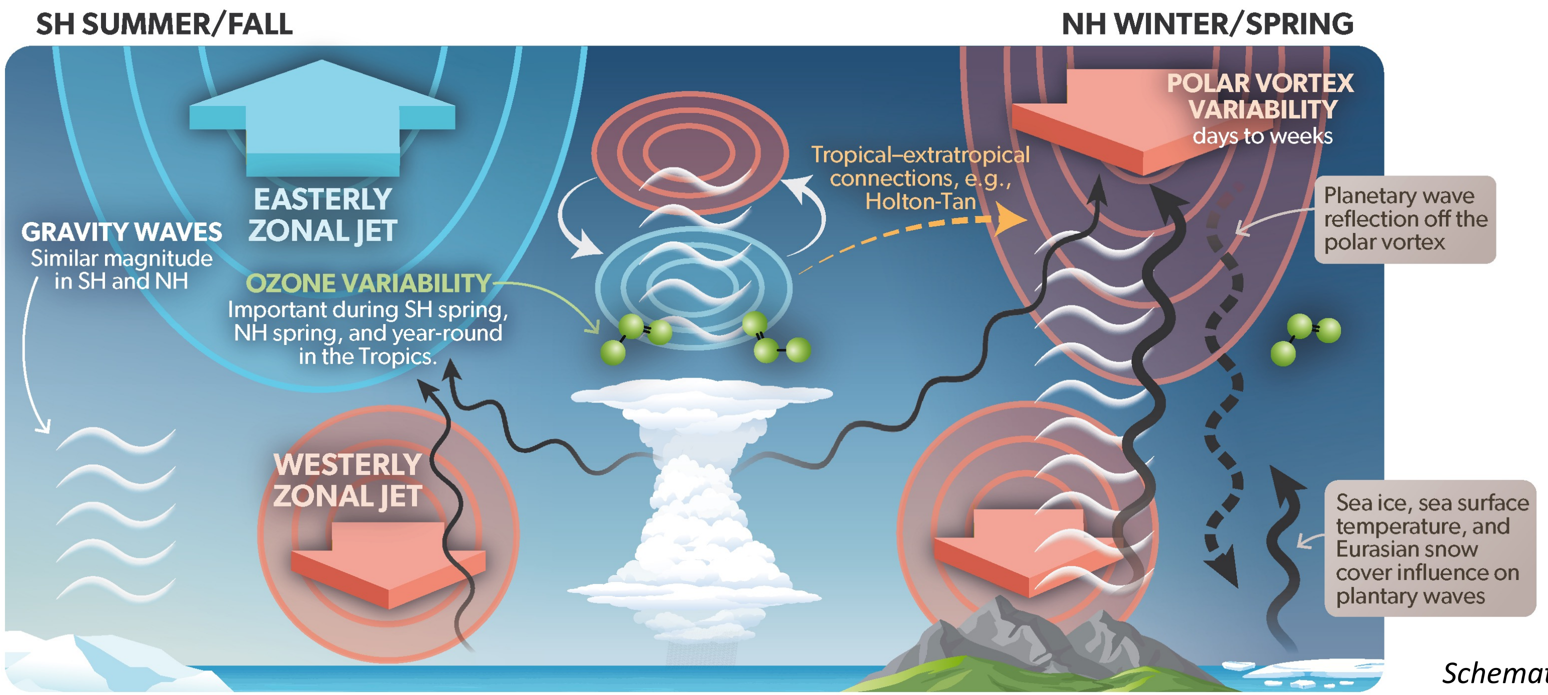
A process-based evaluation of biases in stratosphere-troposphere coupling in subseasonal forecast systems

Chaim I. Garfinkel, Zachary D. Lawrence, **Amy H. Butler** (NOAA CSL)

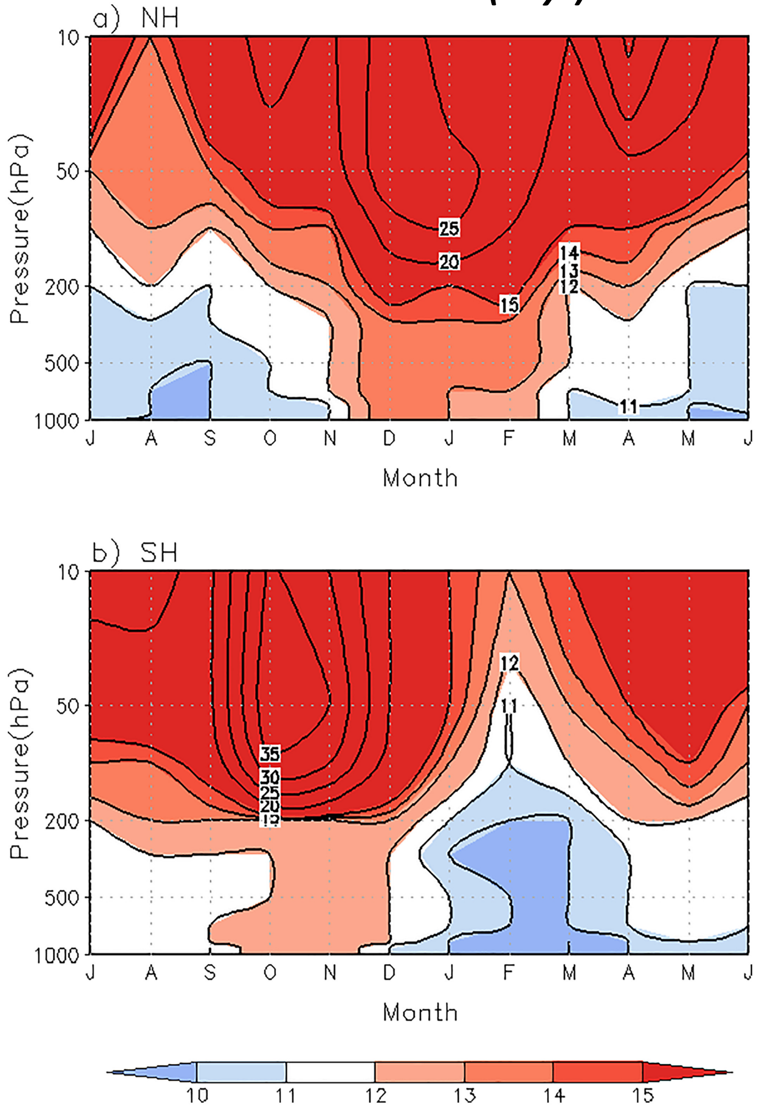
Co-authors: Etienne Dunn-Sigouin, Irina Statnaia, Alexey Karpechko, Gerbrand Koren, Marta Abalos, Blanca Ayarzagüena, David Barriopedro, Natalia Calvo, Alvaro de la Cámara, Andrew Charlton-Perez, Daniela Domeisen, Javier García-Serrano, Neil P. Hindley, Martin Jucker, Hera Kim, Robert Lee, Simon Lee, Marisol Osman, Froila Palmeiro, Inna Polichtchouk, Jian Rao, Jadwiga H. Richter, Chen Schwartz, Seok-Woo Son, Masakazu Taguchi, Nicholas L. Tyrrell, Corwin Wright, and Rachel Wu



