How stationary are planetary waves in the Southern Hemisphere?

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Key Points:

- We devised a quantitative measure of planetary wave stationarity
- In the southern hemisphere, waves 2 and 3 have interseasonal and decadal variations in stationarity

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Abstract

Many studies of quasi-stationary planetary waves in the Southern Hemisphere (SH) assumed their quasi-stationary nature based on van Loon and Jenne (1972). However, that study considered only 2 years of data (1957-1958) before the advent of reanalysis datasets. In this study, we assessed the stationary conditions in the SH and contrasted it with that of the Northern Hemisphere using the NCEP/NCAR reanalysis from 1948 to 2017. We also devised a quantitative measure of planetary-wave stationarity. We confirm that in the SH planetary wave 1 is highly stationary. Planetary waves 2 and 3 have a comparable mixture of stationary and moving components with significant variability on interseasonal and decadal timescales. A deeper knowledge of those variations could help to better understand the the response of the mid-latitude atmospheric circulation to surface forcings, caused either by their strength, or the sensitivity of the atmosphere to them.

Plain language summary

Large-scale waves in the atmosphere can have stationary and travelling components. Many studies that focus on the stationary part assume their stationary nature based on the results of van Loon and Jenne (1972), which studied only 2 years of data (1957-1958) before the existence of modern reanalysis datasets. In this study we evaluated the stationarity nature of large-scale waves in the Southern Hemisphere in contrast with the Northern Hemisphere using the NCEP/NCAR reanalysis from 1948 to 2017. We also created a quantitative measure of wave stationarity. The results show that, in the Southern Hemisphere, waves with one maximum per latitude circle are highly stationary during the whole period and throughout the year. Higher frequency waves (2 or 3 maximums) have a comparable mix of stationary and travelling components that varies in between each season and between decades. These variations could mirror either variations in external factors or the sensitivity of the atmosphere to them.

1 Introduction

Zonal asymmetries of extratropical circulation in the Southern Hemisphere (hereafter called as "planetary waves") strongly modulate weather systems and regional climate through latitudinal transport of heat, humidity, and momentum (K. E. Trenberth (1980)). They may also contribute to the development of blocking events (e.g. K. F. Tren-

berth & Mo, 1985), for example, via quasi-resonant amplifications (Petoukhov, Rahmstorf, Petri, & Schellnhuber, 2013).

In Rossby wave theory, stationary waves are those with zero frequency or phase velocity (Holton & Hakim, 2012). In practice, however, most studies focusing on planetary waves in the Southern Hemisphere (HS) assumed their quasi-stationary nature based on van Loon and Jenne (1972). In this foundational study, the authors analyzed data only from two years, from 1957 and 1958 and found that while extratropical waves with wavenumber 1 to 6 had comparable amplitudes in daily fields, only wavenumbers 1 and 3 featured significantly in the climatological field. From that, they concluded that only waves 1 and 3 recur consistently in the same location and thus have a significant quasi-stationary component on top of a "moving" component. This was a qualitative conclusion and to our knowledge no further study has actually quantified the level of stationarity associated to each wavenumber.

Quantifying planetary wave stationarity in the van Loon and Jenne (1972) sense can be important both in forcasting and process understanging. On one hand, stationary planetary waves mihgt be more predictable than their non-stationary counterpart and on the other, the degree of stationarity is probably an indication of the sensitivity to external forcings. Moreover, it has also methodological implications. For example, interpretation of correlations and regressions between planetary wave amplitudes and other atmospheric and surface variables (e.g. Turner, Hosking, Bracegirdle, Phillips, & Marshall, 2017) are only straightforward in the case of highly stationary planetary waves.

After more than four decades from the publication of van Loon and Jenne (1972), and considering the current availability of different global reanalysis datasets, in this study we assess the stationarity features of planetary waves in the SH. Also, we extend van Loon and Jenne (1972)'s study, deriving a methodology that provides a quantitative measure of planetary wave stationarity. We apply it to both hemispheres.

