

Trends in the frequency of synoptic types in central-southern Chile in the period 1961–2012 using the Jenkinson and Collison synoptic classification

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Abstract Atmospheric circulation patterns in southern Chile (42° 30' S) were studied in order to determine and analyse the most characteristic synoptic types and their recent trends, as well as to gain an understanding of how they are associated with low-frequency variability patterns. According to the Jenkinson and Collison (J&C) classification method, a 16-point grid of sea-level pressure data was employed. The findings reveal that some synoptic types show statistically significant trends with a 95% confidence level, positively for anticyclonic westerly hybrids (AW) and advective types for third and fourth quadrant wind flows (W, NW, and N) and negatively for SW and cyclonic hybrids (CS and CSW). A model has been constructed of the linear regression of some weather types with teleconnections that most affect Chile: the undetermined types (U), AW were associated with El Niño or the warm phase of the Pacific Decadal Oscillation (PDO), whereas the cyclonic northerly and cyclonic northeasterly types (CN and CNE) were associated with La Niña or cool phase of the

PDO. The weather types associated with Antarctic Oscillation (AAO) in its positive phase are anticyclonic northerly and northeasterly and northerly advection types, while in its negative phase are cyclonic southwesterly and advection types.

1 Introduction

Several climate projections conclude that global climate change is happening (Hamilton and Stampone 2013). Regarding precipitation, these projections are more diverse in terms of pattern changes, some projecting increasing precipitations (Donat et al. 2016) whereas other projects decreasing (IPCC 2014). This diversity of projections is the result of modelling scenarios which take as reference twentieth century climate (IPCC 2014). Nevertheless, changes in the systems concerning pressure and synoptic types have not been studied with the same attention worldwide as changes in precipitation and temperature; on the basis of this knowledge, it is therefore considered that valuable information can be contributed to the understanding of climatology.

Synoptic climatology, understood as the study of the mean atmospheric circulation patterns, has become an effective and powerful tool for classifying different weather types. Establishing empirical relations between atmospheric circulation features and local weather is one of its fundamental aspects (Yamal et al. 2001). The first approaches to classifying atmospheric circulation and weather types were executed by Hess and Brezowsky (1952), Lund (1963), and Lamb (1972). For the British Isles, Lamb developed a classification based on daily atmospheric pressure surface data maps, generating 27 weather types caused by various atmospheric flows, highlighting interannual variability and cycles of anticyclonic, cyclonic, and advective periods of westerly and easterly flows in the British Isles, a classification that is known as the Lamb

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Weather Types (LWTs). Among the traditional methods for establishing a climatology of atmospheric circulation patterns are subjective weather map methods. However, their results are not homogenous, as they depend on the researcher's point of view. Still, certain rules and techniques in synoptic climatology exist, and they can be applied confidently (Martín-Vide 2005). However, subjective classification is impractical for addressing the large amount of information needed to cover the period under analysis.

Techniques in synoptic climatology have long been effective in the classification of atmospheric circulation patterns or weather types (Spellman 2017). Synoptic classification methods reveal how the different types of atmospheric circulation patterns are temporally and statistically distributed. The LWTs were adapted in an objective and automatic manner by El-Dessouky and Jenkinson (1975) for Egypt, using nine points of atmospheric sea-level pressure, and subsequently applied by Jenkinson and Collison (1977) for the British Isles, using a total of 16 points. The Jenkinson and Collison (hereinafter referred to as J&C) method is currently one of the most widely used objective classifications due to its simplicity and effectiveness for generating climatic series of weather types. In fact, the Climatic Research Unit (CRU) has kept the J&C daily classification updated up to the present day and has compared it to Lamb's classification (Jones et al. 1993), obtaining very similar findings, even with reanalysis data (Jones et al. 2013). Moreover, Jones et al. (2013) comment that the J&C method can be applied to any mid-to-high latitude region ($\sim 30^{\circ}$ – 70°) (Spellman 2017).

Numerous studies have employed the J&C method. These include the studies conducted by Linderson (2001), Stehlík (2001), Post et al. (2002), Tang et al. (2009), and Spellman (2017) in northern Europe; on the Iberian Peninsula, the method was applied by Spellman (2000), Trigo and DaCamara (2000), Martín-Vide (2002), and Grimalt et al. (2013); and in central Chile by Sarricolea et al. (2014). In the southern hemisphere and in Chile, there are two applications of the J&C method prior to Sarricolea et al. (2014), one undertaken by Frias (2008) and the other by Frias et al. (2009), making use of two 16-point grids (one centred at 35° S and another at 55° S), and based upon atmospheric pressure data from the ECWMF ERA-40 Reanalysis project.

Recent studies by Boisier et al. (2016), pointed that climate change has modified atmospheric circulation patterns, especially subtropical high pressure systems moving to higher latitudes. This change may affect the climate frequency of weather types, increasing high pressure systems circulation and decreasing low-pressure systems in central and southern Chile. Nonetheless, we have to take into account that circulation patterns dependency on decade variability (Boisier et al.

2016) which may intensify or weaken the Southeast Pacific Subtropical Anticyclone (SPSA).

The atmospheric circulation accounting for Chile's climatic characteristics, and particularly its central-southern area, is controlled by the SPSA and the subpolar low-pressure belt (Garreaud et al. 2009). The SPSA affects the zone falling between 30° S and 40° S, and the subpolar low-pressure belt lies between 45° S and 55° S (Sarricolea et al. 2014). This leads to the development of rainfall in this region throughout much of the year, becoming more pronounced in winter, due to the shift of the SPSA towards more tropical latitudes and stimulating the development of frontal systems. According to Ancapichun and Garces-Vargas (2015), SPSA has shown displacement and changes on its intensity with the following patterns: stronger, further south, and farther from the continent, whereas in winter, it is weaker, further north, and closer to the continent. Alternatively, Garreaud and Aceituno (2007) pointed that 40° S, weather is dominated by western winds, being more frequent advective patterns. Then, weather types are expected to show less pronounced trends than central Chile. According to Sarricolea et al. (2014), anticyclonic patterns have decreasing tendencies (-10.45 day decade $^{-1}$), whereas cyclonic weather types have increasing tendencies ($+2.2$ days decade $^{-1}$) and advective patterns also have increasing tendencies ($+5.75$ days decade $^{-1}$).

