Weather Forecasting:
From Woolly Art to Solid Science

Peter Lynch

Met Éireann

Dublin

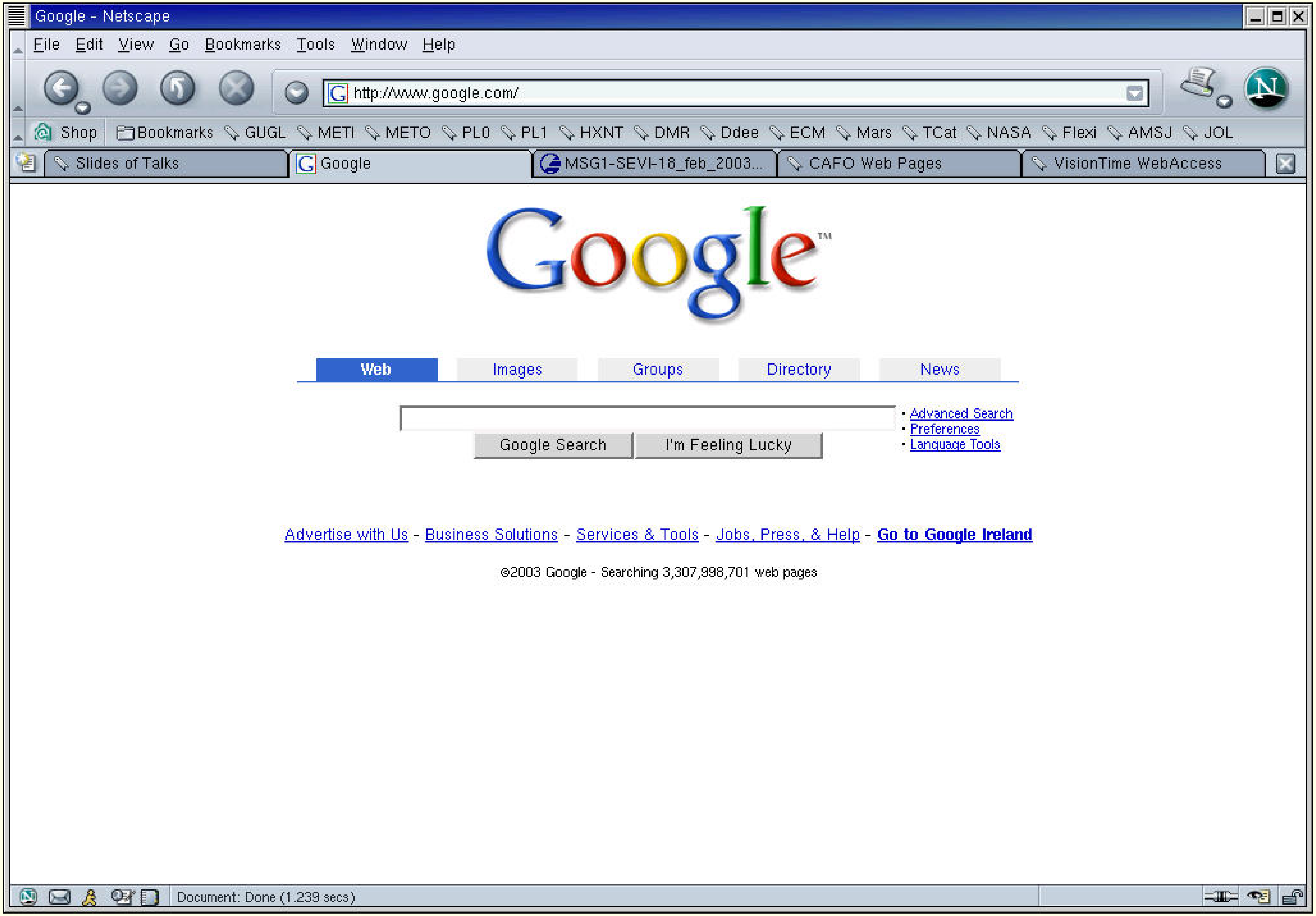
Peter.Lynch@met.ie

Talk to the
Irish Meteorological Society

Acknowledgements

Thanks to

- Irish Meteorological Society (for invitation)
- My Friends and Colleagues in Met Éireann
- Scientific Collaborators in Ireland and Abroad
- Brendan McWilliams, for the plug in IT
- Many anonymous and unwitting sources of information and graphics, most especially . . .


Google - Netscape
File Edit View Go Bookmarks Tools Window Help
http://www.google.com/
Shop Bookmarks GUGL METI METO PL0 PL1 HXNT DMR Ddee ECM Mars TCat NASA Flexi AMSJ JOL
Slides of Talks
Google
MSG1-SEVI-18_feb_2003...
CAFO Web Pages
VisionTime WebAccess
Google
Web
Images
Groups
Directory
News
Advanced Search
Preferences
Language Tools
Google Search
I'm Feeling Lucky
Advertise with Us - Business Solutions - Services & Tools - Jobs, Press, & Help - Go to Google Ireland
©2003 Google - Searching 3,307,998,701 web pages
Document: Done (1.239 secs)

The Information Explosion

Where is the wisdom we have lost in knowledge?
Where is the knowledge we have lost in information?

T. S. Eliot (1888-1976)

The Information Explosion

Where is the wisdom we have lost in knowledge?
Where is the knowledge we have lost in information?

T. S. Eliot (1888-1976)

We must seek the path from information to knowledge!
We must seek the path from knowledge to wisdom!

Guess Who? (2003)

Outline of Talk

- ***Development of Observational Meteorology from Ancient Times***

Outline of Talk

- ***Development of Observational Meteorology from Ancient Times***
- ***Development of Physical Theory***

Outline of Talk

- ***Development of Observational Meteorology from Ancient Times***
- ***Development of Physical Theory***
- ***The Pre-history of Numerical Weather Prediction (c. 1900)***

Outline of Talk

- *Development of Observational Meteorology from Ancient Times*
- *Development of Physical Theory*
- *The Pre-history of Numerical Weather Prediction (c. 1900)*
- *The ENIAC Integrations (c. 1950)*

Electronic Numerical Integrator And Computer

Outline of Talk

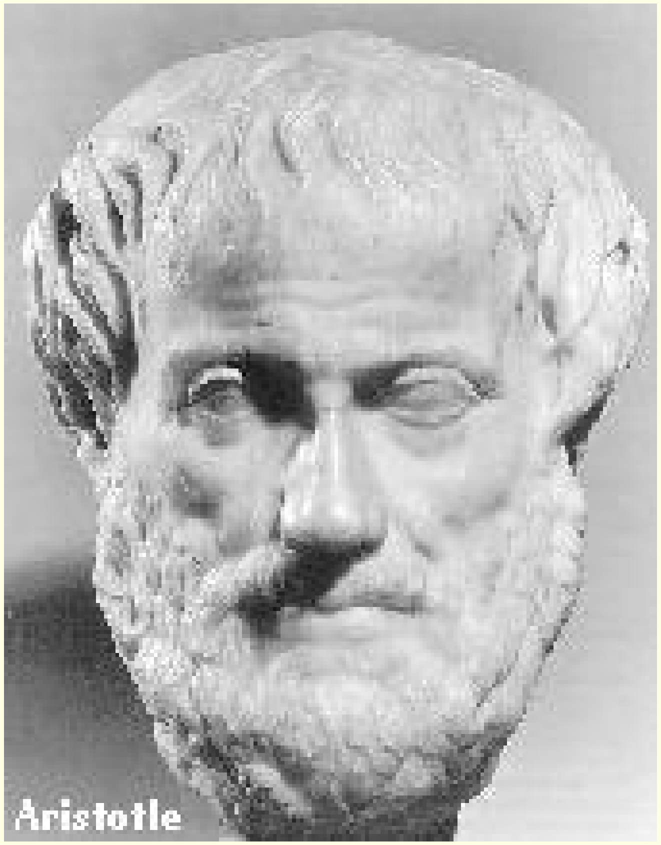
- *Development of Observational Meteorology from Ancient Times*
- *Development of Physical Theory*
- *The Pre-history of Numerical Weather Prediction (c. 1900)*
- *The ENIAC Integrations (c. 1950)*

  ***E**lectronic **N**umerical **I**ntegrator **A**nd **C**omputer*
- *Modern Computer-based Weather Forecasting (c. 2000)*

Observational Meteorology

from Ancient Times

Aristotle's *Meteorologia*



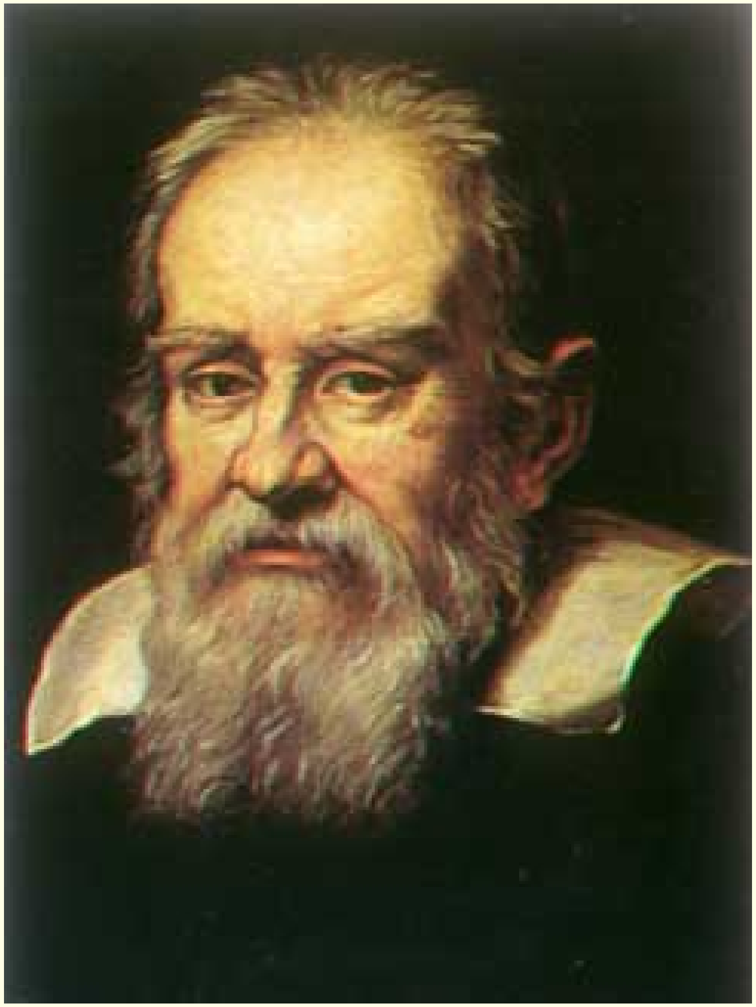
Aristotle (384-322 BC) was a past master at asking questions.

He wrote the first book on Meteorology, the $M\epsilon\tau\epsilon\omega\rho o\lambda o\gamma\iota\alpha$ **(**$\mu\epsilon\tau\epsilon\omega\rho o\nu$**: 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 in the Money

Galileo's Thermometer

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

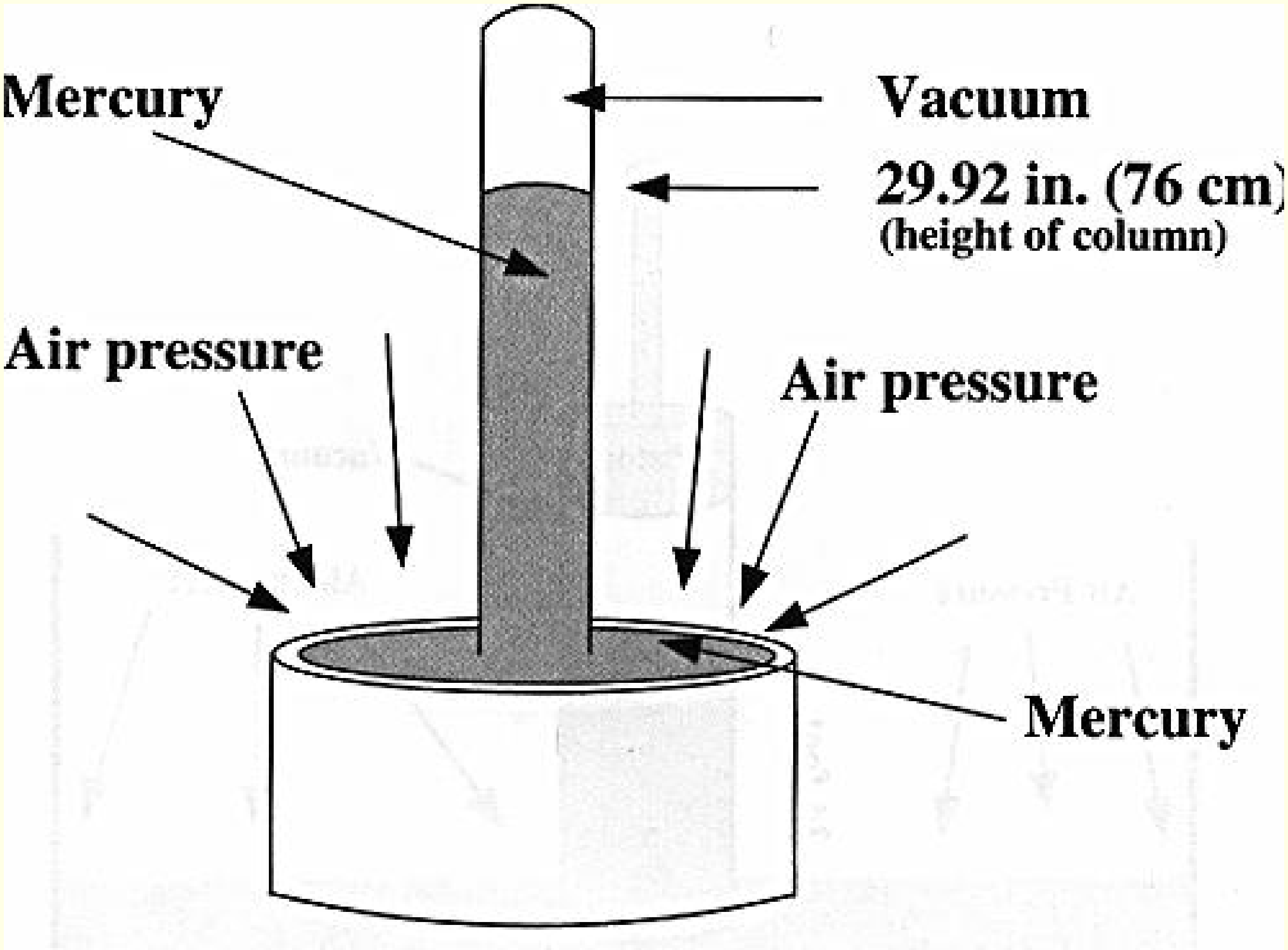
As temperature rises, the fluid expands and its density decreases.

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

Torricelli's Barometer

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

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.

Newton was arguably the greatest scientist the world has ever known.

Newton: the Inventor of Science

The Irish writer John Banville, in his work *The Newton Letters*, go so far as to write that 'Newton invented science'.

This is a debatable and thought-provoking claim.

There is a recent biography of Newton by James Gleick.

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.

Let m be the mass of the body and $\mathbf{V}$ its velocity. Then the momentum is $\mathbf{p} = m\mathbf{V}$.

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.

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

Edmund Halley (1656–1742)

- Edmund Halley attended Queen's College, Oxford.
- In 1683, he published his theory of the variation of the magnet.
- In 1684, he conferred with Newton about the inverse square low in the solar system.
- In 1686, he wrote on the trade winds and the monsoons.
- He undertook three voyages during 1698–1701, to test his magnetic variation theory.
- Then he became professor of Geometry at Oxford.
- At the age of 64, he invented the diving bell.
- Halley died in Greenwich in 1742.

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.

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.

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.

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.

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?

A Tricky Question

If the Astronomers can make accurate 76-year forecasts, why can't the Meteorologists do the same?

- **Size of the Problem**

  The solar system is discrete, with relatively few degrees of freedom; Dynamics is enough.

  The atmosphere is a continuum with (effectively) infinitely many variables; Thermodynamics is essential.

A Tricky Question

If the Astronomers can make accurate 76-year forecasts, why can't the Meteorologists do the same?

- <u>Size of the Problem</u>

  The solar system is discrete, with relatively few degrees of freedom; Dynamics is enough.

  The atmosphere is a continuum with (effectively) infinitely many variables; Thermodynamics is essential.

- <u>Order versus Chaos</u>

  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 on 15 April, 1707 in Basel. Died on 18 September, 1783 in St Petersburg.

Euler 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.

The Navier-Stokes Equations

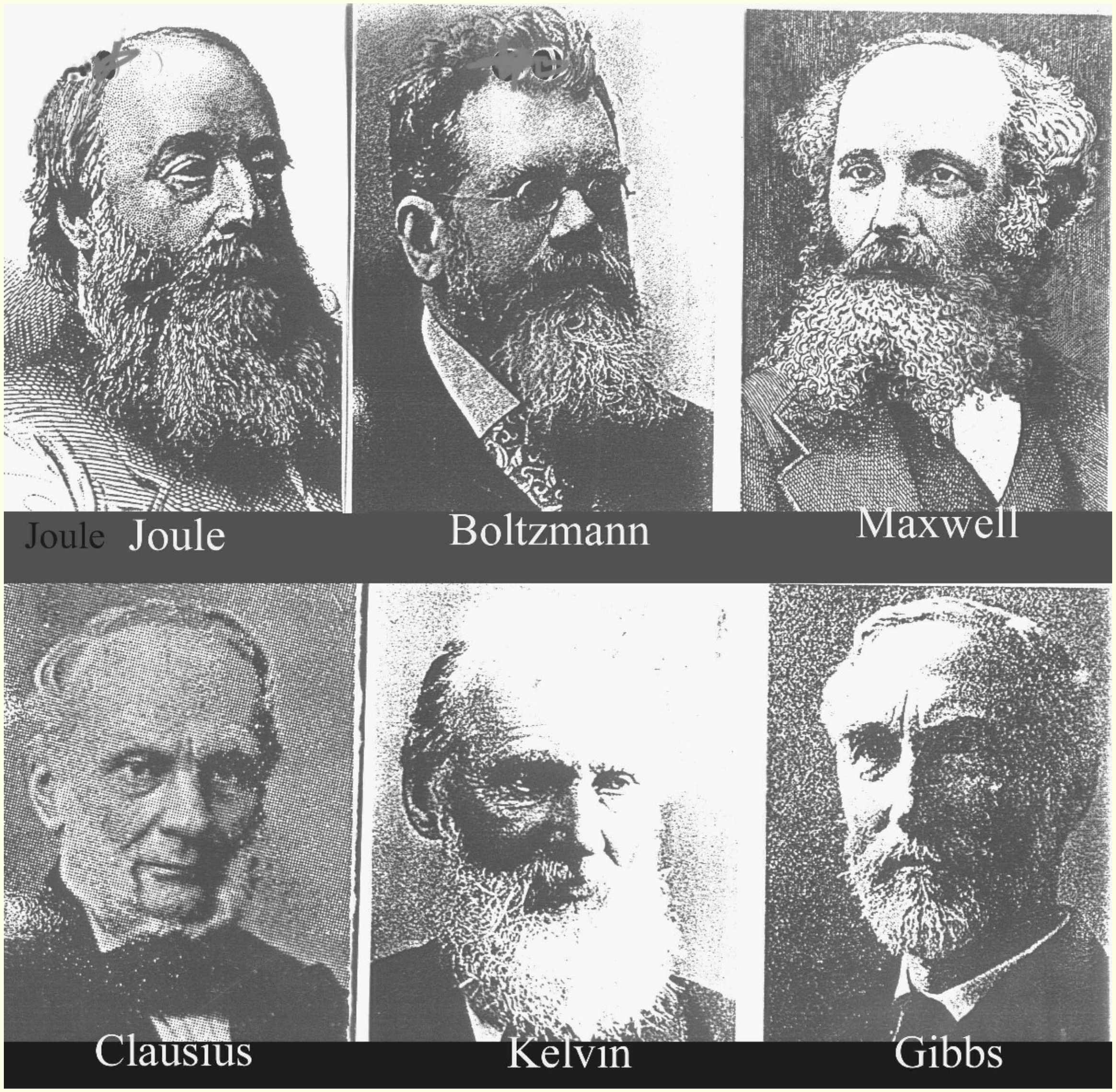
$$\frac{\partial \mathbf{V}}{\partial t} + \mathbf{V} \cdot \nabla \mathbf{V} + \frac{1}{\rho} \nabla p = \nu \nabla^2 \mathbf{V} + \mathbf{g}^\star \,.$$

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.

Physical Laws of the Atmosphere

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

Relates the pressure, temperature and density

Physical Laws 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

Physical Laws 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)

Physical Laws 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

Physical Laws 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.

Physical Laws 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**

Scientific Weather Forecasting in a Nut-Shell

- **The atmosphere is a physical system**
- **Its behaviour is governed by the laws of physics**

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**

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"**

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"**

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**

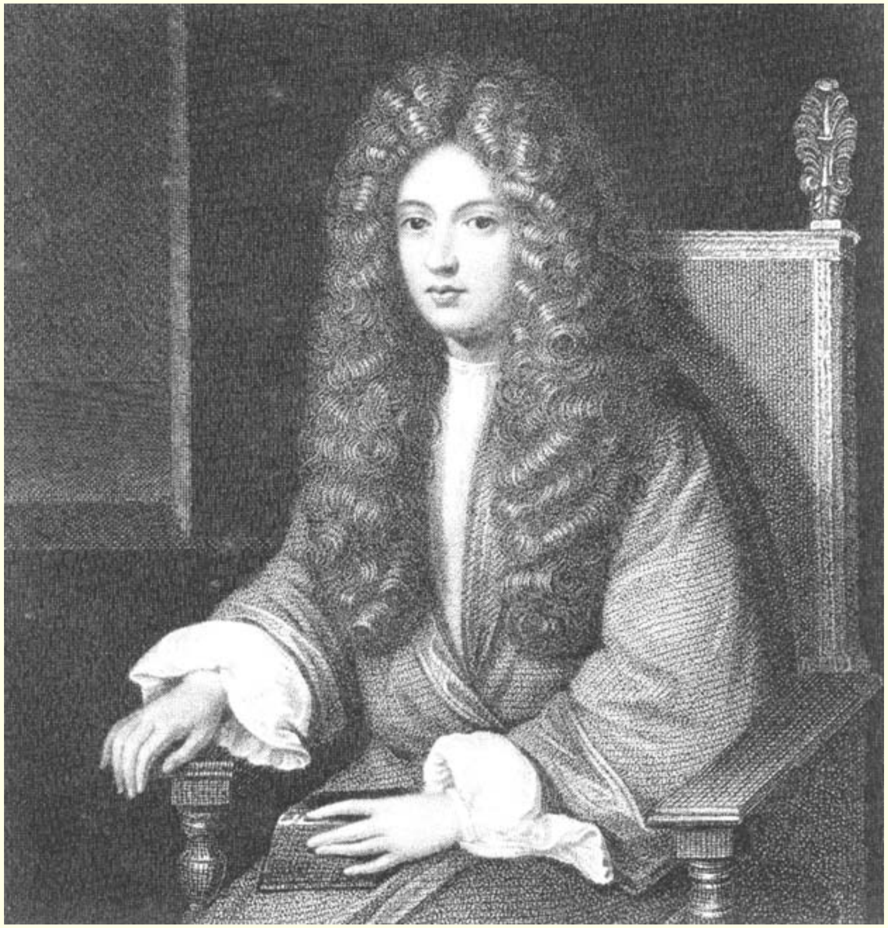
Scientific Weather Forecasting in a Nut-Shell

- **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)

One of the great scientists of the 19th century.

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.

The Tyndall Centre for Climate Change Research, recently established at the University of East Anglia in Norwich, is named in his honour.

See article on Tyndall in yesterday's Irish Times.

George G Stokes, 1819–1903

George Gabriel Stokes, founder of modern hydrodynamics.

Some Contributions of Stokes to Meteorological Science

- ***Stokes' Theorem***
- ***Stokes Drag and Stokes' Law***
- ***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.

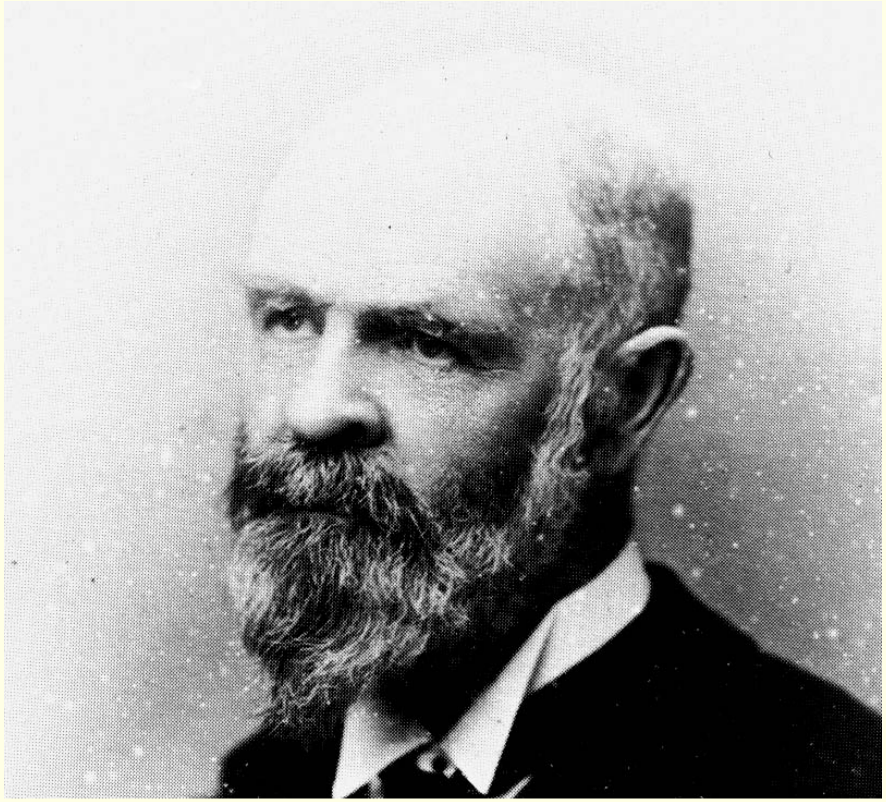
Among the most brilliant scientists of the 19th century.

Professor of Natural Philosophy in Glasgow, 1846 (aged 22) – 1899.

Developed the foundations of thermodynamics.

Introduced the absolute scale of temperature, with the zero at -273°.

Robert Henry Scott (1833–1916)



Robert Scott, born in Dublin, 1833.

Founder of Valentia Observatory

First Director of the British Meteorological Office.

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

All that is about to change!!!

Met Éireann-UCD Link

In October, Met Éireann and University College, Dublin signed an agreement to collaborate in establishing a Centre for Meteorology and Climatology at UCD.

Met Éireann-UCD Link

In October, Met Éireann and University College, Dublin signed an agreement to collaborate in establishing a Centre for Meteorology and Climatology at UCD.

- **The Centre will be based in the Department of Mathematical Physics in Belfield**

Met Éireann-UCD Link

In October, Met Éireann and University College, Dublin signed an agreement to collaborate in establishing a Centre for Meteorology and Climatology at UCD.

- **The Centre will be based in the Department of Mathematical Physics in Belfield**
- **A Professor and Lecturer will be appointed shortly**

Met Éireann-UCD Link

In October, Met Éireann and University College, Dublin signed an agreement to collaborate in establishing a Centre for Meteorology and Climatology at UCD.

- **The Centre will be based in the Department of Mathematical Physics in Belfield**
- **A Professor and Lecturer will be appointed shortly**
- **A Post-graduate course will commence in September, 2004**

Met Éireann-UCD Link

In October, Met Éireann and University College, Dublin signed an agreement to collaborate in establishing a Centre for Meteorology and Climatology at UCD.

- **The Centre will be based in the Department of Mathematical Physics in Belfield**
- **A Professor and Lecturer will be appointed shortly**
- **A Post-graduate course will commence in September, 2004**
- **Doctoral students will be employed to assist in a research programme**

Met Éireann-UCD Link

In October, Met Éireann and University College, Dublin signed an agreement to collaborate in establishing a Centre for Meteorology and Climatology at UCD.

- **The Centre will be based in the Department of Mathematical Physics in Belfield**
- **A Professor and Lecturer will be appointed shortly**
- **A Post-graduate course will commence in September, 2004**
- **Doctoral students will be employed to assist in a research programme**
- **An Undergraduate syllabus will be developed later.**

Met Éireann-UCD Link

In October, Met Éireann and University College, Dublin signed an agreement to collaborate in establishing a Centre for Meteorology and Climatology at UCD.

- **The Centre will be based in the Department of Mathematical Physics in Belfield**
- **A Professor and Lecturer will be appointed shortly**
- **A Post-graduate course will commence in September, 2004**
- **Doctoral students will be employed to assist in a research programme**
- **An Undergraduate syllabus will be developed later.**

Let's hope that, in future, our Stokes's and Kelvins may not have to leave Ireland to make their marks on meteorology.

The Pre-history of Numerical Weather Prediction (c. 1900)

Vilhelm Bjerknes and Lewis Fry Richardson

Vilhelm Bjerknes (1862–1951)

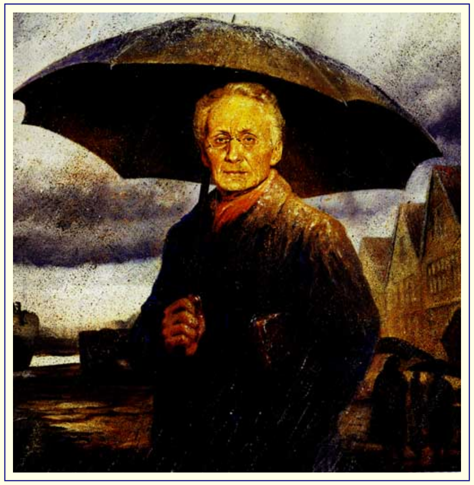
Vilhelm Bjerknes (1862–1951)

- **Born March, 1862.**
- **Matriculated in 1880.**
- **Fritjøf Nansen was a fellow-student.**
- **Paris, 1989–90. Studied under Poincare.**
- **Bonn, 1890–92. Worked with Heinrich Hertz.**
- **Stockholm, 1983–1907.**

– **1898: Circulation theorems**

  – **1904: Meteorological Manifesto**

- **Christiania (Oslo), 1907–1912.**
- **Leipzig, 1913–1917.**
- **Bergen, 1917–1926.**
  – **1919: Frontal Cyclone Model.**
- **Oslo, 1926 — (retired 1937).**
  - **Died, April 9,1951.**



Vilhelm Bjerknes

Bjerknes' 1904 Manifesto

To establish a science of meteorology, with the aim of predicting future states of the atmosphere from the present state.

"If it is true, as every scientist believes, that subsequent atmospheric states develop from the preceeding ones according to physical law, then it is apparent that the necessary and sufficient conditions for the rational solution of forecasting problems are the following:

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.**

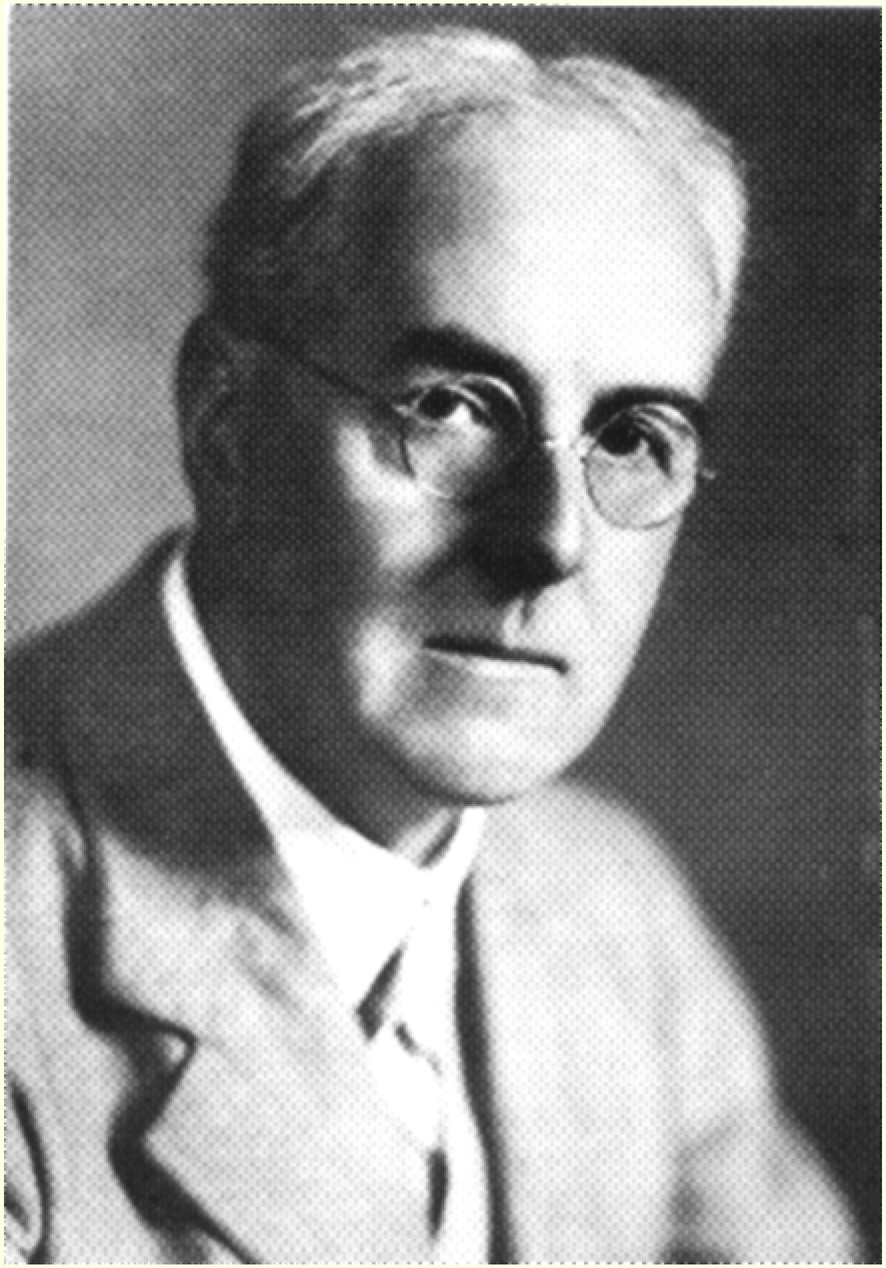
Graphical *v.* Numerical Approach

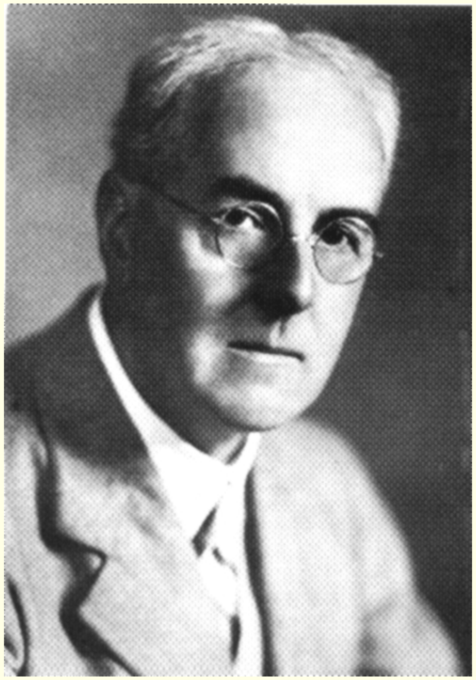
Bjerknes ruled out analytical solution of the mathematical equations, due to their nonlinearity and complexity:

"For the solution of the problem in this form, graphical or mixed graphical and numerical methods are appropriate, which methods must be derived either from the partial differential equations or from the dynamical-physical principles which are the basis of these equations."

However, there was a scientist more bold — or foolhardy — than Bjerknes, who actually tried to calculate future weather. This was Lewis Fry Richardson

Lewis Fry Richardson, 1881–1953.

