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Warming trends in Patagonian subantartic forest

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ABSTRACT

The forests in the Aysén region (ca. 43–49 °S, Chile) have a high degree of wilderness and cover more than 4.8 million hectares, making it one of the largest areas of subantarctic forest in the Southern Hemisphere. The impact of global warming on this region is poorly documented. The main objective of this work was to analyze the normalized difference vegetation index (NDVI), land surface temperature (LST) and precipitation over Aysen forests in the context of ongoing global warming. We used average monthly images of LST and NDVI derived from the MODIS sensor covering the period 2001–2016 and precipitation from gridded datasets. The Aysén region was divided into three nested spatial scales: i) regional, ii) regional considering only forests, iii) local scale considering an evergreen subantarctic forest area covering around 5 × 5 km and a local deciduous forest area (dominated by *Nothofagus pumilio*). Trend analysis showed a warming rate of +0.78 K/decade ($p \leq 0.05$) over the subantarctic forest zone, greening of +0.01/decade for NDVI ($p \leq 0.05$) over the western zone, and a drying trend ($p \leq 0.05$) over the eastern zone. The minimum temperature anomalies showed an increase of about 4.5 K during the period under analysis. LST, NDVI and precipitation were also analyzed here. The recent trends in temperature, greening and precipitation over the forests of Aysén detected in this research contribute to a better understanding of global warming impacts on subantarctic forests in the southern tip of South America. Nevertheless, to get a better estimation of the impact of global warming at multiple scales is needed to have better quality and quantity of data in situ.

1. Introduction

Global warming which correspond to the gradual increase, in global surface temperature, as one of the consequences of radiative forcing caused by anthropogenic emissions, might have unintended consequences on forests located at high latitudes of the world (IPCC, 2014). In fact, an average global temperature increase of 2 °C (or K, for being both decimal scale) is expected for the coming decades (Joshi et al., 2011). Global warming can impact ecosystems in different ways depending on their geography, such as variations in precipitation distribution and abundance, glacier melting rate, ocean level, and forest ecosystem dynamics (Dale et al., 2001; Walther et al., 2002; Pardos, 2010; Veblen et al., 2011; Friend et al., 2014).

South America has large areas of forest ecosystems that have undergone little human disturbance and are being significantly impacted by climate change. For example, Amazonian tropical rainforests have experienced severe droughts in conjunction with high temperatures due to global warming, thus triggering a decrease in net biomass and increased mortality (Jiménez-Muñoz et al., 2013; Brienen et al., 2015; Jiménez-Muñoz et al., 2016). In the subantarctic forests of the southern Chile, however, the response has not been registrated at regional scales to the current trend of global warming.

The forests in the Region of Aysén, Chile (hereafter Chilean Patagonia), cover an area of almost 5 million hectares and have a high degree of wilderness (Álvarez et al., 2010; Ramírez et al., 2014). The subantartic forests of Chilean Patagonia are highly biodiverse and rich in endemism, possessing great richness in terms of ecosystem and landscape (Armesto et al., 1998). Since the 20th century, large swaths of these forests have been lost to fires and deforestation to open land for livestock production (> 3 million ha, Bizama et al., 2011; Jaksic and Fariña, 2015; Úbeda and Sarricolea, 2016). In the same region, information is limited about the impact of climate change on remaining

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forests at regional scale, such as any increase in temperature or decrease in precipitation (Aravena et al., 2002; Veblen et al., 2011).

Due to the scarcity of in-situ meteorological data and the area's inaccessibility, remote sensing tools are highly useful for providing information at different time intervals, which can aide in establishing patterns of climatic variability in these forests and evaluating their vulnerability to global changes both spatially and temporally (Nagendra, 2001; Aplin, 2004; Jiménez-Muñoz et al., 2015, 2016; Mildrexler et al., 2016). Some of the surface parameters derived from the extended use of remote sensing in forests include the *Normalized Difference Vegetation Index* (NDVI), *Land Surface Temperature* (LST), *Leaf Area Index* (LAI) and the *Enhanced Vegetation Index* (EVI), which are associated with the processes of water and energy flow in the soil, vegetational change, atmosphere (Julien and Sobrino, 2009; Julien et al., 2011; Li et al., 2013) and other climatic variables such as precipitation. Of the most widely used platforms, the Moderate Resolution Imaging Spectroradiometer (MODIS) and the Advanced Very High Resolution Radiometer (AVHRR) feature a historical series of over 15 years of data at daily time resolution repetitions (Huete et al., 2002; Houborg et al., 2007; Hmimina et al., 2013; Sobrino and Julien, 2013) and QuikSCAT and its follow-up mission (RapidSCAT, Frolking et al., 2006; Lu et al., 2013), which can be compared with data from climate grids. For example, in the case of the Amazon, similar surface thermal patterns between MODIS and the global atmospheric reanalysis provided by ERA-interim products has been demonstrated (Jiménez-Muñoz et al., 2013, 2015).

In the current context of global change, variations in pattern and magnitude of precipitation and warmer scenarios, it is necessary to analyze recent changes in surface temperature driven by climatological variables in contrast to vegetation changes evidenced by losses in greenness or triggered by drought. We spect the behavior of key variables has a similar behavior of shows at regional scale in similar forest around the world, where in New Zealand forest have been demonstrated increasing temperature, las precipitaciones han variado tendientes a la disminución (Plummer et al., 1999; Ummenhofer et al., 2009) y la productividad de los bosques han presented un aumento, debido al aumento del NDVI (Fensholt and Proud, 2012). Therefore, the aim of this study is to determine, understand and fill the information gap about the effects of global change on key variables of land surface temperature, NDVI and precipitation over the Chilean Patagonian forests using remote sensing imagery and reanalysis, at region, forest and local scale. This information is relevant due the posible changes in quantity and quality of ecosistemic services of the region being able to serve as an input for oportunities and threats identification in multiple scale and in that way, to manage the uncertainty to mitigate the impacts through the knowledge of how the patterns of disturbance behave in the context of global warming and climate change.

2. Study area

The study area is the region of Aysén, Chile, located between 43° 38′ and 49° 16′ S and around 71 °W latitude until reaching the Pacific Ocean (Fig. 1). The precipitation in this region (Fig. 2 a) presents an abrupt decrease eastward from more than 3500 mm to less than 600 mm in approximately 300 km of distance (Quintanilla and Víctor, 2008; Hepp and Stolpe, 2014). According to the Köppen-Geiger classification, the following climatic regions are present in Aysén: a warm temperate climate with dry and warm summers, warm temperate climates with humid and cold summers, a warm temperate climate with warm and humid summers, and tundra climate (Kottek et al., 2006). In the same region, 4.82 million hectares are covered by native forests dominated by a mixed composition of evergreen. broadleaved and conifer tree species (i.e. North Patagonian forests, 60% of the regional area, Veblen et al., 1983), deciduous forests represented by *Nothofagus pumilio* (mainly monospecific forests, 30% of the regional area), evergreen forests represented by *Nothofagus betuloides* (mainly monospecific forests, 12% of the regional area, Corporación Nacional Forestal (CONAF, 2011). Forests in this region closely follow precipitation gradients described before (Luebert and Pliscoff, 2006).

The geomorphology of the region is characterized by the subsidence of the coastal mountain range, whose emerging fractions give rise to fjord and archipelagos in the area of the regional littoral where the largest coverage of North Patagonian forests is located (Atlas Región de Aysén, 2005; Pantoja et al., 2011). The highest concentration of deciduous forests of *Nothofagus pumilio* is in the eastern sector, which shows a marked and abrupt geomorphology due to last glaciation (Pfeiffer et al., 2010) (Fig. 2b).

Because the importance of understanding the behavior of key variables and the global warming effects over different scales, the study area was analyzed in three nested scales (Fig. 1). The first one considered the entire region of Aysen. In the second, we considered all the forests within the study area (i.e. 4.8 mill ha) to analysis. In the third stage, the perennial forest is separated from a deciduous one to reduce the effect of topographic complexity, to understand the differences in the trends associated with the composition of the forests and to isolate the historical antropogenic impact in those sectors. At this stage, two areas (local scale) were selected: one where evergreen rainforest (5.5 × 4.4 km) predominate in the western area, and another where deciduous forests dominated by *Nothofagus pumilio* (4.3 × 4.9 km) mainly represented in eastern area. Regional distribution of type of forest in Appendix A.

