How stationary are planetary waves in the Southern Hemisphere?

Elio Campitelli [1] Carolina Vera [1,2] Leandro Díaz [1,2]

[1]Centro de Investigaciones del Mar y la Atmosfera, UMI-IFAECI (CONICET-UBA-CNRS)
[2]Departamento de Ciencias de la Atmósfera y los Océanos (FCEyN, UBA)

Key Points:

- Zonal waves and Quasi-stationary waves are disctinct but related phenomena
- This distinction has theoretical and practical implications
- The relationship between the mean ZW amplitude and QS amplitude yields an estimate of stationarity

Corresponding author: Elio Campitelli, `elio.campitelli@cima.fcen.uba.ar`

Abstract

Abstract goes here

1 Introduction

Zonal waves, also called planetary waves, that can develop in the extratropical latitudes of the Southern Hemisphere (SH), have received some attention by the scientific community because of its role in modulating weather systems and regional climate (xxREF). Researches typically characterize them by applying Fourier decomposition to hemispheric anomalies of sea-level pressure or geopotential heights. On the other hand, "stationary waves" or "quasi-stationary waves" are terms generally reserved in the literature to the zonal asymmetries of the time mean field ($\overline{\phi}^*$).

van Loon and Jenne (1972) called the zonal asymmetries in the time-mean southern hemisphere geopotential "standing waves" and distinguished them from the asymmetries of the daily fields, which he called "daily waves". Other studies use different terminology: Quintanar and Mechoso (1995) and Rao, Fernandez, and Franchito (2004) called them "quasi-stationary waves", Turner, Hosking, Bracegirdle, Phillips, and Marshall (2017) used "planetary waves" as a synonym, and Raphael (2004) and Irving and Simmonds (2015) called them "zonal waves". Kravchenko et al. (2012) and Lastovicka, Krizan, and Kozubek (2018) used the terms "quasi-stationary waves" and "stationary planetary waves", respectively, but in reference to waves in the individual fields (the "daily waves", following van Loon and Jenne (1972) terminology).

These studies also use different methods. van Loon and Jenne (1972) and Quintanar and Mechoso (1995) averaged the fields and then computed the wave amplitude, while Rao et al. (2004) and Turner et al. (2017) computed the wave amplitudes of the individual fields and then averaged the amplitudes. Raphael (2004) and Irving and Simmonds (2015) constructed indexes of the amplitude of planetary waves, but the former one is sensitive to waves in phase with the mean wave, while the latter captures all waviness irrespective of phase.

Quasi-stationary waves arise from the superposition of individual "daily waves" with similar phase. However, no recent studies assessed *how* similar, and thus, how "stationary" are "quasi-stationary" waves.

In this study we distinguish between quasi-stationary waves and zonal waves and show that the mean amplitude of zonal waves differ from the amplitude of quasi-stationary waves. We exploit this difference to construct a measure of quasi-stationary wave stationarity and show that planetary waves with wavenumbers 2 and 3 are significantly less stationary in the southern hemisphere than in the northern hemisphere.

2 Methods

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:

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

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

where k is wavenumber, λ longitude, and $\mathrm{A_x}$ and α_{x}, amplitude and phase, respectively. ZWk(t) depends on time, but not QSk. From the properties of wave superposition we can deduce that, in general, the stationary phase α_{QSk} does not equal $\overline{\alpha_{\mathrm{ZWk}}}$ and the stationary amplitude A_{QSk} is less or equal $\overline{A_{\mathrm{ZWk}}}$ (Pain, 2005).

These definitions depend on which are the "instantaneous fields" and the averaging time-scales. A dataset of 365 daily mean fields defines 365 daily zonal waves and 1 annual quasi-stationary wave but 12 monthly quasi-stationary waves (per level and latitude). A 30 year dataset of monthly mean fields define 360 monthly zonal waves and 1 30-year quasi-stationary wave. Monthly planetary waves are quasi-stationary waves in one case and zonal waves in the other.

Here we use monthly geopotential 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.

