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# Revisiting the zonally asymmetric extratropical circulation of the Southern Hemisphere spring using complex empirical orthogonal functions

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## Abstract

The large-scale extratropical circulation in the Southern Hemisphere is much more zonally symmetric than that of the Northern Hemisphere, but its zonal departures, albeit highly relevant for regional impacts, have been less studied. In this study we analyse the joint variability of the zonally asymmetric springtime stratospheric and tropospheric circulation using Complex Empirical Orthogonal Functions (cEOF) to characterise planetary waves of varying amplitude and phase. The leading cEOF represents variability of a zonal wave 1 in the stratosphere that correlates slightly with the Symmetric Southern Annular Mode (S-SAM). The second cEOF (cEOF2) is an alternative representation of the Pacific-South American modes. One phase of this cEOF is also

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047 very highly correlated with the Asymmetric SAM (A-SAM) in the tro-  
 048 posphere. Springs with an active ENSO tend to lock the cEOF2 to a  
 049 specific phase, but have no consistent impact on its magnitude. Fur-  
 050 thermore, we find indications that the location of Pacific Sea Surface  
 051 Temperature anomalies affect the phase of the cEOF2. As a result, the  
 052 methodology proposed in this study provides a deeper understanding  
 053 of the zonally asymmetric springtime extratropical SH circulation.

054 **Keywords:** Southern Hemisphere circulation, Teleconnections, Pacific South  
 055 American Mode, Southern Annular Mode, Stratosphere

## 059 1 Introduction

### introduction

060 The large-scale extratropical circulation in the Southern Hemisphere (SH) is  
 061 much more zonally symmetric than that of the Northern Hemisphere, but  
 062 departures from the zonal mean are associated with regional impacts (e.g.  
 063 [Hoskins and Hedges, 2005](#)). They strongly modulate weather systems and  
 064 regional climate through promoting longitudinally varying meridional trans-  
 065 port of heat, humidity, and momentum ([Trenberth, 1980](#); [Raphael, 2007](#)) and  
 066 could even be related to the occurrence of high-impact climate extremes ([Pezza](#)  
 067 [et al, 2012](#)).

068 The zonally asymmetric circulation is typically described by the amplitude  
 069 and phase of zonal waves obtained by Fourier decomposition of geopotential  
 070 height or sea-level pressure at each latitude (e.g. [van Loon and Jenne, 1972](#);  
 071 [Trenberth, 1980](#); [Turner et al, 2017](#)). This approach suggests that zonal waves  
 072 1 and 3 explain almost 99% of the total variance in the annual mean 500 hPa  
 073 geopotential height zonal anomalies at 50°S ([van Loon and Jenne, 1972](#)). [Tren-](#)  
 074 [berth and Mo \(1985\)](#) concluded that wave 3 plays a role in the development  
 075 of blocking events. In addition, previous works have identified wave-like pat-  
 076 terns with dominant wavenumbers 3-4 at extratropical and subpolar latitudes  
 077 with distinctive regional impacts. [Raphael \(2007\)](#) showed that variability in  
 078 the planetary wave 3 projected onto its climatological location is associated  
 079 with anomalies in the Antarctic sea-ice concentration.

080 Fourier decomposition relies on the assumption that the circulation can  
 081 be meaningfully described in terms of zonal waves of constant amplitude  
 082 along a latitude circle. However, this is not valid for meridionally propagating  
 083 waves or zonal waves with localised amplitudes. Addressing this limitation,  
 084 the Fourier technique can be generalized to integrate all planetary wave ampli-  
 085 tude regardless of wave number by computing the wave envelope ([Irving and](#)  
 086 [Simmonds, 2015](#)). The wave envelope can represent planetary waves with dif-  
 087 ferent amplitude at different longitudes, but lacks information about phase  
 088 and wave number. Using this method, [Irving and Simmonds \(2015\)](#) showed  
 089 that planetary wave amplitude in general is associated with Antarctic sea-ice

concentration and temperature, as well as to precipitation anomalies in regions of significant topography in SH mid-latitudes and Antarctica. 093  
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Another extensively-used approach to characterise the SH tropospheric circulation anomalies, is computing Empirical Orthogonal Functions (EOF, also known as Principal Component Analysis). Within the EOF framework, the Southern Annular Mode (SAM) appears as the leading mode of variability 095  
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of the SH circulation ([Fogt and Marshall, 2020](#)). Spatially, the SAM is characterised by a centre of geopotential anomalies over Antarctica surrounded by anomalies of the opposite sign at middle latitudes. Embedded in this zonally symmetric structure is a wave 3 pattern that is more prominent in the Pacific sector. The 2nd and 3rd EOFs, usually known as Pacific–South American Patterns (PSA) 1 and PSA2 patterns, respectively, describe meridionally propagating wave trains that originate in the eastern equatorial Pacific and Australian-Indian Ocean sector, and travel towards the South Atlantic following a great-circle arch along the Antarctic coast ([Mo and Paegle, 2001](#)). These patterns influence precipitation anomalies in South America ([Mo and Paegle, 2001](#)). Although these patterns are usually derived by applying EOF to temporal anomalies, [Raphael \(2003\)](#) also applied EOF methods specifically to zonal anomalies. [Irving and Simmonds \(2016\)](#) proposed a novel methodology for objectively identifying the PSA pattern using Fourier decomposition. More recently [Goyal et al \(2022\)](#) created an index of amplitude and phase of zonal wave 3-like variability by combining the two leading EOFs of meridional wind anomalies.

Some of the zonally asymmetric patterns of the SH circulation variability described previously appear to have experienced secular changes. For instance, [Raphael \(2003\)](#) suggests that the amplitude of the zonal wave 1 experienced a large increase and that the zonal wave 3 experienced changes in its annual cycle between 1958 and 1996. However, little is known yet about variability and trends of these patterns. 116  
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Patterns resulting from EOF analysis are more flexible than Fourier decomposition-derived modes in that they can capture oscillation patterns that cannot be characterised by purely sinusoidal waves with constant amplitude. Nonetheless, they are restricted to standing oscillation modes and cannot properly represent propagating or phase-varying features such as zonal waves. A single EOF can also represent a mixture of two or more physical modes. 122  
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A third methodology commonly used to describe circulation anomalies consists on identifying particular features of interest and creating indices using simple methods such as averages and differences. Examples of this methodology are the SAM Index of [Gong and Wang \(1999\)](#), the SH wave 3 activity index defined by [Raphael \(2004\)](#) and the SH zonally asymmetric circulation index from [Hobbs and Raphael \(2010\)](#). These derived methods are grounded on other methods such as Fourier decomposition or EOF to identify the centres of action for the described phenomena and can be useful to characterise features that are not readily apparent with these methods. These kinds of indices 128  
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#### 4 SH zonally asymmetric circulation with cEOF

139 are generally easy to compute, but they usually do not capture non-stationary  
 140 patterns.

141 An alternative methodology that has been proposed to study travelling  
 142 and standing waves is complex Empirical Orthogonal Functions (cEOF; [Horel](#)  
 143 ([1984](#))). This method extends EOF analysis to capture oscillations with vary-  
 144 ing amplitude and phase and has been applied to the time domain. For  
 145 instance, [Krokhin and Luxemburg \(2007\)](#) applied cEOF to station-based  
 146 monthly precipitation anomalies and monthly temperature anomalies in the  
 147 Eastern Siberia and the Far East region to characterise the main modes of vari-  
 148 ability and their relationship with teleconnection indices. Similarly, [Gelbrecht](#)  
 149 [et al \(2018\)](#) applied cEOF to daily precipitation from reanalysis to study the  
 150 propagating characteristics of the South American Monsoon. To our knowl-  
 151 edge, cEOF analysis has not been applied in the spatial domain to capture  
 152 the phase-varying nature of planetary waves in the atmosphere.

153 The general goal of this study is to improve the description and under-  
 154 standing of the zonally asymmetric extratropical SH circulation using cEOF,  
 155 which can describe phase varying planetary waves with variable amplitude  
 156 along a latitude circle. In addition, we try to expand the knowledge of the  
 157 simultaneous behaviour of SH asymmetric circulation in the troposphere and  
 158 the stratosphere.

159 We restrict this work to the September-October-November (SON)  
 160 trimester. During this season the tropical teleconnections over South America  
 161 are maximised ([Cazes-Boezio et al, 2003](#)), and the SH zonal winds associated  
 162 with the stratospheric polar vortex increase to peak in October and extend  
 163 downward after that ([Lim et al, 2018](#)).

164 In Section 2 we describe the methods. In Section 3.1 we analyse the spatial  
 165 patterns of each complex EOF. In Section 3.2 we study the spatial regressions  
 166 with geopotential height, temperature, and ozone anomalies. In Section 3.3 and  
 167 3.4 we analyse the relationship between cEOF2, the PSA and SAM modes. In  
 168 Section 3.5 we study tropical forcings that explain the variability of each cEOF.  
 169 In Section 3.6 we show the relationship between these modes of variability  
 170 and precipitation and surface temperature anomalies in South America and  
 171 Oceania. In Section 4 we compare our results with previous studies and discuss  
 172 the benefits of our methodology.

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## 174 2 Data and Methods

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methods

### 176 2.1 Data

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data

178 We used monthly geopotential height, air temperature, ozone mixing ratio,  
 179 and total column ozone (TCO) at  $2.5^\circ$  longitude by  $2.5^\circ$  latitude of hori-  
 180 zontal resolution and 37 vertical isobaric levels from the European Centre for  
 181 Medium-Range Weather Forecasts Reanalysis version 5 [ERA; [Hersbach et al](#)  
 182 ([2019](#))] for the period 1979 – 2019. Most of our analysis is restricted to the  
 183 post-satellite era to avoid confounding factors arising from the incorporation  
 184 of satellite observations, but we also used the preliminary back extension of

ERA5 from 1950 to 1978 (Bell et al, 2020) to describe long-term trends. We derived streamfunction at 200 hPa from ERA5 vorticity using the FORTRAN subroutine FISHPACK (Adams et al, 1999) and we computed horizontal wave activity fluxes following Plumb (1985). Sea Surface Temperature (SST) monthly fields are from Extended Reconstructed Sea Surface Temperature (ERSST) v5 (Huang et al, 2017) and precipitation monthly data from the CPC Merged Analysis of Precipitation (CMAP, Xie and Arkin, 1997), with a 2° and 2.5° horizontal resolution, respectively. The rainfall gridded dataset is based on information from different sources such as rain gauge observations, satellite inferred estimations and the NCEP-NCAR reanalysis, and it is available from 1979 to the present.

The Oceanic Niño Index (ONI, Bamston et al, 1997) comes from NOAA's Climate Prediction Center and the Dipole Mode Index (DMI, Saji and Yamagata, 2003) from Global Climate Observing System Working Group on Surface Pressure.

