The story of early **N**umerical **W**eather **P**rediction or *Hydrodynamical Weather Forecasts* at the Met Office, UK

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Early operational Numerical Weather Prediction outside the USA: an historical introduction Part III: Endurance and mathematics – British NWP, 1948–1965

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1. Introduction

> I do not think your views on [the UKMO] in Dunstable will ruffle any feathers of those who worked there. (John Sawyer, personal communication 1993)

The Meteorological Office of the United Kingdom (UKMO) began its operational NWP in November 1965. This marked the start of very successful activity that would gradually bring it to the forefront of NWP development, where it stands today.

However, except for a computer-orientated article by Hinds (1981) very little has been written about the UKMO's road to the operational start of NWP. In an historical exposure about early NWP in general one of the leading actors, Fred Bushby (1986), doesn't tell very much about NWP in his own country, nor do Sir John Mason and John S. Sawyer in their respective interviews for the WMO Bulletin (Taba 1995, 1997). This scarce publicity is in sharp contrast to the rich literature that is available on L. F. Richardson and his pioneering 1922 work.

The lack of historical accounts of the UKMO work on NWP might be explained by lack of information. The British civil service has a reputation for secrecy. And since the UKMO belongs to the Minstry of Defence (previously the War Office) we should not be surprised if most of the documents relating to NWP development in Britain were classified. But the opposite

reviewed papers they also reported on meetings and, uniquely, on the discussions that followed.

And there was much to report on. The British road to operational NWP, 1948–65, was marred by problems and emotions worthy of a BBC drama or a Hollywood blockbuster. Here we find meteorologists with a mixture of admiration for the computer and fears about the future of synoptic forecasting. There are frustrated mathematicians who saw their forecasts getting worse despite improvements to the model. We can, almost verbatim, listen to eminent scientists who put the right questions but got the wrong answers. And finally, the whole drama is imbued with feelings of national pride and independence.

One good reason for treating this well-documented historical development in more detail is that the problems were not unique to British meteorology. The same or similar problems probably affected other centres; although there is little or no documentation of this. Indeed some of the issues are still debated today.

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The history and future of numerical weather prediction in the Met Office

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The Met Office is recognised as a world leader in numerical weather prediction (NWP). In this article we trace the milestones in its development, with recollections of some of those involved, and identify key objectives for the future.

Beginnings (1904–53)

It was 100 years ago that Vilhelm Bjerknes expounded the hydrodynamical basis for weather forecasting that has come to dominate meteorology through its application in NWP (Bjerknes 1904). Its first practical champion was L. F. Richardson who joined the Met Office from the National Physical Laboratory in 1913 with practical experience in the solution of hydrodynamical problems using finite-difference methods (Ashford 1985), and already with a vision of predicting the state of the atmosphere by similar means. His monumental effort to achieve this by manual computation, while serving as an ambulance driver in World War I, was published by Richardson (1922). Meanwhile, developments in theoretical understanding, especially in the Bergen school, coupled with technical developments in observing the 3-dimensional atmospheric structure, were preparing the ground for achievement of Richardson's vision once high-speed computing became available following World War II. In the USA, it was through Von Neumann's Electronic Computer Project that this was first achieved (Platzman 1979), culminating in the ENIAC experiment using Charney's barotropic equation set (Charney *et al.* 1950).

In 1948, the recently formed Meteorological Research Committee advised that application of computational methods to solving the atmospheric equations on "an electric desk calculator" should be pursued. The result was the despatch of Fred Bushby (see also Mason and Flood 2004) on a course in using the EDSAC computer at Cambridge, access to the LEO computer of Lyons Co., and the formulation of a set of equations by Sawyer and Bushby which were first integrated in 1952 using a 12 × 8 grid with a grid spacing of 260 km, a 1-hour time-step, and requiring 4 hours' computing time for a 24-hour forecast (Bushby and Hinds 1954). Unlike Charney's model, this was a baroclinic model with a vertically uniform thermal wind. With the simplifications introduced by the geostrophic approximation, and a parametrization of the local pressure tendency, the equations reduced to three: for the time tendencies of the 1000–200 mbar thickness and its Laplacian, and the time tendency of the 600 mbar height (Sawyer and Bushby 1953). The equations were integrated using a leapfrog predictor step followed by an implicit corrector.

In the Met Office centenary issue of the *Meteorological Magazine* in 1954, it was noted that, whilst tremendous advances had been made in observing the weather, improvements in forecasting had been very slight in the previous decade, but that the experiments in numerical forecasting showed great promise (Peters 1955). It was anticipated that NWP would become a valuable aid in preparing the 24-hour forecast chart, but that deduction of the associated weather would remain a manual task. In spite of this, Sutton (1954) wrote of his concern that the chaotic nature of the atmosphere could make the hydrodynamical equations unpredictable as early as 24 hours ahead due to the exponential growth of unobservable perturbations in the initial conditions. Today, we are struck both by his pessimism and by his prescience as we seek to use ensembles to identify those rare occasions when this may be true.

The first operational system (1954–66)

Following the initial experiments, work moved to the Ferranti Mk I computer at Manchester University Department of Electrical Engineering. Hinds (1981) has given us a wonderful description of these experiments:

> "Since we needed the computer for several hours at a stretch, most of our usage was at night and for some years we used the machine for two nights each alternate week. We stayed at a nearby commercial hotel made up of several elderly terraced houses, now happily demolished. Readily available treats were the sight of sunrise over Manchester from the roof near the computer room or the exhilaration of coping with an old-fashioned Manchester smog in which the buses were led by a man on foot holding a flare. It was sometimes necessary to have one member of the party with sufficient athletic prowess to scale the wrought-iron University gate in order to gain access to the computer building . . ."

At this time, scientists were experimenting with a wide range of possibilities for equation sets, horizontal and vertical resolution, discretization templates, etc. It was generally agreed that the barotropic set was inadequate and that at least three levels were required in the vertical, but the Met Office focus on this more expensive approach probably delayed its move to operational use. In late 1954, the Meteorological Research Committee recommended procurement of a computer, and a Ferranti Mercury, known as 'Meteor', was installed in January 1959 (Fig. 1). By this time several research staff had been trained, and the remaining components of an operational suite had been assembled including observation decoding and quality control, and objective analysis using a local quadric fitting technique (Bushby and Huckle 1957). The new computer was one of the largest and fastest made in England (Knighting 1959), boasting 5000 valves and 3500 diodes, with 1024 floating point stores, a line printer, and a computation speed of about 300 flop (floating-point operations per second).

A trial operational suite was constructed in early 1960, using the improved Bushby–

British NWP had an early and promising start

Computer projects – and computers

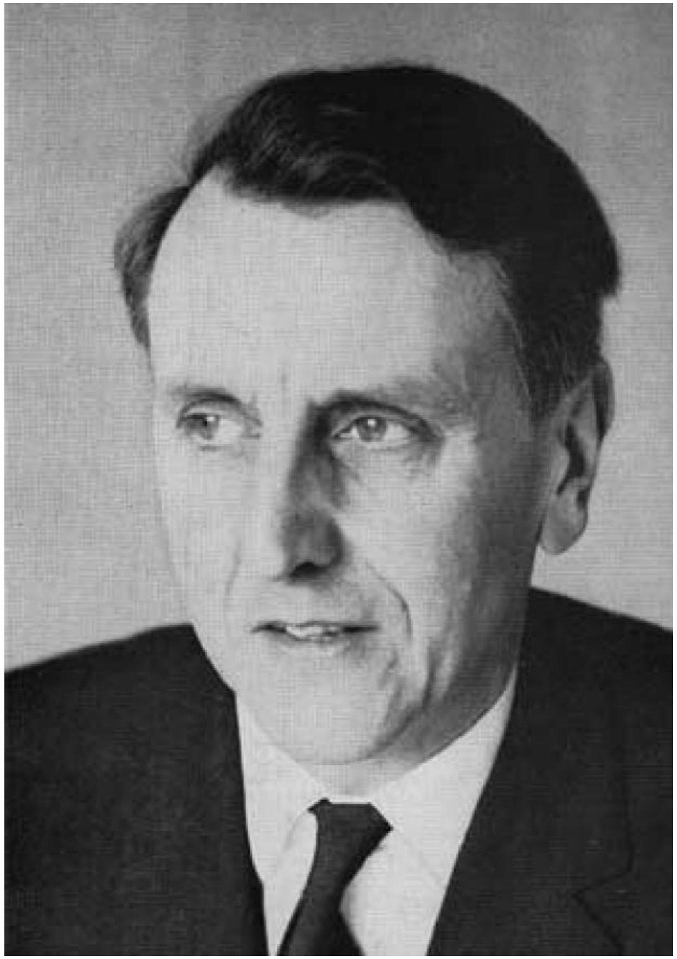
- Teddington 1945 *Visit by John Sawyer and Charles Durst in 1948*
- Manchester 1947
- Cambridge 1949