3 Results

Figure 1 shows the seasonal cycle of the amplitude of planetary waves at 50°S and 50°N using monthly fields from the NCEP/NCAR reanalysis (Kalnay et al., 1996) between 1948 and 2017. We computed the left column (A_{QS}) as the amplitude of the average geopotential field for each month, level and wavenumber, and the right column ($\overline{A_{\mathrm{ZW}}}$) as the average amplitude of the 70 individual fields.

Figure 1a shows that at 50°N for the three wavenumbers A_{QS} and $\overline{A_{\mathrm{ZW}}}$ have a similar seasonal cycle with similar vertical extent. In the southern hemisphere, however, this is true only for wavenumber 1 (Figure 1b). A_{QS2} is much smaller than $\overline{A_{\mathrm{ZW2}}}$ and its seasonal cycle is less defined. A_{QS3} has a smaller magnitude than $\overline{A_{\mathrm{ZW3}}}$ end even though their overall structure is similar (one relative maximum in February-March in the middle troposphere and another in July-August that extends to the lower stratosphere), they differ in the details. A_{QS3} has a local minimum in November that is absent in $\overline{A_{\mathrm{ZW3}}}$. The relative contribution of each wavenumber is also different. While $\overline{A_{\mathrm{ZW2}}}$ dominates over $\overline{A_{\mathrm{ZW3}}}$ in the stratosphere and is of similar magnitude in the troposphere, A_{QS3} dominates over A_{QS2} throughout the year and in every level except in the aforementioned November minimum.

van Loon and Jenne (1972) also recognized these differences. He observed that daily zonal waves 2, 4, 5 and 6 had big amplitudes but, unlike zonal waves 1 and 3, their quasi-stationary wave counterparts were negligible. He deduced that zonal waves 1 and 3 were exceptionally consistent in phase and thus had what he called a “standing wave component”. We quantify this observation as the quotient between A_{QS} and $\overline{A_{\mathrm{ZW}}}$. As an analogy with the constancy of the wind (Singer, 1967), we define quasi-stationary wave stationarity as

$$\hat{S} = \frac{A_{\mathrm{QS}}}{\overline{A_{\mathrm{ZW}}}} \tag{3}$$

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 $\hat{S} = 1$ irrespective of sample size.

While $\hat{S}$ is used –sometimes as $2/\pi \arcsin\left(\hat{S}\right)$ (Singer, 1967)– in the meteorological literature in the context of wind steadiness (e.g Hiscox, Miller, & Nappo, 2010), to our knowledge this is the first time it has been applied to the study of atmospheric waves.

Figure 2 shows $\hat{S}$ for wavenumbers 1 to 3 computed using Equation 3 at 50°N and 50°S. We separate between high and low stationarity with the ad-hoc threshold of 0.4 (black line in Figure 2).

At 50°N planetary waves 1, 2 and 3 are highly stationary in almost every month and level, and even more so planetary wave 1 at 50°S.

In the southern hemisphere, planetary wave 2 stationarity has a semianual cycle. It reaches its maximum in April and in August-September, plummeting to a deep minimum in June. Planetary wave 3 stationarity peaks in February and slowly decreases towards a November deep minimum after witch increases sharply.

Equation 3 is equivalent to

$$\hat{S} = \frac{\sum_t A_{\mathrm{ZW}}(t) \cos\left[\alpha_{\mathrm{zw}}(t) - \alpha_{qs}\right]}{\sum_t A_{\mathrm{ZW}}(t)} \tag{4}$$

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 stationarity in proportion to their amplitude.

We used Equation 4 to compute a timeseries of quasi-stationary wave stationarity. We first calculated α_{qs} for each month and then, applied Equation 4 with a 15-year rolling window approximated using loess regression with degree 0. The results for wavenumbers 1 to 3 at 50°N and 50°S are shown in Figure 3.

Quasi-stationary wave stationarity remained high and constant for wavenumbers 1 to 3 at 50°N and 1 at 50°S but not for wavenumbers 2 and 3 at 50°S. Quasi-sationary wave 3 stationarity jumped from zero to more than 0.5 in less than five years in the 50's and increased again in the late 70's. These could indicate inhomogeneities caused by changes in the observational network –routine satellite observations began in 1979– but the absense of similar breaks for wavenumbers 1 or 2 suggest they represent real changes in the atmospheric circulation with unknown cause.

