

# How stationary are planetary waves in the Southern Hemisphere?

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## 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

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## Abstract

Abstract goes here

## 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 (REFS), and by contributing to the development of blocking events (e.g. Trenberth & Mo, 1985).

In Rossby wave theory, stationary waves are those with zero frequency or phase velocity (Holton & Hakim, 2012). In practice, however, most studies have assumed the “quasi-stationary” nature of southern hemisphere planetary waves based on van Loon and Jenne (1972). In this foundational study, the authors analyzed data 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 contributed significantly to 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 study has quantified the level of stationarity of each wavenumber.

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 southern hemisphere, and extends van Loon and Jenne (1972)’s methodology into a quantitative measure of planetary wave stationarity, which we apply 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:

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

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

where  $k$  is wavenumber,  $\lambda$  longitude, and  $A_x$  and  $\alpha_x$ , amplitude and phase, respectively.  $ZWk(t)$  depends on time, but not  $QSk$ .

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 one 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 one 30-year quasi-stationary wave. Monthly planetary waves are quasi-stationary waves in one case and zonal waves in the other.

## 2.2 Stationarity

From the properties of the superposition of waves we can deduce that, in general, the stationary phase  $\alpha_{QSk}$  does not equal  $\overline{\alpha_{ZWk}}$  and the stationary amplitude  $A_{QSk}$  is less or equal  $\overline{A_{ZWk}}$  (Pain, 2005).

We use this latter property and use the quotient between  $A_{QS}$  and  $\overline{A_{ZW}}$  as a measure of quasi-stationary wave stationarity such as:

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

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.

$\hat{S}$  is used –sometimes as  $2/\pi \arcsin(\hat{S})$  (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.

Equation 3 is equivalent to

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

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.

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

### 2.3 Data

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. Amplitude and phase for each wavenumber was estimated by fitting a fourier transform for each latitude circle, level and monthly record.

We analyzed the data using the statistical programming language R (?), using data.table and metR packages (??) to read and transform it and ggplot2 package (?) to make the plots. The source code is available as Figshare repository (Campitelli, Díaz, & Vera, 2019).

## 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 ( $\overline{A_{ZW}}$ ) as the average amplitude of the 70 individual fields.

Figure 1a shows that at 50°N for the three wavenumbers  $A_{QS}$  and  $\overline{A_{ZW}}$  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  $\overline{A_{ZW2}}$  and its seasonal cycle is less defined.  $A_{QS3}$  has a smaller magnitude than  $\overline{A_{ZW3}}$  and 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  $\overline{A_{ZW3}}$ . The relative contribution of each wavenumber is also different. While  $\overline{A_{ZW2}}$  dominates over  $\overline{A_{ZW3}}$  in the stratosphere and is of similar magnitude in the troposphere,  $A_{QS3}$  domi-

nates over  $A_{QS2}$  throughout the year and in every level except in the aforementioned November minimum.

These observations are quantified in Figure 2, which 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 which increases sharply.

Because we computed  $\hat{S}$  using the whole period, it represents the mean stationarity between. Figure 3 shows how planetary wave stationarity changed for each wavenumber at each latitude. Planetary wave stationarity remained high and constant for wavenumbers 1 to 3 at 50°N and 1 at 50°S but wavenumbers 2 and 3 at 50°S show interdecadal variations.

Planetary wave 2 stationarity oscillated around 0.49 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 0.62 with a strong maximum in the late 80's. These could indicate inhomogeneities caused by changes in the observational network –routine satellite observations began in 1979– but the absence of similar breaks for wavenumbers 1 or 2 suggest they represent real changes in the atmospheric circulation with unknown cause.

## 4 Conclusions

Using a quantitative measure of planetary wave stationarity we showed that, in the southern hemisphere, planetary wave 1 stationarity is high and constant throughout the year and period, while waves 2 and 3 vary both in intraseasonal and interdecadal timescales. Planetary wave 3 stationarity, in particular, increased dramatically in the 50's.