3. Data sets

3.1. MODIS V6 (NDVI, LST) Collection-6

For this work, we derived Land Surface Temperature (LST) from the Collection-6 product of MODIS MOD11C3 have an accuracy better than 1 K (0.5 K in most cases) (Wan, 2014; Nickeson, 2018a, 2018b). We derived NDVI from MODIS MOD13C2, which is the normalized ratio between the reflectance of the near infrared and red bands (Tucker et al., 2005), have an accuracy is now within ± 0.025 (Nickeson, 2018a, 2018b). These products are a key parameter for various physical processes occurring on the surface and are widely used in studies related to climate change and vegetation monitoring (Li et al., 2013). LST is a temperature measurement between the atmosphere-surface interface, as opposed to the air temperature measured under canopy and on the surface. It is related to the physiological activity of the canopy of the forests, while also being responsible for the balance of water, energy and CO_2 at the surface (Sims et al., 2008; Benali et al., 2012; Vlassova et al., 2014). NDVI has been widely used by vegetation and landscape classification, canopy or foliar water stress, insect infestation detection, invasive plant detection, fire fuel mapping, detection and progression mapping of burnt areas, and biomass mapping (Wang et al., 2010). Both products cover the time period 2001 to 2016, with a monthly spatial resolution of 0.05 × 0.05 ° (5.6 km x 5.6 km, Huete et al., 2002; Solano et al., 2010; Wan, 2013).

3.2. Precipitation Dataset

For this study, we used two rainfall databases at different spatial resolution. The first provided by Multi-Source Weighted-Ensemble Precipitation (MSWEP), which covers the period 1979–2015 with a temporal and spatial resolution of every 3 h and 0.5° respectively. MSWEP uses a weighted average between the precipitation anomalies of seven databases based on "interpolation of gauge observations" (CPC

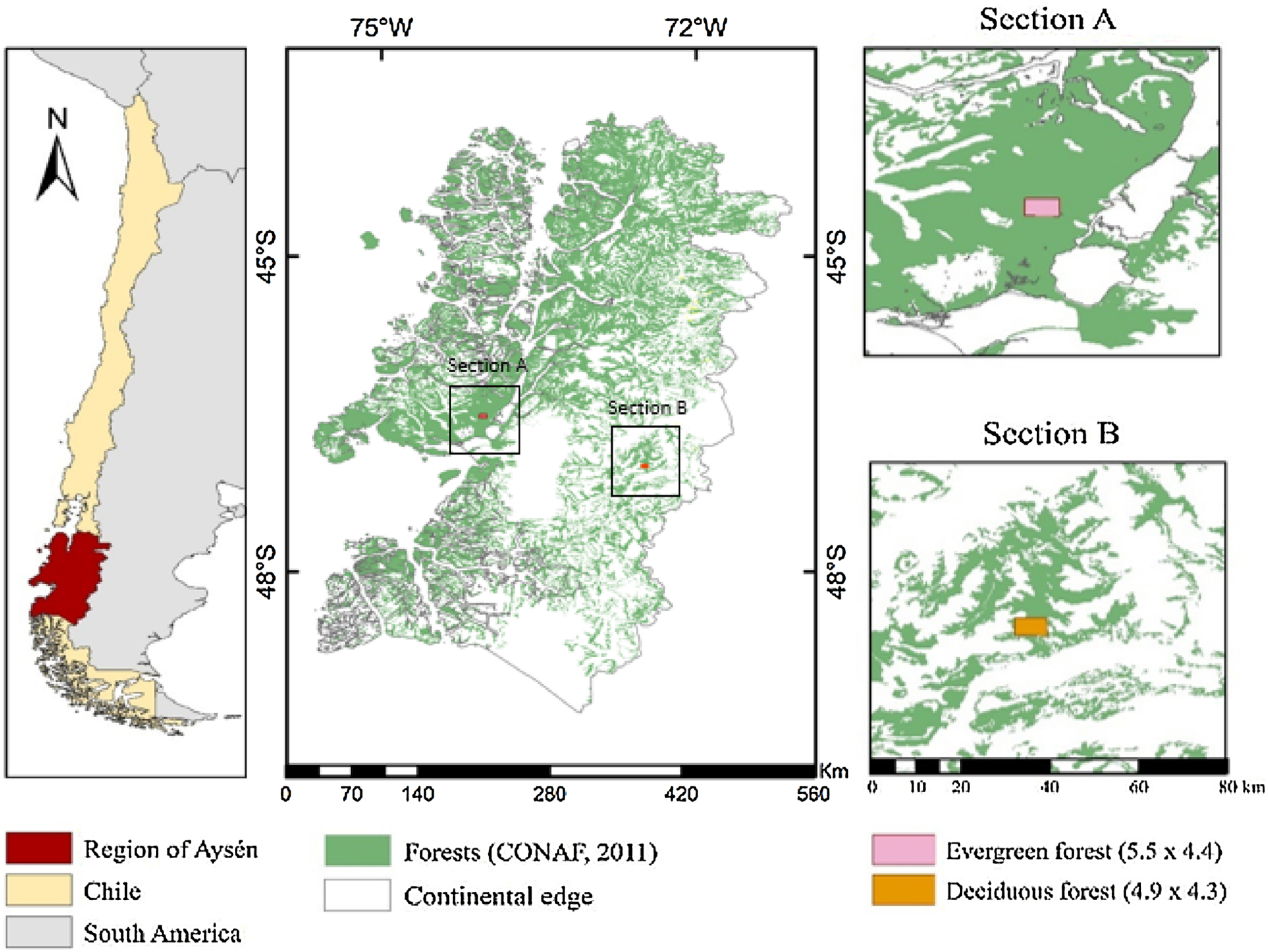

Fig. 1. Nested scales of analysis in the study area: Region of Aysén (left), forest cover at regional level (center), and the local area of evergreen forest (section A) and deciduous forest (section B) (right pannel).

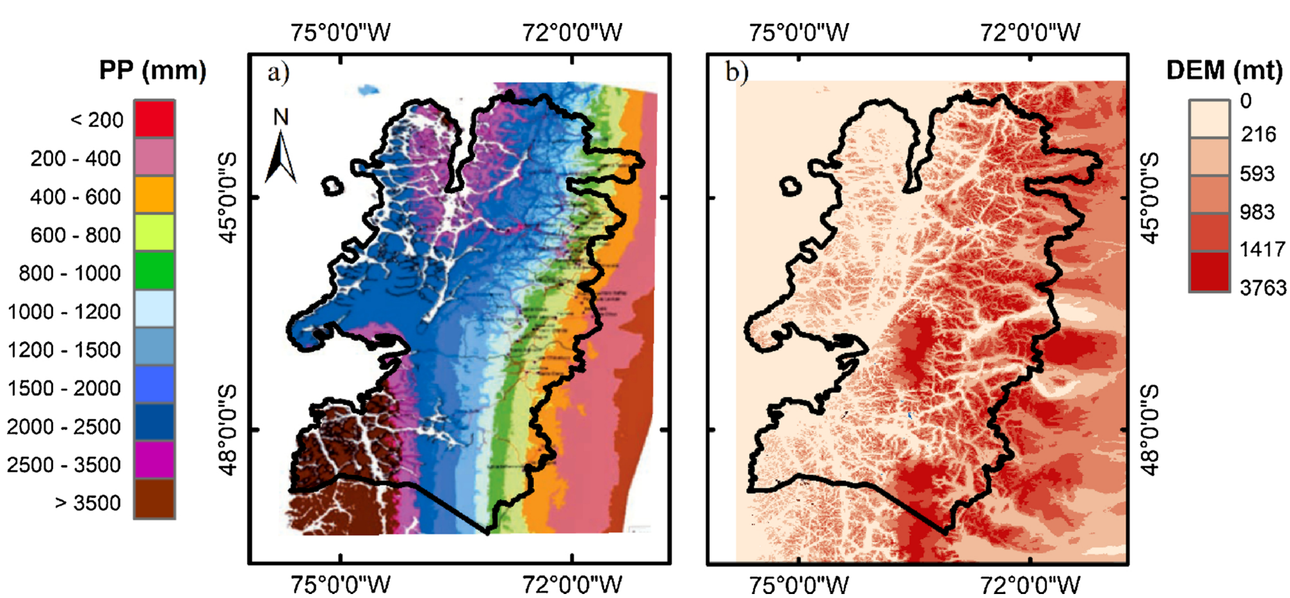

Fig. 2. Annual mean precipitation distribution (a) (Hepp and Stolpe, 2014) and Digital elevation model (DEM) variations from SRTM.

Unified and GPCC), on satellite remote sensing (CMORPH, GSMaP-MVK, and TMPA 3B42RT), and on atmospheric reanalysis models (ERA-Interim and JRA-55), obtained the highest daily correlation coefficient (R) among others P datasets (GPCP1DD, WFDEI-CRU, TMPA 3B42, and CPC Unified) for 60.0% of the stations and a median R of 0.67 vs. 0.44–0.59 for the other datasets (Beck et al., 2017). The second rainfall data comes from multiple satellites and was provided by the Tropical Rainfall Measuring Mission (TRMM) Multi-Satellite Precipitation Analysis (TMPA), developed by the National Aeronautics and Space Administration (NASA) Goddard Space Flight Center (GSFC), at spatial and temporal fine scales of 0.25° × 0.25° and every 3 h, above 50 °N-50 °S covering a period from 1998 to the present in version 7, with practically no bias (0.04%) and a relatively higher correlation coefficient value 0.41 at single grid cel scale (Xue et al., 2013).

