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Observed trends in frost and hours of cold in Majorca

Short title: Cold in Majorca

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Abstract:

The observed trends on some cold indexes in the island of Majorca are analyzed using the available series of the daily minimum temperatures of the Majorca Airport (1972-2008), supplemented with the inspection of eight more climatological stations of the island covering at least thirty simultaneous years. The analysis yields a statistically significant trend to a rise of about 0.6ºC per decade for the ensemble of the stations. There is also a clear shortening of the season with days with T below 0ºC or 7ºC, but the yearly minima or the dates of the first and last occurence of these values do not show so well defined tendencies. A rise in nightime cloud cover could be related to such behaviour.

Keywords: series of minimum temperature, Majorca. warmer winters, frost, hours of cold, cloud cover

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1. Introduction

In the frame of the global warning, a number of issues are relevant locally. In this research note, the August 1972- May 2008 series of the Palma Airport -and eight more series of Majorca of 30 or more years- (Balearic Islands, Western Mediterranean) of minimum temperatures are analyzed to inspect if there is a significant trend to warmer winters and reduction of the risk of frost, mainly with agricultural intention.

A study with a similar purpose for the United States was made by Easterling (2002) with a large number of stations, that showed a significant trend to the reduction of the number of frost days at the national scale, at a rate of 0.8 days per decade for the period 1948-1999, with large regional differences. Other studies include those of Menzel *et al.* (2003), showing many stations in Germany, Austria and Estonia with significant changes in these parameters, for instance 4.9 days per decade more of the frost-free period between 1951 and 2000, or Bartolini *et al.* (2008) that show increases of more than 0.2ºC per decade in the minimum temperatures for Tuscany during 1955-2004. Not all these indices are directly comparable, but they all point in the same direction. The Fourth Assesment Report of the IPCC (Trenberth *et al.,* 2007) provides estimations for land over the northern hemisphere of increases of about 0.3C per decade for the minimum temperatures (based on Vose et al, 2005) and 0.2 perºC decade for the mean temperature over ocean (based on Rayner *et al*, 2006) for the period 1979-2005, similar to the one studied here. The fact that Majorca is a piece of land in the middle of the Mediterranean sea makes interesting to look at its specific behaviour.

Majorca is the largest island of the Balearic archipelago, located in the Western Mediterranean about 200 km offshore of the coast of the Iberian Peninsula (Fig. 1a). The island has a characteristic size of 100 km with a large mountain range (Serra de Tramuntana) occupying all its northwestern side (peaking at 1436 m above sea level –ASL-). The rest of the island consists summarily in three basins, two at the southern side (Palma at west and Campos at the east) and one at the northern side (Alcúdia), with an elevated area in the center of the island (Randa, 556 ASL) and a lower mountain range at the east (Serra de Llevant, peaking at 520 m ASL) -see Figure 1b. A study by Cuxart *et al.* (2007) found that, under clear skies and with weak pressure gradients, when strong local surface cooling may occur, the flow is organized by basins, each having sea-breezes in the daytime and convergence of drainage flows in nighttime, with formation of cold pools in the valleys and cold outflow to the sea. These conclusions were reproduced by Jimenez *et al.* (2008), in a work that verified the structures in the island using the thermal structures produced by infrared satellite imagery. The fact that the island is relatively small and surrounded by an almost closed sea may indicate that a warming there is regionally relevant.

The main agricultural cultures in the archipelago are ornamental plants, fruits (including vines), potatoes and green vegetables. The productivity of the latter is mainly affected by frosts whereas fruit trees have also specific requirements of hours-of-cold (customarily defined as hours with temperature below 7ºC). Any significant trend may induce significant changes in the agriculture of the islands, thus in the economy and the landscape, since 37% of the surface is cultivated land. To illustrate the impact of frost episodes, all cultures of the island are listed in the insurance coverages by the spanish ministry of agriculture, at the same level of continental Spain, the most sensitive sectors being the early potato production for export to North Europe and the almond trees with early floration in January and February. These two sectors amount respectively almost one third and one tenth of the total income of the agricultural sector (Riera and Ripoll, 2009) whereas vegetables and flowers are usually cultivated in greenhouses . To review the fundamentals of frost and how to protect the cultures against it the reader is referred to Kalma *et al.* (1992) or Snyder and Melo de Abreu (2005). In this research note, the series of nine stations located in diferent geomorphological areas of the island are analyzed and the trends of the cold indices discussed.

