

NEDJELJKA ŽAGAR

**A PERFECT STORM:
RICHARDSON'S WEATHER FACTORY,
100 YEARS LATER**



100 YEARS OF THE RICHARDSON'S WEATHER FORECASTING FACTORY

The ongoing major shift in weather forecasting practice takes places 100 years after L.F. Richardson published his book "Weather Prediction by Numerical Process" (1922), describing his attempt to forecast changes in the weather by numerical methods.



FIGURE 1: "Weather Forecasting Factory" by Stephen Conlin, 1986. Based on the description in Weather Prediction by Numerical Process, by L.F. Richardson, Cambridge University Press, 1922, and on advice from Prof. John Byrne, Trinity College Dublin. Image: ink and water colour, c. 50 x 38.5 cm. © Stephen Conlin 1986. All Rights Reserved. (Courtesy: Hendrik Hoffmann, School of Mathematics & Statistics, University College Dublin)

Source: <https://www.emetsoc.org/resources/rff/>

100 YEARS OF THE RICHARDSON'S WEATHER FORECASTING FACTORY

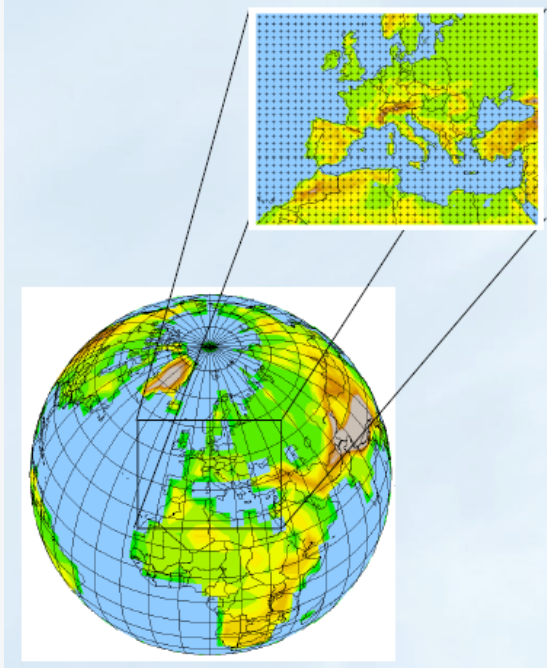
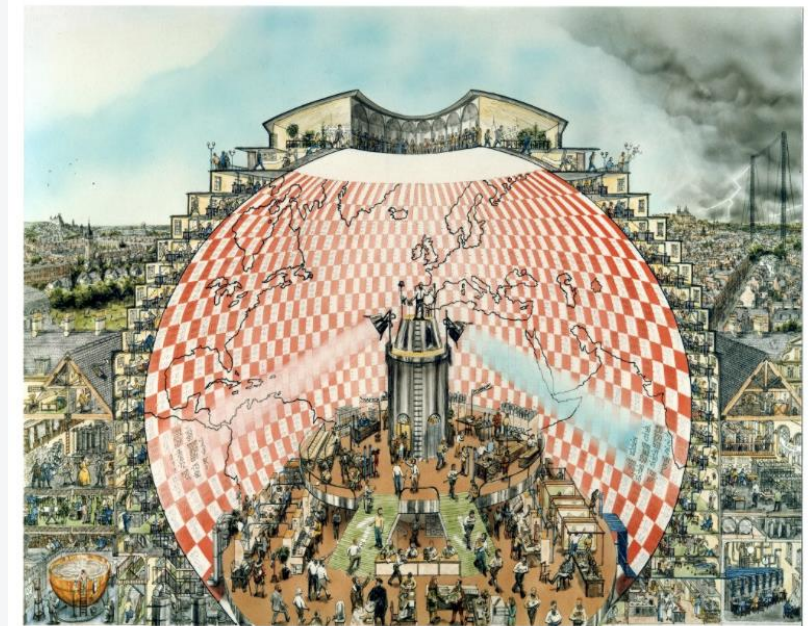