A working group formed in May 1948

- George C. Mc Vittie, *Met Office*
- Charles S. Durst, *Met Office*
- Reginald C. Sutcliffe, *Met Office*
- Eric T. Eady, *Imperial College*

But nothing really happened until Fred Bushby came on the scene in 1951

The men behind the “**Bushby-Sawyer** model”



Outstanding entrepreneur

Fred Bushby 1924-2004

Outstanding scientist

John S. Saywer 1916-2000

Those were the Met Office NWP women

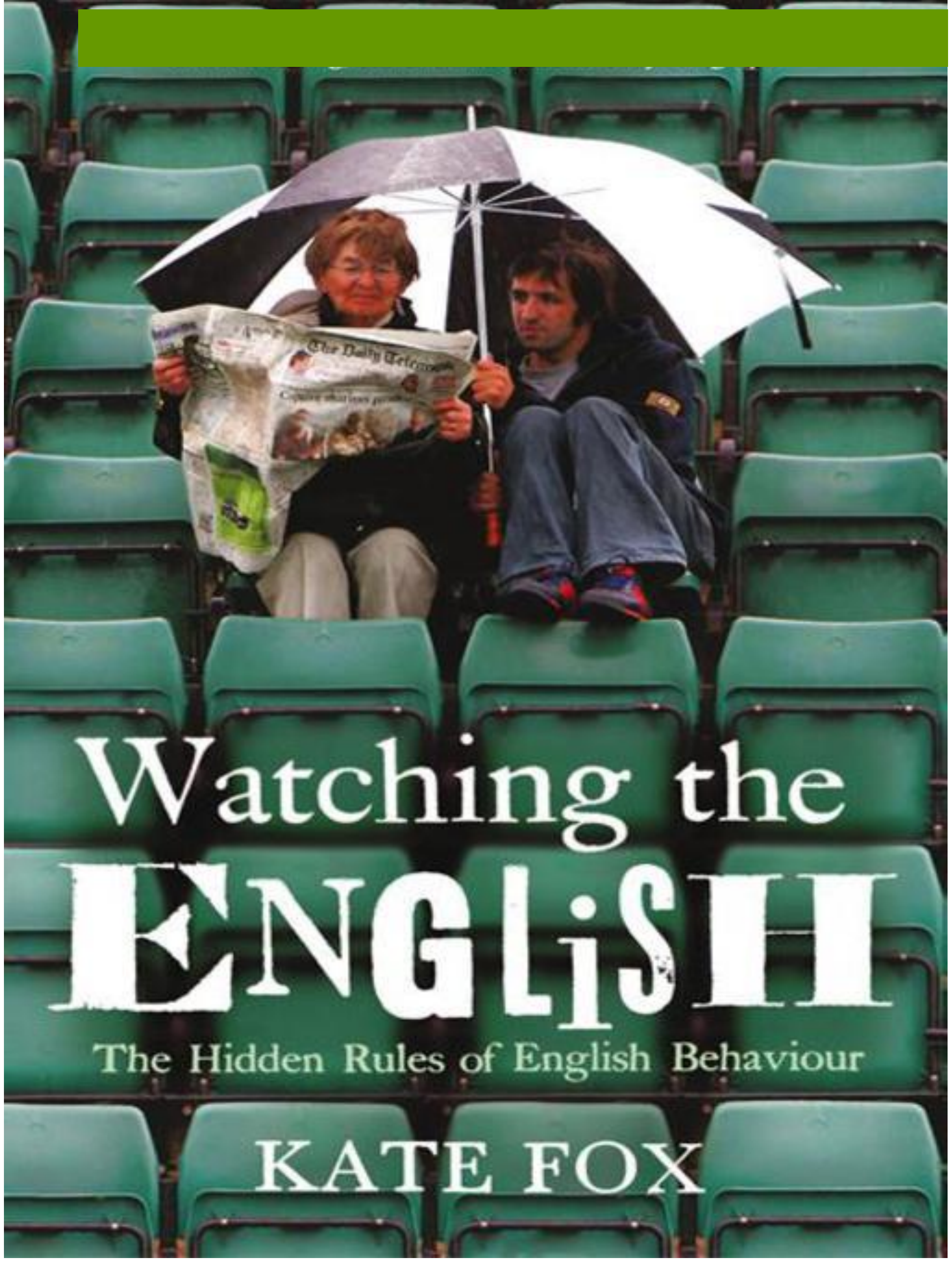
Mavis Hinds 1929-2009

Happy to work with computers dealing with weather: “I wouldn’t been interested in Income Tax computers!”

Vera May Huckle

Claire Jo Whitlam

Margaret Timpson



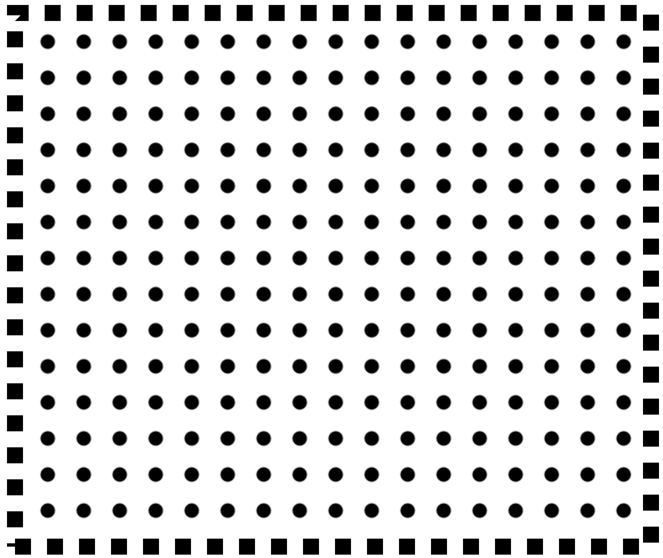
-We want to forecast rain!

. . .which can only be done by baroclinic models

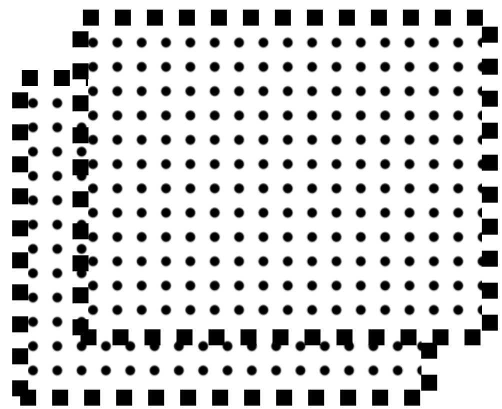
The choice of model resolution and area

Sparse computer resources → the forecasts had to be run on a limited area with **constant boundaries.** Two choices:

- A simple **barotropic model** with a **coarse grid resolution (736 to 300+ km)** over a **large** area



- A more complex **baroclinic model** with a **higher grid resolution (260 km)** over a **smaller** area



Baroclinic or barotropic model?

