Trends of the Drought Indices in Southern Hemisphere Subtropical Regions

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***Abstract*- With the use of droughts indexes on Subtropical South Hemisphere, we have detected: a) statistically stationary conditions on average during the period 1880-1980 and b) an important positive tendency to droughts between 1980-2013.**

This recent tendency to regional droughts is coincident with the actual processes of Global Warming. The hypothesis of an acceleration of the Hadley Circulation (HC) is present with global warming, which would reduce precipitation in subtropical arid-semi arid zone and increase rainfall in the Intertropical Convergence. This process was confirmed by the precipitation data of Reanalysis I, with an inverse correlation between the two regions.

These droughts indexes also show the more presence of an interdecadal variability signal (PDO) and El Niño/South Oscillation (ENSO) at low and high frequencies.

Most of the variances in these regions have been explained by long climate changes. ENSO high frequency changes are present and they behaved in an inverse way as expected between both South Pacific Ocean coasts. When the group was analyzed as a subtropical anticyclone band or regional in Chile, Australia and South of Africa, it did not disturb the large-scale signs that are highlighted in this study.

Keywords*- *Trends; Droughts Index; Subtropical South Hemisphere

I. INTRODUCTION

The most important atmospheric circulation of the planet is the Hadley direct thermodynamic (HC), which covers approximately 60% of the earth's surface. The world largest population gathers there, as well as the main economic activity, especially on the polar zone of the subtropical anticyclones that include USA, Europe-Russia, Canada, Australia and Argentina-Brazil [1]. These regions have been affected by severe droughts in the last decade. They were: Argentina-Brazil 2008 [2], Russia, 2010 [3], USA-2012 [4] and Australia 1997-2009 [5]. This Hadley circulation (HC) and its variability are of importance to the global climate [6].

The main factors associated with this HC are: a) The Inter-Tropical Convergence Zone - ITCZ, b) the subsiding circulations on the Sub-Tropical North and South Hemisphere, c) the surface circulations (trade winds) and d) height circulation (against trade winds). In the past, researchers have specially emphasized the latitudinal change of ITCZ and expansion Sub-tropical anticyclone as a process of change in global warming [5, 7-18]. HC intensification/weakening, in turn, would be associated with the precipitation growth/weakening in the ITCZ and weakening/growth of precipitation in the subtropical band.

The last one might contribute to the increasing drought frequencies in low-mid latitudes of both hemispheres [19]. Using long wave emergent radiation information, Chen et al. [20] suggested that the HC was intensified in the 1990 decade. On the other hand, [9, 19, 21, 22] showed that the HC has been intensified in the last decades with an pole ward expansion. They also pointed out the controversial fact that a large part of climate models showed the opposite effect to the conceptual one when the climate system is forced to Global Warming [23]. It was cautioned too, that an explanation regarding the expansion or displacement towards high latitudes of the subtropical anticyclone position in a Global Warming hypothesis is restrictive for the second half of the 20th century. This is so because the first part of the century had a weak warming of the Earth, therefore the South Pacific anticyclone moved towards low latitudes [12]. This also seems to point out that it would be inadequate to assess the Climate Change (CC) using short series due to the presence of large-scale changes, with disturbances equal or superior to 100 years.

This especial applies for those studies performed with Reanalysis I information series, as in 1948 [24]. In the last decade, drier conditions in the South American Subtropics have been observed (Chile-Argentina) [2], which in turn seem to spread especially over the entire South Hemisphere [25, 26].

Using long pluviometric series of the South Hemisphere arid-semiarid region, the impact produced by global warming will be explored.

II. DATA AND METHODS

Minetti et al. [27] applied a methodology for the elaboration of annual and monthly indexes of droughts. A network of operative pluviometric data from the Meteorological Services of Argentina was used as extensively as possible during the period 1901-2012. The period analyzed in this work corresponds to the subtropical South Hemisphere, Australia, South of Africa and Chile during 1880-2012. While in Argentina the drought index was estimated with a network of 59 localities, in Chile, South Africa and Australia the rate was estimated with fifteen meteorological stations, amounting to five for each country. Earlier work [28] showed that this number of localities (five) can adequately show the drought index without many errors.

These original data have been controlled so as to detect systematic and random errors with the methodology proposed by [29]. The proposed method for the monthly detection of dry conditions does not need the filling of absent data as long as there is an existence of data of 70% or more of the selected stations.

Due to the seasonal nature of precipitations, annual periods were considered as agricultural years from July of the year “t” to June of the year “t+1” in all regions, with the exception of Central Chile and Comahue (smaller area in neighboring Argentina) with periods from January to December of the same year. The idea to find a precipitation that represents a certain geographical area within the grill has been developed by NOAA-USA with Reanalysis I [30] and used in climate research [24, 31, 32].

This objective was fulfilled when the network of measurements was sufficiently dense as the one of 1900 in Argentina and after 1880 in the Subtropical area.

