A diagnostic toolbox: assessing the representation of stratosphere-troposphere coupling in the Global Ensemble Forecast System (GEFSv12)

Presenting: Dillon Elsbury, CIRES/NOAA CSL and Laura Ciasto, NOAA CPC
Team: Zachary D. Lawrence (CIRES/NOAA PSL), Amy H. Butler (NOAA CSL), Judith Perlwitz (NOAA PSL), Eric Ray (CIRES/NOAA CSL)

Funder: NWS OSTI Weeks 3-4 program

PI: E. Ray, **CO-i**: J. Perlwitz, L. Ciasto, **Collaborator**: A. Butler, T. Jensen, J. Levit, **Research Scientists**: Z. Lawrence, D. Elsbury

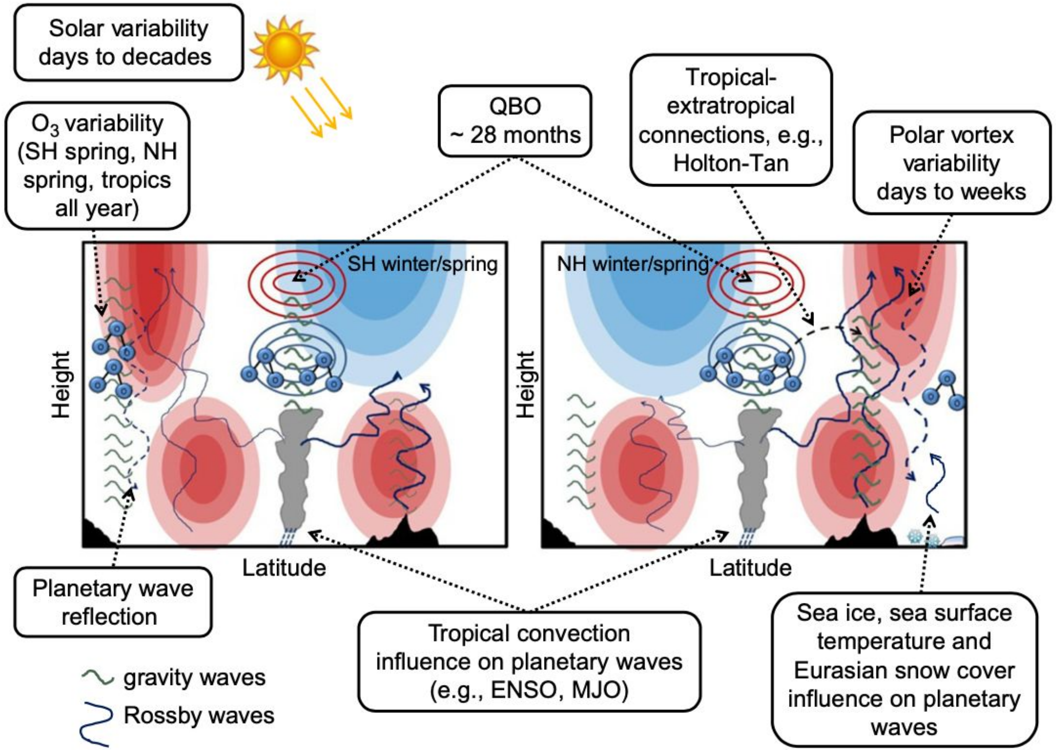
Goals for project

Develop diagnostic toolbox to assess stratospheric forecast biases and stratosphere-troposphere coupling processes, ***and incorporate into METplus***

Formulate new validation and verification metrics designed to exploit opportunistic stratospheric information ***for improving Weeks 3-4 prediction***

Apply these diagnostics and verification metrics to NOAA GEFS-FV3 reforecasts and real-time forecasts ***in collaboration with NCEP CPC***

Beneficial for forecast systems to accurately represent the stratosphere



Outline

1. Zonal mean stratospheric biases in existing in GEFSv12
2. Representation of the Quasi-Biennial Oscillation (QBO)
3. Relationship between the QBO and the Madden Julian Oscillation (MJO)
4. Sudden stratospheric warmings
5. Sensitivity of the North Atlantic Oscillation (NAO) to the polar vortex
6. Current and future status of the toolbox

Butler, A., Charlton-Perez, A., Domeisen, D. I., Garfinkel, C., Gerber, E. P., Hitchcock, P., ... & Son, S. W. (2019). Sub-seasonal predictability and the stratosphere. *Sub-seasonal to seasonal prediction*, 223-241.

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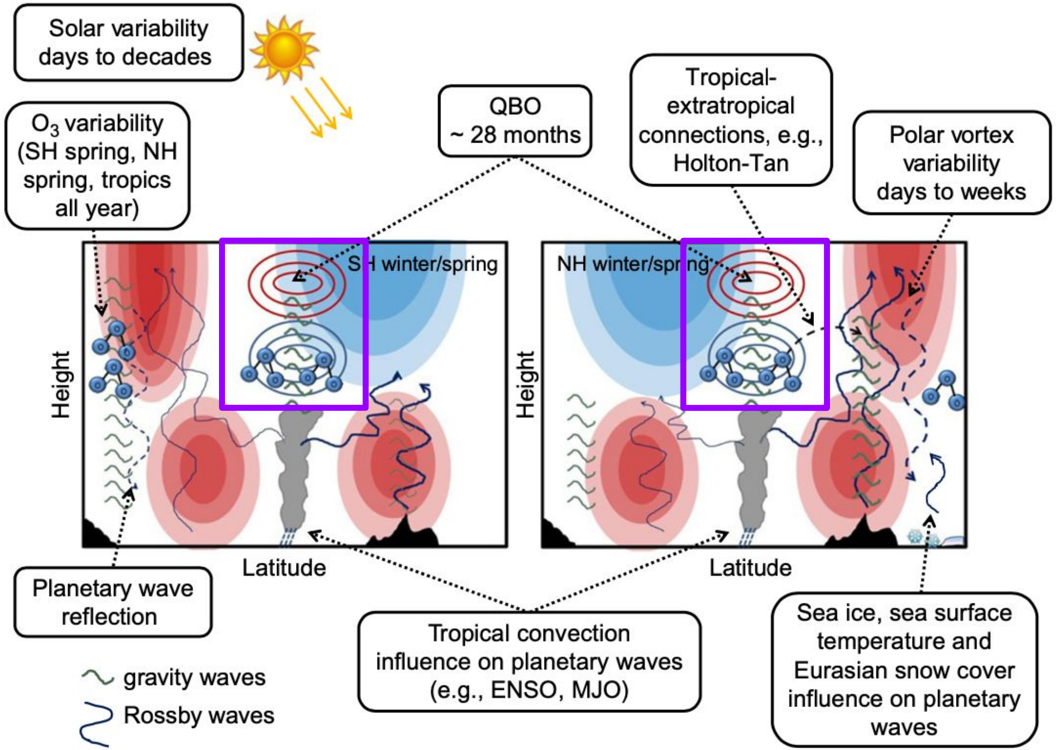

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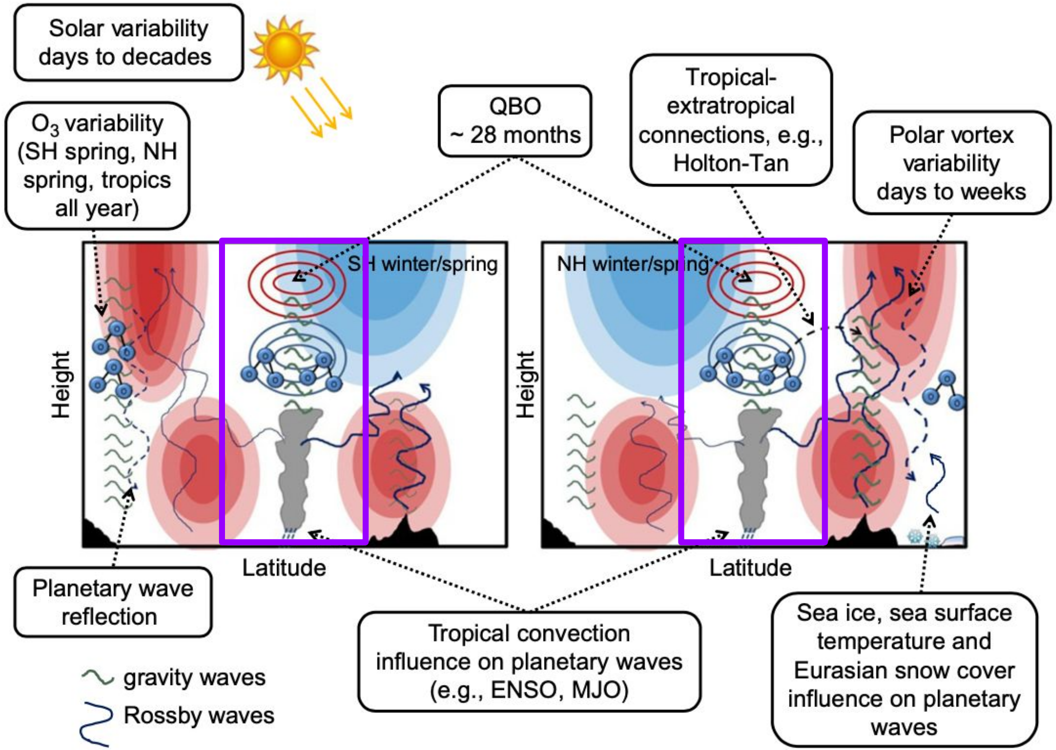

