SPECIAL PROJECT PROGRESS REPORT

All the following mandatory information needs to be provided. The length should *reflect the complexity and duration* of the project.

Reporting year	2024
Project Title:	Flow-dependence of the intrinsic predictability limit and its relevance to forecast busts
Computer Project Account:	spdecrai
Principal Investigator(s):	Prof. George Craig
Affiliation:	Meteorologisches Institut Ludwig-Maximilians-Universität München Theresienstr. 37 80333 München Germany
Name of ECMWF scientist(s) collaborating to the project (if applicable)	
Start date of the project:	2022
Expected end date:	2024

Computer resources allocated/used for the current year and the previous one

		Previous year		Current year	
		Allocated	Used	Allocated	Used
High Performance Computing Facility	(units)	90M	96M	90M	1.7M
Data storage capacity	(Gbytes)	0	0	0	0

Summary of project objectives

Recent numerical experiments suggest that, on average, the accuracy of medium-range weather forecasts in the midlatitudes has not yet reached the intrinsic predictability limit proposed by Lorenz (1969), and further improvements in skill and lead time are possible. However, there is substantial case-to-case variability in error growth, and it is possible that some of the poorest forecasts may already be impacted by the intrinsic limit. To test this hypothesis, we propose to examine the sensitivity of forecast uncertainty growth to the magnitude of initial condition uncertainty for a large number of cases. These experiments will use a relatively low resolution of the ICON model with a stochastic convection scheme to represent small-scale variability.

Summary of problems encountered (10 lines max)

None.

Summary of plans for the continuation of the project (10 lines max)

We have completed a first set of simulations to assess the spatial-temporal variability of the intrinsic limit and the improvement potential of weather forecasts (see below). With the remaining computational resources we aim to extend this dataset to more cases and/or more ensemble members to achieve a higher level of statistical significance. In addition, it is planned to extend the dataset to include selected cases that have shown very poor forecast skill to investigate if intrinsic limit or improvement potential are different in the subset compared to the average statistics. This analysis will indicate if forecast busts are mainly caused by model errors with larger-than-average improvement potential or if they are mainly caused by a transiently short intrinsic limit with smaller-than-average improvement potential.

List of publications/reports from the project with complete references

Selz, T. and G. Craig, 2023: Can artificial intelligence-based weather prediction models simulate the butterfly effect? *Geophysical Research Letters*, 50, e2023GL105747, https://doi.org/10.1029/2023GL105747.

Summary of results

During the first year of this special project we conducted global convection-permitting ensemble simulations with ICON, which were used subsequently to evaluate perturbation growth of lower-resolution ICON simulations and of artificial-intelligence based atmospheric models (see below). The lower-resolution ICON simulations were complemented with a new stochastic convection scheme (Machulskaya and Seifert, 2019) to better account for the unresolved motions and showed good agreement with the convection-permitting reference. Hence, we spent last years computational resources to conduct a large set of ensemble simulations at lower, 40km resolution with the stochastic convection scheme to estimate a climatological distribution of the predictability time from different levels of initial condition uncertainty, ranging from current estimates to 10-times smaller uncertainties. Form the difference predictability time between those experiments, the improvement potential that is left in weather forecasting can be estimated. Because of the large amount of cases (so far 183, i.e. every 4th day of a 2-year period) and the number of ensemble members (so far 25), this analysis goes way beyond previous estimates of the intrinsic limit and the improvement potential, which only used case studies and/or twin experiments or very small ensembles (e.g. Judt, 2018, Zhang et al., 2019, Selz et al., 2022).

With the larger number of cases and ensemble members and the associated smaller sampling uncertainty we are now able to provide an estimate of the spatial-temporal variability of the intrinsic limit and the improvement potential. First results are given in Figure 1, which shows the intrinsic limit estimate and Figure 2, which shows the improvement potential. Though these results are still preliminary and a careful evaluation of their statistical significance has not yet been performed, several features seem to emerge. First intrinsic limit and improvement potential is longer in the tropics compared to the midlatitudes. This result is consistent with Judt 2020, however in addition a clear longitudinal variability of the tropical improvement potential is present in our results. It is largest over the Indian ocean and lowest over the Atlantic, mostly due to variations of the current limit. In the midlatitudes, the longitudinal variations are smaller, but a larger saisonal variability appears. In the northern hemisphere the improvement potential is much shorter in summer. However, for the southern hemisphere, it is mostly independent of saison. Possibly, this is due to strong summertime convection over land, which reduces the intrinsic limit by injecting a higher level of random variability into the synoptic scales.