The atmospheric motions are driven by thermal processes as reflected in *baroclinic* developments

…yes, but the large scale motion can kinematically be described by a *barotropic* model

R. C. Sutcliffe

C. G. Rossby

Phase speeds ***c*** according to Rossby's wave equation

$$c = U - \frac{\beta L^2}{4\pi^2} \approx 10^\circ / day$$

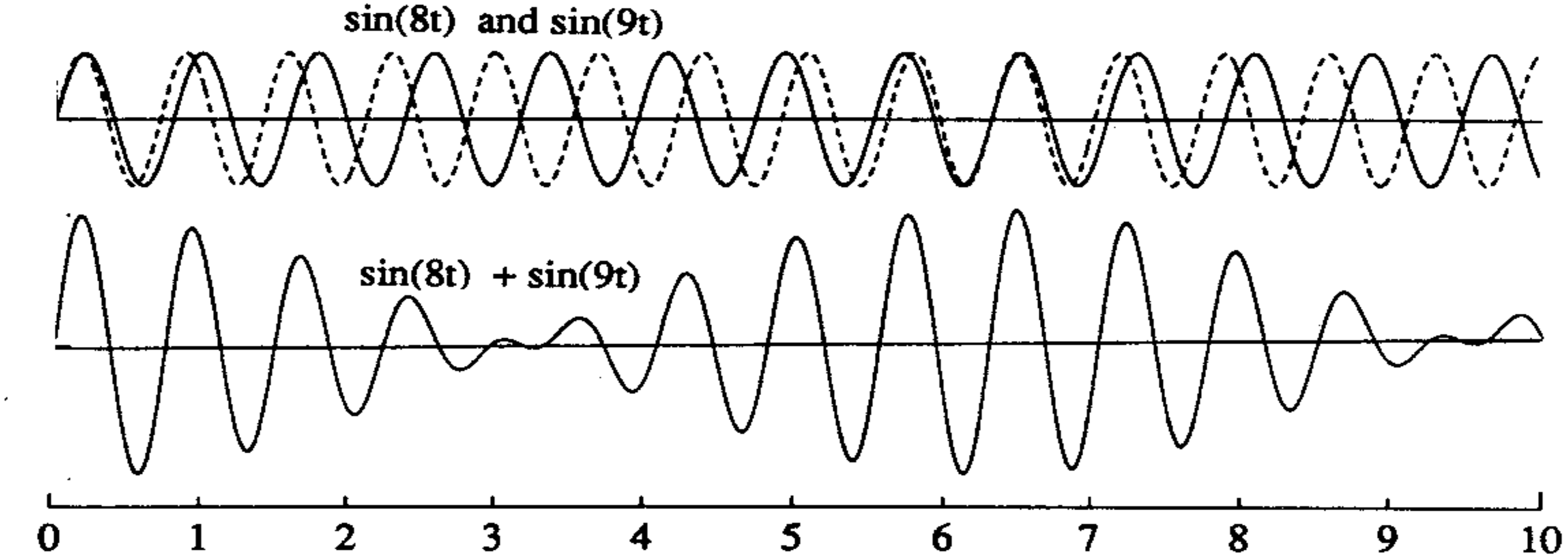
The wave equation is ***dispersive*** and gives rise to "downstream development" by the ***"group velocity"***

$$c_g = U + \frac{\beta L^2}{4\pi^2} \approx 30^\circ / day$$

propagating e.g. constant boundary values rapidly into the forecast heart land

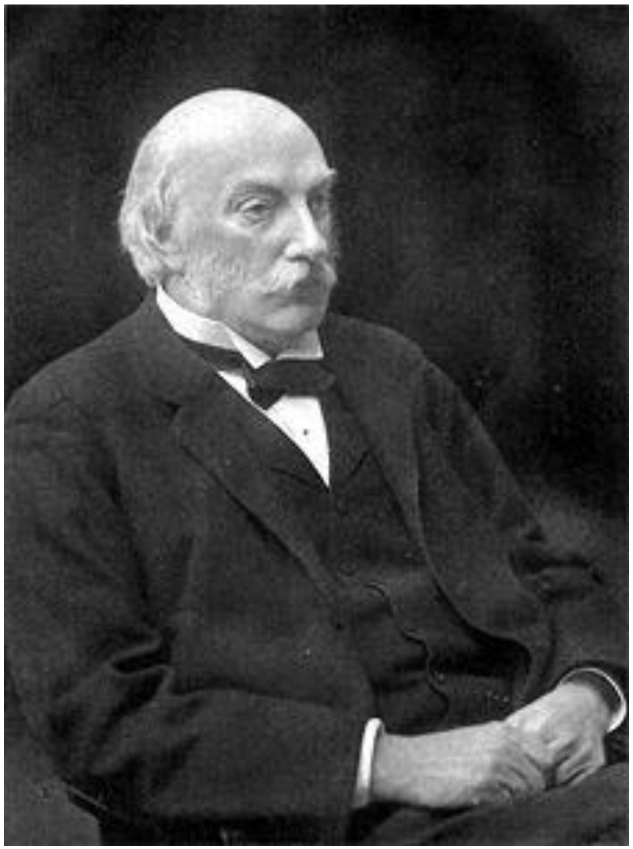
An inconvenient truth?

The choice of model was not a matter of **convenience**, but of **necessity** because of the **group velocity**

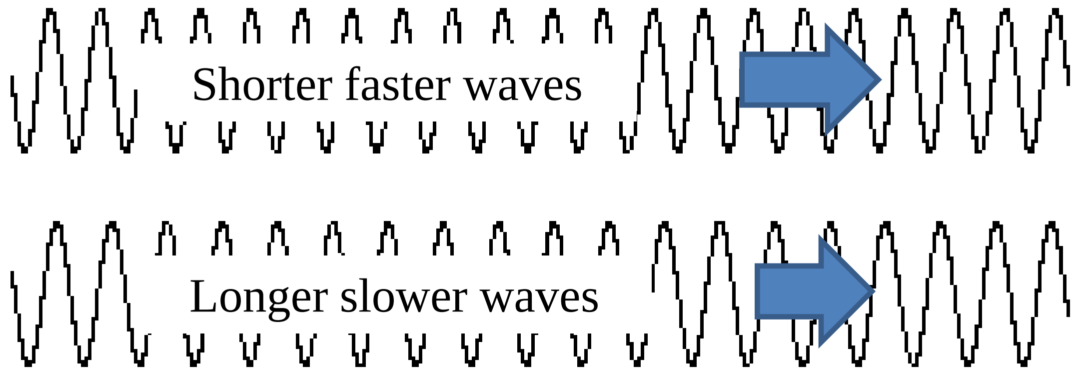


The modulated pattern move with a different speed than each of the superimposed wave patterns

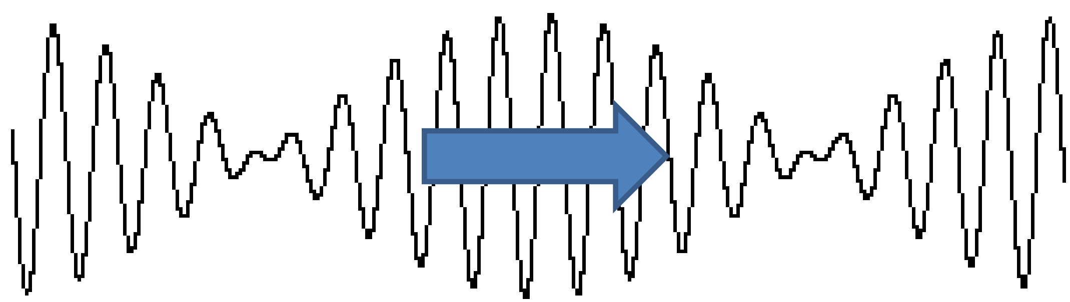
Group velocity is a ***British*** invention



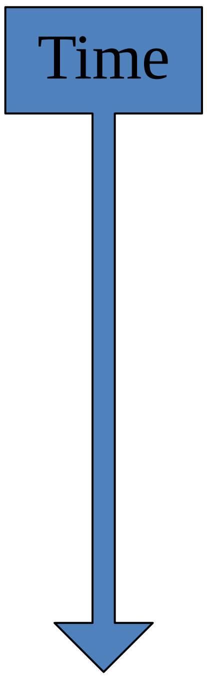
Lord Rayleigh
1842-1919



The modulated electromagnetic wave can be decomposed into a sum of non-modulated waves of different wavelengths and phase speeds