Planetary waves can be both forced by the surface and excited by internal variability. Assuming that the latter process will not result in a phase preference, higher station-

arity would be evidence of stronger forcing or, more strictly, stronger forcing response. In the northern hemisphere, topography and thermal contrast are the main forcings of planetary waves, which explains their highly and not variable stationary nature. In the southern hemisphere, only planetary wave 1 seems to be the result of mainly surface forcings. Planetary waves 2 and 3 seem to be composed of a comparable mix of internal variability and surface forcing.

Interannual and intradecadal variability in planetary wave stationarity may serve to study variability in surface forcing response caused either by the strength of the forcing or the sensitivity of mean state of the atmosphere.

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(Silvestri and Vera (2009))

xxxx The literature on the topic is dominated by two main methodologies that imply different definitions: some studies have defined planetary waves by removing zonal averages from time-mean fields (e.g. van Loon & Jenne, 1972, Quintanar and Mechoso (1995), Raphael (2004)) while others defined them by removing zonal averages from the instantaneous (e.g. daily, monthly or seasonal) fields (e.g. Rao, Fernandez, & Franchito, 2004, Turner, Hosking, Bracegirdle, Phillips, and Marshall (2017), Irving and Simmonds (2015)).

First, researchers should be aware of which phenomena they want to study and use the appropriate methods. The mean amplitude of zonal waves could be appropriate to study the vertical propagation of Rossby waves, for example. But zonal wave 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 issue 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 latter 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.

Although having a consistent nomenclature across papers is important, we believe this problem can be ameliorated by researchers detailing their definitions and methodology. This is also good for clarity and reproducibility. Since planetary waves are gen-

erally 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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We speculate that the level of stationarity responds to the nature of the forcings. Highly stationary planetary waves are explained mainly by stationary forcings while low stationary planetary waves respond mainly to the internal variation of the atmosphere. This suggests that in the southern midlatitudes, wave 2 and 3 consist of forced responses mixed with internal variability. Their annual cycle further suggests that the mean state of the atmosphere can modulate these responses.

