# 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:**

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

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

## 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 from interseasonal and decadal timescales. A deeper knowledge of those variations could help in the future to better understand the variability in the responses of mid-latitudes atmospheric circulation to surface forcing caused either by its strength, or the sensitivity of the atmosphere to it.



## 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 can also contribute to the development of blocking events (e.g. K. F. 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 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 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 further study has actually quantified the level of stationarity associated to 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 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:

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

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

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

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 $\alpha_{\mathrm{QSk}}$ does not equal $\overline{\alpha_{\mathrm{ZWk}}}$, and that the stationary amplitude $A_{\mathrm{QSk}}$ is less or equal to $\overline{A_{\mathrm{ZWk}}}$ (Pain, 2005). We use this latter property and use the quotient between $A_{\mathrm{QS}}$ and $\overline{A_{\mathrm{ZW}}}$ to define a measure of quasi-stationary wave stationarity:

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

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, $\hat{S}$ 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

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

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 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 $\alpha_{qs}$ 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. **?** 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, Hosking, Bracegirdle, Phillips, and Marshall (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 **?** 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 each latitude circle, level and monthly record. For comparison, we also analyzed data from ERA-Interim (Dee et al., 2011) and ERA-20C (Poli et al., 2016).

We analyzed the data using the statistical programming language R (R Core Team, 2018), using data.table (Dowle & Srinivasan, 2018) and metR (Campitelli, 2018) packages to read and transform it and ggplot2 package (Wickham, 2016) to make the plots. The source code is available as Figshare repository (Campitelli, 2019).

## 3 Results

Figure 1 shows the seasonal cycle of the amplitude of planetary waves at 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65°S and 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65°N based on the monthly-mean geopotential height fields computed between 1948 and 2017. We computed the left column ($A_{\mathrm{QS}}$) as the amplitude of the average geopotential height 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 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65°N $A_{\mathrm{QS}}$ and $\overline{A_{\mathrm{ZW}}}$ have a similar seasonal cycle with similar vertical extent for the three wavenumbers. At 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65°S this is true only for wavenumber 1 (Figure 1b). However, $A_{\mathrm{QS2}}$ has much lower values than $\overline{A_{\mathrm{ZW2}}}$ and its seasonal cycle is less defined. Moreover, $A_{\mathrm{QS3}}$ 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. $A_{\mathrm{QS3}}$ 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, $A_{\mathrm{QS3}}$ dominates over $A_{\mathrm{QS2}}$ throughout the year and in every level except in the aforementioned November minimum.

The differences between $A_{\mathrm{QS}}$ and $\overline{A_{\mathrm{ZW}}}$ are quantified in Figure 2, which shows $\hat{S}$ for wavenumbers 1 to 3 computed using Equation 3 at 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65°N and 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65°S.

At 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65°N, planetary waves 1, 2 and 3 are highly stationary in almost every month and level, and even more so planetary wave 1 at 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65°S.

In the SH, planetary wave 2 stationarity has a semiannual cycle. It reaches its maximum 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 -ear overlapping intervals for each wavenumber at both studied latitudes (Figure 3). Planetary wave stationarity remained high and constant for wavenumbers 1 to 3 at 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65°N and 1 at 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65°S but wavenumbers 2 and 3 at 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65°S 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 suggest that the observed decadal variations are not an artifact of the reanalysis. 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. **?**'s index is highly correlated with ours (correlation = 0.73) and the relationship is quite linear in nature. Negative values of **?**'s index are generally associated to zonal waves with negative projection onto the climatological mean. The main difference between **?**'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 forcing 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 composed of a comparable mix of internal variability and surface forcing components.

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 (1995), **?**) 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 **?**'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

A version-controlled repository of the code that generated this article can be found at http://github.com/eliocamp/qs-zw. And a snapshot of said repository can be found at https://figshare.com/s/e72154e67b0cd8cc1045.

Funding statement:

- "Climate Services Through Knowledge Co-Production: A Euro-South American Initiative For Strengthening Societal Adaptation Response to Extreme Events (CLIMAX)", Belmont Forum/ANR-15-JCL/-0002-01. France.
- "Interacciones entre patrones climáticos de gran escala y su impacto en el sur de Sudamérica". UBACYT 20020170100428BA. University of Buenos Aires, Argentina.