2 Methods

2.1 Planetary waves

We define *planetary waves* as waves that extend along a full latitude circle. *Zonal waves* (ZW) are planetary waves of the "instantaneous" fields and *quasi-stationary waves* (QS), planetary waves of the time-mean field such that:

$$\text{ZWk}(t) \quad = \quad A_{\text{ZWk}}(t) \cos\left[k\lambda - \alpha_{\text{ZWk}}(t)\right] \tag{1}$$

$$\overline{\text{ZWk}(t)} = \text{QSk} \quad = \quad A_{\text{QSk}} \cos\left(\text{k}\lambda - \alpha_{\text{QSk}}\right) \tag{2}$$

where k is wavenumber, λ longitude, and A_{ZWk}, α_{ZWk} A_{QSk} and α_{QSk}, are the amplitudes and phases of each wave. ZWk(t) depends on time, but not QSk. Quasi-strationary waves could be more correctly called "climatological planetary waves", but we chose this name for consistency with some of the previous literature (e.g. Quintanar & Mechoso, 1995b; Turner et al., 2017). While these definitions can, in principle, be applied to any wavenumber, only long waves are considered true planetary waves and thus here we limit our analysis to weavenumbers 1 to 3.

These definitions depend on which are the "instantaneous fields" and the averaging time-scales. For example, a dataset of 365 daily mean fields defines 365 daily zonal waves and one annual quasi-stationary wave as well as 12 monthly quasi-stationary waves (per level and latitude). On the other hand, a 30-year dataset of monthly mean fields defines 360 monthly zonal waves and one 30-year quasi-stationary wave. While monthly planetary waves are quasi-stationary waves in the first case, they are zonal waves in the second. The latter shows that the definition of quasi-stationary waves depends on the temporal sampling considered.

2.2 Stationarity

From the properties of the superposition of waves we can deduce that, in general, the stationary phase α_{QSk} does not equal $\overline{\alpha_{\text{ZWk}}}$, and that the stationary amplitude A_{QSk} is less or equal to $\overline{A_{\text{ZWk}}}$ (Pain, 2005). We use this latter property and use the quotient between A_{QSk} and $\overline{A_{\text{ZWk}}}$ to define, for each wavenumber k, a measure of quasi-stationary wave stationarity:

$$\hat{S}_k = \frac{A_{\text{QSk}}}{\overline{A_{\text{ZWk}}}} \tag{3}$$

For a sample of n completely random waves, the expected value of $\hat{S}$ is $n^{-1/2}$ because the average amplitude of the sum of n waves with random phases and mean amplitude A is $An^{-1/2}$ (Pain, 2005). For completely stationary waves, $\hat{S}$ is equal to 1 regardless of sample size.

Some studies consider $\hat{S}$ as $2/\pi \arcsin\left(\hat{S}\right)$ (Singer, 1967) for analyzin wind steadiness (e.g Hiscox, Miller, & Nappo, 2010). To our knowledge this is the first time that this approach is applied to study atmospheric waves.

$\hat{S}$ could be equivalent formulated as

$$\hat{S}_k = \frac{\sum_t A_{\mathrm{ZWk}}(t)\cos\left[\alpha_{\mathrm{ZWk}}(t) - \alpha_{QSk}\right]}{\sum_t A_{\mathrm{ZWk}}(t)} \tag{4}$$

The numerator represents the sum of the zonal waves amplitudes projected onto the direction of the quasi-stationary wave. Waves that deviate from that direction decrease the overall stationarity in proportion to their amplitude. This definition of stationarity depends on the phase distribution and its relationship with amplitude. As it does not depend on the propagating properties of waves, it's a statistical –rather than dynamical– property.

We used Equation 4 to compute a timeseries of quasi-stationary wave stationarity. We first calculated α_{QSk} for each month and then applied Equation 4 with a 15-year rolling window approximated using loess regression with degree 0.