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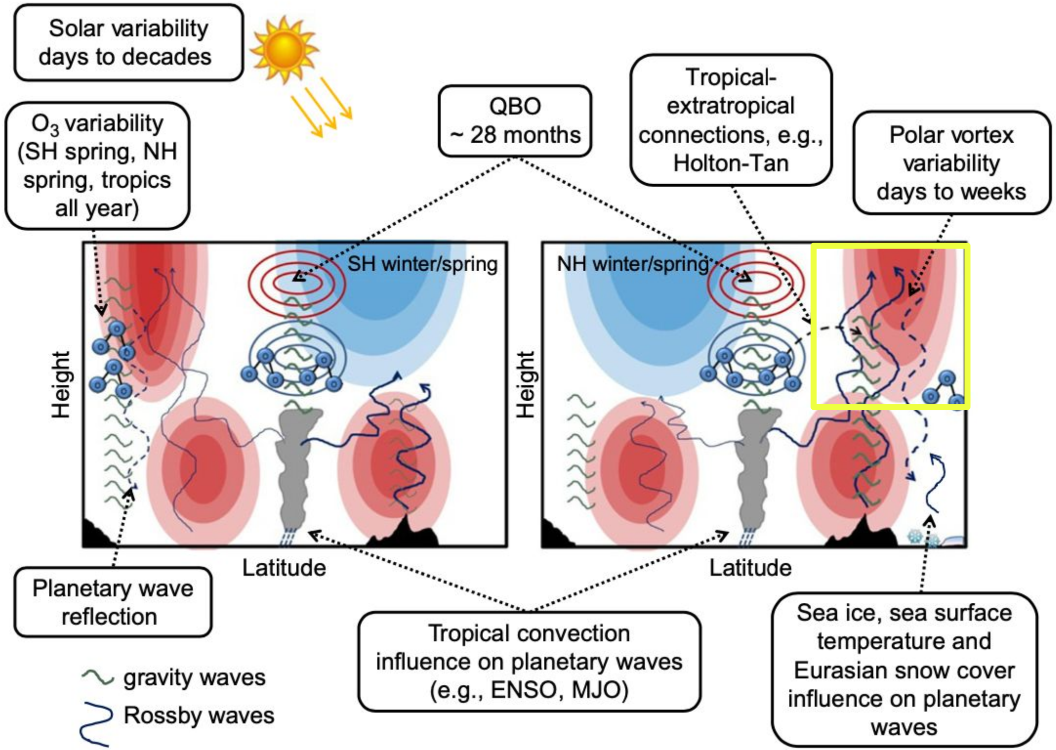

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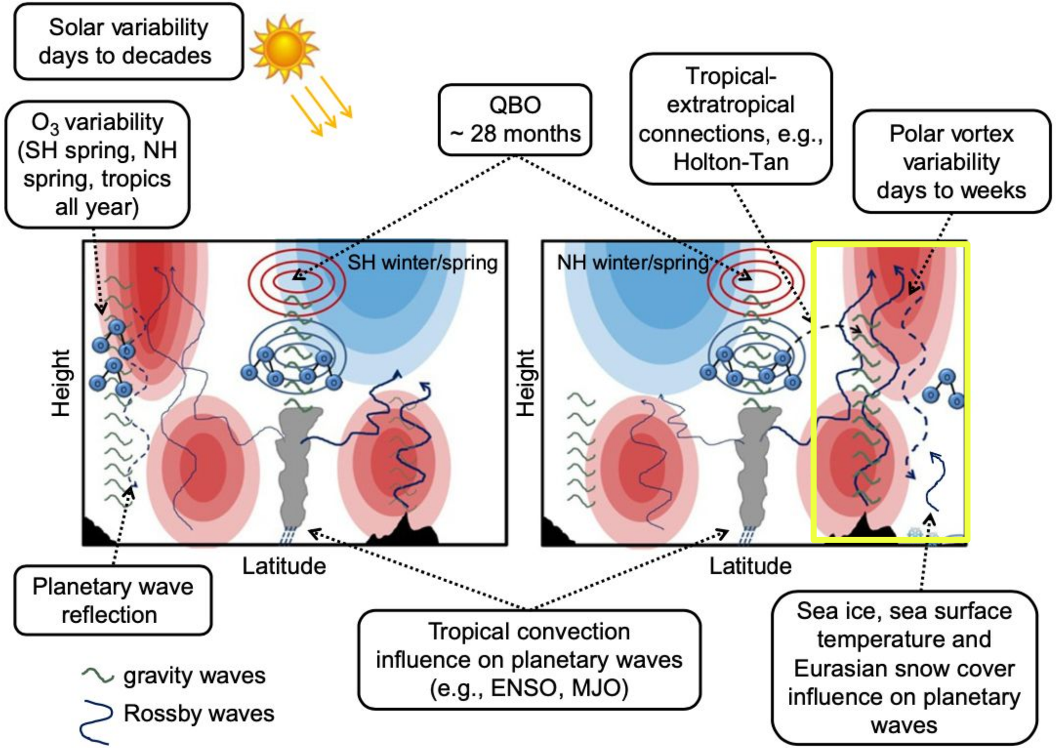

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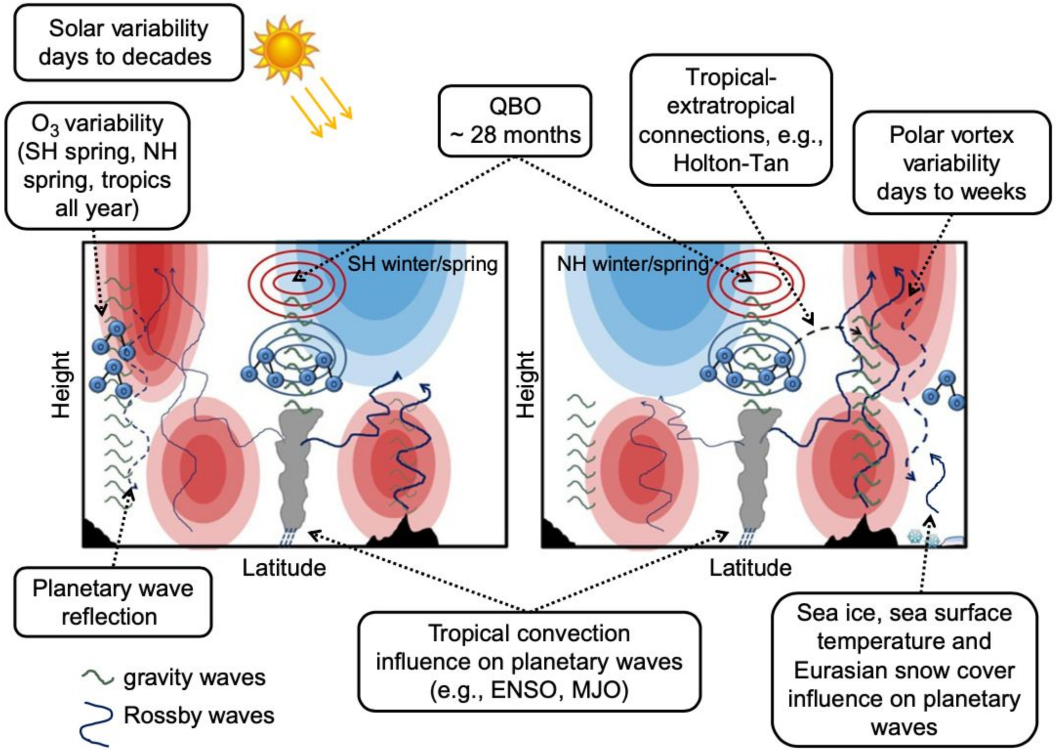

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Diagnostic toolbox

We have developed a diagnostic toolbox that can be used to assess relevant stratospheric and stratosphere-troposphere coupling processes.

Zonal mean biases/errors

QBO characteristics

Sudden stratospheric warmings / Strong vortex events

Annular modes + NAO

QBO-MJO interactions

Wave-mean flow diagnostics

Polar vortex geometry

Sinuosity & circulation variability

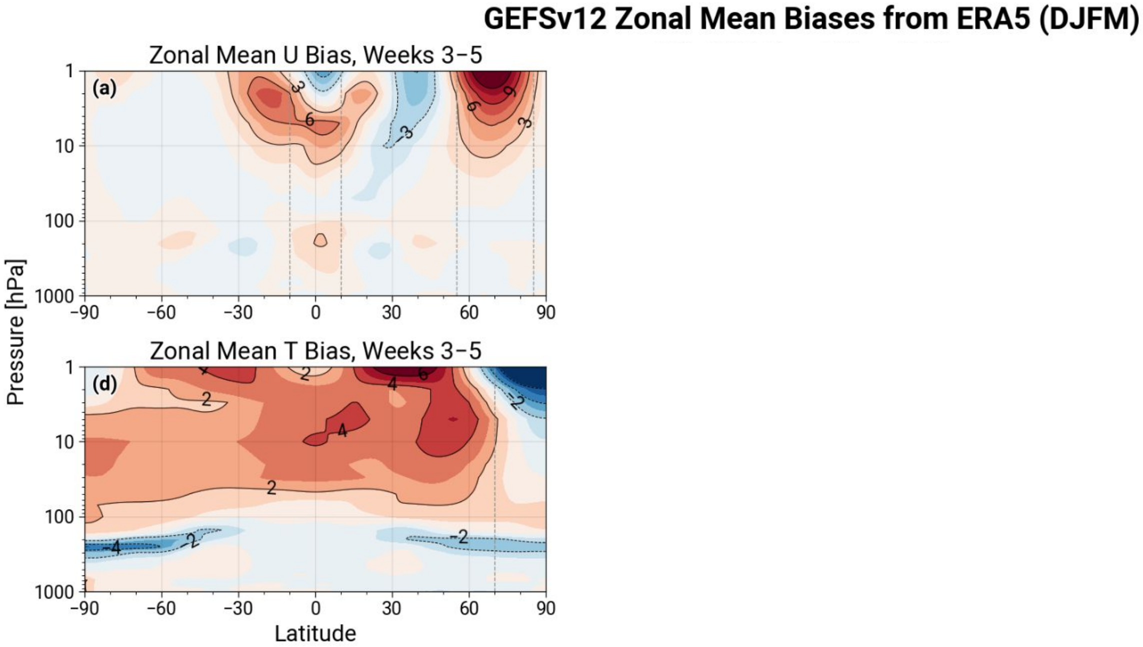
These diagnostics have been applied to GEFSv12 and recent UFS prototype (p5-p7) hindcasts.