The trends experienced by the different atmospheric circulation patterns and whether they are altered by different teleconnection patterns are not known. Therefore, our study seeks to test whether the different J&C types were affected by El Niño Southern Oscillation (ENSO), by means of the Southern Oscillation Indices (SOI) and the El Niño Multivariate Index (MEI), as well as the Pacific Decadal Oscillation (PDO), related to the ENSO (Zhang et al. 1997), and also whether the J&C types for central-southern Chile are related to the Antarctic Oscillation (AAO). Several authors (Quintana and Aceituno 2012; Rubio-Alvarez and McPhee 2010) consider that low-frequency variability patterns explain largely southern-central Chile rainfall, and therefore large scale circulation patterns. During SOI (El Niño) negative phases, SPSA weakens, and it allows frontal systems to reach the continent which similar to what happens with negative phases of AAO (Quintana and Aceituno 2012). When positive phases of SOI (La Niña) take place, SPSA intensifies, and it decreases the frequency of cyclonic weather types (Sarricolea et al. 2014). Garreaud et al. (2009) found interesting correlations between sea-level pressure and MEI, PDO, and AAO index, i.e. the weakening of SPSA due to positive phases of MEI and PDO, while in central-southern Chile, sea-level pressure rises during positive phases of AAO. As regards the interannual variability of J&C types, it is considered that the Antarctic Oscillation index is closely related to the higher

frequency of cyclonic types, particularly in the austral winter months (April to September), which coincide with what is reported by Quintana and Aceituno (2012) with regard to the rise in winter precipitation. Garreaud et al. (2009) states that AAO exhibits a pronounced positive tendency in the last 50 years which implies a larger prevalence of SPSA.

2 Methodology

According to the Köppen-Geiger climate classification, central-southern Chile is defined as the Cfb (Marine West Coast climate) (Sarricolea et al. 2017). Noteworthy among the synoptic conditions of the field of study area are (Romero 1985) the following: (a) the presence of the SPSA in the latitudinal range of 23° S and 42° S and maximum frequency between 27° S and 38° S; (b) the existence of preferred areas for the origin and dissipation of anticyclonic cells, locally known as ‘cradles’ or ‘cemeteries’, located east of the Andes mountain range, at a latitude between 40° S and 45° S (the process is more frequent in summer); and (c) cyclone patterns with a maximum frequency between 39° S and 53° S, reaching lower latitudes in winter, and maintaining strong seasonal behaviour, implying lower frequencies in summer.

Because of its sheer latitudinal size, Chile presents many different synoptic patterns affecting, and also because of its marginal position on the continent and the Pacific Ocean. According to Garreaud and Aceituno (2007), south of 40° S is characterised by high daily variability in the realm of atmospheric pressure, with values that are sometimes lower than 990 hPa. This variability is justified by the permanent passage of frontal systems between 40° S and 60° S (Trenberth 1991), which is associated with the subpolar low-pressure belt.

The J&C synoptic classification is an objective and automatic method that reveals the type of atmospheric circulation in an area of interest, based upon atmospheric pressure reduced to sea level. It can be obtained via 9 or 16 points; in this case, it is applied to 16 points (Fig. 1), which for this study covers daily resolution for the period 1961 to 2012, whose values were obtained from the NCEP/NCAR Reanalysis project.

The NCEP/NCAR Reanalysis Project data was subject to pre-processing to corroborate its quality and the homogeneity of series, and assorted reanalysis data were ob-

tained on all the meteorological variables and at the different atmospheric levels (Kalnay et al. 1996).

The J&C method was devised to capture objectively the 27 atmospheric circulation patterns that exist in the Lamb weather type system (Spellman 2017). J&C comprises eight pure advective (or directional) (N, NE, E, SE, S, SW, W, and NW) types based on wind direction; and C types which represent anticyclonic and cyclonic pressure patterns, respectively, but no coherent flow direction; and 16 hybrid types that represent directional types with either anticyclonic isobaric curvature (AN, ANE, AE, ASE, AS, ASW, AW, and ANW) or cyclonic curvature (CN, CNE, CE, CSE, CS, CSW, CW, and CNW). The final type undetermined or unclassified (U) represents patterns that have weak pressure gradients, and thus, neither flow direction nor vorticity can be identified.

The variables to be calculated for applying the J&C method are the zonal geostrophic wind (W) component (in our case between 37° 30' and 47° 30' S), the meridian geostrophic wind (S) component (in our case between 67° 30' and 77° 30'W), wind direction (D), wind speed in m/s (F), the zonal vorticity (ZW) component, the meridian vorticity (ZS) component, and total vorticity (Z). Weather types are obtained based on the following expressions applied to the field of study's grid:

$$W = \frac{P4 + P5}{2} - \frac{P12 + P13}{2} \quad (1)$$

$$S = 1.356 \left(\frac{P4 + 2P8 + P12}{4} - \frac{P5 + 2P9 + P13}{4} \right) \quad (2)$$

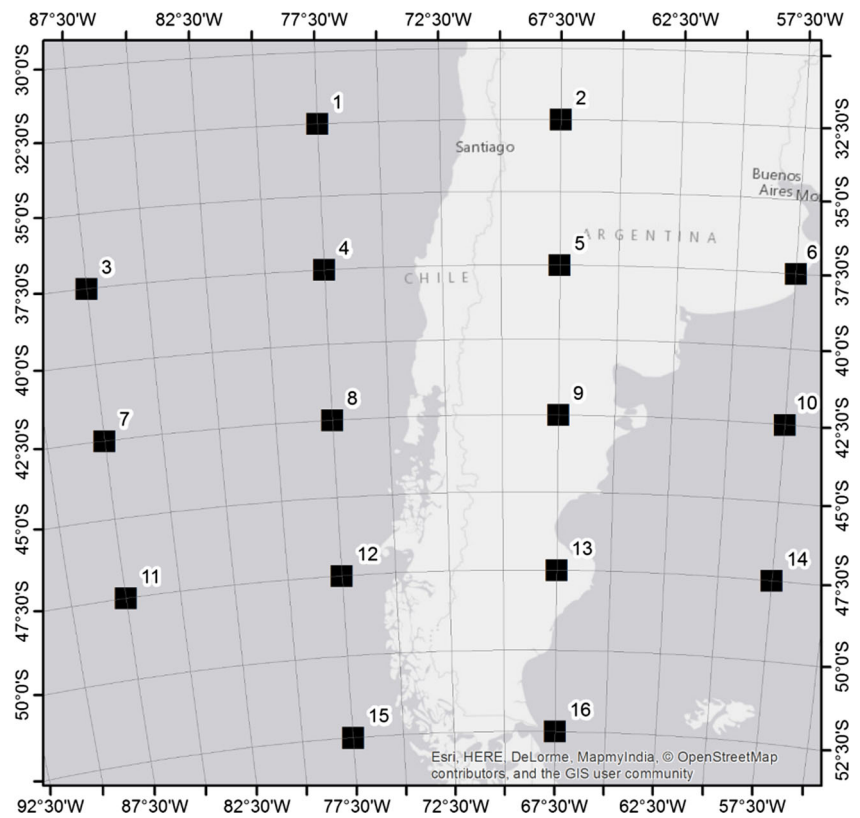
$$D = \tan^{-1} \frac{W}{S} \quad (3)$$

$$F = \sqrt{W^2 + S^2} \quad (4)$$

$$Z_w = 1.109 \left[\left(\frac{P1 + P2}{2} \right) - \left(\frac{P8 + P9}{2} \right) \right] - 0.942 \left[\left(\frac{P8 + P9}{2} \right) - \left(\frac{P15 + P16}{2} \right) \right] \quad (5)$$

$$Z_s = 1.221 \left[\left(\frac{P3 + 2P7 + P11}{4} \right) - \left(\frac{P4 + 2P8 + P12}{4} \right) - \left(\frac{P5 + 2P9 + P13}{4} \right) + \left(\frac{P6 + 2P10 + P14}{4} \right) \right] \quad (6)$$

Fig. 1 Location of the 16 grid points for obtaining the NCEP/NCAR Reanalysis sea-level pressure data, located in central-southern Chile



$$Z = Z_W + Z_S \quad (7)$$

where P is the pressure reduced to sea level of each one of the 16 grid points in the field of study (Fig. 1). W is the zonal component of the geostrophic wind, and S is the meridian component, both are calculated as the pressure gradient between $37^\circ 30' S$ and $47^\circ 30' S$, and between $67^\circ 30' W$ and $77^\circ 30' W$ respectively, and their units are pressure (hPa). The same principle is applied in order to calculate the pressure gradient to determine the two components of the vorticity, also measured in hPa. The coefficients depend on the central parallel of any grid considered to adjust the variation of distance between meridians.

