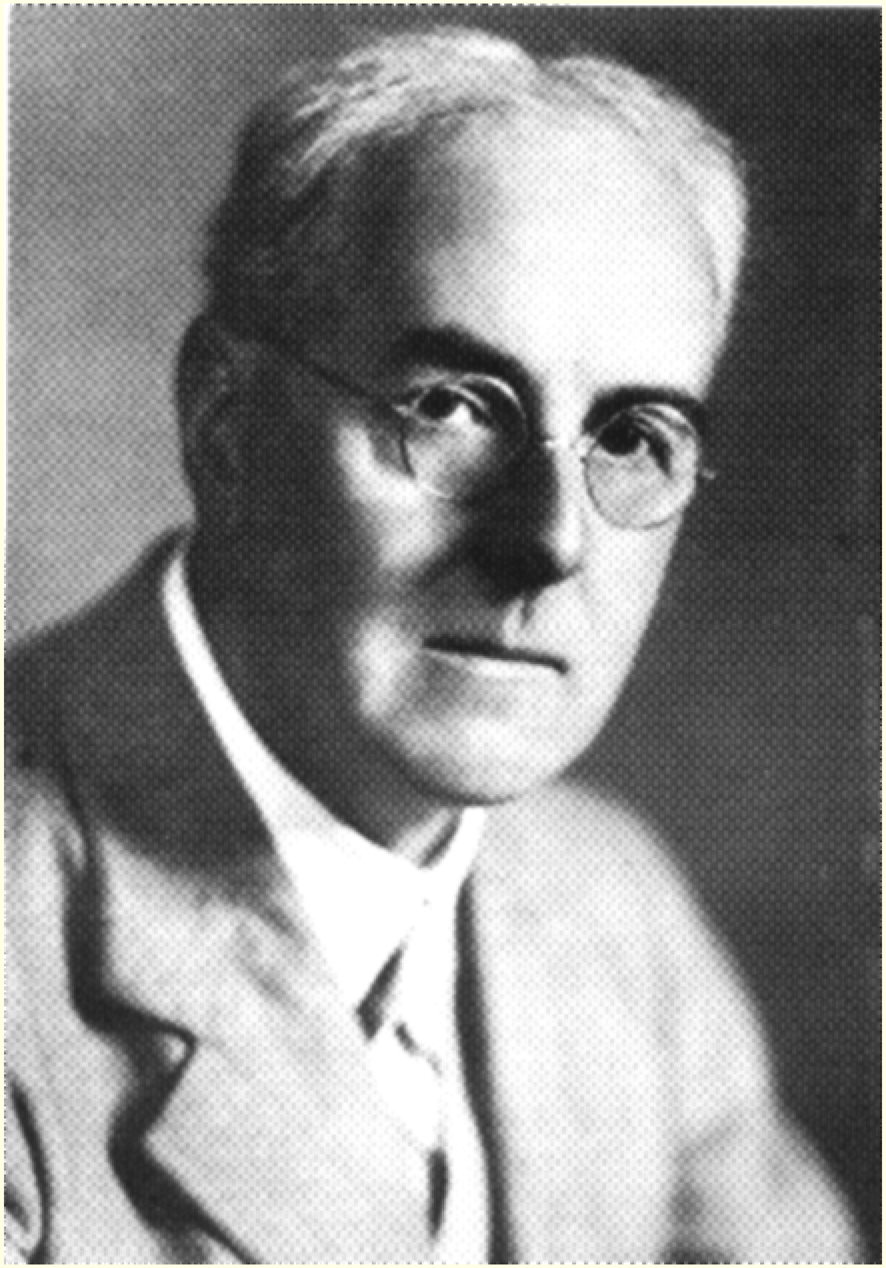
Purpose:
To predict future states of the atmosphere.

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

1. **A sufficiently accurate knowledge of the state of the atmosphere at the initial time**
2. **A sufficiently accurate knowledge of the laws according to which one state of the atmosphere develops from another."**

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

Lewis Fry Richardson, 1881–1953.



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

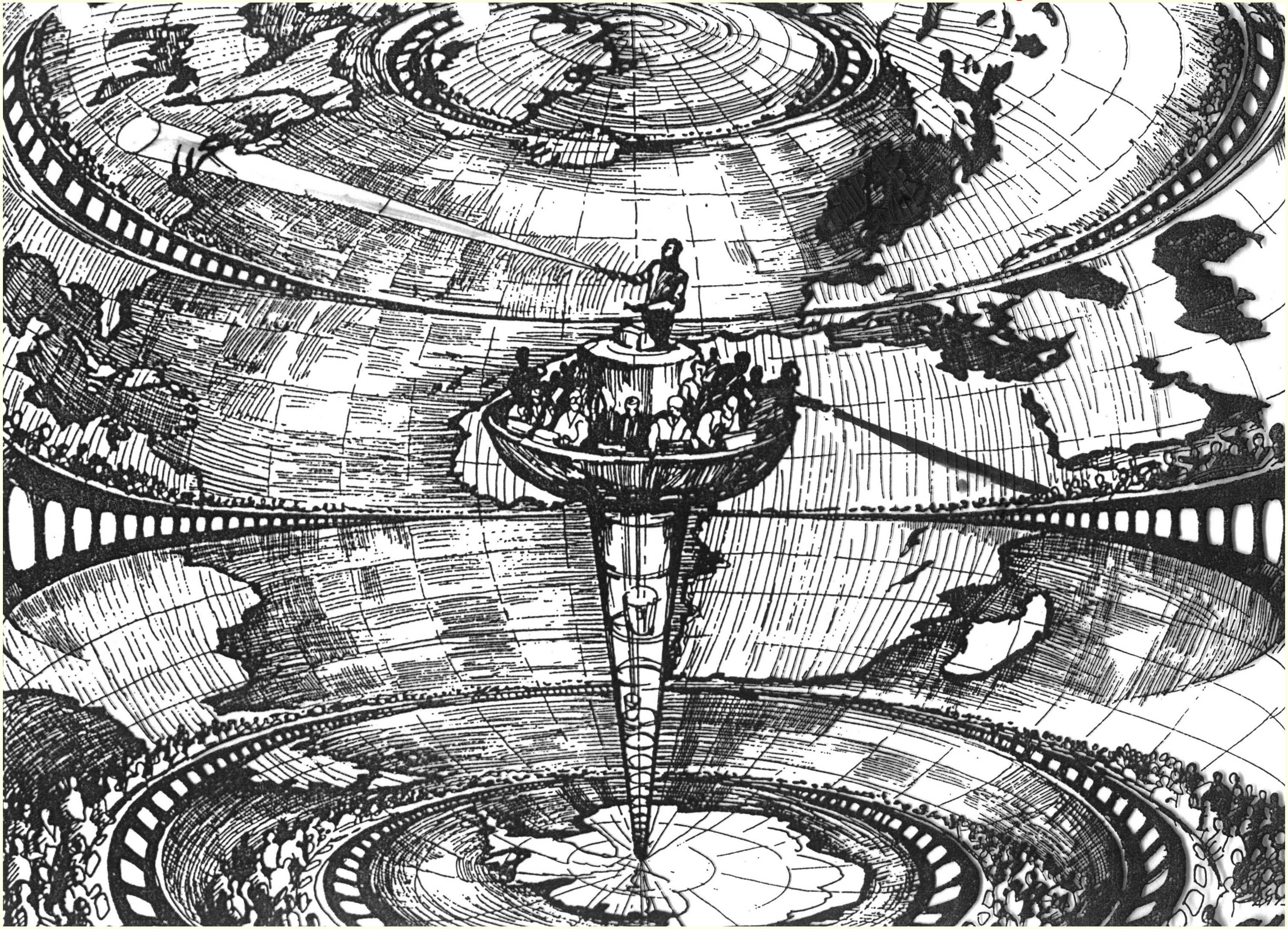
It took him two years !

His 'forecast' was a catastrophic failure:

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

But his method was unimpeachable.

Richardson's Forecast Factory



Dagens Nyheter, Stockholm (*A. Lannerback*). Reproduced from L. Bengtsson, *ECMWF*, 1984

64,000 Computers: The first Massively Parallel Processor

Advances since Bjerknes and Richardson

- ***Dynamic Meteorology***

  Quasi-geostrophic Theory. Baroclinic Instability

- ***Numerical Analysis***

  CFL Stability Criterion. Semi-Lagrangian Techniques

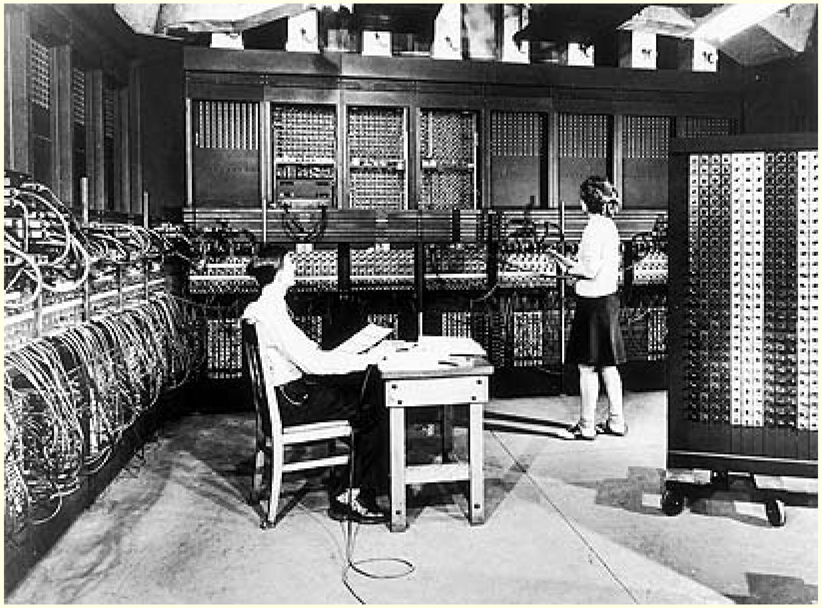
- ***Atmopsheric Observations***

  Radiosondes. Satellite Instrumentation

- ***Electronic Computing***

  ENIAC . . . Moore's Law . . . IBM Blue Gene

The ENIAC

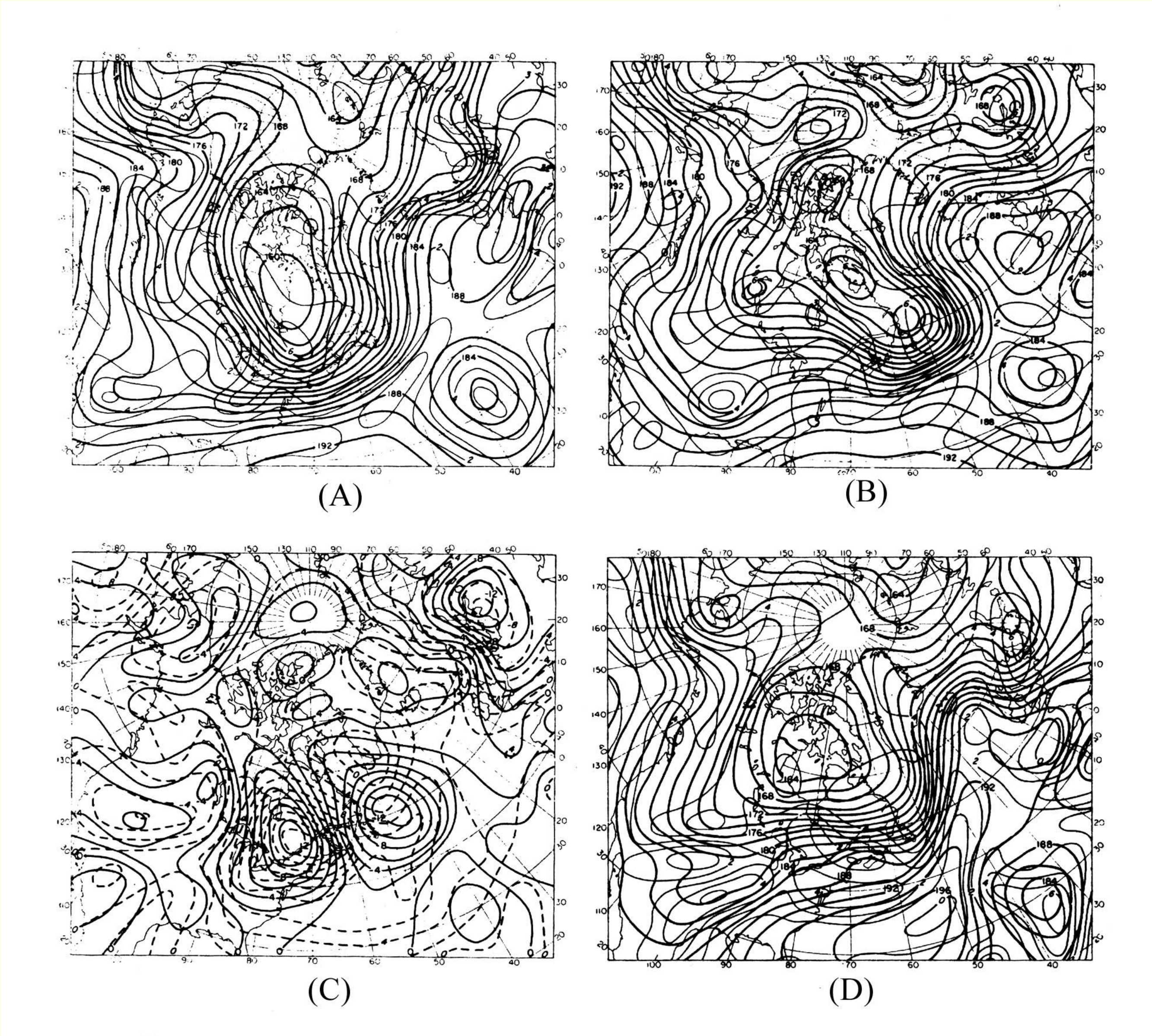


The **ENIAC** (Electronic Numerical Integrator and Computer) was the first multi-purpose programmable electronic digital computer.
It had:

- 18,000 vacuum tubes
- 70,000 resistors
- 10,000 capacitors
- 6,000 switches

Power Consumption: 140 kWatts

1950: The First Computer Forecast

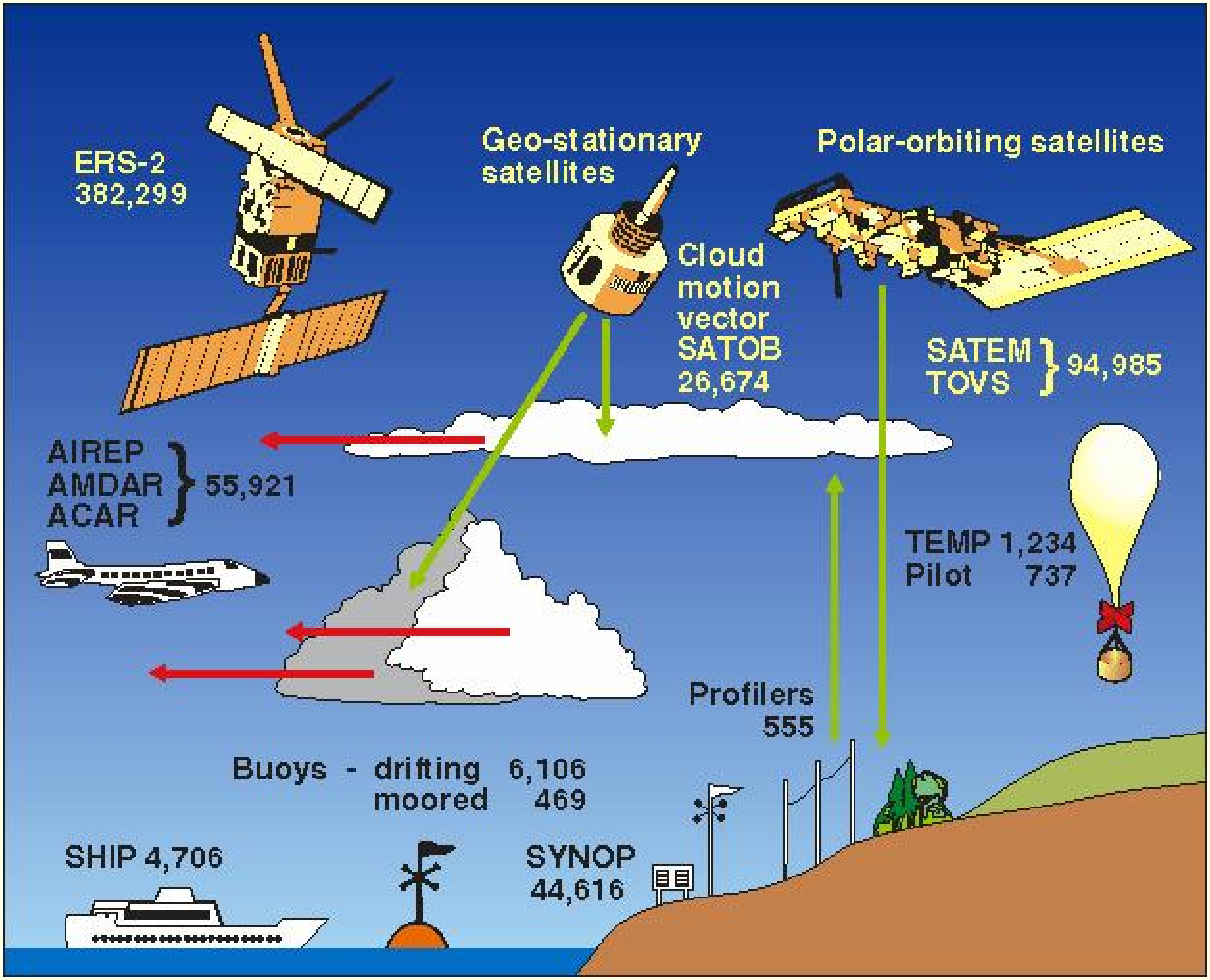


Computer

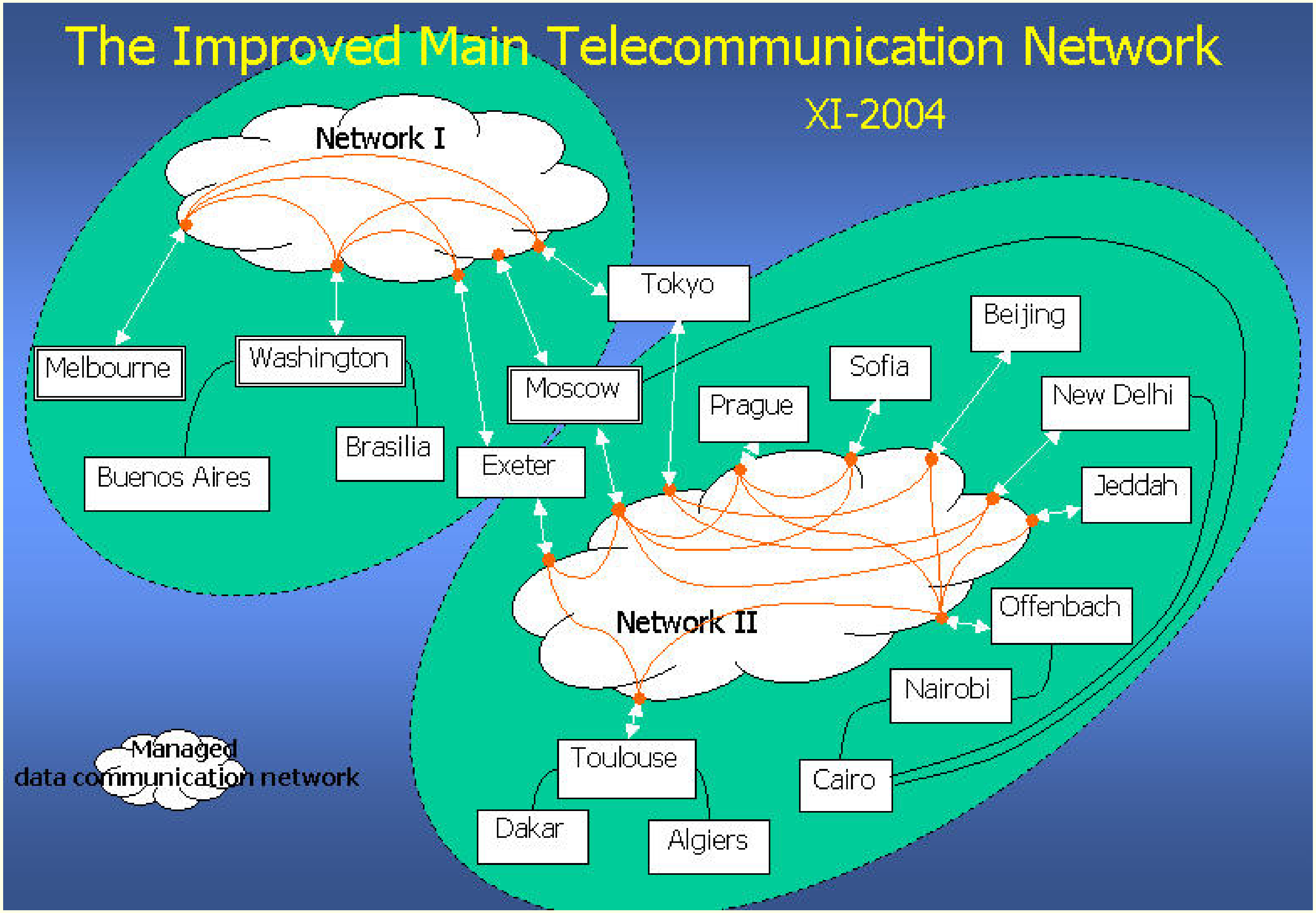
Forecasting

Today

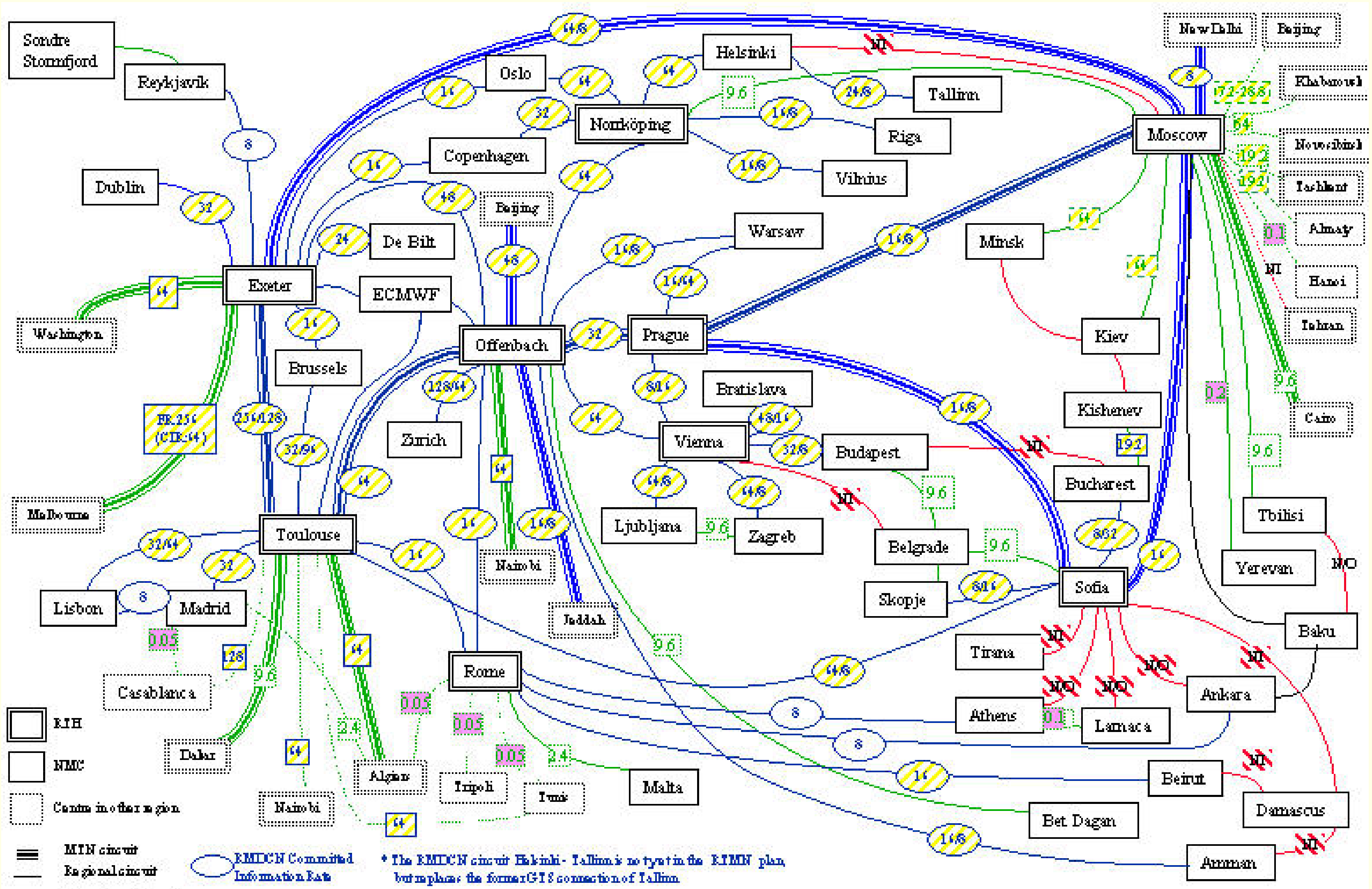
The Global Observing System



The Global Telecommunications System

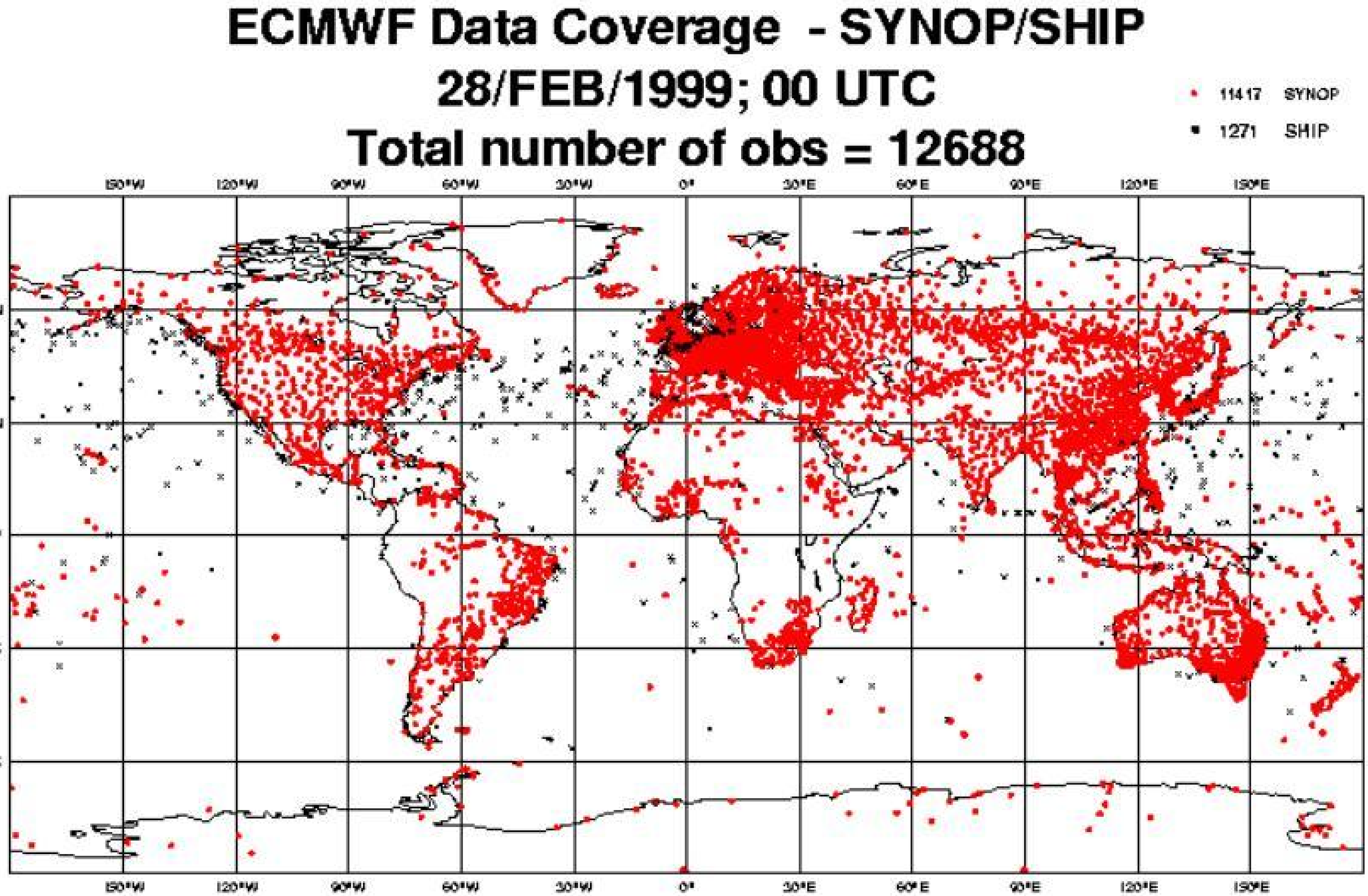


The Global Telecommunications System

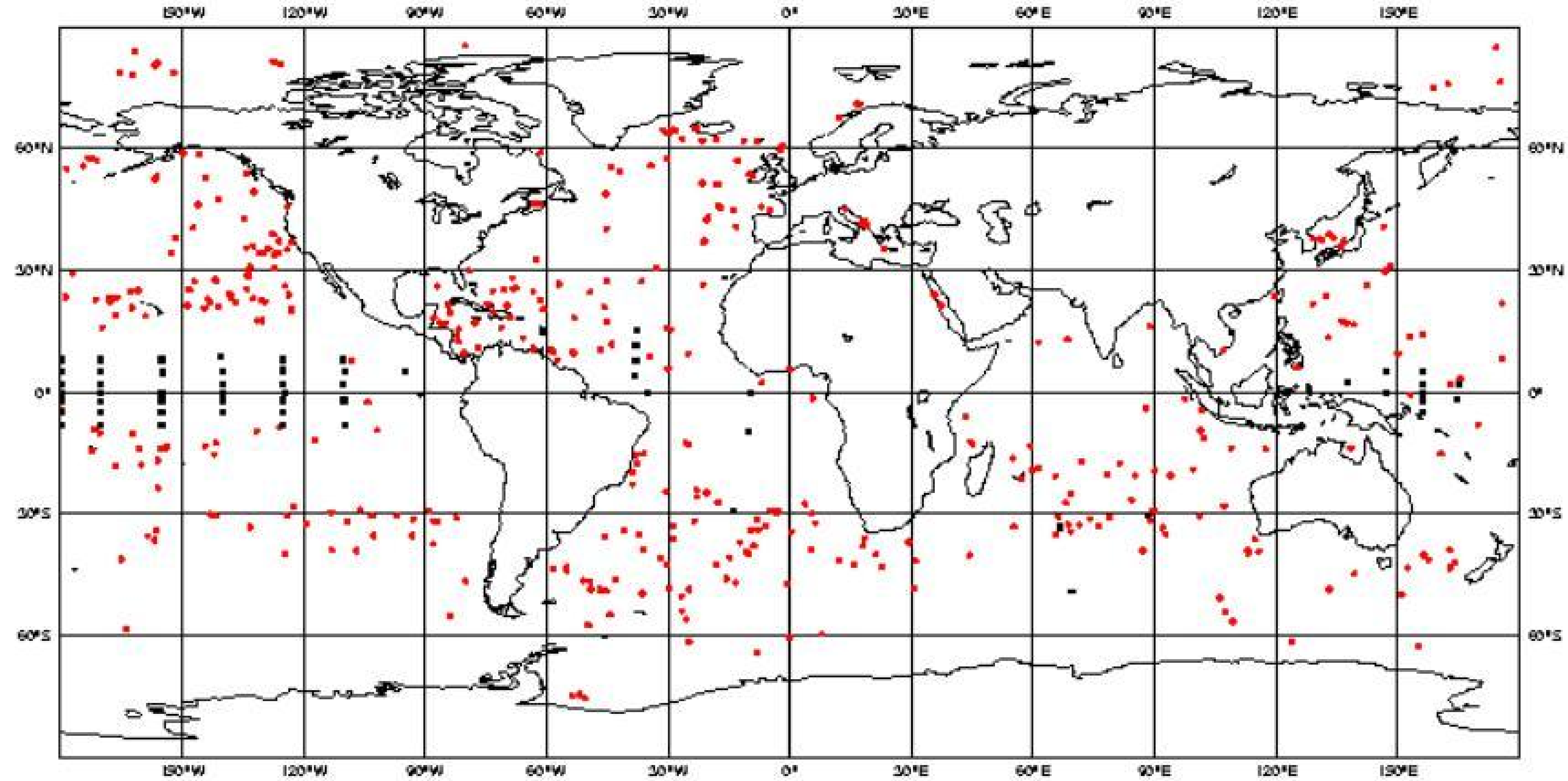


Regional Meteorological Telecommunication Network for Region VI (Europe)

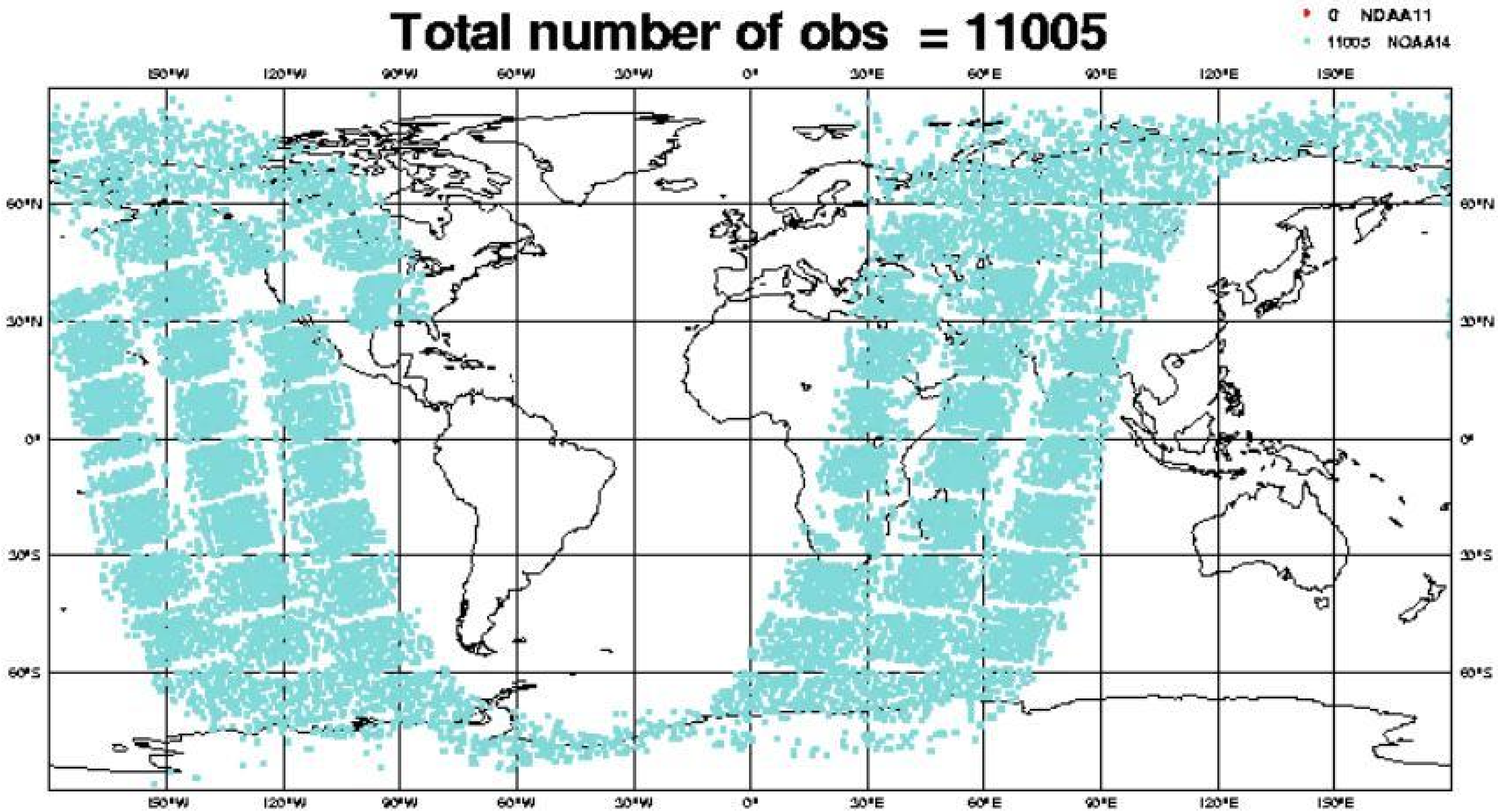
Figure 1 - *point-to-point circuits implementation (transmission speed in kilobit/s)*


ECMWF Data Coverage - SYNOP/SHIP
28/FEB/1999; 00 UTC
Total number of obs = 12688
11417 SYNOP
1271 SHIP
150°W
120°W
90°W
60°W
30°W
0°
30°E
60°E
90°E
120°E
150°E
60°N
30°N
0°
30°S
60°S

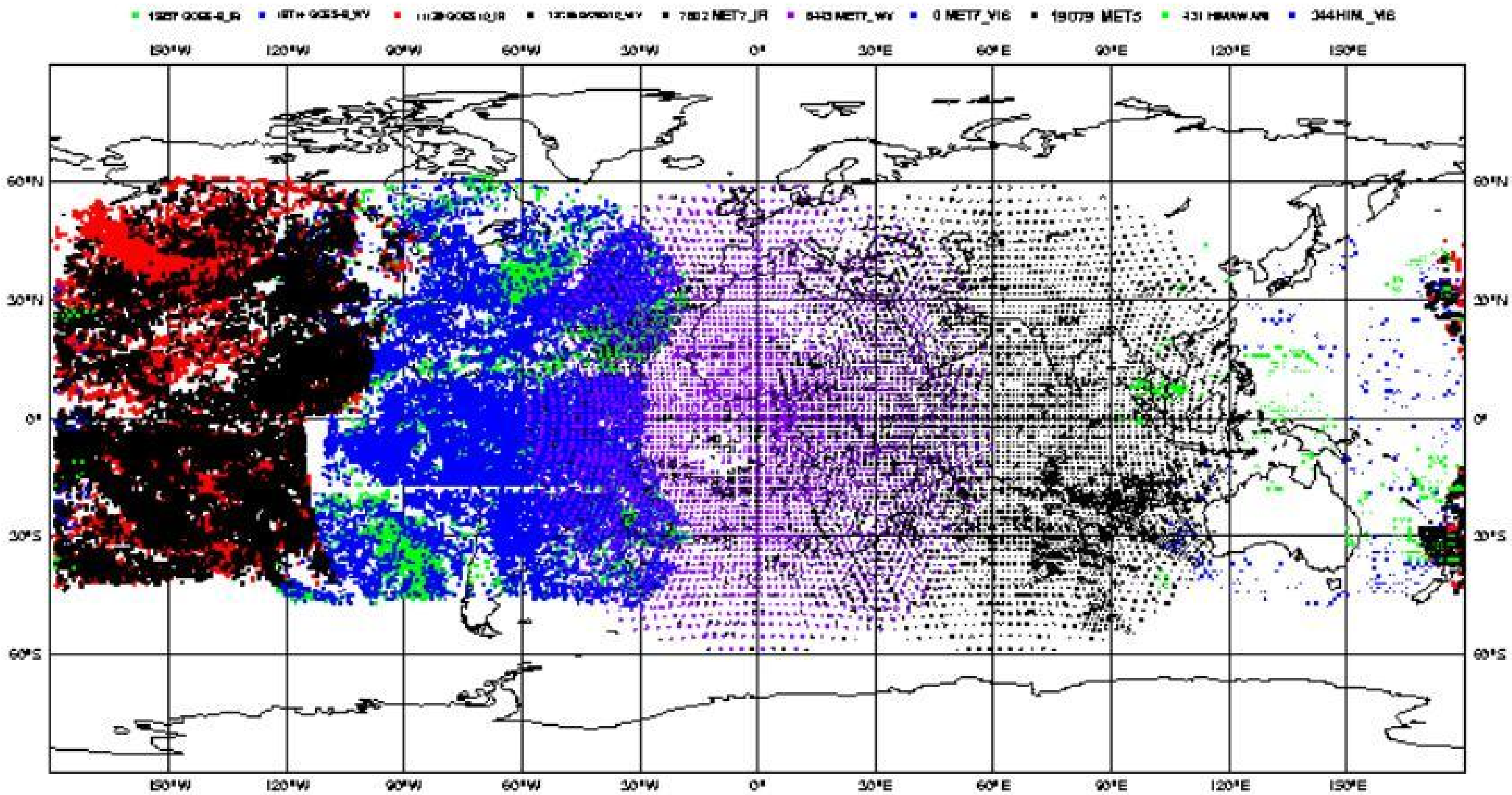
ECMWF Data Coverage - BUOY
28/FEB/1999; 00 UTC
Total number of obs = 1568

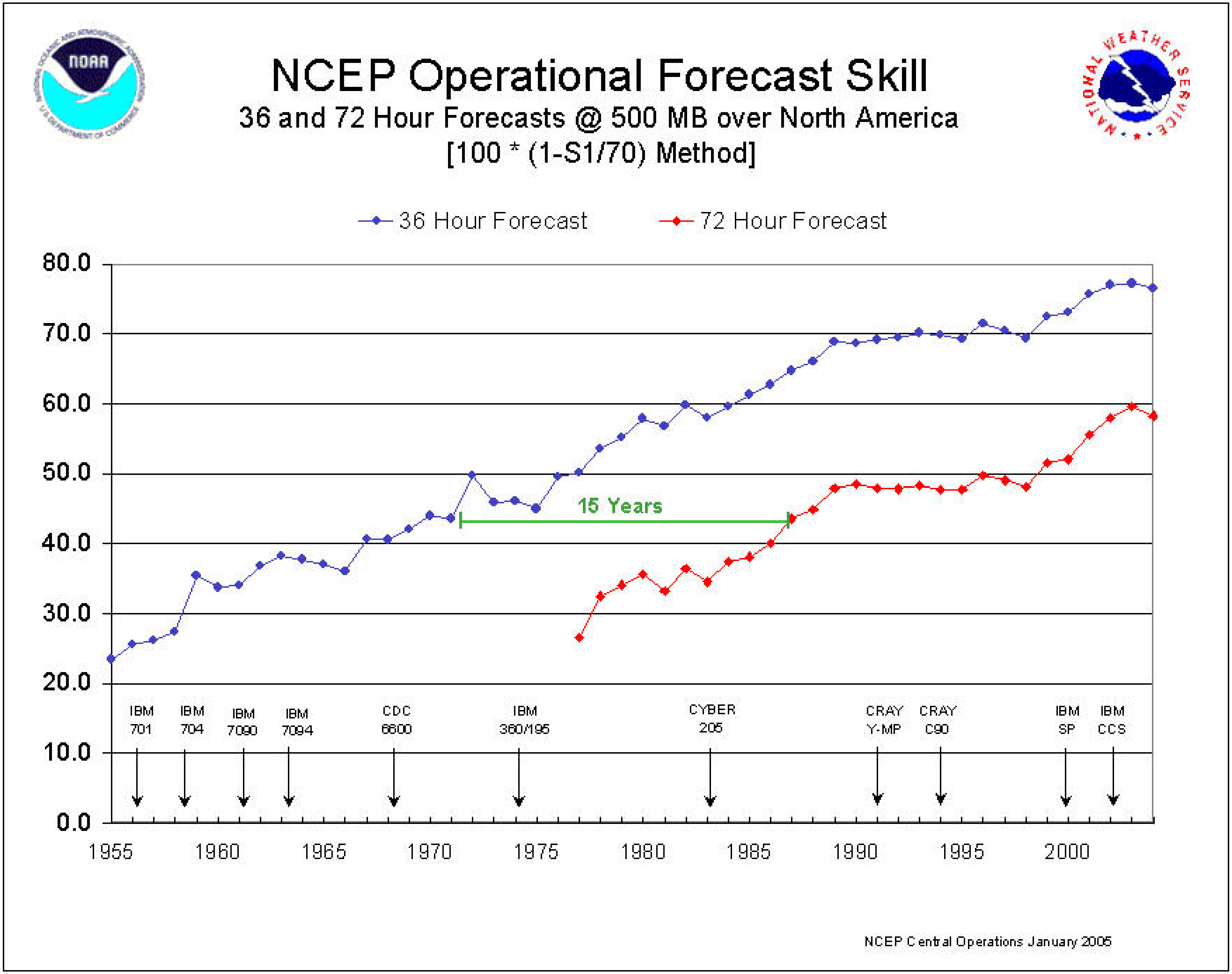


ECMWF Data Coverage - TOVS (120km)
28/FEB/1999; 00 UTC
Total number of obs = 11005



ECMWF Data Coverage - SATOB
28/FEB/1999; 00 UTC
Total number of obs = 91405





NMC/NCEP Scores: The longest verification series in existence.

