TEMPERATURE VARIATIONS DURING THE LAST CENTURY AT HIGH ELEVATION SITES

HENRY F. DIAZ
NOAA/ERL/CDC, 325 Broadway, Boulder, CO 80303, U.S.A.

RAYMOND S. BRADLEY
Department of Geosciences, University of Massachusetts, Amherst, MA 01003, U.S.A.

Abstract. Differential temperature changes with altitude can shed light on the relative importance of natural versus anthropogenic climatic change. There has been heightened interest in this subject recently due to the finding that high-elevation tropical glaciers have been retreating and that significant melting from even the highest alpine regions has occurred in some areas during the past 20 years or so, as recorded in ice core records, which do not reveal any similar period during previous centuries to millennia.

In this paper we find evidence for appreciable differences in mean temperature changes with elevation during the last several decades of instrumental records. The signal appears to be more closely related to increases in daily minimum temperature than changes in the daily maximum. The changes in surface temperature vary spatially, with Europe (particularly western Europe), and parts of Asia displaying the strongest high altitude warming during the period of record.

High-elevation climate records of long standing taken at a number of mountain tops throughout the world, but primarily in Europe, are available from a number of countries. In some cases, meteorological observations at these unique mountain sites have been discontinued for a variety of reasons, usually budgetary. It is hoped that the papers published in this special issue of *Climatic Change* can contribute to a reassessment of the value of continuing climate measurements at these mountain observatories by the appropriate entities, so that we may continue to have access to climate information from the 'tops of the world'.

1. Introduction

Concern has been expressed by a number of researchers that greenhouse-gas-induced climatic changes will severely impact the mountain regions of the world (Schneider, 1990; Hastenrath and Kruss, 1992; Grabherr et al., 1994; Oerlemans, 1994; Beniston, 1994; Diaz and Graham, 1996). One of the most obvious and potentially severe impacts is likely to be the retreat, and in some cases, disappearance of many alpine glaciers throughout the world. Indeed, Oerlemans (1994) suggests, on the basis of an analysis of alpine glacier changes throughout the world during the last hundred years, that the global surface temperature change during this time is about 0.66 °C, a value that is on the high side of estimates made from instrumental records of surface temperature around the world (IPCC, 1992, 1996).

The matter of differential temperature trends as a function of height also has important ecological implications with regard to ecotonal changes which may result from any future global warming (Barry, 1990; Schneider, 1990; Beniston, 1994; Beniston and Fox, 1996). As Schneider (1990) pointed out, even relatively small

Climatic Change **36:** 253–279, 1997.

global temperature changes could have major habitat implications for animal and plant species living in upper mountain environments. Furthermore, recent work with tropical glaciers and ice caps (Hastenrath and Kruss, 1992; Schubert, 1992; Thompson et al., 1992, 1995) demonstrate a significant impact of warmer (and probably more humid) conditions in the high elevation regions of Asia, Africa and South America, where these tropical systems are located.

Recent experiments with high-resolution GCMs, supported by some observational data suggest that there may be appreciable differences in the vertical distribution of temperature below 500 mb in association with projected global climate change (Graham, 1995; Diaz and Graham, 1996; Vinnikov et al., 1996; Tett et al., 1996). In the lower latitudes, recent work suggest that a water vapor feedback may significantly amplify the direct radiative effects of increasing atmospheric greenhouse-gas concentrations (Flohn et al., 1992; Graham, 1995; Diaz and Graham, 1996).

The availability of long-term temperature records at a number of isolated mountain sites, particularly in Europe, allows us to evaluate the spatial pattern of surface temperature changes over approximately the last century in selected extratropical areas (see Stekl and Podzimek, 1993; Weber et al., 1994, 1997; Beniston et al., 1994, 1997; Dessens and Bücher, 1995). These studies have shown that temperatures at these high-elevation mountain stations have risen by 1–2 °C in the last century, with the minimum temperature rising faster than the daytime maximum temperature.

This paper partly addresses itself to the question of elevational differences in long-term temperature trends, using all high-elevation station records available to us. We have compared the temperature trends for different latitudinal bands as a function of station altitude. We regionalize the results for different climate regimes, such as for subtropical regions which display relatively high vertical lapse rates of temperature, and for tropical regions where, in general, high mean annual rainfall results in smaller values of the temperature lapse rate. Station temperature trends were binned by latitudinal bands and elevation zones. In addition to the set of mountain-top observatory records, which are found mainly in Europe, we have supplemented these data with records from rural stations with high ground elevations in Asia and North America; the combined record set will be referred heceforth as the HIGH dataset. This observed pattern of temperature changes from surface stations is evaluated in the context of recent studies showing that tropical sea surface temperature (SST) changes have a strong influence on mid-tropospheric temperature variations on interannual-to-decadal time scales (Diaz and Graham, 1996).

Some results obtained from a couple of GCM experiments with transient and doubled-CO_2 climate simulations, and some experiments focused on the model atmosphere's response to changes in observed sea surface temperature (SST) are used to interpret the changes in surface temperature during the past few decades (Cubasch et al., 1992; Graham, 1995; Vinnikov et al., 1996).

2. Data Sources

A number of data sources were used; the individual high-elevation sites – whether from a mountain observatory or from (largely) rural high-elevation sites – are listed in Table I, and the sources given at the end of the table. In several of the high altitude observatory sites, other types of scientific observations, in addition to meteorological ones, have been carried out by trained observers (see Barry, 1992, Table I.2, for a listing of principal mountain observatories and for additional reference material). The locations of the individual high altitude stations used in this study are given in Figure 1. For comparison, we have also included four high-elevation stations in South America that lie near or to the north of the equator (Table I). One additional piece of background information has been added in Table I, namely, an appraisal of the general topographic setting at the site of the observing station. Seven general terrain categories are listed at the bottom of the table. These were determined by plotting the station on a map using a 5-min (high-resolution) topography data set, and from visual inspection of a regional map using a large-format atlas. The aspect categories are meant to serve as a general guide only, as the actual exposure of some of the stations were not accurately known.

The station data were also composited into 12 regional indices, as illustrated in Figure 1. Table II gives some basic information for each region; except for Region 12, one of two Asian regions, the intersite correlation is quite high, so that, in general, a relatively small sample of sites is capable of calibrating significant amounts of the variance of the full network. The mean correlation coefficient among the pairs of stations in each regional grouping is given in Table II as a measure of the degree to which fewer than the full complement of sites for that region can reproduce each corresponding regional index (Wigley et al., 1984). Mean annual temperatures for many of the European HIGH stations are typically below freezing. The North American sites are generally somewhat warmer, although the average temperature of the coldest month for the Canadian sites is typically lower than those for the other regions. Many data sources were used, but most of the data have been collected into one global data set known as the Global Historical Climate Network (GHCN, see Vose et al., 1992).

3. Analysis Results

3.1. REGIONAL TEMPERATURE CHANGES

3.1.1. *North American Sites*

A total of 18 Canadian stations have been used, 16 of which are located in western Canada. Thirty-six stations were selected in the western United States plus the Mount Washington Observatory record in New Hampshire. We have plotted and manually analyzed the annual average temperature profile along meridional transects for western North America, central and eastern Europe, in order to

Table I
List of stations used in this study

WMO#	Elev. (m)	Station name	Country	Lat.	Long.	Period of record	Aspect code
			SCANDINAVIA				
11655	638	DOMBAS	Norway[1]	62.0° N	9.1° E	1864–1976	6
12380	974	FOKSTUA	Norway[1]	62.1° N	9.2° E	1923–1989	6
12572	995	HAUGASTOL	Norway[1]	60.3° N	7.5° E	1884–1976	5
12880	628	RØROS	Norway[1]	62.4° N	11.2° E	1871–1989	3
13197	1828	GAUSTATOPPEN	Norway[1]	59.9° N	8.7° E	1934–1974	4
15523	2062	FANARAKEN[a]	Norway[1]	61.5° N	7.0° E	1932–1978	1
			EUROPE				
66000	2095	ST. GOTTHARD	Switzer.[2]	46.4° N	8.6° E	1864–1960	5
66800	2496	SANTIS[a,b]	Switzer[3]	47.3° N	9.3° E	1883–1995	1
67190	2460	GRAND ST BERNARD	Switzer[2, 3]	45.9° N	7.2° E	1818–1985	4
67300	3572	JUNGFRAUJOCH[a]	Switzer[3]	46.6° N	8.0° E	1933–1994	1
73001	1452	LE PUY DE DOME	France[4]	45.8° N	2.9° E	1950–1982	4
75600	1567	MONT AIGOUAL	France[4]	44.1° N	3.4° E	1949–1988	3
76001	2860	PIC DU MIDI[a]	France[4]	42.9° N	0.1° E	1882–1984	1
76499	1912	MONT VENTOUX	France[4]	44.1° N	5.2° E	1949–1968	4
81820	1708	MONTSENY	Spain[10]	41.8° N	2.5° E	1941–1987	3
82150	1888	NAVACERRADA	Spain[10]	40.8° N	4.0° W	1941–1989	3
95780	1213	FICHTELBERG[a]	Germany[3]	50.4° N	13.0° E	1891–1980	1
109610	2962	ZUGSPITZE[a, b]	Germany[3]	47.4° N	11.0° E	1951–1995	1
109620	983	HOHENPEISSENBERG[b]	Germany[3]	47.8° N	11.0° E	1781–1990	3
111460	3107	SONNBLICK[a, b]	Austria[3]	47.1° N	13.0° E	1887–1995	4
113995	2044	OBIR	Austria[3]	46.5° N	14.5° E	1851–1944	4
119160	2008	CHOPOK	Slovakia[5]	48.9° N	19.6° E	1956–1989	3
119300	2635	LOMNICKY STIT[a]	Slovakia[5]	49.2° N	20.2° E	1941–1989	1
150520	1536	RARAU	Romania[6]	47.5° N	25.5° E	1951–1989	4
151451	1384	BAISOARA	Romania[6]	46.5° N	23.4° E	1951–1989	6
152601	1454	PALTINIS	Romania[6]	45.7° N	23.5° E	1948–1989	6
152800	2507	VIRFUL OMU[a]	Romania[6]	45.5° N	25.5° E	1941–1989	1
156130	2286	CHERNI VRAH[a]	Bulgaria[7]	42.6° N	23.3° E	1936–1988	1
156150	2925	MUSALA[a]	Bulgaria[7]	42.1° N	23.4° E	1933–1988	1
156270	2376	BOTEV	Bulgaria[7]	42.7° N	24.9° E	1946–1988	2
600100	2367	MT IZAÑA[a] CANARY IS	Spain[10]	28.3° N	16.5° W	1916–1989	1
			CENTRAL ASIA				
305540	1310	BOGDARIN[b]	Russia[3]	54.5° N	113.1° E	1938–1995	3
369740	2049	NARYN[b]	Russia[3]	41.4° N	76.0° E	1886–1990	3
415730	2168	MURREE[b]	Pakistan[3]	33.9° N	73.4° E	1947–1971	3
421470	2311	MUKTESWAR, KUMAUN	India[3]	29.5° N	79.7° E	1897–1995	5
422950	2128	DARJEELING[b]	India[3]	27.1° N	88.3° E	1848–1978	5
435440	3514	LEH KASHMIR[b]	India[3]	34.2° N	77.7° E	1882–1968	3
528360	3191	DULAN (TULAN)[b]	China[3]	36.3° N	98.0° E	1940–1995	5
555910	3685	LHASA[b]	China[3]	29.7° N	91.1° E	1935–1988	6
561370	3241	QAMDO (CHAMDO)[b]	China[3]	31.1° N	96.9° E	1951–1995	6

Table I
(Continued)

