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Spatial and Seasonal Variations of Air Temperature Lapse Rates in Alpine Regions

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ABSTRACT

Air temperature decrease with altitude was estimated by simple linear regression for several regions around northern Italy for minimum, maximum, and mean monthly temperatures. The comparison of the gradients with previous works revealed the absence of a lapse rate seasonal pattern in most earlier studies. Such inconsistencies in other analyses were demonstrated to be largely due to insufficient climatic stations in each area, and incomplete temporal coverage. These problems were solved here by using 269 stations in northern Italy, 205 in the Tyrol area and 166 in the Trentin–Upper Adige region, covering a wide range of elevations and based at least on 30-yr means. Yearly lapse rates ranging from −0.54° to −0.58°C (100 m)$^{-1}$ were obtained. As hypothesized, a seasonal pattern in monthly gradient variations was observed, regardless of location, and with higher lapse rates during summer. Weather stations on valley bottoms were distinguished from those located on slopes, the former group being heavily influenced by a cold-air drainage process. Both differences in temperatures at sea level and lower lapse rates on valley bottoms explained minimum temperature variation with exposure, mainly due to temperature inversions. On the other hand, maximum temperature changes with topography mostly imply differences among the lapse rates themselves, attributed to a stronger sun warming of slopes. Since lapse rates may be used for monthly temperature spatial interpolation, an analysis of cross-validated interpolation errors was performed, to assess the method accuracy. The highest interpolation reliability was founded for maximum temperature, especially for summer values, and even when topographic information was not available (with an accuracy about 1°C in most cases). How much the topographic differences influence the lapse rate determination was also quantified. The addition of topographic information appeared to significantly increase the temperature interpolation reliability, especially for slope sites, and was required for both minimum and winter temperature reconstruction. Thus, the interpolation error of January minimum temperature in slope stations was reduced from 2.8° to 1.1°C by using such technique. Finally, the lapse rate's spatial variability was shown to be a potential source of error, especially when the region exceed a 1° width latitude area, whereas longitude role was shown to be less crucial.

1. Introduction

Climatic factors such as precipitation, solar radiation, air moisture, or temperature show large spatial variations in mountainous areas (Hutchinson 1989; Erpicum 1984), especially along elevation gradients above sea level (Legates and Willmott 1990). They are also strongly dependent upon slope and aspect (Richard and Tonnel 1985). Many research fields require these climatic factors, such as glaciology (Messerli et al. 1978), hydrology (Remenierias 1980), agriculture or vegetation studies (Dobremez and Vartanian 1974; Ozenda 1985; Stoutjesdijk and Barkman 1992), or dendroclimatology (Brugnoli and Gandolfo 1991; Camarero et al. 1996; Rolland et al. 1998). Unfortunately, weather stations measuring precipitation or air temperature are often sparse in mountainous areas, especially at high elevation or in uninhabited areas. It is therefore difficult to obtain precise climatic maps (Carrega 1995). Thus, reconstruction of temperature fields involves interpolating sparse data over large distances (Dodson and Marks 1997).

The rate at which air cools with elevation change varies from about −0.98°C (100 m)$^{-1}$ for dry air (i.e., the dry-air adiabatic lapse rate) to about −0.4°C (100 m)$^{-1}$ (i.e., the saturated adiabatic lapse rate; Dodson and Marks 1997). Average temperature gradients of −0.55°C per 100 m of elevation (Angot 1892), −0.60°C (Dodson and Marks 1997), or −0.65°C (Barry and Chorley 1987) are often used when low precision suffices. However, such average values are known to be rough approximations unsuitable for more precise studies (Douguédroit and De Saintignon 1984).

Therefore, the main goals of this study are 1) to reexamine air temperature lapse rate monthly variations in Alpine regions, 2) to quantify how much adding topographic information may improve their reliability, 3) to explain the inconsistencies in formerly published results, and 4) to assess the accuracy of temperature interpolations based on lapse rates.

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2. Sites and methods

A large network of temperature stations was analyzed throughout the Italian and Austrian Alps, with 30 yr or more for calculations of means, based on four datasets:

- In Northern Italy, 269 stations were used [see list in Gazzolo (1966)], hereafter designated as ''Italy,'' with a period of 30 yr for mean calculations (period 1926–55) (Fig. 1).
- In both Italian and Austrian Tyrol, with 205 stations [see list in Fliri (1975)], hereafter called ''Tyrol,'' during the period 1931–61.
- In the Trentin and Upper Adige region (Italy), with 166 stations of precisely known topographic situation, listed in Gafta and Pedrotti (1996), with means calculated over 55 yr, and all located in a climatically homogenous smaller area. This dataset was divided into two groups: valley bottoms (Tr-VB) and slopes (Tr-SL). As in many other previous studies (De Saintignon 1986; Paul 1986), valley bottoms (VB) were defined as sites located on flat or concave situations such as valleys, depressions, basins, thalwegs, riparian stations, or flat plains. On the other hand, slopes (SL) were defined as convex places, such as mountainsides or hills. In our study, one summit station (Paganella) as well as two sites located near passes (Passo Rolle and Passo Mendola) were discarded, following Paul (1976, 1986), because of specific wind influence on local climate there in such situations. Furthermore, north-slope stations appear to be rare in the studied regions (Ronzo, Centa St. Nicolo, for instance) compared to the numerous south-slope sites. These north-slope stations are not heavily influenced by cold-air drainage processes, contrary to the valley-bottoms group, and therefore they can not be aggregated into the same cohort. They also differ from south-slope sites, due to a lower sunshine duration, so these rare northern stations were discarded. One site with unknown topography was also eliminated. Finally, 105 VB and 61 SL stations were retained in the Trentin area.

Monthly average values of mean, maximum, and minimum temperatures were published in Gazzolo (1966), Fliri (1975), Gafta and Pedrotti (1996) with detailed location maps. A wide range of elevations with many sites was analyzed here to compute the temperature lapse rates (Table 1) on a large statistical base. Carrega (1986, 1995) and Bisci et al. (1989) suggested the use of multiple regression analysis to model temperature variations using both altitude and local topography. However, this method requires the knowledge of detailed characteristics for each weather station, such as its absolute altitude above sea level, the relative altitude above a local base level, the slope, exposure, and distance from sea. Unfortunately, such detailed parameters were not available for all the weather stations analyzed here. Only topographic description was easily available, so the simple regression analysis technique was used here (Dougúedroit and De Saintignon 1970). Thus, the Trentin–Upper Adige dataset was divided according to valley bottom or slope position of the weather stations. Moreover, this simple method provides directly interpretable temperature gradients (Douguédroit and De Saintignon 1984) that can be compared with other results previously published in many areas (Cortemiglia 1989; Cortemiglia et al. 1989; De Saintignon 1986; Paul 1976, 1986; Bisci et al. 1989; etc.). The location map (Fig. 1) indicates where the stations used in this study are distributed compared to other works, and how large of an area each dataset covers.

Linear regression models were calculated to obtain series of linear equations:

$$T_{ijk} = A_{ijk} \times \text{Altitude} + B_{ijk},$$

where T_{ijk} equals air temperature (in °C) modeled by the equation; altitude equals elevation above sea level (in 10^2 m); i equals minimum, mean, or maximum temperature (three temperature parameters); j equals month (from Jan to Dec), and whole year (12 + 1 cases); k equals the four datasets, combining the area and the topographic situation groups, that is, valley bottom or slope position (VB/SL).

For each equation, two coefficients were computed: A_{ijk} = The lapse rate (for temperature parameter i, and month j) [°C (100 m)$^{-1}$.] B_{ijk} = The temperature at sea level (at 0 m), (°C.)

These calculations were repeated for all combinations (temperature parameters × months). Thus, (12 + 1) × 3 series of A and B coefficients were obtained for each of the 4 datasets (Italy, Tyrol, Trentin-VB, and Trentin-SL as described above). In this paper, differences between A and B regression coefficients were analyzed, according to the studied temperature (i), the month (j), and the area–topography combination (k). Finally, a cross-validated analysis of interpolation errors was achieved, by computing the differences between measured temperatures and those calculated using lapse rates and site altitudes. Results were mapped, and the root-mean-squares of such differences were also calculated for each month, to estimate the temperature interpolation accuracy and to quantify how much the use of topographic information may enhance the precision of results.