Based on the values of the previous analytical expressions and following the J&C method, five rules were applied, which allow the weather type each day to be determined. Said rules are as follows:

- 1) The flow direction is indicated by D (8 wind directions are used, taking the W and S signs into consideration);
- 2) If $|Z| < F$, an advective or pure directional type exists, defined according to rule 1 (N, NE, E, SE, S, SW, W, and NW);
- 3) If $|Z| > 2F$, there is a cyclonic type (C) if $Z > 0$ or an anticyclonic type (A) if $Z < 0$;
- 4) If $F < |Z| < 2F$, a hybrid type exists, according to the Z sign (rule 3) and the flow direction obtained from rule 1 (CN,

CNE, CE, CSE, CS, CSW, CW, CNW, AN, ANE, AE, ASE, AS, ASW, AW, and ANW);

- 5) If $F < 6$ and $|Z| < 6$, an undetermined type (U) exists.

The 27 J&C types were analysed individually, which have also been arranged into three different grouping sets (Grimalt et al. 2013; Sarricolea et al. 2014; Spellman 2017):

- Eight groups describe the directional component of circulation. For instance, the northerly direction group
- [N] includes N, CN, and AN days; the westerly direction groups [W] include W, AW, and CW; and so on.
- Three groups assess the directional and vorticity over the region: (i) anticyclonic vorticity advection hybrids (hereinafter ADVA: AN, ANE, AE, ASE, AS, ASW, AW, and ANW); (ii) cyclonic vorticity advection hybrids (hereinafter ADVC: CN, CNE, CE, CSE, CS, CSW, CW, CNW), (iii) pure advection types (hereinafter ADV: N, NE, E, SE, S, SW, W, and NW).
- Three groups: assess the overall strength of vorticity over the region: (i) negative-termed 'anticyclonic' or 'ANT' (A, AN, ANE, AE, ASE, AS, ASW, AW, ANW); (ii) positive vorticity-termed 'cyclonic' or 'CYC' (C, CN, CNE, CE, CSE, CS, CSW, CW, CNW); and (iii) weak vorticity termed 'advective' or 'ADV' (N, NE, E, SE, S, SW, W, NW).

An analysis of the synoptic types for different temporal aggregations was performed: annual for the entire series (1961–2012), annual in two 24-year sub-periods (1961–1986 and 1987–2012), and at monthly and seasonal resolution. The trends were evaluated using the AnClim (Štěpánek 2003) software, thereby allowing changes in the J&C synoptic types and in the different synoptic grouping sets to be assessed. To this end, the trends for the whole period were calculated (1961–2012, 52 years), applying the p value statistical significance test (using the AnClim). The 1961–1986 and 1987–2012 sub-periods were compared to estimate whether the changes in synoptic types were statistically significant, for which the normality (Kolmogorov-Smirnov test) and variances (Levene test) were examined, and the Student t test was subsequently carried out for independent samples, at a 95% confidence level using SPSS 21.

A second goal was to evaluate whether relationships existed between the J&C synoptic types and the teleconnections affecting central-southern Chile: El Niño Southern Oscillation (using the SOI¹ and MEI² indices), PDO³ and AAO⁴. Linear regression models were therefore generated between the teleconnections with the J&C types (p value < 0.05).

3 Results

3.1 Annual and monthly frequencies of the Jenkinson and Collinson weather types (1961–2012)

The most frequent weather types noted in central-southern Chile (centred at 42° 30' S, 72° 30' W) are SW, present 22% of the year, followed by A with 18% of the total. Noteworthy, albeit with lower values, are S and W, each with 10% of the total. These are followed, with somewhat lower values, by ASW with 9% and C with 5%. These six types represent 74% of all the days in an average year (1961–2012), in other words, some 267 days (Table 1). In turn, less frequent atmospheric circulations correspond to those in the east quadrant, notable among which are the CE, AE, CSE, and CNE and the easterly advection type. Undetermined types account for 3% of the days, approximately 12 days per year. The nine most common weather types are shown in Fig. 2.

On a monthly basis, the J&C weather types show that anticyclonic type (A) circulations are quite regular during the year (ranging from 10% to slightly more than 20%), reaching their maximum in the April to September semester, dates that tend to coincide with the rise in cyclonic rotation, and W and

NW; all of them tend to coincide with the rise in precipitation. As regards weather types in summer, noteworthy are the AS and ASW, and S and SW weather types. Finally, undetermined types appear to reach their maximum values in the equinoctial months of March and October (Fig. 3).

An observation of said frequencies classified by direction (Table 2) confirms the low level of representation of easterly flows (less than 4%, taking [E], [SE], and [NE] into account). The most frequent directions are [SW] (33%), [W] (15%), and [S] (15%), which account for two thirds of the days analysed.

Moreover, if the vorticity advection of hybrid types (ADVA and ADVC) is considered, pure advection types (ADV) (Table 3), it is noted that almost 50% of the atmospheric compositions are pure advection types (ADV), followed by anticyclonic (36.8%) hybrid and pure types (ADVA and A). Cyclonic rotation (in grouping C and ADVC together) does not exceed 11% in central-southern Chile. The importance of advection types (ADV) is explained by the transitional position of this region, located between SPSA and the subpolar low-pressure belt.

On a monthly basis, undetermined types are more common in equinoctial months, while their values are lower in summer (Fig. 4). Cyclonic vorticity advection types (ADVC) have a similar distribution, with a maximum in winter, between the months of March and October, despite a sharp drop in their frequency in the month of April. The circulation type less subject to seasonal variations is ADVA, despite somewhat lower values in the winter months, and accordingly, seasonality that is contrary to anticyclonic types.

3.2 Trends of J&C weather types

The trends in J&C types in the entire period have been examined. The statistically significant findings, with statistical significance of 95%, show the only trends that fulfil this criterion correspond to some hybrid and advection types. Their common denominator is that they are exclusively from the third and fourth wind flow quadrants and are primarily westerly. Those with positive trends include AW, W, NW, and N, while the negative trends correspond to SW, CS, and CSW (Table 4). This points to the existence of greater increases in days in the case of W and NW, while decreases are noted in S and SE. The most significant upward trend is the increase in 1.55 days decade⁻¹ for W, while the most significant downward decrease is noted for SW, with 2.81 days decade⁻¹ (Table 4).