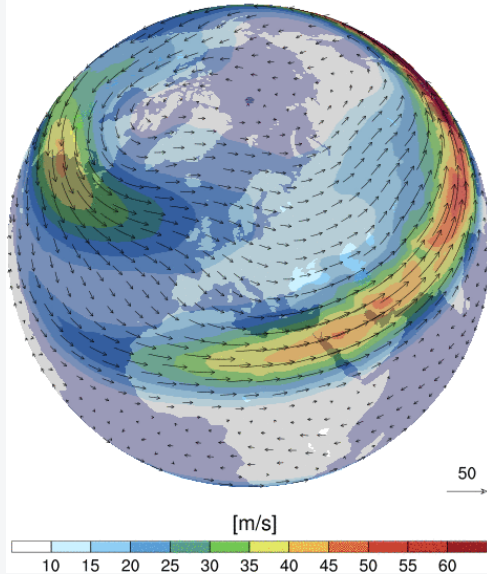
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SPATIO-TEMPORAL FLOW DECOMPOSITION

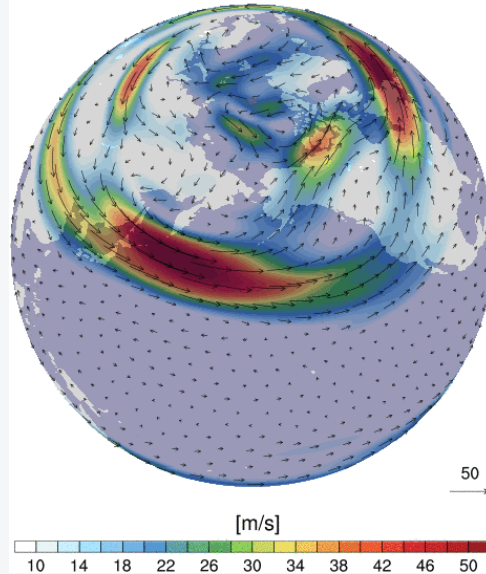
time mean

wind 300hPa DJF



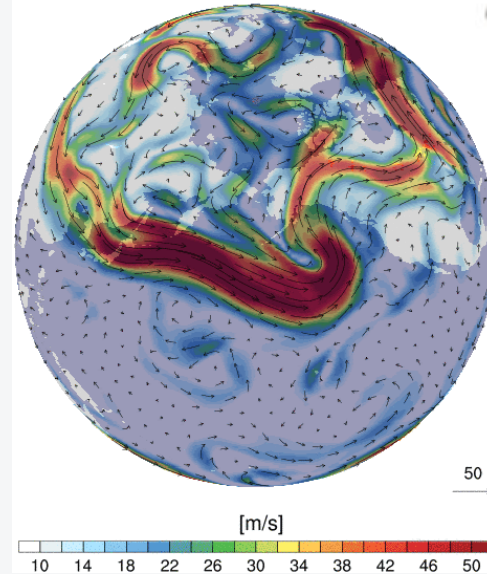
day-by-day, large scales

k=0-3 300hPa 2010-10-01 00 UTC



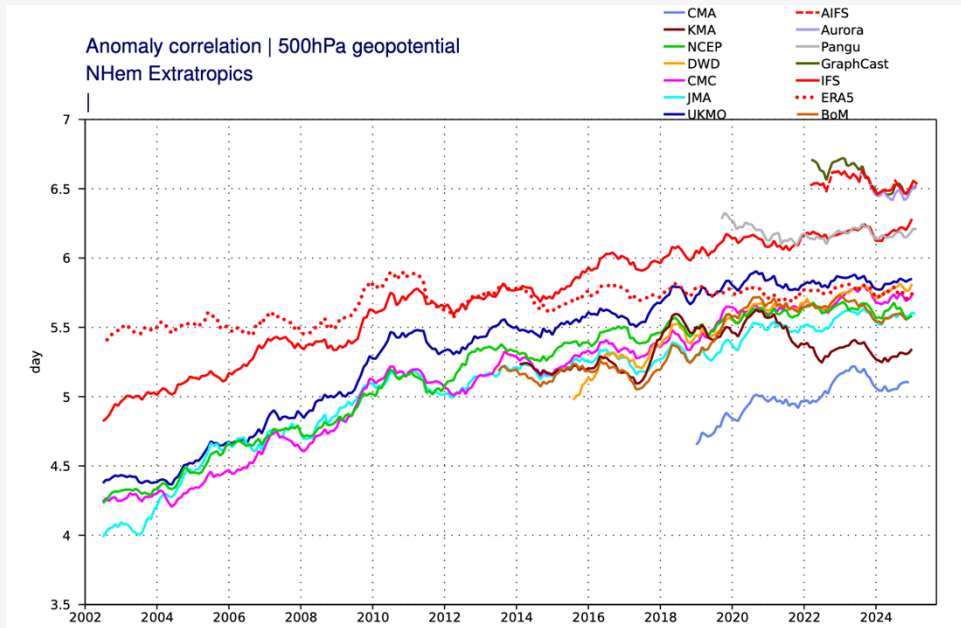
day-by-day, all scales

k=0-100 300hPa 2010-10-01 00 UTC



ERA5 data: 1 Oct-31 Dec 2010

PREDICTABILITY AS A DRIVER OF NWP: A CENTURY OF PROGRESS, DISRUPTED BY ML



Source: www.ecmwf.int, Haiden et al. 2025