In order to validate the previously proposed hydric index, the terrestrial network indexes obtained by means of applying the data from Reanalysis I have been correlated.

The proposed indexes for monthly and annual drought (1) (2) first require establishing the median values of monthly precipitations in order to be taken as reference for normal conditions, knowing a priori the biased nature of the probable distributions in most of the cases.

$$MDI = QDL/TQL \tag{1}$$

where

MDI = Monthly Drought Index, with $0 \leq MDI \leq 1$. (MDI x 100 = percentage of dry localities),

QDL = Quantity of dry localities with precipitation lower than its median value.

TQL = Total Quantity of localities.

Annual Drought Index (ADI) (2) is obtained with the addition of the 12 values of the Monthly Drought Index (MDI).

$$ADI = \sum_{1}^{12} MDI \tag{2}$$

Where:

MDI: Monthly Drought Index, ADI: Annual Drought Index, with $0 \leq ADI \leq 12$.

A normal monthly drought condition may be MDI = 0.5. If this condition persists over a year, the annual drought index ADI = 6. An index ADI $\geq$ 8.4 is indicating the existence of a severe drought, which probably has extended over most of the year.

The sensitivity of this method for detecting droughts in Argentina has been verified with the results obtained from the method used by Palmer and others [33, 37]. All of them have reported important droughts during the same periods analyzed by means of applying this method, in addition to the ones studied by Malaka and Nuñez [38], Lucero and Lucero [39], Alessandro and Lichtenstein [40] and other journalistic reports.

Likewise, this happens with the annual value of the drought indexes. That is to say, the most extensive droughts (area) correspond to the most intense droughts [27].

These indexes will be studied as random events and, in addition, as time-dependent according to Yevjevich [41, 42]. The temporal analyses of trends in ADI were carried out with adjustments of 1-5 polynomial degree with the purpose of analyzing tendencies and interdecadal oscillations within the century and particularly the climate jump of the 1950s [43]. Monthly or annual dry events were contrasted here with a non-persistent white noise random model. In the same way, spectral analyses have been considered [44] in order to analyze the contribution of changes in diverse scales.

For this analysis, monthly pluviometric information from a network of meteorological stations located in the Southern Hemisphere Subtropical Region and the midlatitudes was used (Fig. 1). These annual drought indexes would be affected by the development of the semi-permanent anticyclone.

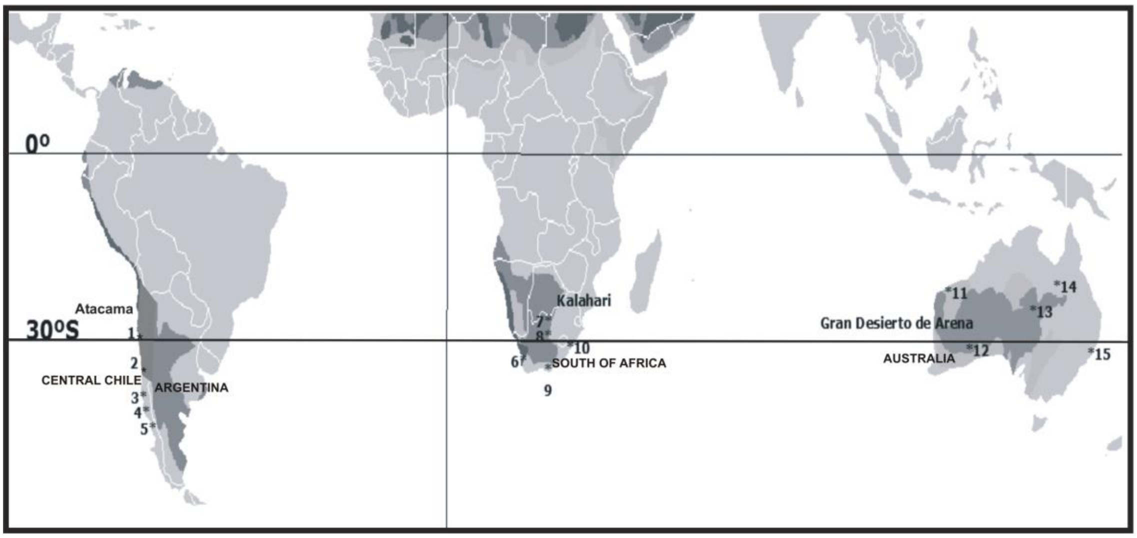


Fig. 1 Meteorological stations network used in annual drought index analysis. The arid zone is plotted with dark gray. Here the regions included in this study can be seen (Central Chile, Argentina, South of Africa and Australia)

This information comes mainly from Central Chile, Australia and South of Africa, with five localities in each region, all of them provided by their respective Meteorological Services (Table 1). In this South Hemisphere Subtropical band, the monthly and annual index drought proposed by Minetti et al. [2] has been estimated. The monthly index was constructed every month by calculating the quantity of dry localities, and was below their medium value regarding their total ones. This index oscillates between 0 and 1 with a central value of 0.5. The annual index is the monthly indexes summation and it ranges between 0 and 12 with a central value of 6. This hydric index has been consistent in the entire South America with rainfalls information from a grid provided by Reanalysis I (http://www.cpc.ncep.noaa.gov/products/wesley/reanalysis.html).

