Project: 1537

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

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Project overview and scientific motivation

Reliable subseasonal forecasts are important for sectors such as energy, public health, and disaster management. However, achieving skillful forecasts on these timescales remains challenging for numerical weather prediction (NWP) models. Equatorial waves are an important source of predictability beyond the medium range, but their representation in NWP models remains challenging. Recent advances in machine learning-based weather prediction (MLWP) models have demonstrated improved skill in representing large-scale atmospheric dynamics, including equatorial waves (Haupt et al., 2026a). Building on these developments, recent studies by Husain et al. (2025) and Polichtchouk et al. (2026) have demonstrated the potential to improve NWP forecasts by nudging them towards MLWP predictions.

This project aims to improve tropical variability and global subseasonal forecast skill in the ICON eXtended Predictions and Projections (XPP) model through data-driven nudging. Its three objectives are to: (1) develop an evaluation framework for equatorial waves and assess their representation in ICON XPP; (2) implement and evaluate data-driven nudging experiments in the tropics; and (3) investigate the effects of nudging on tropical–extratropical teleconnections and subseasonal forecast skill.

Progress during the first project period

During the reporting period, the focus was on establishing the methodological and scientific foundations for implementing data-driven nudging in ICON XPP. Consequently, the allocated CPU node hours have not yet been used for the planned ICON XPP experiments. Substantial progress has nevertheless been made in developing an equatorial wave evaluation framework, identifying suitable data-driven models, and investigating existing nudging approaches. This work provides an important basis for the planned experiments.

Development of the equatorial wave evaluation framework

An objective framework was developed to evaluate equatorial waves in forecast data. It identifies individual wave modes using the filter of Yang et al. (2003) and enables their systematic assessment in medium-range forecasts of up to ten days. The framework evaluates wave structures and pattern correlations and quantifies biases in wave amplitudes and phase speeds, allowing a comprehensive comparison of different forecasting systems.

The framework was applied to several state-of-the-art data-driven and hybrid weather prediction models. The results show that the ECMWF Artificial Intelligence Forecasting System (AIFS) and the hybrid model NeuralGCM represent equatorial waves particularly well. Both capture key wave characteristics more accurately than the numerical Integrated Forecasting System (IFS), making them promising candidates for the nudging approach pursued in this project. These results were presented at the European Geosciences Union (EGU) General Assembly (Haupt et al., 2026a); a scientific publication is in preparation. The framework provides the methodological basis for evaluating the impact of nudging on equatorial waves in ICON XPP.

Investigation of existing data-driven nudging experiments at ECMWF

To investigate the potential and limitations of data-driven nudging, existing experiments at ECMWF were examined. These use global spectral nudging, whereby the numerical IFS is nudged towards predictions from the data-driven AIFS model. The deterministic hybrid forecasting system was implemented and evaluated by Polichtchouk et al. (2026).

The evaluation framework developed in this project was applied to assess the impact of spectral nudging on equatorial waves, particularly atmospheric Kelvin waves. The results show that nudging towards AIFS improves wave

patterns in IFS forecasts. However, this improvement is not accompanied by a corresponding reduction in amplitude biases: although the spatial structures become more realistic, substantial amplitude errors remain.

These findings were presented at the S2S2D (Haupt et al., 2026b) and YSSAR conferences. Ongoing work focuses on analysing the hybrid forecasts in more detail to understand the remaining amplitude biases. The aim is to identify the opportunities and limitations of the spectral nudging approach used at ECMWF and derive insights for its implementation in ICON XPP.

Investigation of non-spectral data-driven nudging in collaboration with NOAA PSL

The spectral nudging approach used at ECMWF cannot be directly transferred to ICON XPP. Unlike IFS and AIFS, ICON XPP is not a spectral model, and implementing spectral nudging would require substantial computational effort. It is therefore important to investigate how data-driven nudging can be implemented in a non-spectral model and how it affects forecast evolution.

To address this, a research collaboration was initiated with the Physical Sciences Laboratory (PSL) at NOAA in Boulder, USA. Within this collaboration, data-driven nudging is being implemented in the Subseasonal Forecast System (SFS), a coupled model designed for subseasonal predictions. The experiments will assess the effects of nudging on forecast evolution and subseasonal forecasts in a non-spectral configuration. This work provides practical experience with implementing and evaluating non-spectral nudging, while helping to identify modelling challenges and understand its benefits and limitations. The results will inform the development of a suitable approach for ICON XPP.

Next steps and planned use of computational resources

The first project period established the methodological basis for evaluating equatorial waves in medium-range and subseasonal forecasts and provided insights into data-driven nudging in spectral and non-spectral model frameworks. The evaluation framework can now systematically assess changes in wave patterns, amplitude biases, and phase speeds.

The next step is to begin the planned data-driven nudging experiments in ICON XPP. These will address the second project objective by assessing the impact of nudging towards data-driven forecasts on tropical variability in the coupled ICON framework. The resulting forecasts will then be evaluated using the wave analysis framework, and effects on tropical–extratropical teleconnections will be investigated. Extending the project period is essential to carry out these experiments, make use of the allocated computational resources, and achieve the project's scientific objectives.

References:

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