2. The series

In Figure 1b, the locations of the nine analyzed stations are displayed. The Airport Meteorological Station (WMO principal station) is located in the eastern part of the Palma basin, at a distance of 9 km from downtown Palma and at 5 km of its continuous urbanized area. The data are taken at the northern end of the runaway, 5 km inland, in a local depression of the terrain where cold air can cumulate in clear and calm nights (Cuxart *et al.,* 2007). The series starts in August 1972, complying with all the requirements of a primary WMO station; it is managed and quality-controlled by the Spanish Meteorological Agency (AEMET). The series of minimum temperatures from 1 August 1972 to 31 May 2008 has been extracted from the data base.

Eight other stations from the climatological database of AEMET have been used provided that they had at least 30 years falling in the period 1972-2008. In the Palma basin, besides the airport, there is Portopí, in the harbour of the city of Palma (1978-2008, 3m ASL) and Sa Cabaneta, close to elevated plateau in the center of the island (1976-2008, 152 m ASL). In the Campos basin, we could consider Llucmajor (1974-2008, 140 m ASL), also in an elevated part between the Palma and Campos basins, and Ses Salines (1972-2008, 3m ASL), very near to the coast but in the center of the valley. In the Alcúdia basin, the station of Muro is available (1974-2008, 50 m ASL) in the flat central part of the basin, and Manacor (1974-2008, 125 m) which is more inland and to the East. Finally, two stations are in the main Tramuntana Range, Lluc (1972-2008, 490 m ASL) and Orient (1975-2008, 455 m ASL), both located at the bottom of elevated closed mountain valleys.

The series consist of the daily minimum temperatures, with very few missing data. The analysis of trends for the main series has been made for complete years to avoid the effect of starting an analysis in winter and finishing it in summer, which would provide spurious warming. All the selected series start and finish in summer for this purpose. To study their relative homogeneity, they were first standardized, and reference series for each station were computed as an average of their neighbours, weighted by an inverse distance function. Then, the differences between the original and computed series were scrutinized in search of possible shifts in the average, by means of applying two sample Student t-tests to two adjacent running windows of four years (48 monthly values per sample) along all the series (in this way, four years is the maximum temporal resolution to detect shifts either consecutive of at the beginning or the end of the series).

This lead to the detection of clear shifts in the mean in two of the series, at the following dates: 1) March 1983 in Muro, due to a documented bad siting of the thermometer (on a terrace); and 2) May 1984 in Manacor, for which no metadata were found to explain this inhomogeneity. Therefore, data previous to the shifts were deleted from the Muro and Manacor series in order to avoid misleading results. The rest of the compared series showed minor differences, indistinguishable from natural variability, and therefore no further corrective measures were attempted. The statistical analyses have been done with the R statistical package (R Development Core Team, 2008), package "Climatol" (Guijarro, 2006), version 2.0.

3. Trends of minimum temperatures and cold indexes

The trends for daily minimum series have been computed for the nine locations and the values are given in Table 1, keeping only the restricted ranges for the two stations with confirmed inhomogeneities. In that table the stations are ordered from warmer to colder in respect to the average minimum temperature. The trends have been computed by the least-squares methods and the confidence levels have been assessed with the non-parametric Mann-Kendall test (1975), to overcome the lack of normality of the series of the daily minimum temperatures. All the stations have positive slopes statistically significant at least with a 95% confidence. An averaged central value for the ensemble of the stations is 0.6ºC per decade, the double of the estimation of the IPCC (Trenberth et al) for the northern hemisphere over land. This indicates that there is a warming of the nocturnal temperatures in the island at all kinds of landscape and height, since stations are near the coast, in the valleys, in plateaux or mountain ranges. In the case of the Airport, the complete series has a correlation coefficient of 0.11, meaning that most of the variability is not explained by the linear regression. This is not strange, since minima for this station can vary from -6 to 27ºC and most of the variance is explained by the annual cycle.

A number of indices have been obtained from each series, namely i) the yearly minimum temperature value; ii) the number of days below 0ºC, iii) the first day with T below 0ºC, iv) the last day below 0ºC, v) the number of days below 7ºC, vi) the first day with T below 7ºC, and vii) the last day below 7ºC. The resulting anual series for the Airport are plotted in Figure 2. The absolute annual minimum temperature is shown to have a smaller trend than the annual anomaly of the same quantity. Although at a first glance the linear adjustments seem to indicate a behaviour consistent with a general warming, some of these results are not statistically significant and deserve further analysis.