The HIRLAM Project

HIRLAM stands for High Resolution Limited Area Model.

Members of the HIRLAM Project

- **Denmark**
- **Finland**
- **Iceland**
- **Ireland**
- **Netherlands**
- **Norway**
- **Spain**
- **Sweden**

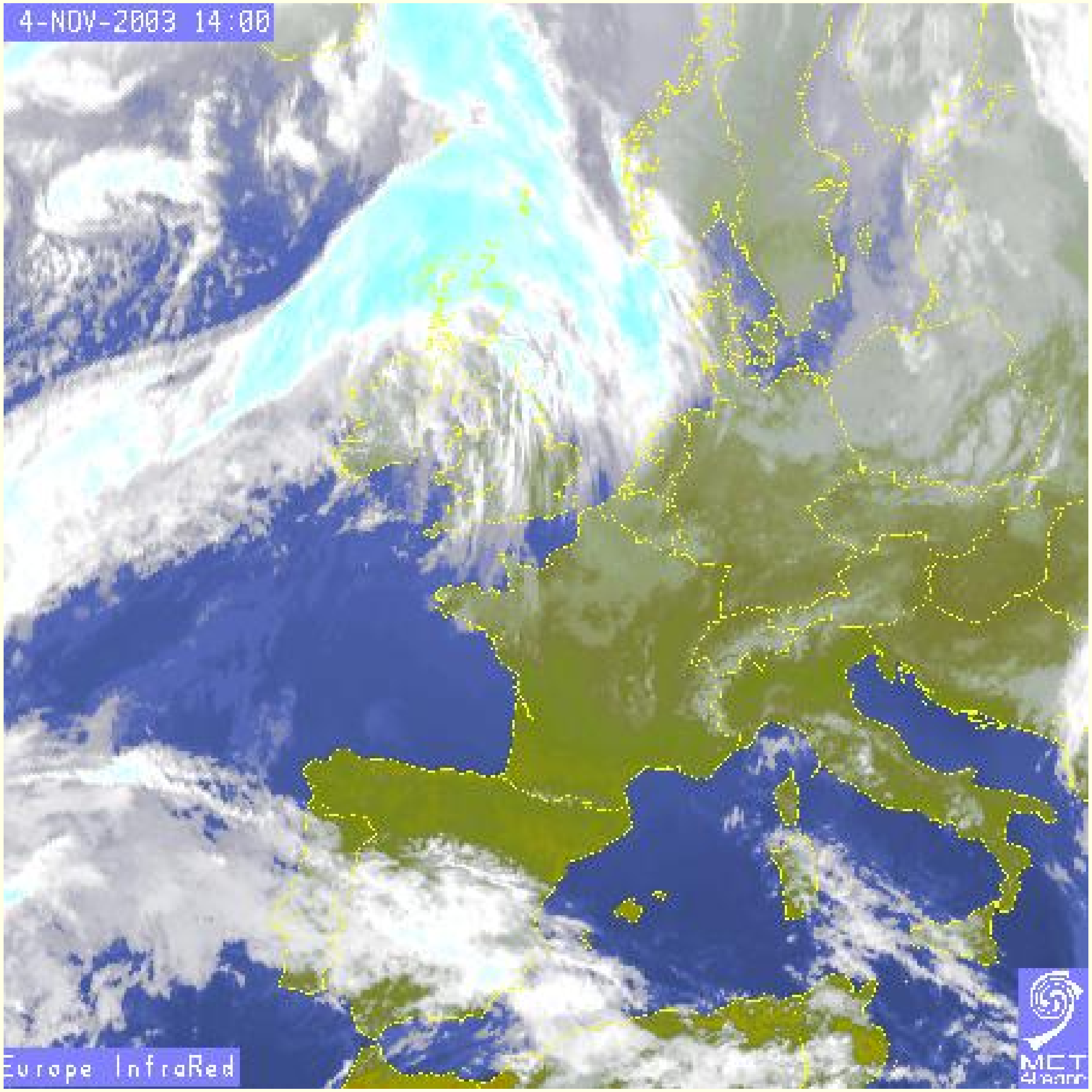
- HIRLAM ***is a state-of-the-art prediction model for short-range forecasting***
- ***It is based on the Primitive Equations***
- ***It has a comprehensive parameterization package for physical processes***
- HIRLAM ***is the basis for short-range forecasting operations at Met Éireann.***

Extensive model documentation is available at http://hirlam.knmi.nl/

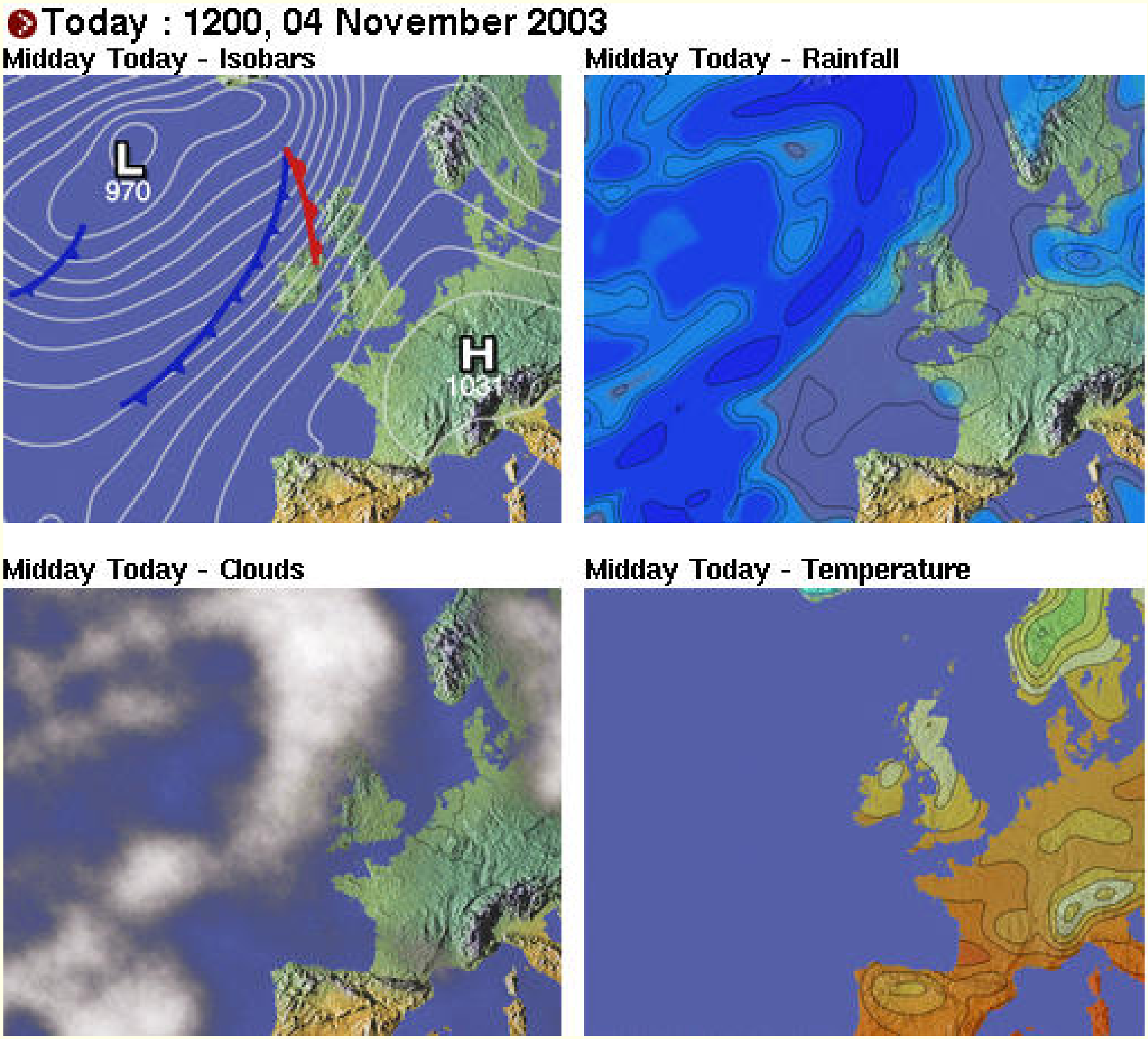
Met Éireann Headquarters

The Met Éireann web site: www.met.ie

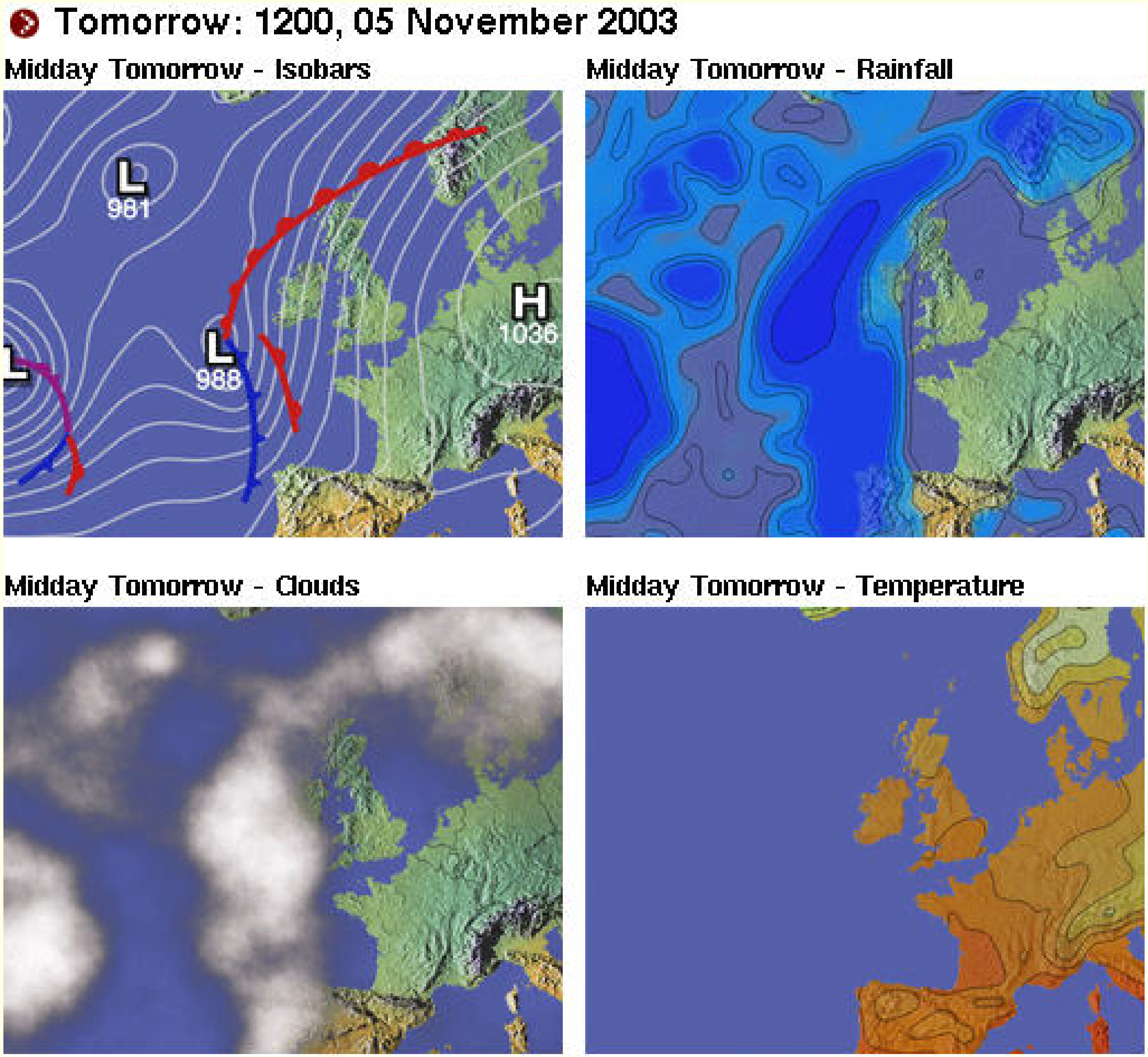
Satellite Imagery



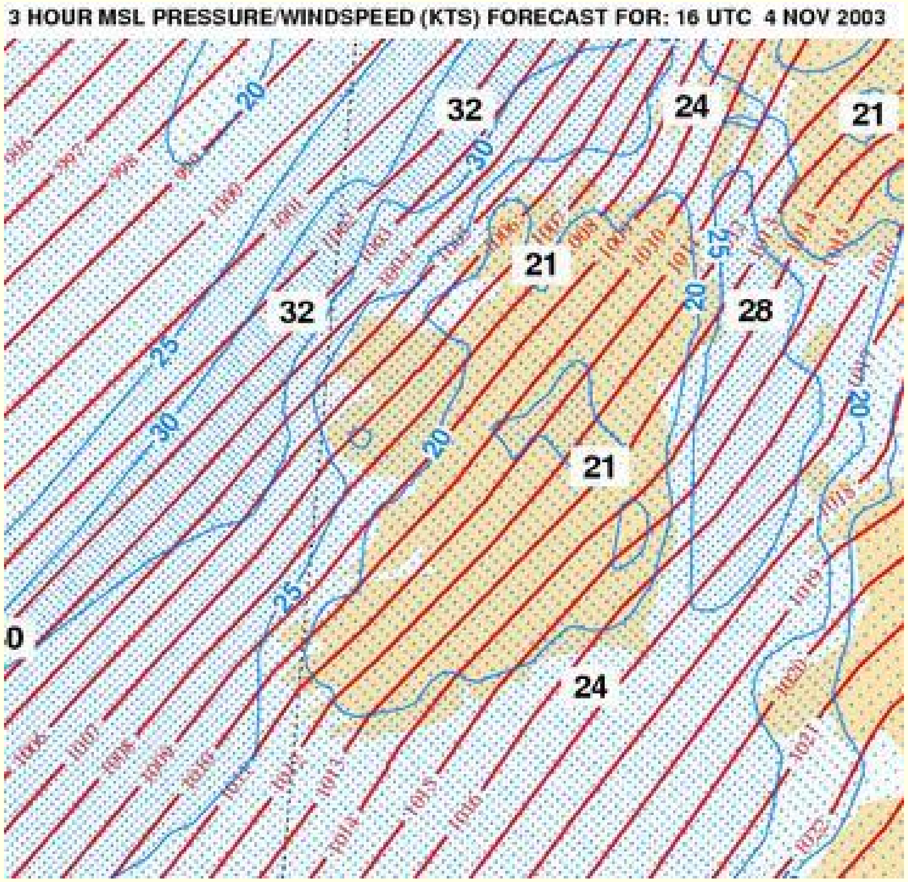
Atlantic Analysis Charts

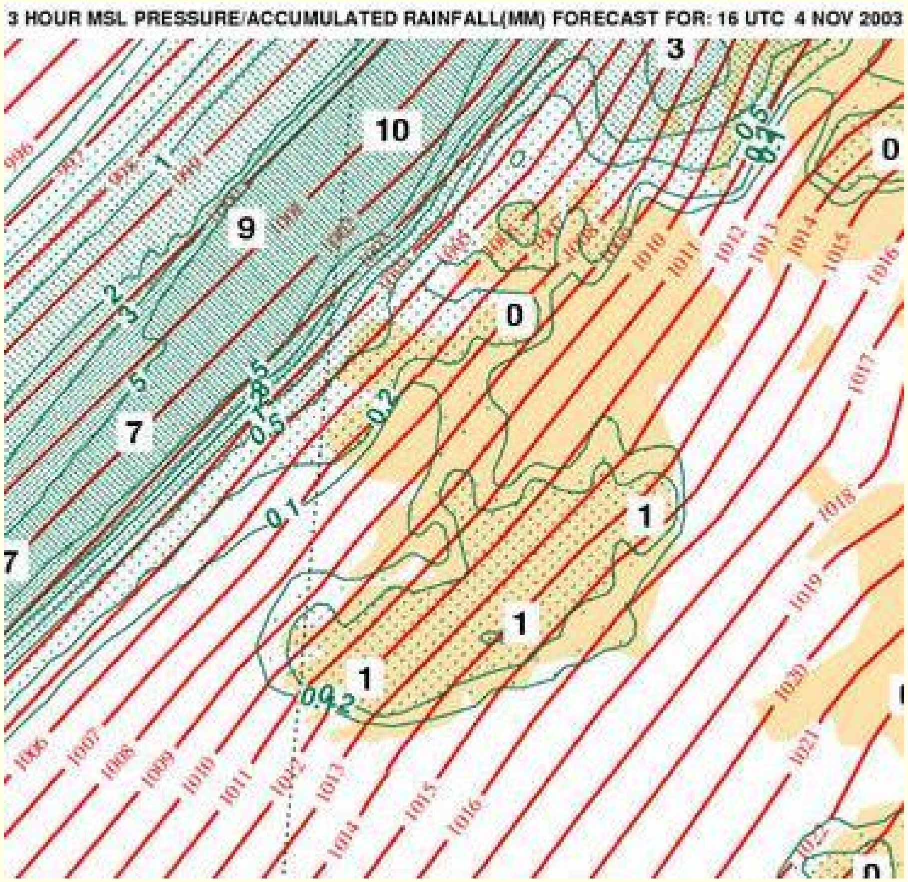


Atlantic Forecast Charts



Hourly HiRLAM Forecast Charts





European Centre for Medium range Forecasts. Reading Headquarters.

