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Current agro-climatic potential of Patagonia shaped by thermal and hydric patterns

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Abstract
Changes in thermal and hydric patterns affect crop growth. This research is aimed to assess temporal and spatial trends of 18 climatic and agro-climatic thermal and hydric indices in the north of Argentine Patagonia (39°–44°, south latitude), to establish the current and potential suitability of this region for agriculture in a context of climate change. The period of study was 1970–2016, and it was focused on the last 20 years. Regional warming was indicated by the average increases of annual mean temperature (+ 0.2 °C decade^{-1}), mean maximum temperature of the warm trimester (+ 0.3 °C decade^{-1}), and extreme maximum temperature of the warmest month (+ 0.6 °C decade^{-1}) during 1970–2016. This trend was also found in the 1996–2017 period. Mean minimum temperature of the cold trimester showed an uneven spatial and temporal trend, with increasing temperatures during 1970–2016 (+ 0.1 °C decade^{-1}), but a negative trend (− 0.1 °C decade^{-1}) over the last 20 years, which leads to an increasing regional trend in temperature amplitude. Negative trends in extreme minimum temperatures of April (− 0.3 °C decade^{-1}), July and October (− 0.2 °C decade^{-1}) imply more significant risks of cold damage for crops that exhibit sensitive phenological stages during this time. Thermal agro-climatic indices showed negative trends in winter chill (− 15.8 chill hours decade^{-1} considering the Weinberger method and − 20.8 chill hours decade^{-1} using Sharpe method) and higher accumulation of warm semester growing degree days (+ 38.8 GDD$_{5\,°C}$ and + 32.3 GDD$_{10\,°C}$ decade^{-1}). Climatic and agro-climatic water indices showed that most of the region experienced decreasing water availability, mainly in the central-south and Andean subregions, showing annual precipitation trends of − 11.5 and − 31.2 mm decade^{-1}, respectively). If these thermal and hydric trends are maintained in the future, the region will evolve into an area of greater energetic availability but with some restrictions: lower winter chill that would affect very high-chill cultivars cultivated in the warmest regions, higher risk of extreme thermal events during crucial phenological periods of specific crops, and decreasing water availability that would mainly affect dryland farming and river basin recharge.

1 Introduction

In recent decades, many regions of the world have experienced changes in the temperature and precipitation at different temporal and spatial scales (Alexander et al. 2006; Brown et al. 2008; Westra et al. 2013). According to the Intergovernmental Panel on Climate Change (IPCC 2013), the global temperature increased by 0.85 °C between 1880

and 2012. Moreover, growing trends in the frequency of extreme weather events and their intensity have been observed during the last 50 years (IPCC 2013). Biological observations indicate that these changes are already affecting living systems (Parmesan and Yohe 2003).

In South America, extreme temperatures have changed over the period 1960–2000. Significant trends were observed in the indices based on minimum daily temperatures. Significant increasing trends in the percentage of warm nights and decreasing trends in the percentage of cold nights were observed at many stations (most of the Argentine and Chilean Patagonian stations) (Vincent et al. 2005). In most parts of non-Patagonian Argentina, the annual mean temperature increased by 0.5 °C between 1960 and 2010, while the precipitation showed the same sign of trend in almost the whole country. This precipitation rise is higher than 100 mm in some

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semiarid areas, which has increased the land use for agriculture in these areas (Secretariat of Environment and Sustainable Development, SAyDS 2015). On the other hand, in the Argentine Pampas region, in the most crucial part of the country from an agricultural point of view, the maximum daily temperatures decreased, whereas the minimum daily temperatures increased during the period 1940–2007 (Fernández-Long et al. 2013). Moreover, Doyle et al. (2012) determined significant positive trends in the annual precipitation in 47 stations located in the Río de La Plata river basin in the period 1960–2005.

In the Patagonian region, in the southernmost part of the country, the main rainfed agricultural activity is extensive domestic livestock, with natural pastures as the fodder source, so their condition and perspective are fundamental in terms of sustainability and development (Oñatibia and Aguiar 2016). North Patagonian intensive agriculture is located in valleys, and it represents the 85% and 75% of the country's total production of apples and pears, respectively (Argentine Board of Integrated Fruit Growers 2018). In this region, the most extreme climate changes are the rise of the average annual or seasonal temperature. Although these changes have been reported since 1970, they became highly relevant since 1990 (Rabassa 2010). Rusticucci and Barrucand (2004) determined that the increase in the number of warm days and nights in winter and the decrease in the number of cold days and nights in summer during the 1959–1998 period in north Patagonia were due to the thermal increase. According to SAyDS (2015), from 1960 to 2010, the annual mean temperature increments recorded in this region were higher than in the rest of the country, whereas the precipitation in the Patagonian Cordillera decreased which is reflected in the water level. However, precipitation has not presented a clear spatial pattern (Rabassa 2010).

Changes in thermal and hydric patterns, like those previously presented, considerably affect the growth and development of plants and ecosystems as a whole (Garcia et al. 2014), as well as the activities related to agriculture (e.g., the selection of crop locations, irrigation or fertilization) (Nasir et al. 2018). Precipitation decrease directly affects crop growth rates, whereas rising temperatures catalyze phenological behavior in both crops and the natural vegetation (Legave et al. 2013).

To date, there is little information on how climatic trends are likely to affect the suitability of the Argentine Patagonia for different types of agricultural production (Brendel et al. 2017; Garcia Martinez et al. 2017). Recently, del Barrio et al. (2020) evaluated the possible impacts of climate change, focusing on thermal patterns and projections on regional cultivation of deciduous fruit and nut trees. The present research aims to assess the temporal and spatial trends in climatic and agro-climatic thermal indices and water indices in the northern region of Argentine Patagonia during the last five decades to illustrate the current agricultural suitability in a context of climate change.

2 Materials and methods

2.1 Study area

Two significant gradients shape the Patagonian climatic heterogeneity: rainfall decreases from west to east, whereas temperature decreases from the northeast to the southwest (Alessandro 2008). The seasonal displacement of the semi-permanent subtropical high-pressure in the Pacific Ocean and the coastal ocean currents with an Equatorial direction, as well as the presence of the Andes mountain range, determine the spatial rainfall patterns, of 800 to 1000 mm year^{-1} in the western mountain or foothill area and up to 200 mm on the central plateau (Barrett et al. 2009). In coastal areas, the north-direction air masses from the Atlantic Ocean generate sporadic convective rainfall during summer and early autumn. Consequently, the annual average is minimum in the central Patagonian and increases to the northeast, with values about 400 mm per year (Bianchi et al. 2016).

Regarding the temperature, this regional climate ranges from temperate to cool temperate, cold summer in the west, and cold arid in the central steppe (Kottek et al. 2006). It is dominated by air masses coming from the Pacific Ocean and by the circulation of moderate to strong westerly winds. The isotherms have a northeast-southwest distribution due to the combined effect of latitude, altitude, and regional circulation. So, the annual mean temperature varies between 8 and 15 °C, with means of 14–22 °C in January and 2–8 °C in July (Alessandro 2012).

