Observed Changes in Extremes in the French Alps (Temperatures, 1949-2001; Precipitation, 1949-2001 and 1966-1999)

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1 Introduction

Changes in extremes have been investigated in four contrasted sub-regions of the French Alps and around: Savoy, Queyras, the Alpes Maritimes, and, more to the west: Roussillon which lies just north of Catalonia. Queyras is an intermediate massif between Northern Alps and Mediterranean southern Alps. A new diagnostic and graphical software for extremes (including non parametrical significance tests) was applied to 3 temperature and precipitation time series from Météo-France (**MF** hereafter): those of Nice (Alpes Maritimes), Perpignan (Roussillon), and Embrun (Queyras, altitude 870m), and to gridded precipitation series from ETH Zürich (Alpine Precipitation Climatology, **APC** hereafter) corresponding to our sub-regions of interest. This diagnostic software was also applied to 20 **MF** french stations temperature series in order to see how the conclusions obtained for the Alpine stations could be generalised or not.

The new software uses our package **ANAXV** together with the generic mapping tools **GMT**. It computes the same diagnostic extreme indices as the **STARDEX** diagnostic software, plus a few other ones. It is more flexible and includes automatic non-parametric tests of trend significance and automatic graphical outputs. Whereas the indices computed by the **STARDEX** diagnostic software were most often relevant ones, we had to face some problems in connection with, *e.g.*, the climate of the French Riviera (Nice) where temperature variations are so small that if one defines hot days as those days with a Tx anomaly $\geq$ 5 deg, the conclusion is that heat waves longer than 5 days **never** occured in Nice for at least 53 years (only two occured with exact five day duration; others were all shorter). So we had to prefer a more universal definition of hot days, requiring a Tx above its 90^{th} percentile (*i.e.* the long term **TxQ90**) and we therefore introduced a new index: **TxHW90**, the maximum duration of periods with a Tx above this long term percentile. The long term percentiles are of course computed in a date dependent way; in order to have a smooth annual cycle, percentiles for a given date are computed taking into account all observations for this calendar date $\pm$ 10 d.

For precipitation, we added two more indices: the 7^{th} one, **PS**, measures the seasonal precipitation accumulation, and an 8^{th} one, **PSQ90**, measures the seasonal accumulation from events > long term **PQ90**. **PSQ95** is defined in a similar way using **PQ95** instead of **PQ90**. The curves displayed on the corresponding lowest pannels of the figures are, very likely, among the most expressive ones for precipitation. One should not forget, indeed, that seasonal precipitation accumulations are not a minor factor from the damage point of view (consider, *e.g.*, landslides, which multiply after repeated heavy precipitation episodes, like was the case during November 2000 in the southern Alps).

Table 1: Indices used to quantify seasonal extremes.

Acronym	Description
TxQ90	90% quantile of daily maximum temperature
TnQ10	10% quantile of daily minimum temperature
TnFd	Number of frost days per season
TxHWDI	Max Heat Wave (Tx > long term + 5 deg) duration (> 5 days)
TxHW90	Max Heat Wave duration (Tx > long term 90% quantile)
PQ90	90% quantile of daily precipitation on wet days (> 1 mm d^{-1})
	(*may be long term 90% quantile or computed every year for a given season*)
Px5D	Seasonal maximum of 5-day total precipitation
PINT	Simple daily Intensity: mean precipitation amount on wet days (> 1 mm d^{-1})
PxCDD	Maximum number of consecutive dry days ($\leq$ 1 mm d^{-1})
Pf90	Percentage of precipitation from events > long term **PQ90**
PN90	Number of days with precipitation > long term **PQ90**
PS	Seasonal amount of precipitation
PSQ90	Seasonal amount of precipitation from events > long term **PQ90**

A list of the parameters introduced to quantify extremes is given in table 1 together with their definitions; whenever possible, we use acronyms and definitions as stated at Interlaken meeting ME4.

Before turning to a description and discussion of observed changes in extremes, we first introduce the non-parametric significance test that we systematically carry out for trends. Then we consider precipitation and comment on the most outstriking features of its seasonal extremes evolution for each of the 4 sub-regions. We finally turn to temperatures; the series are longer, but we had no available one for Savoy.

2 The non-parametric significance test

We always compute and display a linear trend. Although its interpretation may sometimes be questionable, it has the enormous advantage of actually making easier the interpretation by the reader. However, the trend significance tests cannot be based on these linear computations since the distribution functions for extreme indices are basically long-tailed ones. A single exceptional event could biase all the linear trends. In order to circumvent this problem, we always classify the observed values of indices of table 1 into a few categories (typically 6; this choice results from a compromise between the "extreme" character of a particular season and the statistical significance given that the data cover less than 40 years). The significance test operates with these categories, which eliminates the problems tied to the tail of the distribution. We classify, for instance, the 34 (or 53) winter values of the index of interest into 6 equally populated categories; then the non-parametric test easily determines whether the observed trend (of the time series of index categories, not of index values, corresponding to the available winters) is compatible with the absence of any trend, or not. We actually randomly shuffle 500 or 1000 times the observations and are able to set 1% (resp. 5%, 10%, 90%, 95% and 99%) significance level boundaries for the (categorical) trend. Whenever some significance

Table 2: Acronym automatically printed on the corresponding histogram when some trend significance has been detected by the non-parametric categorical test

Sign. Level (%)	< 1	1-5	5-10	10-90	90-95	95-99	> 99
Acronym	$---$	$--$	$-$		$+$	$++$	$+++$

is detected, a message is automatically printed on the higher left corner of the corresponding histogram (see table 2 and figures), with the abbreviation "TS" (for Trend Significance), followed by the symbol $---$ (resp. $--, -, +, ++, and +++$) according to the significance level.