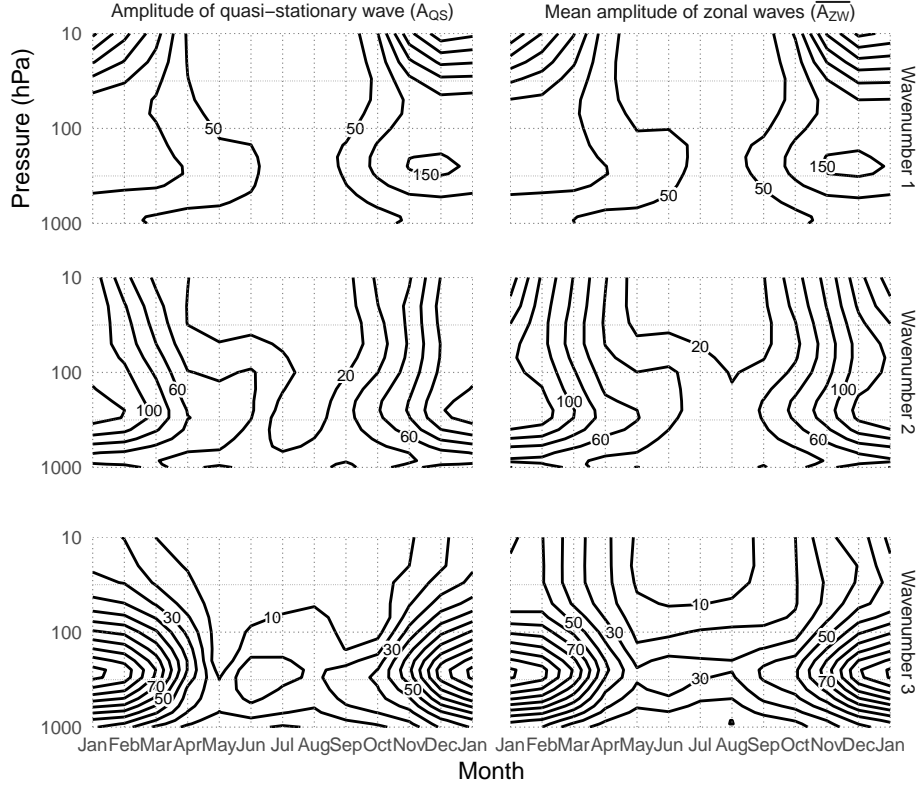
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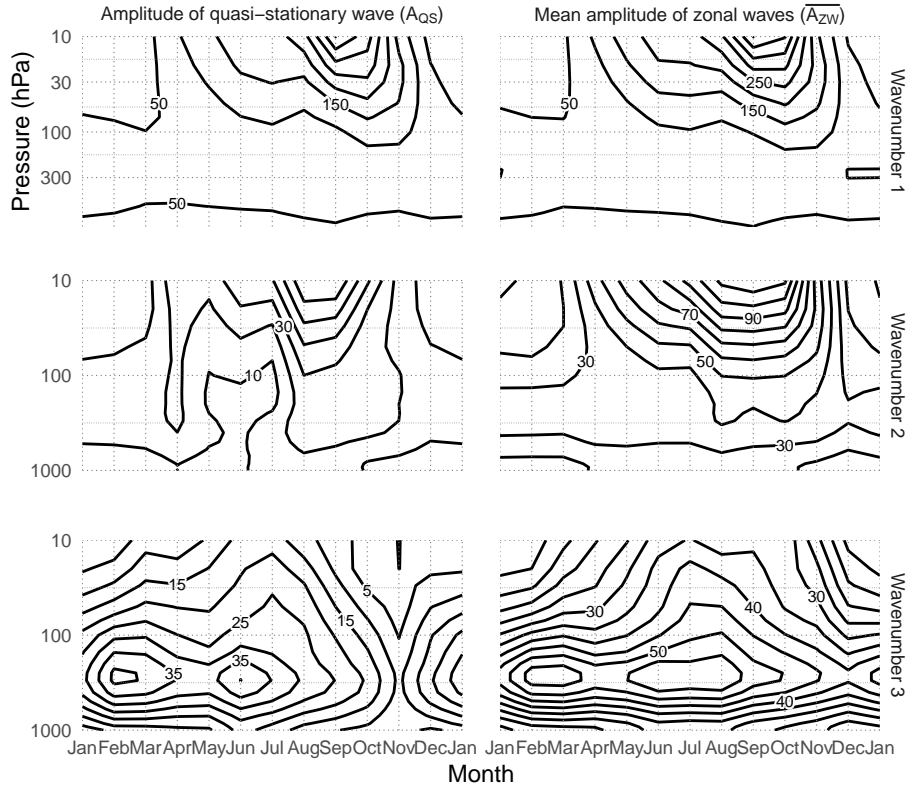
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(a) At 50°N



(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 ( $\overline{A_{ZW}}$ ).

