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# How stationary forcings shape Quasi-stationary waves

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## Background

- The time scales of quasi-stationary waves (QSWs) ranging from 14 days to one month, and the phase preference characteristic of QSWs (Fei and White, 2023), both imply potential links to stationary forcings
- On subseasonal time scales, low-frequency variabilities (LFVs) can develop from barotropic instability. The LFV pattern is influenced by zonal asymmetries, typically occurring over a time scale of approximately 50 days (Simmons, 1983)
- LFVs and QSWs might share a similar mechanism with similar but different (50 days vs. 20 days)time scales

## Data and experiments

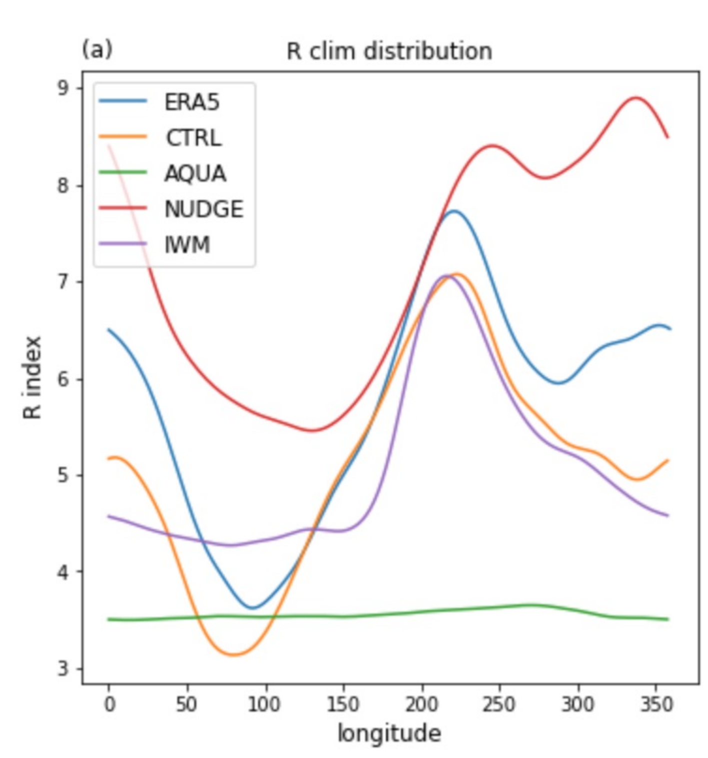
- ERA5 reanalysis: 1940-2022, 1*1 degree resolution
- Idealized experiments (four are shown) feature approximately 2° horizontal resolution, a 100-year run, and a full atmosphere model with

| Experiment name | prescribed SST | topography | land | other forcing |
|---|---|---|---|---|
| CTRL | control SST | real-world topo | real-world land | no nudging |
| IWM | zonally symmetric control SST | idealized mountain 30-60N | no land | no nudging |
| NUDGE | zonally symmetric control SST | no topo | no land | nudged real 3D U,V |
| AQUA | zonally symmetric control SST | no topo | no land | no nudging |