4. Method

To analyze the pixel by pixel behavior of NDVI, LST and the rainfall over the regional forest cover, we calculated the average monthly and annual anomalies using the difference of each pixel and the average of time series (2001-2016) for each pixel available in the study area (Eq. (1), Muster et al., 2015):

$$xa_i = (x_i - \bar{x}) \tag{1}$$

where xa_i is the anomaly for each pixel, x_i is the value of the products obtained from MODIS and Precipitation, and $\bar{x}$ is the average value of the pixel obtained from the time series. To extract the value of the three scales was masking the datas with the corresponding area in those levels. We used the Pearson Test to estimate the degree of correlation between the studied variables. We estimated the slopes of each pixel for NDVI, LST and precipitation using the non-parametric Kendall (1975) with a significance level of 0.05. The magnitude of the slope was estimated using the Sen's slope method (Sen, 1968) through an analysis of the monthly mean of NDVI, LST and precipitation:

$$t = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sign(xj - xi) \tag{2}$$

Where x is the average of the trend, $sign(x)$extracts the sign of the expression according to Eq. (3):

$$sign(x) = \begin{cases} 1\, x > 0 \\ 0\, x = 0 \\ -1\, x < 0 \end{cases} \tag{3}$$

If the t statistic is calculated with more than 10 data, it has an approximate normal distribution. After than, the Mann-Kendall z statistic was calculated, which is a function of t and its variance (*var* in Eq. (4)):

$$var(t) = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{q=1}^{g} tq(tq-1)(2tq+5) \right] \tag{4}$$

To calculate the Mann-Kendall z-statistic, Eq. (5) was used.

$$z = \begin{cases} \frac{t-1}{\sqrt{var(t)}}\, t > 0 \\ 0\, t = 0 \\ \frac{t+1}{\sqrt{var(t)}}\, t < 0 \end{cases} \tag{5}$$

This test has a level of significance of p-level < 0.05.

To visualize the behavior of the variables in the space, maps associated with the trends and anomalies in the study region will be drawn up.

5. Results and analysis

5.1. NDVI, LST, and precipitation spatio-temporal trends

At regional scale, we found a significant trend in monthly mean NDVI ($p < 0.05$) (Fig. 3), with an average slope of 0.01 ± 0.02 per decade for areas covered by forest (forest scale). Positive slopes (0 to 0.05 units per decade) predominated in the western zone, while the eastern zone showed negative values between 0 and -0.05 per decade ($p < 0.05$).

The monthly mean and daytime and nighttime trends in LST increased with magnitudes ranging from 0.78 ± 0.21 K, 0.74 ± 0.28 K and 0.82 ± 0.24 K per decade over forest, respectively (Fig. 4 a, b, c). The exceptions were the areas south of 46 °S in the eastern part of the region for the trends in both monthly mean and the monthly daytime mean ranging from 0.5 K to 2 K. Negative (cooling) trends located south of 46 °S were not statistically significant.

A decreasing trend in precipitation at north of 46 °S and in the eastern sector for both sets of data (Fig. 5 a, b) was found, where the lowest rate is between -6.5 to -4.5 mm and between -36 to −20 mm per decade according to MSWEP and TRMM v7, respectively. Regarding precipitation rates over the forest cover, the values of MSWEP were -3.0 ± 1.7 mm per decade, while the satellite values provided by TRMM v7 were -12.5 ± 8.2 mm per decade.

Those trends are in congruence with the variables evaluated in similar forest of New Zealand, where the temperature show increasing trend, NDVI preset increasing trend in the western part and decrasing in the eastern while precipitation trend is deacreasing (Plummer et al., 1999; Ummenhofer et al., 2009; Fensholt and Proud, 2012)

5.2. NDVI, LST and precipitation anomalies

At regional scale, annual anomalies of NDVI increased notoriously between 2001–2004 and 2013–2016 (Fig. 6). This mainly occurred in the eastern zone where there is a greater concentration of deciduous forest, with values reaching a maximum of 0.3 in the year 2016. In the western zone, there were no abrupt variations in NDVI annual anomaly, although there was a steady increase (greening) over the final five years of the study period (2012–2016). We found two contrasting years (2005 and 2009) with a spatial minimum in observed NDVI.

Annual LST anomalies at the same scale during warmest years (2004, 2008, 2013 and 2016) had a positive anomaly of 0.5 to 2.5 K (Fig. 7). In addition, from 2011 a period with particularly warm anomalies was detected in comparison to previous periods (2001–2004 and 2005–2008), when negative anomalies were more frequent and widespread.

Although the period might not necessarily be a climatologically significant sample due to the period of 16 years of analysis, nevertheless the results reflect the trend at reginal, forest and local scale, showing a short warming trend. In this data, the significance of LST data can be found throughout the eastern and southwestern regions, which had the highest rate of temperature increase (K per decade, Fig. 7). In contrast, the NDVI trends showed a greater significance in the western area, which coincides with areas of positive rates of greenness (Fig. 2). However, it is not possible to delve further into the impact at ecosystem level from variations in NDVI because it may also imply discrepancies with forest growth due to the diversity in the growth conditions local and regional level (Vicente-Serrano et al., 2016). Despite this, our research is the first report of changes over large areas of forests in Chilean Patagonia in response to global warming.

For both databases of precipitation, the years showing a strong

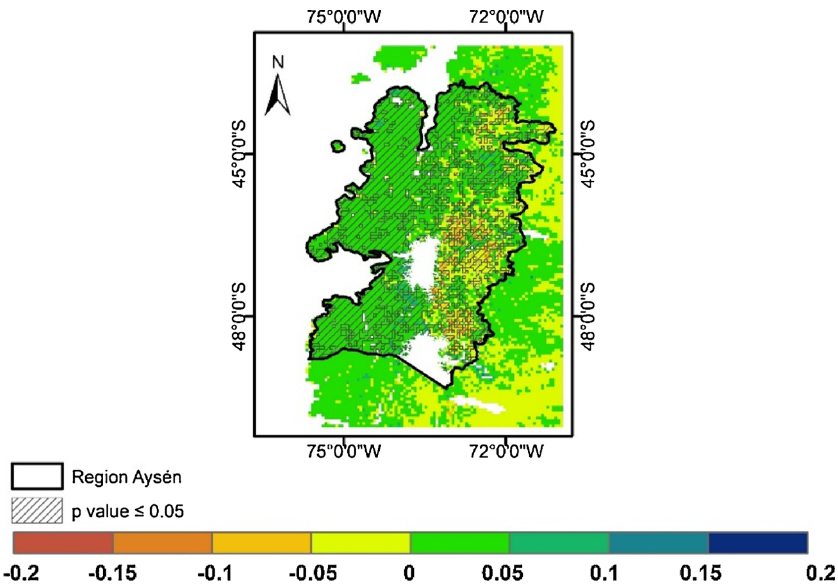

Fig. 3. Trends (i.e. decadal mean slopes) in monthly mean NDVI (5.6 × 5.6 km) in Chilean Patagonia between 2001–2016.

decrease in rainfall at the regional level correspond to 2005, 2007 and 2016 with a deficit of -50 and −30 mm for MSWEP and TRMM, respectively (Fig. 8). This drop increases in area and magnitude in 2004, while for 2007 there is a notable decrease in precipitation (< −30 mm) at the regional level, continuing until 2008 but with less intensity. From 2011–2013, there was a gradual decrease until the anomalies were greater than −10 mm in 2013. In the case of TRMM in the first six years of the series, the eastern sector showed positive anomalies though since 2010 the anomalies were negative. In contrast, the MSWEP database in the first six years does not show a clear spatial trend, though since 2010 there was a decrease in anomalies at regional level.

At forest scale, the monthly mean anomalies in NDVI (Fig. 9) show a slightly positive but non-significant trend ($p > 0.05$). We found three periods marked by the maximum and minimum magnitudes in the NDVI series. A first period (2000–2004) when the maximum values of NDVI anomalies were present. A second period (2005–2011) when minimum anomalies in NDVI and a decrease in the maximum values predominates. A third period (2012–2015) in which the minimum values in NDVI anomalies increased. A possible change due to the increase in the minimum values of the NDVI anomaly can be occurring since 2016. We also observed a two-year period of positive anomalies (from mid-2014) until an unusual increase in NDVI in 2016, yielding the highest values in the time series under analysis.