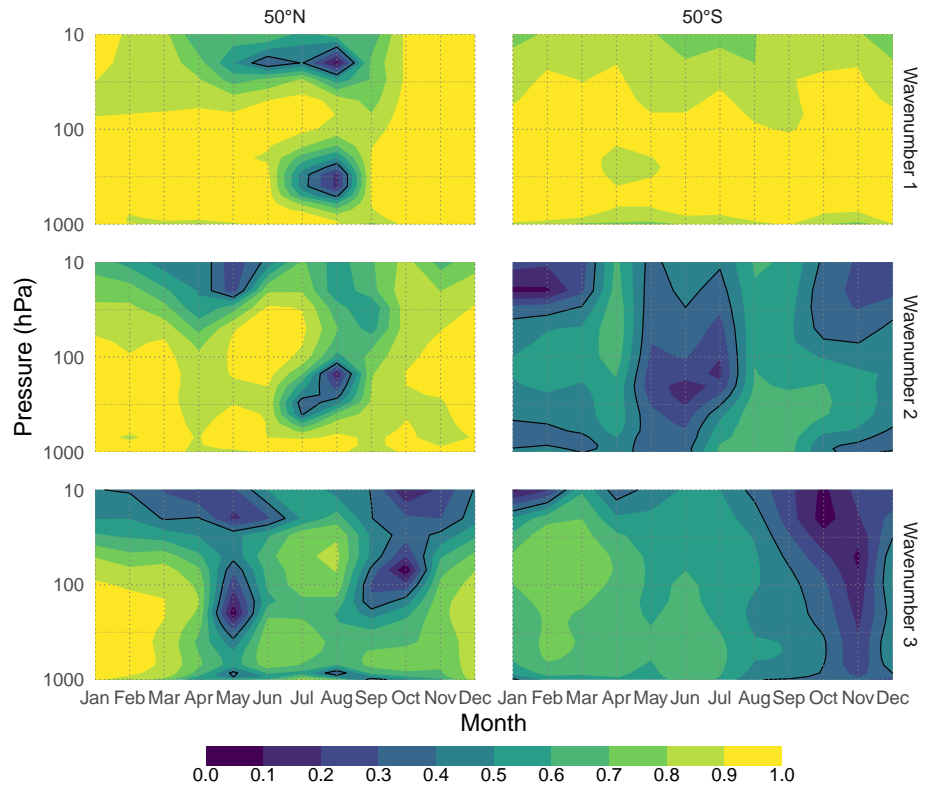


Figure 2: Seasonal cycle of stationarity at 50°S and 50°N computed using Equation 3

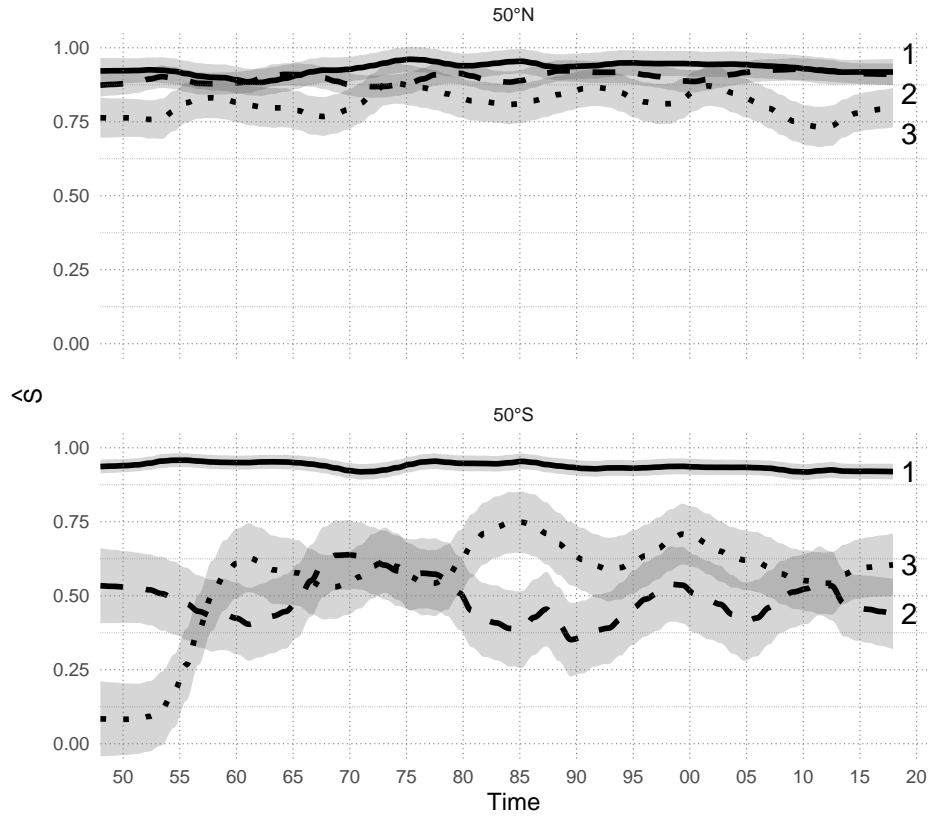


Figure 3: Quasi-stationary wave stationarity for wavenumbers 1 to 3