TABLE 1 LOCALITIES USED IN DROUGHTS ANALYSIS ON THE SH SUBTROPICAL BAND

Order N º	Locality	Lat.	Lon.	Height
Central Chile				
1	La Serena	29.9S	71.2W	32m
2	Santiago Chile	33.4S	70.7W	520m
3	Concepción	39.5S	73.0W	15m
4	Valdivia	39.7S	73.2W	5m
5	Pto. Montt	41.2S	72.6W	110m
South of África				
6	Cape Town	34.0S	18.2E	56m
7	Johannesburg	26.2S	28.1E	1676m
8	Kimberley	28.8S	24.7E	1196m
9	Pto. Elizabeth	33.9S	25.6E	58m
10	Durban	29.8S	31.0E	12m
Australia				
11	Onslow	21.1S	115.9E	11m
12	Kalgoorlie	30.9S	121.1E	427m
13	Alice Spring	24.5S	133.2E	432m
14	Cloncurry	20.7S	140.5E	200m
15	Sydney	33.8S	151.2E	39m

The annual indexes of every sub-region (Central Chile, Australia and South of Africa), have been analyzed in the long term. This was done by means of trends fitted by 5th degree polynomials, using the least square and moving average method [29].

In these regional or global series, variance spectra and correlograms were estimated [44]. Other monthly pluviometric information was used in Argentina, built with 59 localities spread in the East of the Andes Mountain with information from the

Argentina National Meteorological Service, to the effects of showing the current trends in Argentina. Also, precipitation information of a global grid from Reanalysis I has been used to show the existing connection between rains functioning with the HC.

Climatological information derived in this paper is used as the ENSO of Troup [45] and PDO of Mantua and Hare [46]. Monthly SOI and PDO data published by the Meteorological Service of Australia (SOI-Troup) http://www.bom.gov.au/climate/current/soihtm1.shtml PDO and the Joint Institute for the Study of the Atmosphere and Ocean (JISAO).

A. *Estimated Tendencies- Fit Polynomial by Ordinary Least Square*

The polynomial of degree n is obtained:

$$y = a_0 + a_1 x + a_2 x^2 + \ldots + a_n x^n$$

This is solved by the following normal equations:

$$\begin{aligned} na_0 + \left(\sum x_i\right)a_1 + \left(\sum x_i^2\right)a_2 + \ldots + \left(\sum x_i^n\right)a_n &= \sum y_i \\ \left(\sum x_i\right)a_0 + \left(\sum x_i^2\right)a_1 + \left(\sum x_i^3\right)a_2 + \ldots + \left(\sum x_i^{n+1}\right)a_n &= \sum y_i x_i \\ &\ldots\ldots\ldots\ldots \\ \left(\sum x_i^n\right)a_0 + \left(\sum x_i^{n+1}\right)a_1 + \left(\sum x_i^{n+2}\right)a_2 + \ldots + \left(\sum x_i^{2n}\right)a_n &= \sum x_i^n y_i \end{aligned}$$

B. *The Power Spectrum*

Applying the auto-correlogram and harmonic analysis, the spectrum from the autocorrelation function (ACF) is obtained. One of these methods is the Power spectrum developed by Tukey [44], which has the following algorithm:

$$S_k = \frac{r_0}{m} + \frac{2}{m} \sum_{i=1}^{N-1} r_i * \cos\left(\pi * k \frac{i}{m} + \frac{1}{m} * r_m * (-1)^k\right)$$

with m = N/3, S_k = spectral density at frequency k.

r_i = auto correlation coeficiente al lag i.

C. *Moving Averages*

They consist of a series of arithmetic means (simple or weighted) calculated over time for a selected period of length *L*. In other words

$$_L\bar{Y}_i = \frac{1}{Lt} \sum_{t=(1-L)'2}^{(L-1)'2} Y_{i+t}$$

Note that *L* must be odd for the moving average is centred at *tk* where *k* is the period corresponding to the same subscript. The data that are lost are the (*L*-1) / 2 and the first (*L*-1) / 2 last of the series.

D. *Pearson's Correlation Coeficient (rxy)*

With xi and yi, are the bi-variate data series.

$$r = \frac{N\sum xy - \sum x \sum y}{\sqrt{[N\sum x^2 - (\sum x)^2][N\sum y^2 - (\sum y)^2]}}$$

III. RESULTS

Fig. 2 shows the drought index for each region (Central Chile, Australia and South of Africa) with their respective estimated trends as 5th degree polynomials. Fig. 3 shows only the compared trends.