ML-model scores exceed that of the IFS by an amount comparable to the IFS lead over NWP models of other centres.

Multi-stage process:

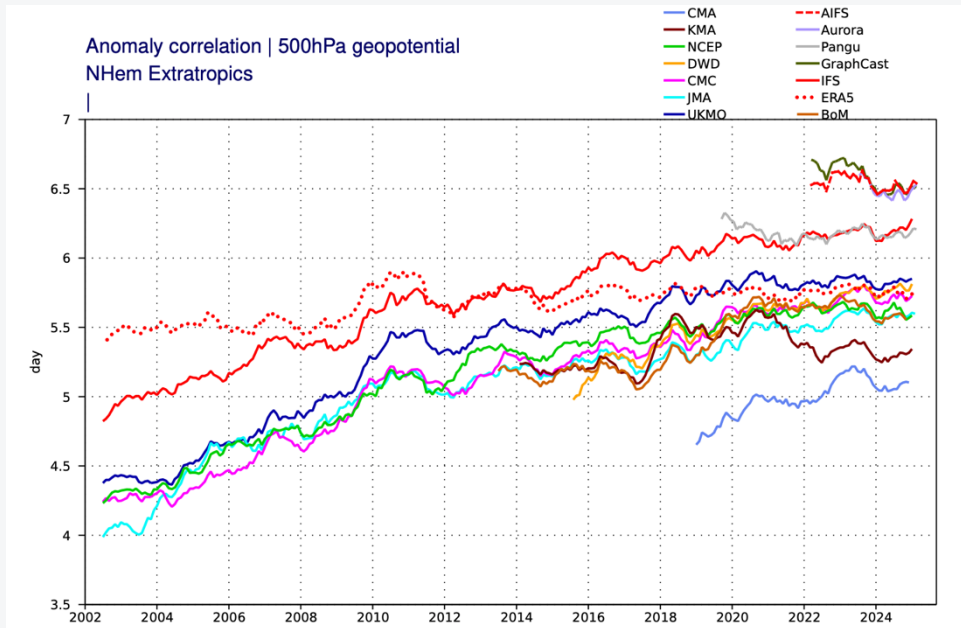
1. Training on ERA5 and analyses

Pangu (2022/2023), GraphCast (2023), GenCast (2024), AIFS (2024)

2. CMIP and forecast data added

Aurora (2024/2025)

PREDICTABILITY AS A DRIVER OF NWP: A CENTURY OF PROGRESS, DISRUPTED BY ML



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1. Training on ERA5 and analyses

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2. CMIP and forecast data added Aurora (2024/2025)

