Met Office

# Numerical Weather Prediction:
## the quest for accurate rainfall forecasts


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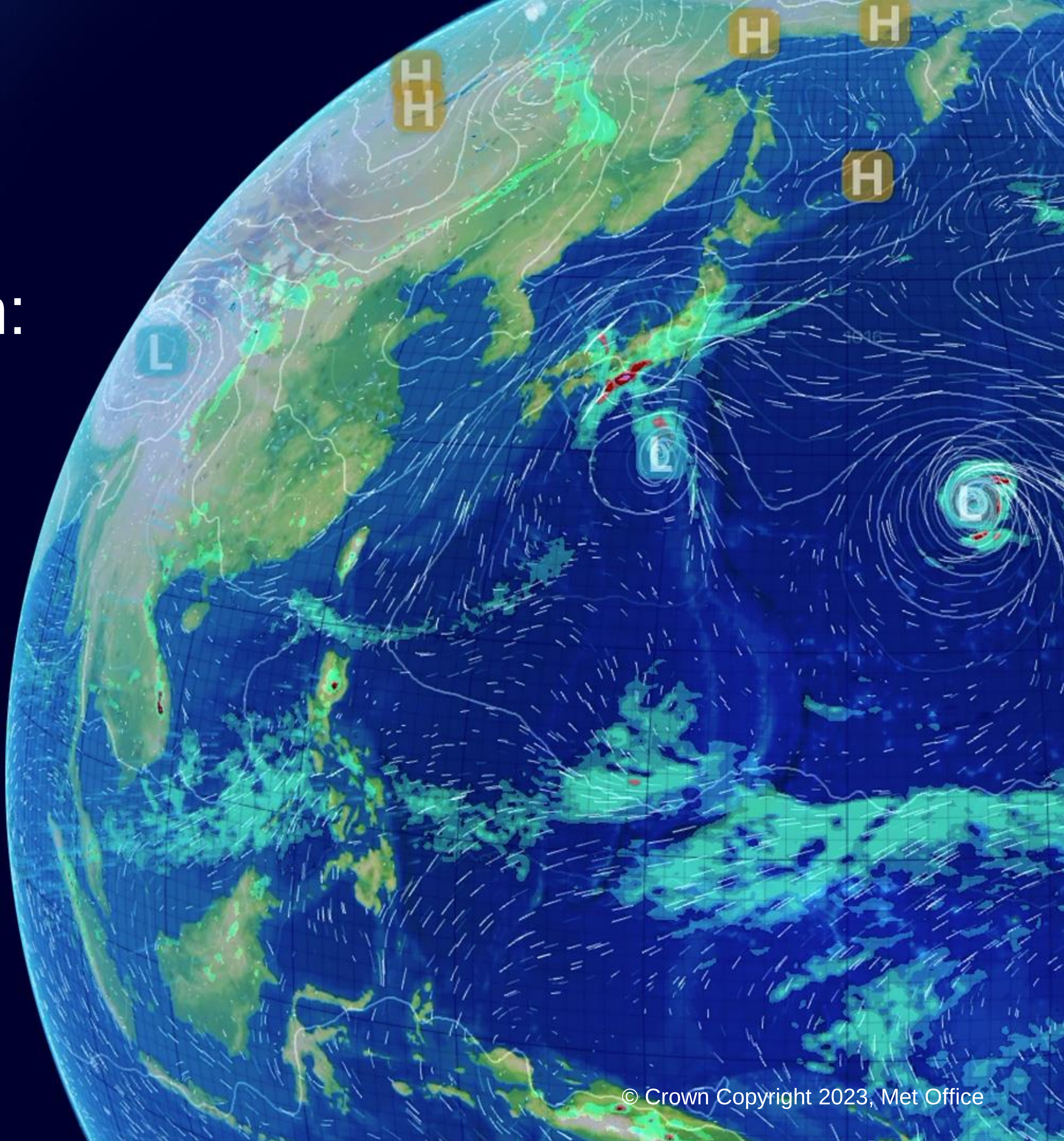

# Introduction

Numerical Weather Prediction was one of the great scientific success stories of the 20th Century.

In this talk I will trace its origins and pick out a few key events that underpin this success.

I will focus mainly on developments in the UK and particularly at the Met Office – because these are the ones I know best and that are best represented in the QJ

Representation of this work in the QJ is quite uneven. Modelling is relatively poorly represented, while Data Assimilation has a host of papers. I have picked two of these but will also point to a number of others that figure in the QJ150 collection.

# Laying Foundations

~1800 Atmospheric thermodynamics

~1850 Navier-Stokes equations

1853

Brussels

Start of Scientific Weather Forecasting

1873

Vienna, IMO, QJ

Bjerknes scientific programme

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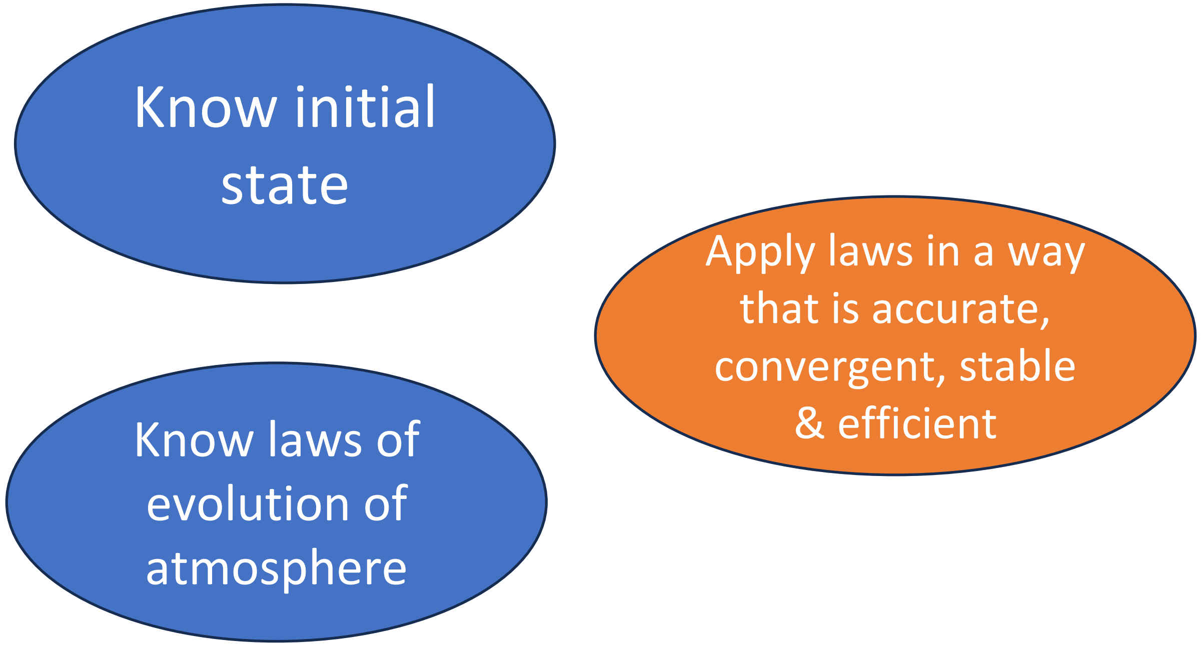
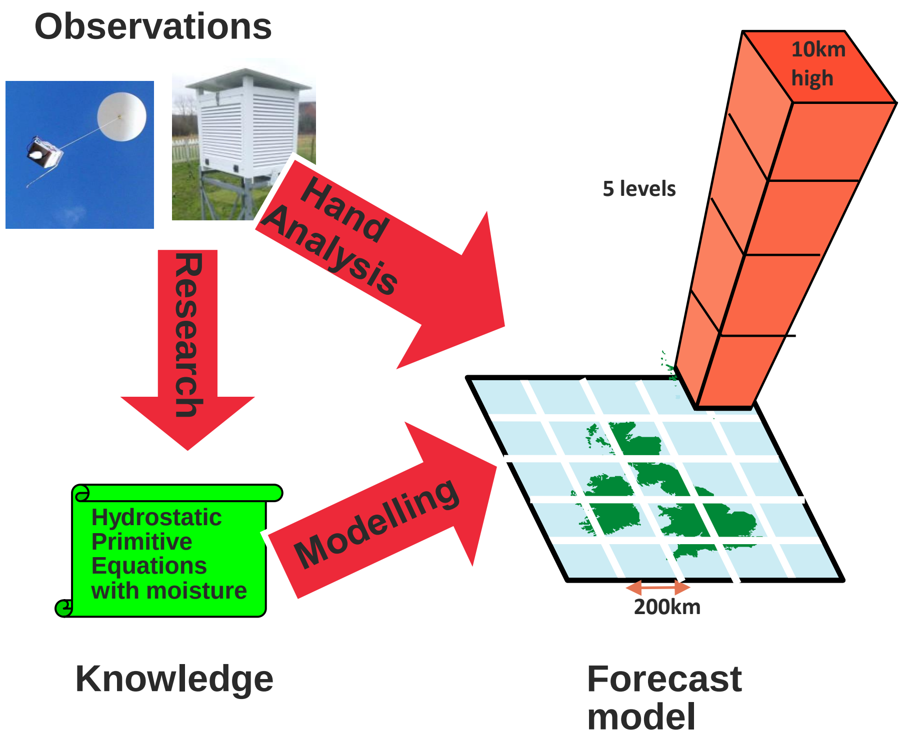
# Bjerknes 1904, Richardson 1922, Charney 1950



