A Diagnostic Toolbox for Evaluating Stratosphere-Troposphere Coupling Processes in NOAA's UFS

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Unifying Innovations in Forecasting Capabilities Workshop (July 2022)
### “Big Picture” Motivation

**Why evaluate the stratosphere?**

<table>
<thead>
<tr>
<th>stratospheric precursor</th>
<th>tropospheric extreme event</th>
<th>impact</th>
<th>affected region</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northern Hemisphere</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>sudden stratospheric warming</td>
<td>(marine) cold air outbreak</td>
<td>infrastructure damage, health impacts</td>
<td>Arctic, northern Europe, North Atlantic</td>
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<td></td>
<td>increased storminess</td>
<td>flooding, wind damage</td>
<td>southern Europe</td>
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<tr>
<td></td>
<td>regional sea ice changes</td>
<td>shipping impacts, resource extraction</td>
<td>Arctic</td>
</tr>
<tr>
<td>strong vortex event</td>
<td>storm series</td>
<td>flooding, wind damage</td>
<td>northern Europe, North Atlantic</td>
</tr>
<tr>
<td></td>
<td>drought</td>
<td>agricultural damage</td>
<td>southern Europe</td>
</tr>
<tr>
<td>wave reflection</td>
<td>cold air outbreak</td>
<td>health impacts</td>
<td>North America</td>
</tr>
<tr>
<td>Quasi-Biennial Oscillation</td>
<td>changes in the Madden-Julian Oscillation</td>
<td>precipitation extremes</td>
<td>tropics, subtropics</td>
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<tr>
<td></td>
<td>atmospheric rivers</td>
<td>flooding</td>
<td>western North America</td>
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<tr>
<td></td>
<td>changes in the monsoon</td>
<td>drought / flooding, agricultural impacts</td>
<td>India, Southeast Asia</td>
</tr>
<tr>
<td>early vortex weakening</td>
<td>heat, drought</td>
<td>wildfires, agricultural losses</td>
<td>Australia, Antarctica</td>
</tr>
<tr>
<td>Southern Hemisphere</td>
<td>cold spell</td>
<td>health impacts</td>
<td>southeastern Africa, South America</td>
</tr>
<tr>
<td>ozone anomalies</td>
<td>poleward shift of storm track</td>
<td>sea ice changes</td>
<td>Southern Ocean</td>
</tr>
<tr>
<td></td>
<td>increased UV radiation</td>
<td>health impacts</td>
<td>Australia</td>
</tr>
<tr>
<td></td>
<td>hot spells</td>
<td>health impacts</td>
<td>southern Africa, Australia, South America</td>
</tr>
</tbody>
</table>

*Domeisen and Butler, “Stratospheric drivers of extreme events at the Earth’s surface” Nature Communications Earth & Environment, 2020*
UFS-Specific Motivation

Why evaluate the stratosphere?

Schematic from Butler et al., 2019, “Sub-seasonal Predictability and the Stratosphere”
Recent and potential future changes to UFS can impact the representation of stratosphere-troposphere coupling processes:

- Changes to model lid height and vertical resolution
- Changes to horizontal resolution
- Updated gravity wave physics
- Coupled/interactive chemistry processes

Radiative and dynamical controls on the stratospheric circulation are well understood, so investigating the stratosphere can help to better understand and tune updates to the UFS.
We have developed a diagnostic toolbox that can be used to assess relevant stratospheric and stratosphere-troposphere coupling processes.

These diagnostics have been applied to GEFSv12 and recent UFS prototype (p5-p7) hindcasts.
GEFSv12: S2S Skill Associated with the Stratosphere

Boreal Winter NAO Correlation Skill: Dependence on Polar Vortex ICs

GEFSv12 shows enhanced NAO correlation skill for forecasts initialized during strong/weak stratospheric polar vortex states.

While these differences between composites are generally not statistically significant, they have been shown to be for other prediction systems with increased number of hindcasts/ensembles.
GEFSv12 shows enhanced weeks 3-4 MJO correlation skill for easterly QBO inits compared to westerly QBO.
These differences in skill can be quite large for hindcasts initialized in specific months.
GEFSv12: Stratosphere-Troposphere Coupling

Upward Strat-Trop Coupling

GEFSv12 exhibits realistic "upward" strat-trop coupling: Anomalous planetary wave forcing earlier in the forecasts are associated with anomalous strength in the vortex later in the forecasts.

The relationship measured with GEFSv12 matches closely to that obtained from reanalysis.

Corr  (99% CI)
r(GEFS) = 0.722
r(GEFS-R) = 0.735 (0.667, 0.789)
r(ERA5) = 0.773 (0.737, 0.805)
GEFSv12 exhibits realistic "downward" strat-trop coupling: Anomalous lower strat polar vortex earlier in the forecasts is associated with anomalous surface Northern Annular Mode later in the forecasts.

The relationship measured with GEFSv12 matches closely to that obtained from reanalysis.

\[
\begin{align*}
\text{Corr} & \quad (99\% \ CI) \\
r(\text{GEFS}) &= 0.458 \\
r(\text{GEFS-R}) &= 0.509 (0.403, 0.605) \\
r(\text{ERA5}) &= 0.560 (0.494, 0.618)
\end{align*}
\]
UFS Prototypes: Relevant Changes from p5-p7

- UFSp5 → p6
  - Increase in model lid height from ~55km to ~80km
  - Increase in model vertical resolution from L64 to L127
  - Addition of parameterization for subgrid scale nonstationary gravity wave drag

- UFSp6 → p7
  - Initial conditions: CFSR → GEFSv12 Reanalysis
  - Update of gravity wave physics package “uGWD” from v0 to v1

UFS prototype runs include only deterministic forecasts initialized twice per month from Apr 2011- Mar 2018
- p5 to p6: *Reduced biases* in tropical stratospheric winds from 100-1 hPa; *slightly reduced* biases in polar vortex winds and polar cap temperatures from 10-1 hPa

- p6 to p7: *Reduced biases* in tropical stratospheric winds from 100-10 hPa; *increased* biases in tropical winds in upper stratosphere; *dramatically enhanced* weak vortex/warm polar cap bias
Using 10 and 40 m/s as arbitrary thresholds to measure strong/weak vortex states we see:

- By week 3 and beyond, UFSp7 has over double the number of days with a weak polar vortex, and roughly half the days with a strong vortex.
- In contrast, p5 and p6 have relatively stable counts across lead times similar to reanalysis.
QBO progresses too quickly in all three prototypes, though p7 shows improvement over p5 and p6 for levels between 100 - 10 hPa.
Sampling variability for estimating the downward coupling relationship in 2011-2018 is *large* (especially with only 2 inits per month, and deterministic runs)

All UFS prototypes fall within this large sampling variability; cannot draw more robust conclusions
Conclusions & Next Steps

What have we accomplished?

- Development of diagnostic toolbox, and application to GEFSv12 + UFS prototypes
- Reports on UFS prototype results provided to model developers
- Relevant components of toolbox incorporated into METplus (thanks to Tina Kalb and Tara Jensen)

What’s next?

- Paper on GEFSv12 results to be submitted soon
- Release of GEFSv12 datasets, including zonal mean diagnostics, NAO/MJO indices, etc.
- Release of new open-source tools on github (“pyzome”)
- Transition of toolbox to CPC for future UFS stratosphere evaluations
- New realtime CPC webpage for verification/monitoring of stratospheric forecasts