Group velocity in water surface waves



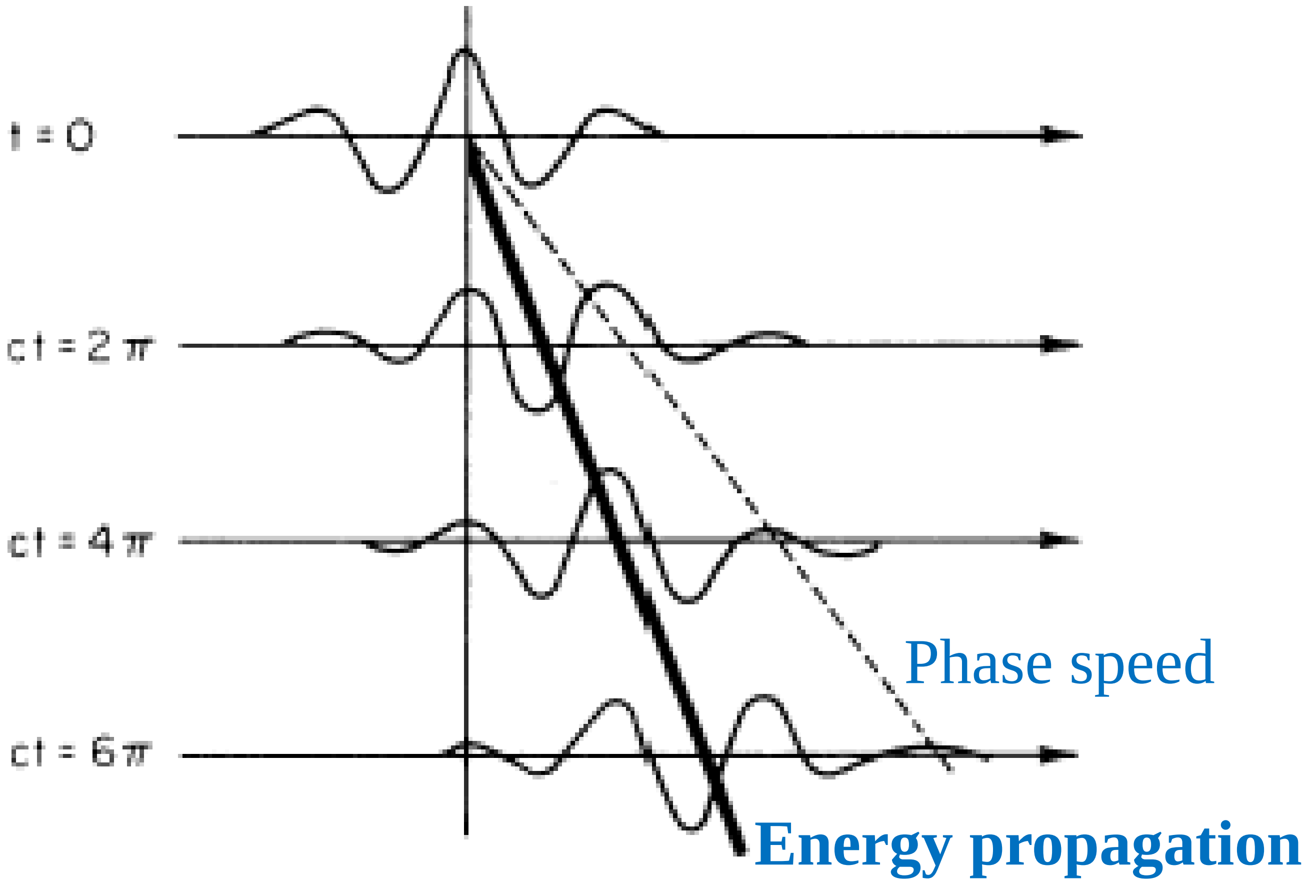


Fig.1 The successive progression of water wave packages. The crest in the centre moves rapidly out, weakens and leaves behind the main energy, into which upstream waves enter and amplify (from Holton, 1992).

Group velocity in the atmosphere

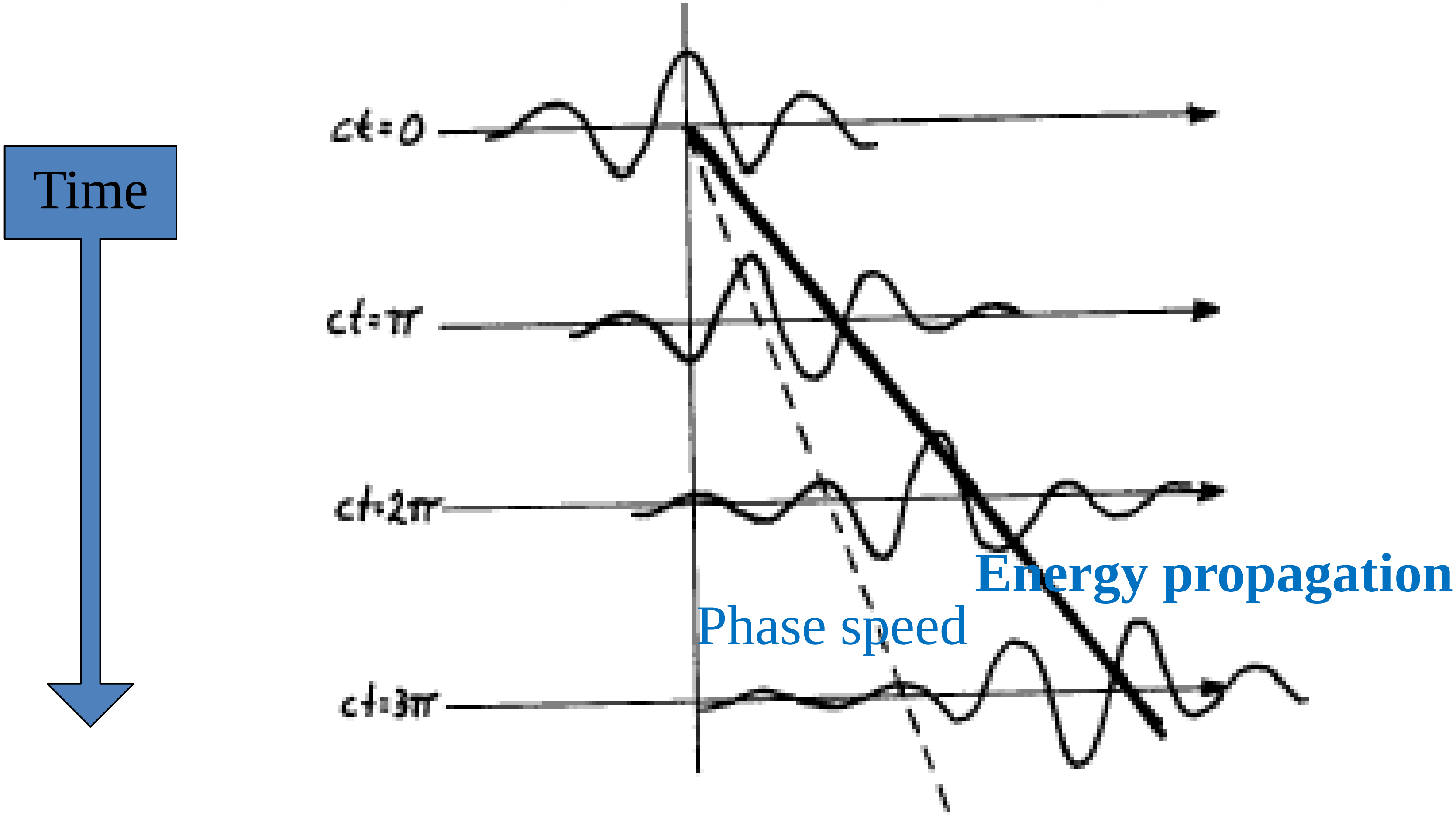
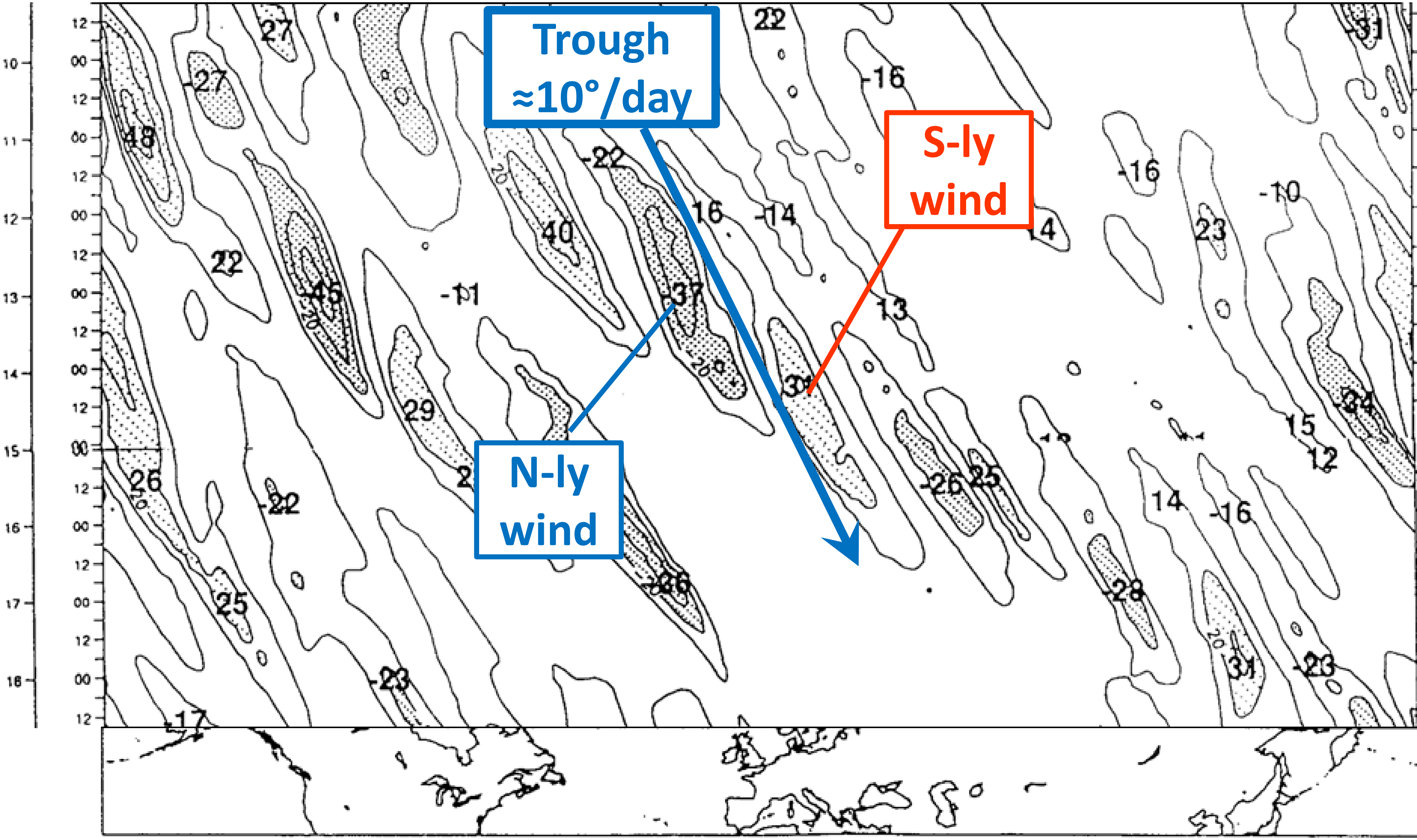


