Zonal index and its variability

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Abstract: The zonal index, defined as the difference in hemisphere-wide averaged mean sea level pressures between 35° N and 55° N, is a tool that allows the study of variations in circulation patterns at mid-latitudes. Apart from an annual periodicity, its variation has a cyclical component called *index cycle*. We have determined that its period is around 5 weeks, based on data from the last four decades. We have also analysed the long-term trend of this index, obtaining a slight growth, in line with other indices such as the NAO. We have computed correlations with several meteorological variables, and we have corroborated its low predictive capacity, which was one of the reasons why it practically disappeared in modern meteorology.

I. INTRODUCTION

The study of the atmosphere at mid-latitudes aroused great interest in meteorology in the early 20th century. The Ferrel cell, located in the mid-latitudes between approximately 30° N and 60° N (in the case of the Northern Hemisphere), has a circulation that is established by continuity with the Hadley cell and the polar cell, the latter two having a direct thermal circulation. Thus, unlike the easterlies of the Hadley cell, the westerlies of the Ferrel cell are considerably weaker and more variable, by means of the strongly disturbed circulation in the mid-latitudes, where, in addition, the Coriolis force plays a primary role. Rossby, in an attempt to characterise the circulation patterns of the Ferrel cell, defined the zonal index in 1939 [1], which provides an idea of the strength of westerlies from the mean pressure gradient between the subtropical high-pressure belt and the subpolar low-pressure belt. This tool has made it possible to describe the cyclic changes throughout the year in the Ferrel cell circulation, which allow periodic communication between the Hadley cell and the polar cell to ensure the necessary hemispheric-scale heat exchange.

In this analysis we have used data from the last 4 decades to study the characteristics of the variations of the zonal index, as well as its long-term trend. We have also studied the possible correlations that could arise in relation to the zonal index, and thus determine the extent of its potential as a predictive tool, which since the middle of the 20th century has been noted to be very limited.

II. DATA COLLECTION AND PROCESSING

The data sets used in the development of the analysis have been obtained from the database corresponding to the NCEP-DOE Reanalysis project (Reanalysis-2), and provided by the NOAA [2]. Reanalysis-2 offers a quality reanalysis global gridded data of numerous atmospheric and oceanic variables in NetCDF4 format. The available data sets start in 1979, and have a time step of 6 hours. The data has a mesh pitch of 2.5 degrees.

For the analysis of the variability of the zonal index we used mean sea level pressure (MSLP) data at mid-latitudes, corresponding to 42 years (from 1 January 1979 to 31 December 2020). We have also used data from other variables to compute correlations, such as temperature at 850 hPa, the zonal and meridional components of the wind at 10 metres or precipitation. Data processing has been carried out using Python.

III. RESULTS AND DISCUSSION

A. Definition and physical meaning

The zonal index is a parameter that allows a generic characterisation of the dominant circulation pattern at mid-latitudes.

It was originally defined by Rossby at 1939 [1] as the average of the zonal winds in the region between the 35° N and 55° N parallels. Therefore, in general it has a positive value, as the Ferrel cell circulation is dominated by a westerly flow, both at the surface and aloft. However, several authors later used a zonal index defined as the difference between the zonally averaged MSLP between the circles of latitude 35° N and 55° N. That is:

$$ZI = \hat{p}_{35N} - \hat{p}_{55N} \tag{1}$$

In this study we adopted the latter definition, and it is to this definition that we refer when using the abbreviation ZI. Using one definition or the other does not imply a great difference, their variabilities are very similar and both equally allow to characterise high- and low-index situations. This is due to the high correlation between both quantities (Figure 1), as a result of the close relationship between pressure gradients and wind at mid and high latitudes through the establishment of a geostrophic

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equilibrium. We determined a correlation of 0.86 between both magnitudes (Pearson's correlation coefficient, PCC), and a relationship between them according to:

$$\frac{\langle u \rangle}{\hat{p}_{35N} - \hat{p}_{55N}} = \frac{\langle u \rangle}{ZI} \simeq 0.29\,\frac{\text{m/s}}{\text{hPa}} \qquad (2)$$

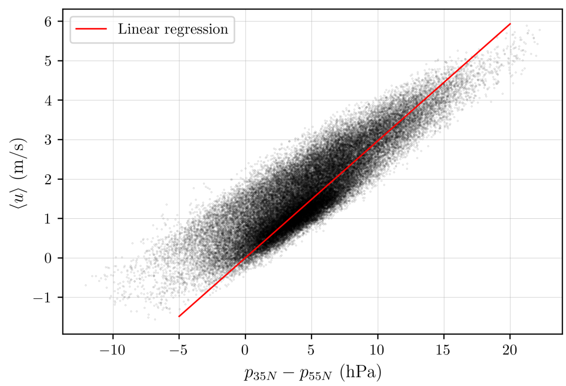

Figure 1: Relationship between two ways of defining the zonal index: as the difference between 35° N and 55° N of zonally averaged MSLP and the average of the wind zonal component at a height of 10 m in the region bounded by these two latitudes.