WMO#	Elev. (m)	Station name	Country	Lat.	Long.	Period of record	Aspect code
377810	3227	ARAGATS	FSU[11]	40.5° N	44.2° E	1930–1990	3
371280	2583	BERMAMYT	FSU[11]	43.7° N	42.4° E	1934–1987	3
374610	2600	KARA-TYUREK	Russia[11]	50.0° N	86.4° E	1939–1990	5
373340	3653	KAZBEGI	FSU[11]	42.7° N	44.5° E	1934–1990	6
373160	2854	MAMISONSKIY	FSU[11]	43.7° N	43.8° E	1934–1990	5
374610	2923	SULAK	FSU[11]	42.4° N	46.3° E	1930–1990	3
387480	2782	ALTYN-MAZAR	FSU[11]	39.2° N	72.2° E	1932–1990	5
387190	3373	ANZOBSKIY	FSU[11]	39.1° N	68.9° E	1940–1990	3
387340	2564	DEHAUZ	FSU[11]	39.5° N	70.2° E	1929–1990	3
389560	3410	DZHAUSHANGOZ	FSU[11]	37.4° N	72.5° E	1934–1990	3
388690	3290	IRKHT	FSU[11]	38.2° N	72.6° E	1940–1990	5
388750	3930	KARAKUL	FSU[11]	39.0° N	73.6° E	1933–1990	4
388780	3576	MURGAB	FSU[11]	38.2° N	74.0° E	1894–1990	6
388710	3207	SARY-TASH	FSU[11]	39.7° N	73.3° E	1933–1990	6
387150	3143	SASHRISTANSKIY	FSU[11]	39.6° N	68.6° E	1934–1990	6
369820	3672	TYAN-SHAN	FSU[11]	41.9° N	78.2° E	1930–1990	4
388620	4169	LEDNIK FEDCHENKO	FSU[11]	38.8° N	72.2° E	1933–1989	3
			NORTH AMERICA				
710056	670	ATLIN	Canada[3]	59.6° N	133.7° W	1899–1989	3
711220	1397	BANFF[b]	Canada[3]	51.2° N	115.6° W	1888–1990	6
712016	750	ANEROID	Canada[3]	49.7° N	107.3° W	1916–1989	7
712296	696	GRAVELBOURG	Canada[3]	49.9° N	106.6° W	1921–1989	7
712408	1064	LINTONEL	Canada[3]	49.7° N	108.9° W	1910–1989	3
712492	1034	OLDS	Canada[3]	51.8° N	114.1° W	1914–1989	3
713140	1352	CARWAY	Canada[3]	49.0° N	113.4° W	1914–1989	3
713324	1212	HIGH RIVER	Canada[3]	50.5° N	114.2° W	1902–1989	3
715060	1278	BEAVER MINES	Canada[3]	49.5° N	114.2° W	1935–1989	3
715352	1055	JASPER	Canada[3]	52.9° N	118.1° W	1926–1990	6
715360	1383	KANANASKIS	Canada[3]	51.0° N	115.0° W	1939–1989	6
715512	1431	PEKISKO	Canada[3]	50.4° N	114.4° W	1905–1989	3
718260	537	NITCHEQUON[b]	Canada[3]	53.2° N	70.9° W	1942–1988	5
718288	329	GRAND LAKE Victoria[b]	Canada[3]	47.8° N	77.4° W	1939–1980	3
718897	868	WISTARIA	Canada[3]	53.8° N	126.2° W	1926–1989	5
718967	1274	BARKERVILLE[b]	Canada[3]	53.0° N	121.6° W	1888–1989	3
719442	732	BEAVERLODGE[b]	Canada[3]	55.2° N	119.4° W	1913–1989	6
719530	685	WATSON LAKE[b]	Canada[3]	60.1° N	128.8° W	1938–1990	6
722684	2691	CLOUDCROFT, NM[b]	USA[3]	33.0° N	105.8° W	1901–1970	5
722687	2068	MESCALERO, NM[b]	USA[3]	33.2° N	105.8° W	1911–1978	5
722699	2149	LUNA R. S., NM[b]	USA[3]	33.8° N	108.9° W	1903–1989	5
723604	2475	TRES PIEDRAS, NM[b]	USA[3]	36.7° N	106.0° W	1905–1989	5
723605	2645	RED RIVER, NM	USA[3]	36.7° N	105.4° W	1906–1989	5
723607	2484	WOLF CANYON, NM[b]	USA[3]	36.0° N	106.8° W	1912–1989	3
723654	2134	FORT WINGATE, NM[b]	USA[3]	35.5° N	108.5° W	1897–1966	5
723657	2031	CORONA, NM[b]	USA[3]	34.3° N	105.6° W	1912–1980	5

Table I
(Continued)

WMO#	Elev. (m)	Station name	Country	Lat.	Long.	Period of record	Aspect code
723656	2393	CHAMA, NM	USA[3]	36.9° N	106.6° W	1889–1989	6
723661	2067	MT PARK, NM	USA[3]	33.0° N	105.8° W	1915–1989	3
723664	2259	LOS ALAMOS, NM	USA[3]	35.9° N	106.3° W	1919–1989	3
723665	1993	MAGDALENA, NM[b]	USA[3]	34.1° N	107.2° W	1906–1989	5
723666	1987	MOUNTAINAIR, NM[b]	USA[3]	34.5° N	106.3° W	1902–1980	5
723702	2239	FORT VALLEY, AZ[b]	USA[3]	35.3° N	111.7° W	1909–1989	5
723745	2152	SPRINGERVILLE, AZ[b]	USA[3]	34.1° N	109.3° W	1911–1989	5
723780	2118	GR CANYON, AZ[b]	USA[3]	36.1° N	112.1° W	1903–1980	5
723651	2842	SILVERTON, CO	USA[3]	37.8° N	107.7° W	1904–1989	6
724682	2096	CHEESMAN, CO[b]	USA[3]	39.2° N	105.3° W	1902–1989	3
724761	2699	CRESTED BUTTE, CO[b]	USA[3]	38.9° N	107.0° W	1910–1989	5
724696	3062	LEADVILLE, CO	USA[3]	39.2° N	106.3° W	1908–1979	4
725703	2609	FRASER, CO	USA[3]	40.0° N	105.8° W	1910–1970	6
729995	3244	W. CREEK PASS, CO	USA[8]	37.5° N	106.8° W	1958–1989	4
729996	3018	NIWOT R. (C1), CO	USA[9]	40.0° N	105.5° W	1951–1989	4
729997	3743	NIWOT R. (D1), CO	USA[9]	40.1° N	105.6° W	1951–1989	4
729998	3448	BERTHOUD PASS, CO	USA[8]	39.8° N	105.8° W	1963–1985	4
724701	1840	BLANDING, UT[b]	USA[3]	37.6° N	109.5° W	1904–1989	3
724801	2146	ALTON, UT[b]	USA[3]	37.4° N	112.5° W	1915–1989	5
724882	2013	AUSTIN, NV[b]	USA[3]	39.5° N	117.1° W	1888–1989	3
725643	2757	FOXPARK, WY[b]	USA[3]	41.1° N	106.1° W	1909–1970	3
725645	2070	SARATOGA, WY	USA[3]	41.5° N	106.8° W	1889–1989	5
725692	2252	ENCAMPMENT, WY	USA[3]	41.2° N	106.6° W	1909–1989	5
725762	1807	PATHFINDER DAM, WY[b]	USA[3]	42.5° N	106.8° W	1906–1989	3
726130	1905	MT WASHINGTON, NH	USA[3]	44.3° N	71.3° W	1933–1990	1
726702	2108	DUBOIS, WY	USA[3]	43.5° N	109.6° W	1907–1989	3
726704	2069	MORAN, WY[b]	USA[3]	43.8° N	110.6° W	1911–1989	6
726773	1899	YELLOWSTONE PK, WY[b]	USA[3]	45.0° N	110.7° W	1886–1989	5
726777	1978	HEBGEN DAM, MT[b]	USA[3]	44.9° N	111.3° W	1913–1989	3
			SOUTH AMERICA				
803930	1495	EL LIBANO[b]	Colombia[3]	4.9° N	75.1° W	1951–1970	6
804001	1042	CAR./CAGIGAL OBS[b]	Venezuela[3]	10.5° N	66.9° W	1891–1989	1
804380	1479	MERIDA[b]	Venezuela[3]	8.6° N	71.2° W	1915–1995	3
840710	2818	QUITO/M. SUCRE[b]	Ecuador[3]	0.2° S	78.5° W	1891–1990	3

Abbreviation codes
[a] High elevation station used to construct Mountain Observatory temperature indices.
[b] Station is part of the set used to construct the gridded surface temperature data (see Jones et al., 1986).
[c] Index numbers are either official WMO station identifyer, or were assigned by us in WMO format for database management purposes. The latter station ids are therefore not part of the WMO station index catalogue.
Data sources
1. Det Norske Meteorologiske Institutt. Courtesy of Froude Stardahl, University of Oslo.
2. Swiss Meteorological Centre, Zurich.
3. U.S. Department of Energy and National Oceanic and AtmosphericAdministration (NOAA) data archives.
4. Direction de la Meteorologie Nationale, Paris.
5. Slovak HydroMeteorological Institute. Courtesy of M. Lapin, Department of Applied Climatology, SHMU.

Table I
(Continued)

6. Institul de Metorologie si Hydrologie Bucuresti. Courtesy of Dr. Jon Dragich.
7. Institute of Hydrology & Meteorology, Sofia, Bulgaria. Courtesy of Dr. L.N. Kristev.
8. Colorado State Climatologist, Colorado State University, Fort Collins.
9. Institute of Arctic and Alpine Research, University of Colorado, Boulder.
10. Data obtained through the courtesy of Prof. Inocencio Font Tullot.
11. Data obtained through the courtesy of Pasha Groisman.

Aspect codes
1. Mountain observatory
2. Mountain top
3. Mountain slope
4. Ridge zone
5. High plateau
6. High valley
7. High plains

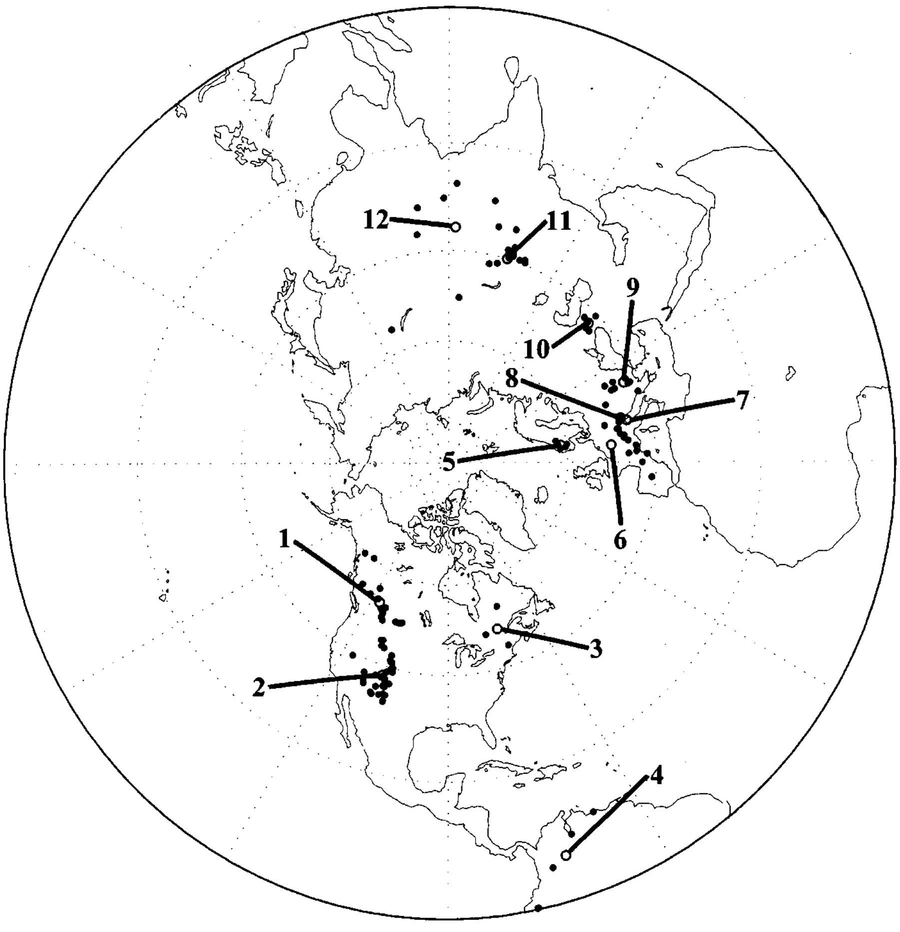


Figure 1. Location of stations used in this study. Data were composited into 12 regions, whose mean coordinates are plotted as open circles. The region name and number are as shown in Table II.