3. Results and discussion

a. Critical comparison of previously published results

A systematic comparison of previously published studies (listed in Table 2) revealed many inconsistent results for temperature lapse rates (coefficients A, in degrees Celcius per 100 m). For instance, Cortemeglia et al. (1989) found a January mean temperature lapse rate $A_{m.\text{jan}} = -0.67$ for slopes in the northern part of the occidental Italian Alps, and Douguédroit (1970) ob-

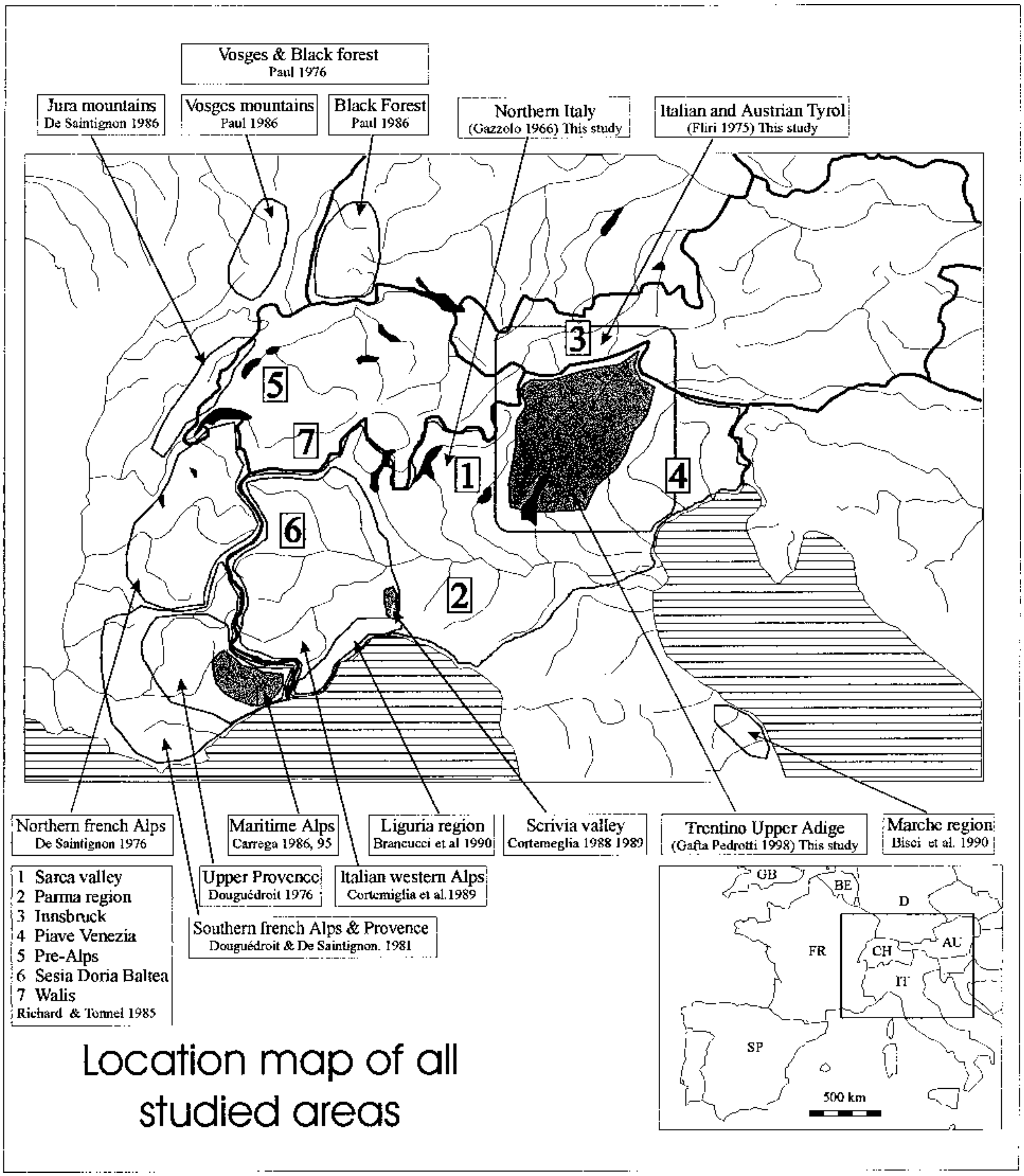

FIG. 1. Location map of the areas where climatic stations were used for this study, with other places analyzed in previous works dealing with monthly air temperature lapse rates over southwestern Europe.

tained a similar value ($A_{m.\text{jan}} = -0.63$) in the southern French Alps but for valley bottoms (Fig. 2b, white bars). Furthermore, lower gradients for slopes were simultaneously reported in literature, for instance -0.39 in the western part of occidental Italian Alps (Cortemeglia et al. 1989), and -0.41 in the Jura Mountains (De Saintignon 1986). A positive gradient was even found ($A_{m.\text{jan}} = +0.28$) in the Scrivia river valley (Cortemeglia 1988), but this value was calculated with only four stations and obtained along a river valley characterized by deep temperature inversions. Surprisingly, high lapse rates were also reported by Cortemeglia et al. (1989) in the occi-

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TABLE 1. Number of climatic stations and percentages in each altitude class (of 150 m width each) for four datasets: northern Italy, Italian–Austrian Tyrol, and Trentin–Upper Adige (subdivided into VB and SL).

Altitude (m)		Number of weather stations				Percentages			
				Trentin				Trentin	
Min	Max	N. Italy	Tyrol	Valley	Slope	N. Italy	Tyrol	Valley	Slope
0	149	57	22	1	3	21	11	2	3
150	299	36	8	1	10	13	4	2	10
300	449	35	11	3	9	13	5	5	9
450	599	23	16	1	6	9	8	2	6
600	749	15	13	1	9	6	6	2	9
750	899	14	18	3	4	5	9	5	4
900	1049	20	25	9	13	7	12	15	12
1050	1199	14	21	9	12	5	10	15	11
1200	1349	20	15	5	16	7	7	8	15
1350	1499	7	15	7	9	3	7	11	9
1500	1649	12	14	7	11	4	7	11	10
1650	1799	4	6	4	0	1	3	7	0
1800	1949	5	8	3	3	2	4	5	3
1950	2099	3	8	5	0	1	4	8	0
2100	2249	2	1	1	0	1	0	2	0
>2250		2	4	1	0	1	2	2	0
TOTAL		269	205	61	105	100	100	100	100
					166				

dental Italian Alps for maximum temperature (Fig. 2c, gray bars), with $A_{\mathrm{max.July}} = -1.27$ for July.

Similarly, several spurious dissimilarities are noticeable in yearly lapse rates (Fig. 2b, black bars). Thus, some sharp gradients such as $A_{m.\mathrm{year}} = -0.80$ or -0.61 were reported, respectively, by Cortemeglia et al. (1989) for the northern part of occidental Italian Alps on slopes, and by De Saintignon (1986) for valley bottoms in the southern French Alps. On the contrary, quite lower gradients were also obtained: for instance, $A_{m.\mathrm{year}} = -0.39$ (Cortemeglia 1988) for Scriva valley, and -0.47 (Bisci et al. 1989) in the Meridional Marches (central Italy). Such discrepancies obviously raise a major problem for using these values in other regions, and even seem to impede a local temperature extrapolation.

Third, gradual transitions in monthly lapse rate variations should be observed. Surprisingly, such an expected pattern is absent in many previous studies, and oscillations in lapse rates for successive months are visible in the results of Douguédroit (1970), Bisci et al. (1989), and Angot (1882; Fig. 3, ''other studies''). On the contrary, multiple regression analysis (with more environmental variables) seems to face this problem (Carrega 1986, 1995). However, despite leading to a clearer pattern in monthly temperature gradient variations, the multiple regression coefficients are neither interpretable nor comparable to real lapse rates, because some other variables are involved in the equations. For instance, very low coefficients for minimum July temperature variations with altitude published by Carrega (1995) or Bisci et al. (1989; respectively, -0.26 and -0.22) are obviously lower than actual summer lapse rates.

Thus, the confrontation of previously published results underlines severe divergences, despite the fact that all authors used the same simple linear regression technique based on temperature and altitude. Surprisingly, the part played by exposure seems to strongly depend on the studied area, and no evident agreement appears among sites. Furthermore, any consistent pattern in monthly lapse rate variation was observed. Therefore, it appears necessary to achieve a complete re-examination of monthly temperature variations with altitude to explain such inconsistent results.

b. Hypotheses

We hypothesized that these problems may be caused by two main methodological artifacts. First, the period lengths used for temperature data may be excessively short, leading to nonrepresentative monthly average values. On the other hand, the number of weather stations may be insufficient for a complete cover of the altitude or spatial ranges. For instance, Douguédroit and De Saintignon (1970) used only 7 yr to calculate mean temperatures in the southern French Alps. Paul studies (1986, 1976) were based on 9 and 10 yr in the Jura and Black Forest. De Saintignon (1986) also used a 10-yr period in the Jura, and Brancucci et al. (1990) used a 15-yr interval (Table 2). Some abnormal years with particular climatic extreme events may have impeded the calculation of monthly average values (such as 1976 dryness, 1956 extreme frost in Feb) (Desplanque et al. 1999).

In some other cases, the number of different climatic stations may be insufficient; Cortemeglia's (1988) results were based on 4 stations in the Scrivia valley, De Saintignon (1986) analyzed 31 sites in the Jura Mountains (divided into 19 on valley bottoms and 12 on slopes), and Bisci et al. (1989) studied 29 sites in the Meridional Marches (Table 2). Therefore, we hypoth-

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TABLE 2. Other studies on lapse rates used for comparisons with our results. For each bibliographical reference (author, year), the studied area is indicated with a country code (FR = France, IT = Italy, AU = Austria, D = Germany, CH = Switzerland), the total number of stations, and the period used for average temperature calculations. Minimum and maximum altitudes for both VB and SL sites are given. An ‘‘x’’ indicates that a lapse rate was calculated in this study for a given month (1 = Jan, 12 = Dec) and parameter combination (n, m, x = min, mean, max temperatures); an ‘‘n’’ means not indicated.