## References


Campitelli, E. (2018). metr: Tools for easier analysis of meteorological fields [Computer software manual]. Retrieved from `https://github.com/eliocamp/metR` (R package version 0.2.9000)

Campitelli, E. (2019). How stationary are planetary waves in the SH?: Supplementary data.
doi: 10.6084/m9.figshare.7599890

Chen, S.-C., & Trenberth, K. E. (1988, February). Forced Planetary Waves in the Northern Hemisphere Winter: Wave-Coupled Orographic and Thermal Forcings. *Journal of the Atmospheric Sciences*, *45*(4), 682-704. doi: 10.1175/1520-0469(1988)045⟨0682:FPWITN⟩2.0.CO;2

Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., … Vitart, F. (2011, April). The ERA-Interim reanalysis: Configuration and performance of the data assimilation system. *Quarterly Journal of the Royal Meteorological Society*, *137*(656), 553-597. doi: 10.1002/qj.828

Dowle, M., & Srinivasan, A. (2018). data.table: Extension of 'data.frame' [Computer software manual]. Retrieved from `http://r-datatable.com` (R package version 1.11.9)

Hiscox, A. L., Miller, D. R., & Nappo, C. J. (2010). Plume meander and dispersion in a stable boundary layer. *Journal of Geophysical Research: Atmospheres*, *115*(D21). doi: 10.1029/2010JD014102

Holton, J. R., & Hakim, G. J. (2012). *An introduction to dynamic meteorology: Fifth edition.* doi: 10.1016/C2009-0-63394-8

Irving, D., & Simmonds, I. (2015, December). A Novel Approach to Diagnosing Southern Hemisphere Planetary Wave Activity and Its Influence on Regional Climate Variability. *Journal of Climate*, *28*(23), 9041-9057. doi: 10.1175/JCLI-D-15-0287.1

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., … Joseph, D. (1996, March). The NCEP/NCAR 40-Year Reanalysis Project. *Bulletin of the American Meteorological Society*, *77*(3), 437-472. doi: 10.1175/1520-0477(1996)077⟨0437:TNYRP⟩2.0.CO;2

Pain, H. J. (2005). Simple Harmonic Motion. In *The Physics of Vibrations and Waves* (p. 1-35). John Wiley & Sons, Ltd. doi: 10.1002/0470016957.ch1

Poli, P., Hersbach, H., Dee, D. P., Berrisford, P., Simmons, A. J., Vitart, F., … Fisher, M. (2016, March). ERA-20C: An Atmospheric Reanalysis of the Twentieth Century. *Journal of Climate*, *29*(11), 4083-4097. doi: 10.1175/JCLI-D-15-0556.1

Quintanar, A. I., & Mechoso, C. R. (1995, November). Quasi-Stationary Waves in the Southern Hemisphere. Part II: Generation Mechanisms. *Journal of Climate*, *8*(11), 2673-2690. doi: 10.1175/1520-0442(1995)008⟨2673:QSWITS⟩2.0.CO;2

R Core Team. (2018). R: A language and environment for statistical computing [Computer software manual]. Vienna, Austria. Retrieved from `https://www.R-project.org/`

Rao, B. V., Fernandez, J. P. R., & Franchito, S. H. (2004, March). Quasi-stationary waves in the Southern Hemisphere during El Niño and La Niña events. *Annales Geophysicae*, *22*(3), 789-806. doi: 10.5194/angeo-22-789-2004

Singer, I. A. (1967, December). Steadiness of the Wind. *Journal of Applied Meteorology*, *6*(6), 1033-1038. doi: 10.1175/1520-0450(1967)006⟨1033:SOTW⟩2.0.CO;2

Smith, K. L., & Kushner, P. J. (2012, July). Linear interference and the initiation of extratropical stratosphere-troposphere interactions: LIN INTERFERENCE AND STRAT NAM. *Journal of Geophysical Research: Atmospheres*, *117*(D13), n/a-n/a. doi: 10.1029/2012JD017587