Schematic by Chelsea Thompson/NOAA
For Butler et al. 2024, in prep

The stratosphere is one of the only sources of persistent signal in the atmosphere on S2S timescales

Prediction Skill (days)



- Skillful forecasts of extratropical geopotential heights in the stratosphere extend to lead-times ~2-3x longer than in the troposphere.
- Extended prediction skill in the troposphere is found in NH winter and SH spring, during periods of active stratosphere-troposphere coupling.
- Following stratospheric polar vortex extremes, anomalies in the lower stratosphere can persist for weeks to months.

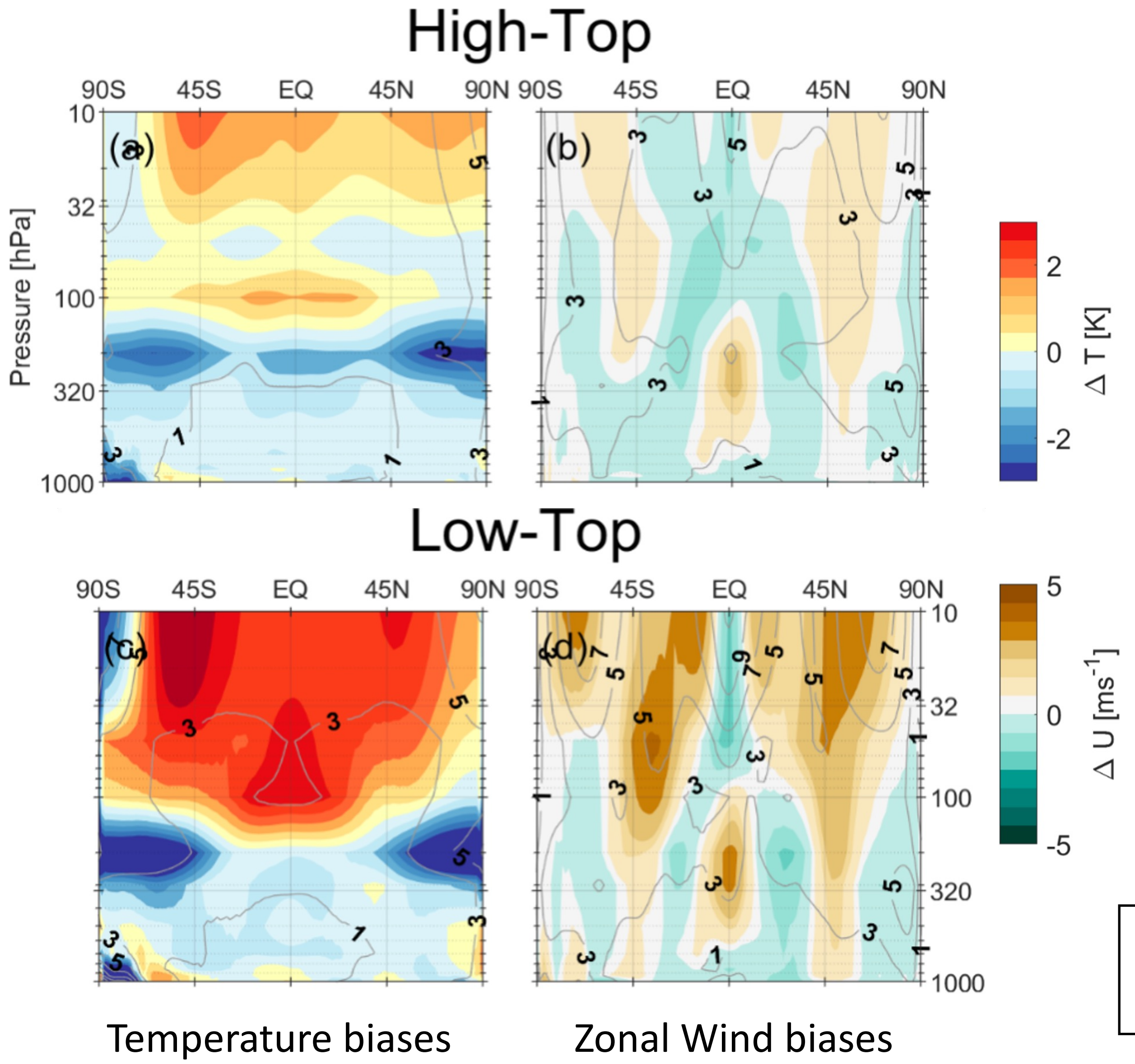
Son et al., 2020

Stratosphere-troposphere coupling processes are linked to a broad range of global extremes

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

Domeisen and Butler, "Stratospheric drivers of extreme events at the Earth's surface", Communications Earth & Environment, 2020

There are known model biases that may affect stratosphere-troposphere coupling



- Generally similar week 4 biases across S2S prediction systems:
  1) Polar vortex wind/T bias in winter hemisphere
  2) Extratropical UTLS cold bias
  3) Global-mean stratospheric warm bias
- Models with lower model lid height on average show larger biases

Composites of biases and mean absolute errors at week 4, verified against ERA-Interim, from **Lawrence et al. (2022)**

Subseasonal Hindcast Datasets

Model biases can lead to poor representation of stratosphere-troposphere coupling.