## 2.2 Methods

The study is restricted to the spring season, defined as the September-October-November (SON) trimester. We compute seasonal means for the different variables, averaging monthly values weighted by the number of days in each month. We use the 200 hPa level to represent the upper troposphere and 50 hPa to represent the lower stratosphere.

We computed the amplitude and phase of the TCO wave 1 by averaging (area-weighted) the data of each SON between 75°S and 45°S, and then extracting the wave-1 component of the Fourier spectrum. We chose this latitude band because it is wide enough to capture most of the relevant anomalies of SH mid-latitudes.

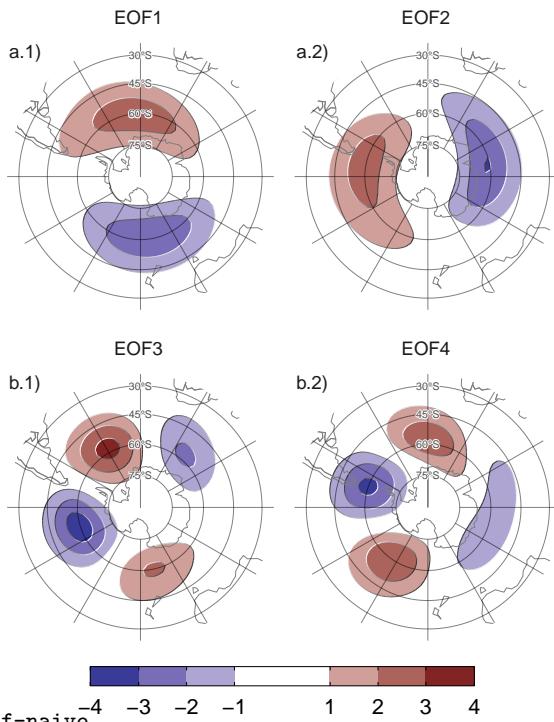
We computed the level-dependent SAM index as the leading EOF of year-round monthly geopotential height anomalies south of 20°S at each level for the whole period (Baldwin and Thompson, 2009). We further split the SAM into its zonally symmetric and zonally asymmetric components (S-SAM and A-SAM indices respectively) following Campitelli et al (2022b). The method consists in first computing the leading EOF of monthly geopotential height anomalies at each level and then computing the zonal mean and the zonal anomalies from its spatial pattern. We then project each level's monthly geopotential height fields onto the corresponding EOF field, the zonally symmetric field and the zonally asymmetric fields to obtain time series corresponding to the full SAM, the symmetric SAM and the asymmetric SAM, respectively.

Seasonal indices of the PSA patterns (PSA1 and PSA2) were calculated, in agreement with Mo and Paegle (2001), as the third and fourth EOFs of seasonal mean anomalies for 500-hPa geopotential heights at SH.

Linear trends were computed by Ordinary Least Squares (OLS) and the 95% confidence interval was computed assuming a t-distribution with the appropriate residual degrees of freedom (Wilks, 2011).

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**Fig. 1:** Spatial patterns of the four leading EOFs of SON geopotential height zonal anomalies at 50 hPa south of 20° S for the 1979 – 2019 period (arbitrary units).

### 2.3 Complex Empirical Orthogonal Functions (cEOF)

ceof-methods

In the standard EOF analysis, zonal waves may appear as pairs of (possibly degenerate) EOFs representing similar patterns but shifted in phase (Horel, 1984). Figure 1 shows the four leading EOFs of SON geopotential height zonal anomalies at 50 hPa south of 20° S. It is clear that the first two EOFs represent a single phase-varying zonal wave 1 pattern and the last two represent a similarly phase-varying pattern with higher wavenumber and three centres of action shifted by 1/4 wavelength (90° in frequency space).

To describe the phase-varying nature of these two wave patterns, one way is to combine each pair of EOFs into indices of amplitude and phase. So, for instance, the amplitude of the wave 1-like EOF could be measured as  $\sqrt{PC1^2 + PC2^2}$  and its phase as  $\tan^{-1}(\frac{PC2}{PC1})$  (where PC1 and PC2 are the time series associated with each EOF). However, this rests on visual inspection of the spatial patterns and only works properly if both phases appear clearly in different EOFs, which is not guaranteed by construction. In particular, this does not work with the wave 1 pattern depicted as the leading EOF in 200 hPa geopotential height zonal anomalies (not shown).

On the other hand, a better alternative for describing phase-varying waves is to use Complex Empirical Orthogonal Functions (cEOF) analysis (Horel, 1984). Each cEOF is a set of complex-valued spatial patterns and time series. The real and imaginary components of the complex spatial pattern can be thought of as representing two spatial patterns that are shifted by 1/4 wavelength by construction, similar to EOF1 and EOF2 in Figure 1. In this paper we use the term 0° cEOF and 90° cEOF to refer to each part of the whole cEOF. The actual field reconstructed by each cEOF is then the linear combination of the two spatial fields weighted by its respective time series. This is analogous to how any sine wave can be constructed by the sum of a sine wave and cosine wave with different amplitude but constant phase. This means that cEOFs naturally represent phase-varying wave-like patterns that change location as well as amplitude.

For instance, when the phase of the wave matches the 0° phase, then the 0° phase time series is positive, and the 90° phase time series is zero. Similarly, when the phase of the wave matches the 90° phase, the 90° phase time series is positive, and the 0° phase time series is zero. The intermediate phases have non-zero values in both time series.

In traditional EOFs, the resulting modes are not unique, and instead are defined up to sign, which corresponds to a rotation in the complex plane of either 0 or  $\pi$ . In the same way, cEOFs are defined up to a rotation in the complex plane of any value between 0 and  $2\pi$  (Horel, 1984).

cEOFs are computed in the same way as traditional EOFs except that the data is first augmented by computing its analytic signal. This is a complex number whose real part is the original series and whose imaginary part is the original data shifted by 90° at each spectral frequency – i.e. its Hilbert transform. The Hilbert transform is usually understood in terms of time-varying signal. However, in this work we apply the Hilbert transform at each latitude circle, level, and at each SON mean (i.e. the signal only depends on longitude). Since each latitude circle is a periodic domain, this procedure does not suffer from edge effects.

We first applied cEOF analysis to geopotential height zonal anomalies south of 20°S at 50 and at 200 hPa. Figure 2 a.1 shows the spatial patterns of the two leading cEOF. The 0° phase is plotted with shaded contours and the 90° phase, with black contours. The two phases of the leading cEOF are very similar to the two leading EOFs shown in Figure 1 and represent a zonal wave 1 pattern; the 0° phase is roughly the EOF1 and the 90° phase is roughly the EOF2).

Table 1 shows the coefficient of determination between time series of the amplitude of each cEOF across levels. There is a high degree of correlation between the magnitude of the respective cEOF1 and cEOF2 at each level. The spatial patterns of the 50 hPa and 200 hPa cEOFs are also similar (not shown).

Both the spatial pattern similarity and the high temporal correlation of cEOFs computed at 50 hPa and 200 hPa suggest that these are, to a large extent, modes of joint variability. This motivates the decision of performing

8 *SH zonally asymmetric circulation with cEOF*

323 **Table 1:** `tab:corr-ceof-splitted`  
 324 Coefficient of determination ( $r^2$ ) between the time series of the  
 325 absolute magnitude of complex EOFs computed separately at 200 hPa and 50  
 326 hPa (p-values lower than 0.01 in bold).

	50 hPa				
	200 hPa	cEOF1	cEOF2	cEOF3	
		cEOF1	<b>0.29</b>	0.01	0.03
330	cEOF2	0.00	<b>0.59</b>	0.02	
331	cEOF3	0.00	0.00	0.01	

333 cEOF jointly between levels. Therefore cEOFs were computed using data from  
 334 both levels at the same time. In that sense each cEOF has a spatial component  
 335 that depends on longitude, latitude and level, and a temporal component that  
 336 depends only on time.

337 Because we are computing the cEOFs of zonal anomalies and not temporal  
 338 anomalies, the cEOFs need to account for the time-mean zonal anomalies.  
 339 These will tend to be represented by the leading cEOF, which therefore will  
 340 have a non-zero temporal mean.

341 As mentioned before, the choice of phases is arbitrary and equally valid.  
 342 But to make the interpretation easier, we chose the phase of each cEOF so  
 343 that either the  $0^\circ$  cEOF or the  $90^\circ$  cEOF is aligned with meaningful variables  
 344 in our analysis. This procedure does not create spurious correlations, it only  
 345 takes an existing relationship and aligns it with a specific phase.

346 Preliminary analysis showed that the first cEOF was closely related to the  
 347 zonal wave 1 of TCO and the second cEOF was closely related to ENSO.  
 348 Therefore, we chose the phase of cEOF1 so that the time series corresponding  
 349 to the  $0^\circ$  cEOF1 has the maximum correlation with the zonal wave 1 of TCO  
 350 between  $75^\circ\text{S}$  and  $45^\circ\text{S}$ . Similarly, we chose the phase of cEOF2 so that the  
 351 coefficient of determination between the ONI and the  $0^\circ$  cEOF2 is minimised,  
 352 which also nearly maximises the correlation with the  $90^\circ$  cEOF2.

353 In Section 3.6 we show regressions of precipitation and temperature asso-  
 354 ciated with intermediate phases. For those plots, we rotated the cEOFs by  $1/4$   
 355 wavelength by multiplying the complex time series by  $\cos(\pi/4) + i \sin(\pi/4)$   
 356 and computing the regression on those rotated timeseries.

357 While we compute these complex principal components using data from  
 358 1979 to 2019, we extended the complex time series back to the 1950 – 1978  
 359 period by projecting monthly geopotential height zonal anomalies standardised  
 360 by level south of  $20^\circ\text{S}$  onto the corresponding spatial patterns.

361 We performed linear regressions to quantify the association between the  
 362 cEOFs and other variables (e.g. geopotential height, temperature, precipita-  
 363 tion, and others). For each cEOF, we computed regression maps by fitting a  
 364 multiple linear model involving both the  $0^\circ$  and the  $90^\circ$  phases. To obtain the  
 365 linear coefficients of a variable  $X$  with the  $0^\circ$  and  $90^\circ$  phase of each cEOF we  
 366 fit the equation

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$X(\lambda, \phi, t) = \alpha(\lambda, \phi) \text{cEOF}_{0^\circ} + \beta(\lambda, \phi) \text{cEOF}_{90^\circ} + X_0(\lambda, \phi) + \epsilon(\lambda, \phi, t)$	371
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where  $\lambda$  and  $\phi$  are the longitude and latitude,  $t$  is the time,  $\alpha$  and  $\beta$  are the linear regression coefficients for  $0^\circ$  and  $90^\circ$  phases respectively,  $X_0$  and  $\epsilon$  are the constant and error terms respectively.

We evaluated statistical significance using a two-sided t-test and, in the case of regression maps, p-values were adjusted by controlling for the False Discovery Rate (Benjamini and Hochberg, 1995; Wilks, 2016) to avoid misleading results from the high number of regressions (Walker, 1914; Katz and Brown, 1991).

