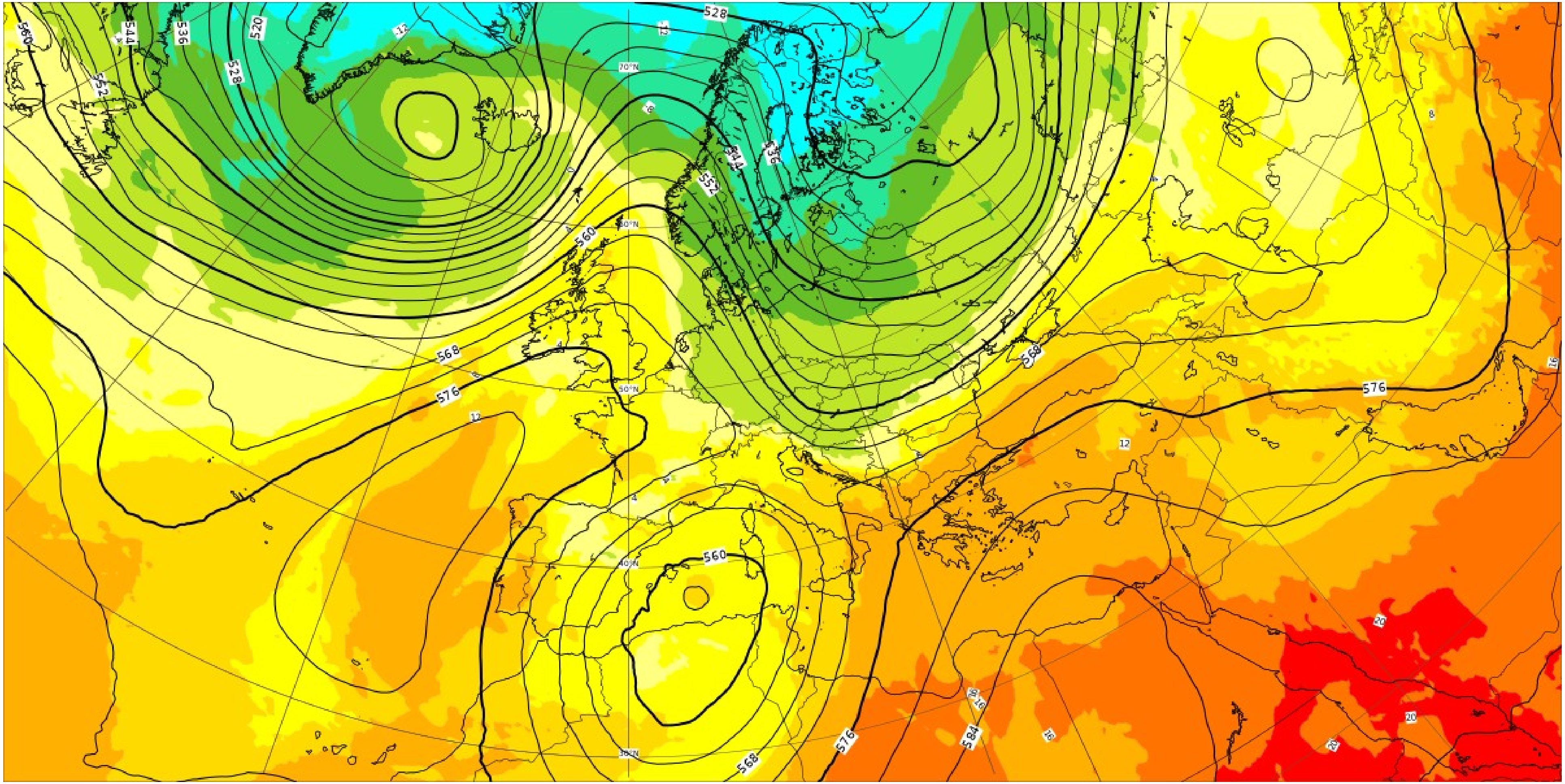
Numerical Weather Prediction (NWP) and specific challenges

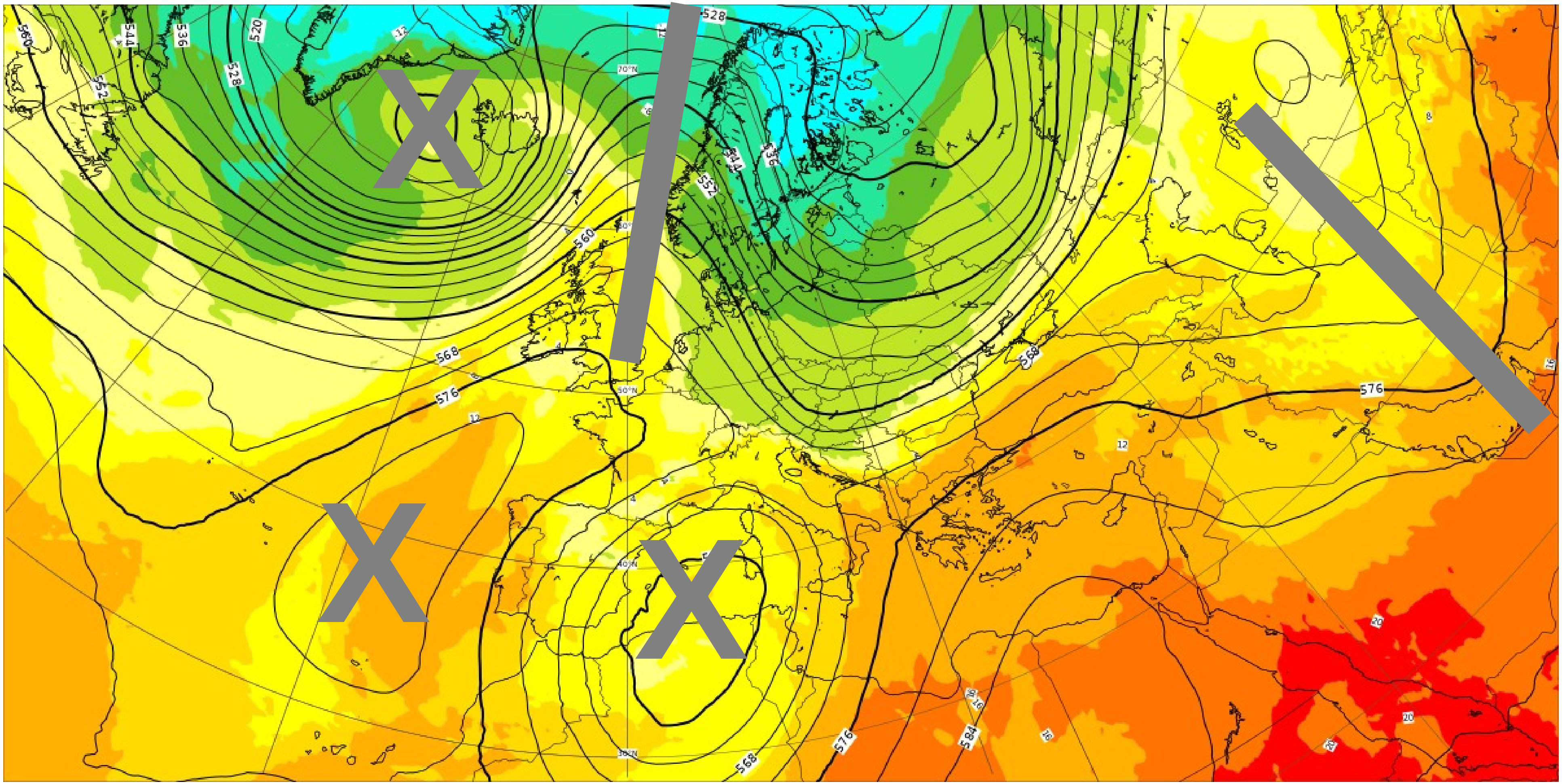
Reima Eresmaa
Finnish Meteorological Institute

Thanks:
Peter Bauer *et al.*, Anton Beljaars, Massimo Bonavita,
Matti Huutonen, Karoliina Hämäläinen *et al.*



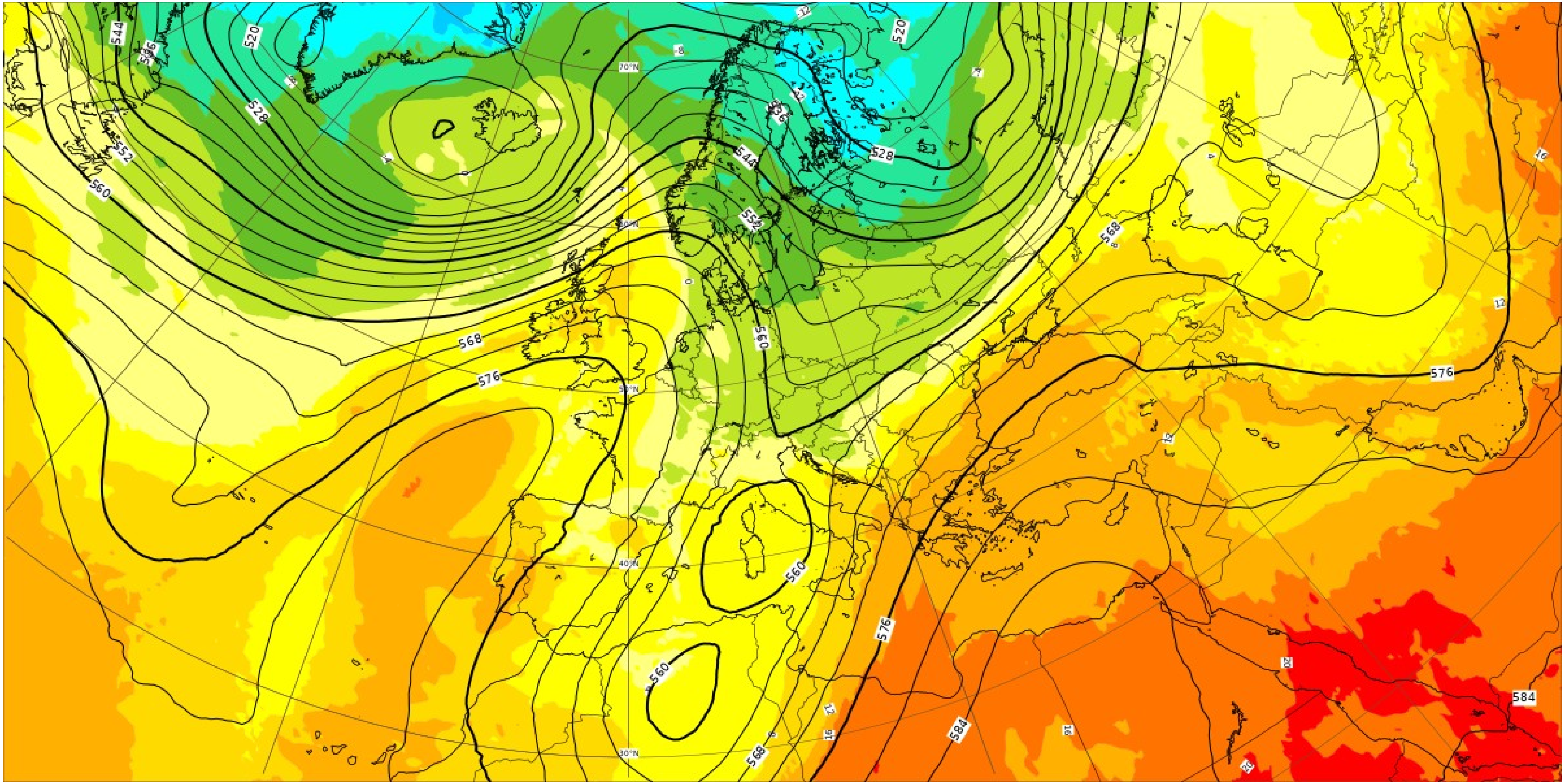
5-day forecast of *geopotential height at 500 hPa* (contours) and *temperature at 850 hPa* (colour shading)
Validity time 00 UTC, 9th November 2021

Source: www.ecmwf.int



5-day forecast of *geopotential height at 500 hPa* (contours) and *temperature at 850 hPa* (colour shading)
Validity time 00 UTC, 9th November 2021

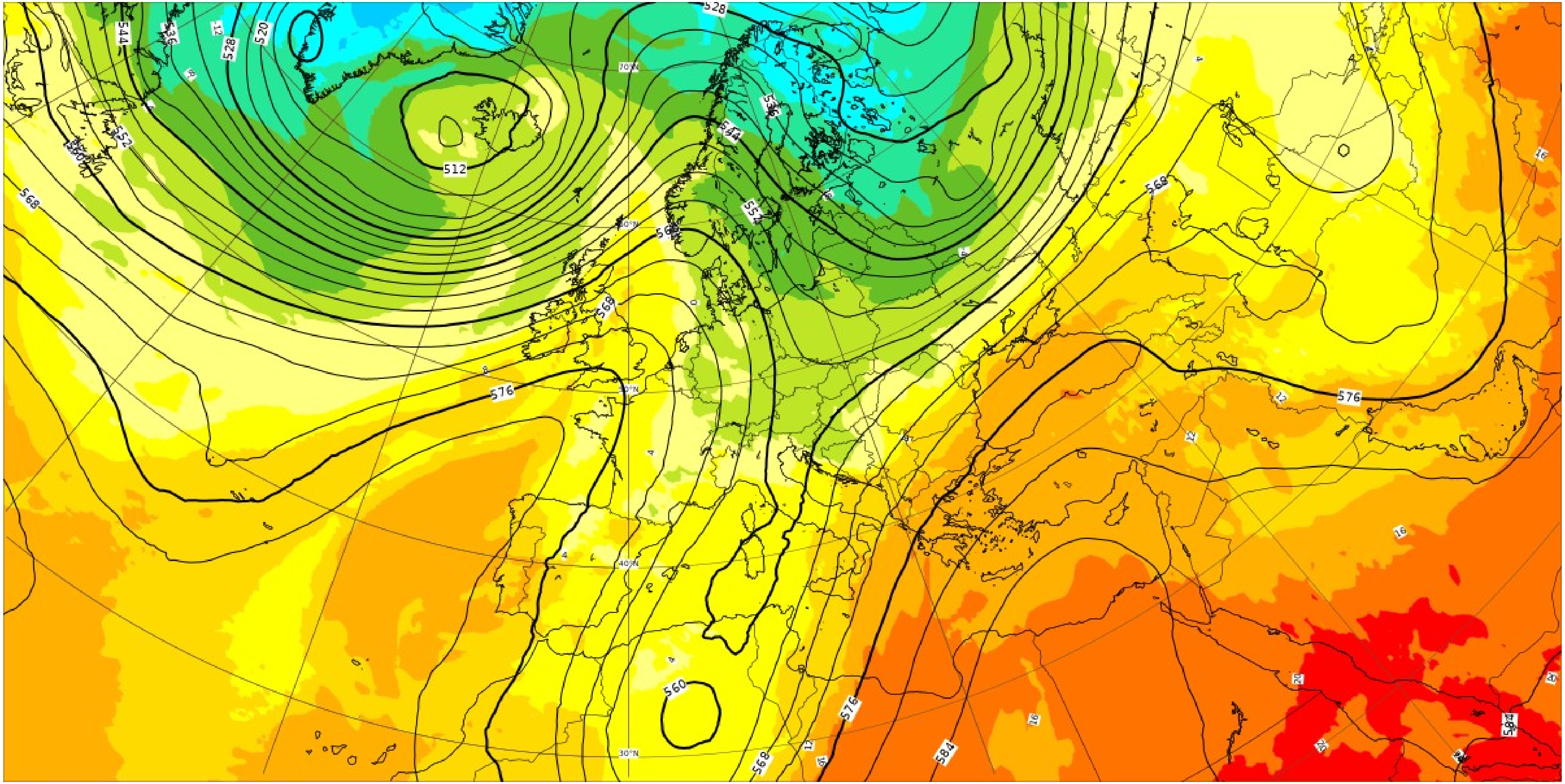
Source: www.ecmwf.int



4-day forecast of *geopotential height at 500 hPa* (contours) and *temperature at 850 hPa* (colour shading)

Validity time 00 UTC, 9th November 2021

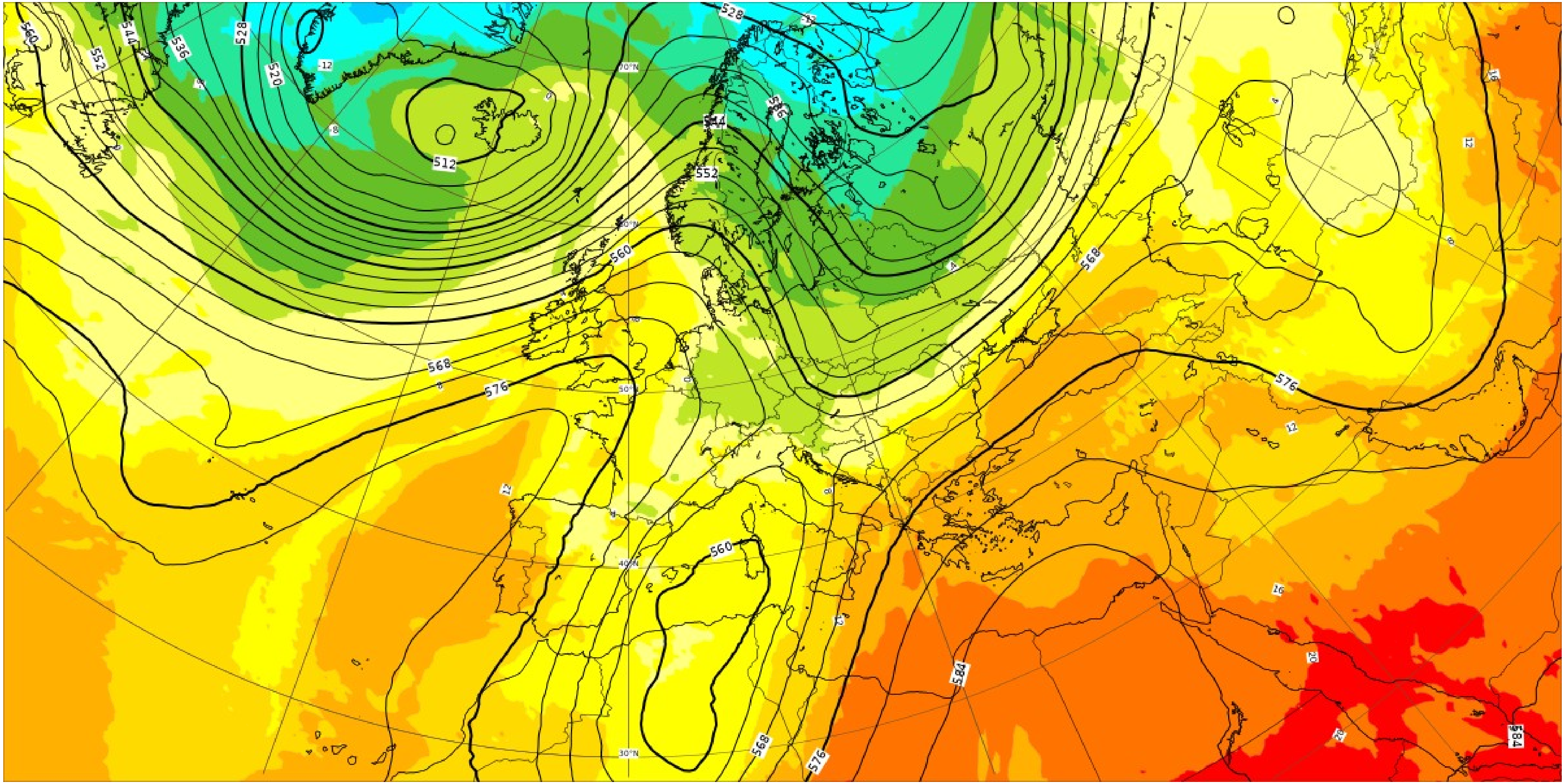
Source: www.ecmwf.int



3-day forecast of *geopotential height at 500 hPa* (contours) and *temperature at 850 hPa* (colour shading)