# Richardson's Forecasting System



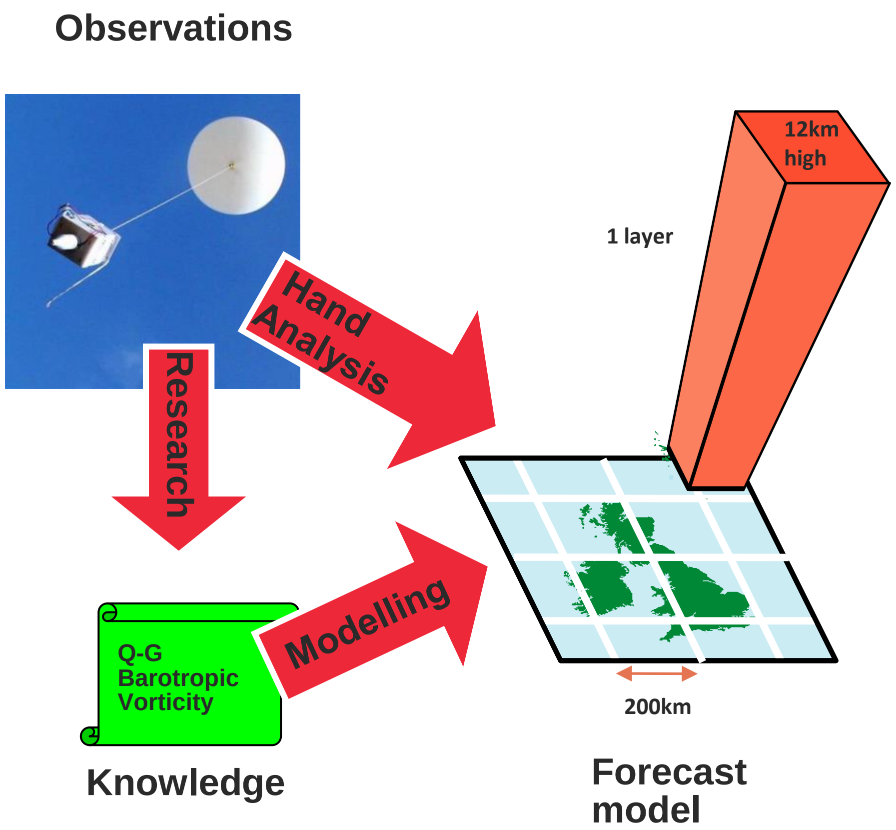

**Bjerknes 1904**

- One has to know with sufficient accuracy the state of the atmosphere at a given time → Initial Value Problem! → no observations from sea or upper air, but technical capabilities exist
- One has to know with sufficient accuracy the laws according to which one state of the atmosphere develops from another → Boundary evolution as well as interior evolution

**Richardson 1922**

- Initial conditions from International Balloon Observing Days by hand extraction from analysis charts
- The equations can be solved by finite differences
- The results diverge from reality and take too long to produce

# Charney's Forecasting System




**<u>Rossby 1940 Planetary Flow patterns in the atmosphere</u>**

**Charney 1950**

- Routine upper air hand analyses now available
- Use of the barotropic vorticity equation enables a useful forecast to be produced
- The process needs to be faster, vertical motion needs to be inferred, water cycle needs to be included

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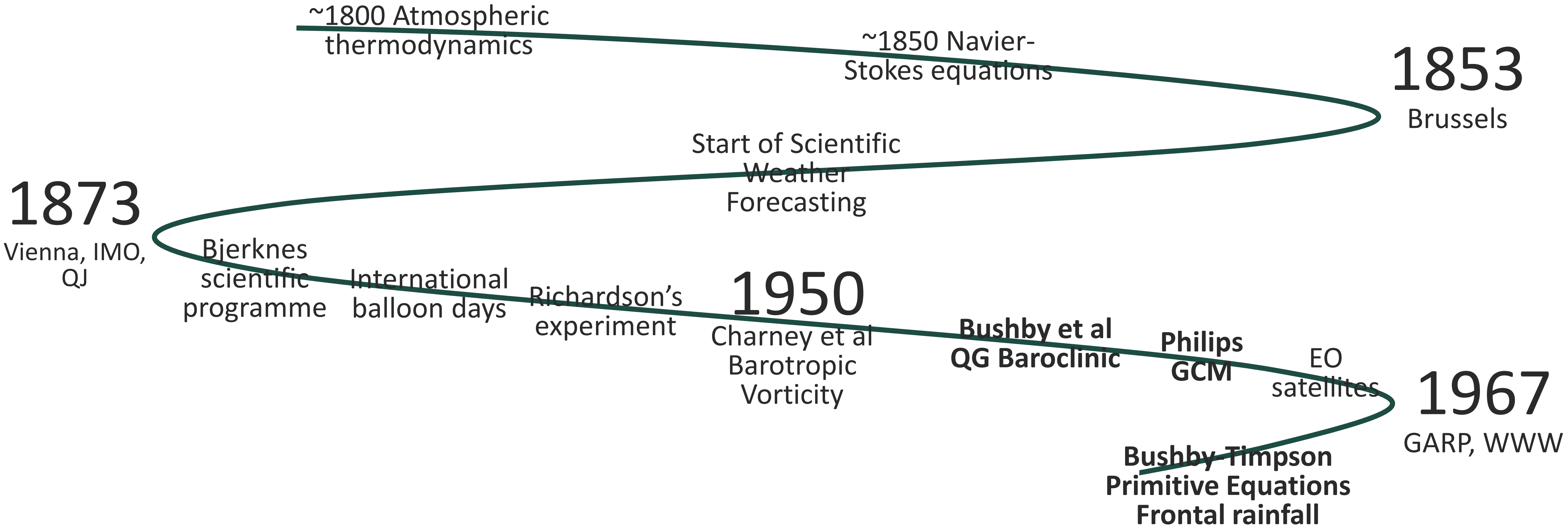
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Bushby et al QG Baroclinic
Philips GCM
EO satellites
1967
GARP, WWW
Bushby-Timpson Primitive Equations Frontal rainfall

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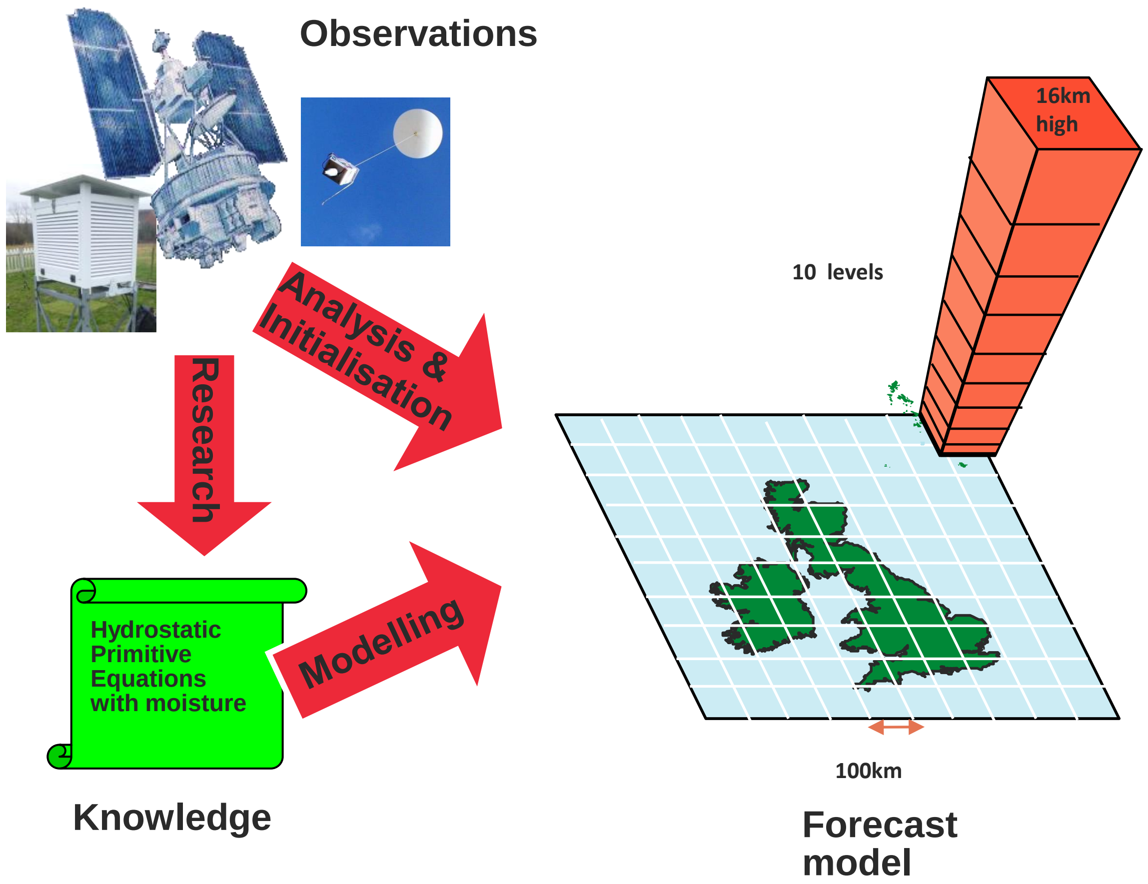
# 10-level model on a fine mesh