Bibliography author and year	Studied regions		N climatic stations	Topography		Climate years	Station altitudes Valley		Slope	
	area	Country	Total	Valley	Slope		Min	Max	Min	Max
Paul 1976	Vosges, Black Forest	FR, D	40	25	15	10	250	960	377	1484
Paul 1986	Vosges, Black Forest	FR, D	48	29	19	9	idem	idem	idem	idem
Douguédroit, De Saintignon 1970	Southern french Alps	FR	44	22	22	7	145	1660	211	2010
Douguédroit 1970	Southern french Alps	FR	nc	nc	nc	nc	nc	nc	nc	nc
Douguédroit, De Saintignon 1981	Southern french Alps, Provence collinéenne	FR	41	20	21	17	80	1675	185	2010
De Saintignon 1986	Jura	FR, CH	31	19	12	10	~250	~1200	~250	~1600
Cortemeglia 1988	Bacino della Scrivia (Piémont méridio-nal)	IT	4	4	0	30	141	764	nc	nc
Cortemeglia et al. 1989	Occidental Italian Alps	IT	52	14	nc	20	250	1400	700	1700
Carrega 1986	Maritimes Alps	FR	25	13	12	25	3	1674	74	1510
Carrega 1995	Maritimes Alps (Var, Tinée, Vésubie)	FR	24	—	—	30	3	1610	—	—
Brancucci et al. 190	Ligurie	IT	42	—	—	15	2	1600	—	—
Bisci et al. 1989	Meridional Marches (Adriatique central Italy)	IT	29	—	—	n	5	2100	—	—
Angot 1892	France	FR	nc	—	—	n	n	n	—	—
Richard 1985	Sarca	IT	33	—	—	n	20	1850	—	—
	Parma	IT	45	—	—	n	20	1200	—	—
	Innsbruck	AU	24	—	—	n	600	2050	—	—
	Piave Venezia	IT	102	—	—	n	5	1950	—	—
	Préalpes, avant pays Suisse	CH	45	—	—	n	400	1600	—	—
	Sesia Doria Baltea	IT	36	—	—	n	80	1825	—	—
	Valais	CH	14	—	—	n	450	1750	—	—
This study	Tyrol	IT, AU	205	—	—	36	2	3106	—	—
	Northern Italy	IT	269	—	—	30	1	2526	—	—
	Trentino–Alto Adige	IT	166	105	61	>30	64	1879	121	2600

esized that low number of stations or sites with particular conditions may have biased the results.

c. *Sampling strategy*

Consequently, it was chosen here to use both long periods for the calculation of temperature means (≥30 yr), and large numbers of measuring sites (a minimum of 61 in the smallest data subset). It was expected to overcome the problems of previous studies, based on small number of sites and short time periods. Our minimum values were chosen because many works based on a 30-yr period proved it to be sufficient to obtain stable and reproducible monthly means (Gazzolo 1966; Primault 1972; Fliri 1975; Gafta and Pedrotti 1996). Since the minimum number of climatic sites is not known a priori, large datasets were tried here, with up to 269 stations over all off northern Italy. Then an a posteriori analysis of interpolation errors was performed, by mapping the differences between measured temperatures and those reconstructed using lapse rates calculated over the entire area. Thus, the drawbacks due to a possible heterogeneity in regional climate over a large area (Gafta and Pedrotti 1996) can be assessed.

The altitudes of our stations comprise between 2 and 3106 m in the Tyrol, between 1 and 2526 m in northern Italy, and between 64 and 1879 m (VB), and 121 m and 2600 m (SL) in the Trentin–Upper Adige region. Such

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TABLE 2. (Extended)

Calculated lapse rates																		
Temperature			Topography			Months												whole
Max	Min	Mean	VB	SL	All	j	f	m	a	m	j	j	a	s	o	n	d	year
x	x	x	x	x														x
x	x	x	x	x		x			x			x			x			x
x	x	x	x	x														x
x	x	x	x	x		x	x	x	x	x	x	x	x	x	x	x	x	x
x	x	x	x	x					x			x			x			x
						x												
x	x	x	x	x		x			x	x		x						x
x	x	x	x			x	x	x	x	x	x	x	x	x	x	x	x	x
x	x		x	x		x						x						x
x	x				x	x						x						x
x	x				x	x	x	x	x	x	x	x	x	x	x	x	x	x
x	x				x	x						x						x
								x										
x	x	x			x	x	x	x	x	x	x	x	x	x	x	x	x	x
		x			x	x	x		x	x	x	x	x	x	x	x	x	x
		x			x													
		x			x							x	x	x				
		x			x							x	x	x				
		x			x							x	x	x				
		x			x							x	x	x				
												x	x	x				
		x			x							x	x	x				
		x			x							x	x	x				
x	x	x			x	x	x	x	x	x	x	x	x	x	x	x	x	x
x	x	x			x	x	x	x	x	x	x	x	x	x	x	x	x	x
x	x	x	x	x		x	x	x	x	x	x	x	x	x	x	x	x	x

large altitude cover permits us to analyze lapse rates over the entire elevation range. Table 1 indicates that there is a low elevation bias in the networks of measurement stations, as commonly observed in most of them, but some high-altitude sites were included in the dataset, with 28 and 41 stations above 1500 m in northern Italy and Tyrol, respectively.

d. Lapse rates (A)

As hypothesized, each of the four datasets show a gradual seasonal trend in monthly variations of lapse rates (Fig. 3). All monthly gradients reach a maximum value during summer, and a minimum during winter months. Thus, the absence of this seasonal pattern in most other studies (Douguédroit and De Saintignon 1981; Angot 1892; Bisci et al. 1989; among others) may be attributed to an insufficient number of stations covering the whole altitude range (especially at high elevations), and too short periods to calculate temperature means. Therefore, the absence of a clear regular seasonal trend in monthly gradients appears to be involved by statistical artifacts in these studies. It may also explain the surprisingly high January lapse rate ($A_{\mathrm{min.Jan}} = -0.76$) found by Douguédroit (1970) in the French Alpine valleys, which was probably overestimated. Our results are self-consistent and reproducible since all datasets lead to similar conclusions. They are also con-

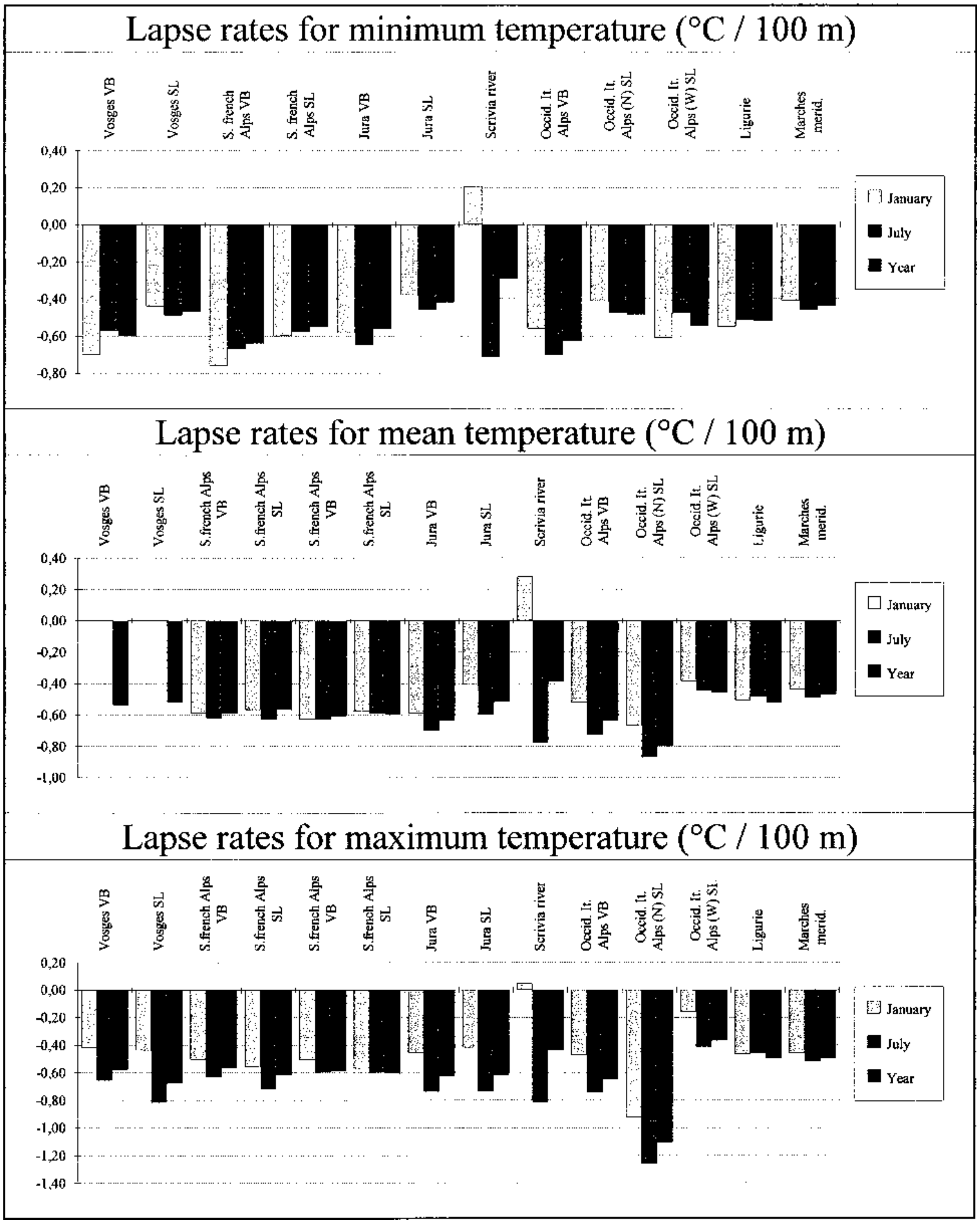

FIG. 2. Vertical lapse rates [in °C (100 m)$^{-1}$] for min (1a), mean (1b), and max temperatures (1c) in Jan, Jul, and for whole year according to various studies: in the Vosges and Black forest (Paul 1976), southern French Alps (Douguédroit and De Saintignon 1981; Douguédroit 1970), Jura (De Saintignon 1986), Scrivia valley (Cortemeglia 1988), occidental Italian Alps (Cortemeglia et al. 1989) divided into northern and western region, Ligurie (Brancucci et al. 1990), and Meridional Marches (central Italy; Bisci et al. 1989).