Validity time 00 UTC, 9th November 2021

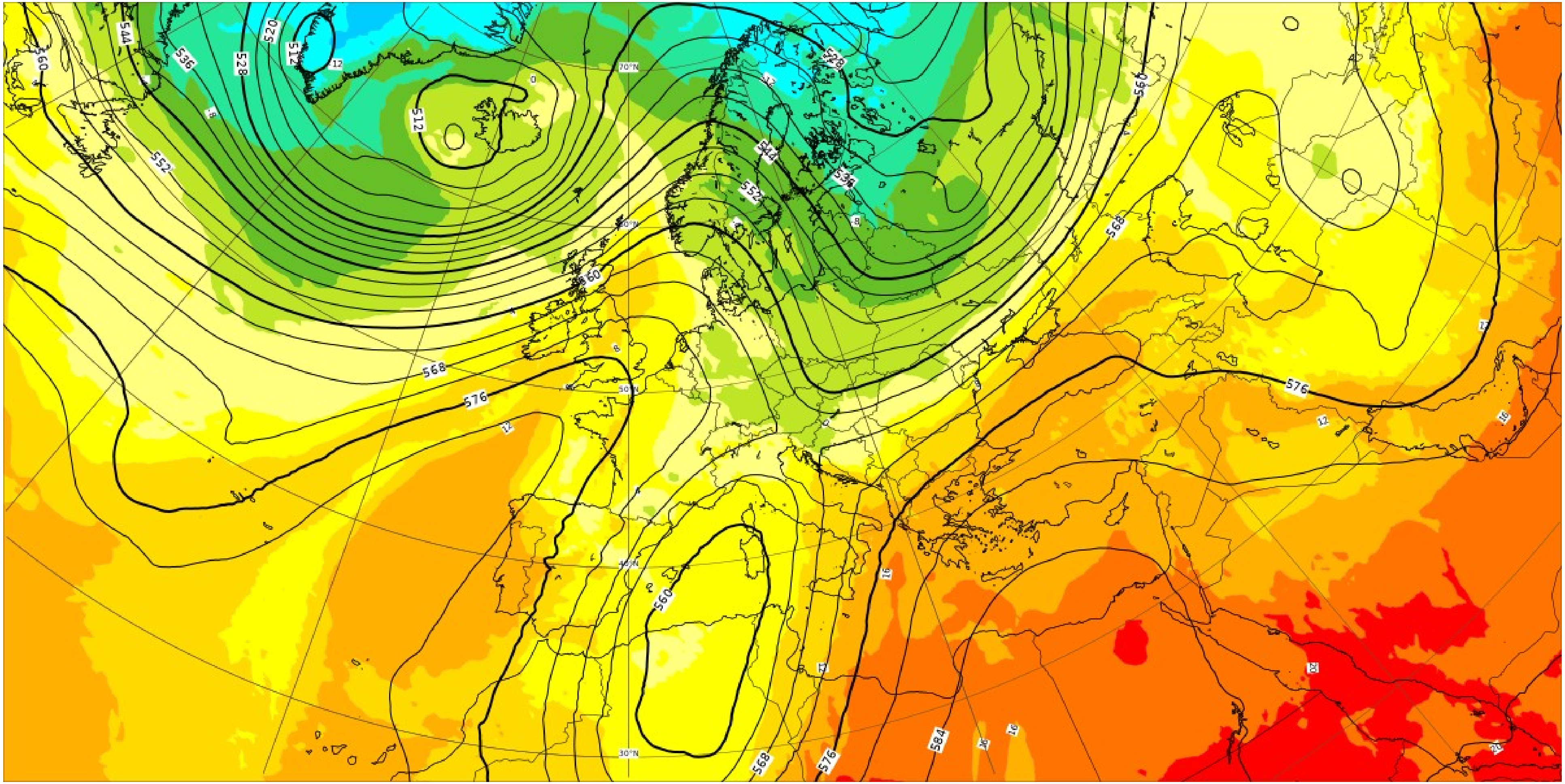
Source: www.ecmwf.int



2-day forecast of *geopotential height at 500 hPa* (contours) and *temperature at 850 hPa* (colour shading)

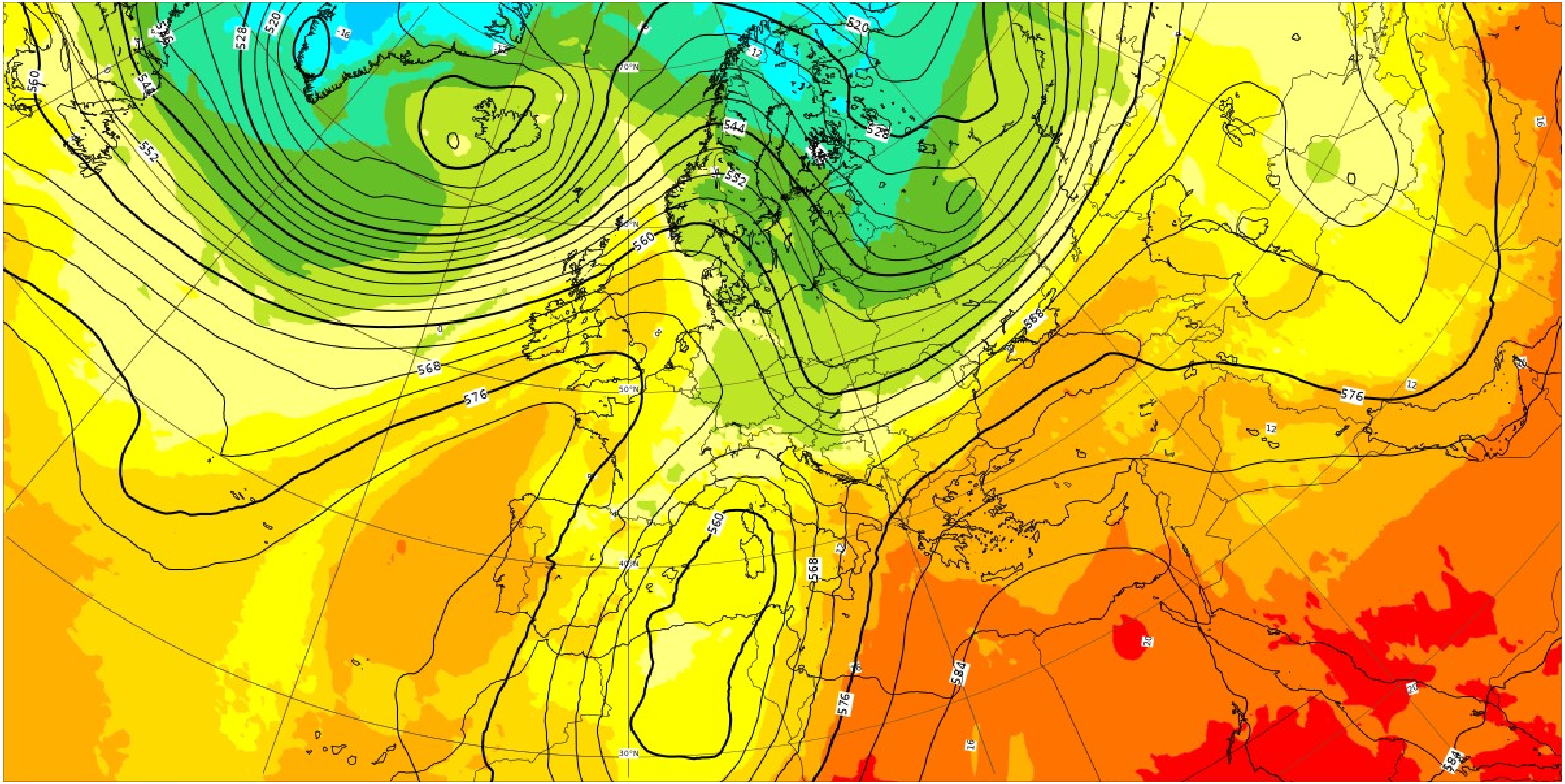
Validity time 00 UTC, 9th November 2021

Source: www.ecmwf.int



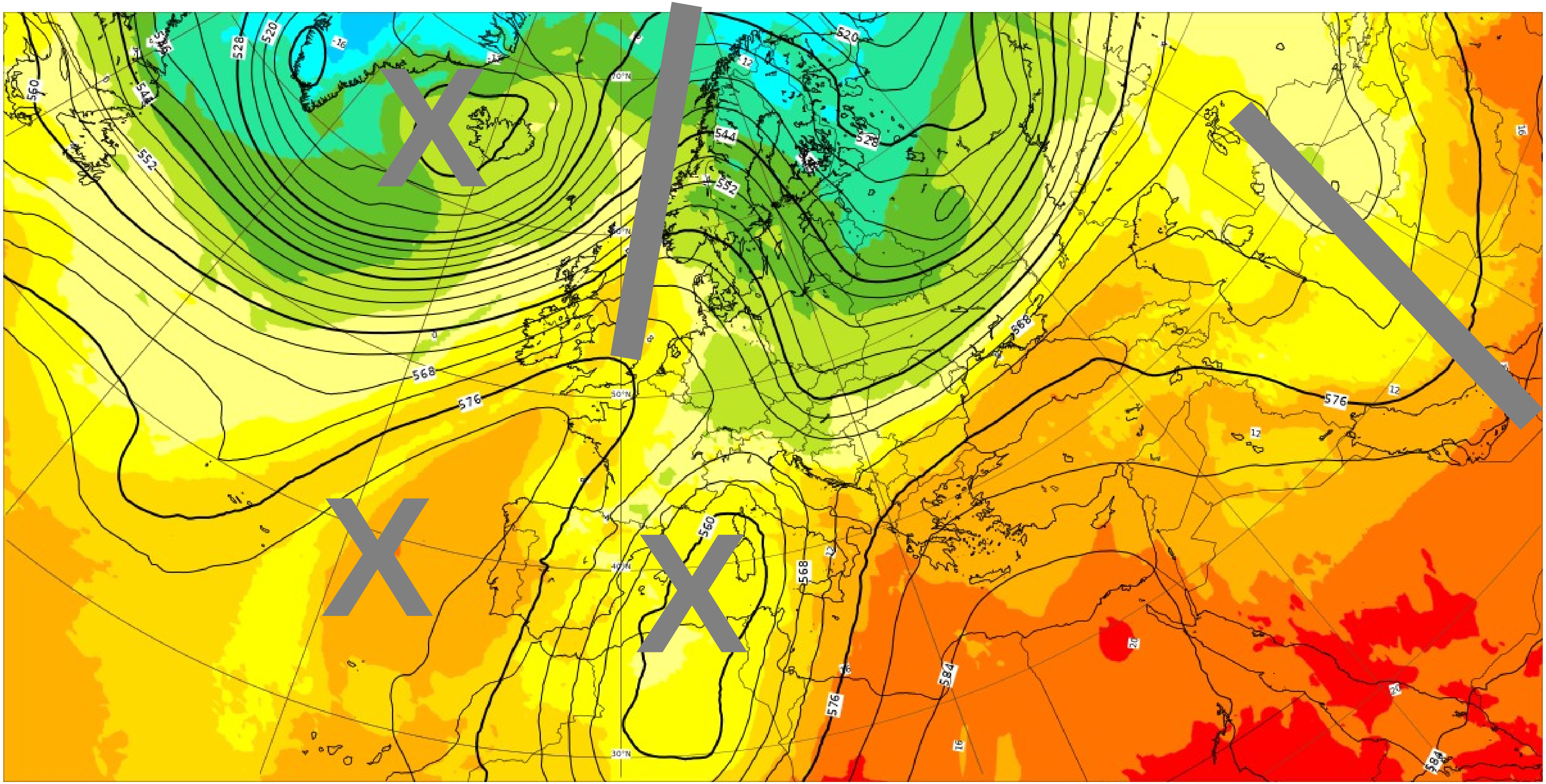
1-day forecast of *geopotential height at 500 hPa* (contours) and *temperature at 850 hPa* (colour shading)
Validity time 00 UTC, 9th November 2021

Source: www.ecmwf.int



Analysis of *geopotential height at 500 hPa* (contours) and *temperature at 850 hPa* (colour shading)
Validity time 00 UTC, 9th November 2021

Source: www.ecmwf.int

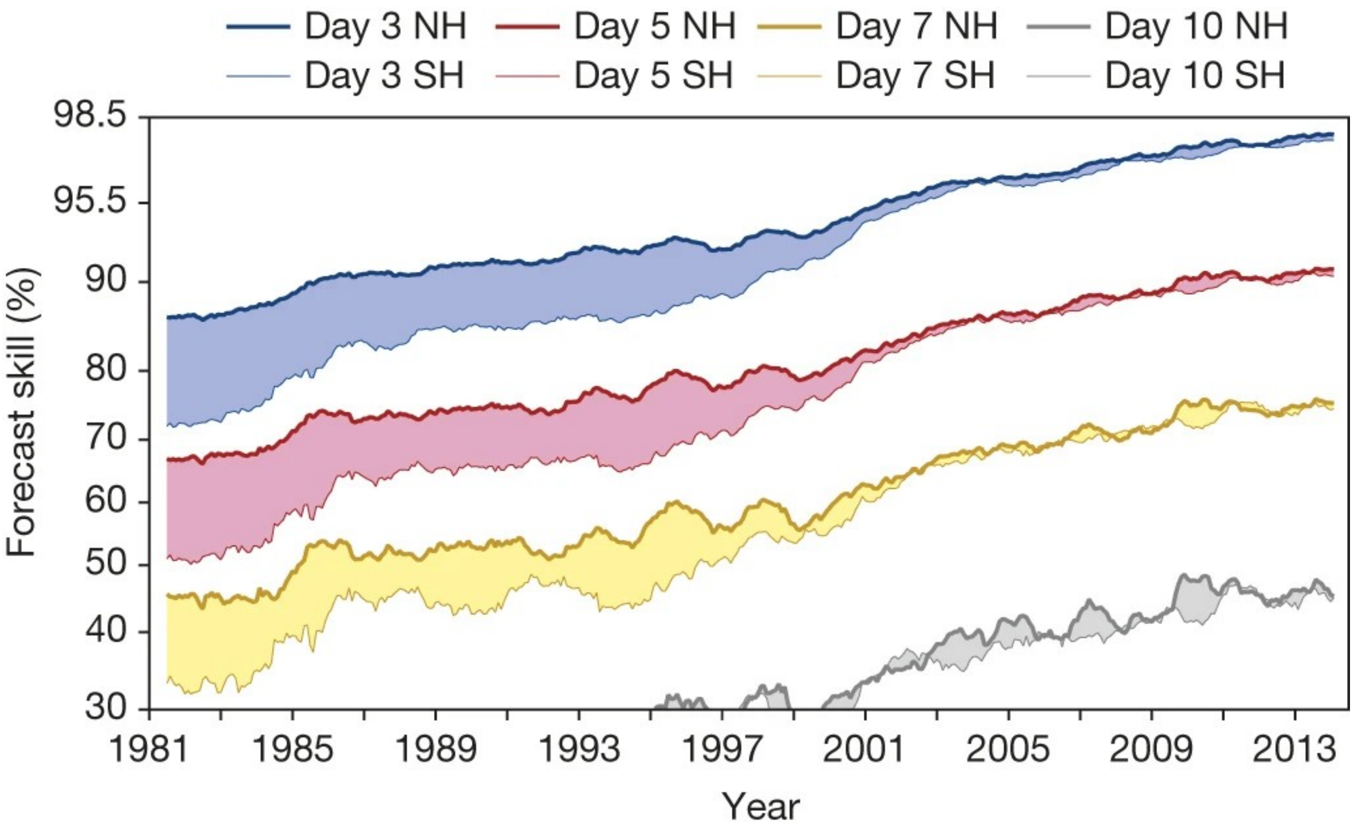


Analysis of *geopotential height at 500 hPa* (contours) and *temperature at 850 hPa* (colour shading)

