

How stationary are planetary waves in the Southern Hemisphere?

Elio Campitelli ¹Carolina Vera ^{1,2}Leandro Díaz ^{1,2}

¹Centro de Investigaciones del Mar y la Atmosfera, UMI-IFAECI (CONICET-UBA-CNRS)

²Departamento de Ciencias de la Atmósfera y los Océanos (FCEyN, UBA)

Key Points:

- Zonal waves and Quasi-stationary waves are distinct 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). They are typically characterized 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 ($\bar{\phi}^*$). These terms are sometimes used interchangeably in the SH circulation related studies (e.g. Irving & Simmonds, 2015; Kravchenko et al., 2012; Lastovicka, Krizan, & Kozubek, 2018; Rao, Fernandez, & Franchito, 2004; Raphael, 2004; Turner, Hosking, Bracegirdle, Phillips, & Marshall, 2017). This leads to both inter and intra-studies inconsistencies.

As an example of the former, Quintanar and Mechoso (1995) use the term “quasi-stationary waves (QS)” as defined by the zonally asymmetric component of the climatological mean field. Raphael (2004) used the term “zonal wave (ZW)” when describing her index of planetary waves with wavenumber 3 that coincided in phase with the phase of the QS wave. Irving and Simmonds (2015) compare Raphael (2004)’s QS index with their own index computed as the integrated southern hemisphere zonal “waviness” irrespective of phase.

As for intra-studies inconsistencies, Rao et al. (2004) follow the nomenclature of Quintanar and Mechoso (1995) for QS, but they analyze the mean amplitude of ZW instead of the amplitude of QS. Kravchenko et al. (2012) analyze temperature ZW amplitude as a predictor of total ozone, but call it “quasi-stationary amplitude”. Turner et al. (2017) use the terms “planetary wave k”, “quasi-stationary wave k” and “wave number k” to describe analysis of QS associated with different wavenumbers k. Furthermore, Lastovicka et al. (2018) study QS and ZW but they use the term “stationary planetary wave (SPW)” to refer to both.

Here we establish a clear distinction between ZW and QS and show that the differences between the two convey meaningful information.

It is evident from the recent literature that both terms, QS and ZW, have been used interchangeably. However, there are not recent studies assessing how “stationary” or “quasi-stationary” the zonal waves are in the SH. The focus of this study is then to assess the...

2 Zonal waves and quasi-stationary waves

In this study we define *planetary waves* as waves that extend along a full latitude circle. Planetary waves of the “instantaneous” fields are called in this study, *zonal waves* (ZW), and the ones of the field mean will be called *quasi-stationary waves* (QS). They are characterized by their wavenumber, amplitude and phase such that

$$ZW_k(t) = A_{ZW_k}(t) \cos[k\lambda - \alpha_{ZW_k}(t)] \quad (1)$$

$$\overline{ZW_k(t)} = QSk = A_{QSk} \cos(k\lambda - \alpha_{QSk}) \quad (2)$$

where k is the wavenumber, λ the longitude, and A_x and α_x , the amplitude and phase of each wave, respectively. Note that $ZW_k(t)$ is, by construction, explicitly dependent on time, while QSk is not. Furthermore, from the properties of wave superposition it can be seen that, in general, α_{QSk} does not equal $\overline{\alpha_{ZW_k}}$ and that A_{QSk} will always be less or equal than $\overline{A_{ZW_k}}$ (Pain, 2005).

While these definitions depend on which are the “instantaneous field” in question (monthly, daily, sub daily, etc...) and the averaging time scale, they illustrate that ZW are properties of the *elements* of the set, while QS are properties of the set as a whole. This is an important distinction with theoretical and methodological implications that is not always differentiated in the literature.

Figure 1 shows the seasonal cycle of the amplitude of planetary waves at 60°S using monthly fields from the NCEP/NCAR reanalysis (Kalnay et al., 1996) between 1980 and 2017. The left column (A_{QS}) is computed by taking the amplitude of the averaged geopotential field for each month, level and wavenumber. The right column ($\overline{A_{ZW}}$) is computed by taking the average amplitude of the 49 individual ZW.