In a second line of work, we have investigated the ability of current artificial intelligence-based weather prediction models to simulate the butterfly effect, that is the very fast initial growth of uncertainty from tiny amplitudes of initial condition uncertainty, which eventually leads to the existence of an intrinsic limit. Although computing AI simulations is cheap and has not been done at ECMWF, the ICON simulations used as reference have been calculated with the Special Project's resources, in particular the global convection-permitting ensemble. An evaluation of the AI model PANGU has already been published (Selz and Craig, 2023), but has been complemented by several other AI models since then. Figure 3 shows a comparison of four AI-models and ICON with respect to uncertainty growth. While for current level of initial condition uncertainty (100%) all AI models basically reproduce the growth rate of ICON (disregarding an initial drop due to low effective resolution), they fail to reproduce the butterfly effect (0.1%) and incorrectly suggest an infinite predictability of the atmosphere. Only GraphCast seem to simulate a somewhat accelerated growth rate from the tiny initial condition uncertainty. However, first it slows down too quickly and second, a closer inspection revealed that the increase in growth rate is only due to unphysical gridscale noise.

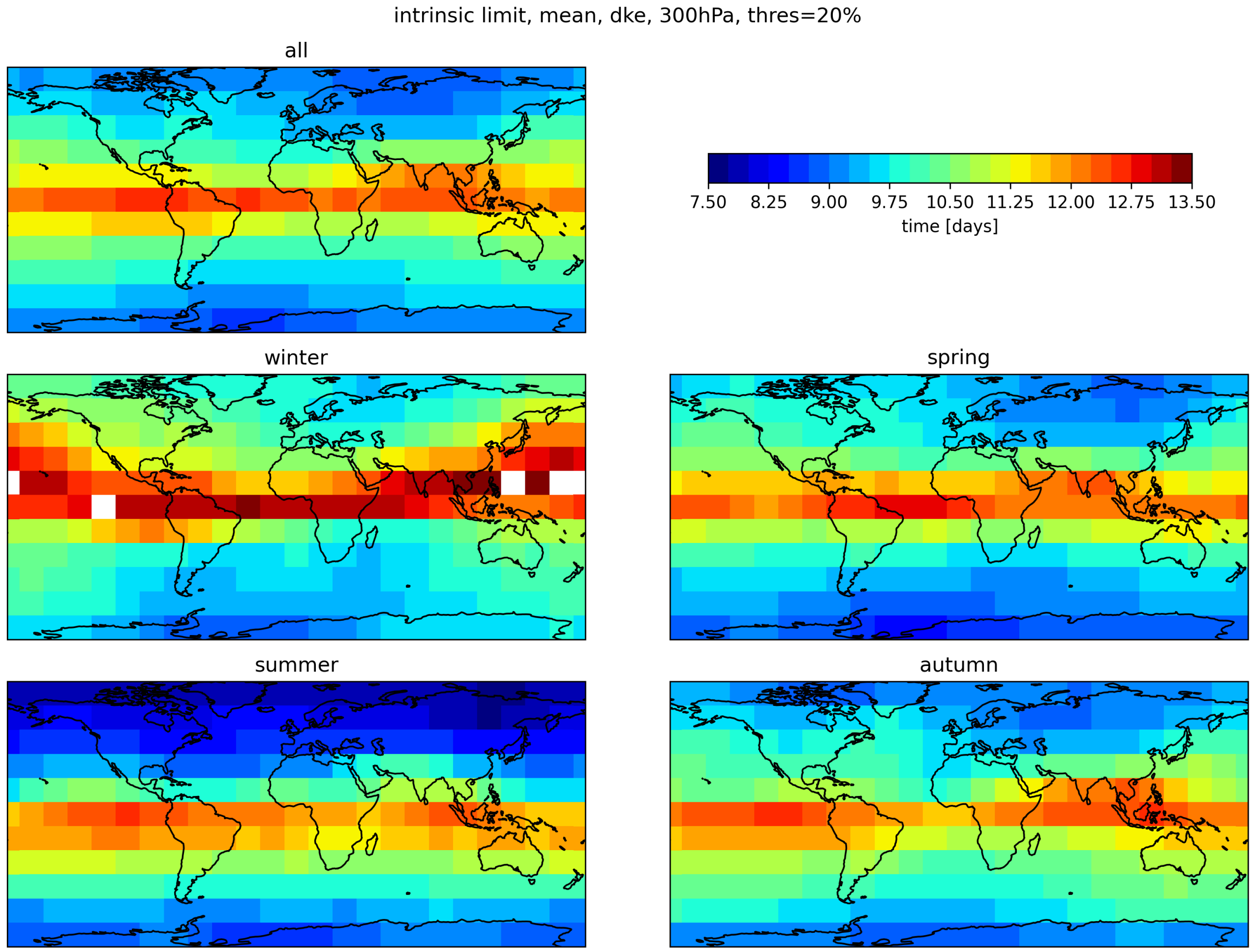

Figure 1: Estimate of the intrinsic limit from the 10%-initial condition experiments, based on 300hPa difference kinetic energy (DKE) and based on a 20% threshold with respect to climatological variability. The estimate was computed over 60°x40° boxes, shifted all over the globe. The colors in the plot show the box center. White boxes indicate that more than 1% of cases could not be evaluated because the 20%-threshold was not reached at the end of the forecast lead time (16 days). The labelling of the seasons refer to the northern hemisphere.