Validity time 00 UTC, 9th November 2021

Source: www.ecmwf.int

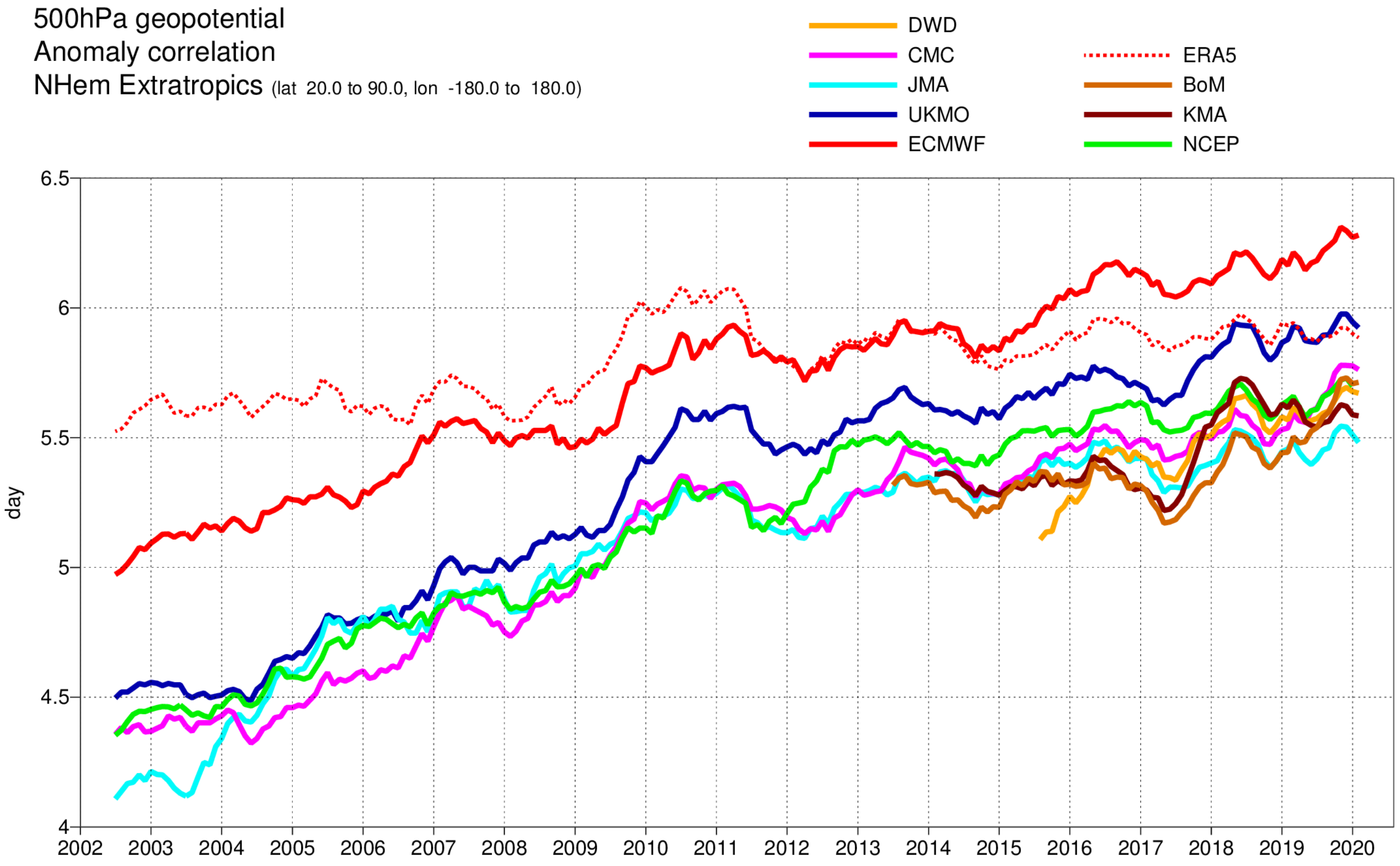
Evolution of forecast skill in global NWP



Values greater than 60% → “Useful forecasts”
Values greater than 80% → “High degree of accuracy”

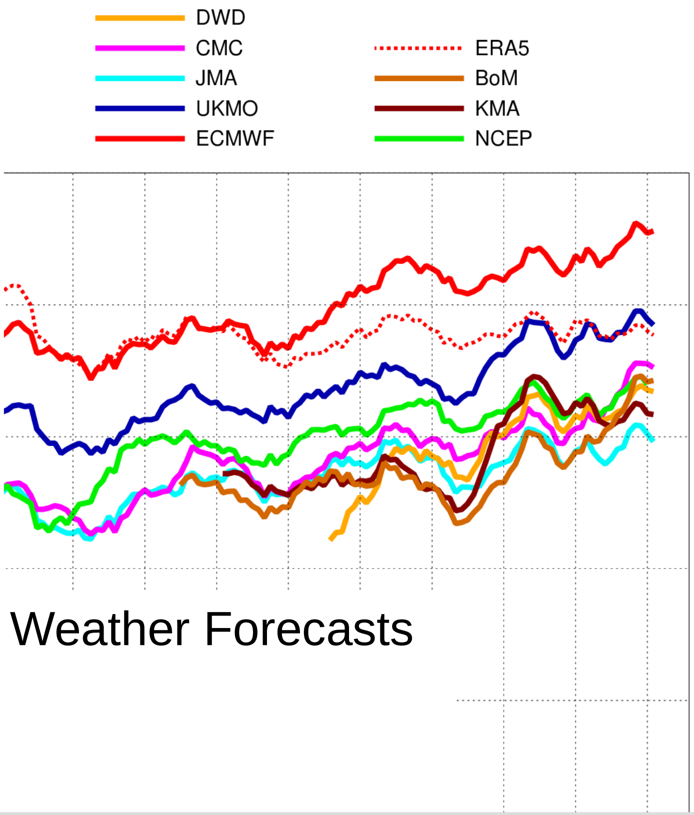
Nature **525** (3rd September 2015)

Global NWP centres



"Lead time at which forecast skill falls below 80%"

Global NWP centres

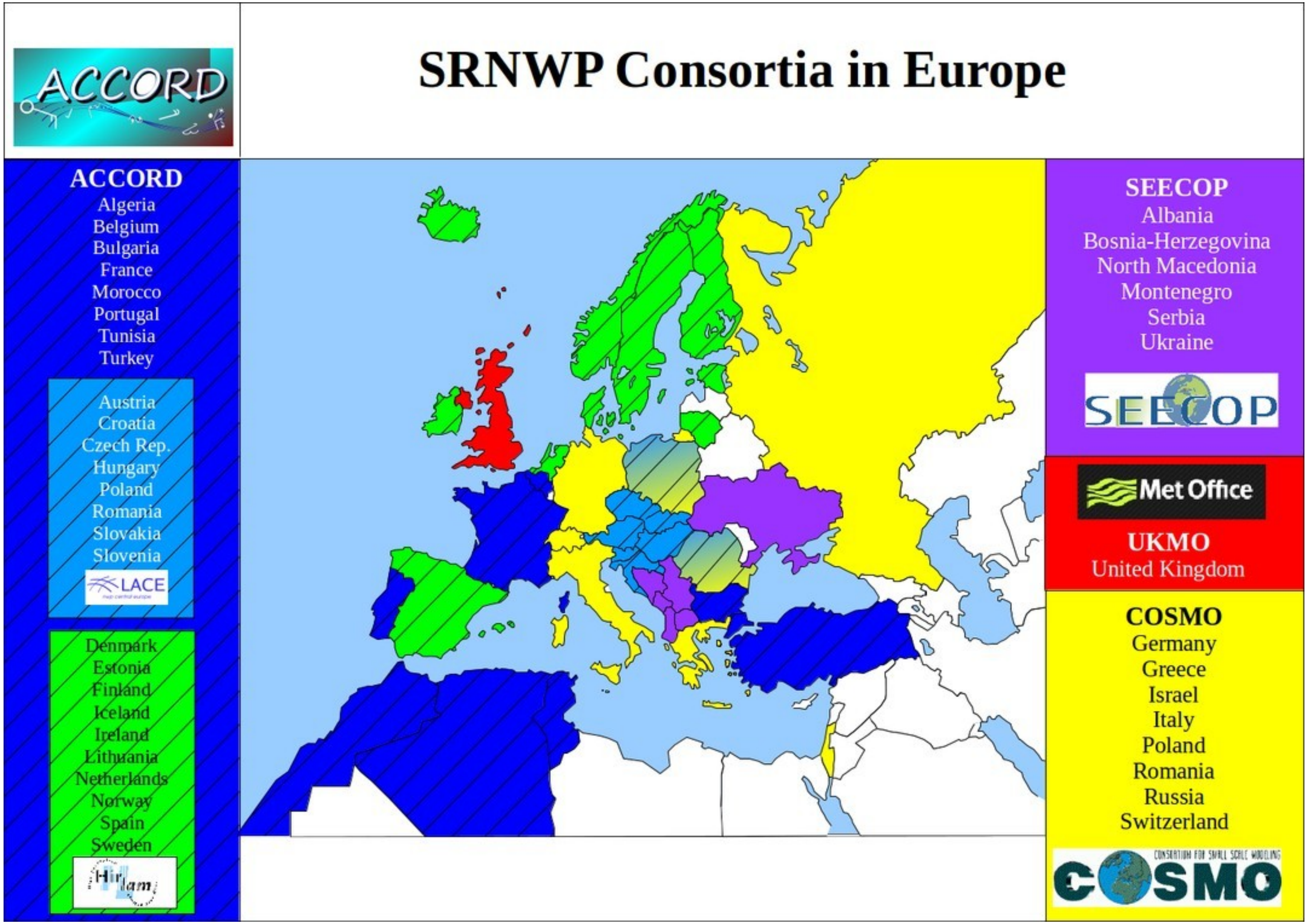


DWD :: Deutscher Wetterdienst (*Germany*)
CMC :: *Canadian* Meteorological Center
JMA :: *Japan* Meteorological Agency
UKMO :: *United Kingdom* Met Office
BoM :: Bureau of Meteorology (*Australia*)
KMA :: *Korea* Meteorological Administration
NCEP :: National Centers for Environmental Prediction (*USA*)

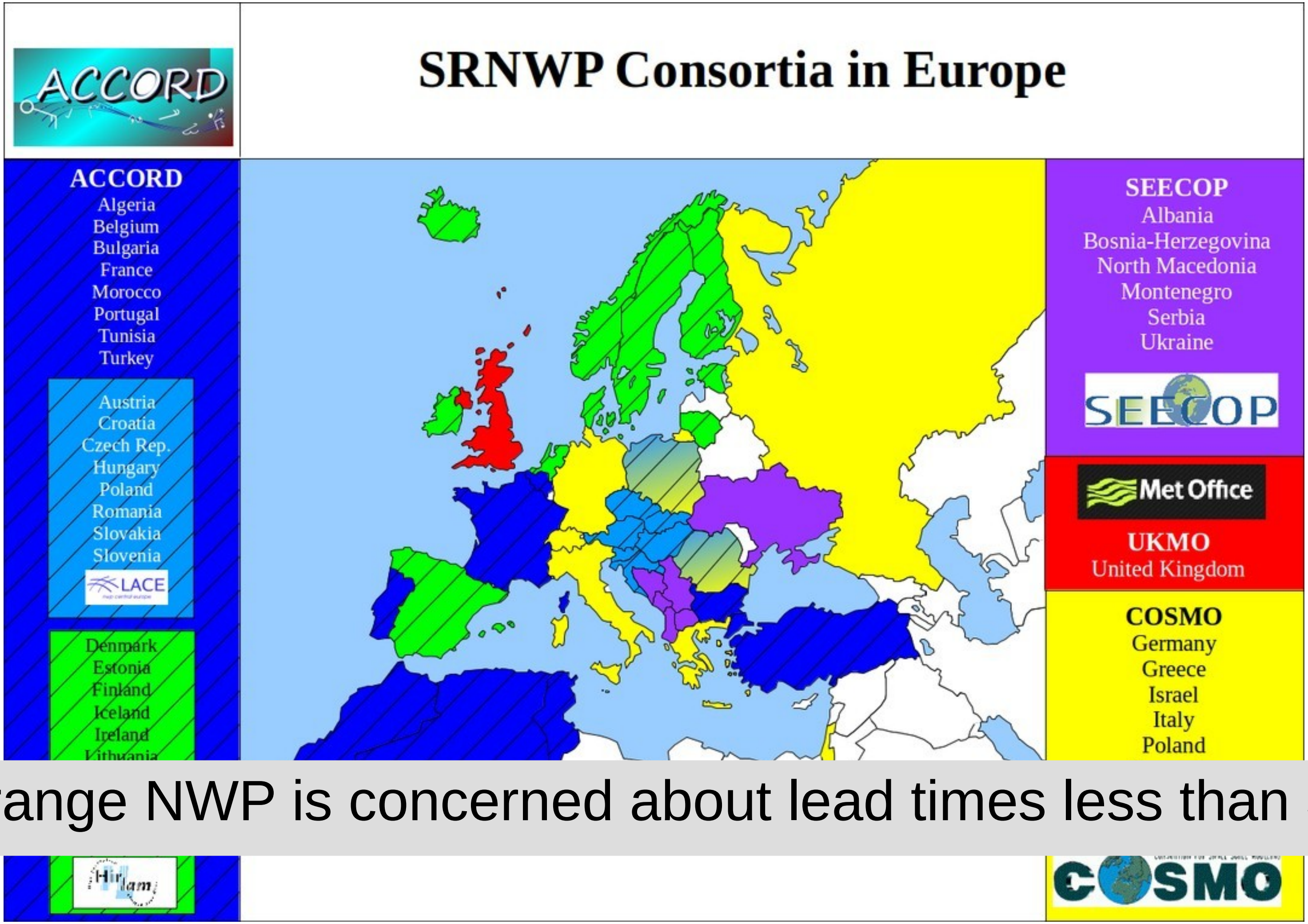
ECMWF :: European Centre for Medium-range Weather Forecasts
ERA5 :: ECMWF 5th-generation re-analysis

Global centres focus on medium-range forecasting (~3–10 days ahead)

Short-range NWP consortia: limited-area modelling



Short-range NWP consortia: limited-area modelling

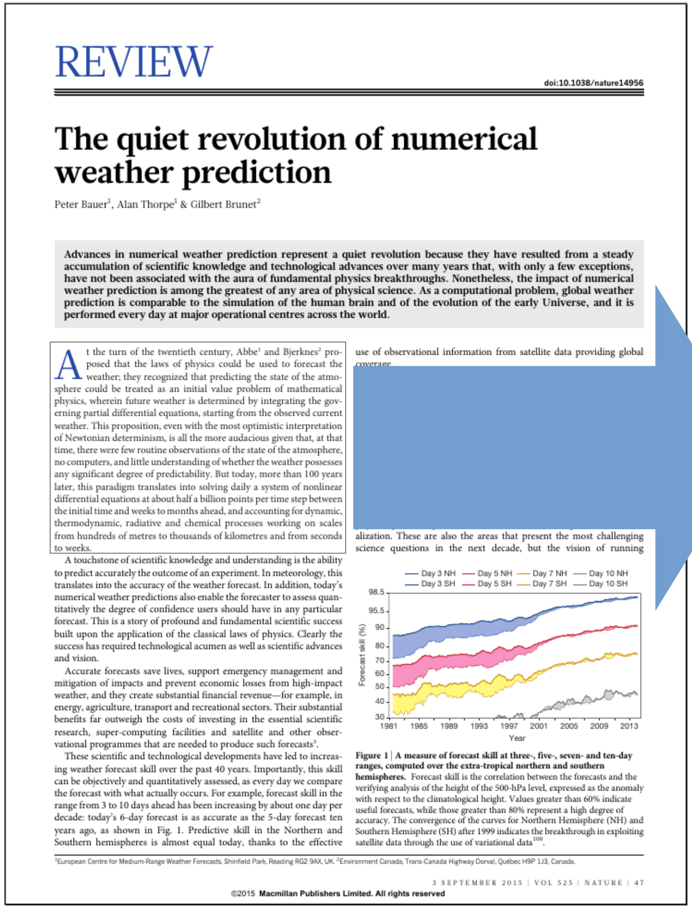


Short-range NWP is concerned about lead times less than 3 days

ACCORD Strategy 2021-2025

Table of Contents

Nature **525** (3rd September 2015)


REVIEW

doi:10.1038/nature14956

The quiet revolution of numerical weather prediction

Peter Bauer[1], Alan Thorpe[1] & Gilbert Brunet[2]

Advances in numerical weather prediction represent a quiet revolution because they have resulted from a steady accumulation of scientific knowledge and technological advances over many years that, with only a few exceptions, have not been associated with the aura of fundamental physics breakthroughs. Nonetheless, the impact of numerical weather prediction is among the greatest of any area of physical science. As a computational problem, global weather prediction is comparable to the simulation of the human brain and of the evolution of the early Universe, and it is performed every day at major operational centres across the world.

At the turn of the twentieth century, Abbe[1] and Bjerknes[2] proposed that the laws of physics could be used to forecast the weather; they recognized that predicting the state of the atmosphere could be treated as an initial value problem of mathematical physics, wherein future weather is determined by integrating the governing partial differential equations, starting from the observed current weather. This proposition, even with the most optimistic interpretation of Newtonian determinism, is all the more audacious given that, at that time, there were few routine observations of the state of the atmosphere, no computers, and little understanding of whether the weather possesses any significant degree of predictability. But today, more than 100 years later, this paradigm translates into solving daily a system of nonlinear differential equations at about half a billion points per time step between the initial time and weeks to months ahead, and accounting for dynamic, thermodynamic, radiative and chemical processes working on scales from hundreds of metres to thousands of kilometres and from seconds to weeks.

A touchstone of scientific knowledge and understanding is the ability to predict accurately the outcome of an experiment. In meteorology, this translates into the accuracy of the weather forecast. In addition, today's numerical weather predictions also enable the forecaster to assess quantitatively the degree of confidence users should have in any particular forecast. This is a story of profound and fundamental scientific success built upon the application of the classical laws of physics. Clearly the success has required technological acumen as well as scientific advances and vision.

Accurate forecasts save lives, support emergency management and mitigation of impacts and prevent economic losses from high-impact weather, and they create substantial financial revenue—for example, in energy, agriculture, transport and recreational sectors. Their substantial benefits far outweigh the costs of investing in the essential scientific research, super-computing facilities and satellite and other observational programmes that are needed to produce such forecasts[3].

These scientific and technological developments have led to increasing weather forecast skill over the past 40 years. Importantly, this skill can be objectively and quantitatively assessed, as every day we compare the forecast with what actually occurs. For example, forecast skill in the range from 3 to 10 days ahead has been increasing by about one day per decade: today's 6-day forecast is as accurate as the 5-day forecast ten years ago, as shown in Fig. 1. Predictive skill in the Northern and Southern hemispheres is almost equal today, thanks to the effective use of observational information from satellite data providing global coverage

...

alization. These are also the areas that present the most challenging science questions in the next decade, but the vision of running

Figure 1 | A measure of forecast skill at three-, five-, seven- and ten-day ranges, computed over the extra-tropical northern and southern hemispheres. Forecast skill is the correlation between the forecasts and the verifying analysis of the height of the 500-hPa level, expressed as the anomaly with respect to the climatological height. Values greater than 60% indicate useful forecasts, while those greater than 80% represent a high degree of accuracy. The convergence of the curves for Northern Hemisphere (NH) and Southern Hemisphere (SH) after 1999 indicates the breakthrough in exploiting satellite data through the use of variational data[100].

[1]European Centre for Medium-Range Weather Forecasts, Shinfield Park, Reading RG2 9AX, UK. [2]Environment Canada, Trans-Canada Highway Dorval, Québec H9P 1J3, Canada.

3 SEPTEMBER 2015 | VOL 525 | NATURE | 47

©2015 Macmillan Publishers Limited. All rights reserved

At the turn of the twentieth century, Abbe[1] and Bjerknes[2] proposed that the laws of physics could be used to forecast the weather; they recognized that predicting the state of the atmosphere could be treated as an initial value problem of mathematical physics, wherein future weather is determined by integrating the governing partial differential equations, starting from the observed current weather. …

… today, more than 100 years later, this paradigm translates into solving daily a system of nonlinear differential equations at about half a billion points per time step between the initial time and weeks to months ahead, and accounting for dynamic, thermodynamic, radiative and chemical processes working on scales from hundreds of metres to thousands of kilometres and from seconds to weeks.