In order to see to what extent this relationship corresponds to a geostrophic equilibrium, we have made a theoretical estimate assuming that the average wind zonal component is indeed purely geostrophic:

$$\langle u_g \rangle = -\frac{1}{\rho \hat{f}}\frac{\partial p}{\partial y} \simeq \frac{1}{\rho \hat{f}}\frac{ZI}{\Delta y} \quad \Rightarrow \quad \frac{\langle u_g \rangle}{ZI} \simeq 0.33\,\frac{\text{m/s}}{\text{hPa}} \qquad (3)$$

Where $\rho \simeq 1.2\,\text{kg/m}^3$ is the average air density, $\Delta y \simeq 2224$ km the meridional distance between the two considered latitudes, and $\hat{f}$ the average Coriolis parameter in that region, estimated as $\hat{f} = \frac{1}{\Delta\phi}\int_{35^\circ N}^{55^\circ N} 2\Omega \sin\phi d\phi \simeq 1.023 \cdot 10^{-4}\,s^{-1}$.

We notice that the theoretical and experimental estimates fit well enough. However, it is worth emphasising that the reality is more complex than a simple geostrophic equilibrium: in the Ferrel cell the westerlies at the surface continuously transfer angular momentum to the Earth through friction. Still, this does not prevent them from ceasing because, in turn, eddies on both sides of the westerlies belt transfer energy to them through shear [3].

Apart from that, westerlies aloft also depend to a greater extent on the intensity of the temperature gradients and their arrangement. Indeed, they have a significant thermal wind component. The disposition of the fronts (where the greatest thermal gradients are concentrated) is linked to the positions of the centres of action, and these depend on whether we are in a high- or low-index situation, so the value of the ZI also has a strong relationship with the circulation patterns aloft.

B. Seasonal variability

The periodic variability of the ZI is known to have a cyclical component with an irregular period of the order of weeks, known as the index cycle, and a seasonal component, with an annual period.

Plotting the monthly means calculated with the data between 1979 and 2020 (Figure 2) we observe that the ZI describes an annual cycle by which it reaches its highest value on average in late autumn and early winter, leading to strong westerlies capable of rapidly dragging cyclonic disturbances eastwards, while it decreases during spring and remains low during summer, leading to an average weakening of the intensity of the westerlies, and a stronger meridional flow.

The annual periodicity of the ZI is closely linked to that of the general atmospheric circulation and the mean pressure patterns seasonal displacements. These seasonal displacements, far from being simple and uniform, are highly conditioned by the distribution of continental masses. The different thermal characteristics between continents and oceans lead to the establishment of important semi-permanent centres of action (both highs and lows) whose variations in position, extent and intensity have an important effect on the value of the ZI [1].

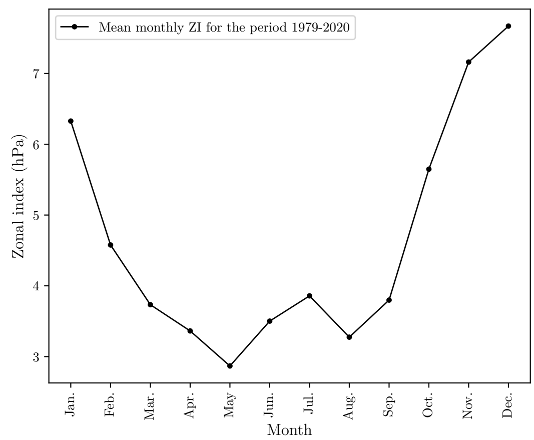

Figure 2: Mean annual variation of ZI, computed for each month from data between 1979 and 2020.

The centres of action which have a greater impact on the ZI are the Icelandic Low and the Aleutian Low, systems associated with the sub-polar low pressure belt that exhibit a pronounced variation in intensity throughout the year. They reach their greatest development in winter, around January (on average 1002 hPa for the Aleutian Low and 996 hPa for the Icelandic Low), while in summer they weaken and can manifest themselves as a simple trough. This marked annual variability of these sub-polar lows is in agreement with that found for the ZI, since the pressures of these lows mainly contribute to the negative term in the equation 1.