3 Precipitation

- **Nice station** (**MF** data) (Figs.1 and 2): On Figs.1 and 2, we display for each season of the year (spring=MAM, summer=JJA, etc...) the main indices used to quantify changes in extremes during the period 1966-2001 for precipitation in Nice. Although **MF** supplied us with data covering the longer period 1949-2001, we limit our analysis to the shorter period 1966-2001 in order to make easier the comparison with the observations one can make using the **APC** gridded data. **PQ90** has been used to define "extreme" events on Fig.1, and **PQ95**, the 95% quantile on Fig.2, which actually corresponds to "more extreme" events. The first horizontal line pannels display the mobile **PQ90** (or **PQ95**). While **PQ90** (Fig.1) shows no significant trends, **PQ95**, the mobile 95% quantile (Fig.2) exhibits highly significant ones (with 95 and 99% significance levels) for 3 seasons out of 4. **PQ95** decreases by roughly 10 mm for spring and summer, but increases from $\approx$ 46 mm up to 62 mm for automn between the mid-sixties and the turn of the century, which is far from negligible... However, we should remind that the significance test are not performed directly on the **PQ90** or **PQ95** values, but on their categorical ranks, in order to eliminate problems with long-tailed distribution. Most other histograms point to the same conclusions, namely that several indices significantly decrease during spring and summer, contrasting with poorly significant changes for winter, whereas fall is the only season with a few significant positive trends. It is clearly evident from an eye-inspection of the last horizontal line pannels of both figures that automn (SON) is the only period of the year with a net increase (by $\approx$ 150 mm) of seasonal precipitation, mainly due to the contribution of daily precipitation $>$ long term **PQ90**.

- **Alpes Maritimes** (**APC** gridded data): Fig.3 is the equivalent of Fig.1, but with the **APC** precipitation series corresponding to the gridpoint closest to Nice. One **APC** gridpoint corresponds on average to 6 stations. Very similar conclusions may be drawn from this figure. Although there are less significance messages printed on the histograms, the qualitative trends are clearly the same as on Fig.1. This is especially true for the seasonal accumulation, with the only signal of increase for automn, whereas a tendency to aridification appears for the 3 other seasons. However, for spring and summer, this tendency appeared somewhat more pronounced with the **MF** station data of Figs.1-2.

  If we now turn to an high altitude gridpoint corresponding to the "massif du Mercantour" (2000/3000m., Fig.4), some conclusions differ: whereas the only clear increase (although not statistically significant) of seasonal precipitation always occurs for automn, there are no more signals of aridification at all for other seasons, and even some significant signals of increase for winter extreme indices.

For the area averaged precipitation over the Alpes Maritimes (not shown), no significant trends occur; precipitation however clearly increases during fall, and decreases by a similar amount ($\approx$ 100 mm) during winter (DJF).

- **Embrun station** (**MF** data) and **Queyras** (**APC** gridded data): the changes in precipitaion indices for Embrun station data are not that many. The total seasonal accumulations show little changes, except for some (non significant) increase for intermediate seasons. But there are some signals of a significant increase of heavy precipitation during spring, and of "extreme" ones (**PQ95**) during winter (not shown).

  With the **APC** gridded data, we define a Queyras region like in *PSD2001*. Conclusions are mostly similar, with a few significant increases of indices quantifying extreme precipitations during spring, fall, and winter. The maximum drought duration also increases for spring (but decreases for fall). The seasonal accumulations show negligible trends, except for some increase during fall like for the Alpes Maritimes.

- **Perpignan station** (**MF** data) and **Roussillon** (**APC** gridded data): There are very few significant trends in Perpignan **MF** series, except for a decrease in **PINT**, the simple day intensity for spring, together with a decrease in **PN90** and **PS** and **PSQ90** for the same season (not shown).

  For the Roussillon region as a whole (9 **APC** gridpoints, see *PSD2001*), there is only some marginally significant increase of **PN90** in winter and decrease of **PxCDD** during fall; both point to slightly increasing wetness, which the linear trends on seasonal accumulations confirm (not shown).

- **Savoy** (**APC** gridded data) (Fig.5) is a particular case in our study of Alpine subregions: **ALL** the indices connected to extreme precipitation display at least some increase for all 4 seasons. **PQ90** and **Px5D**, the greatest 5-day total rainfall show their most significant increase during winter, like **PINT**, the simple day intensity. The most striking increases of **Pf90**, the percentage of total rainfall from events > long-term **PQ90** and **PN90**, the number of events > long-term **PQ90**, also occur for winter and are highly significant (there are several "+++" printed on Fig.5). **PN90** has grown from 2.2 events per winter in the mid-sixties, up to 5.2 events at the end of the century. Seasonal rainfall increased by $\approx$ 100 mm for both automn and winter; the increase of precipitation from events > long-term **PQ90** was strongest for winter and itself $\approx$ 100 mm: all the increase of winter precipitation over Savoy is accounted for by these events. It is amazing to observe that **PxCDD**, the max number of consecutive dry days also (weakly) increases for all seasons: dry period durations do not exhibit trends to lower values, but wet days get wetter.

  The behaviour of extreme indices for Savoy stands out against that observed on the southern flank of the Alps.

- **More general observations**: A more general investigation of **MF** station data actually points to the very different behaviours to the north (even farther north) and to the south of the Alps: to the north, like for Savoy, most stations receive more intense precipitation during all seasons, except summer, and a number of extreme indices increases are highly significant, especially during winter. Opposite behaviours also tend to dominate for spring between north and south. To the south, automn is the only season with a significant increase of some indices quantifying extreme precipitation.

- **Low frequency variability**: we end this discussion about precipitation trends by a *caveat*: low frequency variability should not be neglected; we may, for instance, outline the occurence of 6 consecutive dry winters for Savoy in the early seventies, or of a similar series of dry winters in the Alpes Maritimes in the late eighties (after a series of wet ones in the late seventies). The early 90's automns were also especially wet over all 4 areas. With the **MF** data, one can look further in the past. In Perpignan, the contrast is striking between the wet automns of the sixties and the dry ones of the following 14 years. However, there are no other stations with such a dramatic low frequency behaviour, and the case of Perpignan may be an isolated one in France, in relation with its boarder position near Catalonia. We futher comment the behaviour of Perpignan series im section 4.

  In all the ways, we have to set an important *caveat* **concerning future future climate scenarios investigations**: one should not try to draw any conclusion using only 10, or even 20 years of an end of the 21^{st} century simulation, since natural interdecadal fluctuations could significantly bias the estimation of long term extreme tendencies.

4 Temperatures

With temperatures series, warming signals accumulate.