Table II
Names of regions shown in Figure 1 and other particulars

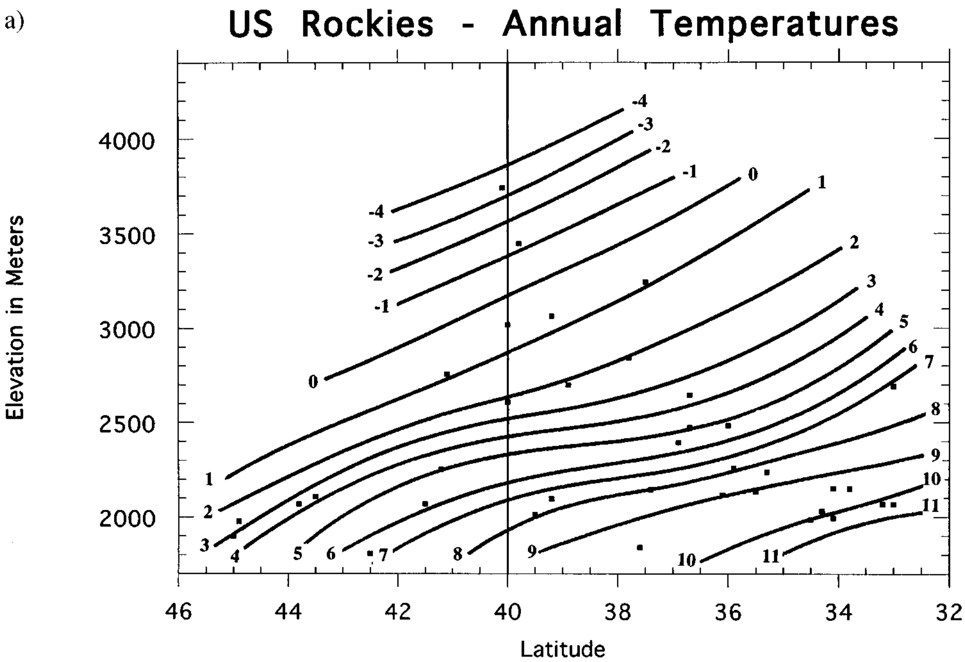
Name		Mean latitude	Mean longitude	Mean elevation	Mean R	N stations
Region 1	Canadian Rockies	52.3° N	117.0° W	1055 m	0.83	16
Region 2	United States Rockies	38.0° N	107.8° W	2377 m	0.58	36
Region 3	Eastern North America	48.4° N	73.2° W	1147 m	0.78	3
Region 4	Northern South America	6.0° N	72.9° W	1709 m	0.61	4
Region 5	Scandinavia	61.4° N	8.8° E	1188 m	0.90	6
Region 6	Western European Peaks	49.6° N	6.1° E	2748 m	0.62	4
Region 7	Europe	45.3° N	13.1° E	2143 m	0.47	24
Region 8	Central European Peaks	46.5° N	14.2° E	2480 m	0.80	4
Region 9	Eastern European Peaks	43.4° N	24.1° E	2573 m	0.90	3
Region 10	Caucasus Mountains	42.6° N	44.2° E	3048 m	0.86	5
Region 11	Asia I	40.0° N	73.6° E	3310 m	0.67	12
Region 12	Asia II	35.3° N	88.3° E	2622 m	0.21	9

demonstrate that this network of high-elevation stations closely approximates the mean temperature surfaces of the free atmosphere. This also helped us to get some idea regarding the climatic representativeness of the individual stations.

The meridional gradient of annual mean temperature as a function of station height along the U.S. and Canadian Rockies is illustrated in Figure 2. The U.S. portion of the Rocky Mountain chain (top panel of Figure 2) displays a relatively steep vertical temperature lapse rate compared to the Canadian Rockies (Figure 2, bottom panel), but somewhat smaller mean meridional temperature gradients compared to the Canadian sector. Note that the U.S. stations also have much higher ground elevations than those in Canada.

At 40 °N, the vertical lapse rate of temperature is approximately 6.3 °C/km (Figure 2), close to the standard atmospheric value of 6.5 °C/km, and the annual average freezing level is found around 3200 m above sea level. In the Colorado Rockies this is not far from the location of the upper tree-line, which is found closer to 3500 m a.s.l. (Barry, 1992). At 52 °N, the average freezing level is found near 1500 m, and the temperature lapse rate is just under 4 °C/km (Figure 2). One reason contributing to the relatively small vertical lapse rate in this region of western Canada, is that, for a substantial part of the year, temperature inversions develop in the atmospheric boundary layer (a few hundred meters above the ground), resulting in the more isothermal mean structure shown here (Barry and Chorley, 1992, pp. 50–51).

For a seasonal comparison, Figure 3 displays mean summer (June–August) temperature profiles for the entire Rocky Mountain region anlysed here. At 40° N, mean summer temperature near the 3200 m level is about 10 °C, and this value is also consistent with the nearby position of the upper tree-line. The lapse rates a)



b)

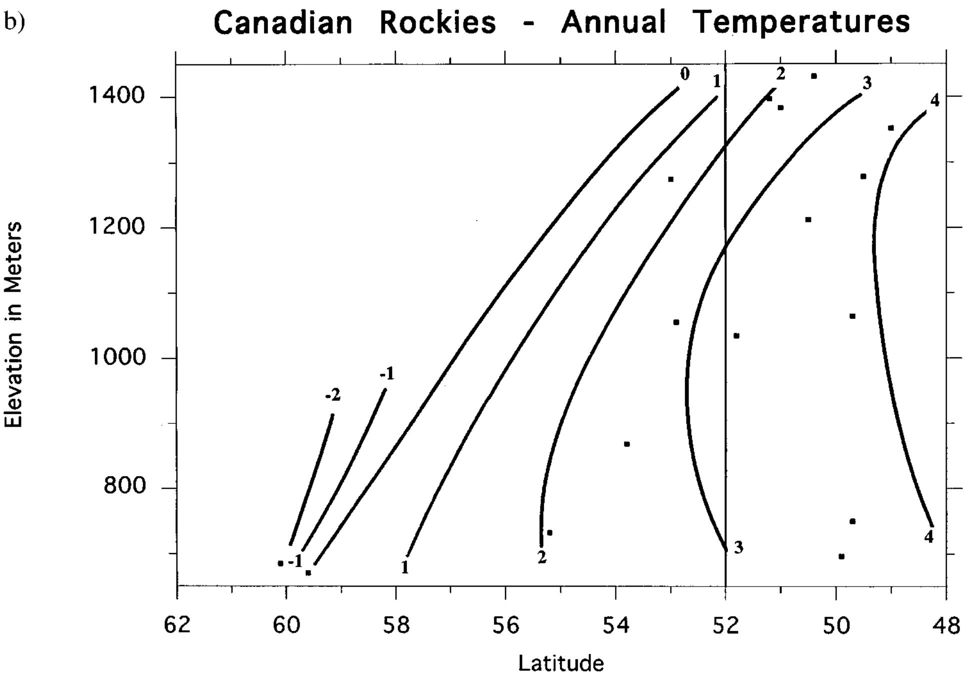


Figure 2. Annual mean temperature profiles (ground elevation versus latitude) for the U.S. (top panel) and Canadian Rockies (bottom) regions. Values were plotted at the location of the black dots and hand-analyzed. Countours are in Celsius degrees at one-degree intervals.

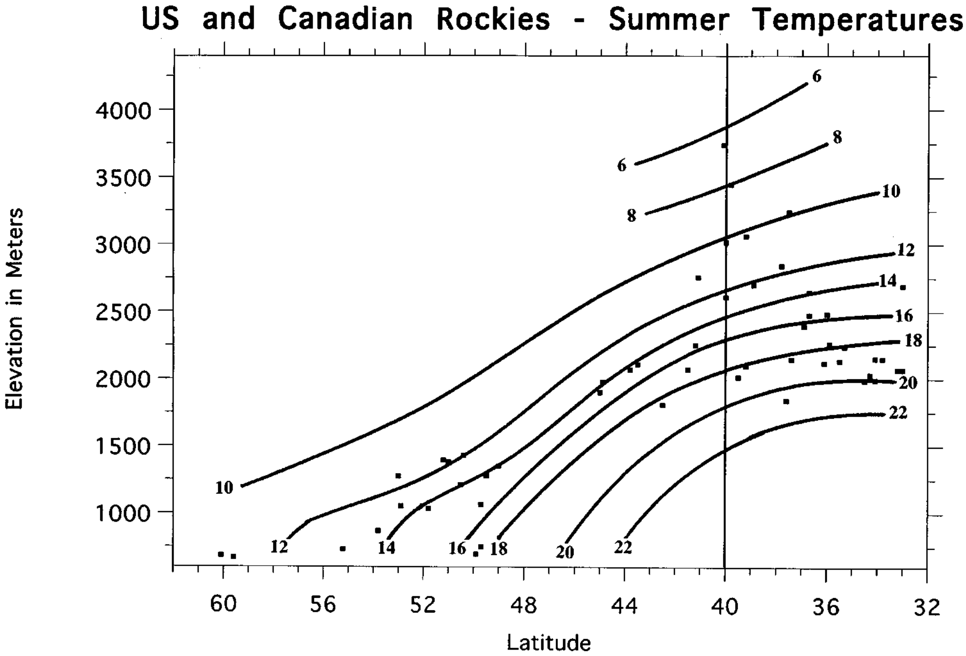


Figure 3. Same as in Figure 2, but for the summer season. Both U.S. and Canadian stations are shown together.

are only slightly higher in summer than for the year as a whole (about 6.4 °C/km at 40° N and 4.2 °C/km at 52° N), which is somewhat surprising, considering the stronger vertical mixing and convective activity that occurs at this time. The reader is referred to Barry and Chorley (1992) and Hastenrath (1968) for discussions of regional and seasonal variations of vertical temperature lapse rate and other related topics.