The study area is a sub-region of Argentine Patagonia, called North Patagonia, which includes the south of the Buenos Aires province and the provinces of Río Negro, Neuquén, and Chubut, between 39° and 44° SL (Fig. 1). It comprises 20% of the national territory, but it only has 4.3% of its inhabitants with an average population density of 3.2 inhabitants km^{-1}. Due to the climate conditions, regional agriculture is currently dominated by extensive livestock farming: cattle in the north and west, and sheep and goats in the central and southern plateaus of the region. In the main river valleys, fruits, vegetables, and forages for fattening cattle production are reliant on irrigation. Most of the Argentine apple and pear production (~ 85%) is located along the Neuquén and Negro river valleys. In the Colorado river basin, we found the same scenario but to a lesser extent. On the other hand, towards the south, the lower Chubut River valley featured pastures, vegetables, and cherry production.

2.2 Meteorological data

To characterize the local climatic and agro-climatic conditions, monthly air temperature and rainfall data from 1 1 meteorological stations located in the study area (Table 1, Fig. 1) were analyzed. The meteorological data were obtained from
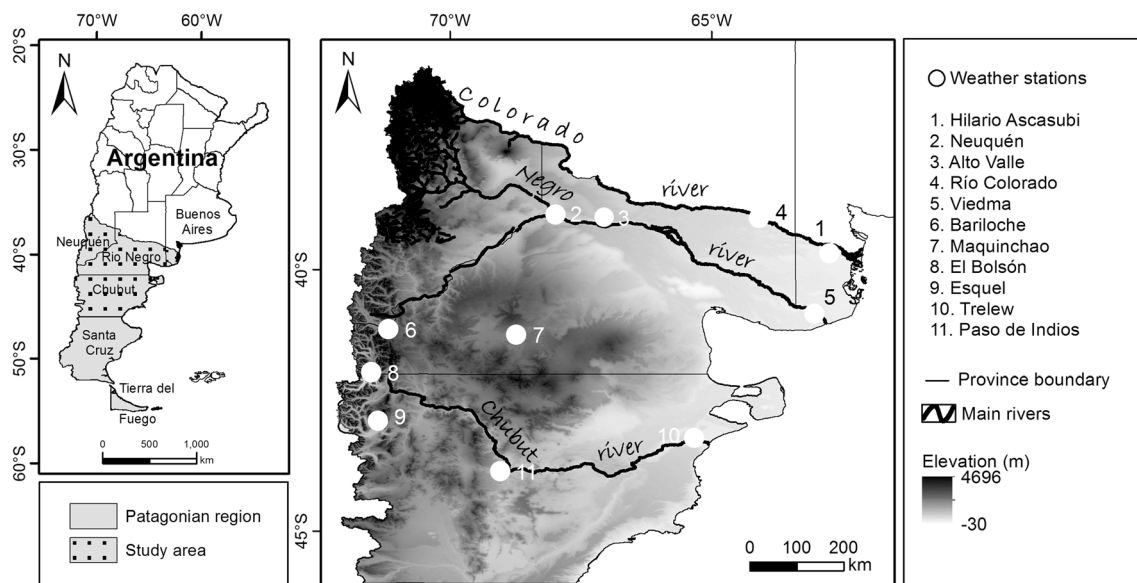
Fig. 1 Location map of North Patagonia (Argentina), the weather stations and elevation

the National Weather Service (SMN) and the National Institute of Agricultural Technology (INTA).

The scarcity of meteorological stations with extensive historical records is related to the low population, which is concentrated mainly along the rivers in a vast and otherwise climatically inhospitable territory. The period of study is 1970–2016. We conducted separate analyses for the period from 1997 to 2016 to detect possible changes in climatic trends, as indicated in previous studies (i.e., Rabassa 2010; Brendel et al. 2017). The partitioned analysis of a time series is typical in climatology and agro-climatology to establish possible differences between the complete records and the records of the recent past (Fernández-Long et al., 2013; Adnan et al. 2017; Chen et al. 2017). We implemented a data quality assessment by using the guide of the World Meteorological Organization (WMO 2011).

2.3 Climatic and agro-climatic indices

We calculated 18 climatic and agro-climatic indices to describe the local temperature and precipitation regimes (Table 2). Both types of indices to consider phenological times and bioclimatic requirements of the main deciduous fruit trees possible to be grown in the region. This strategy is widely supported by previous research using similar indices for different crops and regions (Moonen et al. 2002; Qian et al. 2013; Fernández-Long et al. 2013; Adnan et al. 2017). The choice of indices was supported by previous work on the suitability of the region for various crops, such as apple (Pascale et al. 2003), cherry (Cittadini et al. 2008), olive (Martín and Gallo 2007), walnut and hazelnut (del Barrio and Martín 2011), and grapes (del Barrio et al. 2016). Brendel et al. (2017) previously described some of these

thermal indices (i.e., the absolute maximum temperature of the warmest month January) focusing on the agro-climatic feasibility for walnut production; however, in the current study we analyzed the trend of each index and we also developed a map containing the statistical significance of each index and the results obtained on the agro-climatic potential of Patagonia for the main deciduous temperate fruit tree production.

Besides computing the annual mean temperature (AMT), we also calculated aggregated temperature metrics for certain parts of the year. The mean maximum temperature during the warmest quarter of the year (December, January, and February) (MeMaxTDJF) allows an approximation of thermal energy available during the most active period of the local vegetation. In contrast, the mean minimum temperature during the coldest quarter of the year (June, July, and August) (MeMinTJJA) provides information on frost severity and chill availability, which are critical site parameters for most perennial crops from temperate climates. Following the previous indices, the annual thermal amplitude (ATA) is another relevant parameter for crop physiology. In the present study, this index was calculated from the difference between the mean maximum temperature in January, and the mean minimum temperature in July.

Extreme monthly and annual temperatures, both minimum and maximum, are indicative of the severity of extreme thermal events. Regarding intensity, recurrence, and trend, they are of great importance because of their impact on crop productivity. Accordingly, we also analyzed trends in the absolute (extreme) maximum temperature of the warmest month—January—(aMAXTJa), which we considered a thermal stress approach that can impact crops in several ways, including changes in sugar concentration and variation in fruit color,

Table 1 Locations of weather stations used in this study in the period 1970–2016

Weather station	Province	Lat.	Long.	Elev. (m)	T_{max} January (°C) and Sd	T_{min} July (°C) and Sd	Pp. annual (mm) and Sd
Hilario Ascasubi	Buenos Aires	−39.38	−62.62	22	30.0 ± 1.1	1.6 ± 1.5	492 ± 105.7
Neuquén	Neuquén	−38.57	−68.08	271	31.7 ± 1.2	0.3 ± 1.3	194 ± 82.2
Alto Valle	Río Negro	−39.03	−67.74	242	30.5 ± 1.8	− 0.7 ± 1.3	234 ± 92.3
Rio Colorado	Río Negro	−39.01	−64.05	59	31.7 ± 1.2	2.7 ± 1.5	464 ± 125.5
Viedma	Río Negro	−40.85	−63.02	7	29.3 ± 1.3	1.6 ± 1.3	377 ± 114
Bariloche	Río Negro	−41.15	−71.17	840	22.4 ± 2.3	− 1.5 ± 1.3	809 ± 180.5
Maquinchao	Río Negro	−41.25	−68.73	887	26.3 ± 1.6	− 4.0 ± 1.9	202 ± 77.5
El Bolsón	Río Negro	−41.97	−71.50	337	24.7 ± 2.4	− 0.8 ± 1.3	866 ± 171.8
Esquel	Chubut	−42.90	−71.37	787	21.6 ± 1.9	− 2.6 ± 1.9	493 ± 109.3
Trelew	Chubut	−43.23	−65.30	10	28.9 ± 1.4	0.6 ± 1.3	203 ± 72.2
Paso de Indios	Chubut	−43.87	−69.03	590	26.5 ± 1.8	− 2.3 ± 2.1	172 ± 75.6

Lat. latitude, *Long.* longitude, *Elev.* elevation, T_{max} mean maximum temperature in January, T_{min} mean minimum temperature in July, *Pp. Annual* mean annual precipitation, *Sd* standard deviation

size, and quality. On the other hand, the absolute minimum temperature of the coldest month (July) (aMINTJl) indicates the intensity of winter frost, which can damage plant tissue even during the dormant season, if temperatures drop below plant-specific thresholds. Furthermore, the absolute minimum temperatures in April (aMINTAp) and October (aMINTO) were used to indicate the early/autumn and late/spring frost intensities, respectively, associated with the critical phenological stages of the crops in the region studied.