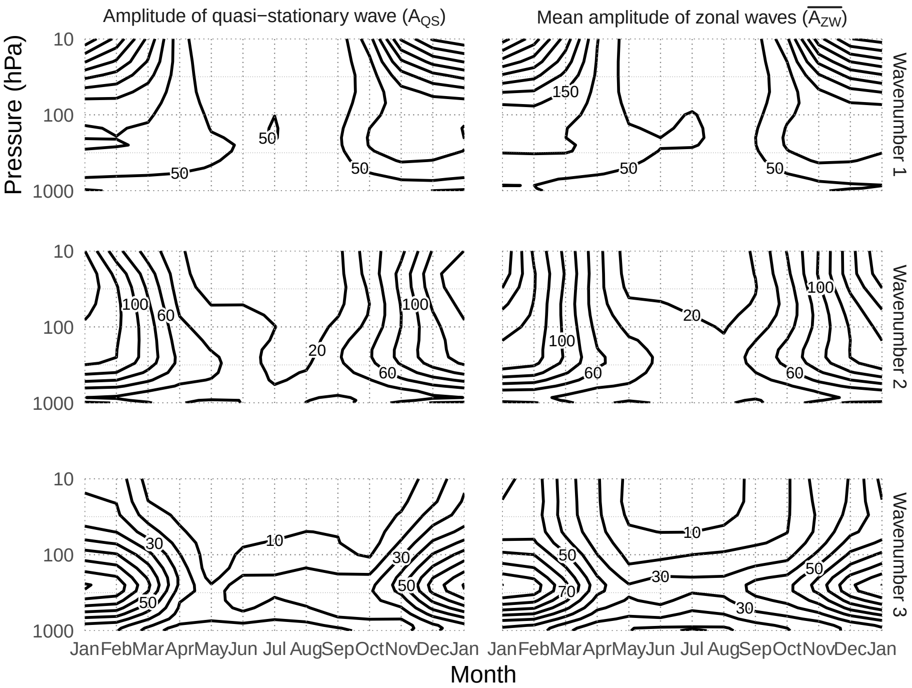
Trenberth, K. E. (1980, September). Planetary Waves at 500 mb in the Southern Hemisphere. *Monthly Weather Review*, *108*(9), 1378-1389. doi: 10.1175/1520-0493(1980)108⟨1378:PWAMIT⟩2.0.CO;2

Trenberth, K. F., & Mo, K. C. (1985, January). Blocking in the Southern Hemisphere. *Monthly Weather Review*, *113*(1), 3-21. doi: 10.1175/1520-0493(1985)113⟨0003:BITSH⟩2.0.CO;2

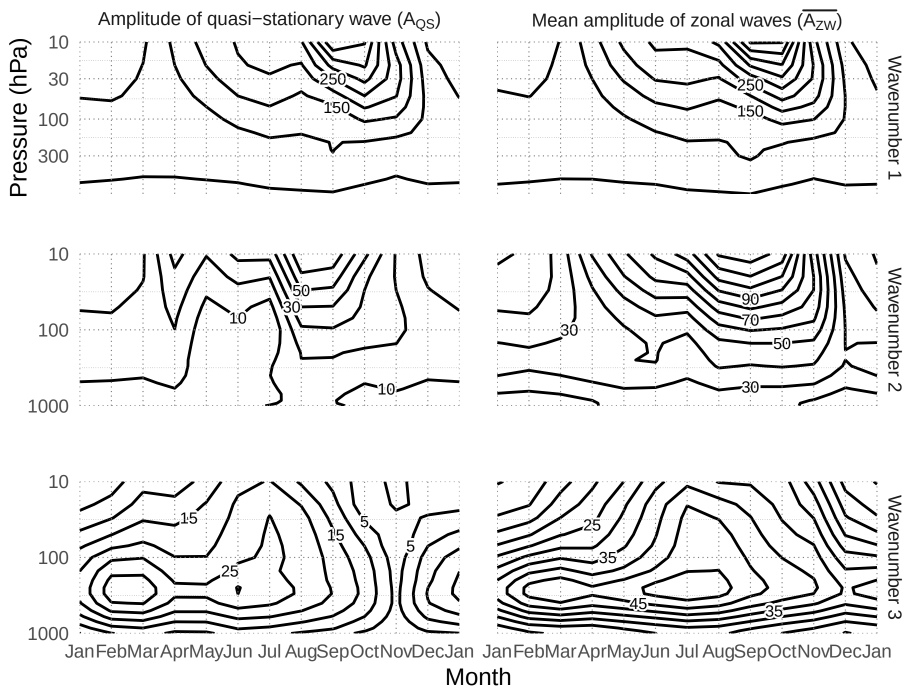
Turner, J., Hosking, J. S., Bracegirdle, T. J., Phillips, T., & Marshall, G. J. (2017, April). Variability and trends in the Southern Hemisphere high latitude, quasi-stationary planetary waves: SOUTHERN HEMISPHERE PLANETARY WAVES. *International Journal of Climatology*, *37*(5), 2325-2336. doi: 10.1002/joc.4848