Greatest challenges in modern-day NWP

1) Timely forecast production with ever increasing resolution in time and space

2) Initialization of model state close to observed current weather everywhere on the globe

3) Realistic representation of the effect of unresolved physical processes

4) Description of uncertainty in analysis and forecast

Greatest challenges in modern-day NWP

1) Timely forecast production with ever increasing resolution in time and space

2) Initialization of model state close to observed current weather everywhere on the globe

3) Realistic representation of the effect of unresolved physical processes

4) Description of uncertainty in analysis and forecast

High-Performance Computing facilitates time-critical production

Forecast Runs (base time)	Forecast step frequency	Forecast Dissemination schedule
00 UTC	• 0 to 90 by 1 • 93 to 144 by 3 • 150 to 240 by 6	• 5:45 --> 6:12 • 6:12 --> 6:27 • 6:27 --> 6:55
06 UTC	• 0 to 90 by 1	• 11:45 --> 12:12
12 UTC	• 0 to 90 by 1 • 93 to 144 by 3 • 150 to 240 by 6	• 17:45 --> 18:12 • 18:12 --> 18:27 • 18:27 --> 18:55
18 UTC	• 0 to 90 by 1	• 23:45 --> 00:12

Source: www.ecmwf.int

Key components of the ECMWF forecasting system

ECMWF bases its operational medium-range forecast products on version Cy47r3 (as of November 2021) of the Integrated Forecasting System (IFS)

HRES: Atmospheric Model high resolution
– Global 10-day deterministic forecast in ~9 km horizontal grid resolution
– Vertical discretization using 137 levels from surface up to 0.01 hPa
– Produced twice per day from 00 UTC and 12 UTC initial times

ENS: Ensemble – Atmospheric Model
– 51-member ensemble of global 15-day forecasts
– ~18 km horizontal grid resolution and 137 levels in vertical

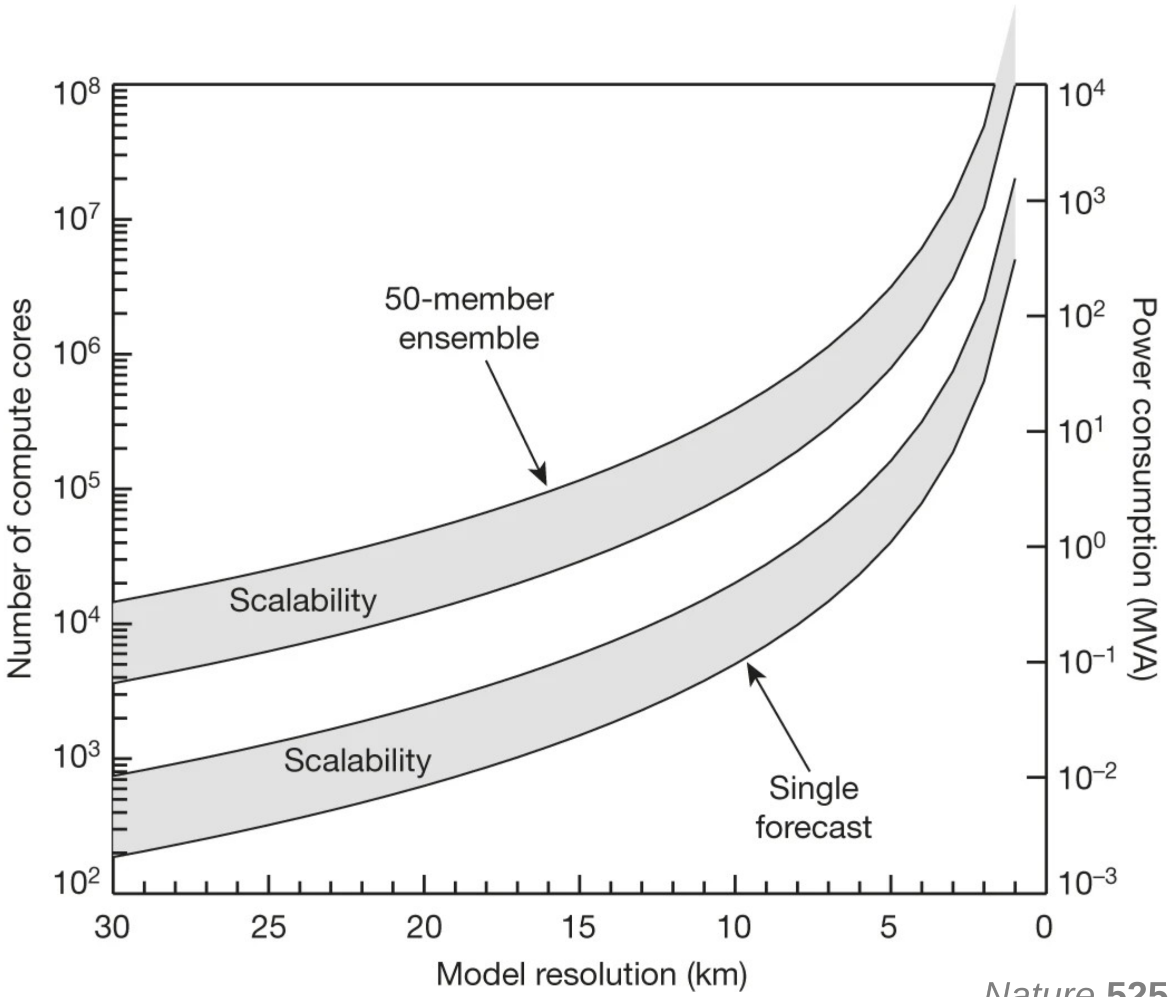
4DVAR: Four-dimensional data assimilation
– Global analysis based on variational data assimilation

~$6.3 \cdot 10^6$ grid points for global coverage

450 second time steps in forecast integration
→ Production of 10-day forecast involves 1920 time steps

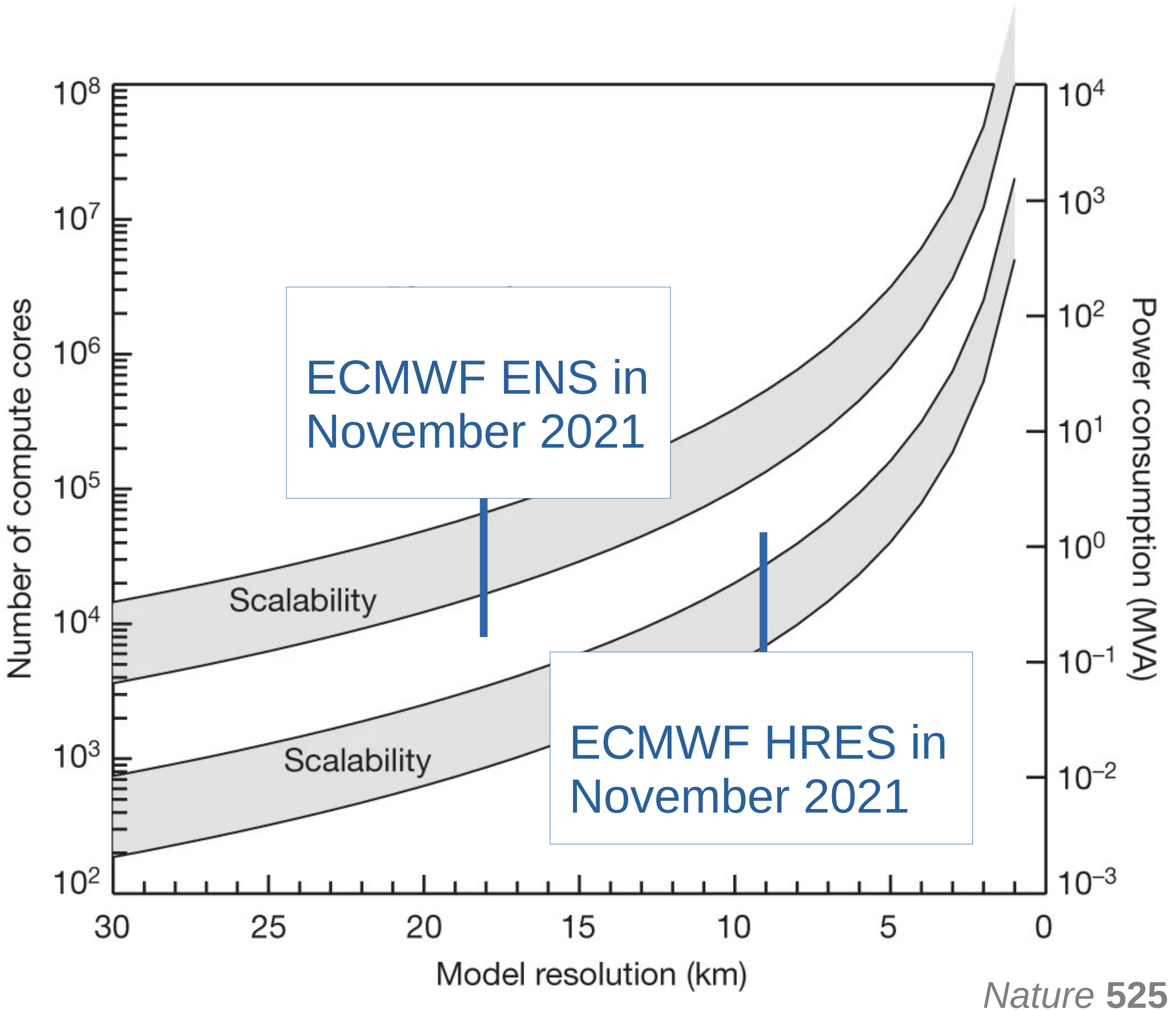
Source: www.ecmwf.int

Demand on high-performance computing



Nature **525** (3rd September 2015)

Demand on high-performance computing



Nature **525** (3rd September 2015)

Greatest challenges in modern-day NWP

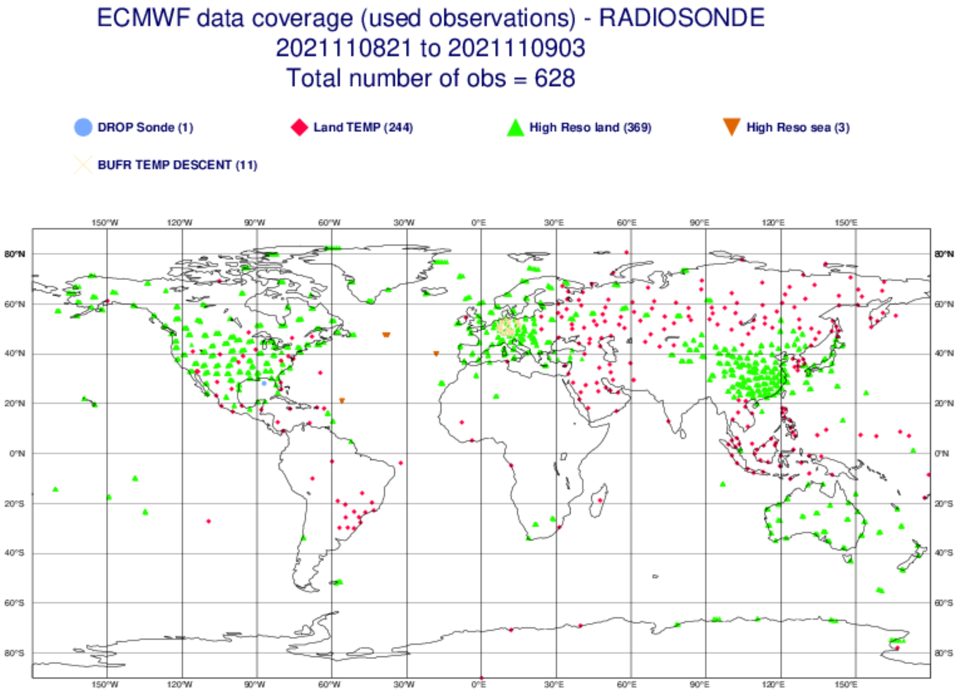
1) Timely forecast production with ever increasing resolution in time and space

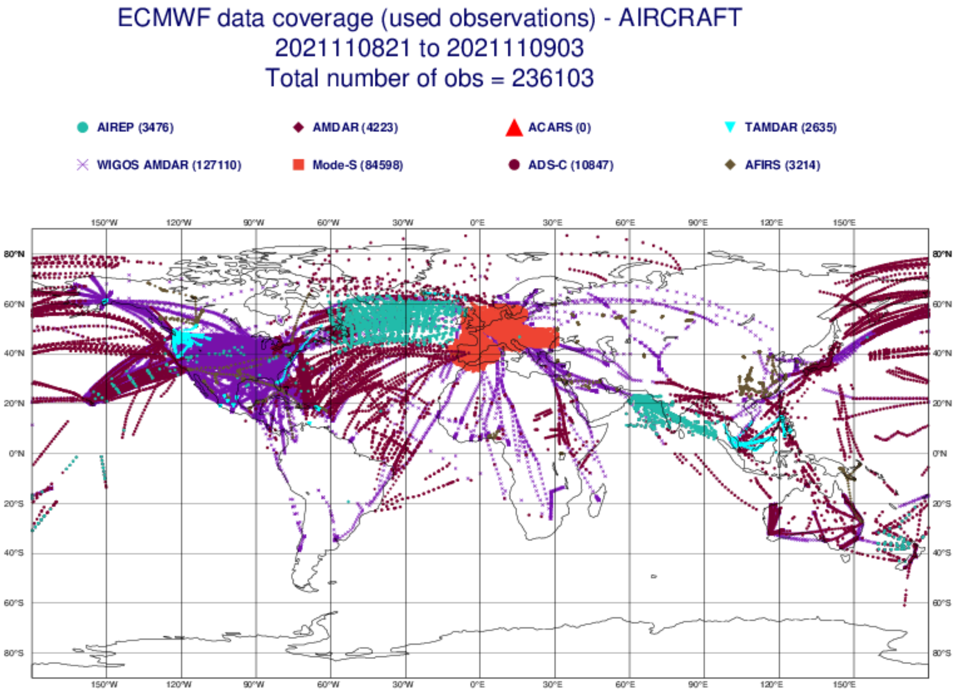
2) Initialization of model state close to observed current weather everywhere on the globe

3) Realistic representation of the effect of unresolved physical processes

4) Description of uncertainty in analysis and forecast

“ … starting from the observed current weather … “

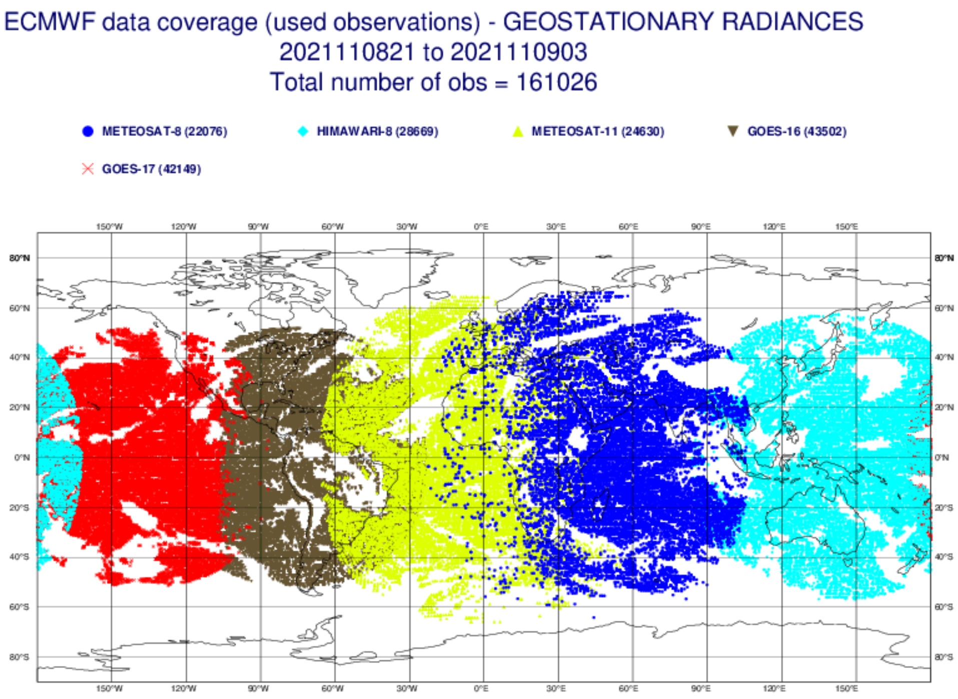


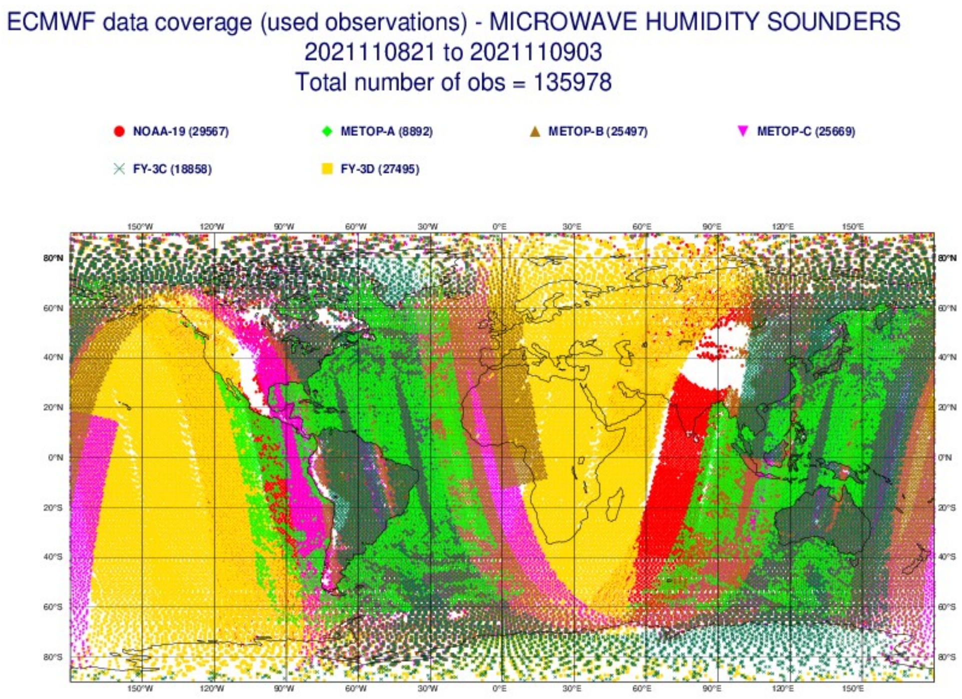


It’s a huge challenge to observe global weather!