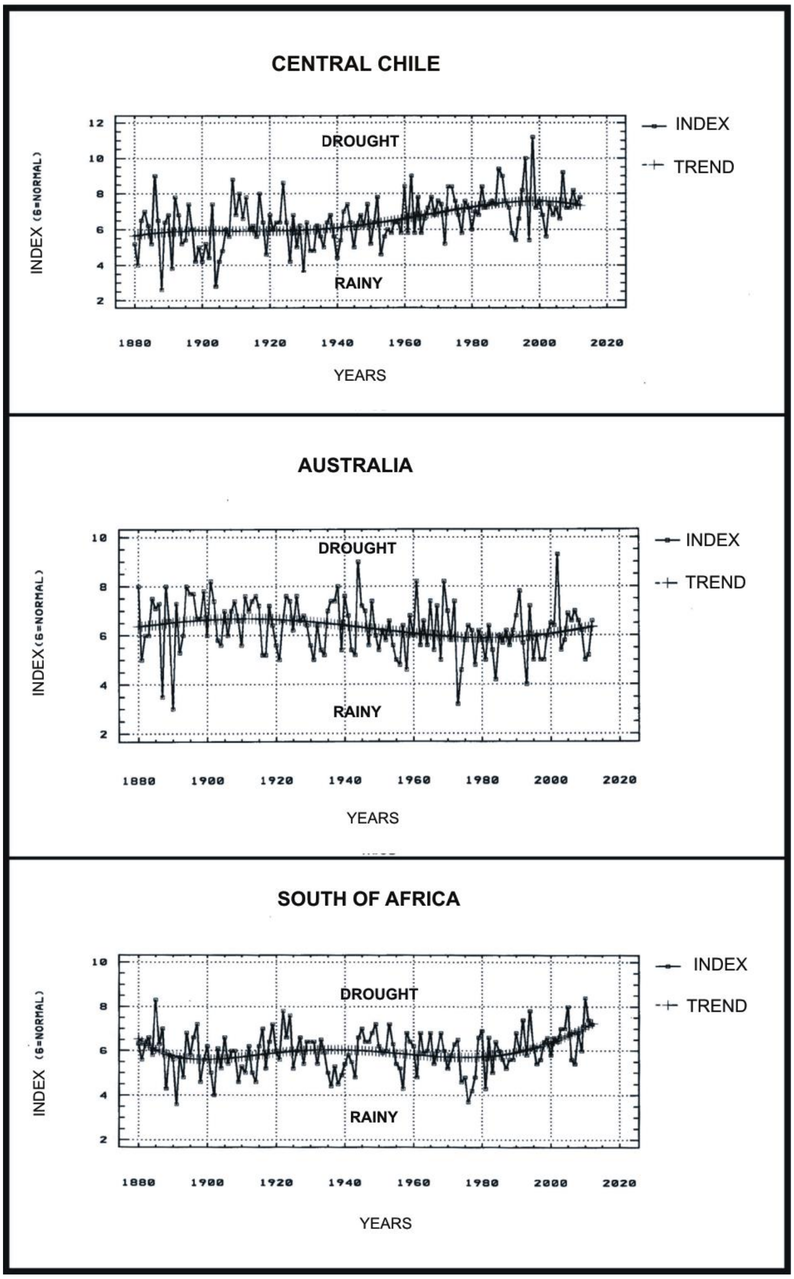


Fig. 2 Annual drought index in Central Chile, Australia and South of Africa with trends (polynomial 5th degree). Median index = 6 (left)

In the latter, the indexes growth in three sub regions between 1980 and 2012 can be observed. It has been observed that the greatest growth in the drought indexes is registered in the center of Chile. This region has received a severe impact on its agriculture and hydroelectric power generation from 1970 to the present [2, 43, 47].

This contrast is very noticeable in Argentina, over the North Salado River basin in 1997-2003 (with flooding in Santa Fe city), and then the 2008-09 intense droughts [2, 48]. In Australia, this new dry period is designated as “The Great Drought or Millennium drought” [5]. Subsequently, an extraordinary drought in Russia in 2010 [3] and USA in 2012 [4] contributed to the observed volatility of international grain market.

Some works associate the increase of drought conditions with Global Warming [3, 49, 50]. Other researchers associated the change in tendencies of the drought indexes with variations in the phase of the Pacifical Decadal Oscillation's index (PDO).

This period has initiated a new period of cold temperatures on decadal O. Pac fico [51]. This cooling O. Pac fico in long scale can also be seen in the slow changes of SOI and winter temperature of SM Tucuman (Argentina) (Fig. 4) [52].