## 2.4 Computation procedures

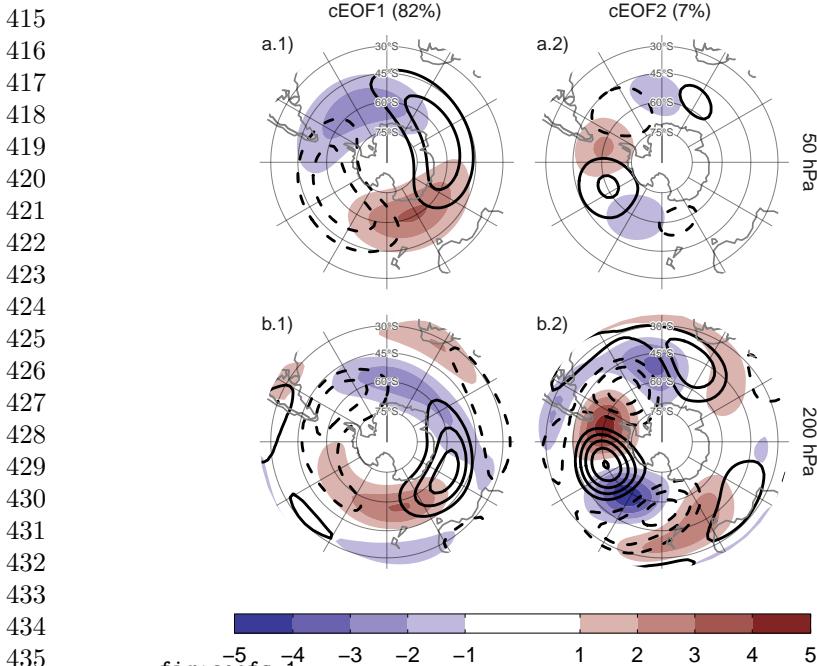
We performed all analysis in this paper using the R programming language (R Core Team, 2020), using data.table (Dowle and Srinivasan, 2020) and metR (Campitelli, 2020) packages. All graphics are made using ggplot2 (Wickham, 2009). We downloaded data from reanalysis using the ecmwfr package (Hufkens, 2020) and indices of ENSO and Indian Ocean Dipole (IOD) with the rsoi package (Albers and Campitelli, 2020). The paper was rendered using knitr and rmarkdown (Xie, 2015; Allaire et al, 2020).

## 3 Results

### 3.1 cEOF spatial patterns

To describe the variability of the circulation zonal anomalies, the spatial and temporal parts of the first two leading cEOFs of zonal anomalies of geopotential height at 50 hPa and 200 hPa, computed jointly at both levels, are shown in Figures 2 and 3. The first mode (cEOF1) explains 82% of the variance of the zonally anomalous fields, while the second mode (cEOF2) explains a smaller fraction (7%). In the spatial patterns (Fig. 2), the  $0^\circ$  and the  $90^\circ$  phases are in quadrature by construction, so that each cEOF describe a single wave-like pattern whose amplitude and position (i.e. phase) is controlled by the magnitude and phase of the temporal cEOF. The wave patterns described by these cEOFs match the patterns seen in the standard EOFs of Figure 1.

The cEOF1 (Fig. 2 column 1) is a hemispheric wave 1 pattern with maximum amplitude at high latitudes. At 50 hPa the  $0^\circ$  cEOF1 has the maximum of the wave 1 at  $150^\circ\text{E}$  and at 200 hPa, the maximum is located at around  $175^\circ\text{E}$  indicating a westward shift with height. The cEOF2 (Fig. 1 column 2) shows also a zonal wave-like structure with maximum amplitude at high latitudes, but with shorter spatial scales. In particular, the dominant structure at both levels is a wave 3 but with larger amplitude in the pacific sector. There is no apparent phase shift with height but the amplitude of the pattern is greatly reduced in the stratosphere, which is consistent with the the fact that

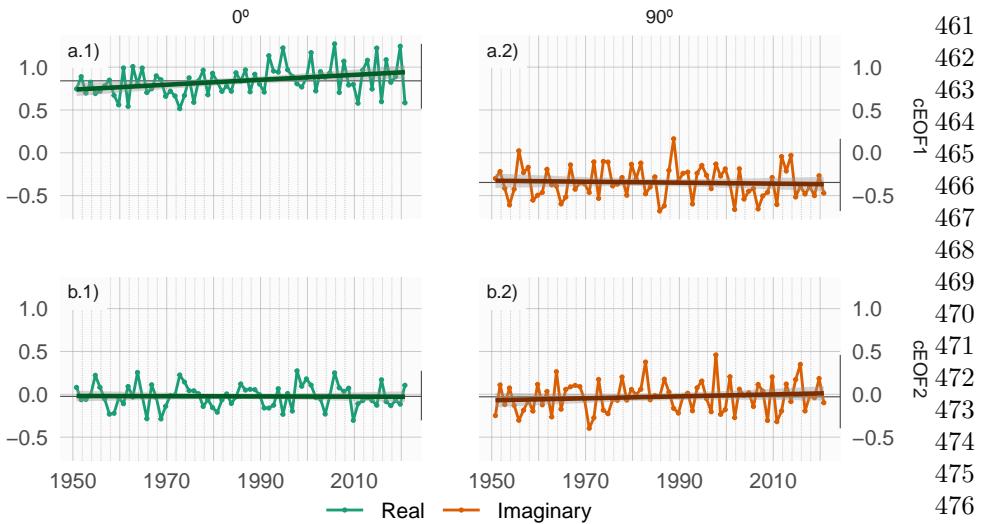


**Fig. 2:** Spatial patterns for the two leading cEOFs of SON geopotential height zonal anomalies at 50 hPa and 200 hPa for the 1979 – 2019 period. The shading (contours) corresponds to 0° (90°) phase. Arbitrary units. The proportion of variance explained for each mode with respect to the zonal mean is indicated in parenthesis.

the cEOF2 computed separately for 200 hPa explains a bit more variance than the cEOF2 computed separately for 50 hPa (11% vs. 3%, respectively). This suggest that this barotropic mode represents mainly tropospheric variability.

There is no significant simultaneous correlation between cEOFs time series. Both cEOFs show year-to-year variability but show no evidence of decadal variability (Fig. 3). The 0° cEOF has a non-zero temporal mean which, as discussed in Section 2.3, is due to the fact that the temporal mean of zonal anomalies need to be captured by the cEOFs. The other indices have almost zero temporal mean, which indicates that only cEOF1 includes variability that significantly projects onto the mean zonal anomalies. This is consistent with the fact that the mean zonal anomalies of geopotential height are very similar to the cEOF1 ( $r^2 = 98\%$ ) and not similar to the cEOF2 ( $r^2 = 0\%$ ).

A significant positive trend in the 0° phase of cEOF1 is evident (Fig. 3a.1, p-value = 0.0037) while there is no significant trend in any of the phases of cEOF2. The positive trend in the 0° cEOF1 translates into a positive trend in cEOF1 magnitude, but not systematic change in phase (not shown). This long-term change indicates an increase in the magnitude of the high latitude zonal wave 1.



**Fig. 3:** Time series of the two leading cEOFs of SON geopotential height zonal anomalies at 50 hPa and 200 hPa. cEOF1 (row a) and cEOF2 (row b) separated in their 0° (column 1) and 90° (column 2) phase. Dark straight line is the linear trend. Black horizontal and vertical line mark the mean value and range of each time series, respectively.

fig:extended-series

## 3.2 cEOFs Regression maps

### 3.2.1 Geopotential

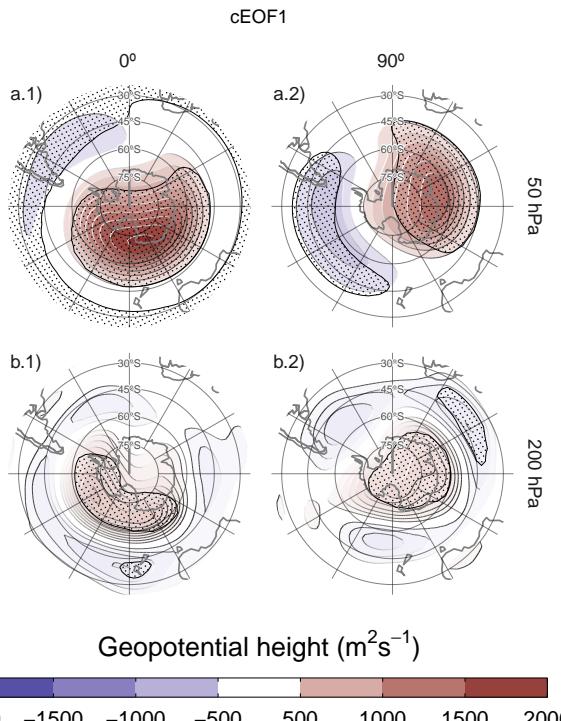
In the previous section, cEOF analysis was applied to zonal anomalies derived by removing the zonally mean values in order to isolate the main characteristics of the main zonal waves characterizing the circulation in the SH. In this section we compute regression fields using the full fields of the variables in order to describe the influence of the cEOFs on the temporal anomalies.

Figure 4 shows regression maps of SON geopotential height anomalies upon cEOF1. At 50 hPa (Figure 4 row a), the 0° cEOF1 is associated with a positive centre located over the Ross Sea. The correlation between the 0° cEOF1 and the zonal mean zonal wind at 60°S and 10hPa is -0.59 (CI: -0.76 – -0.35), indicating a moderate relationship with the SON stratospheric jet. The 90° cEOF1 is associated with a distinctive wave 1 pattern with maximum over the coast of East Antarctica. At 200 hPa (Figure 4 row b) the 0° cEOF1 shows a single centre of positive anomalies spanning West Antarctica surrounded by opposite anomalies in lower latitudes, with its centre shifted slightly eastward compared with the upper-level anomalies. The 90° cEOF1 shows a much more zonally symmetrical pattern resembling the negative SAM phase (e.g. [Fogt and Marshall, 2020](#)). Therefore, the magnitude and phase of the cEOF1 are associated with the magnitude and phase of a zonal wave mainly in the stratosphere.