GEFSv12: version 12 of the Global Ensemble Forecast System

- Applied diagnostics to GEFSv12 reanalysis (not shown today)
- UFS prototypes, p5-p7

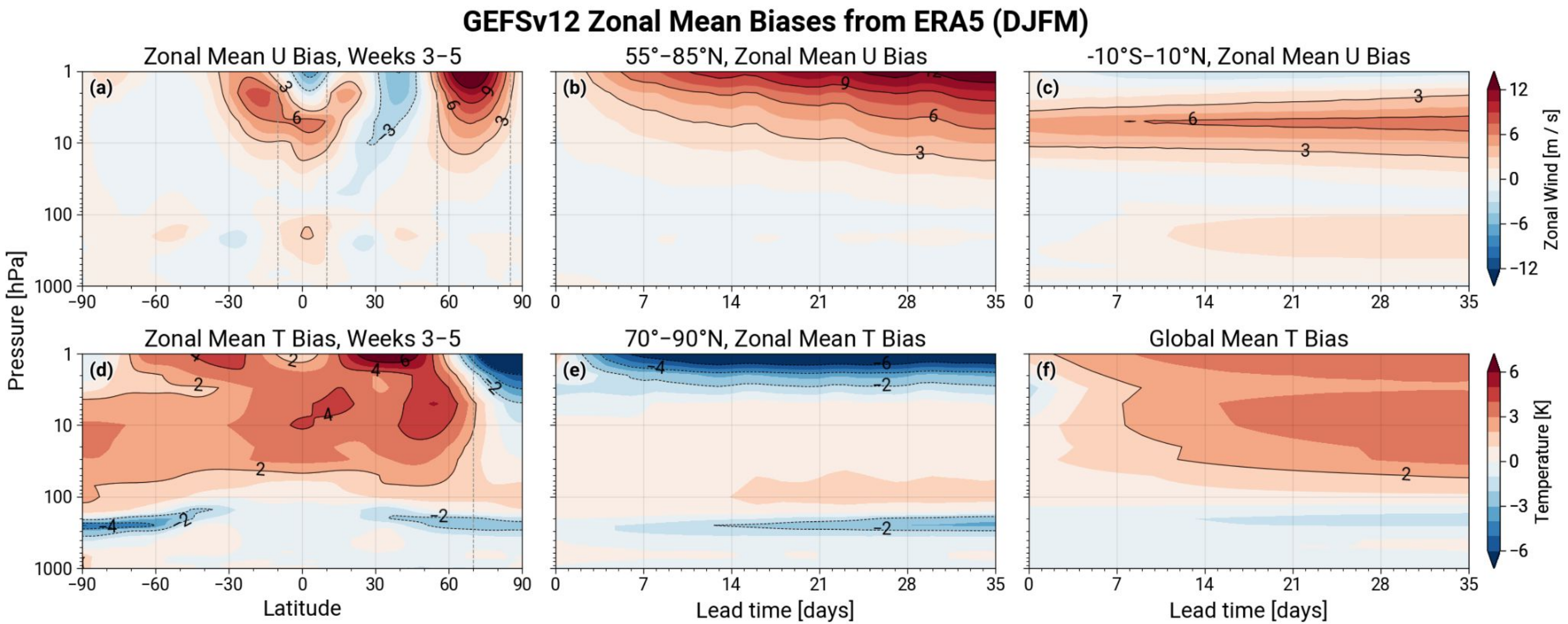
Dataset	Hindcast Details	Additional Notes	Verification
GEFSv12	Once-weekly inits from 2000-2019; 11 member ensemble out to 35 days		GEFSv12 Reanalysis
UFSp5	Inits on 1st and 15th of each month from Apr 2011 thru Mar 2018; deterministic runs out to 35 days		CFSR
UFSp6	Inits on 1st and 15th of each month from Apr 2011 thru Mar 2018; deterministic runs out to 35 days	This prototype includes the change to GFSv16 physics with increase in model lid height from ~55 km to 80 km and vertical resolution from 64 to 127 levels	CFSR

Zonal mean biases in GEFSv12 hindcasts



- Westerly polar vortex/cold temperature bias
- Global warm stratospheric bias
- Upper troposphere/lower stratosphere cool bias

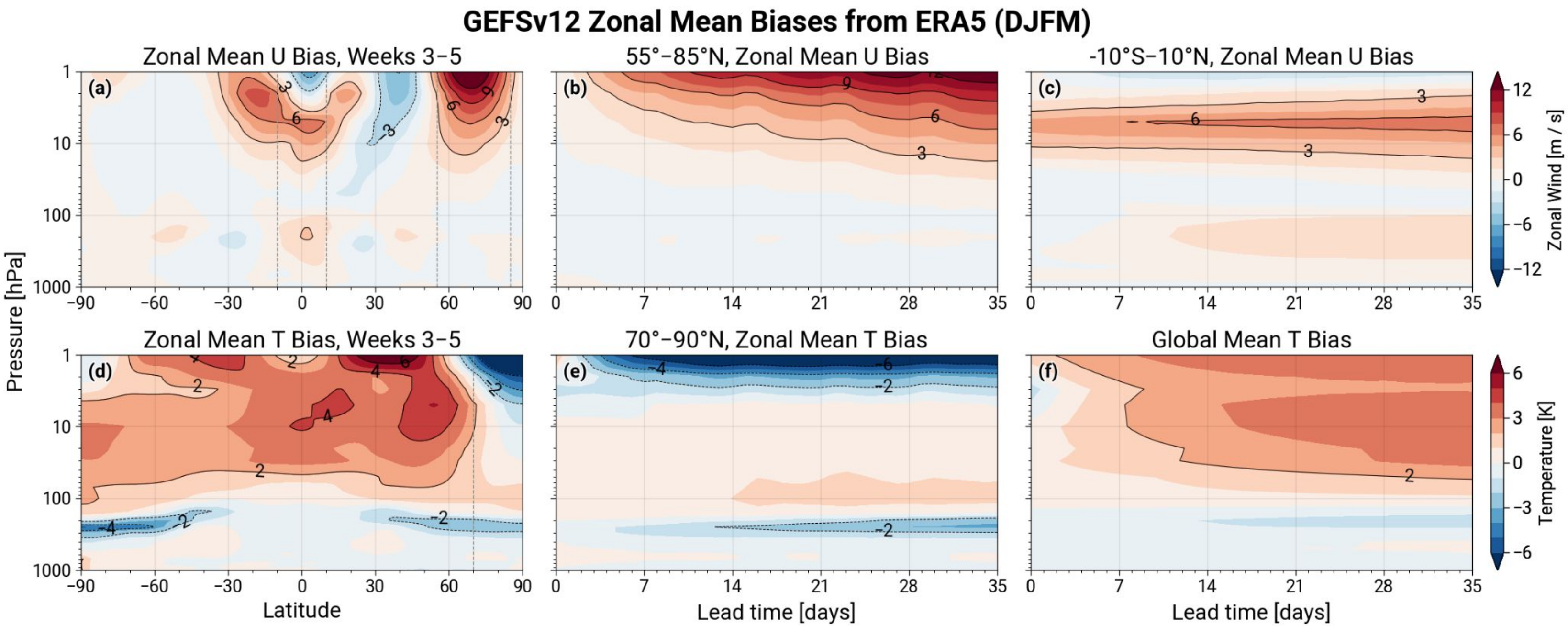
Zonal mean biases in GEFSv12 hindcasts



- Westerly polar vortex/cold temperature bias
- Global warm stratospheric bias
- Upper troposphere/lower stratosphere cool bias

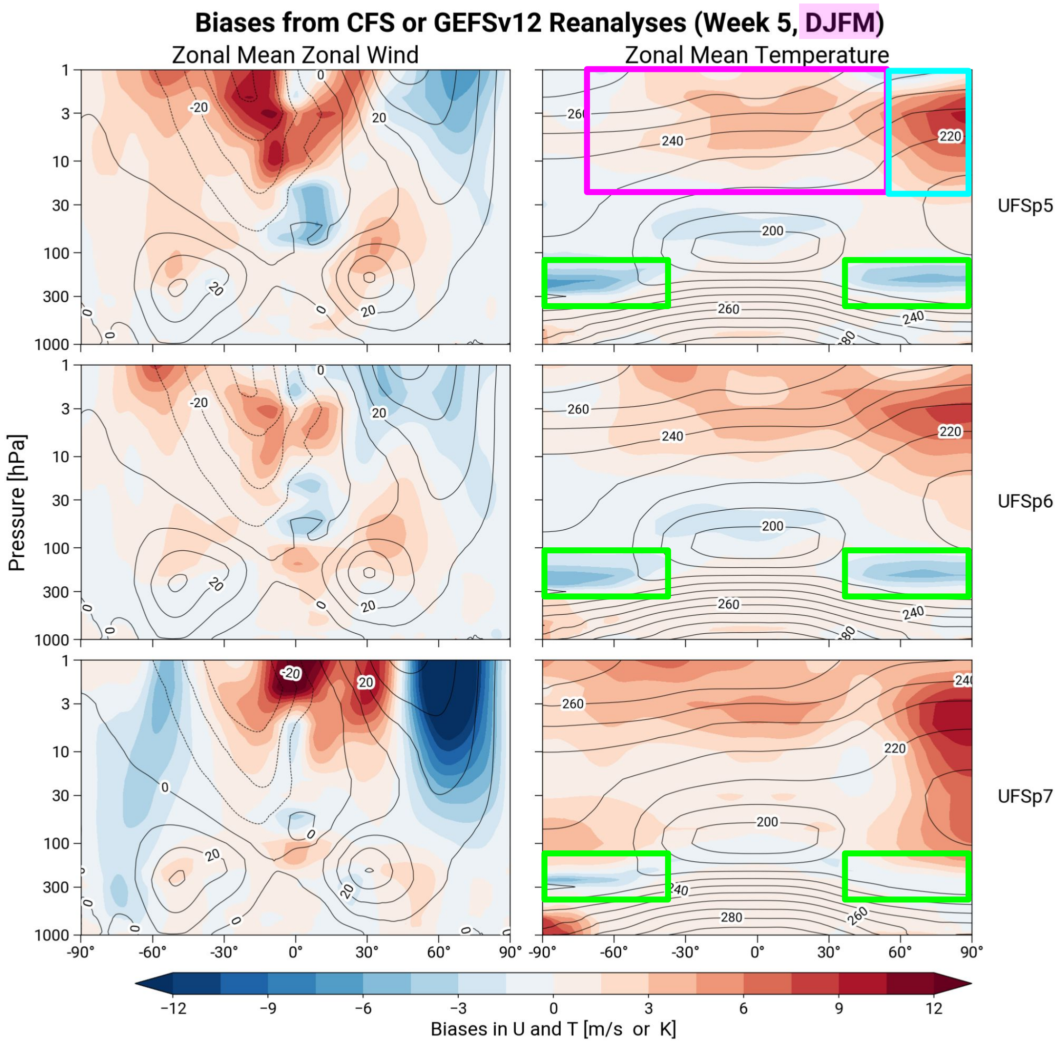
- Polar vortex biases develop rapidly and persist
- Migration of warm bias towards pole over time
- 5 hPa: bias is present in initial conditions and persists

Zonal mean biases in GEFSv12 hindcasts



Lawrence, Z. D., Abalos, M., Ayarzaguena, B., Barriopedro, D., Butler, A. H., Clavo, N., … Wu, R. W. Y (2022). Quantifying stratospheric biases and identifying their potential sources in subseasonal forecast systems. Weather and Climate Dynamics Discussions, 1-37.