We have computed the fast Fourier transform (FFT) for the ZI (Figure 3). Besides observing the annual variation (together with a semi-annual period component) we were not able to detect a variation according to the solar cycle, with a period of about 11 years, although different authors have detected that some centres of action show variations of position and intensity in correlation with the solar activity [4].

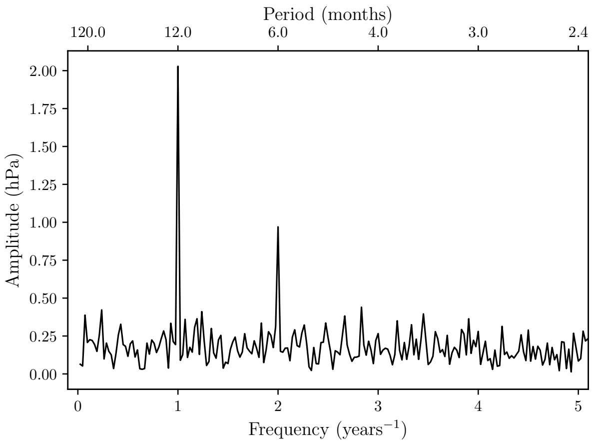

Figure 3: FFT of the ZI computed with data between 1979 and 2020.

C. The index cycle

In 1948, about 10 years after Rossby introduced the concept of the zonal index, he and Willett first described what they called the index cycle [5], a cyclic variation in the ZI value that shifts the circulation pattern in the Ferrel cell with a period of the order of a few weeks. Namias, who studied it two years later [6], established that its period ranges from 4 to 6 weeks; however, the range of possible periods that the index cycle can take was later extended to between 3 and 8 weeks.

When computing the FFT of the ZI (Figure 3) no frequency signal has been detected that could correspond to this cycle. This occurs because, in comparison, the periodicity of the index cycle is much more irregular than that of the annual component. Therefore, it is necessary to apply a seasonal adjustment and thus remove the annual variation. To do so, we have used a definition of a seasonally adjusted zonal index as the ZI from which the monthly means of the corresponding month (the values depicted in Figure 2) have been subtracted. Once this has been done, we can see how this deseasonalised ZI alternates throughout the year between periods of high and low values (corresponding to high- and low-index patterns, respectively).

When plotting the FFT of the deseasonalised ZI (Figure 4) we can see that now the signal corresponding to the index cycle does emerge. It is roughly centred on a 5-week period.

The index cycle starts in a high-index situation, in which we find strong surface westerlies, often reaching

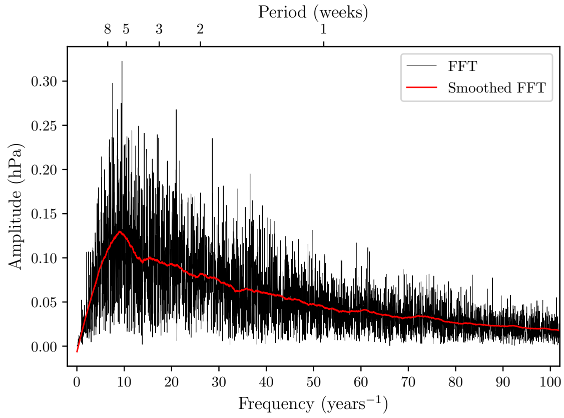

Figure 4: FFT of the deseasonalised ZI computed with data between 1979 and 2020.

their maximum speed at latitudes further north than average, and a stretched wave pattern aloft, preventing considerable air mass exchanges in the north-south direction. In this situation the meridional temperature gradient is at its maximum.

A gradual decrease in the ZI value leads to a weakening of surface westerlies, whose maximum migrates to lower latitudes, as well as a shortening of wave patterns aloft, which allows cyclonic activity to emerge, enabling an exchange of air masses at mid-latitudes.

Eventually, the minimum value of the ZI is reached, resulting in a total dissolution of the westerly wind pattern at sea level and the formation of centers of action, which bring with them a large exchange of air masses in the north-south direction, which dominates over the exchange in the zonal direction. In this situation there is a breakdown in the wave pattern aloft; indeed, pronounced ridges and troughs aloft coupled to a very meandering jet stream eventually break up, giving rise to cold cyclones at lower latitudes and warm anticyclones at higher latitudes.