ECMWF: World leader in NWP

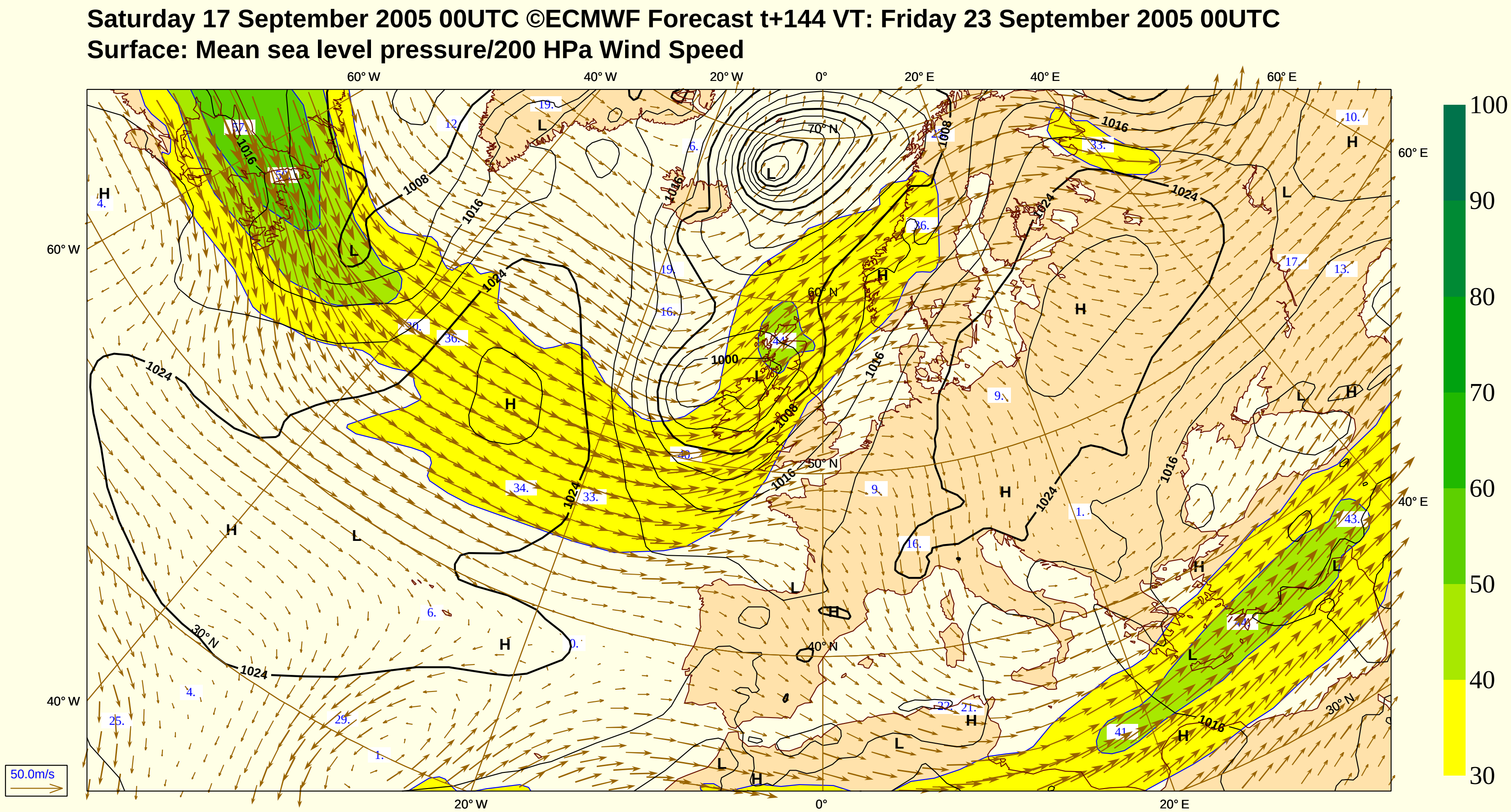
Established in 1975, ECMWF is situated in Reading, Berkshire, with a staff of 216.

The Centre is renowned worldwide as providing the most accurate medium-range global weather forecasts to ten days and seasonal forecasts to six months.

Its products are provided to the European National Weather Services, as a complement to the national short-range and climatological activities.

Eighteen Member States, including Ireland, support ECMWF.

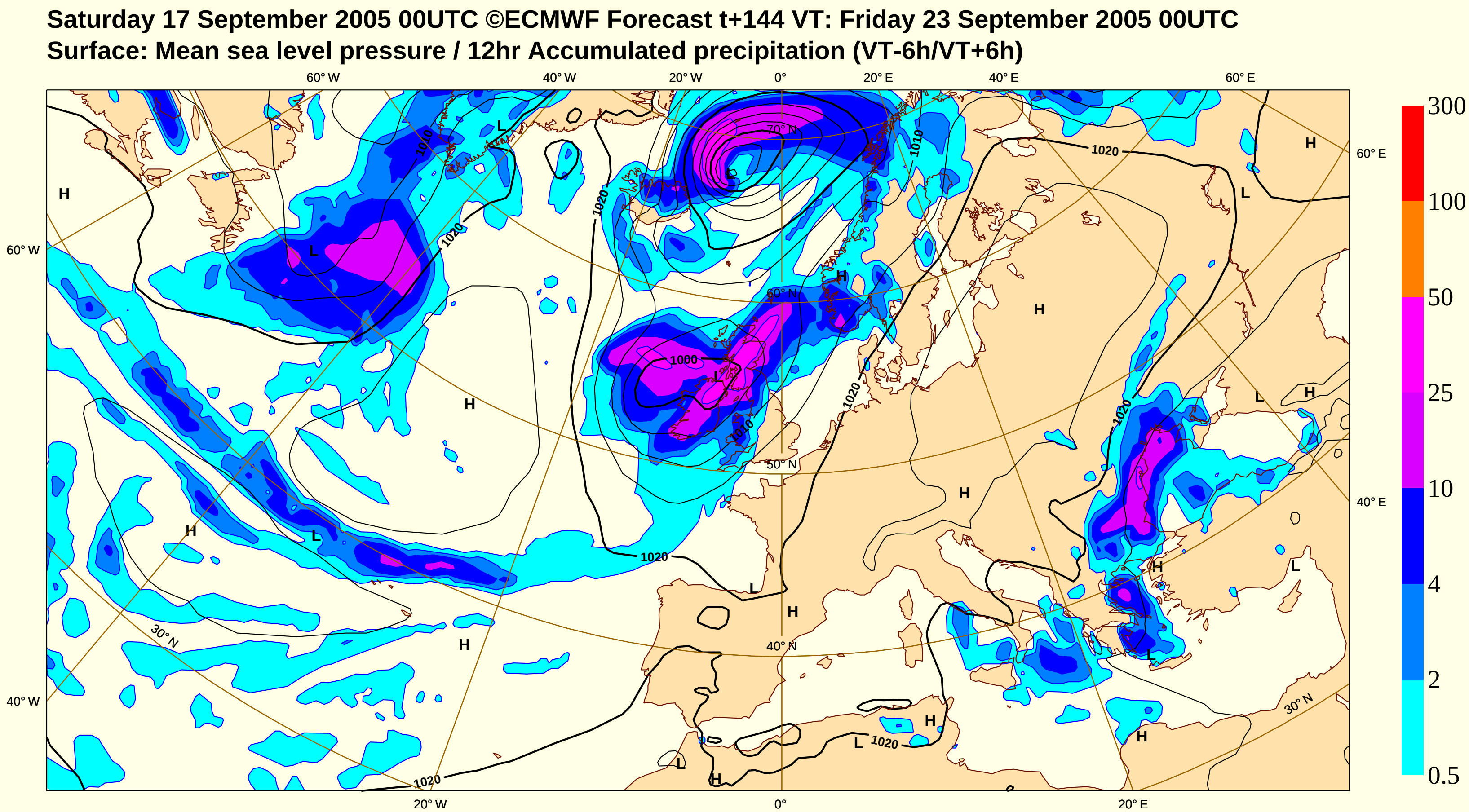
Six-day Forecast from ECMWF



Mean sea-level pressure and 200 hPa winds

Valid time: Midnight tonight

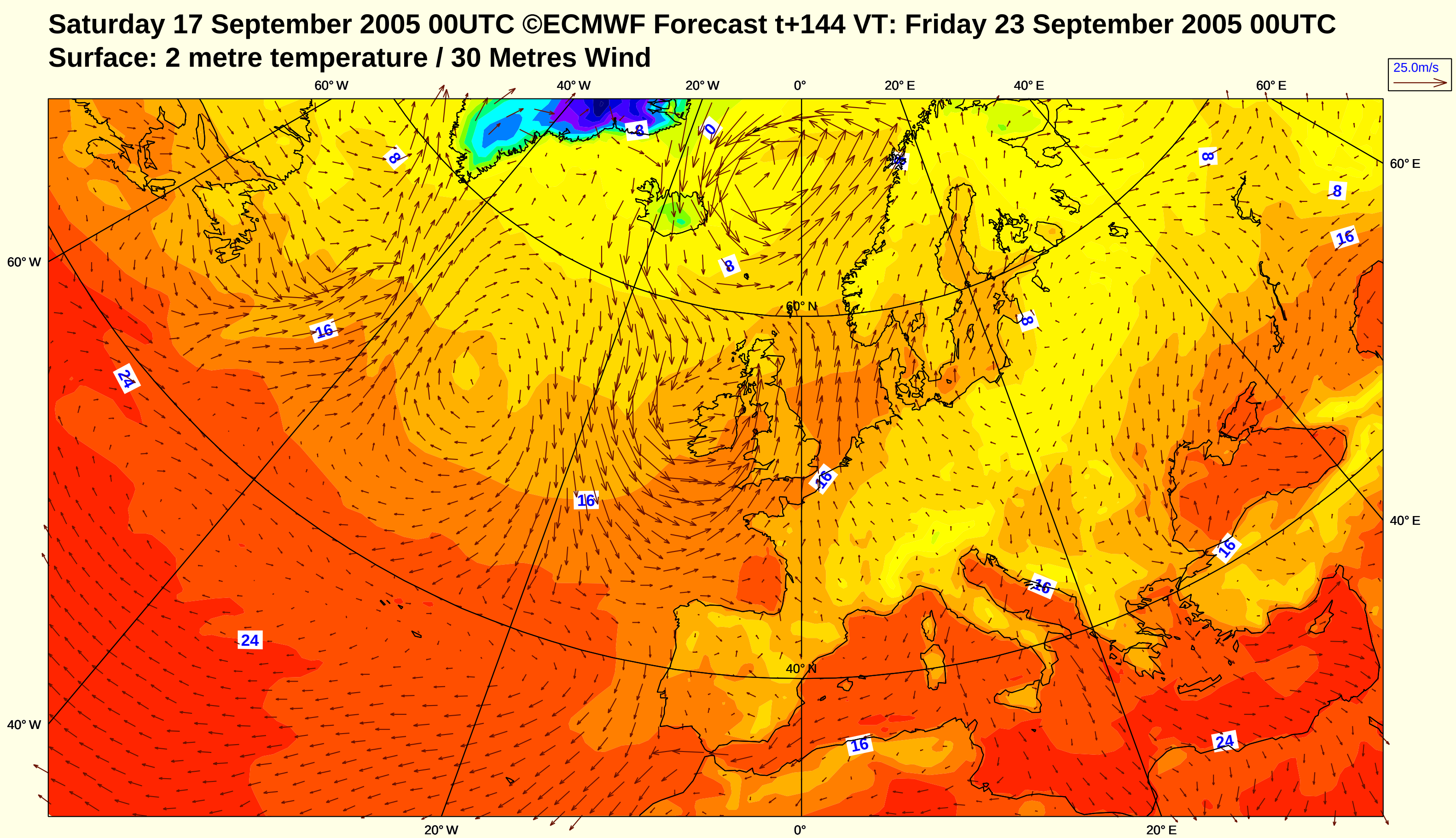
Six-day Forecast from ECMWF



Mean sea-level pressure and 12 hour precipitation

Valid time: Midnight tonight

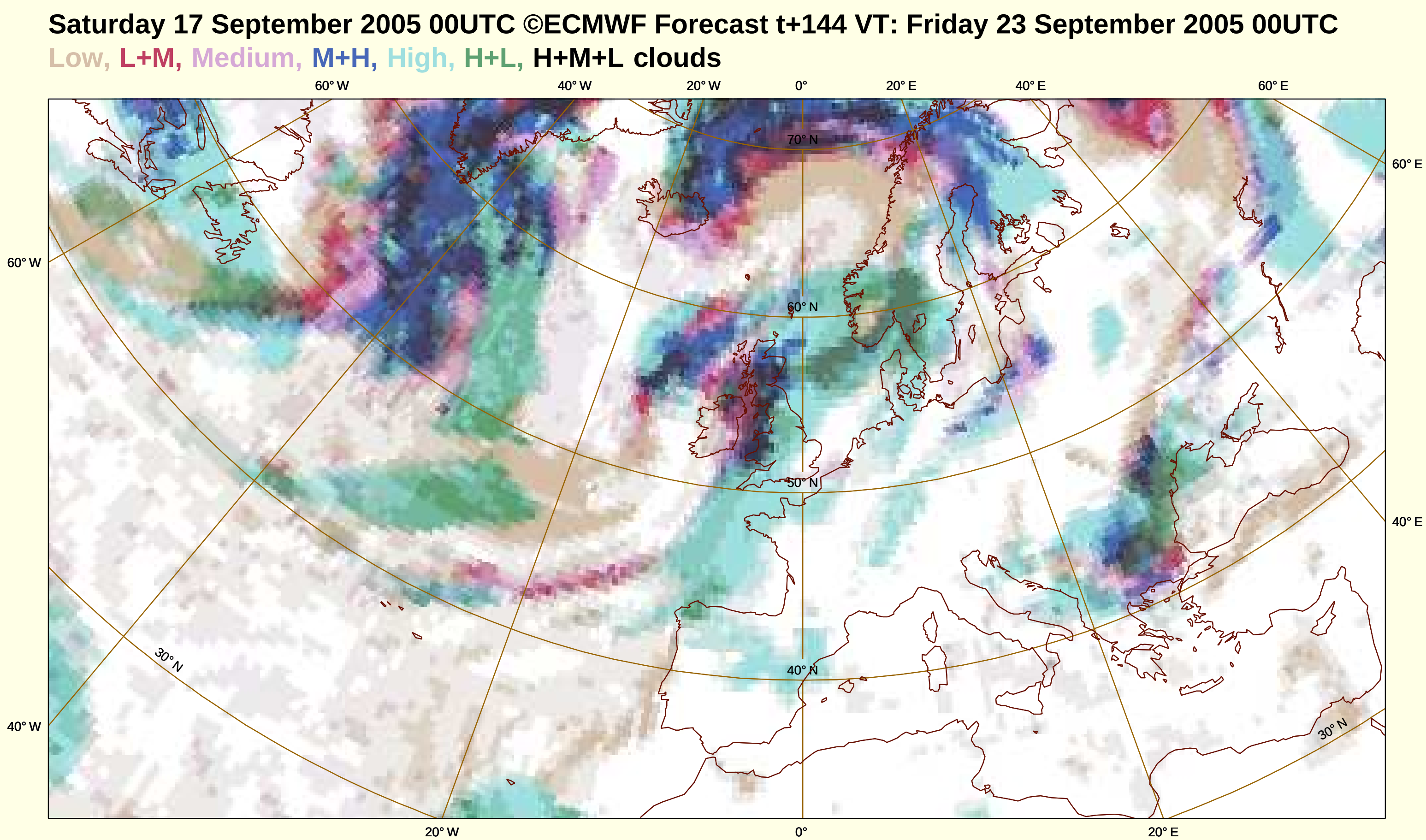
Six-day Forecast from ECMWF



2m Temperature and 30m Wind Forecast

Valid time: Midnight tonight

Six-day Forecast from ECMWF

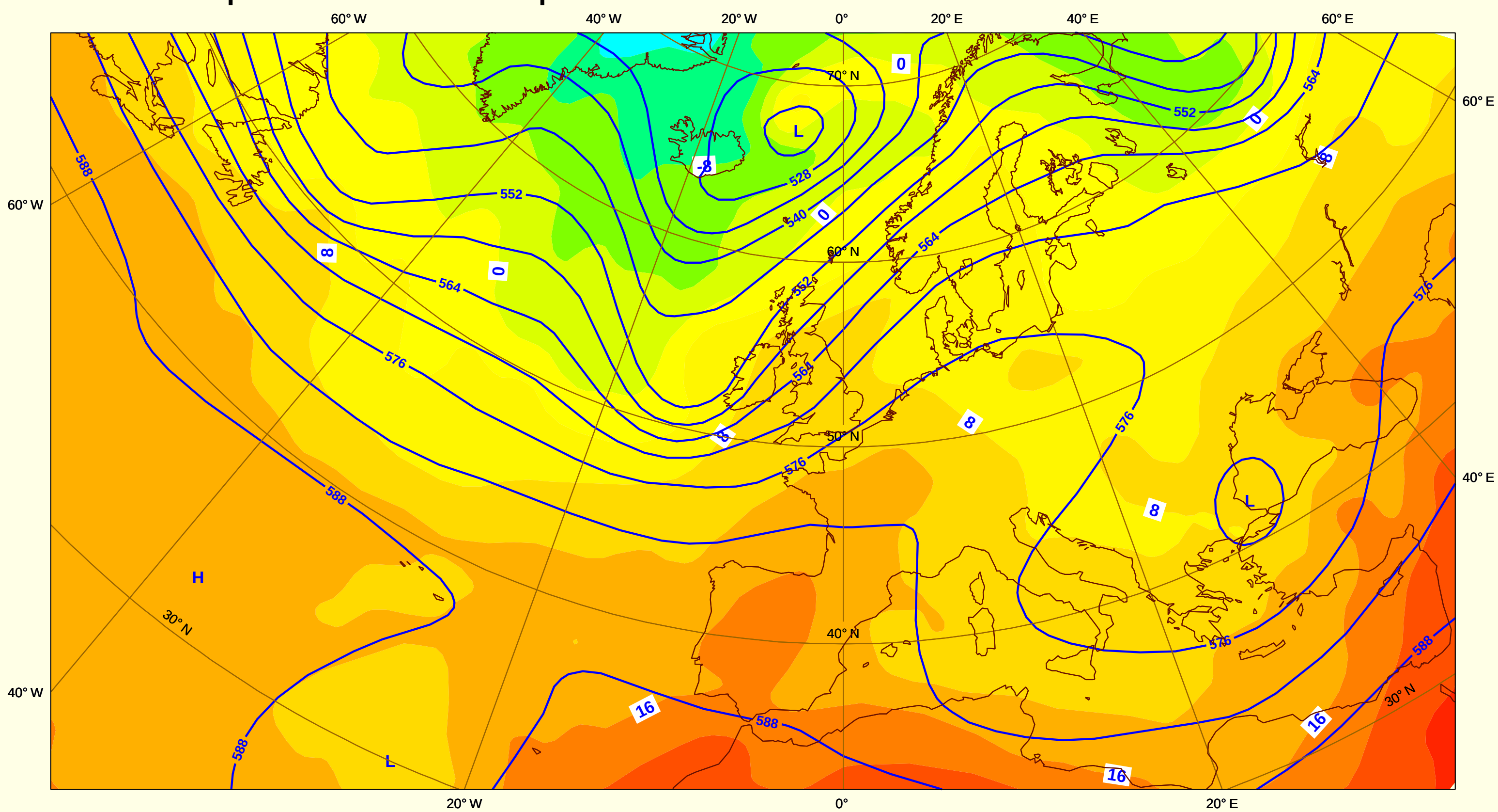


Forecast of cloud cover

Valid time: Midnight tonight

Six-day Forecast from ECMWF

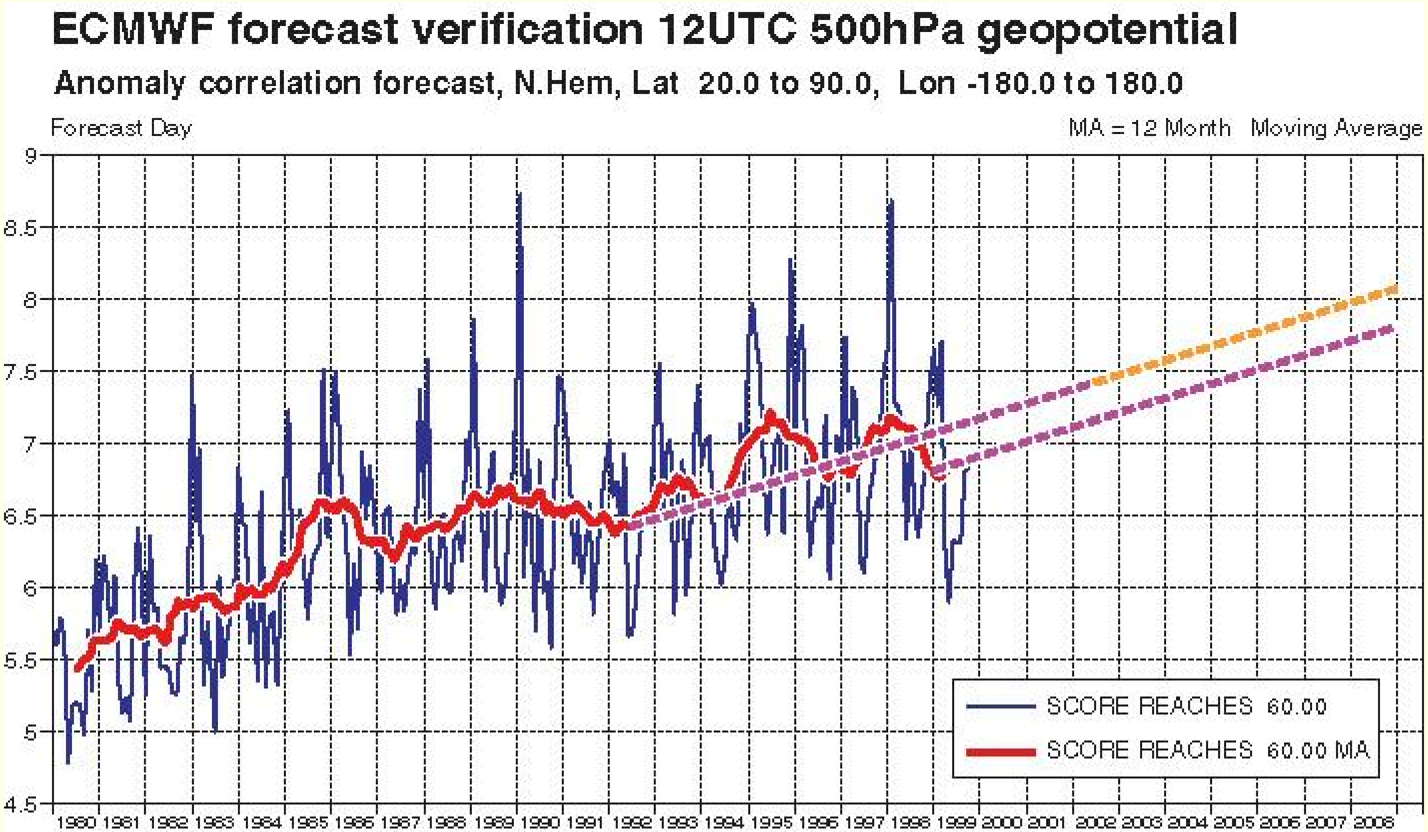
Saturday 17 September 2005 00UTC ©ECMWF Forecast t+144 VT: Friday 23 September 2005 00UTC
850 hPa Temperature / 500 hPa Geopotential