Source: www.ecmwf.int

“ … starting from the observed current weather … “

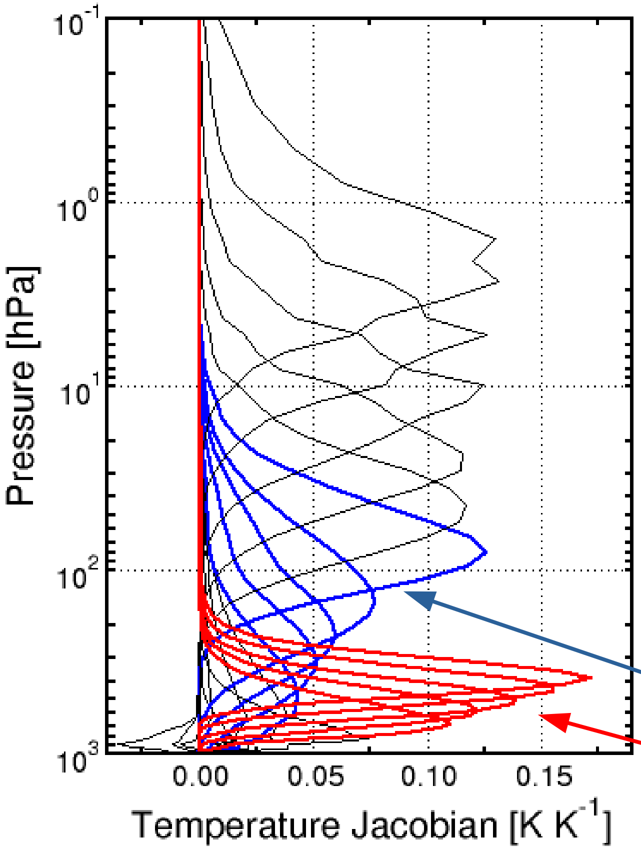




It’s a huge challenge to observe global weather!

Source: www.ecmwf.int

Measurement from space: Advanced Technology Microwave Sounder (ATMS)



ATMS measures upwelling radiation at microwave frequencies near 54 and 183 GHz

Radiation measurement is used as an observation of temperature and humidity (not straightforward)

The measurement may be interfered by cloud, rain, or snow

*T*emperature sounding channels (54 GHz)

Humidity sounding channels (183 GHz)

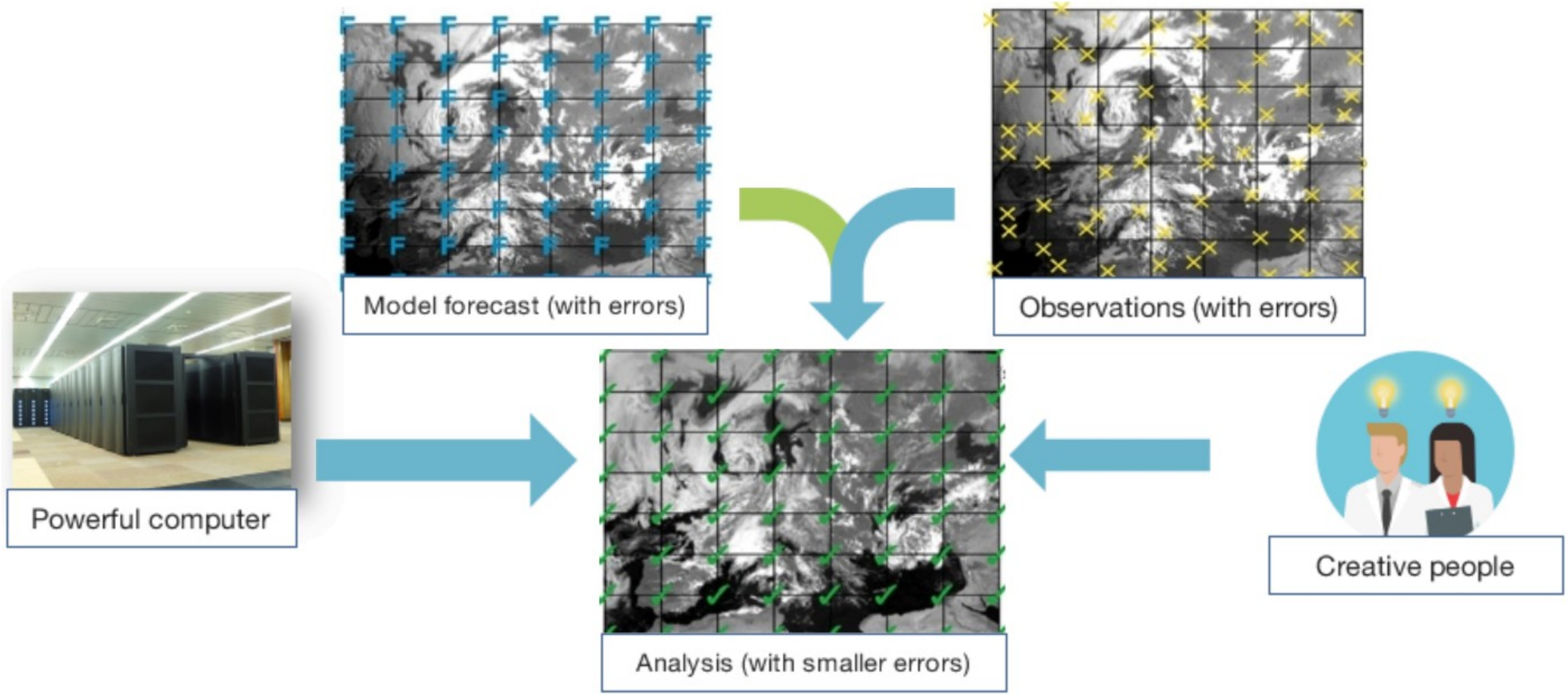
Initialization of the NWP model to “observed current weather”

In practice no amount of available observations comes close to the degrees of freedom in NWP model state – so initializing to observed current weather is practically impossible!

The problem is made worse by the fact that all observations are inherently inaccurate.

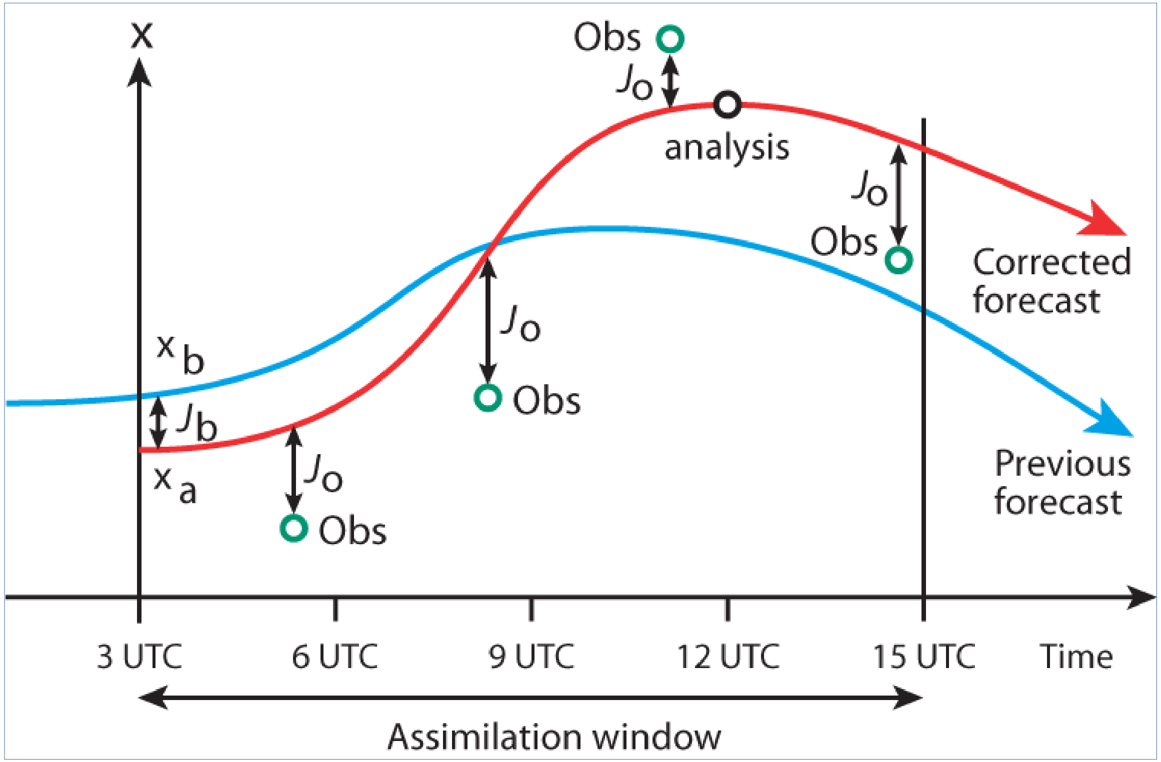
The solution is to build on Bayesian probability theory to develop and apply methods of *data assimilation: use observations to correct for errors in short-range NWP forecast, and do this at frequent update intervals*

Data assimilation: what it takes and what it gives?



Source: www.ecmwf.int/assets/elearning

Four-dimensional variational data assimilation (4D-Var)



– Use latest observations to update the NWP model trajectory
– Produce a dynamically-justified analysis that is consistent with all observations across the time range of the assimilation window

Four-dimensional variational data assimilation (4D-Var)

Find the maximum-likelihood estimate for the atmospheric model state *x* by *minimizing the cost function* *J(x)*:

$$J(x) = (x - x_b)^T \mathbf{B}^{-1}(x - x_b) + (y - \mathrm{H}[x])^T \mathbf{R}^{-1}(y - \mathrm{H}[x])$$

where

x_b is a short-range model forecast (=background field),

y is a vector consisting of meteorological observations,

H[*x*] is an observation operator that transforms model state x into the space of observations (including model integration in time),

B is the background error covariance, and

R is the observation error covariance

Four-dimensional variational data assimilation (4D-Var)

Find the maximum-likelihood estimate for the atmospheric model state *x* by *minimizing the cost function* *J(x)*:

$$J(x) = \underbrace{\boxed{(x - x_b)^T \mathbf{B}^{-1} (x - x_b)}}_{\text{Background constraint}} + \underbrace{\boxed{(y - \mathrm{H}[x])^T \mathbf{R}^{-1} (y - \mathrm{H}[x])}}_{\text{Observation constraint}}$$

where

x_b is a short-range model forecast (=background field),

y is a vector consisting of meteorological observations,

H[x] is an observation operator that transforms model state x into the space of observations (including model integration in time),

B is the background error covariance, and

R is the observation error covariance

Four-dimensional variational data assimilation (4D-Var)

Find the maximum-likelihood estimate for the atmospheric model state *x* by <u>*minimizing the cost function*</u> *J(x)*:

$$J(x) = (x - x_b)^T \mathbf{B}^{-1}(x - x_b) + (y - \mathrm{H}[x])^T \mathbf{R}^{-1}(y - \mathrm{H}[x])$$

where *notable challenges* are involved with

(1) identifying the best possible composition of *y* (i.e. choosing observations)

(2) specification of H[*x*], **B**, and **R**,

(3) computing inverses of **B** and **R**

(4) finding the minimum of J(x)

Greatest challenges in modern-day NWP

1) Timely forecast production with ever increasing resolution in time and space

2) Initialization of model state close to observed current weather everywhere on the globe

3) Realistic representation of the effect of unresolved physical processes

4) Description of uncertainty in analysis and forecast

ECMWF model dynamical equations (1/2)

The momentum equations are

$$\frac{\partial U}{\partial t} + \frac{1}{a\cos^2\theta}\left\{U\frac{\partial U}{\partial \lambda} + V\cos\theta\frac{\partial U}{\partial \theta}\right\} + \dot{\eta}\frac{\partial U}{\partial \eta} - fV + \frac{1}{a}\left\{\frac{\partial \phi}{\partial \lambda} + R_{\mathrm{dry}}T_{\mathrm{v}}\frac{\partial}{\partial \lambda}(\ln p)\right\} = P_U + K_U \qquad (2.1)$$

$$\frac{\partial V}{\partial t} + \frac{1}{a\cos^2\theta}\left\{U\frac{\partial V}{\partial \lambda} + V\cos\theta\frac{\partial V}{\partial \theta} + \sin\theta(U^2+V^2)\right\} + \dot{\eta}\frac{\partial V}{\partial \eta} + fU + \frac{\cos\theta}{a}\left\{\frac{\partial \phi}{\partial \theta} + R_{\mathrm{dry}}T_{\mathrm{v}}\frac{\partial}{\partial \theta}(\ln p)\right\} = P_V + K_V \qquad (2.2)$$

where a is the radius of the earth, $\dot{\eta}$ is the η-coordinate vertical velocity $(\dot{\eta} = \mathrm{d}\eta/\mathrm{d}t)$, ϕ is geopotential, R_{dry} is the gas constant for dry air, and T_{v} is the virtual temperature defined by

$$T_{\mathrm{v}} = T[1 + \{(R_{\mathrm{vap}}/R_{\mathrm{dry}}) - 1\}q - \sum_k q_k]$$

where T is temperature, R_{vap} is the gas constant for water vapour, q is specific humidity and q_k denotes other thermodynamically active moist species namely cloud liquid water, ice, rain, snow. P_U and P_V represent the contributions of the parameterised physical processes, while K_U and K_V are the horizontal diffusion terms.

Documentation of the Integrated Forecasting System, www.ecmwf.int

ECMWF model dynamical equations (2/2)

The thermodynamic equation is

$$\frac{\partial T}{\partial t}+\frac{1}{a\cos^2\theta}\left\{U\frac{\partial T}{\partial\lambda}+V\cos\theta\frac{\partial T}{\partial\theta}\right\}+\dot{\eta}\frac{\partial T}{\partial\eta}-\frac{\kappa T_{\mathrm{v}}\omega}{(1+(\delta-1)q)p}=P_T+K_T \qquad (2.3)$$

where $\kappa=R_{\mathrm{dry}}/c_{p_{\mathrm{dry}}}$ (with $c_{p_{\mathrm{dry}}}$ the specific heat of dry air at constant pressure), ω is the pressure-coordinate vertical velocity ($\omega=\mathrm{d}p/\mathrm{d}t$), and $\delta=c_{p_{\mathrm{vap}}}/c_{p_{\mathrm{dry}}}$ (with $c_{p_{\mathrm{vap}}}$ the specific heat of water vapour at constant pressure).

The moisture equation is

$$\frac{\partial q}{\partial t}+\frac{1}{a\cos^2\theta}\left\{U\frac{\partial q}{\partial\lambda}+V\cos\theta\frac{\partial q}{\partial\theta}\right\}+\dot{\eta}\frac{\partial q}{\partial\eta}=P_q+K_q \qquad (2.4)$$

In (2.2) and (2.3), P_T and P_q represent the contributions of the parameterised physical processes, while K_T and K_q are the horizontal diffusion terms.

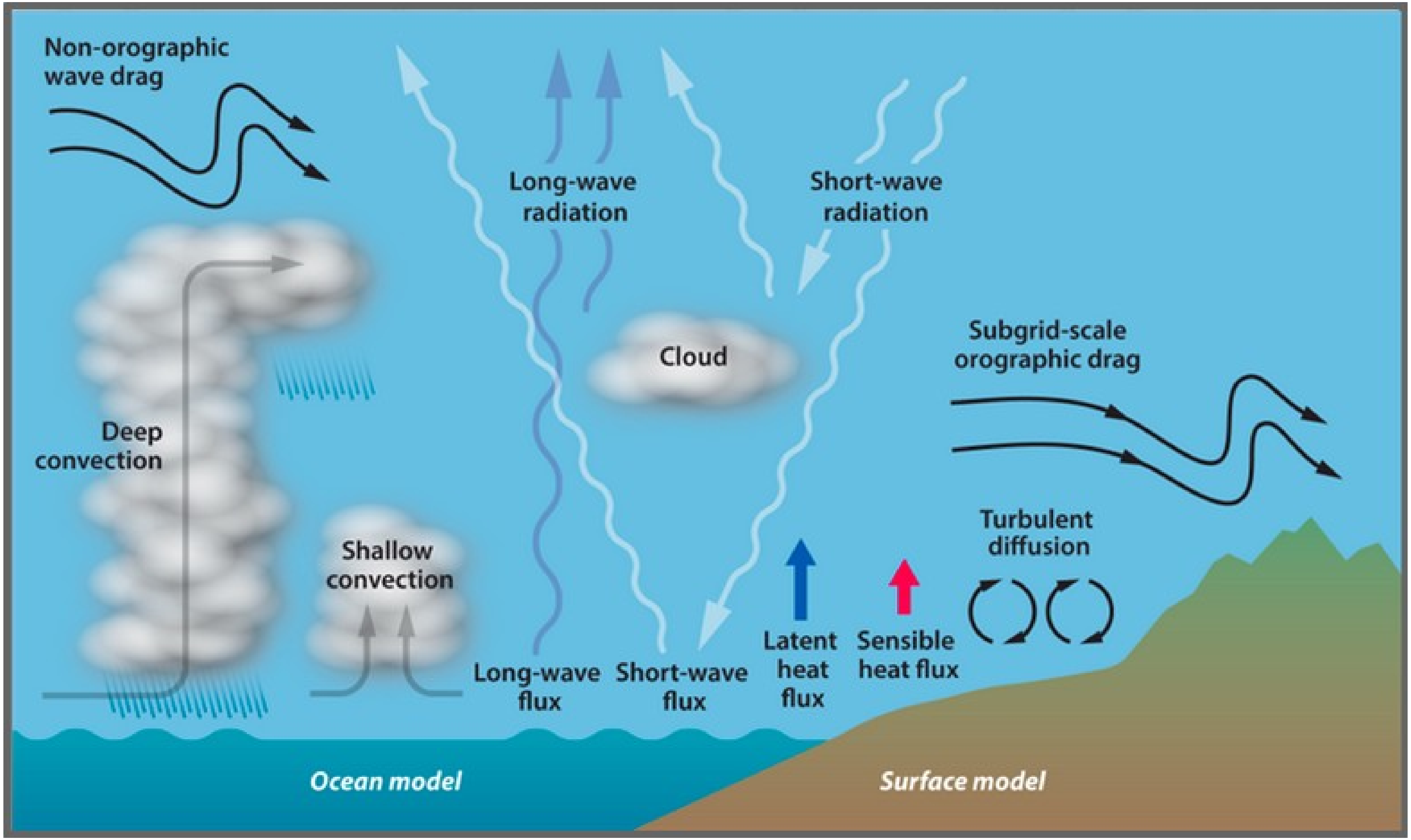
The continuity equation is

$$\frac{\partial}{\partial t}\left(\frac{\partial p}{\partial\eta}\right)+\nabla\cdot\left(\mathbf{v}_{\mathrm{H}}\frac{\partial p}{\partial\eta}\right)+\frac{\partial}{\partial\eta}\left(\dot{\eta}\frac{\partial p}{\partial\eta}\right)=0 \qquad (2.5)$$

where ∇ is the horizontal gradient operator in spherical coordinates and $\mathbf{v}_{\mathrm{H}}=(u,v)$ is the horizontal wind.