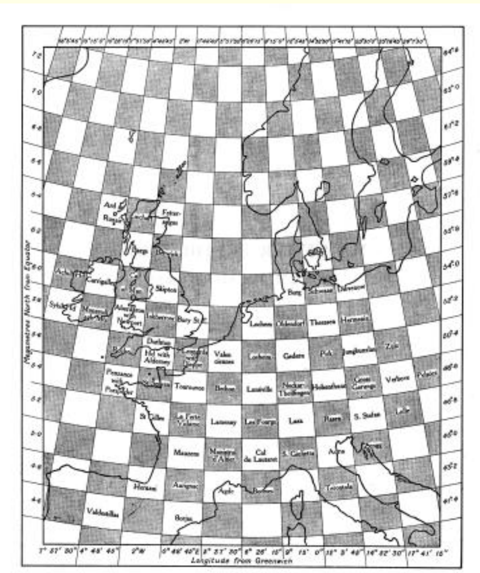




- **Born, 11 October, 1881, Newcastle-upon-Tyne**
- **Family background: well-known quaker family**
- **1900–1904: Kings College, Cambridge**
- **1913–1916: Met. Office. Superintendent, Eskdalemuir Observatory**
- **Resigned from Met Office in May, 1916. Joined Friends' Ambulance Unit.**
- **1919: Re-employed by Met. Office**
- **1920: M.O. linked to the Air Ministry. LFR Resigned, on grounds of concience**
- **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 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:

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

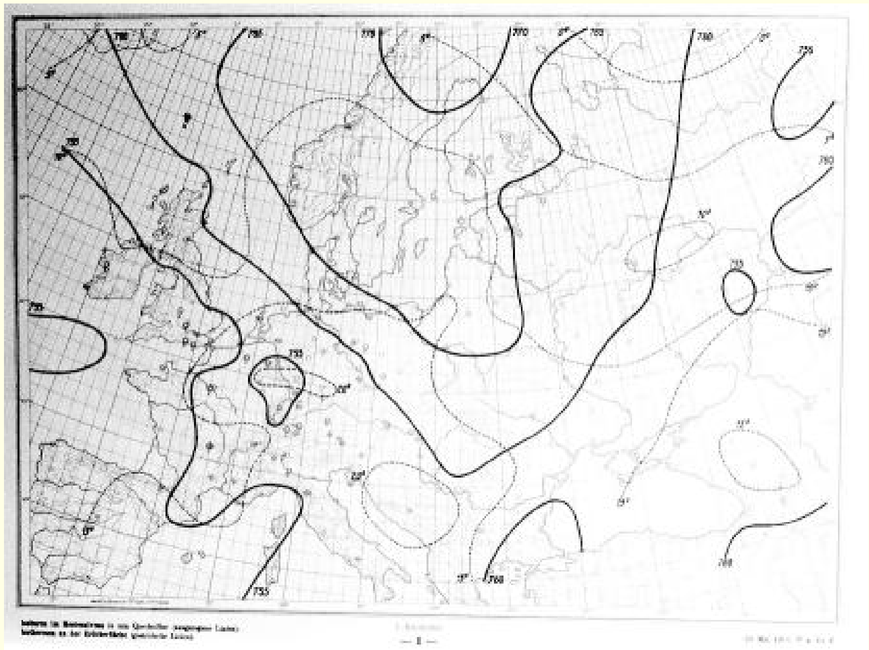
This can immediately be solved for Q^{n+1}:

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

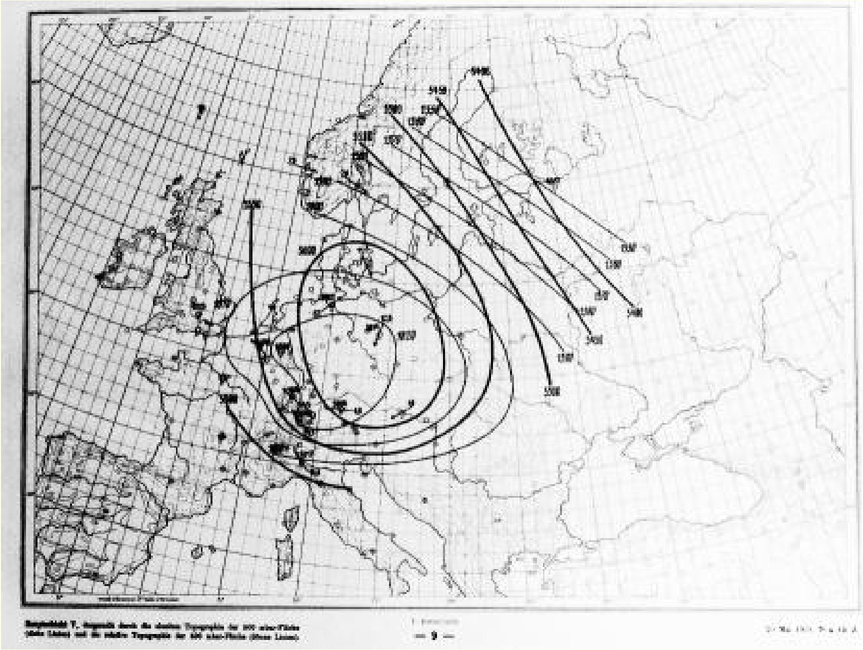
By repeating the calculations for many time steps, we can get a forecast of any length.

Richardson calculated only the initial rates of change.

The Leipzig Charts for 0700 UTC, May 20, 1910



Bjerknes' sea level pressure analysis.



Bjerknes' 500 hPa height analysis.

Some of the initial data for Richardson's "forecast".

Richardson's *Spread-sheet*

Computing Form P xiii. Divergence of horizontal momentum-per-area. Increase of pressure

The equation is typified by : $-\frac{\partial R_{86}}{\partial t} = \frac{\partial M_{E86}}{\partial e} + \frac{\partial M_{N86}}{\partial n} - M_{N86}\frac{\tan\phi}{a} + m_{H6} - m_{H8}{}^{*} + \frac{2}{a}M_{H86}$. (See Ch. 4/2 #5.)

* In the equation for the lowest stratum the corresponding term $-m_{G8}$ does not appear

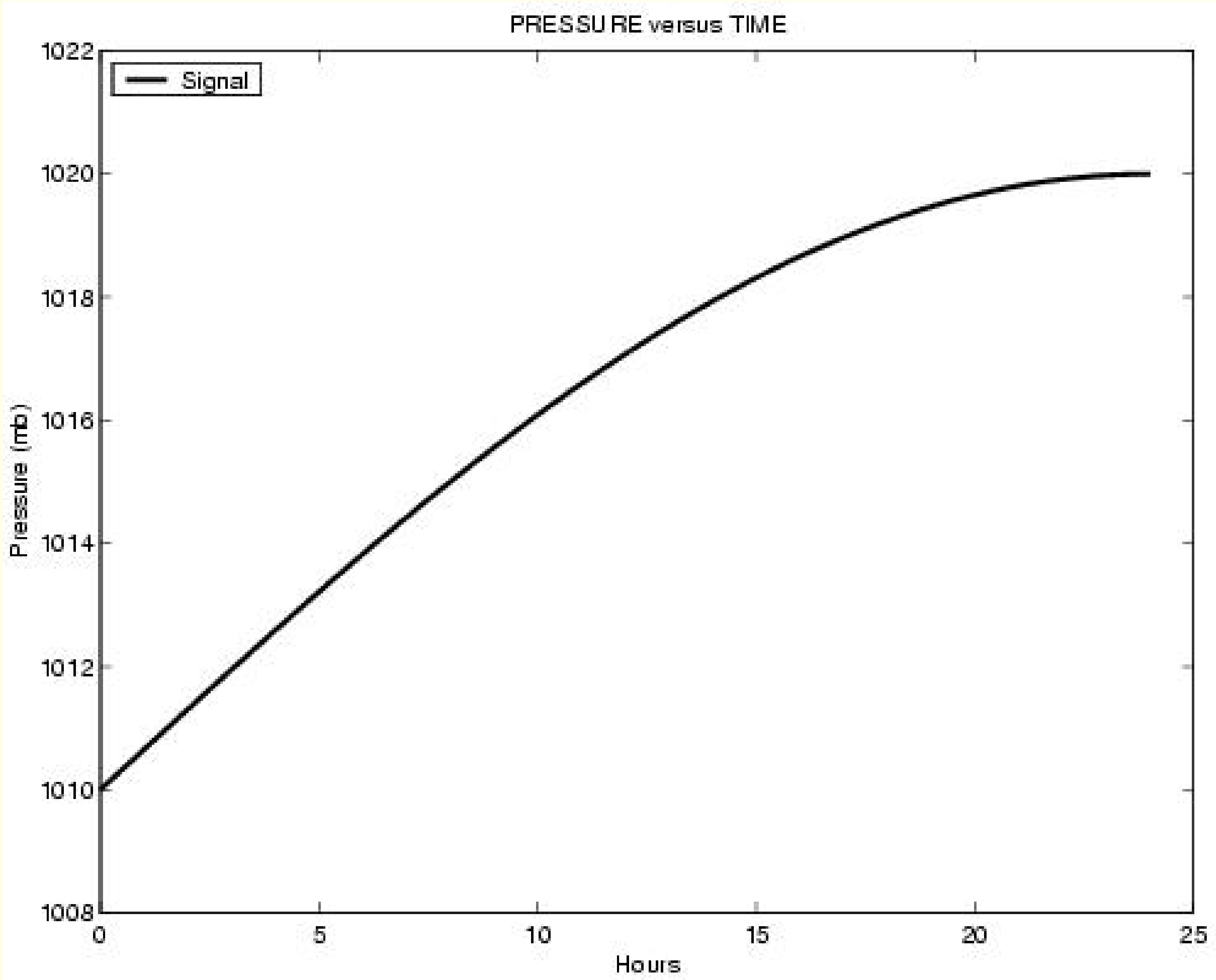
Longitude *11° East*, $\delta e = 441 \times 10^5$ — Latitude *5400 km North*, $\delta n = 400 \times 10^5$ — Instant *1910 May 20ᵈ 7ʰ G.M.T.*, $a^{-1}.\tan\phi = 1{\cdot}78 \times 10^{-9}$ — Interval, δt *6 hours*, $a = 6{\cdot}36 \times 10^8$

Ref.:—				previous 3 columns	previous column		Form P xvi	Form P xvi	equation above	previous column	previous column	previous column
h	$\frac{\delta M_E}{\delta e}$	$\frac{\delta M_N}{\delta n}$	$-\frac{M_N \tan\phi}{a}$	$\mathrm{div}'_{EN}M$	$-g\delta t\,\mathrm{div}'_{EN}M$	Leave the subsequent columns to be filled up after the vertical velocity has been computed on Form P xvi	m_H	$\frac{2M_H}{a}$	$-\frac{\partial R}{\partial t}$	$+\frac{\partial R}{\partial t}\delta t$	$g\frac{\partial R}{\partial t}\delta t$	$\frac{\partial p}{\partial t}\delta t$
	$10^{-5}\times$	$10^{-5}\times$	$10^{-5}\times$	$10^{-5}\times$	$100\times$		$10^{-5}\times$	$10^{-5}\times$	$10^{-5}\times$		$100\times$	$100\times$
h_0							0					0
(h_0–h_2)	−61	−245	−6	−312	656				−229	49·5	483	
h_2							−83					483
(h_2–h_4)	367	−257	2	112	−236			0·06	−136	29·4	287	
h_4							165					770
(h_4–h_6)	93	−303	−16	−226	478			0·11	−124	26·8	262	
h_6							63					1032
(h_6–h_8)	32	− 55	−12	− 35	74			0·07	−110	23·8	233	
h_8							138					1265
(h_8–h_G)	−256	38	− 8	−226	479			0·03	− 88	19·0	186	
h_G												1451
Note: $\mathrm{div}'_{EN}M$ is a contraction for $\frac{\delta M_E}{\delta e} + \frac{\delta M_N}{\delta n} - M_N\frac{\tan\phi}{a}$					SUM = 1451 $= \frac{\partial p_G}{\partial t}\delta t$							check by $\Sigma - g\delta t\,\mathrm{div}'_{EN}M$

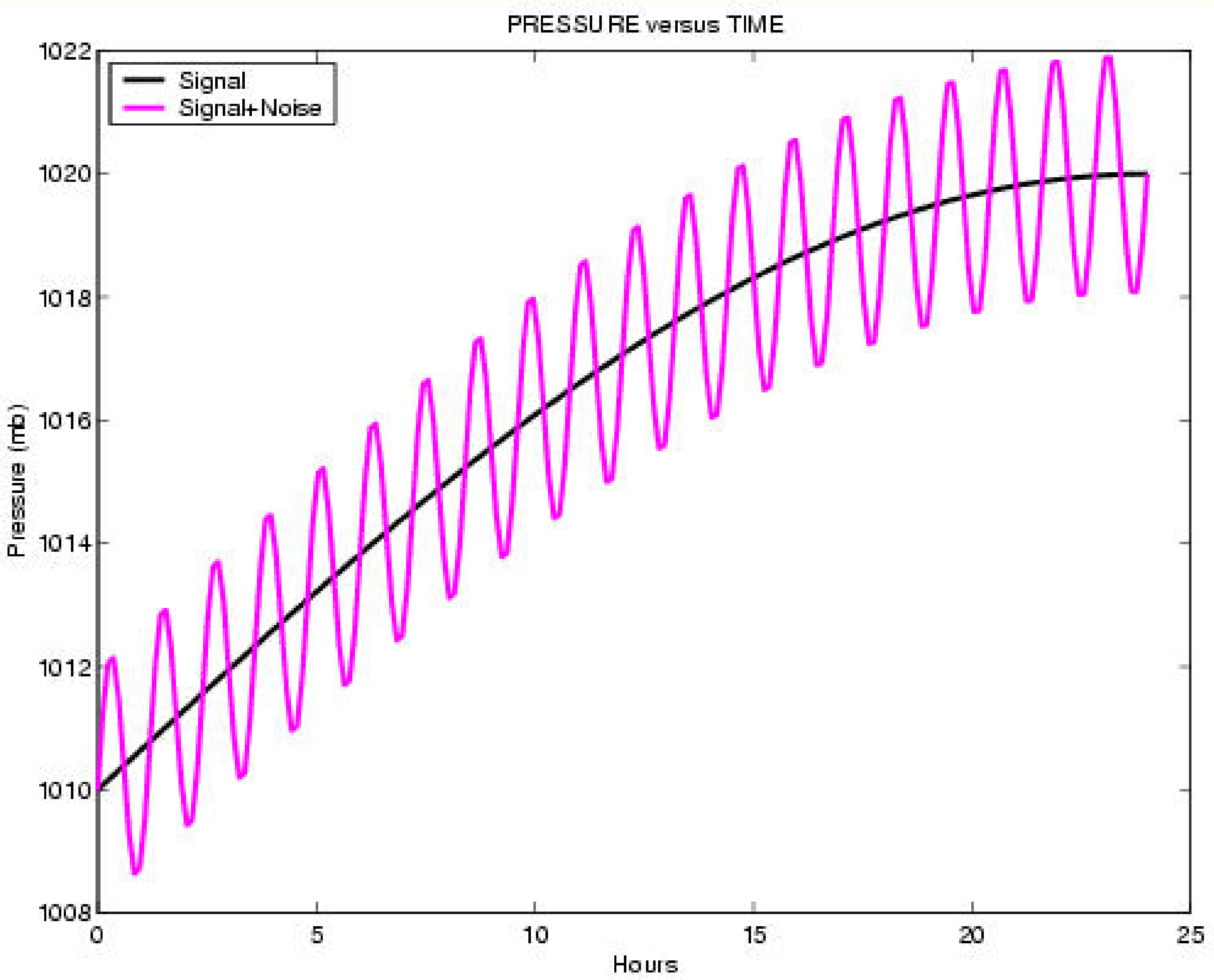
Richardson's Computing Form P$_{\text{XIII}}$

The figure in the bottom right corner is the forecast change in surface pressure: 145 mb in six hours!

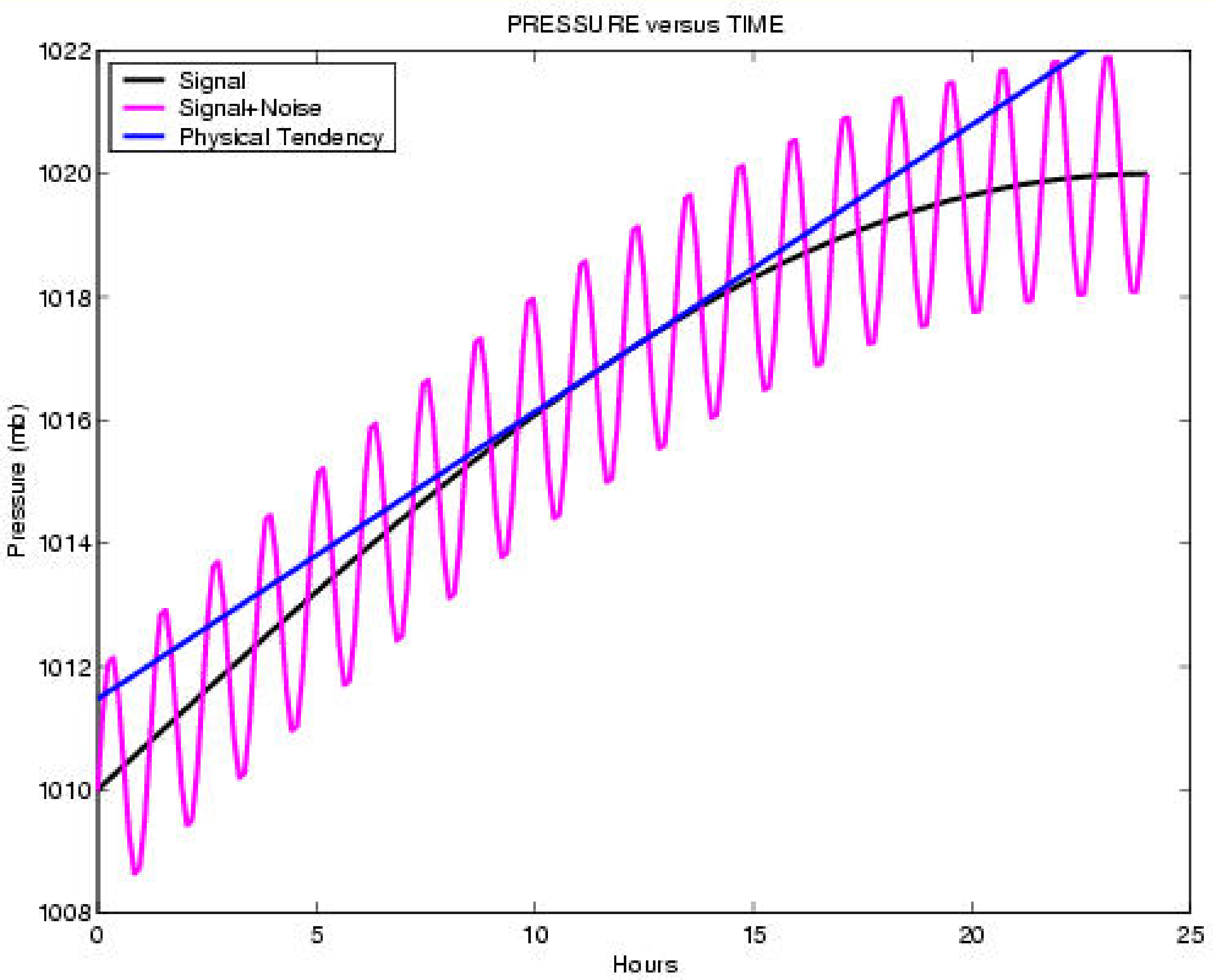
Smooth Evolution of Pressure



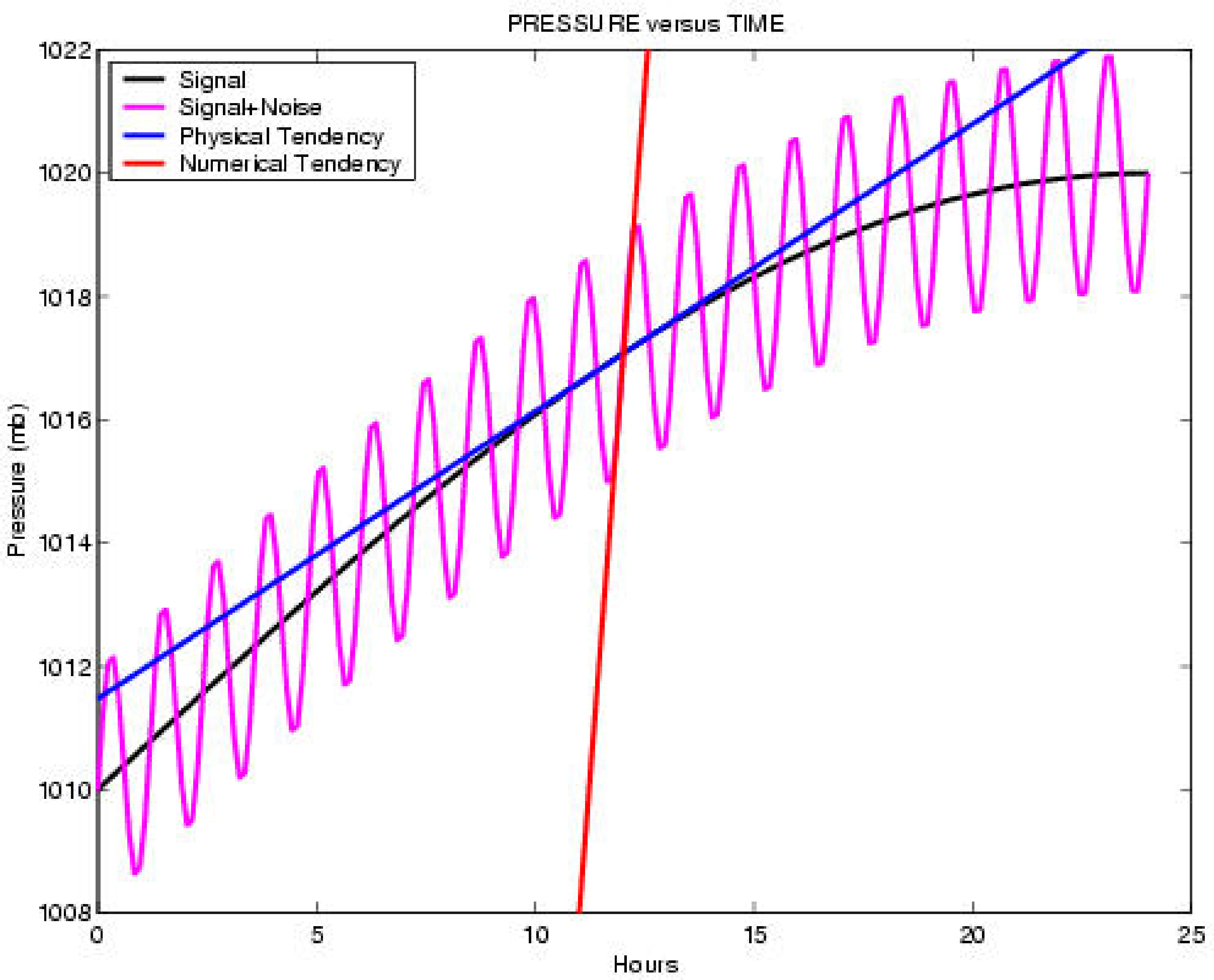
Noisy Evolution of Pressure

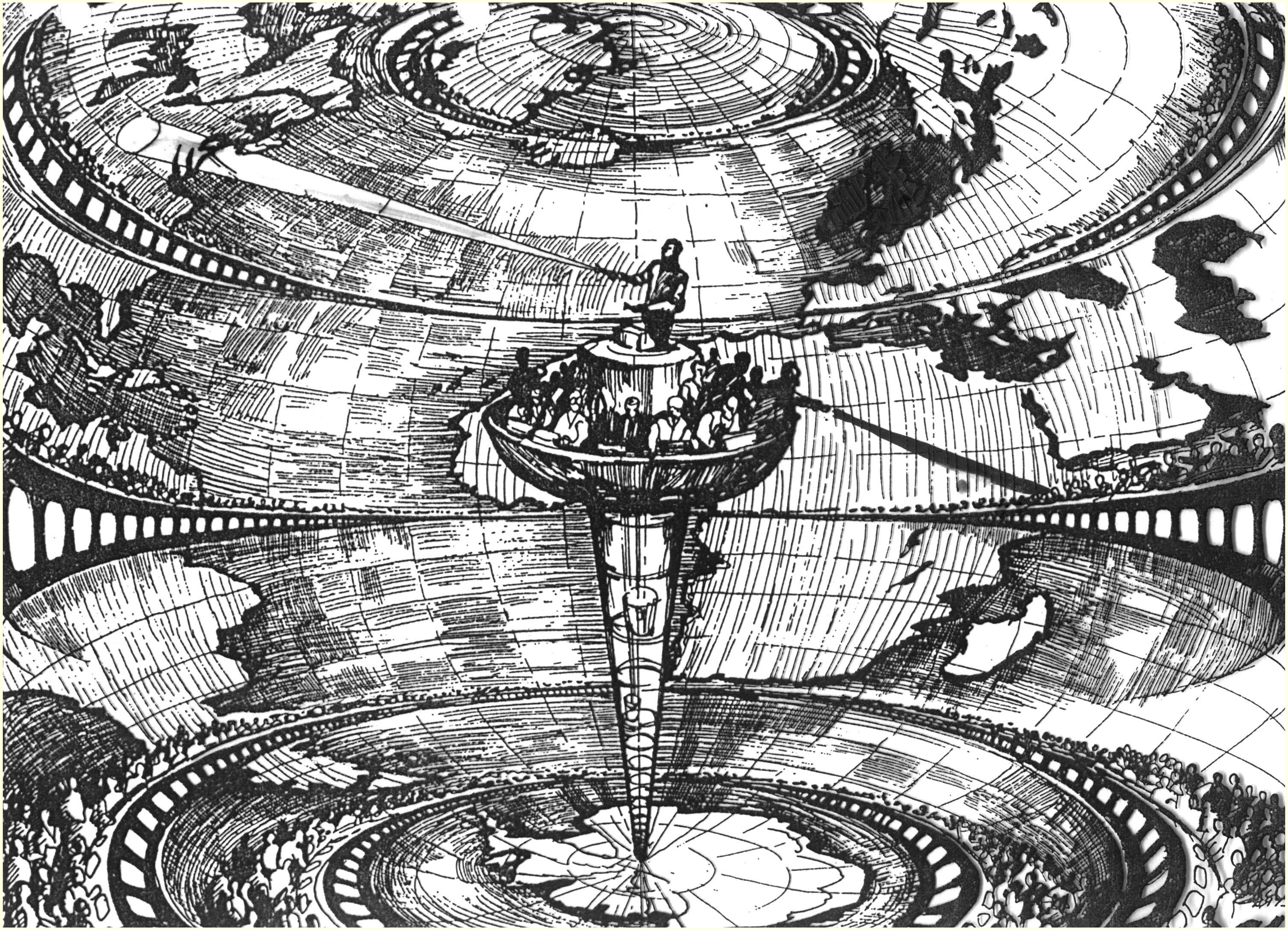


Tendency of a Smooth Signal



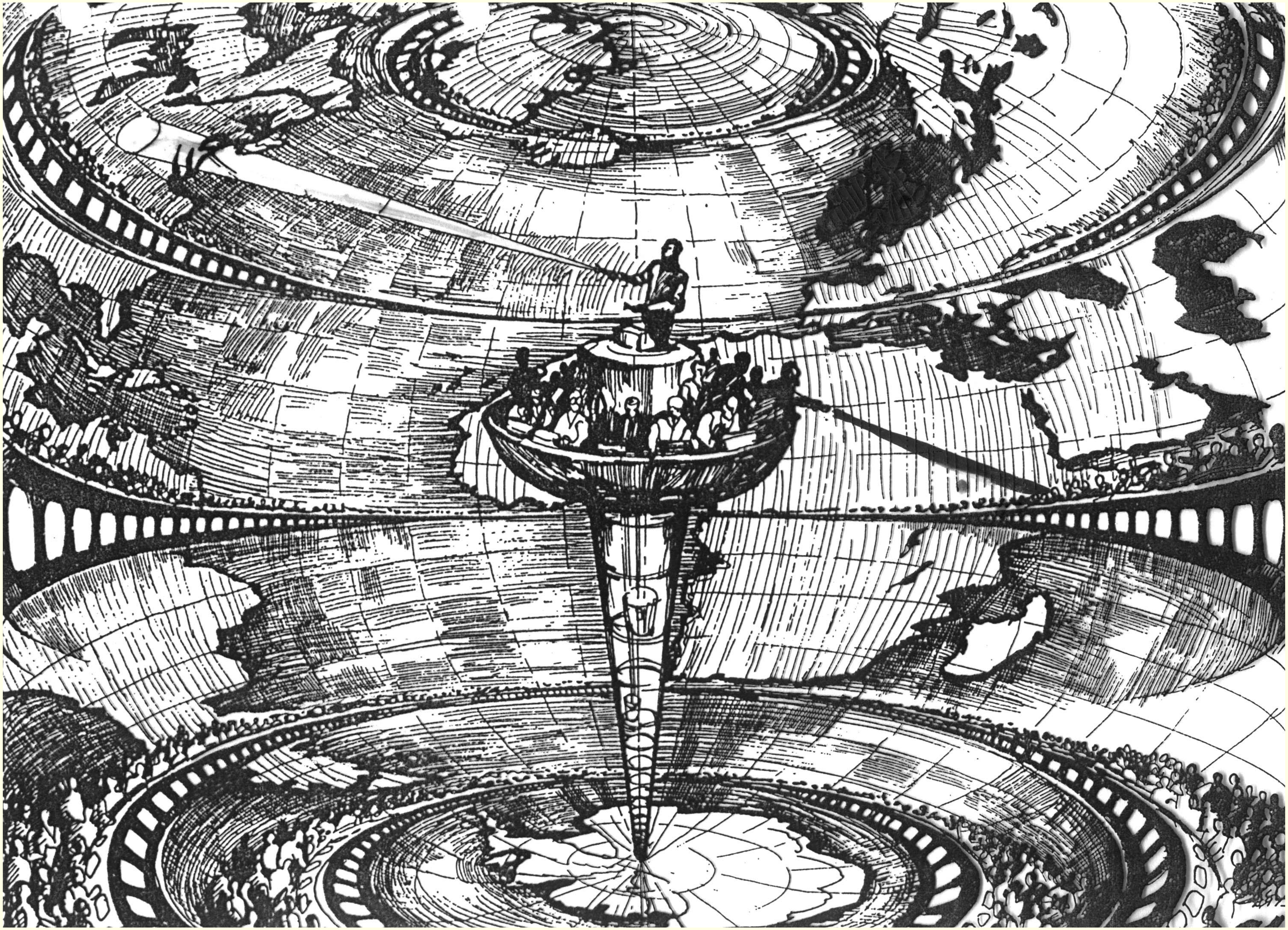
Tendency of a Noisy Signal





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

Advances 1920–1950

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

The ENIAC Integrations

(ENIAC: Electronic Numerical Integrator and Computer)

Electronic Computer Project, 1946 (under direction of John von Neumann)

Von Neumann's idea:

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

The objective of the project was to study the problem of predicting the weather by simulating the dynamics of the atmosphere using a digital electronic computer.

A Proposal for funding listed three "possibilities":

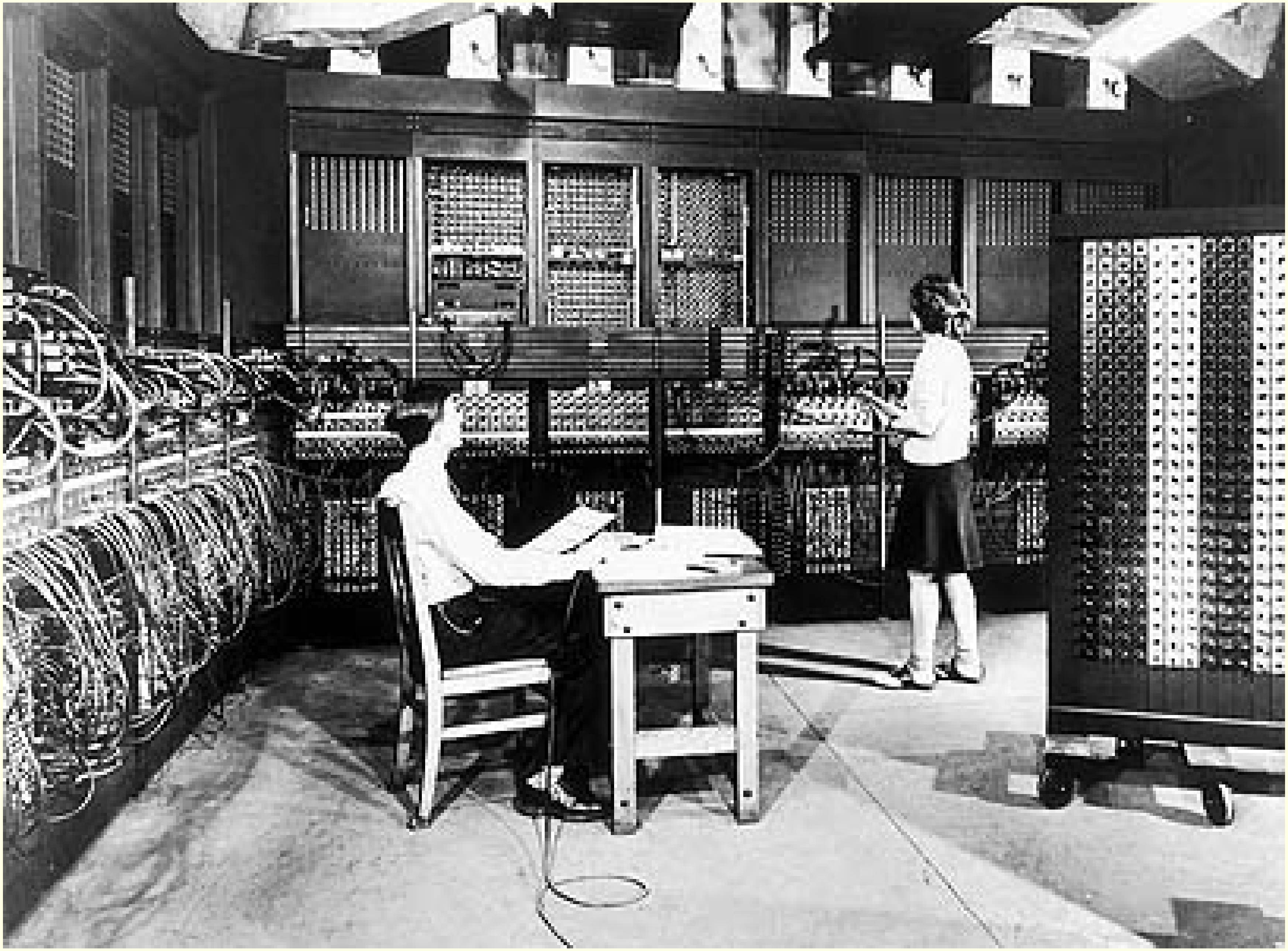
1. **Entirely new methods of weather prediction by calculation will have been made possible;**
2. **A new rational basis will have been secured for the planning of physical measurements and field observations;**
3. **The first step towards influencing the weather by rational human intervention will have been made.**

“Conference on Meteorology”

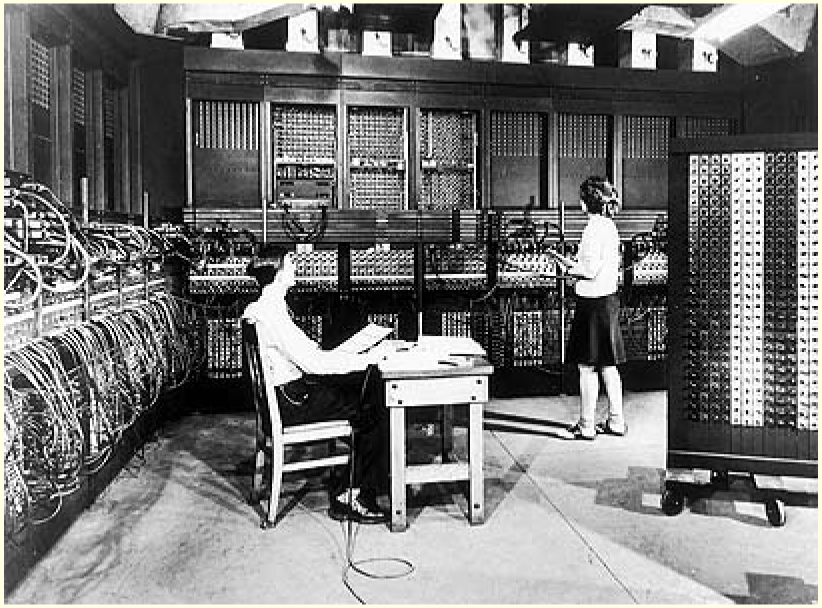
A “Conference on Meteorology” was arranged in the Institute for Advanced Studies (IAS), Princeton on 29–30 August, 1946. Participants included:

- **Carl Gustav Rossby**
- **Jule Charney**
- **George Platzman**
- **Norman Phillips**
- **Ragnar Fjørtoft**
- **Arnt Eliassen**
- **Joe Smagoinsky**
- **Phil Thompson**

The ENIAC



The ENIAC



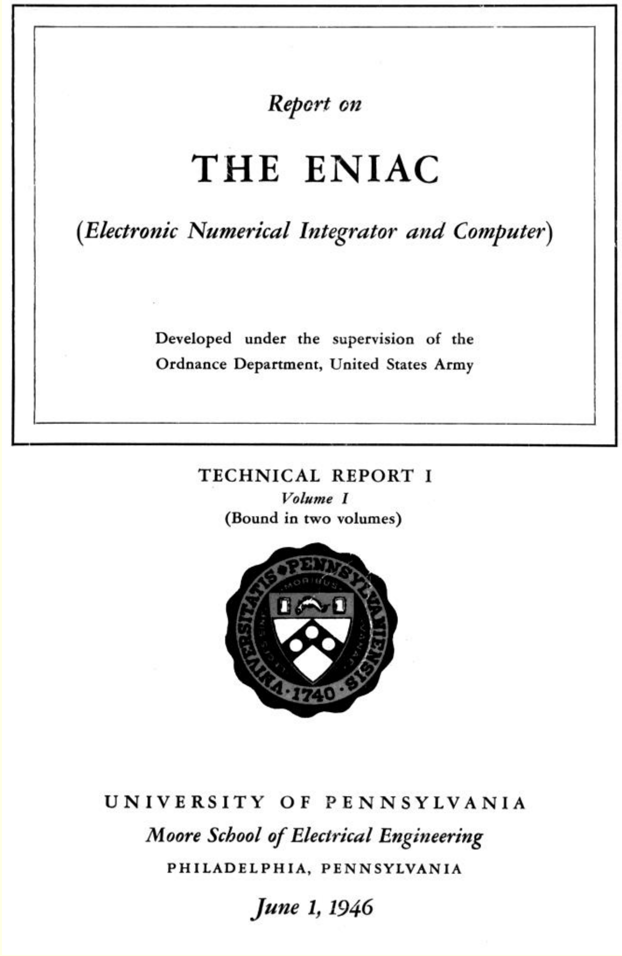
The **ENIAC** (Electronic Numerical Integrator and Computer) was the first multi-purpose programmable electronic digital computer.
It had:

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

Power Consumption: 140 kWatts

The ENIAC: Technical Details.

ENIAC was a decimal machine. No high-level language.
Assembly language. Fixed-point arithmetic: $-1 < x < +1$.
10 registers, that is,
Ten words of high-speed memory.
Function Tables:
624 6-digit words of "ROM", set on
ten-pole rotary switches.
"Peripheral Memory":
Punch-cards.
Speed: FP multiply: 2ms
(say, 500 Flops).
Access to Function Tables: 1ms.
Access to Punch-card equipment:
You can imagine!