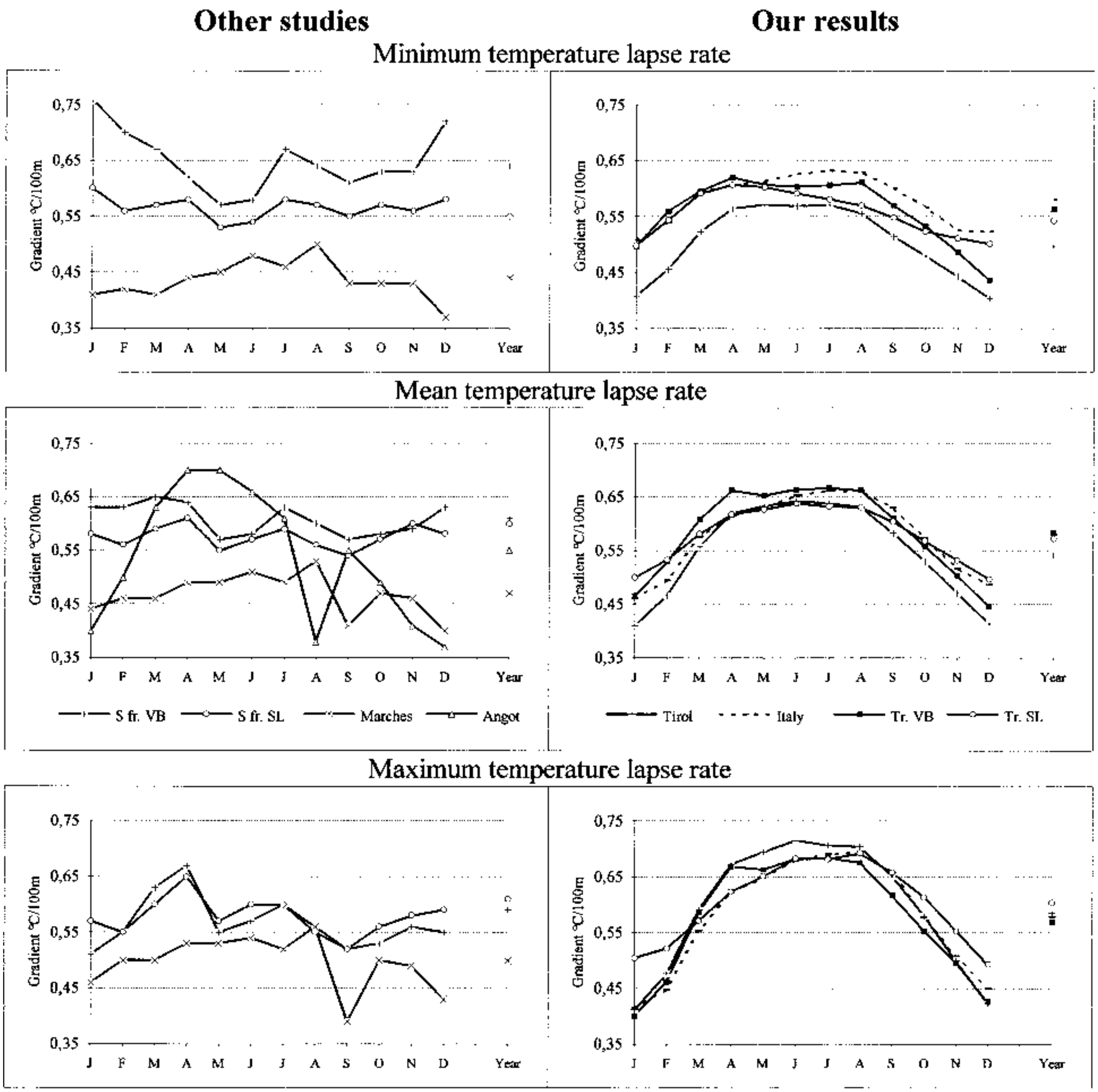

FIG. 3. Seasonal variations of lapse rates [A in °C (100 m)$^{-1}$] for min (3a), mean (3b), and max (3c) temperatures. Our results obtained in Tyrol, northern Italy, and in the Trentin–Upper Adige region divided into VB and SL, compared with those published in literature in the southern French Alps (S fr; Douguédroit and De Saintignon 1981), Meridional Marches (in central Italy; Bisci et al. 1989) and France (Angot 1892).

sistent with Ozenda (1985), who similarly described higher lapse rates during summer [mean values of −0.7°C (100 m)$^{-1}$] in summer and −0.4 in winter). Similarly, Hutchinson (1991) obtained higher lapse rates for maximum temperatures [about −0.8°C (100 m)$^{-1}$] and a consistent seasonal pattern in minimum temperature lapse rates, varying between around −0.3°C (100 m)$^{-1}$ in winter and −0.5°C (100 m)$^{-1}$ in summer (in Tasmania). Therefore, the existence of a lapse rate seasonal trend seems to be a general phenomenon and common to minimum, mean, and maximum temperatures.

Lapse rates are lower in winter compared to summer values. They are also lower for minimum temperatures (at night; Fig. 3a) than for maximum ones (during day) (Fig. 3c). Therefore, inversions of temperature appeared to be responsible for low temperatures during winter near valley bottoms (VB). This phenomenon involves strongly reduced gradients in December and January, especially for minimum night temperatures, which also show higher site variability. The differences between lapse rate for maximum and minimum temperature are likely due mostly to inversions for the minimum temperatures, rather than stronger sunshine warming for maximum temperatures. The maximum temperature lapse rates are simply closer to the dry adiabatic lapse rate, as indicated by the increased stability of these rates. Similarly, Dodson and Marks (1997) found that the lapse rate is more stable over space for maximum temperature than that of minimum values, because minimum temperature is more susceptible to cold-air drainage effects that would tend to create local temperature inversions.

The gradients in Tyrol are always below gradients observed for all of northern Italy for minimum temperatures, but most of the time they are higher for maximum values. This is consistent with the inner climate of the Tyrol, with stronger temperature contrasts (Fliri 1975). Paul (1976) also found (for the slopes) higher lapse rates for maximum temperature compared to those for minimum values. Moreover, differences between gradients on valley bottoms and slopes position clearly appear with our dataset. Douguédroit (1970) observed higher gradients for VB during all months, especially for minimum temperatures. On the contrary, our results reveal this pattern only during summer, whereas it is reversed with lower VB gradients during winter, in November and more especially in December for minimum temperature. This difference in lapse rates according to the topographic position is also visible for maximum temperature, with sharp differences from September to February, whereas Douguédroit's (1970) results did not reveal a clear pattern but only little differences.

e. Temperature at sea level (B)

The temperature at sea level (*B* coefficient, in °C) is logically dependent on the studied area, especially on the latitude position. Thus, the northern Italy network led to warmer conditions compared to the Tyrol dataset (Fig. 4). Similarly, mean and maximum temperatures T_0 in the southern French Alps (Douguédroit 1970) are clearly warmer than T_0 in the other regions (from 3° to 5°C more). Moreover, temperatures at sea level show little differences between valleys and slopes for maximum temperatures (Fig. 4c), whereas minimum values are warmer on southern slopes than on valley bottoms (Fig. 4a). Therefore, our results confirm Douguédroit's (1970) observations, explained by night temperature inversions.

f. Coefficients of linear correlation (R^2)

Correlation coefficients (R^2) between temperature and altitude are lower during winter, particularly in December and January (Fig. 5). Hence, temperature decrease with altitude presents a more scattered relationship during these months, suggesting that local conditions may play a greater part. More fog periods may enhance temperature inversion effects, and slope warming may be affected by snow cover that changes soil albedo. Note that in most other studies, seasonal trends were visible neither for gradients, nor for R^2 values.

g. Lapse rates spatial variations

Yearly lapse rates were compared for various regions in the Alps (in both France and Italy), the Vosges, and the Jura Mountains (Table 3a). Our results [with A ranging from −0.54° to −0.58°C $(100\ \mathrm{m})^{-1}$] are slightly lower than Douguédroit and De Saintinon's (1981) findings, but higher than those reported in the Vosges (Paul 1976), in Ligurie (Brancucci et al. 1990), in Meridional Marches (Bisci et al. 1989), and in Scriva valley (Cortemeglia 1988). As expected, mean yearly temperatures at sea level (B) show large variations, linked with latitude changes and topography. They range from 10.7°C in the Vosges Mountains on valley bottoms (Paul 1976) to 17.4°C in the northern part of the occidental Italian Alps on southern slopes (Cortemeglia et al. 1989).

