Direct assessment of the surface impacts of the January 2021 sudden stratospheric warming with S2S ensemble forecasts

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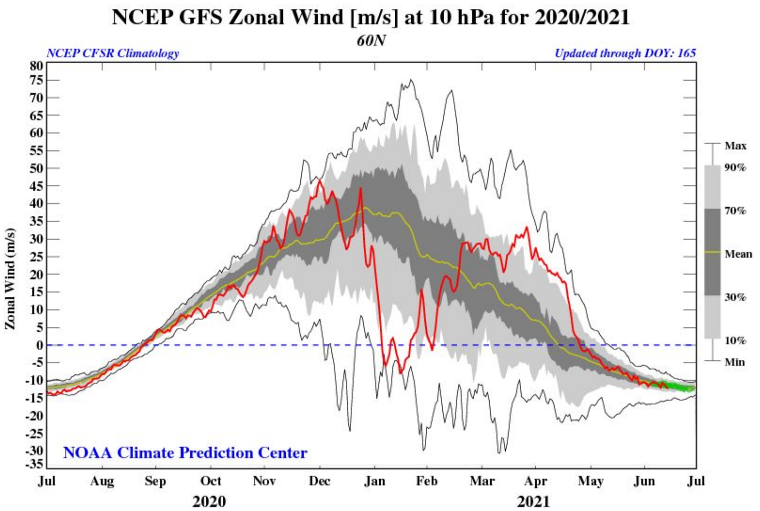
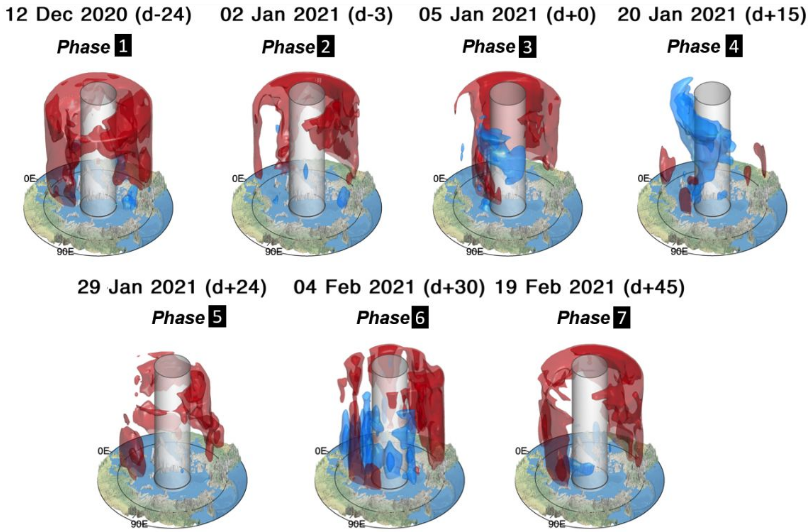
June 6th, 2022

Sudden stratospheric warmings (SSWs)





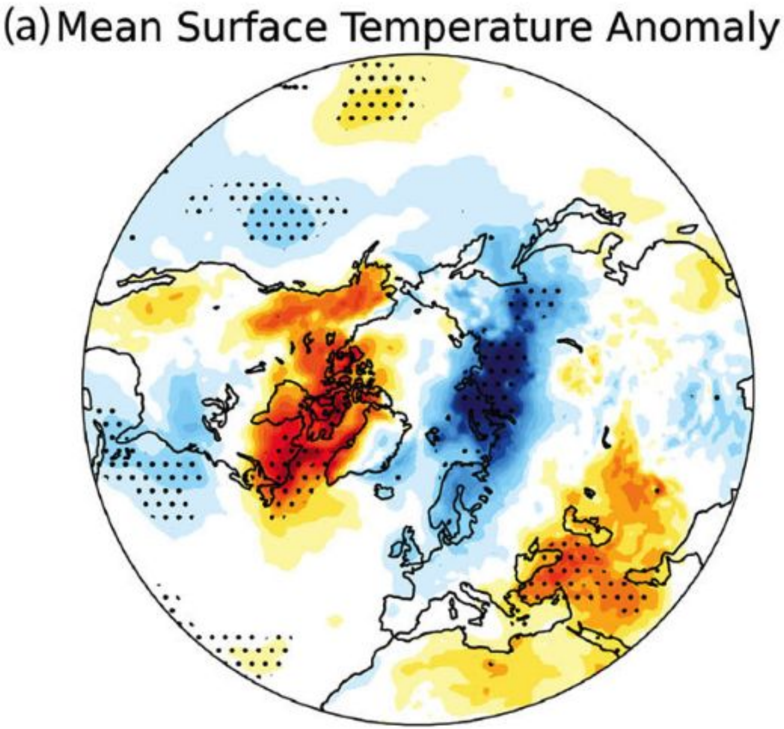
- Sudden deceleration of the polar vortex and warming of the polar cap, predictable 1-2 weeks in advance
- SSW occurred on January 5th, 2021