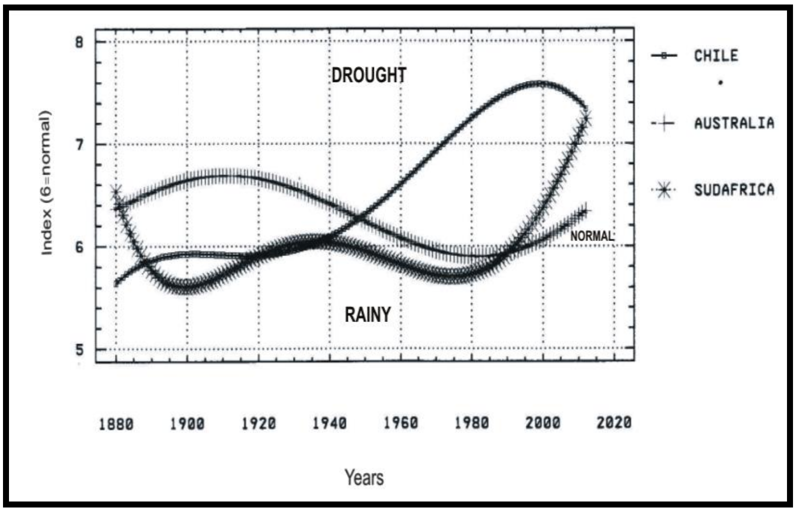


Fig. 3 Only shows the amplified trends

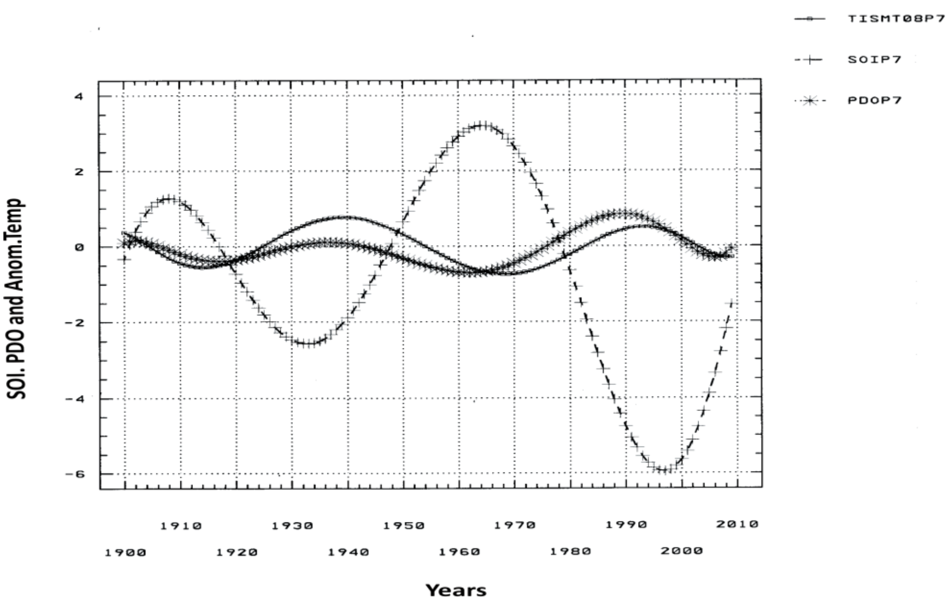


Fig. 4 Polynomial of 7th degree in: SOI, PDO and S.M. of Tucumán-Argentina mean minimum temperature in August month

Long simultaneous drier periods are also observed in Australia and Argentina (Fig. 5) for 1930 and 1940 decades, designated as "the Second World War Drought" [25]. This drought had severe impacts in the West and Northwest of the Argentine Humid Pampas where acute desertification and dunes movement processes were observed [53-55]. Fig. 5 shows Argentina annual drought index calculated for 59 localities spread to the East of Cordillera de los Andes (left figure). This series of data started during the years 1901-1902 and extended over the years 2012-2013.

It outlines the 21st century trends signal change, leading the current averages to the values of the first half of the 20th century. This drying process had already been warned in 2004 [2] and it caused important droughts in the Argentine plain with losses in the grains production that reached 30 million tons for the 2008-2009 years campaign.