The selection of agro-climatic thermal indices was based on general criteria related to agricultural activities, mainly fruit growth, with pome fruit (apple and pear), nut fruit (walnut and hazelnut), stone fruit (peach and plum, and to a small extent cherries), grapes, and olive being cultivated in the region.

In deciduous fruit trees, the dormant season can be divided into two main stages (paradormancy—correlative inhibition—is not considered here). During the first phase, often termed endodormancy, the chilling requirement has not been fulfilled. After that, during the ecodormancy phase, the tree no longer accumulates chilling, and leaf out or bloom will occur after the respective forcing or heat requirements for these stages have been fulfilled (Luedeling et al. 2009a).

Trees require a winter chill to overcome their endodormancy period, and chill availability is an essential factor for the suitability of species and cultivars in a given area (Campoy et al. 2011). Various models have been proposed for estimating chill, with the so-called Dynamic Model currently the front-runner (Luedeling 2012). To ensure

Table 2 Analyzed climatic and agro-climatic indices

Climatic	Agro-climatic
Thermal	
Annual mean temperature (AMT)	Thermal sums on base 10 °C October–March (ΣT 10 °C)
Mean maximum temperature December-January-February quarter (MeMaxTDJF)	Thermal sums on base 5 °C October–March (ΣT 5 °C)
Mean minimum temperature June–July-August quarter (MeMinTJJA)	Chilling hours Weinberger (CHW)
Annual thermal amplitude (ATA)	Chilling hours Sharpe (CHS)
Absolute maximum temperature January (aMAXTJa)	
Absolute minimum temperature July (aMINTJl)	
Absolute minimum temperature April (aMINTAp)	
Absolute minimum temperature October (aMINTO)	
Water	
Annual precipitation (AnnualPP)	Annual Precipitation minus Potential Evapotranspiration (Thornthwaite) (annual PP-PET)
Precipitation accumulated in the warm semester (October–March, WarmPP)	Precipitation minus Potential Evapotranspiration (Thornthwaite) accumulated in the warm semester (October–March, Warm PP-PET)
Precipitation accumulated in the cold semester (April–September, ColdPP)	Precipitation minus Potential Evapotranspiration (Thornthwaite) accumulated in the cold semester (April–September, Cold PP-PET)

comparability with earlier analyses, and because the Dynamic Model requires hourly data which cannot easily be generated from the monthly information used in this study, we opted for an alternative method for estimating chill that is based on established relationships between mean temperatures during the winter months and the number of Chilling Hours.

We used two alternative models for this estimation. The first model, (according to Weinberger 1950) CHW, derives chill from mean monthly temperatures in June (tJn) and July (tJl) as defined in Eq. (1):

$$CHW = 2124.95 - 125.23 * \left(\frac{tJn + tJl}{2} \right) \qquad (1)$$

A second procedure according to Sharpe (1970) is CHS, who established a correlation between chill hours and the monthly mean temperatures of May, June, July, August, and September. The CHS was calculated using the following equation (Eq. 2):

$$CHS = \sum CH_{month}$$
$$CH_{month} = 638 - 33,007 * T_{mean} \qquad (2)$$

where CH month is the monthly chill hour estimate, and T_{mean} is the monthly mean temperature of the respective month (May, June, July, August, and September). The total (CHS) is the sum of all monthly chill estimates.

While this method of estimating chill would not be acceptable in warm climates, where the Chilling Hours model has produced inferior results (Benmoussa et al. 2017), it should be effective under the cool temperate conditions of our study area (Luedeling and Brown 2011). Perennials also need heat in spring to leaf out and bloom, and for all subsequent development periods. Heat requirements are often quantified in Growing Degree Days (GDD) that express thermal sums. Since the base temperatures used as a lower threshold for heat accumulation vary between species, varieties, or cultivars, we conducted separate calculations for base temperatures of 5 °C and 10 °C, which spans the values suggested in the literature for temperate-zone fruit trees with potential suitability in the region: walnut (Vahdati et al. 2012), olive (Galán et al. 2005; Pérez-López et al. 2008), and grapevine (Duchêne et al. 2010). According to equations reported by Pascale and Damario (2004), we estimated monthly heat availability as (Eq. 3):

$$\sum T_{LN} = 0.5 \frac{(tM - tb)^2}{tM - tm} \qquad (3)$$

where tM is the monthly mean maximum temperature, tm is the monthly mean minimum temperature, and tb is the base temperature (5 °C and 10 °C) during October–March.

Precipitation represents the primary water source in Argentine Patagonia. The region is characterized by low average annual rainfall. The coastal zone and the central plateau

and valleys show different annual precipitation regimes (Aravena and Luckman 2009). In the Andean region, precipitation falls predominantly during the cold semester (González and Vera 2010), whereas the coastal and central zones present a relatively homogeneous distribution throughout the year, with slightly higher precipitation during the warm semester (Bianchi et al. 2016). Therefore, we computed the annual accumulated precipitation (AnnualPP), the precipitation collected in the warm semester October–March (WarmPP), and the precipitation accumulated in the cold semester April–September (ColdPP) to characterize regional moisture regimes (Table 2).

To characterize the water use as well as the water supply, we added an analysis of the accumulated precipitation minus potential evapotranspiration (PP-PET) (Table 2). The use of PET allowed us to identify, analyze, and monitor the soil water balance and drought events more precisely (Martínez-Fernández et al. 2015). The PP-PET (mm) may be calculated at different scales. In this study, it was applied at an annual scale (annual PP-PET) and during the warm (warm PP-PET) and cold (cold PP-PET) semesters (Table 2). This selection was made to know the intensity, magnitude, and duration of dry and moist events during those periods. For the estimation of potential evapotranspiration, several methodologies are found in the literature. Although, Penman–Monteith's method on a daily scale is strongly recommended by the Food and Agriculture Organization (FAO), where the amount and type of variables involved in its calculation are available (Allen et al. 1998). However, the simplicity of Thornthwaite's method (Thornthwaite 1948) allows it to be applied in a broader area monthly (Pántano et al. 2017).

2.4 Trend analysis

The non-parametric Mann-Kendall test (Mann 1945; Kendall 1955) was used to test whether significant trends were present in the agro-climatic and climatic indices, and we used Sen's slope estimator to quantify rates of change in the R Studio software. These procedures are commonly used for time series analysis.