Time series of annual mean temperature anomalies for both the Canadian and U.S. Rockies regions are depicted in Figure 4. We have also plotted mean June–August temperature anomalies for each region used in this study, as this comprises the bulk of the ablation season, and we wished to see if the seasonal change departed substantially from that of the annual mean. However, unless a significant seasonal difference is present, we only show here the figures for the annual time series. The Canadian Rockies data set covers the period 1888–1990, has a maximum of 16 stations, a mean station elevation of 1055 m, and a mean intersite correlation (for annual mean temperature) of $r = 0.83$. The mean correlation coefficient among the set of constituent stations or sites in a series ensemble can be used to give a measure of the signal strength or variance retained by subsamples of the the full series set (see Wigley et al., 1984). It is included in Table II for comparison purposes. The U.S. Rockies index has a maximum of 36 stations, a mean elevation of 2377 m, and a mean intersite correlation of $r = 0.58$. For ease of comparison, the data values

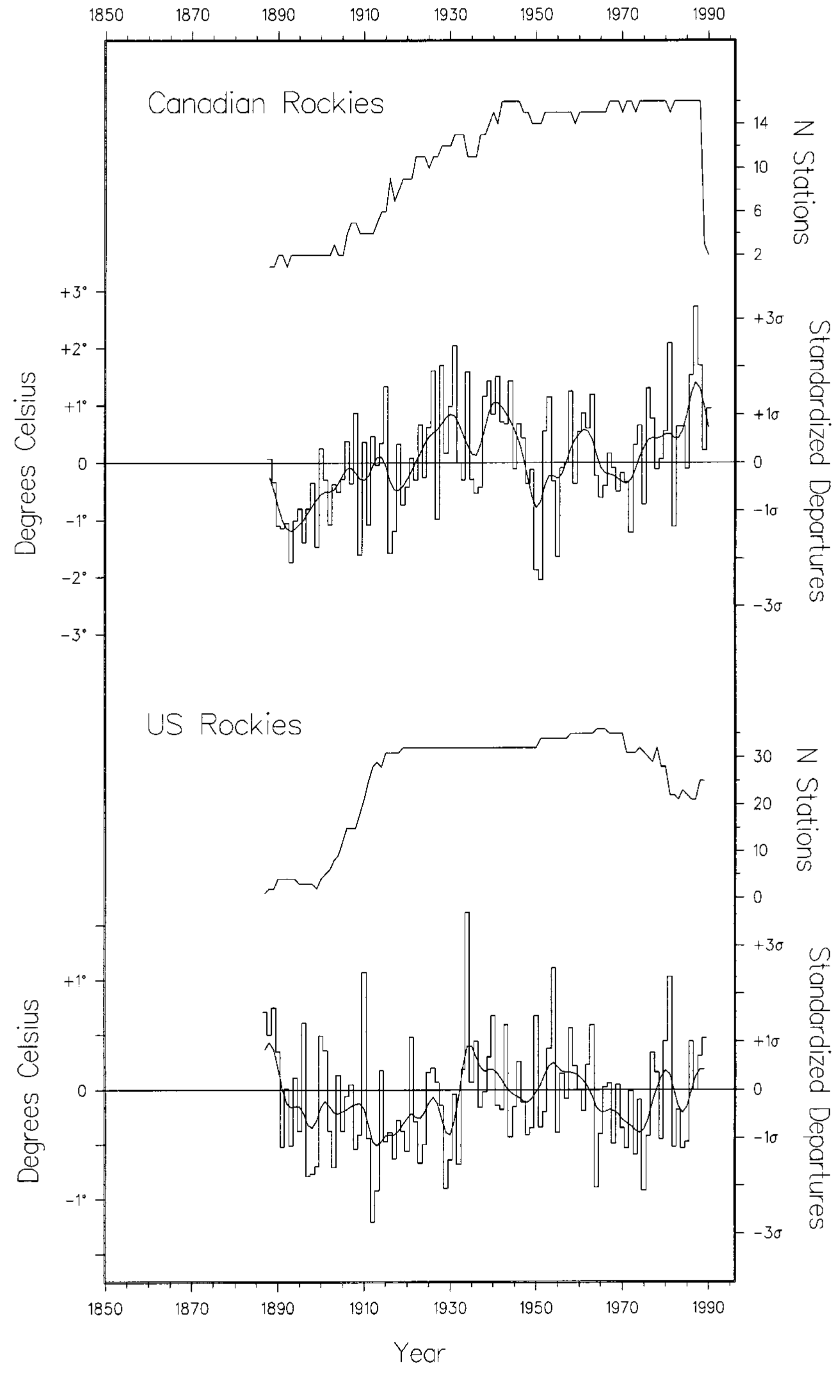


Figure 4. Time series of annual mean temperature anomalies (referenced to the period 1951–1970) for the Canadian (top panel) and U.S. Rockies (bottom) regions. Values are shown in units of Celsius degrees (left axis) and standardized departures (right axis).

are all plotted on the same standardized unit scale (referenced to the 1951–1970 period), on the right axis, as well in dimensional units on the left axis. Considerable interannual and decadal scale temperature variability is evident in both series. A cool period early in this century is evident in the U.S., as are relatively warm years thereafter, a return to cooler conditions during the 1960s and 1970s (although cold years are also evident in the Canadian Rockies during the late 1940s to mid-1950s), and somewhat warmer conditions prevalent since about 1980. In this respect, the western U.S. regional record resembles that of larger continental and hemispheric scale averages (Diaz and Kiladis, 1995; Diaz and Bradley, 1995; Diaz, 1996). There is a suggestion that annual temperatures in Canada in the first decade or two of the available instrumental record were relatively low, but because of the few stations available, the magnitude of the anomalies may be overstated. Quite cold conditions are evident in the period around 1950.

Three 'high-elevation' stations comprise the eastern North America HIGH temperature index (two in Canada and one, Mount Washington, NH, in the U.S.A., see Figure 1). Although Table II gives a mean elevation of 924 m, Mt. Washington is considerably higher than the other two stations, but are combined here because their mean (intersite) correlation is relatively high ($r = 0.78$), and because the two sites represent relatively pristine environments at relatively higher elevations than the bulk of the stations in the region. The record for eastern North America is relatively short (Figure 5), compared to the others, but the warmer period of the 1930s, and the subsequent cooling trend are evident in this figure. For comparison purposes, a four-station 'high-elevation' index for northern South America (Figure 1) is given in Figure 6. Confidence in the values before the early 1930s is low, so the index values are only plotted since 1934. In particular, the cool period in the first three decades of this century (not shown), and subsequent decadal-scale temperature fluctuations are similar to those of continental areas in the Southern Hemisphere (Jones et al., 1986), and is also quite similar to the behavior of global surface temperature indices published in the IPCC (1996) Report.

3.1.2. *Europe and Scandinavia*

The distribution of European and Scandinavian sites are depicted in Figure 1 and the particulars for each site and region are given in Tables I and II. We divided the continent into four main groupings: West, Central and Eastern European 'peaks' and 'Scandinavia'. We note, however, that for the latter, all the HIGH sites are situated in Norway. Twenty-four stations were used in Europe with a mean elevation of 2143 m, and mean intersite correlation of $r = 0.47$. Six Norwegian stations were used to represent Scandinavia, with a mean elevation of 1188 m and average correlation of $r = 0.9$.

Two meridional transects (for eastern and western Europe) of mean annual temperature for the European continent are presented (Figure 7). In both figures the Scandinavian (Norwegian) stations were used to provide an anchor to the north. The vertical temperature lapse rate at 50° N derived from the western Europe transect

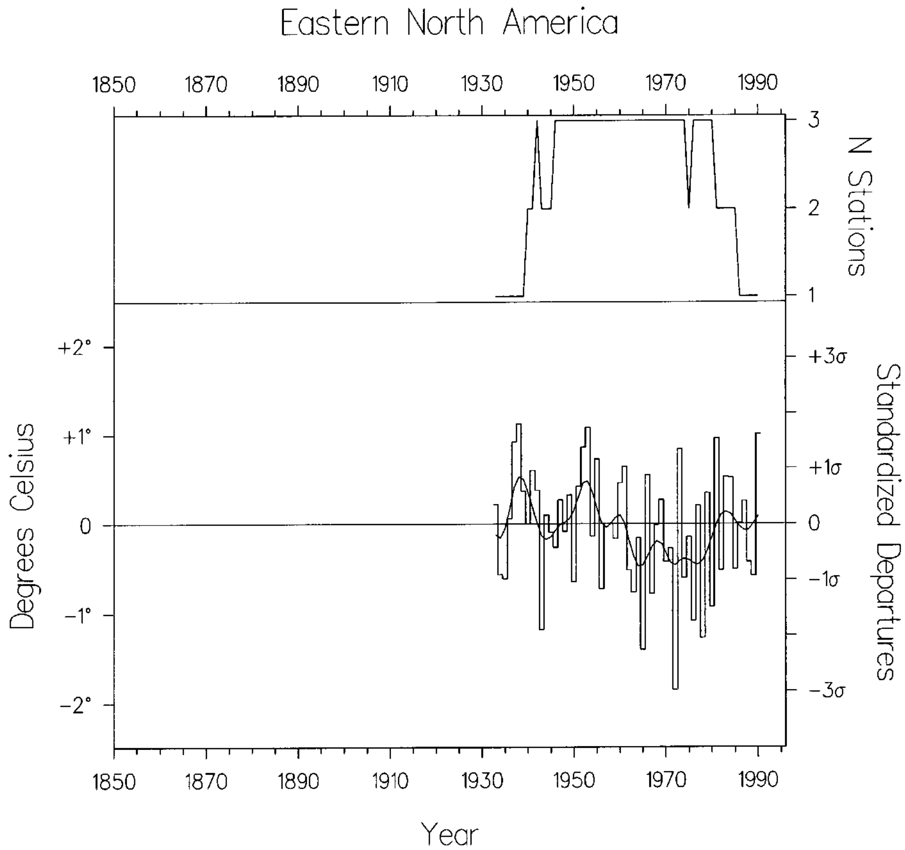


Figure 5. As in Figure 4, except for the eastern North America region.

(top panel of Figure 7) is close to 5.2 °C/km, with the height of the 0 °C isotherm located at about 1800 m. For Eastern Europe at this same latitude, the lapse rate is about 5.5 °C/km and the average freezing level is near 1700 m.

An index of annual mean temperature changes over time for the HIGH stations in Europe (excluding the Scandinavian stations) is shown in Figure 8a. We considered that changes in summer mean temperature for Europe differed somewhat from that of the annual mean, and the summer temperature anomaly series is shown in Figure 8b We note that, although prior to about 1870, the temperature record is derived from relatively few stations (fewer than five), the suggestion is that both annual and summer mean temperatures around the mid-1800s were quite similar to those in the mid-1900s. The last decade or so shows up as significantly warmer than other such periods in the available instrumental record (see Beniston et al., 1997). The occurrence of a cold interval that lasted several decades from around 1870 to about 1920 (as in North America) is one reason why the warming trend for the 20th century tends to be accentuated.