The temperature anomalies in forest scales had its greatest

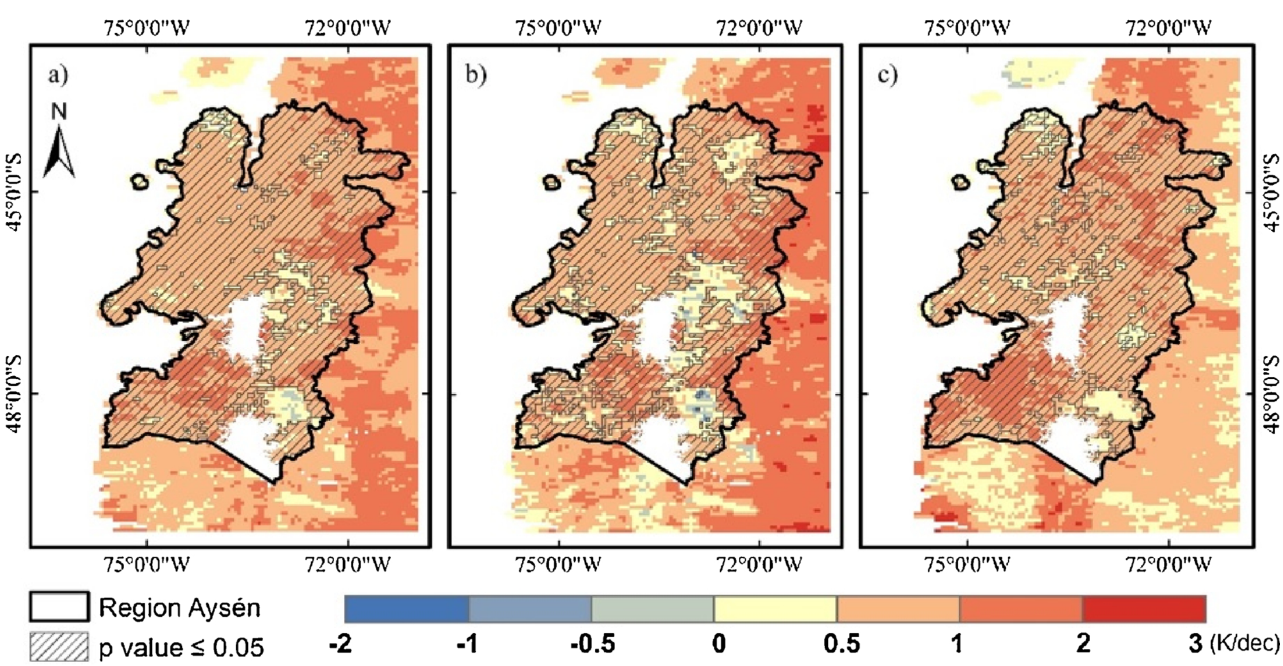

Fig. 4. Trends (i.e. decadal mean slopes) in mean (a), day (b) and night (c) land surface temperature (5.6 × 5.6 km) in chilean Patagonia between 2001–2016. Dashed lines correspond to statistical significance level ($p < 0.05$). Northern and Southern Patagonia ice fields are shown in white.

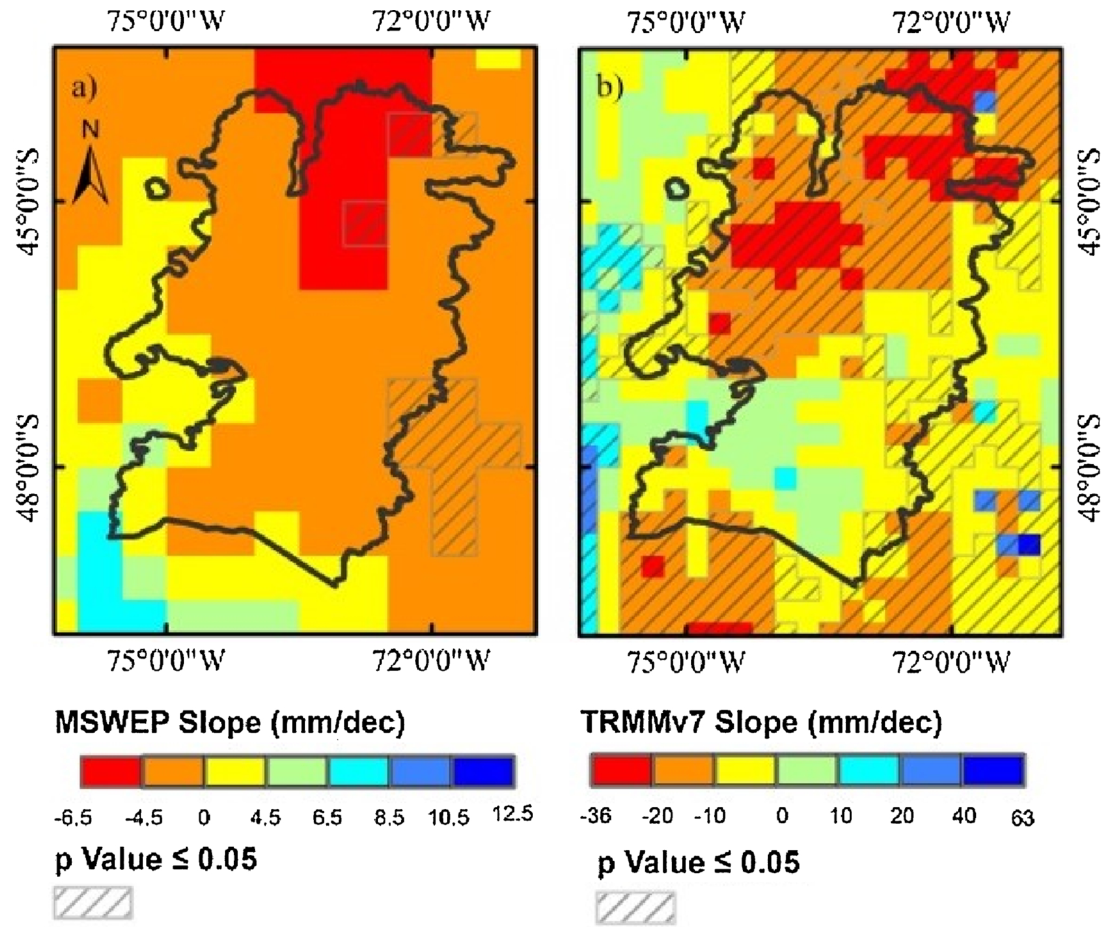

Fig. 5. Trends in precipitation (i.e. decade mean slopes) in Chilean Patagonia, from (a) data base MSWEP (0.5°x0.5°) (from 1979 to 2016) and (b) TRMM V7 (0.25°x0.25°) (from 1998 to 2016).

magnitude (+6 K) in 2008 (December), whereas the lowest (-5.5 K) occurred in early 2001 (Fig. 10). In 2004, 2011 and 2013 ocurred a temperature increase, with values exceeding 4 K between December and February. The months with more abrupt increases were December and January. LST anomalies were mainly positive in the final three years of the study period (Fig. 10), with an increase in minimum values and with 2016 notably as the warmest year during the entire period.

The series of mean yearly, maximum and minimum NDVI anomalies for forest scale between 2001 and 2016 showed fluctuating variability between -0.15 and 0.1 (Fig. 11). In addition, a slight increase in the variation of annual NDVI minimum values can be seen in the final years of the study period (2010–2015). In the case of maximum values, there was a decrease in 2006 and 2009, possibly associated with insect defoliation (Mazia et al., 2012; Piper et al., 2015) and later in 2012 and 2015. However, unlike temperature, the NDVI was stable and non-significant ($p > 0.05$) in the final 5 years.

For other hand, at local scale, the values of monthly mean maximum and minimum anomalies of NDVI (Fig. 11) in the area with deciduous forest, it showed a greater amplitude than did the evergreen forest, with maximum values occurring in the years 2003, 2007, 2012 and 2016; while the minimum anomalies occurred in 2005, 2009, 2010 and 2014 with approximate values of -0.3, -0.35, -0.35 and -0.3, respectively, in both cases (maximum and minimum for deciduous forests) exceeding the standard deviation of the annual maximum and minimum anomalies at forest scales which suggests a greater influence of the insitu conditions, and can not be extrapolated from regional scales or at the forest level, but also it could be related to historical use that has been given to the eastern section dating back to the 19th century, with the colonization of these lands and the practices of thinning forests using fire, affecting approximately 3 million hectares, changing forests into meadowlands, schrubland and agricultural use (Bizama et al., 2011). Such unsustainable practices could generate local warming as has been suggested by Li et al. (2015), thus furthering the rapid degradation of forests.