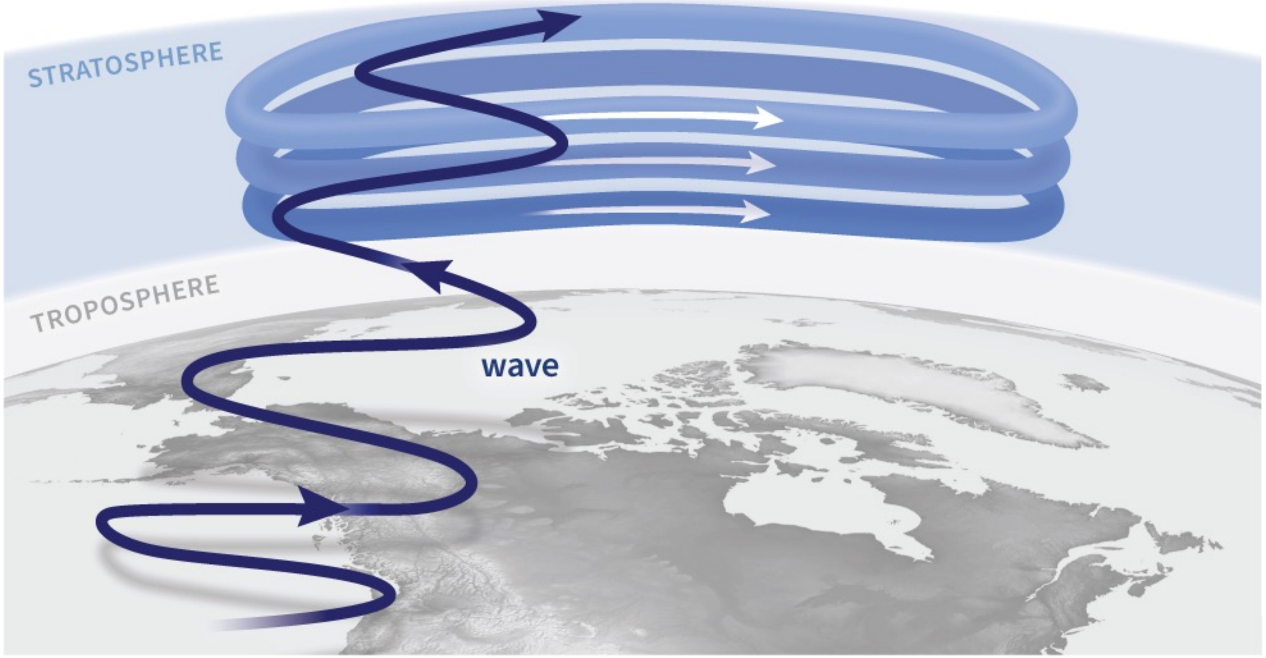
- Focus primarily on hindcasts in S2S database
  - Also use NOAA GEFSv12, CESM2-CAM, CESM2-WACCM where possible
- Systems with high-top vs low-top models
  - High-top = having a model lid at or above 0.1 hPa with several levels above 1 hPa.
  - **Low-top systems are usually highlighted with dotted lines or asterisks**
- Determine biases relative to ERA5 reanalysis
- Leadtime-dependent climatologies for each model are removed

Subseasonal-to-Seasonal S2S Prediction Project

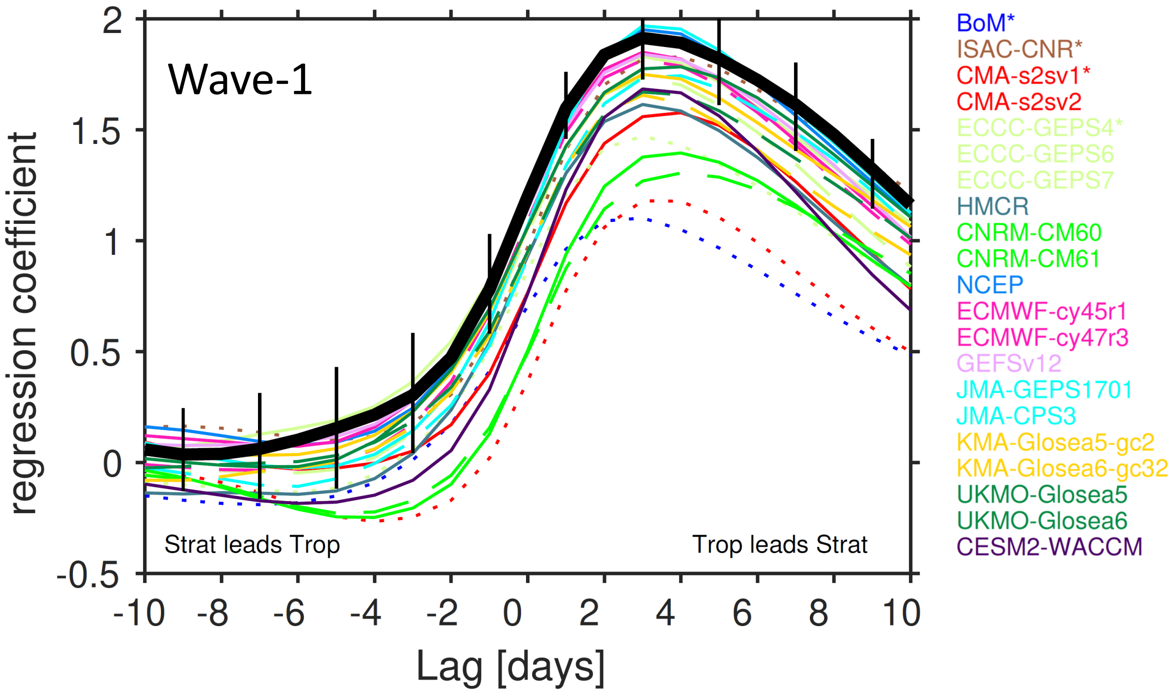
Possible analyses are limited by the S2S Database data only being provided on a sparse set of stratospheric levels (100, 50, and 10 hPa).