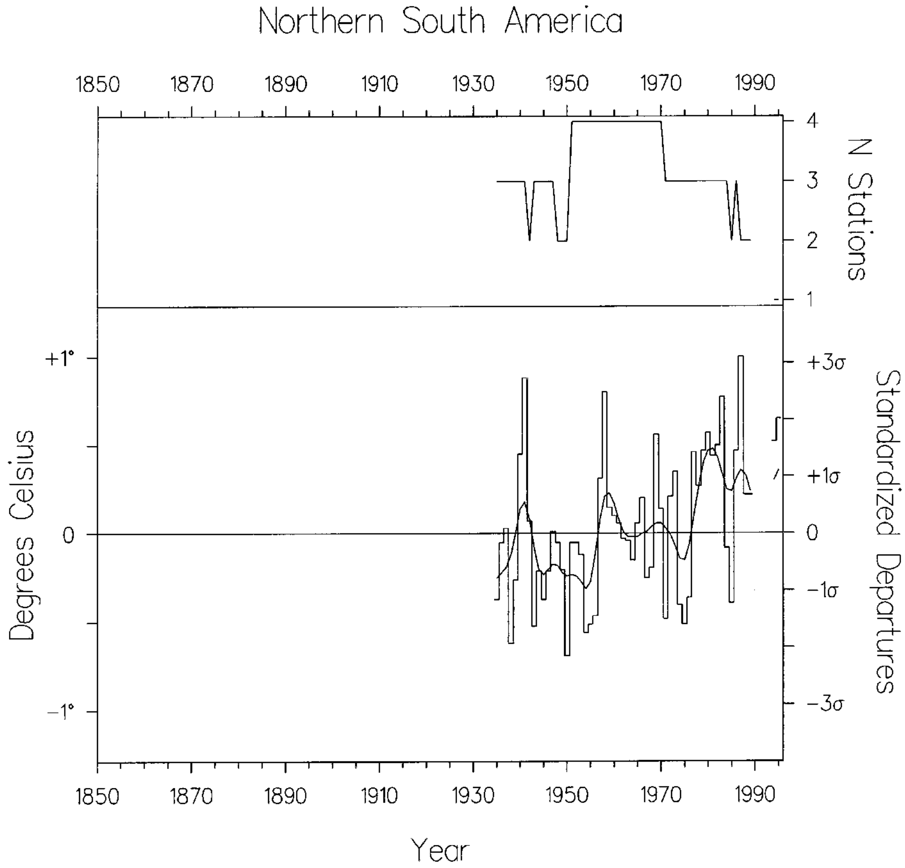
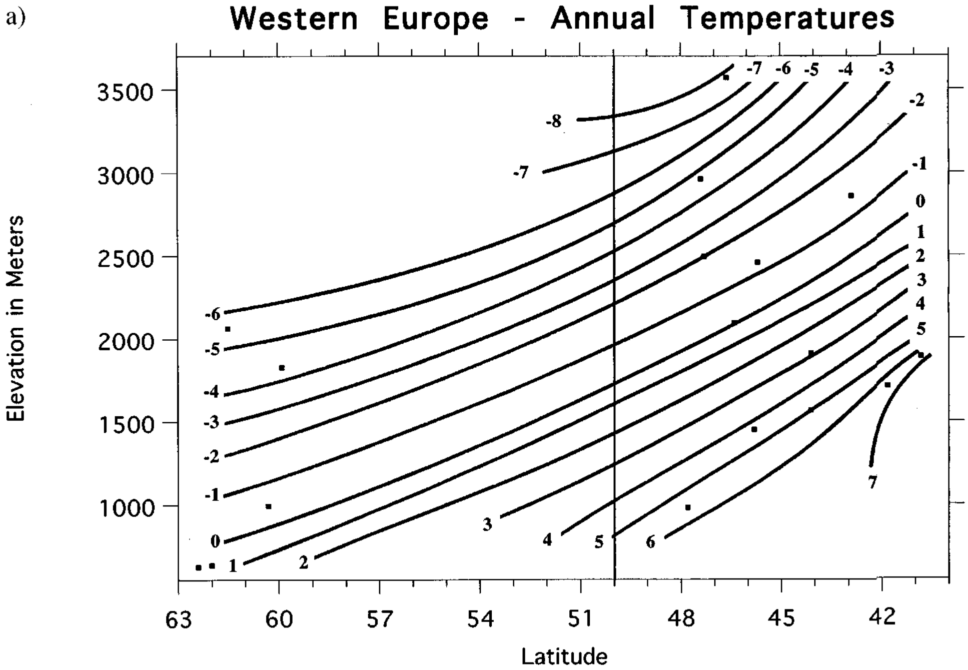


Figure 6. As in Figure 4, except for the northern South America region.

Mean temperature changes in 'Scandinavia' (Figure 9), are similar to those in the rest of Europe, only at the longest time scales. The decadal variations do not always coincide with the European regional index (Figure 8); both indices display relatively little trend since the mid-1930s, and the 'Scandinavia' index displays little of the recent warming (see Hurrell and van Loon, 1997). As with most other indices, much of the instrumental temperature increase takes place before 1940. There are some differences in the summer temperature record (not shown), which is generally similar in character to that for the rest of Europe.

Table I also identifies the isolated mountain stations that were used to create a temperature index for western, central and eastern Europe, shown in Figure 10. We note that most of these records have been analyzed elsewhere (e.g., Beniston et al., 1994; Dessens and Bücher, 1994; Weber et al., 1997). They are included here only for completeness. Of particular interest, however, are the temperature indices for central and eastern Europe (Figure 10, bottom two panels). The easternmost region does not share in the recent warming evident for the western European mountain a)



b)

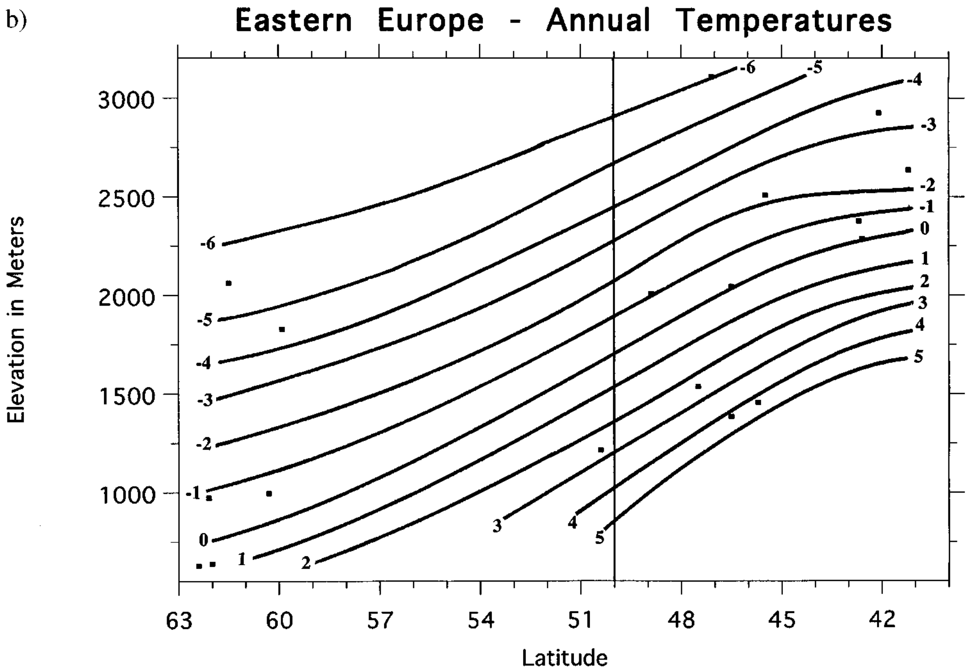


Figure 7. As in Figure 2, but for western (top panel) and eastern Europe (bottom panel), see Figure 1 and Table II for location of sites.

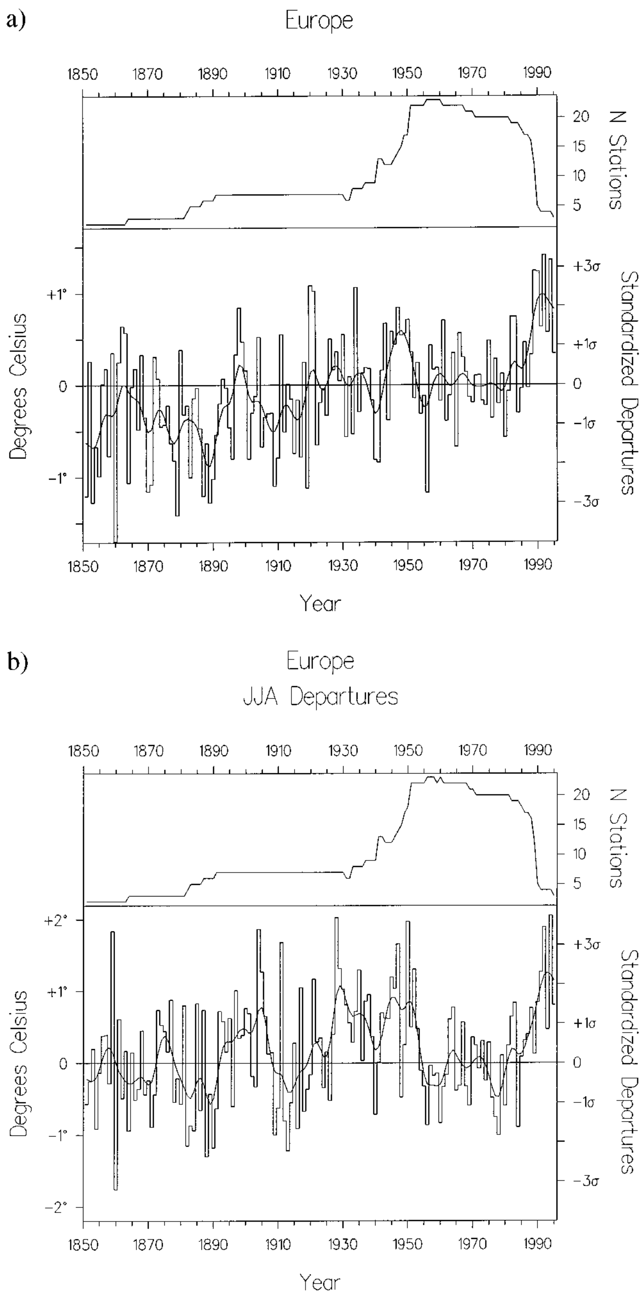


Figure 8. As in Figure 4, except for Europe (minus the Norwegian stations) region; (a) annual mean temperature anomalies, (b) summer (June–August) anomalies.

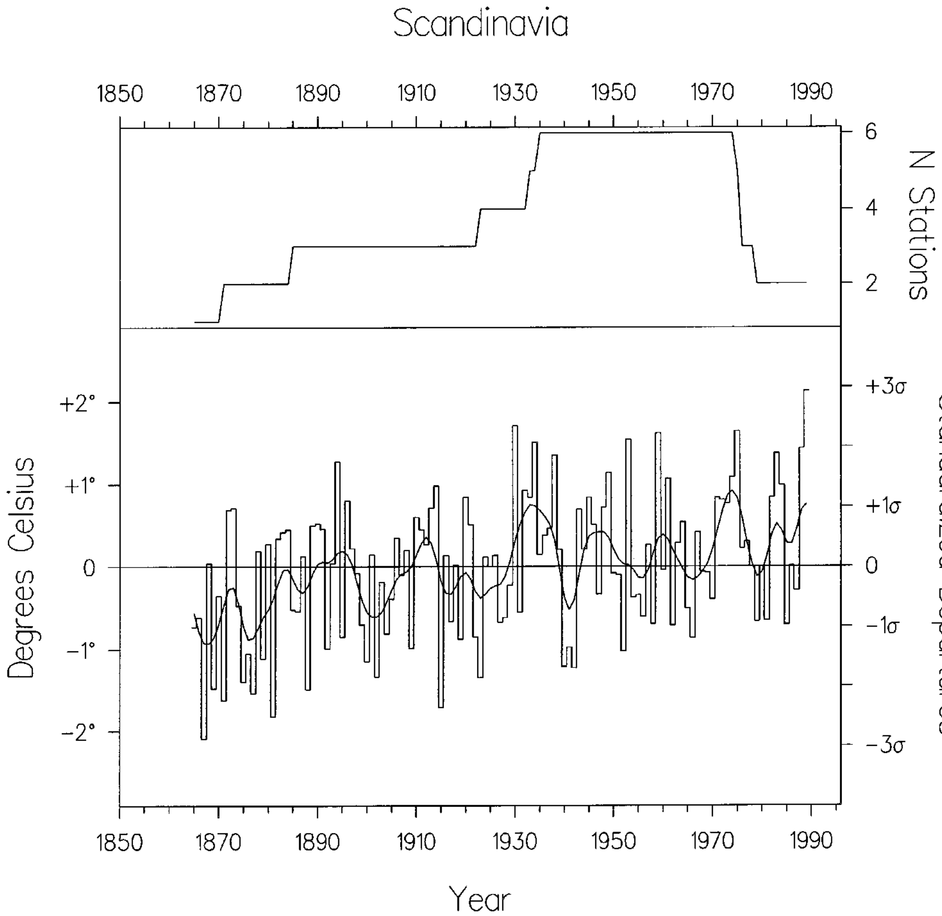


Figure 9. As in Figure 4, except for the ‘Scandinavia’ region.

index (Figure 10, top and middle panels). The ‘Central European Peaks’ series displays a temperature drop after about 1950, which is particularly pronounced in the summer temperature series (not shown), and which appears to us to be an artefact arising possibly from unknown instrumentation or exposure changes. The region labelled ‘Caucasus Mountains’ (Figure 11, see Figure 1 for location) also does not display much of a warming trend in recent decades. Overall, the indications are that the strongest warming in recent decades at the higher elevations of the European and North American continent has been experienced principally in western Europe (but much reduced in the Scandinavian (Norwegian) region).