regressions

geopotential

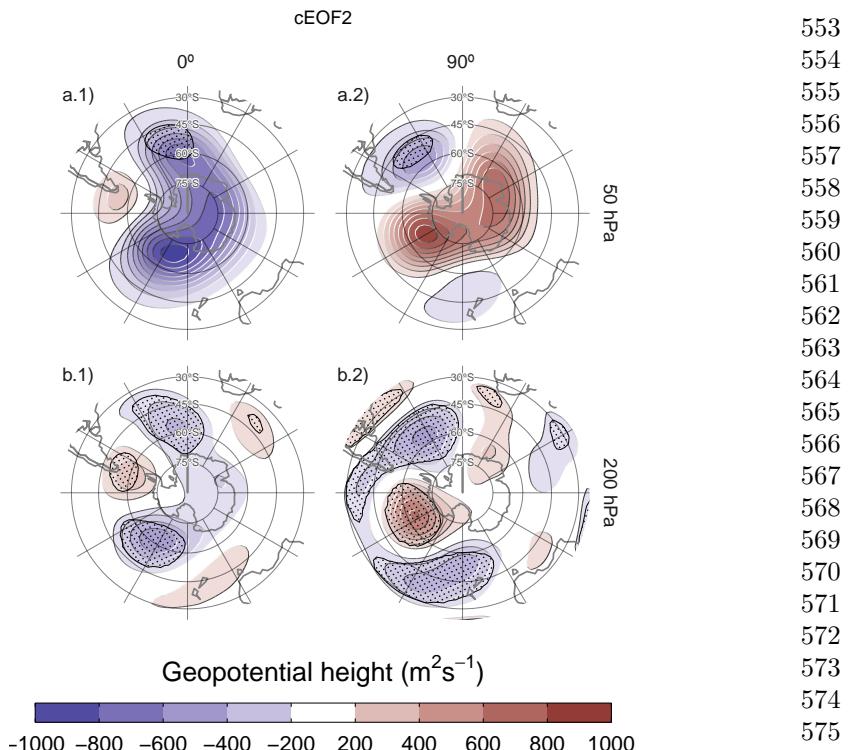
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**Fig. 4:** Regression of SON geopotential height anomalies ( $m^2 s^{-1}$ ) with the (column 1)  $0^\circ$  and (column 2)  $90^\circ$  phases of the first cEOF for the 1979 – 2019 period at (row a) 50 hPa and (row b) 200 hPa. These coefficients come from multiple linear regression involving the  $0^\circ$  and  $90^\circ$  phases. Areas marked with dots have p-values smaller than 0.01 adjusted for False Detection Rate.

Figure 5 shows the regression maps of geopotential height anomalies upon the cEOF2. In the troposphere (Fig. 5 row a) the regression maps show wave trains similar to those identified for cEOF2 patterns (Fig 2). Regressed anomalies associated with the  $0^\circ$  cEOF2 are  $1/4$  wavelength out of phase with those associated with the  $90^\circ$  cEOF2. All fields have a dominant zonal wave 3 limited to the western hemisphere, over the Pacific and Atlantic Oceans. cEOF2 then represents an equivalent barotropic wave train that is very similar to the PSA Patterns ([Mo and Paegle, 2001](#)). Comparing the location of the positive anomaly near  $90^\circ\text{W}$  in column 2 of Figure 5 with Figures 1.a and b from [Mo and Paegle \(2001\)](#), the  $0^\circ$  cEOF2 regression map could be identified with PSA2, while the  $90^\circ$  cEOF2 resembles PSA1.

These wave patterns are also present in the stratosphere (Fig. 5 row a) supporting their equivalent barotropic nature. But also present is a monopole over the pole with negative sign associated with the  $0^\circ$  cEOF2 and positive sign associated with the  $90^\circ$  cEOF2. This monopole might indicate strengthening of the polar vortex associated with positive values of the  $0^\circ$  cEOF2 and weakening



**Fig. 5:** Same as Figure 4 but for cEOF2.

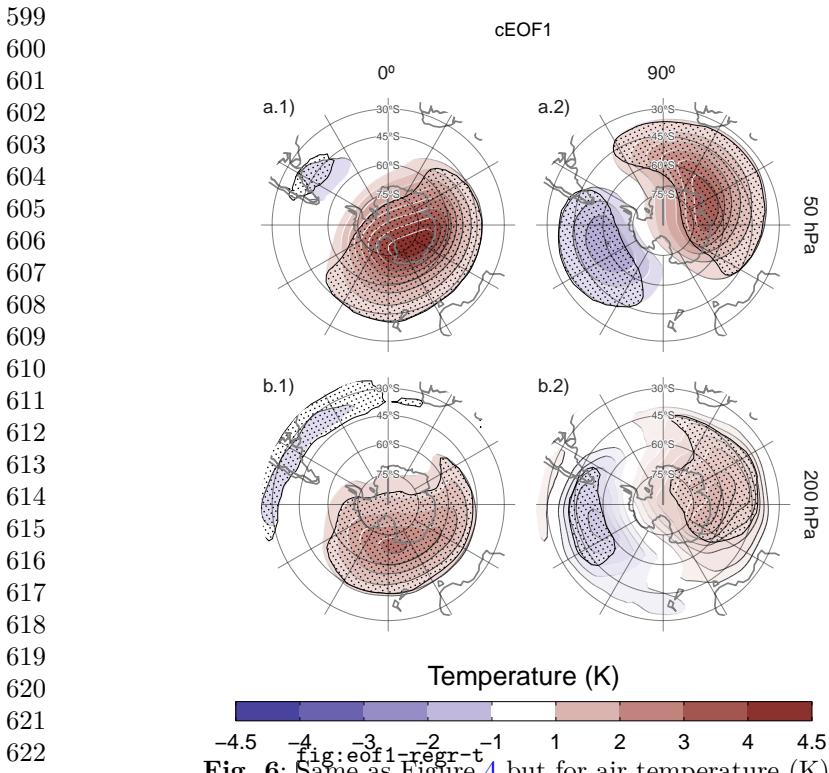
associated with negative values of 0° cEOF2. However, since these anomalies are not statistically significant, this feature should not be overinterpreted.

### 3.2.2 Temperature and Ozone

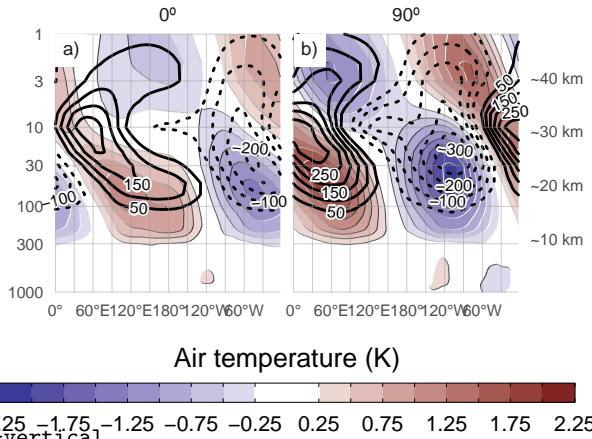
The signature of cEOFs variability on air temperature was also evaluated. Figure 6 shows regression maps of air temperature anomalies at 50 hPa and 200 hPa upon cEOF1. The distribution of temperature regression coefficients at 50 hPa and at 200 hPa mirror the geopotential height regression maps at 50 hPa (Fig. 4). In both levels, the 0° cEOF1 is associated with a positive centre over the South Pole with its centre moved slightly towards 150°E (Fig. 6 column 1). On the other hand, the regression maps on the 90° cEOF1 show a clearer wave 1 pattern with its maximum around 60°E.

Figure 7 shows the vertical distribution of the regression coefficients on cEOF1 from zonal anomalies of air temperature and of ozone mixing ratio averaged between 75°S and 45°S. Temperature zonal anomalies associated with cEOF1 show a clear wave 1 pattern for both 0° and 90° phases throughout the atmosphere above 250 hPa with a sign reversal above 10 hPa. As a result of the hydrostatic balance, this is the level in which the geopotential anomaly have maximum amplitude (not shown).

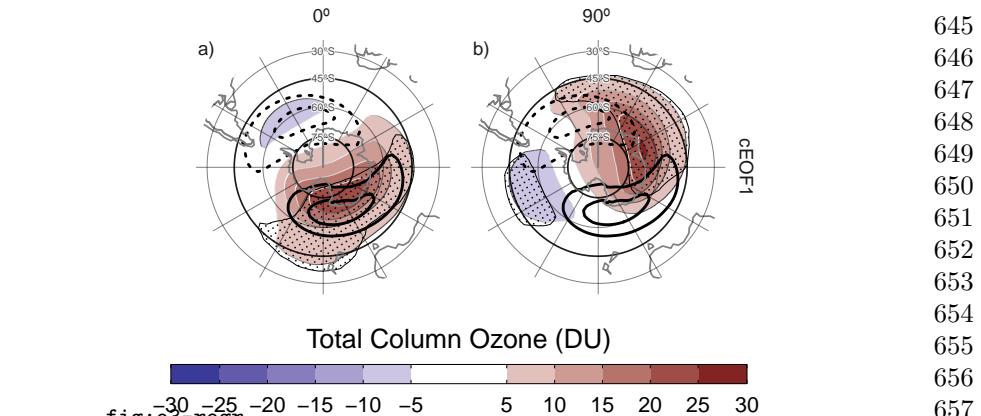
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**Fig. 6:** Same as Figure 4 but for air temperature (K).



**Fig. 7:** Regression of SON zonal anomalies averaged between 75°S and 45°S of mean air temperature (shaded, Kelvin) and ozone mixing ratio (contours, negative contours with dashed lines, labels in parts per billion by mass) with the (a) 0° and (b) 90° phase of the cEOF1 for the 1979 – 2019 period.



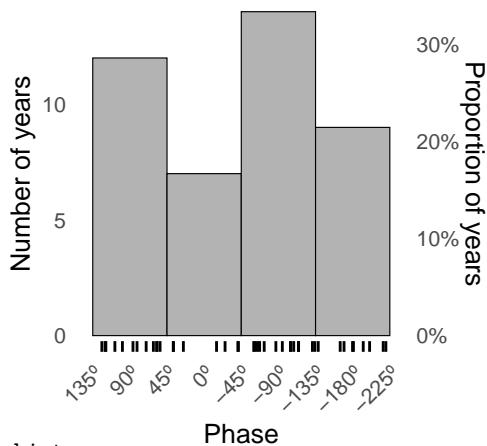
**Fig. 8:** Regression of SON mean Total Column Ozone anomalies (shaded, Dobson Units) with the (a)  $0^\circ$  and (b)  $90^\circ$  phases of the cEOF1 for the 1979–2019 period. On contours, the mean zonal anomaly of Total Column Ozone (negative contours in dashed lines, Dobson Units). Areas marked with dots have p-values smaller than 0.01 adjusted for False Detection Rate.

The maximum ozone regressed anomalies coincide with the minimum temperature anomalies above 10 hPa and with the maximum temperature anomalies below 10 hPa (Fig. 7). Therefore, the ozone zonal wave 1 is negatively correlated with the temperature zonal wave 1 in the upper stratosphere, and positively correlated in the upper stratosphere. This change in phase is observed in ozone anomalies forced by planetary waves that reach the stratosphere. In the photochemically-dominated upper stratosphere, cold temperatures inhibit the destruction of ozone, explaining the opposite behaviour for both variables as were elucidated with dynamical chemical models (Hartmann and Garcia, 1979; Wirth, 1993; Smith, 1995). On the other hand, in the advectively-dominated lower stratosphere, ozone anomalies are 1/4 wavelength out of phase with horizontal and vertical transport, which are in addition 1/4 wavelength out of phase with temperature anomalies, resulting in same sign anomalies for the response of both variables (Hartmann and Garcia, 1979; Wirth, 1993; Smith, 1995).