Figures from NOAA CPC and Wright et al. 2021.

Surface variability after SSW's

- Often followed by negative phase of the Northern Annular Mode (NAM) - equatorward shift of the jet
- *At surface*: cold Eurasia and North America, warm Northeastern Canada and Greenland
- *Predictability*: degrades in Europe, improves in North America, Asia, and the Middle East

Figure from Domeisen and Butler (2020).



Cold air outbreaks during disturbed vortexes

Study: Warmer Arctic led to killer cold in Texas, much of US

By SETH BORENSTEIN   September 2, 2021

- In early February 2021, polar vortex was stretched, reflected planetary waves back down toward troposphere
- Hypothesized to invigorate trough, intensify cold air outbreak [Cohen et al. 2021]

Image/title from the Associated Press.

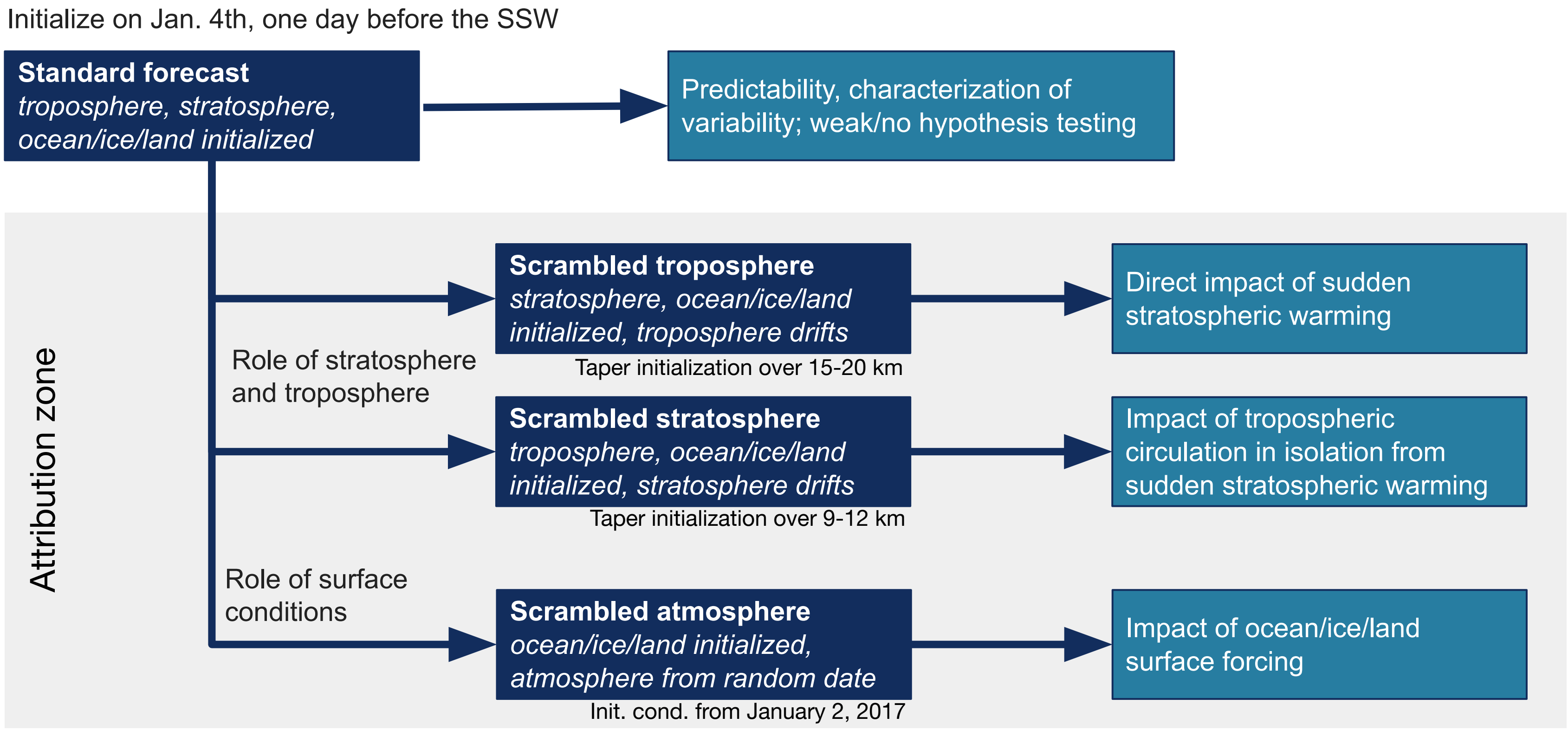
CESM2 Earth System Prediction Framework

CESM2(WACCM6) with prognostic atmosphere, ocean, sea ice, and land surfaces reinitialized weekly

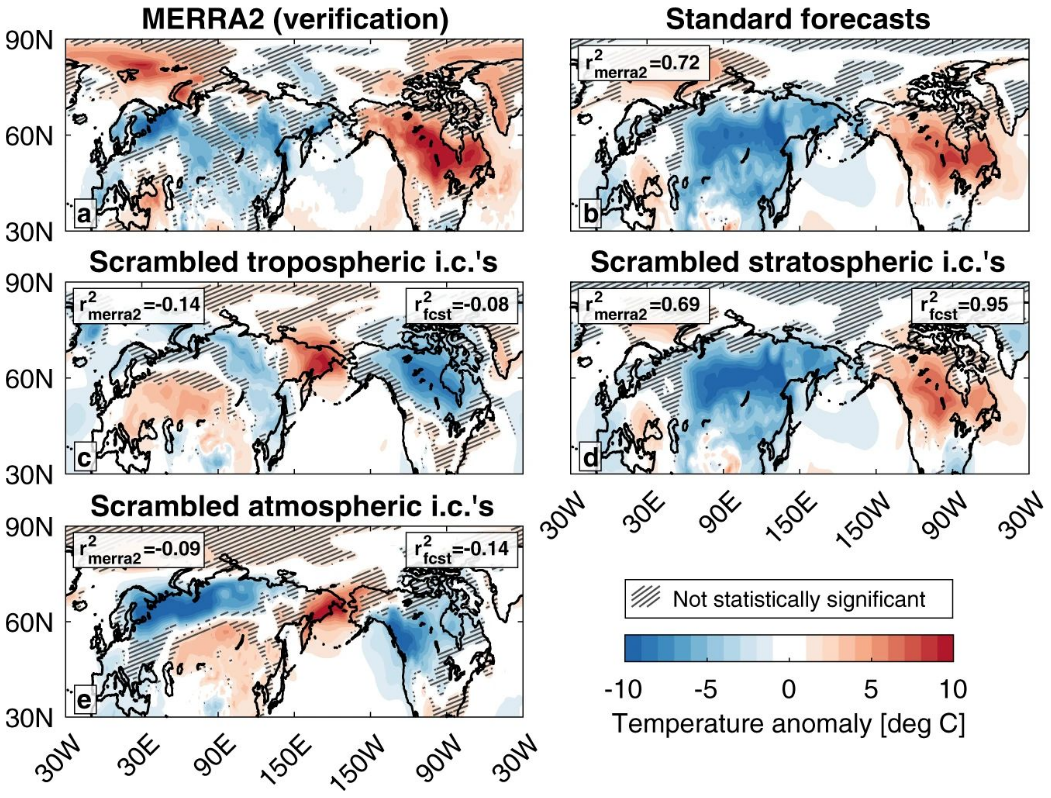
- 1 deg. resolution, 70 vertical levels from surface to 140 km
- Interactive troposphere-stratosphere-mesosphere-lower thermosphere chemistry, aerosols
- Atmosphere, ocean initial conditions sourced from specified dynamics simulation nudging atmosphere to NASA FP-IT (near real-time reanalysis)
- Interactive land model spun-up with NOAA/NCEP CFSv2
- Random field perturbation method applied to generate 21-member ensemble

Details and evaluation in Richter et al. (2022).