Also in Table 1 the average values and the trends for the yearly minimum temperature are given. Average values below zero are found in the mountain range and in the bottom of the valleys. However only half of the stations show a significant increase, making less clear the trend to higher absolute yearly minimum temperatures in the Island.

Table 2 displays statistics related to frost days. Averages above 1 day per year are found only in four stations in the mountain and in the valleys and at all these stations there is a significant trend to diminish the number of days, with an ensemble central value of -4.7 days per decade, a trend that would indicate that frost would disappear from the valleys in about 4 decades. However the bottom end of the 95% interval is very low for three of the four stations (-0.2, -0.9 and -1.4 days/decade) and it suggests to be prudent in any conclusion regarding this issue. There is not a well defined trend for the occurence of the first frost for these stations, although one can see that the last spring frost seems to come earlier (about 12 days per decade).

Similar conclusions are reached with the same indices using days with temperatures below 7ºC (Table 3). Eight of the nine stations show a decrease in the number of days, since Llucmajor does not yield any significant trend. It cannot be said that the first day with temperature below 7ºC has a well defined tendency for the ensemble of stations, but six of nine stations show statistically significant trend to earlier end of cold days. Since some hundreds of hours below 7ºC are needed by fruit trees in their winter rest, and the average computed decrease is about 12 days below 7ºC per decade, some of the current plantations in the Balearic Islands may cease to be possible, at least with the present-day plant varieties.

4. Trends on cloudiness and relative insolation

The fact that minimum temperatures seem to be increasing and the number of days of frost (T < 0ºC) and of cold (T < 7ºC) decreasing in a statistical significant way, while less significance is reached for the absolute yearly minimum temperature or the dates of the first and last dates for the ensemble of the stations, may indicate some link to changes in cloud cover. If the amount of clouds during night (or the number of cloudy nights) increased, it might explain the rising of the minimum temperatures, whereas the clear nights would cool as much as usual, thus allowing for similar yearly minimum temperatures. The dates of first and last frost not significantly changed would then be related to the fact that, whenever a clear and calm night occurs, similar intense cooling as before can occur.

In table 4, the trends are computed for the humanly estimated cloud cover at 7, 13 and 18 local solar time plus the relative insolation extracted from the burned heliograph bands. These measurements have a larger amount of uncertainty than temperatures, due to the human factor in estimation of cloud cover and portion of band burned.

There is a statistically significant increase of clouds (low and total) at 7 local solar time, a moment normally close to the time of the minimum temperature and a decrease of low clouds at 13 and 18. This is combined with a small increase for the relative insolation. This increase of late-night clouds would lead to higher minima for cloudy nights and would be compatible with less significant trends for values usually found in clear and calm nights, such as yearly minimum temperature. The increase of minimum temperatures could thus be related, at least partially, to higher nocturnal thermal stability, with more inversions -and therefore fog and low clouds-, while this stability would also be compatible with a lower daily cloudiness and the corresponding increase in relative sunshine hours.

The connection between these variables has been investigated by adjusting a multiple regression model to the minimum daily temperatures, using cloudiness and relative insolation as the independent variables. But first, all the variables have been detrended, and their seasonal components removed by substracting the annual cycle and the first two harmonics of a Fourier analysis adjusted to the original data. In this way, the variance of the minimum temperatures was reduced by a 75% (standard deviation of 6.3ºC in the original data and 3.1ºC in the deseasonalized one).

The residual series were then used to adjust the multiple regression model and, although the explained variance of the minimum temperatures amounts only to 15%, only the low cloudiness at 18 UTC was not significant at the 95% confidence level. The signs of the significant contributions (Table 4) of the independent variables are in accordance with the aforementioned interpretation of their trends.

5. Conclusions

For the ensemble of the studied stations located in the island of Majorca in the Western Mediterranean, the analysis of the minimum temperatures for the last three decades seems to imply that there is a statistically significant trend to increase, at about 0.6ºC per decade at a 95 % confidence level, more than the hemispheric estimations provided by IPCC of about 0.3ºC per decade . This goes together with a diminition of the number of days of frost (T < 0ºC) or of cold (T < 7ºC). Instead, the absolute yearly minimum temperature or the dates of the first and last frost days do not show a significant trend in the ensemble. A possible link to cloud cover is considered, since this quantity has significantly increased at 7 AM local solar time, that may partially explain the rise of the minimum temperatures. In summary, warmer winters seem to be on place that may induce relevant changes in the agricultural landscape of the region, but being aware that frost events can take place as it has been usual in the last decades.