Fig. 2: The corresponding mechanism in the atmosphere: the central wave moves more slowly than the bulk of the energy which propagates downstream amplifying waves on its arrival.

Trough-ridge (Hovmöller) Diagram

of 250 hPa meridional wind component 10-18 September 1993



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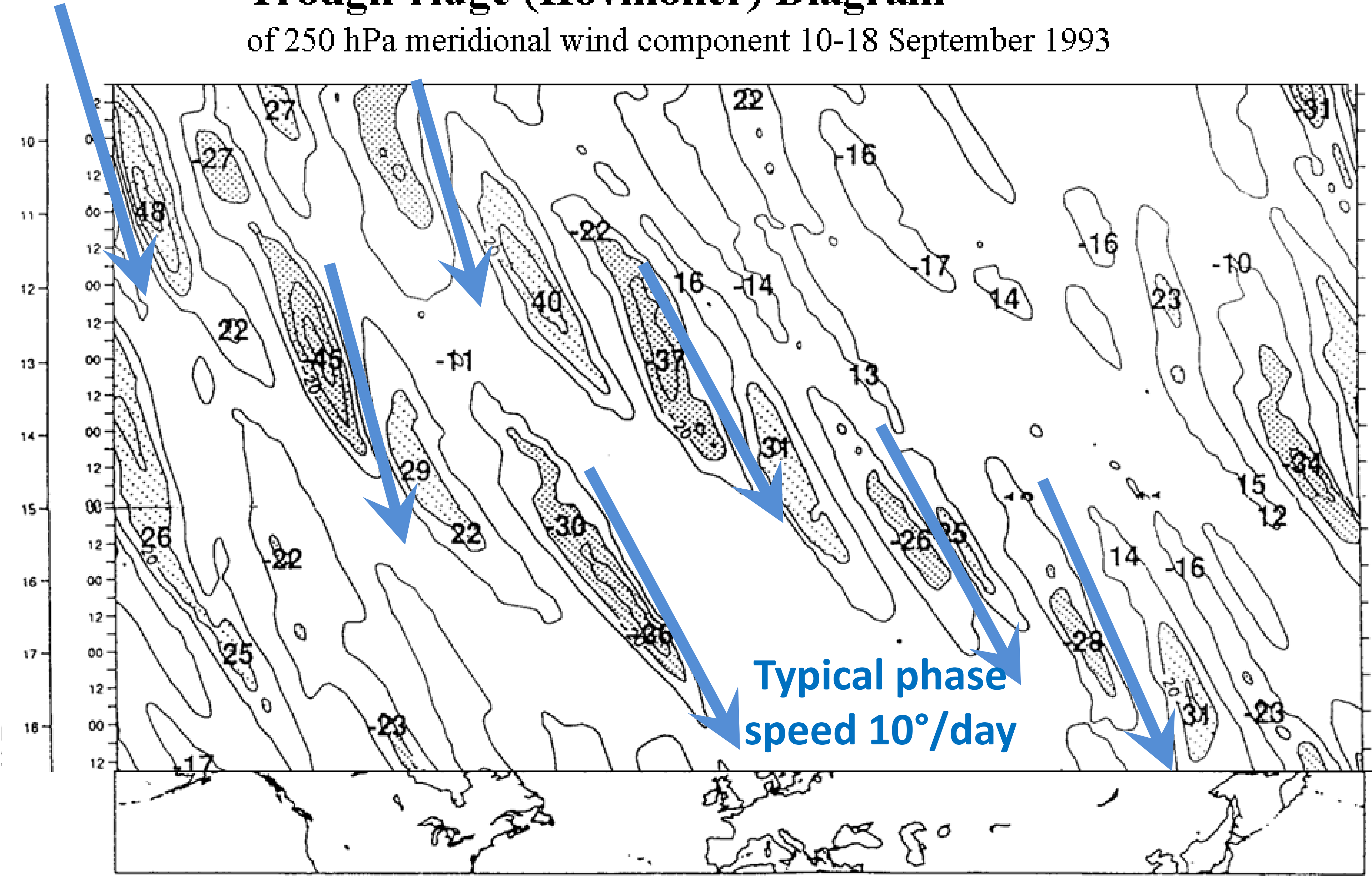