The regression maps of TCO anomalies upon cEOF1 (Fig. 8) show zonal wave 1 patterns associated with both components of cEOF1. The climatological position of the springtime Ozone minimum (ozone hole) is outside the South Pole and towards the Weddell Sea (e.g. Grytsai, 2011). Thus, the  $0^\circ$  cEOF1 regression field (Figure 8a) coincides with the climatological position of the ozone hole, while it is  $90^\circ$  out of phase for the  $90^\circ$  cEOF1. The temporal correlation between the amplitudes of TCO planetary wave 1 and the amplitude of cEOF1 is 0.79 (CI: 0.63 – 0.88), while the correlation between their phases is -0.85 (CI: -0.92 – -0.74). Consequently, cEOF1 is strongly related with the SH ozone variability.

691 **Table 2:** Correlation coefficients ( $r$ ) between cEOF2 components and the  
 692 PSA1 and PSA2 modes computed as Mo and Paegle (2001) for the 1979 –  
 693 2019 period. 95% confidence intervals in parenthesis. p-values lower than 0.01  
 694 in bold.

PC	cEOF2	
	Real	Imaginary
PSA1	0.26 (CI: -0.04 – 0.52)	<b>0.82 (CI: 0.69 – 0.9)</b>
PSA2	<b>0.79 (CI: 0.63 – 0.88)</b>	-0.02 (CI: -0.32 – 0.29)

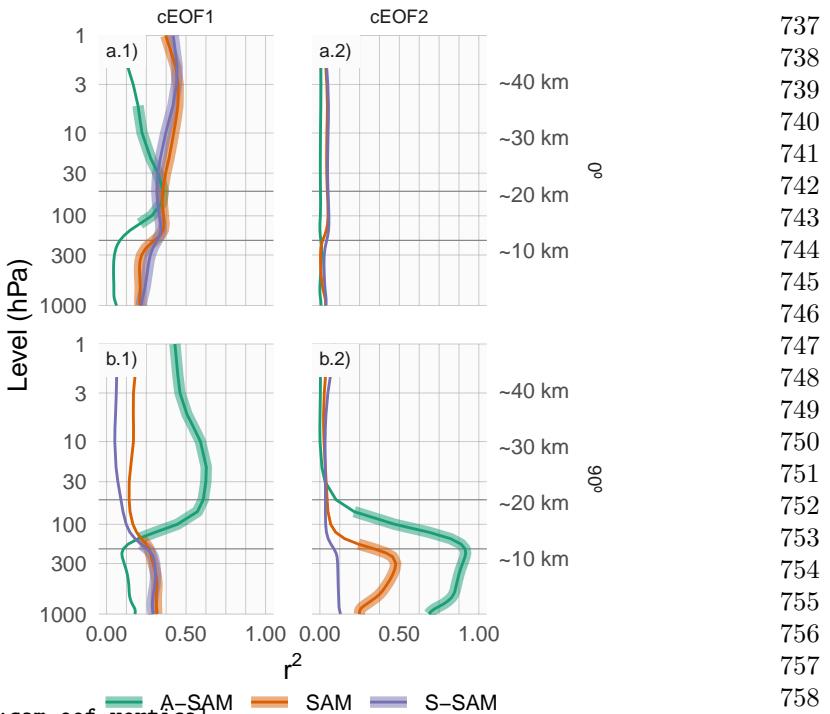


702 **Fig. 9:** `fig:phase-histogram`  
 703 Histogram of phase distribution of cEOF2 phase for the 1979 – 2019  
 704 period. Bins are centred at 90°, 0°, -90°, -180° with a binwidth of 90°. The  
 705 small vertical lines near the horizontal axis mark the observations.  
 706

### 707 3.3 PSA

708 Given the similarity between the cEOF2 related-associated structures (Fig. 5)  
 709 and documented PSA patterns, we study the relationship between them.  
 710 Table 2 shows the correlations between the two PSA indices and the time series  
 711 for 0° and 90° phases of cEOF2. As visually anticipated by Figure 5, there is a  
 712 large positive correlation between PSA1 and 90° cEOF2, and between PSA2  
 713 and 0° cEOF2. On the other hand, there is no significant relationship between  
 714 PSA1 and 0° cEOF2, and between PSA2 and 90° cEOF2. As a result, cEOF2  
 715 represents well both the spatial structure and temporal evolution of the PSA  
 716 modes, so it is possible to make an association between its two phases and the  
 717 two PSA modes. That is, the phase election for cEOF2 that maximises the  
 718 relationship between ENSO and 90° cEOF2, also maximises the association  
 719 between cEOF2 components and PSA modes (not shown).

psa



**Fig. 10:** fig:sam\_eof\_vertical Coefficient of determination ( $r^2$ ) between each component of cEOFs and the SAM, Asymmetric SAM (A-SAM) and Symmetric SAM (S-SAM) indices computed at each level for the 1979 – 2019 period. Thick lines represent estimates with  $p < 0.01$  corrected for False Detection Rate (Benjamini and Hochberg, 1995).

Figure 9 shows an histogram that counts the number of SON seasons in which the cEOF2 phase was close to each of the four particular phases (positive/negative of  $0^\circ$  and  $90^\circ$  phases), with the observations for each season marked as rugs on the horizontal axis. In 62% of seasons cEOF2 has a phase similar to either the negative or positive  $90^\circ$  phase, making the  $90^\circ$  phase the most common phase. This is also the phase that is most correlated with ENSO by the definition of the  $0^\circ$  phase as described in Section 2.

Therefore, by virtue of being the most common phase, the  $90^\circ$  cEOF2 explains more variance than the  $0^\circ$  cEOF2. Conventional EOF analysis will therefore tend to separate them relatively cleanly, with the EOF representing the  $90^\circ$  cEOF2 always leading the one representing the  $0^\circ$  cEOF2. This phase preference is in agreement with Irving and Simmonds (2016), who found a bimodal distribution to PSA-like variability (compare our Figure 9 with their Figure 6).

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783 **3.4 SAM**<sup>sam</sup>

784 We now explore the relationship between SAM and the cEOFs motivated by  
 785 the resemblance between cEOFs regression maps and SAM patterns shown in  
 786 Section 3.2. We computed the coefficient of determination between the cEOFs  
 787 time series and the three SAM indices (SAM, A-SAM and S-SAM) defined  
 788 by Campitelli et al (2022b) at each vertical level (Fig. 10). The SAM index  
 789 is statistically significantly correlated with the 0° cEOF1 in all levels, and  
 790 with the 90° cEOF1 and 90° cEOF2 in the troposphere. On the other hand,  
 791 correlations between SAM and the 0° cEOF2 are non-significant.

792 The relationship between the SAM and cEOF1 in the troposphere is  
 793 explained entirely by the zonally symmetric component of the SAM as shown  
 794 by the high correlation with the S-SAM below 100 hPa and the low and sta-  
 795 tistically non-significant correlations between the A-SAM and either the 0°  
 796 or 90° cEOF1. In the stratosphere, the 0° cEOF1 is correlated with both A-  
 797 SAM and S-SAM, while the 90° cEOF1 is highly correlated only with the  
 798 A-SAM. These correlations are consistent with the regression maps of geopo-  
 799 tential height in Figure 4 and their comparison with those obtained for SAM,  
 800 A-SAM and S-SAM by Campitelli et al (2022b).

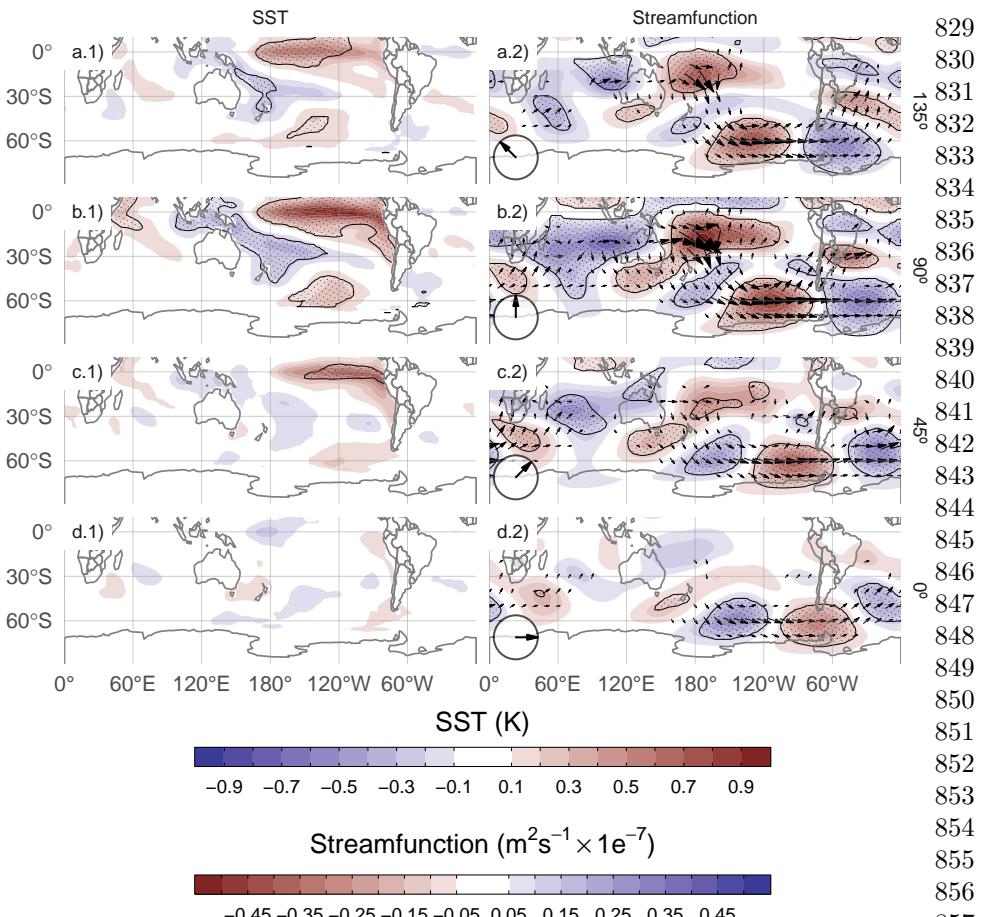
801 In the case of 90° cEOF2, its correlation with the SAM for the troposphere  
 802 is associated with the asymmetric variability of the SAM. Indeed, the 90°  
 803 cEOF2 shares up to 92% variance with the A-SAM and only 12% at most with  
 804 the S-SAM (Figure 10.b2). Such extremely high correlation between A-SAM  
 805 and 90° cEOF2 suggests that the modes obtained in this work are able to char-  
 806 acterise the zonally asymmetric component of the SAM described previously  
 807 by Campitelli et al (2022b).

