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Hydroclimatic response of the River Têt (southern France) to recent temperature increase

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Abstract This paper presents detailed trend analyses of the hydroclimatic patterns in the Têt River basin, a typical coastal river in the south of France. We investigated the period 1980–2000. Average temperatures during this period were among the warmest of the last century, and possible trends may allow an evaluation of the response of this river to future climate change. Our results show that the average annual temperature in the basin shows a highly significant trend towards increasing temperatures. Mean annual runoff from the basin is highly variable and shows no clear trend over the study period. Annual maximum discharge values, however, follow a trend towards increasing values. This trend is only present in the downstream part of the basin, at the gauging station close to the river mouth, but it is absent further upstream, in the mountainous part of the basin. The evolution of precipitation is consistent with this pattern. Although mean annual precipitation over the entire basin also shows no clear evolution in terms of its absolute values, it is found that the contribution from the highest basin parts decreased whereas the contribution from the middle and lower basin parts increased.

Keywords climate change; flash floods; Têt River (France); trend analyses

INTRODUCTION

In the Mediterranean region, the hydrology of the coastal rivers is characterized by a strong temporal variability of the water flow. In some areas along the Mediterranean coast, the recorded maximum daily rainfall is close to the mean annual rainfall. As a consequence, the ratio of peak discharge to mean annual discharge is frequently about one order of magnitude greater than for rivers in non-Mediterranean areas (Estrela *et al.*, 2001). Often, most of the water discharge occurs during very brief flash floods, which can cause considerable damage for the population in this region. The hydrological response of this region to the predicted global temperature increase is therefore of broad interest.

The purpose of this paper is to present trend analyses of the hydroclimatic patterns in the Têt River basin, a typical coastal river in the south of France, for the period 1980–2000. Average temperatures during this period were among the warmest of the

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last century (IPCC, 2001), and possible trends may allow an evaluation of the response of this river to future climate change. Focusing on the Têt River basin is interesting mainly for two reasons. One is the strong geomorphic gradient in the basin; the upper and lower zones of the basin may respond differently with respect to climate change. The other reason is the strong anthropogenic pressure on the water resources of the basin. As in many other parts of the Mediterranean area, water use strongly impacts the hydrology of the Têt River, and a key question is, naturally, how water use may respond to future climate change.

DATA AND METHODS

Our approach is based on exploitation of hydrological and meteorological station data collected by public French monitoring agencies during 1980–2000. Water discharge data were obtained from the HYDRO database hosted at the French Ministry of Environment, whereas precipitation and temperature data were taken from the Pluvio-Transclim database of the national French monitoring agency, Meteo-France. All data were obtained either as daily (Q) or as monthly (Q, P, T) averages and then transformed to annual averages, which form the basis of our calculations.

For the spatial extrapolation of the T and P data, we analysed the Têt River basin on the basis of a digital elevation model (DEM) in order to extract the basin contours of the entire drainage basin, as well as the contours of the sub-catchments to which the gauging stations correspond (Ludwig *et al.*, 2003). Overall, we distinguished 13 sub-catchments in the river basin (Fig. 1(a)). Annual precipitation climatologies for the years 1980–2000 were created by applying triangular interpolation routines to the station data, and the results were then gridded at the same resolution as our DEM (Fig. 1(b)). For temperature, the climatologies were derived by a series of regression analyses between the station data and their elevations and latitudes, and then extrapolated spatially on the basis of our DEM. Table 1 shows different geomorphic and hydroclimatic characteristics of the Têt River basin and its different sub-catchments.

Trend analyses were performed by using the Mann-Kendall (MK) non-parametric test for trend. This test was found to be an excellent tool for trend detection, and many scientists have used it to assess the significance of trends in geochemical and hydro-climatic time series such as water quality, streamflow, temperature and precipitation (e.g. Burn & Hag Elnur, 2002; Yue *et al.*, 2002).