The lapse rates for mean summer temperatures (Table 3b) are lower in the Swiss pre-Alps and Valais (Richard and Tonnel 1985) compared to our results [from −0.63° to −0.66°C $(100\ \mathrm{m})^{-1}$], whereas they were found to be higher in the Scriva river valley and Sarca region in Italy. Hence, our findings based on a large sampling lead to intermediate values and seem probably more suitable for extrapolations.

Such differences according to the area suggest the need to evaluate the effects of air temperature spatial variability on the lapse rate distribution. For each weather station of the northern Italy network, the measured temperature was compared with the interpolated value calculated using the lapse rate (obtained for the entire region) combined with site altitude. The differences were mapped for January, July, and yearly values for the three temperature parameters (minimum, maximum, and mean). This cross-validated analysis of interpolation errors reveals that air temperature is underestimated by interpolation in the southern part of the studied area (Fig. 6, white circles). It is especially the case for minimum temperature in spring (Jan) in sites below latitude 44°30′ (Appenins and Ligure). However, this underestimation phenomenon appears sharply reduced during summer (Jul). Contrarily, the lapse rate model overestimates temperatures in the northeastern part (Dolomites; Fig. 6, black circles), whereas interpolation accuracy is better in the intermediate areas. As previously seen, maximum temperatures are better estimated than minimum values, especially for yearly data.

Some established interpolation techniques can address this spatial variation of gradients, as well as robustly determining lapse rates from limited networks over large areas. Thus, Hutchinson (1991) used a partial spline analysis for just 80 stations over an area of 600 × 600 km. Such a method implemented a spatially varying sea level temperature and a constant lapse rate, all determined from the data.

h. Interpolation accuracy

The root-mean-squares of differences between actual and calculated temperatures were computed to assess the

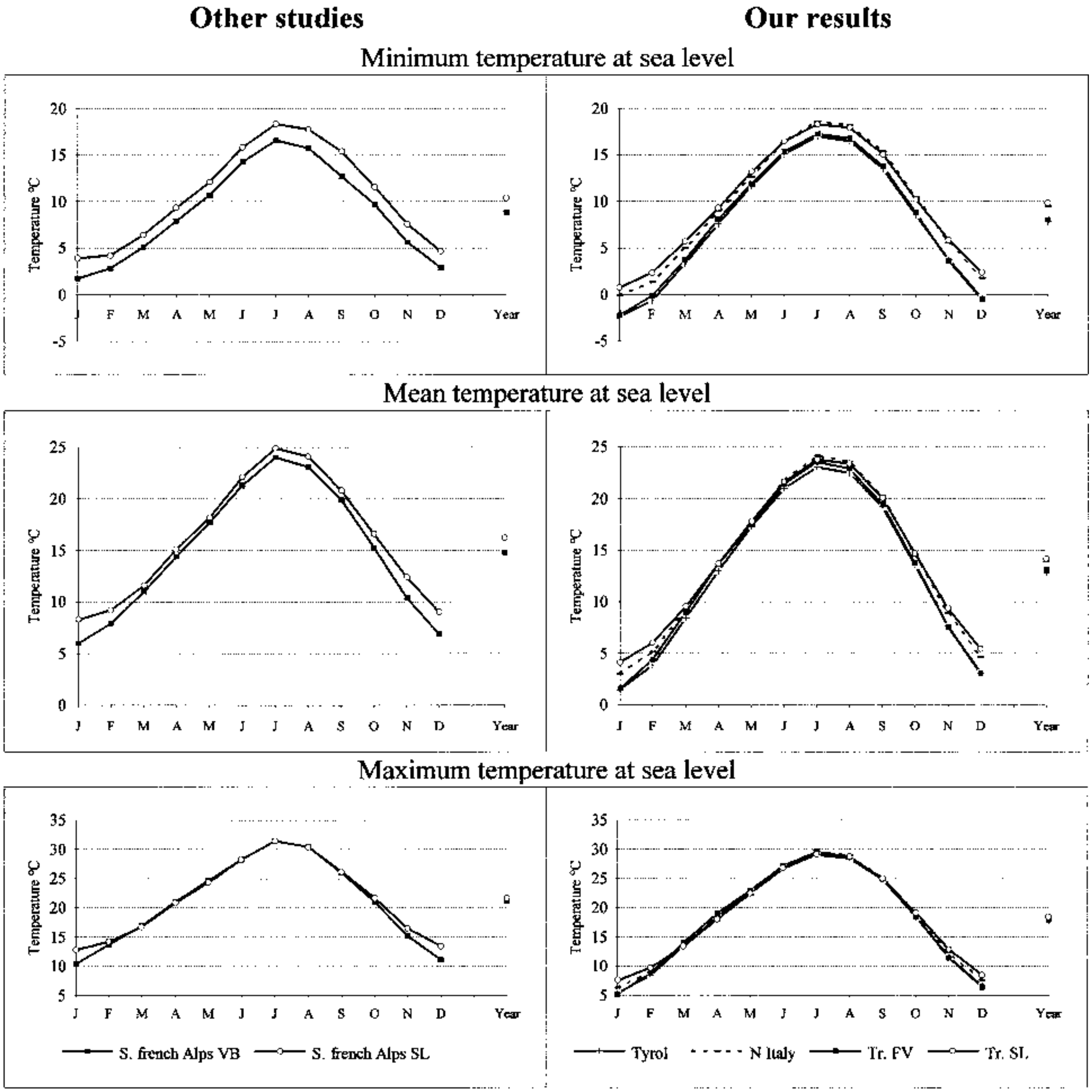

FIG. 4. Seasonal variations of temperature at sea level T_0 (B coefficient in °C) for min (4a), mean (4b) and max (4c) temperatures obtained with our four sampling networks: Tyrol, northern Italy, and Trentin–Upper Adige region (divided into Tr-VB and Tr-SL). Results obtained in the southern French Alps (Douguédroit 1970) were added for comparisons.

interpolation accuracy. This analysis was performed for each month and temperature parameter in the Trentin and Upper Adige regions, where the topographic situation was known for each station. We compared the results obtained with the topographic information and those obtained without it, to quantify how much the topographic information may enhance the interpolation accuracy.

As expected, the lapse rates that were calculated without regard to the climatic station topographic situation led to quite high interpolation errors (Fig. 7, black cross), especially in winter and spring. For yearly temperature data, the errors for minimum, maximum, and mean values are, respectively, 1.34°, 1.16°, and 1.43°C. These errors appear mainly due to slope stations (white triangles), where air temperature is poorly estimated when the exact topography is ignored. The addition of topographical information (black symbols) for the lapse rate calculations significantly enhances the accuracy of results, especially for these slope sites (black triangles). The maximum temperatures show the highest interpolation reliability, especially for summer values and even without topography data; whereas the use of topography