A variety of indices that are used in the literature to study zonal waves / planetary waves. Raphael (2004) explicitly defined a "zonal wave 3 index" based on averaging the (temporal) anomalies of the three-monthly geopotential height mean at three points that roughly coincide with the position of the climatological zonal wave 3 ridges. Turner et al. (2017), on the other hand, used the fourier amplitude of the wave 3. To make these indices more intercomparable between themselves and our data, we replicate them with slight diferences. We compute Raphael (2004) baed on monthly means instead of three-monthly means and we compute Turner et al. (2017)'s fourier amplitude at 50S instead of using the mean geopotential height between 55S and 65S.

2.3 Data

We use monthly geopotential height fields from the NCEP/NCAR Reanalysis (Kalnay et al., 1996) for the period 1948 to 2017 and compute one quasi-stationary wave for the whole period for each month, level and wavenumber. Amplitude and phase for each wavenumber was estimated by fitting a fourier transform to the mean geopotential height between 45\degree and 65\degree South and North for each level and monthly record. For com-

128 parison, we also analyzed data from ERA-Interim (Dee et al., 2011) and ERA-20C (Poli

129 et al., 2016).

130 We analyzed the data using the statistical programming language R (R Core Team,

131 2018), using data.table (Dowle & Srinivasan, 2018) and metR (Campitelli, 2018) pack-

132 ages to read and transform it and ggplot2 package (Wickham, 2016) to make the plots.

133 The source code is available as Figshare repository (Campitelli, 2019).

3 Results

135 Figure 1 shows the seasonal cycle of the amplitude of planetary waves N based on

136 monthly mean geopotential height fields computed between 1948 and 2017. We computed

137 the left column (A_{QS}) as the amplitude of the average geopotential height field for each

138 month, level and wavenumber, and the right column ($\overline{A_{\mathrm{ZW}}}$) as the average amplitude

139 of the 70 individual fields.

140 Figure 1a shows that in the Northern Hemisphere A_{QS} and $\overline{A_{\mathrm{ZW}}}$ have a similar sea-

141 sonal cycle with similar vertical extent for the three wavenumbers. In the Southern Hemi-

142 sphere this is true only for wavenumber 1 (Figure 1b). However, A_{QS2} has much lower

143 values than $\overline{A_{\mathrm{ZW2}}}$ and its seasonal cycle is less defined. Moreover, A_{QS3} has a smaller

144 magnitude than $\overline{A_{\mathrm{ZW3}}}$ and even though their overall structure is similar (one relative max-

145 imum in February-March in the middle troposphere and another in July-August that ex-

146 tends to the lower stratosphere), they differ in the details. A_{QS3} has a local minimum

147 in November that is absent in $\overline{A_{\mathrm{ZW3}}}$. The relative contribution of each wavenumber is

148 also different. While $\overline{A_{\mathrm{ZW2}}}$ dominates over $\overline{A_{\mathrm{ZW3}}}$ in the stratosphere and is of similar

149 magnitude in the troposphere, A_{QS3} dominates over A_{QS2} throughout the year and in

150 every level except in the aforementioned November minimum.

151 The differences between A_{QS} and $\overline{A_{\mathrm{ZW}}}$ are quantified in Figure 2, which shows $\hat{S}$

152 for wavenumbers 1 to 3 computed using Equation 3.

153 In the Nothern Hemisphere, planetary waves 1, 2 and 3 are highly stationary in al-

154 most every month and level, and even more so planetary wave 1 in the Southern Hemi-

155 sphere.

156 In the SH, planetary wave 2 stationarity has a semiannual cycle. It reaches its max-

157 imum in April and in August-September, decreasing to a deep minimum centered in June.

On the other hand, planetary wave 3 stationarity peaks in February and slowly decreases towards a November deep minimum after which increases sharply.