RESULTS AND DISCUSSION

The reconstructed temperature evolution for the entire Têt basin follows a highly significant (SL $\geq$ 99%) positive trend (Fig. 2). We estimate the amplitude of this temperature increase to be about 1.3°C, which is considerable for a time span of only 21 years. According to our data, 1980 was the coldest year with an average temperature of 8.5°C, whereas 1997 was the warmest year with an average of 11.1°C. The average discharge of the Têt River during the 1980–2000 period was 10.2 $m^3 s^{-1}$,

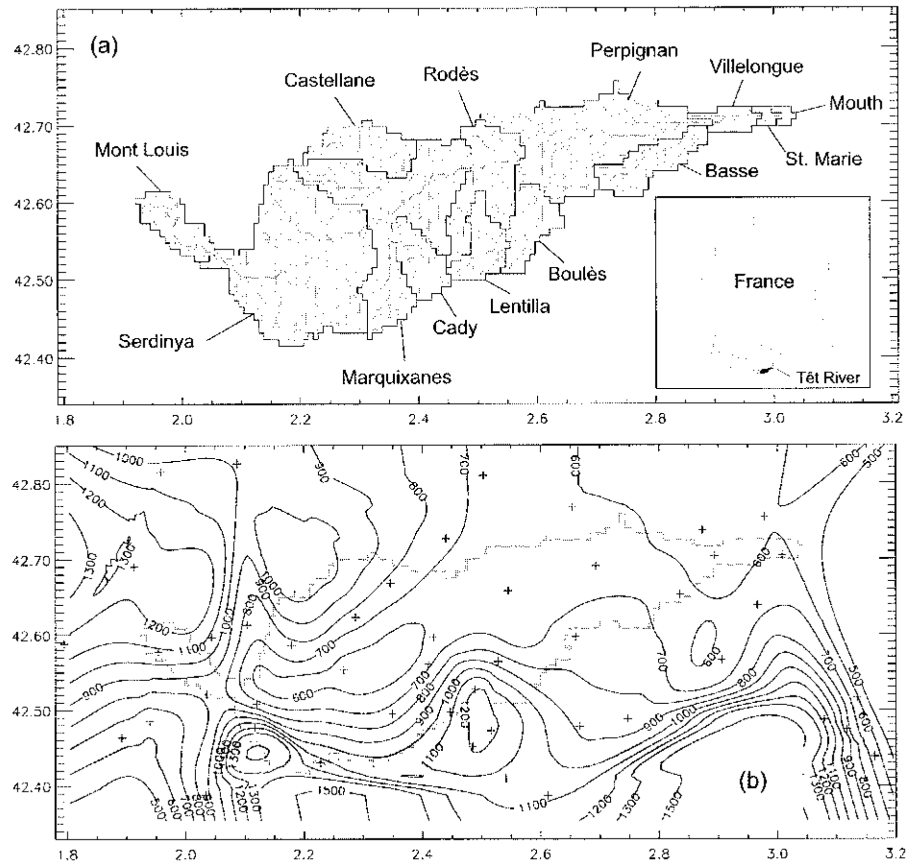

Fig. 1 (a) DEM derived map of the different sub-catchments in the Têt basin that are distinguished in this study. (b) Distribution of the annual precipitation total (average of 1980–2000, in mm) in the Têt basin. The crosses indicate the position of the meteorological stations that were considered for spatialization.

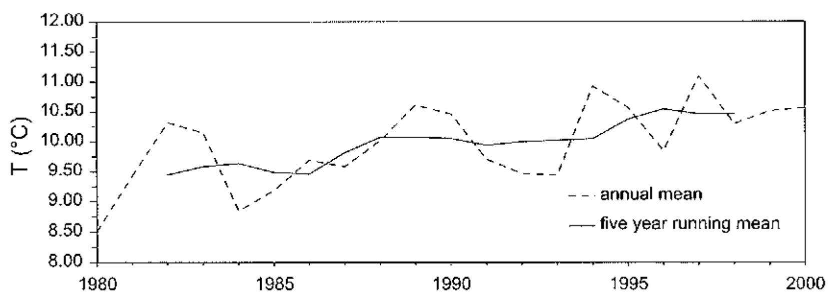

Fig. 2 Evolution of the average basin temperature in the Têt basin.

corresponding to an average drainage intensity of 238 mm. No trend can be observed for the considered period (Fig. 3(a)). The most striking feature is the strong interannual variability of the Têt discharge, as this is also typical for many other Mediterranean rivers. Note that the annual water discharge varied by almost one order of magnitude.