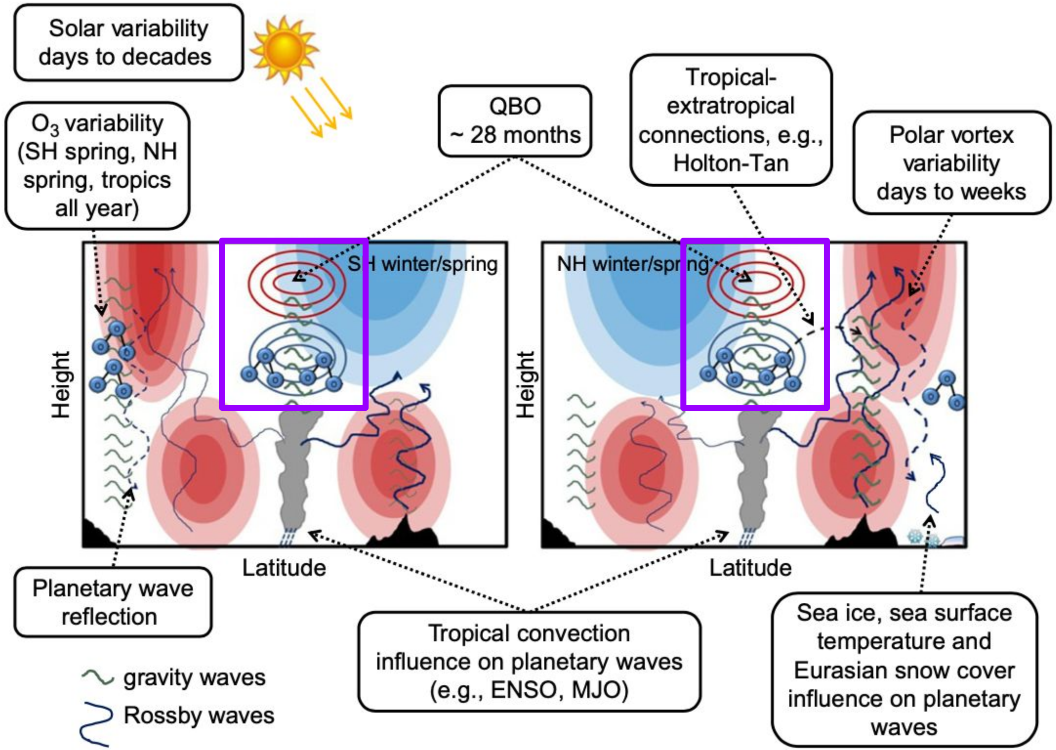
Lawrence, Z. D., Elsbury, D., Butler, A. H., Perlwitz, J., Ciasto, L., and Ray, E. Evaluation of processes related to stratosphere-troposphere coupling in GEFSv12 subseasonal hindcasts. In preparation.



- Week 5 biases for DJFM initializations
- Shaded: Zonal-mean zonal wind biases (left) and zonal mean temperature biases (right)
- Climatologies: contoured in black

- Global stratospheric warm bias
- Warm polar cap bias in p5-p7
  - Coincident with easterly polar vortex bias
- Cold bias upper troposphere - lower stratosphere
- Varying tropical middle stratospheric wind biases amongst prototypes
- DJFM account for annual mean biases

Beneficial for forecast systems to accurately represent the stratosphere



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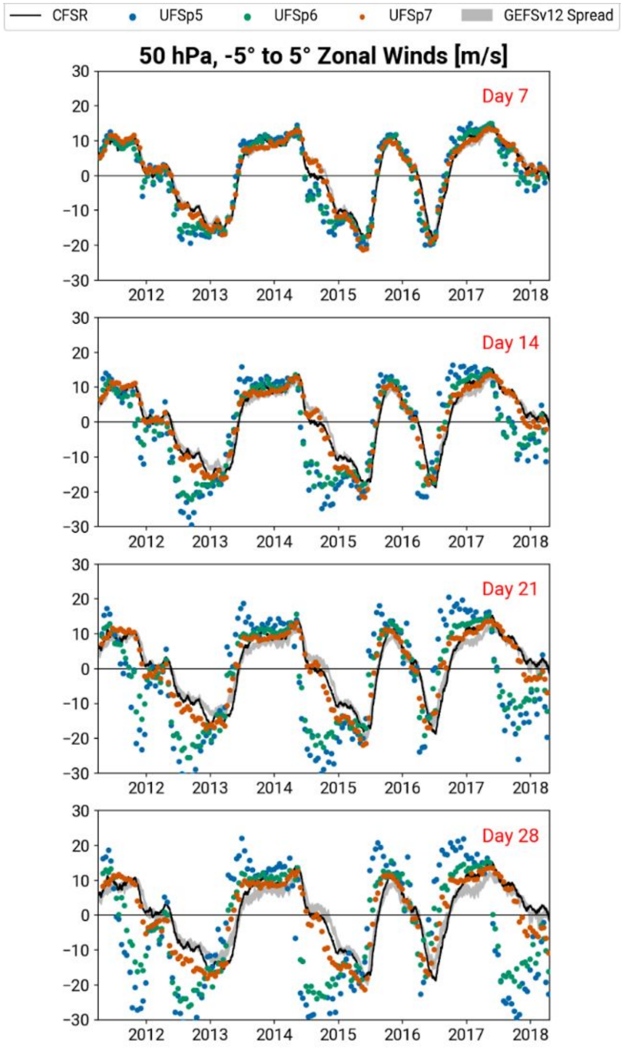
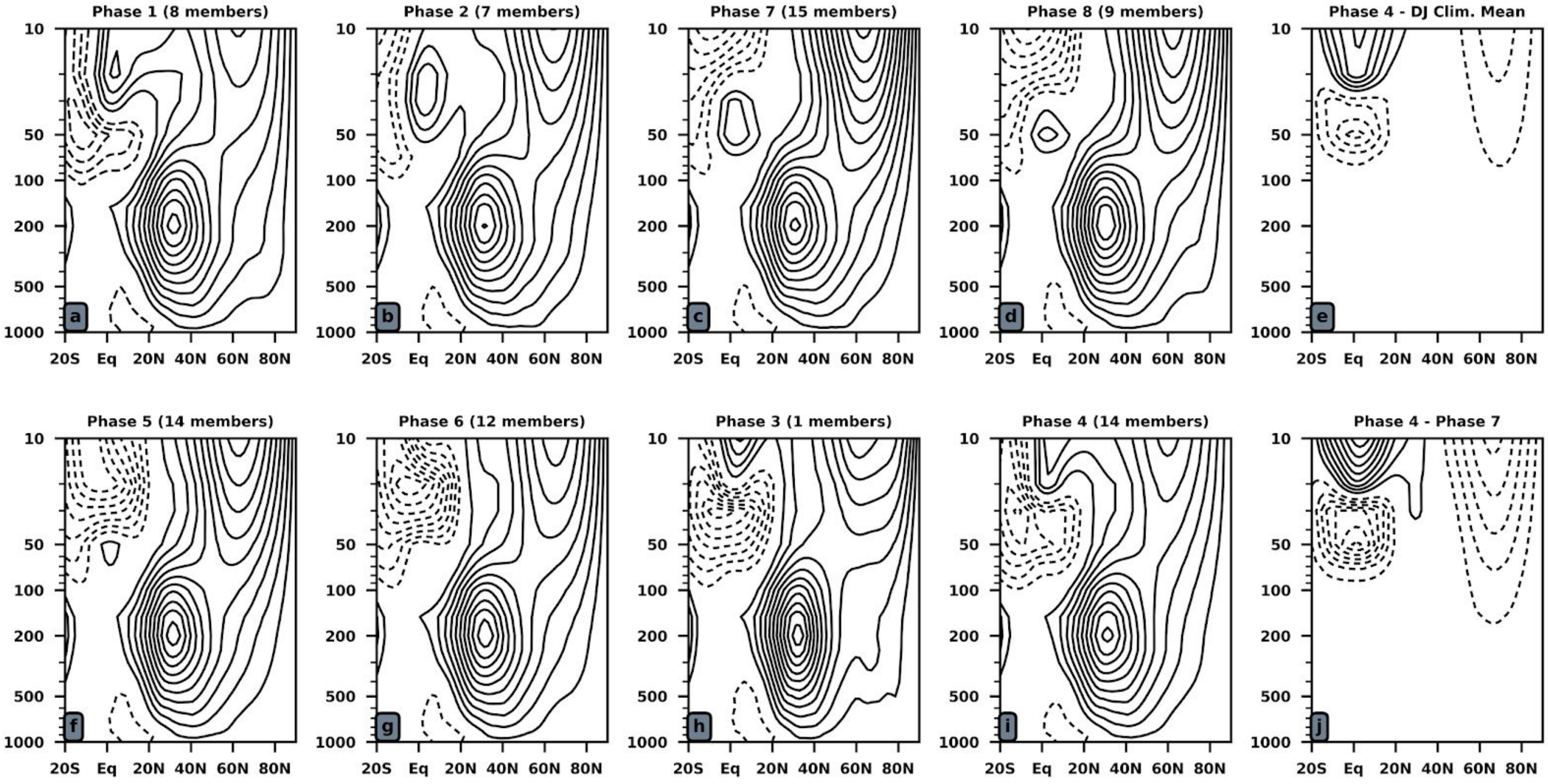