Report on

THE ENIAC

(Electronic Numerical Integrator and Computer)

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

TECHNICAL REPORT I
Volume I
(Bound in two volumes)

UNIVERSITY OF PENNSYLVANIA
Moore School of Electrical Engineering
PHILADELPHIA, PENNSYLVANIA

June 1, 1946

Evolution of the Project:

- **Plan A: Integrate the Primitive Equations**

  Problems similar to Richardson's would arise

Evolution of the Project:

- **Plan A: Integrate the Primitive Equations**

  Problems similar to Richardson's would arise

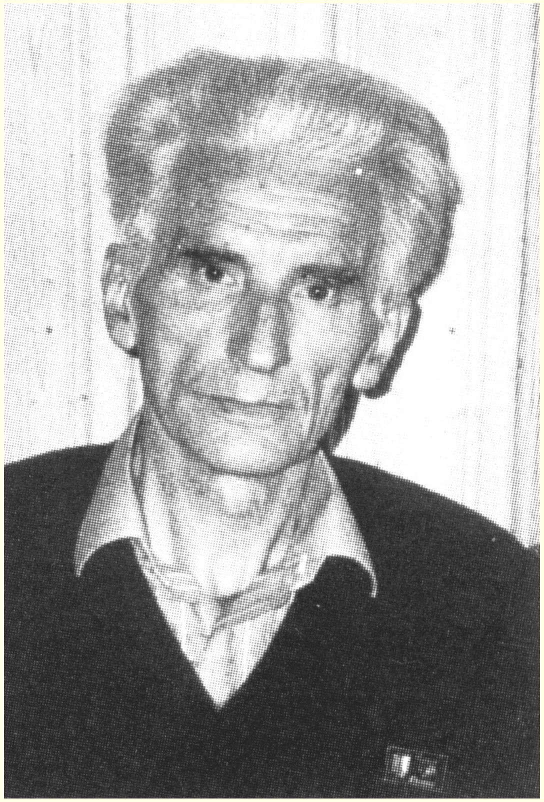
- **Plan B: Integrate baroclinic Q-G System**

  Too computationally demanding

Evolution of the Project:

- **Plan A: Integrate the Primitive Equations**
  Problems similar to Richardson's would arise
- **Plan B: Integrate baroclinic Q-G System**
  Too computationally demanding
- **Plan C: Solve barotropic vorticity equation**
  Very satisfactory initial results

Charney, Fjørtoft, von Neumann


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

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

The atmosphere is treated as a single layer, and the flow is assumed to be nondivergent. Absolute vorticity is conserved following the flow.

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

This equation looks deceptively simple. But it is nonlinear:

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

Or, in more detail:

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

Solution method for BPVE

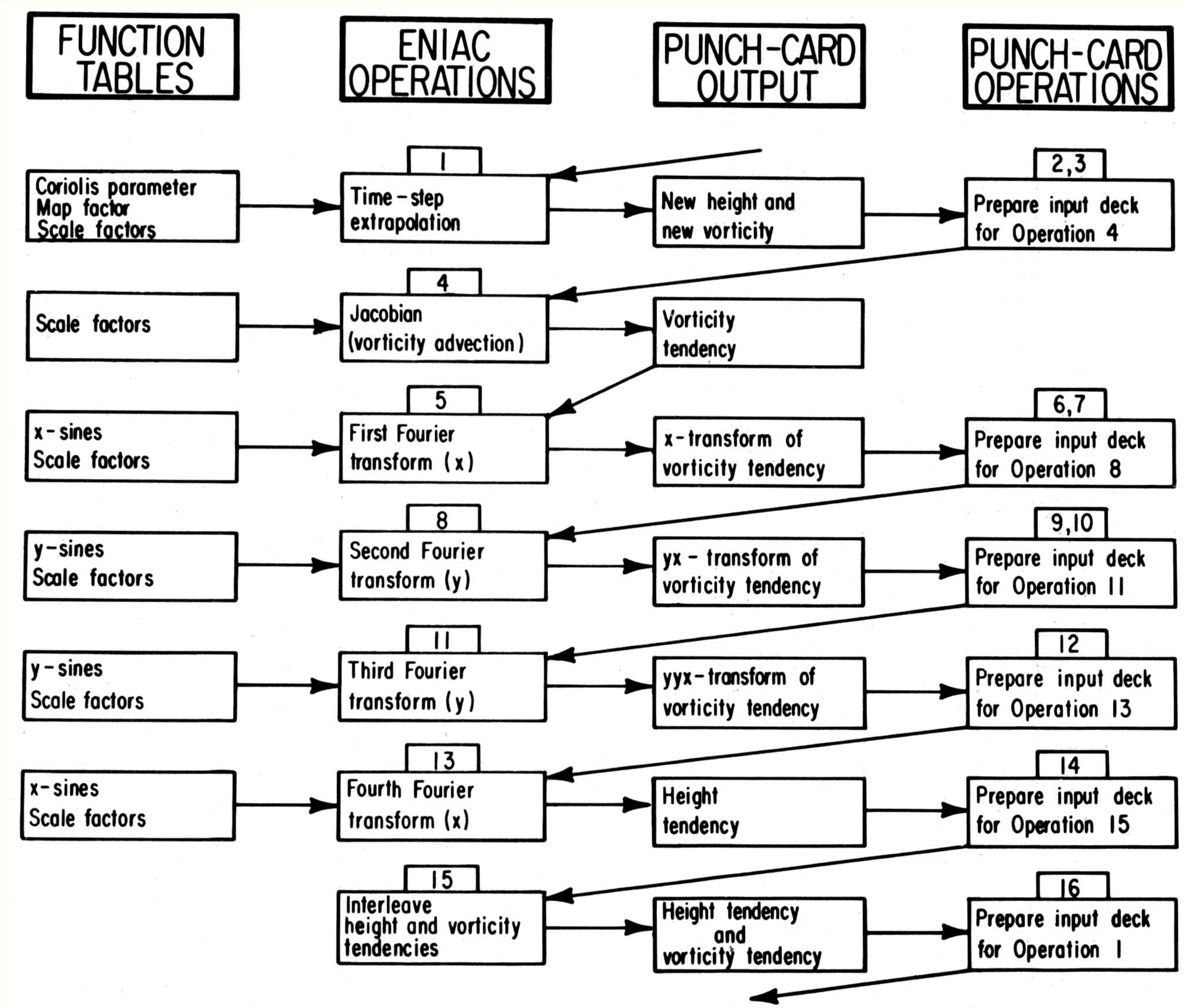
$$\frac{\partial \zeta}{\partial t} = \mathbf{J}(\psi, \zeta + f)$$

1. **Compute Jacobian**
2. **Step forward (Leapfrog scheme)**
3. **Solve Poisson equation for ψ (Fourier expansion)**
4. **Go to (1).**

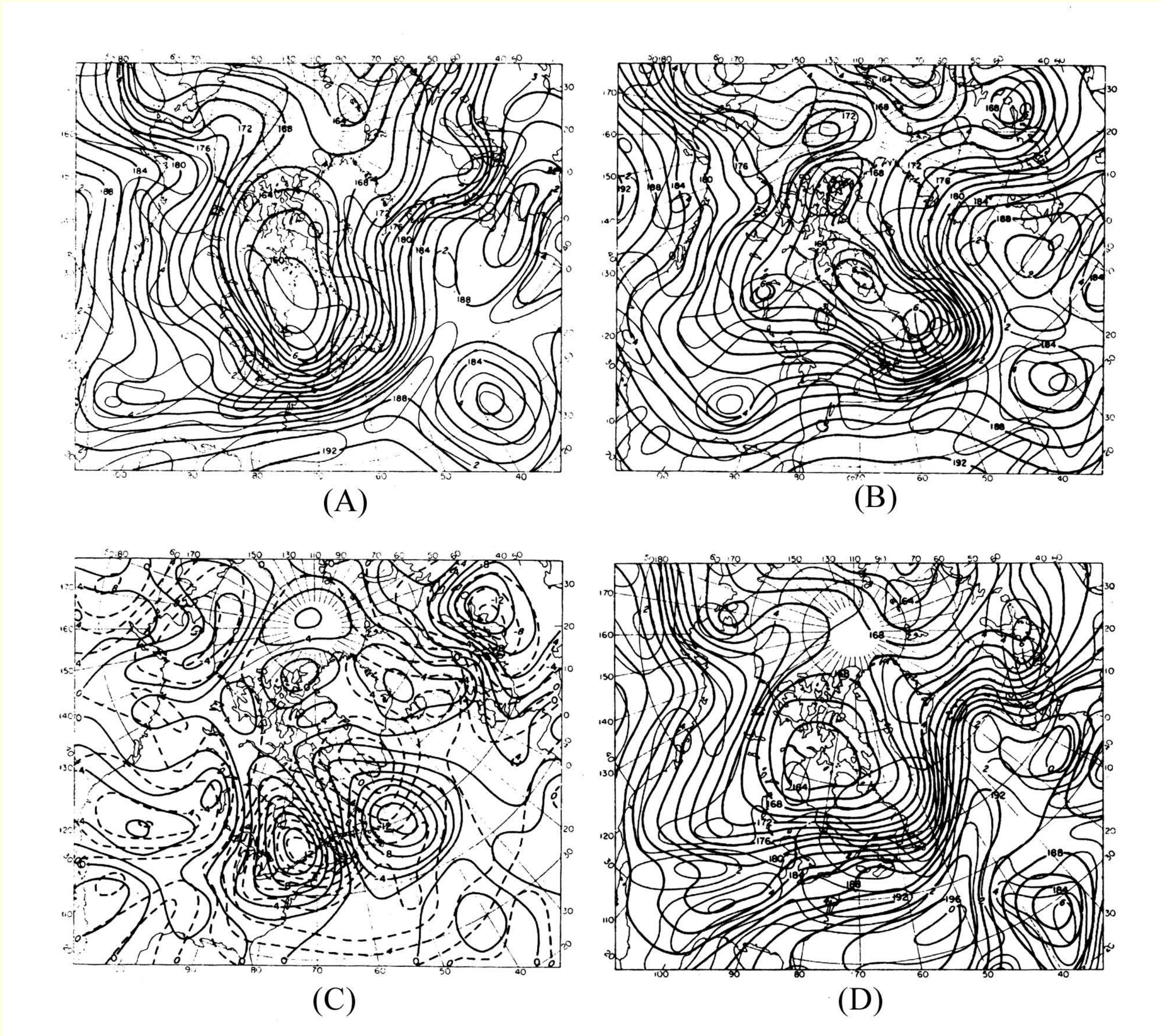
- **Timestep : Δt = 1 hour (2 and 3 hours also tried)**
- **Gridstep : Δx = 750 km (approximately)**
- **Gridsize : 18 x 15 = 270 points**
- **Elapsed time for 24 hour forecast: About 24 hours.**

Forecast involved punching about 25,000 cards. Most of the elapsed time was spent handling these.

ENIAC Algorithm



ENIAC: First Computer Forecast



Richardson's reaction

- ***"Allow me to congratulate you and your collaborators on the remarkable progress which has been made in Princeton.***
- ***"This is . . . an enormous scientific advance on the single, and quite wrong, result in which Richardson (1922) ended."***

NWP Operations

The Joint Numerical Weather Prediction (JNWP) Unit was established on July 1, 1954:

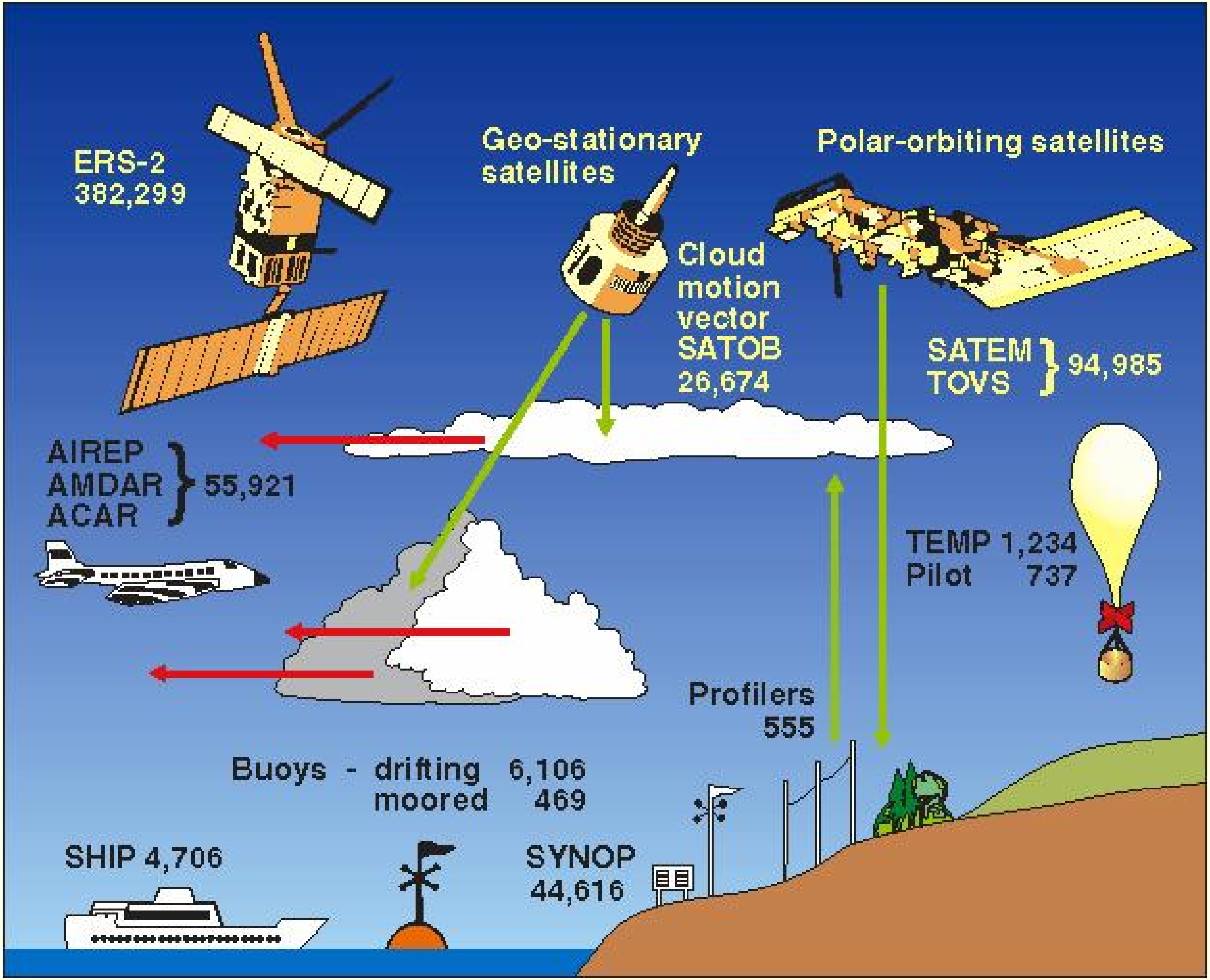
- ***Air Weather Service of US Air Force***
- ***The US Weather Bureau***
- ***The Naval Weather Service.***

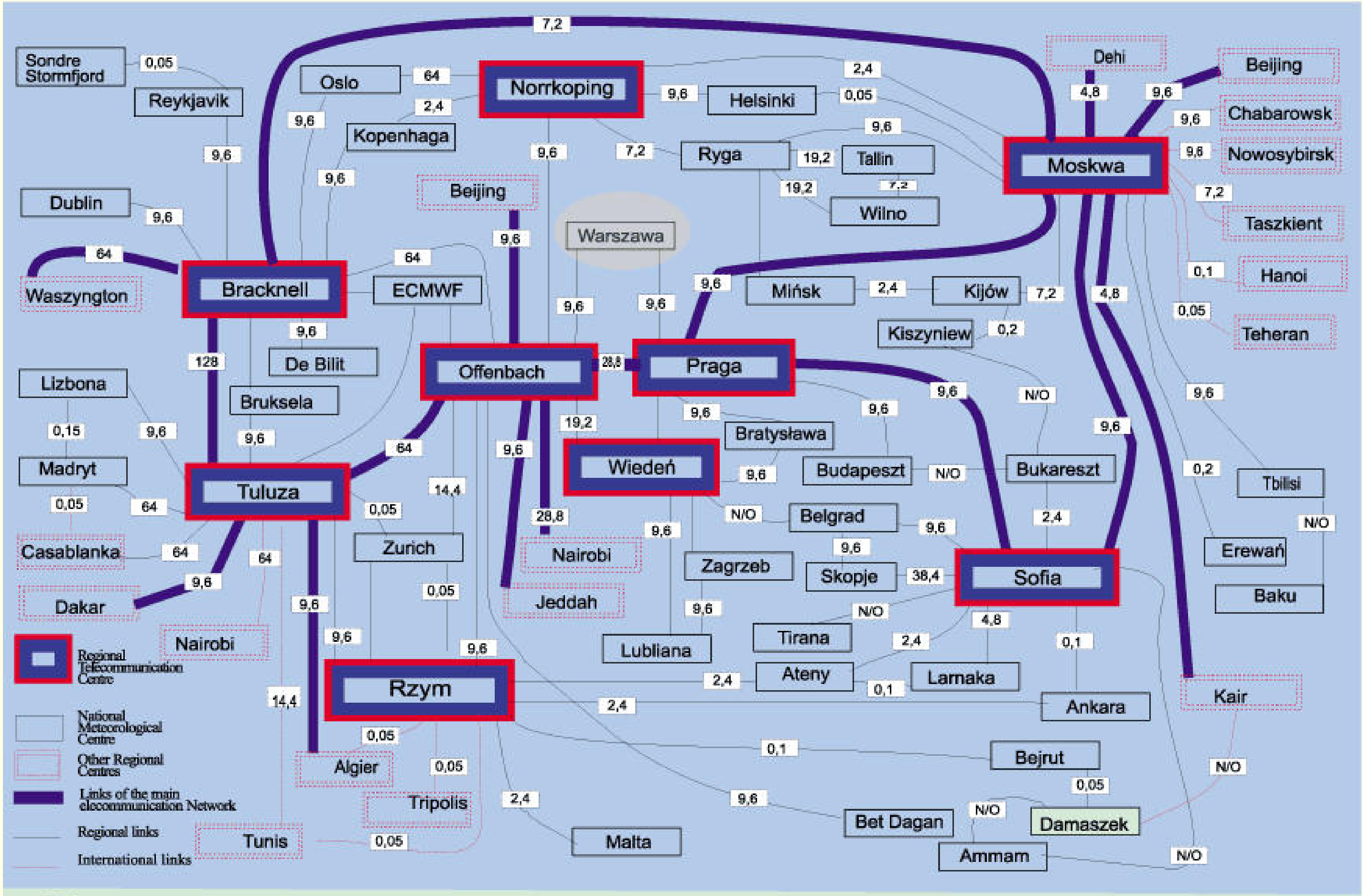
Operational numerical forecasting began on 15 May, 1955, using a three-level quasi-geostrophic model.

Computer

Forecasting

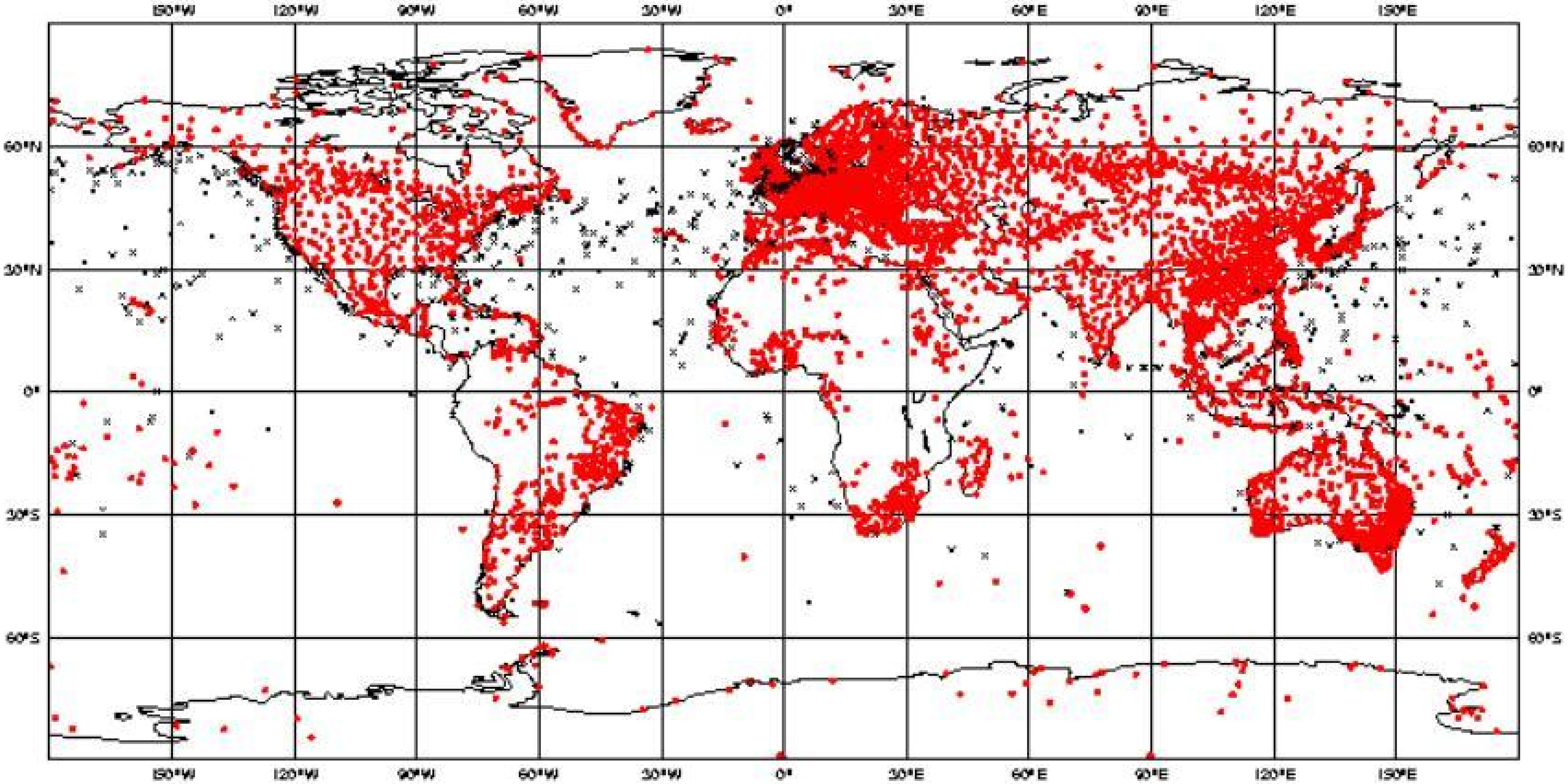
Today


ERS-2
382,299
Geo-stationary
satellites
Polar-orbiting satellites
Cloud
motion
vector
SATOB
26,674
SATEM
TOVS
94,985
AIREP
AMDAR
ACAR
55,921
TEMP 1,234
Pilot 737
Profilers
555
Buoys - drifting 6,106
moored 469
SHIP 4,706
SYNOP
44,616

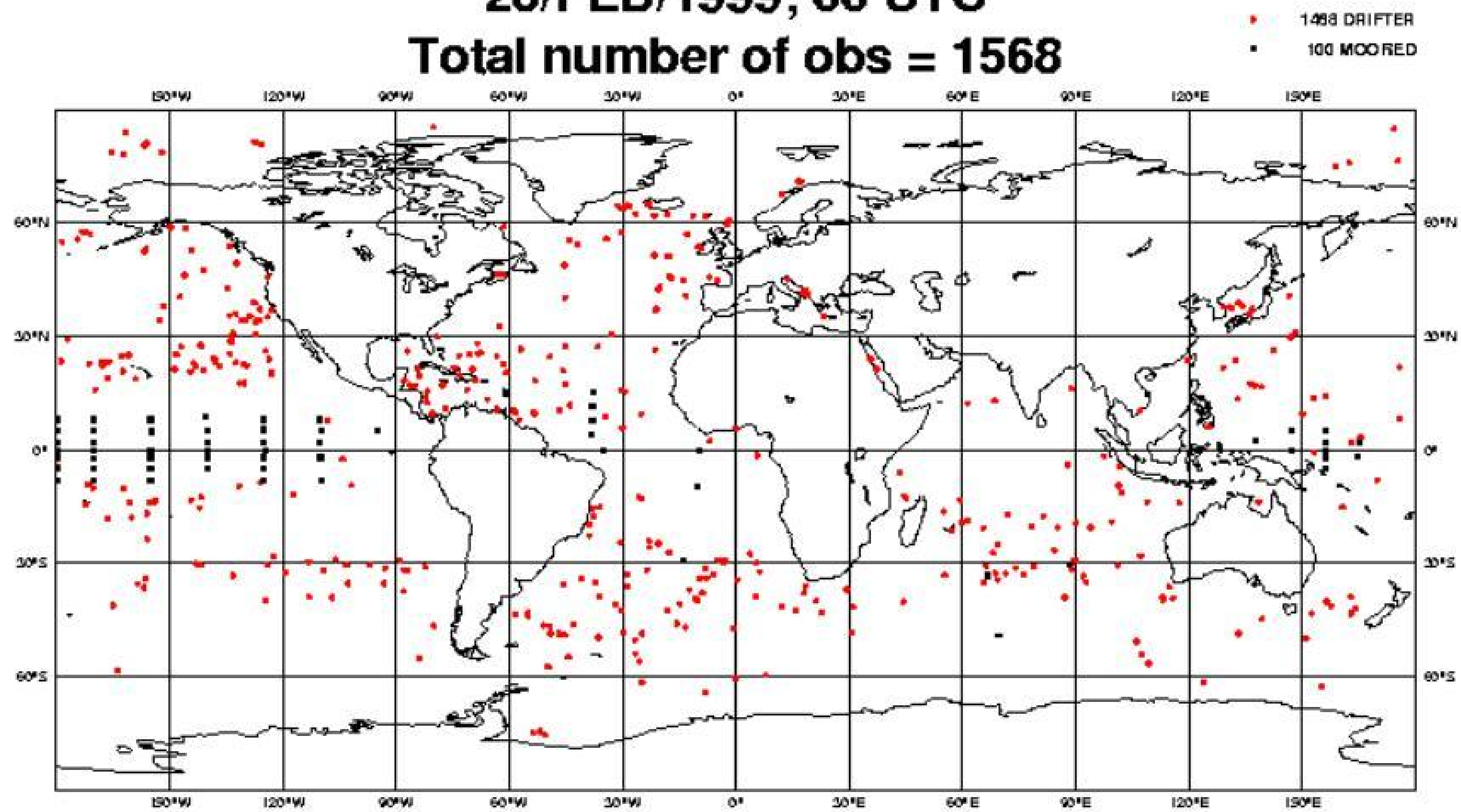


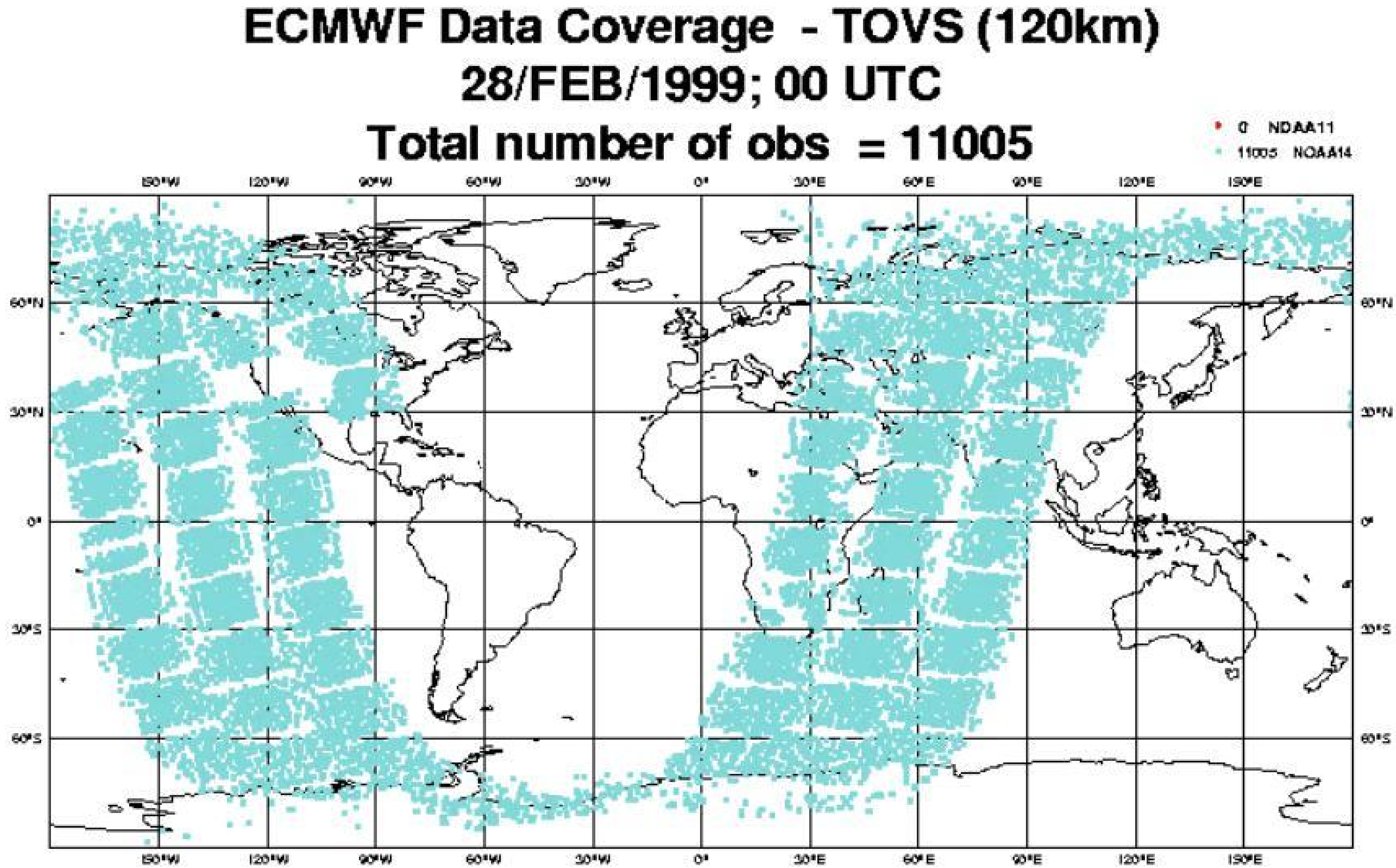
Global Telecommunication System of the World Meteorological Organization
(transmission in kilobits per second)

ECMWF Data Coverage - SYNOP/SHIP
28/FEB/1999; 00 UTC
Total number of obs = 12688

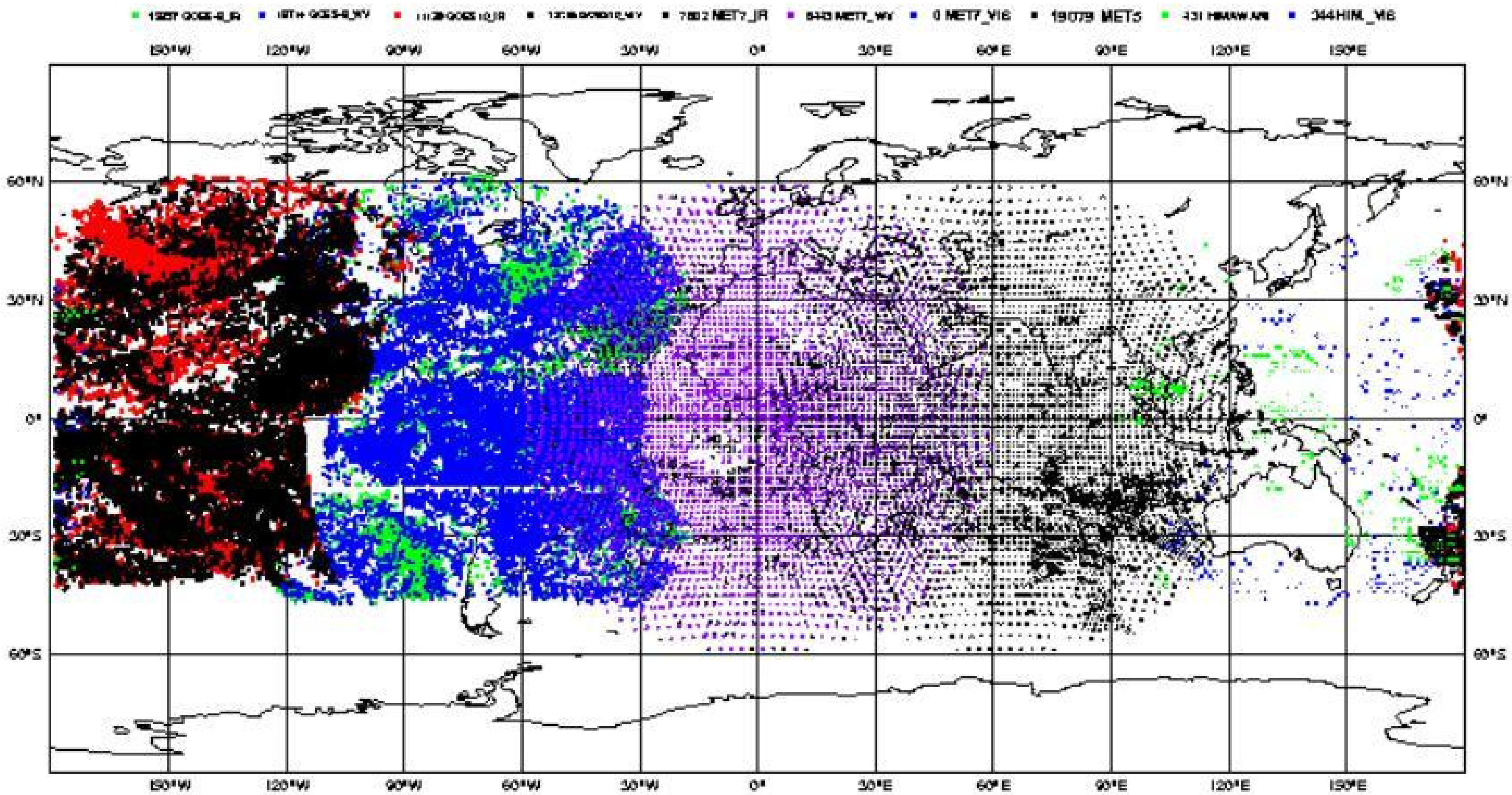


ECMWF Data Coverage - BUOY
28/FEB/1999; 00 UTC
Total number of obs = 1568




ECMWF Data Coverage - TOVS (120km)
28/FEB/1999; 00 UTC
Total number of obs = 11005
0 NOAA11
11005 NOAA14

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



Met Éireann Headquarters

The Met Éireann web site: www.met.ie

- 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.*

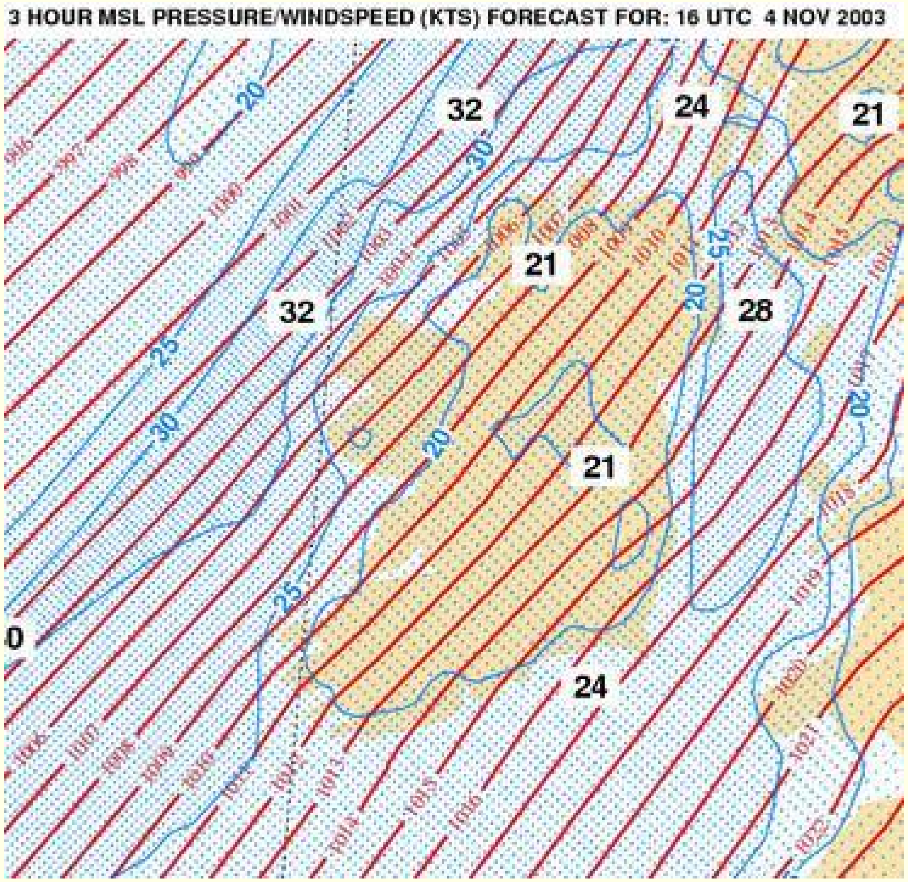
Extensive model documentation is available at http://hirlam.knmi.nl/