3.1.3. *Asian Indices*

Two Asian regions (Figure 12, see Figure 1 for location) are shown. Region 11 (Asia I in Table I) is the higher region, and also comprises the highest collection of sites in our study. The temperature series for both these Asian regions share

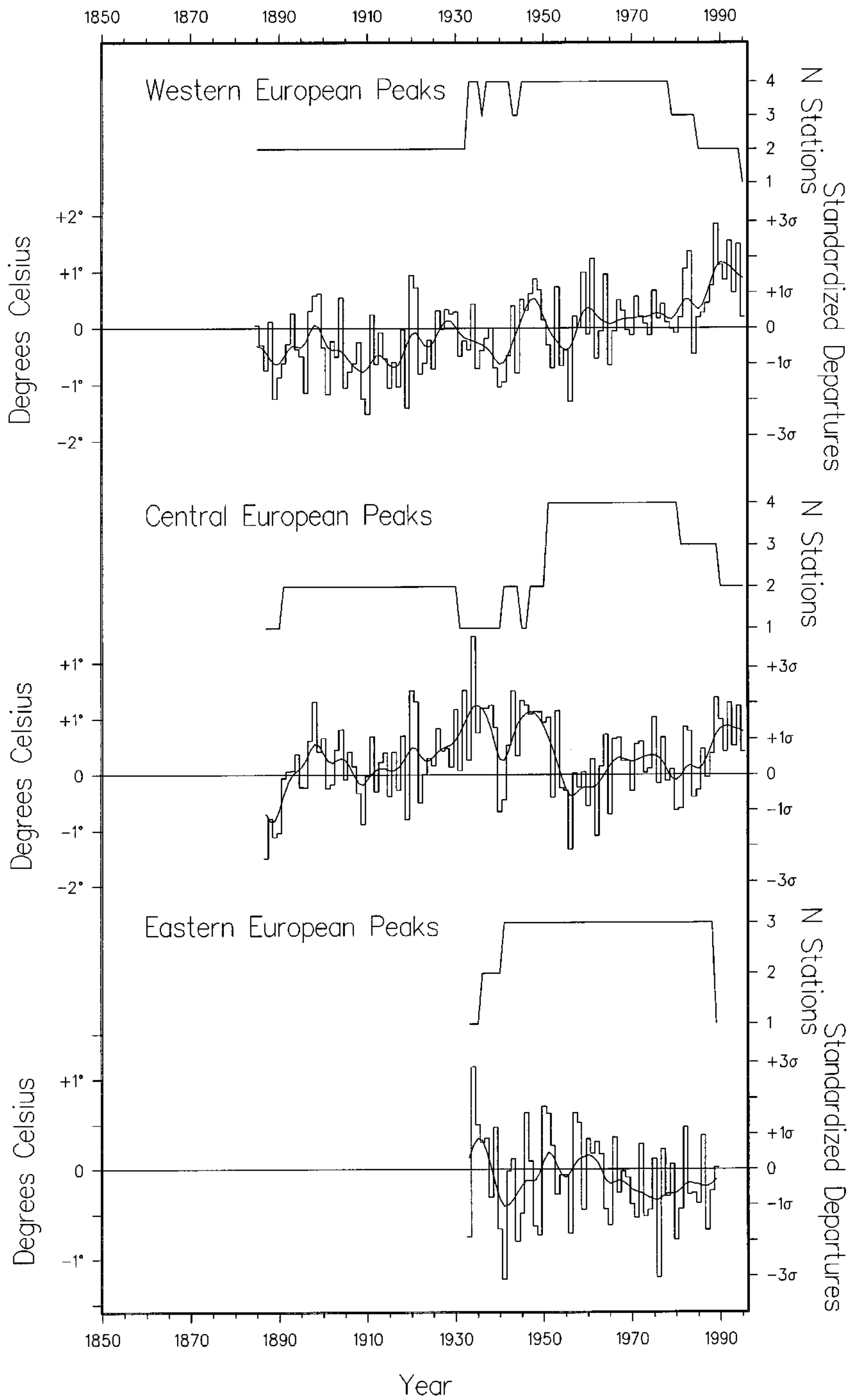


Figure 10. As in Figure 4, except for the three regions labelled ‘Western, Central and Eastern European Peaks’.

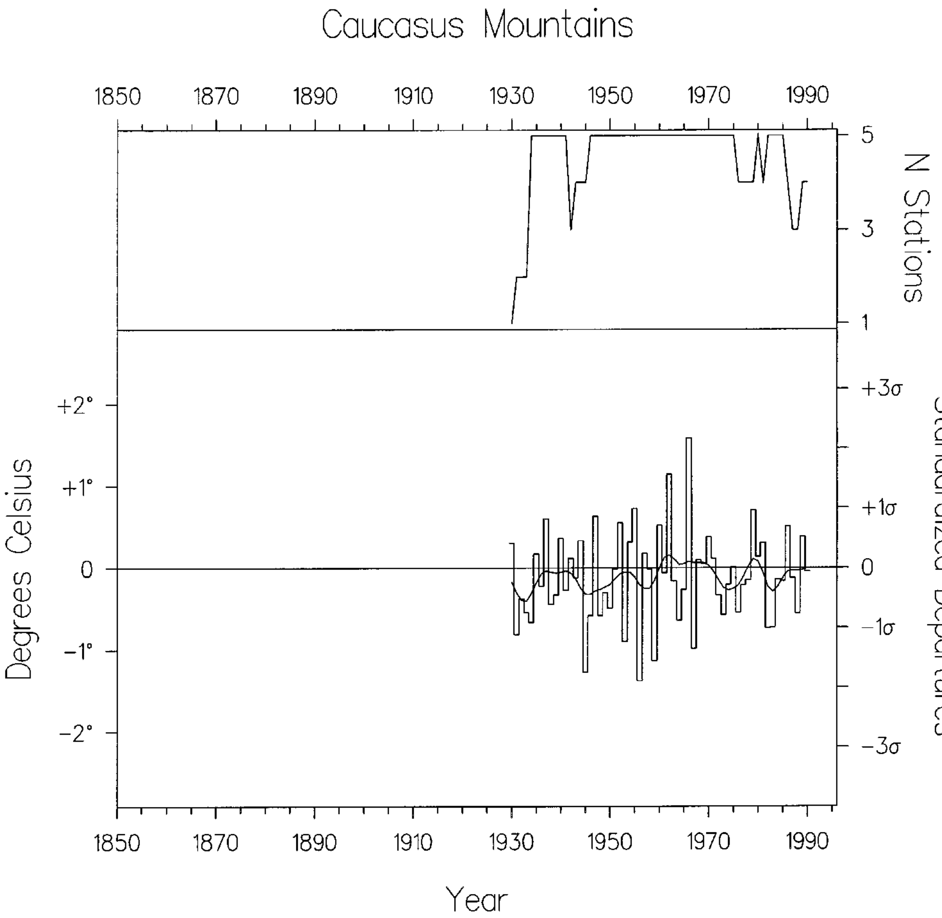


Figure 11. As in Figure 4, except for the Caucasus Mt. region.

the same general warming features as the western European sites. The data also suggest that in areas of eastern Europe and southwest Asia (the region of the Caucasus Mountains) the warming of recent decades is muted or largely absent.

3.1.4. *An Island Observatory in the Eastern North Atlantic*

Climate observations have been taken at Mt. Izaña, Canary Islands, Spain, since 1916. Because of its unique geographical position, the observatory is located for most of the year above the northeast trade winds, and above the trade wind temperature inversion layer that caps the well-mixed lower atmosphere in the subtropical eastern North Atlantic Ocean. Figure 13, illustrates the annual temperature changes at Mt. Izaña, together with changes in sea surface temperature (SST) in an area approximately 15° $\times$ 15° surrounding the islands. The SST data are from the GOSTA (Bottomley et al., 1990) compilation through 1949, and from the COADS data set (Woodruff et al., 1987) thereafter.

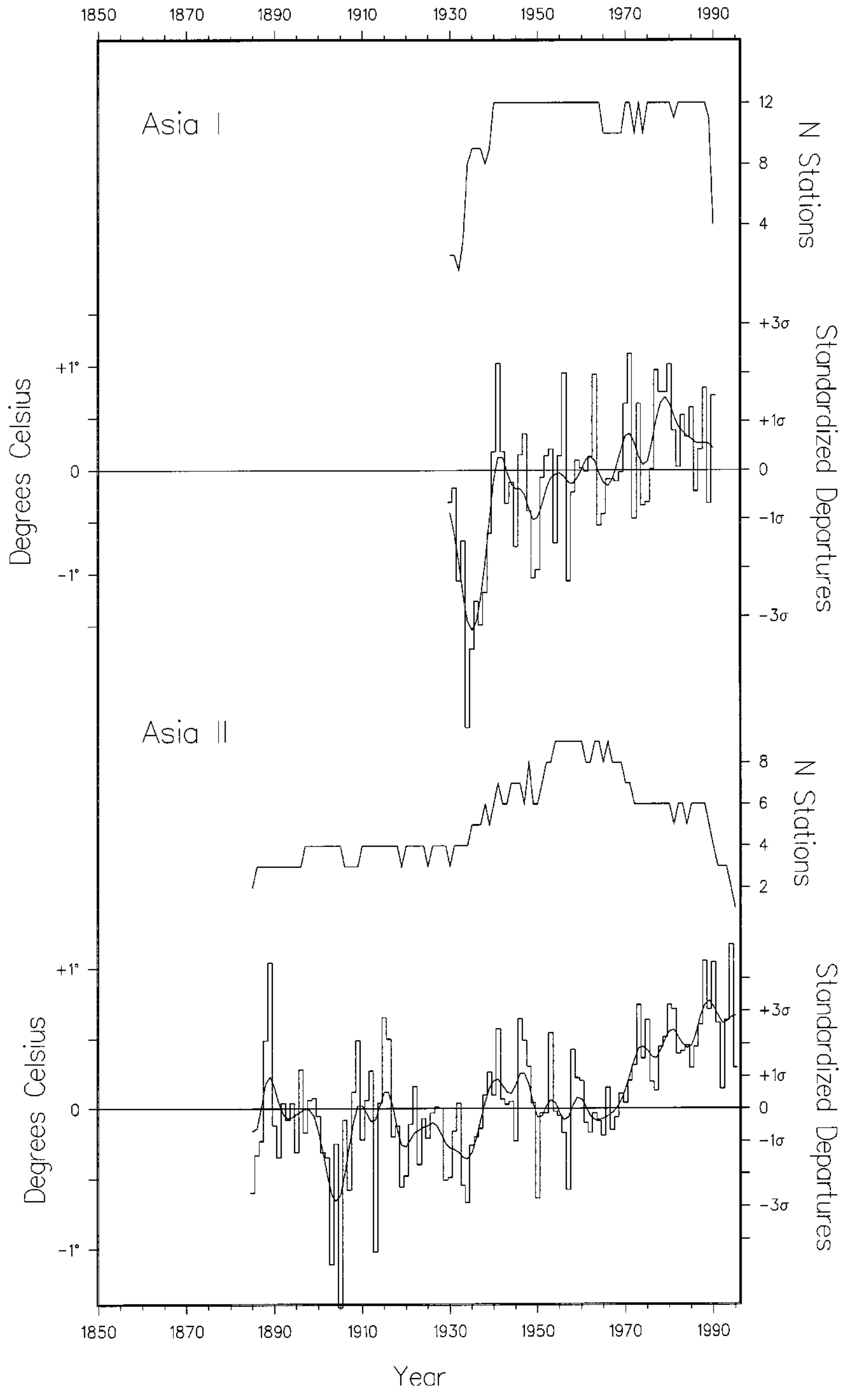


Figure 12. As in Figure 4, except for the two Asian regions.