3 Results

3.1 Thermal climatic indices

Thermal climatic indices show the trends (°C decade^{-1}) of annual mean temperature (AMT) (Fig. 2a, 1970–2016 and Fig. 2b, 1997–2016), the mean maximum temperature of the warmest quarter of the year (MeMaxTDJF) (Fig. 2c, 1970–2016 and Fig. 2d, 1997–2016), the absolute maximum temperature of the warmest month (aMAXTJa) (Fig. 2e, 1970–2016 and Fig. 2f, 1997–2016), and the annual thermal
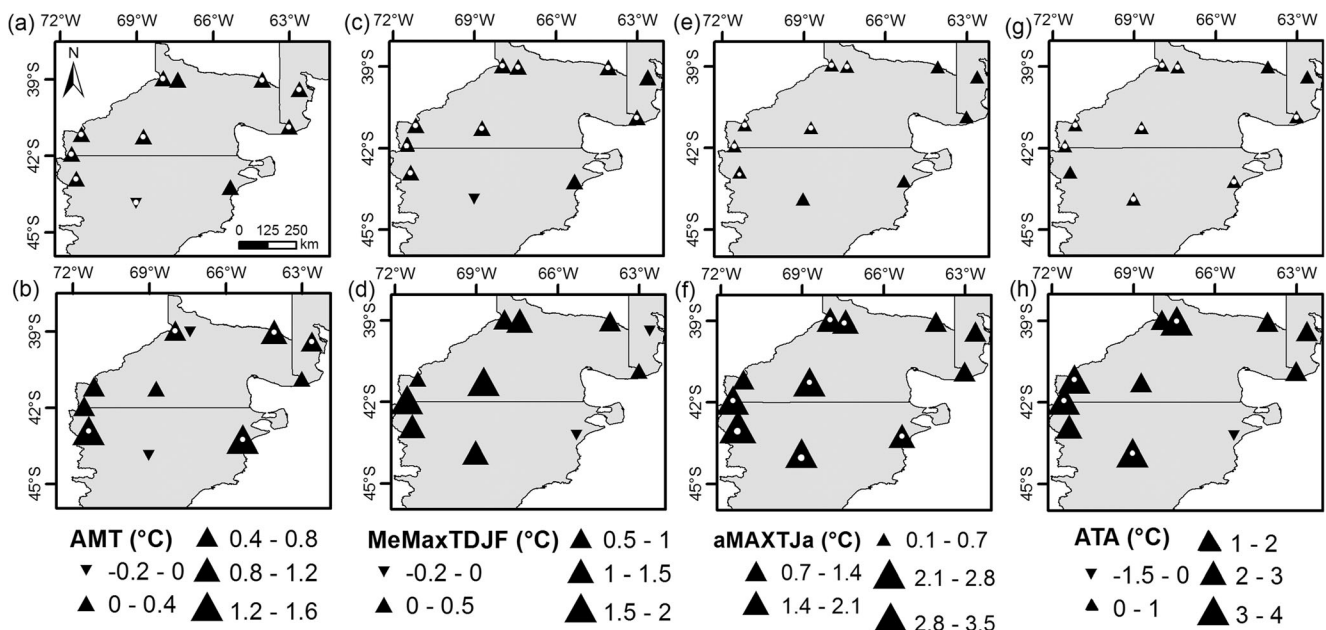
Fig. 2 Spatial distribution of the trend (°C decade^{-1}) of annual mean temperature (AMT) (**a** and **b**), mean maximum temperature in the warmest quarter (MeMaxTDJF) (**c** and **d**), absolute maximum temperature of the warmest month (January) (aMAXTJa) (**e** and **f**) and annual thermal amplitude (ATA) (**g** and **h**). The top panels correspond to 1970–2016 and those below to 1997–2016. Upward/downward pointing triangles show increasing/decreasing trends every 10 years, respectively, and points within the triangles correspond to statistically significant trends (significant at the 0.05 level)

amplitude (ATA) (Fig. 2g, 1970–2016 and Fig. 2h, 1997–2016) for the study area. Thus, the AMT was positive in ten of the 11 stations studied (91%) in which the increase was statistically significant in nine of them (82%) during the period 1970–2016 (Fig. 2a). For these stations, the average thermal increase was + 0.17 °C decade^{-1}. During the last 20 years, the trend was also positive in 82% of the study area, but there were increments of about 0.5 °C decade^{-1} with a greater magnitude in the west region (Esquel, Bariloche, and El Bolsón, + 0.9 °C decade^{-1}) (Fig. 2b).

On the other hand, the MeMaxTDJF showed a positive trend in 91% of the study area during the series 1970–2016 (Fig. 2c) and 82% in the shorter period (Fig. 2d). This index was statistically significant in eight of the stations analyzed (73%) during 1970–2016 (+ 0.3 °C decade^{-1}), and during the subseries 1997–2016, it showed an increased (but not significant) trend of + 0.8 °C decade^{-1} (Fig. 2d).

North Patagonia showed a clearly increasing pattern in aMAXTJa and ATA in both periods analyzed. As regards aMAXTJa, the 11 stations assessed showed an incremental trend of this parameter, even though significant changes were only recorded in six stations (55% of the study area) during the most extended period (Fig. 2e), whereas this happened in seven stations (64%) in the series 1997–2016. Regionally, the average aMAXTJa increase during 1970–2016 was of + 0.4 °C decade^{-1} increasing up to + 0.7 °C decade^{-1} in the west of the study area (Esquel, Bariloche, and El Bolsón) (Fig. 2e). During the subseries, the aMAXTJa variation was intensified,

and an average regional increase of + 1.8 °C decade^{-1} was recorded (Fig. 2f).

The ATA trend was positive in the whole region during the most extended series (Fig. 2g), and it was statistically significant in eight of the stations (75% of the study area) with an average of + 0.8 °C decade^{-1}. During the shorter period, 91% of the region recorded a positive and significant trend in four localities (36%) (Fig. 2h).

The trends (°C decade^{-1}) of thermal climatic indices calculated from the minimum temperatures are shown in Fig. 3. The mean minimum temperature of the coldest quarter of the year (MeMinTJJA) for the period 1970–2016 (Fig. 3a) showed a positive trend in seven localities (64%) with statistical significance in five of them (45%). Regionally, the average increase was of + 0.1 °C decade^{-1}. During the subseries (Fig. 3b), a change in trend was observed concerning the most extended series. It was negative in 64% of the study area with an average decrease of − 0.1 °C decade^{-1}, and it continued being more critical, as in the series 1970–2016, in the center of the region (− 0.8 °C decade^{-1}).