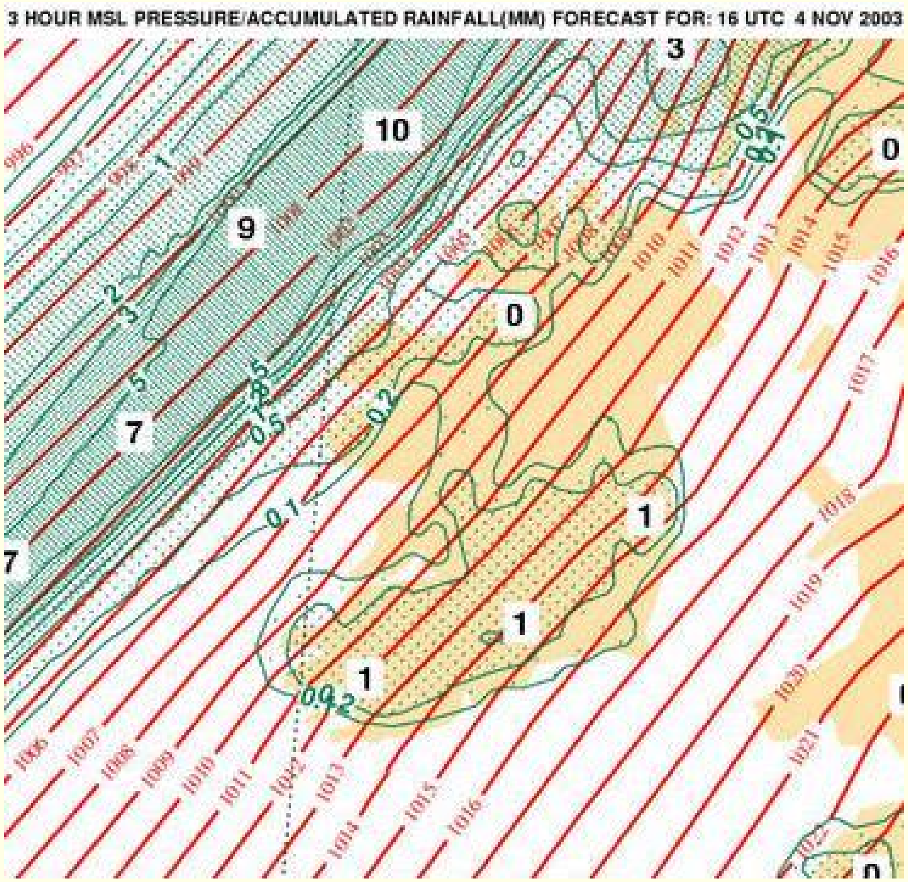
The HIRLAM Project

HIRLAM stands for **High Resolution Limited Area Model.**
The members of the HIRLAM Project are:

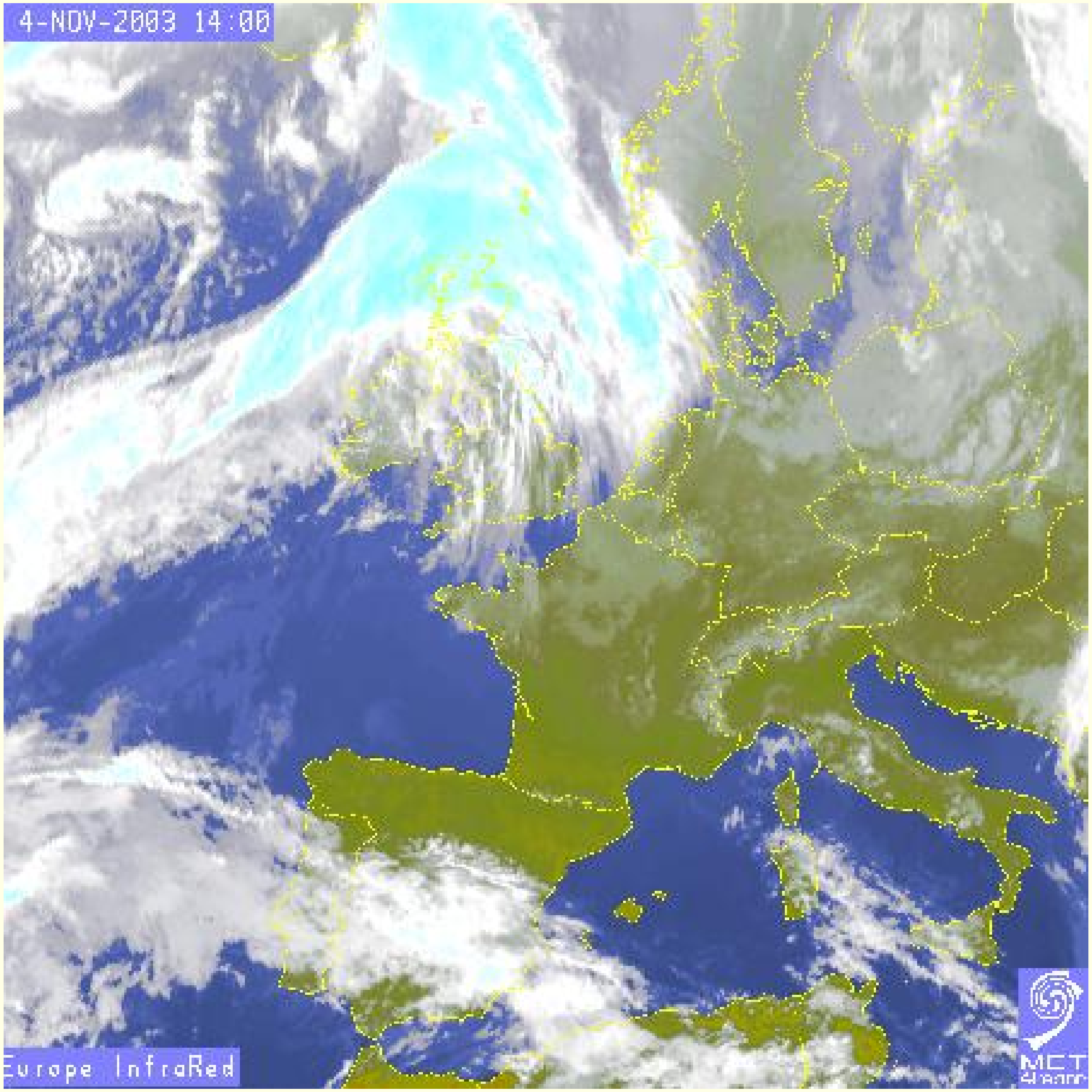
- **Danish Meteorological Institute (DMI)**
- **Finnish Meteorological Institute (FMI)**
- **Icelandic Meteorological Office (VI)**
- **Met Éireann, Ireland (IMS)**
- **Royal Netherlands Meteorological Institute (KNMI)**
- **The Norwegian Meteorological Institute (`met.no`)**
- **Spanish Meteorological Institute (INM)**
- **Swedish Meteorological and Hydrological Institute**

Hourly HIRLAM Forecast Charts

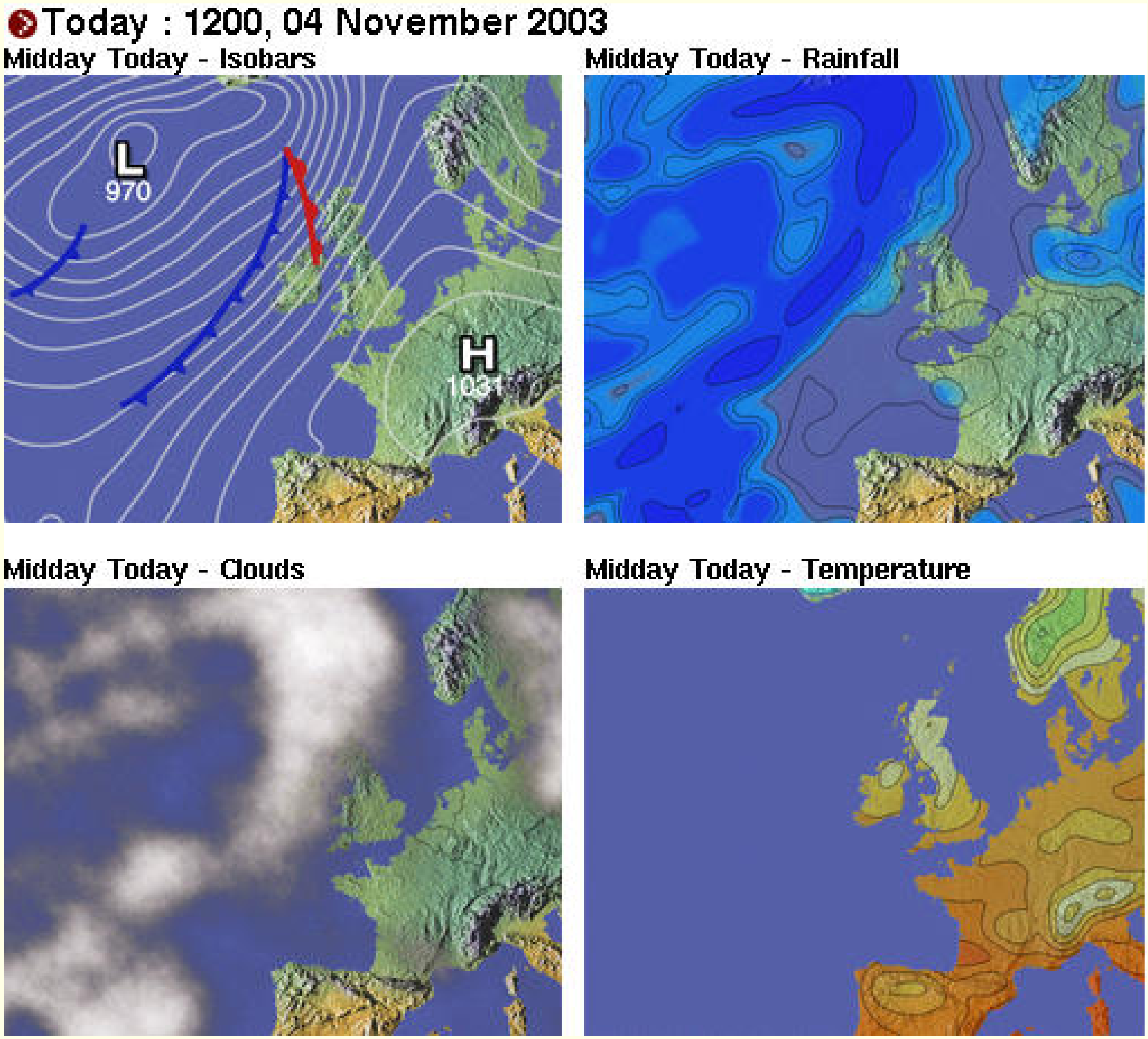




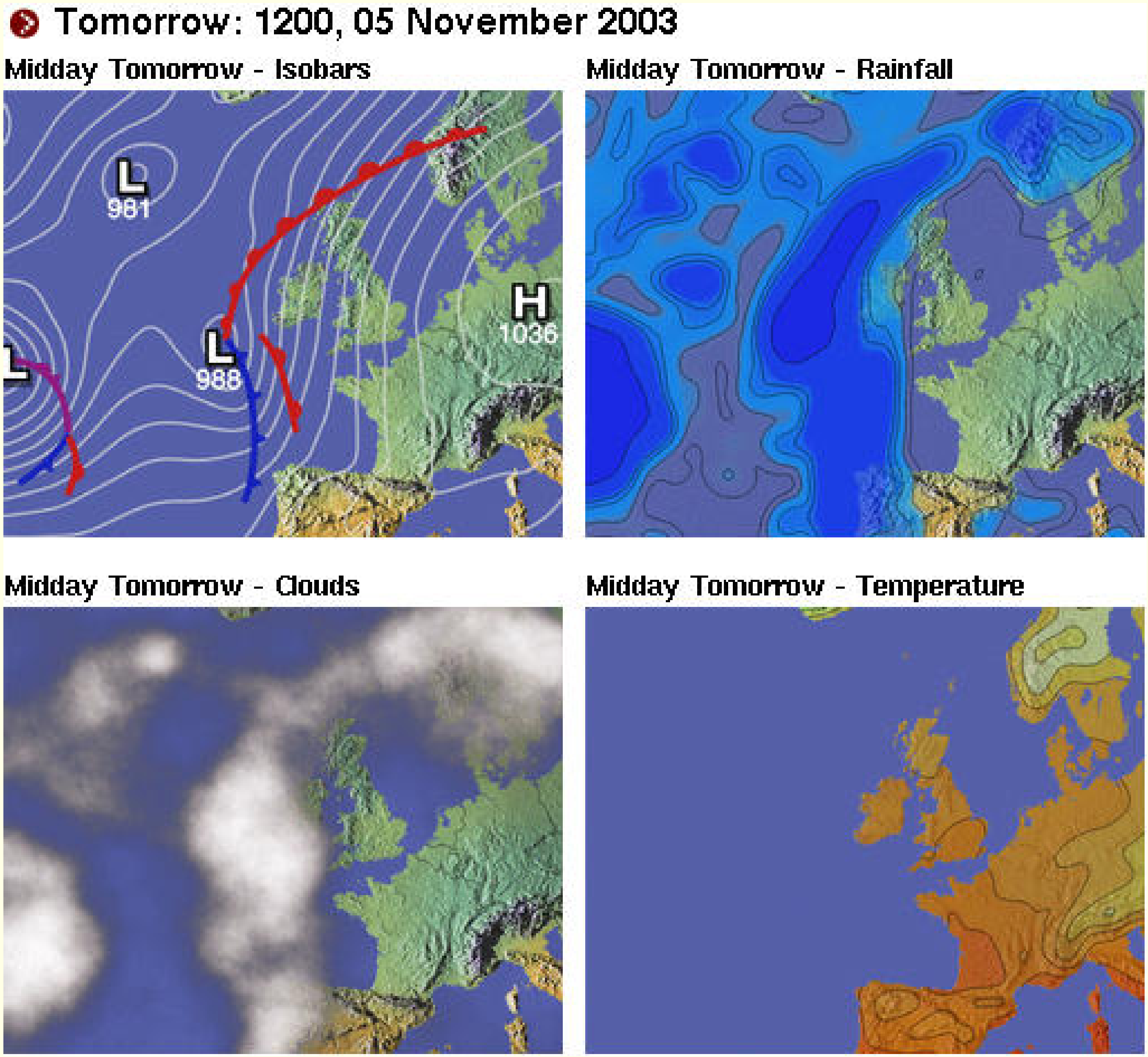
Satellite Imagery



Atlantic Analysis Charts



Atlantic 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.

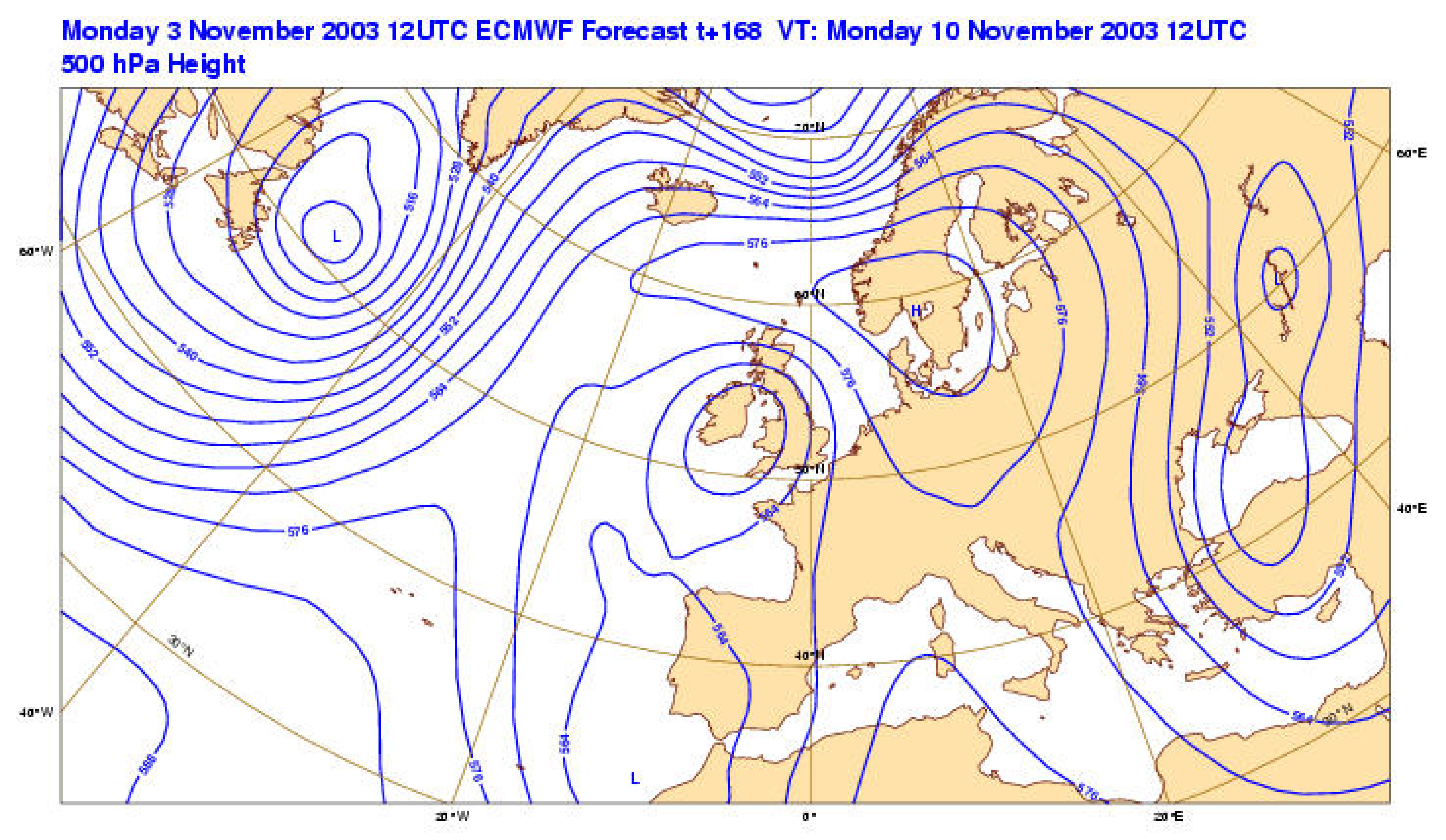
Eighteen Member States, including Ireland, support ECMWF.

PRESS RELEASE (2 Dec., 2003)

New Director of ECMWF

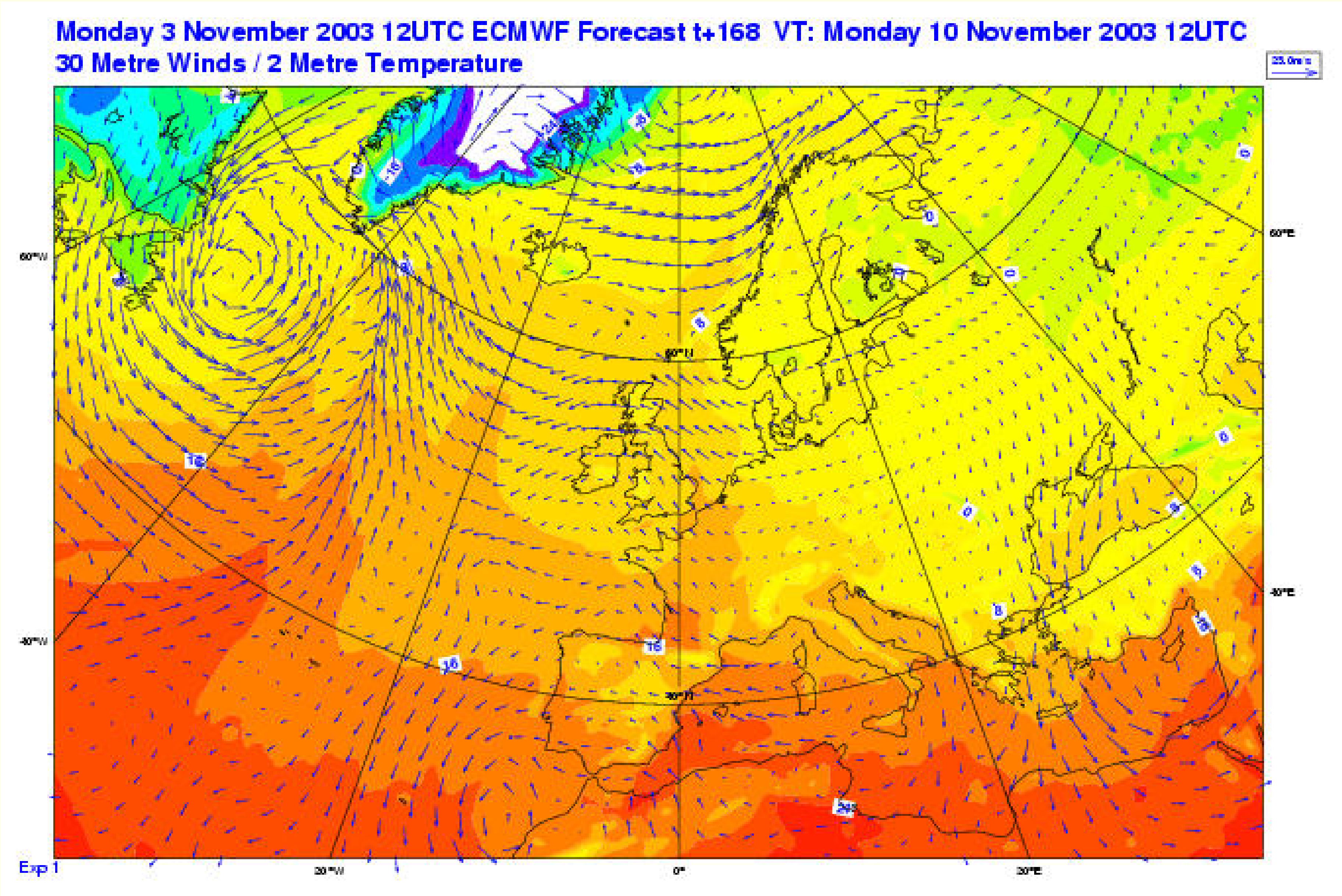
The Council of the European Centre for Medium-Range Weather Forecasts as appointed Mr. Dominique Marbouty as Director of ECMWF from 18 June 2004.

Seven-day Forecast from ECMWF



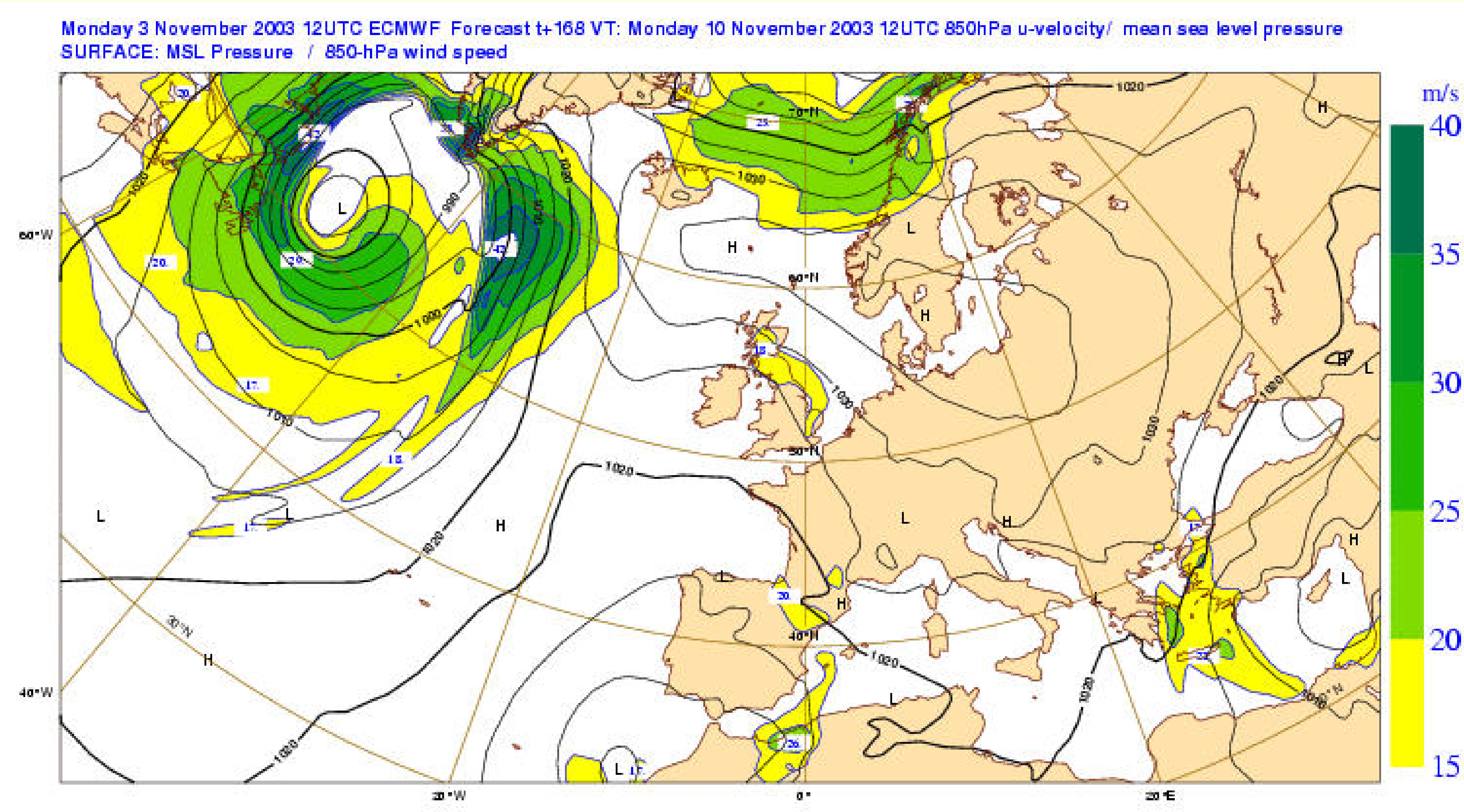
500 hPa Height Forecast

Seven-day Forecast from ECMWF



2m Temperature and 30m Wind Forecast

Seven-day Forecast from ECMWF



MSL Pressure and 850hPa Wind Forecast

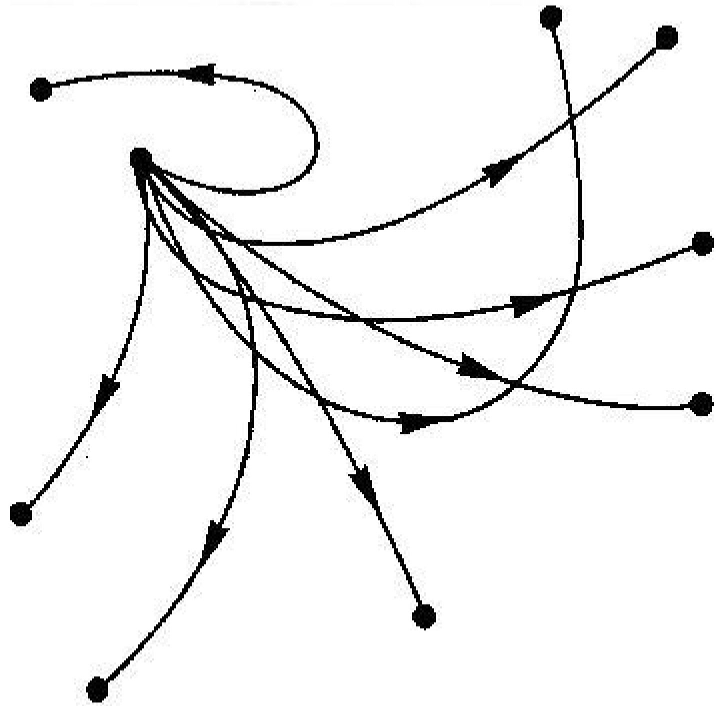
Atmospheric Predictability

and

Ensemble Forecasting

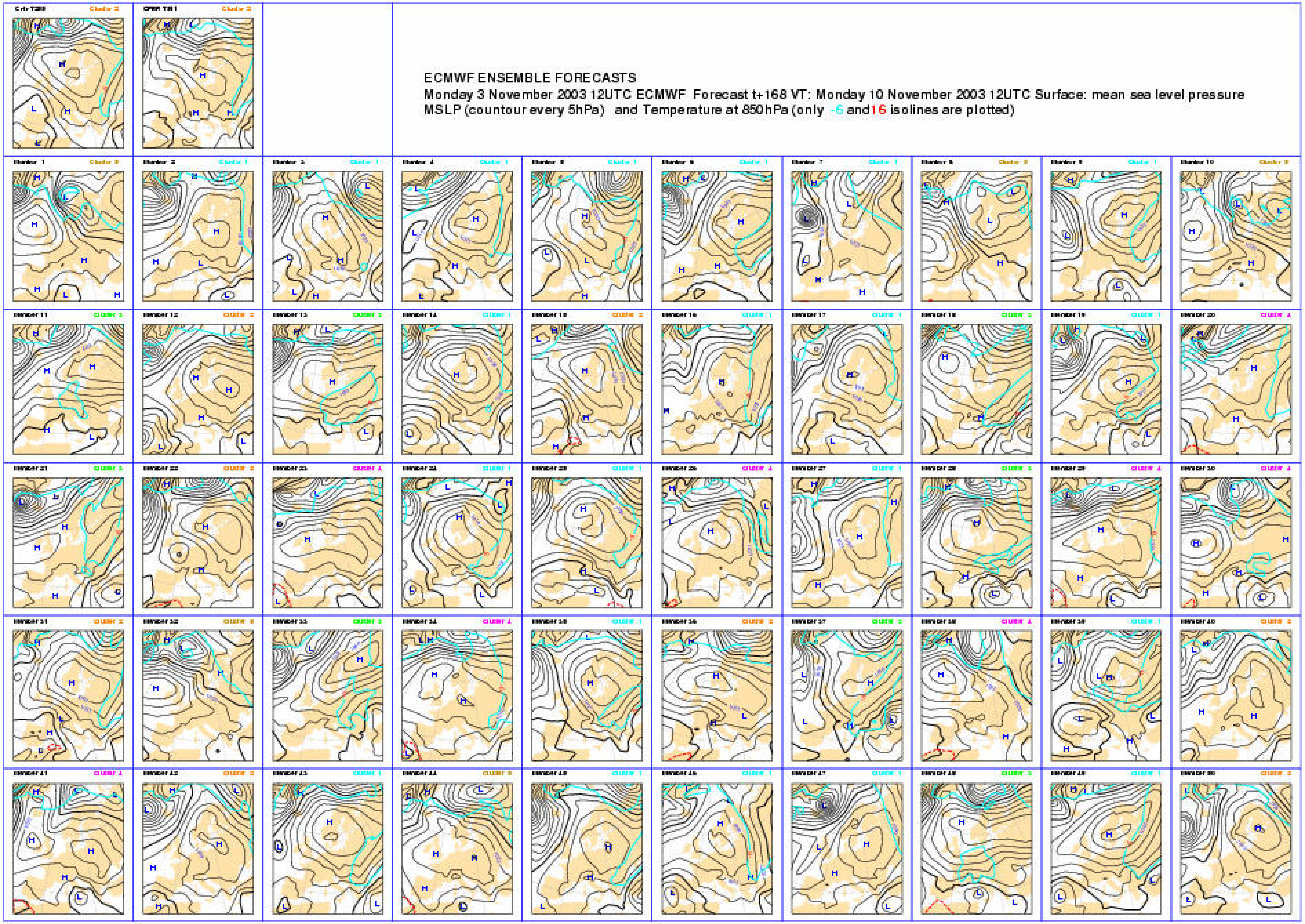
Variation in Predictability

Highly Predictable

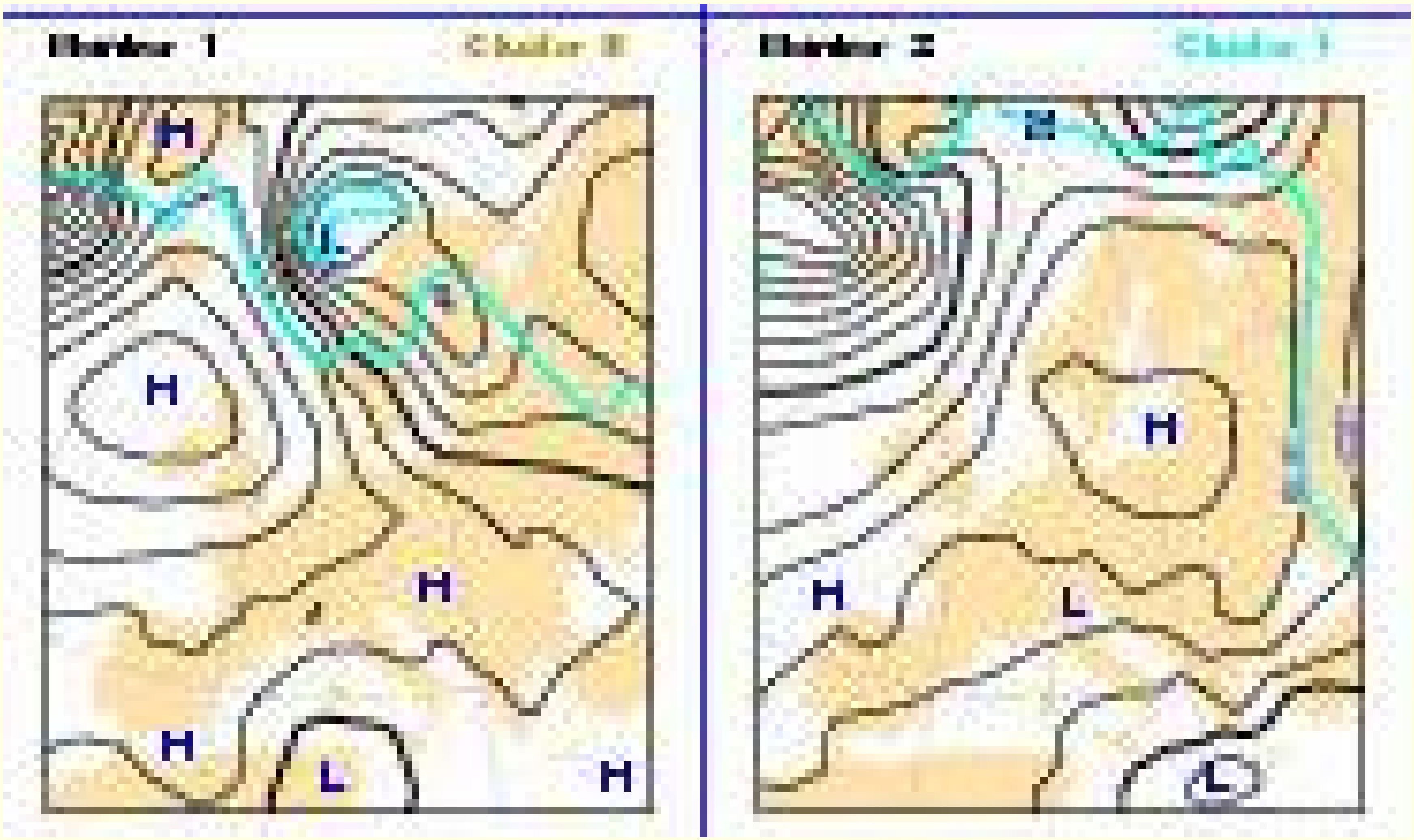


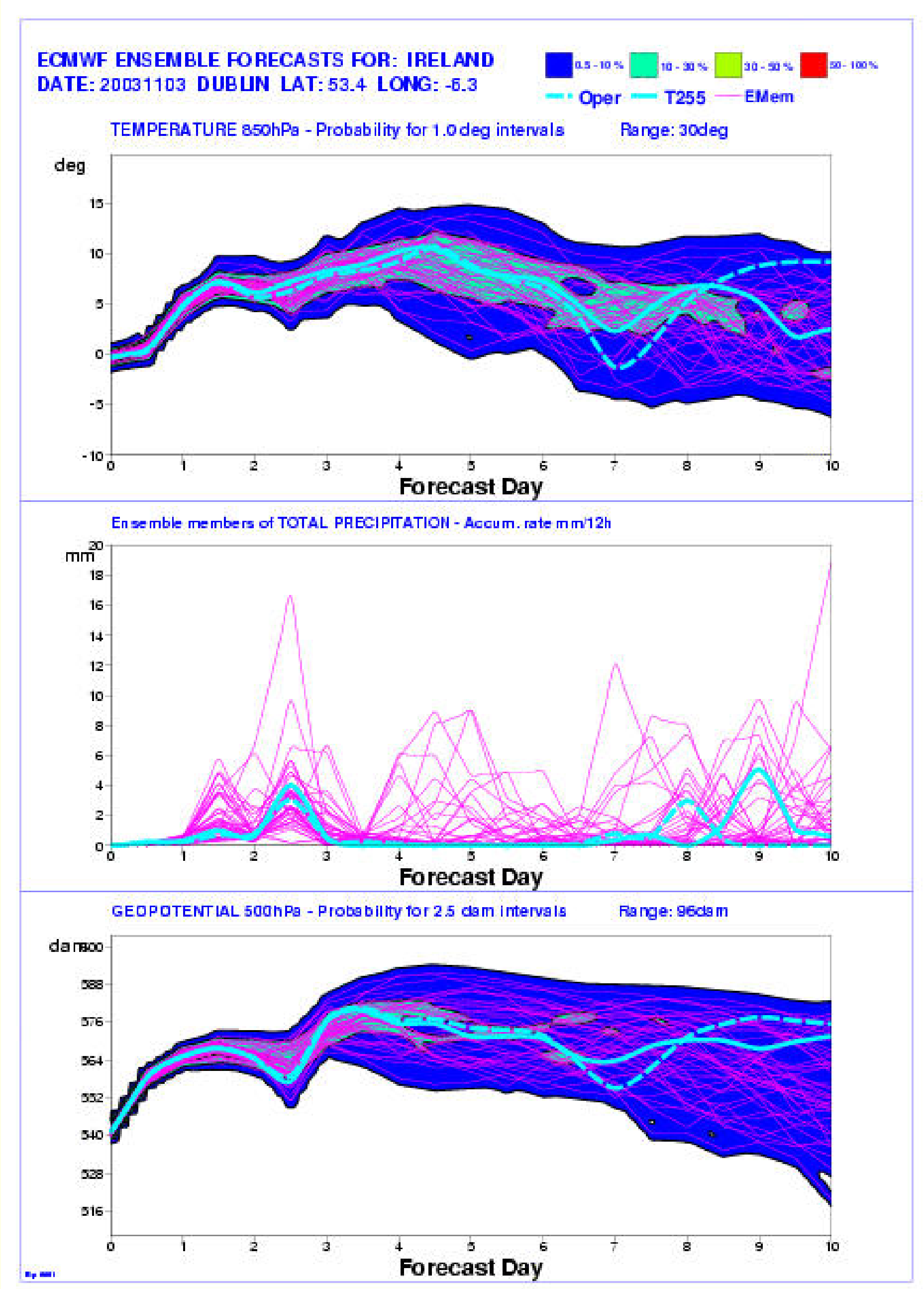
Highly Unpredictable

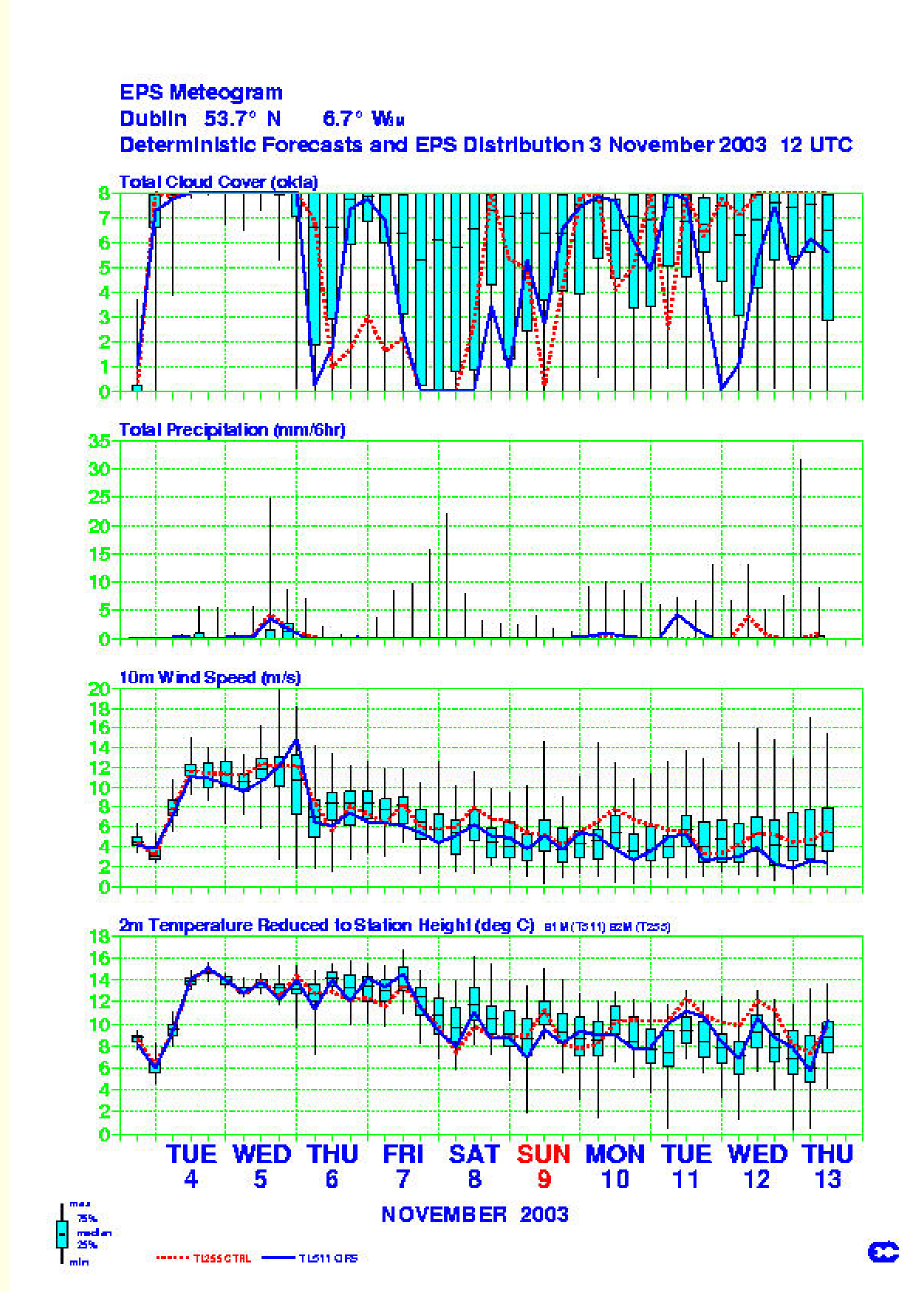
Laminar and Turbulent Flow


ECMWF ENSEMBLE FORECASTS
Monday 3 November 2003 12UTC ECMWF Forecast t+168 VT: Monday 10 November 2003 12UTC Surface: mean sea level pressure
MSLP (countour every 5hPa) and Temperature at 850hPa (only -6 and 16 isolines are plotted)