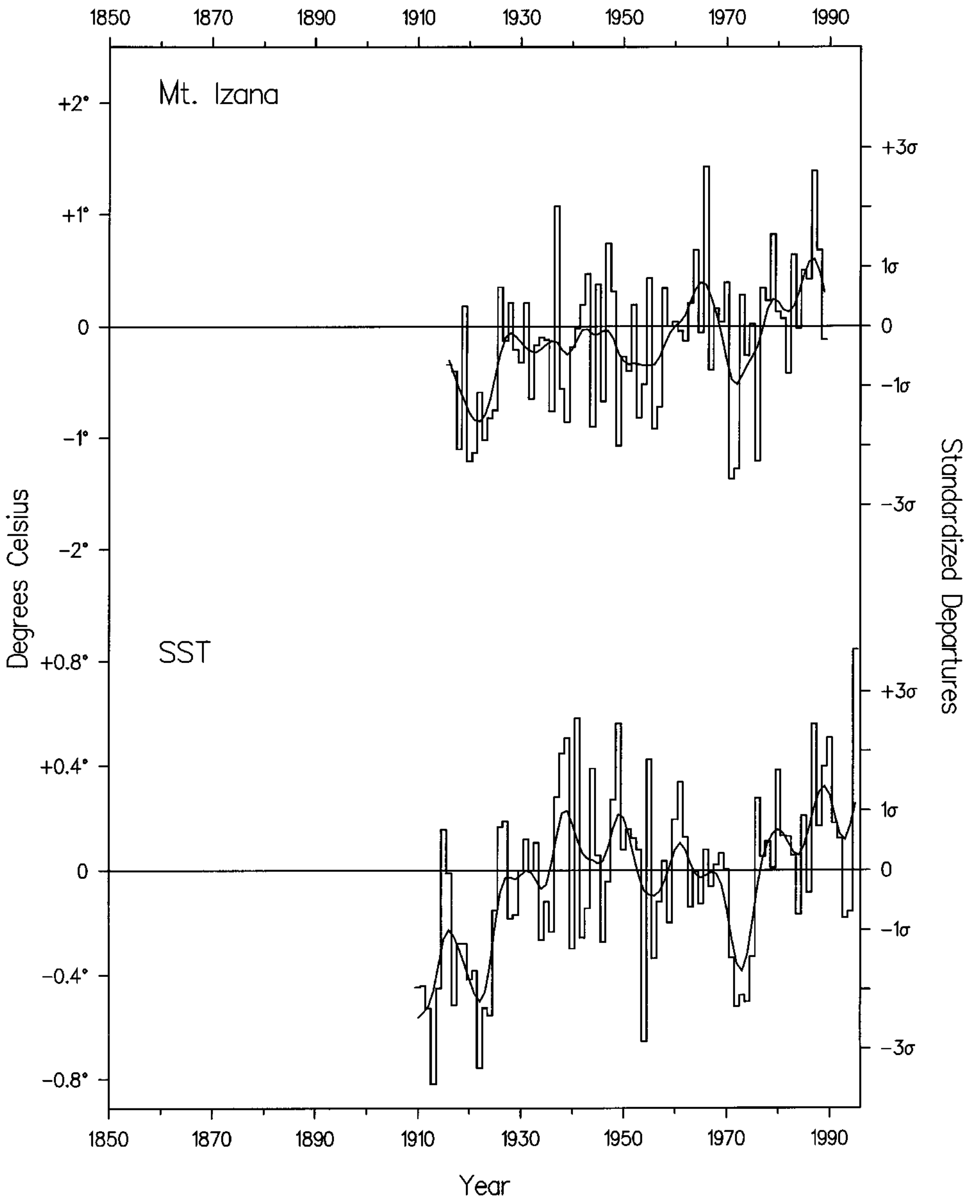


Figure 13. Time series of annual mean temperature anomalies for Mt. Izaña, Canary Islands, Spain (top graph, 1916–1989) and sea surface temperature (SST) anomalies in the surrounding region. SST values end in 1995.

The correlation between the two curves in Figure 13 is $r = 0.33$ for the non-detrended series and $r = 0.25$ for the detrended series (significant at the 5% level); the net warming from 1916–1989 is 0.74 °C for the observatory record, and 0.28 °C for the ocean surface temperature series. Hence, at the Mt. Izaña Observatory, at an altitude of 2367 m above sea level, an additional warming of about 0.5 °C has been recorded, which presumably is related mainly to changes in atmospheric circulation and cloudiness at the site. The suggestion of an amplification of recent temperature changes with elevation is explored further below.

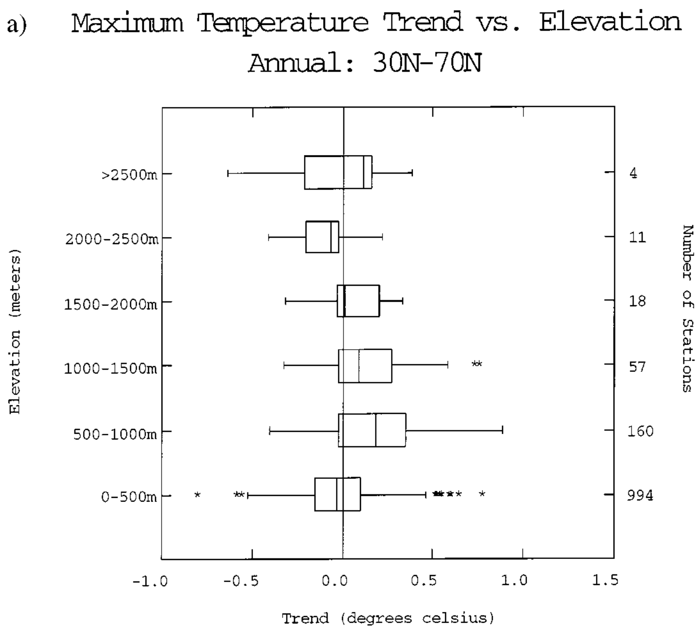
3.2. TEMPERATURE CHANGES AS A FUNCTION OF HEIGHT

Most of the available station data used in this study are located in the Northern Hemisphere extratropics. We have taken all the available station temperature data, plus an additional set of time series of annual mean minimum and maximum temperatures and calculated the temperature changes over the station period of record (a rough idea of the numbers of station available in time can be gleaned from the regional indices discussed above). Figure 14 gives the distribution of the linear trends (1951–1989 period) for the mean maximum and minimum temperature as a function of discrete elevational zones in the latitudinal range 30° N to 70° N. Although the number of stations declines rapidly above 500 m in station elevation, the suggestion is that at least with regard to minimum temperature (Figure 14, bottom panel), the changes with height are equal to or greater than those near the surface. Table III summarizes the differences in maximum and minimum temperature trends with elevation for the Northern Hemisphere extratropical belt. Changes in mean maximum temperature (Figure 14, top panel) are more subdued throughout the elevational ranges shown here. In fact, there is a clear tendency for maximum temperature trends to be smaller above about 2000 m compared to those at lower elevations. A similar plot done for the global land areas shows essentially the same story (not shown). This difference between changes in the maximum and minimum temperature over time for a number of large regional series has been reported on by Karl et al. (1993).

Nevertheless, significant regional differences do show up. Some of these regional differences have been documented by Barry (1990) for mountainous areas in Europe and the United States.

4. Summary and Discussion

The analysis of surface temperature changes presented here is focused mainly on high-elevation areas of the Northern Hemisphere extratropics. A recent study by Diaz and Graham (1996), which focused attention on decadal changes in temperature of tropical regions (specifically, changes in tropical freezing heights) concluded that rising tropical sea surface temperatures since the 1970s have resulted in average upward displacement of freezing heights on the order of 100 m (a temperature increase of approximately 0.5 °C) over about a 20-year period. Those results, as well as the ones documented here, and in some of the other papers appearing in this special volume of *Climatic Change* suggest that one could expect to encounter



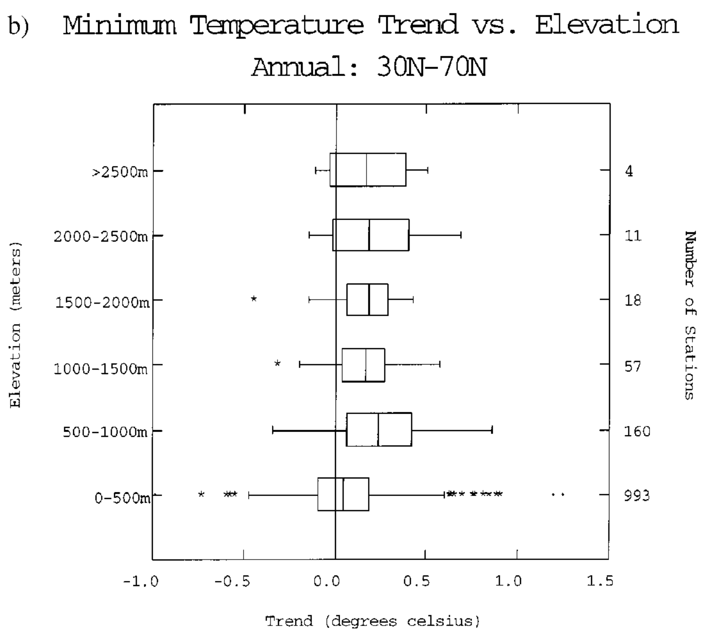


Figure 14. Distribution of linear trends (in °C/decade) in mean maximum (top graph) and minimum temperature for the period 1951–1989 for stations located in different elevational ranges in the latitudinal band 30° N–70° N. Graphs are known as 'box and whisker diagrams', where the central box denotes the central 50% of values. Also shown are the median value, 95th percentile values (outer fences) and individual values exceeding this limit, but below the 99% (asterisks) and beyond the 99% (open circles) levels.

Table III

Student's *t* value and significance level for differences in linear trends of annual mean maximum and minimum temperature for stations in the different elevational zones illustrated in Figure 14 for the region 30° N to 70° N. Station elevation in meters, *t*-values are differences in mean linear trends from the indicated level minus the corresponding surface value, with one and two asterisks denoting *t*-values statistically different from zero at the 5% and 1% level, respectively

Station elev.	Station elev. 500–1000	1000–1500	1500–2000	2000–2500	>2500
		Maximum temperature			
0–500	10.8**	5.7**	1.8	–1.3	–0.56
500–1000		–0.9	–1.8	–3.7**	–1.9*
1000–1500			–1.7	–3.2**	–1.6
1500–2000				–2.4*	–1.1
2000–2500					0.2
		Minimum temperature			
0–500	9.2**	3.8**	2.2	2.7**	1.7
500–1000		–1.8	–0.9	0.1	0.1
1000–1500			0.1	1.1	0.8
1500–2000				0.8	0.8
2000–2500					0.1

considerable regional differences in temperature trends, both spatially, and with respect to elevation in the middle latitudes. On the other hand, changes in the tropics may exhibit broader spatial coherence in both the horizontal and vertical dimensions.