Given these trends in the different grouping sets put forward in the methodology, the values obtained are not significant for ANT, CYC, and ADV types, while for J&C types grouped by directional flow, statistically significant change values are reached for [W] directions, which increase (+ 2.2 days decade⁻¹), and [SW] that decrease at - 5.0 days decade⁻¹.

¹ Available at <http://www.cru.uea.ac.uk/cru/data/soi/soi.dat>

² Available at <http://www.esrl.noaa.gov/psd/enso/mei.ext/table.ext.html>

³ Available at <http://jisao.washington.edu/pdo/PDO.latest>

⁴ Available at <http://www.jisao.washington.edu/aao/slp/>

Table 1 Descriptive statistics of the series of J&C types in central-southern Chile for the period 1961–2012

J&C type	Total (days)	Annual mean (days)	Percentage (%)	Maximum (days per year)	Minimum (days per year)	Standard deviation	Coefficient of variation (CV)
U	624	11.99	3	23	2	4.58	0.38
A	3375	64.86	18	102	41	12.83	0.20
ANE	76	1.46	0	4	0	1.43	0.98
AE	33	0.63	0	3	0	0.86	1.36
ASE	127	2.44	1	6	0	1.67	0.69
AS	807	15.51	4	29	3	4.82	0.31
ASW	1625	31.23	9	58	16	9.30	0.30
AW	648	12.45	3	22	3	4.59	0.37
ANW	197	3.79	1	11	0	2.30	0.61
AN	95	1.83	1	8	0	1.49	0.82
NE	129	2.48	1	10	0	2.05	0.83
E	75	1.44	0	5	0	1.24	0.86
SE	215	4.13	1	12	0	2.59	0.63
S	1908	36.67	10	59	19	8.67	0.24
SW	4205	80.81	22	123	61	13.21	0.16
W	1857	35.69	10	54	18	7.88	0.22
NW	592	11.38	3	20	2	4.39	0.39
N	288	5.53	2	15	0	2.84	0.51
C	926	17.80	5	38	2	7.10	0.40
CNE	56	1.08	0	6	0	1.30	1.20
CE	27	0.52	0	2	0	0.70	1.35
CSE	47	0.90	0	5	0	1.01	1.12
CS	158	3.04	1	8	0	1.81	0.60
CSW	359	6.90	2	18	1	3.34	0.48
CW	296	5.69	2	11	1	2.59	0.45
CNW	158	3.04	1	9	0	2.11	0.70
CN	90	1.73	0	5	0	1.42	0.82

By splitting the series into two 26-year periods (1961–1986 and 1987–2010), it was found that some types do not show a normal distribution, having applied the Kolmogorov-Smirnov test. The cases correspond to ten J&C types, 80% of which are N, NE, and E, while the remaining 20% have a SE. Therefore, the mean comparison of independent groups cannot be applied to the aforementioned cases (Student's *t* test). As regards the equality of variances (Levene test), it is noted that those groups that do not have it are anticyclonic, SW, AE, ASW, and CNE (Table 5).

Trend changes in J&C types, showing statistical significance with a 95% confidence level, when analysing the sub-periods (1961–1986 and 1987–2012) correspond to five circulation types. Those that increase correspond to three advection flows, W, NW, and N; and those that decrease are two hybrid types, ASW and CS.

3.3 Relationship between the J&C types and the ENSO, PDO, and AAO teleconnections

Linear regression models were executed for the 27 J&C weather types and ENSO (SOI and MEI), PDO, and AAO teleconnections. In total, ten weather types allowed statistically significant regression models with a 95% confidence level to be generated. It should be pointed out that these weather types are equivalent to an average of 137 days per year, in other words, 37% of all the weather types.

Those weather types associated with El Niño (negative phase of SOI and positive phase of MEI) correspond to undertermined circulations (U) and cyclonic northerly types (CN). In the case of U, their behaviour can be determined by way of linear regression with SOI (atmospheric teleconnection), which is quite reasonable if it is borne in mind that MEI is a

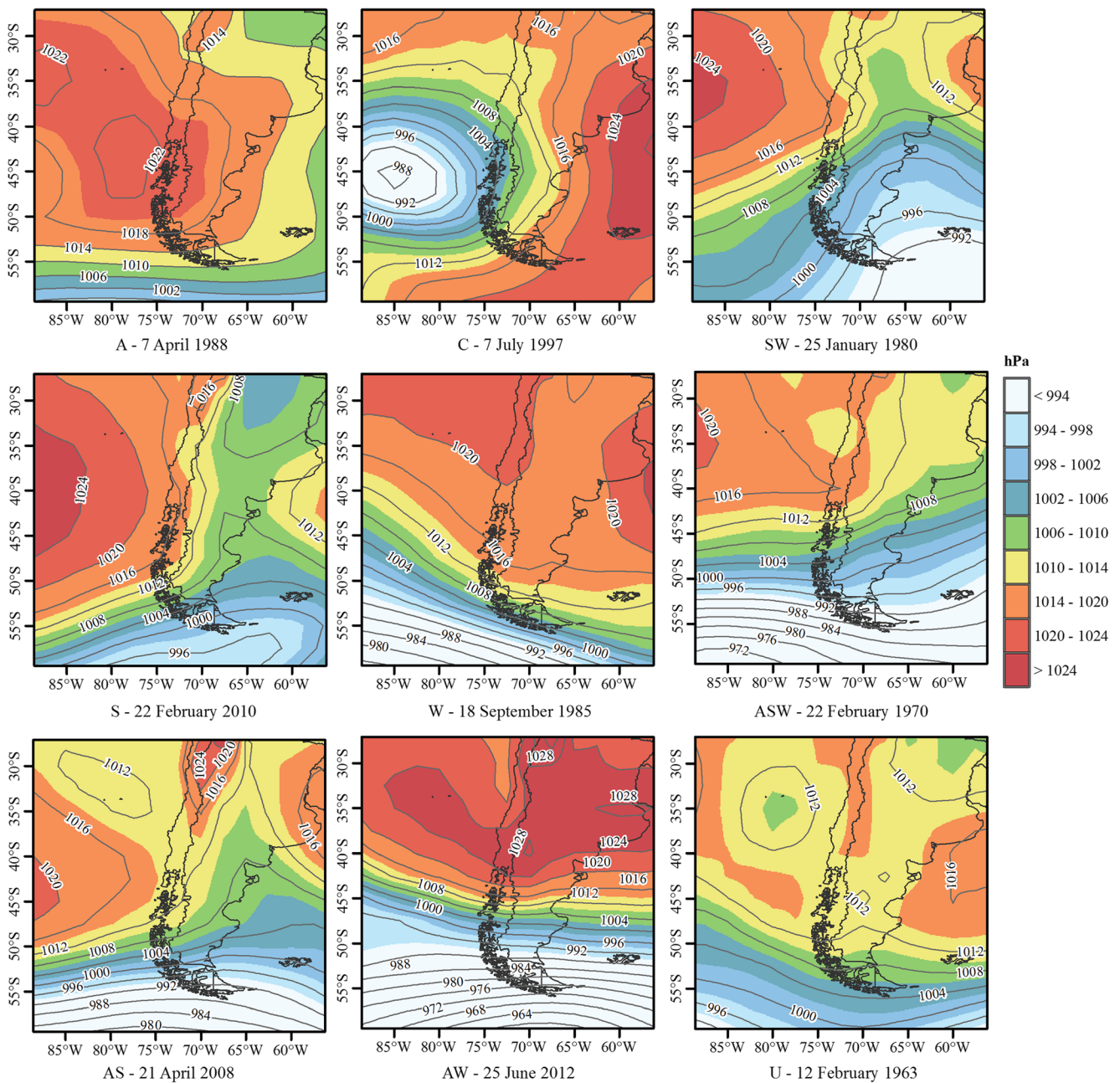


Fig. 2 Depiction of the nine more common weather types, according to the sea-level pressure data from the NCEP/NCAR Reanalysis database