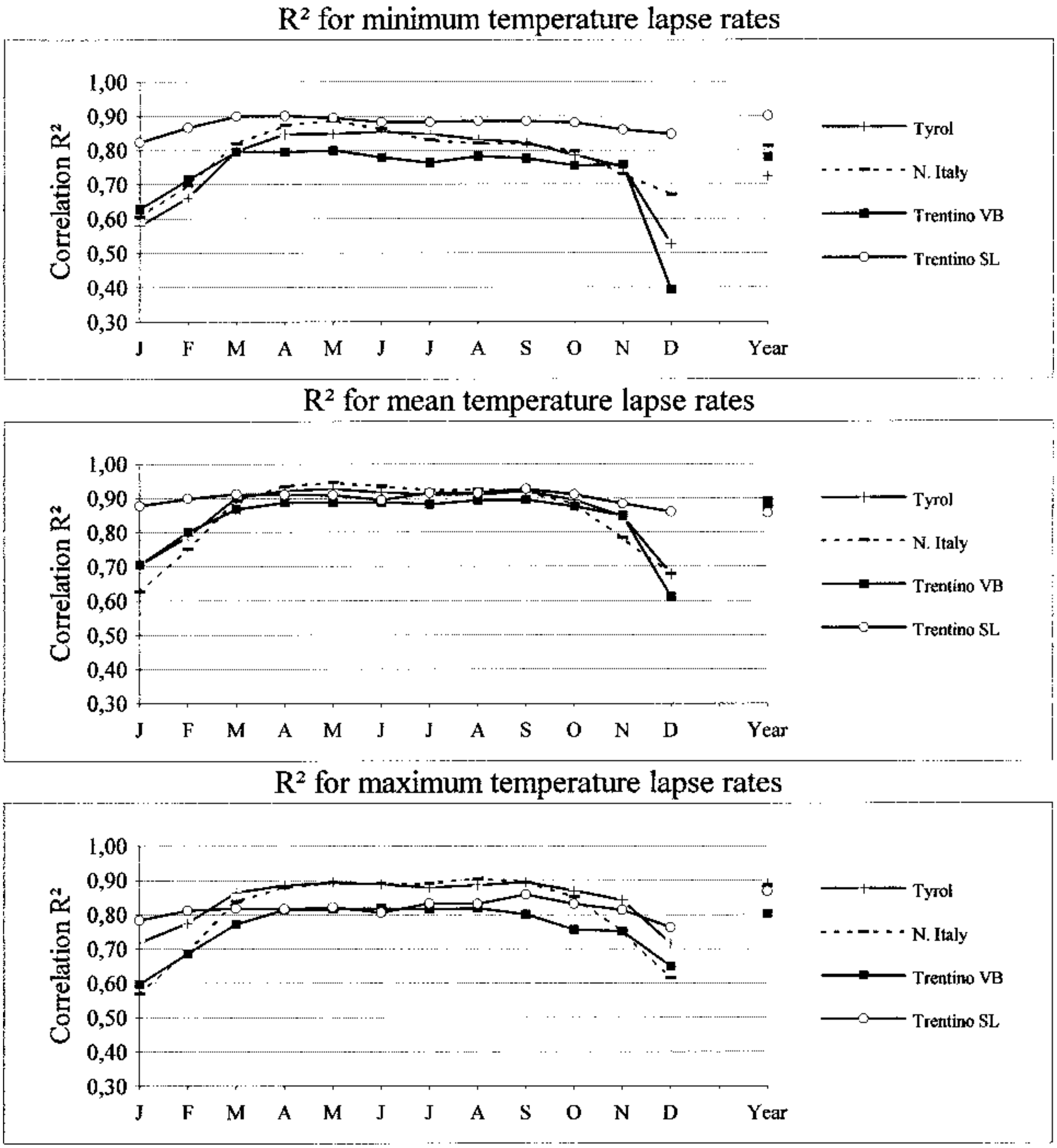

FIG. 5. Seasonal variations of correlation coefficients R^2 between temperature and altitude, for min (5a), mean (5b), and max (5c) temperatures calculated with our four sampling networks: Tyrol, northern Italy, and Trentin–Upper Adige region for both VB SL.

appears highly required for minimum or winter temperature reconstruction.

4. Conclusions

Altitude is well known to play the major part in climatic spatial changes in mountainous areas, for both temperature (Stoutjesdijk and Barkman 1992) and precipitation (Pache et al. 1996a,b). In occidental Europe, the pioneer study of Angot (1892) led to a −0.55°C $(100\ m)^{-1}$ yearly temperature lapse rate. Douguédroit and De Saintignon (1970, 1984) provided more detailed results and investigated in the southern French Alps how site exposure influences this gradient. Similar works were published for the Vosges Mountains and the Black Forest (Paul 1976, 1986), the French Jura (De Saintignon 1986), the Scrivia River valley (Cortemeglia 1988), the occidental Italian Alps (Cortemeglia et al. 1989),

TABLE 3. Comparisons of mean yearly (3a) temperature decrease with altitude ($T = A \times$ Alitude $+ B$) in Vosges Mountains, Jura, Ligurie, Tyrol, Scrivia River valley, Trentin–Upper Adige, occidental Italian Alps, northern Italy, Meridional Marches (central Italy), and southern French Alps. Richard and Tonnel (1985) results for summer temperature variations (3b) in seven Alpine regions are also given.

Yearly mean temperature lapse rate		°C (100 m^{-1})	°C at 0 m
Authors	Region	*A*	*B*
Cortemeglia et al. 1989	Occid. It. Alps VB	−0.64	14.0
	Occid. It. Alps (N) SL	−0.80	17.4
	Occid. It. Alps (W) SL	−0.46	13.7
De Saintignon 1986	Jura VB	−0.64	11.8
	Jura SL	−0.52	11.8
Douguédroit 1970	Southern French Alps VB	−0.61	14.8
	Southern French Alps SL	−0.60	16.2
Douguédroit and De Saintignon 1981	Southern French Alps VB	−0.59	14.5
	Southern French Alps SL	−0.57	15.6
This study	Trentin VB	−0.58	13.1
	Trentin SL	−0.57	14.2
This study	Northern Italy	−0.58	13.9
	Tyrol	−0.54	12.8
Angot 1892	France	−0.55	no data
Paul 1976	Vosges VB	−0.54	10.7
	Vosges SL	−0.52	11.5
Brancucci et al. 1990	Ligurie	−0.52	12.1
Bisci et al. 1989	Meridional Marches	−0.47	14.3
Cortemeglia 1988	Scrivia river	−0.39	13.0
Mean summer (Jun–Jul–Aug) lapse rate		**°C (100 m^{-1})**	**°C at 0 m**
Authors	**Region**	***A***	***B***
Richard and Tonnel 1985	Swiss Pre-Alp (CH)	−0.53	19.6
	Valais (CH)	−0.56	21.0
	Innsbruck region (AU)	−0.62	21.2
	Piave Venezia (IT)	−0.63	23.0
	Sarca region (IT)	−0.69	23.5
	Sesia Doria Baltea (IT)	−0.60	23.8
	Parma region (IT)	−0.57	24.1
Angot 1892	France	−0.55	no data
Douguédroit 1970	Southern French Alps VB	−0.60	22.80
	Southern French Alps SL	−0.57	23.70
Cortemeglia 1988	Bascino della Scriva	−0.75	16.81
This study	Tyrol	−0.64	22.18
	Northern Italy	−0.66	23.17
This study	Trentin VB	−0.66	22.62
	Trentin SL	−0.63	22.92

the French Maritime Alps (Carrega 1986, 1995), the Ligurie (Brancucci et al. 1990), and the Meridional Marches in central Italy (Bisci et al. 1989). Despite all these studies, temperature variations with altitude still raise problems. Many results appear to be inconsistent, with spurious dissimilarities when they are compared, and any clear seasonal pattern in lapse rate variations was found.

That is why a complete reinvestigation of the variations of monthly temperature gradients in mountainous regions was carried out. First, the efficiency of simple regression analysis for assessing temperature decrease with altitude was confirmed. For the whole year, a lapse rate ranging from −0.54 to −0.58°C (100 m)$^{-1}$ was found for our four datasets. Similarly, Paul (1976) found −0.52 for slopes and −0.54 for valleys in the Jura Mountains, Carrega (1986) obtained −0.51 in the Maritime Alps, Brancucci et al. (1990) −0.51 in Ligurie, Bisci et al. (1989) −0.47 in Meridional Marches (central Italy), Cortemiglia et al. (1989) from −0.46 to −0.80 in the occidental Italian Alps, and Douguédroit and De Saintignon (1981) from −0.57 to −0.59 in the southern French Alps. Thus, all these values exceed Dodson and Marks's (1997) results [−0.39°C (100 m)$^{-1}$] obtained in the Columbia River valley (U.S. Pacific Northwest and Canada). However, their result was an average of 365 daily mean temperatures for a single ''typical'' year, and not an annual mean using multiple-year time series. Furthermore, Dodson and Marks (1997) analyzed an area extending over 600 km north–south and east–west. The spatial variation over larger areas may lead to smaller values. Thus, the lapse rate of −0.39°C (100 m)$^{-1}$ calculated by Dodson and Marks (1997) was obtained by regressing all stations in the 830 000-km^2 study area, whereas a lapse rate of −0.65°C (100 m)$^{-1}$ was obtained by these authors when they used a moving-spatial-window regression technique with a radius of 100 km.