Figure 1 shows that both amplitudes have different annual cycles and vertical structures. A_{QS2} has a strong minimum in the low stratosphere during the austral autumn that is not apparent in $\overline{A_{ZW2}}$. Similarly, the austral winter mid-tropospheric maximum is very well defined in $\overline{A_{ZW3}}$ but not so in A_{QS3} . The relative individual contribution of

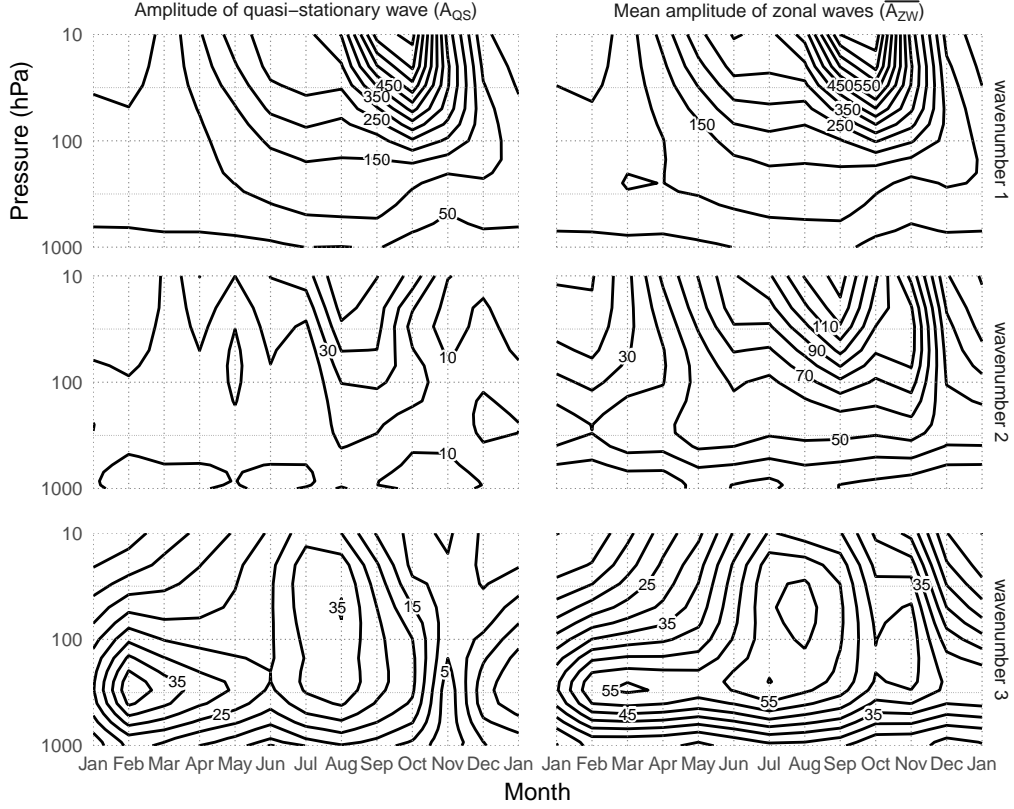


Figure 1. Seasonal cycle of amplitude of the geopotential planetary waves 1 to 3 at 60°S computed as the amplitude of the mean wave (A_{QS}) and as the mean amplitude of the monthly waves ($\overline{A_{ZW}}$).

each wavenumber is also different. $\overline{A_{ZW}}$ fields shows a preponderance of wave 2 over 3 in almost every level and month. However, A_{QS3} is larger than A_{QS2} in the first half of the year. In contrast with wavenumbers 2 and 3, $\overline{A_{ZW1}}$ and A_{QS1} fields are very similar.