Table 1 Geomorphic and hydroclimatic (1980–2000 average) characteristics of the Têt River basin

Basin name	Area (km^2)	Elev. (m)	Slope[b] (°)	*T* (°C)	*P* (mm)	*F*-index[c] (% P)	*Q*-net[d] (mm)	*E*[e] (mm)	*RR*[f]
Entire basin	1396	1023	12.44	10.0	757	14.3	238	519	0.31
Mont Louis	56	2148	11.09	3.7	1044	10.3	672	372	0.64
Serdinya	370	1672	17.62	6.5	798	12.7	314	485	0.39
Cady	56	1497	17.66	7.5	812	13.5	462	350	0.57
Marquixanes	258	1051	15.16	9.8	718	13.8	263	455	0.37
Castellane	74	1153	14.54	8.9	842	12.4	405	437	0.48
Lentilla[a]	56	1278	20.58	8.7	1005	14.5	464	541	0.46
Rodès	114	651	11.58	12.0	699	15.9	274	424	0.39
Boulès[a]	62	740	12.40	11.7	786	15.7	258	528	0.33
Perpignan	241	204	3.70	14.3	646	16.7	–241	887	–0.37
Basse	70	94	1.43	15.1	666	16.1	423	244	0.63
Villelongue	25	24	0.77	15.3	572	17.6	--	--	--
St. Marie	8	9	0.48	15.3	608	17.7	--	--	--
Mouth	6	2	0.19	15.4	596	17.7	--	--	--

[a] Time series of water discharge have been completed by linear correlation to neighbouring stations for many years, which may affect the reliability of the *Q*-net, *E* and *RR* parameters.
[b] Average grid point slope.
[c] Fournier index (sum of [(monthly $P)^2$/ annual *P*]) (Corine, 1992); it is expressed as percentage of annual *P*.
[d] *Q*-net is the difference between water discharge at a given gauging station and the water discharge at the upstream gauging station; when this value is negative, there is a water loss between two stations.
[e] $E = P - Q$-net.
[f] RR = runoff ratio = Q-net/P.

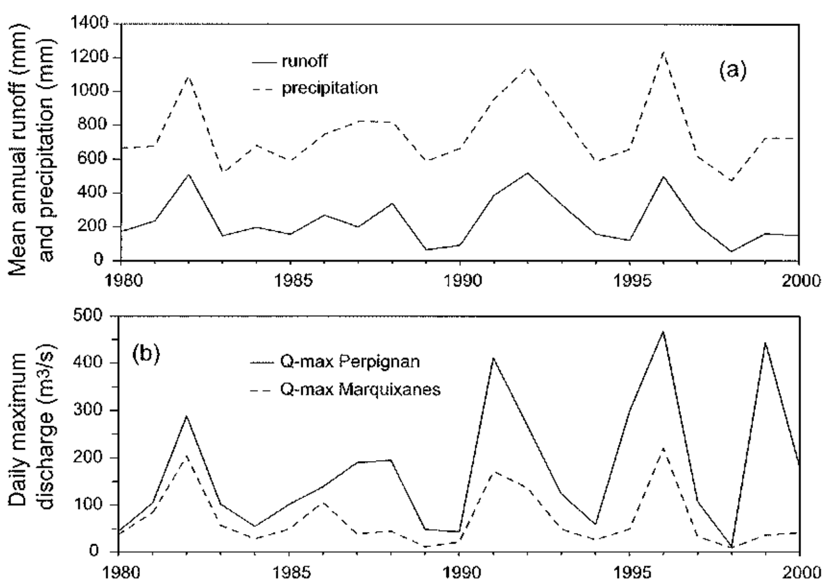

Fig. 3 Evolution of (a) total annual discharge and total annual precipitation in the Têt basin; (b) daily maximum discharge at Perpignan and at Marquixanes.