Second, spurious results previously published (such

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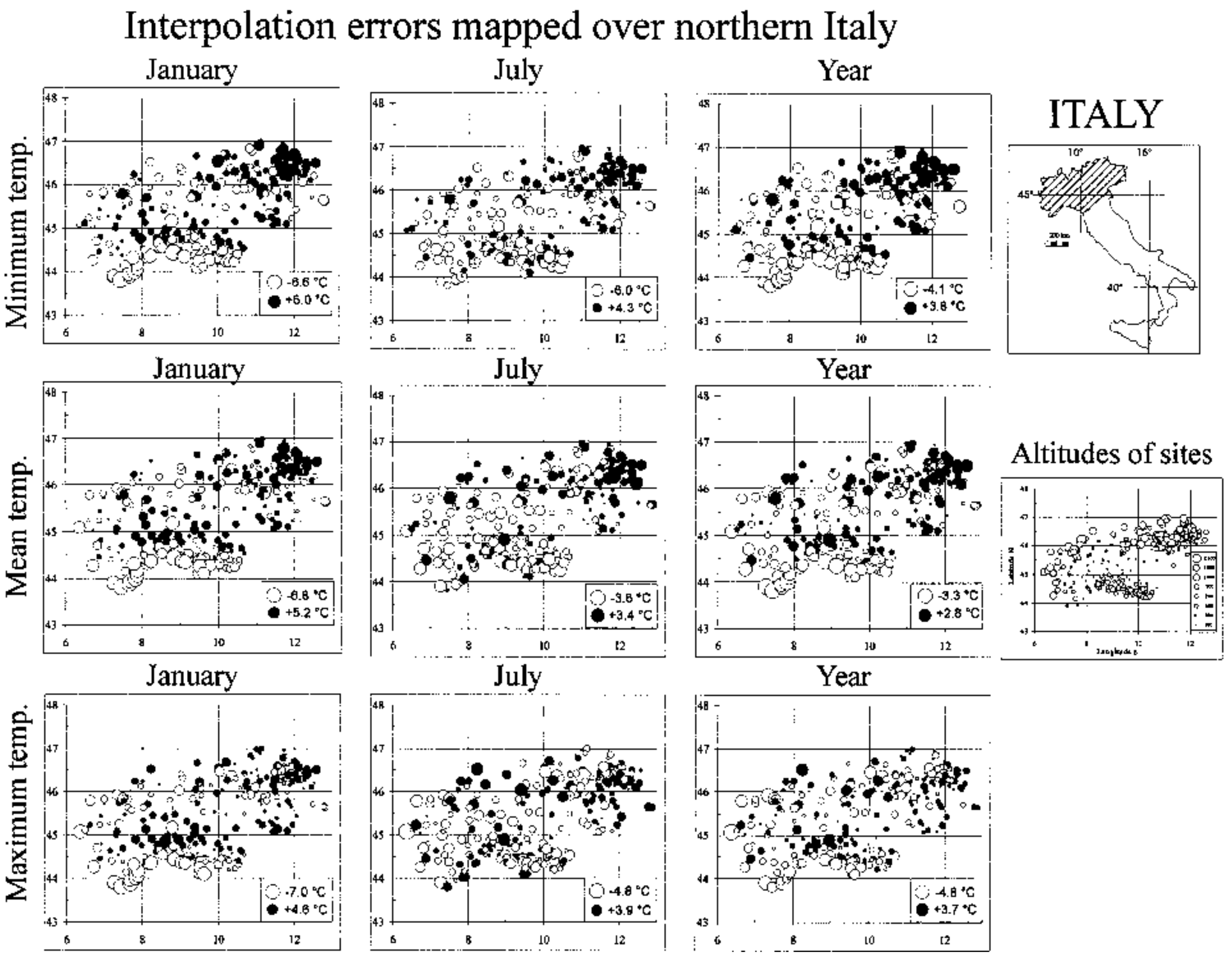

FIG. 6. Maps of cross-validated air temperature interpolation errors over entire northern Italy (site latitudes from 43°49′ to 46°58′N, longitudes from 6°22′ to 12°52′E) in Jan, Jul, and a complete year. For each site, circle surface is proportional to the difference between the observed temperature and the interpolated value, calculated using lapse rate and site altitude. Negative values (interpolation underestimations) are indicated by white circles, whereas black circles show positive differences (overestimations). Site altitudes range from 1 to 2526 m.

as abnormal high or low lapse rates) were demonstrated to be caused by statistical artifacts, due to an insufficient number of climatic stations (especially at high elevations), and/or by excessively short periods for climatic average values calculation (Table 2). These problems are faced when more than 60 stations and at least 30-yr average values are used, as already assumed by Paul (1976). Moreover, the existence of a lapse rate seasonal pattern was clearly established, regardless of the studied area. In all cases, variations of lapse rates show a quite sinusoidal wave seasonal form, with higher values during summer. This important feature was not visible in many previous studies, which show inconsistent gradient oscillations for successive months. The summer–winter magnitude difference of the lapse rate seasonal pattern seems to vary from place to place, but the understanding of that complex phenomenon seems to require complementary studies.

The specificity of valley bottoms appeared mainly associated with shifts in minimum temperatures, as previously reported by De Saintignon (1986). The lapse rate ($A_{\mathrm{min.year}}$) differences between valleys and slopes for minimum yearly temperature are dependant upon region, with V − S difference of −0.13°C $(100\ \mathrm{m})^{-1}$ (−0.60 and −0.47) in the Vosges (Paul 1986); −0.08 in the southern French Alps (−0.61 and −0.53; Douguédroit and De Saintignon 1981); −0.14 in the Jura (−0.56 and −0.42); −0.14 (−0.63 and −0.49) in the occidental Italian Alps (Cortemeglia et al. 1989); and −0.02 (−0.56 and −0.54) in the Trentin–Upper Adige area (this study).

Such differences due to topography may seem slight, but remember that they are calculated with yearly lapse rates. At monthly scale, the two lapse rates seasonal curves for valley bottom and slopes cross each other (at two times, in Feb and Sep), and differences are higher.

The part played by exposure on temperature gradients appears mainly caused by two different phenomena.

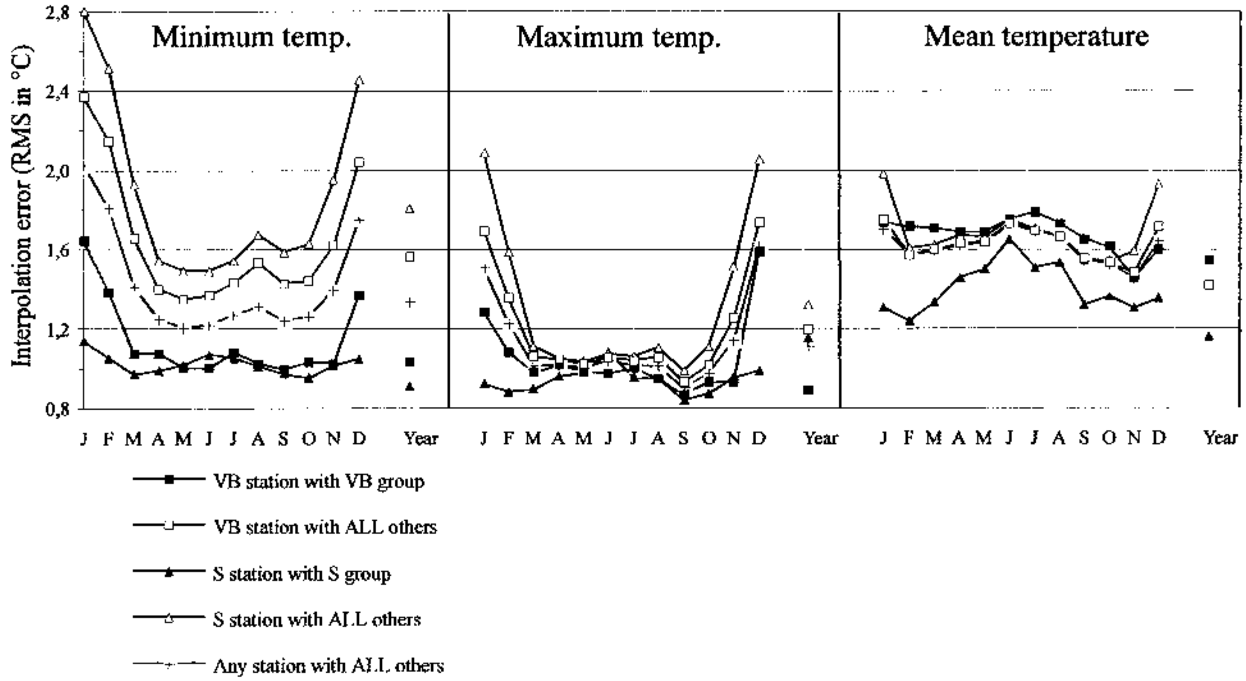

FIG. 7. Cross-validated analysis of interpolation errors for min, max, and mean air temperature, for each month (Jan–Dec) and yearly means (12) Root-mean-squares of differences between actual and calculated temperatures are indicated for VB, SL, or stations of unknown topography (any station), computed with lapse rates of VB and S groups, or with all sites together.

Minimum temperature (during night) dependence on exposure is due both to differences between temperatures at sea level (*B* coefficients), and lower gradients on valley bottoms (*A*). On the contrary, maximum temperatures (during day) are more especially linked with differences among lapse rates (*A*) only. The first phenomenon is enhanced in winter, and can be attributed to temperature inversions with cold-air accumulation in valleys during nights, whereas the second one seems linked with sun warming during day, stronger on slopes.

Our detailed results may permit interpolations over a wide altitude range (Dodson and Marks 1997), since all measurement networks of stations include high-altitude sites. Thus, isotherms may be more precisely calculated at a monthly scale (Hutchinson 1989), for instance, using a digital elevation model (DEM). Temperatures may also be accurately estimated for climatic applications, vegetation studies or glacier mass-balance analysis. On the basis of the cross-validated interpolation error analysis, it appears that better interpolation results are obtained when weather stations are aggregated within 1° of latitude only, whereas longitude is less crucial, even over a 4° large area. The reconstruction of maximum temperature during summer is the most reliable, with an accuracy about 1°C in all cases. Conversely, minimum temperature raises more interpolation problems. In this latter case, it was shown highly efficient to combine site altitude with the addition of simple topographic information (valley bottom vs slope situation). Thus, the interpolation error of January minimum temperature in slope stations can be reduced from 2.8° to 1.1°C by using such technique.

Our study was restricted to regions small enough for the sea level temperature to be constant, since it was simply based on temperature regression on elevation, hence, its inability to cope with large latitudinal extent as compared to longitudinal extent. However, for interpolation over larger areas, partial spline analysis and kriging (Hutchinson 1993) with external drift (on elevation) are two related ways of allowing for spatially varying sea level temperature, while fitting a constant lapse rate.

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REFERENCES

Angot, A., 1892: Sur la décroissance de la température de l'air avec la hauteur. *C. R. Acad. Sci,* **115,** 1272–1273.