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Tables

Table 1: Statistics of the daily and annual series of minimum temperatures for 8 selected Majorca stations. Average of the daily series is 0.60 C/decade. In bold regressions with confidence level higher than 95 %.

	Average Daily T min	Slope and 95% conf interval (C/decade)	Average annual T min	Slope and 95% conf. interval (C/ decade)
Palma Harbour (78-08) –Coast-	14.5 C	**0.59 (0.48,0.71)**	3.0 C	0.32 (-0.30, 0.94)
Sa Cabaneta (76-08) –Plateau-	13.1 C	**0.62 (0.51,0.73)**	1.2 C	0.45 (-0.18, 1.08)
Muro *(83-08) –Valley-	12.8 C	**0.69 (0.52,0.85)**	0.4 C	**1.28 (0.62, 1.64)**
Llucmajor (74-08) –Plateau-	12.6 C	**0.34 (0.23,0.45)**	1.2 C	0.03 (-0.45, 0.52)
Manacor* (84-08) –Valley-	11.8 C	**0.70 (0.53,0.84)**	-1.0 C	**1.43 (-0.55, 2.31)**
Ses Salines (72-08) – Valley-	10.5 C	**0.31 (0.18,0.44)**	-2.8 C	**1.38 (0.61, 2.16)**
Airport (72-08) –Valley--	10.3 C	**0.64 (0.54,0.75)**	-2.9 C	0.30 (-0.05, 0.65)
Orient (75-08) –Mountain-	8.4 C	**0.99 (0.89,1.09)**	-2.9 C	**0.88 (0.37, 1.38)**

Lluc (72-08) -Mountain-	8.0 C	**0.55** **(0.45,0.65)**	-4.6 C	**0.62** **(0.13, 1.11)**

* after removal of parts of the series before the shifts in the mean: Muro (74-83), Manacor (74-84)

Table 2: days with T<0 (definition of day with frost). Day 1 is 1st January.

	Average Number of days	Slope 95% (per decade)	Average First day	Slope 95% (per decade)	Average Last day	Slope 95% (per decade)
Palma Harbour	0	N.A.	N.A.	N.A.	N.A.	N.A.
Sa Cabaneta	0.4	N.A.	N.A.	N.A.	N.A.	N.A.
Muro	0.8	N.A.	N.A.	N.A.	N.A.	N.A.
Llucmajor	0.1	N.A.	N.A.	N.A.	N.A.	N.A.
Manacor	0.8	N.A.	N.A.	N.A.	N.A.	N.A.
Ses Salines	13	**(-8.8, -4.3)**	-9 (23D)	**(2.8, 17.2)**	62 (3M)	**(-28.9, -13.1)**
Airport	13	**(-5.4, -0.9)**	-9 (23D)	(-1.5, 13.7)	70 (11M)	**(-17.4, -3.8)**
Orient	12	**(-7.7, -1.4)**	-2 (30D)	(-6.1, 20.5)	71 (12M)	**(-21.6,-5.1)**
Lluc	36	**(-9.7, -0.2)**	-29 (3D)	(-1.7, 11.6)	85 (26M)	(-12.0, 5.6)

Table 3: Number of days with T<7 (definition of day with hours-of-cold). Day 1 is 1st January.

	Average number of days	Slope 95% (per decade)	Average first day	Slope 95% (per decade)	Average last day	Slope 95% (per decade)
Palma Harbour	28	**(-13.5, -2.0)**	-20 (12D)	(-9.8, 9.9)	78 (19M)	(-16.9, 2.9)
Sa Cabaneta	49	**(-13.4, -0.5)**	-33 (29N)	(-1.0, 11.0)	97 (7A)	**(-15.6, -2.6)**
Muro	72	**(-21.4, -1.7)**	-43 (19N)	(-2.8, 12.6)	104 (14A)	**(-18.0, -3.8)**
Llucmajor	62	(-5.6, 7.2)	-40 (22N)	(-5.2, 5.6)	100 (10A)	(-7.9, 0.4)
Manacor	91	**(-23.8, -4.9)**	-47 (15N)	(-9.4, 14.3)	115 (25A)	**(-13.0, 2.3)**
Ses Salines	110	**(-29.7, -7.5)**	-55 (7N)	**(5.0, 17.2)**	117 (27A)	**(-35.4, -9.7)**
Airport	127	**(-16.8, -7.3)**	-63 (29O)	**(2.8, 10.5)**	133 (12My)	**(-13.5, -6.1)**
Orient	145	**(-33.7, -16.6)**	-77 (15O)	**(1.5, 11.1)**	141 (12My)	**(-14.9, -5.4)**
Lluc	159	**(-25.2, -3.8)**	-80 (12O)	(-10.9, 1.6)	139 (18My)	(-13.6, 6.9)