Breaking stratosphere-troposphere coupling in the NH into upward and downward processes….

1) Upward flux of wave activity from troposphere to stratosphere



Regression of 500hPa heat flux (days 11-22) with 100hPa heat flux , DJF



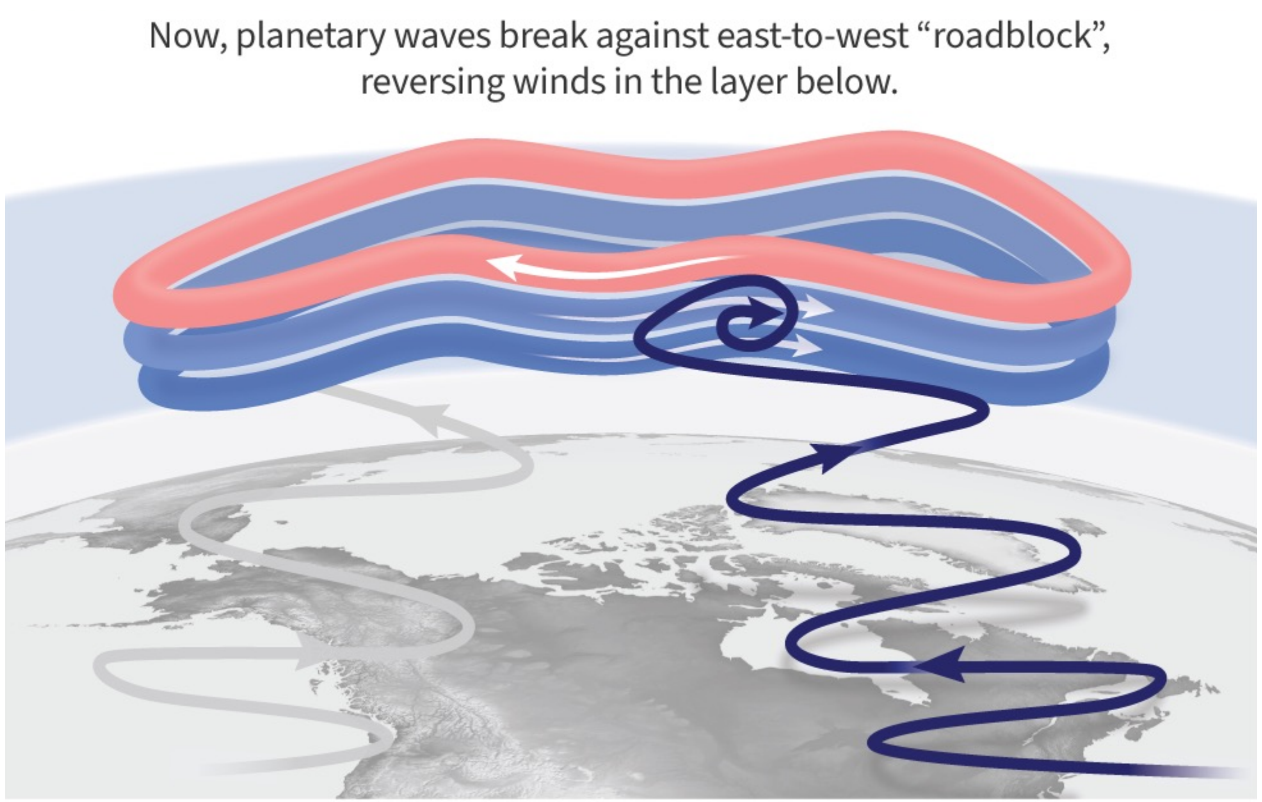
Only the largest Rossby waves (wavenumbers 1-2) can travel into the stratosphere

S2S models underestimate upward flux of largest atmospheric waves from troposphere into stratosphere.