3. Observations added in training WeatherGenerator (2025/2026)

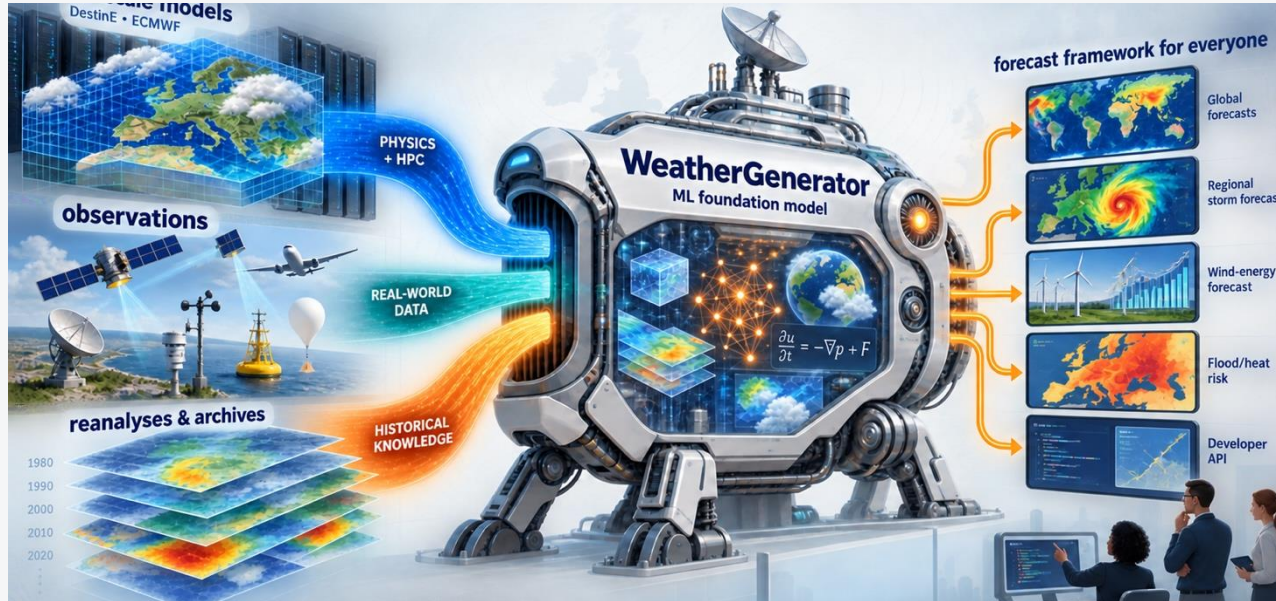
4. Observation-only (end-to-end) forecasting

AIFS-DOP (2026/2027)