Table 4: Averages (octas and percent) and trends (percent per decade) for cloudiness and relative insolation at Palma airport (1972-2008). Trends statistically significant at the 95% level are in bold. The third row displays the sign of the significant coefficients of a multiple regression between daily minimum temperature and these variables ("b" is the regression coefficient in Var=a+bTmin).

	Low clouds 7	Total clouds 7	Low clouds 13	Total clouds 13	Low clouds 18	Total clouds 18	Relative insolation
Average	2.0	3.7	2.3	3.9	1.8	3.6	60.8%
Trend	**1.9%**	**2.2%**	**-2.4%**	-0.3%	**-1.7%**	0.3%	**1.3%**
Sign of significant b	+	+	-	+	0	+	-

Figure 1: (a) Majorca in the Western Mediterranean; (b) Topographic map of the Majorca island with the locations of the stations used.

Figure 2. *Top:* annual anomaly of the minimum temperature and absolute annual minimum temperature, *second:* number of days below 0 C; *third*: number of days below 7 C; *fourth*: first day below 0ºC and below 7 C; *bottom*: last day below 0 and below 7ºC. Each figure has regression lines for the complete series.

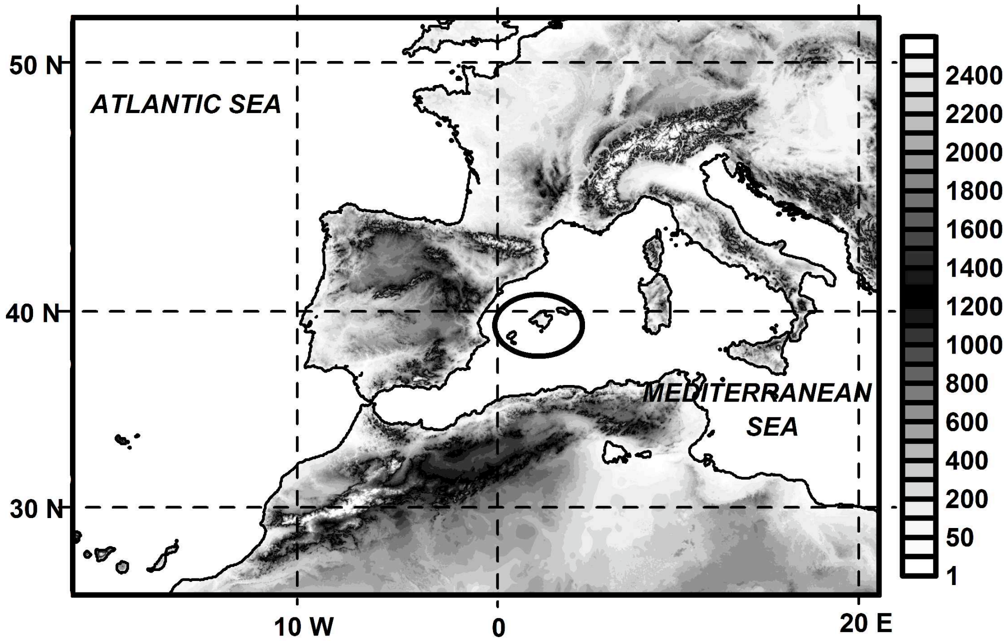

Figure 1: (a) Majorca in the Western Mediterranean
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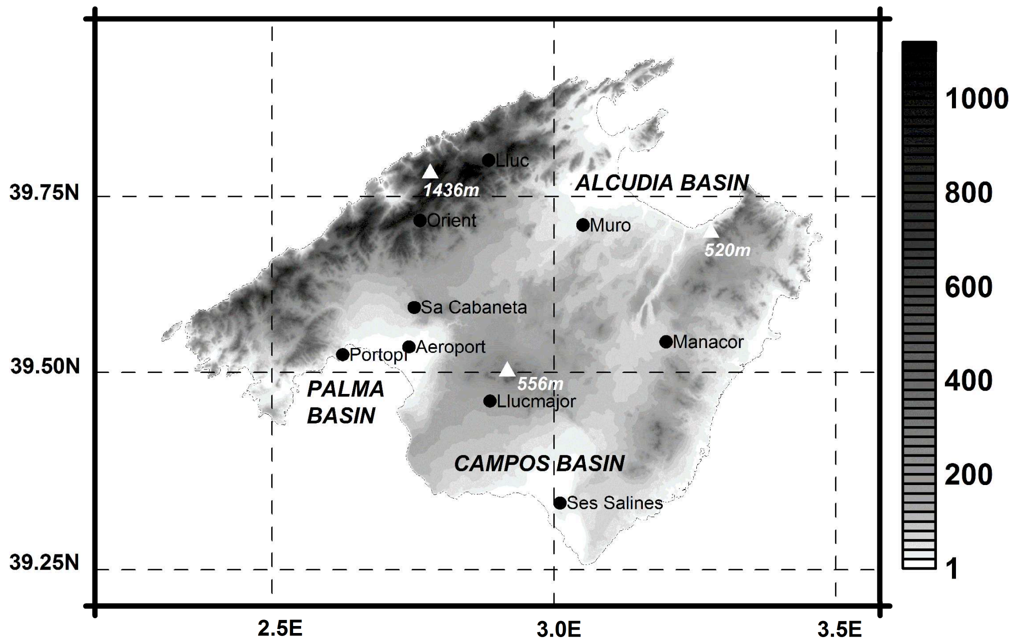

Figure 1: (b) Topographic map of the Majorca island with the locations of the stations used.
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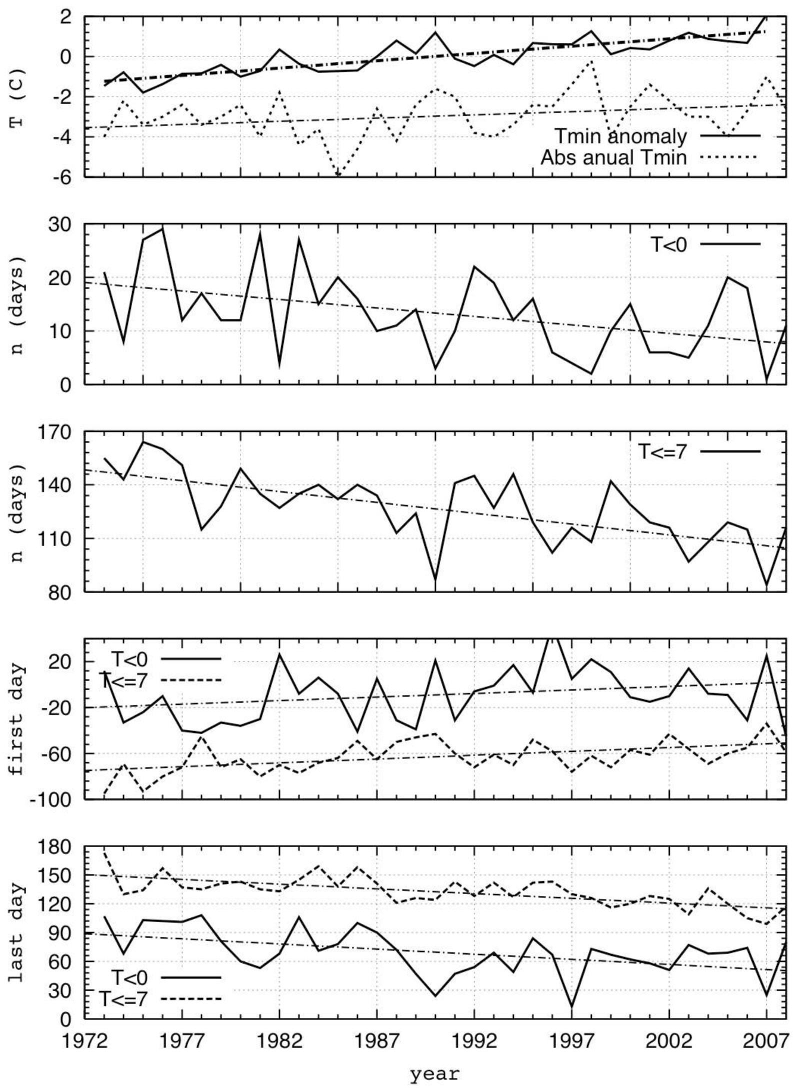

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