1953 Sawyer & Bushby: A baroclinic model atmosphere suitable for numerical integration

**1956 Phillips: The general circulation of the atmosphere: A numerical experiment**

**1957 Bushby & Huckle: Objective analysis in numerical forecasting**

**1958 Knighting, Jones & Hinds: Numerical experiments in the integration of the meteorological equations of motion**

1959 Met Office's first in-house computer

**1959 Sawyer: Introduction of the effects of topography into methods of numerical weather forecasting**

**1961 Bushby & Whitelam: A three-parameter model of the atmosphere suitable for numerical integration**

1961 Call by President Kennedy & UN

1965 KDF9 computer – first operational forecasts

**1967 Bushby and Timpson: A 10-level model and frontal rainfall**

**1967 Robinson Some current projects for global meteorological observation and experiment (WWW & GARP)**

# 1967

Transform initial state to satisfy laws

Know initial state

Apply laws in a way that is accurate, convergent, stable & efficient

Know laws of evolution of atmosphere

Represent latent heat release, radiation & drag of lower boundary

Use finer resolution to capture frontal rainfall systems

# 1967 Bushby & Timpson: A 10-level model and frontal rainfall

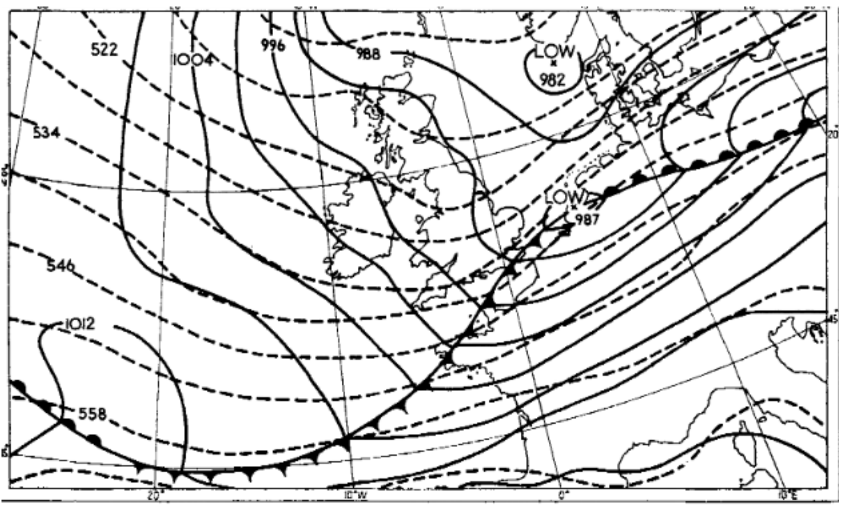



Figure 4. Actual Synoptic Situation 0000 GMT 2 December 1961.
surface isobars ——— 500 mb contours - - - - - -

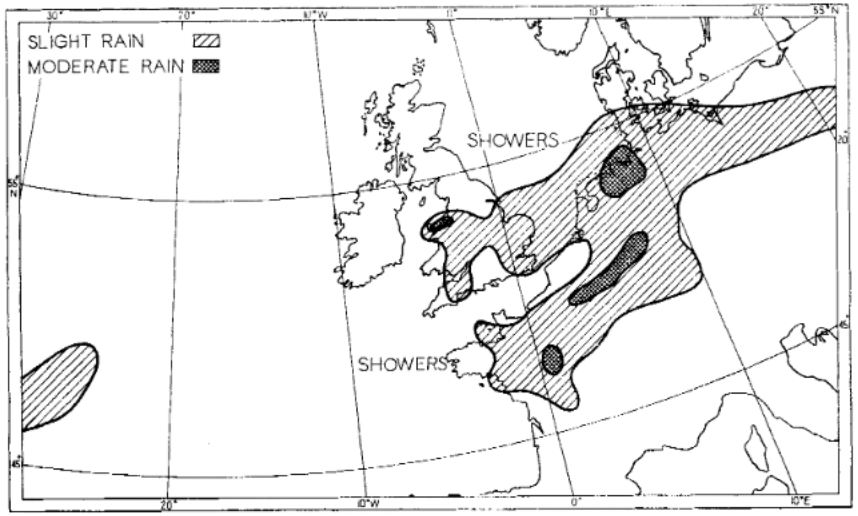



Figure 8. Present Weather 0000 GMT 2 December 1961.

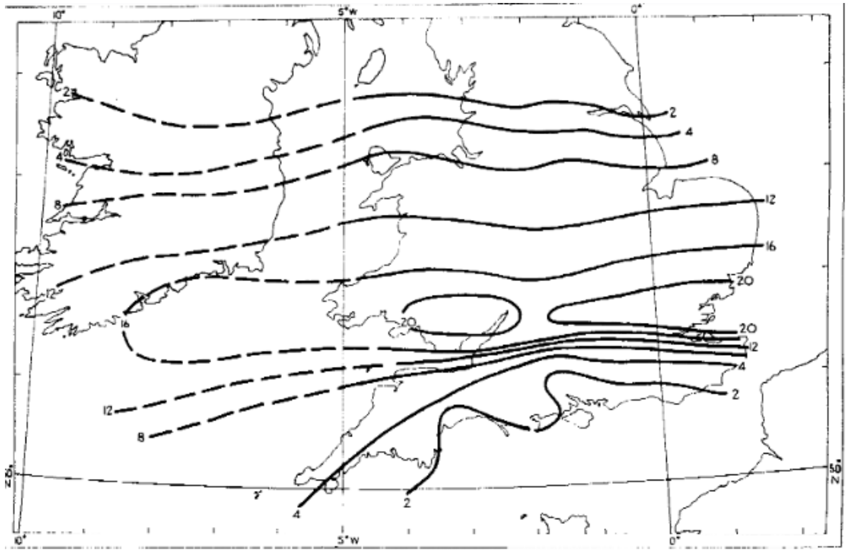



Figure 10. Total Rainfall mm observed over the British Isles 0000-2400 GMT 1 December 1961 (Irish totals 0600-1800 GMT).

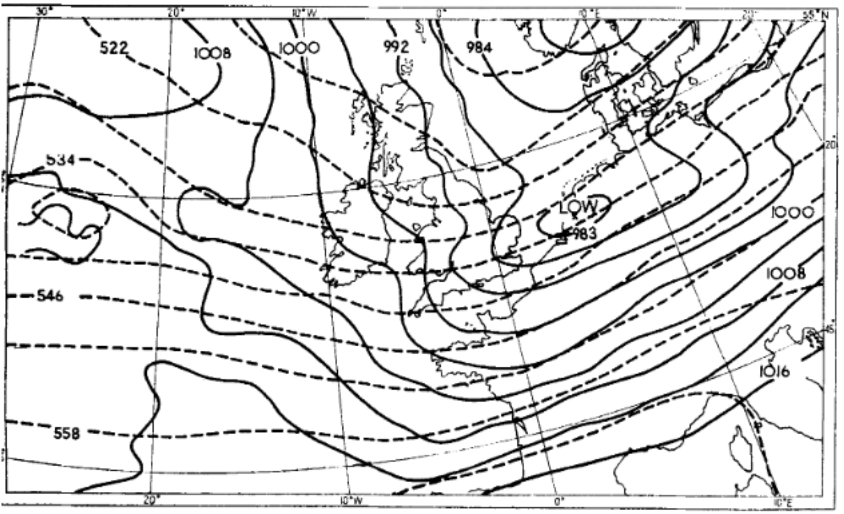



Figure 5. 24 hr Forecast of Synoptic Situation 0000 GMT 2 December 1961.
surface isobars ——— 500 mb contours - - - - - -

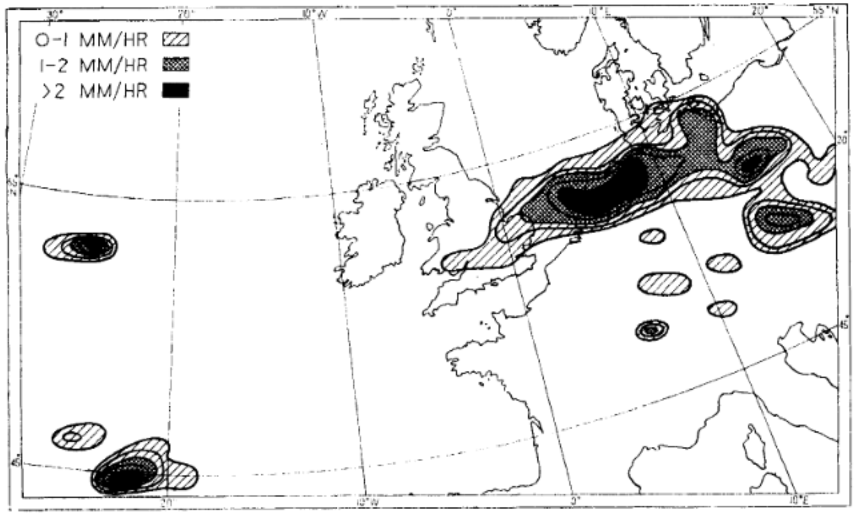



Figure 9. Forecast Rate of Rainfall mm/hour 0000 GMT 2 December 1961.