Direct attribution through initial condition "scrambling"



Week 1-2 forecasts



- Ensemble mean explains 72% of variance in first two weeks (*b*)
- No impact from stratospheric initial conditions (*compare d, b*)
- Tropospheric initial conditions highly influenced by surface (*compare c, e*)

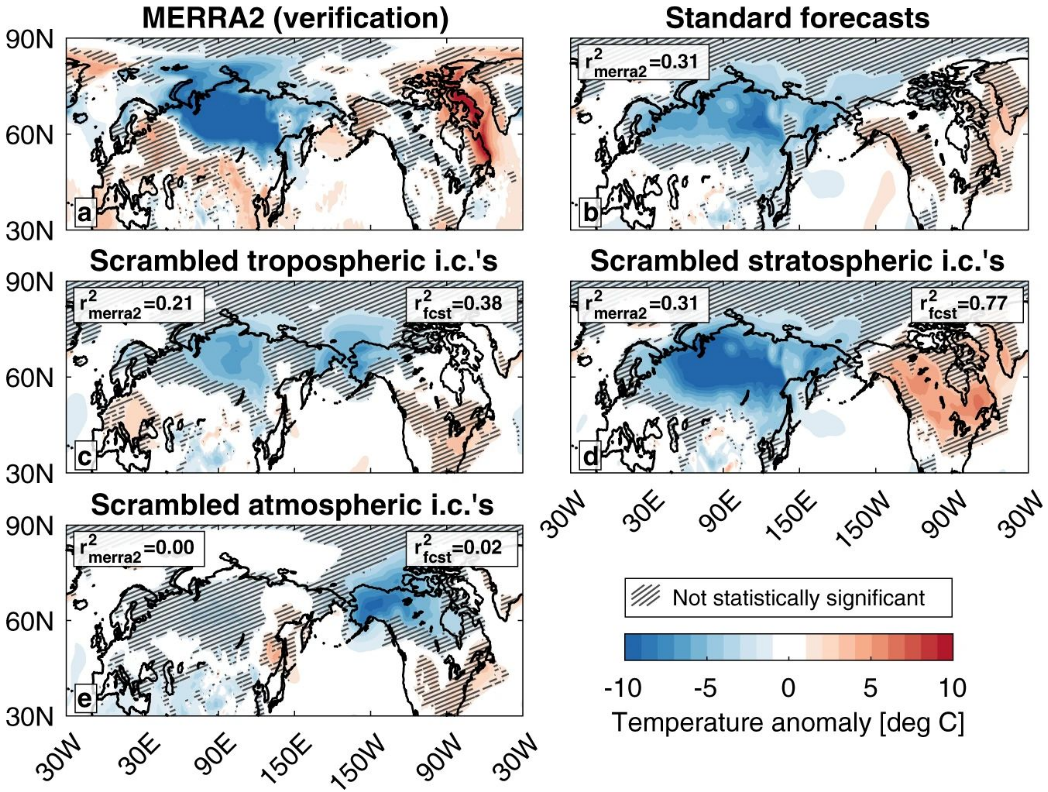
r^2_{merra2} = anomaly correlation coefficient squared with MERRA2, preserving sign

r^2_{fcst} = anomaly correlation coefficient squared with standard forecasts, preserving sign