As we computed $\hat{S}$ using the whole period for Figure 2, it represents the mean stationarity between 1948 and 2017. So, to analyse stationarity chances over time, we computed $\hat{S}$ using 10-year overlapping intervals for each wavenumber at both studied latitudes (Figure 3). Planetary wave stationarity remained high and constant for wavenumbers 1 to 3 in the Northern Hemisphere and 1 in the Southern Hemisphere but wavenumbers 2 and 3 in the Southern Hemisphere show interdecadal variations. Planetary wave 2 stationarity oscillated around 0.3 with maximums in the 50's, 70's and 00's. Planetary wave 3 stationarity jumped from zero to more than 0.5 in less than five years in the 50's and then oscillated around 0.6 with a strong maximum in the late 80's.

The study was also made using ERA Interim reanalysis and the results for the overlapping period are similar (not shown). The latter lends some credence the observed decadal variations not being an artifact of the reanalysis model. However, the sudden shift in planetary wave 3 stationarity observed between 1950 and 1960 is probably spurious and we couldn't find it using data from ERA 20C (not shown).

3.1 Comparison with other indices

(This needs to be integrated)

Figure 4 shows the relationship between the amplitude of the projection of the zonal wave 3 onto the climatological wave 3 and two zonal wave indeces propsed in the literature. Raphael (2004)'s index is highly correlated with ours (correlation = 0.73) and the relationship is quite linear in nature. Negative values of Raphael (2004)'s index are generally associated to zonal waves with negative projection onto the climatological mean. The main difference between Raphael (2004)'s index is that it consideres temporal anomalies instead of zonal anomalies. Computing the index using zonal anomalies instead increases the correlation to 0.95.

The relationship with Turner et al. (2017)'s approach is very different. While the correlation is not low (0.59), but the relationship is far from linear. Mainly, Turner et al. (2017)'s index fails to capture the fact that in a considerable number of dates, zonal wave 3 has a big amplitude but with negative centers where climatologically there are

positive centers. Since this leads to oposite patterns of circulation, corrlations derived from this index are not physically meaningful.

4 Conclusions

We assessed the stationarity levels of planetary waves at both hemispheres using different quantitative measures. We confirmed that planetary wave stationarity associated with SH planetary wave 1 is high and constant throughout the year and period. Instead stationarity levels for both waves 2 and 3 vary on intraseasonal and interdecadal timescales. On the other hand, as it was described in the literature, planetary wave stationarity in the Northern Hemisphere is higher and varies much less.

Planetary waves can be both forced by the surface and excited by internal variability. Assuming that the later process will not result in a phase preference, higher stationarity would be evidence of stronger forcing or, more strictly, stronger response. In the Northern Hemisphere, topography and thermal contrasts are the main forcings of planetary waves (Chen & Trenberth, 1988), which explains their highly and not variable stationary nature. In the SH, only planetary wave 1 seems to be the result of mainly surface forcings. Planetary waves 2 and 3 seem to be a product of internal variability and surface forcing components in similar magnitude.

Since in the SH the amplitude of the mean planetary wave can differ greatly from the mean amplitude of planetary waves, care must be taken when interpreting the literature. Some studies analyze the former (e.g. van Loon & Jenne, 1972, Quintanar and Mechoso (1995a), Raphael (2004)) while others analyze the later (e.g. Rao, Fernandez, & Franchito, 2004, Turner et al. (2017), Irving and Simmonds (2015)). For instance, Irving and Simmonds (2015) compare their planetary wave activity index with Raphael (2004)'s wave 3 index and conclude that the later cannot account for events with waves far removed from their climatological position. However, being an index of the zonal wave component in phase with the quasi-stationary wave, this is by design.

The explorations of both zonal waves and quasi-stationary waves can lead to novel levels of analysis. For example, Smith and Kushner (2012) used their phase relationship to show that linear interference between the zonal waves 1 and quasi-stationary wave 1 was related to vertical wave activity transport at the tropopause. Here, we showed it can

be used to define a metric of stationarity of quasi-stationary waves, but other applications are also possible.