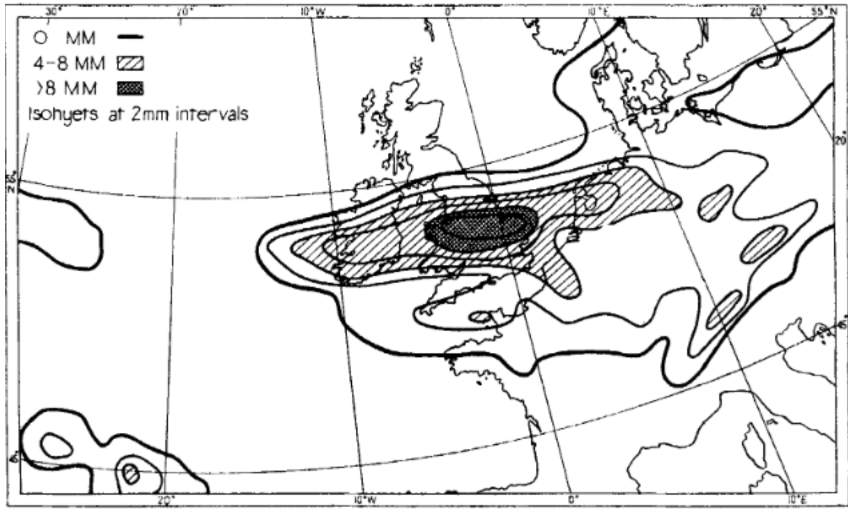
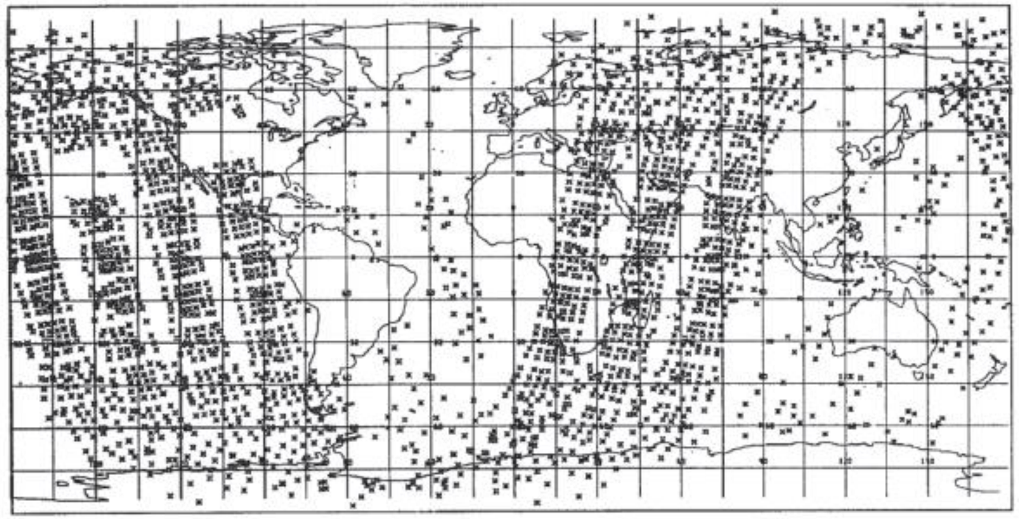


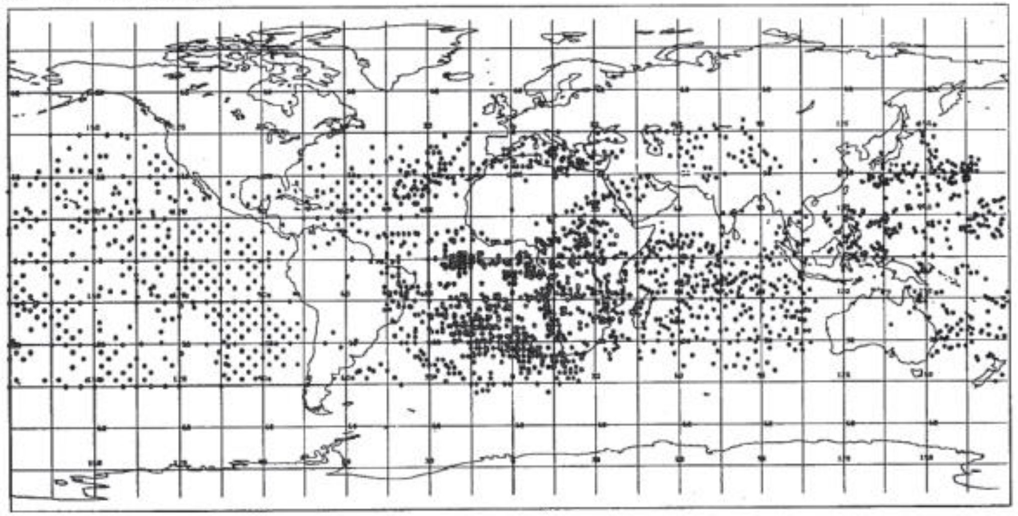

Figure 11. Forecast Total Rainfall mm 0000-2400 GMT 1 December 1961.