For the other hand, the low variability in NDVI anomalies in the western zone, and local scale of evergreen forest could be due to the greater influence of the ocean (Allen et al., 2015; Held and Soden, 2006), accompanied by conservation goals of large national parks such as the San Rafael Lagoon and the Katalalixar National Reserve, along with its geographical inaccessibility.

We found a similar behavior between the maximum anomalies of temperature between local and forests scales, with similar magnitudes for the year 2008, unlike in 2004, 2011 and 2013 (Fig. 12). In addition, the maximum values of the evergreen forests showed years below the standard deviation. We also detected maximum and minimum over deciduous and evergreen forests, and positive trends, with the period from 2009 to 2013 showing a 4 K increase in maximum anomalies. In the case of minimum trends, we found a significant increase estimated at 3 K between 2010 and 2016. These results are in line with Mao et al. (2017) analysis at global scale of temperatures measured by the MODIS sensor. This is also consistent with studies prior to 2000, which documented an increase in minimum temperatures (Vose et al., 2005)

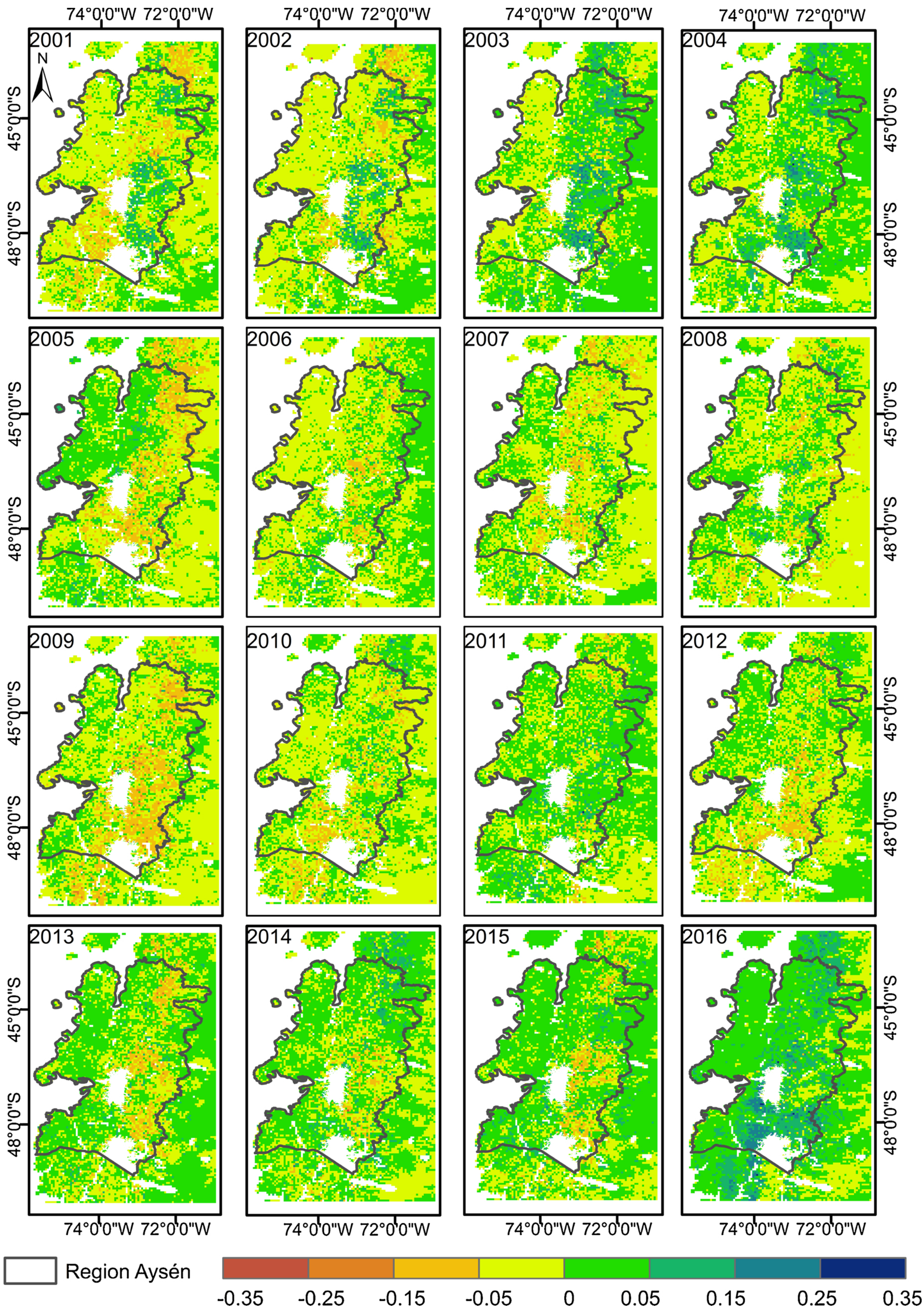

Fig. 6. Annual mean anomaly of NDVI (5.6 × 5.6 km) between 2001–2015 in Chilean Patagonia.

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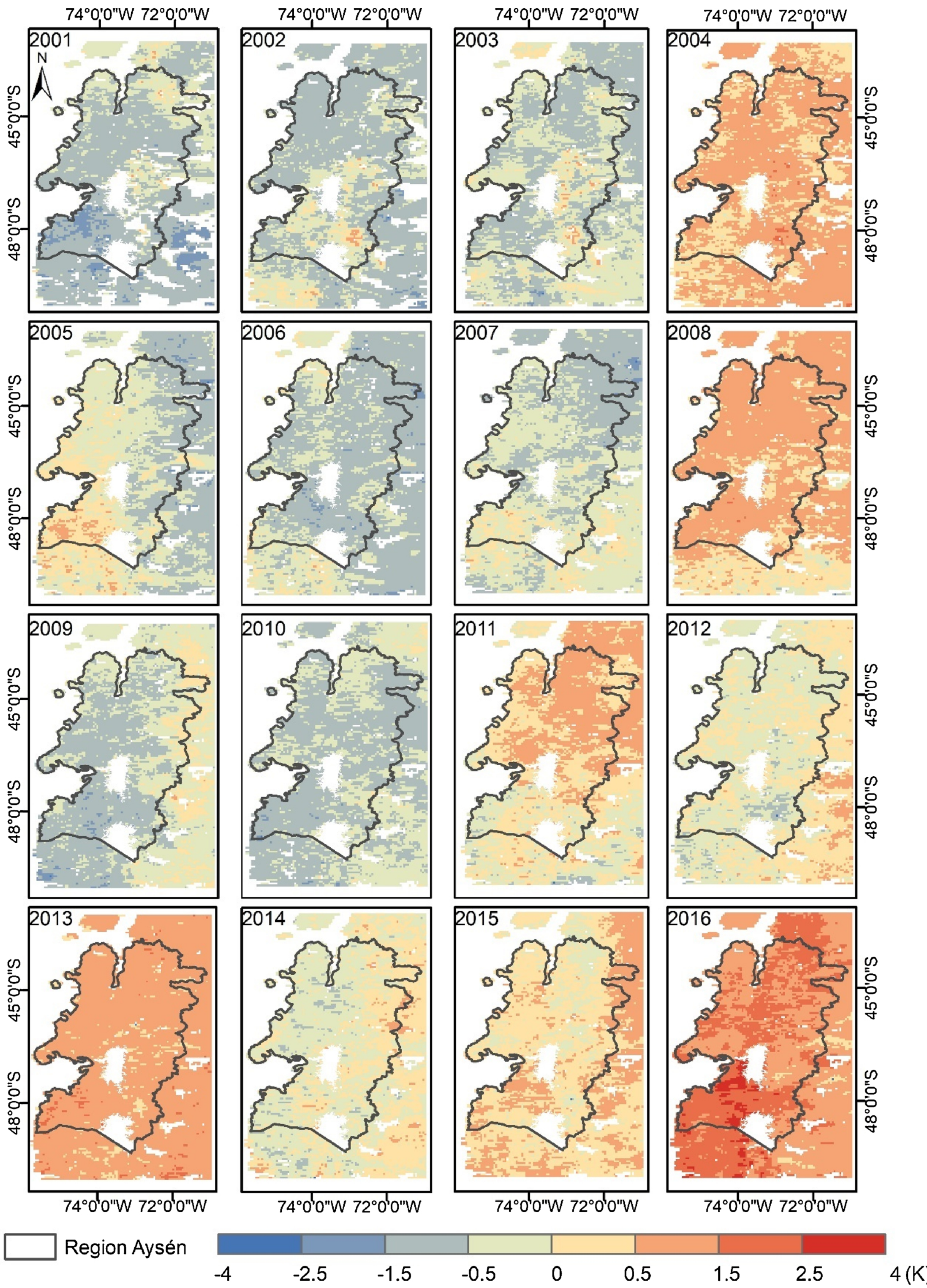

Fig. 7. Annual mean anomaly of land surface temperature (5.6 × 5.6 km) for the period 2001–2016 in the Chilean Patagonia. North and Shouthern Patagonia icefields are shown in white.