These differences are location-dependent. Figure 2 show the horizontal distribution of A_{QS} and $\overline{A_{ZW}}$ at 300hPa, for the three wavenumbers considered. In the northern hemisphere there is a strong seasonal cycle of A_{QS} that is matched by the seasonal cycle of $\overline{A_{ZW}}$ for all wavenumbers. In contrast, in the southern hemisphere the seasonal cycles of A_{QS} and $\overline{A_{ZW}}$ are similar only for wavenumber 1. Wavenumbers 2 and 3 have much lower A_{QS} than $\overline{A_{ZW}}$.

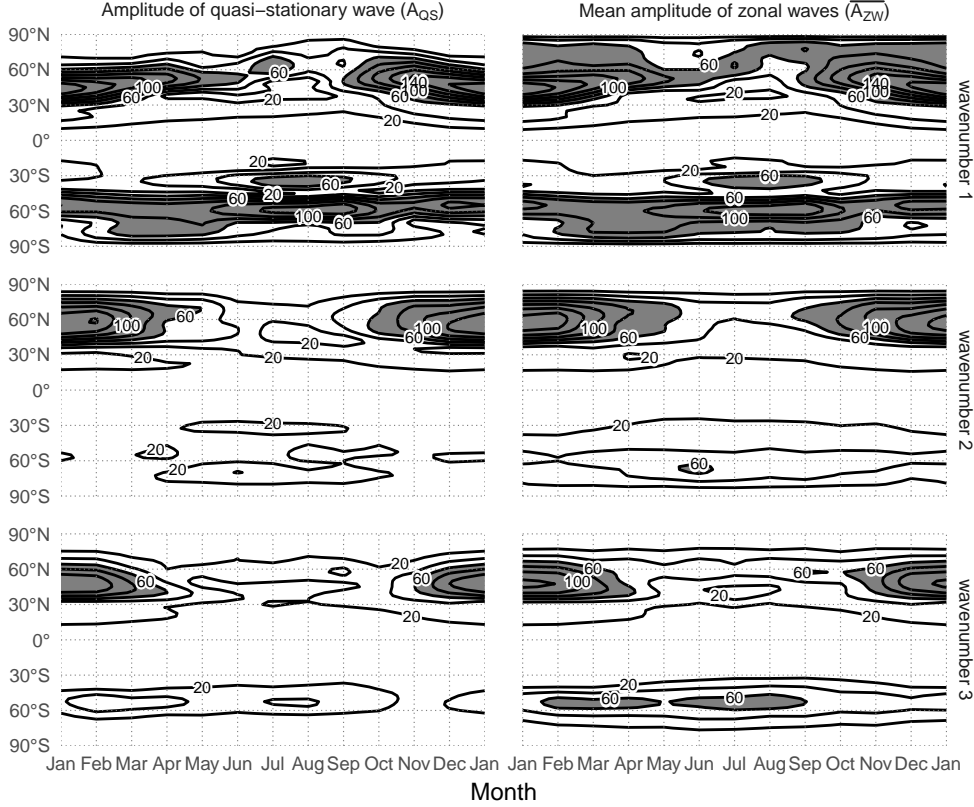


Figure 2. Seasonal cycle of amplitude of the geopotential planetary waves 2 at 300hPa computed as the amplitude of the mean wave (A_{QSk}) and as the mean amplitude of the monthly waves ($\overline{A_{ZW}}$).