AIFS+DOP+WeatherGenerator

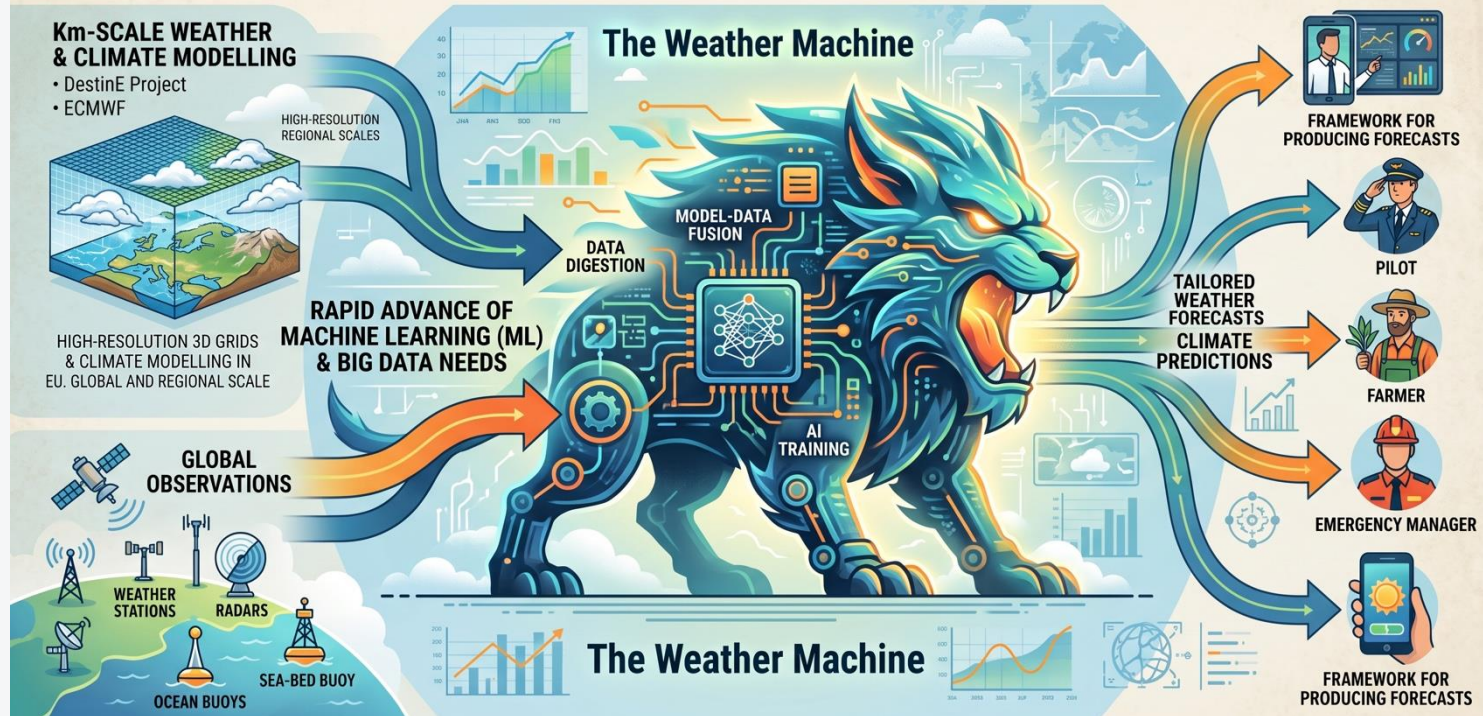
A PERFECT STORM: KM-SCALE MODELLING MEETS RAPID ADVANCES IN MACHINE LEARNING

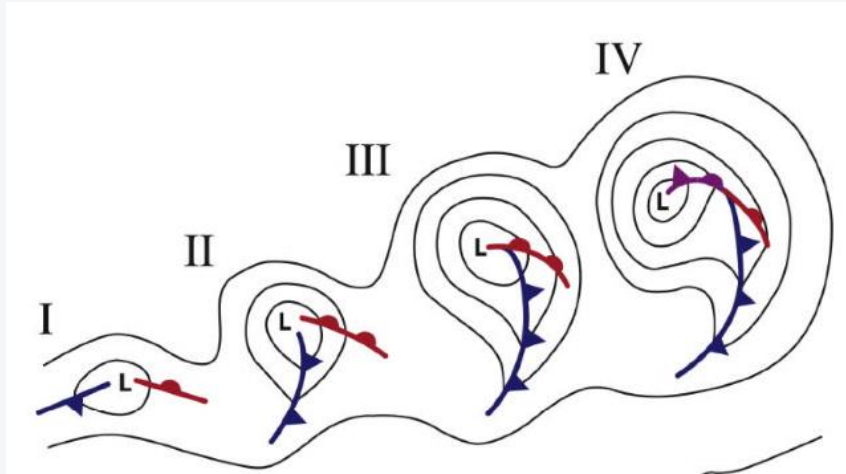
Richardson's weather factory has become weather machine



WEATHER MACHINE

21st CENTURY WEATHER FACTORY: THE WEATHER MACHINE





<https://weathertogether.net/weather-101/extratropical-cyclones/>



<https://www.imdb.com/title/tt0177971>

1. Training on ERA5 and analyses

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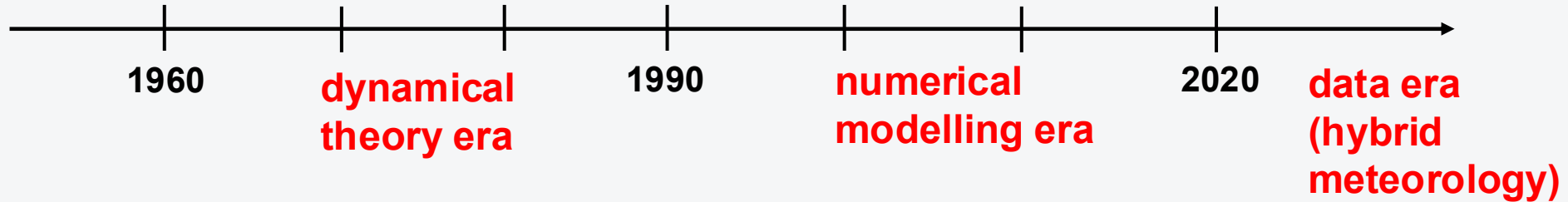
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HARMONIE-AROME?