500 hPa height and 850 hPa temperature

Valid time: Midnight tonight

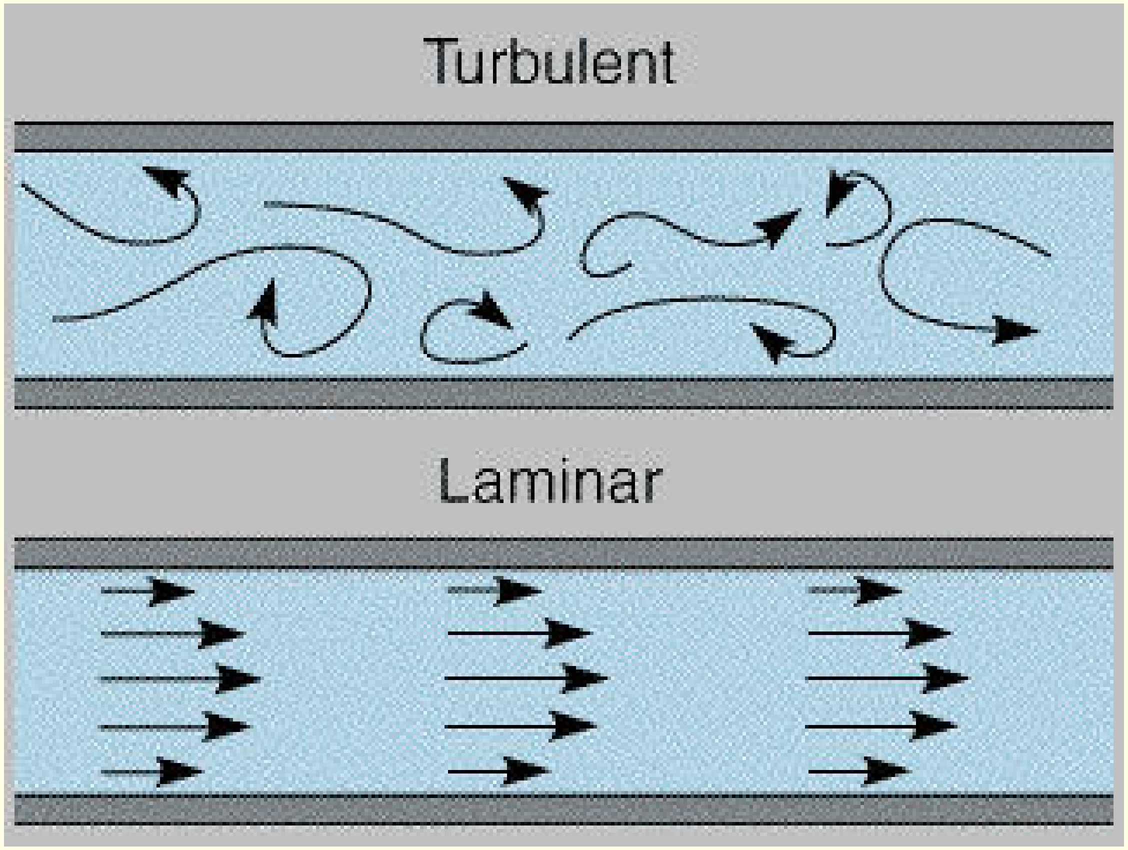
Progress in numerical weather prediction over the past fifty years has been quite dramatic.

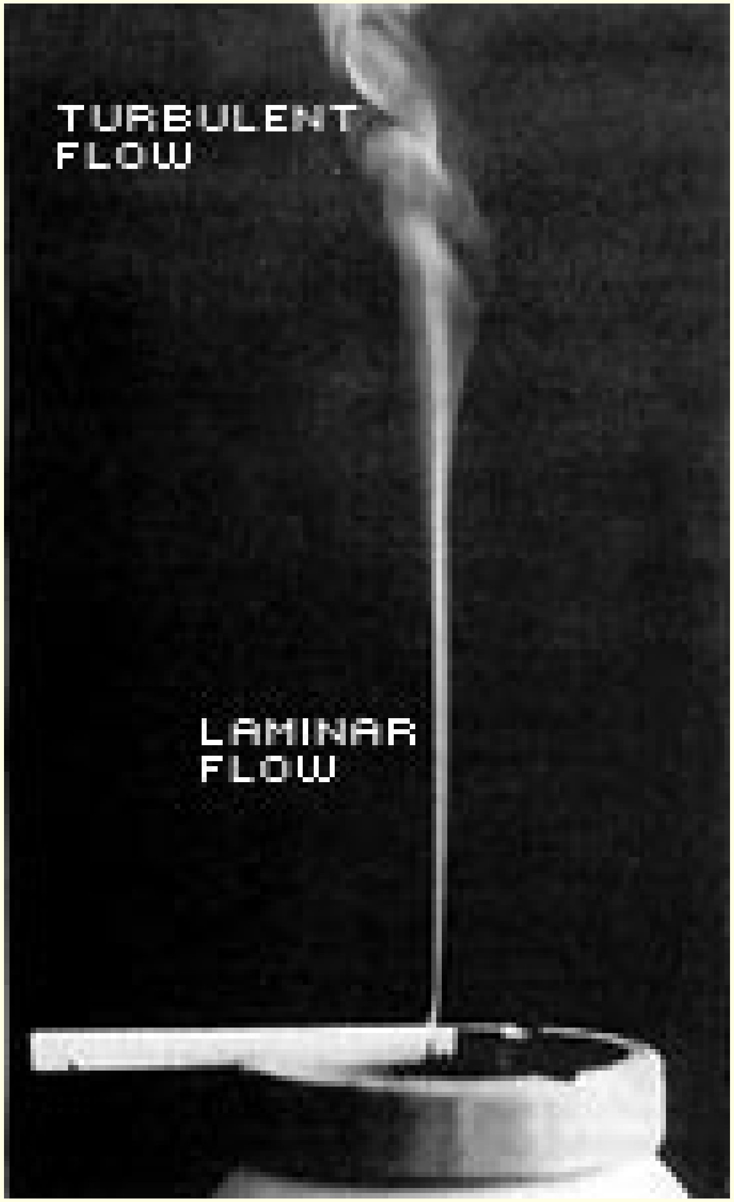


Forecast skill continues to increase . . .
by one day per decade.

However, there is a limit . . .

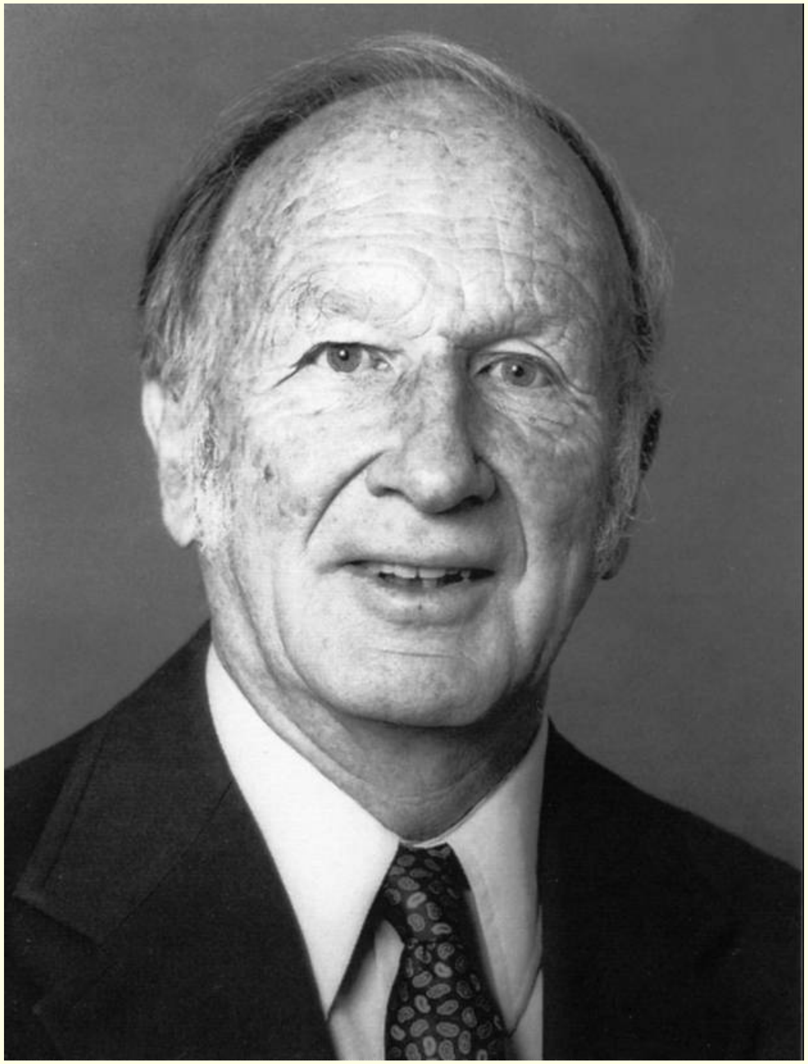
Laminar and Turbulent Flow





Just in case you're tempted to light up . . .

Chaos in Atmospheric Flow



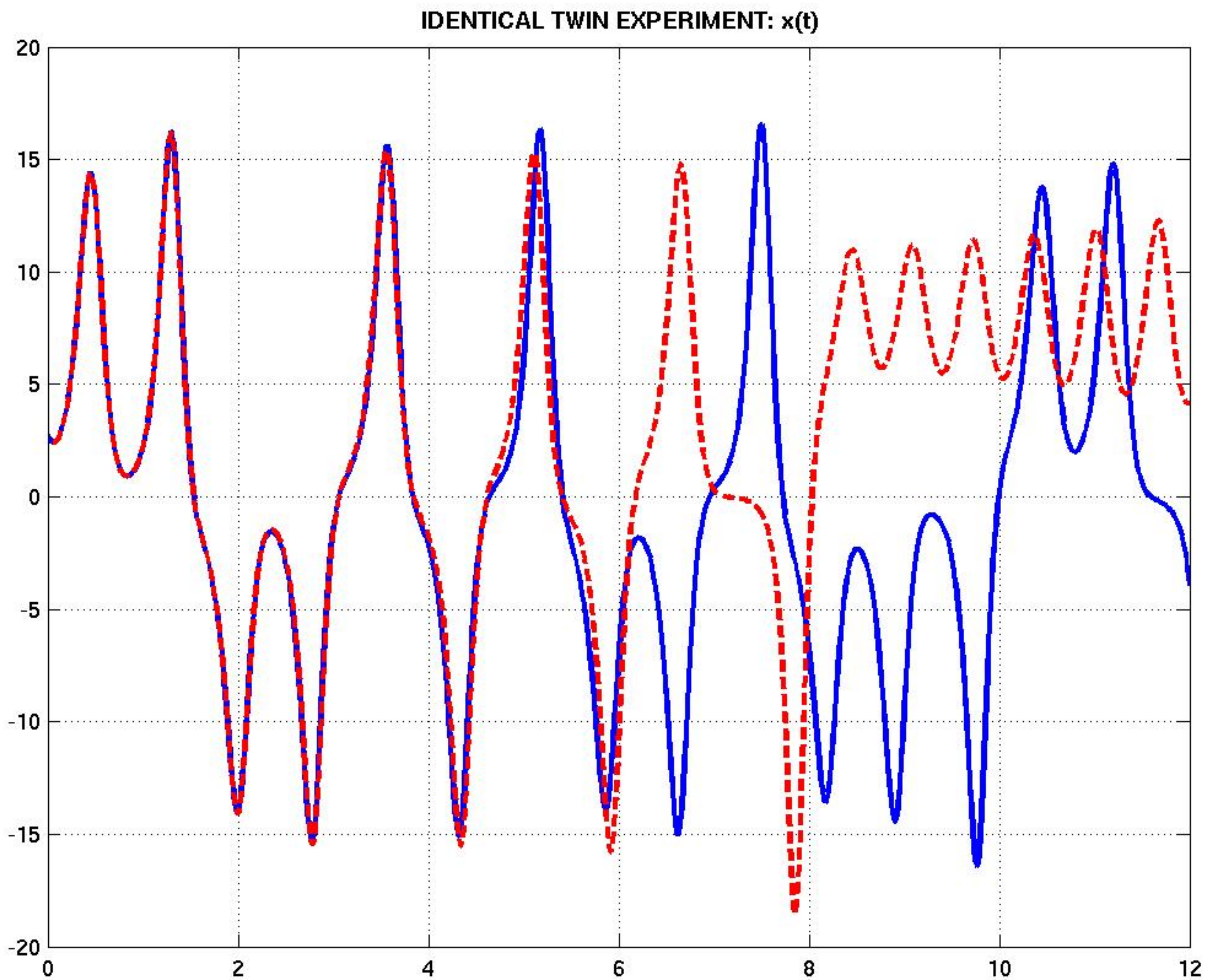
Edward Lorenz (b. 1917)

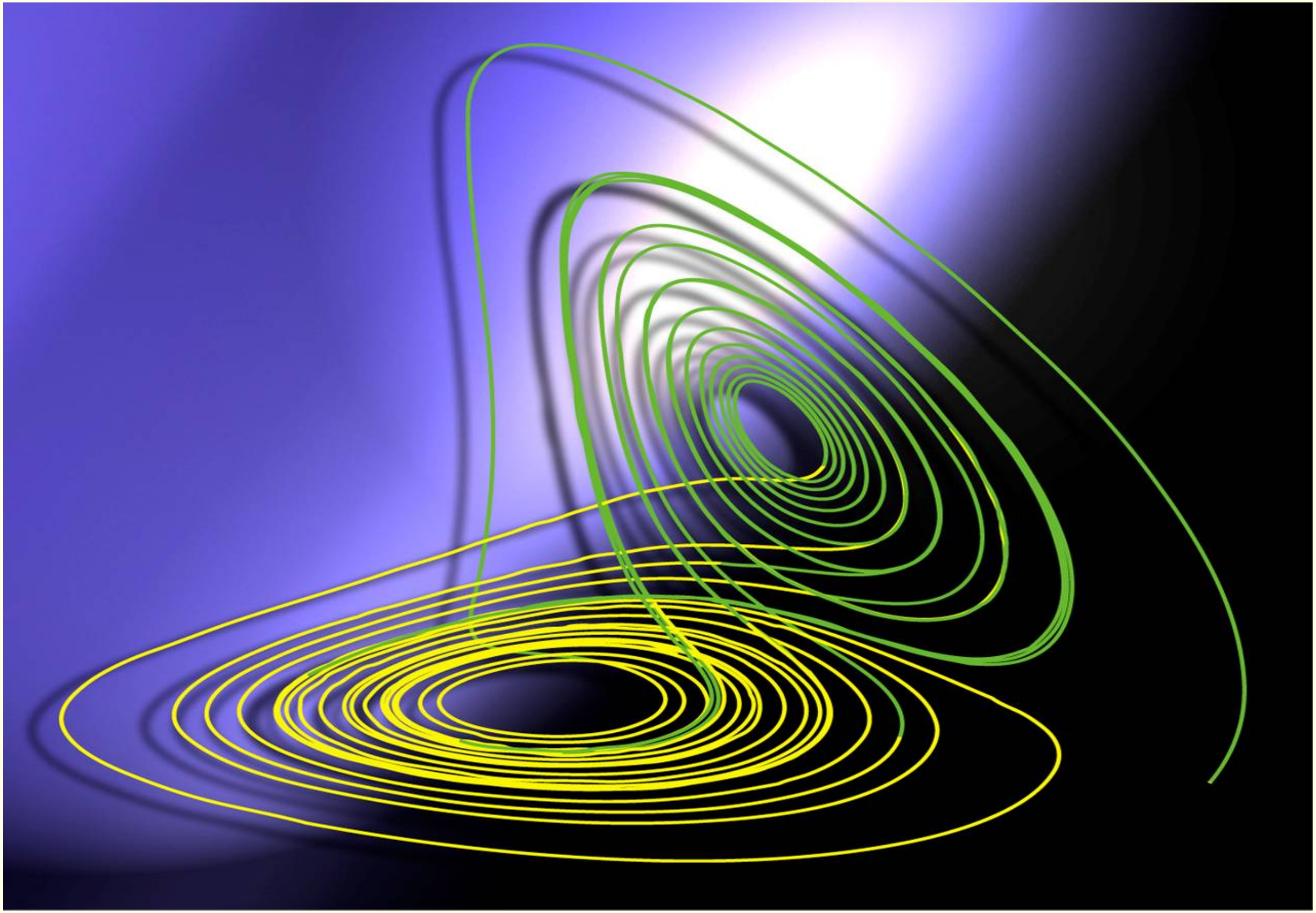
In a paper published in 1963, entitled *Deterministic Nonperiodic Flow*, Edward Lorenz showed that the simple system

$$\dot{x} = -\sigma x + \sigma y$$
$$\dot{y} = -xz + rx$$
$$\dot{z} = +xy - bz$$

has solutions which are highly *sensitive to the initial conditions.*

Identical Twin Experiment





The characteristic *butterfly pattern* in Lorenz's Equations.

Lorenz's work demonstrated the practical impossibility of making accurate, detailed long-range weather forecasts.

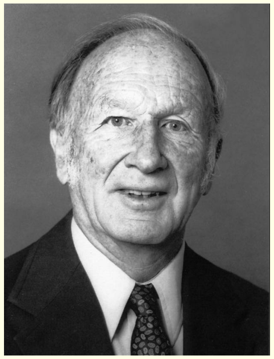
In his 1963 paper he wrote:

"... one flap of a sea-gull's wings may forever change the future course of the weather."

Within a few years, he had changed species:

"Predictability:
does the flap of a butterfly's wings in Brazil set off a tornado in Texas?"

[Title of a lecture at an AAAS conference in Washington.]

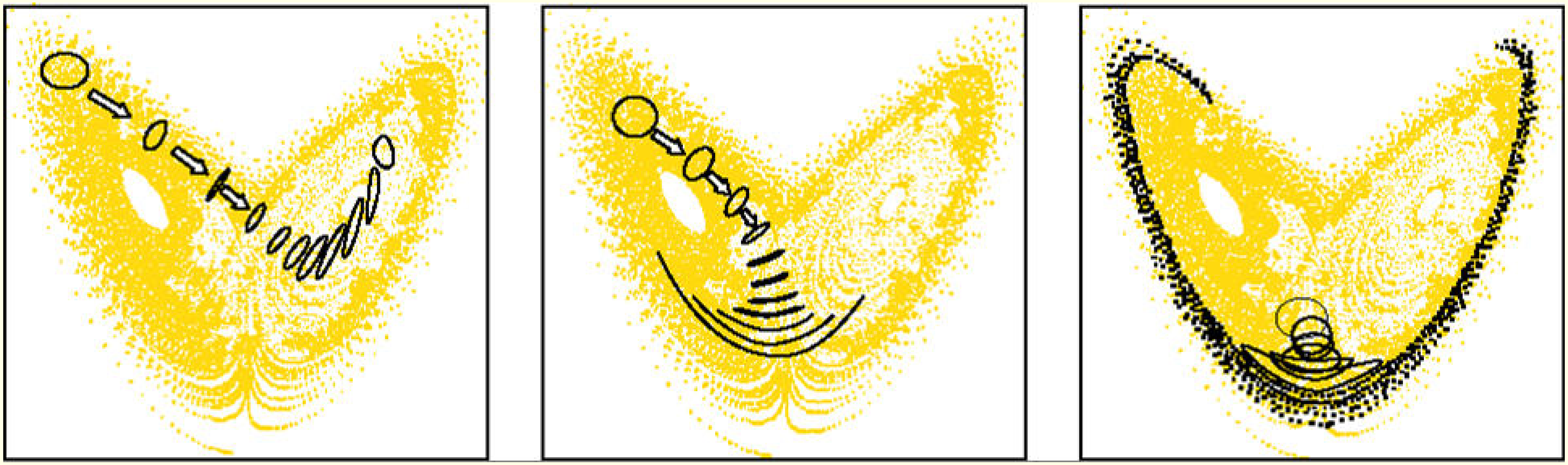


Lorenz demonstrated, with skill,
The chaos of heat-wave and chill:
Tornadoes in Texas
Are formed by the flexes
Of butterflies' wings in Brazil.