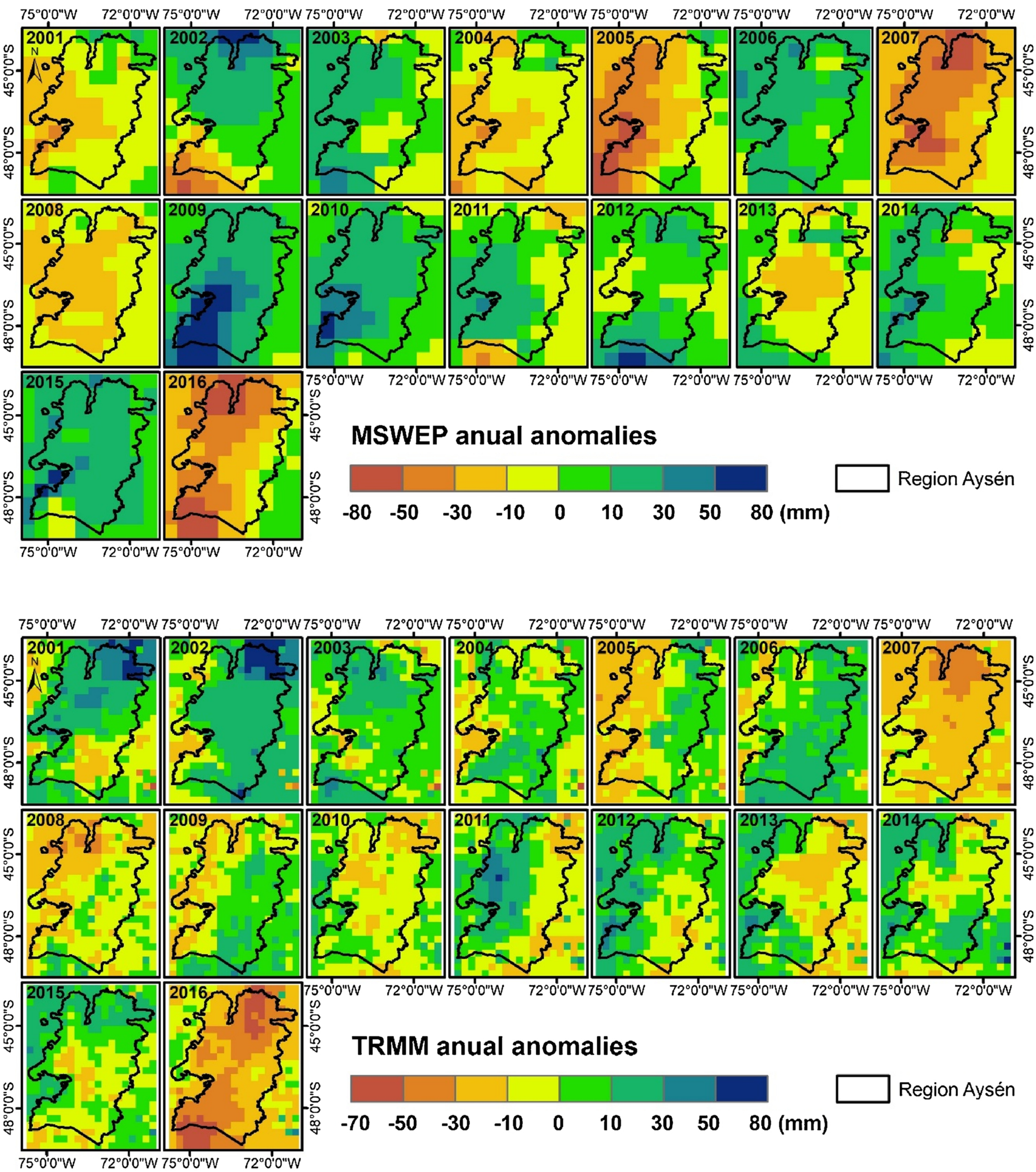

Fig. 8. Annual mean anomaly precipitation for the time 2001–2016 in Chilean Patagonia. Upper and lower maps correspond to MSWEP (0.5°x0.5°) and TRMM (0.25°x 0.25°) data base respectively.

similar to those observed in this work.

This increase in minimum temperatures might restrict the treeline, which is controlled physiologically by low temperatures (Grace et al., 2002; Fajardo and Piper, 2014). However, in this direction Srur et al. (2018) have demonstrated the sensitivity of the upper tree line and the expansion on the Argentine side of the Nothofagus pumilio forest between 5–10 meters by the increase in temperature, which facilitates tree recruitment, and its interaction with the variation of precipitation. However, this process at the local level can be affected by other in situ factors such as soil type, exposure among others. In the same way, rising minimum temperatures would impact degree-days thus heightening the proliferation of insect plagues (e.g. *Ormiscodes* spp.). Our

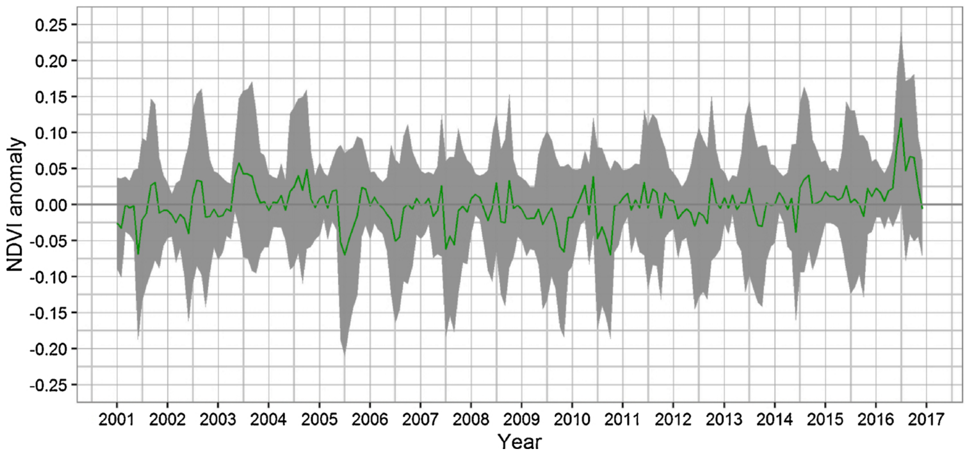

Fig. 9. Monthly mean NDVI anomalies (solid line) for March 2001 to December 2016. Grey area indicates the standard deviation.

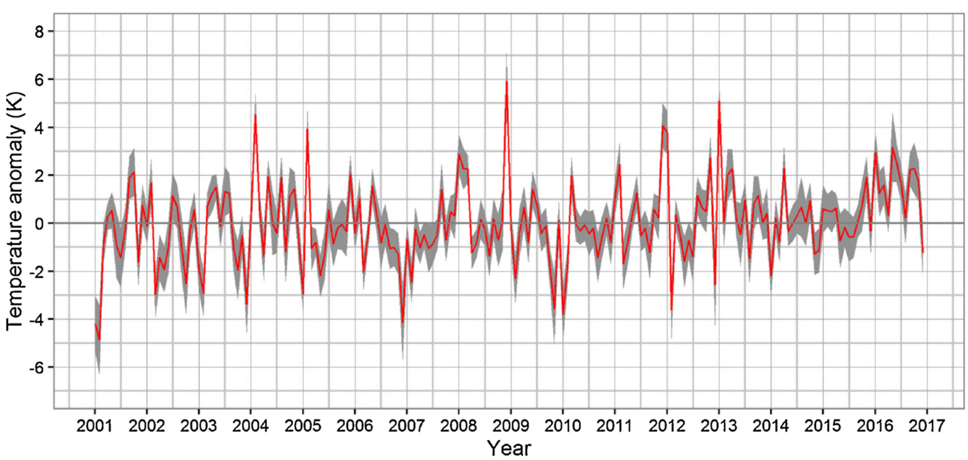

Fig. 10. Annual NDVI anomalies for maximum values and standard deviation (Amax&SD), mean value and standard deviation (Amean&SD), minimum values (Amin&SD), evergreen forest maximum and minimum values (Egmax and Egmin respectively) and deciduous forest maximum and minimum values (Dmax and Dmin respectively).