3.1 Considerations about phase

For defining local impacts, the phase of planetary waves is as important as their amplitude. One way of dealing with the phase of ZW is to fix it. Yuan and Li (2008) use

Principal Component Analysis on the meridional wind field to obtain a spatial pattern of the leading mode that is very similar to the QS3. The timeseries associated to this mode is, then, an indication of the intensity of the ZW3 that is similar to the QS3. A more direct approach is the index created by Raphael (2004). Since it is based on the geopotential height anomalies at the maximums of the QS3, it is sensitive to ZW3 patterns with phase close to the stationary phase. An almost mathematically equivalent approach (with correlation = 0.98) is to compute the projection of each ZW onto the direction of the QS (i.e. the expression inside the sum of the numerator in Equation 4). This methodology has fewer constrains in that the phase of interest can be changed depending on the application.

4 Conclusions

The fact that zonal waves (ZW) and quasi-stationary waves (QS) are two distinct but related phenomena has both practical and theoretical implications.

First, researchers should be aware of which phenomena they want to study and use the appropriate methods. The mean amplitude of the ZW could be appropriate to study the vertical propagation of Rossby waves, for example. But ZW amplitude could lead to misleading results if used as the basis of local impacts studies because they are probably more influenced by phase effects.

Secondly, comparison between results should also be made having this issues in mind. 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, in light of the discussion in Section 3.1, this limitation becomes a feature, not a bug.

Although having a consistent nomenclature across papers is desirable, we believe that this problems can be ameliorated by researchers detailing their definitions and methodology. This is also good for clarity and reproducibility. Since planetary waves are generally more stationary in the northern hemisphere, these issues are more critical for studies of the southern hemisphere.

Thirdly, the explorations of both ZW and QS can lead to novel levels of analysis. Here, we showed it can be used to define a metric of stationarity of quasi-stationary waves, but other applications are also possible. Smith and Kushner (2012) used the phase relationship between ZW1 and QS1 to show that linear interference between the QS1 and ZW1 was related to vertical wave activity transport at the tropopause.

