Diagnostics of Tropical Variability for Numerical Weather Forecasts

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Introduction

Tropical precipitation and circulation are often coupled and span a vast spectrum of scales from a few to several thousands of kilometers and from hours to weeks. Current operational numerical weather prediction (NWP) models struggle with representing the full range of scales of tropical phenomena. Synoptic to planetary scales are of particular importance because improved skill in the representation of larger scale features such as convectively coupled equatorial waves (CCEWs) have the potential of reducing forecast error propagation from the tropics to the midlatitudes.

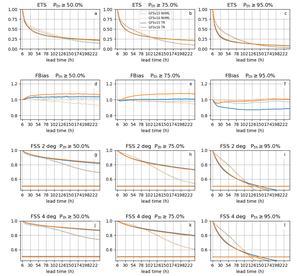

Figure 1. Precipitation skill scores for tropics (20S-20N) and Northern Hemisphere midlatitudes (35N-50N). Shown are equitable threat score (a-c), frequency bias (d-f), fraction skill score.

Here we introduce and apply diagnostics from a recently developed tropical variability diagnostics toolbox, where we focus on a comparison between two recent versions of NOAA's Unified Forecast System (UFS): operational GFSv15 forecasts and parallel real-time GFSv16 forecasts from April through October 2020.

The diagnostics include space-time coherence spectra to identify preferred scales of coupling between circulation and precipitation, pattern correlation of Hovmöller diagrams to assess model skill in zonal propagation of precipitating features, CCEW skill assessment, plus a metric aimed at evaluating moisture - convection coupling in the tropics.

Precipitation hovmöller diagrams and pattern correlation

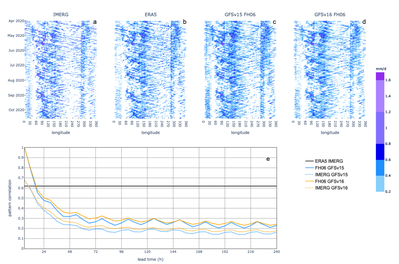

Figure 2. Hovmöller diagrams of precipitation averaged from 10S - 10N.

Bottom panel (e) shows pattern correlation of latitude averages (10S-10N) between ERA5 and IMERG (black curve), GFSv15 and GFSv15 FH06, GFSv15 and IMERG, GFSv16 and GFSv16 FH06 and GFSv16 and IMERG. 95% confidence intervals are shown in shading.

GFSv16 has higher pattern correlation with both IMERG and FH06 precipitation than GFSv15 and the differences are small, but statistically significant.

Main points

Results show that the GFSv16 forecasts **do not** have more realistic coupling between precipitation and column moisture, but are slightly **more realistic** in their coherence between precipitation and model dynamics at synoptic to planetary scales scales.

This improved performance does not necessarily translate to a significant improvement in traditional precipitation skill scores.

This contrast highlights the utility of these physically based diagnostics in the pursuit of better understanding of NWP model performance in the tropics, while also demonstrating the challenges in translating model advancements into improved skill.

Convectively coupled equatorial waves

ERA5 skill for the MJO and MRG waves is about 0.8 for this time period, and about 0.7 for Kelvin and ER waves. GFSv16 has slightly higher skill correlation values for the first 48h into the forecast for the MJO. Performance of GFSv16 is comparable to GFSv15 for ER, MRG and MJO in this diagnostic. Skill for ER for GFSv16 is comparable to IMERG-ERA5 correlation until 12h lead time. MJO skill correlations are higher initially than for the Hovmöller pattern correlations (Fig. 2). This is conceivably due to the EOFs picking up larger zonal scales of variability which the models can forecast more robustly than the smaller scales.

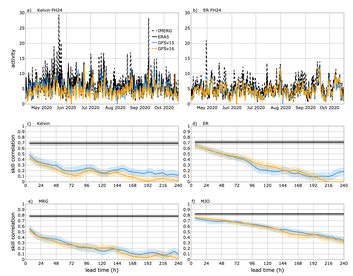

Figure 3. Precipitation based Kelvin and ER wave activity for 202004-202010. CCEW skill is shown for Kelvin, ER, MRG and MJO.

Space-time coherence spectra

Coherence-squared wave number-frequency spectra between two variables highlight temporal and spatial scales where the two variables have significant correlation.