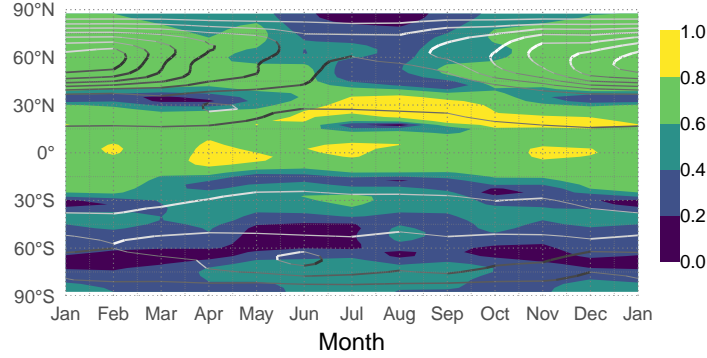
2.1 Stationarity Index

van Loon and Jenne (1972) recognised the distinction between $\overline{A_{ZW}}$ and A_{QS} and, deduced that “the daily phases of waves 2 and 4-6 at 50°S must therefore be random since the waves almost cancel themselves when added, whereas 1 and 3 must recur consistently in certain longitudes since they are significantly large in the climatological mean”. This observation motivates that stationary conditions in the circulation of the SH could be measured using the quotient between the two quantities. As an analogy with the constancy of the wind (Singer, 1967), the stationarity of the QS can be estimated as

$$\hat{S} = \frac{A_{QS}}{\overline{A_{ZW}}} \quad (3)$$

It can be shown that $\hat{S} = 1$ for completely stationary waves. On the other hand, it can be demonstrated that the expected amplitude of the sum of n waves with random

98 phases and mean amplitude A is $An^{-1/2}$ (Pain, 2005). Thus, for completely non station-
 99 ary waves, the expected value of \hat{S} is $n^{-1/2}$.



100 **Figure 3.** Seasonal cycle of stationarity of the 300hPa geopotential QS2 computed using
 101 Equation 3 (shaded) and $\overline{A_{ZW2}}$ (contours). From monthly NCEP/NCAR Reanalysis, 1980 to
 102 2017.

103 As an example, Figure 3 shows \hat{S} for QS2 computed using Equation 3. At the north-
 104 ern mid latitudes the seasonal cycle of stationarity is similar to that described by $\overline{A_{ZW}}$
 105 (Figure 2) with maximum values in boreal summer and minimum in the boreal winter.
 106 On the other hand, the SH circulation shows a lower degree of QS2 stationarity than that
 107 of the northern hemisphere or the tropics. At the SH is no clear annual cycle and, even
 108 more, at 60°S, stationarity and $\overline{A_{ZW}}$ appear to be anticorrelated.

109 \hat{S} can equivalently be mathematically defined as

$$110 \quad \hat{S} = \frac{\sum_t A_{ZW}(t) \cos[\alpha_{ZW}(t) - \alpha_{qs}]}{\sum_t A_{ZW}(t)} \quad (4)$$

111 The numerator is the sum of the projections of each ZW onto the direction of the
 112 QS. Equation 4 has some advantages over Equation 3. First, it makes is clear that sta-
 113 tionarity is a mixture of a phase effect and an amplitude effect. Secondly, one can, in
 114 principle, replace α_{qs} with any direction of interest, allowing to evaluate $\hat{S}(\alpha)$. This can
 115 also be useful for removing variability due to the seasonal cycle. The position of the monthly
 116 QS3 has a shift of about 15° between January and July (van Loon & Jenne, 1972), so by
 117 replacing α_{qs} with $\alpha_{qs}(month)$ (one for each month) one can evaluate stationarity with
 118 respect to the seasonal changing position of the mean wave. Finally, it is possible to trans-

form the sums into running sums with window w and obtain $\hat{S}(w, t)$ and analyse variations of stationarity with time.

While \hat{S} is used –sometimes as $2/\pi \arcsin(\hat{S})$ (Singer, 1967)– in the meteorological literature in the context of wind steadiness, to our knowledge this is the first time it has been applied to the study of atmospheric waves. However, its statistical properties are not well studied. One problem with \hat{S} is that, as seen above, its estimation from a finite sample has a positive bias, but its convergence properties are not explored.

2.2 Considerations about phase

For defining local impacts, the phase of planetary waves is as important as their amplitude if not more. 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 constraints in that the phase of interest can be changed depending on the application.

3 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 2.2, 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.

xx me falta un final acá xx

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