- **Nice station** **MF** temperatures series: Like what is the case for most french station series, the increase of **TxQ90**, the 90^{th} percentile of Tx, is highly significant for summer (it reaches the 99% level, as pointed out by the "+++" sign on the corresponding pannel of Fig.6). **TxQ90** exhibits some positive, but non significant, trends during other seasons. On the contrary, the **TnQ10** increase is highly significant all along the year, except for automn where only the lowest significance level (90%) is reached. We already mentioned that the definition of heat waves in **THWDI** was fully inoperant for Nice where positive $\geq$ 5 deg Tx anomalies lasted more than 5 d. only twice in 53 years! **TxHW90**, the new index measuring heat wave duration, is much more relevant (see the lowest hitograms on Fig.6). It increases more or less for all seasons, but some significance level is only found for automn. In all the ways, even with this definition, heat waves remain rather short in Nice, although warmth is an almost permanent feature of the Côte d'Azur climate! But Nice warmth is not heatwave, it's simply local climate.

- **Embrun station** **MF** temperatures series (Fig.7): Except for **TxQ90** in spring (resp. summer) which display significant increase at the 90% (resp. 99%) level, winter is the only calendar season with clear warming signals: the positive trends of **TxQ90** and **TxHW90** are significant at the 95% confidence level, whereas the increase of **TnQ10** (from $\approx$ -9 up to $\approx$ -6 degC) and the corresponding decrease of **TnFd** (by more than 10 days per winter) achieve the 99% significance level. On the contrary, for spring, neither **TnQ10**, nor **TnFd** or **TxHW90** (the max. heat wave duration) show the least warming trend; the same is true for automn (except for a non significant decrease of **TnFd**).

  The behaviour of **TnQ10**, the 10^{th} quantile of Tn stands in contrast with that observed in Nice where its increase is striking for at least 3 seasons. Embrun is a mid-altitude (870 m.) station in montainous terrain, whereas Nice airport station lies within a few tens meters from the sea, with more and more buildings and urban environment to the opposite side. So any direct comparison would raise many problems.

Table 3: Balance sheet of trend significance for 20 french stations

Number of + acronyms in trend significance messages for **TxQ90** and **TnQ10**				
Index	Spring	Summer	Automn	Winter
TxQ90	11	48	0	22
TnQ10	50	39	12	45
Number of − acronyms in trend significance messages for **TxQ90** and **TnQ10**				
Index	Spring	Summer	Fall	Winter
TxQ90	0	0	0	0
TnQ10	0	0	0	0

- **More general observations for TxQ90 and TnQ10 for french stations** We may however compare these observations with the evolution of extremes in other french cities. Taking into account 20 **MF** french stations, we are lead to the following conclusions which can be inferred from table 3 below:

  1. For **TxQ90**, most stations, whether in the Alps or elsewhere, behave like Embrun. The maximum warming trends for Tx extremes are usually observed for summer; winter follows, with positive trends that are less significant and less frequent; **TxQ90** warming signals occur even more infrequently for spring, whereas they are never observed during fall which seems to stand apart.
  2. For **TnQ10**, on the contrary, a majority of stations behave like Nice. The automns again stand apart, with very tiny significance levels of increase, if any. But for the other 3 calendar seasons, highly significant warming trends for extreme Tn are observed almost everywhere, especially during the extreme seasons. This seasonal behaviour is confirmed by the observations on **TnFd** changes, where frost days occur: in most cases, **TnFd** quite significantly decreases during winter and spring, whereas the changes in the number of early season (automn, SON) frost days almost never reach any significance level.

- **Perpignan station MF** temperatures series: The Perpignan station temperature series looks somewhat atypic when compared to other french series: the changes in extremes are quite different from those observed in other (alpine or not) french stations. The 90% significance level is never reached for the index **TxQ90**. For **TnQ10**, it is only attained during winter and spring. Conversely, the decrease of **TnFd** during winter is significant at the 95% level. **TxHW90** (the max. heat wave duration) histograms are quite flat, or even display some tiny decrease. (Like for Nice, the STARDEX index **THWDI** remains almost tied to the null value!).

  This atypic behaviour of temperatures in Perpignan could be due to the fact that, given the position and the specific orography of this region, the local climatic extremes are brought about by specific Large Scale Circulation patterns and Weather Regimes which exert quite different influences on other sub-regions; we may for instance remind that the extreme precipitation in Roussillon often occur with **Blocking** like circulation patterns (*PSD2001*). Although the **Blocking** patterns are likely to play a similar role for

Catalonia, this is a very peculiar behaviour compared to our other regions of interest in France.

- <u>**Summary**</u>: In Nice, **TxQ90** only increases for Summer, whereas the **TnQ10** increases are quite large and highly significant for all seasons but fall. In Embrun, except for a highly significant increase of **TxQ90** during summer (and a marginally significant one for spring), only winter indices show clear warming trends; on the contrary, fall indices never increase in Embrun. There are a very limited number of warming indications for Perpignan which seems to stand apart, like for precipitation.

  The changes of extremes observed in Nice and Embrun may be compared to those observed elsewhere in France. Like in Embrun, the maximum warming trends for **TxQ90** mostly occur during summer; winter follows, then spring. Fall stands apart. Like in Nice, **TnQ10** increases are usually highly significant during three seasons, whereas the case of automns is very particular, with some tiny significance level in a few cases, if any.

  Thus, as a whole, the behaviour of french stations **TxQ90** and **TnQ10** appears very homogeneous (see again table 3 which allows to infer these clear conclusions, thanks to our categorical significance test for trend).