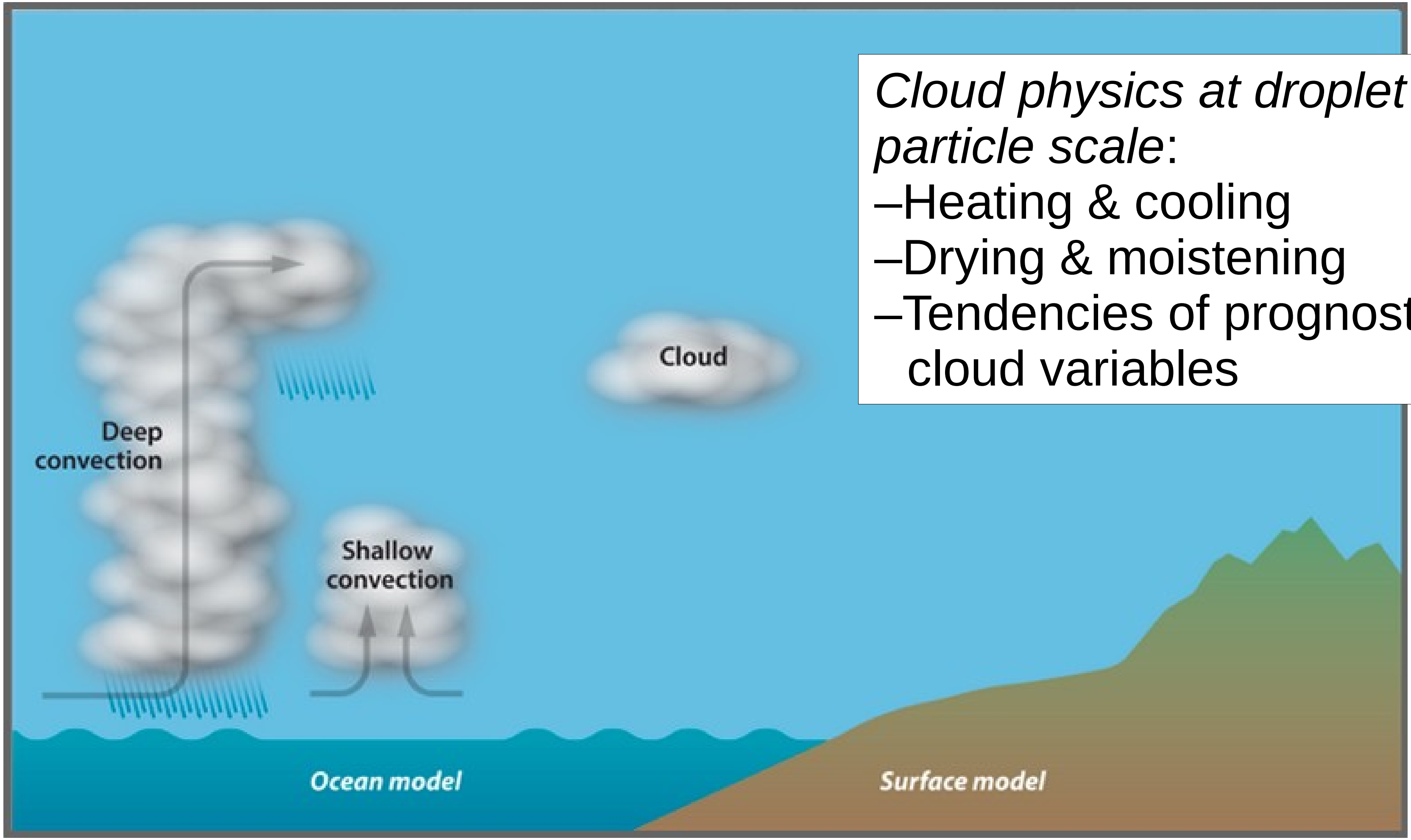
Documentation of the Integrated Forecasting System, www.ecmwf.int

Unresolved processes represented via physical parameterizations



Source: www.ecmwf.int/assets/elearning

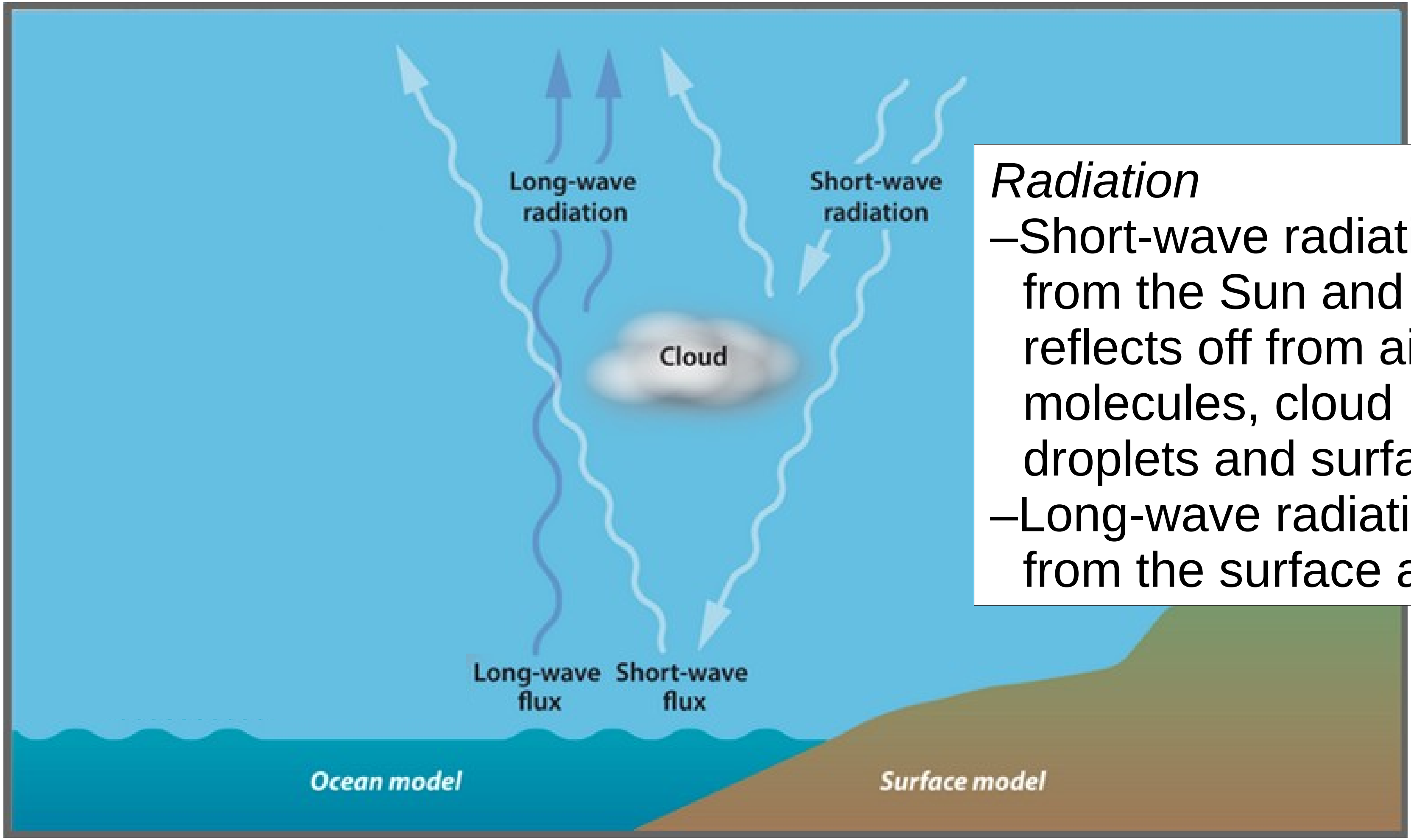
Unresolved processes represented via physical parameterizations



Cloud physics at droplet particle scale:
– Heating & cooling
– Drying & moistening
– Tendencies of prognostic cloud variables

Source: www.ecmwf.int/assets/elearning

Unresolved processes represented via physical parameterizations

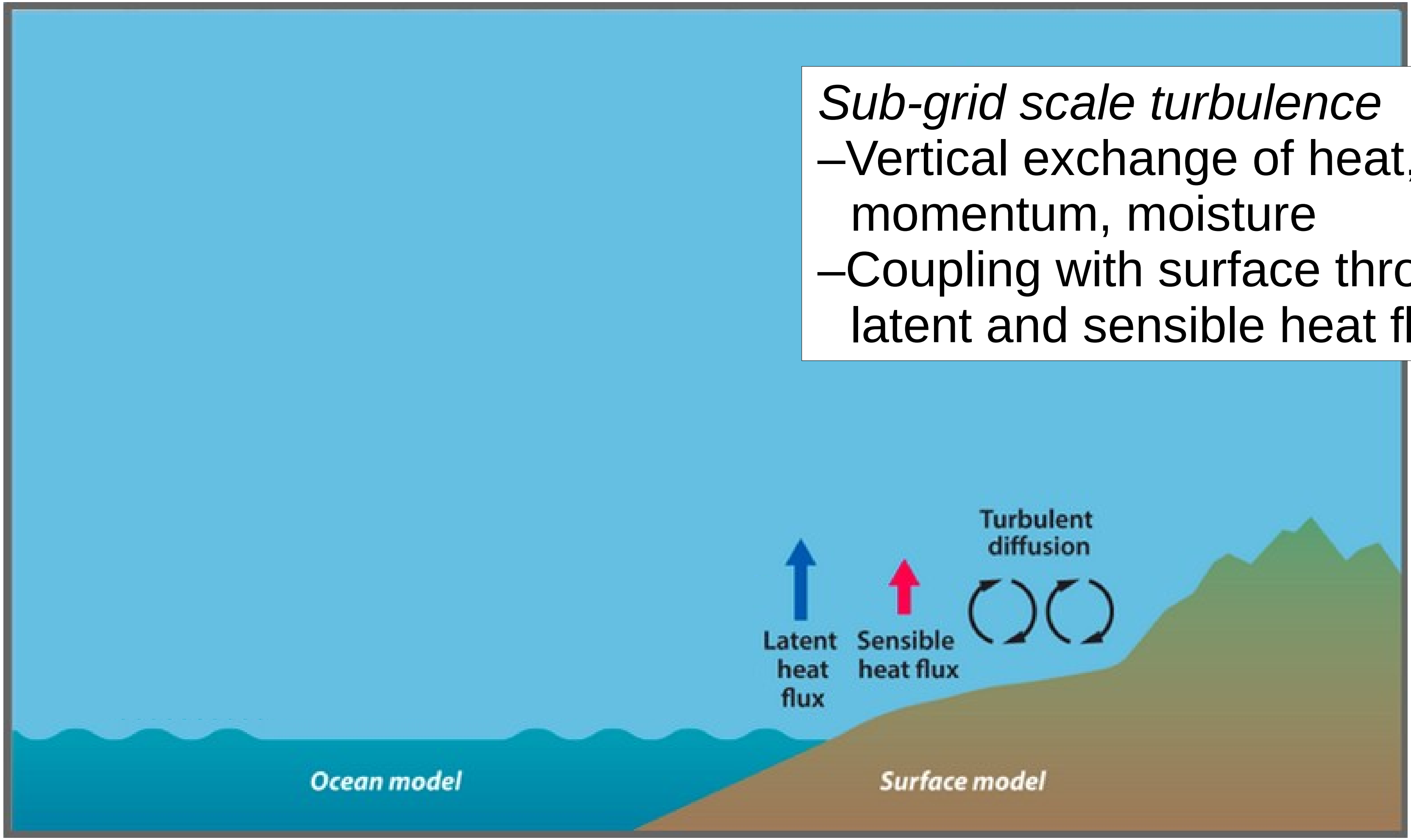


Radiation

- Short-wave radiation from the Sun and how it reflects off from air molecules, cloud droplets and surface
- Long-wave radiation from the surface and air

Source: www.ecmwf.int/assets/elearning

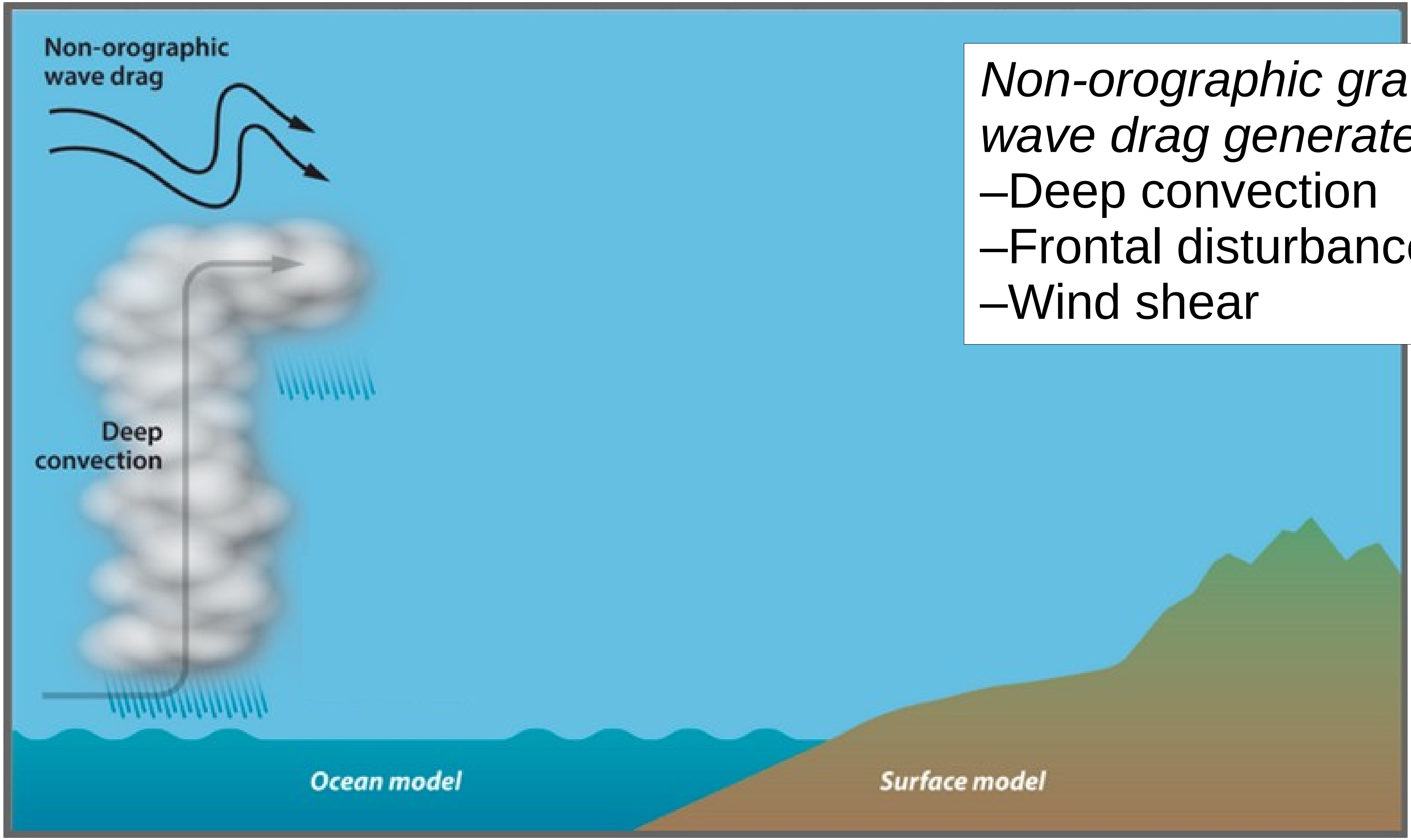
Unresolved processes represented via physical parameterizations



Sub-grid scale turbulence
– Vertical exchange of heat, momentum, moisture
– Coupling with surface through latent and sensible heat fluxes

Source: www.ecmwf.int/assets/elearning

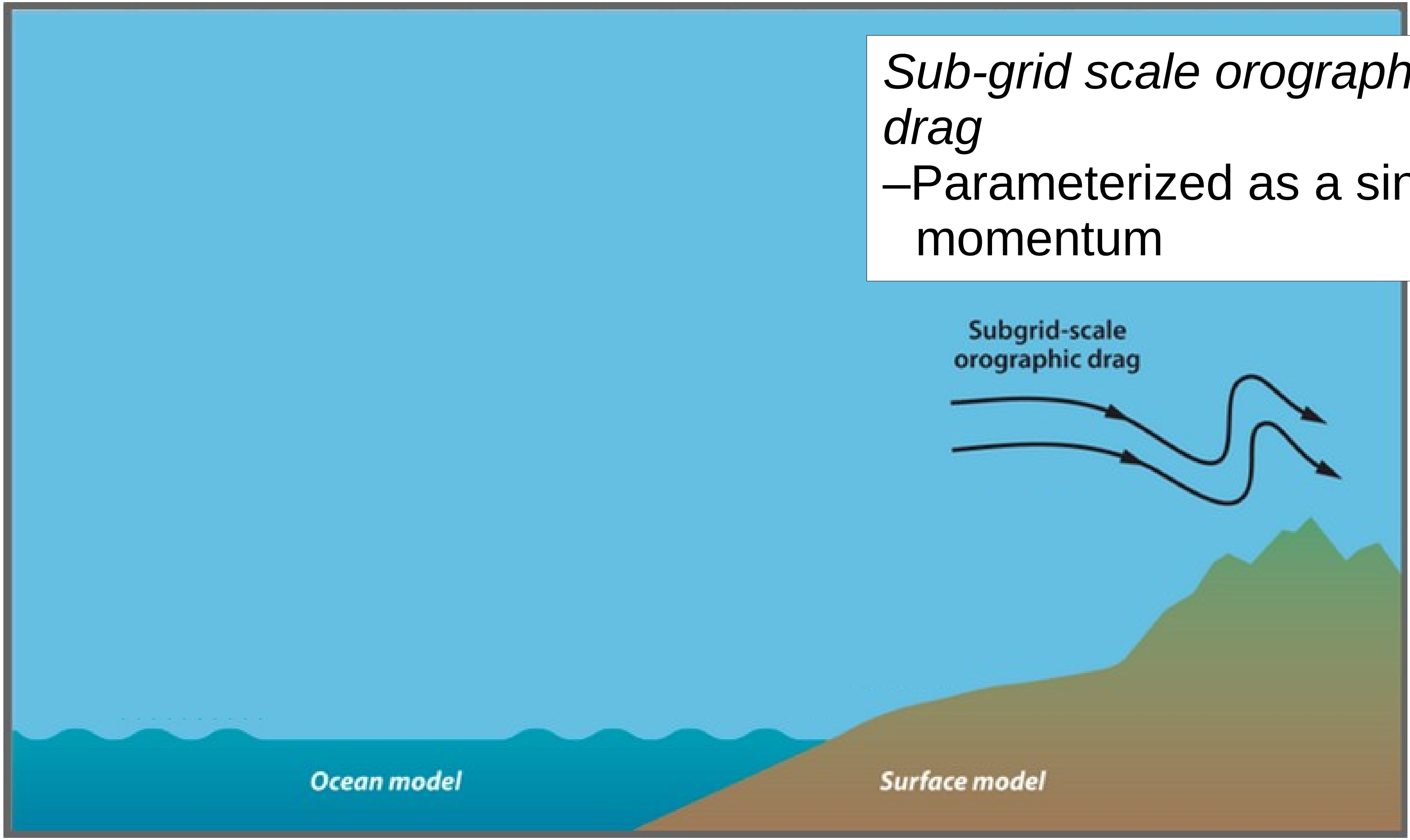
Unresolved processes represented via physical parameterizations