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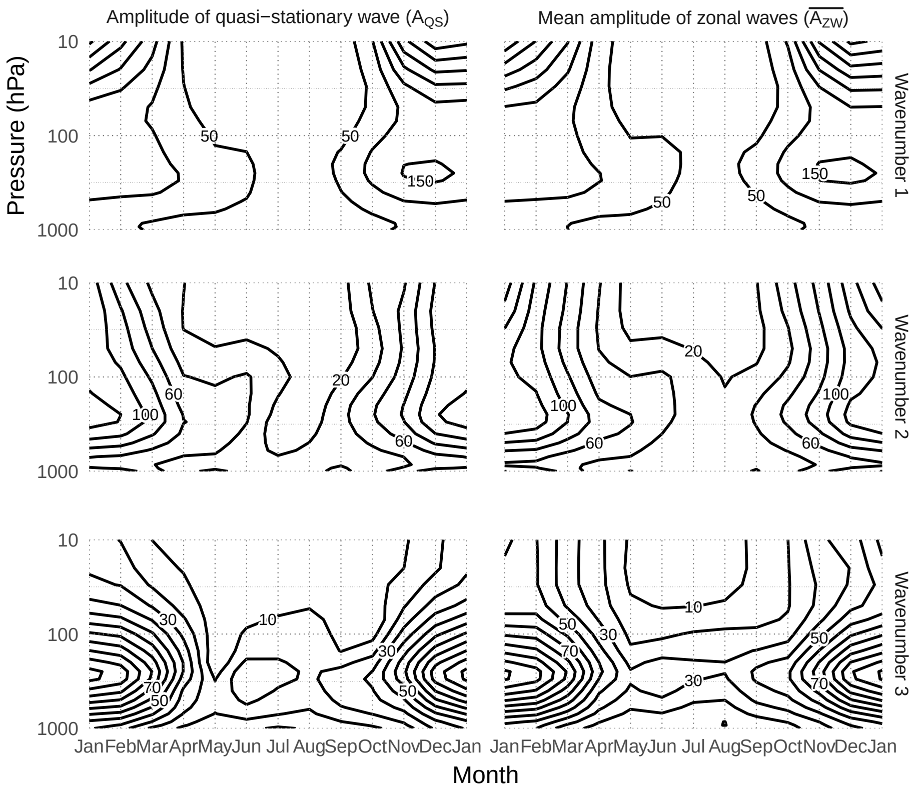
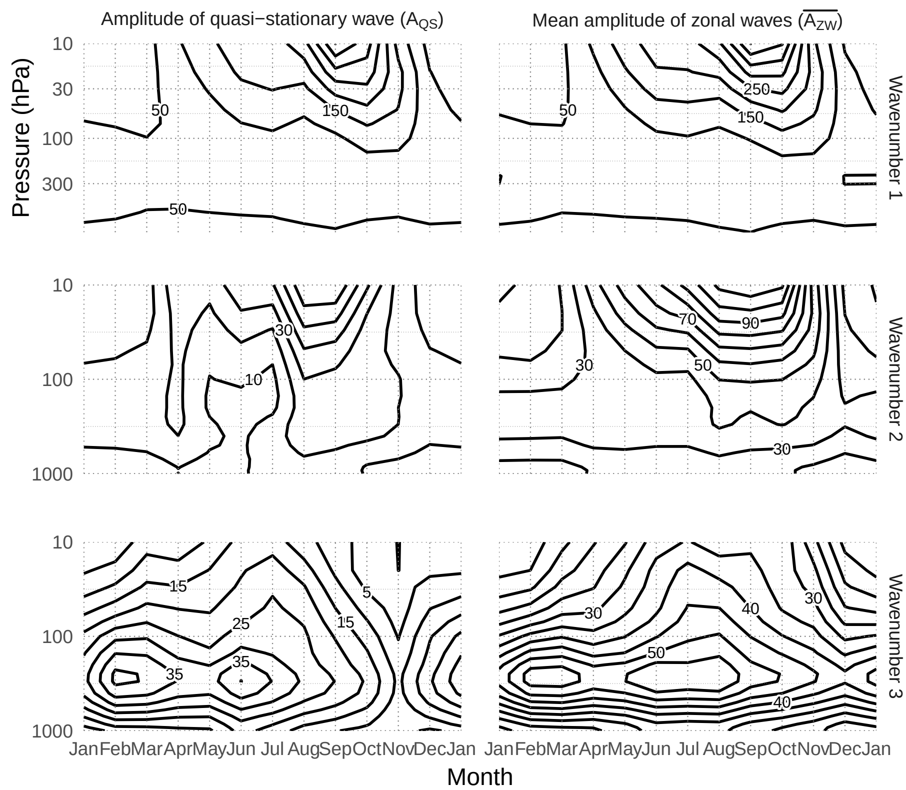


(a) At 50°N



(b) At 50°S

Figure 1: Seasonal cycle of amplitude of the geopotential planetary waves 1 to 3 computed as the amplitude of the mean wave (A_{QSk}) and as the mean amplitude of the monthly waves ($\overline{A_{\mathrm{ZW}}}$).