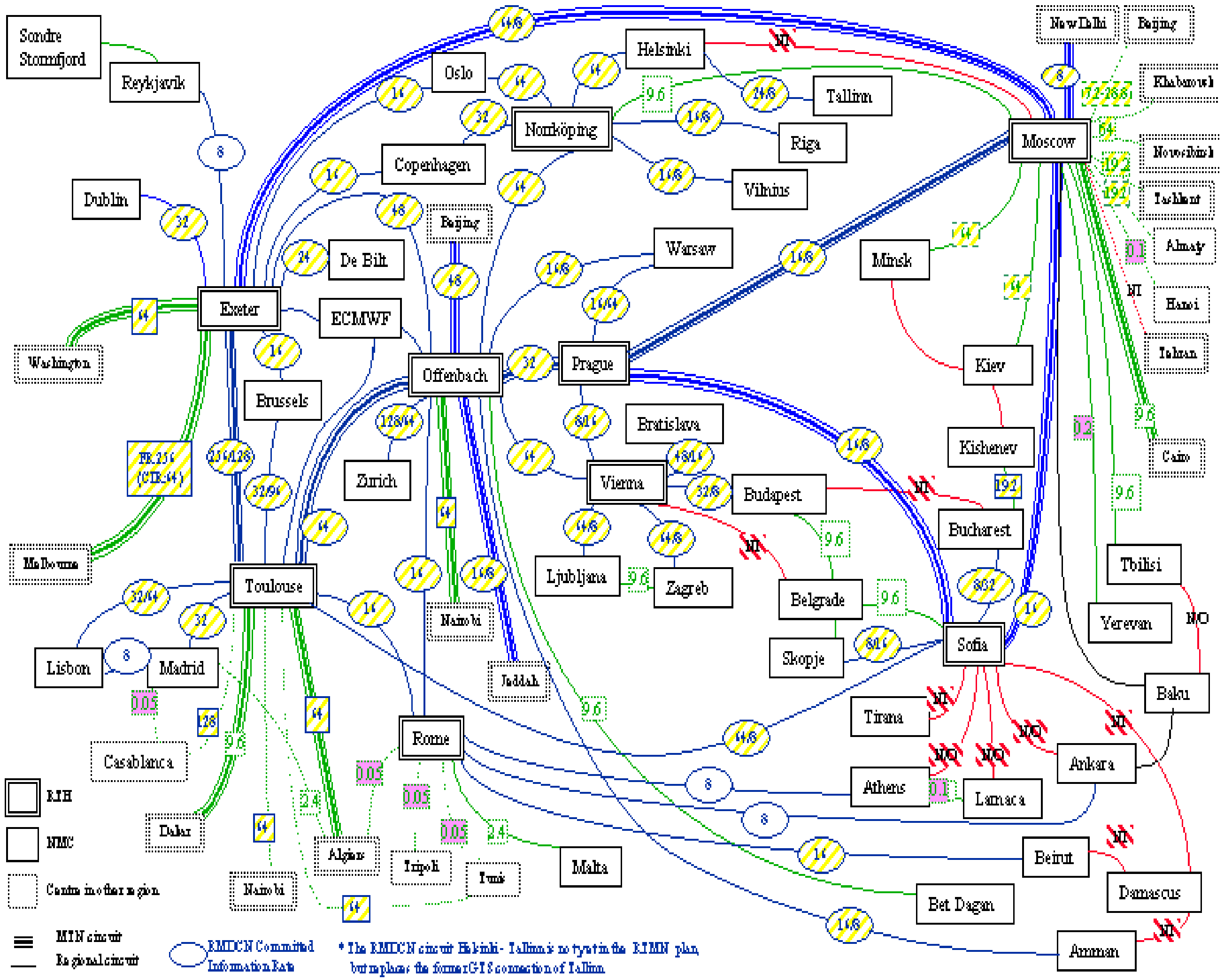
# WWW: GOS & GTS

(a) POSITION OF SATEM OBSERVATIONS
0Z ON 27/2/1979



(b) POSITION OF SATOB OBSERVATIONS
0Z ON 27/2/1979





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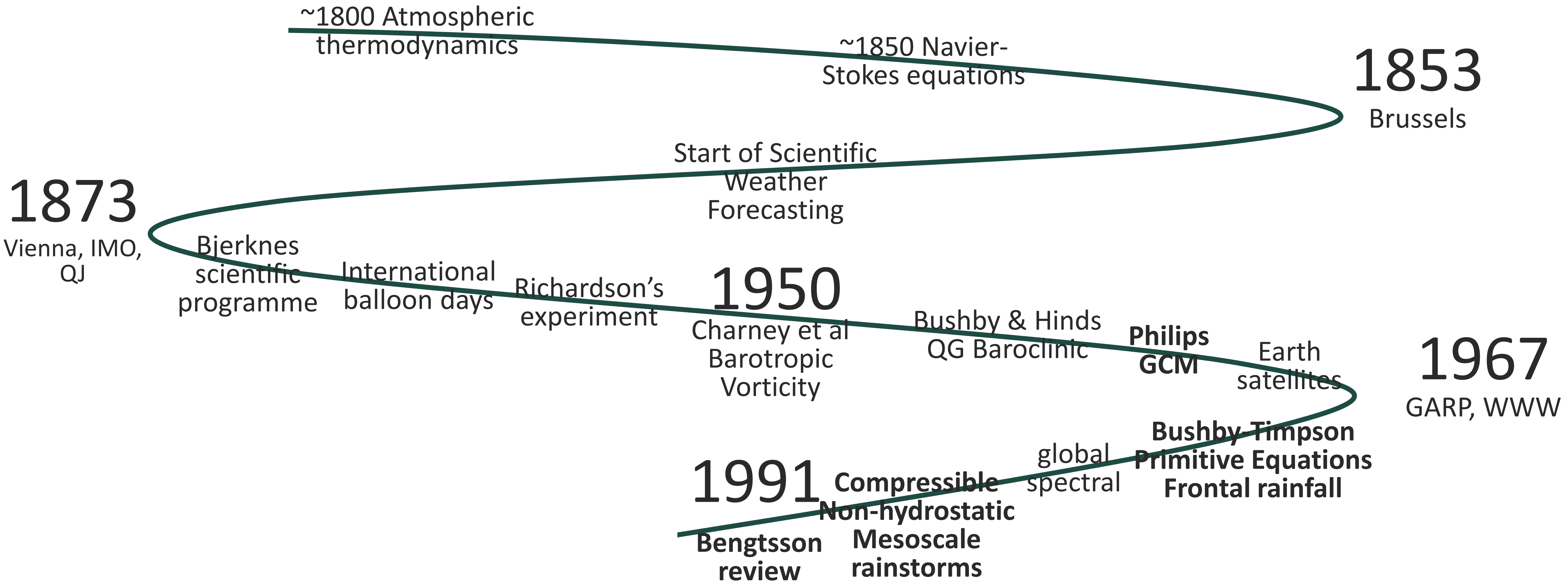
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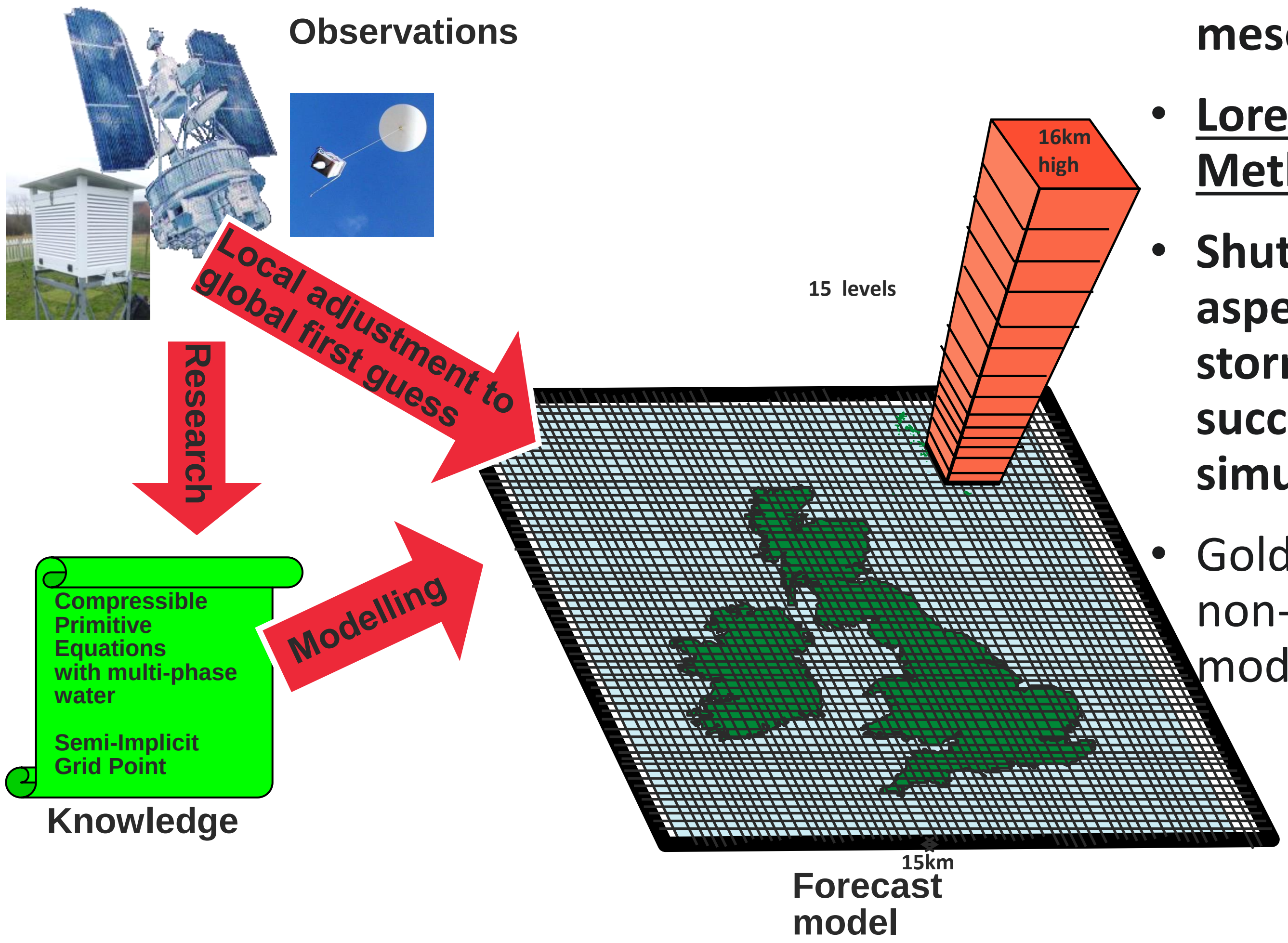
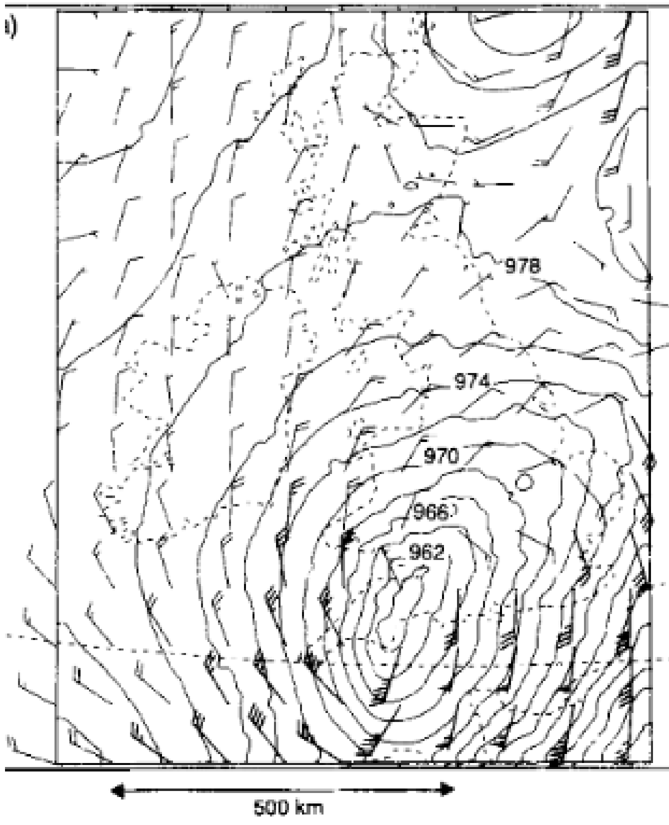
global spectral
Compressible Non-hydrostatic Mesoscale rainstorms
1991
Bengtsson review