Non-orographic gravity wave drag generated by
–Deep convection
–Frontal disturbances
–Wind shear

Source: www.ecmwf.int/assets/elearning

Unresolved processes represented via physical parameterizations

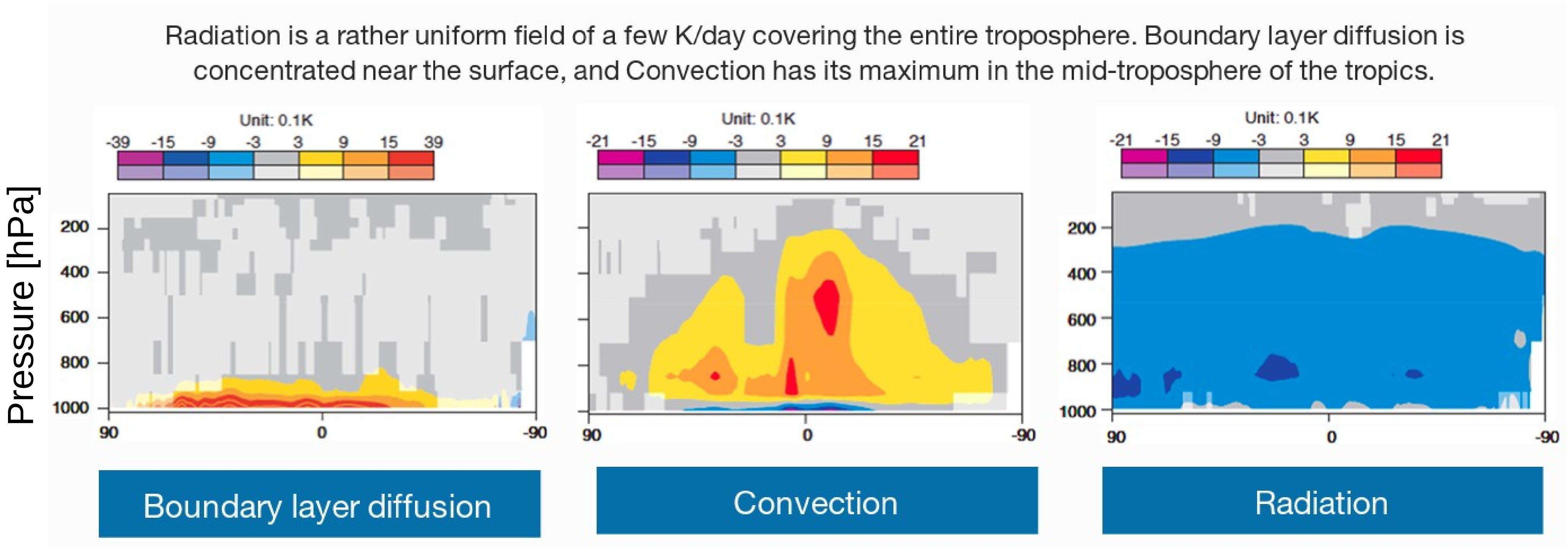


Sub-grid scale orographic drag

–Parameterized as a sink of momentum

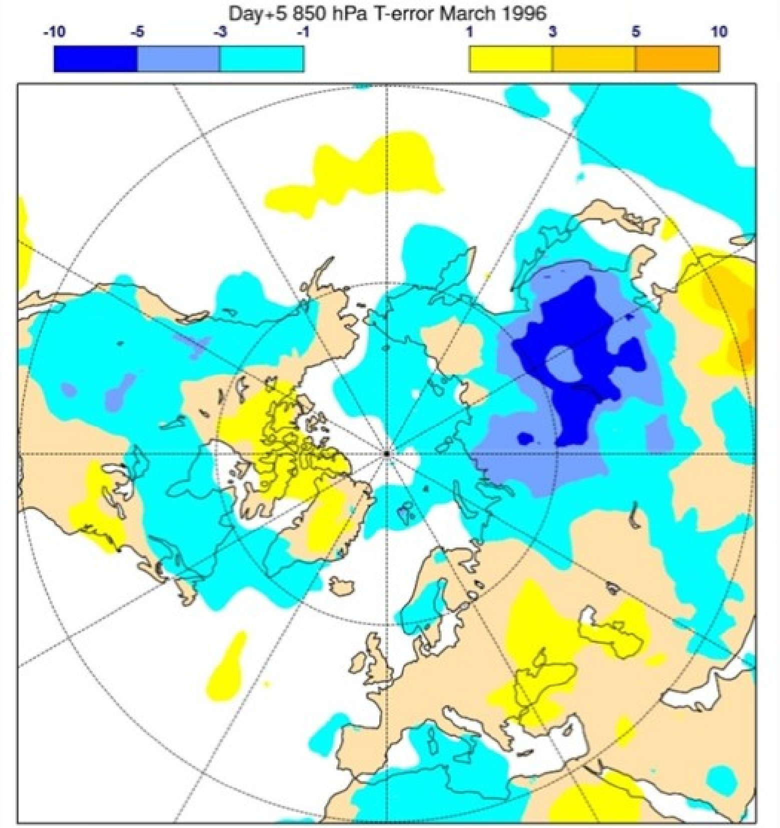
Source: www.ecmwf.int/assets/elearning

Temperature tendencies associated with some physical processes

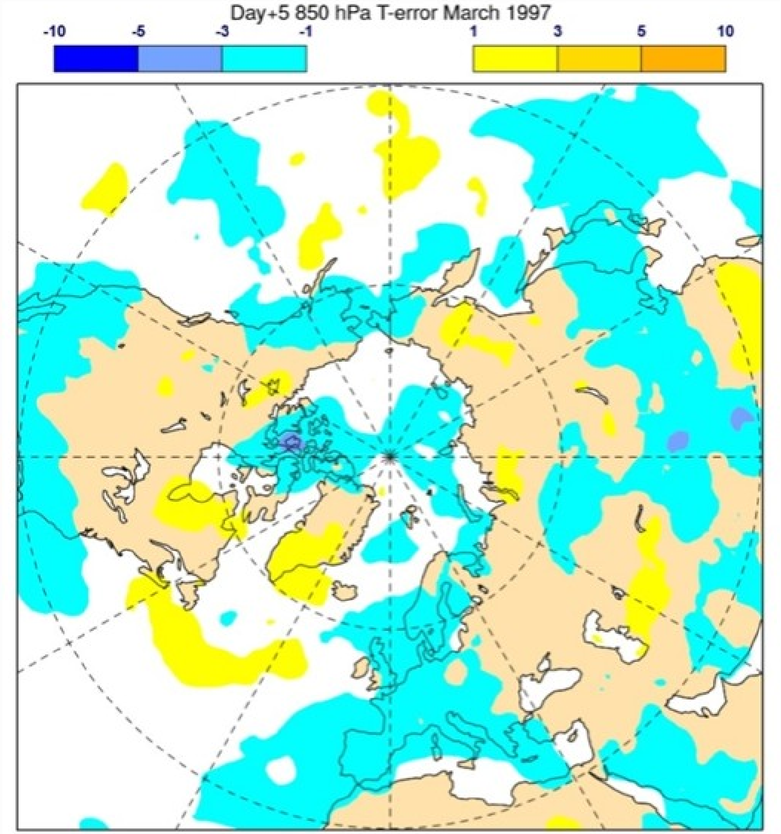


Source: www.ecmwf.int/assets/elearning

High snow albedo in forest



Low snow albedo in forest



Source: www.ecmwf.int/assets/elearning

Greatest challenges in modern-day NWP

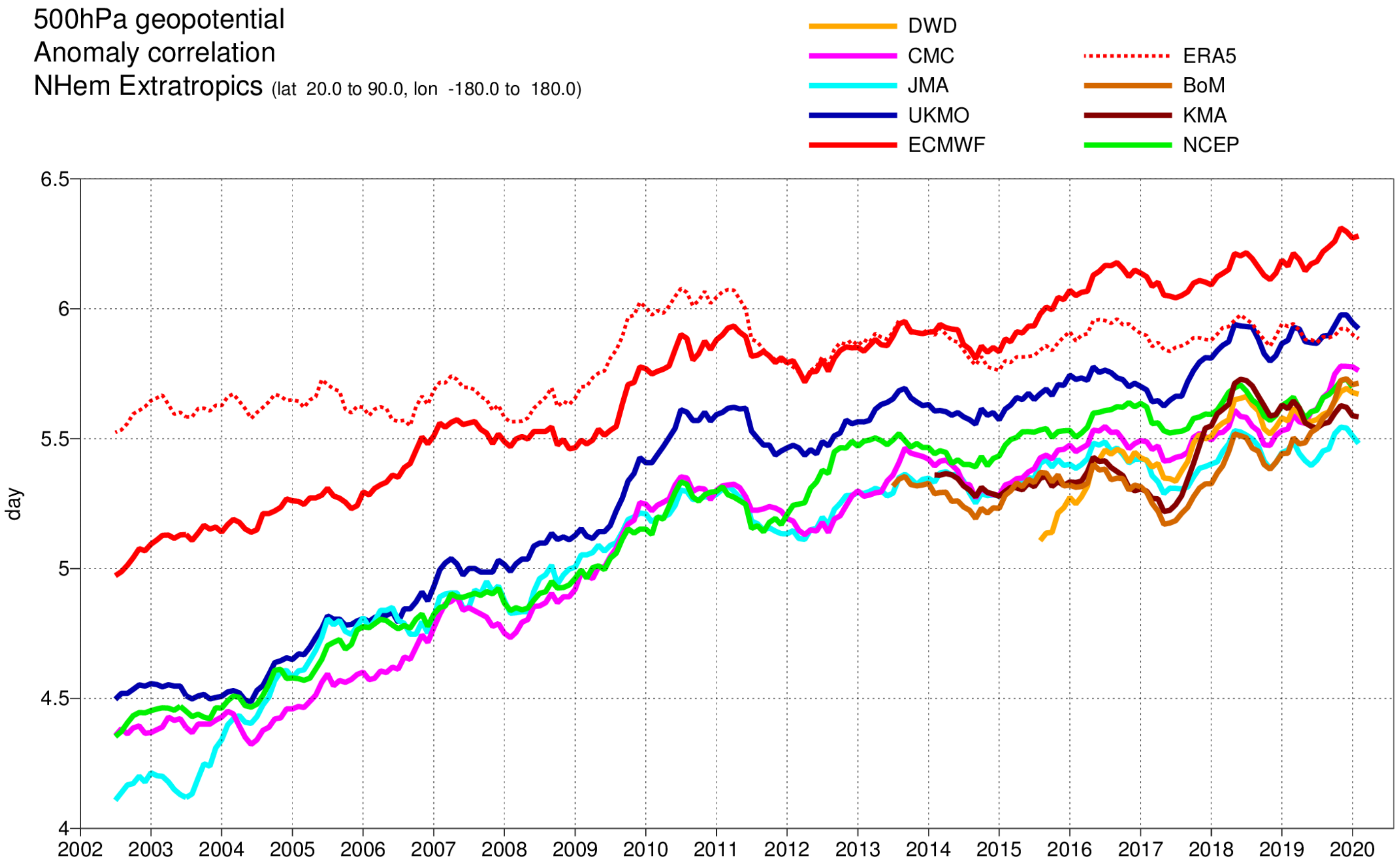
1) Timely forecast production with ever increasing resolution in time and space

2) Initialization of model state close to observed current weather everywhere on the globe

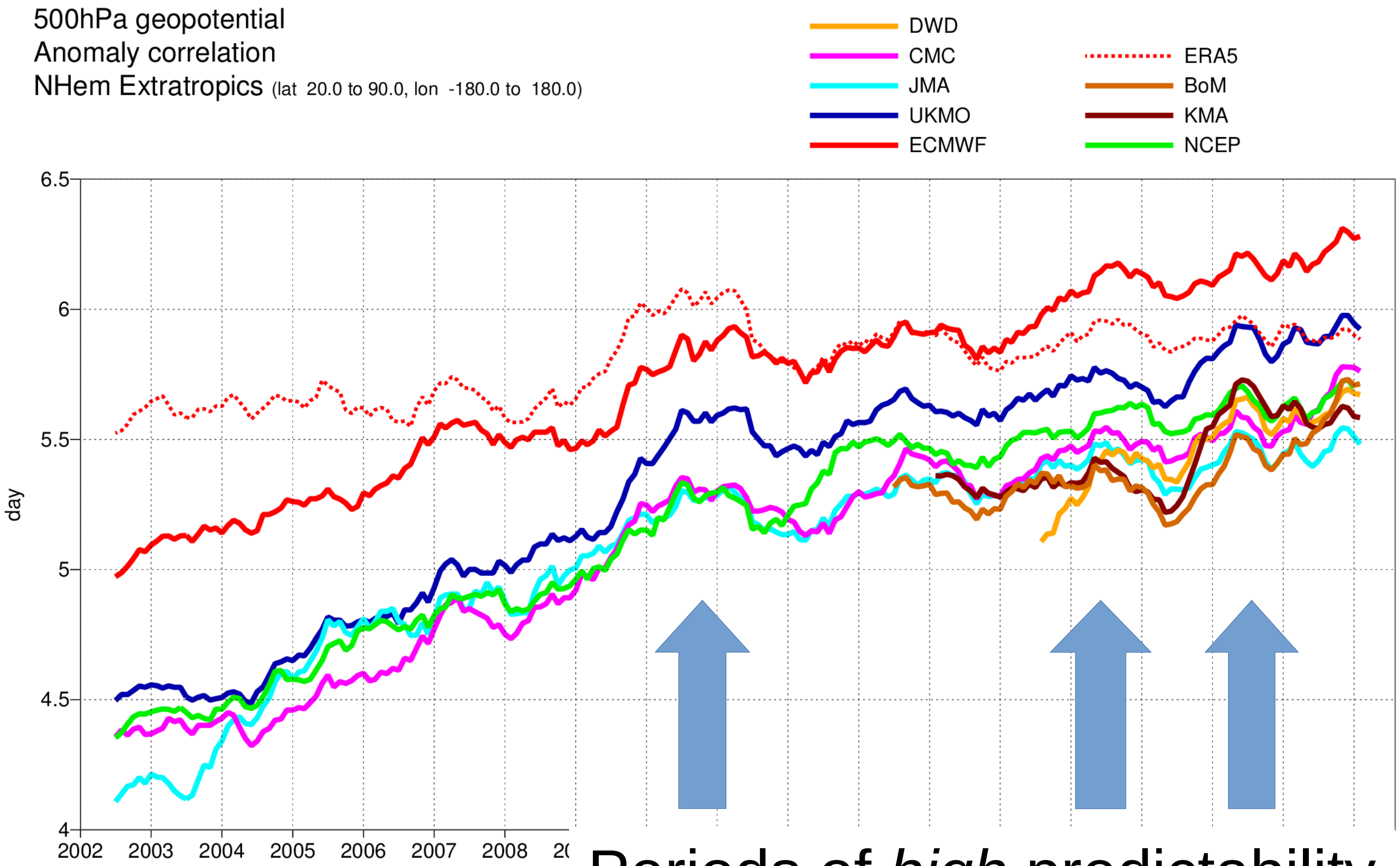
3) Realistic representation of the effect of unresolved physical processes