Flow-dependent Predictability

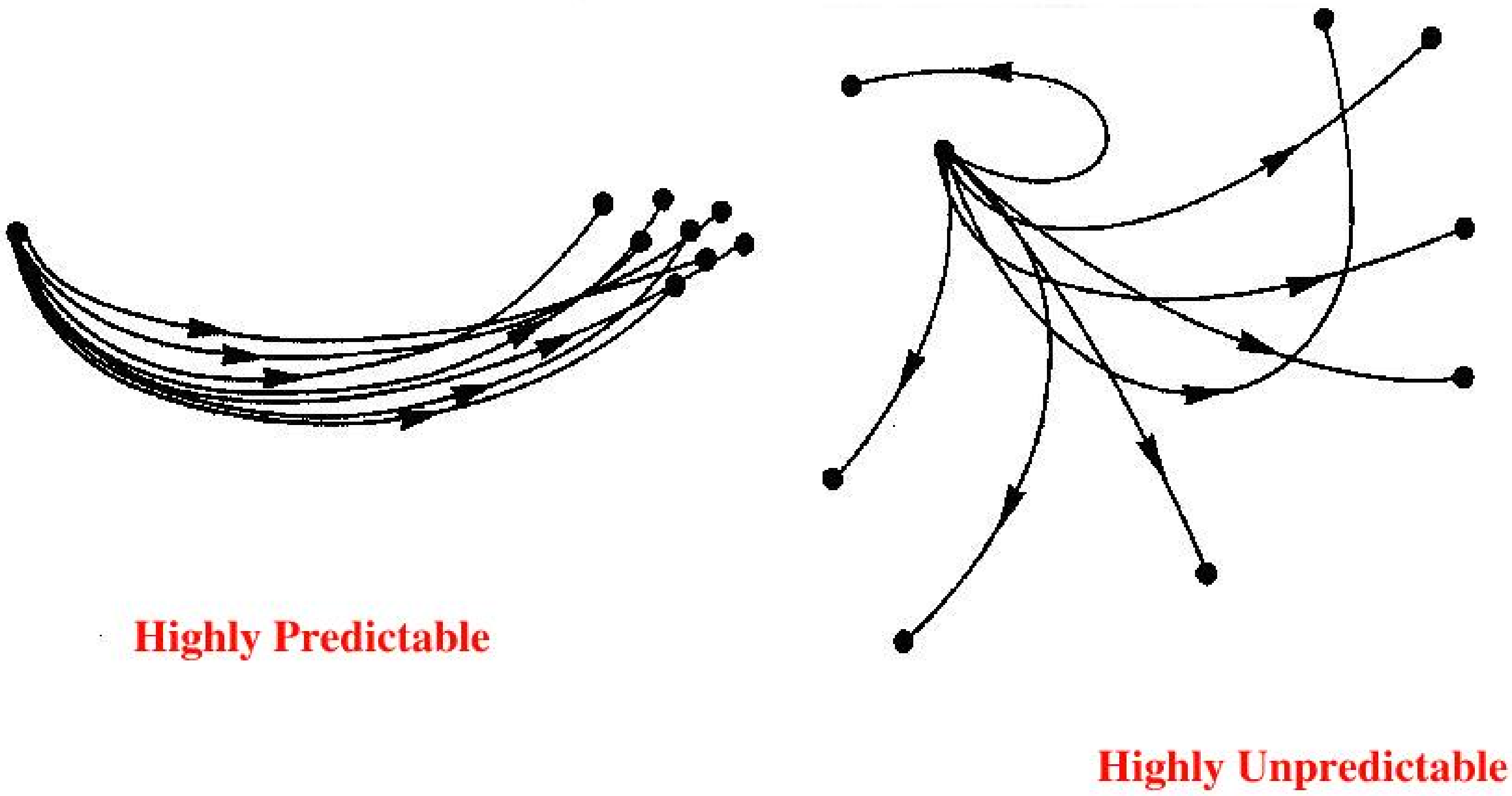
Weather forecasts lose skill because of the growth of errors in the initial conditions (initial uncertainties) and because numerical models describe the atmosphere only approximately (model uncertainties).

As a further complication, predictability is flow-dependent.

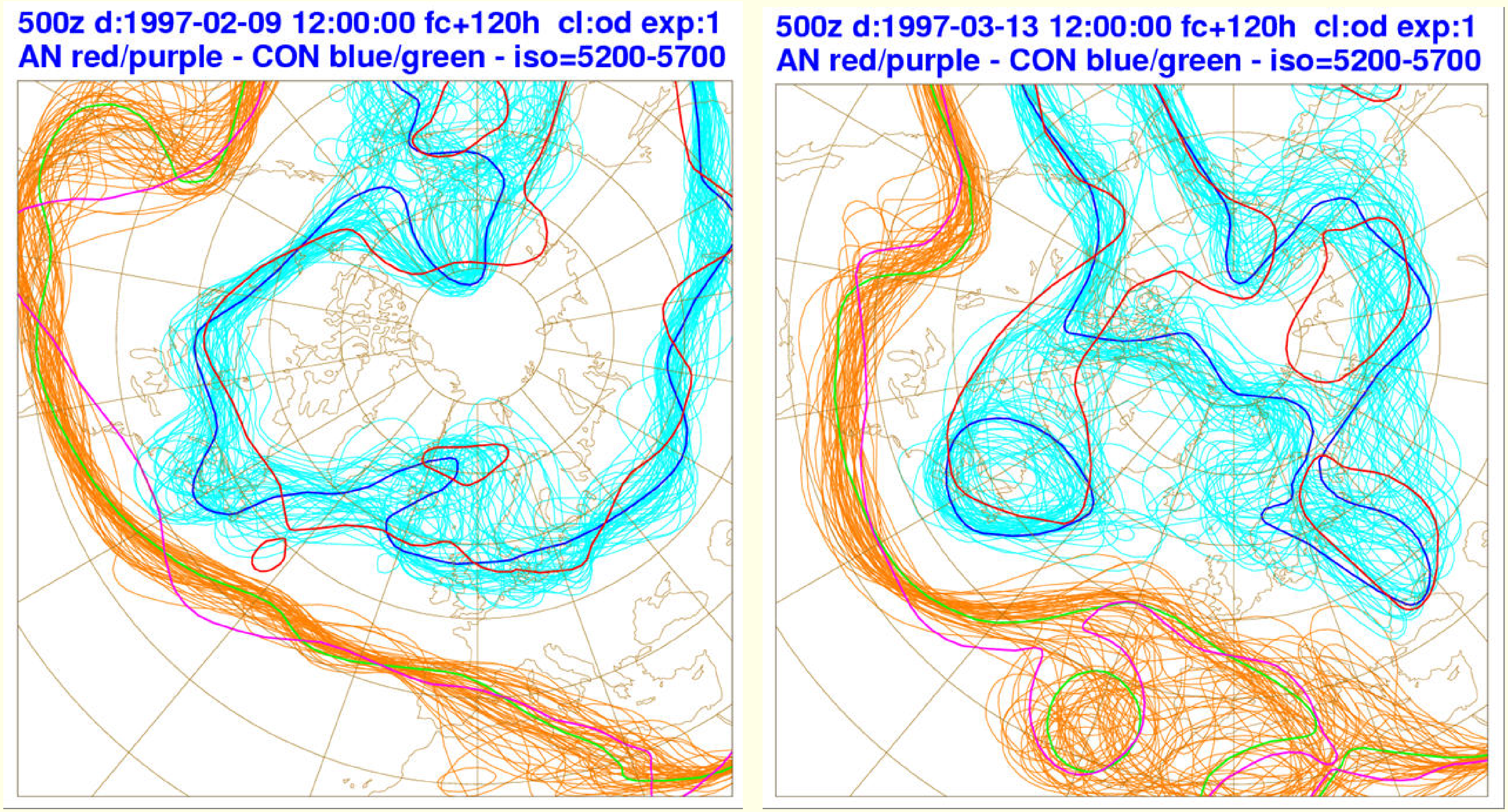


The Lorenz model illustrates variations in predictability for different initial conditions.

Variation in Predictability



Ensemble remains compact **Ensemble spreads out**



Spaghetti plots for ensembles from two starting times.

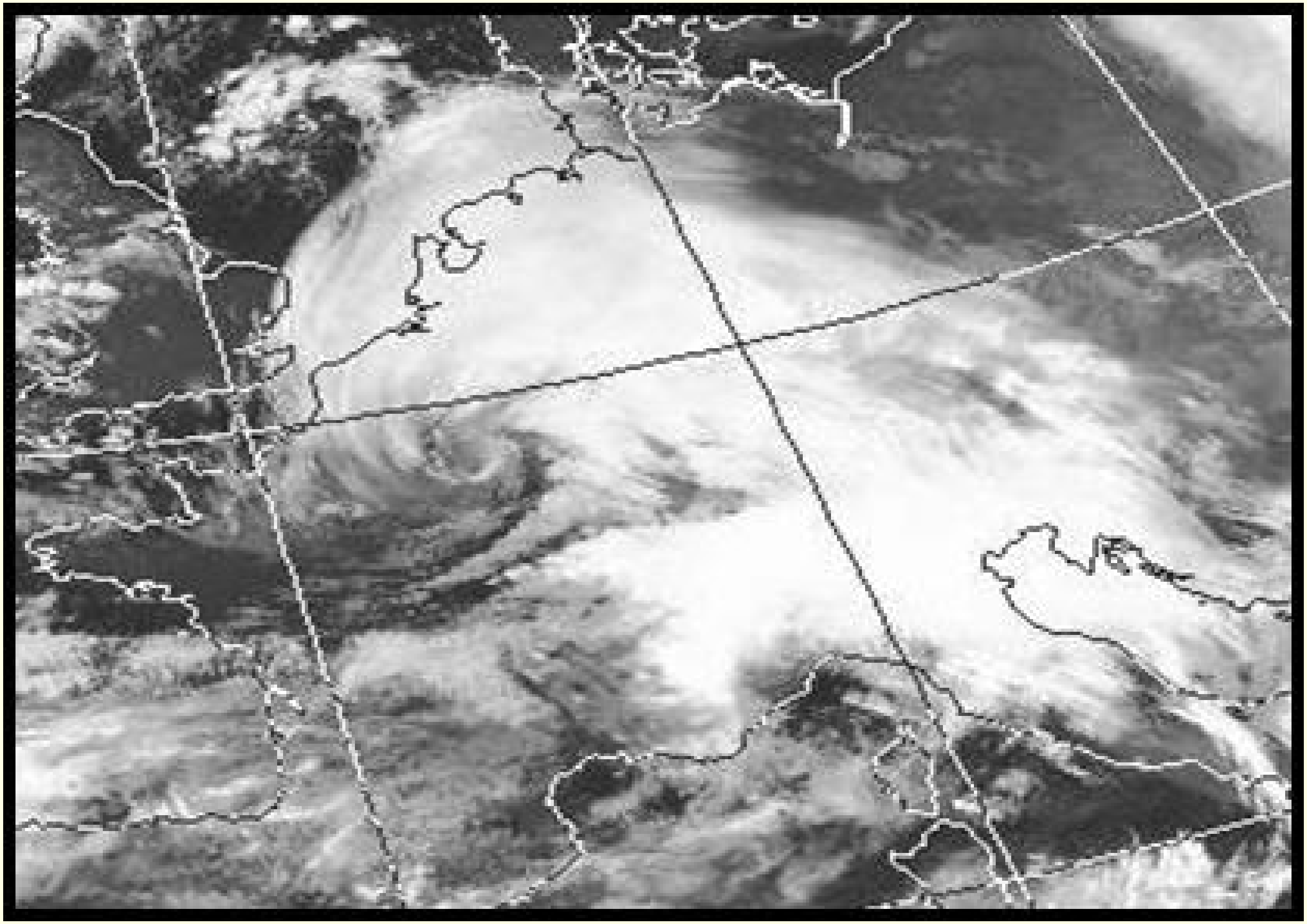
Ensemble Forecasting

In recognition of the chaotic nature of the atmosphere, focus has now shifted to predicting the probability of alternative weather events rather than a single outcome.

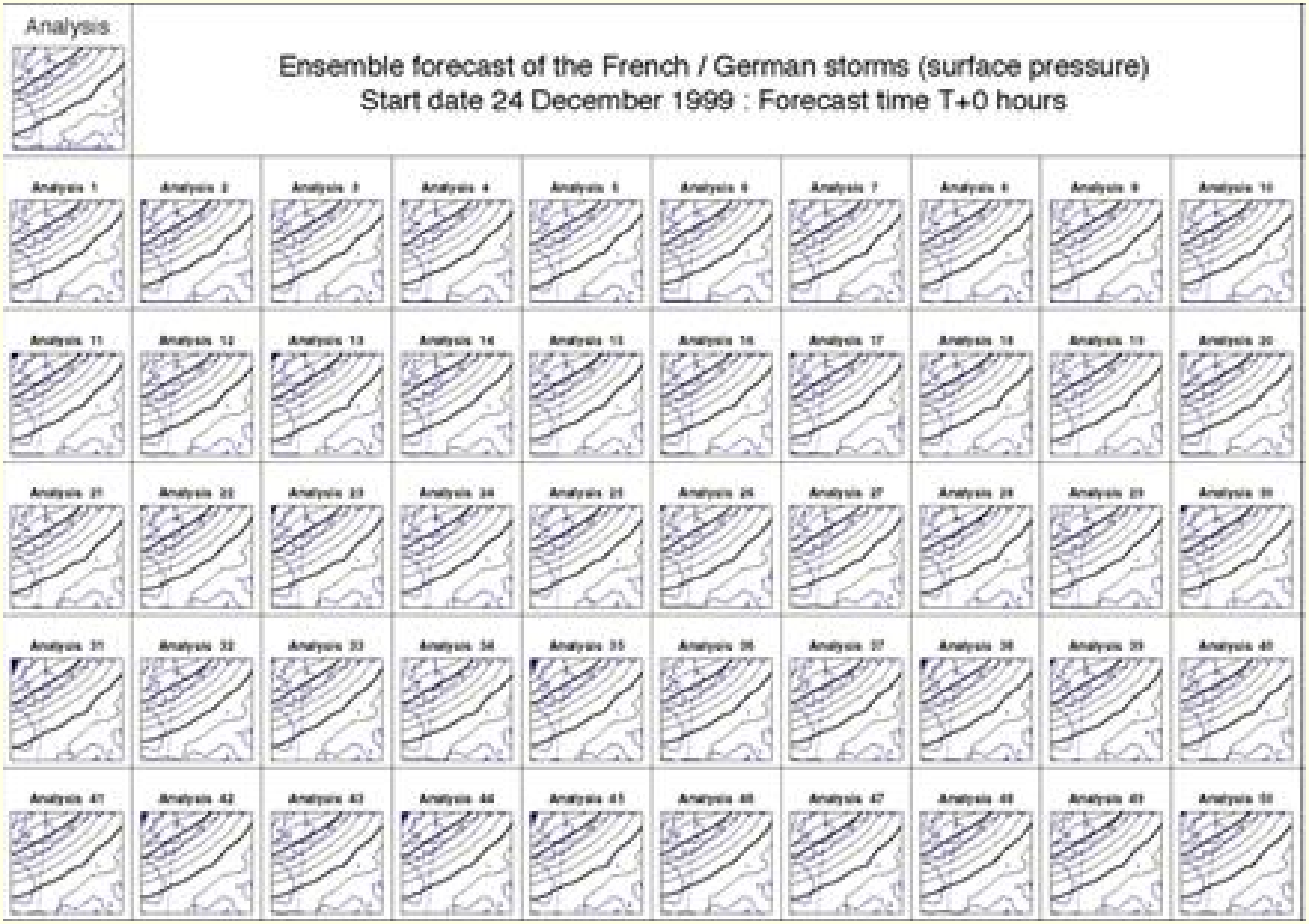
European Centre for Medium range Forecasts. Reading Headquarters.

The mechanism is the *Ensemble Prediction System* (EPS) and the world leader in this area is the European Centre for Medium-range Weather Forecasts (ECMWF).

The Storm of Christmas, 1999

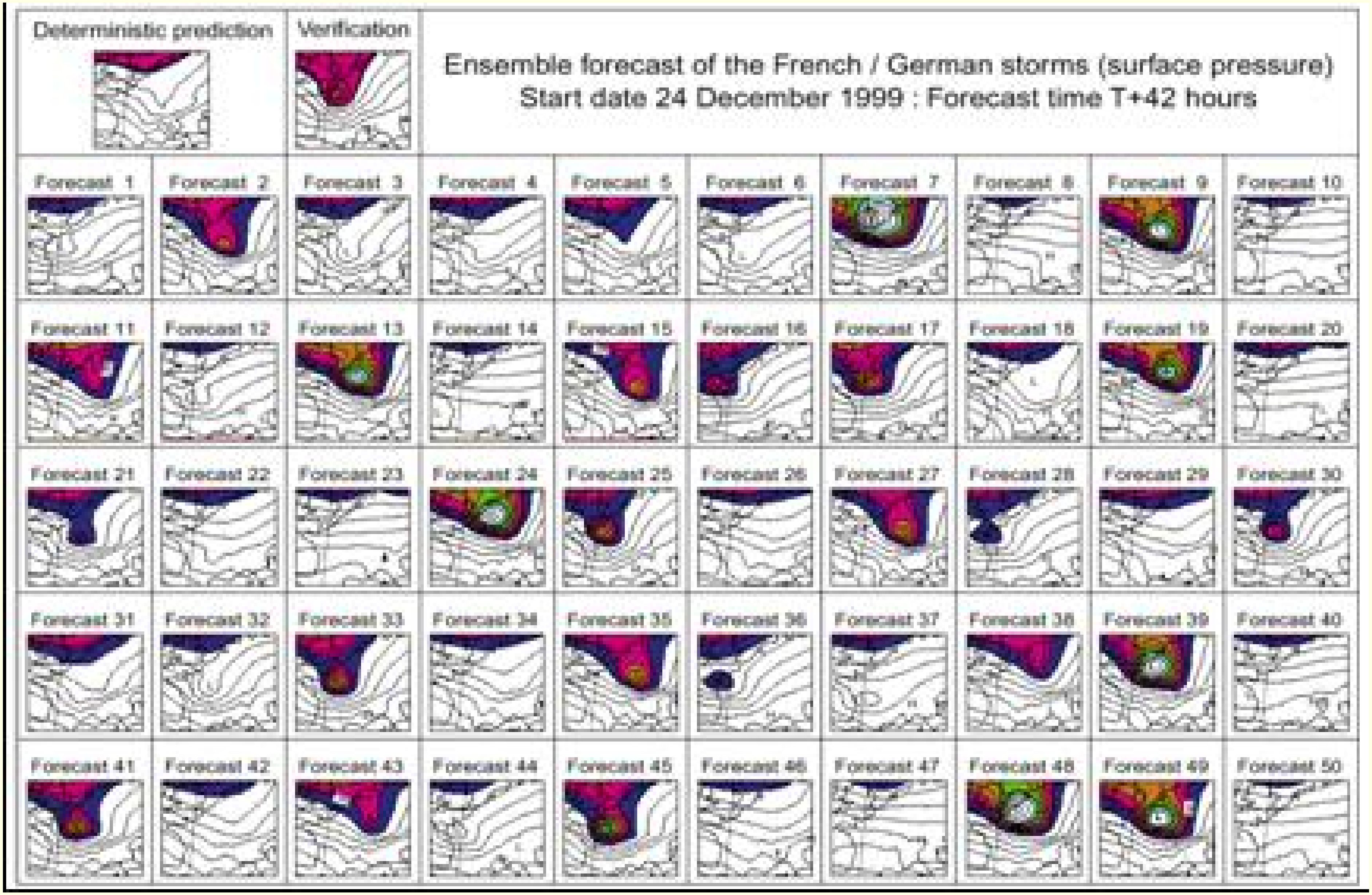


Lothar: 0800 UTC, 26 December, 1999



Ensemble of fifty perturbed initial states.

Initial time: 1200 UTC, 24th December, 1999



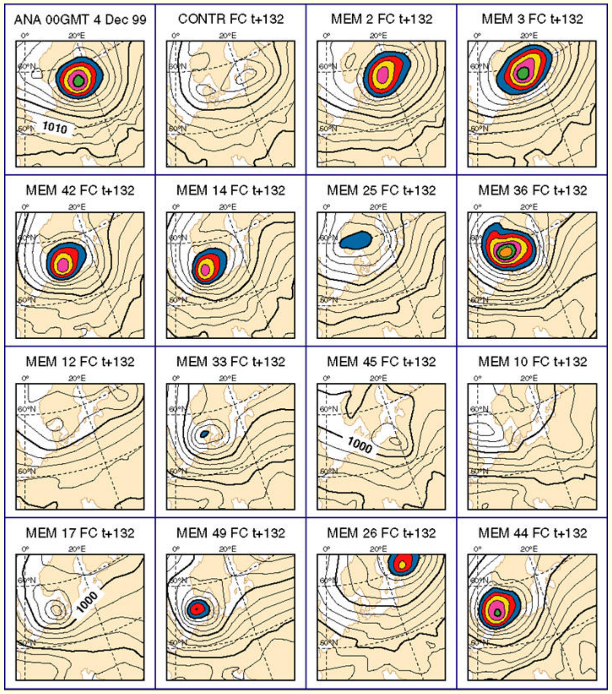
Ensemble of fifty 42-hour forecasts.

Valid time: 0600 UTC, 26th December, 1999

Overcoming Chaos

Ensemble prediction is our means of overcoming the obstacle of chaos in the atmosphere.