composite index of oceanic and atmosphere anomalies, i.e. it is less linked to sea-level pressure than SOI. Moreover, the weather type associated with La Niña is AW, both in SOI and MEI. This is consistent with the intensification of SPSA and negative thermal anomaly in the equatorial Pacific (mainly its region El Niño 3.4) (Table 6).

Regarding the linear regression of J&C types and the Pacific Decadal Oscillation, it was established that three weather types are linked to said teleconnection in its positive

phase, i.e. CNE, CNW, and CN, the latter also being linked to El Niño (Table 6). Therefore, those cyclonic types with a northerly component (N, NW, and NE) must point to higher frontal activity in central-southern Chile.

The Antarctic Oscillation is also satisfactorily linked to some J&C types. In its positive phase (i.e. presence at 42° 30' S of anticyclonic patterns and low pressure located further south, $\pm 55^\circ$ S), there are significant linear regressions for AN, NW, and N circulations, types that seem to indicate greater

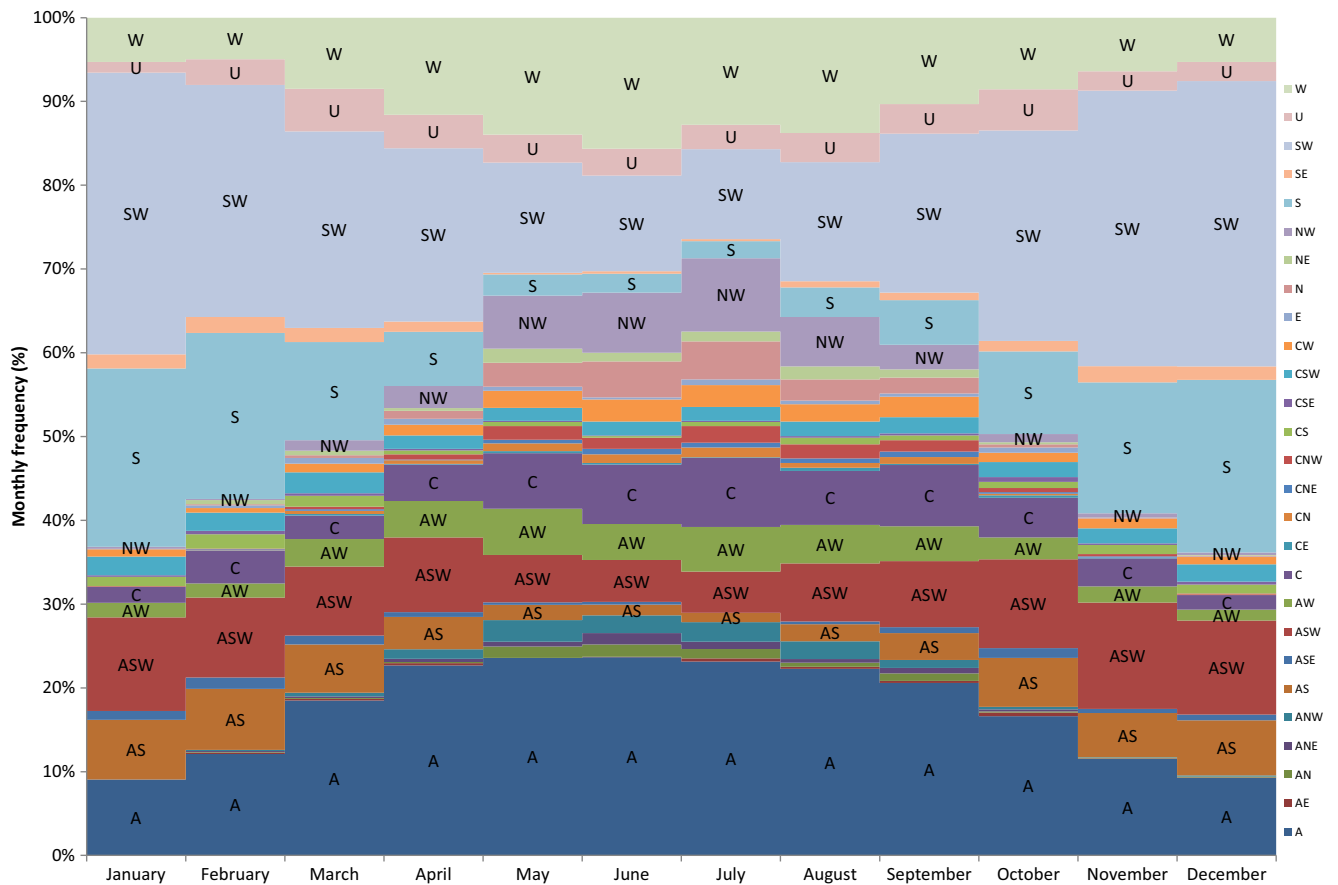


Fig. 3 Monthly frequency of the J&C synoptic types for central-southern Chile, between 1961 and 2012

influence from the South Atlantic Anticyclone (SAA), even in those northerly advection type (Table 6). As regards the negative phase of the AAO, regression models are satisfactory for weather types CSW and SW, which indicates more continental low pressure, possibly on the Argentinian pampas.

4 Discussions and conclusions

The transitional situation in central-southern Chile, between two pressure systems like the SPSA and subpolar low-pressure belt, results in the most common weather types being

Table 2 Descriptive statistics of the series of J&C types, classified by directional flow, in central-southern Chile for the period 1961–2012

J&C directions	Total (days)	Annual mean (days)	Percentage (%)	Maximum (days per year)	Minimum (days per year)	Standard deviation	Coefficient of variation (CV)
U	624	12.0	3	23	2	4.5	0.38
A	3375	64.9	18	102	41	12.7	0.20
C	926	17.8	5	38	2	7.1	0.40
[NE]	261	5.0	1	14	0	3.2	0.64
[E]	135	2.6	1	7	0	1.6	0.62
[SE]	389	7.5	2	19	1	3.7	0.49
[S]	2873	55.3	15	87	33	11.2	0.20
[SW]	6189	119.0	33	169	92	17.8	0.15
[W]	2801	53.9	15	82	35	9.8	0.18
[NW]	947	18.2	5	31	5	6.1	0.34
[N]	473	9.1	2	24	0	4.3	0.47