However, when studying the daily maximum discharge, one can observe that the evolution was not uniform. Especially during the 1990s, which was the warmest decade of the last century (IPCC, 2001), daily maximum discharge values at the Perpignan gauging station were clearly greater on average than during the 1980s (Fig. 3(b)). There is a general trend of increasing maximum values during the 1980–2000 period, although it is only weakly significant (SL ≥ 80%). The irregularity of flood occurrence leads to a great interannual variability of daily maximum discharge, which complicates the detection of trends. When smoothing the curves, e.g. by deriving the 5-year running mean, the trend becomes highly significant (SL ≥ 99%). Moreover, it is remarkable that the evolution towards increasing maximum discharge is only detectable in the downstream part of the Têt basin, but not in the upstream part. This can be seen when comparing the daily maximum discharge values at Perpignan with those of Marquixanes (Fig. 3(b)), covering about 815 km^2 of the Têt basin in its upper part. As a consequence, the ratios of the annual maximum discharge at Marquixanes and at Perpignan follows a highly significant trend (SL ≥ 99%) of decreasing values. This means that, even if the total discharge of the Têt River did not evolve significantly during the 21-year study period, there is a clear trend towards an increasing impact of peak discharge on total discharge. And, the floods are more and more often generated in the downstream part of the basin without affecting the upstream parts.

The 1980–2000 average annual precipitation total over the entire Têt basin is 757 mm according to our precipitation climatologies. The evolution of the annual P values matches closely with the evolution of Q (Fig. 3(a)). Interannual variability of P is less important than for Q, but still considerable. As in the case of Q, no significant trend was found for the evolution of precipitation.

Also, at the level of the individual sub-catchments, clear trends for P are not present (Table 2). However, the absence of clear precipitation trends in the different parts of the basin may be overwhelmed by the great interannual variability of precipitation, which is also controlled by the climatic patterns at larger scales. When calculating the relative contribution of the individual basin parts to the total basin precipitation, trends become more abundant. Particularly in the middle basin, the relative contributions seem to increase, and positive trends at the SL ≥ 95% level were found in the Marquixanes and Boulès catchments.

It is nevertheless a general feature that there is a general tendency of decreasing precipitation values in the uppermost basin parts, and of increasing values in the middle and lower basin parts. This can be shown best by grouping the catchments. When calculating the ratio of the average precipitation falling in the elevated basin parts (all catchments with an average elevation >1200 m) over the average precipitation falling in the lower basin parts (<1200 m), one finds a highly significant trend (SL ≥ 95%) of decreasing ratios (Fig. 4). These groups account for about 43% (>1200 m) and 57% (<1200 m) of the total precipitation falling on the entire Têt basin.

This trend is consistent with the changes in water discharge. Even if the average values did not change significantly over the 1980–2000 period, it seems that the middle and lower part become more important for the hydroclimatic functioning of the Têt River, both in catching the rainfall in the basin and in the generation of peak discharge. It is possible that the evolution of the rainfall patterns is directly related to

Table 2 Results of the MK tests for trend for the 1980–2000 evolution of different hydroclimatic parameters in the sub-catchments of the Têt River basin

Basin name	Area (km^2)	Elev. (m)	*Q*-net (mm)	*Q*-net (%)[b]	*P* (mm)	*P* (%)[b]	*E* (mm)	*E* (%)[b]	*F*-index (mm)	*F*-index (%)[b]
Entire basin	1396	1023								
Mont Louis	56	2148			-	-	---	----	--	
Serdinya	370	1672								
Cady	56	1497		+						
Marquixanes	258	1051	--	-		+++	++++	++++		
Castellane	74	1153					++			
Lentilla[a]	56	1278				-				+
Rodès	114	651								
Boulès[a]	62	740				+++	++			
Perpignan	241	204								
Basse	70	94								+++
Villelongue	25	24							+	++
St. Marie	8	9								
Mouth	6	2								

Only trends with significance levels ≥ 80% are shown. Trends are positive for + and negative for –; one, two, three or four signs indicate significance levels ≥ 80, 90, 95, and 99%, respectively.

[a] see Table 1.

[b] The unit percent represents the contribution of the sub-catchment to the total basin value.