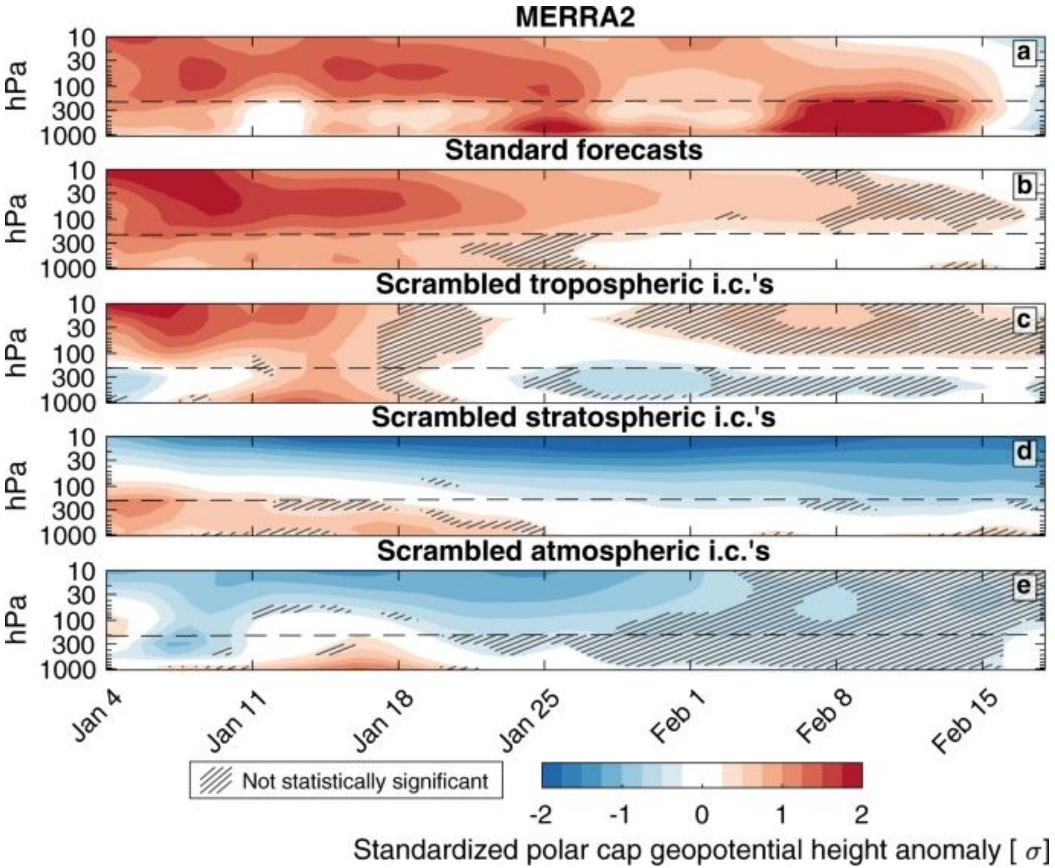
Why r^2 and not just r? Physical interpretation of percent variance shared.

Week 3-4 forecasts

- Ensemble mean explains 31% of variance in weeks 3-4
- Small impact from stratospheric initial conditions (*compare d, b*)
- Primarily governed by tropospheric initial conditions (*compare c, b*)



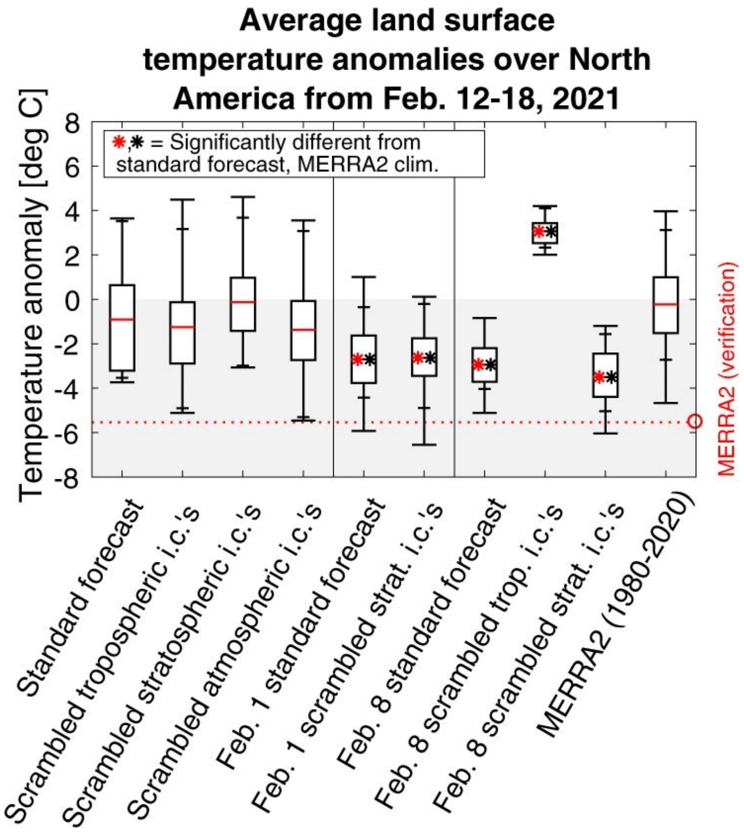
Polar cap geopotential height



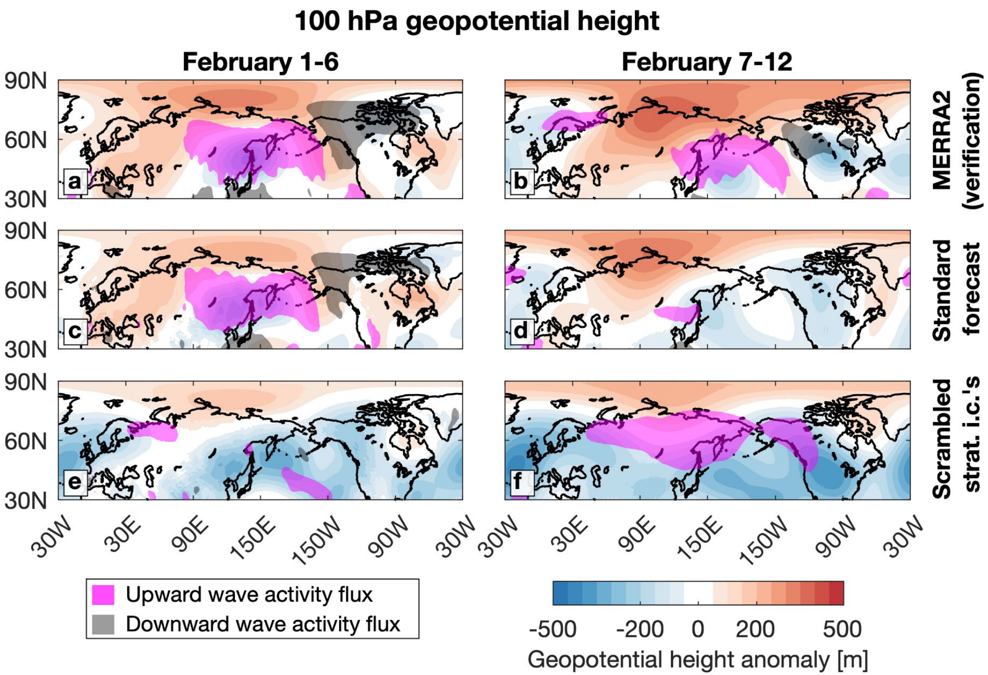
- Classic "downward-coupling" (*a, b*)
- Positive surface NAM after one week could be due to surface forcing, not SSW (*compare c, e*)
- Without tropospheric forcing, positive geopotential height anomalies do not descend as far down, dissipate faster (*compare c, b*)
- Both tropospheric and stratospheric initial conditions are crucial for sustaining positive geopotential height anomalies (*compare c and d to b*)

Cold air outbreak surface temperature forecasts

- Cold air outbreak was coldest event on record since MERRA2 began
- No deterministic impact of SSW on February cold air outbreak, but beyond predictability limit
- Forecasts initialized close to event (Feb. 1, Feb. 8) show no impact from stratospheric initial conditions on cold air outbreak