Table 3 Descriptive statistics of the series of J&C types, classified by hybrid vorticity, in central-southern Chile for the period 1961–2012

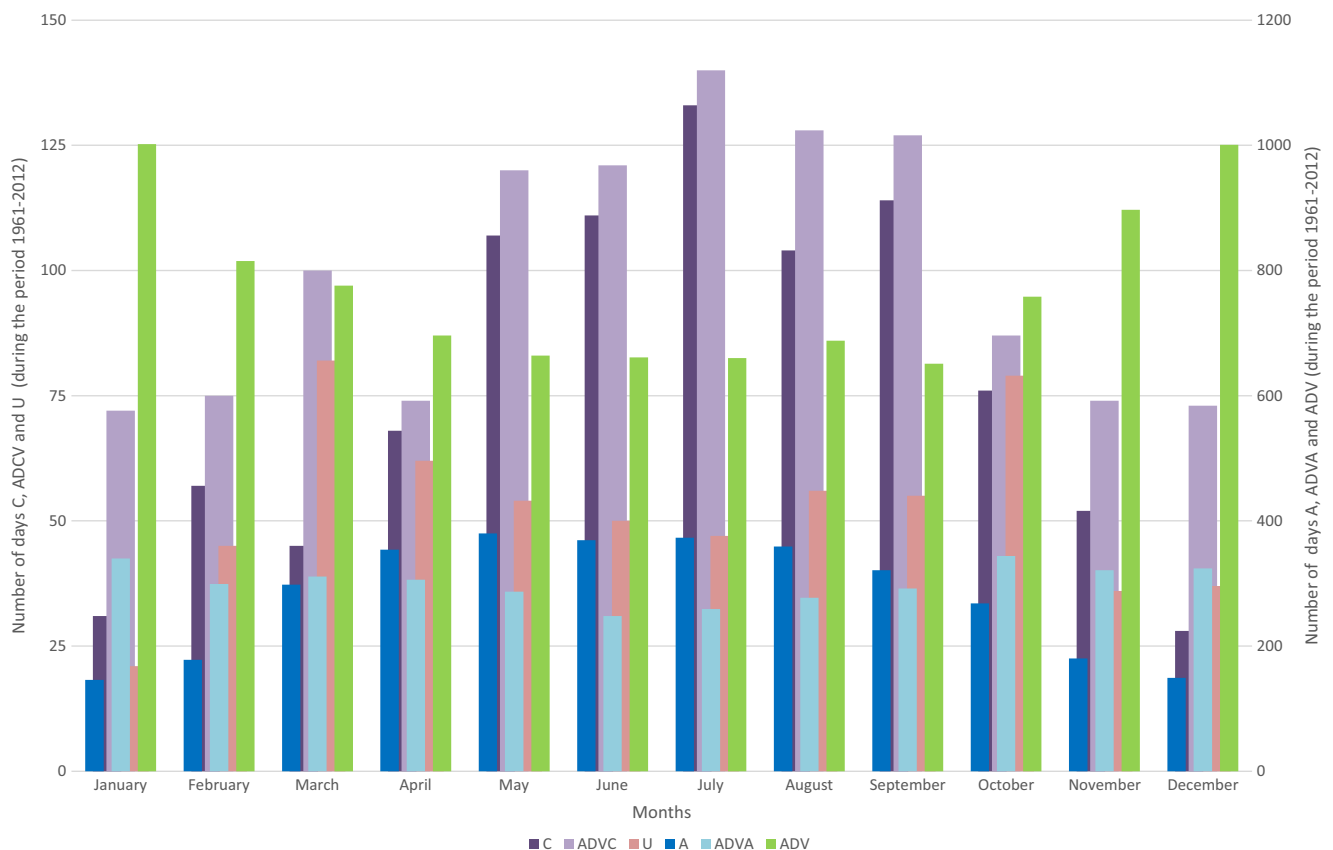
J&C types grouped in 6	J&C types grouped in 4	Total (days)	Annual mean (days)	Percentage (%)	Maximum (days per year)	Minimum (days per year)	Standard deviation	Coefficient of variation (CV)
U	U	624	12.0	3	23	2	4.5	0.38
A	ANT	3375	64.9	18	102	41	12.7	0.20
ADVA		3608	69.4	19	95	51	10.3	0.15
C	CYC	926	17.8	5	38	2	7.1	0.40
ADVC		1191	22.9	6	35	5	6.3	0.28
ADV	ADV	9269	178.3	49	203	149	13.2	0.07

SW advection (22%) and A (18%) types, the less frequent circulations being those in the first quadrant; the types CE, AE, CSE, CNE, and E are representative. The undetermined types represent only 3% of the days and with higher frequency in autumn and spring which is consistent with findings from Garreaud and Aceituno (2007), and all in all this region is more subjected to directional fluxes than cyclonic or anticyclonic patterns.

Anticyclonic type circulations (A) are quite stable (little variability associated with the coefficient of variation), which is due to the persistence of SPSA, reaching its maximum in the

6 months between April and September, coinciding with the rise in cyclonic rotation, and W and NW flows. Regarding the weather types in summer, notable are the AS and ASW types and S and SW advection types.

The most frequent directions are in the third quadrant, noteworthy are [SW] (33%), [W] (15%), and [S] (15%), which account for almost two thirds of the days. Nearly 50% of atmospheric circulations are ADV, followed by ANT (37%) and CYC (11%). Our results are consistent with results from Garreaud et al. (2009) being the prevalence of western winds the main reason explaining this pattern.

**Fig. 4** Number of days of J&C synoptic types regrouped for central-southern Chile, between 1961 and 2012

Trends in the J&C types over the complete period (statistical significance of 95%) are exclusively in the third and fourth quadrant of wind flows, positive trends being shown by weather types AW, W, NW, and N, while the negative trends correspond to SW, CS, and CSW. In synthesis, the most significant changes in central-southern Chile occur for advective and hybrid weather types. Increasing tendencies on AW weather types might be explained by Hadley cell (Boisier et al. 2016) and the tendency of AAO detected by Garreaud et al. (2009) in the last 50 years. The latter may cause a replacement on weather types, for example an increasing on W weather types in dislike of SW, while an increase of NW and N weather types in return of CS and CSW.

Considering two sub-periods (1961–1986 and 1987–2010), the trend variations in the J&C types, with 95%

statistical significance, correspond to five types of circulation. Those that increase are three advection flows: W, NW, and N; and those that decrease are two hybrids: ASW and CS.

In total, ten weather types had 95% statistically significant correlations with teleconnections, representing 37% of all synoptic types. Weather types linked to El Niño correspond to undetermined and cyclonic northerly circulations. The weather type associated with La Niña is AW, which is consistent with the intensification of SPSA and the negative thermal anomaly in the equatorial Pacific. The latter is consistent with results found by Quintana and Aceituno (2012), and it is explained by the lesser gradient during SOI phases (El Niño) and the entrance of cyclonic circulations.