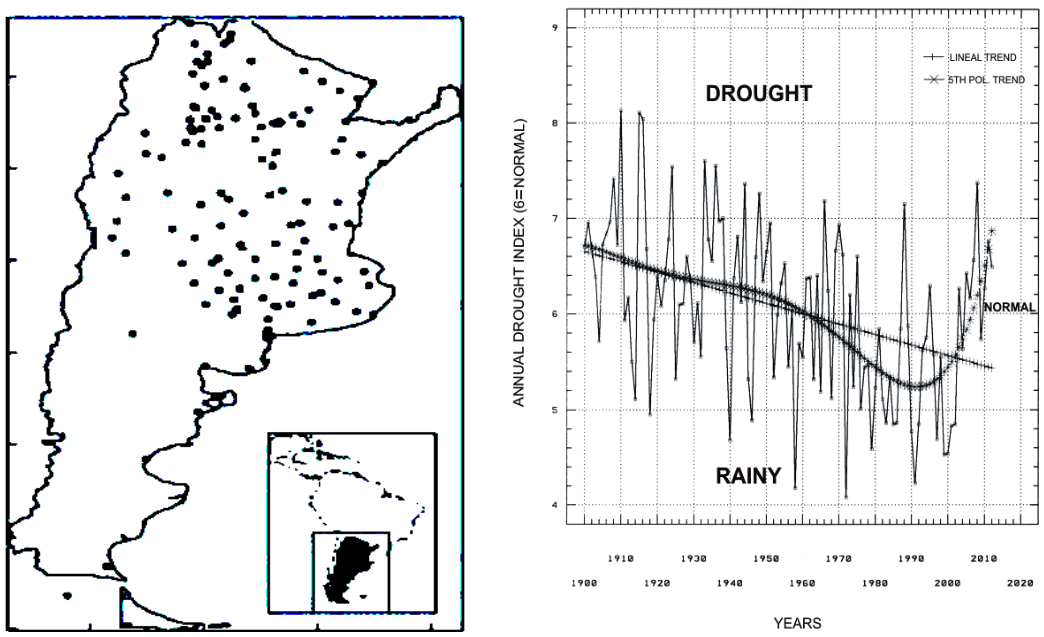


Fig. 5 Annual drought index in Argentina (Hydrological year Jl/Jn) at right; the 59 localities used in the period 1900-01/2012-13 at left. Furthermore, the trend is added with 5th degree polynomial

The temporary series of drought in South of Africa have no similarities with the other discussed regions, with exception of the bi-decadal oscillations mentioned by Tyson and Dyer [26] and Vargas et al. [56]. Table 2 presents a correlations matrix among the three regional droughts indices in the Southern Hemisphere. It can be seen that there are no significant correlations in Table 2 for droughts indexes between South of Africa and the rest, which coincides with Rouault and Richard's [57] findings.

TABLE 2 CORRELATION MATRIX FOR ANNUAL DROUGHT INDICES. CRITICAL CORRELATION WITH STATISTICAL SIGNIFICANCE AT 5%, RC = 0.18 WITH N = 130 DATA (YEARS).

INDICES	CHILE	AUSTRALIA	SUDAFRICA
CHILE	1	**-0.26**	0.10
AUSTRALIA	**-0.26**	1	-0.04
SOUTH OF AFRICA	0.10	-0.04	1

The significant and inverse correlation of the ENSO functioning corresponds to the one existing between Chile and Australia [58]. Fig. 6 shows the annual drought throughout the subtropical region. A stationary statistically condition between the years 1880-1980 can be seen, followed by a period of increased frequency and intensification of the droughts after 1980.

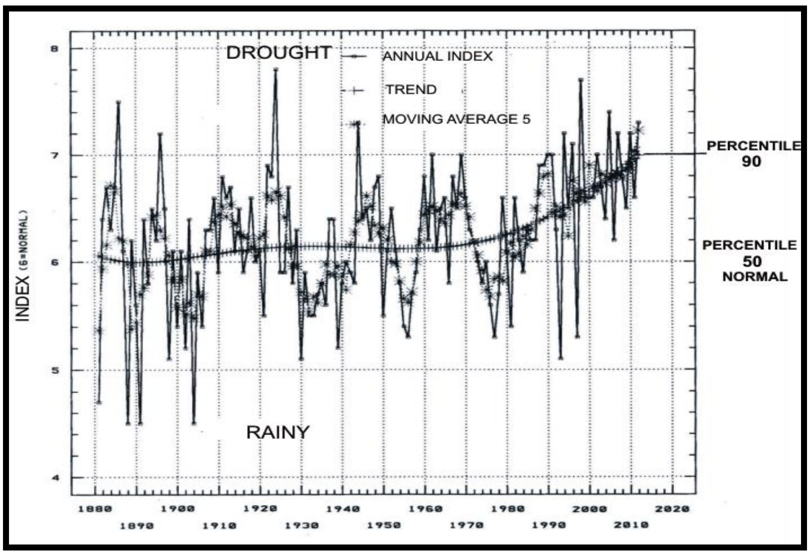


Fig. 6 Annual drought index in the subtropical region of Southern Hemisphere.6 = (median or 50%). 90% is added as a limit for extraordinary values. Trend as 5th Degree Polynomial and 5 annual moving averages are added too.

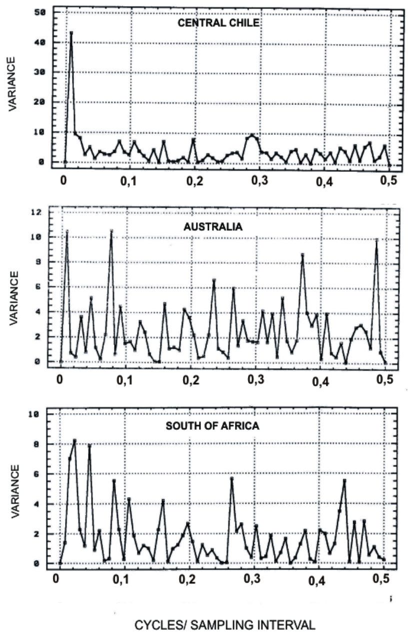
In this figure the central (average) value appears to have been displaced towards percentile 90.