Evolution of atmospheric science and weather forecasting

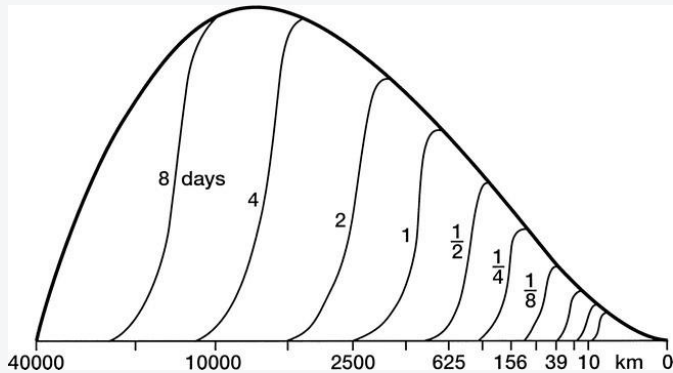


- What does it mean to be a meteorologist as we increasingly work with a weather machine?
- How should we practice weather and climate research as data, physical models, and weather machines become increasingly intertwined?
- How do we educate meteorologists to work effectively with increasingly capable weather machines while still being able to explain why the atmosphere behaves as it does?

UNDERSTANDING PREDICTABILITY

Atmospheric predictability: traditional picture vs. NWP reality

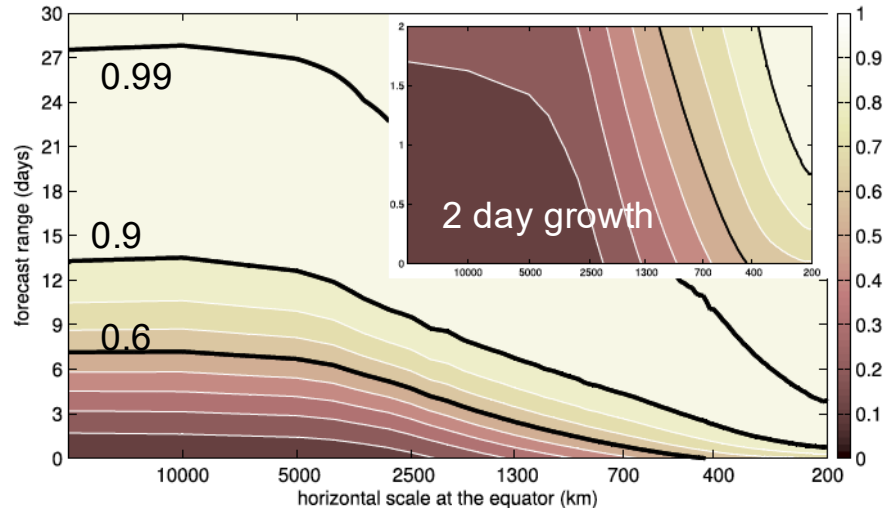
Barotropic vorticity equation, upscale cascade of small-scale initial errors



Source: Lorenz, 1969

Updated picture: Tribbia and Baumhefner (2004), Rotunno and Snyder (2008), Durran and Gingrich (2014), and many others.