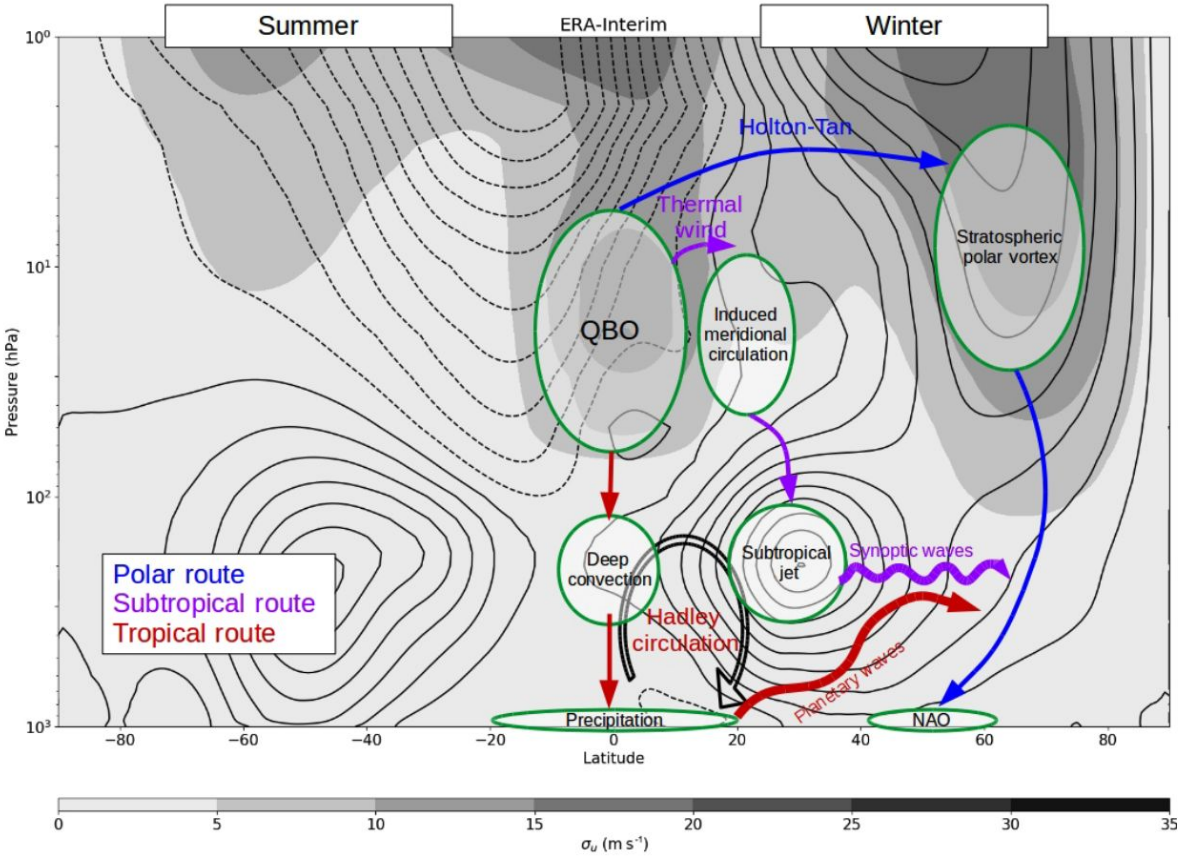
- Time series of **50 hPa** tropical winds (left column) comparing reanalysis (black) with the UFS prototypes (blue, green, orange dots) and GEFSv12 hindcast spread (grey lines) at different leads.

- Degradation of the QBO beyond 2 weeks
- UFS p5 and p6 show pronounced 50 hPa QBO wind biases, particularly with too strong easterlies.
- P7 shows a distinct improvement; it does not show the same issues.

ERA5 DJ Zonal Mean U-wind (m/s) Phase Angle QBO Indexing



- Successive sets of downward propagating and alternating easterly and westerly winds w/28 month periodicity



- QBO has 3 pathways to interact with the troposphere
- Tropical = QBO-MJO coupling
- Subtropical = QBO-jet
- Polar = modulates the strength of the polar vortex

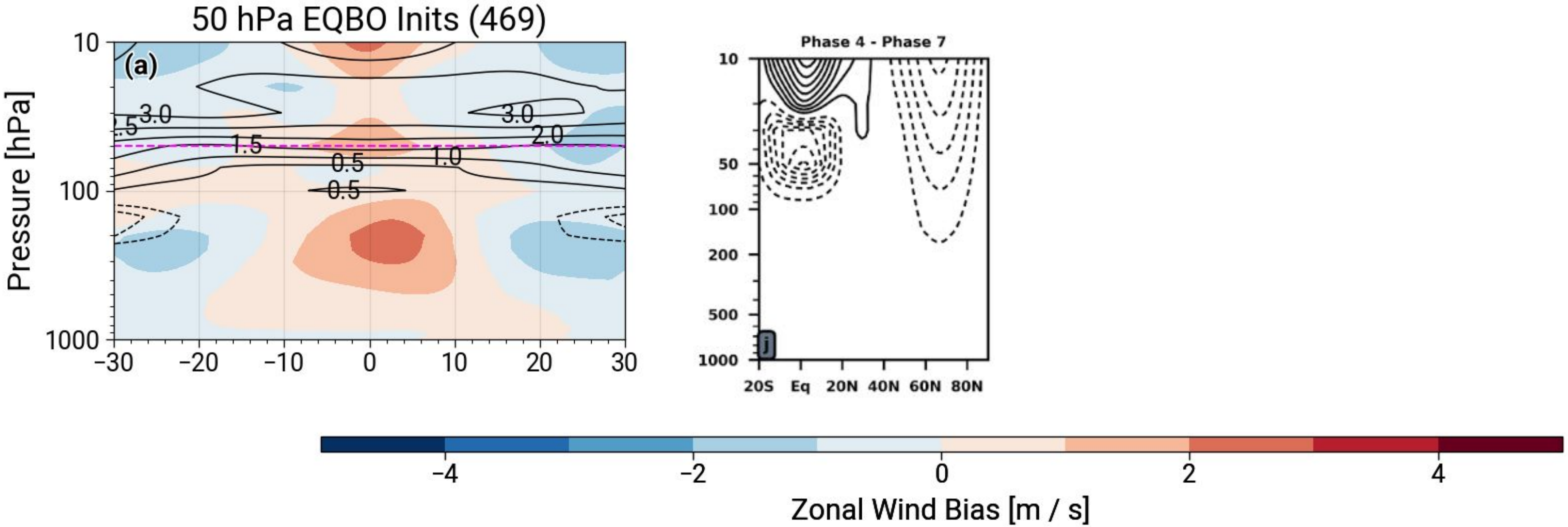
- Representation of teleconnection varies in response to representation of QBO

Gray, L. J., Anstey, J. A., Kawatani, Y., Lu, H., Osprey, S., & Schenzinger, V. (2018). Surface impacts of the quasi biennial oscillation. *Atmospheric Chemistry and Physics*, *18*(11), 8227-8247.

Representation of the QBO

Lawrence et al. in prep.

GEFSv12 QBO Biases (Weeks 3–5)

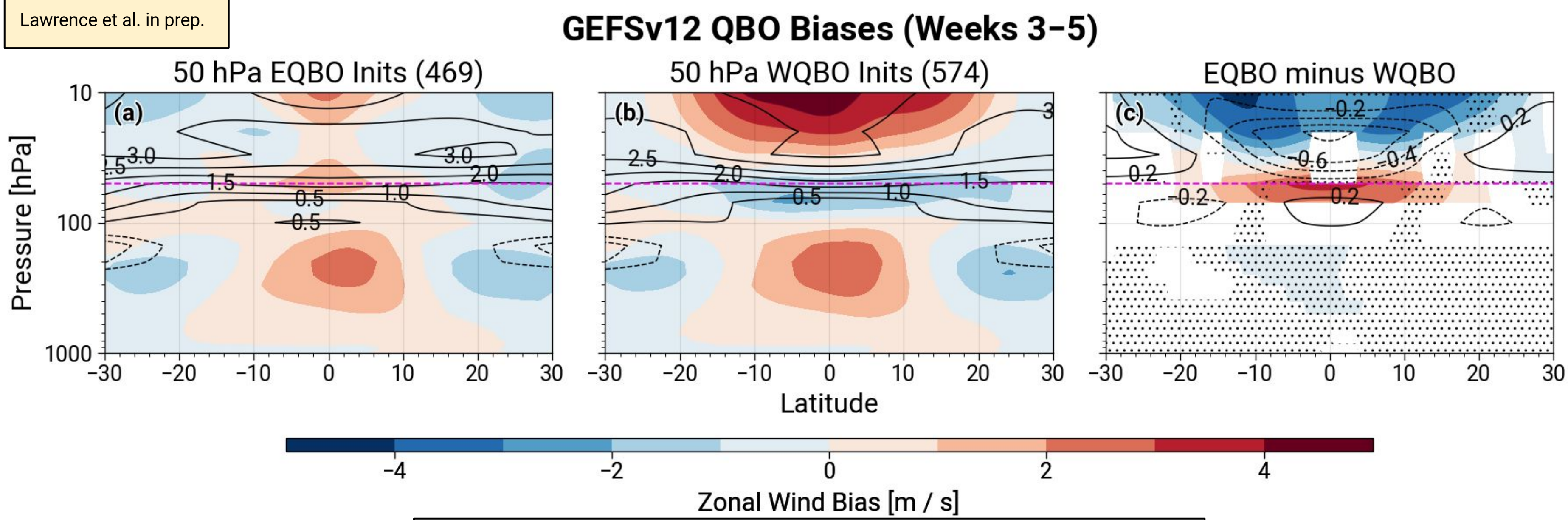


- Contours = temperature/shading = zonal wind

- QBOE: GEFSv12 underestimates (overestimates) amplitude of lower stratospheric QBO easterlies (westerlies)

Representation of the QBO

Lawrence et al. in prep.