As regards the absolute minimum temperature of the coldest month (aMINTJl) in the series 1970–2016 (Fig. 3c), 55% of the area recorded a negative trend (not significant), and 45% of the region marked a positive trend (one significant station) and an average regional trend of − 0.2 °C decade^{-1}. The trend in this index was maintained and intensified since it was reported in 75% of the study area with a variation of − 0.9 °C decade^{-1} during the last 20 years (Fig. 3d).
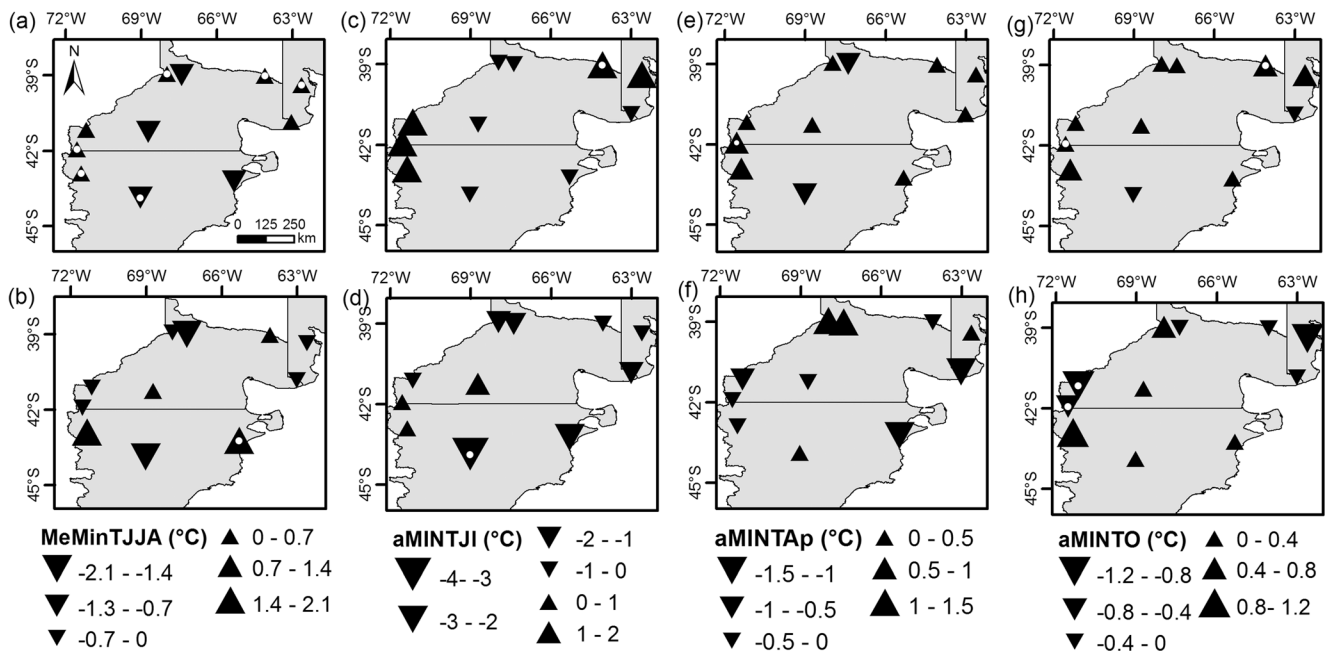
Fig. 3 Spatial distribution of the trend (°C decade^{-1}) of the mean minimum temperature in the coldest quarter (MeMinTJJA) (**a** and **b**), absolute minimum temperature of the coldest month (July) (aMINTJl) (**c** and **d**), absolute minimum temperatures of April (aMINTAp) (**e** and **f**), and the absolute minimum temperatures of October (aMINTO) (**g** and **h**). The top panels correspond to the 1970–2016 and those below to 1997–2016. Upward/downward pointing triangles show increasing/ decreasing trends every 10 years, respectively, and the points within the triangles correspond to statistically significant trends (significant at the 0.05 level)

Finally, the absolute minimum temperature of April (aMINTAp) (Fig. 3e, 1970–2017 and 3F 1997–2016) and the absolute minimum temperature of October (aMINTO) (Fig. 3g, 1970–2016 and Fig. 3h, 1997–2016) also showed a change in trend during the shorter series. The negative trend was observed in 73% of the study area in the first case, whereas it was 64% for the second index (Fig. 3f and h). The average decrease for aMINTAp was − 0.3 °C decade^{-1}, whereas for aMINTO, it was − 0.2 °C decade^{-1} (Fig. 3f and h).

3.2 Thermal agro-climatic indices

Figure 4 shows the trends of thermal agro-climatic indices of thermal sums on a base of 5 °C ($\sum$T5 °C) and 10 °C ($\sum$T10 °C) (°C decade^{-1}) (Fig. 4a, 1970–2016 and Fig. 4b, 1997–2016 for the first index and Fig. 4c, 1970–2016 and Fig. 4d, 1997–2016 for the second one) and the chill hours based on Weinberger's method (CHW) (h decade^{-1} (Fig. 4e, 1970–2016 and Fig. 4f, 1997–2016) and Sharpe's method (CHS) (h decade^{-1})(Fig. 4g, 1970–2016 and Fig. 4h, 1997–2016).

Thus, in $\sum$T5 °C and $\sum$T10 °C indices, 91% (81% statistically significant) of the study area showed a positive trend during the period 1970–2016. The average increase was of + 38.8 ($\sum$T5 °C) and +32.3 ($\sum$T10 °C) Growing Degree Days (GDD) decade^{-1}. This trend also predominated during the shorter series with an average regional increase of + 136.4 ($\sum$T5 °C) and + 118.3 ($\sum$T10 °C) GDD decade^{-1} during the period 1997–2016. The above shows a generalized rise in regional energy availability during the last decades (Fig. 4).

Regarding the CHW and CHS indices, the 1970–2016 series showed negative trends in 91% and 82% of the region, with average regional decreases of − 20.8 chill hours (CH) and − 15.8 CH decade^{-1}, respectively. These indices maintained negative trends during the shortest period in most of the region, decreasing by − 39.1 CHW and − 101.3 CHS decade^{-1} (Fig. 4).

Fruit trees require a winter chill to overcome their endodormancy period and need heat in spring to leaf out and bloom for subsequent development periods. Thermal sums are measured in Growing Degree Days (GDD) that express thermal sums and Weinberger's and Sharpe's method in chill hours (CH). Mean values ± SE (1970–2016) of these agro-climatic thermal indices are shown in Table 3. This allows us to have a reference for the mean values of these metrics and their geographical variability in the studied region.

