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in

Porqueddu C. (ed.), Ríos S. (ed.).
The contributions of grasslands to the conservation of Mediterranean biodiversity

Zaragoza : CIHEAM / CIBIO / FAO / SEEP
Options Méditerranéennes : Série A. Séminaires Méditerranéens; n. 92

2010
pages 187-192

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Climate change at the temperate-Mediterranean interface in southern France and impacts on grasslands production

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Abstract. Because of increasing impacts of summer droughts on grasslands in southern France, the climate change 1950-2008 was analysed at the temperate-Mediterranean interface (11 sites in the triangle Marseille-Toulouse-Lyon). Annual, monthly and seasonal temperatures (T), rainfall (R) and potential evapotranspiration (ET_p) had no significant trends of evolution along 1950-1979; their expectancies (expected values eT, eET_p, eR) followed flat lines eY = k (k being the periodic means). From 1979 to 2008, T and ET_p had positive linear trends, R no trend. Regression lines eT and eET_p had significantly positive slopes in all sites: around +0.5℃/dec (℃ per decade) for annual means, +0.75℃/dec for the hot dry months MJJA, only +0.3℃ for the cold wet months NDJF, and +73 mm/dec for annual eET_p from which 2/3 for the period MJJA. In this period, the total increase in thirty years of eT (+2.2℃) and eET_p (+137 mm) moved isotherm and iso-ET_p lines 250-300 km towards the N and NW in plains. Aridity indexes eET_p-eR and eR/eET_p calculated on this period show that Mediterranean climate boundaries moved by around 100 km to the N and NW (a 30 to 40,000 km² surface area increase in France, of which 30% are grasslands). Impacts on grasslands and livestock feeding systems are shortly presented.

Keywords. Climate change – Temperature – Rainfall – Evapotranspiration – Aridity index.

Le changement climatique dans l'interface tempéré-méditerranéen dans le sud de la France et ses impacts sur la production des prairies

Résumé. *L'impact croissant des sécheresses sur les prairies a conduit à analyser le changement climatique 1950-2008 à l'interface tempéré-méditerranéen au sud de la France (11 stations dans le triangle Marseille-Toulouse-Lyon). Les variables températures (T), pluviométrie (R) et évapotranspiration potentielle (*ET_p*), annuelles, mensuelles et saisonnières n'ayant pas évolué sur 1950-79, leurs espérances (eT, eR,* eET_p*) suivent des modèles linéaires plats eY = k (moyenne de la période). Sur 1979-2008, R reste sans tendance; T et* ET_p *varient autour de tendances linéaires croissantes. Les pentes des droites de régression représentant eT et* eET_p *sont : +0,5℃/déc (℃ par décennie) pour la température moyenne annuelle, +0,75℃/déc pour celle des mois secs et chauds (MJJA), +0,3℃/déc pour les mois froids et humides (NDJF), et +73 mm/déc pour* eET_p *annuelle dont 2/3 sur la période chaude MJJA. Sur celle-ci, les augmentation en 30 ans de eT(+2,2℃) et* eET_p *(+137 mm) ont déplacé les lignes isothermes et iso-*ET_p *de 250-300 km au N et N0. Même avec eR fixe, les indices d'aridité* eET_p*-eR et eR/*eET_p *de la période sèche indiquent une avancée au N-NO du climat méditerranéen de près de 100 km, soit sur 30 à 40 000 km² en France, dont 30% de prairies. Les impacts sur les prairies et les systèmes fourragers sont brièvement présentés.*

Mots-clés. *Changement climatique – Température – Pluviométrie – Évapotranspiration – Indice d'aridité.*

I – Introduction

After centuries without significant trend of variation, the annual temperature of the world increased from 1900 (Mann *et al.*, 1999). The warming rate is defined by the slope of a linear model applied to its variations over the last century, close to +0.07℃/dec (ºC per decade) at world level (IPCC, 2007). This global value does not represent the recent regional evolutions of climate parameters influencing ecosystems, agrosystems, and economical activities. Over the past 110 years, warming was not constant along time; its rates were higher on continents than on oceans and different between continents and regions. In France, a study using 70 meteorological stations over 1900-2000 confirmed that warming was slow during 1900-1979 (+0.03℃/dec) but accelerated (+0. 5℃/dec) in 1980-2000 (Moisselin *et al.,* 2002). In Europe and the Mediterranean Basin, these modifications have already produced significant impacts on plants, eco- and agro-systems. For perennial covers like forests and grasslands: (i) in cold and mild wet regions like northern Europe, annual biomass production is increasing by the combination of longer growth cycles in days and thermal time and [CO_2] increase; and (ii) conversely, in dry regions like southern Europe, the increase of durations and intensities of summer-autumn droughts seems prevailing through shorter growth periods and more frequent damages to plants (Tubiello *et al.,* 2007). The different impacts of climate change between wet mild temperate regions and dry hot Mediterranean areas being superimposed to the opposed growing seasons (spring-summer-autumn *vs* autumn-winter-spring), it is necessary to understand the resulting effects at temperate-Mediterranean climates interface. This study had two objectives: (i) to analyse along the last sixty years (1950-2008) in southern France the evolution trends of the main climatic variables determining grasslands production (temperatures, potential evapotranspiration, rainfall and water availability, aridity indexes); (ii) to analyse impacts of these trends on growth and dry matter yields of grasslands in this region.