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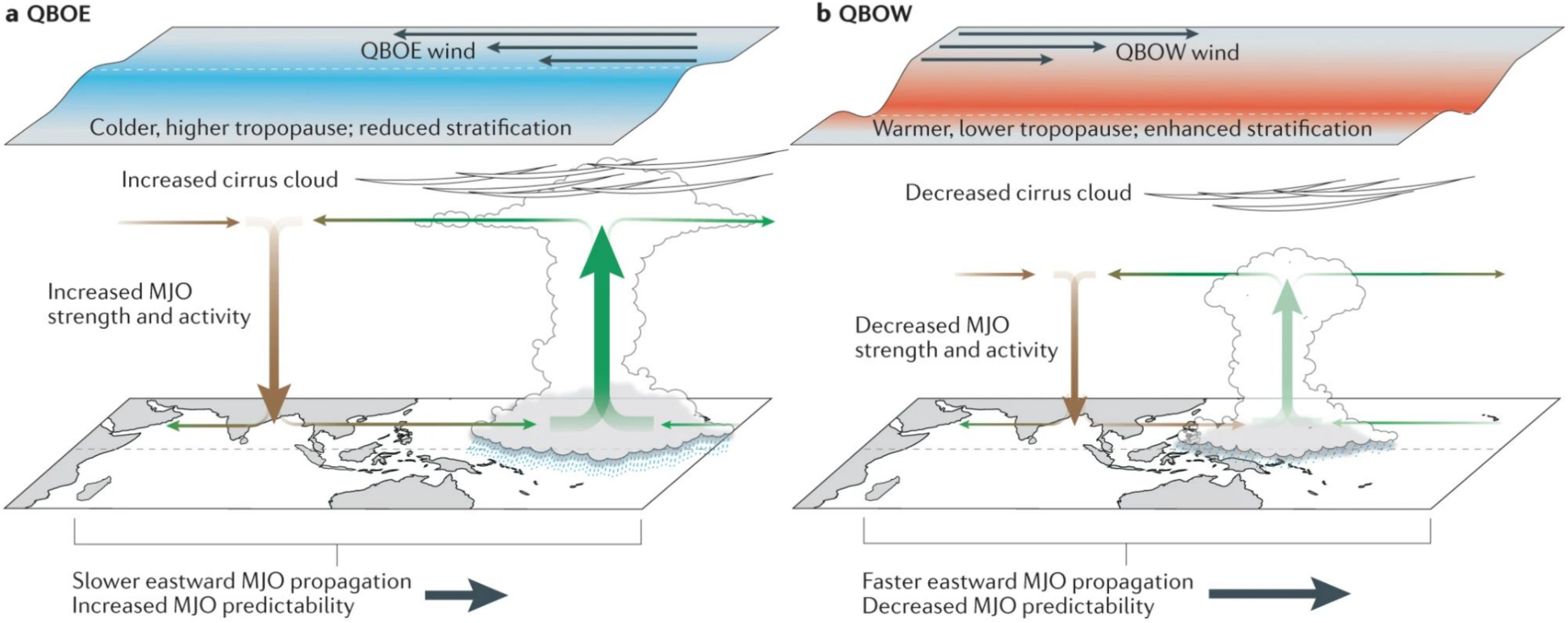
- QBOE: GEFSv12 underestimates (overestimates) amplitude of lower stratospheric QBO easterlies (westerlies)

- QBOW: both the easterlies and westerlies are too weak

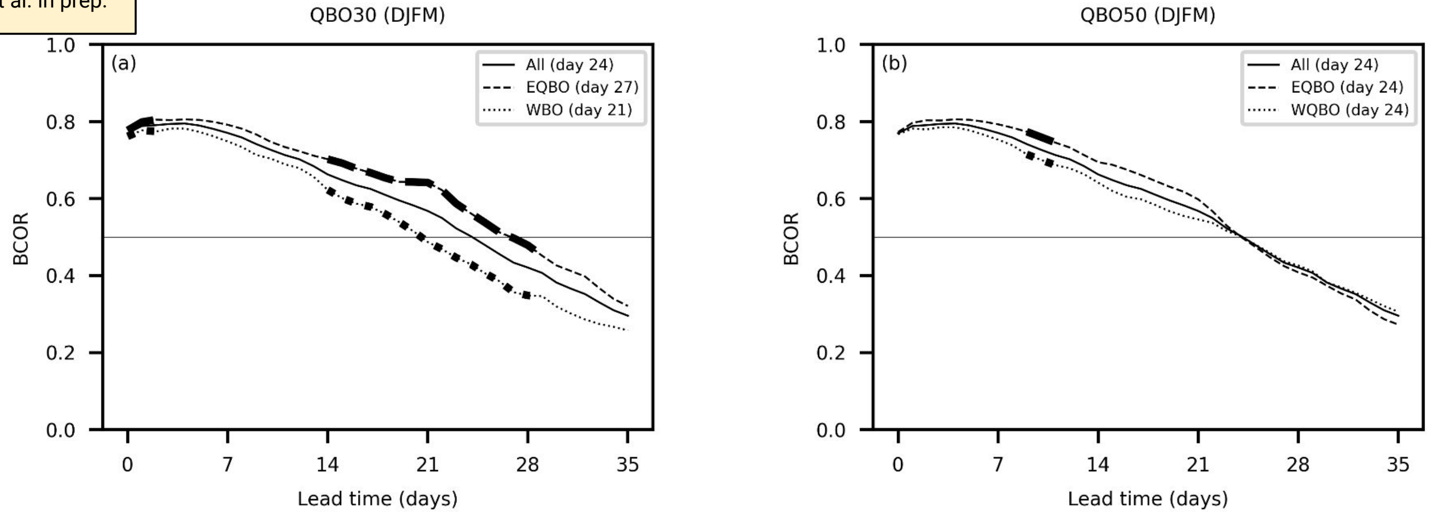
Some QBO-MJO literature



Martin, Z., Son, S. W., Butler, A., Hendon, H., Kim, H., Sobel, A., ... & Zhang, C. (2021). The influence of the quasi-biennial oscillation on the Madden–Julian oscillation. *Nature Reviews Earth & Environment*, *2*(7), 477-489.

Impact of QBO on MJO predictive skill

Lawrence et al. in prep.

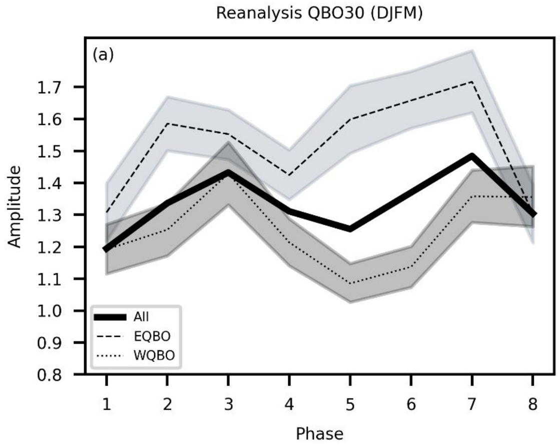


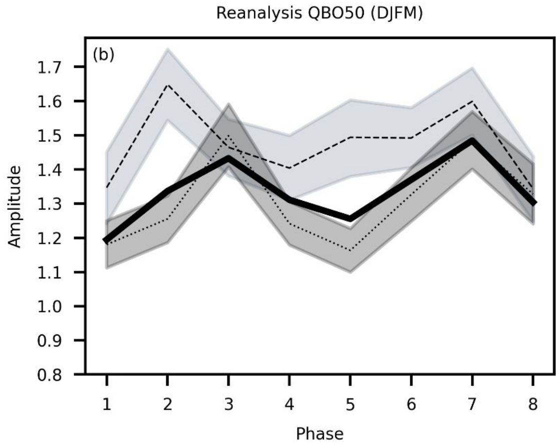
$$\mathrm{COR}(\tau) = \frac{\sum_{t=1}^{t=N} [a_1(t)b_1(t,\tau) + a_2(t)b_2(t,\tau)]}{\sqrt{\sum_{t=1}^{t=N} [a_1^2(t) + a_2^2(t)]}\sqrt{\sum_{t=1}^{t=N} [b_1^2(t,\tau) + b_2^2(t,\tau)]}},$$

- Predictive skill of MJO is higher for initialization during easterly QBO (EQBO)
- Define the QBO at 30 hPa: MJO prediction skill is 6 days longer during EQBO than WQBO
- Define the QBO at 50 hPa: no sensitivity of MJO to the QBO in hindcasts

Lawrence et al. in prep.

Impact of QBO on MJO amplitude by phase

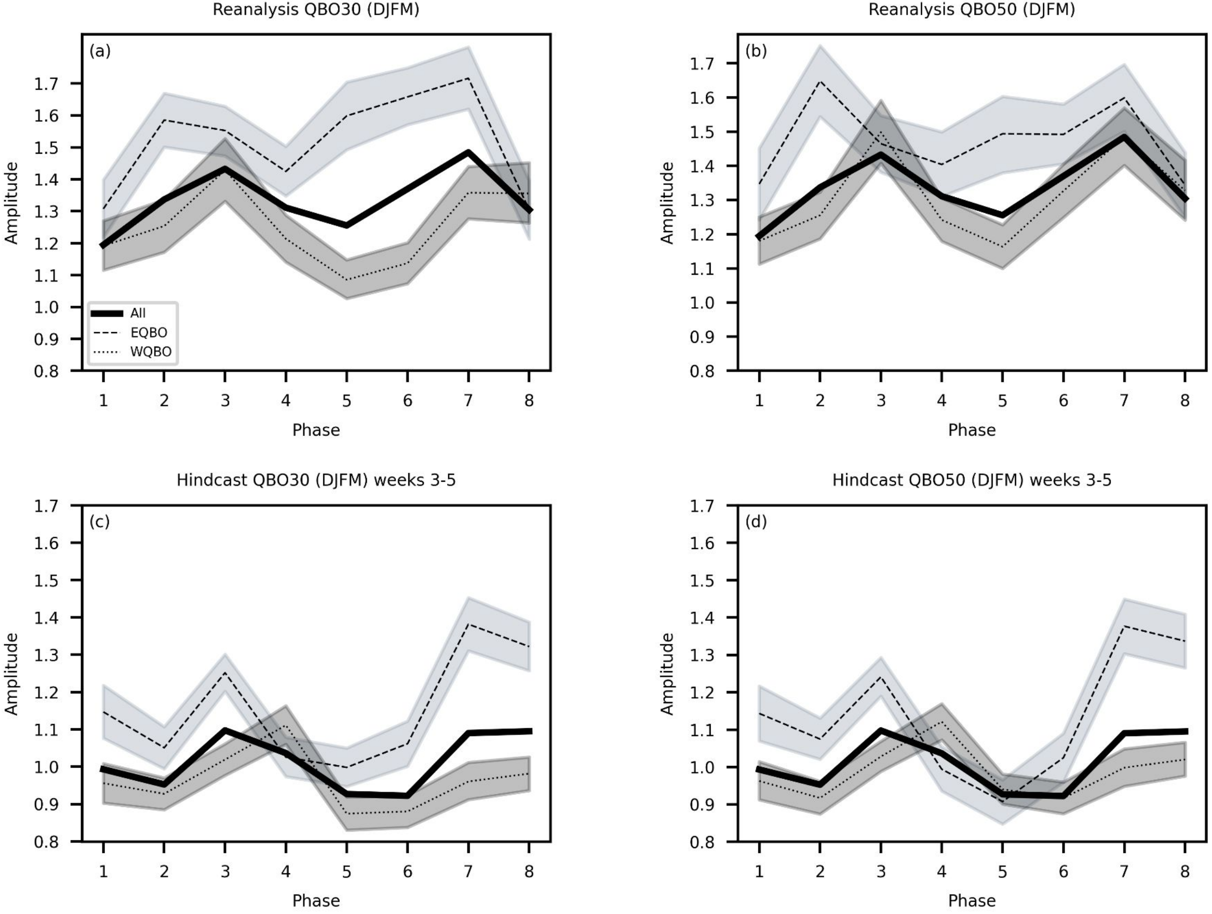




- MJO amplitude is larger during EQBO vs WQBO
- Differences again are more pronounced when QBO is defined at 30 hPa
- Phase 6-7

Lawrence et al. in prep.