3.3 Water climatic indices

Figure 5 represents the annual precipitation trend (mm decade^{-1}) (Fig. 5a, 1970–2016 and Fig. 5b, 1997–2016), mean precipitation the warmest semester (October–March) (Fig. 5c, 1970–2016 and Fig. 5d, 1997–2016) and the coldest semester (April–September) (Fig. 5e, 1970–2016 and Fig. 5f, 1997–2016) in the study area. Considering the annual precipitation during the period 1970–2016 (Fig. 5a), the region showed a
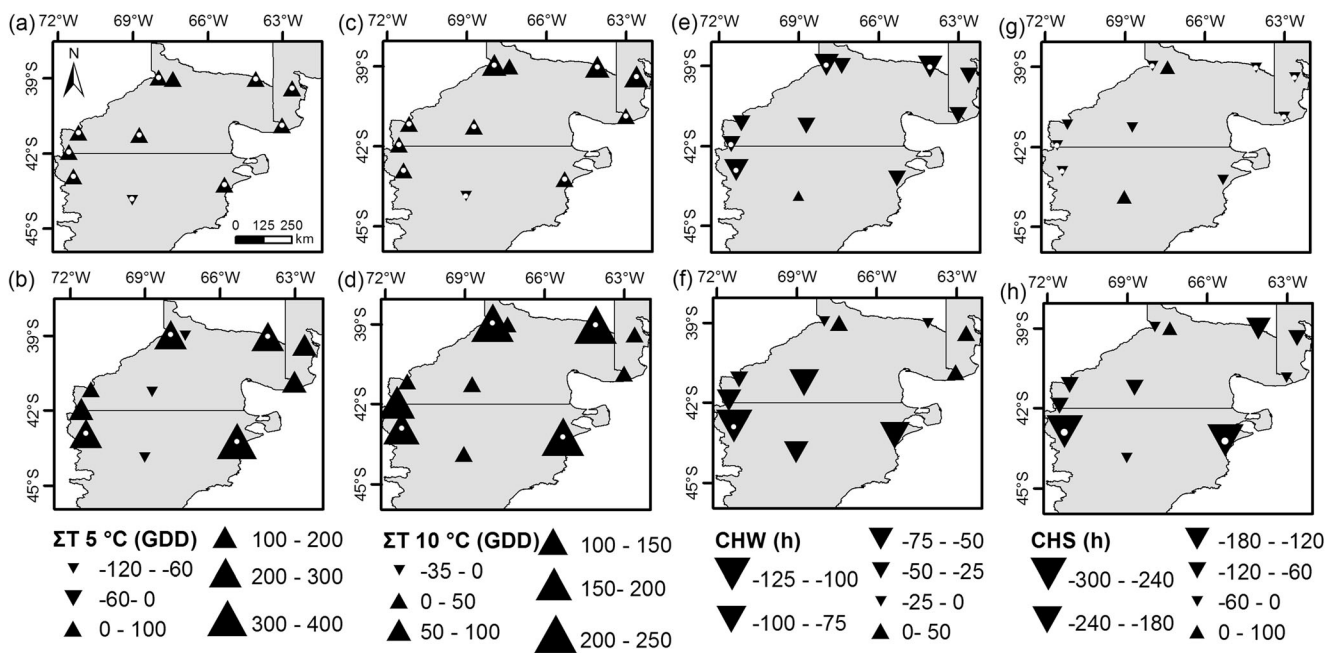
Fig. 4 Spatial distribution of the trend (°C decade^{-1}) of thermal sums on a base of 5 °C (ΣT 5 °C) (**a** and **b**), thermal sums on a base of 10 °C (ΣT 10 °C) (**c** and **d**), chill hours based on Weinberger's method (CHW) (h decade^{-1}) (**e** and **f**) and Sharpe's method (CHS) (h decade^{-1}) (**f** and **g**).

The top panels correspond to 1970–2016 and those below to 1997–2016. Upward/downward pointing triangles show increasing/decreasing trends every 10 years, respectively, and points within the triangles correspond to statistically significant trends (significant at the 0.05 level)

decrease in nine localities (82%), out of which three were statistically significant. This average decrease was of − 12.5 mm decade^{-1}. The most critical variation was recorded in the west (− 31.2 mm decade^{-1}) (El Bolsón, Bariloche, and Esquel). During the shortest period, the trend in this index increased since the precipitation decreased over the whole study area (− 51.2 mm decade^{-1}) (Fig. 5b). The annual rainfall decrease was higher in the west of the region during the period 1997–2016 (− 67.7 mm decade^{-1}) just as happened in the 1970–2016 series.

The trend in accumulated precipitation during the warm and cold semesters also decreased in both periods studied. As the precipitation of the warm semester (October–March) was considered during the period 1970–2016, nine localities (82%) showed this sign in the trend, being statistically significant in 27% of the study area (Fig. 5c). The average regional decrease was of − 4.1 mm decade^{-1}. During 1997–2016, ten localities presented a negative trend (Fig. 5d). In this case, the precipitation variation of the warm semester was of − 8.2 mm decade^{-1} during the sub-period.

Finally, the precipitation accumulated in the cold semester (April–September) also showed a negative trend in nine localities (82%), two of which were significant during the series 1970–2016 (Fig. 5e). This index reduction, during the last period mentioned, was of − 13.2 mm decade^{-1}. On the contrary, during the period 1997–2016, the whole study area experienced a reduction in this index, in the cold semester but without any statistical significance (Fig. 5f). This index of regional decrease for the shortest series was of − 31.9 mm decade^{-1}.

3.4 Water agro-climatic indices

Figure 6 shows the precipitation minus potential evapotranspiration trend (mm decade^{-1}) on an annual scale (annual PP-PET) (Fig. 6a, 1970–2016 and Fig. 6b, 1997–2016) and on a six-monthly scale during the warm semester (warm PP-PET) (Fig. 6c, 1970–2016 and Fig. 6d, 1997–2016) and the cold one (cold PP-PET) (Fig. 6e 1970–2016 and Fig. 6f, 1997–2016) in the study area. Considering annual PP-PET, for the complete series, ten localities (91%) presented a negative trend, being statistically significant in six of them (Fig. 6a). This sign in the trend also predominated during the shortest series (Fig. 6b). The predominance of dry conditions was also reflected in the warm PP-PET with a negative trend in nine localities in both periods (Fig. 6c and d) and in the cold one with a negative trend in nine locations during 1970–2016 (Fig. 6e) and in the total of the area during the 1997–2016 (Fig. 6f).

4 Discussion

The evaluation of the thermal climatic and agro-climatic indices in the North Patagonian region indicated an increment of the caloric feasibilities over the last decades. This situation was following studies at a global level (Brown et al. 2008; Buckley and Huey 2016) and a regional level (Vincent et al. 2005). Thus, the region presented an average increase in the annual mean temperature of + 0.8 °C during 1970–2016, and of + 0.6 °C during 1997–2016. This fact could be associated

Table 3 Mean values and standard deviation of agro-climatic thermal indices (1970–2016). Chill hours based on Weinberger's method (CHW) and Sharpe's method (CHS). Thermal sums (GDD) on base 5 °C ($\sum T_{LN5}$) and 10 °C ($\sum T_{LN10}$)

Weather station	CHW	CHS	$\sum T_{LN5}$	$\sum T_{LN10}$
Hilario Ascasubi	1143 ± 110.4	1604 ± 87	2939 ± 181.4	1757 ± 134.3
Neuquén	1339 ± 127	1814 ± 107	3396 ± 167.9	1959 ± 133.7
Alto Valle	1301 ± 111.4	1782 ± 95	2783 ± 138.8	1694 ± 130.2
Rio Colorado	1118 ± 121.5	1544 ± 108	3349 ± 222	2106 ± 167.3
Viedma	1188 ± 107	1694 ± 94	2876 ± 168	1695 ± 131
Bariloche	1808 ± 127	2581 ± 98	1313 ± 137.5	593 ± 100
Maquinchao	1915 ± 192.8	2583 ± 165	1803 ± 166.2	950 ± 120.6
El Bolsón	1592 ± 97.9	2253 ± 86	1655 ± 144.7	825 ± 109.3
Esquel	1836 ± 191.4	2549 ± 137	1401 ± 140	612 ± 98.5
Trelew	1301 ± 138	1801 ± 116	2699 ± 144.9	1574 ± 109.6
Paso de Indios	1680 ± 206.2	2311 ± 179	1916 ± 178.9	1025 ± 118

with the rise in summer temperatures since records of the mean maximum temperatures during the warm quarter (Fig. 2c and d) showed an average increase of + 1.3 °C in the 47 years of study, having become accentuated in the last two decades. The behavior of the mean minimum temperatures of the cold trimester of the year showed an uneven spatial trend, having a negative trend increment over the last 20 years (Fig.