van Loon, H., & Jenne, R. L. (1972, February). The zonal harmonic standing waves in the southern hemisphere. *Journal of Geophysical Research*, *77*(6), 992-1003. doi: 10.1029/JC077i006p00992

Wickham, H. (2016). *ggplot2: Elegant graphics for data analysis*. Springer-Verlag New York. Retrieved from `http://ggplot2.org`




(a) At 50°N




(b) At 50°S

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 mean amplitude of the monthly waves ($\overline{A_{\mathrm{ZW}}}$, left column) the amplitude of the mean wave ($A_{\mathrm{QSk}}$, right column)

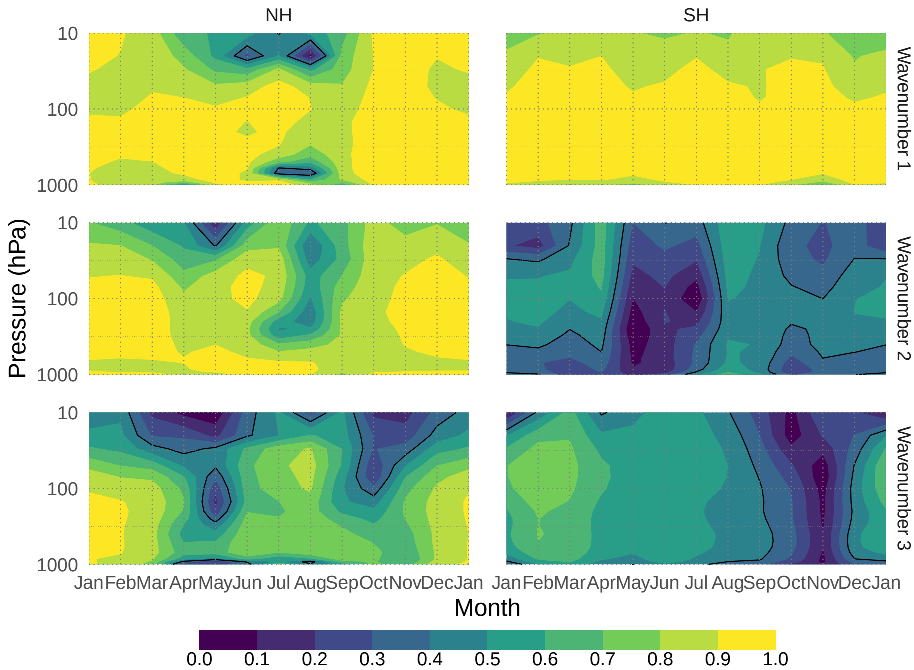



Figure 2: Seasonal cycle of stationarity of the geopotential height planetary waves 1, 2 and 3 (top, middle and bottom rows, respectively) at 50°N and 50°S (left and right columns, respectively) computed using Equation 3. The black line marks $\hat{S} = 0.4$ for reference.