Ensemble Forecast for Today

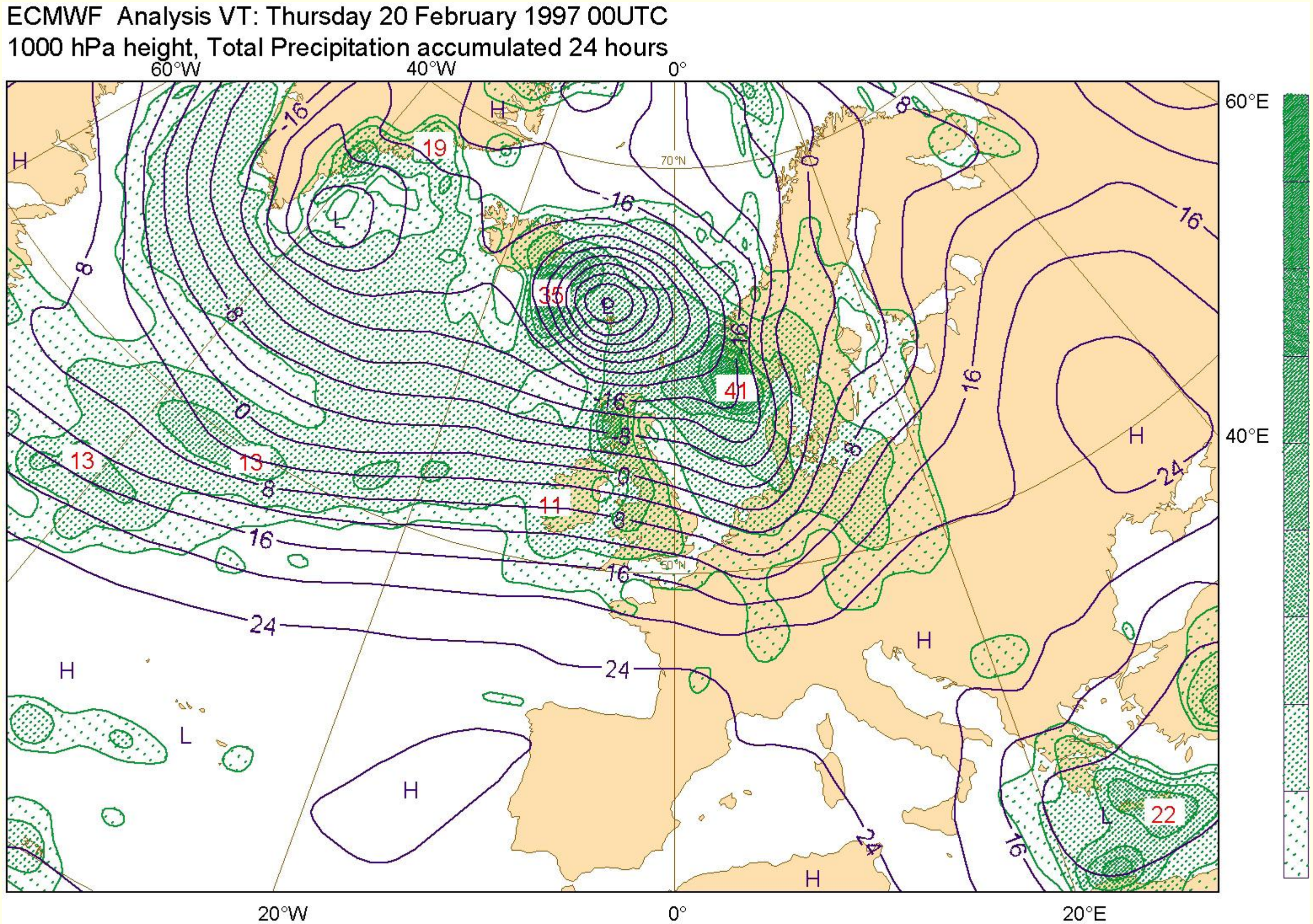



ECMWF ENSEMBLE FORECASTS FOR: IRELAND
DATE: 20031103 DUBLIN LAT: 53.4 LONG: -6.3
Oper
T255
EMem
TEMPERATURE 850hPa - Probability for 1.0deg intervals
Range: 30deg
deg
Forecast Day
Ensemble members of TOTAL PRECIPITATION - Accum. rate mm/12h
mm
Forecast Day
GEOPOTENTIAL 500hPa - Probability for 2.5 dam intervals
Range: 96dam
dam
Forecast Day


EPS Meteogram
Dublin 53.7° N 6.7° W
Deterministic Forecasts and EPS Distribution 3 November 2003 12 UTC
Total Cloud Cover (okta)
Total Precipitation (mm/6hr)
10m Wind Speed (m/s)
2m Temperature Reduced to Station Height (deg C)
TUE 4
WED 5
THU 6
FRI 7
SAT 8
SUN 9
MON 10
TUE 11
WED 12
THU 13
NOVEMBER 2003
max
75%
median
25%
min
T255 CTRL
TL511 OPS

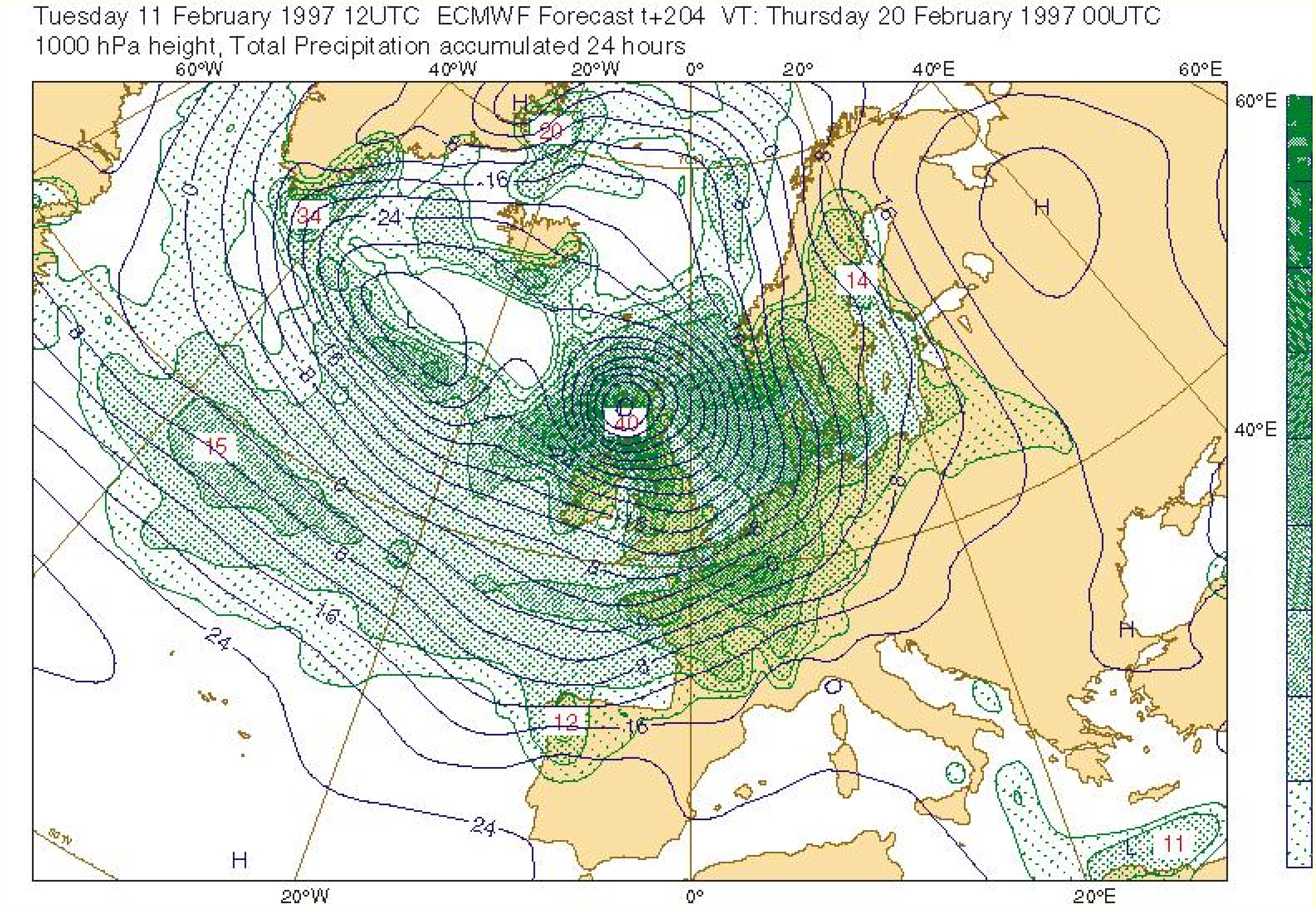
Deterministic Forecast Accuracy

Objective Analysis of Pressure



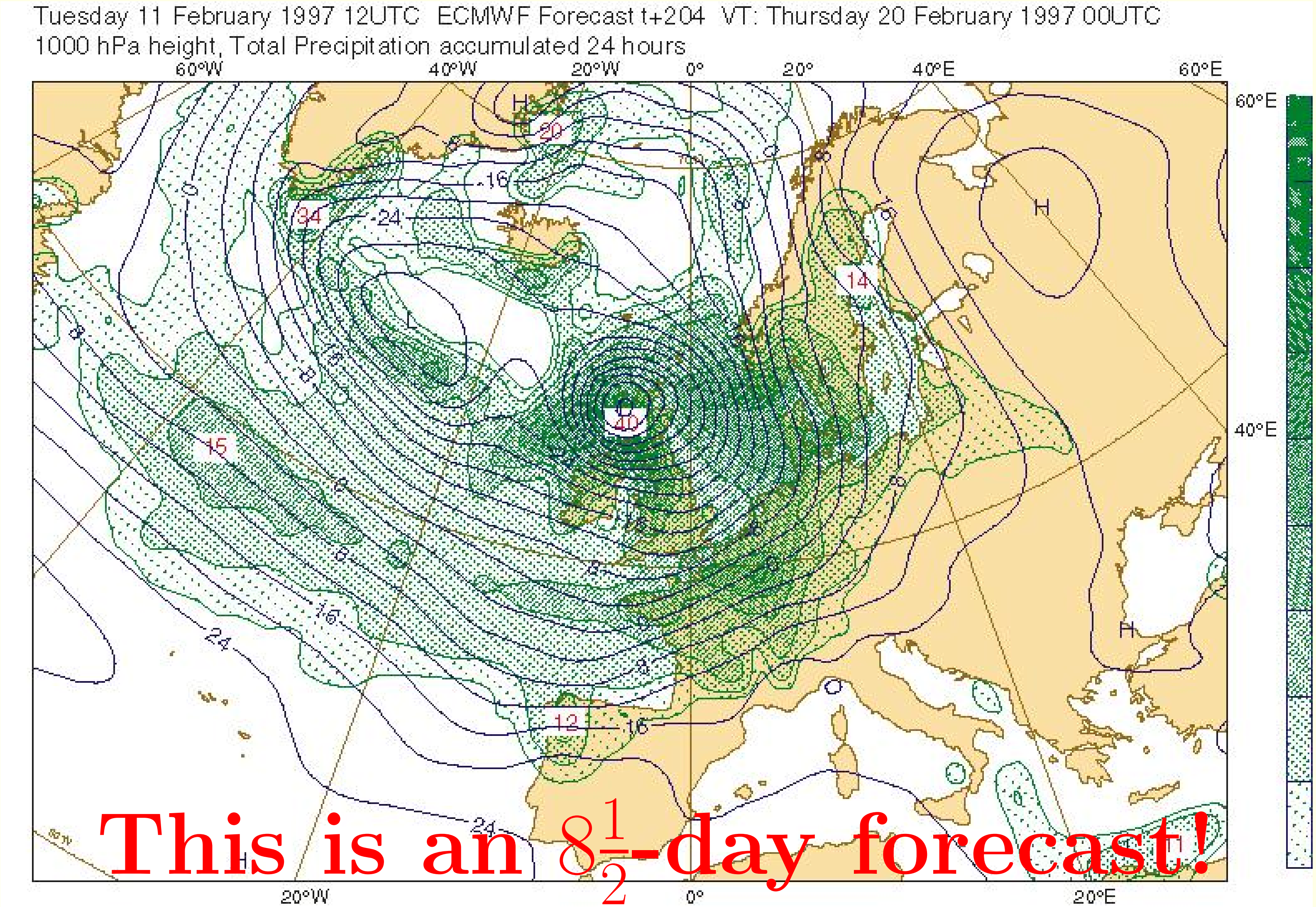
Analysis of 1000hPa height and 24hr precipitation.

Prediction of Surface Conditions



Forecast of 1000hPa height and 24hr precipitation.

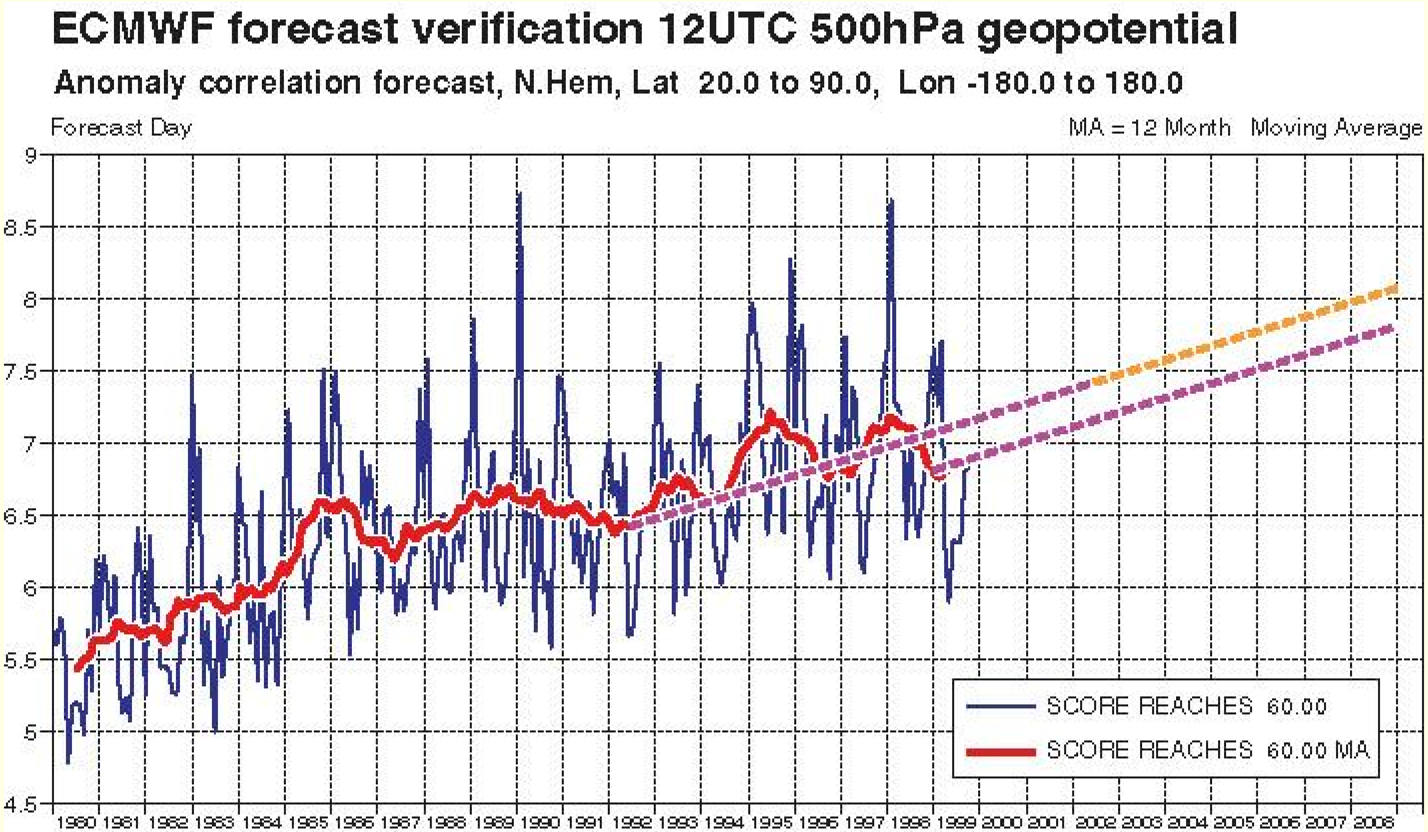
Prediction of Surface Conditions



This is an $8\frac{1}{2}$-day forecast!

Forecast of 1000hPa height and 24hr precipitation.

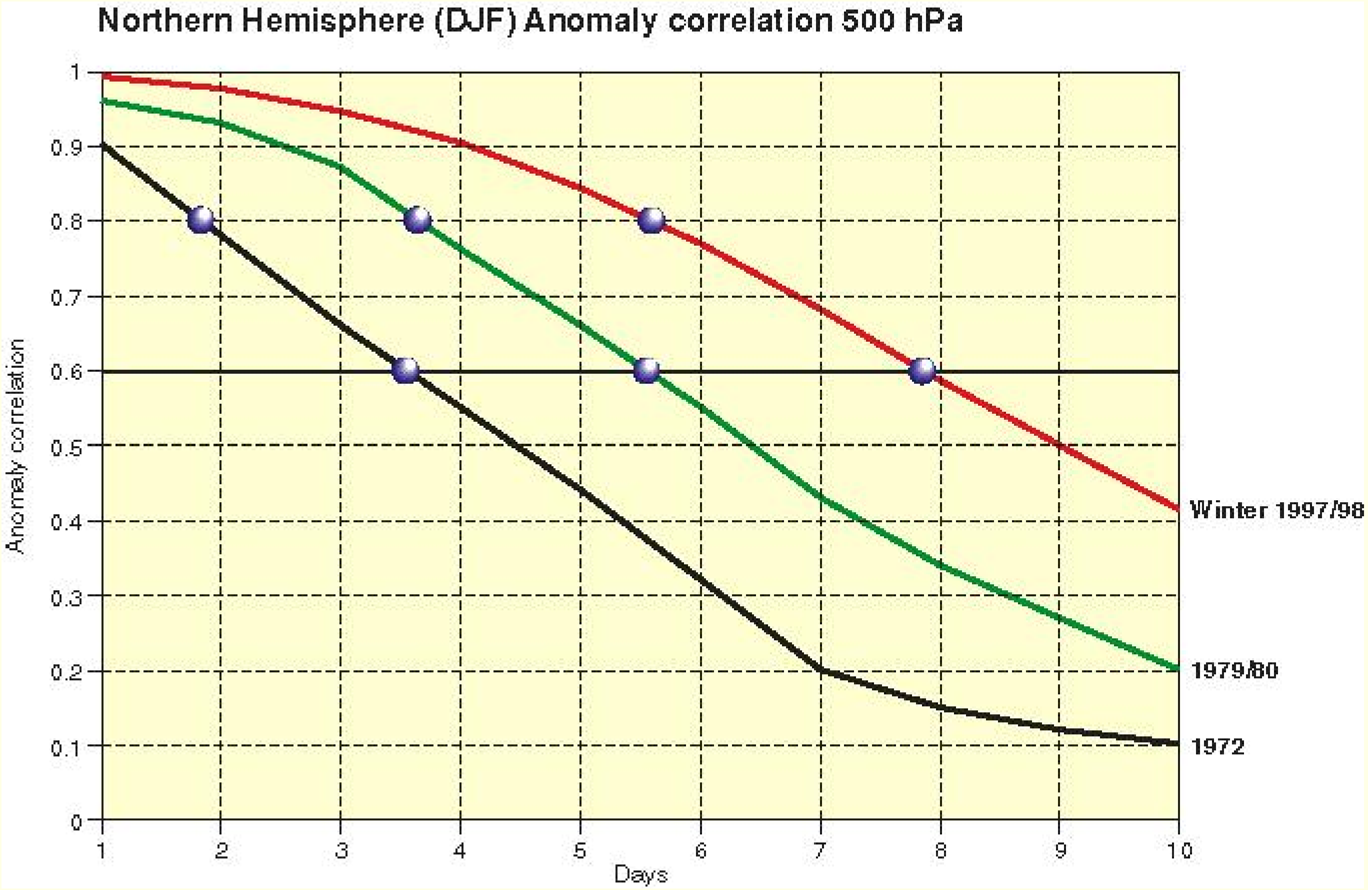
Objective Measure of Skill



Skill of 500 mb geopotential height. Forecast day when Anomaly Correlation falls to 0.6

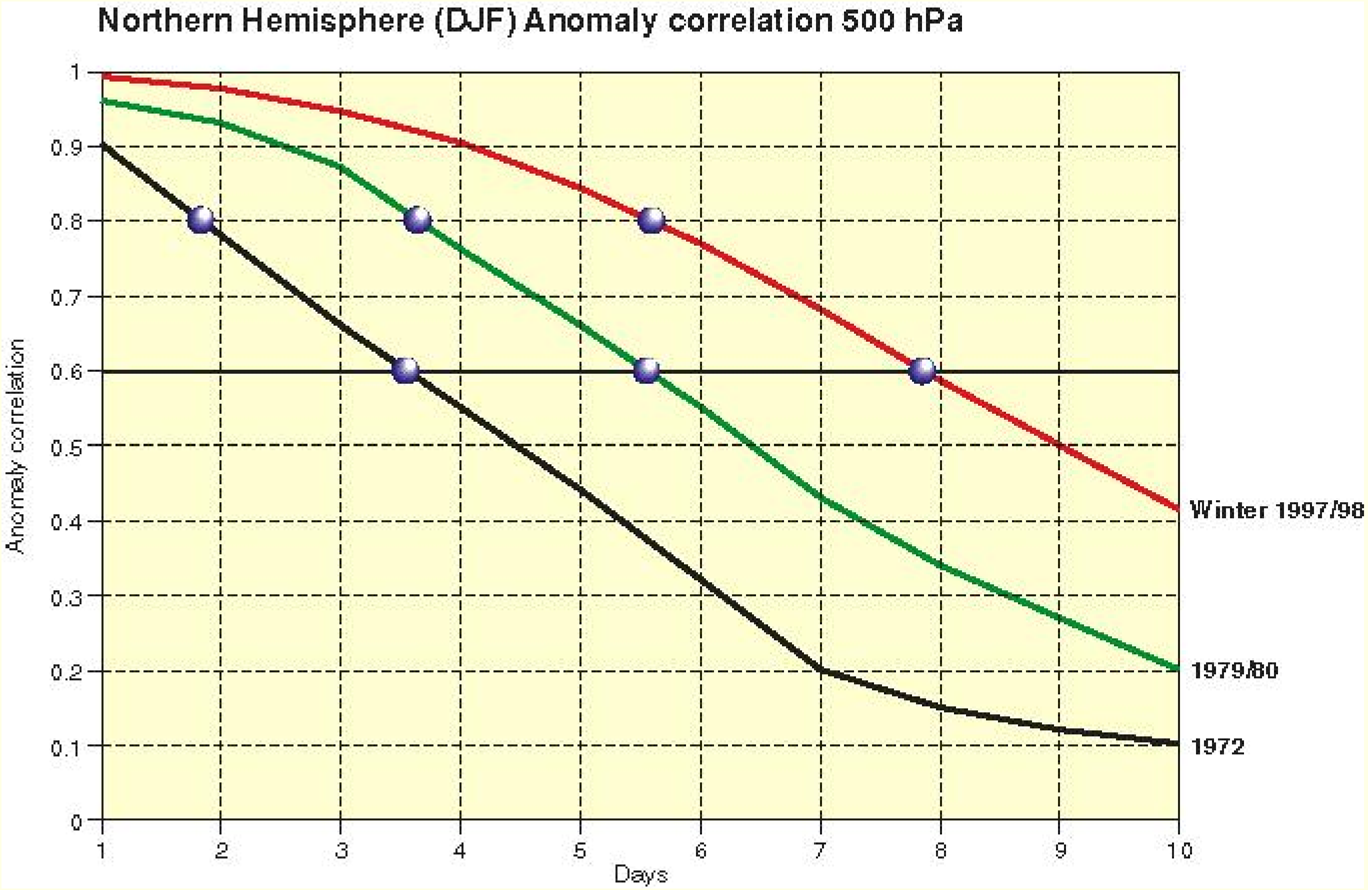
This is a measure of the useful forecast range.

Objective Measure of Skill



Comparative skill of 500 mb forecasts.

Objective Measure of Skill



Comparative skill of 500 mb forecasts.
The six-day forecasts now are as good as the two-day forecasts were in 1972.

Current Status of NWP

- ***Much remains to be done in improving the acuracy of short range forecasts.***
- ***We need more accurate prediction of rainfall and of extreme weather events***
- ***The problem of seasonal forecasting remains to be solved***
- ***However, the prospects for future advances are excellent.***

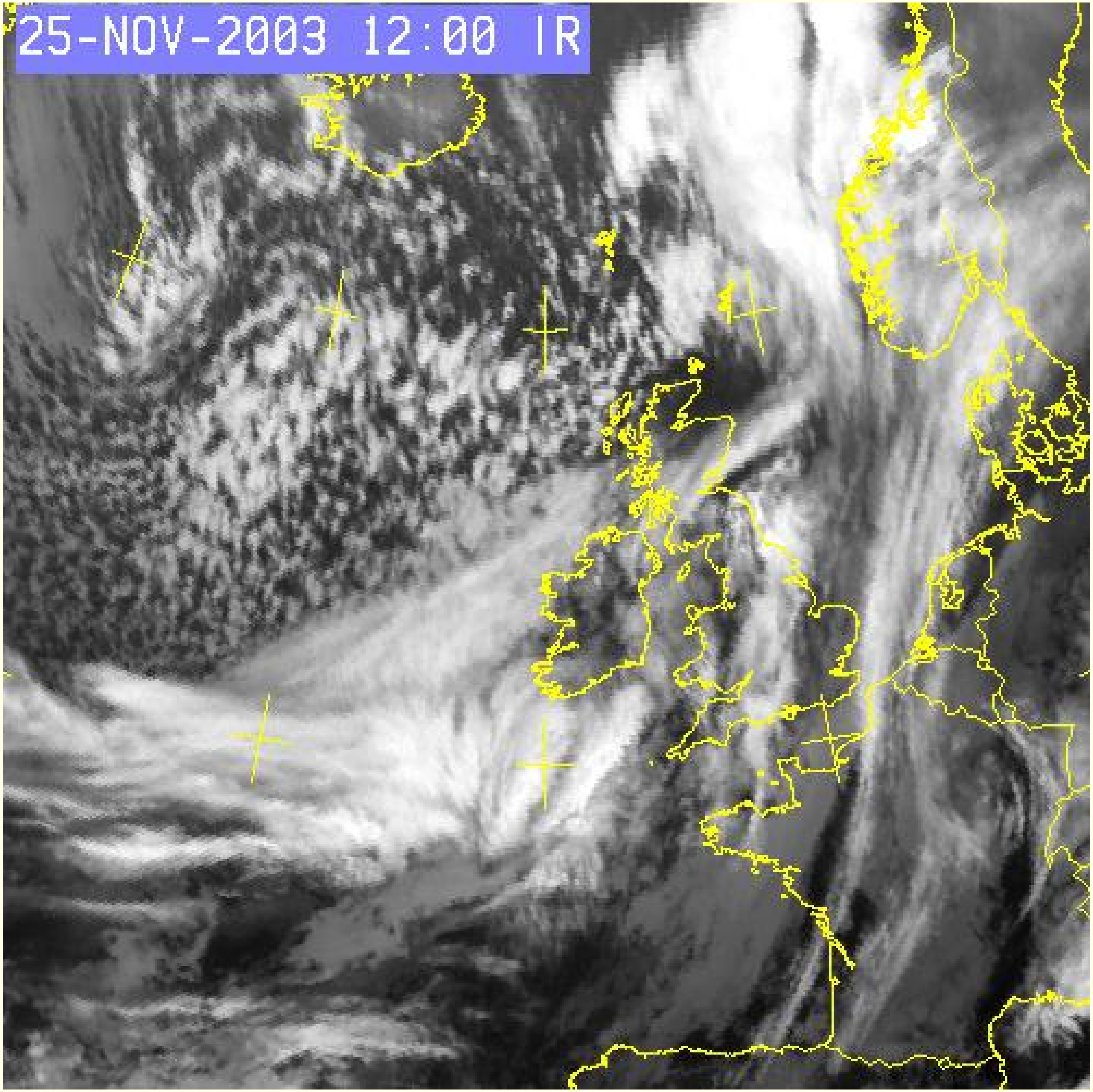
Nowcasting

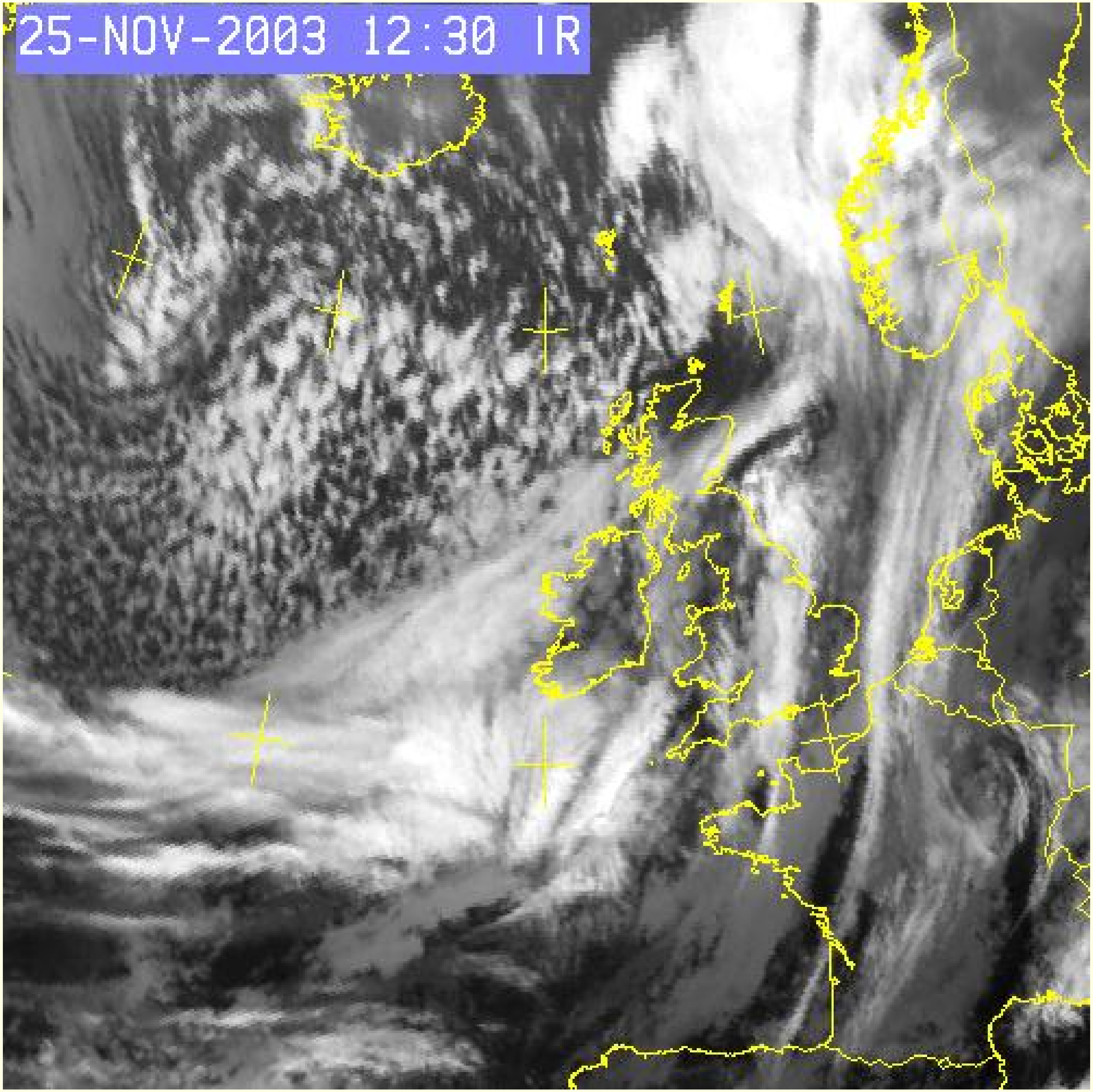
For Very-Short Range Prediction — up to 6 hours ahead — direct observational guidance is vital, in addition to computer model guidance. We look at two sources of guidance:

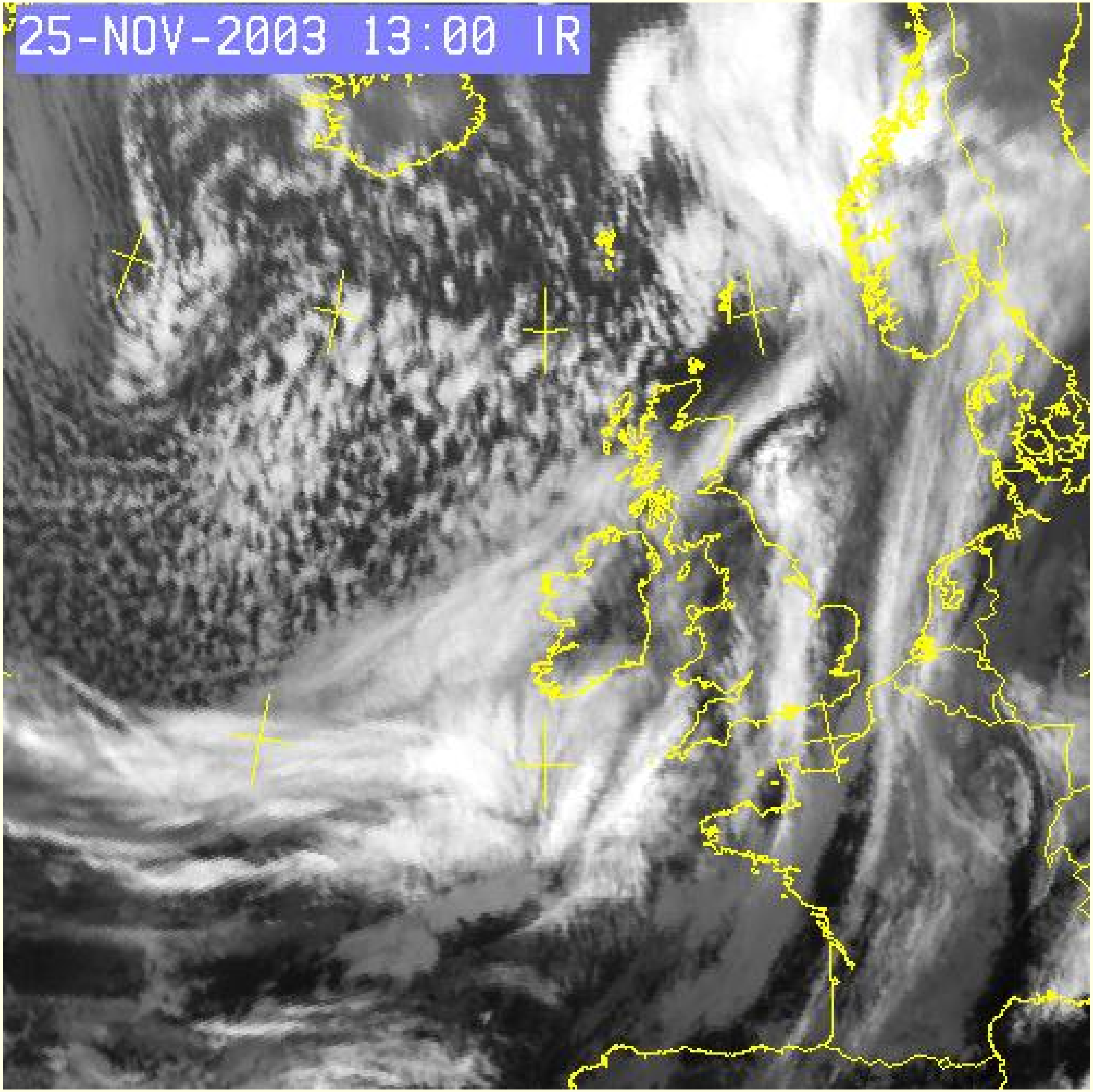
- ***Satellite Imagery***
- ***Radar Data***