Initially larger coherence values indicate that model precipitation in both GFSv15 and GFSv16 in the first 12 - 24h past initialization is largely able to initialize and maintain large scale CCEW events. Compared to observations the models have peaks at slightly higher frequencies, indicating faster moving waves.

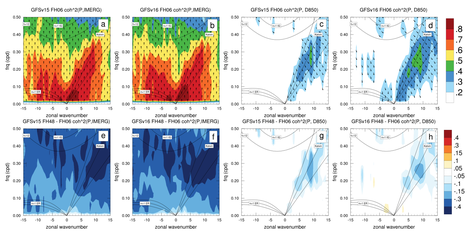

Figure 4. Coherence-squared wave number-frequency spectra between observed precipitation and a) GFSv15 precipitation, b) GFSv16 precipitation at FH06, between model 850hPa divergence and precipitation for c) GFSv15 and d) GFSv16.

The coherent evolution of observed and modeled precipitation decreases rapidly with lead time. This is likely related to the model propagating convectively coupled phenomena at the wrong speed along with the model not being able to maintain those phenomena for long lead times.

Convective adjustment time scale and precipitation pick-up

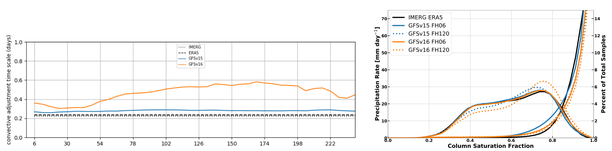

Figure 5. Convective adjustment time scale computed by regressing PW anomalies onto normalized precipitation anomalies (left). Column saturation fraction (CSF) distribution and CSF conditionally averaged precipitation rates (right).

Moisture convection coupling

Modeling and observational studies indicate that the progressive deepening of convective heating, and the associated transition to increasingly top-heavy large-scale circulations, plays a crucial role in driving the coupled evolution of column moisture and convection.

After some initial adjustment, GFSv15 and GFSv16 exhibit erroneous counter-clockwise co-evolution of column saturation fraction (CSF) and precipitation, with convection often resulting in an excessive drying of the column.

Having realistic moisture-convection coupling is central to coupling the convection-circulation correctly. The reverse is likely also true, without realistic convection-circulation coupling, how can the model get realistic moisture-convection coupling? This connection is illustrated here by the improvement of the GFSv16 over GFSv15 in the dynamics-convection coupling represented by the coherence spectra in Fig. 4, but no improvement in the moisture-convection coupling.

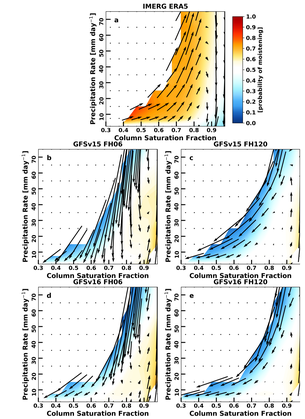

Figure 6. Coevolution of binned precipitation and column saturation fraction for a) IMERG - ERA5, b) GFSv15 FH06, c) GFSv15 FH120 and d) GFSv16 FH06 and e) GFSv16 FH120. Vectors represent the bin-mean temporal difference of precipitation and CSF, and color shading indicates the fraction of observations having a positive CSF difference within each bin.

Conclusions

These diagnostics highlight, that while GFSv16 shows improvement over GFSv15 in some precipitation scores and in convection-circulation coupling, the moisture convection coupling is not improved.

- **Precipitation scores**
  - ETS is very slightly improved in GFSv16.
  - Frequency bias is improved in GFSv16 for very high rain thresholds, but not for the 50th and 75th percentiles.
  - Fraction skill score is slightly improved for short lead times and deteriorates (very slightly) for later lead times.
- **Hovmöller and space-time spectra** These show clear improvement in GFSv16. The coherence spectra indicate clear improvement in convection-circulation coupling in GFSv16.
- **Convective adjustment time scale** precipitation becomes less sensitive to atmospheric moisture with lead time in GFSv16. This can also be seen in the CSF conditionally averaged precipitation rates for GFSv16 at FH120 and the larger shift in the CSF distribution for GFSv16.

The connection between moisture-convection coupling and convection-circulation coupling is puzzling; we see improvement in convection-circulation coupling, but not moisture-convection coupling.

References

[1] Maria Gehne, Brandon Wolding, Juliana Dias, and George N. Kiladis. Diagnostics of tropical variability for numerical weather forecasts. *Weather and Forecasting*, under Review, 2022.

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