4) Description of uncertainty in analysis and forecast

Variation of predictability in planetary scale

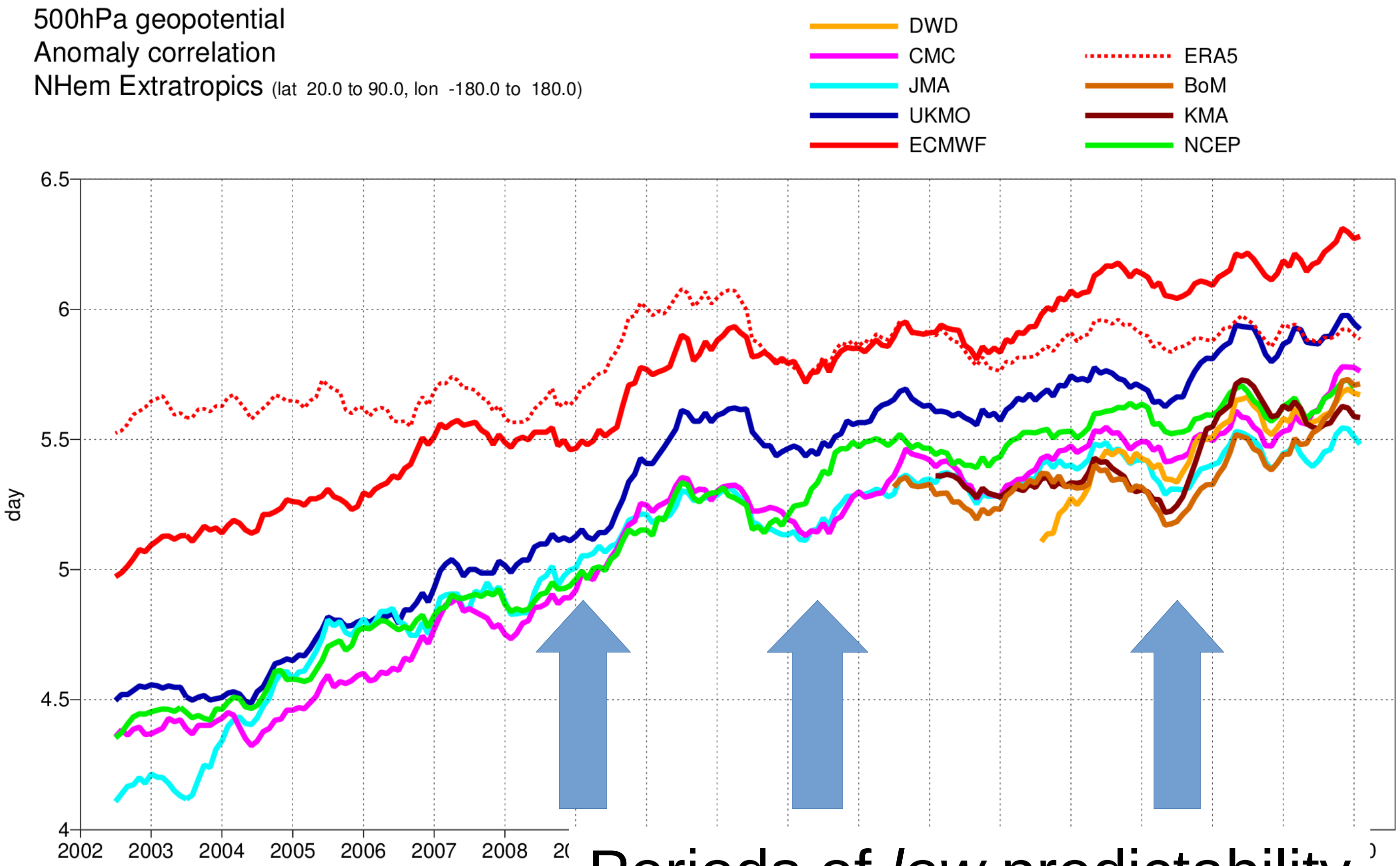


Variation of predictability in planetary scale



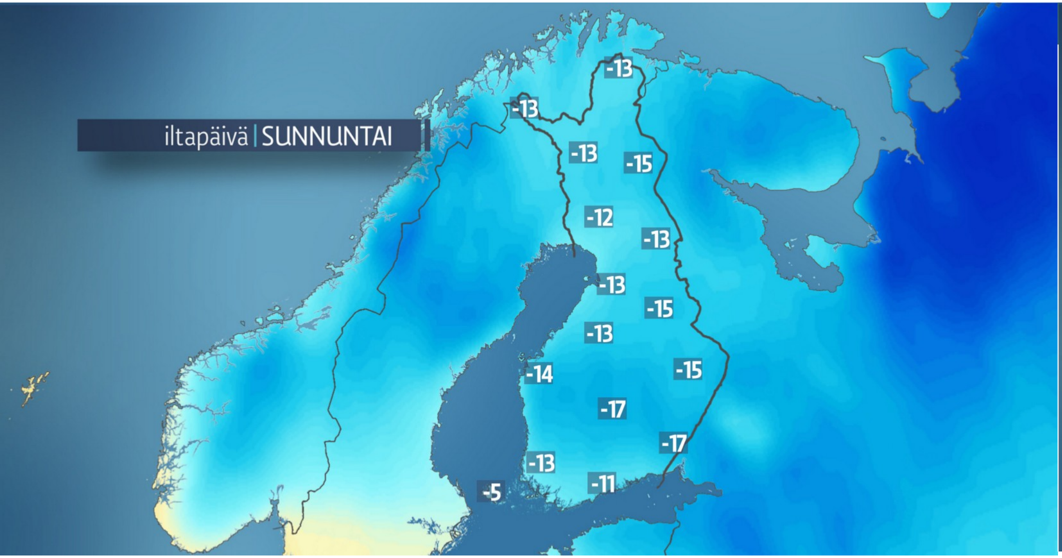
Periods of *high* predictability

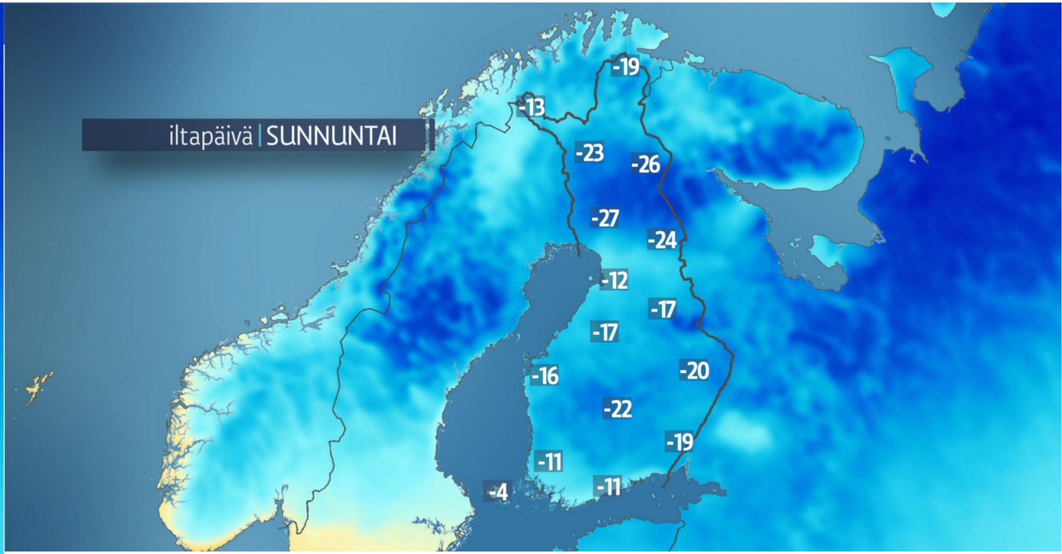
Variation of predictability in planetary scale



Periods of *low* predictability

A case of low predictability in local scale

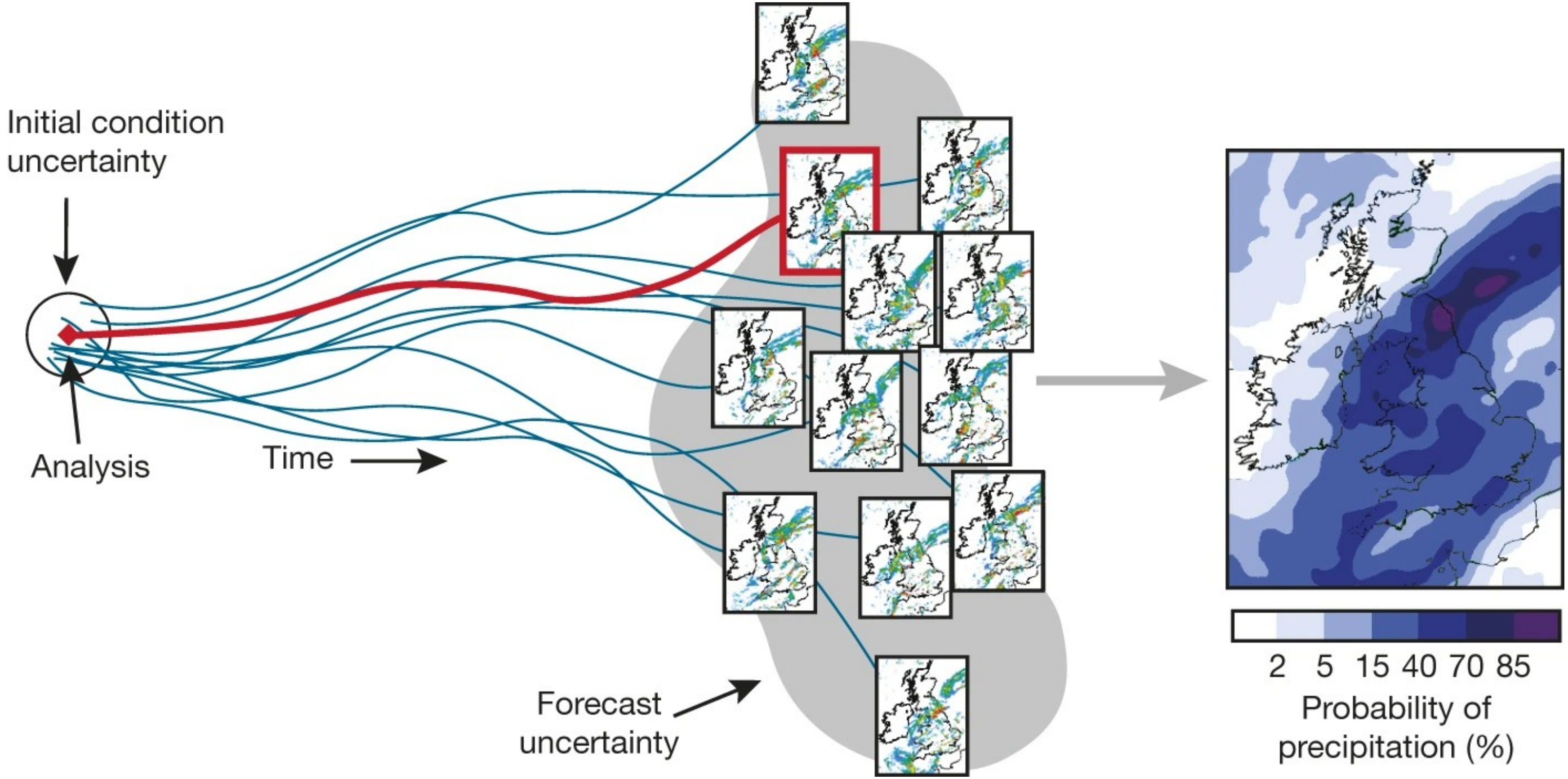




Two NWP models' predictions of 2-meter temperature in the afternoon of the next day

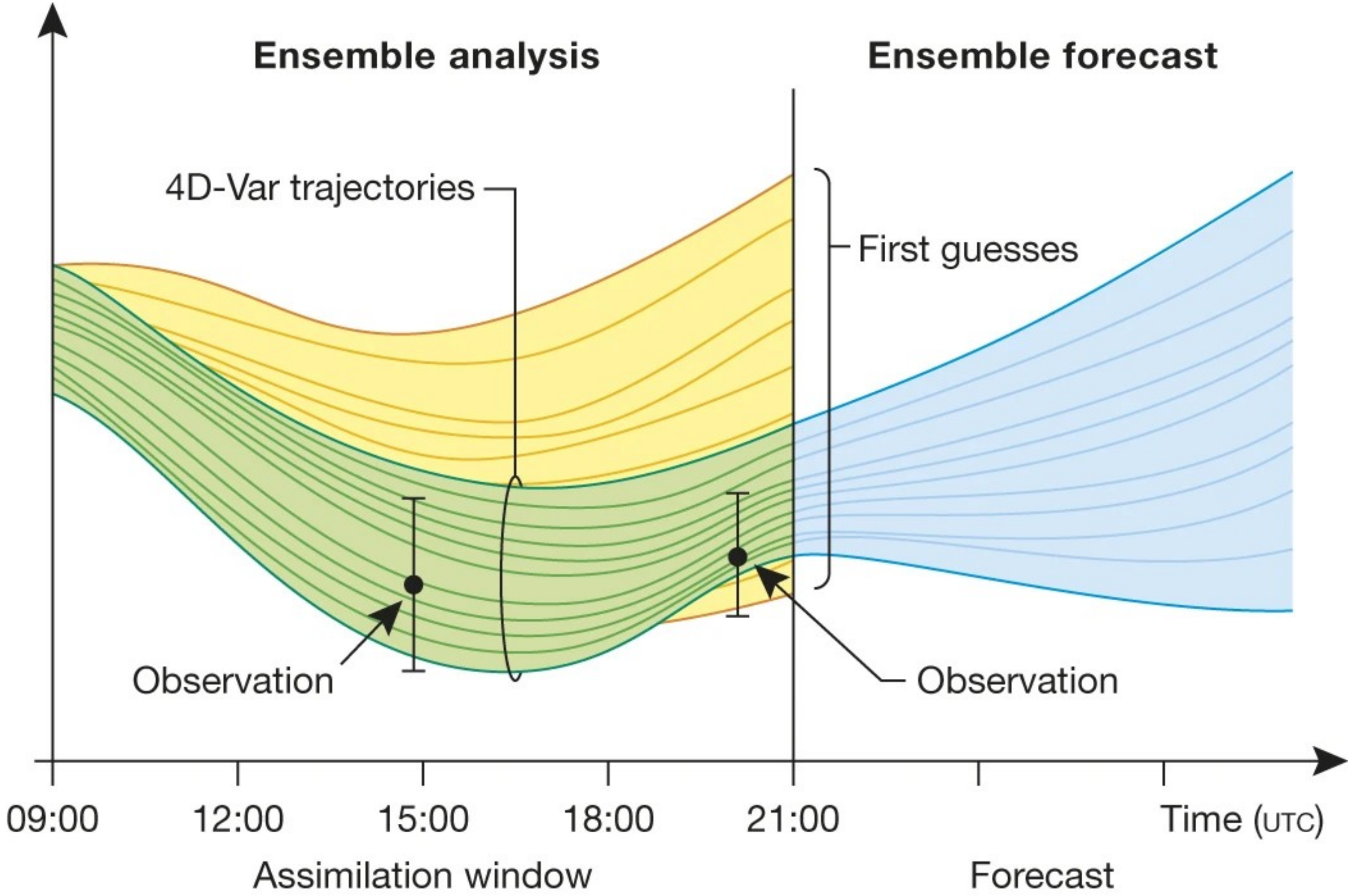
Twitter / @MattiHuu_YLE 9th January 2016

Enabling probabilistic forecasts by the method of perturbed ensembles



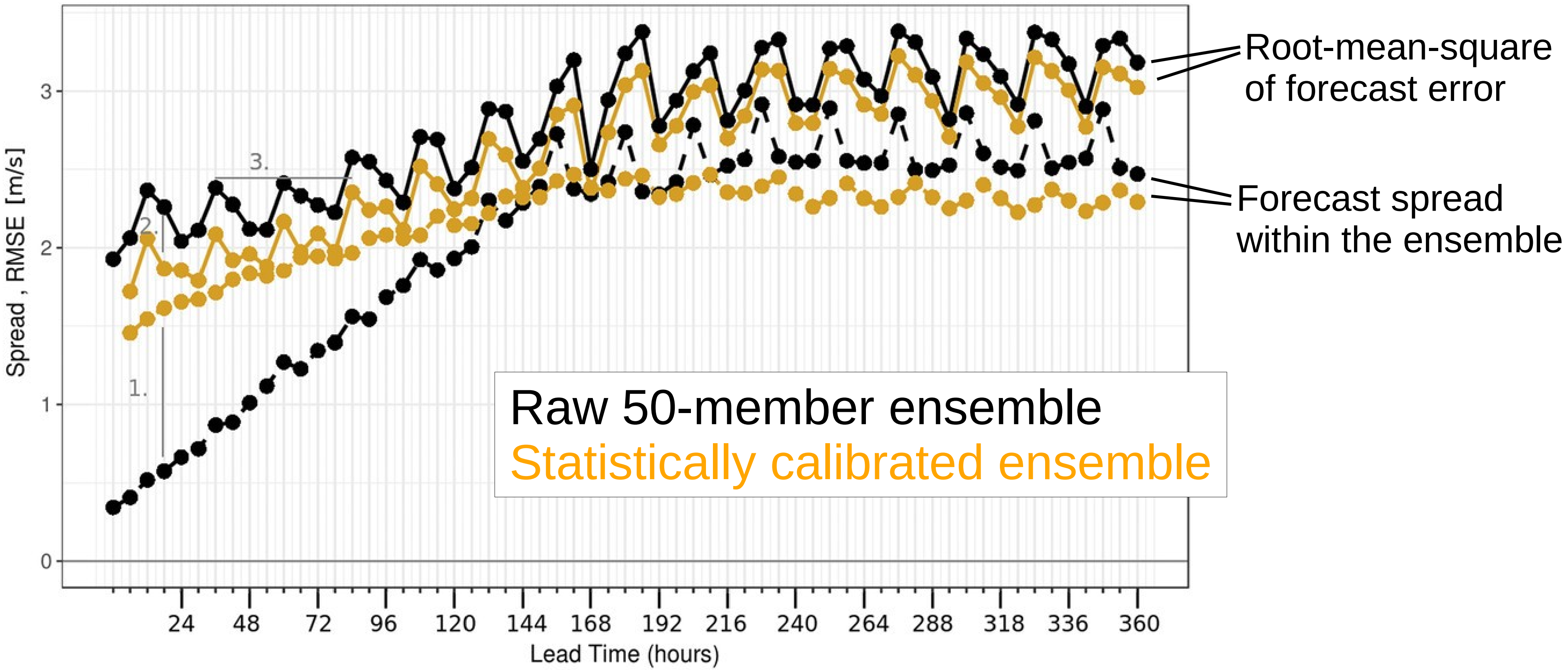
Nature **525** (3rd September 2015)

Ensemble analysis and forecast cycle



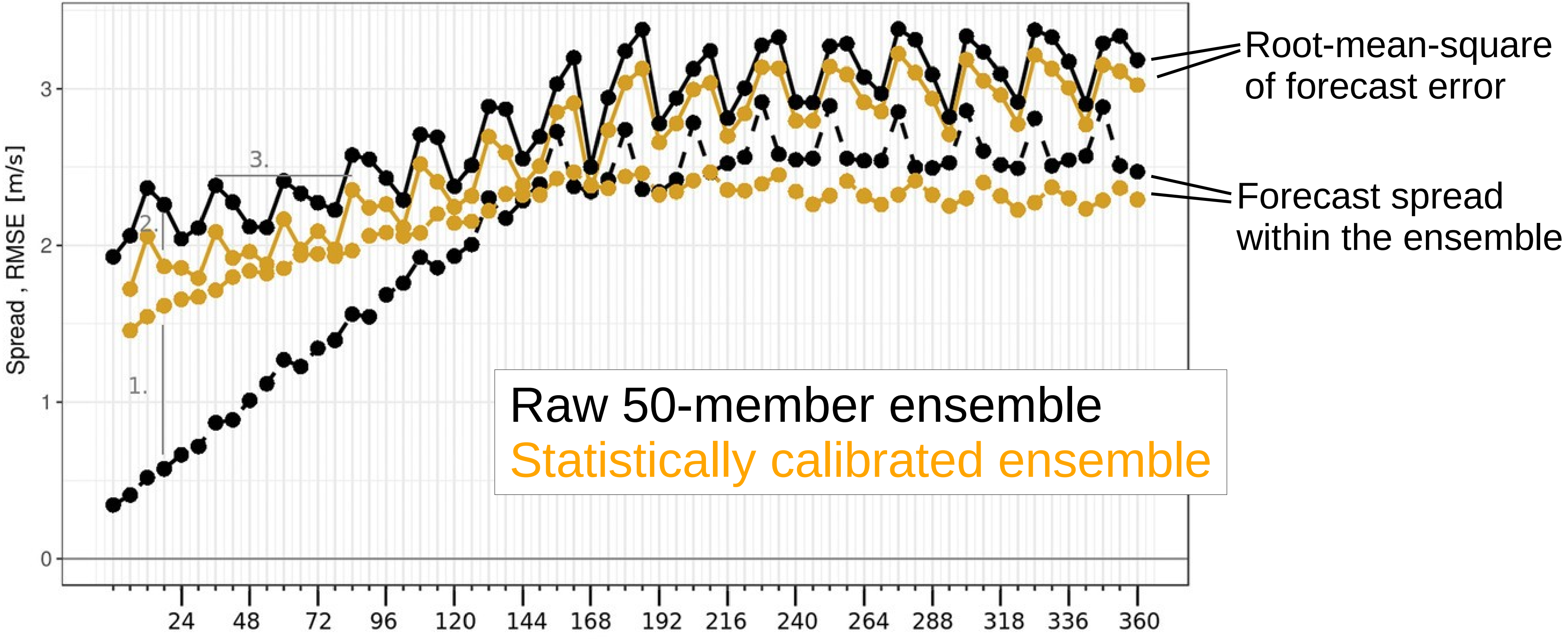
Nature **525** (3rd September 2015)

Ensemble spread vs. skill



Hämäläinen et al., Mon. Wea. Rev. ***148****, 2020*

Ensemble spread vs. skill



Realistic description of uncertainty would imply that spread ~ skill

Greatest challenges in modern-day NWP

1) Timely forecast production with ever increasing resolution in time and space

2) Initialization of model state close to observed current weather everywhere on the globe

3) Realistic representation of the effect of unresolved physical processes

4) Description of uncertainty in analysis and forecast