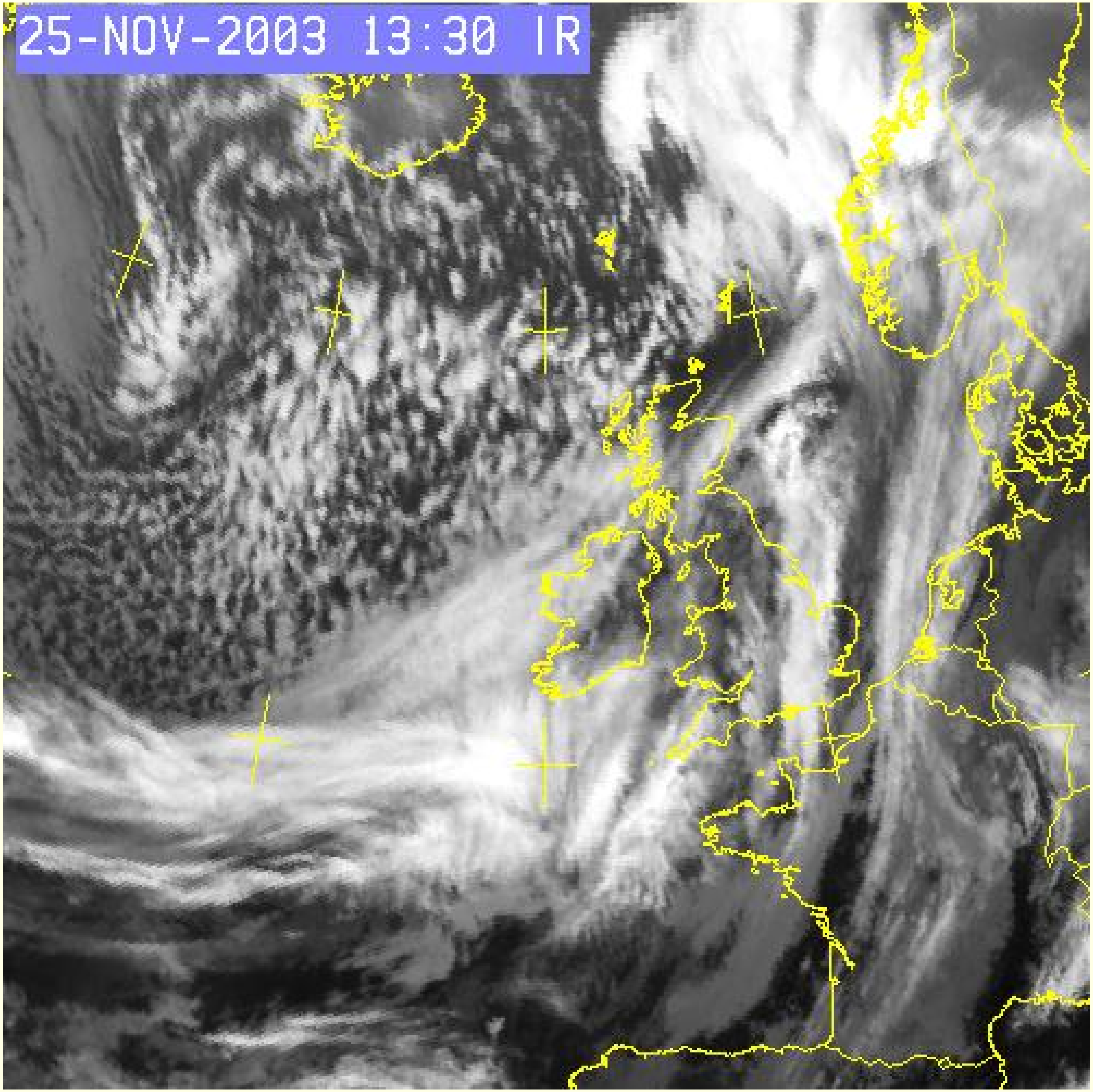
Satellite Imagery

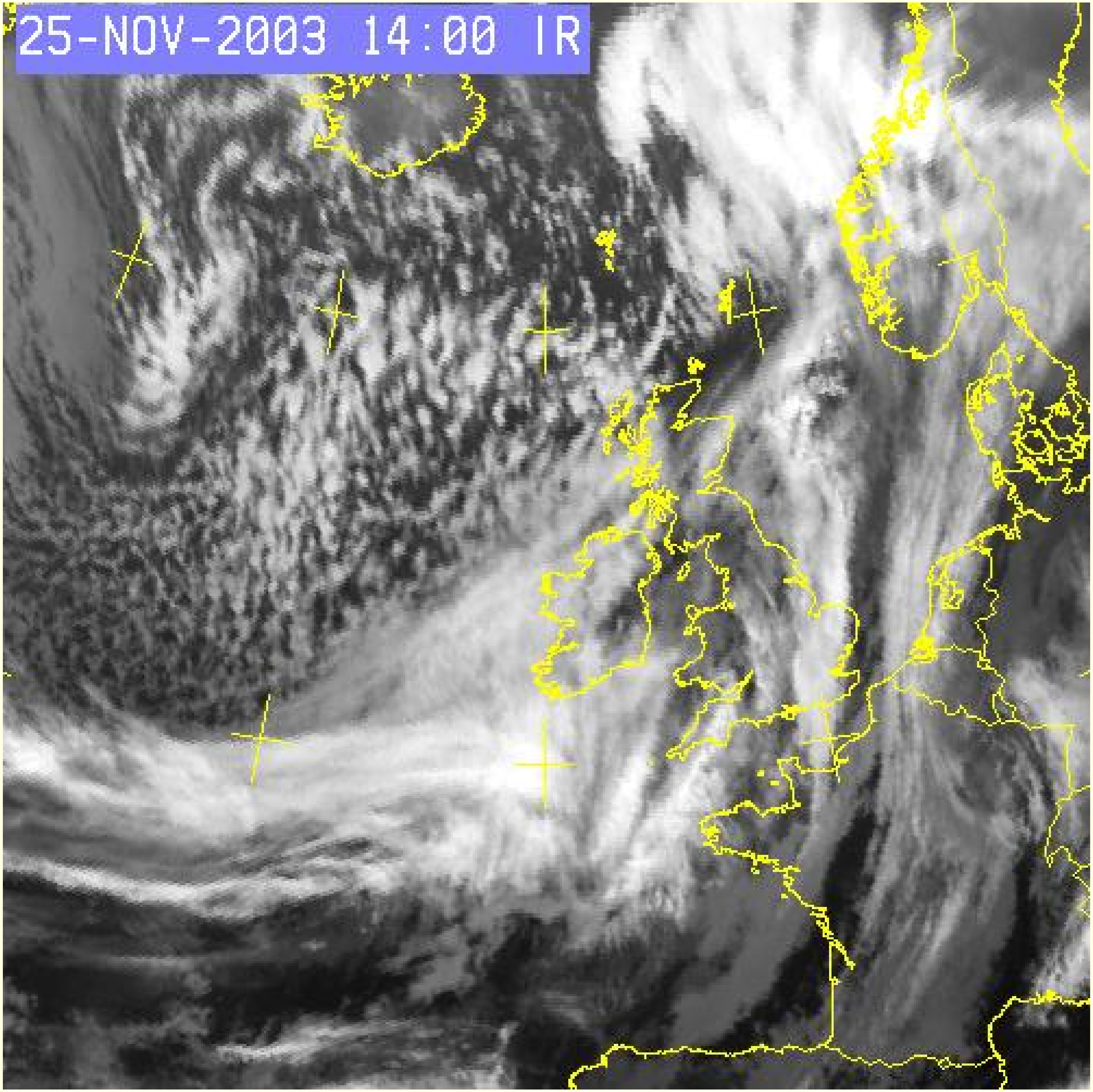
Images from Meteosat, 25 November, 2003, 1200–1800Z