# Met Office Mesoscale Model 1990




- **Tapp & White, 1976, A non-hydrostatic mesoscale model**
- **Lorenc, 1986 Analysis Methods for NWP**
- **Shutts, 1990, Dynamical aspects of the October storm, 1987: A study of a successful fine-mesh simulation**
- Golding, 1992, An efficient non-hydrostatic forecast model



# Bengtsson 1991 Advances and prospects in numerical weather prediction (IAMAP presidential address)

## Advances:

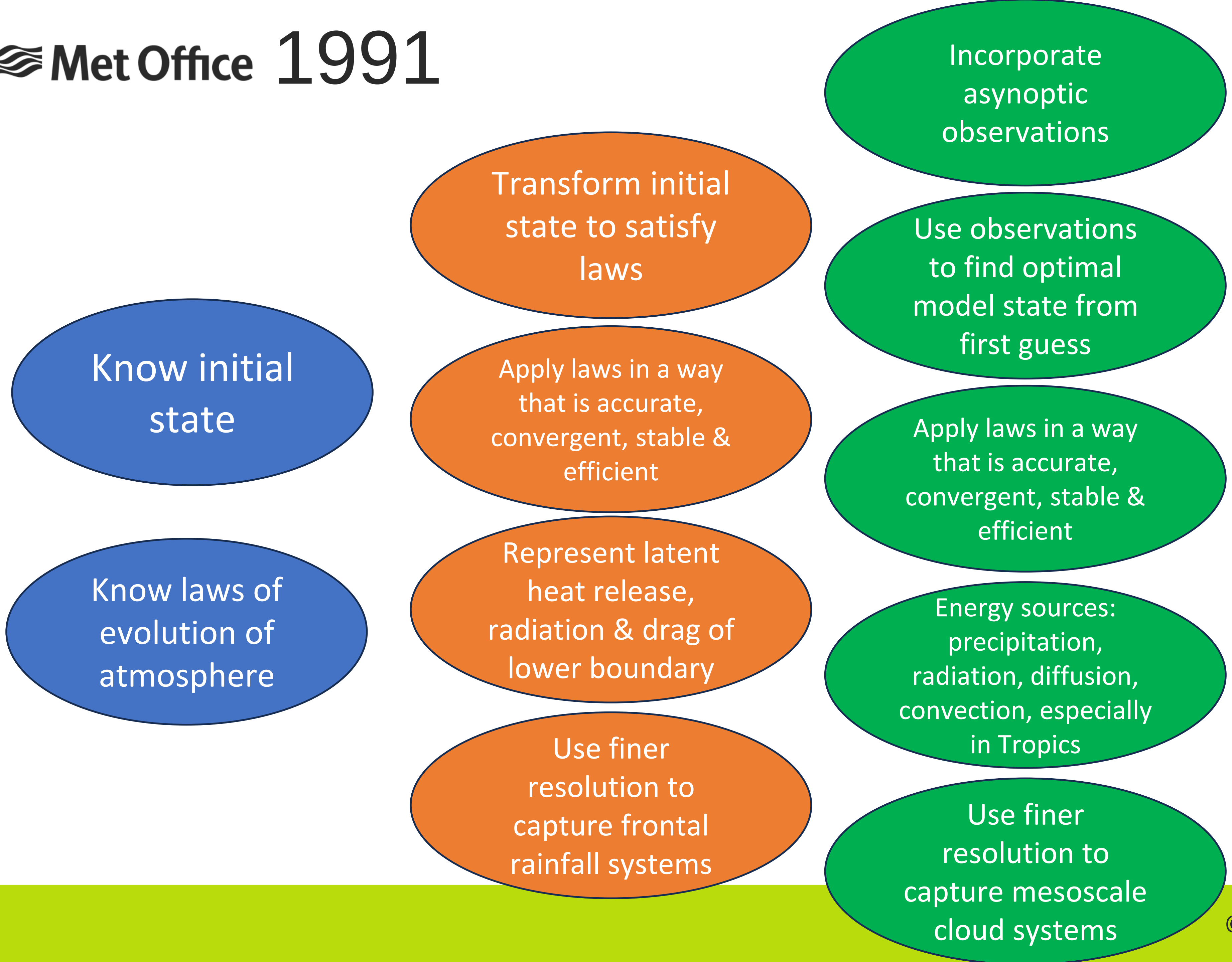
Understanding of atmospheric dynamics and physics
Computer technology
Economical semi-implicit integration methods; use of the spectral transform technique
Horizontal and vertical resolution
Physical processes, largely based on research with FGGE data, including:
- Orographic effects (envelope orography)
- Convection (Kuo, Betts)
- Stratiform Precipitation (condensation only)
- Radiation

Global observing systems, as demonstrated during the FGGE
4DDA data-assimilation methods for assimilation of asynoptic observations from satellites, aircraft & drifting buoys based on Optimal Interpolation followed by Non-Linear Normal Mode Initialisation

## Prospects:

Improved initialization and data-assimilation to overcome observational problems - lack of satellite data impact
Critical role of latent heat release
Model solutions to excessive zonalisation/loss of blocking with time
Predictability studies show current models should be able to extend period of useful forecasts

# Met Office 1991



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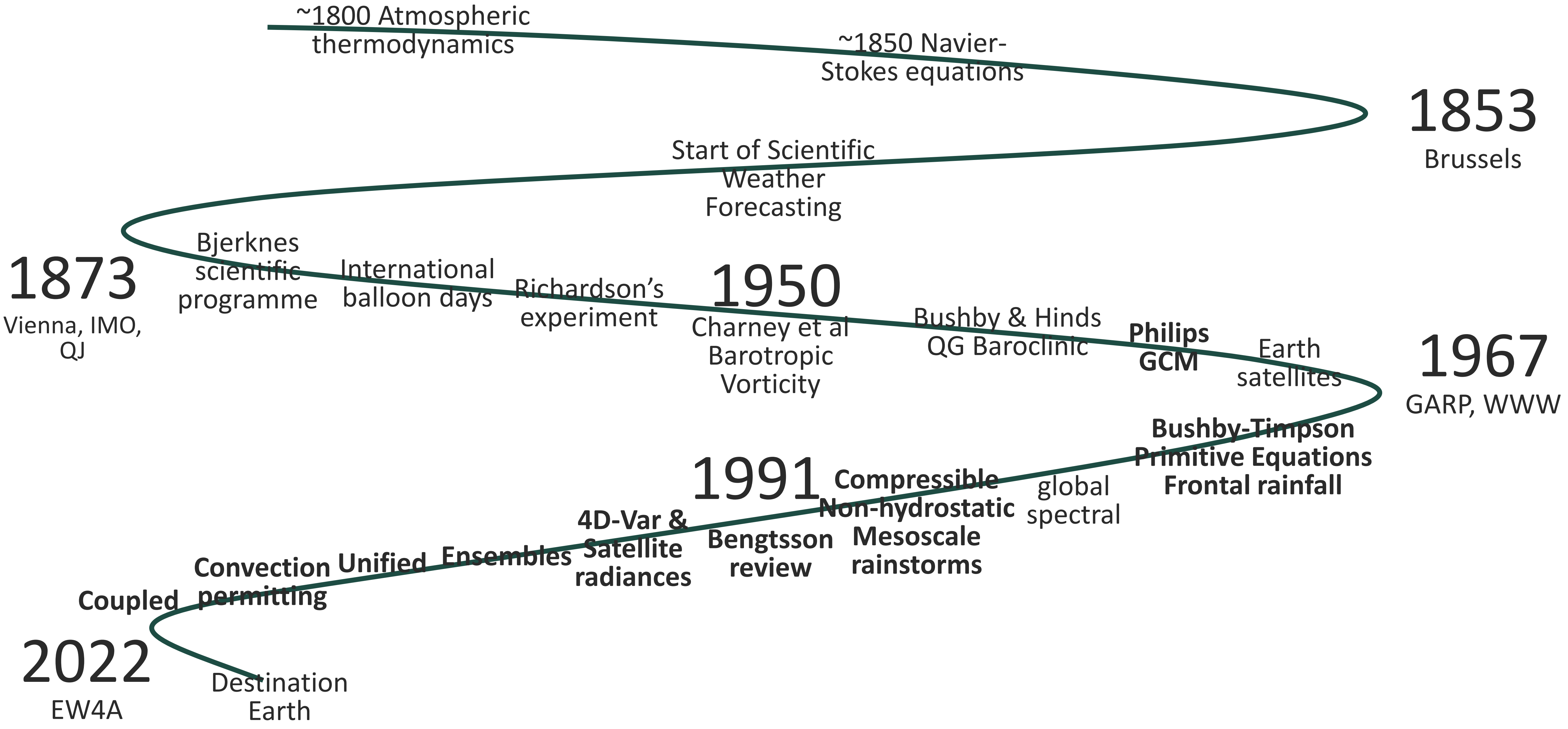
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Mesoscale rainstorms
1991
Bengtsson review
4D-Var & Satellite radiances
Ensembles
Unified
Convection permitting
Coupled
2022
EW4A
Destination Earth

