

Project title: Improving Subseasonal Forecasts through Data-Driven Nudging of ICON XPP in the Tropics

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Abstract of the project

Reliable subseasonal weather forecasts with lead times from two weeks to two months over Europe are of growing importance for sectors such as energy, public health, and disaster management (Robertson and Vitart, 2019). However, even state-of-the-art numerical weather prediction (NWP) models exhibit a marked decline in forecast skill beyond two weeks of lead time.

This loss in predictability on subseasonal timescales arises from several challenges, summarized by Robertson and Vitart (2019). Within the first days of prediction, atmospheric forecasts are strongly influenced by the initial conditions. However, due to the chaotic nature of the atmosphere and imperfect models, the influence of these initial conditions diminishes rapidly after the first few days. On the other hand, slowly evolving boundary conditions - such as oceanic processes - dominate on seasonal to interannual timescales, but exert only limited influence on the subseasonal range. On this challenging timescale, forecast accuracy can be enhanced through slowly evolving modes of the atmosphere, providing guidance in the forecast as the influence of initial conditions declines (Vitart and Robertson, 2019). Equatorial waves represent such atmospheric modes that evolve on subseasonal timescales. They are large-scale, coherent anomalies in wind and pressure that propagate zonally within the tropics (Matsuno, 1966). As eigenmodes of the tropical atmosphere, these waves operate on timescales from several days to a few weeks, making them promising candidates for enhancing subseasonal predictability (Straub and Kiladis, 2003).

In subseasonal forecasting, slowly evolving components of the Earth system, such as the ocean, play a crucial role (Woolnough et al., 2007). To capture these interactions, Earth system models that couple the atmosphere, ocean, and land components are employed on this timescale. One such model is the newly developed ICON eXtended Predictions and Projections (XPP) model (Müller et al., 2025). The key innovation of ICON XPP lies in its integration of numerical weather prediction (NWP) and climate model components within a single framework, thereby eliminating the need for two separate systems. This unified approach is particularly beneficial for subseasonal predictions, which bridge the gap between the timescales traditionally covered by NWP and climate models. First insights into the model performance show that ICON XPP is competitive with other climate models. However, Müller et al. (2025) demonstrated that ICON XPP has difficulties in representing the mean daily precipitation in the tropics, especially in the region of the intertropical convergence zone (ITCZ). The precipitation in the ITCZ and its variability are impacted by convectively coupled equatorial waves Dias and Pauluis (2009). ICON XPP shows good results for modelling, for example, Kelvin waves and Equatorial Rossby waves in the higher resolution setup with a horizontal resolution of 80 km in the atmosphere and 20 km in the ocean (Müller et al., 2025). In general, the spectral power in the wave-number frequency spectrum for the tropics of ICON XPP is smaller compared to ERA5, indicating a lower wave amplitude. Dias et al. (2018) showed for numerical weather models that the coupling between the moist convective processes and the large-scale flow is a major issue in tropical forecasting. However, even leading numerical models like the Integrated Forecasting System (IFS) from ECMWF exhibit substantial

deficiencies in the representation of convectively coupled equatorial waves amplitudes (Dias et al., 2023).

Recent research developments provide an opportunity to address these challenges and offer the potential to improve subseasonal to seasonal predictions in both the tropics and extra-tropics. First, machine learning-based weather prediction (MLWP) models provide skillful medium-range predictions at computational costs that are several orders of magnitude lower than those of NWP models. A recent study on equatorial wave modeling highlights the superior performance of MLWP models – particularly the AIFS model – over the IFS model, a leading NWP system. In a comparison of the IFS forecast with MLWP models, the ML approaches demonstrate improved skill in forecasting equatorial waves. In particular, they provide more accurate amplitudes and more consistent wave patterns at lead times beyond four days for Kelvin, Equatorial Rossby, and westward-moving mixed Rossby–Gravity waves (Haupt et al. (2025), publication in preparation). In addition, Zahid Husain et al. (2024) demonstrated that the skill of the Canadian operational NWP model increases when it is spectrally nudged toward the MLWP model GraphCast. Spectral nudging can be understood as an online correction of the NWP model: after solving the physical equations in the dynamical core, the model’s large-scale output is corrected with the output of a MLWP model before being passed through the NWP parametrizations. This innovative combination of NWP and ML strengths has shown promising improvements in forecasting skill (Zahid Husain et al., 2024).

In this project, we aim to implement a state-of-the-art nudging method of the ICON XPP model towards forecasts of an MLWP model for the tropical belt only. The purpose is manifold. (1) The conduction of reference experiments and the objective wave identification, building on Yang et al. (2003), will allow us to verify tropical waves in ICON XPP systematically and to document systematic errors. (2) In regions of the largest tropical forecast errors, we will nudge the ICON model towards an MLWP model. This will provide one way of assessing the benefit of the nudging technique for a coupled system and highlight possible avenues for an operational implementation. (3) The benefit of nudging will be specifically investigated for tropical-extratropical teleconnections, as these still pose a major challenge for NWP models. By contrasting runs with and without nudging, composite studies centered on the tropical waves will enhance our dynamical understanding of error pathways from the tropics towards the midlatitudes.

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