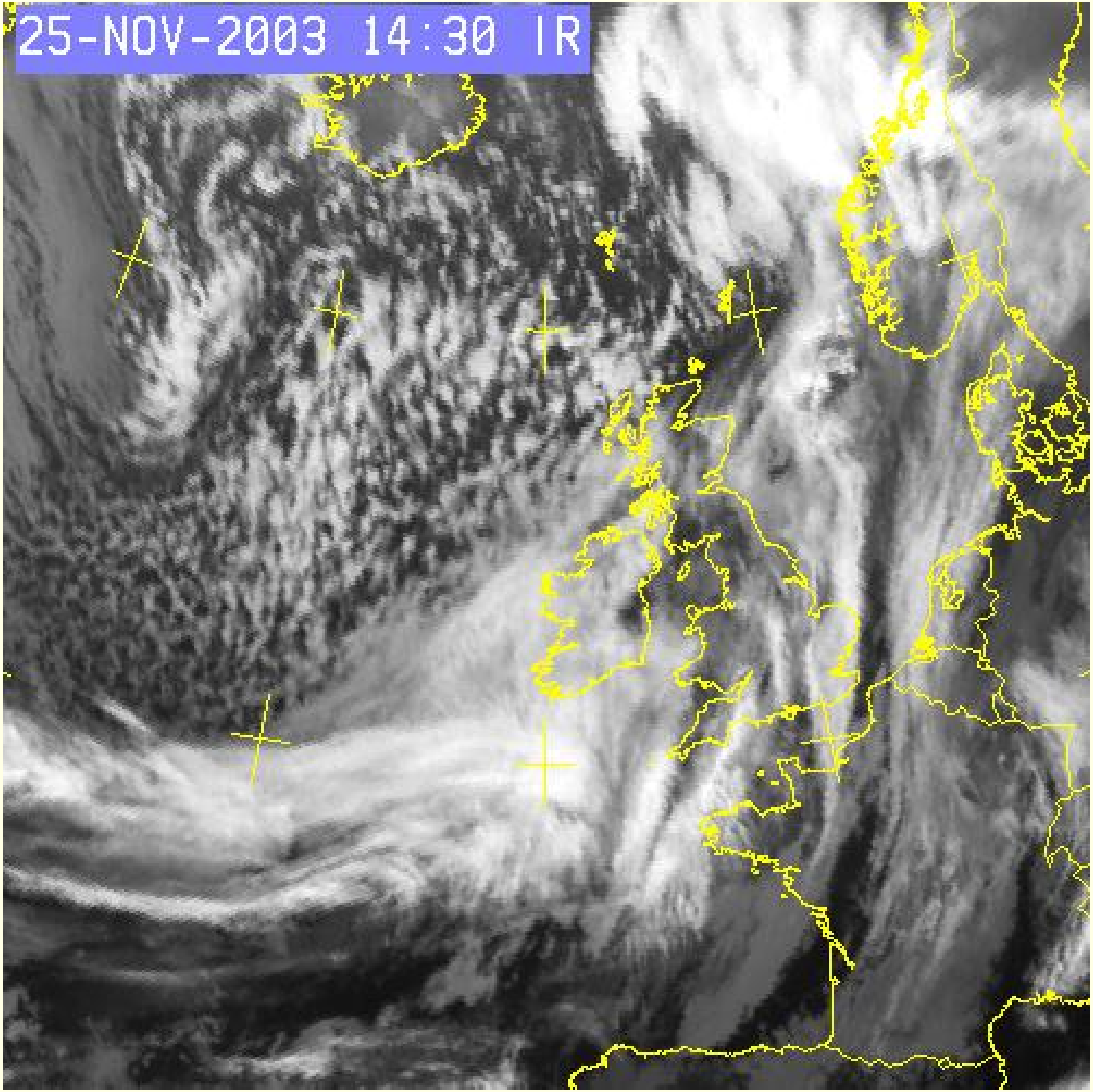

25-NOV-2003 12:00 IR

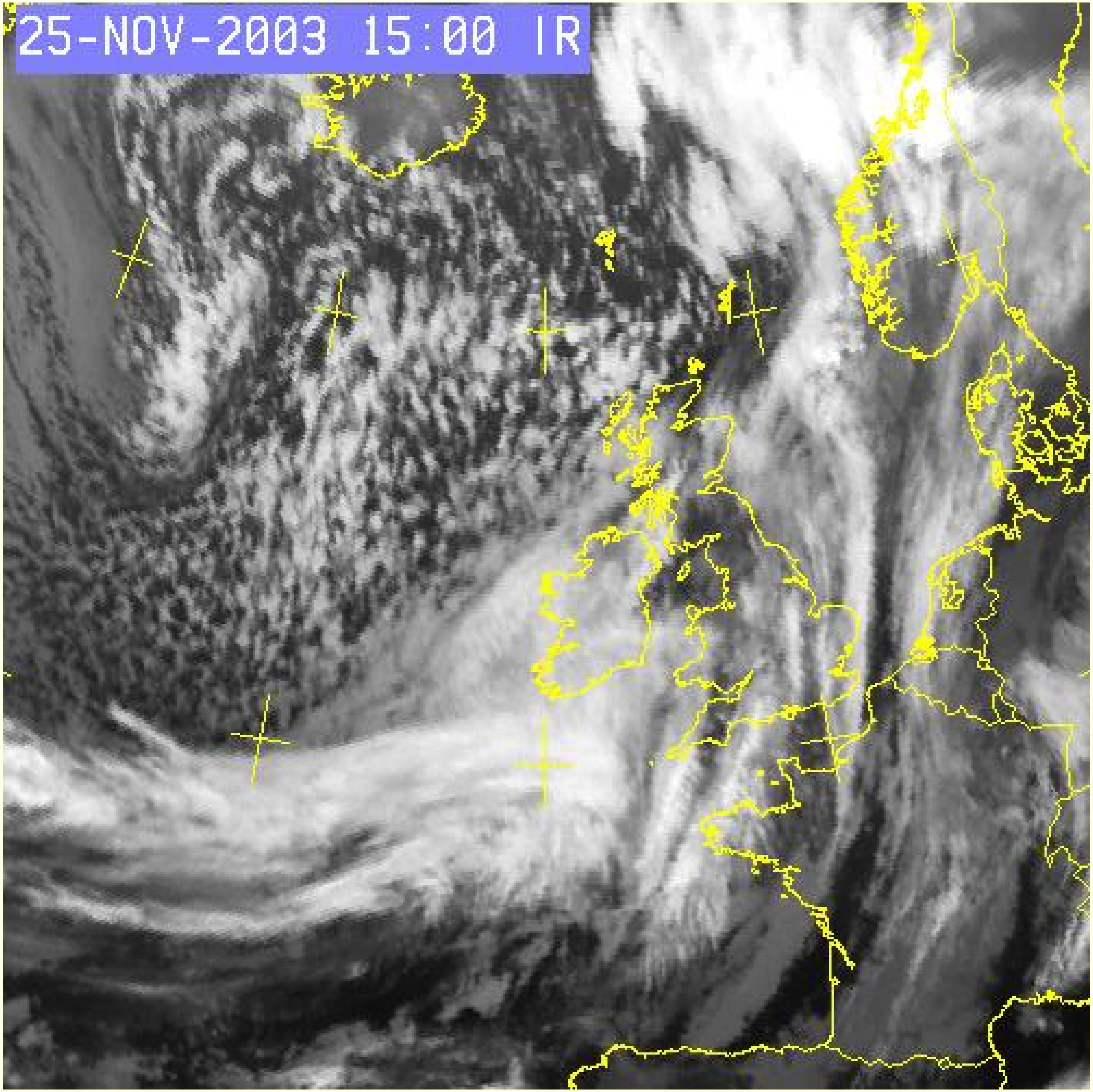

25-NOV-2003 12:30 IR

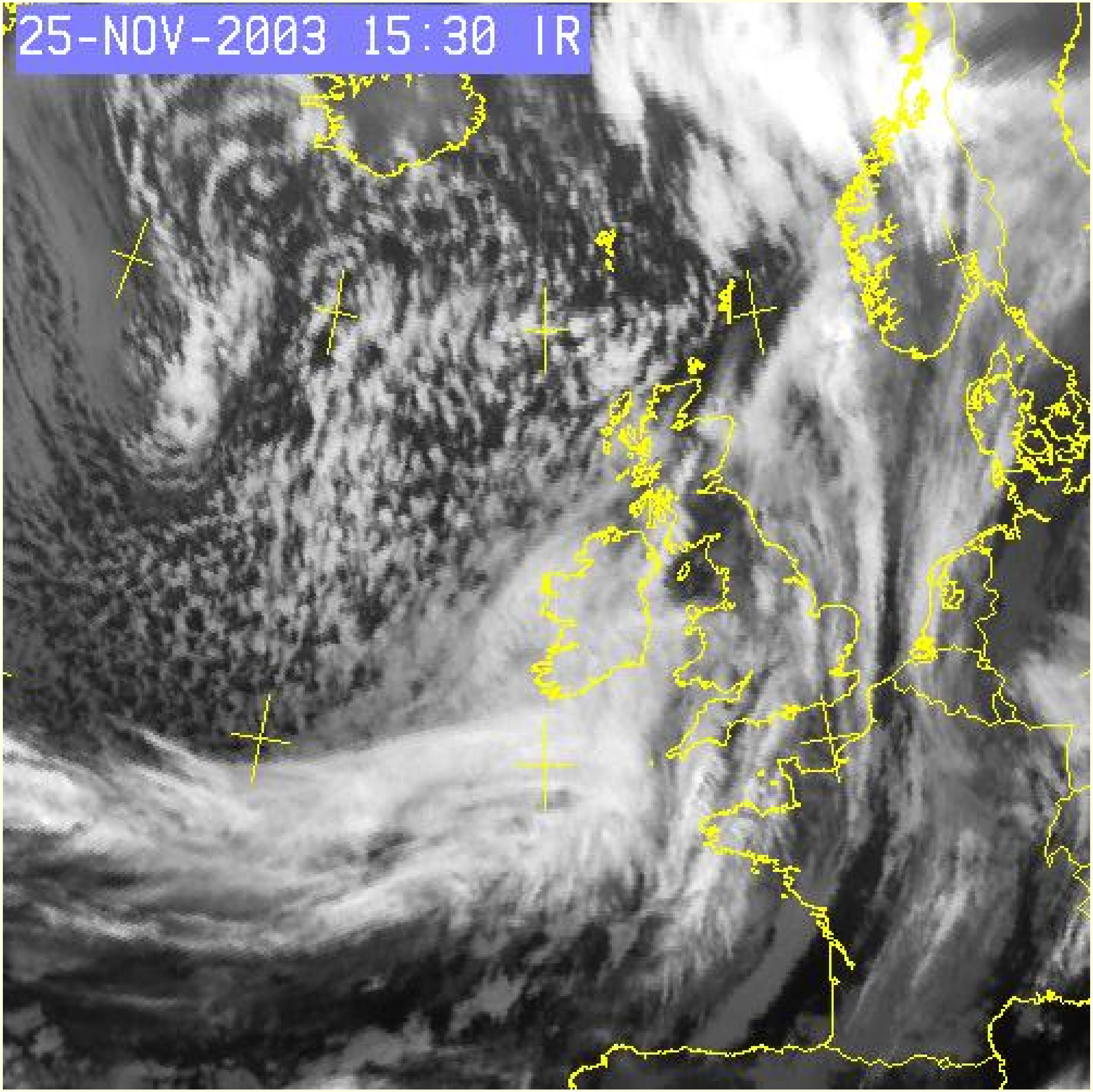

25-NOV-2003 13:00 IR

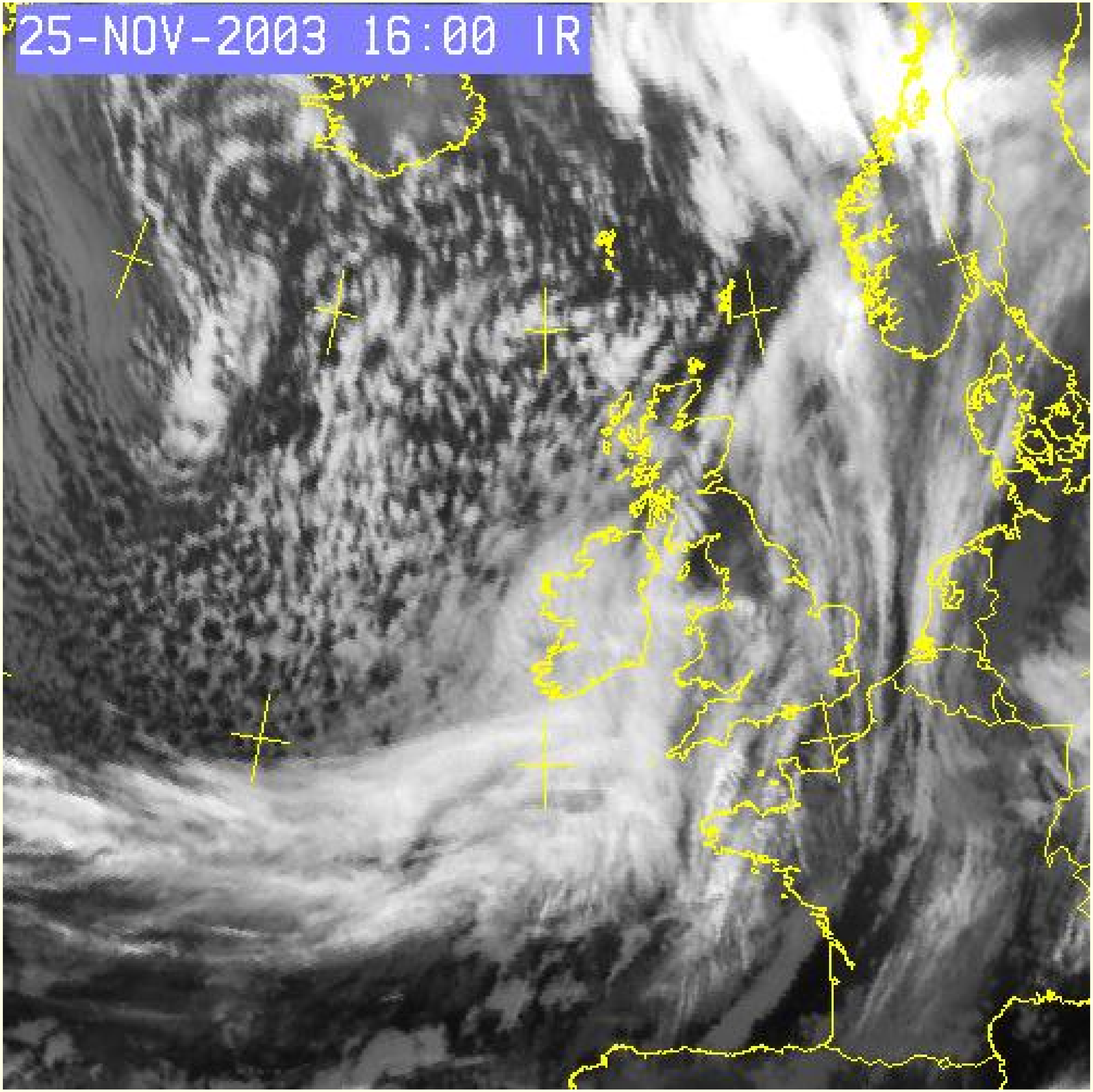

25-NOV-2003 13:30 IR

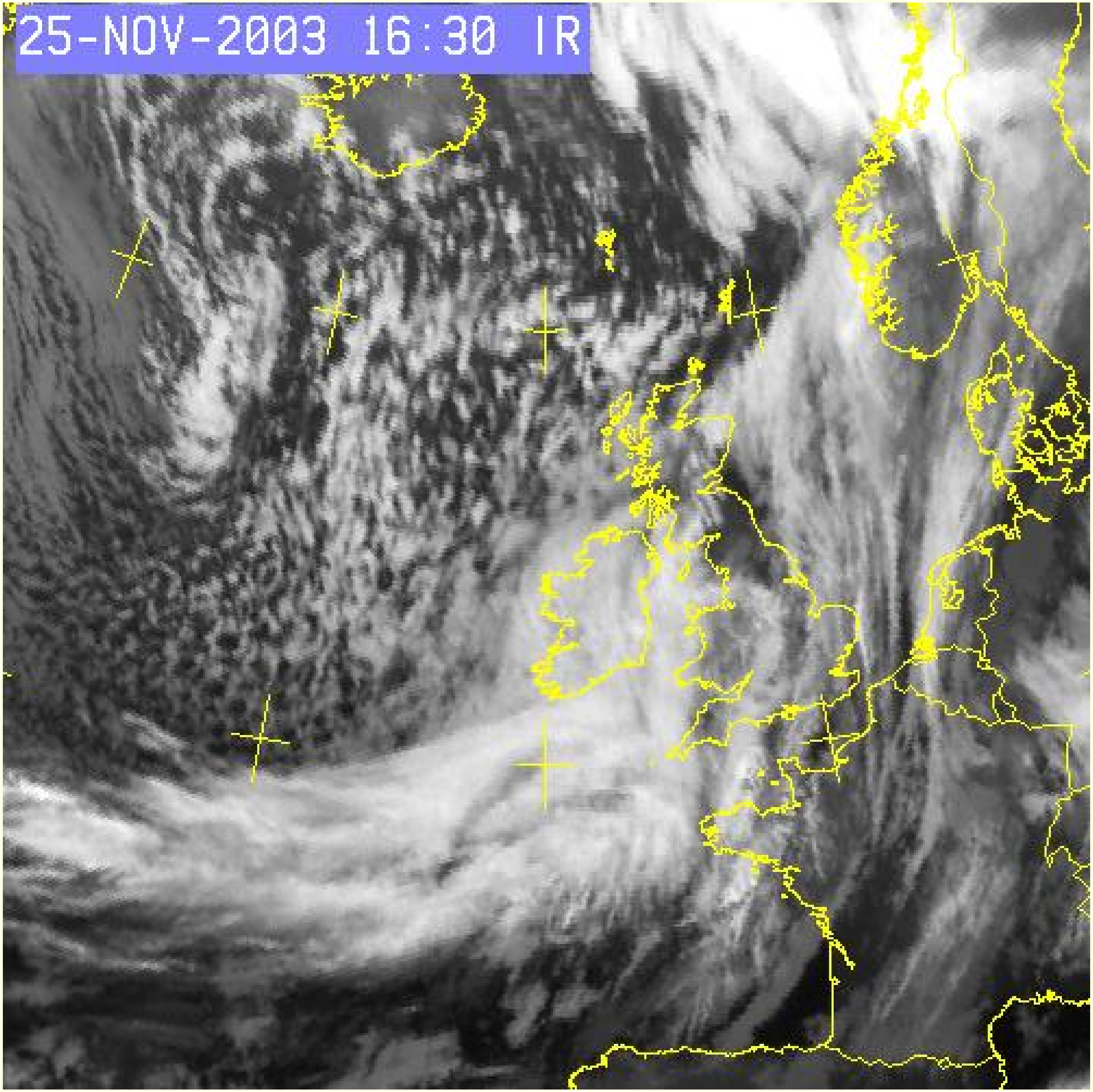

25-NOV-2003 14:00 IR

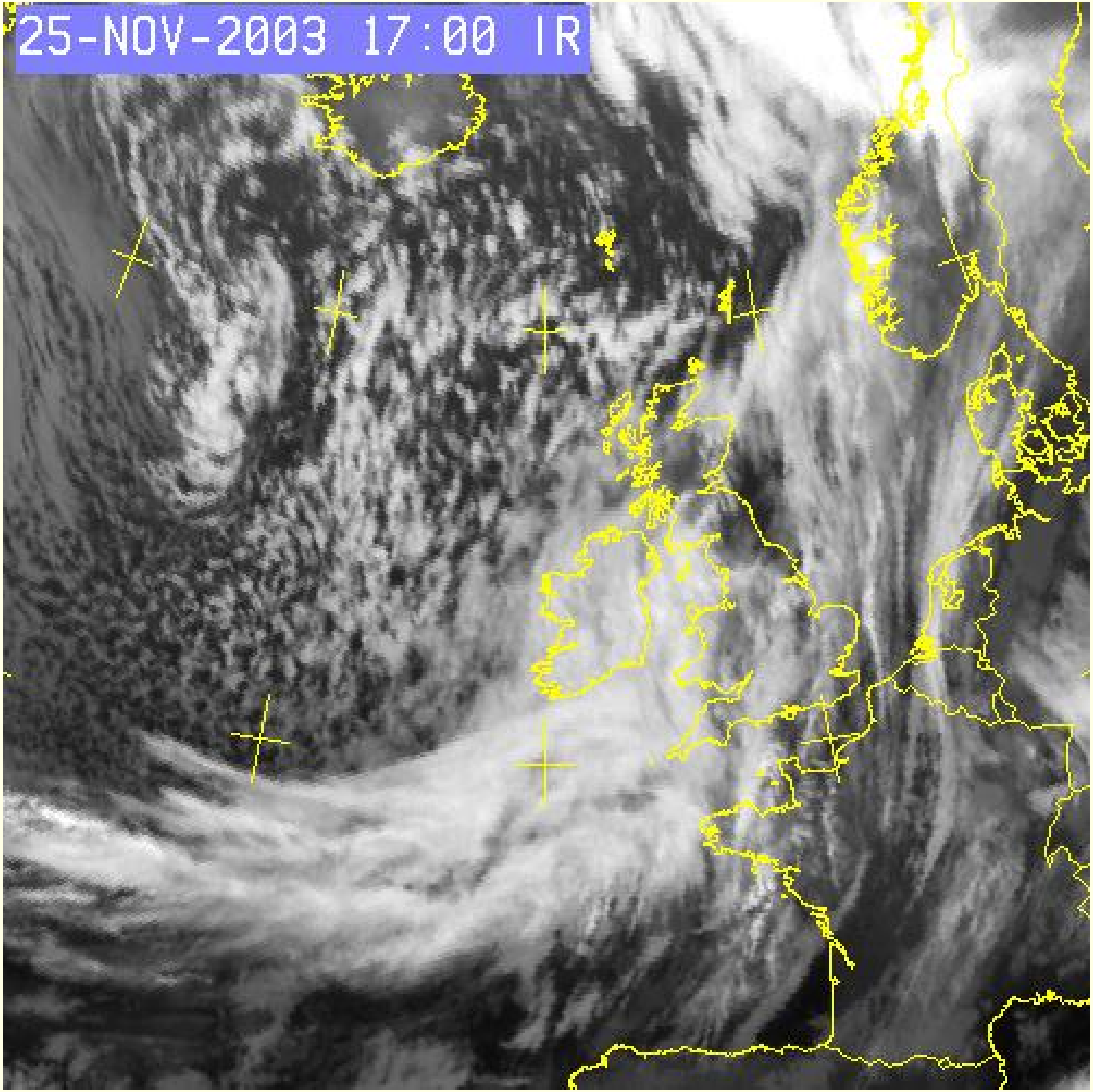

25-NOV-2003 14:30 IR

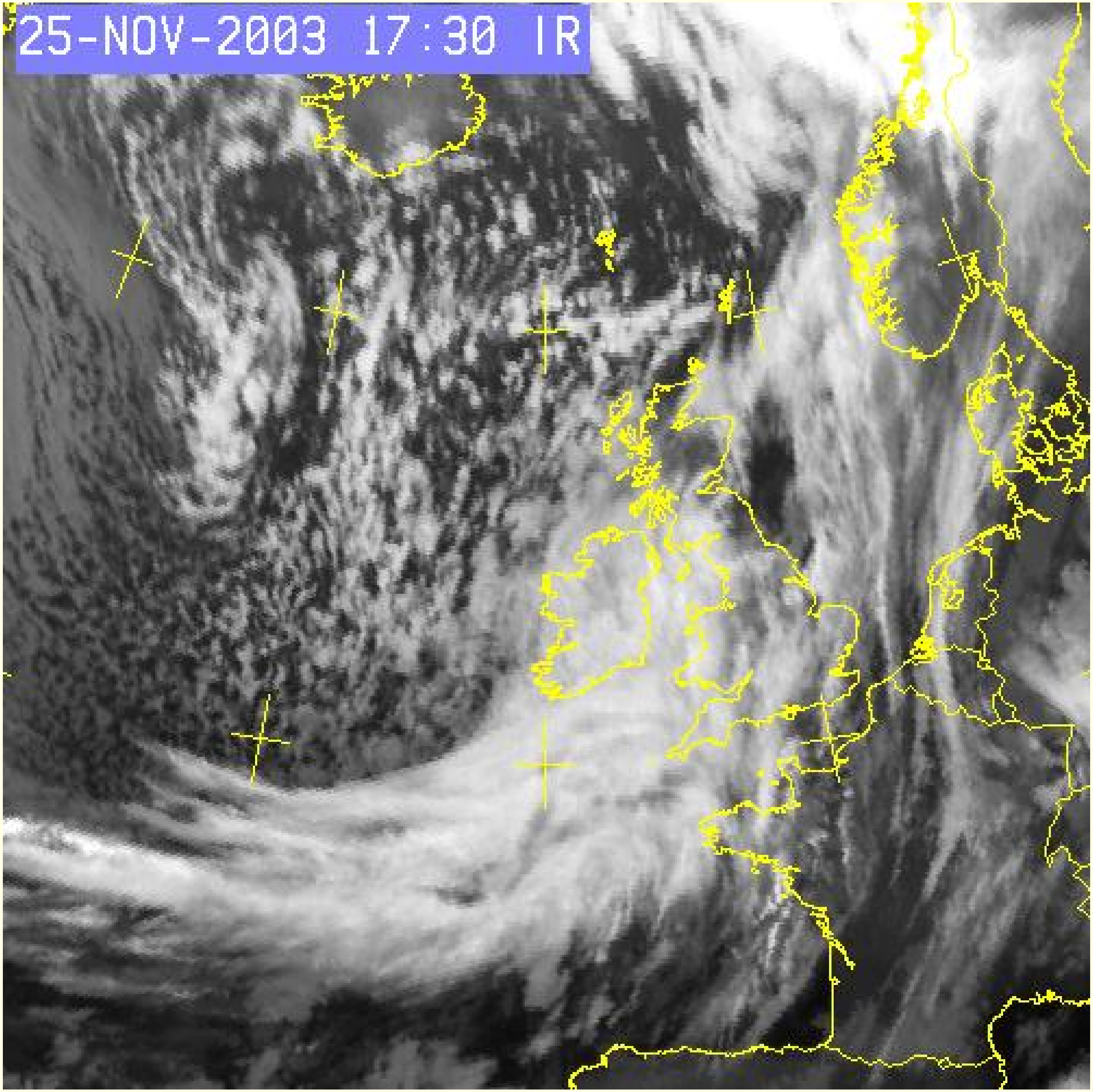

25-NOV-2003 15:00 IR

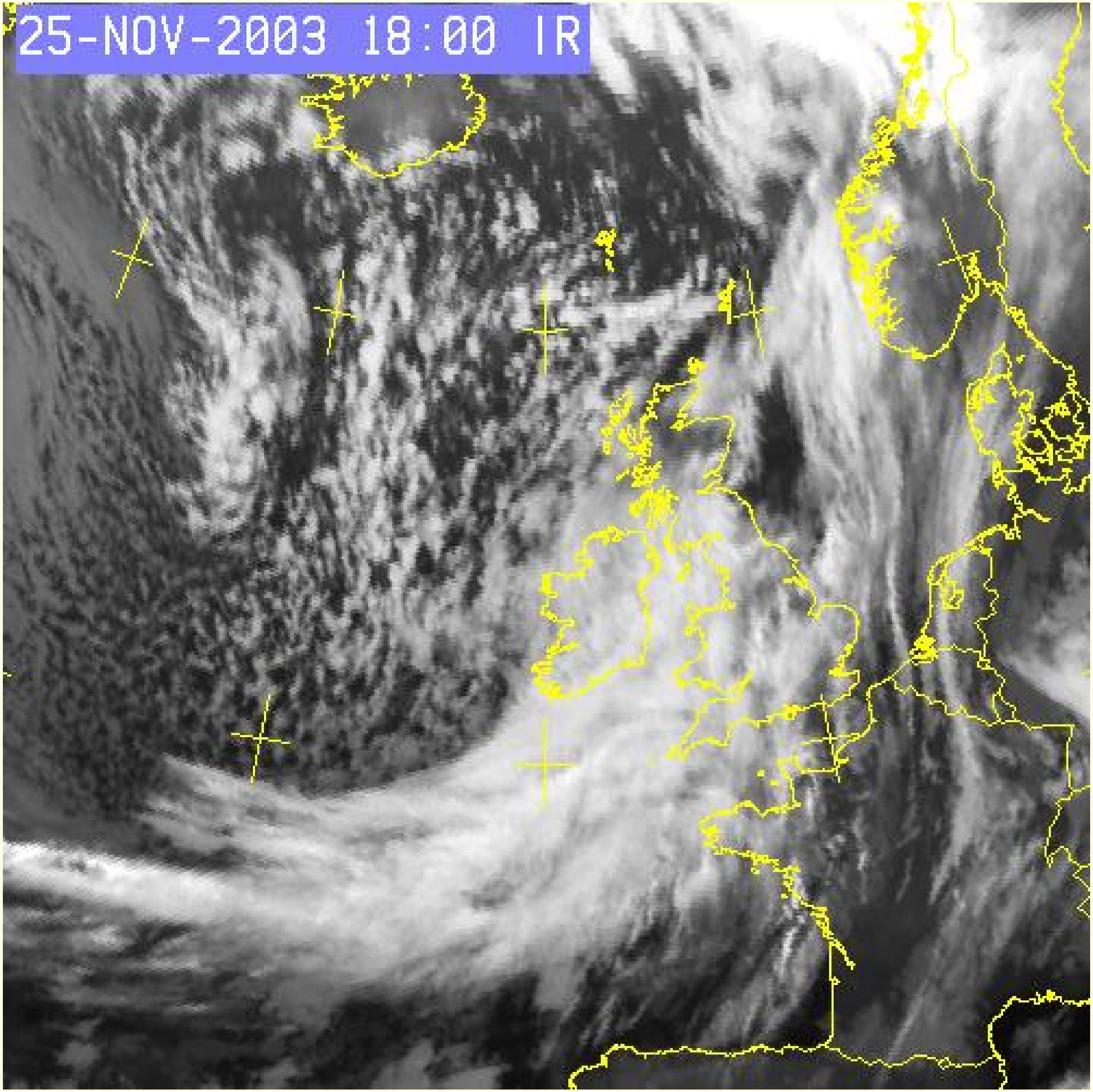

25-NOV-2003 15:30 IR


25-NOV-2003 16:00 IR


25-NOV-2003 16:30 IR

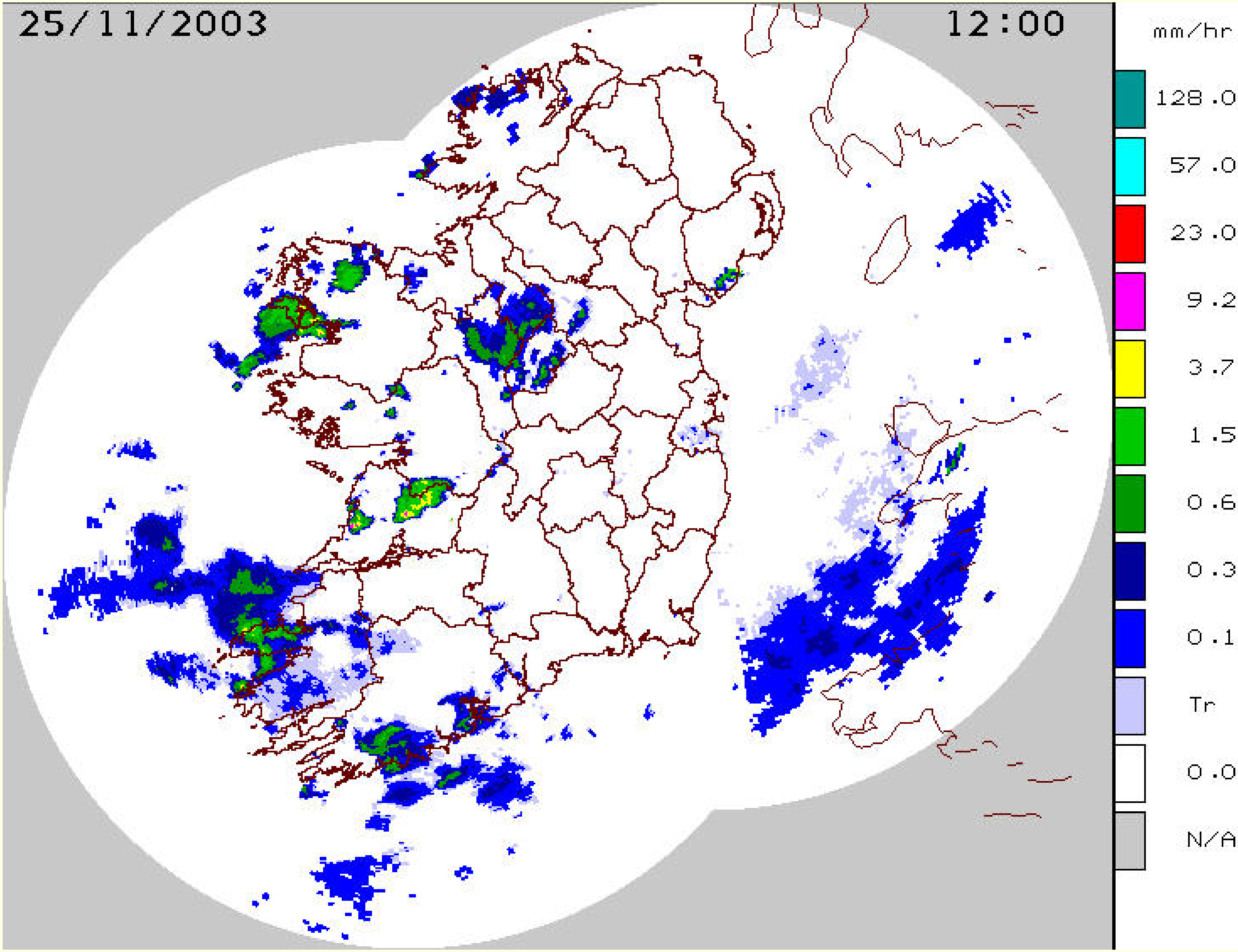

25-NOV-2003 17:00 IR

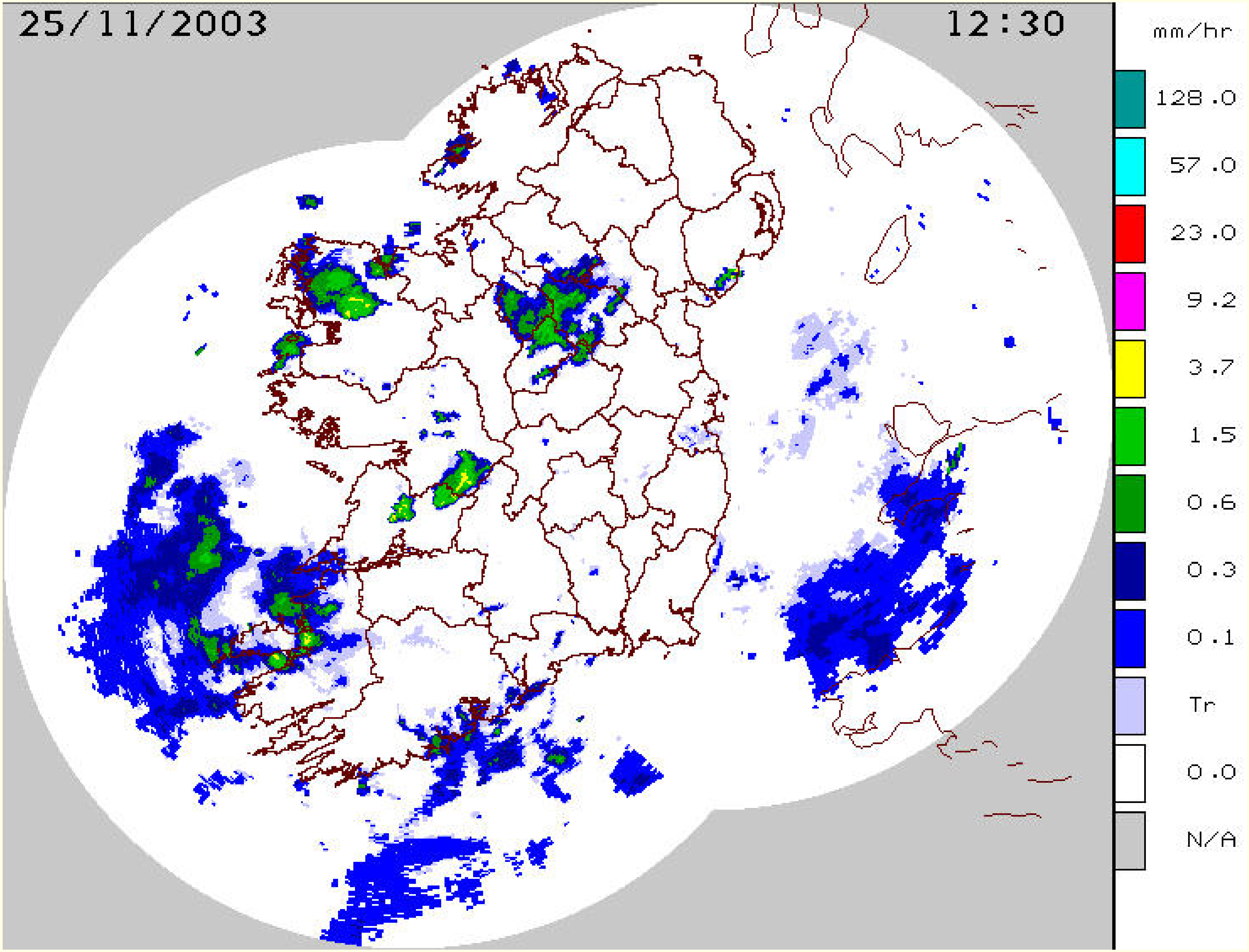

25-NOV-2003 17:30 IR

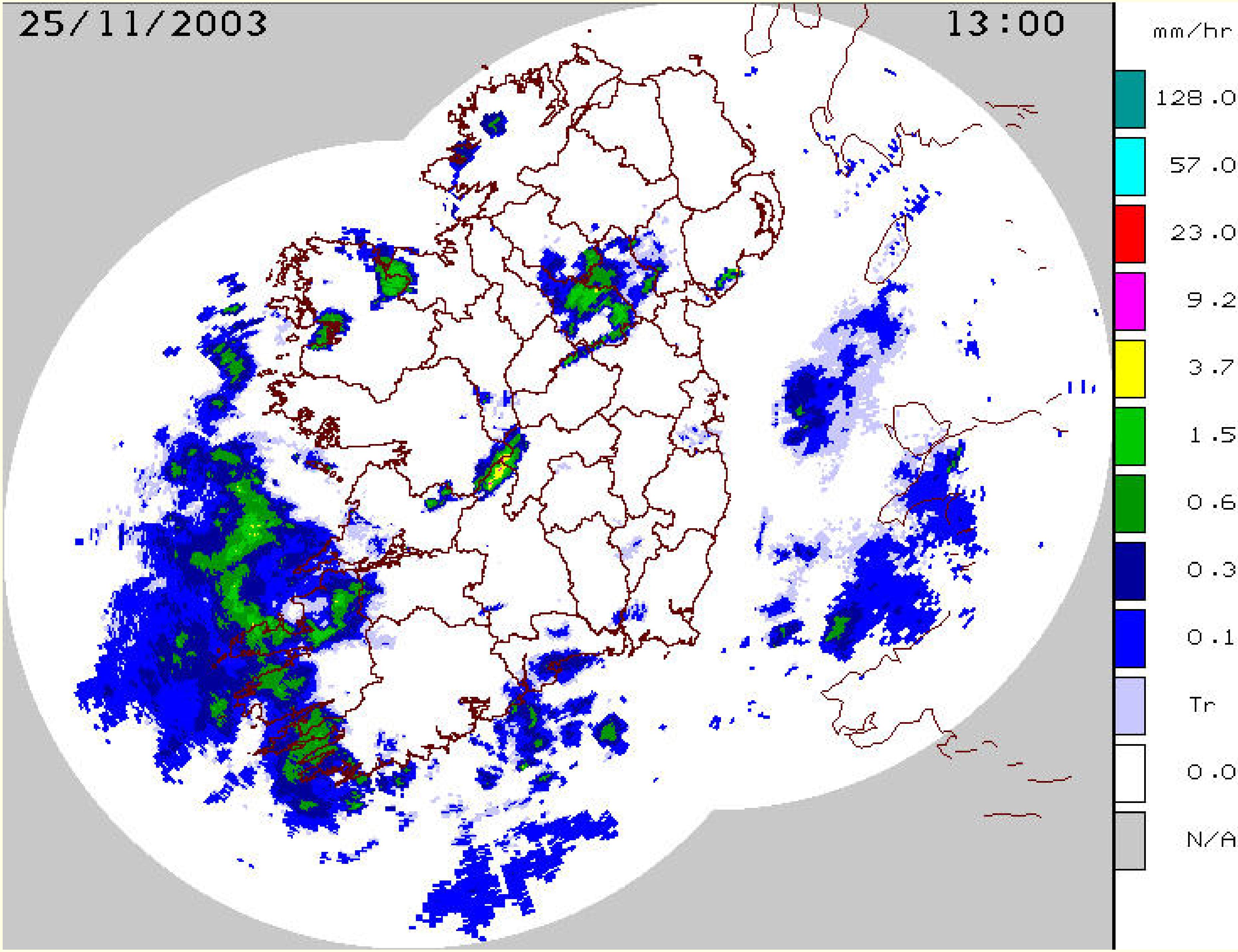

25-NOV-2003 18:00 IR

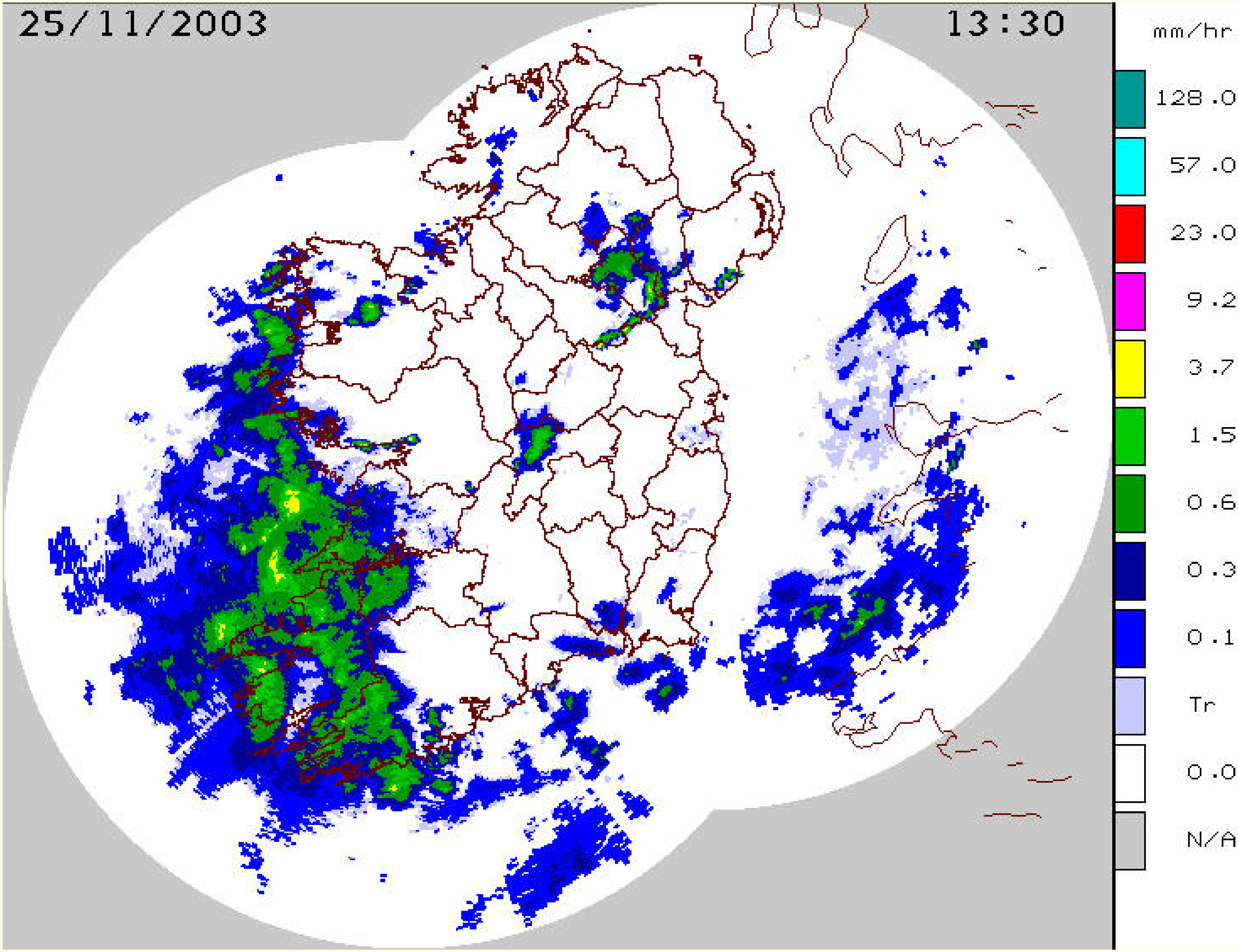
Radar Imagery

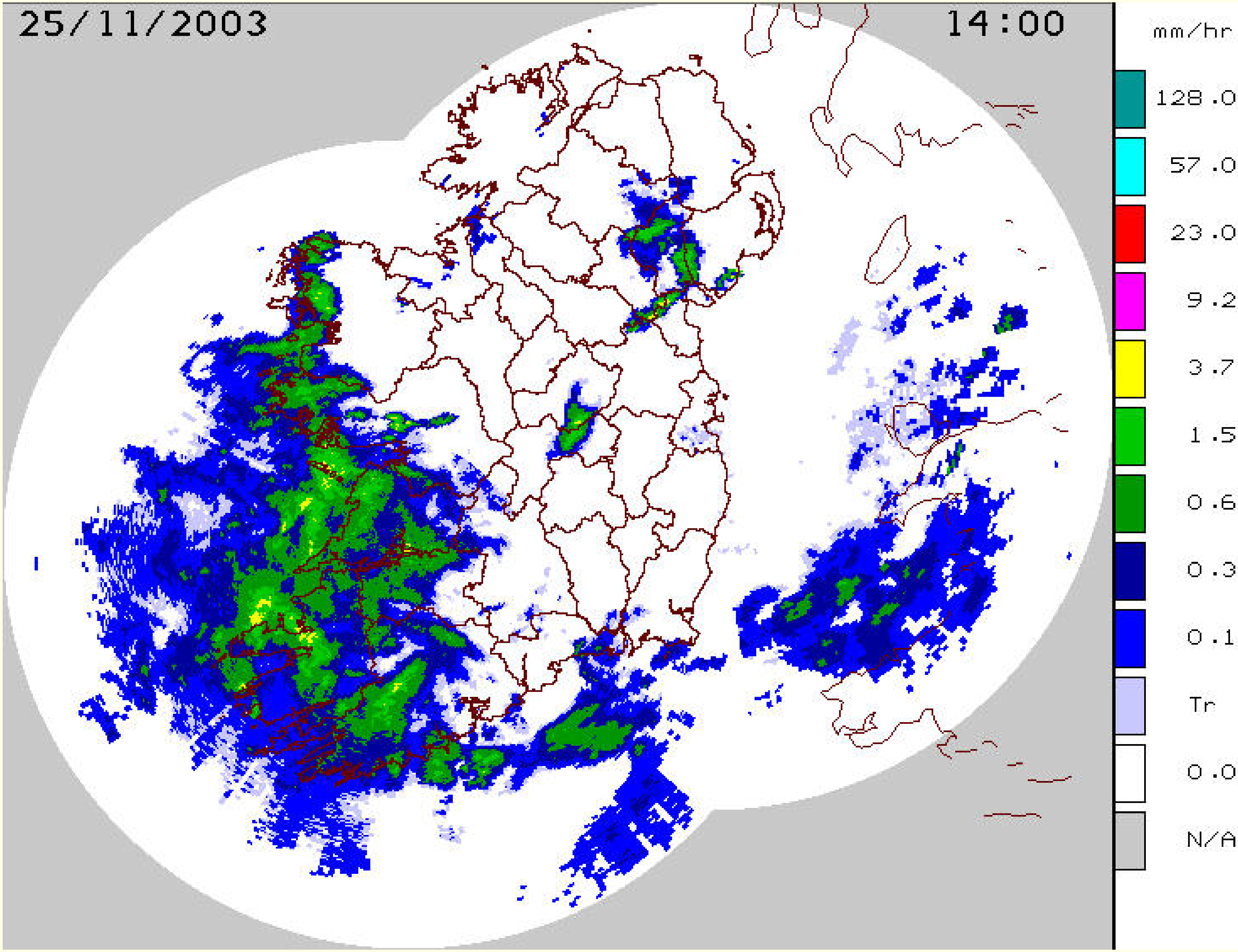
25 November, 2003, 12–1800Z

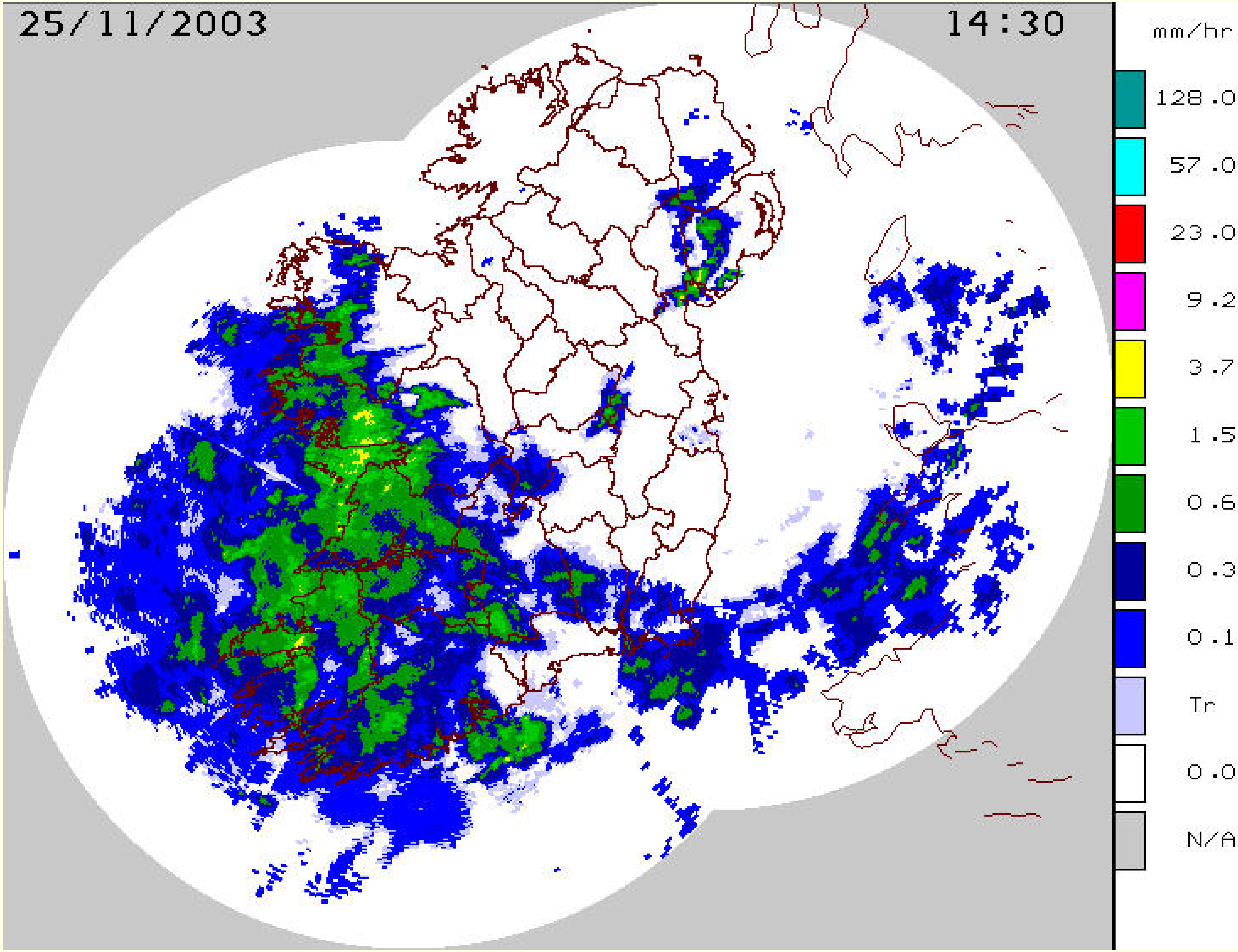

25/11/2003
12:00
mm/hr
128.0
57.0
23.0
9.2
3.7
1.5
0.6
0.3
0.1
Tr
0.0
N/A

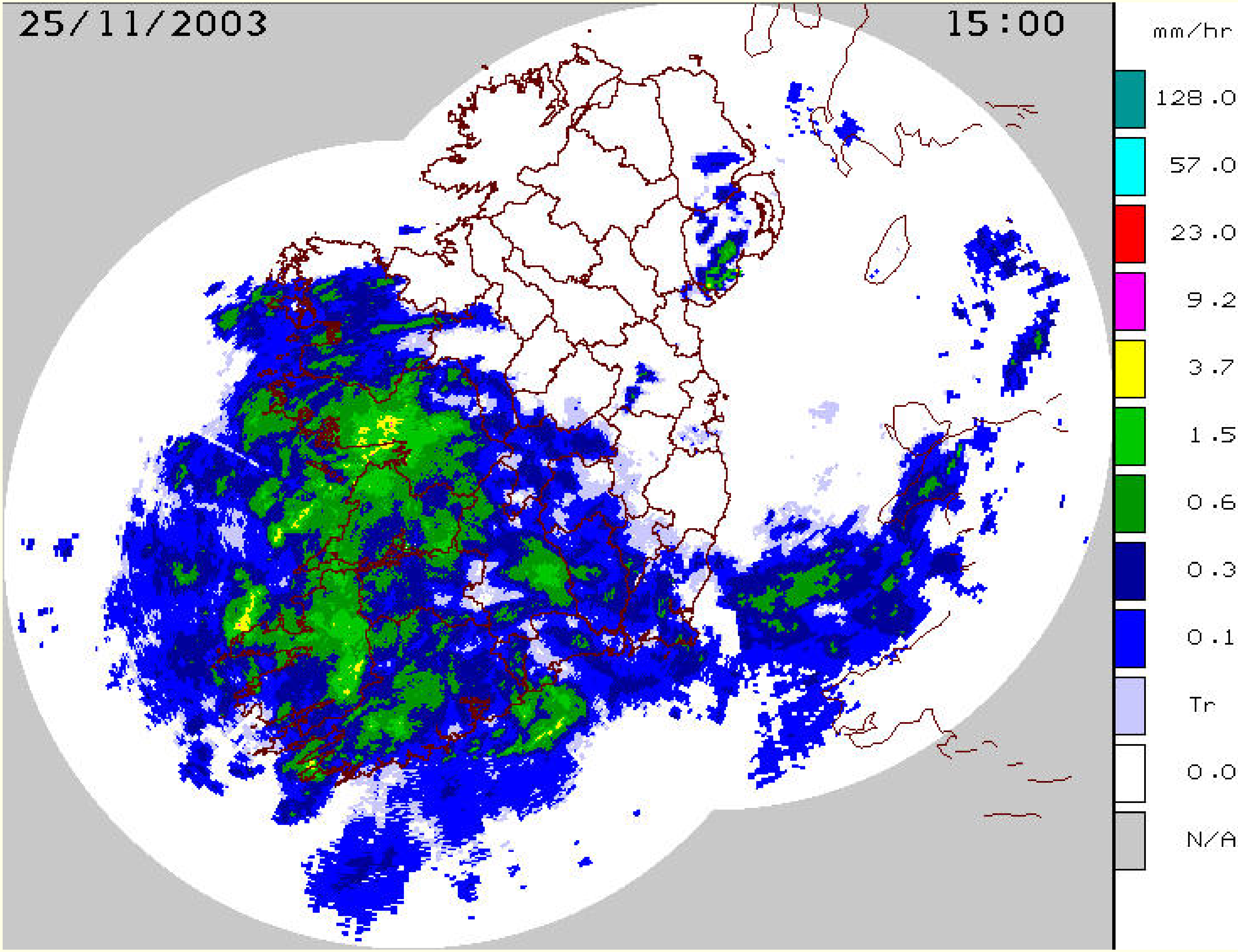

25/11/2003
12:30
mm/hr
128.0
57.0
23.0
9.2
3.7
1.5
0.6
0.3
0.1
Tr
0.0
N/A


25/11/2003
13:00
mm/hr
128.0
57.0
23.0
9.2
3.7
1.5
0.6
0.3
0.1
Tr
0.0
N/A

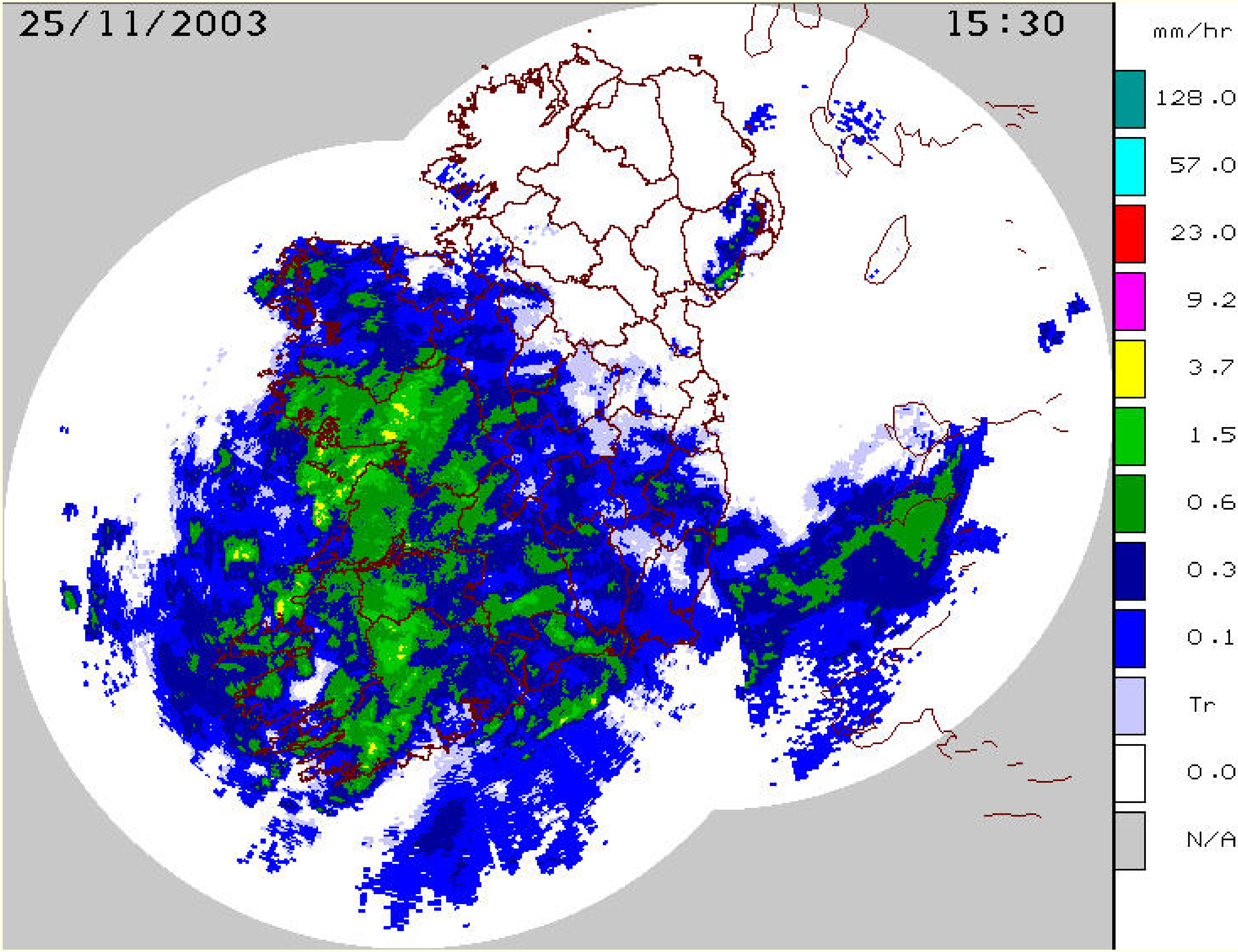

25/11/2003
13:30
mm/hr
128.0
57.0
23.0
9.2
3.7
1.5
0.6
0.3
0.1
Tr
0.0
N/A

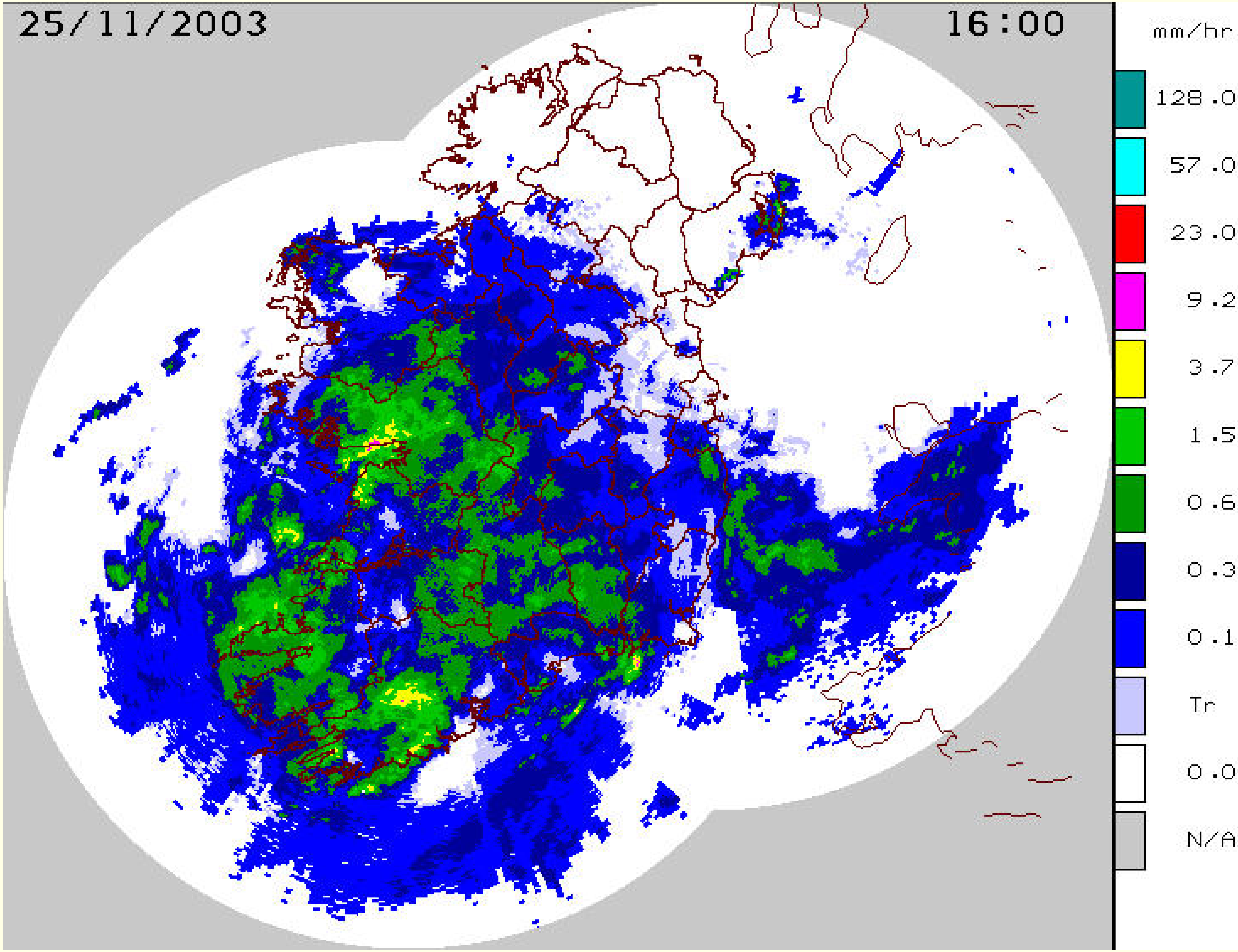

25/11/2003
14:00
mm/hr
128.0
57.0
23.0
9.2
3.7
1.5
0.6
0.3
0.1
Tr
0.0
N/A


25/11/2003
14:30
mm/hr
128.0
57.0
23.0
9.2
3.7
1.5
0.6
0.3
0.1
Tr
0.0
N/A

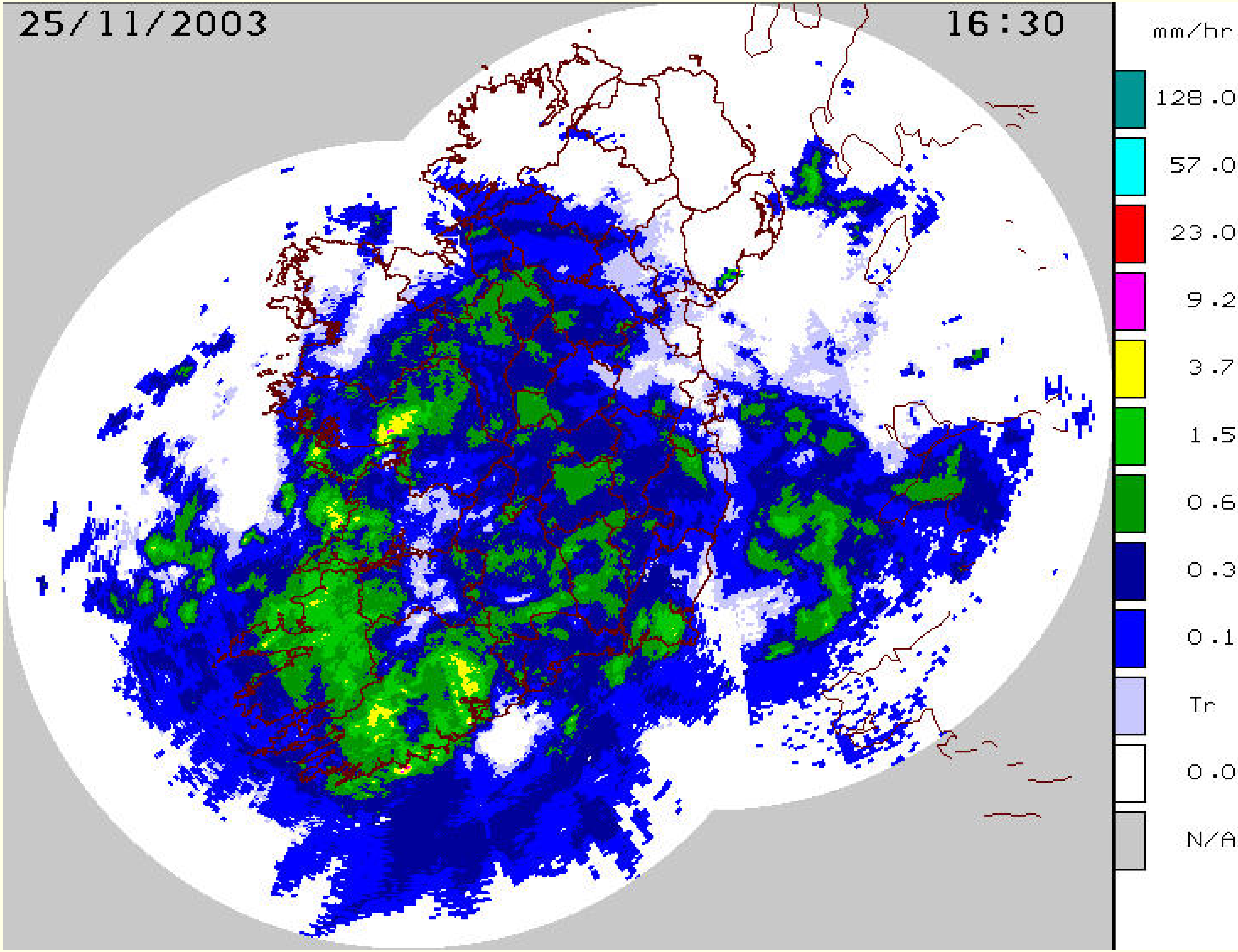


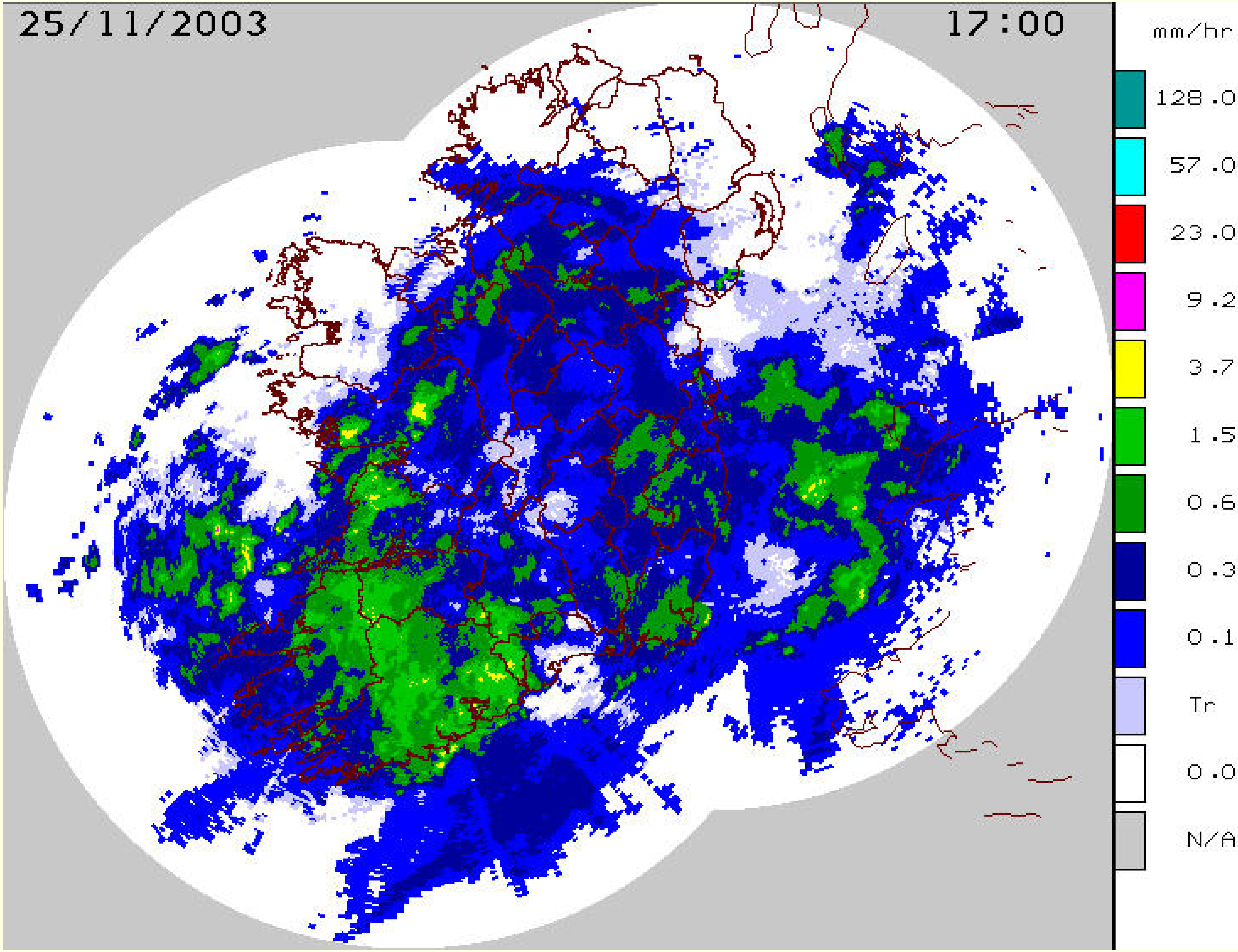
25/11/2003
15:00
mm/hr
128.0
57.0
23.0
9.2
3.7
1.5
0.6
0.3
0.1
Tr
0.0
N/A