This breaking of the meandering pattern aloft allows a zonal flow with a long wavelength pattern to be reestablished. The ZI value increases again, the centres of action tend to dissipate or to migrate towards the subtropical high-pressure belt, in the case of anticyclones. This makes it possible to restore a strong zonal flow of westerlies [3] [6].

We have plotted the annual variations of the seasonally adjusted ZI for each of the years of the studied period (Figure 5 shows the one corresponding to 2009, as an example), and we have been able to see that, broadly speaking, for the great majority of years the index cycle is much more evident and its amplitude is considerably greater during the winter, especially during the second half of the season. In summer, on the other hand, the index cycle is diluted; that is, at that time of the year there are no such abrupt shifts in the mid-latitude circulation patterns. This fact was already noticed and described by Namias from the analysis of data from the second half of the 1940s [6], who identified that each year there is a particular index cycle noticeably more pronounced than the rest, which takes place at late February. This fact could also be identified in the analysed data of the last four decades.

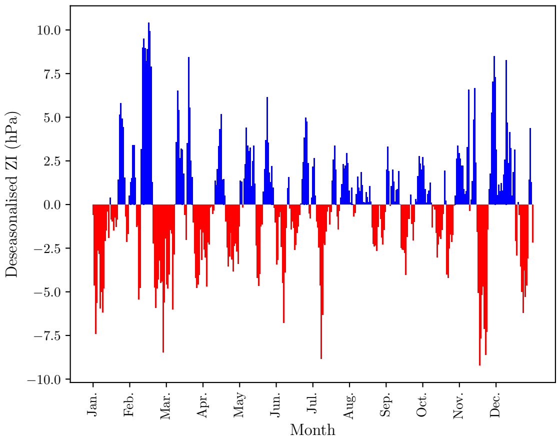

Figure 5: Deseasonalised ZI evolution during 2009. It can be observed that the highest index cycle takes place at late February.

The reason why the index cycle takes place has to do with the balance of heat and momentum that must occur in the atmosphere: a flow is needed to connect the equatorial latitudes with the polar latitudes. Hence, the pattern of surface and aloft westerlies, which is spontaneously configured in the mid-latitudes, has to break down periodically to allow for these necessary meridional flows [5].

This mechanism helps to explain why throughout the year the period and intensity of the index cycle is not constant. In boreal winter, the polar night and the increased snow cover allow for a large reservoir of cold air at high latitudes. On the other hand, blocking situations are more frequent, in which centres of action become interlocked with the wind pattern aloft, providing time for the thermal contrast to intensify further. Thus, when the situation finally becomes unblocked, a large index cycle occurs, as a large meridional heat exchange is required. Both of these situations are statistically more likely in February, which explains the large index cycle that tends to occur at that time [6] [7].

D. Long-term trend

Some studies have investigated the long-term trend for other zonal indices of atmospheric circulation, such as the North Atlantic Oscillation (NAO) or the Arctic Oscillation (AO) indices. In both cases, an upward trend has been found in recent decades, which has been statistically analysed using palaeoclimatic reconstructions, ruling out that it is due to internal variability of the index [8]. These rises have been associated by several authors with various forcing processes, mainly with the effect of greenhouse gases. However, the physical mechanism that explains this trend is still under debate. It should be noted, however, that despite this trend of strengthening westerly winds, both at the surface and at altitude, there has been a tendency for the stratospheric polar vortex to weaken, so it is suggested that the mechanisms explaining the two processes may be largely independent [9].

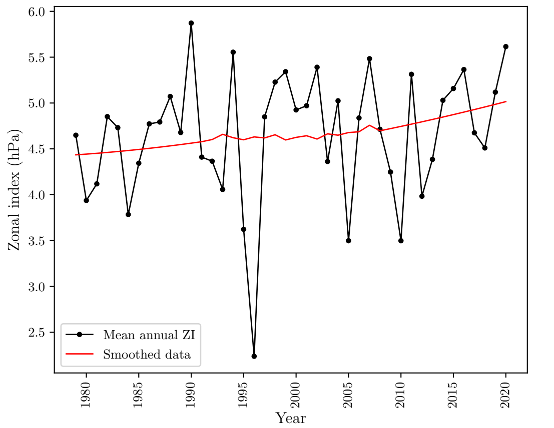

Figure 6: Long-term trend of the ZI.

When calculating the ZI trend (Figure 6), a slight increasing trend has also been observed, which could perhaps be attributed to the same causes that lead to the growth of the NAO index, as both indices are defined between similar latitudes.