808 **3.5 Tropical sources of cEOFs variabitliy**<sup>tropical</sup>

809 The connections between cEOFs and tropical sources of variability were also  
 810 assessed. Figure 11 shows the regression maps of Sea Surface Temperature  
 811 (SST) and streamfunction anomalies at 200 hPa upon standardised cEOF2.  
 812 As well as regression maps for the 0° and 90° phases, we include corresponding  
 813 regressions for two intermediate directions (corresponding to 45° and 135°).

814 The 90° cEOF2 (second row) is associated with strong positive SST anom-  
 815 alies on the Central to Eastern Pacific and negative anomalies over an area  
 816 across northern Australia, New Zealand the South Pacific Convergence Zone  
 817 (SPCZ) (Figure 11.b1). The regression field of SST anomalies bears a strong  
 818 resemblance with canonically positive ENSO (Bamston et al, 1997). Indeed,  
 819 there is a significant and very high correlation (0.76 (CI: 0.6 – 0.87)) between  
 820 the ONI and the 90° cEOF2 time series. In addition to the Pacific ENSO-like  
 821 pattern, there are also positive anomalies in the western Indian Ocean and  
 822 negative values in the eastern Indian Ocean, resembling a positive IOD (Saji  
 823 et al, 1999). Consistently, the correlation between the 90° cEOF2 and the DMI  
 824 is 0.62 (CI: 0.38 – 0.78).

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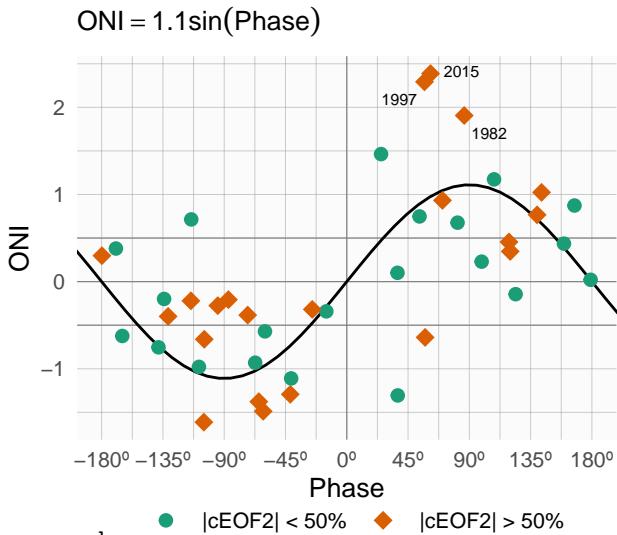
**Fig. 11:** Regression of SST (K, left column) and streamfunction zonal anomalies ( $m^2/s \times 10^{-7}$ , shaded) with their corresponding activity wave flux (vectors) (right column) upon cEOF2 different phases (illustrated in the lower-left arrow) for the 1979 – 2019 period. Areas marked with dots have p-values smaller than 0.01 adjusted for FDR.

fig:sst-psi-2

The  $90^\circ$  cEOF2 is associated with strong wave-like streamfunction anomalies emanating from the tropics (Figure 11.b2), both from the Central Pacific sector and the Indian Ocean. The atmospheric response associated with  $90^\circ$  cEOF2 is then consistent with the combined effect of ENSO and the IOD on the extratropics: with SST anomalies inducing anomalous tropical convection that in turn excite Rossby waves propagating meridionally towards higher latitudes (Mo, 2000; Cai et al., 2011a; Nuncio and Yuan, 2015).

However, the cEOF2 is not associated with the same tropical SST anomaly patterns at all their phases Figure 11.d1 and d2 show that the  $0^\circ$  cEOF2 is not associated either with any significant SST nor streamfunction anomalies

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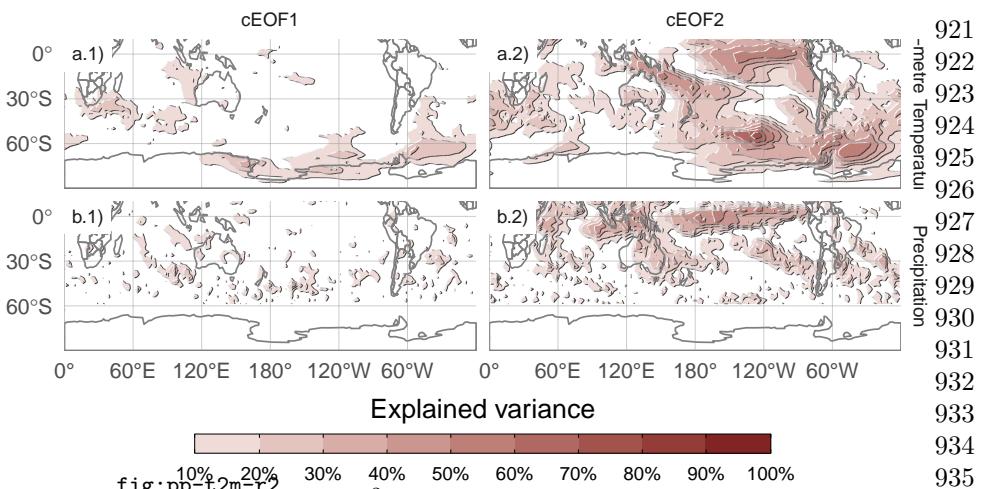


**Fig. 12:** SON ONI values plotted against cEOF2 phase for the 1979 – 2019 period. Years with magnitude of cEOF2 greater (smaller) than the 50th percentile are shown as orange diamonds (green circles). Black line is the fit  $\text{ONI} \sim \sin(\text{phase})$  computed by weighted OLS using the magnitude of the cEOF2 as weights.

898 in the tropics. As a result, the correlation between the  $0^\circ$  cEOF2 and ENSO  
899 is not significant (0 (CI:  $-0.3 - 0.3$ )). Meanwhile, Rows a and c in Fig. 11 show  
900 that the intermediate phases are still associated with significant SST regressed  
901 anomalies over the Pacific Ocean, but at slightly different locations. The  $135^\circ$   
902 phase is associated with SST anomalies in the central Pacific (Fig. 11a.1),  
903 while the  $45^\circ$  phase is associated with SST anomalies in the eastern Pacific,  
904 which correspond roughly to the Central Pacific and Eastern Pacific “flavours”  
905 of ENSO, respectively (Fig. 11c.1) (Kao and Yu, 2009). Both phases are also  
906 associated with wave trains generated in the region surrounding Australia  
907 and propagates toward the extra-tropics, although less intense than the ones  
908 associated with the  $90^\circ$  phase.  
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910 To further explore the relationship between tropical forcing and phases of  
911 the cEOF2, Figure 12 shows the ONI plotted against the cEOF2 phase for  
912 each SON trimester between 1979 and 2019, highlighting years in which the  
913 magnitude of cEOF2 is above the median. In years with positive (negative)  
914 ONI, the cEOF2 phase is mostly around  $90^\circ$  ( $-90^\circ$ ). In the neutral ENSO  
915 seasons, the cEOF2 phase is much more variable. The black line in Figure 12  
916 is a sinusoidal fit of the relationship between ONI and cEOF2 phase. The  $r^2$   
917 corresponding to the fit is 0.57, statistically significant with p-value  $< 0.001$ ,  
918 indicating a quasi-sinusoidal relation between these two variables.

919 The correlation between the absolute magnitude of the ONI and the cEOF2  
920 amplitude is 0.45 (CI: 0.17 – 0.66). However, this relationship is mostly



**Fig. 13:** Explained variance ( $r^2$  as percentage) of 2-metre temperature (row a) and precipitation (row b) anomalies by the regression upon cEOF1 (column 1) and cEOF2 (column 2).

driven by the three years with strongest ENSO events in the period (2015, 1997, and 1982) which coincide with the three years with strongest cEOF2 magnitude (not shown). If those years are removed, the correlation becomes non-significant (0.04 (CI: -0.28 – 0.35)). Furthermore, even when using all years, the Spearman correlation –which is robust to outliers– is also non-significant (0.2, p-value = 0.21). Therefore, although the location of tropical SST anomalies seem to have an effect in defining the phase of the cEOF2, the relationship between the magnitude of cEOF2 and ONI remains uncertain and might be only evident in very strong ENSO events, that are scarce in the historical observational record.

We conclude that the wave train represented by cEOF2 can be both part of the internal variability of the extratropical atmosphere and forced by tropical SSTs. In the former case, the wave train has little phase preference. However, when cEOF2 is excited by tropical SST variability, it tends to remain locked to the  $90^\circ$  phase. This explains the relative over-abundance of years with cEOF2 near positive and negative  $90^\circ$  phase in Figure 9.

Unlike the cEOF2 case, there are no significant SST regressed anomalies associated with either the  $0^\circ$  or  $90^\circ$  cEOF1 (Sup. Figure A.1). Consistently, streamfunction anomalies do not show any tropical influence. Instead, the  $0^\circ$  and  $90^\circ$  cEOF1 are associated with zonally propagating wave activity fluxes in the extra-tropics around  $60^\circ\text{S}$ , except for an equatorward flow from the coast of Antarctica around  $150^\circ\text{E}$  in the  $0^\circ$  phase. This suggests that the variability of cEOF1 is driven primary by the internal variability of the extra-tropics.

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967 **3.6 cEOFs surface impacts**

968 The influence of cEOFs variability in the anomalies of both 2-metre air tem-  
 969 perature and precipitation in the SH was also explored. Figure 13 shows the  
 970 2-meter temperature and precipitation anomalies explained variance by the  
 971 multiple linear model of both 0° and 90° cEOF1 (column 1), and both 0° and  
 972 90° cEOF2 (column 2). The variance explained by cEOF1 for precipitation  
 973 anomalies and temperature anomalies in most regions is extremely low, except  
 974 for the northern tip of the Antarctic Peninsula, northern Weddell Sea and the  
 975 Ross Sea coast (Fig. 13a.1).