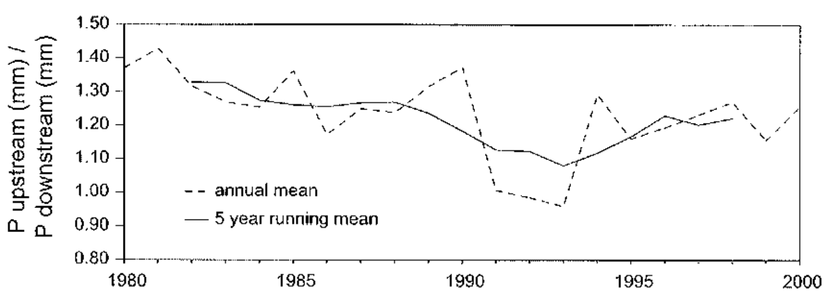

Fig. 4 Evolution of the ratio of upstream precipitation (grouping all catchments >1200 m) over downstream precipitation (grouping all catchments <1200 m) in the Têt basin.

the temperature increase during that period. Rainfall in this part of France is often derived from the landwards movement of humid air masses over the Mediterranean Sea by east and southeast winds, especially in the case of heavy downpours (Bechtold & Bazile, 2001). Higher temperatures may increase the probability of the occurrence of such events, or provoke earlier saturation of the air masses when they move towards the basin relief. Such explanations are, of course, speculative, and should be confirmed by detailed studies on the evolution on general meteorological and climatic patterns during that period, which is beyond the scope of our study.

CONCLUSIONS

In this study, we draw a detailed portrait of the average geomorphic and hydroclimatic characteristics of the Têt River basin, and reconstruct the evolution of these patterns during the period 1980–2000. Our work was initiated by the observation that these decades were the warmest of the last century, and we investigated the idea that this may have changed the hydrological functioning of the river basin.

Our results show indeed a highly significant trend of increasing average temperatures for the investigated period. For the entire basin, we estimate the amplitude of this increase to be about 1.3°C, which is considerable for a time period of only 21 years. This is, however, not accompanied by significant evolutions of the annual averages of Q and of P for the whole basin, implying, on first sight, that the hydrology of the river was not affected by the temperature increase. But detailed study shows clear modifications of the hydroclimatic functioning. The principal modifications are a trend towards increasing maximum discharge values, and that floods become more important for the total discharge. Moreover, these floods are more and more often generated in the downstream part of the basin without affecting the upstream parts. At the same time, precipitation is moving downstream in the basin. The upper basin parts became less important for catching precipitation in the basin, whereas the contrary is the case for the middle and lower basin parts. If it holds true that our observations are related to the temperature change, flood frequency of the river may increase in the future, with increasing impacts in the downstream basin parts. Of course, one has to be careful in postulating general trends on the basis of only a 21-year period, and further investigations are needed to confirm and/or reject our findings.

REFERENCES

Bechtold, P. & Bazile, E. (2001) The 12–13 November 1999 flash flood in southern France. *Atmos. Res.* **56**, 171–189.

Burn, D. H. & Hag Elnur, M. A. (2002) Detection of hydrological trends and variability. *J. Hydrol.* **255**, 107–122.

IPCC (2001) *Climate Change: Third assessment report of the Intergovernmental Panel on Climate Change*, WG 1 & 2. Cambridge University Press, Cambridge, UK.

Estrela, T., Menéndez, M., Dimas, M., Marcuello, C. Rees, G., Cole, G., Weber, K., Grath, J., Leonard, J., Ovesen, N. B, Fehér, J. & Consult, V. (2001) *Sustainable water use in Europe. Part 3: Extreme hydrological events: floods and droughts.* Environmental issue report no. 21, EEA, Copenhagen, Denmark (available at http://www.eea.eu.int).

Ludwig, W., Serrat, P., Cesmat, L. & Garcia-Esteves, J. (2003) Evaluating the impact of climate change on the hydrology of the Têt River (southern France). *J. Hydrol.* (submitted).

Yue, S., Pilon, P. & Cavadias, G. (2002) Power of the Mann-Kendall and Spearman's rho tests for detecting monotonic trends in hydrological series. *J. Hydrol.* **259**, 254–271.