# Met Office Unified Model (MOGREPS-UK) km-scale ensemble

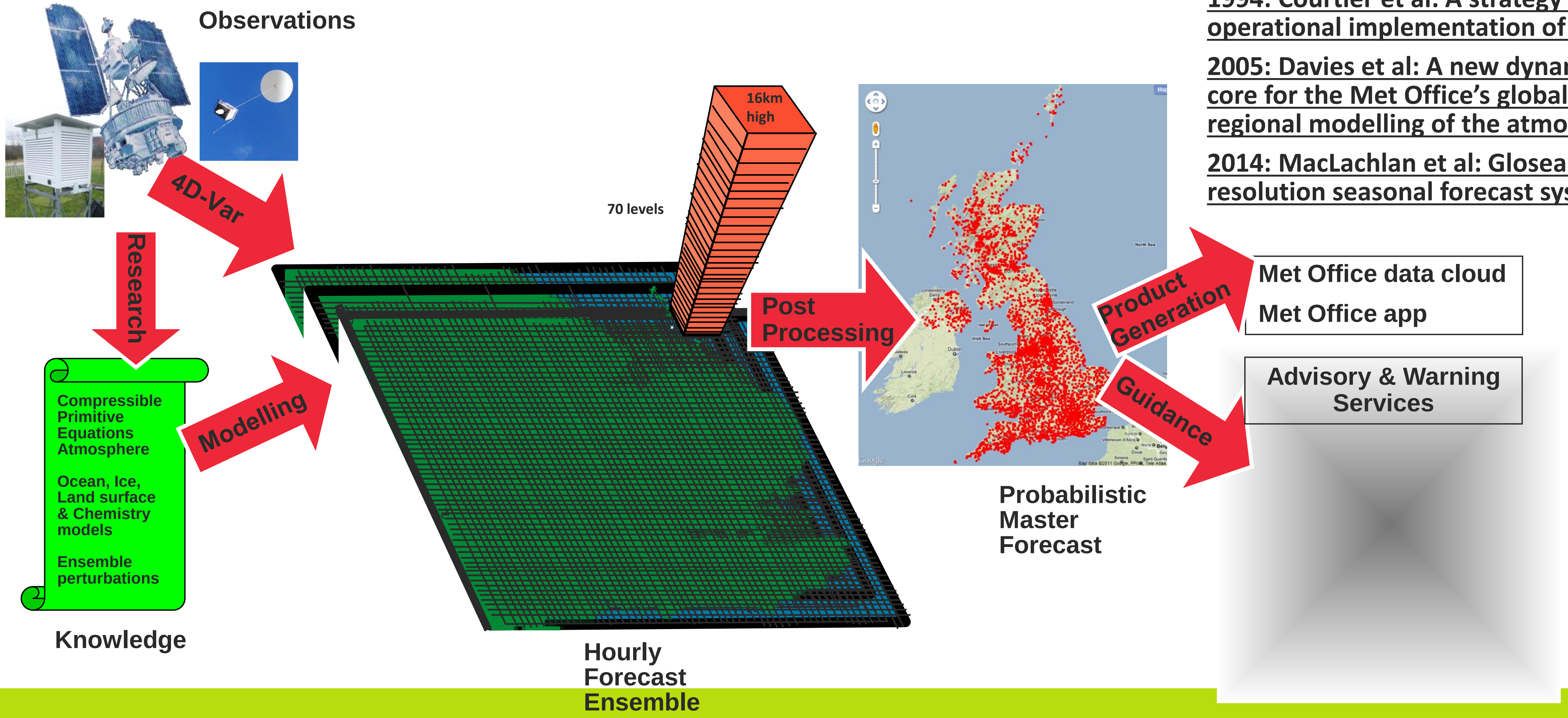
1990: Murphy: Assessment of the practical utility of extended range ensemble forecasts

1993: Eyre et al: Assimilation of TOVS radiance information through 1D-Var

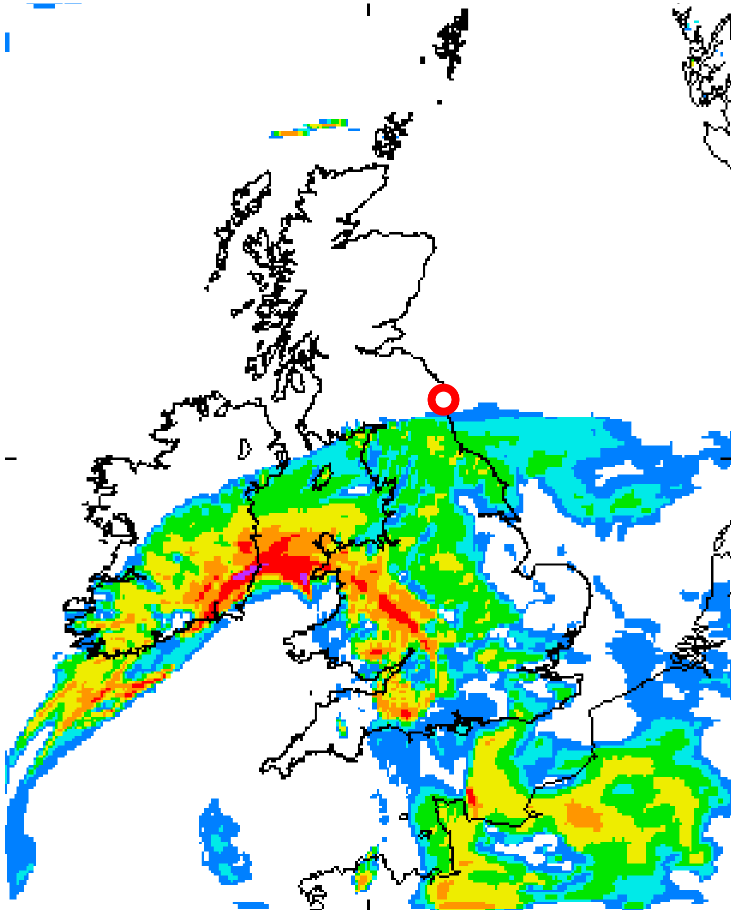
1994: Courtier et al: A strategy for operational implementation of 4D-Var

2005: Davies et al: A new dynamical core for the Met Office's global & regional modelling of the atmosphere

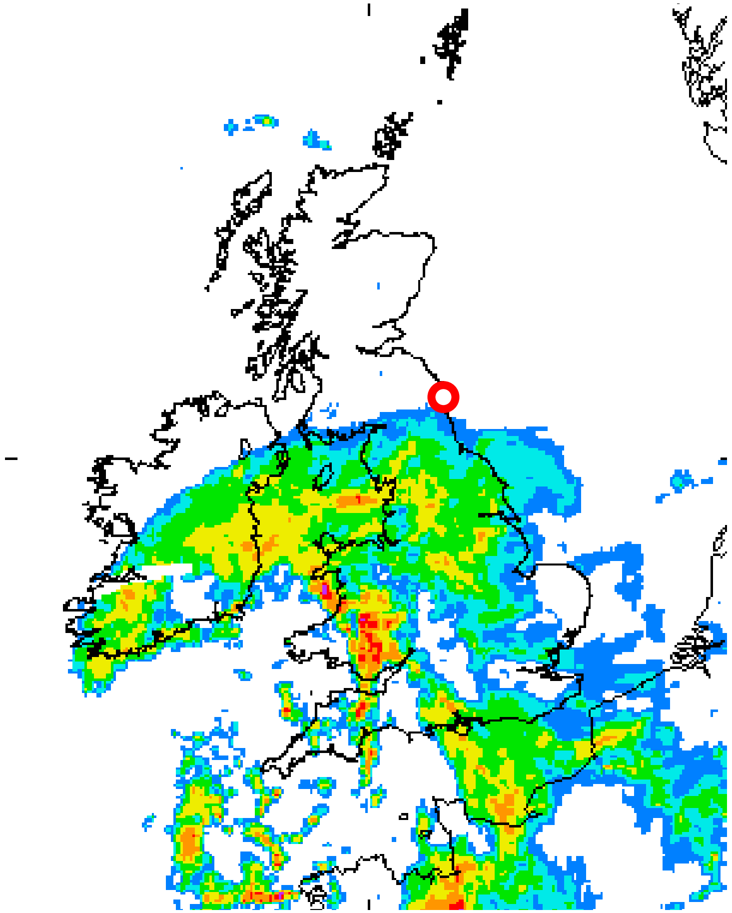
2014: MacLachlan et al: Glosea5: A high resolution seasonal forecast system