From the NOAA Polar Vortex Blog on Climate.gov

Garfinkel et al. 2024, in prep

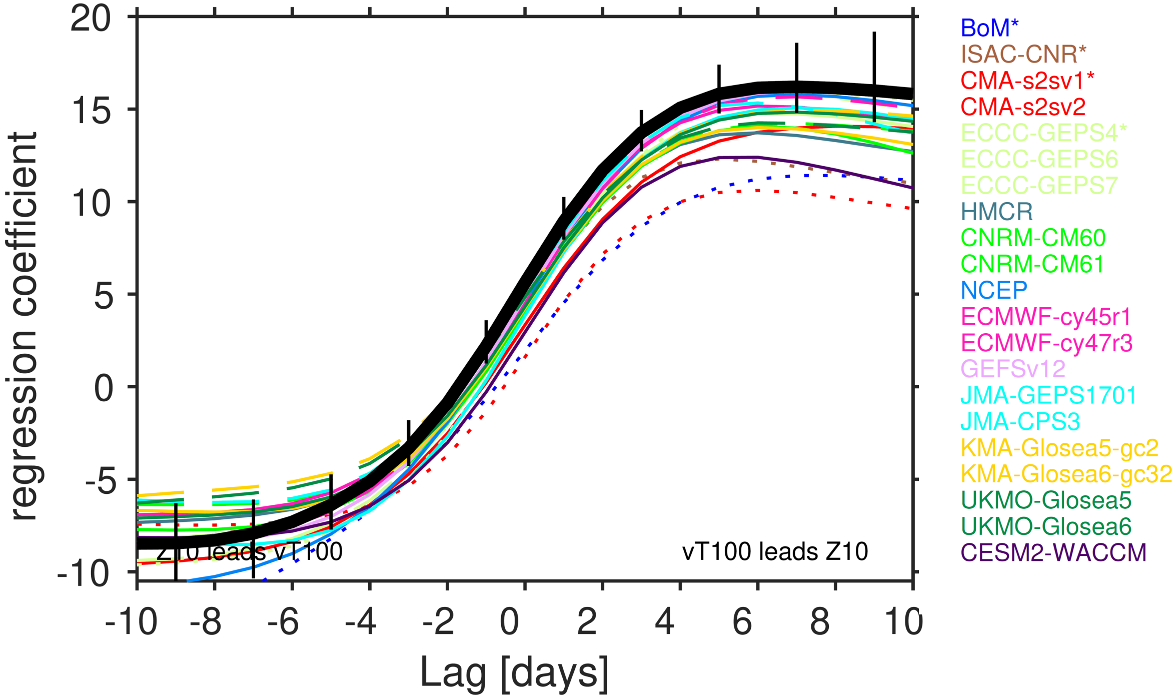
2) Polar stratospheric winds respond to upward flux of atmospheric waves



Combination of stratospheric vortex state and strength/location of tropospheric waves can cause waves to break, depositing easterly momentum and slowing the stratospheric winds.

From the NOAA Polar Vortex Blog on Climate.gov

Regression coefficient of 100hPa heat flux (days 11-22), with polar cap height at 10hPa, DJF

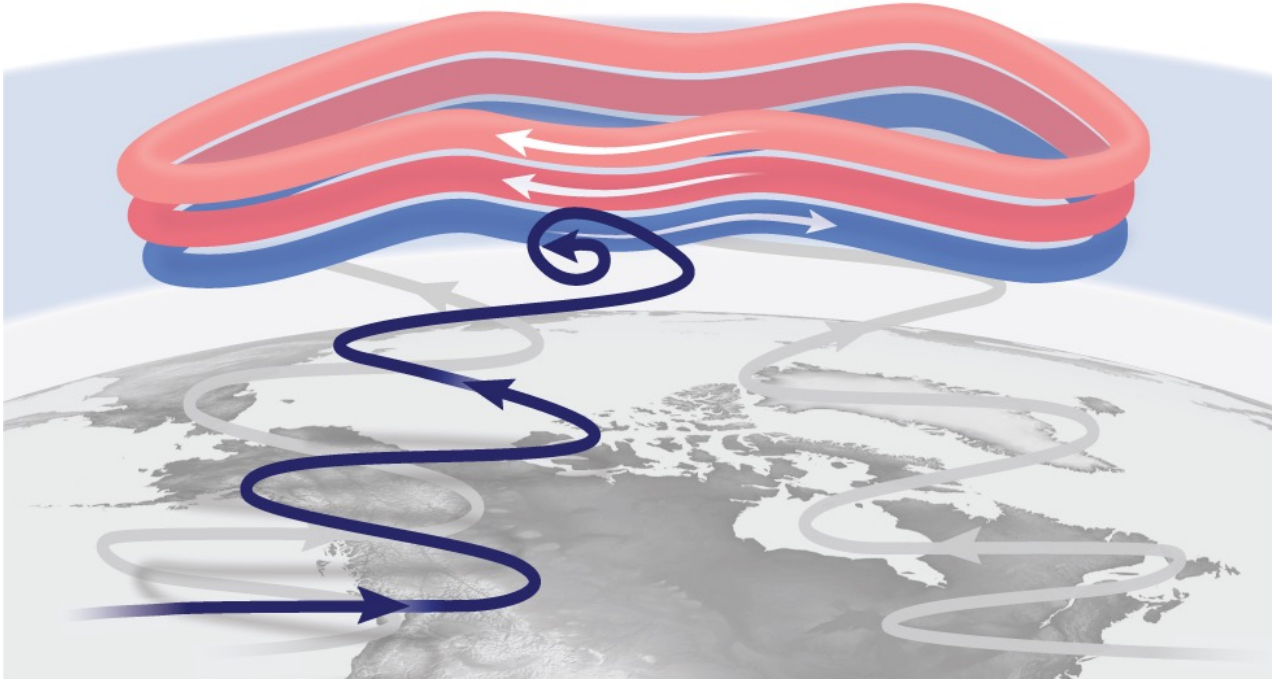


S2S models underestimate sensitivity of polar stratospheric winds to upward wave flux