A deeper knowledge of interseasonal and decadal variations in planetary wave stationarity could help to better understand the variability in the responses of mid-latitudes atmospheric circulation to surface forcing caused either by the strength of the forcing or the sensitivity of the atmosphere to the forcing.
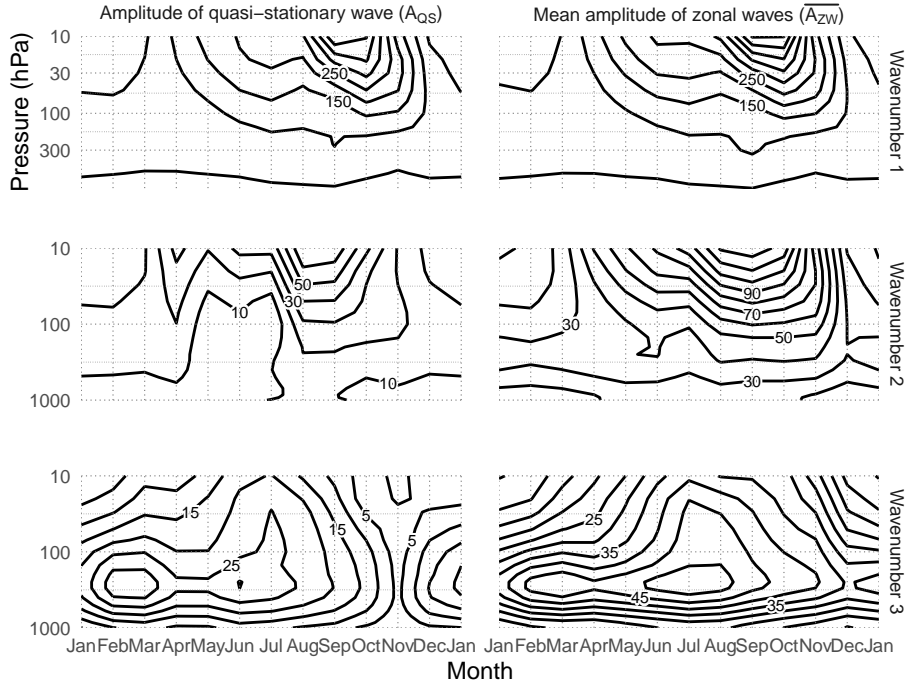
Acknowledgments

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Amplitude of quasi–stationary wave (A$_{QS}$)   Mean amplitude of zonal waves ($\overline{A_{ZW}}$)

(a) Northern Hemisphere.

Amplitude of quasi–stationary wave (A$_{QS}$)   Mean amplitude of zonal waves ($\overline{A_{ZW}}$)
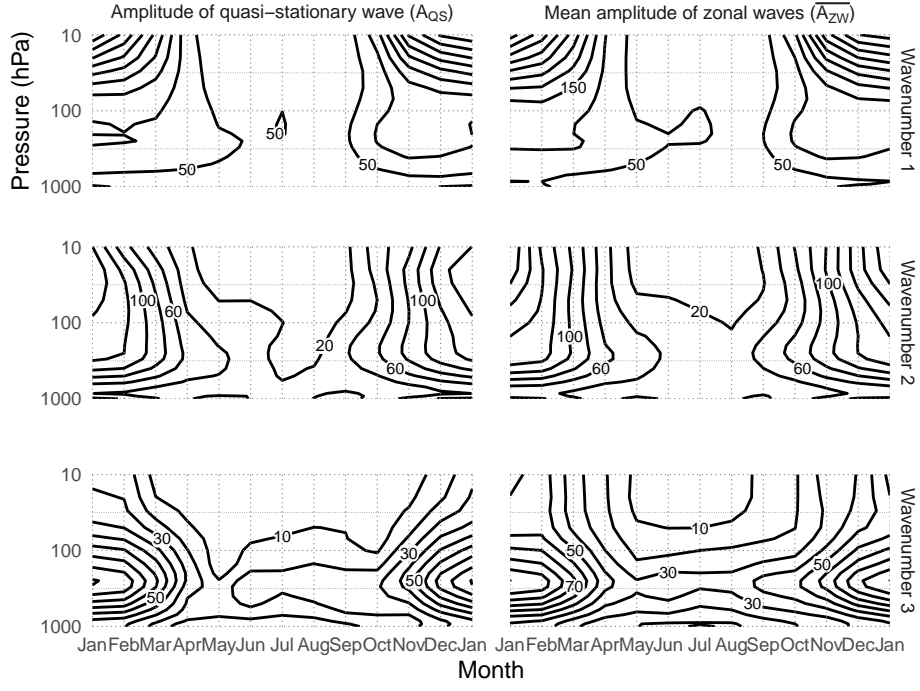
(b) Southern Hemisphere.