3a and b), which also leads to a regional ATA incremental trend (Fig. 2g and h). This previous increase in the index is mainly related to the higher summer thermal availabilities. These results comply with what was previously found out for the region by Brendel et al. (2017) and partially differed from previous studies that indicate a uniform regional increase in the winter minimum temperatures over the last decades
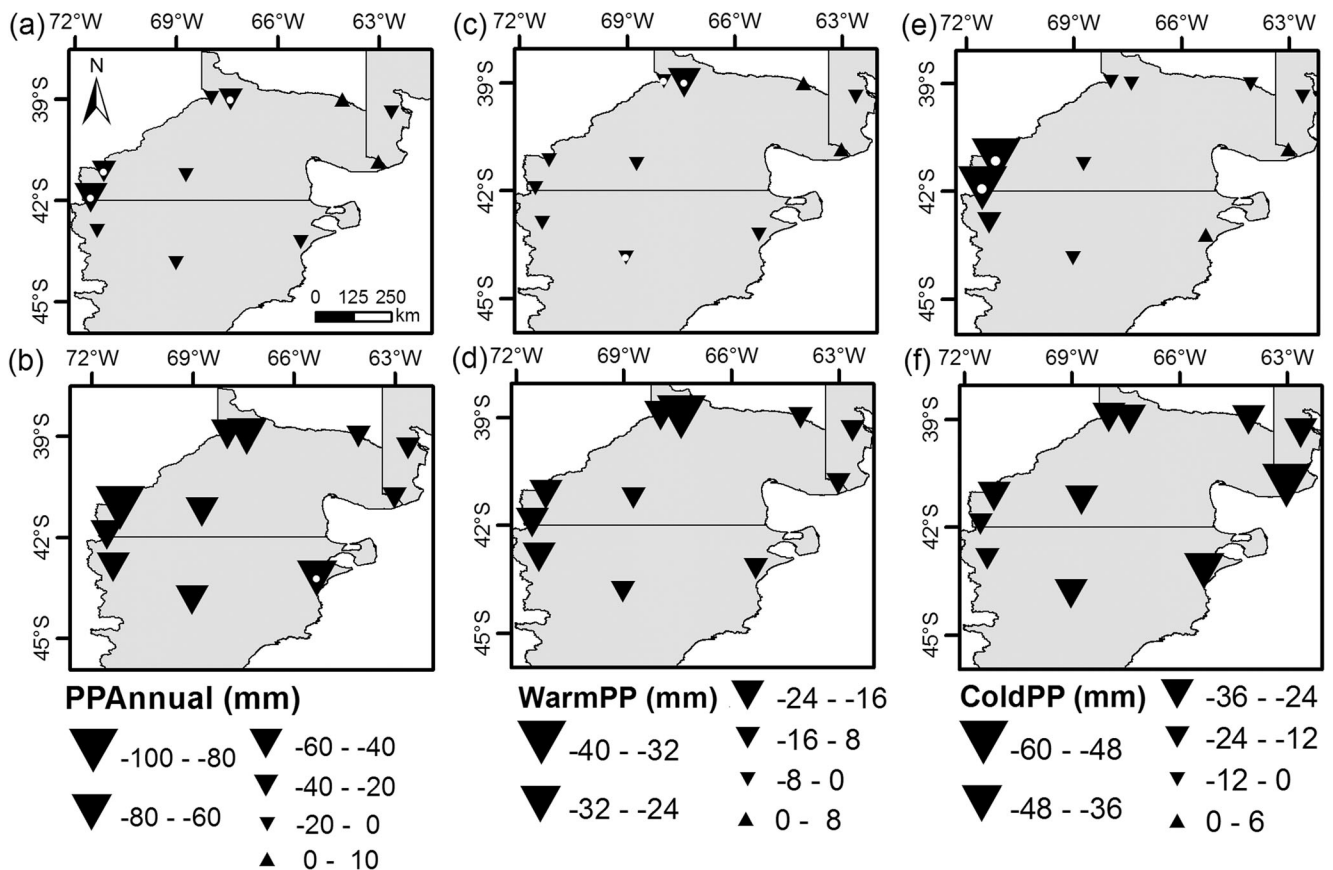

Fig. 5 Spatial distribution of the trend (mm decade^{-1}) of annual rainfall (**a** and **b**), mean rainfall of the warmest semester (**c** and **d**), and coldest semester (**e** and **f**). Top panels correspond to the 1970–2016 and those below to 1997–2016. Upward/downward pointing triangles show increasing/decreasing trends every 10 years, respectively, and points within the triangles correspond to statistically significant trends (significant at the 0.05 level)

Fig. 6 Spatial distribution of trend (mm decade^{-1}) of annual Precipitation minus the Potential Evapotranspiration (Annual PP-PET) (**a** and **b**), PP-PET in the warm semester (Warm PP-PET) (**c** and **d**), and PP-PET during the cold semester (Cold PP-PET) (**e** and **f**). Top panels correspond to the 1970–2016 and those below to 1997–2016. Upward/downward pointing triangles show increasing/decreasing trends every 10 years, respectively, and points within the triangles correspond to statistically significant trends (significant at the 0.05 level)
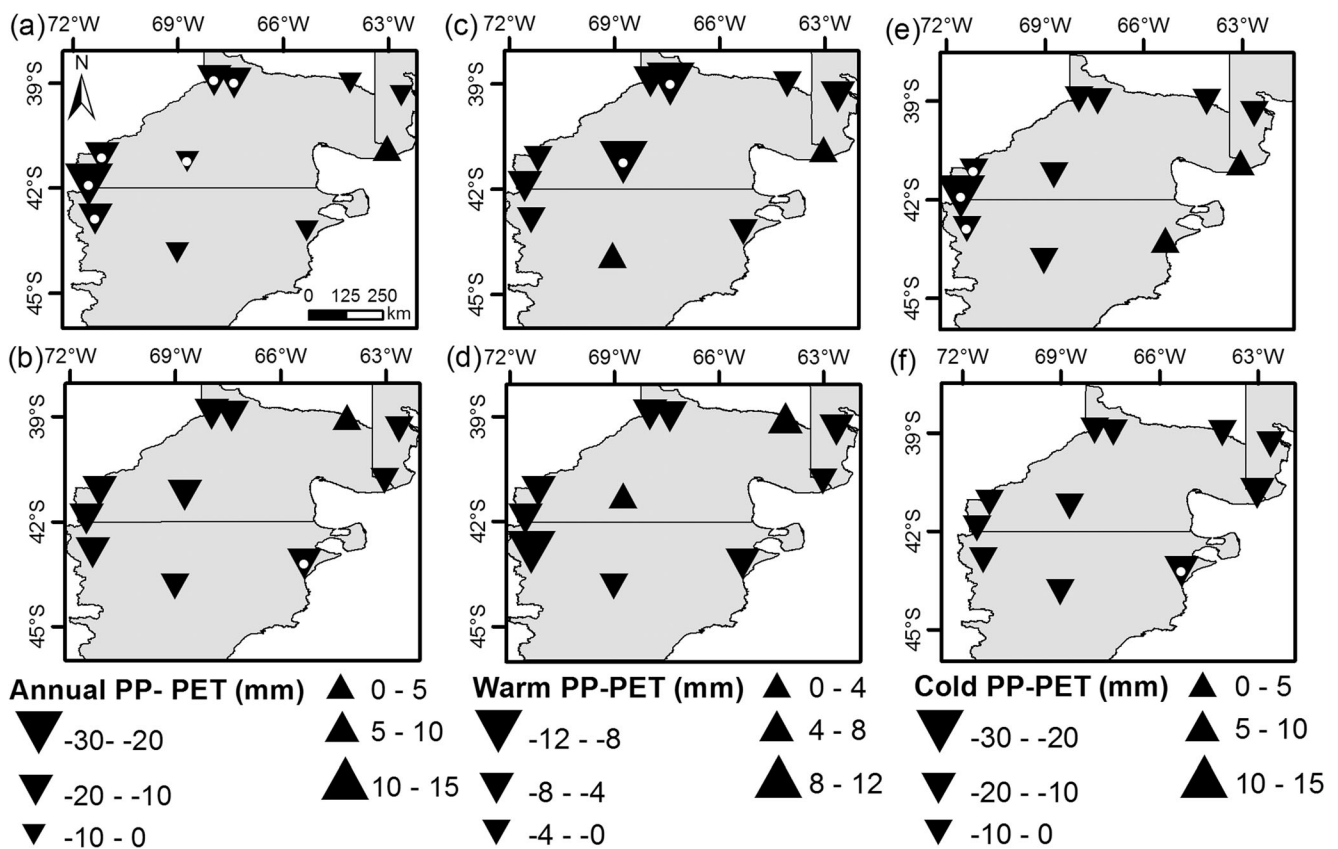
(Puga et al. 2008) or significant increments of the summer mean maximum temperatures only in the Patagonian Andean region (Zalazar and Serio 2012).