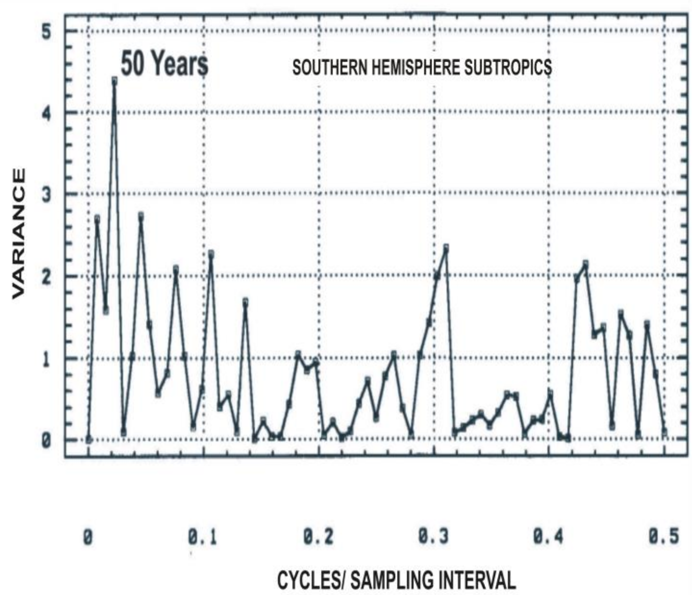
This would be the principal change observed over the climate of the subtropical region. By using 14 simulation models, Dai [59] showed that arid climate over the Earth would grow 23% by drier subtropical due to global warming between the years 2012-2100.

Anderson [60] was able to play with proxy data nine complete cycles of the slow oscillation of ENSO or PDO between 1525 and1984. This fact indicates the stability of these processes.

However, the condition of increasing drought in the subtropical region during the past 30 years is unlike any other event since 1880.

Fig. 7a shows each sub-region variance spectra [44] and Fig. 7b shows the whole spectrum. The domain of large-scale signals can be observed in the short term as tendencies. But what actually happens is the presence of oscillations of 50-100 years.





(a) (b)

Fig. 7 a: Spectra of the variance in Central Chile, Australia and South of Africa for annual droughts index; b: same as 7a but for the whole set. This is shown on the axis of abscissa (frequencies or inverse length in years), and the variances are explained in the ordinate.

The phenomena known in these wave lengths corresponds to the Pacifical Decadal Oscillation (PDO), due to Mantua and Hare [46], the ENSO slow oscillations [60] and the slow changes in the solar activity cycle [61]. Mitas and Clement [22] show that there is no trend but a 70 years order oscillation, similar to the 50's PDO. This could be caused by the difficulty of analyzing with shorter climatic series.

Other important variances in faster frequencies of the spectrum are observed in ENSO lengths. This shows that there are reverse climatic conditions between the coast of Central Chile and Australia.

By observing the trends of droughts in sub-regional areas (Fig. 3), it can be seen that there is a PDO oscillation that coincides with stadiums of more rain/drought in its rising/falling phase. During the last period 2000-2013, the exaggeration in the tendency of the annual drought indexes would be marking a possible effect of global warming.

The inverse relation in the hydric conditions for both South Pacific coasts, can be seen in the existing correlations between Central Chile drought index and the Southern Hemisphere most anticyclogenetic region, with the precipitations of the rest of the world in Fig. 8. Such estimations were performed by means of Reanalysis I data, already shown for South America [22].