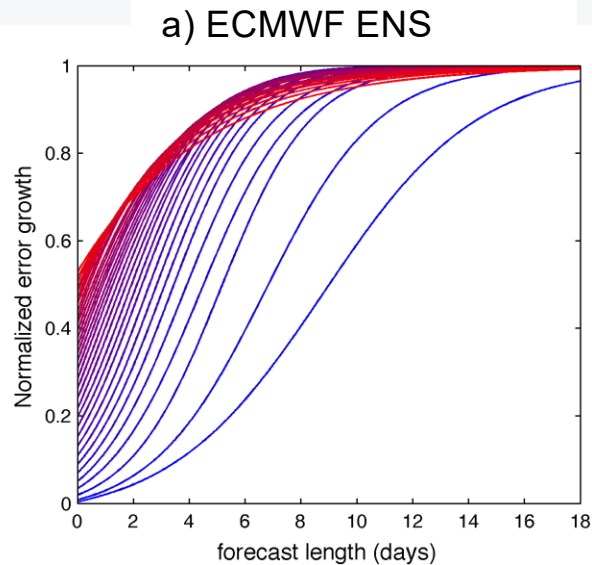
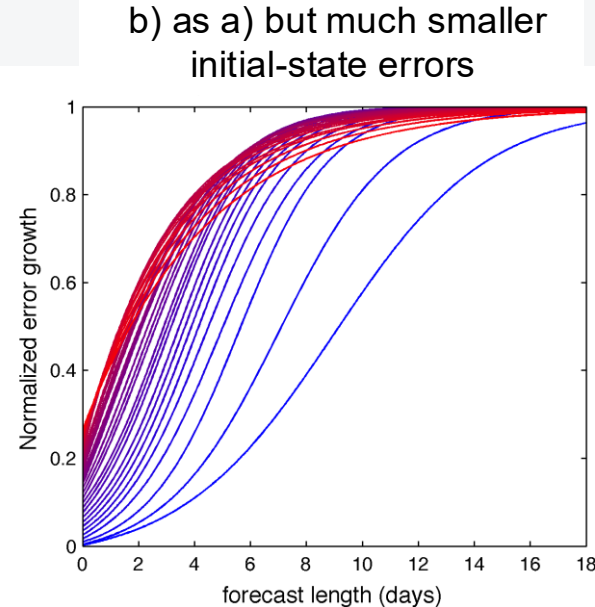
Simulated forecast errors in different zonal wavenumbers normalized by their asymptotic values at 60-day forecast range (ECMWF ENS)



Source: Žagar et al., 2017

NWP PROGRESS: DEVIL LIES AT LARGE SCALES

Potential improvements in predictability by a better initial state

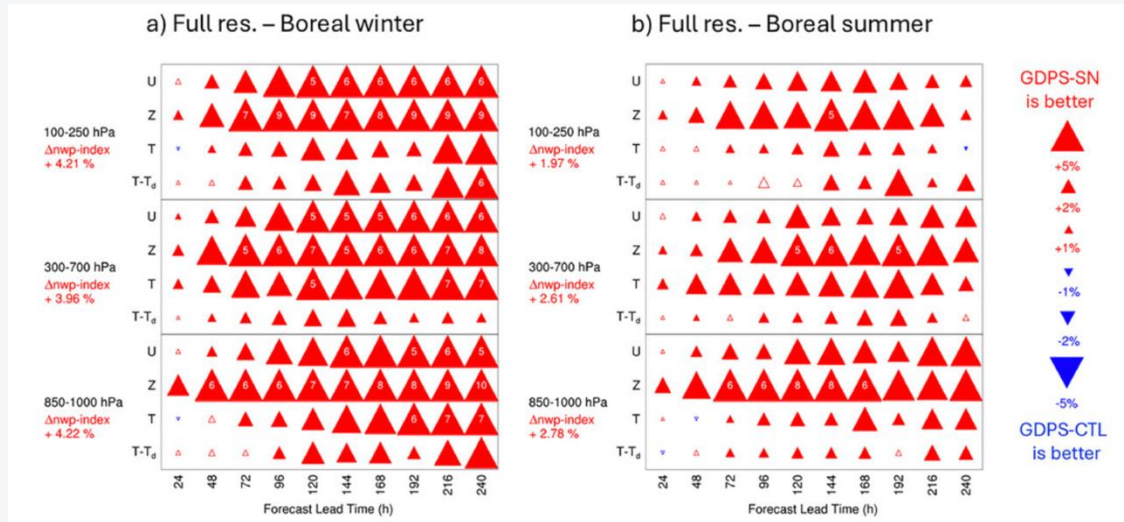


Source: Žagar
and Szunyogh,
2020

Large gains in subsynoptical scales: $k=100$ would have the same predictability at day 2 as now $k=40$, and $k=70$ would have the same predictability at day 1 as now $k=43$.

NWP VS. ML FORECASTING: PROCESSES?