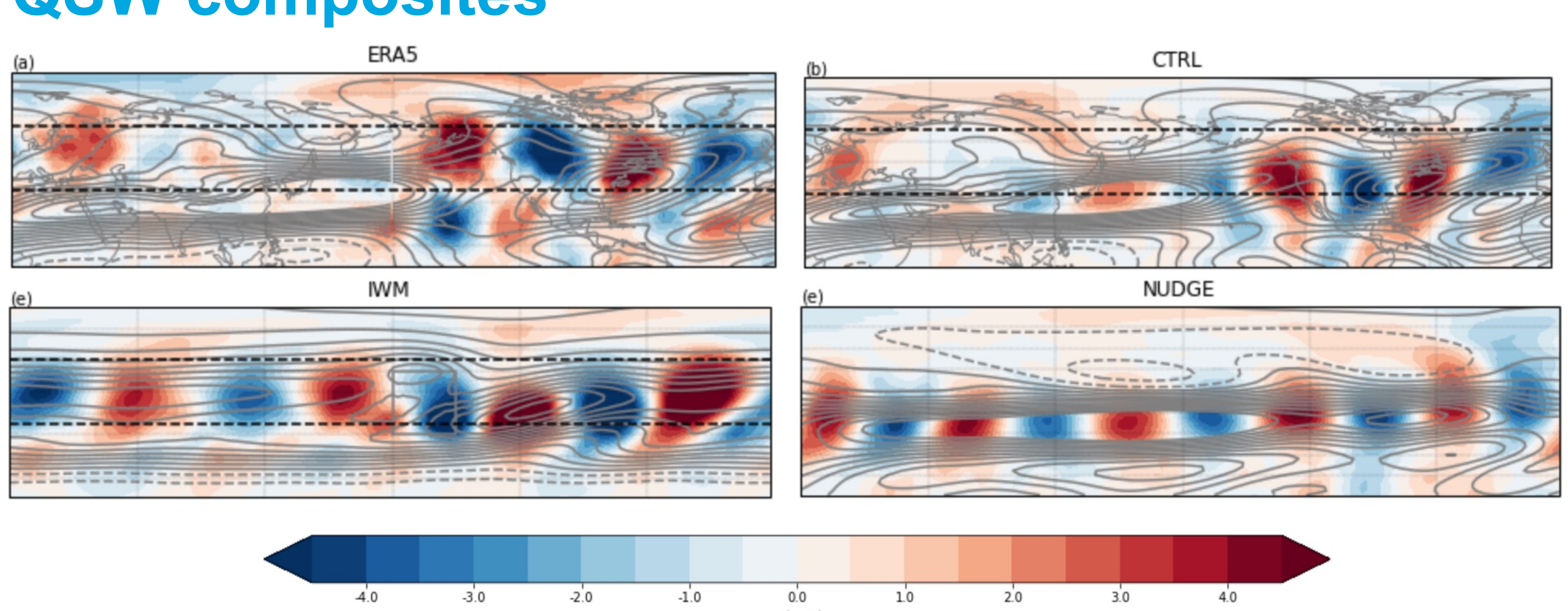
- The QSWs are defined based on the Fourier transform of a 15-day running mean of meridional wind averaged in 35N and 65N (Rothlisberger, 2019)
- Events are defined within different regions spanning a 60-degree longitudinal range, with a duration threshold of 8 days and an amplitude threshold based on the QSW metric mentioned above.

## R climatology

- CTRL reproduced the climatological distribution of QSWs in ERA5 effectively.
- **QSWs are amplified downstream of an idealized Gaussian water mountain in IWM** (180-150W,30-60N).
- There are QSWs in AQUA, though much weaker than in other experiments.




## QSW composites




*The shading shows the composite of meridional wind anomalies during North American QSW events, while contour lines show the climatological zonal wind. The black dashed line shows the 35N-65N range where the QSW metric is defined.*

**the asymmetry of the background flow is sufficient for QSWs to grow, rather than relying on stationary forcing**

## Summary

- Asymmetric background flow is sufficient to amplify QSWs.
- QSWs may develop from barotropic instability (**which, with the current metric, is not significantly different from barotropic waveguides**), leading to QSWs for about one week; baroclinic processes can help in their development in a secondary role.
- The phase preference ratio of QSWs is associated with the strength of stationary waves, though the relative importance of zonal and meridional wind may vary in different cases