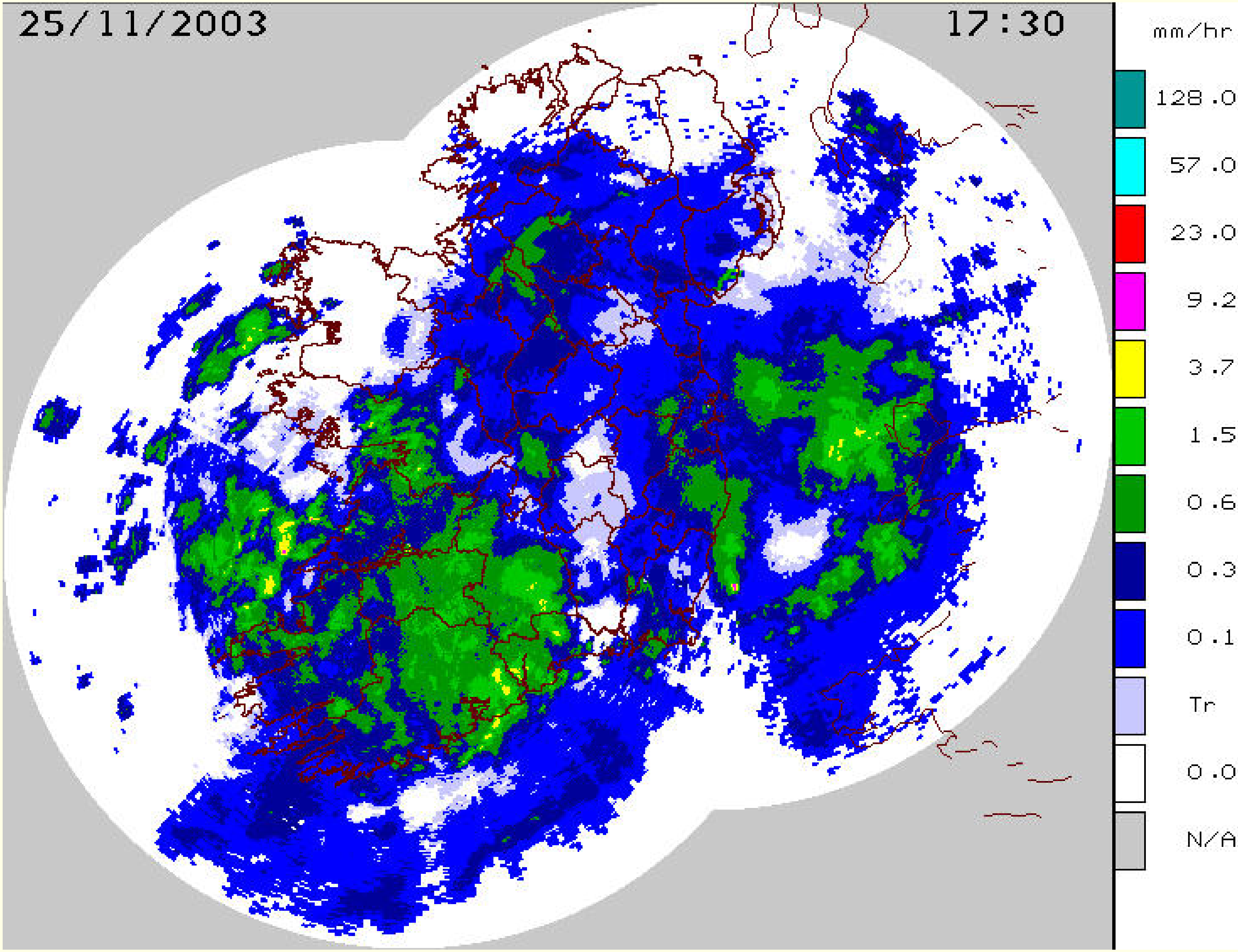

25/11/2003
15:30
mm/hr
128.0
57.0
23.0
9.2
3.7
1.5
0.6
0.3
0.1
Tr
0.0
N/A

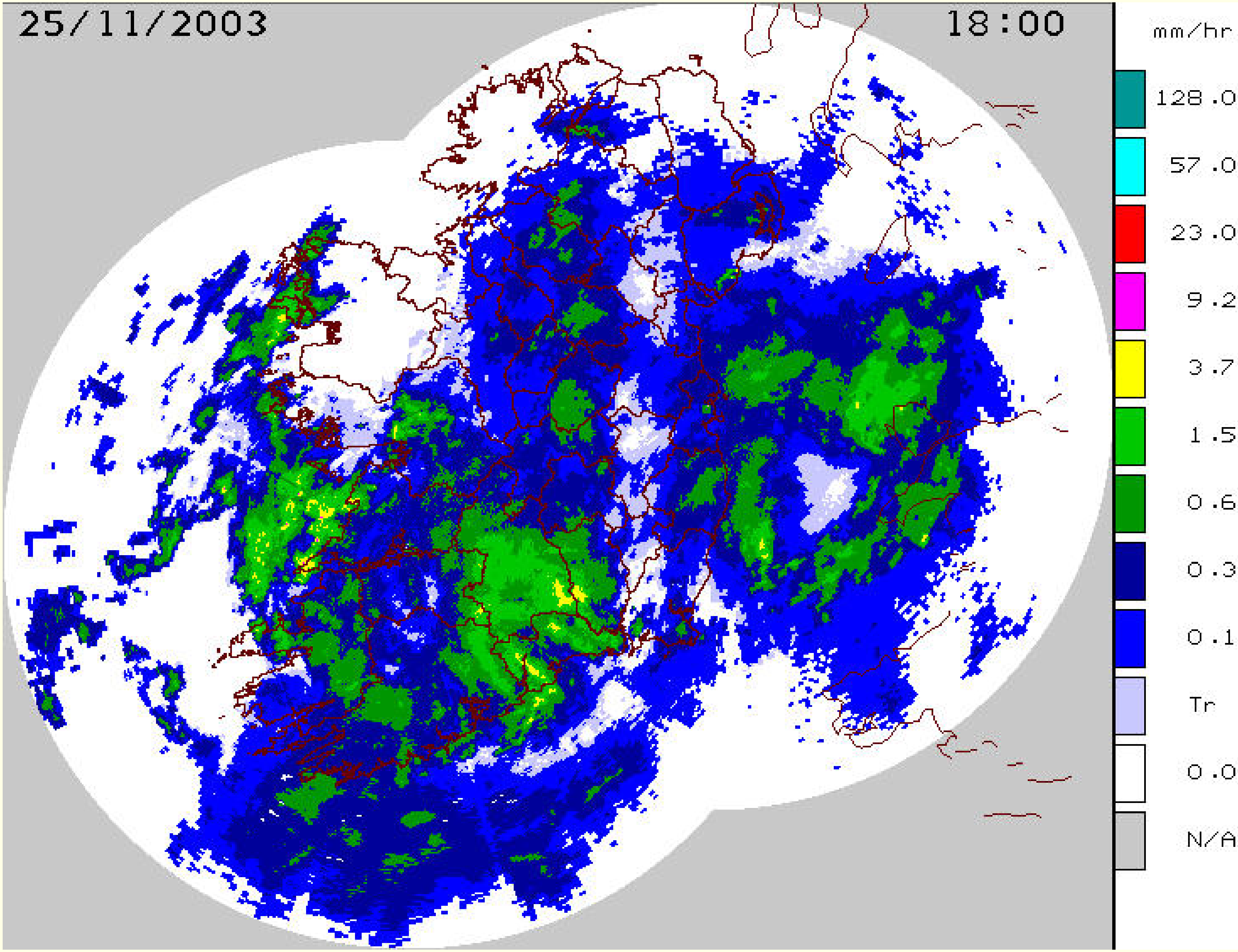


25/11/2003
16:00
mm/hr
128.0
57.0
23.0
9.2
3.7
1.5
0.6
0.3
0.1
Tr
0.0
N/A


25/11/2003
16:30
mm/hr
128.0
57.0
23.0
9.2
3.7
1.5
0.6
0.3
0.1
Tr
0.0
N/A


25/11/2003
17:00
mm/hr
128.0
57.0
23.0
9.2
3.7
1.5
0.6
0.3
0.1
Tr
0.0
N/A


25/11/2003
17:30
mm/hr
128.0
57.0
23.0
9.2
3.7
1.5
0.6
0.3
0.1
Tr
0.0
N/A


25/11/2003
18:00
mm/hr
128.0
57.0
23.0
9.2
3.7
1.5
0.6
0.3
0.1
Tr
0.0
N/A

Some Current Developments

- ***Very Short Range Forecasting***
  - Quantitative Precipitation Forecasting
  - Ensemble Limited Area Modelling
- ***Short to Medium Range Forecasting***
  - Better prediction of weather extremes
  - Better exploitation of probability forecasts
- ***Long Range Forecasting***
  - Extension of Deterministic Range
  - Seasonal Forecasting with Coupled Models

Conclusions

- ***Computer forecasts have improved dramatically since the ENIAC integrations.***

Conclusions

- *Computer forecasts have improved dramatically since the ENIAC integrations.*
- *NWP is an indispensible source of guidance for preparing* **subjective forecasts.**

Conclusions

- *Computer forecasts have improved dramatically since the ENIAC integrations.*
- *NWP is an indispensible source of guidance for preparing* **subjective forecasts.**
- *Beyond the deterministic limit,* **EPS** *provides valuable probabilistic forecasts.*

Conclusions

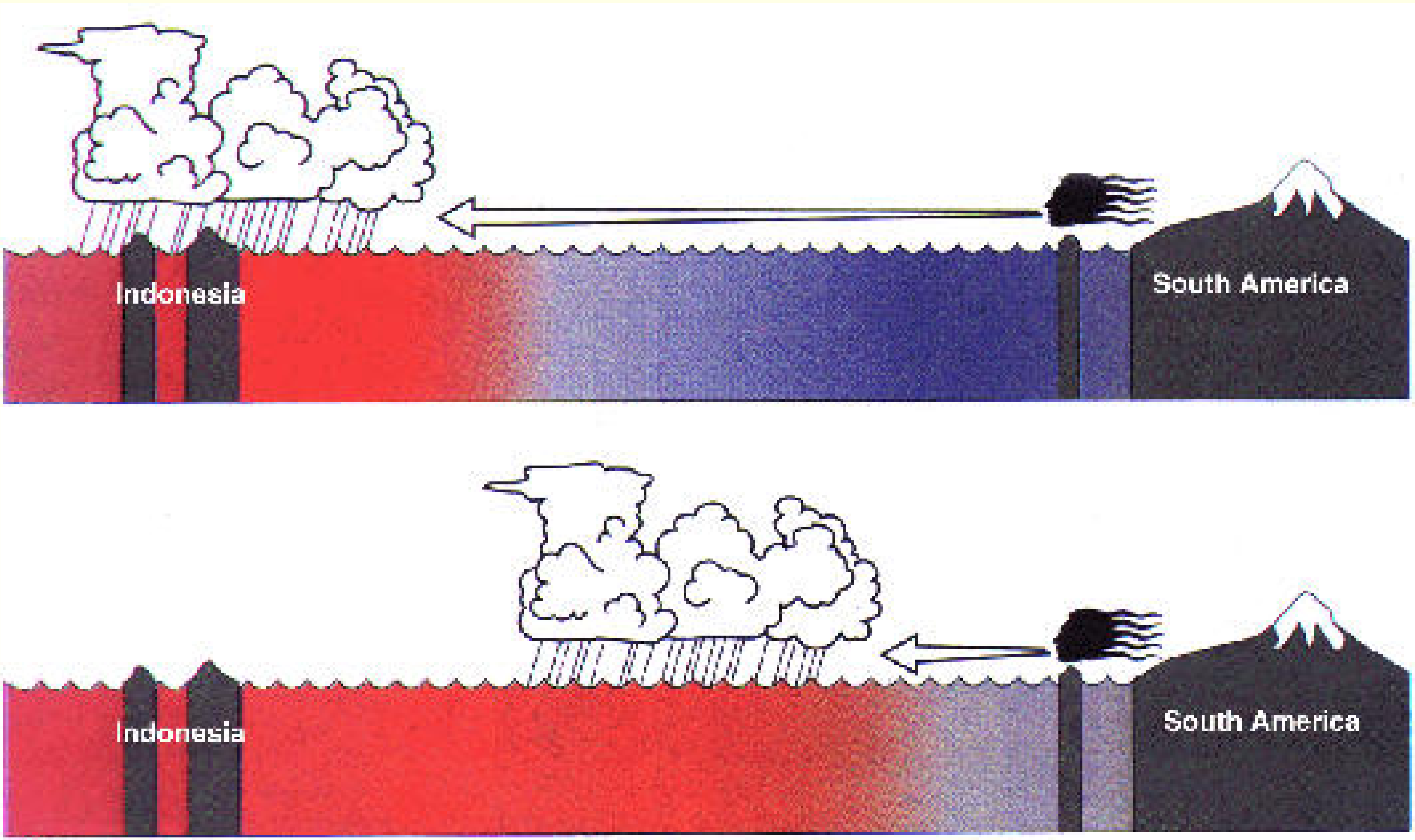
- *Computer forecasts have improved dramatically since the ENIAC integrations.*
- *NWP is an indispensible source of guidance for preparing* subjective forecasts.
- *Beyond the deterministic limit,* EPS *provides valuable probabilistic forecasts.*
- *Prospects are excellent for* further increases in accuracy *and scope of NWP.*

Let us follow the path from information to knowledge!
Let us follow the path from knowledge to wisdom!

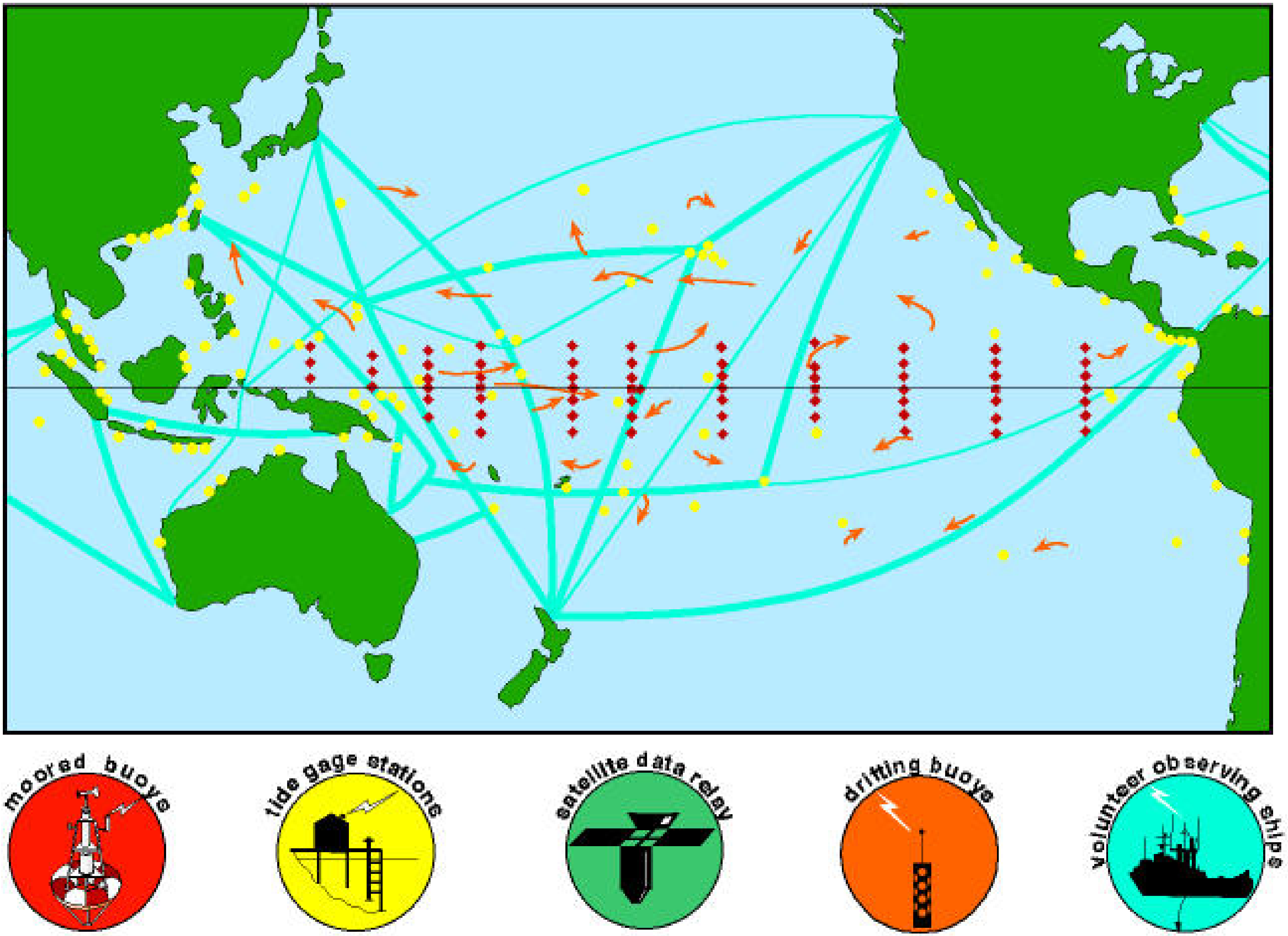
The End

Typesetting Software: TEX, *Textures*, LATEX, `hyperref`, `texpower`, Adobe Acrobat 4.05
Graphics Software: Adobe Illustrator 9.0.2
LATEX Slide Macro Packages: Wendy McKay, Ross Moore

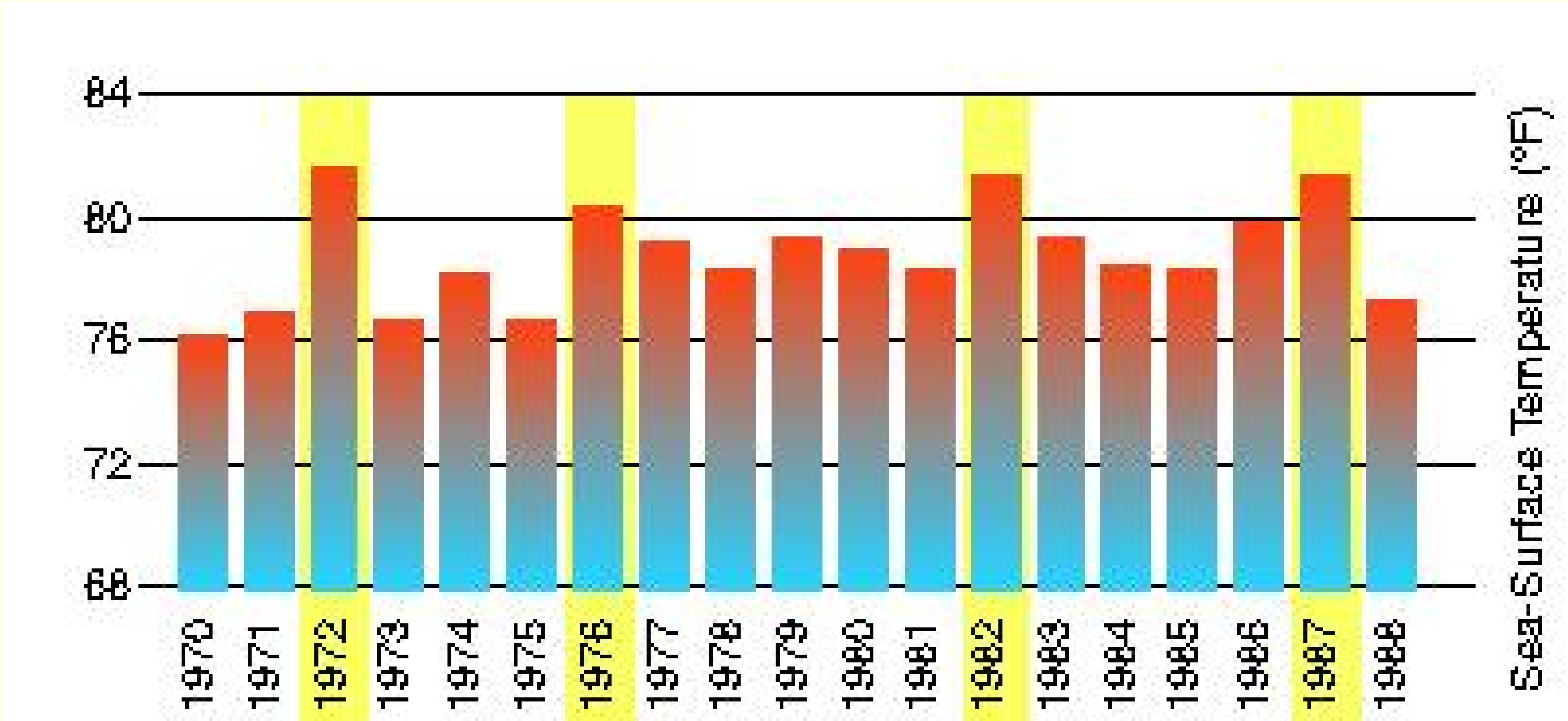
El Niño: Weakening Trade Winds



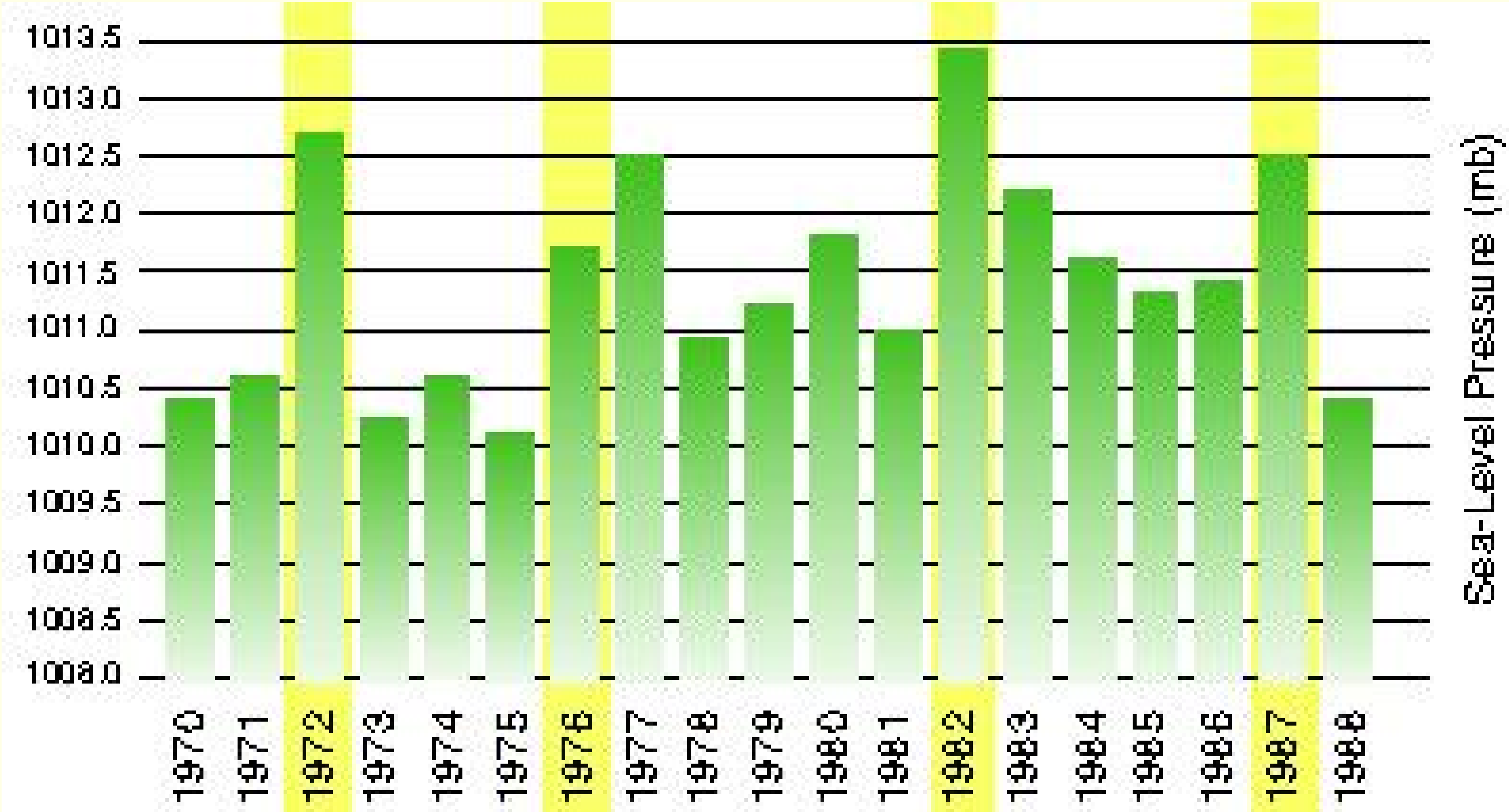
ENSO Observing System



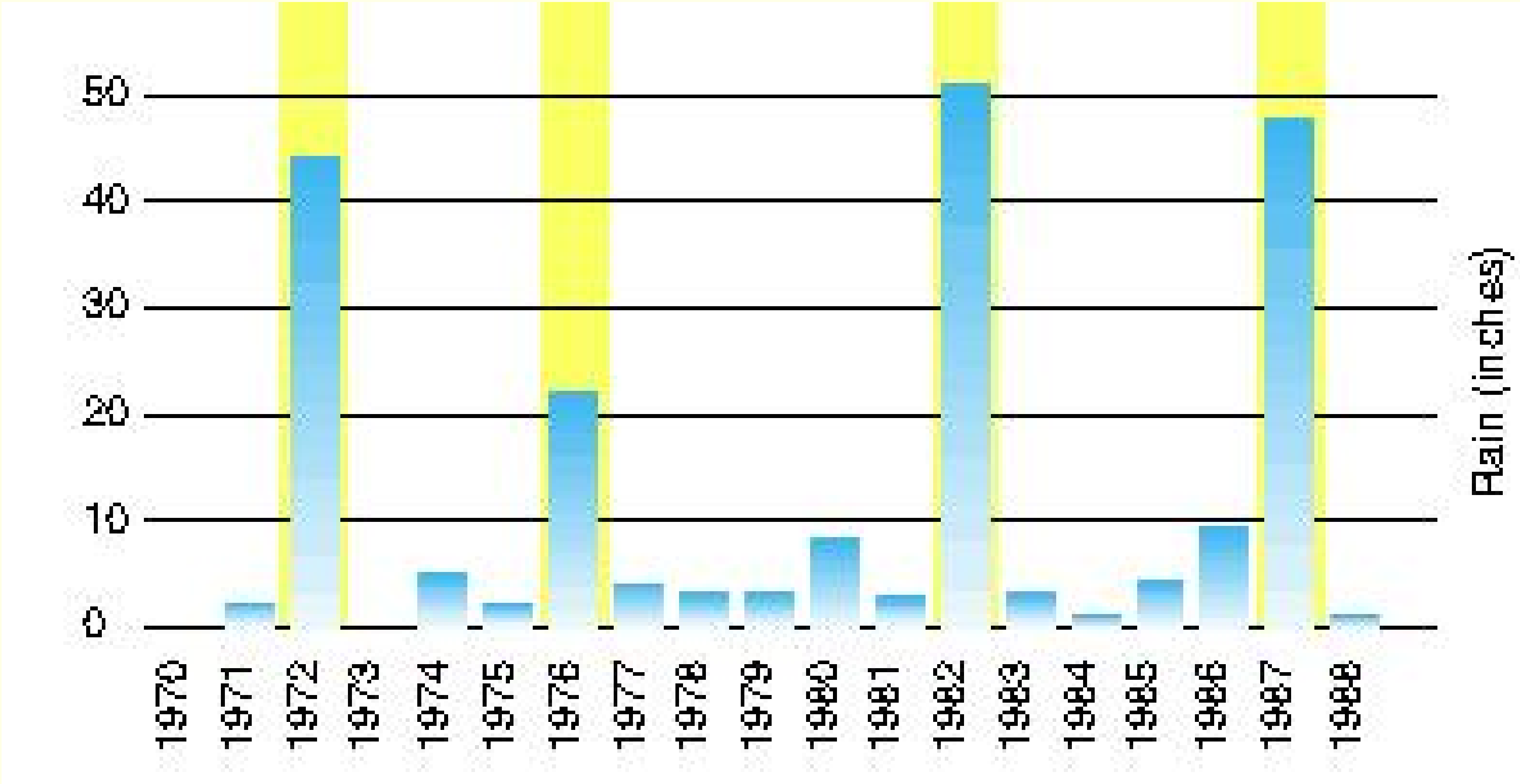
El Niño: Sea Surface Temperature

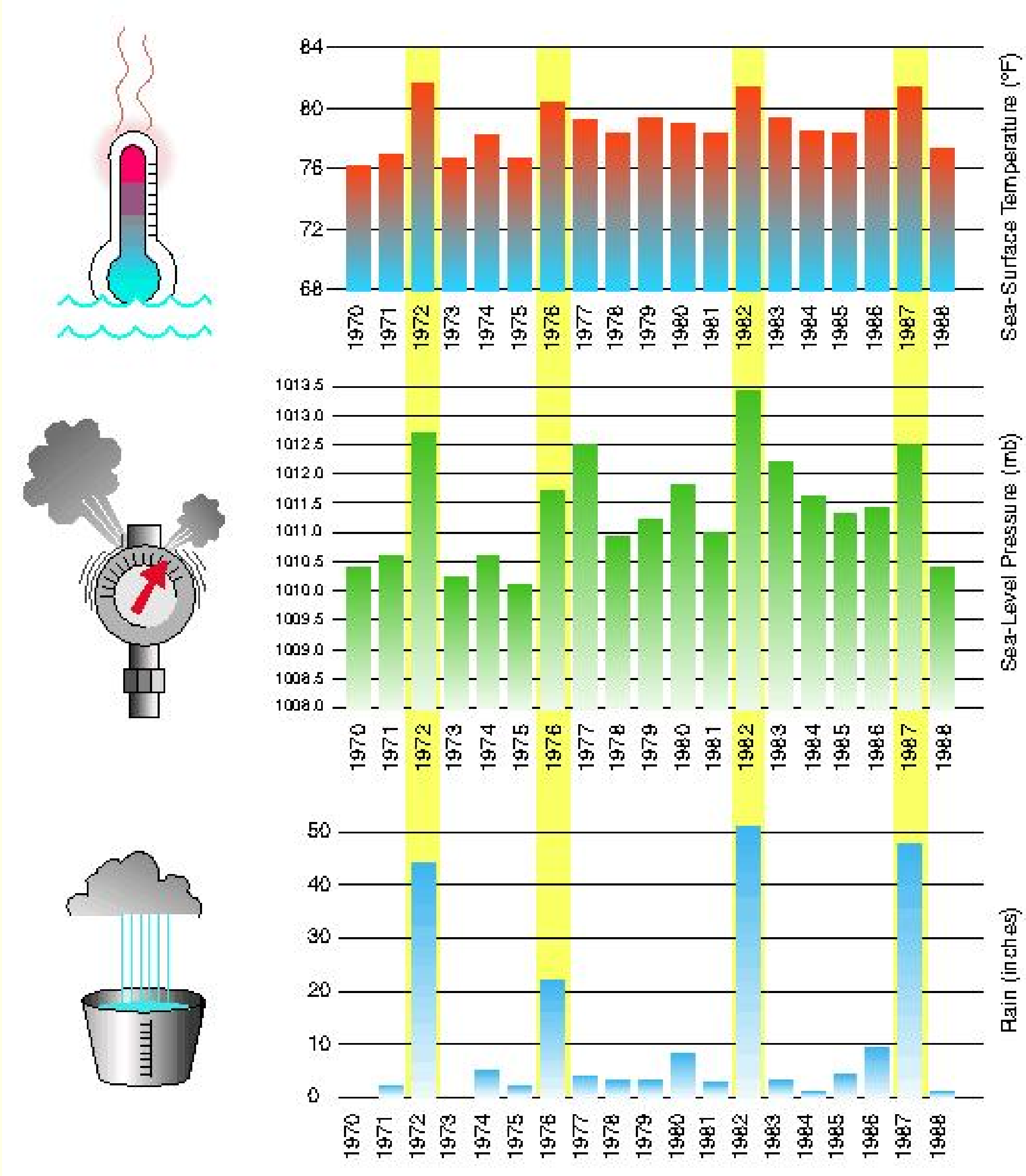


El Niño: Atmospheric Pressure



El Niño: Rainfall in Tahiti





Sea-Surface Temperature (°F)
84
80
76
72
68
Sea-Level Pressure (mb)
1013.5
1013.0
1012.5
1012.0
1011.5
1011.0
1010.5
1010.0
1009.5
1009.0
1008.5
1008.0
Rain (inches)
50
40
30
20
10
0
1970
1971
1972
1973
1974
1975
1976
1977
1978
1979
1980
1981
1982
1983
1984
1985
1986
1987
1988