Regarding the correlations of J&C types and the Pacific Decadal Oscillation, it was established that three

Table 4 Decadal trends of J&C types in central-southern Chile and their statistical significance for the period 1961–2012. Significant trends (< 95%) appear in italics

J&C type	Decadal trend (days decade ⁻¹)	<i>P</i> value
U	- 0.46	0.28
A	+ 1.14	0.34
ANE	+ 0.06	0.65
AE	+ 0.14	0.07
ASE	+ 0.15	0.35
AS	+ 0.11	0.81
ASW	- 1.40	0.10
AW	+ 0.94	0.02
ANW	+ 0.28	0.19
AN	+ 0.22	0.12
NE	+ 0.17	0.37
E	+ 0.04	0.74
SE	+ 0.12	0.63
S	- 0.95	0.24
SW	- 2.81	0.02
W	+ 1.55	0.03
NW	+ 1.13	0.00
N	+ 0.62	0.02
C	+ 0.02	0.97
CNE	+ 0.19	0.12
CE	+ 0.01	0.83
CSE	- 0.01	0.88
CS	- 0.44	0.01
CSW	- 0.79	0.01
CW	- 0.26	0.28
CNW	+ 0.11	0.58
CN	+ 0.14	0.29
[W]	+ 2.20	0.05
[SW]	- 5.00	0.05

Table 5 Student's *t* test for J&C types grouped into two sub-periods, 1961–1986 and 1987–2012, in central-southern Chile and their statistical significance. Significant tests appear in italics

J&C type	Mean 1961–1986	Mean 1987–2012	Change	Normality (KS)	Levene's test	<i>P</i> value <i>t</i> test
U	12.2	11.8	Decrease		0.556	0.81
A	64.5	65.3	Increase		0.018	0.82
ANE	1.4	1.5	Increase	No	0.774	–
AE	0.4	0.9	Increase	No	0.019	–
ASE	2.3	2.6	Increase	No	0.753	–
AS	15.5	15.6	Increase		0.222	0.93
ASW	34.1	28.4	Decrease		0.004	0.03
AW	11.5	13.5	Increase		0.518	0.12
ANW	3.3	4.2	Increase		0.140	0.17
AN	1.5	2.2	Increase	No	0.711	–
NE	2.4	2.6	Increase	No	0.461	–
E	1.4	1.5	Increase	No	0.190	–
SE	4.0	4.3	Increase		0.110	0.63
S	38.0	35.4	Decrease		0.533	0.28
SW	84.1	77.6	Decrease		0.003	0.08
W	32.8	38.7	Increase		0.100	0.00
NW	9.9	12.9	Increase		0.854	0.01
N	4.6	6.5	Increase		0.626	0.02
C	17.6	18.0	Increase		0.353	0.85
CNE	0.7	1.5	Increase	No	0.022	–
CE	0.4	0.6	Increase	No	0.754	–
CSE	1.0	0.8	Decrease	No	0.808	–
CS	3.5	2.5	Decrease		0.590	0.05
CSW	7.7	6.1	Decrease		0.090	0.07
CW	6.2	5.2	Decrease		0.259	0.17
CNW	2.8	3.2	Increase		0.793	0.52
CN	1.5	2.0	Increase	No	0.276	–

Table 6 Linear regressions between the J&C synoptic types in central-southern Chile in the period 1961–2011 ($N = 51$) and SOI, MEI, PDO, and AAO teleconnection patterns

J&C type	Linear regression with SOI; R^2	Linear regression with MEI; R^2	Linear regression with PDO; R^2	Linear regression with AAO; R^2
U	$U = -2.069 \times + 11.723$; 0.114	Not sig.	Not sig.	Not sig.
AW	$AW = 1.834 \times + 12.707$; 0.089	$AW = -1.7359 \times + 12.624$; 0.079		Not sig.
AN	Not sig.	Not sig.	Not sig.	$AN = 0.984 \times + 1.339$; 0.114
SW	Not sig.	Not sig.	Not sig.	$SW = -11.157 \times + 86.435$; 0.186
NW	Not sig.	Not sig.	Not sig.	$NW = 3.656 \times + 9.560$; 0.181
N	Not sig.	Not sig.	Not sig.	$N = 2.319 \times + 4.382$; 0.174
CNE	Not sig.	Not sig.	$CNE = 0.496 \times + 1.0955$; 0.095	Not sig.
CSW	Not sig.	Not sig.	Not sig.	$CSW = -1.900 \times + 7.933$; 0.085
CNW	Not sig.	Not sig.	$CNW = 0.771 \times + 3.0674$; 0.086	Not sig.
CN	$CN = -0.6487 \times + 1.644$; 0.117	$CN = 0.5869 \times + 1.6759$; 0.095	$CN = 0.5026 \times + 1.7496$; 0.082	Not sig.

R^2 between weather types and teleconnections explain low levels of the variance, despite the ten weather types from Table 6 are significant at 95%. Other factors might explain weather types. Climate change may contribute on the unexplained variance. This can be explained by Fig. 5 where anticyclonic types are standardised and represented jointly with PDO a relationship exist between them, but no statistically significant

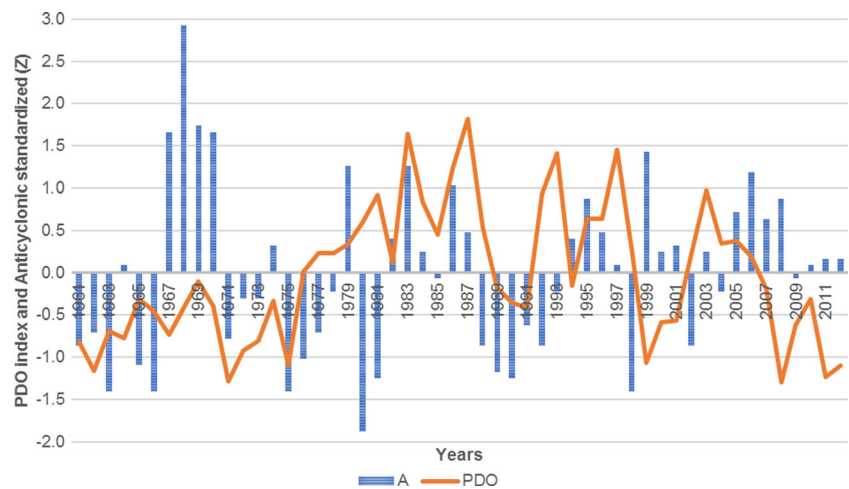
Not sig. no statistically significant relationship between the synoptic types and teleconnection indices

synoptic scenarios are linked to its positive phase, all cyclonic (CNE, CNW, and CN) and must point to higher frontal activity in central-southern Chile. Garreaud et al. (2009) show similar results, and this might be explained by the significant decrease of sea-level pressure off central-southern Chile during the positive phases of PDO.

The Antarctic Oscillation, in its positive phase, is also linked to the AN, NW, and N circulation types, which imply greater influence of the SAA, even in those N type (Table 6). As regards the negative phase of the AAO, linear regressions are satisfactory for

weather types CSW and SW, which indicates more continental low pressure, possibly on the Argentinian pampas.