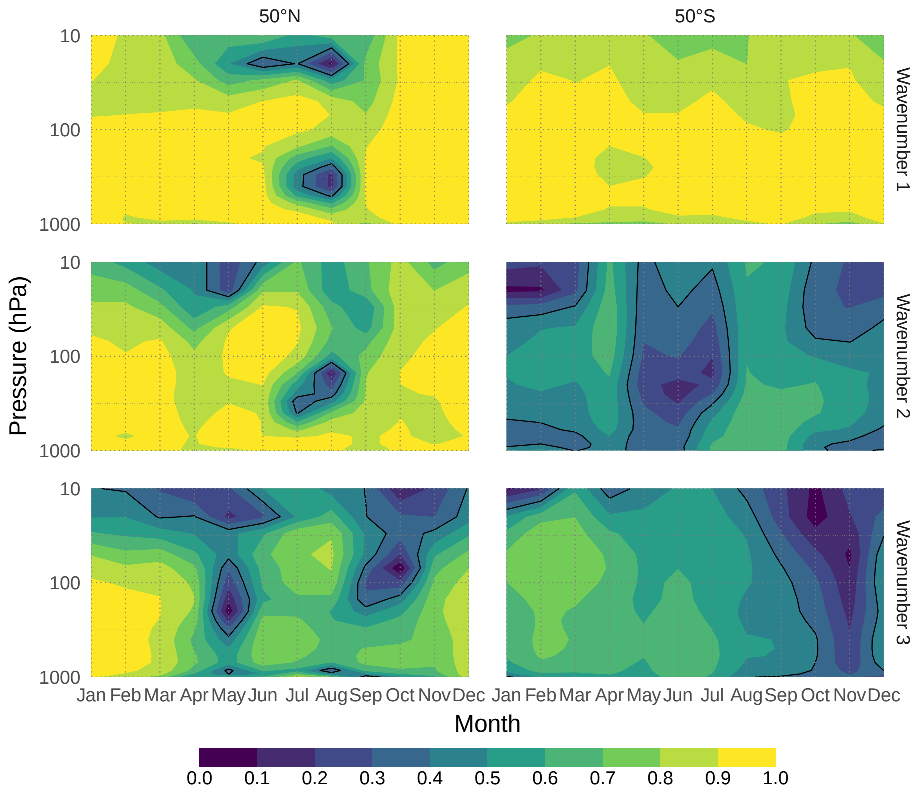


Figure 2: Seasonal cycle of stationarity at 50°S and 50°N computed using Equation 3

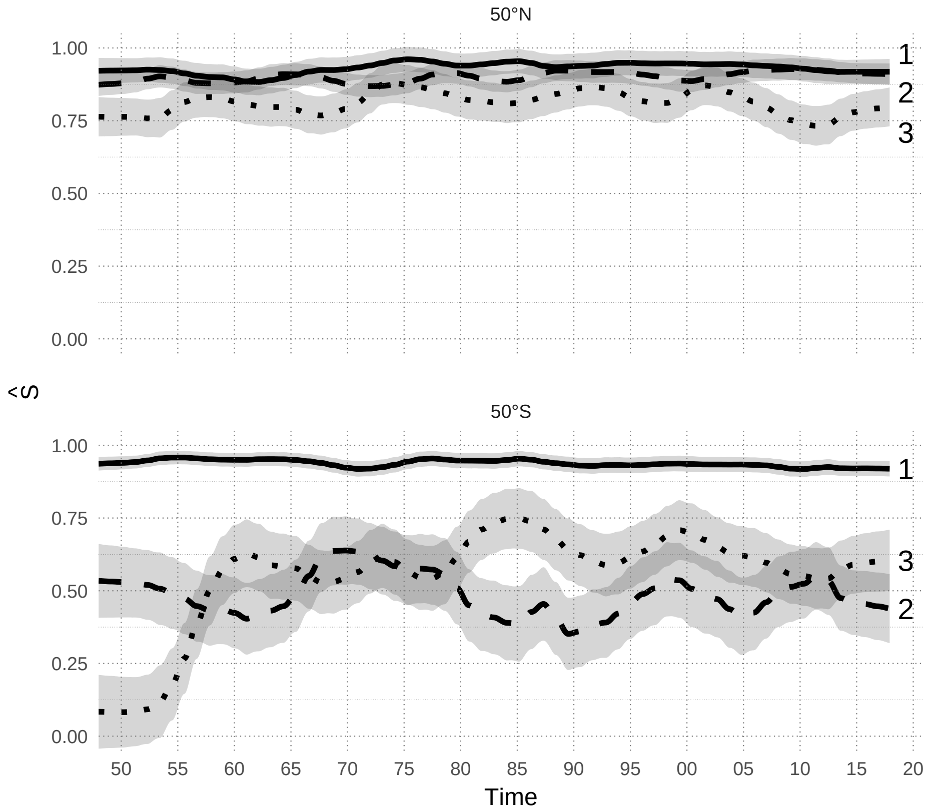


Figure 3: Quasi-stationary wave stationarity for wavenumbers 1 to 3