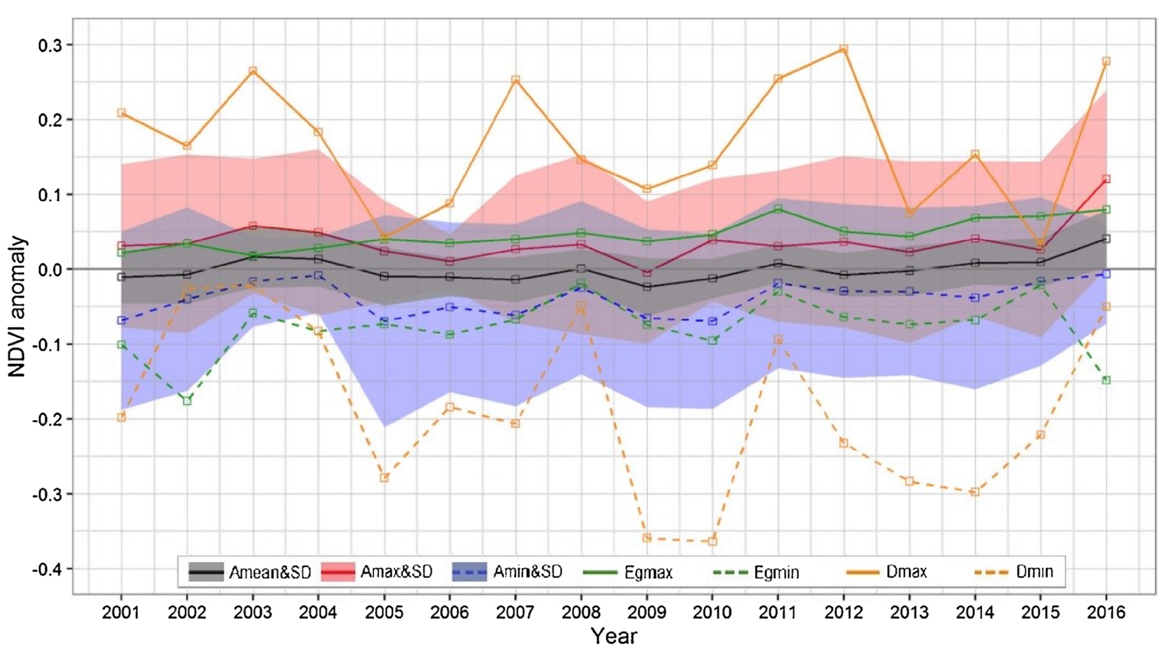

Fig. 11. Annual NDVI anomalies for maximum values and standard deviation (Amax&SD), mean value and standard deviation (Amean&SD), minimum values (Amin&SD), evergreen forest maximum and minimum values (Egmax and Egmin respectively) and deciduous forest maximum and minimum values (Dmax and Dmin respectively).

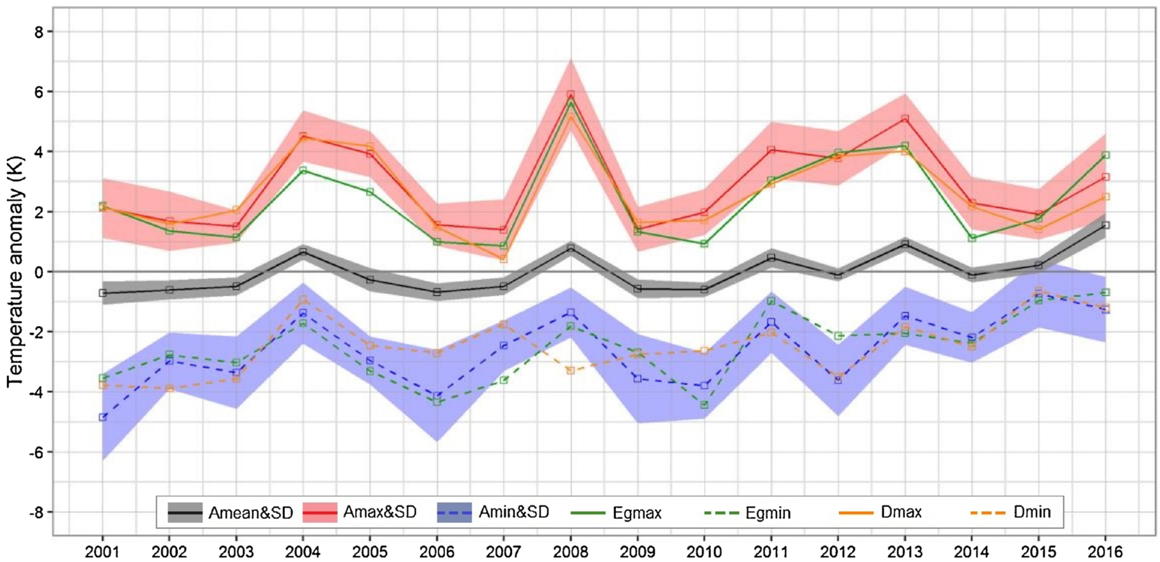

Fig. 12. Annual LST anomalies between 2001 and 2016 in Chilean Patagonia at different spatial scales and forest types. At regional scale, maximum values and standard deviation (Amax&SD), mean value and standard deviation (Amean&SD), minimum values (Amin&SD) are shown. At local scale, evergreen forest maximum and minimum values (Egmax and Egmin respectively) and deciduous forest maximum and minimum values (Dmax and Dmin respectively) are shown.

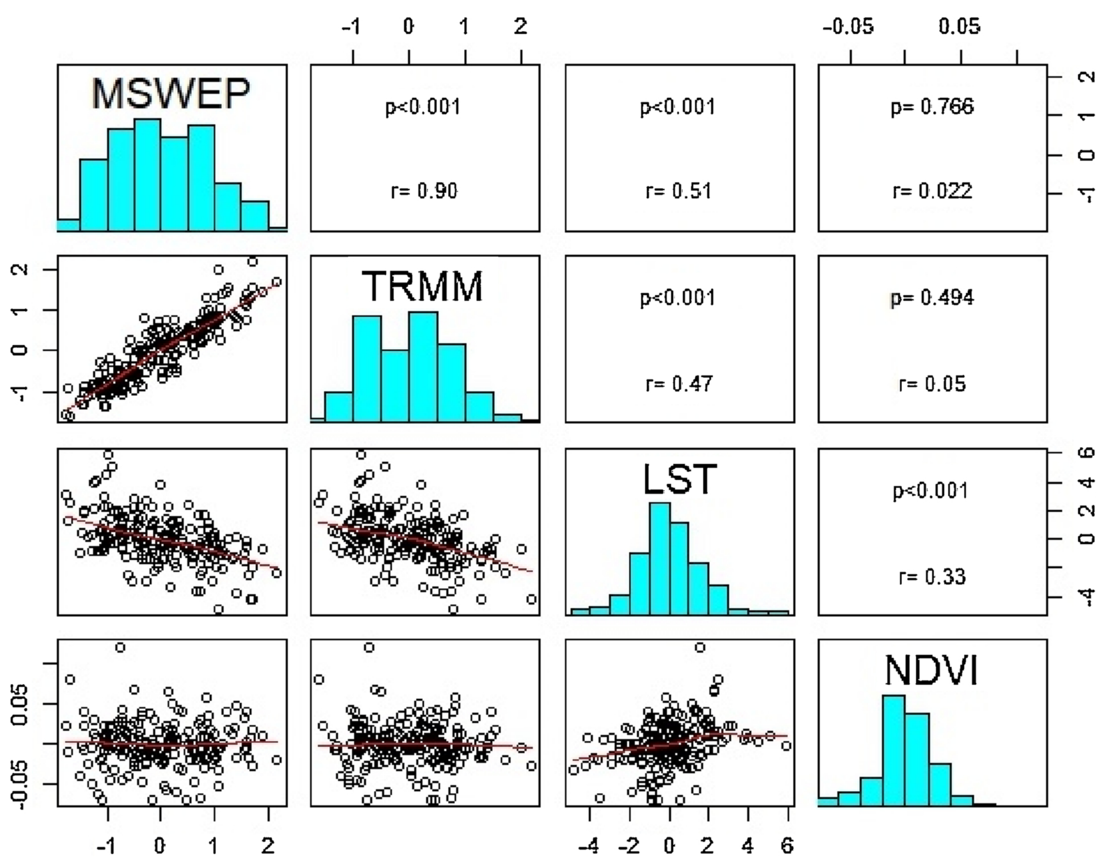

Fig. 13. Matrix correlation between MSWEP, TRMM, LST and NDVI variables.

results support the idea that this increase in temperatures coupled with anthropic pressure (Bizama et al., 2011) and climate factors such as precipitation might increase the vulnerability of Patagonian forests, mainly in its eastern part to ongoing global warming.