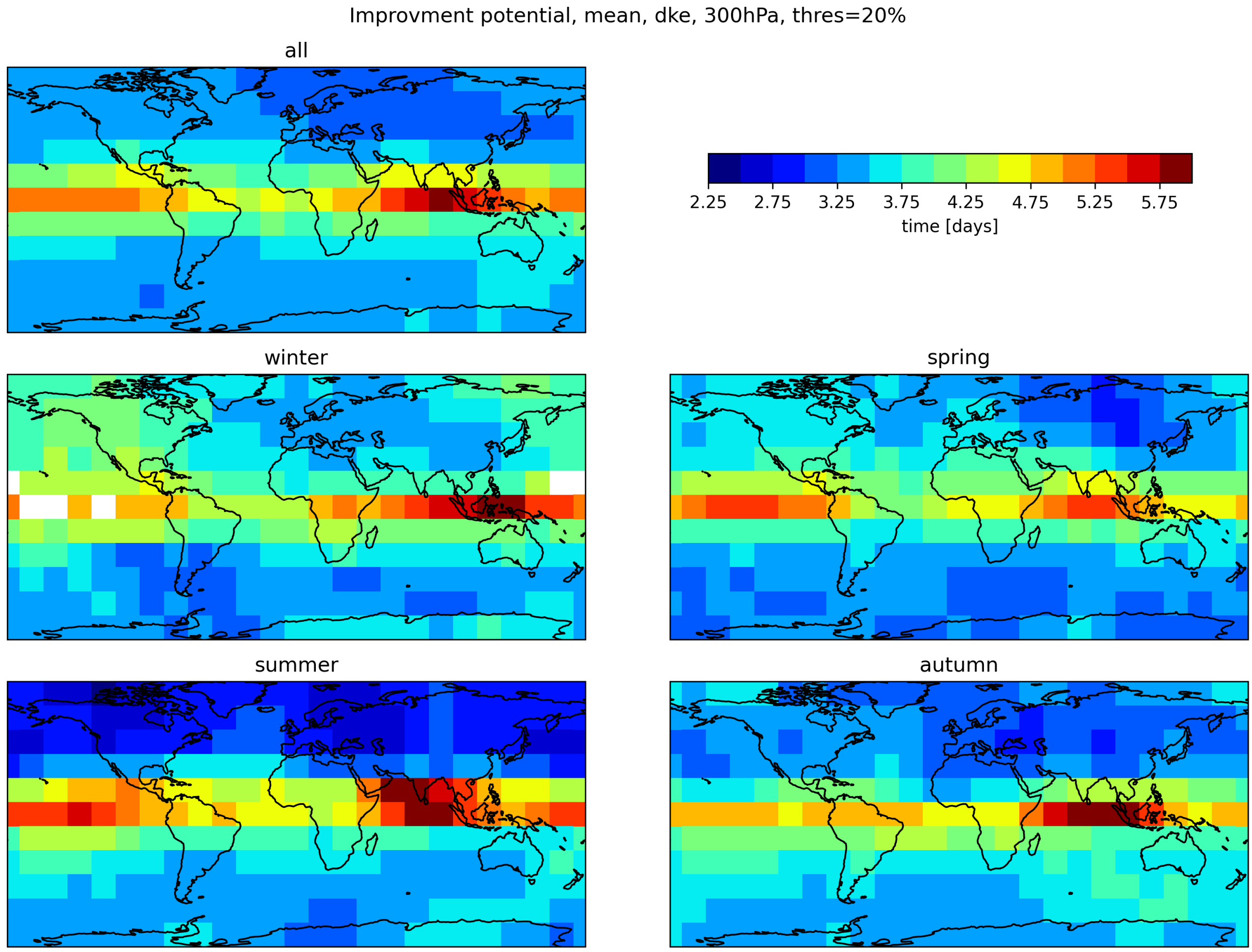

Figure 2: Forecast improvement potential estimated from the predictability time difference between the 100% and the 10%-initial condition experiments. Computation details like Fig. 1.

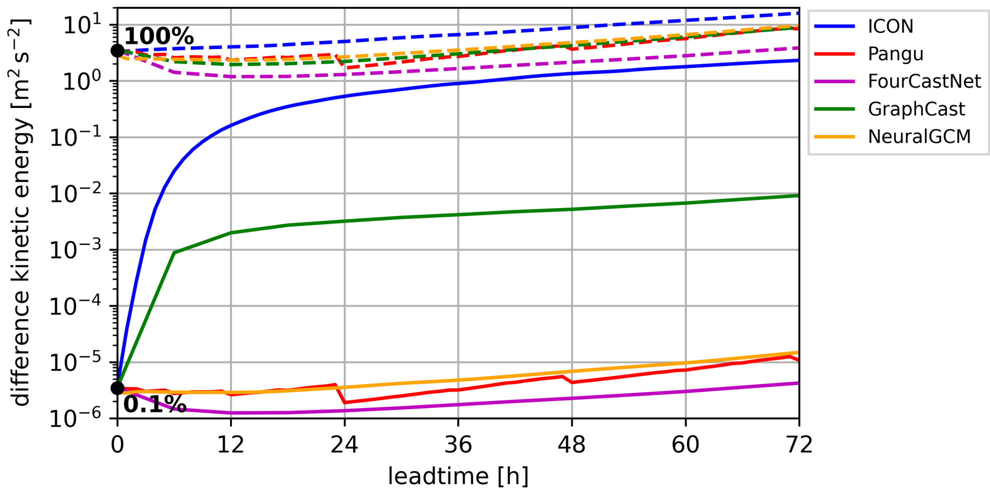

Figure 3: Time series of globally-integrated 300hPa difference kinetic energy for two levels of initial condition uncertainty (100%, 0.1%) and for four different AI-models (Pangu, FourCastNet, GraphCast, NeuralGCM). ICON as a "classic" PDE-based weather prediction model serves as a reference, with the ICON-0.1% experiment computed at global convection-permitting resolution (2.5km gridsize).

References

Judt, F., 2018: Insights into Atmospheric Predictability through Global Convection-Permitting Model Simulations. J. Atmos. Sci., 75, 1477–1497, https://doi.org/10.1175/JAS-D-17-0343.1.

Judt, F., 2020: Atmospheric Predictability of the Tropics, Middle Latitudes, and Polar Regions Explored through Global Storm-Resolving Simulations. J. Atmos. Sci., 77, 257–276, https://doi.org/10.1175/JAS-D-19-0116.1.

Machulskaya, E., and A. Seifert, 2019: Stochastic Differential Equations for the Variability of Atmospheric Convection Fluctuating Around the Equilibrium, *J. Adv. Model. Earth Syst.*, 11, 2708–2727. doi:https://doi.org/10.1029/2019MS001638

Selz, T., M. Riemer, and G. C. Craig, 2022: The Transition from Practical to Intrinsic Predictability of Midlatitude Weather. *J. Atmos. Sci.*, 79, 2013–2030, https://doi.org/10.1175/JAS-D-21-0271.1

Zhang, F., Y. Q. Sun, L. Magnusson, R. Buizza, S. Lin, J. Chen, and K. Emanuel, 2019: What Is the Predictability Limit of Midlatitude Weather? J. Atmos. Sci., 76, 1077–1091, https://doi.org/10.1175/JAS-D-18-0269.1.