Considering the thermal extremes, the increments found in the aMAXTJa in both study periods (Fig. 2e and f) increase the risk of fruit sunburn and burn, particularly in the north of the region under analysis (Benegas and Rodríguez 2007), and modification in the organoleptic features of the vine (Sepúlveda et al. 1986). As regards the aMINTJl, the increase in the negative trends over the last 20 years (Fig. 3d) has already been causing losses of young olive plants (Martín and Gallo 2007) and walnut trees (del Barrio and Martín 2011) in the region due to winter frost injuries (Charrier et al. 2015). The abovementioned, together with the negative trends found in the aMINTAp (Fig. 3f) and aMINTO (Fig. 3h), imply more significant risks of damage due to thermal decrease during crucial phenological periods of the plants (Charrier et al. 2011).

The higher thermal availability of the warm semester is also supported by the observed results of the agro-climatic indices of thermal sums on a 5 °C base (ΣT 5 °C) (Fig. 4a and b) and a 10 °C base (ΣT 10 °C) (Fig. 4c and d). The heat availability in spring and summer for the effective completion of the

ontogenic cycle varies significantly according to the species and the variety or cultivar. For example, from sprouting to physiologic maturity, on a ΣT 10 °C, 1300 to 1700 Growing Degree Days (GDD) must be reached in walnut trees (Villaseca 2007), 700 to 1500 GDD in apple trees (Pascale et al. 2003), 500 to 1200 GDD in vines (del Barrio et al. 2016), or 500 to G700 GDD in cherry trees (Luedeling et al. 2013). Considering our database set (Table 3) and the results obtained in this research, these thermal requirements are met in the localities close to the Atlantic coast and those located in the North. Still, they are not enough to satisfy the crop needs (except for cherry trees) in the Andean localities (west) and those located in the center-south region. However, in the Patagonian Andean zone, the trends observed over the last two decades make it feasible, having an increased rate of an average 150 GDD every 10 years, and if the same trends continue, there is a possibility of meeting those energetic needs in the near future.

The air temperature and the development processes of the regional perennial crops, such as the deciduous fruit trees previously mentioned, are also linked using the winter chill requirements. The chill hours (CH) for the correct induction, maintenance, and later breaking of dormancy and sprouting

are significantly varying according to the species and variety or cultivar considered. Thus, for example, the cherry tree requires from 800 to 1300 CH (Alburquerque et al. 2008; Luedeling et al. 2013); the walnut tree, from 500 to 1500 CH (Vahdati et al. 2012); the hazelnut, from 700 to 1200 CH (del Barrio and Martín 2011); and the vine, from 400 to 1200 CH (del Barrio et al. 2016). According to the applied methodology, the study area has lost between 5.5 and 12% of its average winter chill availability over the last 47 years (Fig. 4e and g). Considering the previous two decades, the CH average decrease has become accentuated, reaching a regional average of -39 CHW decade^{-1} and -101 CHS decade^{-1} by Weinberger and Sharpe, respectively (Fig. 4f and h). In the future, this decrease in the winter chill could be a limitation for high-chill cultivars cultivated in the warmer regions of North Patagonia. However, it should be highlighted that projections of winter chill that use the Chilling Hour Model have projected substantial declines in future winter chill in warm regions (Baldocchi and Wong 2008; Luedeling et al. 2009b, 2011), whereas changes indicated by the Dynamic Model tend to be less severe (Luedeling et al. 2009c,d). Still, historical winter chill changes between the Chilling Hour Model and the Dynamic Model were not very high in cold Germany (Luedeling et al. 2009e) with similar conditions as cold Patagonia, which supports the validity of Chilling Hour Model as a first approach.

The water climatic indices did not present a similar spatial trend during the period 1970–2016. Thus, the annual precipitation increased in some locations of the coastal zone (Fig. 5a). In contrast, it decreased in the south-center of the region and over the Andes (average of -54 mm and -147 mm, respectively, over the 47 years assessed). These decreasing rates were higher in the last 20 years than those obtained during 1970–2016 (Fig. 5b). During the last two decades, in the coastal zone, the precipitation decreased -24 mm and -54 mm decade^{-1} in the south-center. The principal reduction was found in the Andean area showing -67 mm decade^{-1}, mainly due to the decrease recorded in the precipitation that took place during the cold semester (Fig. 5e and f). If this negative regional trend is maintained in the future, it will lead to erosion and desertification processes. Moreover, the lower water availability in the western Andean area would affect the recharge of the upper watersheds of the principal regional rivers and, consequently, the intensive agriculture under irrigation further downstream (Rivera et al. 2017). The water availability analysis conducted from annual and semesterly PP-PET indices also presented a negative trend in most of the localities studied during the period 1970–2016 (Fig. 6a). The use of PP-PET at different scales and periods of the year allowed a more accurate assessment of the water situations relating to gains and losses of soil water (Bohn and Piccolo 2019). Most of the negative values found in these indices are directly related to the combination of lower precipitation and higher energetic availability for potential evapotranspiration.

5 Conclusion

The current agricultural aptitude of north Argentine Patagonia presents availabilities and restrictions expressed by temporal and spatial changes in their thermal and hydric conditions, as found over the last five decades. Thus, the positive trend observed in the thermal indices, if maintained in the future, will evolve into a greater energetic availability that will improve the possibilities of crop growth and development in the region studied. However, there could be two restrictions related to this increase: on the one hand, the smaller availability of winter chill needed for the development of very high-chill cultivars or species, specifically in the north and northeast of the region and, on the other hand, the higher intensity of extreme thermal events. The latter may be expressed in the trends of the absolute temperature of the warmest and coldest months as well as the absolute minimum temperatures in autumn and spring (risk of early and late frosts) with consequences in crop phenology and yield.

In addition, the decreasing water availabilities will have a more significant impact on the dry farming in the plateaus of the coastal and center-south zones of the area studied, where the decline associated with the degradation of natural grassland will be maintained. Moreover, if these trends are maintained, the water availability for agricultural irrigation in the valleys of the river basins with less abundant water, e.g., the Colorado and Chubut rivers, could be affected in the future.

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