II – Materials and methods

Three conditions determined the choice of the 11 meteorological stations employed in this study: (i) to cover the historical temperate-Mediterranean transition, in the triangle Lyon-Toulouse-Marseille, at two altitudes (plains under 200 m and plateaus at 500-700 m); (ii) to provide continuous and reliable climatic data for the period P3 (1980-2008), in order to analyze its climatic evolution and, if possible, for the previous 30 years P2 (1950-79), as a reference of the last stable period; and (iii) for period P3, to provide daily values of climatic variables necessary to run the STICS-Grass model simulating grass growth (Ruget *et al*., 2009): maximum, minimum and mean temperatures (Tmax, Tmin, T), rainfall (R), potential evapotranspiration (ETp Penman-Monteith method), global radiation (GR), wind speed (WS), air hygrometry (AH).

The eleven stations were chosen in the national meteorological networks (Meteo-France, INRA-Agroclim-France) covering the area. Among them, eight fulfilled the three conditions, and three had no data during P2. Historically, these stations had the following climates: (i) *Mediterranean* (Montpellier, Avignon, Carcassonne); (ii) *temperate sub-Mediterranean* (Toulouse, Montélimar, Millau-Plateau); and (iii) *temperate* (Albi, Lyon, Valence, Colombier, Mende). Eight are in plains (Table 1), only three on plateaus (Millau-Plateau, Mende, Colombier).

In each station, annual and monthly means of the measured variables T, R, ET_p were studied over years (Fig. 1). Along the period 1950-79 (8 stations), after confirmation of the absence of significant trend of evolution of any climatic variable Y, its expectancy eY (more probable value of Y) is written as a linear model (a): eY = k (where k is the mean of the 30 annual values). Along 1980-2008 (29 years, 11 stations), when Y varied around positive linear trends, it was fitted to linear regressions representing eY. The significance of slopes was tested (Student-t at p = 0.05). Regression lines were calculated twice: (b) without constraints using 29 years (1980-2008) for each station; (c) using 30 years after adding the point (X=1979; Y=k) imposed as origin (only possible for the eight stations with 1950-79 data). The two regression lines (b, c) were generally very close but (c) was preferably used because it imposed the continuity of eY between 1950-79 (a, flat) and 1979-2008 (c, increasing). The model composed of (a-c) represents the evolution of eY between 1950 and 2008; it follows well decadal smoothed means (Fig. 1). The slopes were expressed as ΔeY/dec (average variation of eY per decade along 1979-2008). This analysis was performed for T, R, ET_p by year, by month, and by periods of four months: January to April (JFMA), May to August (MJJA), September to December (SOND), and November to February (NDJF) to compare hot/cold periods (MJJA/NDJF). Aridity indexes (eET_p-eR and eR/eET_p) were calculated for the hot and dry MJJA period. The total evolution 1979-2008 of any variable Y was calculated as the difference eY_{2008}-eY_{1979}.

III - Results and discussion

1. Temperature expectancies (eT)

All annual and monthly eT were constant along 1950-79. From 1979 to 2008, annual eT increased linearly and significantly in each station, as shown in the example of Carcassonne (Fig. 1). Annual eT progressed at rates ranging from +0.39 to +0.67℃/dec (average regional rate: +0.5℃/déc (+1.5℃ in 30 y). It was not equally distributed among months (Fig 2a). Warming rate was everywhere much more important in the hot dry months (+0.75℃/dec in MJJA) than in the cold wet months (+0.30℃/dec in NDJF). In summer (MJJA), temperature increase was so important in the region (+2.2℃) that all stations in plains have nowadays higher eT than the 20℃ of the hottest stations Montpellier and Avignon in 1979 (Table 1). Summer isotherm lines have moved between 250-300 km towards N and NW in 30 years.