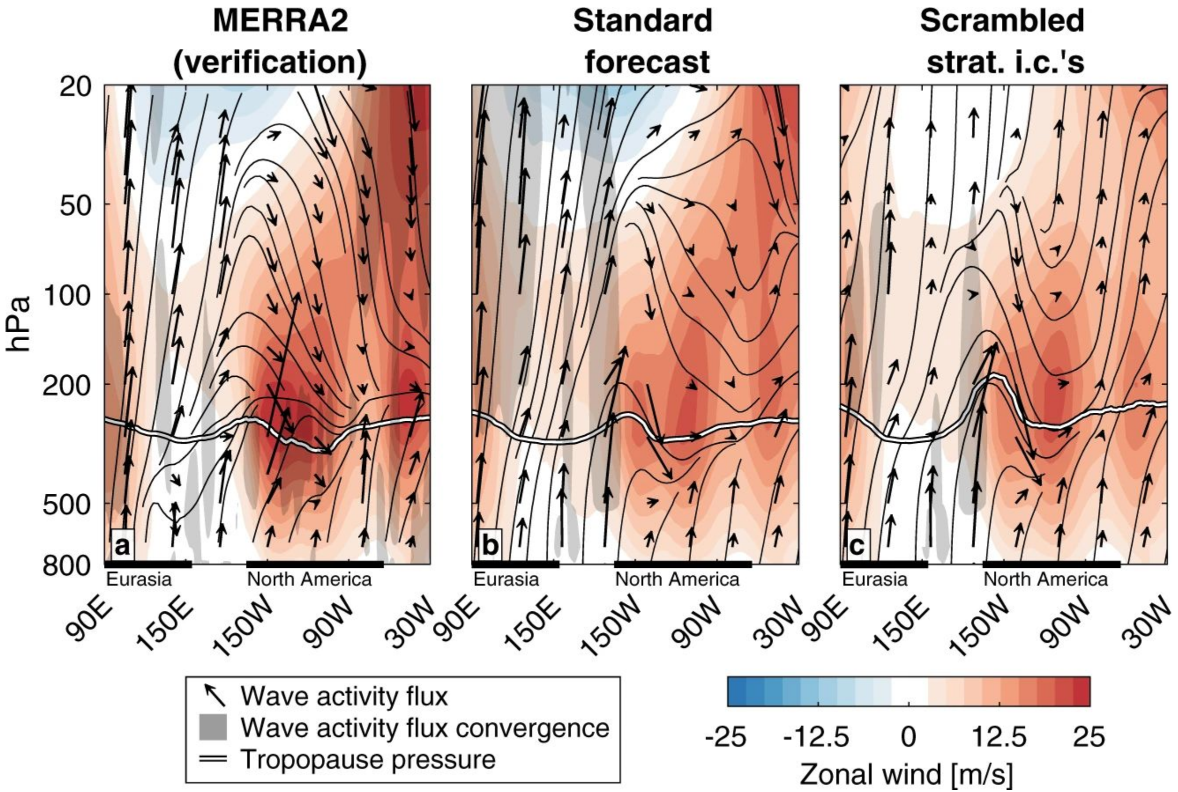
Wave reflection



- Evidence of reflected wave activity before event (*a, b*)
- Standard forecasts predicts some wave activity reflection (*c, d*), but forecast with scrambled stratospheric initial conditions does not (*e, f*)
  - Wave reflection has no impact on surface temperature forecasts

Meridional mean dynamics

- Wave activity flux converging into ridge and trough never traveled above 200 hPa (a-c)
    - It was never reflected off of the polar vortex, so preventing the reflection from occurring had no impact
- Reflected waves reach lower stratosphere, but downstream of trough near US East Coast



Conclusions

- Stratosphere-troposphere coupling after the January 5th SSW was more of a feedback process than "downward" coupling
  - Tropospheric NAM driven by persistence, surface forcing
  - Tropospheric circulation drew stratospheric NAM downward toward tropopause
  - Alone, NAM in troposphere and stratosphere would have dissipated faster
- Vortex stretching/wave reflection do not seem to have played a role in the February cold air outbreak
- Streamlines based on proper wave vector scaling is critical for analyzing wave propagation [Jucker 2021]
  - To discuss the source/path of wave activity, you need to scale it physically and geometrically
- Initial condition scrambling of forecast ensembles is an excellent hypothesis/causality test
  - Cannot deduce any "hidden" behavior from observations or standard forecasts, even with sophisticated techniques like machine learning
- Simple initialization procedures (nudging) with an Earth system model can produce reasonable forecasts, support hypothesis testing with minimal effort

Davis, N. A., Richter, J. H., Glanville, A. A., Edwards, J., and LaJoie, E. Limited surface impacts of the January 2021 sudden stratospheric warming. Nat. Commun., 13, 1136, (2022).

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Extra: initial condition similarity for Feb. 1 forecasts

Initial conditions in the standard forecast are more similar to MERRA2 than to the initial conditions in the forecast with scrambled stratospheric initial conditions