E. Correlations and predictability

As early as the studies that were carried out during the decade after Rossby introduced the concept of the zonal index, researchers realised that its usefulness in forecasting is frankly limited. Although it is very useful for classifying patterns in the atmosphere and characterising the circulation in the Ferrel cell, it has been shown that it does not correlate well with the different meteorological variables because, as a hemisphere-wide averaged index, it condenses information from very distant locations whose corresponding synoptic situations may not be well correlated.

This situation, together with the widespread use of other zonal indices that allowed the characterisation of more specific regions in the mid-latitudes with much better correlations (such as the NAO index), led to the almost disappearance of the concept of the zonal index in modern meteorology. Nevertheless, there have been attempts to redefine the concept so as to maximise the signal-to-noise ratio and correlations [10]. It is also worth noting that the zonal index for the Southern Hemisphere has been somewhat more widely used. As the mid-latitudes in the Southern Hemisphere have almost no continental masses, the circulation patterns are more ideal, and the zonal index even lends itself to having its variation modelled mathematically [7].

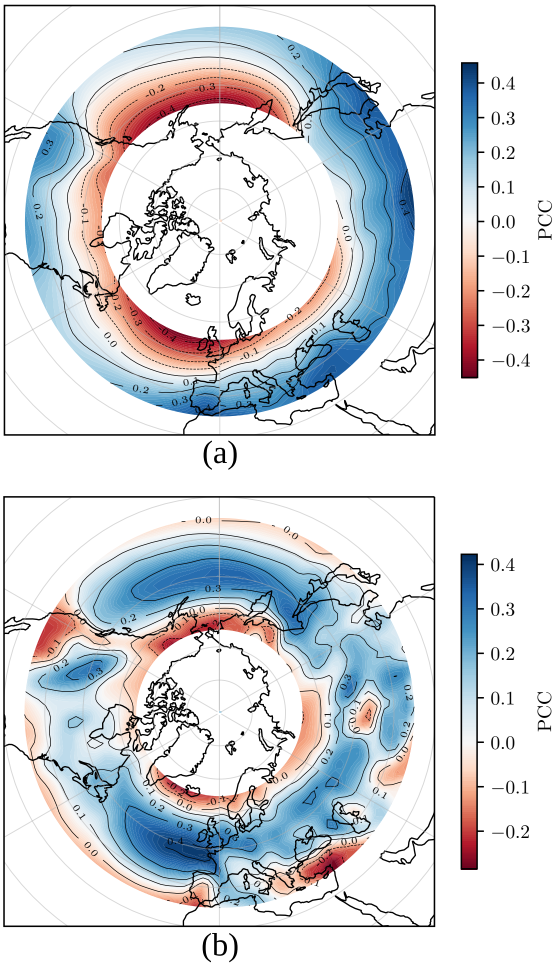

Figure 7: Correlations of the ZI with MSLP (a) and with the zonal wind component at a height of 10 m (b). The depicted region extends from 35° N to 55° N in (a) and from 35° N to 65° N in (b).

We have calculated some correlations of the ZI with different meteorological variables in the mid-latitudes of the Northern Hemisphere, and found that these are indeed quite modest. The correlation coefficient hardly exceeds 0.4 (or -0.4). The variables that are most correlated with the ZI are MSLP and the zonal wind component (Figure 7), as expected from its physical sense.

In Figure 7a we can corroborate how, as we have previously argued, the Icelandic Low and the Aleutian Low are the semi-permanent centres of action whose intensity most determines the value of the ZI.

With regard to Figure 7b, the region of positive correlation of the zonal wind with the ZI determines the westerlies belt. It is interesting to note that the highest correlations are found in the oceanic regions, where the westerlies have no topographic obstacles and the surface has fairly uniform thermal properties. The region with the highest correlation is found in the eastern part of the North Atlantic, just where the NAO index is defined.

IV. CONCLUSIONS

We have corroborated the usefulness of the ZI for characterising circulation patterns at mid-latitudes, testing the validity of an average geostrophic equilibrium on a hemispheric scale. When studying its variability, we found a clear annual periodicity and a much more irregular index cycle period of around 5 weeks, with a much higher intensity in winter. We found an upward trend over the four decades analysed, probably caused by greenhouse gas forcing. As it is an index that condenses information from the whole hemisphere, we have been able to verify its low predictive capacity, with correlations that hardly exceed 0.4, and being very low for variables other than MSLP and zonal wind speed.

Acknowledgments

I would like to show my gratitude to Dr. Bernat Codina for his guidance and patience during the development of this work.

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