Garfinkel et al. 2024, in prep

3) Downward coupling from the mid to lower stratosphere

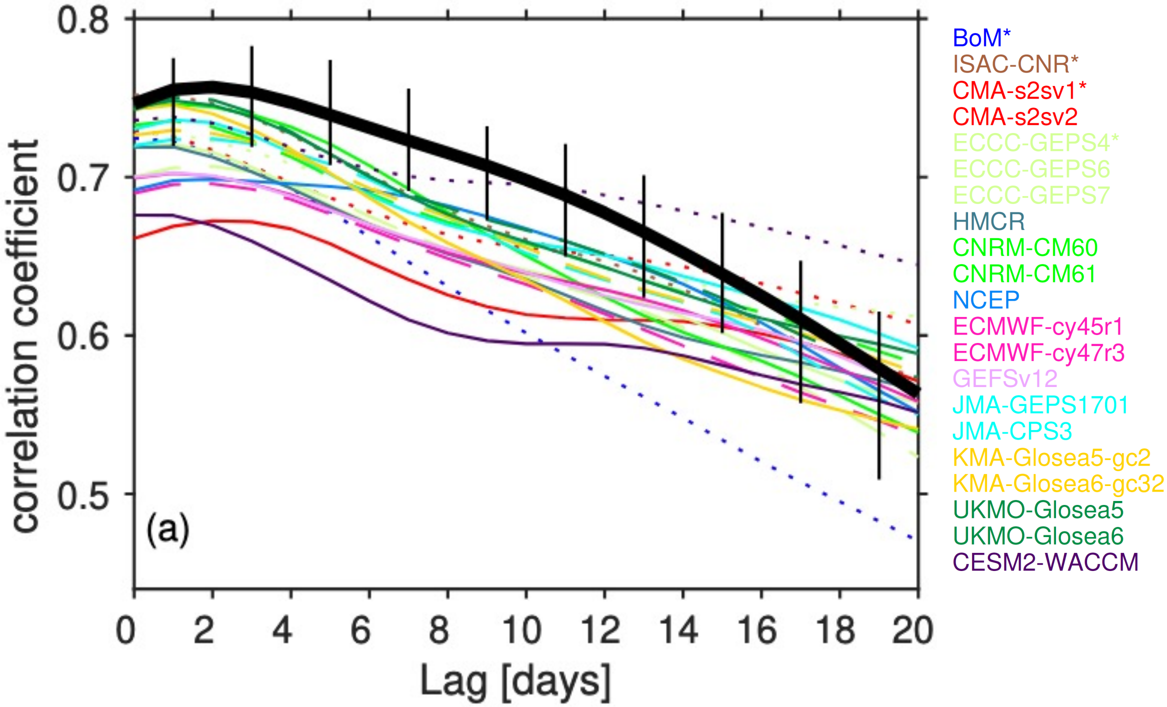
Planetary waves break at lower and lower altitudes in the stratosphere.



Wave-mean flow interactions drive the downward propagation of anomalies within the stratosphere.

From the NOAA Polar Vortex Blog on Climate.gov

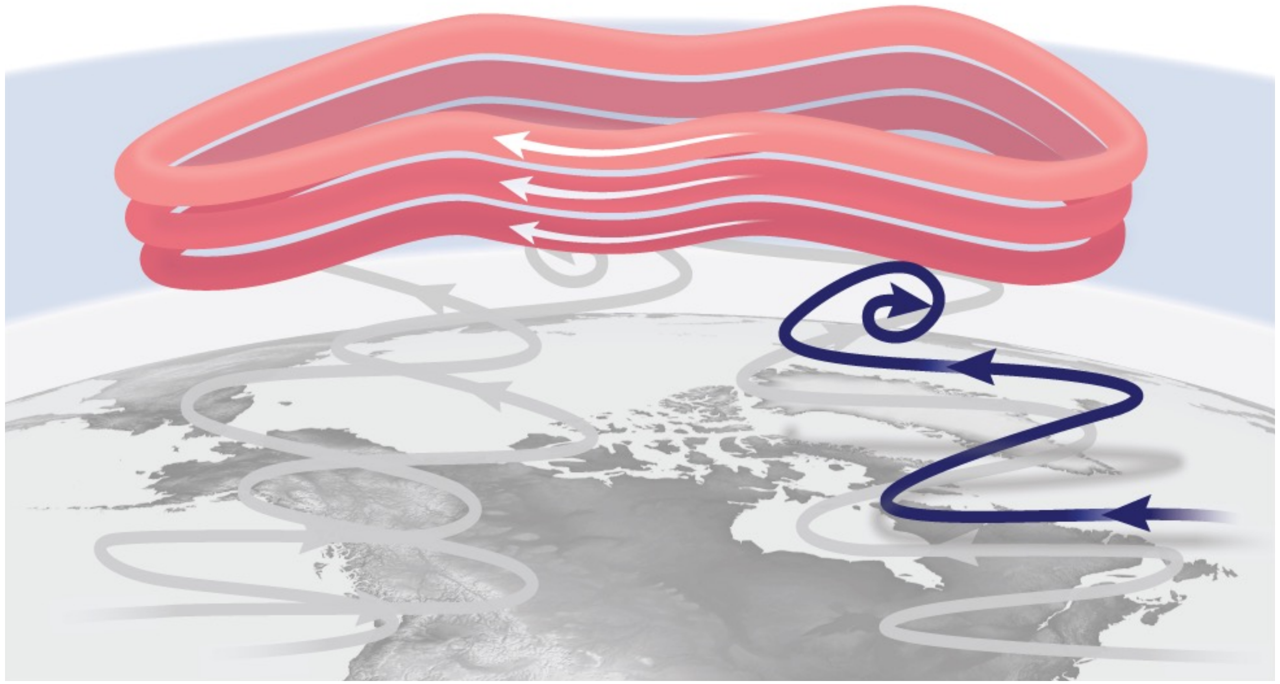
Correlation coefficient of 10 hPa polar-cap height (days 9-12), with 100 hPa polar cap height, DJF