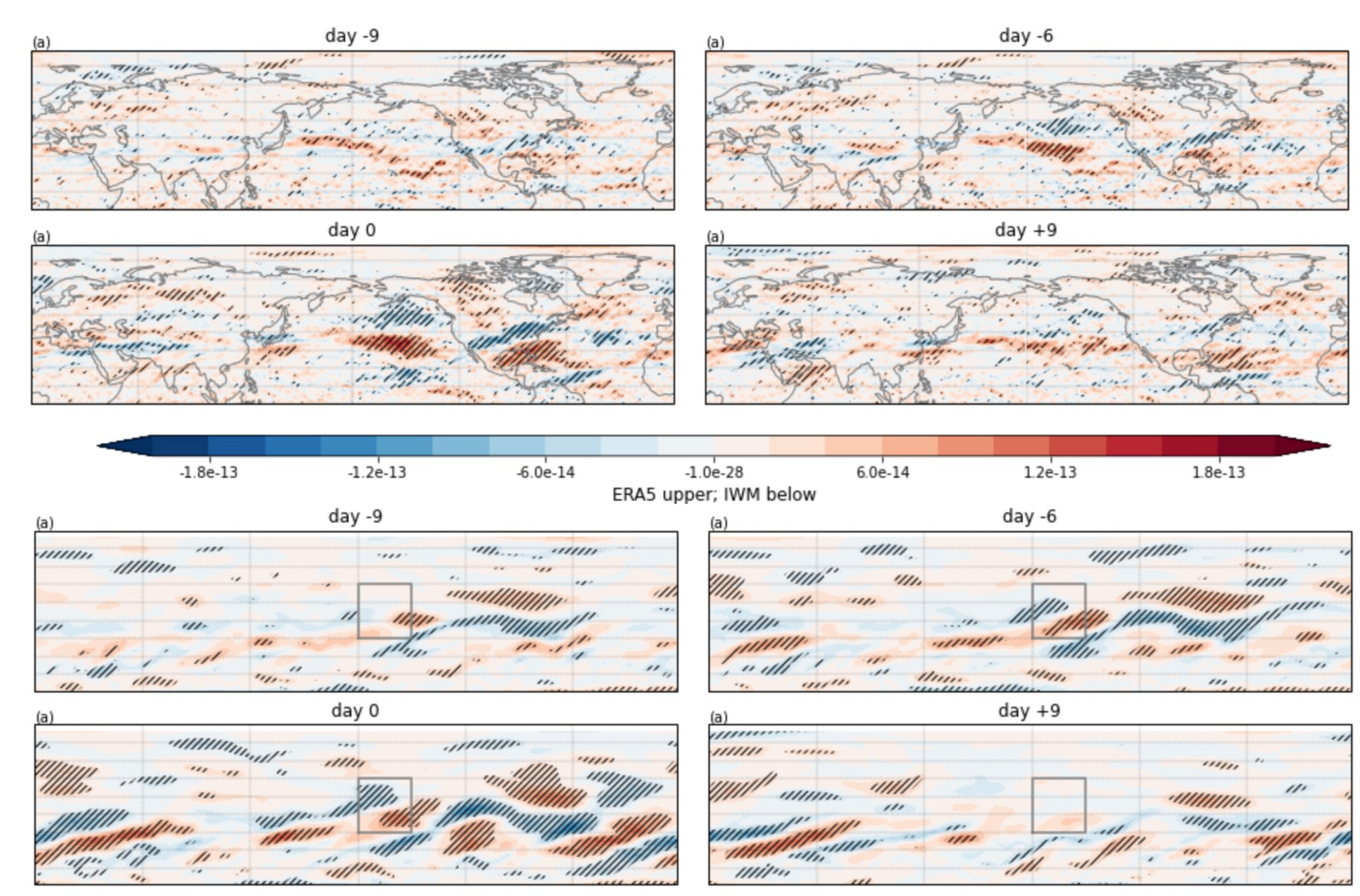
## QSW events and barotropic instability

$\frac{d\,f+\bar{\zeta}}{dy} = \beta - \frac{\partial^2 \bar{u}}{\partial y^2} = 0$ may imply barotropic instability

To clarify the time lead-lag relationship between QSW events and $\beta - U_{yy}$ we employ the following linear regression approach:

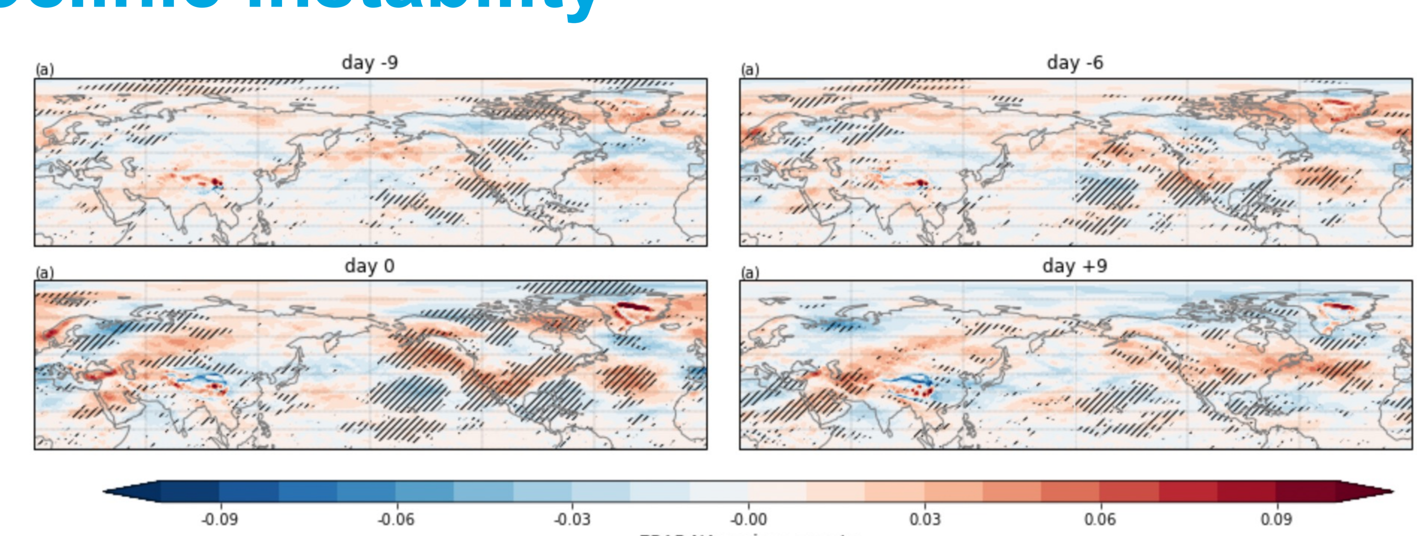
1. Compute the average meridional wind anomalies composite for each QSW event.
2. Perform EOF analysis on the meridional wind across different events
3. Conduct (lead-lag) linear regression with $\beta - U_{yy}$ anomalies (associated with barotropic instability) and meridional temperature gradient (associated with baroclinic instability) on PC1 of the EOF, representing the pattern of meridional wind composites.