# Sep 2008 Morpeth Flood



UKV 4-20hr forecast
1.5km gridlength
convection permitting model



UK radar network

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# 2023

Know initial state

Know laws of evolution of atmosphere

Transform initial state to satisfy laws

Apply laws in a way that is accurate, convergent, stable & efficient

Represent latent heat release, radiation & drag of lower boundary

Use finer resolution to capture frontal rainfall systems

Incorporate asynoptic observations

Use observations to find optimal model state from first guess

Apply laws in a way that is accurate, convergent, stable & efficient

Energy sources: precipitation, radiation, diffusion, convection, especially in Tropics

Use finer resolution to capture mesoscale cloud systems

Multiple forecasts from perturbed states/parameters

Optimise initial state using ensemble first guess

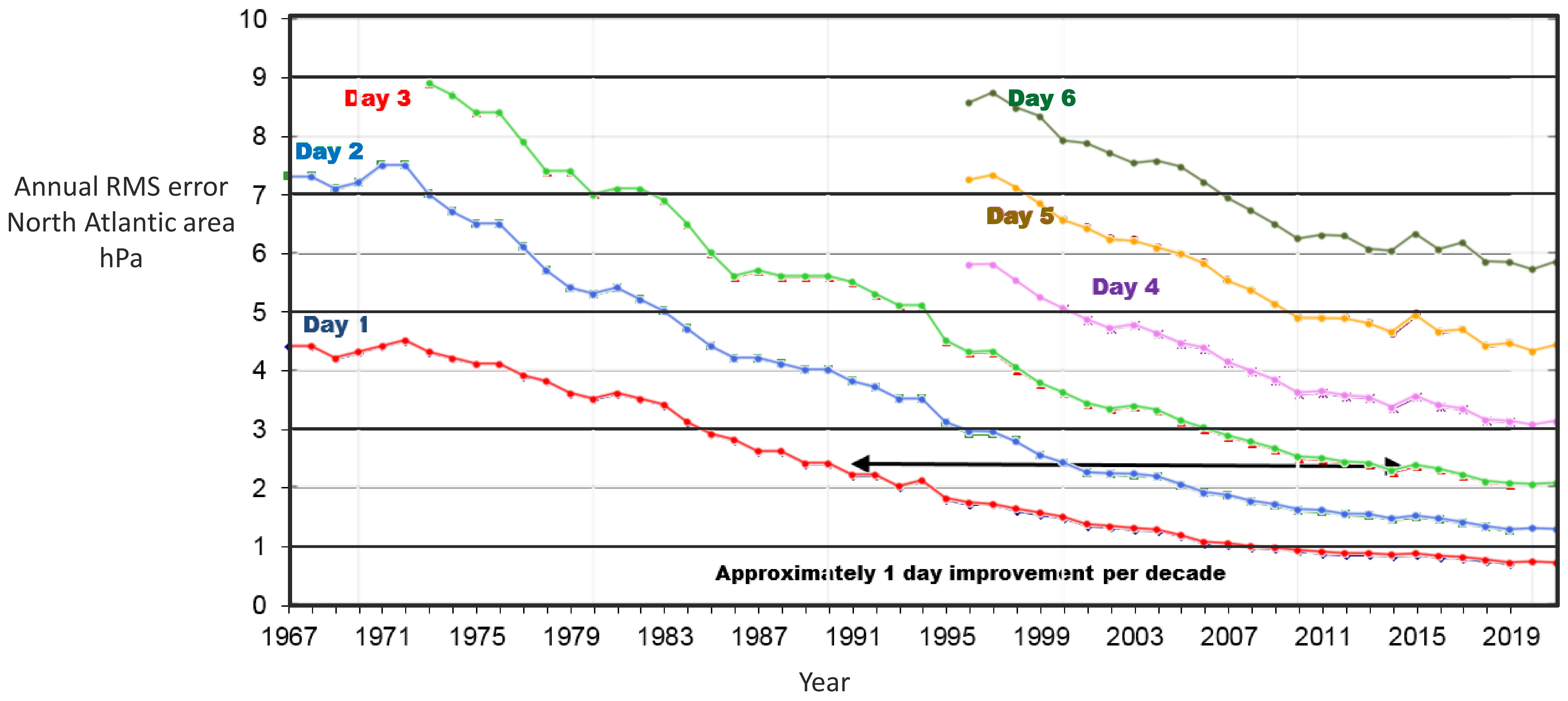
Apply laws in a way that is accurate, convergent, stable & efficient

Coupled evolution of land, ocean, ice & atmospheric chemistry

Use finer resolution to capture convective storms

Automated post-processing for risk assessment etc

# Improvements in Surface Pressure Accuracy



# T+9h top10% precipitation“Skill Distance” UK 1.5km model vs radar

## 3-year running mean

# Early Warnings For All

We must invest equally in adaptation and resilience. That includes the information that allows us to anticipate storms, heatwaves, floods and droughts. Communities and nations need adequate warning and the ability to respond to incoming extreme weather events. To that end, I have called for every person on Earth to be protected by early warning systems within five years, with the priority to support the most vulnerable first. The facts are clear. Early warnings save lives and deliver vast financial benefits. Now is the time to implement Early Warnings for All.

H.E. António Guterres – March 2022
Secretary-General of the United Nations

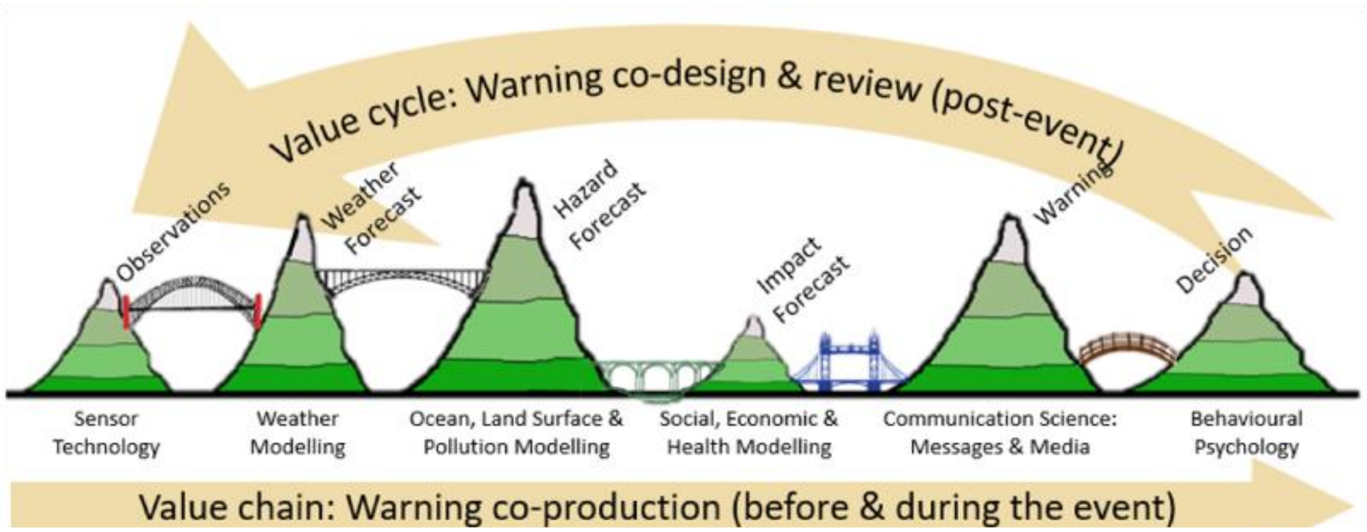
Disaster knowledge & management: people know what to expect & to do

Observe, monitor and forecast: comprehensive observations and accurate forecasts


Be prepared and anticipate: people act to protect their communities

Disseminate and Communicate: reaching everyone with a relevant and comprehensible message

# Looking forward: NWP as part of the forecasting & warning value chain




Metrics of success:

- Inputs (Observations, Data Assimilation, Resolution, Ensemble),
- Outputs (AC Z500, RMS Pmsl, FSS precipitation, RPSS extreme temperatures)
- Outcomes (lives saved, losses avoided, essential services maintained)

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# Questions?