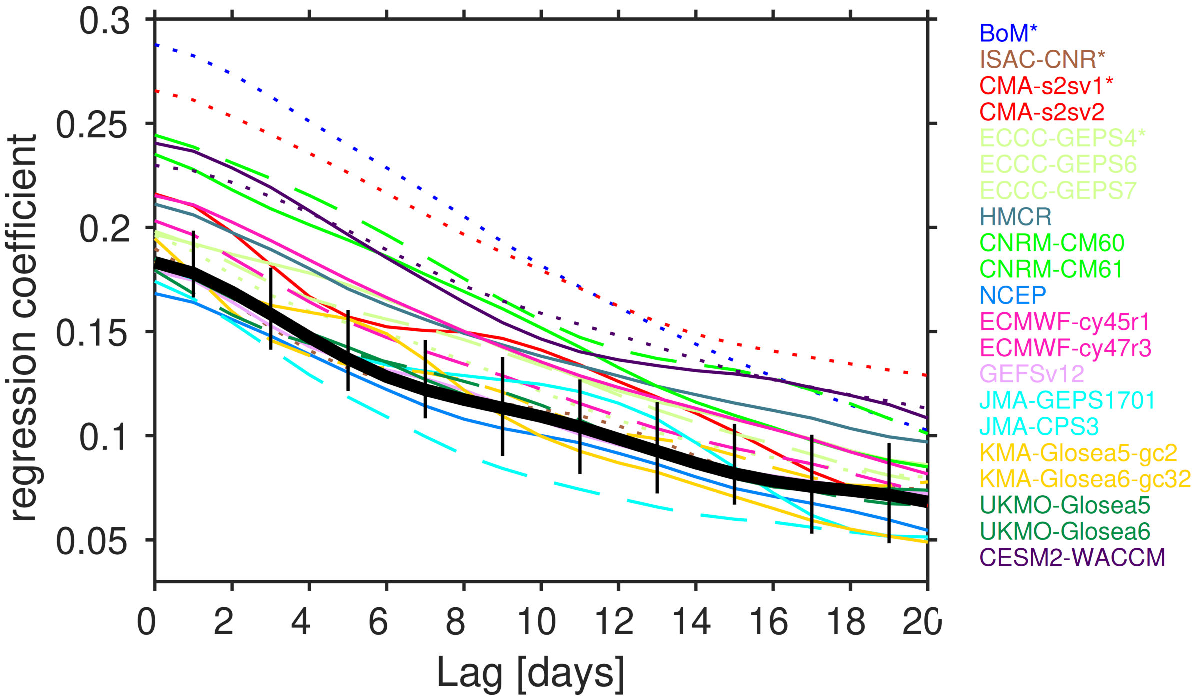
S2S models underestimate magnitude of downward coupling within the stratosphere.

Garfinkel et al. 2024, in prep

4) Downward coupling from the lower stratosphere to troposphere



Regression coefficient of 100hPa polar cap height (days 9-12) with 850hPa polar cap height, DJF



Persistent anomalies in lower stratospheric winds likely drive feedbacks with tropospheric eddies that affect weather patterns for weeks to months.

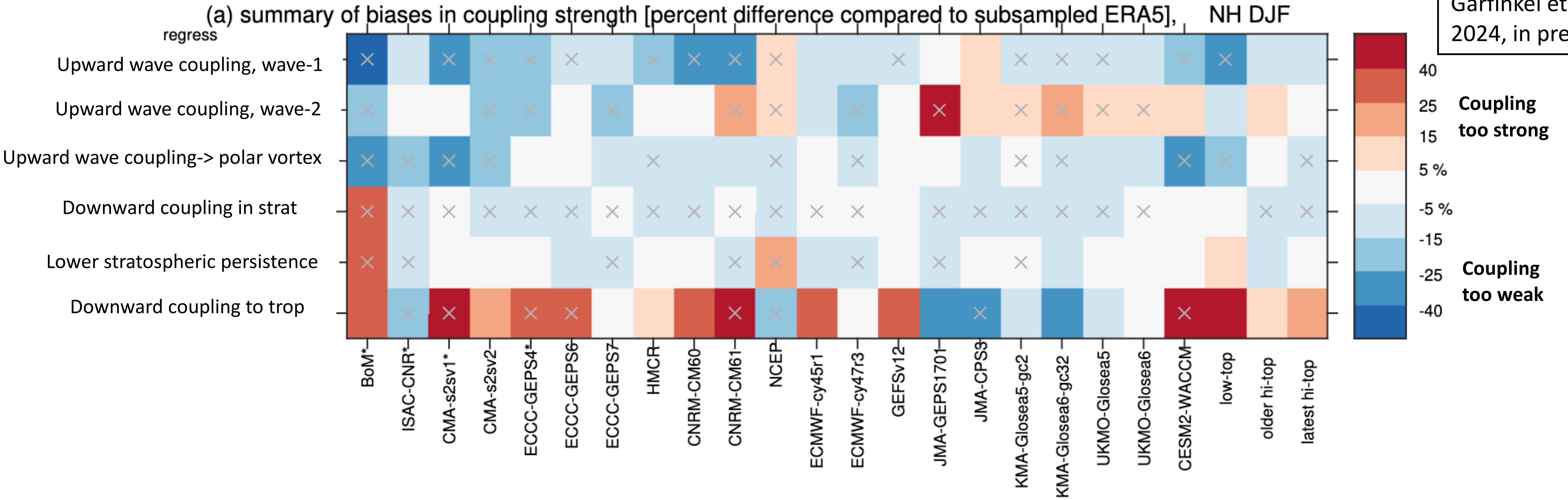
Some S2S systems overestimate downward coupling from the lower stratosphere to the surface (in part due to systematic positive bias in variance of 850 hPa polar cap heights)

From the NOAA Polar Vortex Blog on Climate.gov

Garfinkel et al. 2024, in prep

Summary of S2S model biases in stratosphere-troposphere coupling

Garfinkel et al. 2024, in prep



In the NH winter, most S2S models underestimate upward wave coupling and downward coupling within the stratosphere. A few models overestimate downward coupling to the lower troposphere.