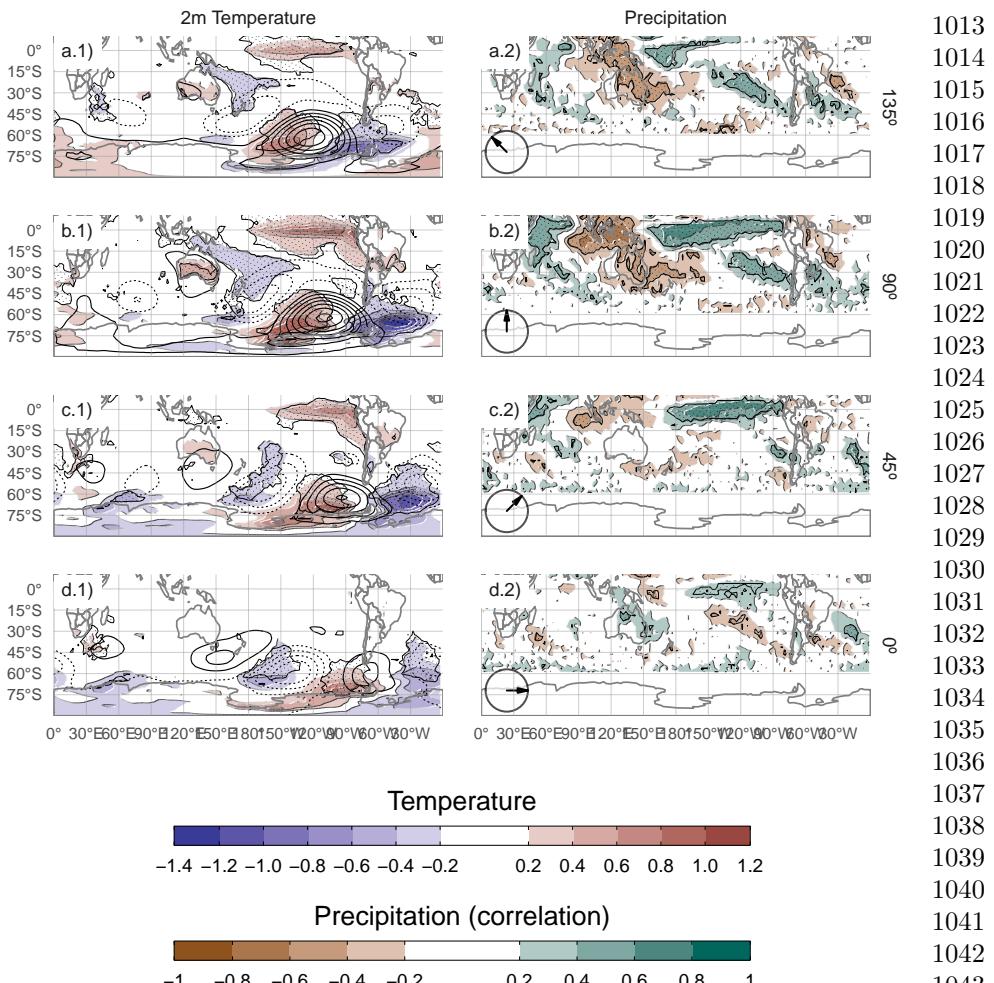
976 This lack of strong relationship between the cEOF1 and SST, temperature  
 977 and precipitation might be surprising considering the correlation between the  
 978 cEOF1 and the SAM (Fig. 10 column 1) and the correlation between SAM and  
 979 Central Pacific SST, temperature east and west of the Antarctic Peninsula,  
 980 and with precipitation in western Australia (Fogt and Marshall, 2020). There  
 981 are two main reasons for this. First, the correlation between cEOF1 and the  
 982 SAM in the troposphere is modest, with less than 50% of shared variance (Fig.  
 983 10 column 1), so these indices are not expected to be equivalent to each other.  
 984 Second, Campitelli et al (2022b) showed that the strong relationship between  
 985 the SAM and Pacific SSTs and temperature anomalies around the Antarctic  
 986 Peninsula is mainly due to the asymmetric part of the SAM. Meanwhile, the  
 987 cEOF1 is significantly correlated only with the symmetric part of the SAM  
 988 (Fig. 10 column 1), which by itself is not significantly correlated with surface  
 989 temperatures in that area.

990 On the other hand, the cEOF2 explained variance is greater than 50% in  
 991 some regions for both variables (Fig. 13 column 2). For 2-metre temperature,  
 992 there are high values in the tropical Pacific and the SPCZ, as well as the  
 993 region following an arc between New Zealand and the South Atlantic, with  
 994 higher values in the Southern Ocean. Over the continents, there are moderate  
 995 values of about 30% variance explained in southern Australia, Southern South  
 996 America and the Antarctic Peninsula. For precipitation, there are high values  
 997 over the tropics. At higher latitudes, moderate values are observed over eastern  
 998 Australia and some regions of southern South America.

999 Since the cEOF1 has a relatively weak signal in the surface variables  
 1000 explored here, we will only focus on the cEOF2 influence. Figure 14 shows  
 1001 regression maps of 2-metre temperature (column 1) and precipitation (column  
 1002 2) anomalies upon different phases of standardised cEOF2.

1003 Temperature anomalies associated with the 90° cEOF (Fig. 14.b1) show  
 1004 positive values in the tropical Pacific, consistent with SSTs anomalies associ-  
 1005 ated with the same phase (Fig. 11.b1). At higher latitudes there is a wave-like  
 1006 pattern of positive and negative values that coincide with the nodes of the  
 1007 850 hPa geopotential height regression patterns. This is consistent with tem-  
 1008 perature anomalies produced by meridional advection of temperature by the  
 1009 meridional winds arising from geostrophic balance. Over the continents, the  
 1010 90° cEOF2 (Fig. 14b.1) is associated with positive regressed temperature  
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**Fig. 14:** `fig:pp-temp-2` Regression of SON mean 2-meter temperature (K, shaded) and 850 hPa geopotential height (m, contours) (column 1), and precipitation (correlation, column 2) upon different phases of cEOF2. For the 1979 – 2019. Areas marked with dots have p-values smaller than 0.01 adjusted for False Detection Rate.

anomalies in southern Australia and negative regressed anomalies in southern South America and the Antarctic Peninsula, that are a result of the wave train described before.

The temperatures anomalies associated with the  $0^\circ$  cEOF2 (Fig. 14d.1) are less extensive and restricted to mid and high latitudes.

Over the continents, the temperature anomalies regressions are non significant, except for positive anomalies near the Antarctic Peninsula.

24 *SH zonally asymmetric circulation with cEOF*

1059 Tropical precipitation anomalies associated with the 90° cEOF2 are strong,  
 1060 with positive anomalies in the central Pacific and western Indian, and negative  
 1061 anomalies in the eastern Pacific (Fig. 14b.2). This field is consistent with  
 1062 the SST regression map (Fig. 14b.1) as the positive SST anomalies enhance  
 1063 tropical convection and the negative SST anomalies inhibits it.

1064 In the extra-tropics, the positive 90° cEOF2 is related to drier conditions  
 1065 over eastern Australia and the surrounding ocean, that it is similar signal as  
 1066 the one associated with ENSO (Cai et al, 2011a). However, the 90° cEOF2  
 1067 is not the phase most correlated with precipitation in that area. The 135°  
 1068 phase (an intermediate between positive 90° and 180° cEOF2) component  
 1069 is associated with stronger and more extensive temporal correlations with  
 1070 precipitation over Australia and New Zealand, consistent with the effect of  
 1071 ENSO on precipitation in that region. These anomalies are probably related  
 1072 to the direct effect of vertical anomalies of the Southern Oscillation and less  
 1073 so to the large-scale circulation anomalies described by cEOF2 (Cai et al,  
 1074 2011b). Circulation anomalies associated with the Indian Ocean Dipole could  
 1075 also play a role (Cai et al, 2011b).

1076 Over South America, the 90° cEOF2 has positive correlations with precipi-  
 1077 tation in South Eastern South America (SESA) and central Chile, and negative  
 1078 correlations in eastern Brazil. This correlation field matches the springtime  
 1079 precipitation signature of ENSO (e.g. Cai et al, 2020) and it is also similar  
 1080 to the precipitation anomalies associated with the A-SAM (Campitelli et al,  
 1081 2022b). This result is not surprising considering the close relationship of the  
 1082 90° cEOF2 with both ONI and A-SAM index, which was shown previously.  
 1083 Furthermore, it consolidates the identification of the cEOF2 with the PSA  
 1084 pattern. Resembling the relationship between ONI and the phase of cEOF2  
 1085 (Fig. 12), there is a cEOF2 phase dependence of the precipitation anomalies  
 1086 in SESA (not shown).

1087 The correlation coefficients between precipitation anomalies and the 0°  
 1088 cEOF2 (Fig. 14d.2) are weaker than for 90° cEOF2. There is a residual pos-  
 1089 itive correlation in the equatorial eastern Pacific and small, not statistically  
 1090 significant positive correlations over eastern Australia and negative ones over  
 1091 New Zealand.

1092

## 1093 4 Discussion and conclusions

1094 discussion  
 1095 In this study we assessed extratropical Southern Hemisphere zonally asym-  
 1096 metric circulation in austral spring. For this purpose, we derived two complex  
 1097 indices using Complex Empirical Orthogonal Functions and used to charac-  
 1098 terise both amplitude and phase of planetary waves.

1099 The cEOF1 represents the variability of the zonal wave 1 in the strato-  
 1100 sphere and is closely related to stratospheric variability such as anomalies in  
 1101 Total Column Ozone. Otherwise, this complex EOF is not related with SST  
 1102 variability and continental precipitation in the Southern Hemisphere. On the  
 1103 other hand, the cEOF2 represents a wave-3 pattern with maximum magnitude  
 1104

in the Pacific sector, that is an alternative representation of the PSA1 and PSA2 patterns (Mo and Paegle 2001). The 90° cEOF2 can be identified with the PSA1 and the 0° cEOF2 with the PSA2. While the cEOF2 variability is related to surface impacts, the cEOF1 surface influence is almost negligible. For instance, precipitation anomalies in South America associated with the 90° cEOF2 show a clear ENSO-like impact, with positive anomalies in South-eastern South America, negative anomalies in Southern Brazil and positive anomalies in central Chile for positive 90° cEOF2 phase.

Variability patterns that arise from cEOF methodology describe the zonally asymmetric springtime extratropical SH circulation, reproducing previous features such as the variability related to PSAs or A-SAM.

Since the spatial fields obtained from both components of cEOF2, which resemble PSA patterns, are in quadrature by construction, the cEOF methodology allows to derive, for the first time to our knowledge, a joint PSA index from the resulted amplitude and phase. These patterns are not forced to be orthogonal to other modes of circulation, like they are in standard EOF methodology. This allows us to show for example, that the 90° cEOF2, corresponding to PSA1 variability, is closely associated with the SAM in the troposphere. Previous research in the SAM–PSA relationship had the issue that the SAM and the PSA patterns are not independently derived and so the correlation between these indices had to be zero by construction (e.g. Yu et al. 2015).

Most studies on the relationship between ENSO and SAM rely on correlations between an ENSO index and the SAM index (e.g. L'Heureux and Thompson, 2006, Cai et al (2011c)) or between the SAM index and other variables associated with tropical convection, such as OLR or tropical SSTS (e.g. Carvalho et al, 2005). However, Campitelli et al (2022b) showed that the correlation between ENSO and SAM is almost completely explained by the asymmetric component of the SAM. In this work we show that the asymmetric component of the SAM can be identified with the PSA1. Therefore, the correlation between ENSO and SAM in SON is predominantly the correlation between ENSO and PSA1, at least in SON. This sheds new light into the previous literature, as it cannot be assumed that a high correlation between ENSO and SAM indexes indicates a relationship between ENSO and zonally symmetric variability.