Impact of QBO on MJO amplitude by phase



- MJO amplitude is larger during EQBO vs WQBO
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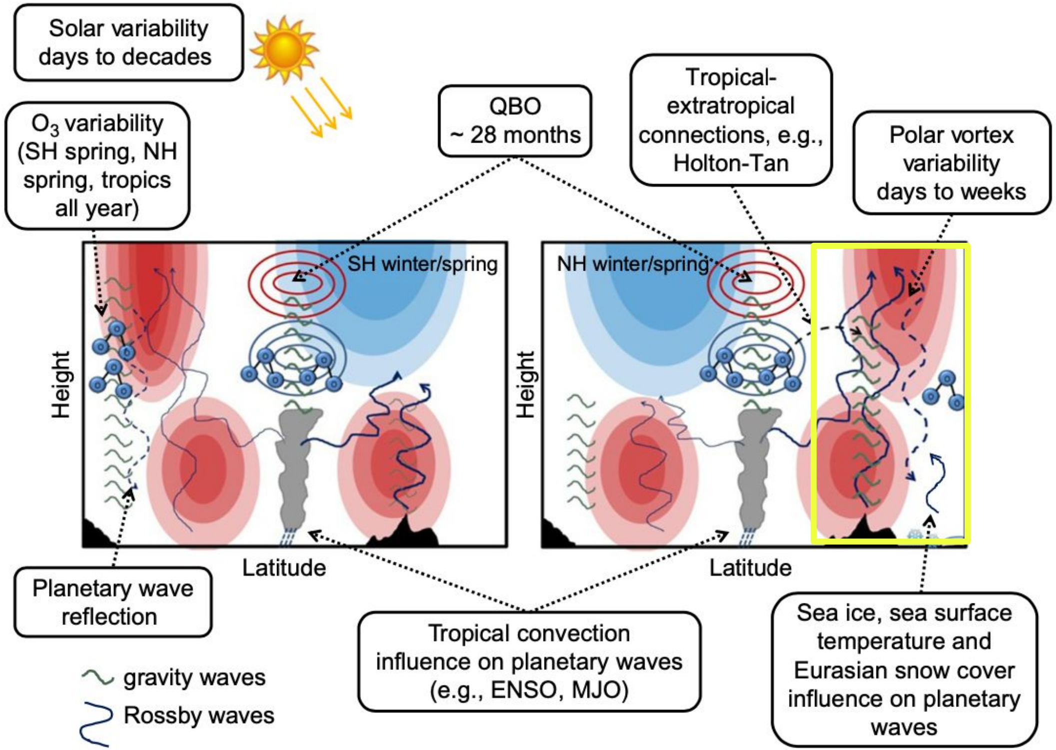
- Phase 6-7

- Hindcasts weeks 3-5
- MJO amplitude is higher during EQBO than WQBO
- Even after degradation of QBO during weeks 3-5, EQBO promotes higher amplitude MJO
- Maritime Continent prediction barrier

Beneficial for forecast systems to accurately represent the stratosphere



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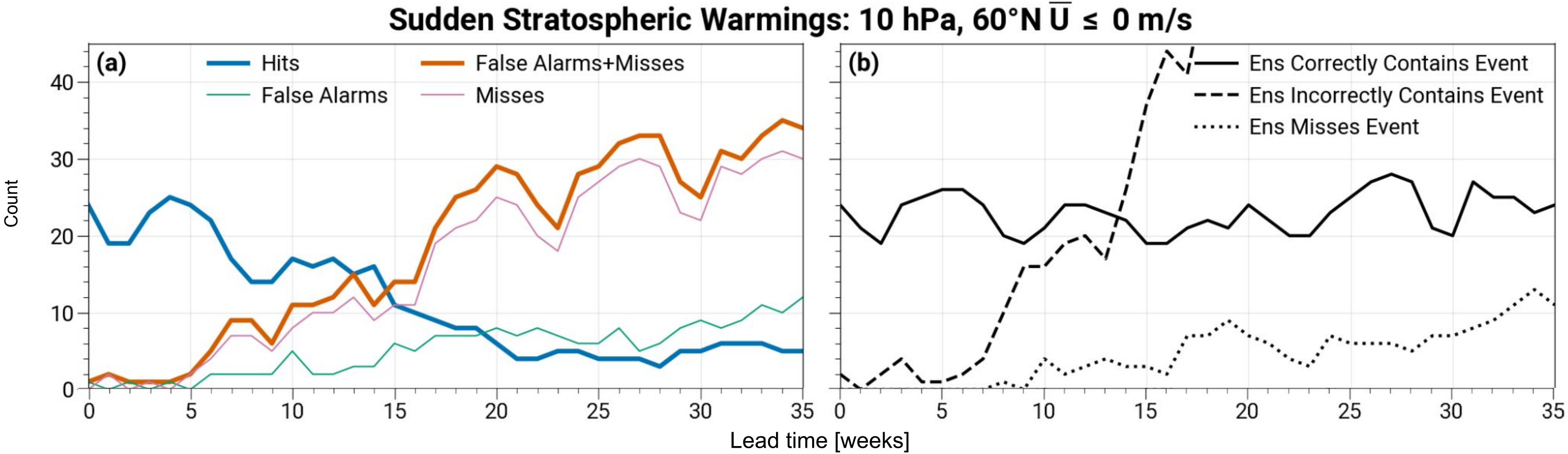
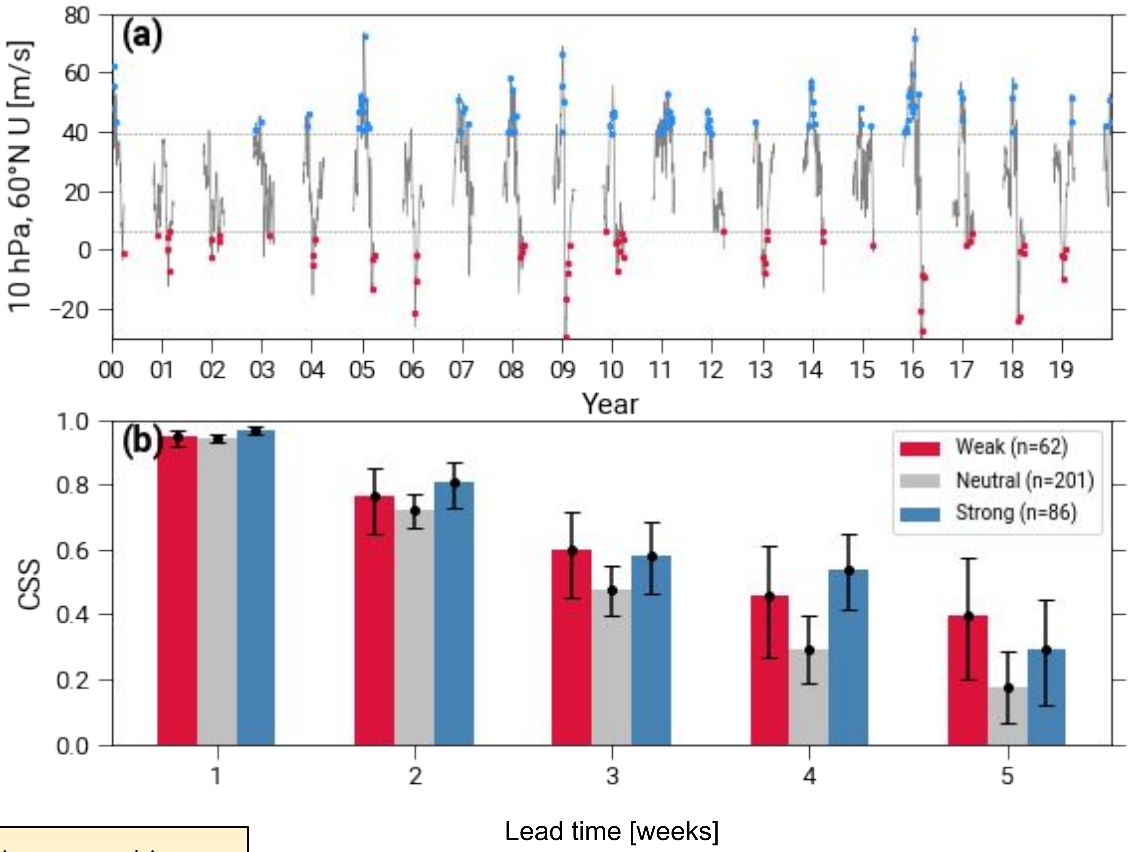
Predicting sudden stratospheric warmings

Lawrence et al. in prep.



- Left: “hit” = success, 6/11 of the ensemble members include an SSW that is observed
- Higher fraction of successful SSW forecasts out to 13 days than false alarms + misses
- Right: limiting case in which the ensemble spread needs to have one members containing the SSW
- Ensemble more frequently contains an observed SSW out to 13 days, when the frequency of “incorrectly contained” (false alarms) becomes to frequent

North Atlantic Oscillation vortex relationships



- Generally speaking, weak vortex = - NAO and strong vortex = + NAO

- GEFSv12 exhibits enhanced NAO correlation skill at weeks 3-5 for both strong/weak polar vortex events
- Differences are not statistically significant

Lawrence et al. in prep.