5.3. Correlation test

The MSWEP and TRMM databases presented a high degree of positive correlation (Fig. 13) with statistical significance (r = 0.90,

$p < 0.001$), while the correlation of the precipitacicon with LST was negative, approximately 0.49 ($p < 0.001$). On the other hand, NDVI correlated with LST positively with $r = 0.33$, while it had a low correlation with precipitation ($r < 0.1$, with no statistical significance).

A positive trend has been demonstrated in the Southern Annular Mode and ENSO generating a reduction on precipitation by 10 a 20% during strong El Niño events (SOI < -1.5) (Schneider and Gies, 2004). This evidence is supported by the results of precipitation for the period 2015–2016 presenting a strong decrease, being 2015/16 El Niño among the three strongest El Niño event since 1979 (Xue and Kumar, 2017; Jacox et al., 2016). This climatic variaibility can affect the vulnerability of Aysén forests, at multiple scale, to extreme climatic events together with potential increased fires probability, drought, insect outbreaks, among other contributing factors (Veblen et al., 2011; Álvarez et al., 2015).

The forests of Chilean Patagonia belong to a group of subantarctic forest with diverse characteristics that act as an important carbon sink (Pan et al., 2011). A temperature increase in these forests could produce spring seasonality that starts earlier and more temperate, as well as later autumns that may boost carbon absorption while extreme frost events in spring or droughts have the opposite effect, leading to decreased carbon absorption (Piper et al., 2013; Keenan et al., 2014). However, this behaviour has not been proven to be the case for Aysén forests. Our study might aid in bearing evidence of certain tendencies over forests that might impact its health. In fact, the results suggest that the eastern zone of Aysen, which is mainly covered by deciduous forests (e.g. *Nothofagus pumilio*), was affected by the warming as suggested by the increase of thermal anomalies (Fig. 8). This trend in surface temperature can be explained by reduction in forest cover towards the east, where shrulands and steppe starts to predominate following the decrease in rainfall, thus reducing the cooling effect of forests (Li et al., 2015). Futhermore, the rainfall gradient (i,e, eastward reduction) plus the negative trend detected (Fig. 10) may disminish the evapotraspiration cooling in the eastern zone (Bréda et al., 2006).

In this type of ecosistem, the management practices historically often have been unsustainable in terms of maintaining forest ecosystem structure and function, where Agricultural and settlement activities have modifie to cober an richeness of native spicies (associated to crops and livestock mainly) and alteration of natural water drainage (Currie and Bergen, 2008; Gilliam, 2016). In this direction, decrasing precipitation could be affect, the economy and lifestyle of the region because the region has agricultural livestock producers, where subsistence agriculture for instance, would be more affected by the reduction of flows. (Delgado et al., 2015)

Two years of notable warming (2004 and 2008) accompanied by drops in NDVI (2005 and 2009) were detected in this paper. This drop in NDVI and its relationship with the increase in temperatures is consistent with previous studies that have shown a significant increase in insect defoliation (Adams et al., 2012; Edburg et al., 2012). One example is the case of the insect *Ormiscodes amphimone*, which is estimated to have affected thousands of hectares of *Nothofagus pumilio* in 2009 (following the 2008 warming) in the Aysén region (Bale et al., 2002; Garibaldi et al., 2011; Mazia et al., 2012; Piper et al., 2015). However, droughts, declining rainfall, and extreme weather events (Aravena and Luckman, 2009; Veblen et al., 2011; Quintana and Aceituno, 2012) may also be contributing factors leading to declines in foliage cover and greenness at regional scales in Chilean patagonia, where the actions of insects might be one of the factors (among others, e.g. pathogens, deforestation) contributing to, or accelerating, the drop in vigorousness of these forests (Paritsis et al., 2012; Gaylord et al., 2013; Rodríguez-Catón et al., 2016).

A regional increase in LST areas that also showing decreased precipitation and NDVI minimums (e.g. the eastern area) due to the phenology associated with seasonality or defoliation could increase the probability of fire, potentially causing a positive feedback in LST in the future. The latter could be explained by the higher incidence of solar irradiance as well as a decrease in the moisture content of vegetation and soil (Carlson et al., 1994; Lavergne et al., 2015; James et al., 2016).

Previous studies demostrated the robustness of NDVI values delivered by MODIS in humid areas as compared to other sensors (Tian et al., 2015). In addition, analyses similar to those performed in this work using MODIS NDVI and LST in areas of equal cloud cover (e.g. the Amazons) have returned robust results with regard to warming, drought, loss of vigorousness and even decrease in biomass (van Leeuwen et al., 2011; Samanta et al., 2012; Jiménez-Muñoz et al., 2013, 2015; Jiménez-Muñoz et al., 2016)

The results presented in this paper can be complemented with the use of additional databases delivered by other remote sensors with more data recording, as in the case of AVHRR GIMMS (Fensholt et al., 2009; Fensholt and Proud, 2012; Beck et al., 2011) or QuickSCAT. This latter sensor uses principles of microwave scaterometry and allows for the measurement of forest canopy, thus avoiding the atmospheric effect and clouds. Through this technique, tree canopies were observed and possible impacts on the foliar structure of the forest were determined, as has been shown in previous studies on tropical forests (Saatchi et al., 2013; Zhou et al., 2014).

6. Conclusions

In a context where the global temperature tends to warmig, we focused on estimating the variations in vigorousness, temperature and precipitation at different scale of the Aysén, resulting an increasing in temperature by 0.78 K per decade at while the trend was increase in NDVI was a 0.01 per decade with higher statistical significance in the western zone of the forests, whereas in the eastern zone there was a noticeable decrease while precipitation in the eastern zone decreased. This trend present similar behavior to another similar forest (New Zealand). Also, LST-Precipitation correlated negatively but LST-NDVI correlated positively. The forests showed changing NDVI patterns possibly attributable to this warming (peaks temperature). At local level, the deciduous forest showed a significant amplitude in NDVI, with the minimum temperatures increasing dramatically of almost 4 K in 16 years, which suggest these forests are more vulnerable to global warming and also to antropic activities. The results obtained from this research are of great importance for understanding the extent to which the most densely forested region of southern South America, and the one that concentrates the greater surface area of subantarctic forest in the southern hemisphere, help to visualize patterns of behavior of the key variables, offering a temporal and spatial perspective of the disturbances associated to fisical and biological factor (for instance warming and proliferation of defoliating insects) being useful for the creation of adaptive management policies associated to increase the resilience to the climatic camabio. Nevertheless, it is requiring more insitu data both ecological and meteorological in all the extent of the region, in order to improve the understanding of the effects of global warming al multiple scales.

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Appendix A

Fig. A1

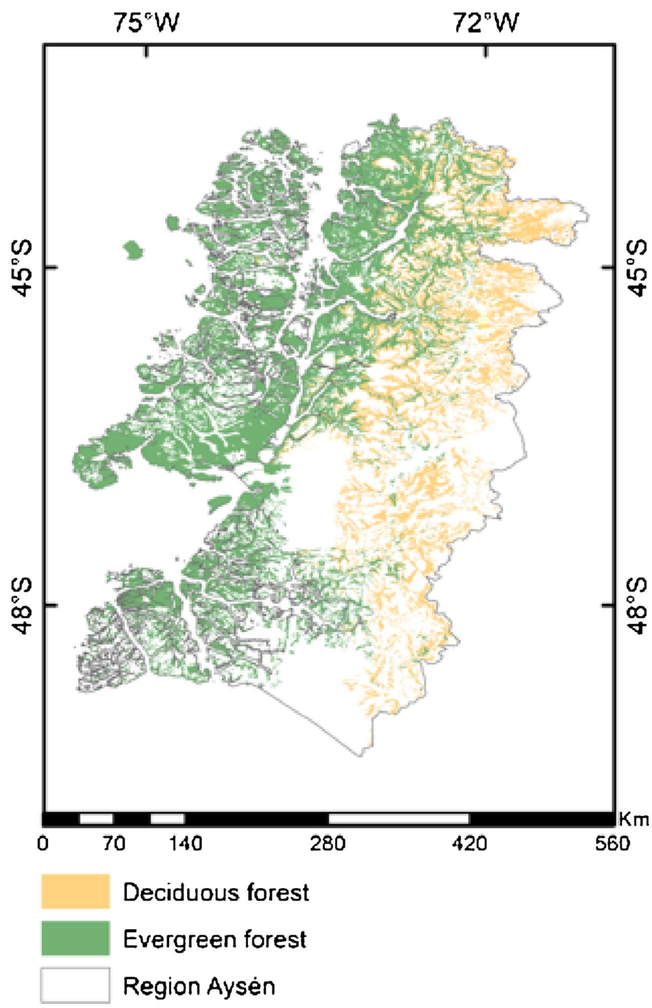

Fig. A1. Regional distribution of type of forest y Region os Aysén.

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