Barry, R. G., and R. J. Chorley, 1987: *Atmosphere, Weather and Climate.* 5th ed. Routledge, XXX pp.

Bisci, C., M. Cellini, P. Farabollini, and C. Pittori, 1989: Le gradient thermique dans les Marches méridionales (Italie Centrale): Actes du colloque de Pavia, Italie, 1–3 Juin 1989. *Publ. Assoc. Int. Climatol.,* **2,** 27–33.

Brancucci, G., G. C. Cortemiglia, and R. Rossetti, 1990: Variations thermiques en fonction de l'altitude en Ligurie (Italie): Satellites et climatologie: Actes du colloque de Lanion-Rennes (France), 20–22 Juin 1990. *Publ. Assoc. Int. Climatol.,* **3,** 381–389.

Brugnoli, A., and C. Gandolfo, 1991: Analisi dendroclimatica sull'abete rosso (*Picea abies* (L.) Karst.) del Trentino orientale: Primi risultati. *Monti Boschi,* **6,** 51–56.

Camarero, J. J., J. Guerrero-Campo, and E. Gutiérrez, 1996: Fenología del anillo de crecimiento de *Pinus uncinata* Ramond y *Pinus sylvestris* en un gradiente altitudinal en los Pireneos Centrales. *Pirineos Jaca,* **147–148,** 3–26.

Camuffo, D., and S. Enzi, 1995: Reconstructing the climate of northern Italy from archive sources. *Climate since A.D. 1500,* R. S. Bradley and P. D. Jones, Eds., Routledge, 143–154.

Carrega, P., 1986: Une méthode pour l'estimation des températures en relief contrasté dans les Alpes Maritimes. XXXX, *Int. Symp. on Topoclimatology and its Applications,* Liège, Mont-Rigi, Belgium, XXXX, 3–12.

——, 1995: A method for the reconstruction of mountain air temperatures with automatic cartographic applications. *Theor. Appl. Climatol.,* **52,** 69–84.

Cortemiglia, G. C., 1988: Variazoni termometriche con la quota nel bacino della Scrivia (Piemonte meridionale). *Proc. CIMA '88: 20th Congresso Int. di Meteorologia Alpina,* Sestola, Italy, XXXX, 329–340.

——, 1989: Validità dell'elaborazione statistica nel calcolo del gradiente termico verticale in valle Scrivia. *Julia Dertona, 2d serie,* **68,** 63–84.

——, R. Rossetti, A. Ghezzi, and M. Tortelli, 1989: Variations thermiques avec l'altitude dans les Alpes occidentales italiennes: Actes du colloque de Pavia, Italie, 1–3 Juin 1989. *Publ. Assoc. Int. Climatol.,* **2,** 19–26.

De Saintignon, M. F., 1976: Décroissance des températures en montagne de latitude moyenne: Exemple des Alpes françaises du Nord. *Rev. Geogr. Alp.,* 483–494.

——, 1986: Décroissance de la température avec l'altitude dans le Jura français en fonction du site des postes de mesure: Comparison avec les Alpes et les Vosges. *Proc. Int. sym. on Topoclimatology and its Applications,* Liège, Mont-Rigi, Belgium, XXXX, XX–XX.

Desplanque, C., C. Rolland, and F. H. Schweingruber, 1999: Influence of species and abiotic factors on extreme tree ring modulation: *Picea abies* and *Abies alba* in Tarentaise and Maurienne (French Alps). *Trees,* **13,** 218–227.

Dobremez, J. F., and M. C. Vartanian, 1974: Climatologie des séries de végétation des Alpes du Nord. *Doc. Cart. Ecol.,* **13,** 29–48.

Dodson, R., and D. Marks, 1997: Daily air temperature interpolated at high spatial resolution over a large mountainous region. *Climate Res.,* **8,** 1–20.

Douguédroit, A., and M. F. De Saintignon, 1970: Méthode d'étude de la décroissance des températures en montagne de latitude moyenne: Exemple des Alpes françaises du Sud. *Rev. Geogr. Alp.,* **58,** 453–472.

——, and ——, 1981: Décroissance des températures mensuelles et annuelles avec l'altitude dans les Alpes du Sud et en Provence (séries 1959–1978). Grenoble, Mélanges géographiques offerts en hommage à C. P. Péguy, ER 30. *Eaux et Climat,* 179–194.

——, and ——, 1984: Les gradients de température et de précipitation en montagne. *Rev. Geogr. Alp.,* **72,** 225–239.

Erpicum, M., 1984: Variabilité spatiale et possibilité d'extrapolation des extrêmes quotidiens de la température dans une région à relief accidenté. *Bull. Soc. Geogr. Liege,* **20,** 129–137.

Fliri, F., 1975: *Das Klima der Alpen im Raume von Tirol, Monographien zur Landskunde Tirols,* Folgel, Universität Wagner, Innsbruck, München, 454 pp.

Gafta, D., and F. Pedrotti, 1996: Fitoclima del Trentino-Alto-Adige/Südtirol Studi Trentini di Scienze Naturali. *Acta Biol.,* **73,** 55–100.

Gams, H., 1932: Die klimatische Begrenzud von Pflanzenarealen und die Verteilung des hygrischen Kontinentalität in den Alpen. *Z. Ges. Erdk. Berlin,* **52–68,** 178–198.

Gazzolo, T., 1966: Distribuzione della temperatura dell'aria in Italia nel trentino 1926–1955. Publicazione 21 del Servizio II Edizione, Fascicolo 1, Italia Settentrionale, Roma, Istituto Poligrafico Dello Stato, Liberia, 563 pp.

Gennaro Di Napoli, and L. Mercalli, 1996: Moncalieri: 130 anni di meteorologica 1865–1994. *Società Meteorologia Subalpina,* 305 pp.

Hutchinson, M. F., 1989: A new objective method for spatial interpolation of meteorological variables from irregular networks applied to the estimation of monthly mean solar radiation, temperature, precipitation and windrum. Tech. Memo. 89 (5), CSIRO, Division of Water Resources, Canberra, Australia, 95–104.

——, 1991: The application of thin plate smoothing splines to continent-wide data assimilation. BMRC Research Rep. 27, Bureau of Meteorology, Melbourne, Australia, 104–113.

——, 1993: On thin plate splines and kriging. *Computing Science and Statistics: Proceedings of the 25th Symposium on the Interface,* Vol. 25, M. E. Tarter and M. D. Lock, Eds., Interface Foundation of North America, 55–62.

Legates, D. R., and C. J. Willmott, 1990: Mean seasonal and spatial variability in global surface air temperature. *Theor. Appl. Climatol.,* **41,** 11–21.

Messerli, B., P. Messerli, C. Pfister, and H. J. Zumbühl, 1978: Fluctuations of climate and glaciers in the Bernese Oberland, Switzerland, and their geoecological significance, 1600 to 1975. *Arct. Alp. Res.,* **20,** 247–260.

Ozenda, P., 1985: La Végétation de la Chaîne Alpine dans L'espace Montagnard Européen. Masson, 331 pp.

Pache, G., S. Aimé, and R. Michalet, 1996a: A simple model for the study of the altitudinal rainfall gradient, applied in the Tyrolian orographic complex. *Rev. Ecol. Alp.,* **3,** 13–21.

——, R. Michalet, and S. Aimé, 1996b: A seasonal application of the Gams (1932) method, modified Michalet (1991): The example of the distribution of some important forest species in the Alpine chain. *Diss. Bot.,* **258,** 31–54.

Paul, P., 1976: La décroissance de la température avec l'altitude dans les Vosges et la Forêt-Noire: Aspects locaux et régionaux. *Rech. Geogr. Strasbourg,* **4,** 55–67.

——, 1986: Topoclimats et décroissance de la température avec l'altitude dans les Vosges et le Forêt Noire. *Proc. Int. Symp. on Urban and Local Climatology,* Freiburg, Germany, XXXX, 293–304.

Pfister, C., 1995: Monthly temperature and precipitation in central Europe 1525–1979: Quantifying documentary evidence on weather and its effects. *Climate since A.D. 1500,* R. S. Bradley and P. D. Jones, Eds., Routledge, 118–142.

Primault, B., 1972: Etude mésoclimatique du canton de Vaud. Office Cantonal Vaudois de l'Urbanisme, Cahiers de l'aménagement régional 14, Lausanne, Switzerland, 186 pp.

Remenierias, G., 1980: *L'hydrologie de L'ingénieur. Ed* Eyrolles, 465 pp.

Richard, L., and A. Tonnel, 1985: Contribution à l'étude bioclimatique de l'arc alpin. *Doc. Cartogr. Ecol.,* **28,** 33–64.

Rolland, C., V. Petitcolas, and R. Michalet, 1998: Changes in radial tree growth for *Picea abies*, *Larix decidua*, *Pinus cembra* and *Pinus uncinata* near the alpine timberline since 1750. *Trees,* **13,** 40–53.

Schweingruber, F. H., K. R. Briffa, and P. D. Jones, 1991: Yearly maps of summer temperatures in Western Europe from A.D. 1750 to 1975, and Western North America from 1600 to 1982. *Vegetatio,* **92,** 5–71.

Stoutjesdijk, P., and J. J. Barkman, 1992: *Microclimate, Vegetation and Fauna.* Opulus Press, 216 pp.