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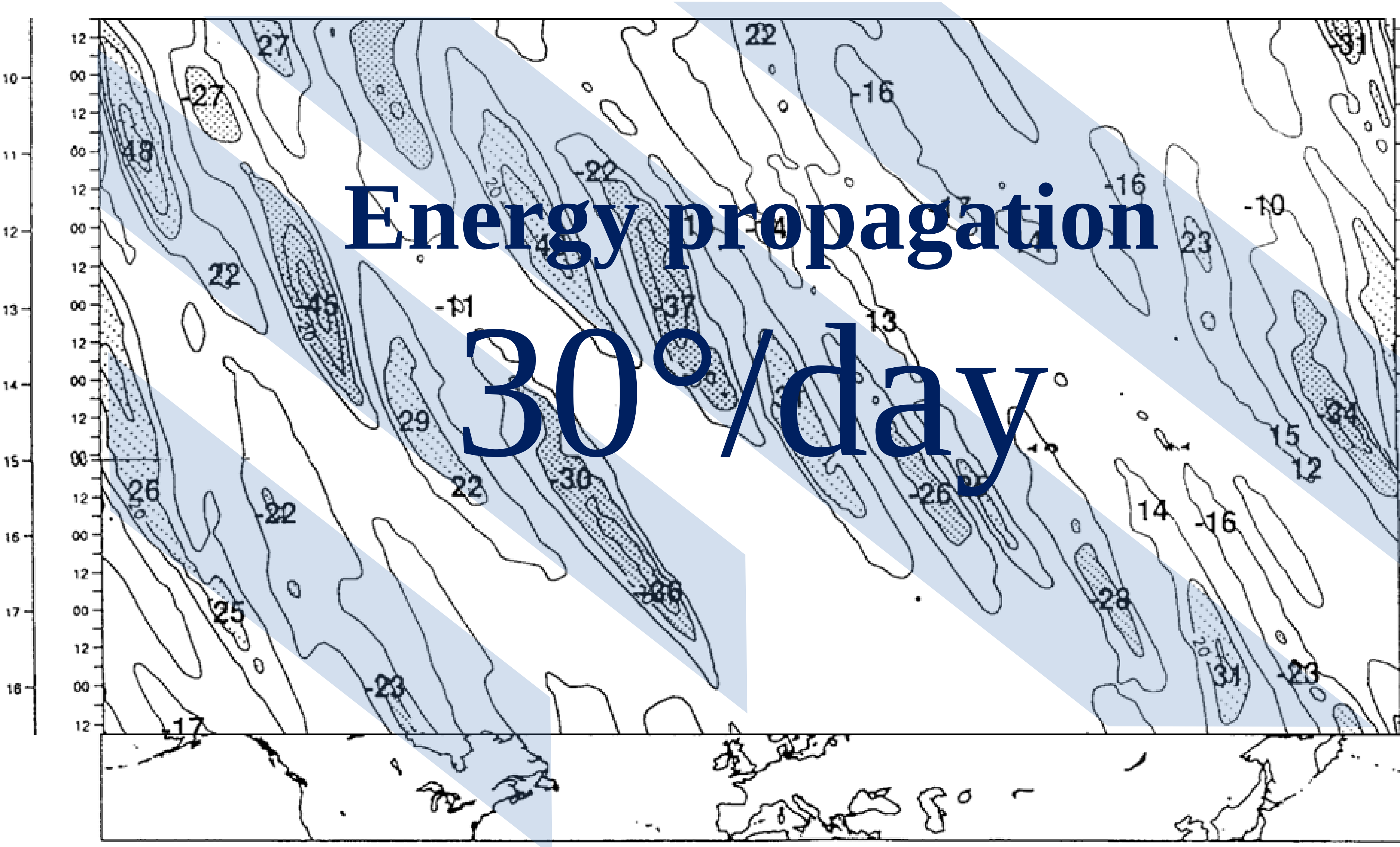
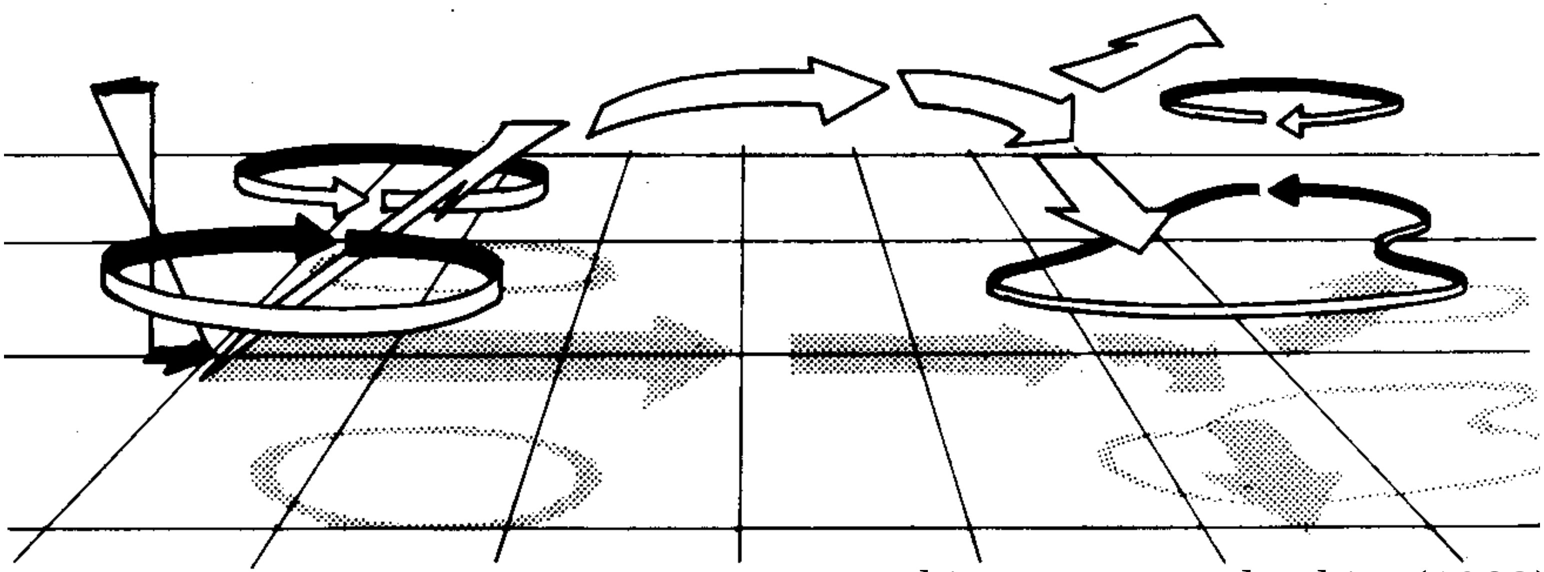


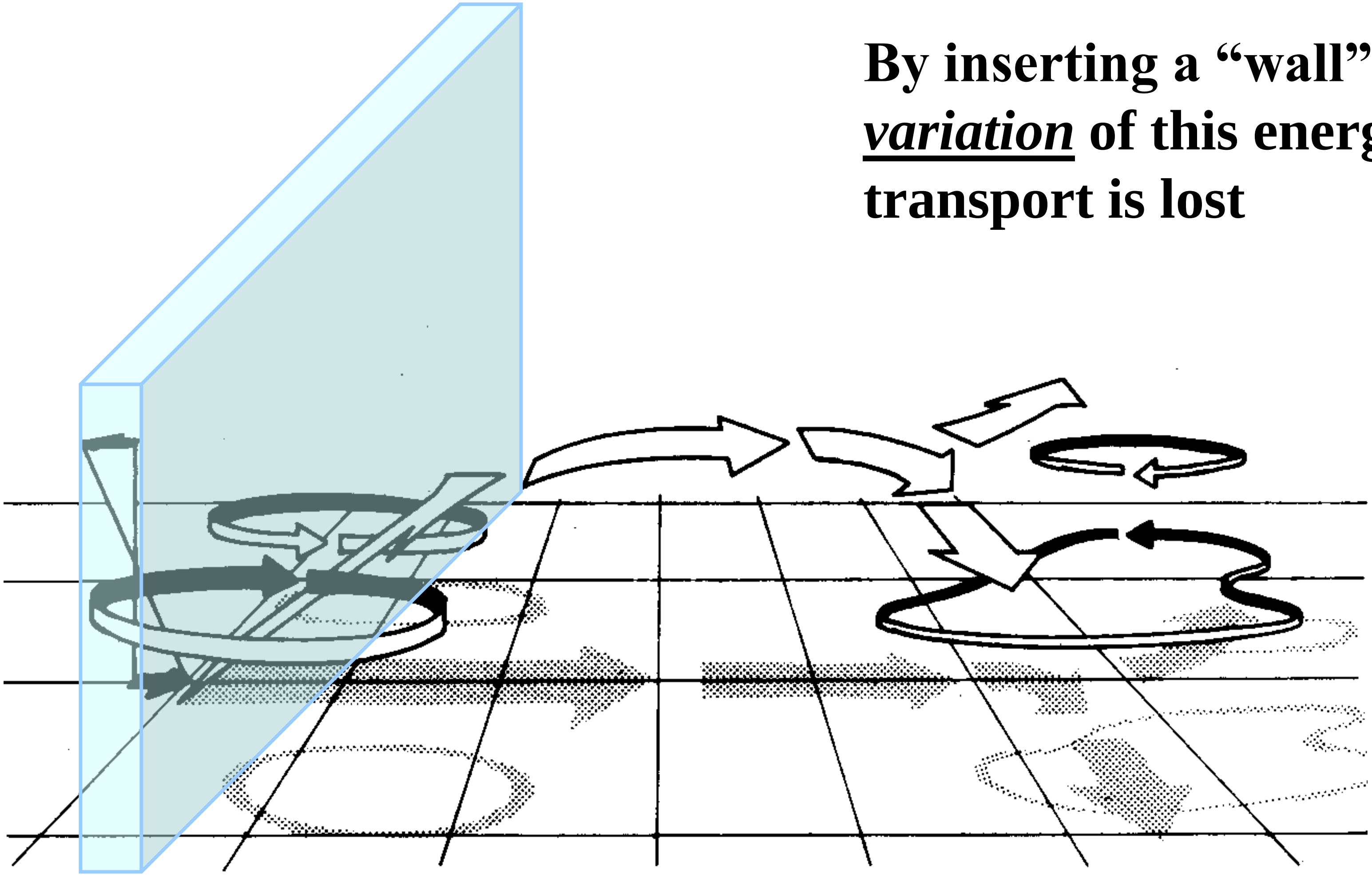
What is going on physically?