Nudging NWP forecasts into ML forecasts at large scales greatly improves all forecast scores



Verification against radiosonde data

Source: Husain et al., 2025

Nudging large-scale IFS forecasts into the AIFS forecasts is now under implementation for operational use at the ECMWF => better LBs for our operational LAMs.

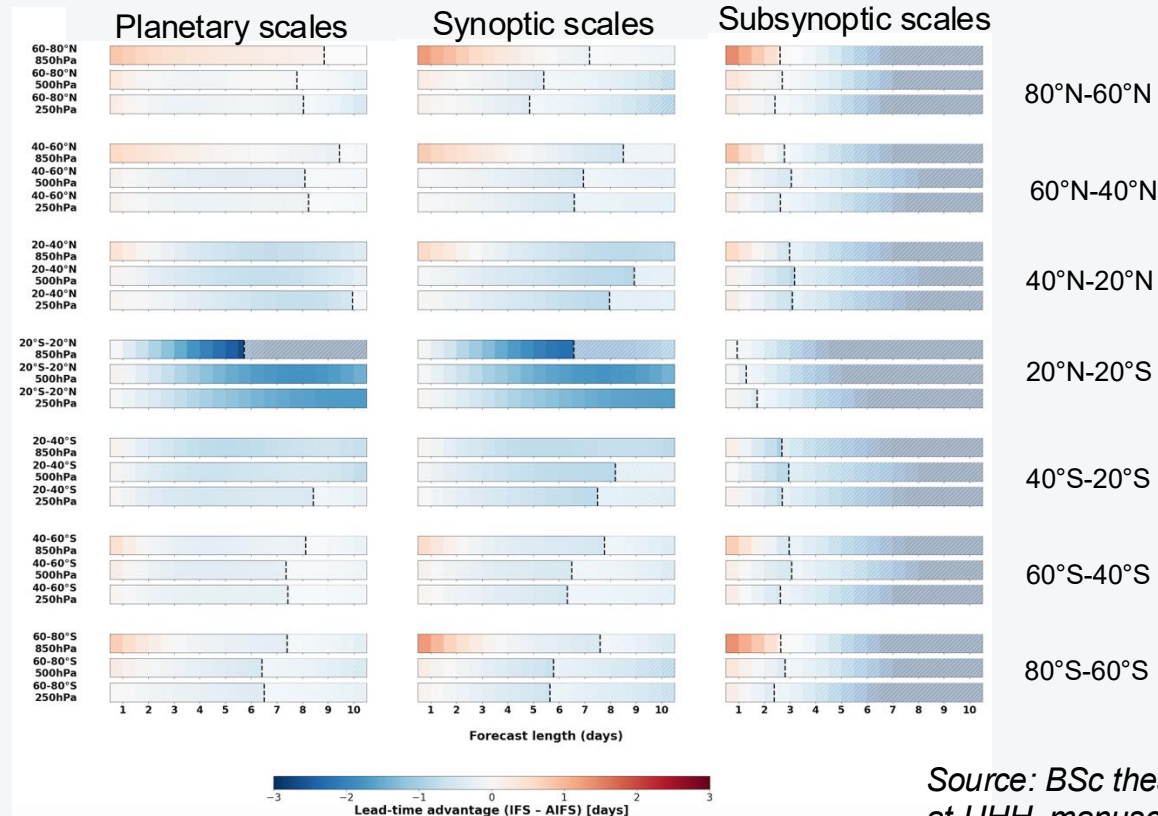
NWP VS. ML FORECASTING: POLAR PROCESSES?

zonal wind

red: IFS better than AIFS

blue: AIFS better than IFS

Gray shade:
predictability in IFS
reached 60% of
saturation
according to the
parametric model
fit



Source: BSc thesis by J. Kuegler
at UHH, manuscript in progress

WEATHER MACHINE & PHYSICAL METEOROLOGY

Prediction is not understanding

Weather machines can learn complex relationships from data, but physical understanding remains essential for interpreting why the atmosphere behaves as it does.

Machines accelerate, physics guides

Weather machines would dramatically accelerate forecasting, while physical modelling provides insight and physical consistency.

The future is hybrid: weather machine + physical modelling

Weather machines and physical models capture atmospheric behaviour in fundamentally different ways; using both gives us more powerful prediction systems than relying on either alone.



Thank you very much for your attention!