Conclusions

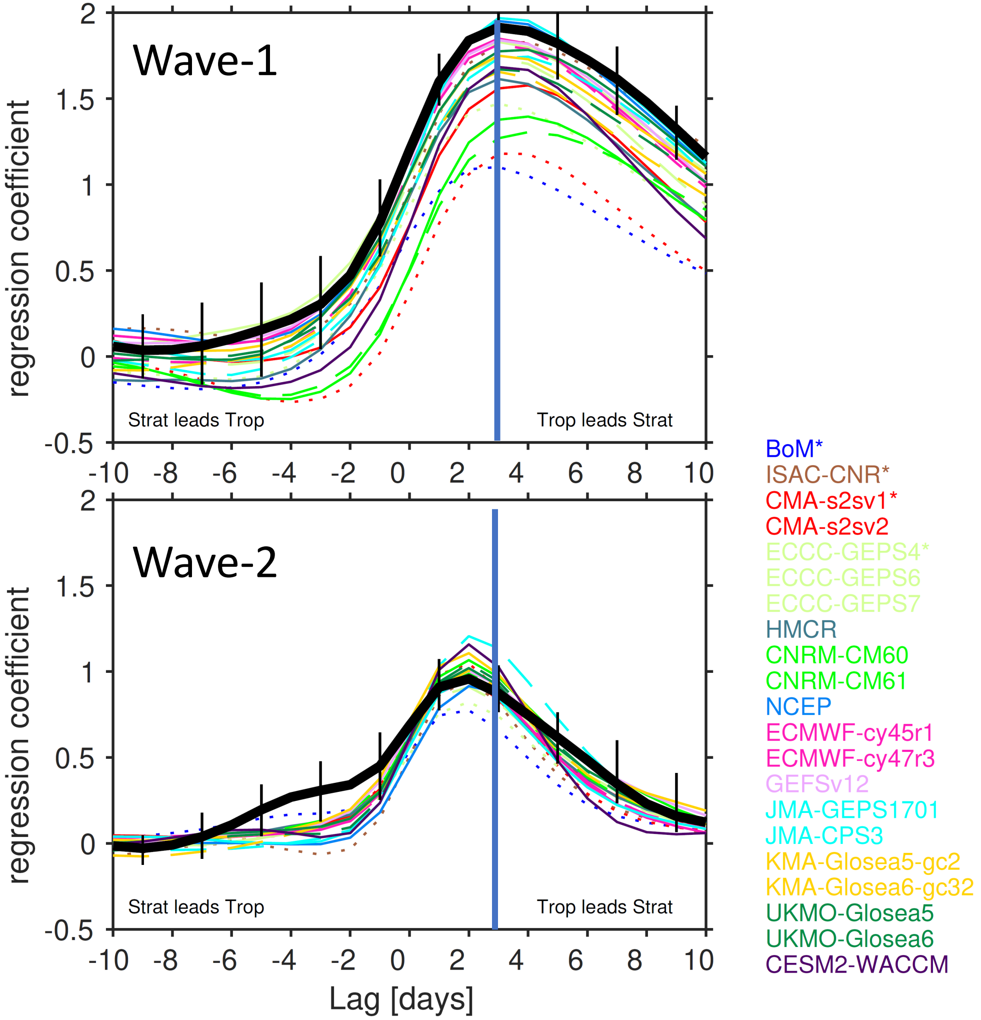
- The NH polar vortex in most S2S forecasting systems is insufficiently coupled to tropospheric variability.
- This result is consistent with the too-weak impact of predictable tropospheric modes of variability such as the Madden Julian Oscillation on the stratosphere (Garfinkel et al. 2020, Stan et al. 2022).
- We find that these processes are better captured in models with less bias in the climatological quasi-stationary waves and higher model tops.
- The implications of poor coupling for surface climate and predictability in specific regions where the stratosphere is known to have a large impact need to be explored.

Questions/Comments?

Contact: amy.butler@noaa.gov or chaim.garfinkel@mail.huji.ac.il

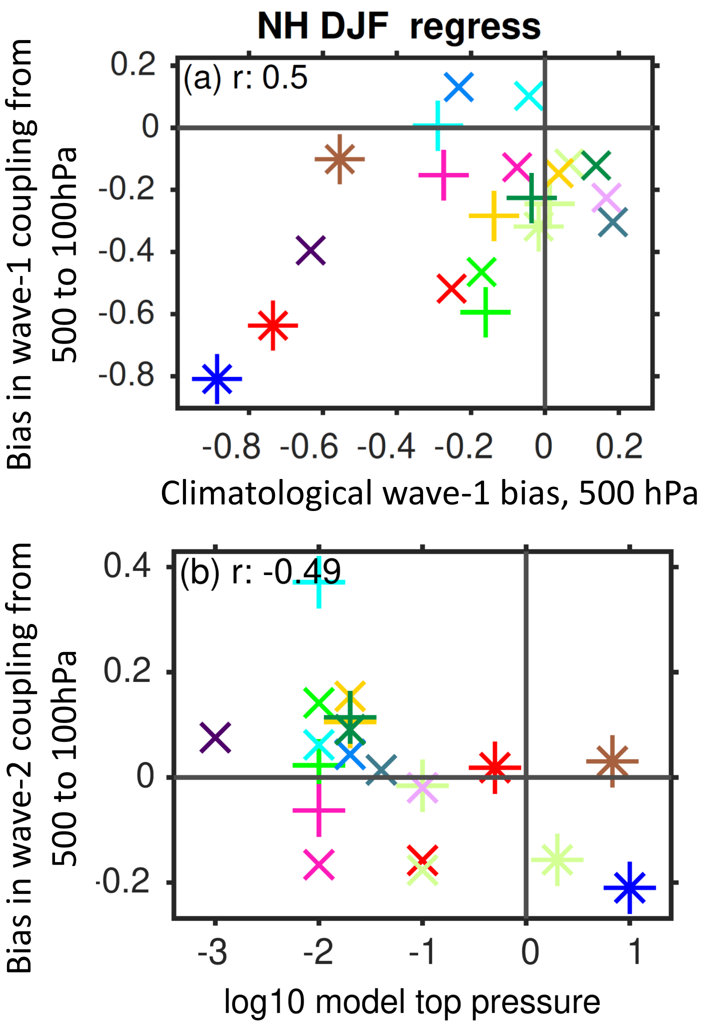
S2S models underestimate upward flux of atmospheric waves

Regression coeff of 500hPa heat flux (days 11-22) with 100hPa heat flux , DJF



Garfinkel et al. 2024, in prep

What explains intermodel spread in the regression coefficients?



Models with worse tropospheric quasi-stationary wave-1 biases tend to have too-weak wave-1 upward coupling.

Models with lower tops tend to have too-weak wave-2 coupling.