Summary of scientific results

Evaluation of GEFSv12 subseasonal hindcasts focused on stratospheric biases, extreme stratospheric events, and tropical stratosphere-troposphere coupling

1. GEFSv12 has stratospheric biases similar to other forecast systems (too strong polar vortex, cold upper troposphere-lower stratosphere, global warm bias in stratosphere)
2. Underestimates the amplitude of the QBO, particularly its easterlies; may impact QBO's teleconnections to extratropics
3. MJO skill is higher during easterly QBO (27 days) compared to westerly QBO (21 days) when the QBO easterlies are in the middle stratosphere (30 hPa) as opposed to lower stratosphere (50 hPa)
4. Predictive skills of SSWs out to two weeks, on par with other forecast systems
5. Predictive skill of NAO is higher when reforecasts are initialized with strong/weak polar vortex

Outcomes of the project

1. Two publications (screenshots below!)
2. Submitted the GEFSv12 reanalysis/hindcast NAO and MJO indices to NCEI
3. Provided EMC with evaluations of UFS prototypes
4. Pyzome python module/toolbox scripts
5. Working with METplus/CPC to transition the toolbox

Weather Clim. Dynam., 3, 977–1001, 2022
https://doi.org/10.5194/wcd-3-977-2022

Weather and Climate Dynamics
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Quantifying stratospheric biases and identifying their potential sources in subseasonal forecast systems

Zachary D. Lawrence[1,2], Marta Abalos[3], Blanca Ayarzagüena[3], David Barriopedro[3], Amy H. Butler[4], Natalia Calvo[3], Alvaro de la Cámara[3], Andrew Charlton-Perez[5], Daniela I. V. Domeisen[6,7], Etienne Dunn-Sigouin[8], Javier García-Serrano[9], Chaim I. Garfinkel[10], Neil P. Hindley[11], Liwei Jia[12,13], Martin Jucker[14,15], Alexey Y. Karpechko[16], Hera Kim[17], Andrea L. Lang[18], Simon H. Lee[19], Pu Lin[13,20], Marisol Osman[21,a], Froila M. Palmeiro[9], Judith Perlwitz[2], Inna Polichtchouk[22], Jadwiga H. Richter[23], Chen Schwartz[10], Seok-Woo Son[17], Irina Statnaia[16], Masakazu Taguchi[24], Nicholas L. Tyrrell[16], Corwin J. Wright[11], and Rachel W.-Y. Wu[7]

Evaluation of processes related to stratosphere-troposphere coupling in GEFSv12 subseasonal hindcasts

Zachary D. Lawrence[a,b] Dillon Elsbury,[a,c] Amy H. Butler,[c] Judith Perlwitz,[b] Laura Ciasto,[d] Eric Ray[a,c]

Implementation of Toolbox at CPC

- Prior to OSTI project → GEFS/GFS evaluations were largely provided by C. Long (CPC)
- **Post OSTI project→ comprehensive stratosphere evaluation package**
    - **Implement the diagnostics at CPC**
    - Provide additional diagnostics (collaboration with EMC)
    - Used for continued comparison of UFS evaluations with previous versions

Many of these components already exist in some format → combine and automate where possible

- Automate formatting of data to be read in by the toolbox
- Implement toolbox and add diagnostics currently in Jupyter notebooks
- Add additional diagnostics (ozone, specific humidity, etc)
- Visualization of diagnostics

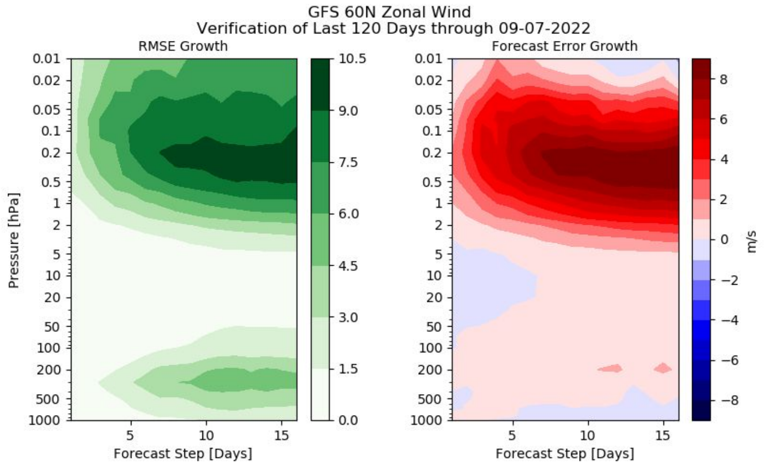
Goal: Have evaluation package completed for GEFSv13/GFSv17 evaluations

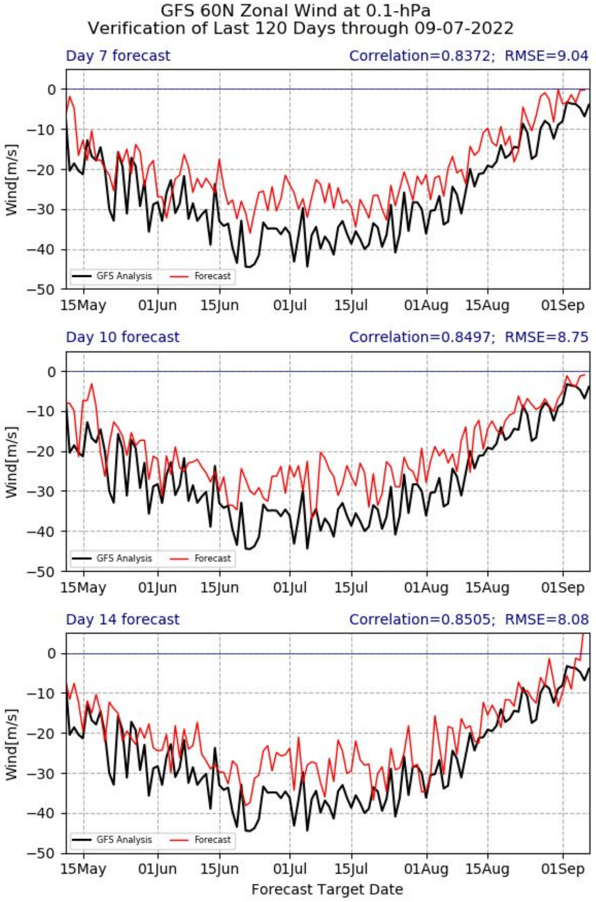
Real-time verification

Stratosphere GFS/GEFS forecasts graphics are available at CPC but real-time verification is limited

Updates are developmental (internal only)

GFSv16
- Extend forecast graphics to include upper levels (up to 0.01 hPa)
- Add verification metrics for previous 120 days
    - RMSE, correlation for Days 7, 10, 14
    - RMSE/Forecast Error Growth





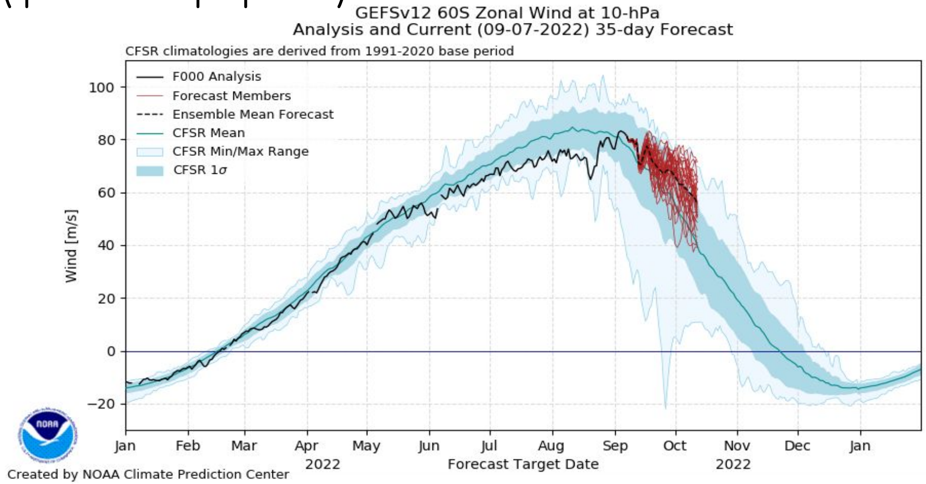
GFS Forecast graphics available for both hemispheres:
<u>Variables:</u> Zonal Wind (60°), Temperature (60°-90°), Eddy heat fluxes (45°-75°)
<u>Pressure Levels:</u> 100, 50, 10, 5, 1, 0.1, 0.01-hPa

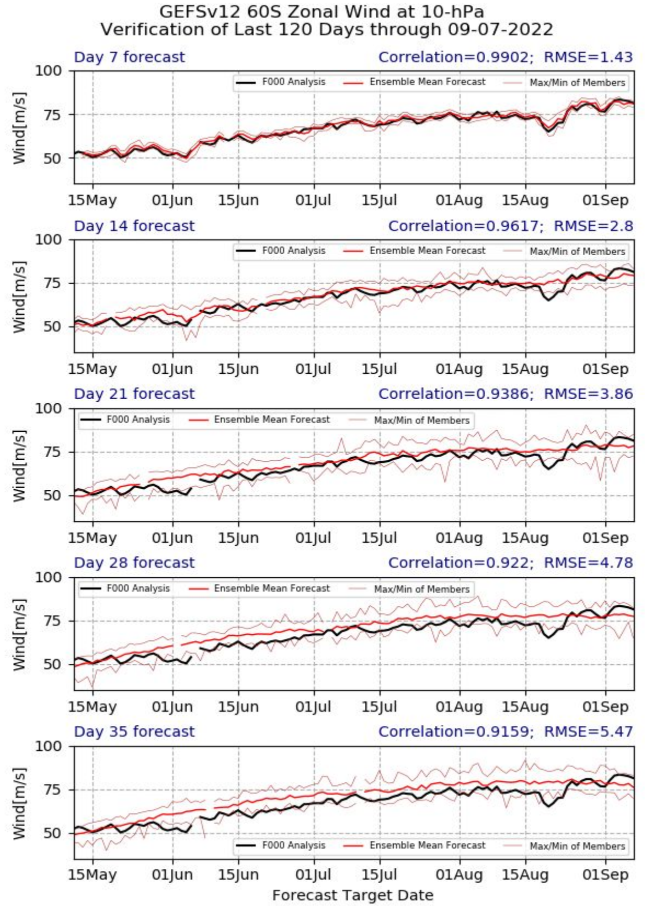
Real-time verification

GEFSv12

- Extend forecasts graphics to full 35 days
- Include ensemble members
- Add verification metrics for previous 120 days
    - RMSE, correlation for WK 1-5
    - RMSE/Forecast Error Growth
    - Rank Histograms

Future work: zonal mean pressure vs. time forecasts (“paint-drip” plots)





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