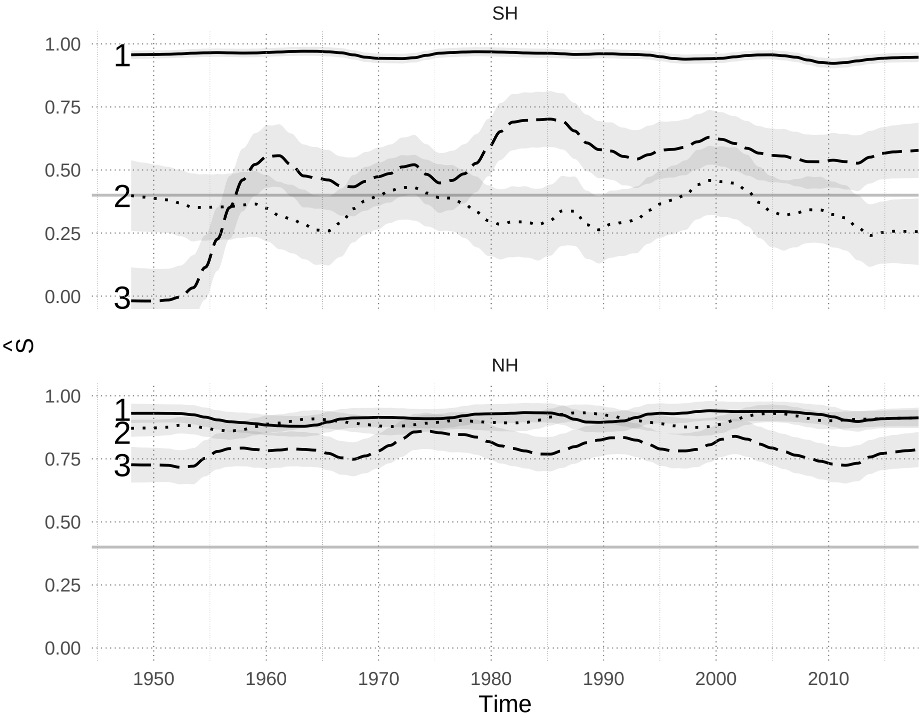



Figure 3: Stationarity for wavenumbers 1 to 3 at 50°N and 50°S (top and bottom panels, respectively) at 500hPa.

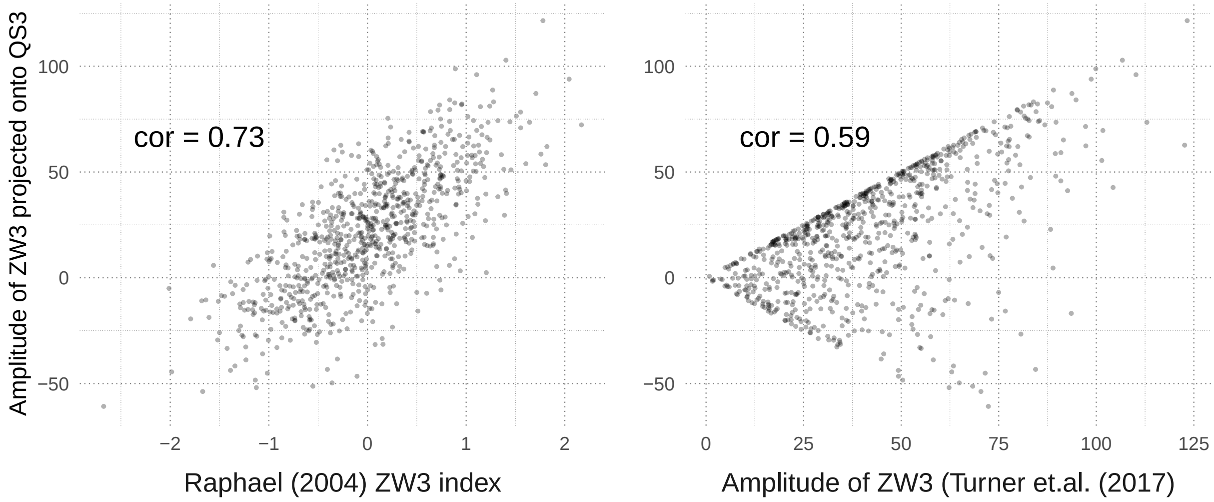



Figure 4: Raphael (2003) and Turner et.al. indices compared with the amplitude of the zonal wave projected onto the climatological zonal wave. All of them computed at 500hPa and 50°S.