Further investigation is necessary to determine the connection between the symmetric component of the SAM and the PSA. It is possible that the PSA may force a zonally symmetric response (or vice versa) via wave-zonal mean flow interactions (Kim and Lee, 2004), or that this correlation is simply a statistical artefact resulting from the EOF methodology used to define the SAM and the fact that the spatial structure of the PSA projects onto the spatial structure of the symmetric SAM.

Irving and Simmonds (2016) argued that there is some disagreement in the literature of whether the phase of the PSA pattern is affected by the location of tropical SST anomalies. With the methodology used in this study, we were

26 *SH zonally asymmetric circulation with cEOF*

1151 able to show not only that the cEOF2 tends to be in the positive or negative  
 1152 90° phase (~PSA1) when the ENSO region is warm or cold, respectively, but  
 1153 also that central Pacific SST anomalies tend to align the cEOF towards the  
 1154 negative 0° phase and eastern Pacific SST anomalies tend to align it towards  
 1155 positive 0° phase. When ENSO phase is neutral, the cEOF2 is still as active,  
 1156 but with no preferred phase. The latter agrees with the results of Cai and  
 1157 Watterson (2002), who showed that the CSIRO Model can develop PSA-like  
 1158 variability even in the absence of ENSO forcing (i.e. with a climatological  
 1159 run), but that the variability of one of the PSA modes was enhanced when  
 1160 adding the ENSO signal. The sensitivity of the phase of the PSAs to the  
 1161 location of the tropical SST anomalies was also seen by Ciasto et al (2015),  
 1162 who detected similar Rossby wave patterns associated with central Pacific and  
 1163 eastern Pacific SST anomalies but with a change in phase.

1164 The method used in this study has similarities to the one used by Goyal  
 1165 et al (2022) as they construct an index of amplitude and phase of zonal  
 1166 wave 3-like variability by combining the two leading EOFs of meridional wind  
 1167 anomalies. The patterns obtained by them bear high resemblance with cEOF2.  
 1168 Although a detailed comparison is out of scope for this paper, the cEOF anal-  
 1169 ysis has the advantage of constructing the indices based on patterns that are  
 1170 exactly in quadrature by construction.

1171 The methodology proposed in this study allows for a deeper understanding  
 1172 of the zonally asymmetric springtime extratropical SH circulation such as a  
 1173 better description of PSA like variability using a unique complex index and the  
 1174 understanding of relationship between PSAs and ENSO or SAM variability.  
 1175 Further work should extend this analysis to other seasons and further study  
 1176 the relationship between the cEOF2 and the SAM.

1177

## 1178 **Declarations**

1179 declarations

## 1180 **Funding**

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 1186

1187

## 1188 **Conflict of interest/Competing interests**

1189 conflict-of-interestcompeting-interests

1190 The authors have no relevant financial or non-financial interests to disclose.

1191

## 1192 **Ethics approval**

1193 ethics-approval

1194 Not applicable.

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<b>Consent to participate</b>	consent-to-participate	1197
Not applicable.		1198
		1199
<b>Consent for publication</b>	consent-for-publication	1200
Not applicable.		1201
		1202
		1203
<b>Availability of data and materials</b>	availability-of-data-and-materials	1204
All data used in this paper available in a Zenodo repository (Campitelli et al, 2022a) ( <a href="https://zenodo.org/record/6612429">https://zenodo.org/record/6612429</a> ). Indices updated monthly and daily will be made available at <a href="http://www.cima.fcen.uba.ar/~elio.campitelli/shceof/">http://www.cima.fcen.uba.ar/~elio.campitelli/shceof/</a> .		1205
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<b>Code availability</b>	code-availability	1231
A version-controlled repository of the code used to create this analysis, including the code used to download the data can be found at <a href="https://github.com/eliocamp/shceof">https://github.com/eliocamp/shceof</a> .		1232
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<b>Authors' contributions</b>	authors-contributions	1236
E.C. made the data curation, formal analysis and prepared all the figures.		1237
E.C. and L.D. wrote the main manuscript text. All authors reviewed the manuscript.		1238
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**1243 A Extra figures**

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**extra-figures**

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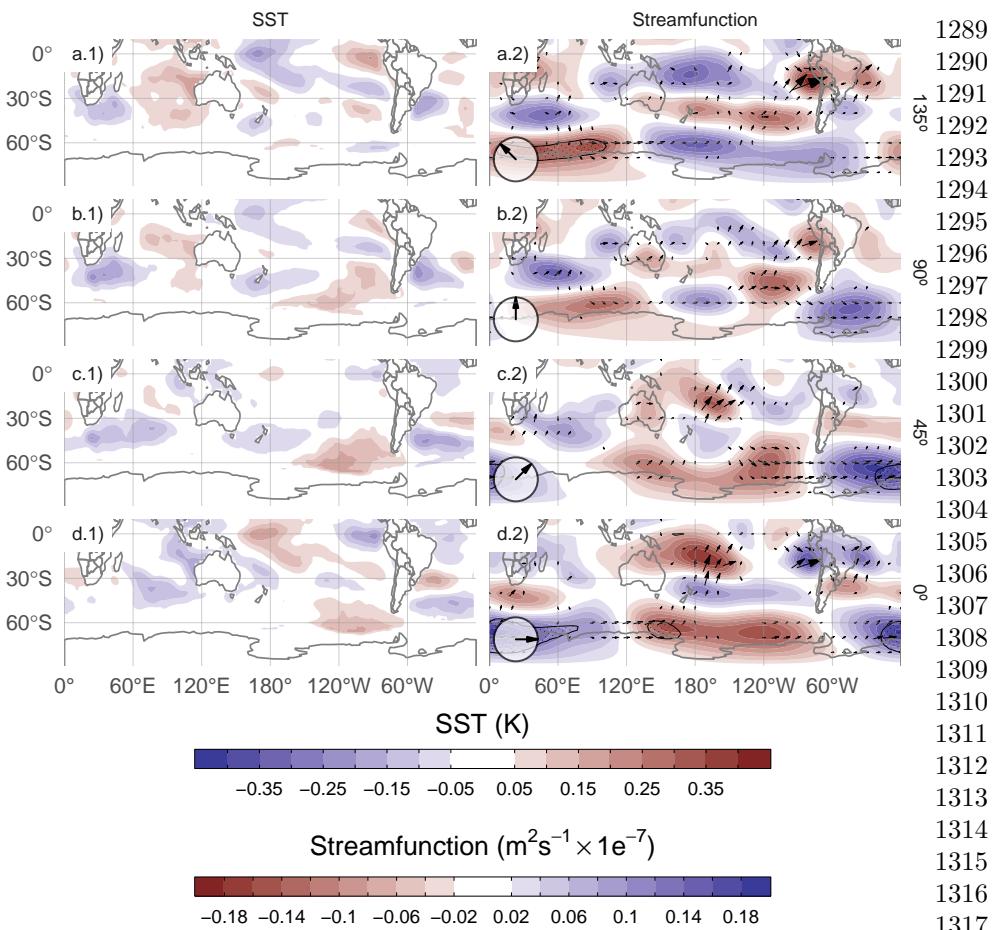
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**Fig. A.1:** Same as Figure 11 but for cEOF1.

fig:sst-psi-1

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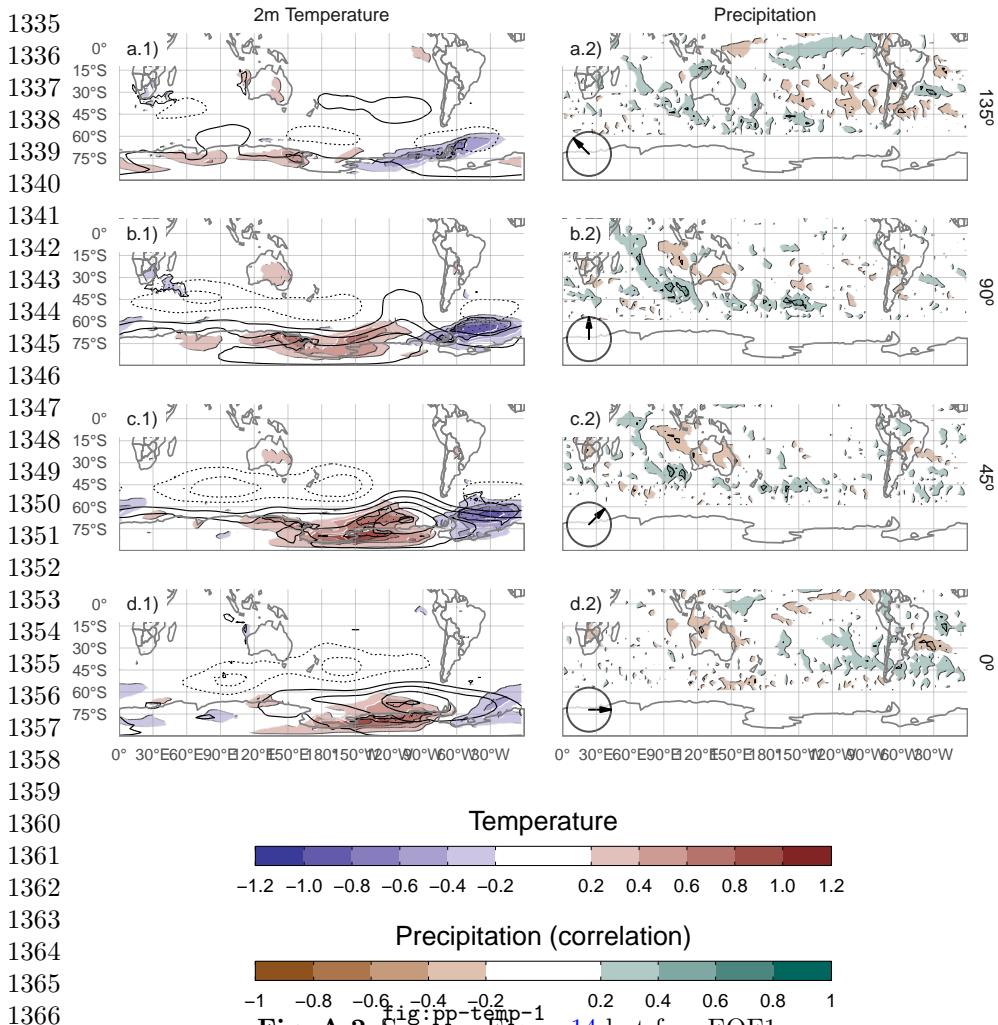
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Fig. A.2: Same as Figure 14 but for cEOF1.

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 1379 [pressure-levels-monthly-means-preliminary-back-extension?tab=overview](https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-pressure-levels-monthly-means-preliminary-back-extension?tab=overview)  
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