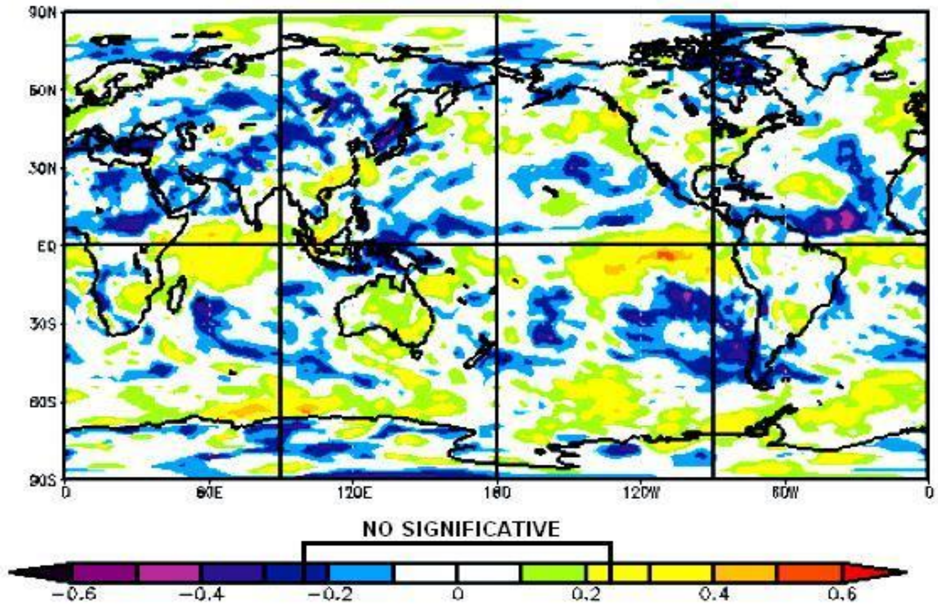
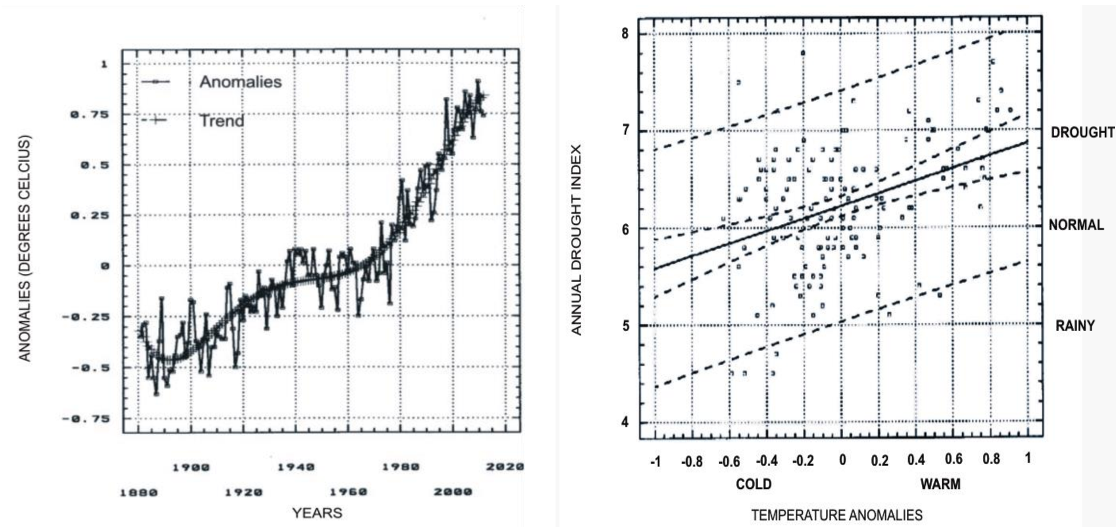


Fig. 8 Correlation between the Center of Chile drought index and the world's precipitations, using Reanalysis data I (NOAA/ESRL Physical Sciences Division). Critical correlation Rc = +/- 0.24, blue and yellow. No significant correlations are indicated.

ENSO inverse correlation between Chile-Australia can be seen in this figure, in addition to the existing inversion between the ITCZ and the subtropical anticyclone, two branches of the HC (upward and downward).

The regression and correlation between the anomalies of annual global temperatures (Fig. 9a) provided by NASA [62] and annual drought index are shown in Fig. 9b. This significant correlation persists even after filtering linear trends in both series. A conceptual hypothesis has been verified statistically.

Trends in Fig. 9a shows the three thermal phases observed in global temperature: (I) warming trend after Krakatoa volcano eruption in 1883 [63], (II) stationary global temperature during 1950-1980. This behavior occurs after 1950 climatic jump [21], and (III) the present trend towards warming of greater trend than that of the initial period (phase I). This behavior is similar to the annual drought index for the Southern Hemisphere Subtropical.



(a) (b)

Fig. 9 a: Anomalies in Earth air temperature (only lithosphere) and trend according to NASA (2013); b: Linear regression and correlation (R) between anomalies in air temperatures in Earth and annual drought index in the Subtropical Southern Hemisphere R = 0.37 st. sig. 1/ ººº. Filtered linear trend in series R= 0.23 st. sig 1%.

IV. CONCLUSIONS

The tendencies of the annual drought index progress in the Southern Hemisphere subtropical zone in a similar way as the annual temperatures at global scale (Global Warming).

In the trend, it can be seen that there is an apparent presence of weak PDO or ENSO signals at low frequency with 50 or more years of length.

In the more rapid fluctuations, the presence of the ENSO and an inversion in the oscillation between the center of Chile and Australia can be seen.

With Reanalysis I data and the annual drought indexes of the center of Chile, the opposite correlation between equatorial and subtropical regions can be seen.

This fact confirms that the Hadley Circulation is intensified/ weakened by the global warming/cooling.

The individual spectra of the three sub-regions considered show that the dominant variance pattern in the subtropical regions is the trend or long range oscillation (PDO, ENSO, or solar activity).

The principal trend in the subtropical regions is observed in Central Chile.

The fact that the trend of Southern Hemisphere Subtropical drought index is reaching the percentile 90, indicates the intensification of the average change since 1980 up to the present day.

The area of Central Chile has the greatest trend component observed, and at the moment the other regions (Australia and South Africa) are growing faster than the first one.

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