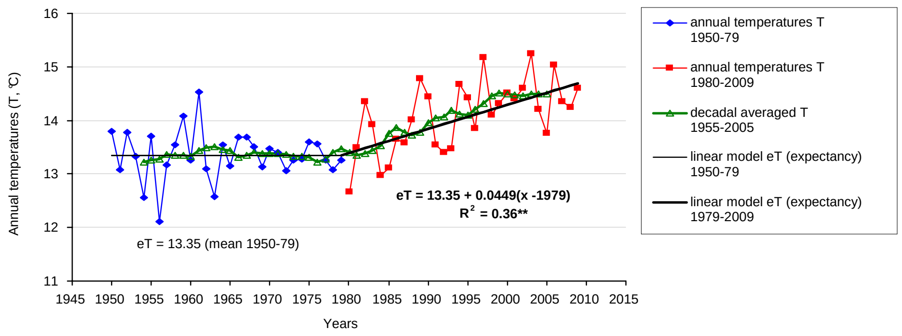

Fig. 1. Evolution of annual temperature in Carcassonne (Southern France), 1950-79 and 1979-2008.

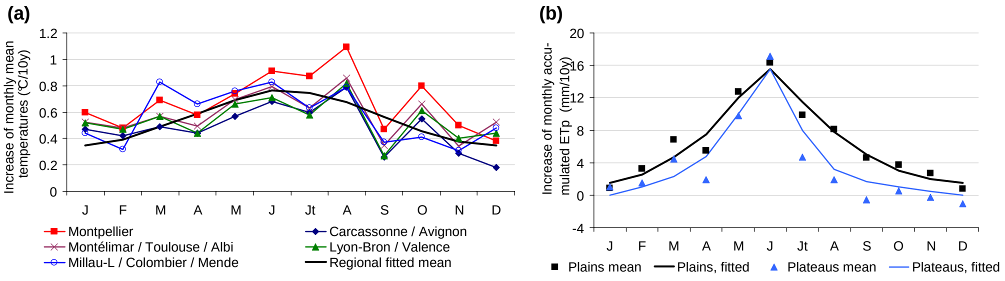

Fig. 2. Monthly Increase rate 1979-2008 of (a) expected mean temperature and (b) expected monthly evapo-transpiration, respectively in ℃ per decade and mm per decade.

2. Rainfall expectancies (eR)

No significant evolution was found along 1950-79 or 1979-2008 in any station, but trends may be hidden by the high inter-annual variability of R.

Table 1. **Characterization of climate evolution 1979-2008 in plains of southern France, through expectancies of rainfall eR, temperature eT, evapotranspiration eET$_p$, and aridity indexes (eET$_p$-eR and eR/eET$_p$), calculated (a) annually and (b) for the dry period May-August**

Stations	**Lyon**	**Valence**	**Albi**	**Toulouse**	**Montél.**	**Carcass.**	**Avignon**	**Montpel.**
Latitude North	45°43'	44°93'	43°54'	43°37'	44°35'	43°12'	43°91'	43°35'
Longitude East	5°02'	4°93'	2°07'	1°23'	4°44'	2°19'	4°85'	3°58'
Climate type 1979	Temper.	Temper.	Temper.	Temper.	Temper.	Medit.	Medit.	Medit.
Climate type 2008	Temper.	Temper.	Temper.	Medit.	Medit.	Medit.	Medit.	Medit.
(a) Annual values								
eR (mean 1979-2008, mm)	834	862	735	642	887	654	664	620
eT 1979 (°C)	11.4	11.9	12.6	12.7	12.8	13.4	13.6	13.9
eT 2008 (°C)	13.4	13.4	14.1	14.5	14.5	14.8	15.3	15.9
eET$_p$ 1979 (mm)	854	891	828	878	1051	1030	927	1127
eET$_p$ 2008 (mm)	1126	1033	1046	1120	1235	1204	1204	1366
eET$_p$-eR 1979 (mm)	20	29	93	236	164	376	263	507
eET$_p$-eR 2008 (mm)	292	171	311	478	348	550	540	746
ER/eET$_p$ 1979	0.98	0.97	0.89	0.73	0.84	0.63	0.72	0.55
eR/eET$_p$ 2008	0.74	0.83	0.70	0.57	0.72	0.54	0.55	0.45
(b) Dry hot period, months May to August (bold values are typically Mediterranean)								
eR (mean 1979-2008, mm)	293	266	245	221	255	179	175	124
eT 1979 (°C)	18.2	18.6	18.5	18.6	19.6	19.4	**20.1**	**20.0**
eT 2008 (°C)	**20.7**	**20.5**	**21.0**	**20.9**	**21.6**	**21.2**	**22.6**	**22.5**
eET$_p$ 1979 (mm)	505	543	465	499	**614**	**586**	**562**	**611**
eET$_p$ 2008 (mm)	**664**	**638**	**620**	**648**	**714**	**698**	**737**	**755**
eET$_p$-eR 1979 (mm)	212	277	220	278	359	**407**	**387**	**487**
eET$_p$-eR 2008 (mm)	371	372	375	**427**	**459**	**519**	**562**	**631**
eR/eET$_p$ 1979	0.58	0.49	0.53	0.44	0.42	0.31	0.31	0.20
eR/eETp 2008	0.44	0.42	0.39	0.34	0.36	0.26	0.24	0.16

3. Potential evapotranspiration expectancies (eETp)

Annual eET$_p$ were stable along 1950-79, but increased significantly everywhere between 1979 and 2008, at higher rates in plains (+73 mm/dec) than on plateaus (around +40 mm/dec). Two third of the annual increase was realised in the hot dry months MJJA in plains, more than 90% on plateaus (Fig. 2b). Accumulated eET$_p$ in the dry hot period MJJA is nowadays higher in all the studied stations (including plateaus not reported in Table 1) than the maximum in 1979 (Montpellier), indicating that in 30 y, summer iso-ET$_p$ lines have moved around 300 km towards the N and NW.