Figure 1: Seasonal cycle of amplitude of the geopotential height planetary waves 1, 2 and 3 (top, middle and bottom rows, respectively) computed as the amplitude of the mean wave (A_{QSk}, left column) and the mean amplitude of the monthly waves ($\overline{A_{ZW}}$, right column) in meters.
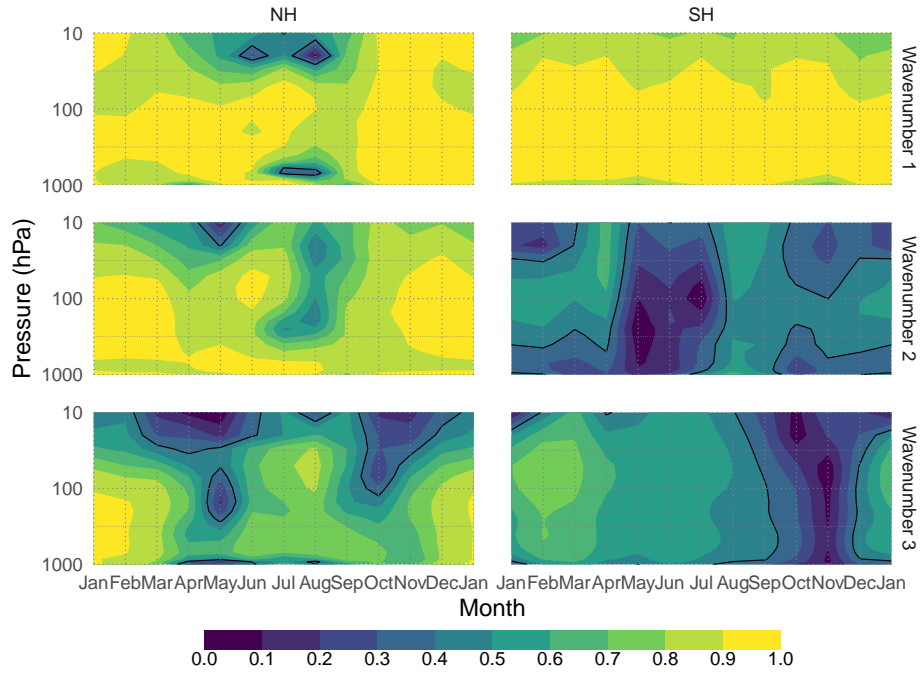
Figure 2: Seasonal cycle of stationarity of the geopotential height planetary waves 1, 2 and 3 (top, middle and bottom rows, respectively) at 50°N and 50°S (left and right columns, respectively) computed using Equation 3. The black line marks $\hat{S} = 0.4$ for reference.
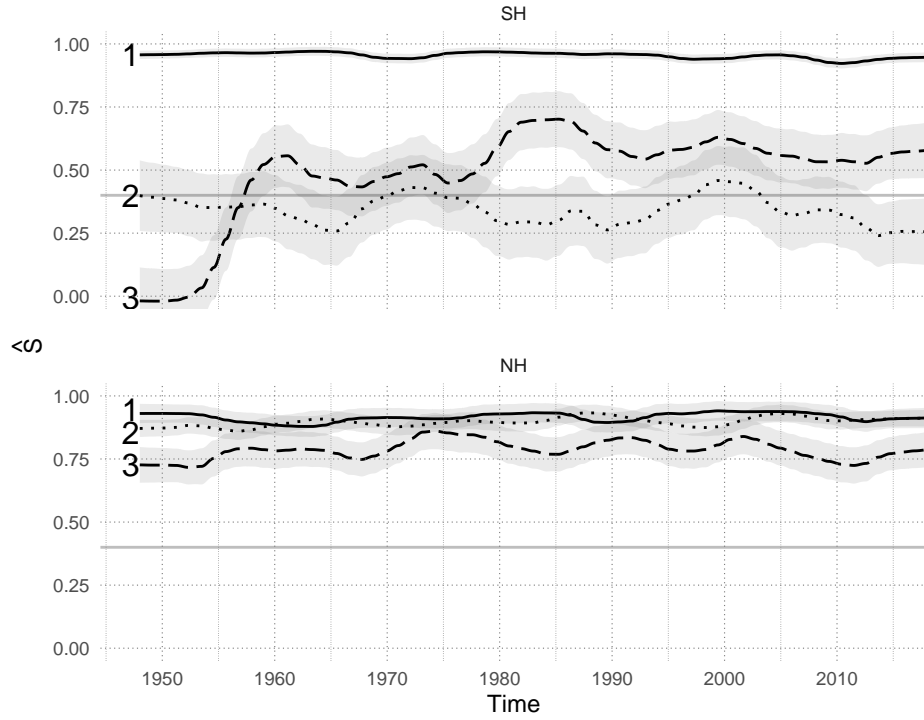
Figure 3: Stationarity for wavenumbers 1 to 3 at 50°N and 50°S (top and bottom panels, respectively) at 500hPa.
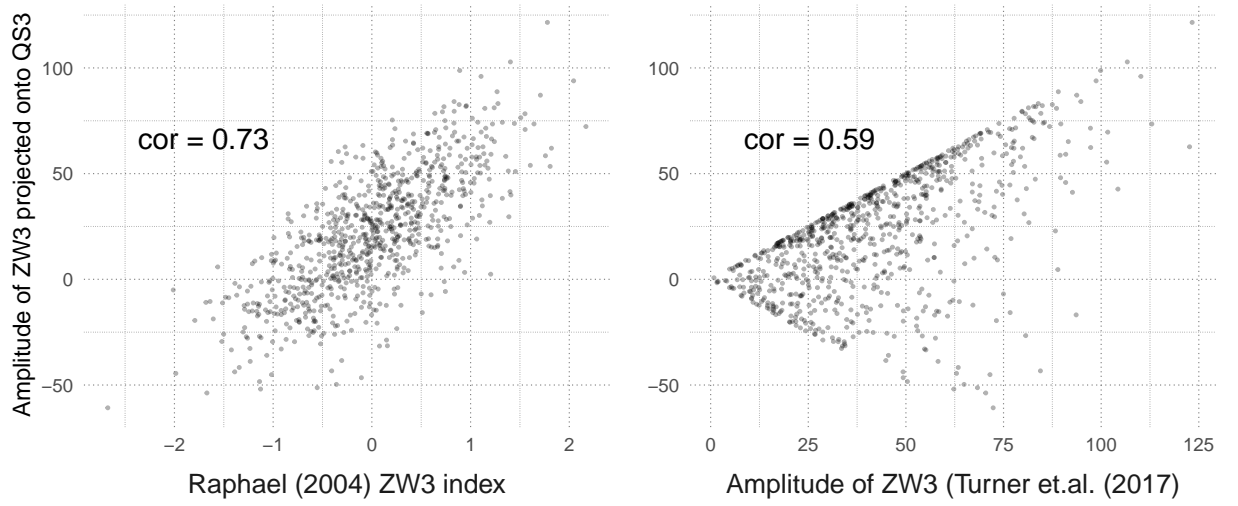

Figure 4: Raphael (2003) and Turner et.al. indices compared with the amplitude of the zonal wave projected onto the climatological zonal wave. All of them computed at 500hPa and 50°S.