While our research is a contribution to describe with higher detail central-southern Chile weather types, we believe the results do not contribute as we expected to study climate change. The main reason is the length of data series (1961–2012) is insufficient, and it only may confirm climate variability. This climate variability might be influenced by Hadley's cell. Next steps in this research should use larger data series and contribute effectively to this purpose.

Fig. 5 Relation between A types and PDO index for central-southern Chile (1961 and 2012)

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References

- Ancapichun S, Garcés-Vargas J (2015) Variability of the Southeast Pacific Subtropical Anticyclone and its impact on sea surface temperature off north-central Chile. *Cienc Mar* 41(1):1–20
- Boisier JP, Rondanelli R, Garreaud RD, Muñoz F (2016) Anthropogenic and natural contributions to the Southeast Pacific precipitation decline and recent megadrought in central Chile. *Geophys Res Lett* 43(1):413–421
- Donat M, Lowry A, Alexander L, O’Gorman P, Maher N (2016) More extreme precipitation in the world’s dry and wet regions. *Nat Clim Chang* 6:508–513. <https://doi.org/10.1038/NCLIMATE2941>
- El-Dessouky TM, Jenkinson AF (1975) An objective daily catalogue of surface pressure, flow and vorticity indices for Egypt and its use in monthly rainfall forecasting. Synoptic Climatology Branch Memorandum no. 46, Bracknell, Meteorological Office, London
- Frias TF (2008) Padrões de circulação atmosférica no Chile. Tese de Mestrado em ciências físicas (Meteorologia), Universidade de Lisboa
- Frias T.F., Trigo R., Garreaud, R.D. (2009) Weather type classification over Chile; patterns, trends, and impact in precipitation and temperature. *Geophysical Research Abstracts*, Vol. 11, EGU–8432
- Grimalt M, Tomàs M, Alomar G, Martín-Vide J, Moreno-García MC (2013) Determination of the Jenkinson and Collison’s weather types for the Western Mediterranean basin over the 1948–2009 period. *Temporal analysis Atmosfera* 26:75–94
- Garreaud RD, Aceituno P (2007) Atmospheric circulation over South America: mean features and variability. Veblen T., Young K. and Orme A. *The Physical Geography of South America*, Oxford University Press, In Chapter 2
- Garreaud RD, Vuille M, Compagnucci R, Marengo J (2009) Present-day south american climate. *Palaeogeogr Palaeoclimatol Palaeoecol* 281(3):180–195
- Hamilton LC, Stampone MD (2013) Blowin’ in the wind: short-term weather and belief in anthropogenic climate change. *Weather, Climate, and Society* 5(2):112–119
- Hess P, Brezowsky H (1952) Katalog der grosswetterlagen Europas. *Berichte Deutsche Wetterdienstes* 15(113):39
- Intergovernmental Panel on Climate Change (2014) *Climate change 2014—impacts. Regional Aspects*. Cambridge University Press, Adaptation and Vulnerability
- Jenkinson AF, Collison P (1977) An initial climatology of gales over the North Sea. Synoptic Climatology Branch Memorandum no. 62, Bracknell, Meteorological Office, London
- Jones PD, Hulme M, Briffa KR (1993) A comparison of Lamb circulation types with an objective classification scheme. *Int J Climatol* 13:655–663
- Jones PD, Harpham C, Briffa KR (2013) Lamb weather types derived from reanalysis products. *Int J Climatol* 33:1129–1139
- Kalnay E, Kanamitsu M, Kistler R, Collins W, Deaven D, Gandin L, Iredell M, Saha S, White G, Wollen J, Zhu Y, Chelliah M, Ebisuzaki W, Higgins W, Janowiak J, Mo KC, Ropelewski C, Wang J, Leetmaa A, Reynolds R, Jenne R, Joseph D (1996) The NCEP/NCAR 40 year reanalysis project. *Bull Am Meteorol Soc* 77: 437–471
- Lamb HH (1972) *British Isles weather types and a register of daily sequence of circulation patterns, 1861–1971*. Geophysical memoir 116, HMSO, London
- Linderson M (2001) Objective classification of atmospheric circulation over southern Scandinavia. *Int J Climatol* 21:155–169
- Lund IA (1963) Map-pattern classification by statistical methods. *J Appl Meteorol* 2:56–65
- Martín-Vide J (2002) Aplicación de la clasificación sinóptica automática de Jenkinson y Collison a días de precipitación torrencial en el este de España. In: Cuadrat JM, Vicente SM, Saz MA (eds) *La información climática como herramienta de gestión ambiental*. Universidad de Zaragoza, Zaragoza, pp 123–127
- Martín-Vide J (2005) Los mapas del tiempo. *Mataró, Davinci Continental Post* P, Truija V, Tuulik J (2002) Circulation weather types and their influence on temperature and precipitation in Estonia. *Boreal Environ Res* 7:281–289
- Quintana J, Aceituno P (2012) Changes in the rainfall regime along the extratropical west coast of South America (Chile): 30–43° S. *Atmósfera* 25(1):1–22
- Romero H (1985) *Geografía de los climas de Chile*. Tomo XI Colección de Geografía de Chile, Instituto Geográfico Militar (IGM)
- Rubio-Álvarez E, McPhee J (2010) Patterns of spatial and temporal variability in streamflow records in south central Chile in the period 1952–2003. *Water Resour Res* 46(5)
- Sarricolea P, Meseguer-Ruiz Ó, Martín-Vide J (2014) Variabilidad y tendencias climáticas en Chile central en el período 1950–2010 mediante la determinación de los tipos sinópticos de Jenkinson y Collison. *Boletín de la Asociación de Geógrafos Españoles* 64:227–247
- Sarricolea P, Herrera-Ossandon M, Meseguer-Ruiz Ó (2017) Climatic regionalisation of continental Chile. *Journal of Maps* 13(2):66–73
- Spellman G (2000) The use of an index-based regression model for precipitation analysis on the Iberian Peninsula. *Theor Appl Climatol* 66:229–239
- Spellman G (2017) An assessment of the Jenkinson and Collison synoptic classification to a continental mid-latitude location. *Theor Appl Climatol* 128(3–4):731–744
- Štěpánek P. (2003) AnClim - software for time series analysis. Dept. of Geography, Fac. of Natural Sciences, MU, Brno. 1.47 MB
- Stehlík J (2001) Weather to weather links: relationships between Czech circulation pattern classification and other European regional classification schemes. *Acta Universitatis Carolinae Geographica* 2:155–167
- Tang L, Chen D, Karlsson P, Gu Y, Ou T (2009) Synoptic circulation and its influence on spring and summer surface ozone concentration in southern Sweden. *Boreal Environ Res* 14:889–902
- Trenberth KE (1991) Storm tracks in the Southern Hemisphere. *Journal of Atmospheric Sciences* 48:2159–2178
- Trigo R, DaCamara C (2000) Circulation weather types and their influence on the precipitation regime in Portugal. *Int J Climatol* 20:1559–1581
- Yarnal B, Ac C, Frakes B, Brown D (2001) Developments and prospects in synoptic climatology. *Int J Climatol* 21:1923–1950
- Zhang Y, Wallace JM, Battisti DS (1997) ENSO-like interdecadal variability: 1900–93. *J Clim* 10:1004–1020