The kinetic energy from an upstream baroclinic development is, by the upper tropospheric flow, transported downstream to the next cyclone

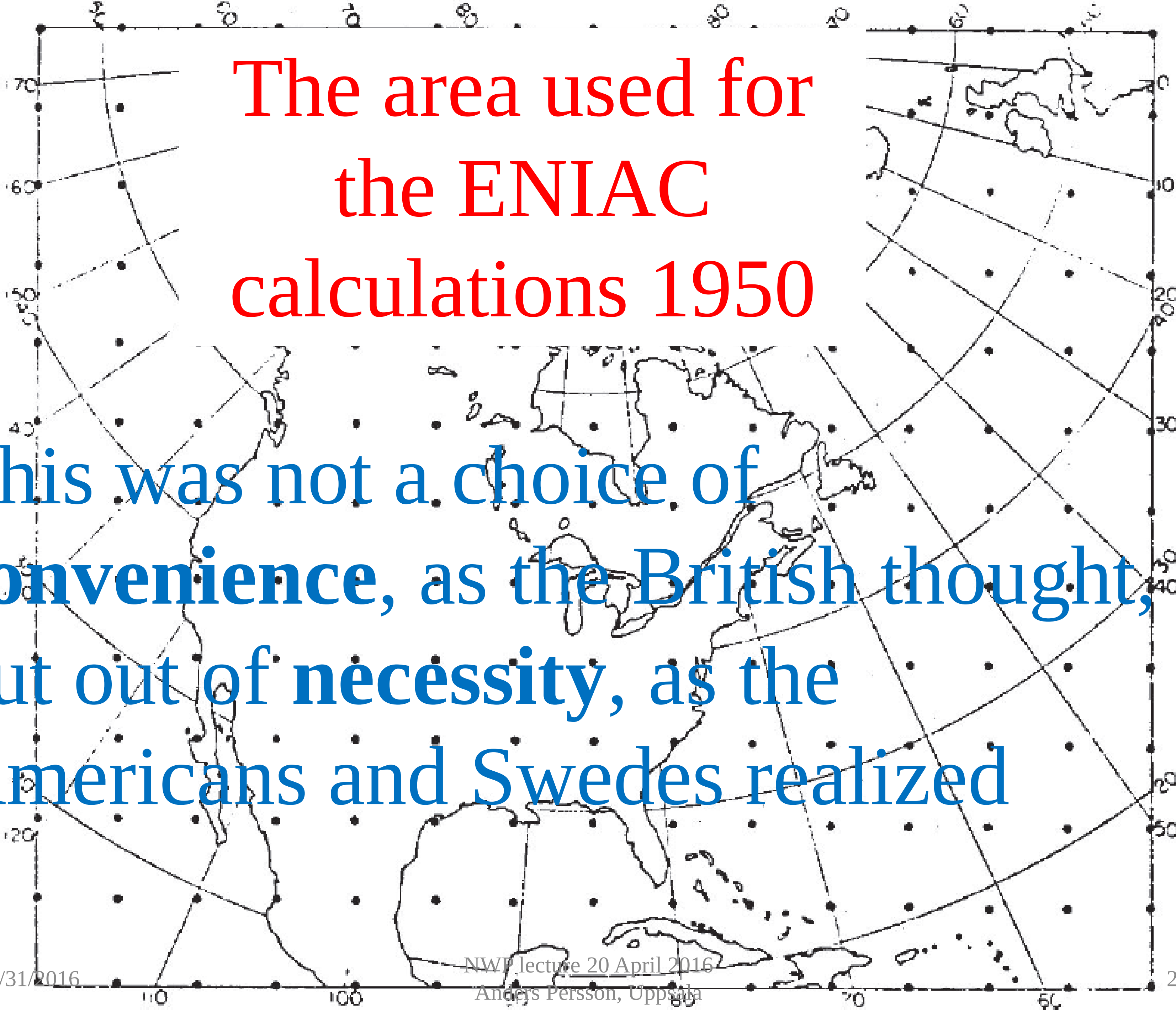


From Hoskins, James and White (1983)

What is going on physically?



By inserting a "wall" the *variation* of this energy transport is lost

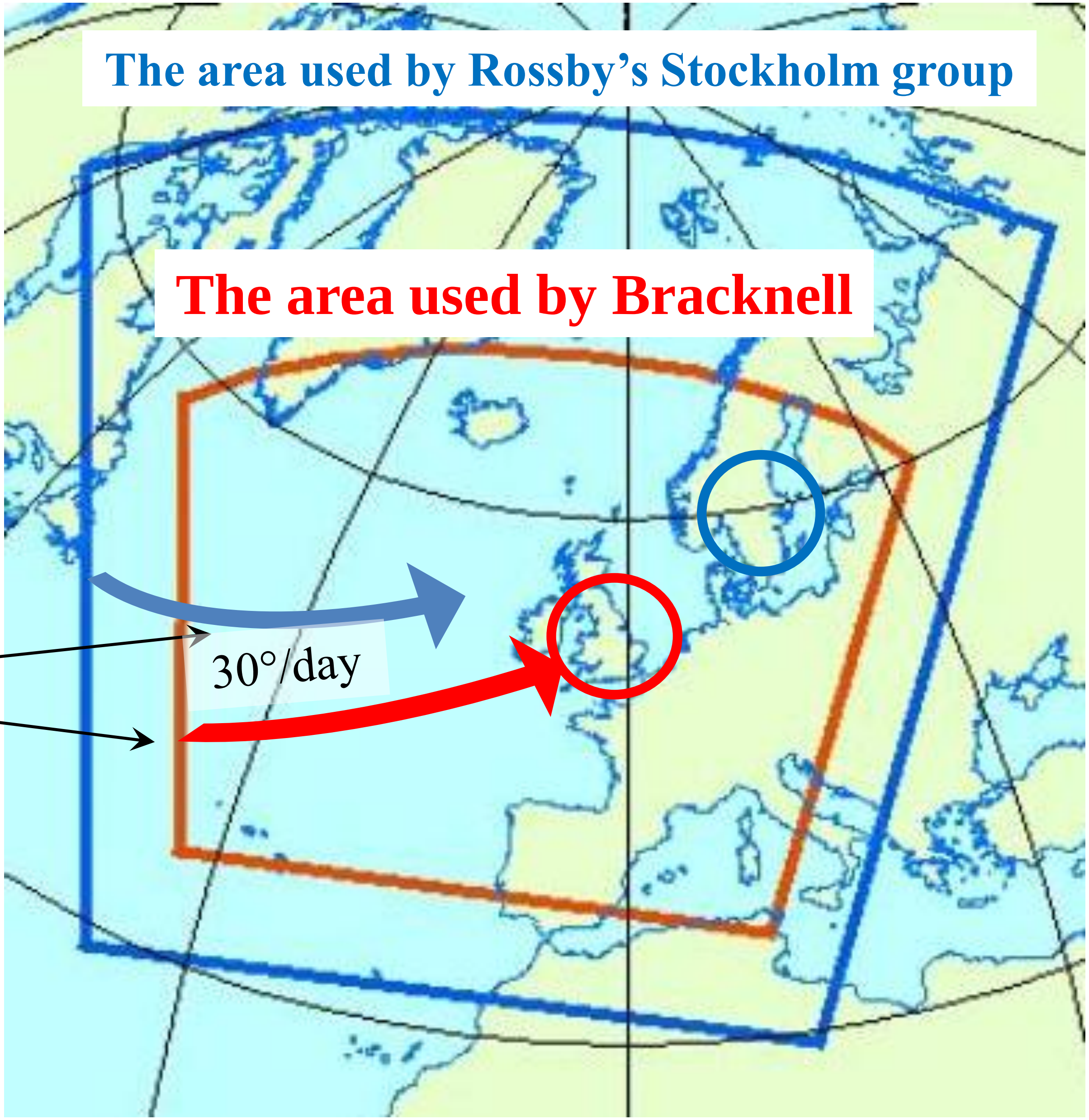


The area used for the ENIAC calculations 1950

This was not a choice of **convenience**, as the British thought, but out of **necessity**, as the Americans and Swedes realized

The effects of the constant boundaries should not reach the forecast heart land

The typical **"group velocity"** is about the same us the upper-tropospheric flow