The subtitle indicates the lead-lag time of the $\beta - U_{yy}$ signal to EOF PC1. Shading represents the regression slope, and dashed regions indicate significant regression. The top four plots display the regression in ERA5 composites, while the lower plots show the composite in IWM, both using the same colorbar




**In ERA5, IWM, and all other idealized experiments (not shown), the significant barotropic instability signal appears approximately one week before QSW events and diminishes around one week after their onset, indicating a robust causal relationship**.

## Baroclinic instability

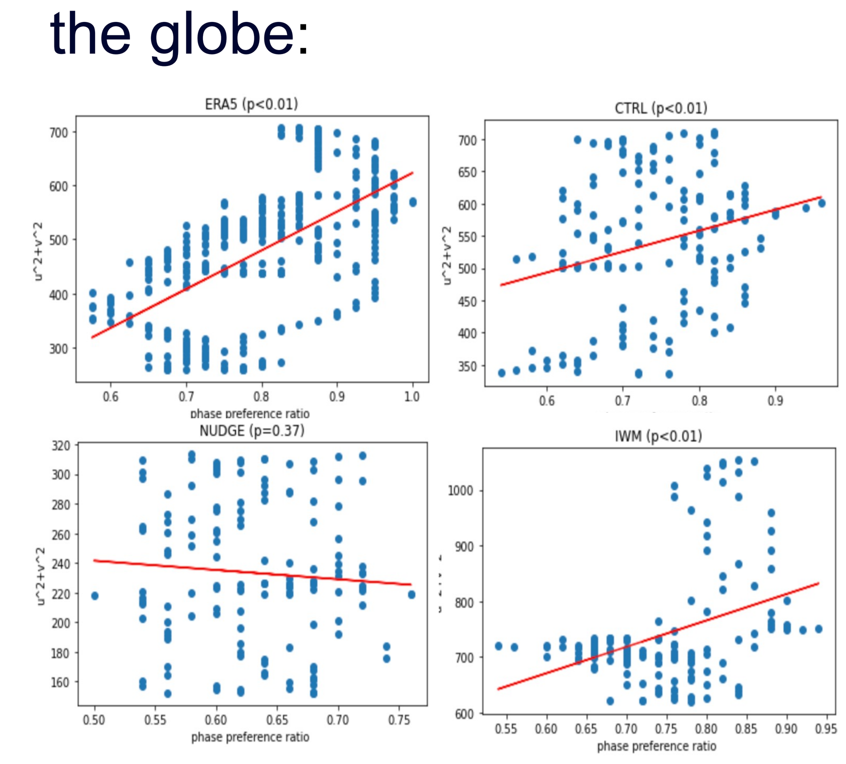



Similarly, the linear regression of the meridional temperature gradient at 700 hPa on EOF PC1 **becomes significant no earlier than the $\beta - U_{yy}$ and decays no later than the signal, suggesting the secondary role of baroclinic processes.**

## Phase preference ratio and stationary waves

We define the phase preference ratio by projection (Kim and Lee, 2022), in the 60-degree longitudinal range selecting events and repeat it around the globe:

$$\mathrm{SWI}(t) = \frac{\sum_i \sum_j \psi'^*(\lambda_i,\theta_j,t)\,\overline{\psi'}(\lambda_i,\theta_j,d)\,\cos(\theta)}{\sum_i \sum_j \left[\overline{\psi'}(\lambda_i,\theta_j,d)\right]^2 \cos(\theta)},$$




*The x-axis represents the phase preference ratio from 0 to 1, the y-axis is the sum of u^2 and v^2, representing the strength of stationary waves*

- In NDUGE, the regression is not significant. This may be due to the strong and circumglobal 'u' in NUDGE, where the effect of zonal asymmetries is predominantly represented by the 'v', which has much smaller values. The regression becomes significant if we use 'v^2' to regress on the ratio (not shown).
- Consequently, the strength of the stationary circulation is closely linked to the phase preference ratio, though it does not necessarily follow a linear relationship