4. Aridity index expectancies (eETp–eR and eR/eETp) calculated on the hot and dry period (months MJJA)

The evolution of indexes between 1979 and 2008 show an important progress of aridity resulting of eET$_P$ increase (Table 1). Stations that were temperate sub-Mediterranean in 1980 (Montélimar and Toulouse in plains, Millau-Plateau) have nowadays aridity indexes corresponding to Mediterranean climates. Stations that were temperate in 1980 (Albi, Valence, Lyon, as well as Colombier and Mende on plateaus) have now sub-Mediterranean indexes. From 1980, boundaries of Mediterranean climate moved to the N and NW at 30-40 km/dec. In southern France, a surface of around 40,000 km², of which 30% are grasslands, turned to Mediterranean climate in 30 years.

5. Impacts on grasslands yields at the temperate-Mediterranean climate interface

Yields variations were modelled starting from a standard pasture before climate change in southern temperate plains (Montélimar, Valence, Lyon, Toulouse, Albi), yielding in average 1.8, 4.5, 1.8 t DM/ha respectively for the three parts of the year (JFMA, MJJA, SOND), the effects of climate change 1979-2008 were: (i) JFMA: the main effect was directly warming, early growth increasing proportionnally to degree-days (sum of eT) from 1 February to 30 April : +15 to +20%, and +0.3 to +0.4 t DM/ha depending on stations; (ii) MJJA: the main effect was a decrease of yields resulting of additionnal water deficits (eET_p-eR), from +95 to +175 mm (Table 1). It was calculated from variations of the estimated evapotranspiration ratios eET/eET_p with eET = eR + eSW (eSW being the expectancy of SW, the soil water reserve variation between 1st May and 31st August, obtained from a water balance). The results were from -15 to -30% and -0.7 to -1.3 t DM/ha; (iii) SOND: there was a slight positive effect of temperature increase (less than in spring), but counterbalanced by negative effect of droughts in September. Variations between years increased but not the expected yield; (iv) Whole year: the [CO_2] increase in 30 years (+50 ppm) improved yields by around +3% (Tubiello *et al.* 2007); (v) finally, the initial yields of the standard pasture evolved to 2.2, 3.6, 1.8 respectively for the three periods. The important summer yield decline of almost 1 t DM/ha in 30 y was partly (40-50%) compensated by earlier growth in spring and [CO_2] effect, but a loss of annual yield is remaining. More integrated modelling was performed with the STICS-Grass model, including CO_2 functions and adapted to Mediterranean conditions (Ruget *et al.*, 2009). The outputs confirmed the precedent evolutions and values in the three periods. These impacts are consistent with climate change characterisation, markedly with the moving of temperate-Mediterranean transition. The reasons why warming rates in summer (months MJJA) are so high in this region are unclear. It could be a specific character of the transition from temperate to Mediterranean climate along time like along latitude. It was observed that in southern Europe, this transition was a narrow strip (N-S distance of 200-350 km, 2-3°N) along which grasslands yields from May to August fall rapidly from 4-5 t/ha to insignificant levels due to the rapid increase of aridity ratios eR/eET_p (from 0.6-0.5 to 0.1-0.2 during MJJA), while yields from September to April increased slowly along the same N-S segment (Lelièvre and Volaire, 2009). The evolution could accelerate if rainfall declines in next decades as forecasted for southern Europe (IPCC, 2007).

IV – Conclusions

Completed at scales (regional, seasonnal, last 30 years) relevant to farming activities, this study shows that during the last 30 years, local climates changed rapidly at the temperate-Mediterranean interface in southern France. This changing climate could not be characterised by means of climatic variables, but by modelled expectancies (expected values). The importance of climate change 1979-2008 justifies complementary works to adapt livestock farming systems to the new conditions in these regions. But there is absolutely no evidence that rapid summer warming will continue at this rate in next years, and linear models used to describe1979-2008 evolutions of climatic variables must absolutely not be prolonged out of the observed period.

Acknowledgements

Acknowledgements to regions Languedoc-Roussillon, Rhône-Alpes, and Midi-Pyrénées for financial support, and to Météo-France and Agroclim-INRA for free access to climatic data (Climfourel project).

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