We have examined atmospheric temperature differences between a control run and a doubled CO_2 experiment with the Max Planck Institute coupled GCM* (see, e.g., Cubasch et al., 1992), sampling at gridpoints corresponding to land locations around the tropics where we had station temperature data at different elevations. The results (not shown) indicate changes in vertical lapse rate of approximately 0.1 °C/km, such that mean temperatures at about 5–6 km, where modern tropical freezing surfaces are found, would warm by about 0.5–0.6 °C *relative* to the surface (i.e., by an additional half-degree beyond the surface warming caused by the CO_2-doubling). The results of a similar study using the NOAA/GFDL GCM by Vinnikov et al. (1996) show enhancements of the surface warming signal of 20–25% at about 5 km, roughly consistent with the changes in the MPI model. Observed changes in temperature, based on the radiosonde record compiled by Oort and Liu (1993) and summarized in Vinnikov et al. (1996) show tropical amplification of changes in

* The experiment was performed with the ECHAM3 T106 version of the MPI model (horizontal resolution of about 125 km). We wish to thank Martin Wild of the Swiss Federal Institute of Technology (ETH) in Zurich for providing us with the model data.

surface temperature at about 5 km over the past few decades on the order of 0.5 °C (see also Tett et al., 1996).

Regardless of the degree to which these high-elevation records reflect natural climatic variability of the climate system or a host of other forcing agents, whether natural or anthropogenic, the fact remains that invaluable climate records have been compiled at a number of mountain sites throughout the world. A few of these records are a century or more in length. These long-term measurements are in some of the most pristine environments on earth, far from human influences. They thus represent a unique resource of background climate monitoring sites, often geographically close to urbanized areas, yet far above the disturbed lower tropospheric boundary layer. In spite of these attributes, the weather observing programs at some of these mountain observatories have terminated in recent years. We feel such actions are short-sighted and should be carefully reconsidered. We hope that this special issue of *Climatic Change* serves to highlight the closure threat faced by a number of these unique weather observing stations.

Acknowledgements

Many of the high elevation records used in this study have been graciously furnished by a number of individuals, some of whose names appear at the bottom of Table I. We appreciate their contributions. Dr. P. Groisman was very helpful in obtaining data from the Russian Federation and parts of the former Soviet Union. We thank Roger Barry for constructive suggestions to improve the manuscript and Jon Eischeid for help in processing voluminous amounts of data. Parts of this work have been supported by grants from the U.S. Department of Energy, and the NOAA Office of Global Programs.

References

Barry, R. G.: 1990, 'Changes in Mountain Climate and Glacio-Hydrological Responses', *Mountain Res. Develop.* **10**, 161–170.

Barry, R. G.: 1992, *Mountain Weather and Climate*, Routledge, London, p. 402.

Barry, R. G. and Chorley, R. J.: 1992, *Atmosphere, Weather and Climate*, Routledge, London, p. 392.

Beniston, M. (ed.): 1994, *Mountain Environments in Changing Climates*, Routledge, London, p. 461.

Beniston, M. and Fox, D. G.: 1996, 'Impacts of Climate Change on Mountain Regions', in Watson, R. T., Zinyowera, M. C., and Moss, R. H. (eds.), *Climate Change 1995, Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses*, Intergovernmental Panel on Climate Change (IPCC), Cambridge University Press, Cambridge, pp. 191–213.

Beniston, M., Rebetez, M., Giorgi, F., and Marinucci, R.: 1994, 'An Analysis of Regional Climate Change in Switzerland', *Theor. Appl. Climatol.* **49**, 135–159.

Beniston, M., Diaz, H. F., and Bradley, R. S.: 1997, 'Climatic Change at High Elevation Sites: An Overview', *Clim. Change* (this issue).

Bottomley, M., Folland, C. K., Hsiung, J., Newell, R. E., and Parker, D. E.: 1990, *Global Ocean Surface Temperature Atlas*, U.K. Met Office, Bracknell.

Cubasch, U., Hasselmann, K., Höck, H., Maier-Reimer, E., Mikolajewicz, U., Santer, B. D., and Sassen, R.: 1992, 'Time-Dependent Greenhouse Warming Computations with a Coupled Atmosphere-Ocean Model', *Clim. Dyn.* **8**, 55–69.

Dessens, J. and Bücher, A.: 1994, 'Changes in Minimum and Maximum Temperatures at the Pic du Midi in Relation with Humidity and Cloudiness, 1882–1984', *Atmos. Res.* **37**, 147–162.

Diaz, H. F.: 1996, 'Temperature Changes on Long Time and Large Spatial Scales: Inferences from Instrumental and Proxy Records', in Jones, P. D,. Bradley, R. S., and Jouzel, J. (eds.), *Climatic Variations and Forcing Mechanisms of the Last 2000 Years*, Springer-Verlag, Berlin, pp. 585–601.

Diaz, H. F. and Bradley, R. S.: 1995, 'Documenting Natural Climatic Variations: How Different is the Climate of the 20th Century from that of Previous Centuries?', in Martinson, D. G., Bryan, K., Ghil, M., Hall, M. M., Karl, T. R., Sarachik, E. S., Sorooshian, S., and Talley, L. D. (eds.), *Natural Climate Variability on Decade-to-Century Time Scales*, National Research Council, National Academy Press, Washington, D.C., pp. 17–31.

Diaz, H. F. and Graham, H. F.: 1996, 'Recent Changes in Tropical Freezing Heights and the Role of Sea Surface Temperature', *Nature* **383**, 152–155.

Diaz, H. F. and Kiladis, G. N.: 1995, 'Climatic Variability on Decadal to Century Time Scales', in Henderson-Sellers, A. (ed.), *Future Climates of the World: A Modelling Perspective, World Survey of Climatology*, Elsevier Publ. Co., pp. 191–244.

Flohn, H., Kapala, A., Knoche, H. R., and Mächel, H.: 1992, 'Water Vapor as an Amplifier of the Greenhouse Effect: New Aspects', *Meteorol. Z.* N.F. **1**, 122–138.

Grabherr, G., Gottfried, M., and Pauli, H.: 1994, 'Climate Effects on Mountain Plants', *Nature* **369**, 448.

Hastenrath, S. L.: 1968, 'Der regionale und jahrzeitliche Wandel des vertikalen Temperaturgradienten und seine Behandlung als Wärmhaushaltsproblem', *Meterol. Rundsch.* **1**, 46–51.

Hastenrath, S. and Kruss, P.: 1992, 'The Dramatic Retreat of Mount Kenya's Glaciers between 1963 and 1987', *Ann. Glaciol*. **16**, 127–133.

Hurrell, J. W. and van Loon, H.: 1997, 'Decadal Variations in Climate Associated with the North Atlantic Oscillation', *Clim. Change* (this issue).

Intergovernmental Panel on Climate Change (IPCC): 1992, Houghton, J. T., Callander, B. A., and Varney, S. K. (eds.), *Climate Change 1992, The Supplementary Report to the IPCC Scientific Assessment*, Cambridge University Press, Cambridge, p. 198.

Intergovernmental Panel on Climate Change (IPCC): 1996, Houghton, J. T. et al. (eds.), 'Climate Change 1995, The Science of Climate Change', Cambridge University Press, Cambridge, p. 572.

Jones, P. D., Raper, S. C. B., and Wigley, T. M. L.: 1996: 'Southern Hemisphere Surface Air Temperature Variations, 1851–1984', *J. Clim. Appl. Meteor.* **25**, 1213–1230.

Karl, T. R., Jones, P. D., Knight, R. W., Kukla, G., Plummer, N., Razuvayev, V., Gallo, K. P., Lindseay, J., Charlson, R. J., and Peterson, T. C.: 1993, 'A New Perspective on Recent Global Warming: Asymmetric Trends of Daily Maximum and Minimum Temperature', *Bull. Amer. Met. Soc.* **74**, 1007–1023.

Oerlemans, J.: 1994, 'Quantifying Global Warming from the Retreats of Glaciers', *Science* **264**, 243–245.

Oort, A. H. and Liu, H.: 1993, 'Upper-Air Temperature Trends over the Globe', *J. Clim.* **6**, 292–307.

Schneider, S. H.: 1990, 'The Global Warming Debate Heats Up: An Analysis and Perspective', *Bull. Amer. Meteror. Soc.* **71**, 1292–1304.

Schubert, C.: 1992: 'The Glaciers of the Sierra Nevada de Merida (Venezuela): A Photographic Comparison of Recent Deglaciation', *Erdkunde* **46**, 58–64.

Stekl, J. and Podzimek, J.: 1993, 'Old Mountain Meteorological Station Milesovka (Donnersberg) in Central Europe', *Bull. Amer. Meteorol. Soc.* **74**, 831–834.

Tett, S. F. B., Mitchell, J. F. B., Parker, D. E., and Allen, M. R.: 1996, 'Human Influence on the Atmospheric Vertical Temperature Structure: Detection and Observations', *Science* **274**, 1170–1173.

Thompson, L. G., Mosley-Thompson, E., Davis, M. E., Lin, P. N., Yao, T., Dyurgerov, M., and Dai, J.: 1993, ' "Recent Warming": Ice Core Evidence from Tropical Ice Cores with Emphasis on Central Asia', *Global Planet. Lett.* **7**, 145–156.

Thompson, L. G., Mosley-Thompson, E., Davis, M. E., Lin, P. N., Hendeson, K. A., Cole-Dai, J., Bolzan, J. F., and Liu, K.-B.: 1995, 'Late Glacial Stage and Holocene Tropical Ice Core Records from Huascarán, Peru', *Science* **269**, 48–50.

Vinnikov, K. Ya, Robock, A., Stouffer, R. J., and Manabe, S.: 1996, 'Vertical Patterns of Free and Forced Climate Variations', *Geophys. Res. Lett.* **23**, 1801–1804.

Vose, R. S., Schmoyer, R. L., Steurer, P. M., Peterson, T. C. R., Heim, Karl, T. R., and Eischeid, J. K.: 1992, *The Global Historical Climatology Network: Long-Term Monthly Temperature, Precipitation, Sea Level Pressure, and Station Pressure Data*, ORNL/CDIAC-53, NDP-041, Carbon Dioxide Analysis Center, p. 100.

Weber, R. O., Talkner, P., and Stefanicki, G.: 1994, 'Asymmetric Diurnal Temperature Change in the Alpine Region', *Geophys. Res. Lett.* **21**, 673–676.

Weber, R. O., Talkner, P., Auer, I., Böhm, R., Gajić-Čapka, M., Zaninović, K., Brázdil, R., and Faško, P.: 1997, '20th-Century Changes of Temperature in the Mountain Regions of Central Europe', *Clim. Change* (this issue).

Wigley, T. M. L., Briffa, K. R., and Jones, P. D.: 1984, 'On the Average Value of Correlated Time Series, with Applications in Dendroclimatology and Hydrometeorology', *J. Clim. Appl. Meteorol.* **23**, 201–213.

Woodruff, S. D., Slutz, R. J., Jenne, R. L., and Steurer, P. M.: 1987, 'A Comprehensive Ocean-Atmosphere Data Set', *Bull. Amer. Met. Soc.* **68**, 1239–1250.

(Received 12 November 1996; in revised form 18 February 1997)