5 Conclusion

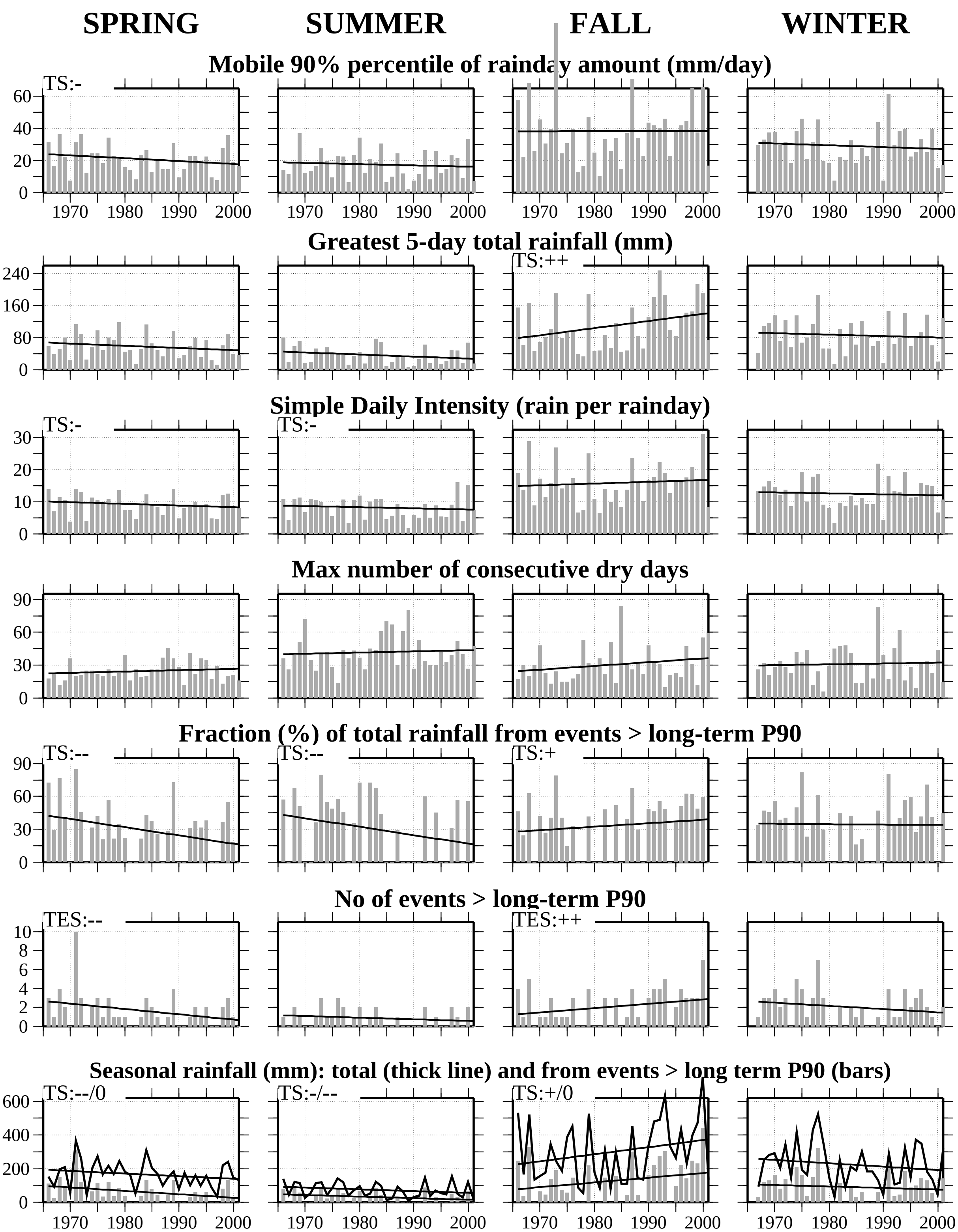
For precipitation extremes, the only common features of all sub-regions is their trend to wetter automn, whereas for winter and spring opposite signals tend to be observed to the north and to the south of the Alps. To the south of the Alps, during 3 seasons out of 4, (more or less significant) aridification signals occur for extreme as well as for mean precipitation in most stations. To the north, winter is the season with the highest positive trends of most indices quantifying extreme precipitation.

Warming trends for extreme temperature indices abound; however, one season (automn) seems to stand apart. The highest warming trends for **TxQ90** are observed during summer, whereas they most often occur all over the year (except during fall) for **TnQ10**. These tendencies are confirmed by the changes of **TnFd** (at least where frost days are not an exception): the number of frost days exhibits very significant negative trends almost everywhere during winter and spring, whereas things continue on their way for early (SON) frosts.

The importance of Low or very Low Frequency variability of seasonal precipitation extremes indices may raise problems when looking for future Climate scenarios and has to be taken carefully into account.

Reference

[*PSD2001*]: Plaut, G., Schuepbach, E. and Doctor, M., Heavy precipitation events over a few Alpine sub-regions and the links to large-scale circulation, 1971-1995, *Climate Research* **17**, CR Special 9 **ACCORD: Atmospheric Circulation Classification and Regional Downscaling**, pp 285-302, 2001.



Precip indices & 90% percentile statisics for NICE station precipitation

(Raingauge data from Meteo-France)

Figure 1:

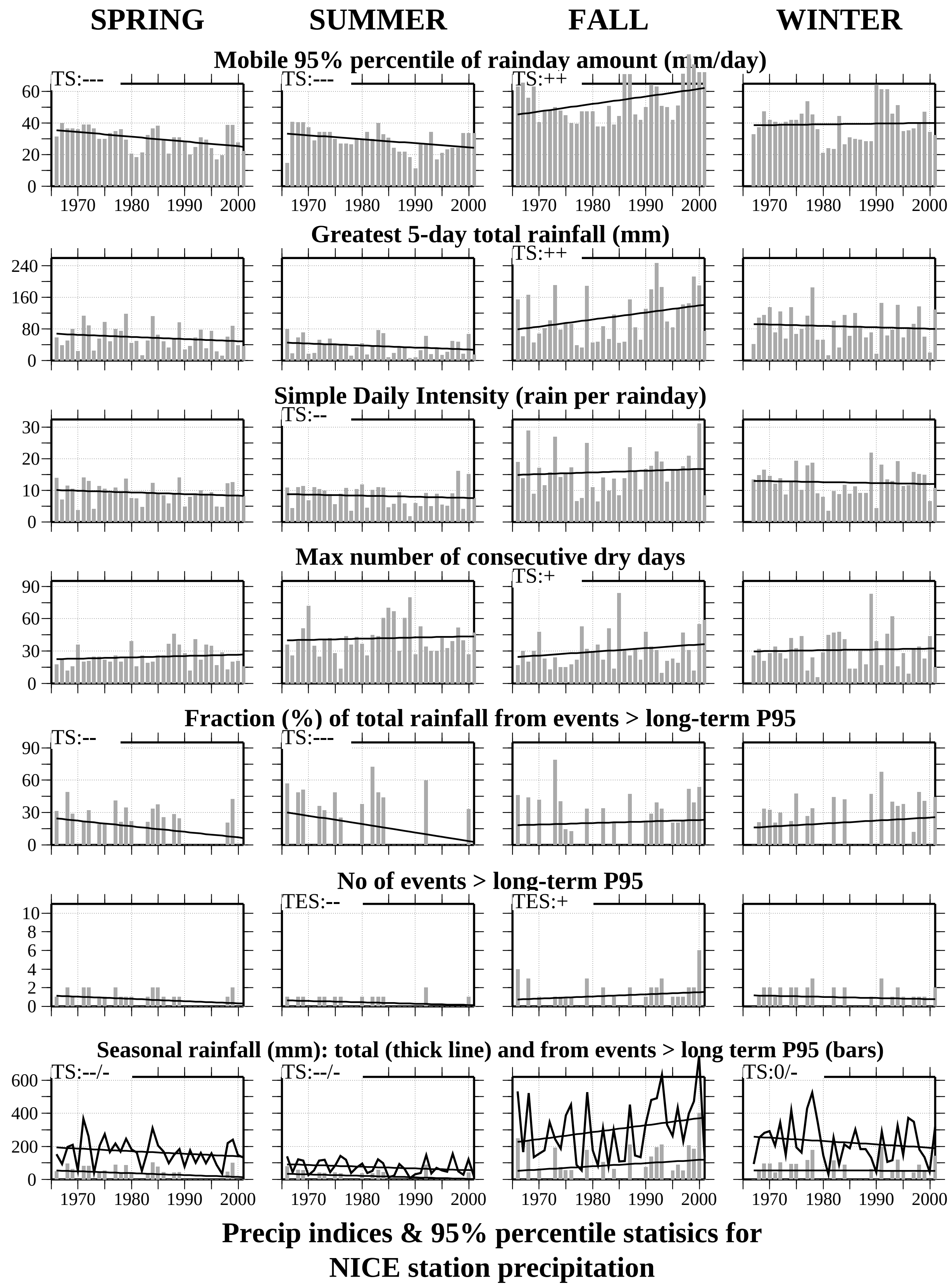

SPRING
SUMMER
FALL
WINTER
Mobile 95% percentile of rainday amount (mm/day)
TS:---
TS:---
TS:++
Greatest 5-day total rainfall (mm)
TS:++
Simple Daily Intensity (rain per rainday)
TS:--
Max number of consecutive dry days
TS:+
Fraction (%) of total rainfall from events > long-term P95
TS:--
TS:---
No of events > long-term P95
TES:--
TES:+
Seasonal rainfall (mm): total (thick line) and from events > long term P95 (bars)
TS:--/-
TS:--/-
TS:0/-
1970
1980
1990
2000
Precip indices & 95% percentile statisics for
NICE station precipitation

Figure 2:

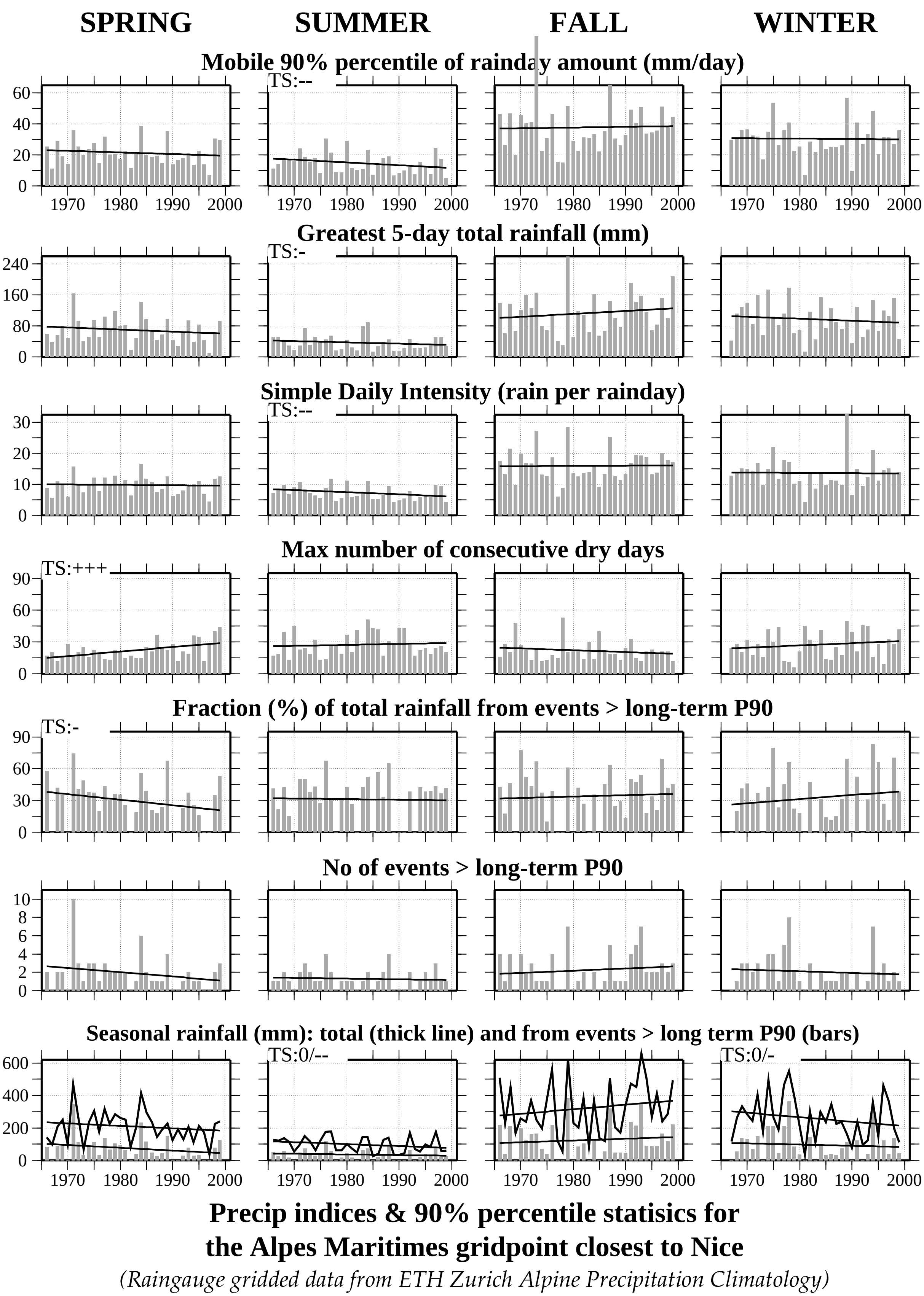
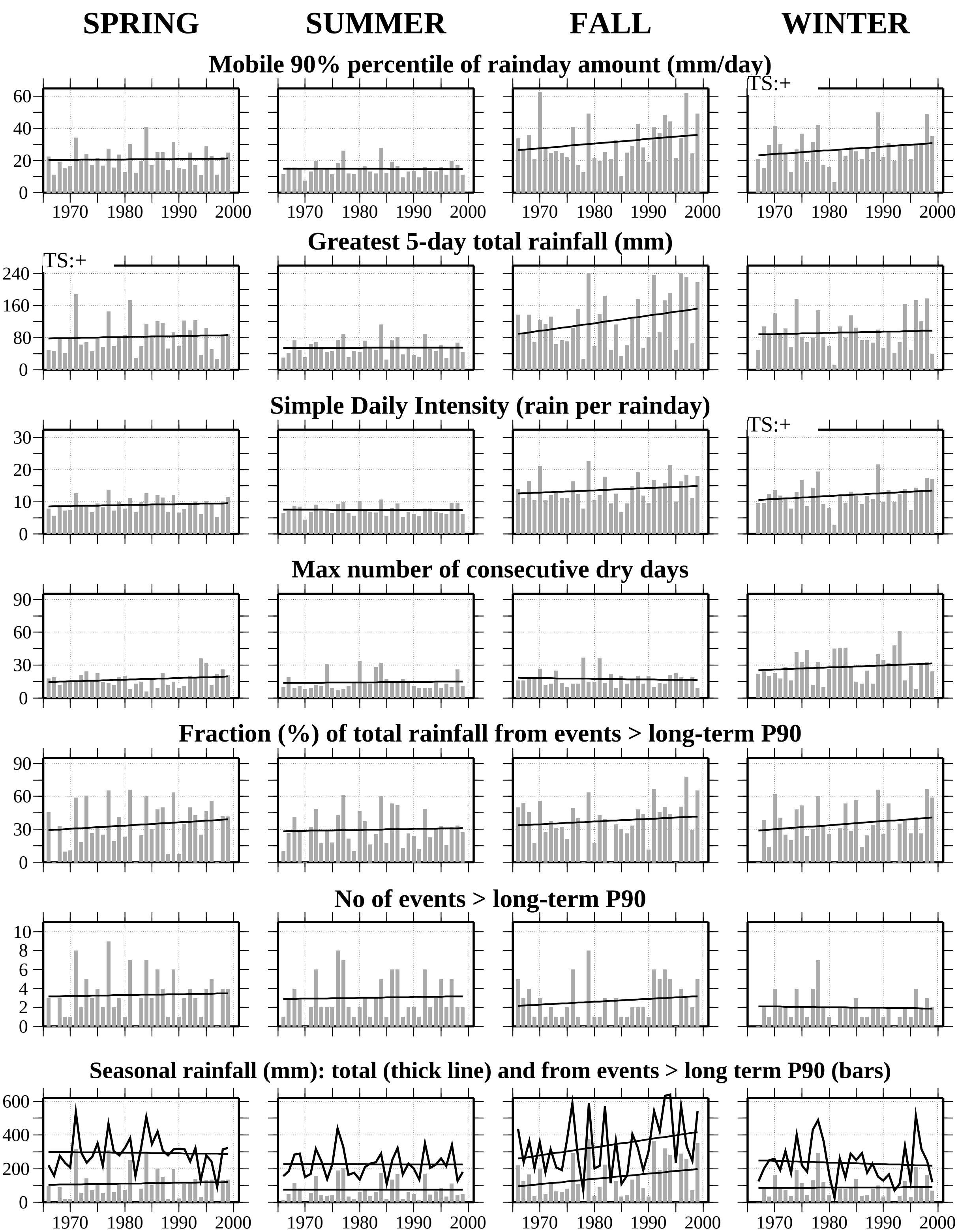

SPRING
SUMMER
FALL
WINTER
Mobile 90% percentile of rainday amount (mm/day)
TS:--
Greatest 5-day total rainfall (mm)
TS:-
Simple Daily Intensity (rain per rainday)
TS:--
Max number of consecutive dry days
TS:+++
Fraction (%) of total rainfall from events > long-term P90
TS:-
No of events > long-term P90
Seasonal rainfall (mm): total (thick line) and from events > long term P90 (bars)
TS:0/--
TS:0/-
1970
1980
1990
2000
Precip indices & 90% percentile statisics for
the Alpes Maritimes gridpoint closest to Nice
(Raingauge gridded data from ETH Zurich Alpine Precipitation Climatology)

Figure 3:



Precip indices & 90% percentile statisics for
an high altitude (Mercantour) Alpes Maririmes gridpoint

(Raingauge gridded data from ETH Zurich Alpine Precipitation Climatology)

Figure 4:

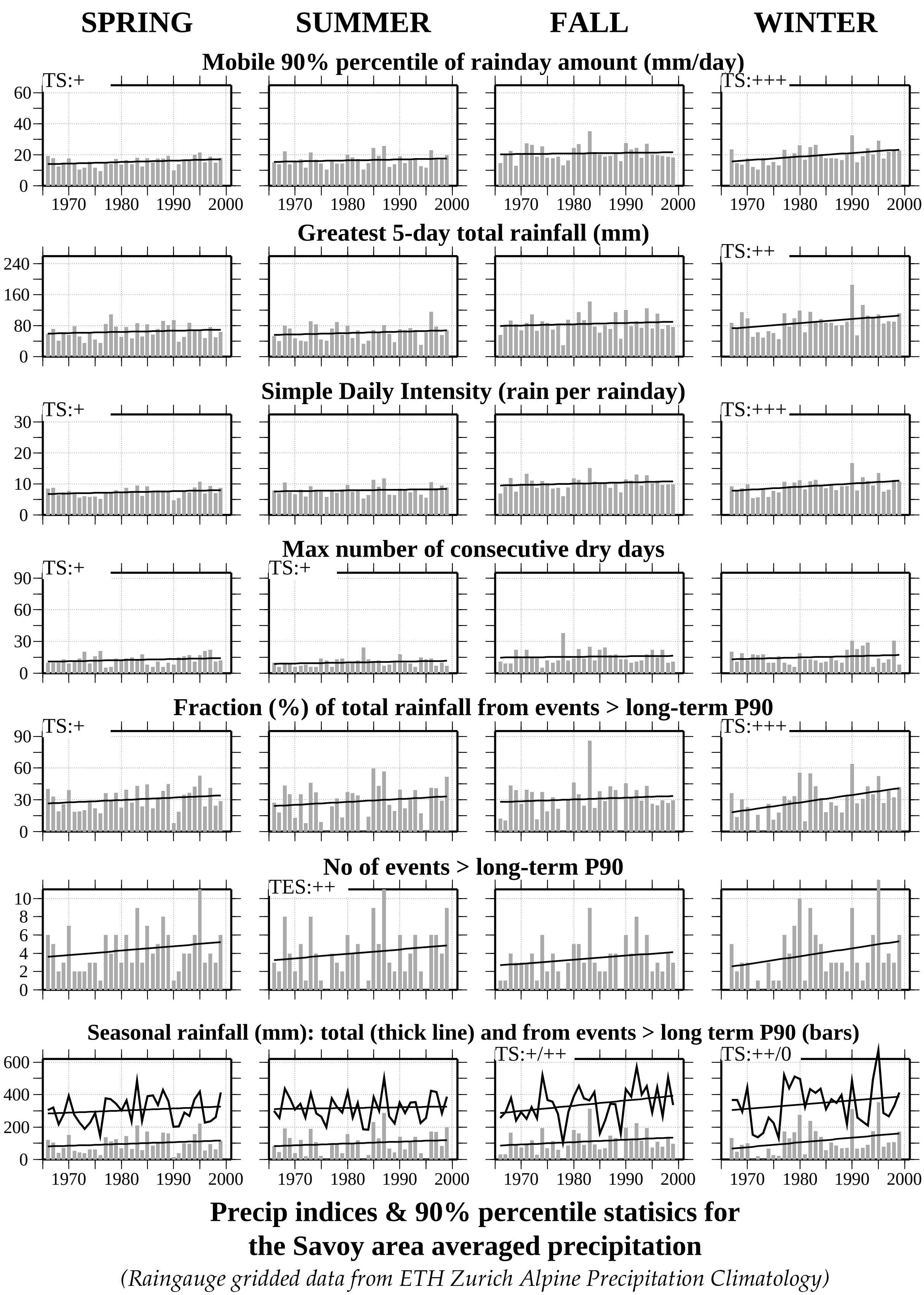
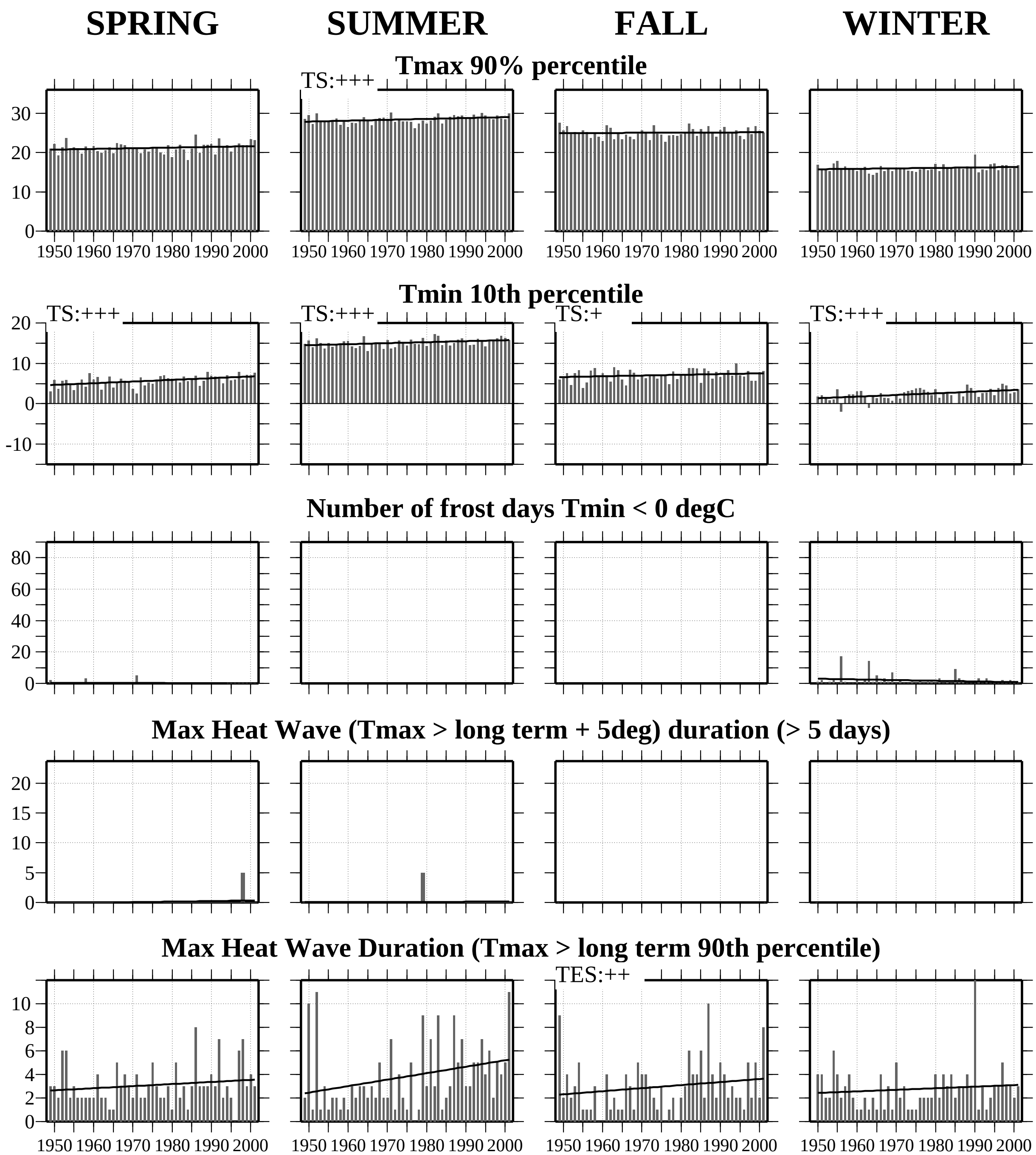