Analysis (top left), and 15 132-hour forecasts of sea-level pressure starting from slightly different conditions.

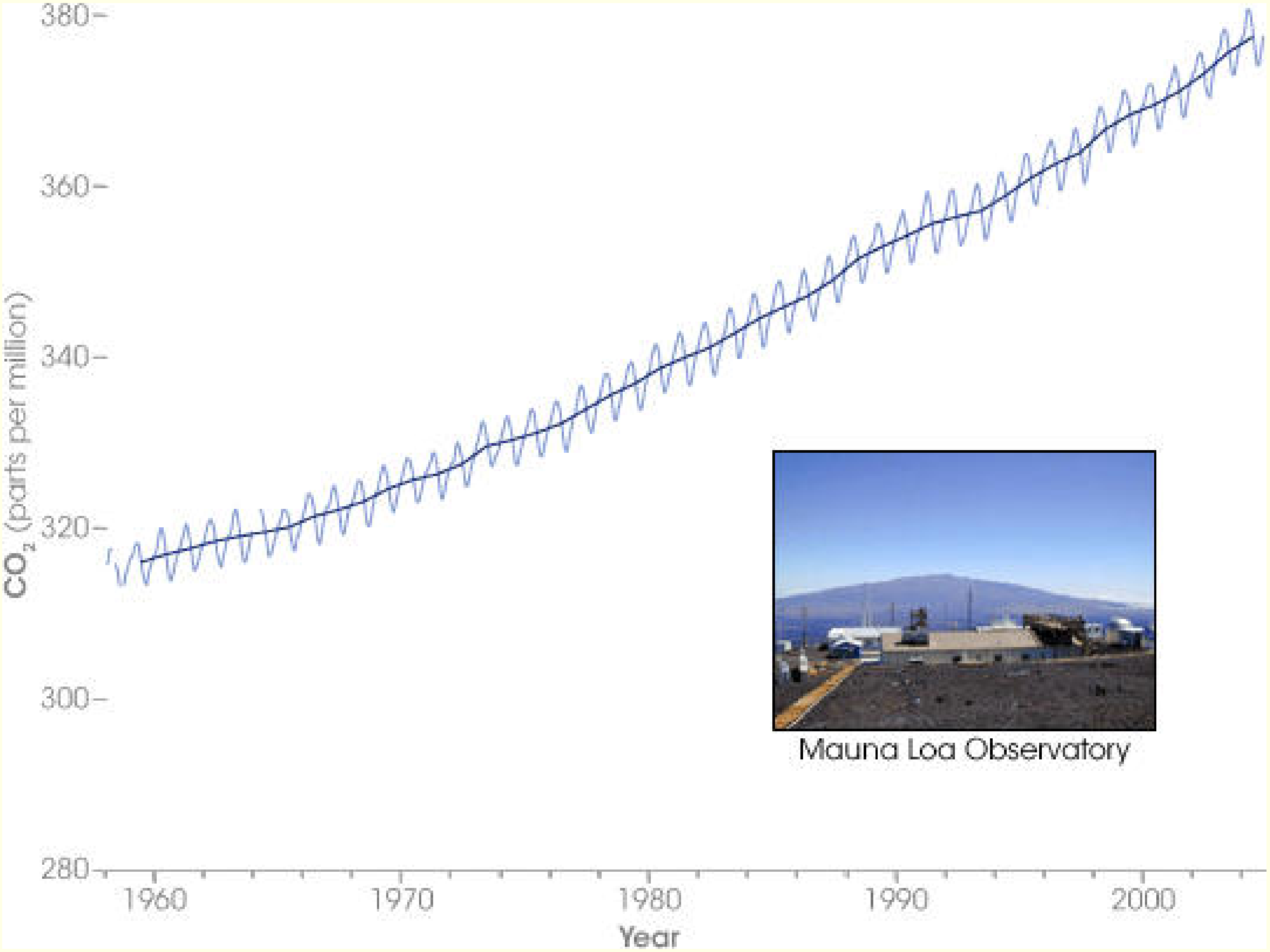


Deterministic forecasts

are replaced by

probability forecasts.

Climate Change: is it Real?



Concentration of CO_2 at Mauna Loa, 1958–2004

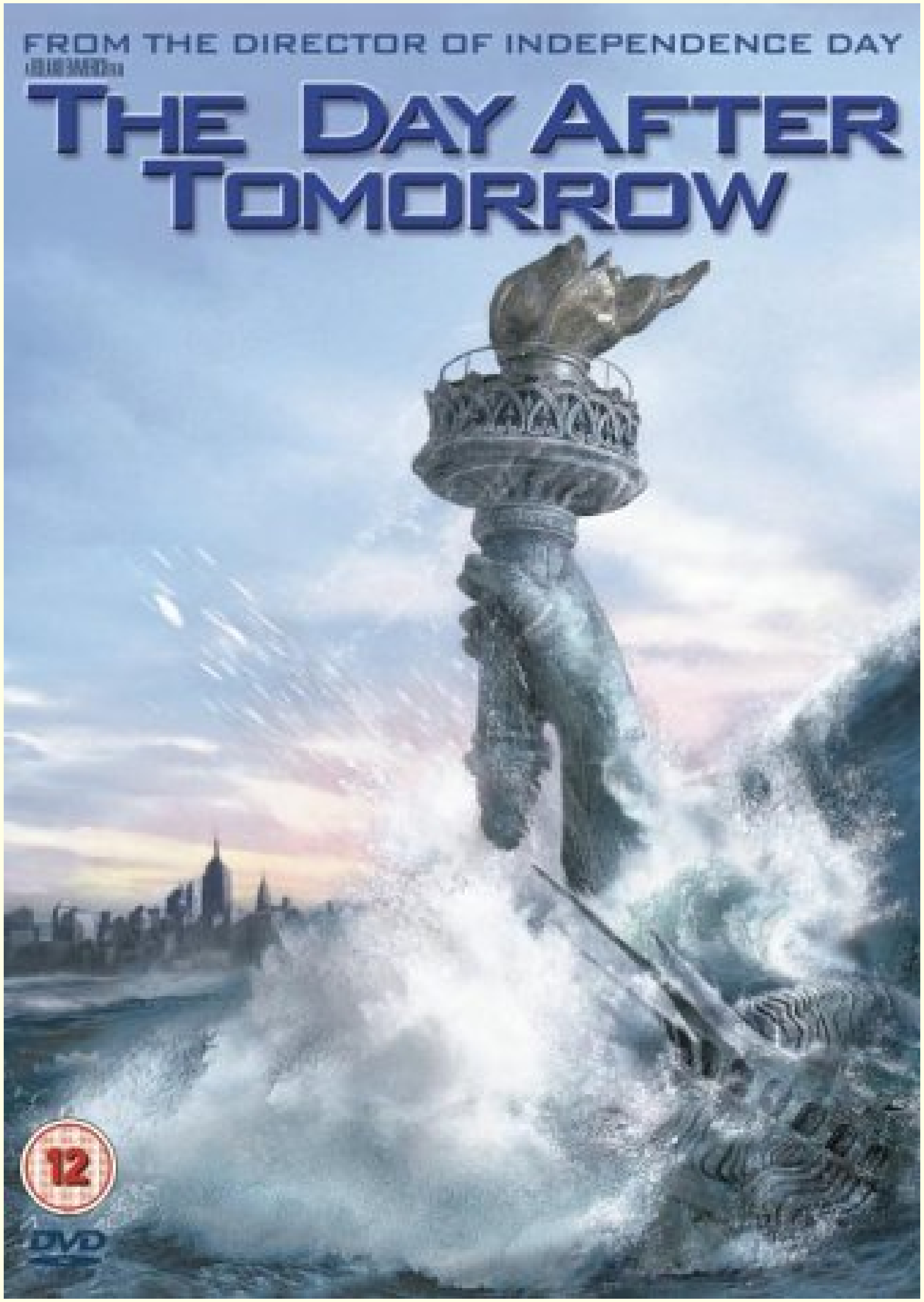

WHERE WILL YOU BE?
THE DAY AFTER TOMORROW
IN THEATRES WORLDWIDE MAY 28, 2004


THE DAY AFTER
TOMORROW
AVAILABLE ON DVD
OCTOBER 12, 2004

Fiction is *sometimes* stranger than fact . . .

. . . but fact *may* turn out to be stranger than fiction.

Climate change is a fact!



European Heatwave, Summer of 2003

The Summer of 2003 was the hottest Summer in 500 years.

There were more than 27,000 excess deaths due to the heat.

Was this merely a rare meteorological event or a first glimpse of climate change to come?

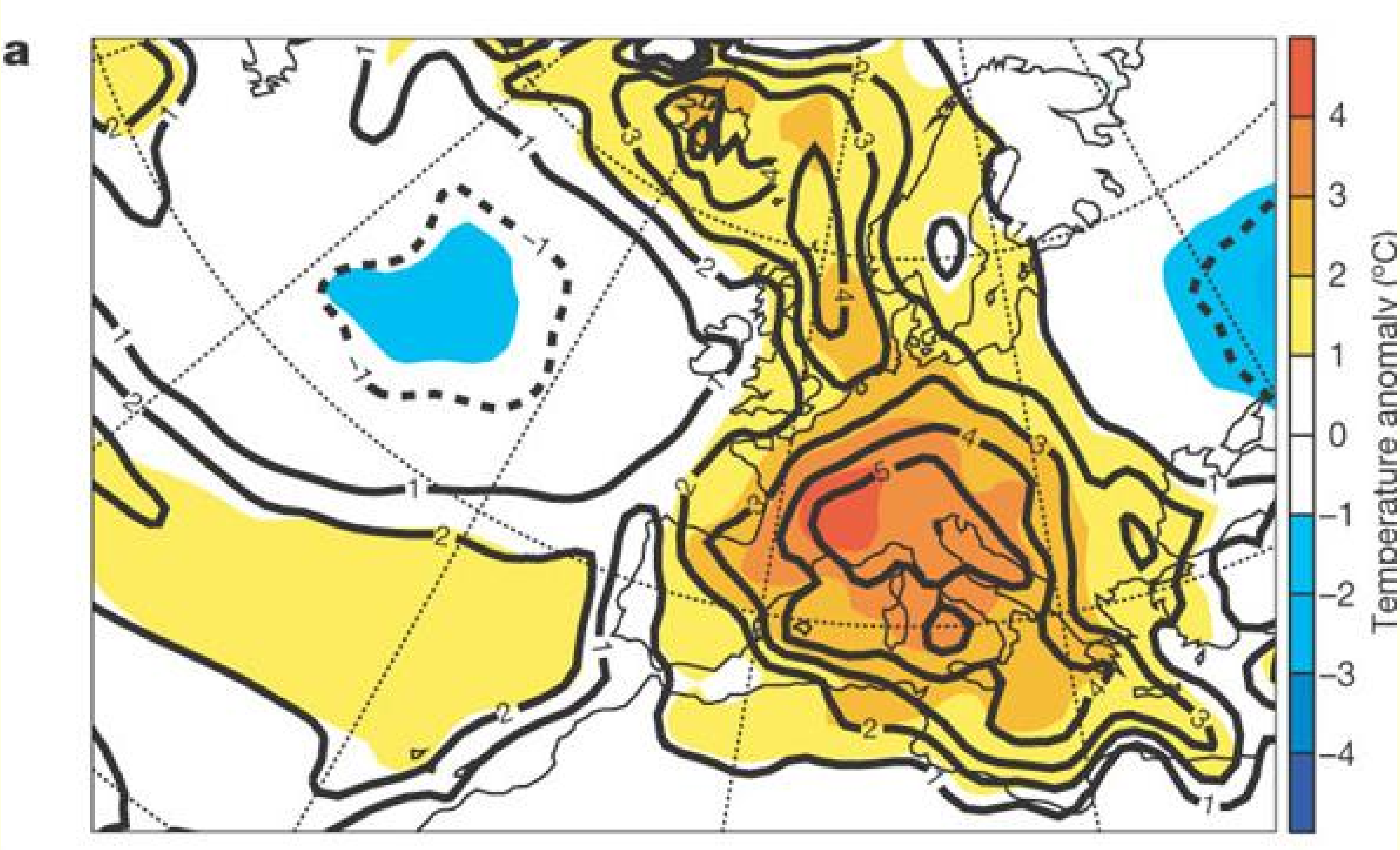
Probably both:

The summer has been simulated with and without the effect of mankind's activities.

Conclusion: It is very likely that greenhouse gases have increased the risk of such events.

Such heatwaves are now four times more likely, as a result of human influence on climate.

Temperature Anomaly, June–August, 2003

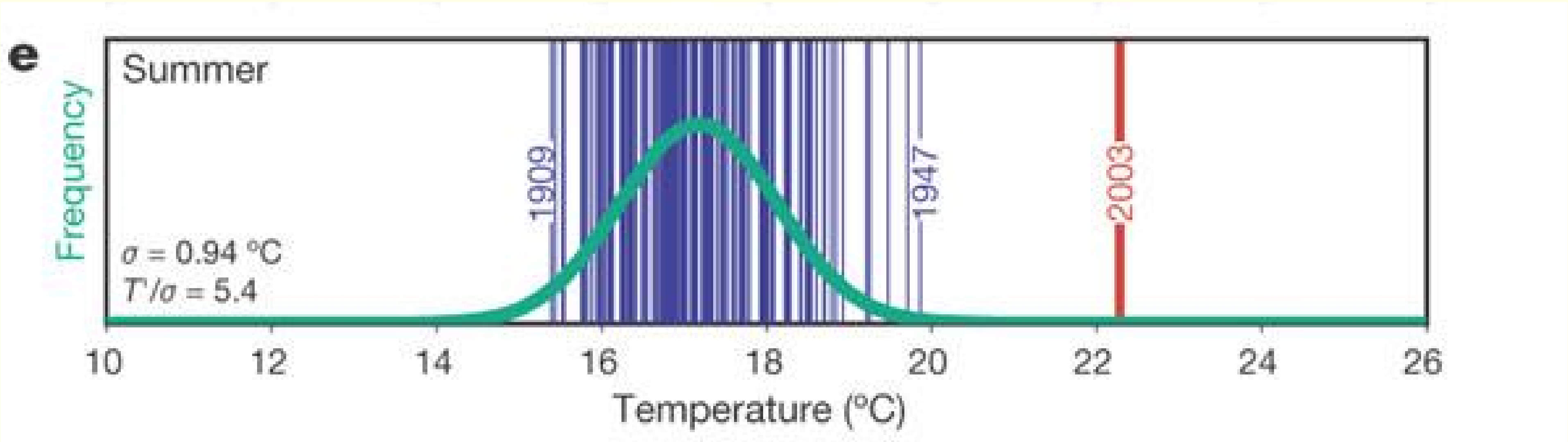


Colour: **Deviation of temperature from 1961–1990 mean.**

Contours: T' **normalized by standard deviation.**

Estimation of Return Period

Swiss temperature series, 1864–2003 (mean of 4 stations)



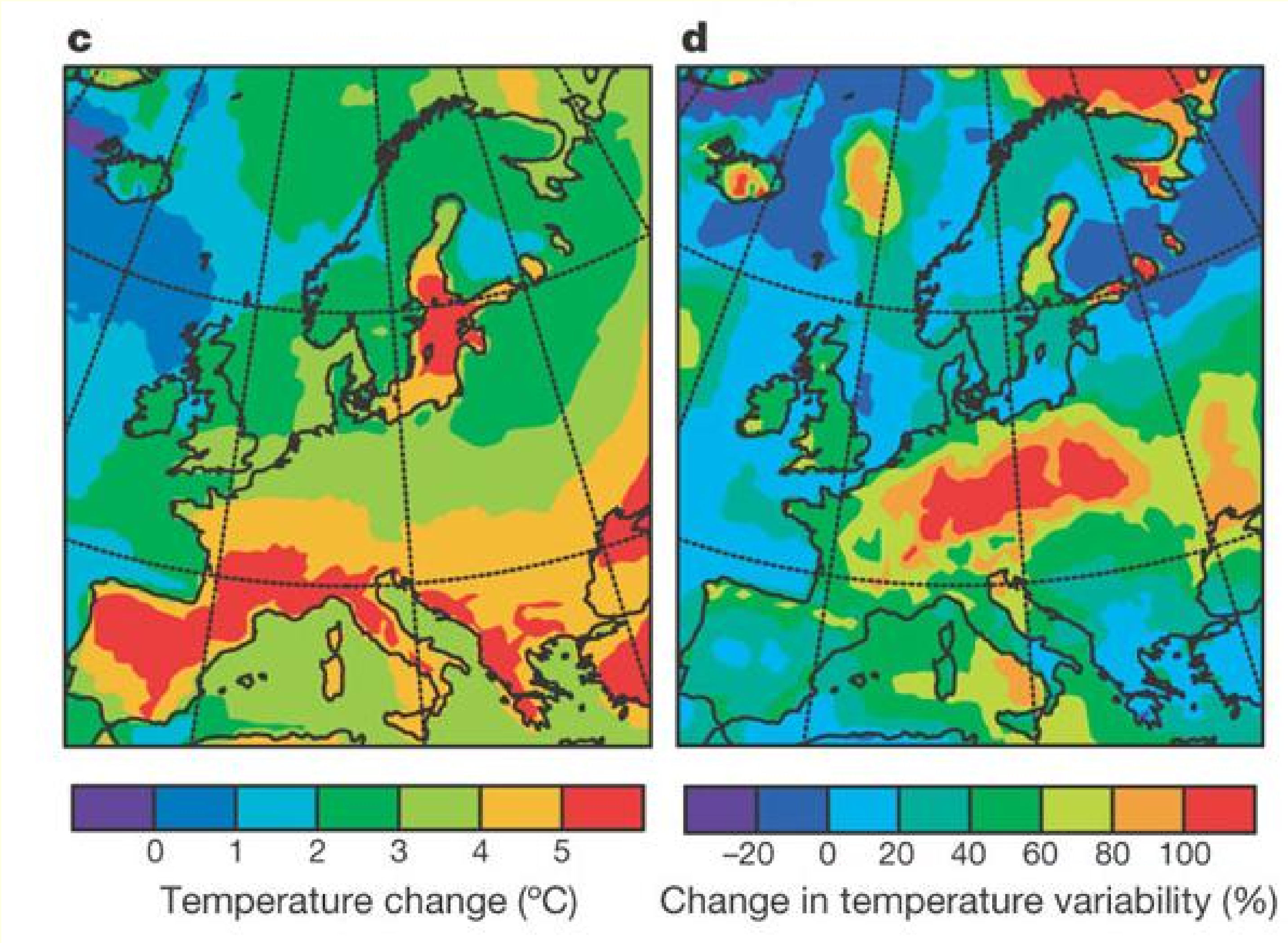
[Source: Schär, *et al.*, Nature, 427, Jan 22, 2004]

The 2003 heatwave was far outside the expected range;
it was an extremely rare event.

$$\sigma = 0.94\,\mathbf{K}$$

$$T_{2003}/\sigma = 5.4$$

Predicted Temperature Changes, 2070–2100

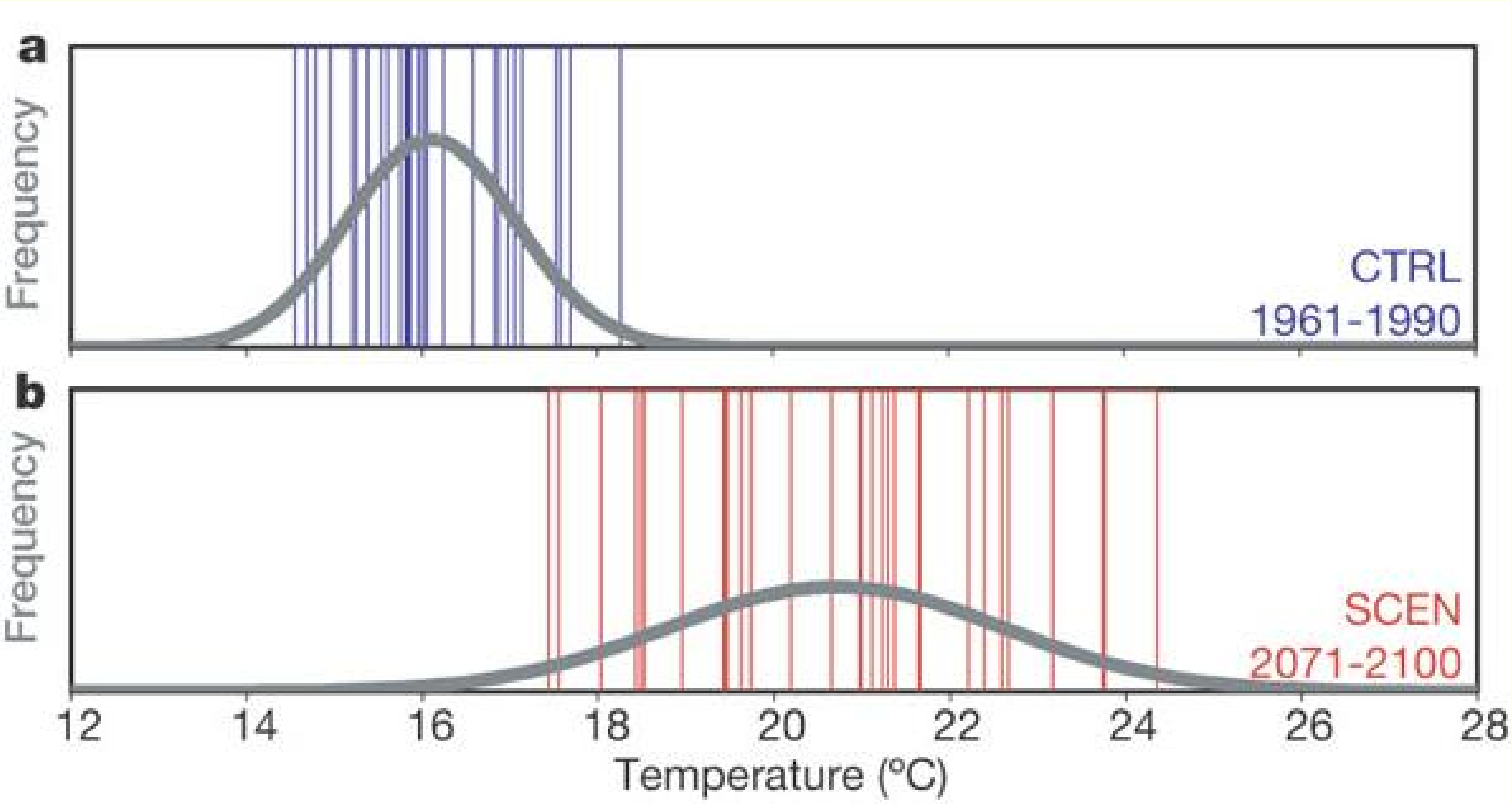


Results from an RCM climate change scenario

Past (1961–90) ***versus*** **future (2071–2100) conditions.**

Predicted Change in Distribution

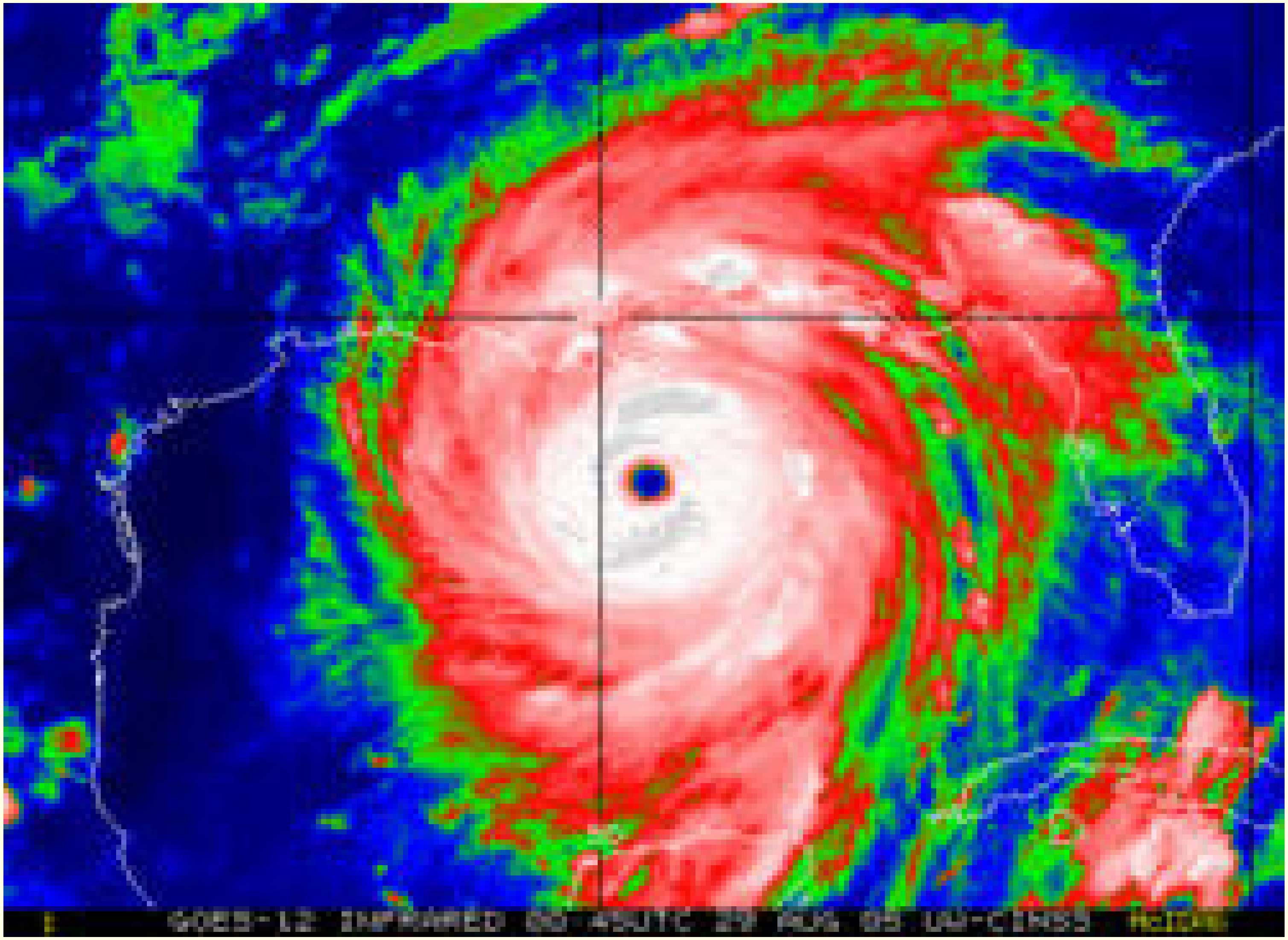
Both the mean and standard deviation will change.



Top: Distribution in past: $\bar{T} = 16.1°$**C,** $\sigma = 0.97°$**C**

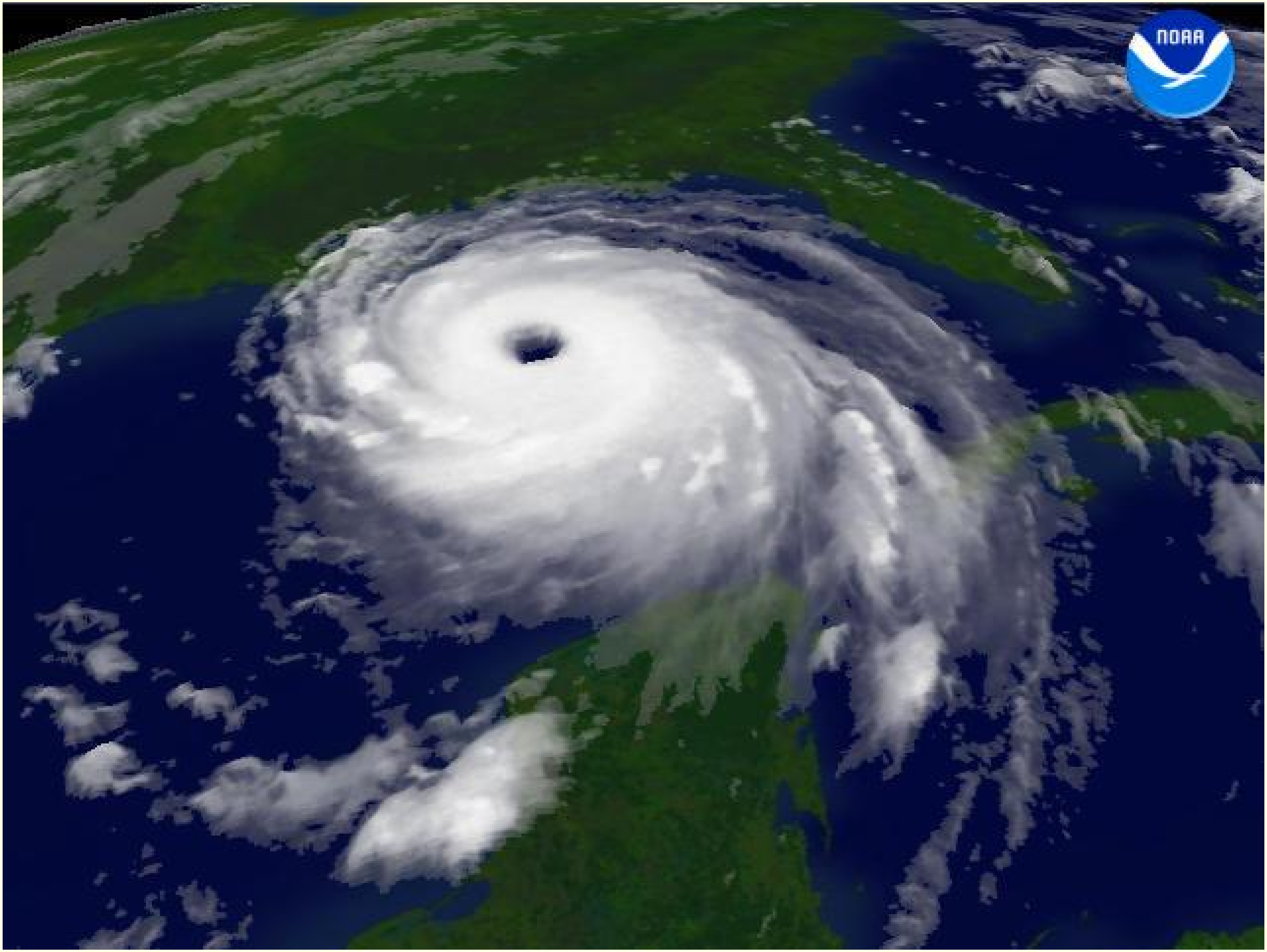
Bottom: Distribution in future: $\bar{T} = 20.7°$**C,** $\sigma = 1.84°$**C**

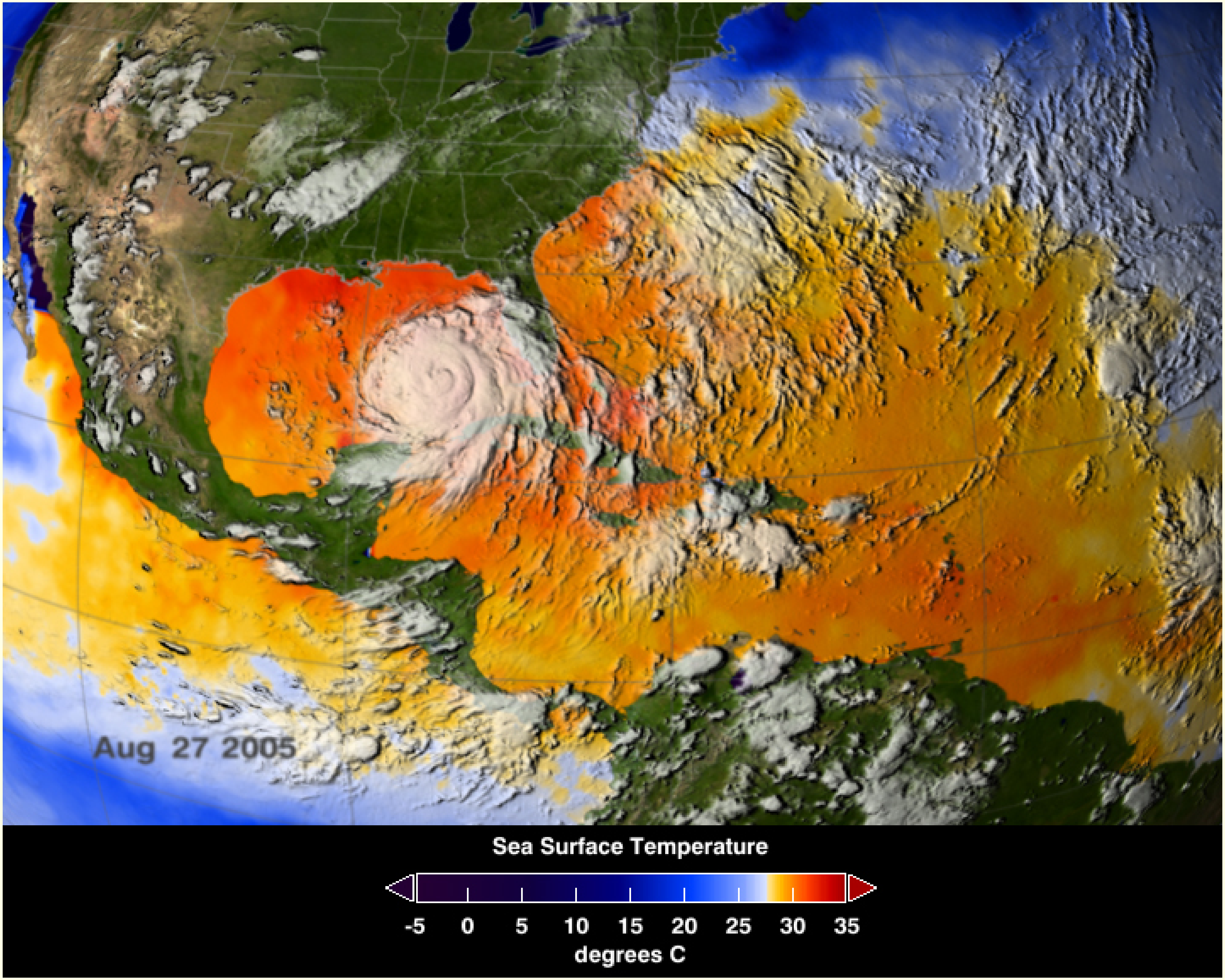
Hurricane Katrina, August, 2005

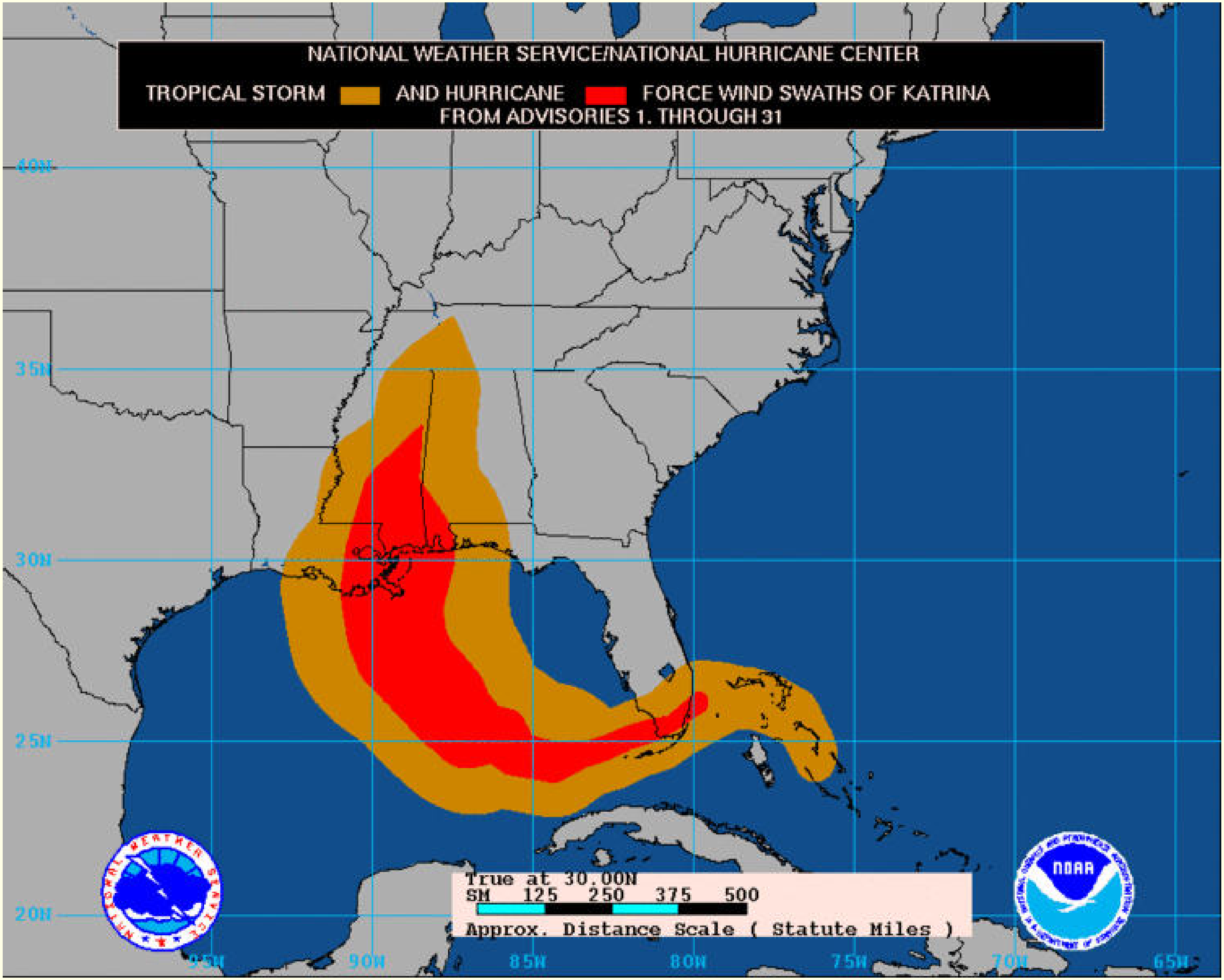


Hurricane Katrina

- *Sustained winds 175 mph*
- *Category 5 storm at maximum*
- *Category 4 on landfall*
- *150 miles wide: as big as Ireland*
- *10 metre storm surge*
- *Torrential rainfall.*

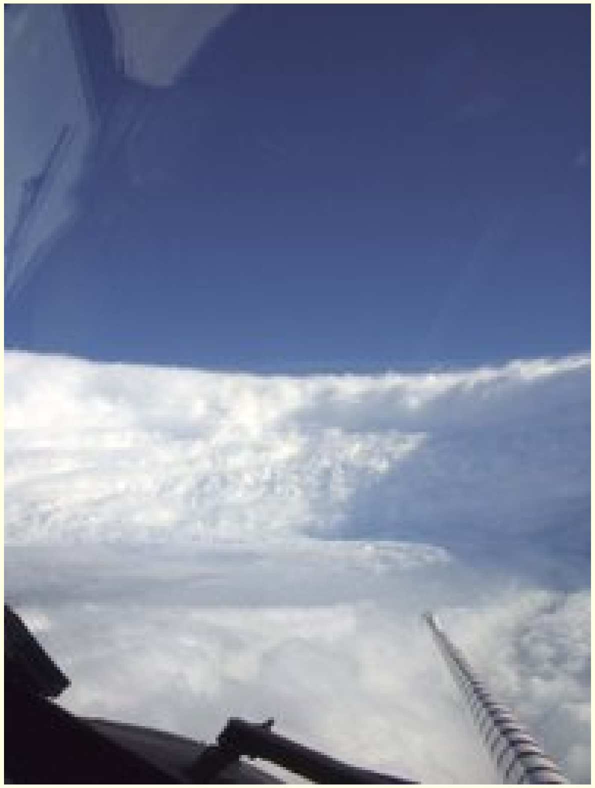

NOAA


Aug 27 2005
Sea Surface Temperature
-5 0 5 10 15 20 25 30 35
degrees C


NATIONAL WEATHER SERVICE/NATIONAL HURRICANE CENTER
TROPICAL STORM AND HURRICANE FORCE WIND SWATHS OF KATRINA
FROM ADVISORIES 1. THROUGH 31
40N
35N
30N
25N
20N
95W
90W
85W
80W
75W
70W
65W
True at 30.00N
SM 125 250 375 500
Approx. Distance Scale (Statute Miles)


IN1TF
PETZL

Someone to watch over you . . .



Never fear: George W Bush keeping his eye on the storm.

Katrina's Impacts

- ***Fatalities: ∼300 direct; ∼600 total***
- ***Hundreds of thousands homeless***
- ***Serious public health concerns***
- ***Insured damage: $25–30 billion***
- ***Total damage: ∼$200 billion***

Equivalent to $50,000 for every man, woman and child in Ireland

- ***Major political implications . . .***

Perhaps the Bush Administration will now take Climate Change more seriously!

Katrina and Global Warming

Was Hurricane Katrina caused by climate change?

We cannot be sure, but probably not. Storms like this have occurred before.

However, violent hurricanes will become more common in a warmer world.

- ***Higher temperatures*** $\Longrightarrow$
- ***Warmer oceans*** $\Longrightarrow$
- ***More moisture and energy*** $\Longrightarrow$
- ***Larger, fiercer storms.***

Future Shock

Hollywood brought you
The Day After Tomorrow

We now present
The Year After Next, by Jove!

The Year After Next, by Jove

The Great Red Spot is
a circulation system
in the Jovian atmosphere.

It is a storm that has been
raging for centuries.

Could such a semi-permanent storm occur in our atmosphere?

- ***Nonlinear systems undergo bifurcations. That is, qualitative behaviour changes occur when conditions are changed***
- ***Example: Hurricanes require SST*** $> 26^\circ$
- ***If SST were everywhere below*** 26°***C,*** ***we would not know about hurricanes***
- ***A qualitative regime change cannot be ruled out. Atmospheric systems we have yet to dream of may be possible***
- ***There is an unquantifiable risk of dramatic change if we continue to pollute the atmosphere.***

Concluding Remarks

- *Weather Prediction is now based on solid scientific foundations*
- *Forecast skill is increasing by one day per decade*
- *Predictability horizon is overcome by means of probability forecasts*
- *Climate models give useful guidance on a decadal time range*
- *There remains much to do, especially on smaller space and time scales.*

The End

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