A +24 hour forecast 27 January 1952 15 UTC

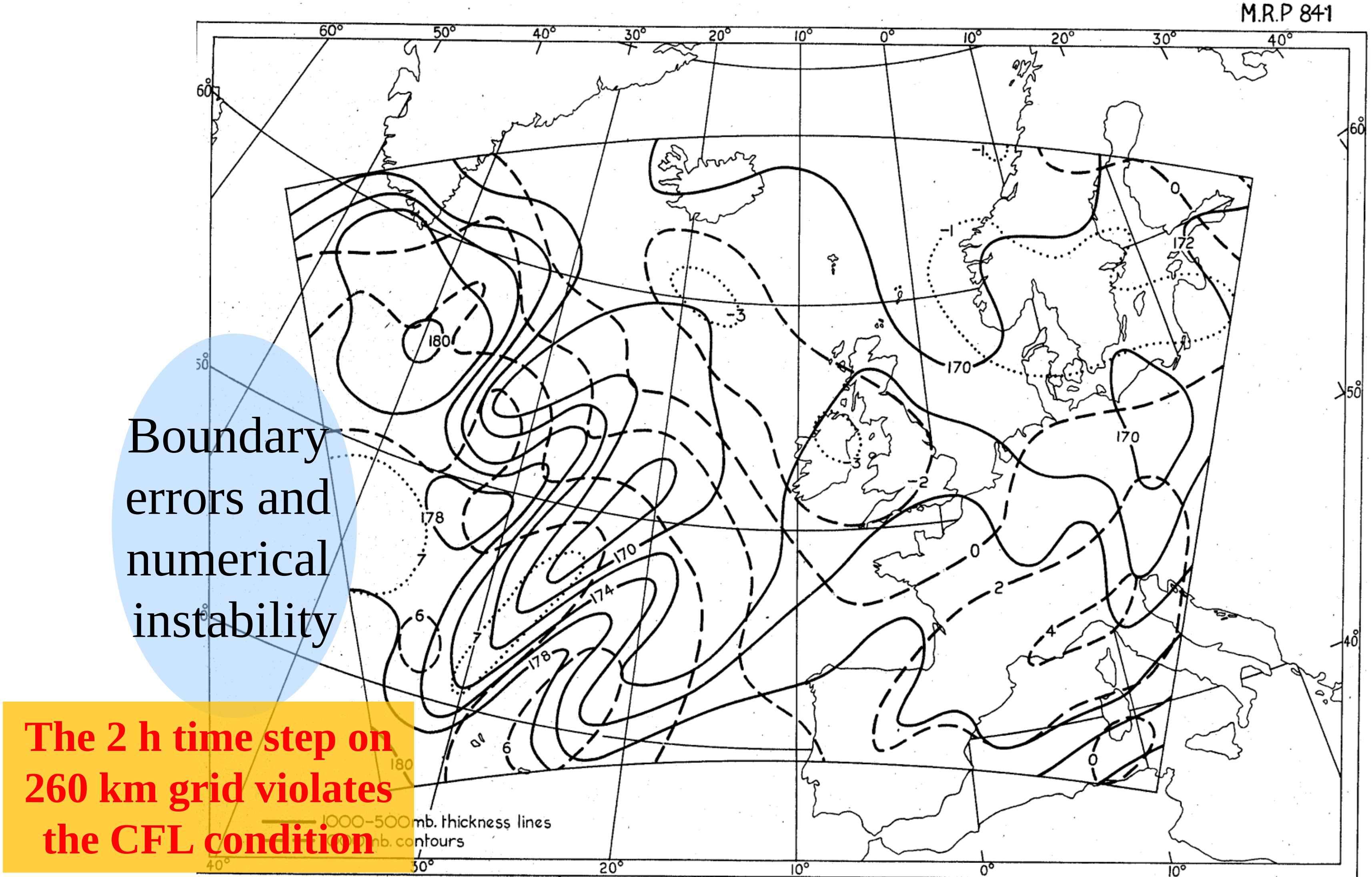


Fig.5(d) Computed 1000–500 mb. thickness and 1000 mb. contour charts for 1500 G.M.T. 28.1.52

The late 1950's was a time of problems and frustration in the world wide NWP community:

1. Britain: Problems with error propagation from the western boundary into the heart of the forecast area

2. The US: Problems with retrogression of the planetary waves in their hemispheric barotropic model

3. Sweden: Problems to extend the 1-parameter barotropic model into a 2-parameter baroclinic model

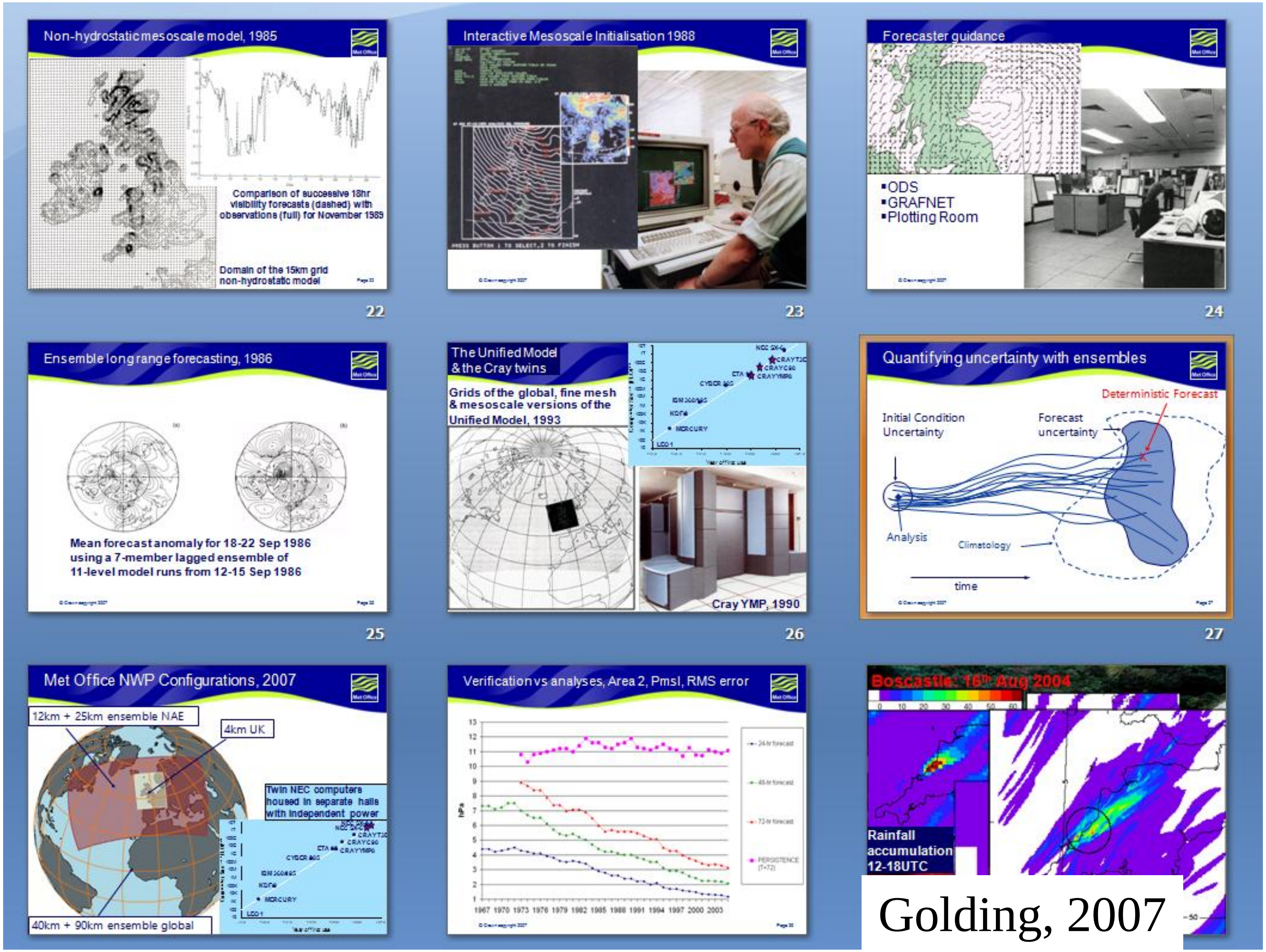
A turn of the tide 1960-65

- ❖Computer upgrades in 1959 (Meteor) and 1965 (Comet)
- ❖Extension to the whole hemisphere made problems disappear
- ❖John Mason became Director of the Met Office in October 1965

John Mason initiated full scale operational forecasting, preceded by a press conference 2 November 1965, something that the Met Office had “never done before”.

Only in 1965 did the UKMO go operational with NWP after a personal intervention by the new Director General John Mason

And soon the UK Met Office became one of the leading NWP centres



Thank you