SPRING
SUMMER
FALL
WINTER
Mobile 90% percentile of rainday amount (mm/day)
TS:+
TS:+++
Greatest 5-day total rainfall (mm)
TS:++
Simple Daily Intensity (rain per rainday)
TS:+
TS:+++
Max number of consecutive dry days
TS:+
TS:+
Fraction (%) of total rainfall from events > long-term P90
TS:+
TS:+++
No of events > long-term P90
TES:++
Seasonal rainfall (mm): total (thick line) and from events > long term P90 (bars)
TS:+/++
TS:++/0
1970
1980
1990
2000
Precip indices & 90% percentile statisics for
the Savoy area averaged precipitation
(Raingauge gridded data from ETH Zurich Alpine Precipitation Climatology)

Figure 5:



Temperature indexes for NICE

(Station temperature data from Meteo-France)

Figure 6:

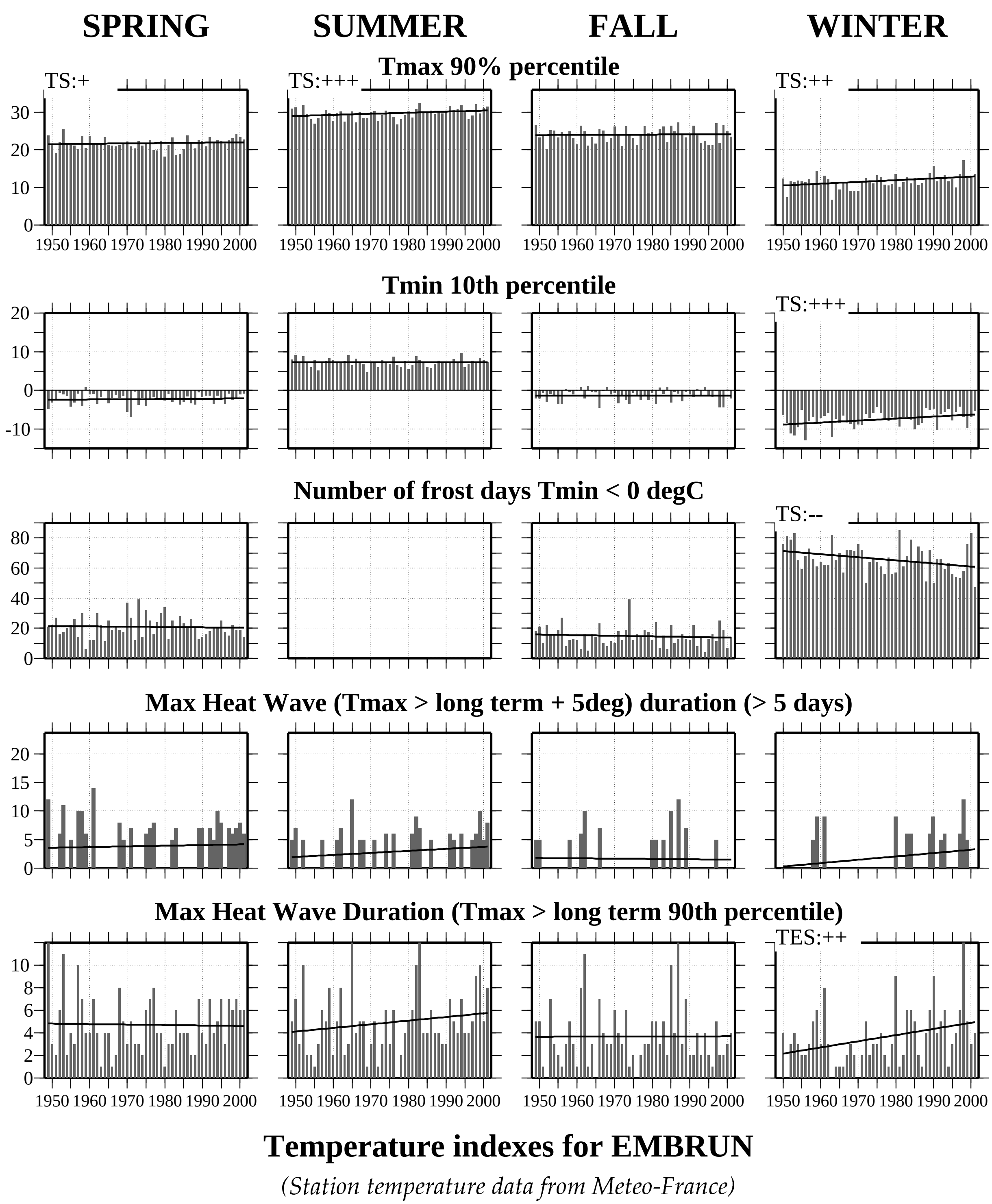

SPRING
SUMMER
FALL
WINTER
Tmax 90% percentile
TS:+
TS:+++
TS:++
Tmin 10th percentile
TS:+++
Number of frost days Tmin < 0 degC
TS:--
Max Heat Wave (Tmax > long term + 5deg) duration (> 5 days)
Max Heat Wave Duration (Tmax > long term 90th percentile)
TES:++
1950 1960 1970 1980 1990 2000
Temperature indexes for EMBRUN
(Station temperature data from Meteo-France)

Figure 7: