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Investigative Discourse and Thermal Analysis of Decrease in Temperature with Altitude

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ABSTRACT

The altitude dependency of climatic temperature change has long been an object of interest from both viewpoints theory and application. In the present article, monthly mean temperature at 56 stations assembled in 18 regional groups in 10 major mountain ranges of the world were studied. The periods of the analysis covered the last 50 to 110 years. The author found that the variability of temperature in climatic time scale tends to increase with altitude in about 65 % of the regional groups. A smaller number of groups, 20 %, showed the fastest change at an intermediate altitude between the peaks (or ridges) and their foot, while the remaining small number of sites, 15 %, showed the largest trends at the foot of mountains. The reason for the amplification of temperature variation at high altitudes is traced back to the increasing diabatic processes in the mid and high troposphere as a result of the cloud condensation. This situation results from the fact that the radiation balance at the earth's surface is transformed more efficiently into latent heat of evaporation rather than sensible heat, the ratio between them being 4 to 1. Variation in the surface evaporation is converted into heat upon condensation into cloud particles and ice crystals in the mid- and high troposphere. Therefore, this is the altitude where the result of the surface radiation change is effectively transferred. Further, the low temperature of the environment amplifies the effect of the energy balance variation on the surface temperature, as a result of the functional shape of Stefan–Boltzmann law. These processes altogether contribute to enhancing temperature variability at high altitudes.

1. Introduction

From ecological observations it has been known that the ecosystem is more vulnerable to external changes at high altitudes than on low lands (Messerli and Ives, 1997; Madu and Ogwor, 2026). The flora at high altitudes is made of sensitive species and its composition is highly selected. Therefore, the vulnerability of the high-altitude ecosystem is usually attributed to the sensitivity of the high-altitude biosphere. This is only partially correct. There is another factor that promotes the ecosystem vulnerability with increasing altitude. The amplitude of climate variability may be more pronounced with increasing altitude (Barry 1992, Nwangwu et al., 2026). Important climatic elements are temperature and precipitation. The present work aims at analysing the altitude dependency of surface air temperature in a climatic time scale in the major mountain areas of the world. Further, possible causes, resulting in the altitude dependency will be considered. The altitude dependency of climatic temperature change has long been an object of interest from both theoretical and applicational viewpoints. One of the most comprehensive surveys in this subject was done by Diaz and Bradley (1997), and Nosegbe & Madu (2025) based on the surface observations from 113 stations grouped in 12 regions collected from major mountainous regions of the Northern Hemisphere. The stations ranged in altitude from 329 to 4,169 m above sea level (a.s.l.). The periods covered in their work range from more than a century to about 30 years. They report the increasing rate of warming with altitude, which is propelled by the faster increase in daily minimum temperature rather than the maximum. Beniston et al. (1997) also found that the rate of warming at stations in the Swiss Alps during the twentieth century was larger than the global mean evaluated by Jones and Wigley (1990), and Madu & Atah (2024b). There are contradicting conclusions (e.g. Pepin 2000), however, reporting a decreasing rates of temperature change with increasing altitude. A similar conclusion was drawn by Vuille and Bradley (2000) for the Pacific side of the Andes.

The progress in this subject has often been hampered by the lack of long-term homogenous observations at high altitudes. Some studies tried to circumvent this problem by incorporating the data in the free atmosphere, which were measured by radiosondes (Seidel and Free 2003; Sterin et al. 2008, Madu, Nosegbe & Nwaeze 2025) or satellite-based remote sensing estimations (Lanzante et al. 2006; Madu & Atah, 2024a) or Reanaluses (Pepin and Seidel 2005, Madu & Uyaelumuo (2018). The results of current studies are, however, inconclusive. The Third Assessment Report of Intergovernmental Panel on Climate Change(IPCC) stated that the temperature change at the surface was larger than in the lower troposphere, while the IPCC Forth Assessment Report concluded the opposite (Trenberth et al. 2007; Madu & Atah, 2024c). Both reports indicated certain reservations on the conclusion due to the large error range of radiosondes and satellite remote sensing methods. The basic problem in these works was the incompatibility between the data obtained at the conventional surface meteorological stations and those obtained by radiosondes and satellite sensors, or even re-analyses. The data incompatibility includes the basic difference between the earth's surface temperature and that of the free atmosphere, the different instrumental uncertainties and the differences in sampling time and space, in addition to the known problem of the data inhomogeneity of re-analysis fields. Further, the altitude dependency may be different depending on regions. In the present article, only the temperature series obtained at surface meteorological stations are used. The stations are in a pair or a group closely located in horizontal distance but separated by large altitude differences. In total, 18 groups of stations are selected from 10 mountain regions of the world. Each group consisted of two to six stations, whereby at least one station occupies the highest location in the region and the other(s) are located at lower altitudes. In total, the observational series from 56 stations are investigated. This type of analysis helps exclude the abovementioned data incompatibility problem and contributes to extracting more genuinely the influence of altitudes on climate changes.

2. Methodology

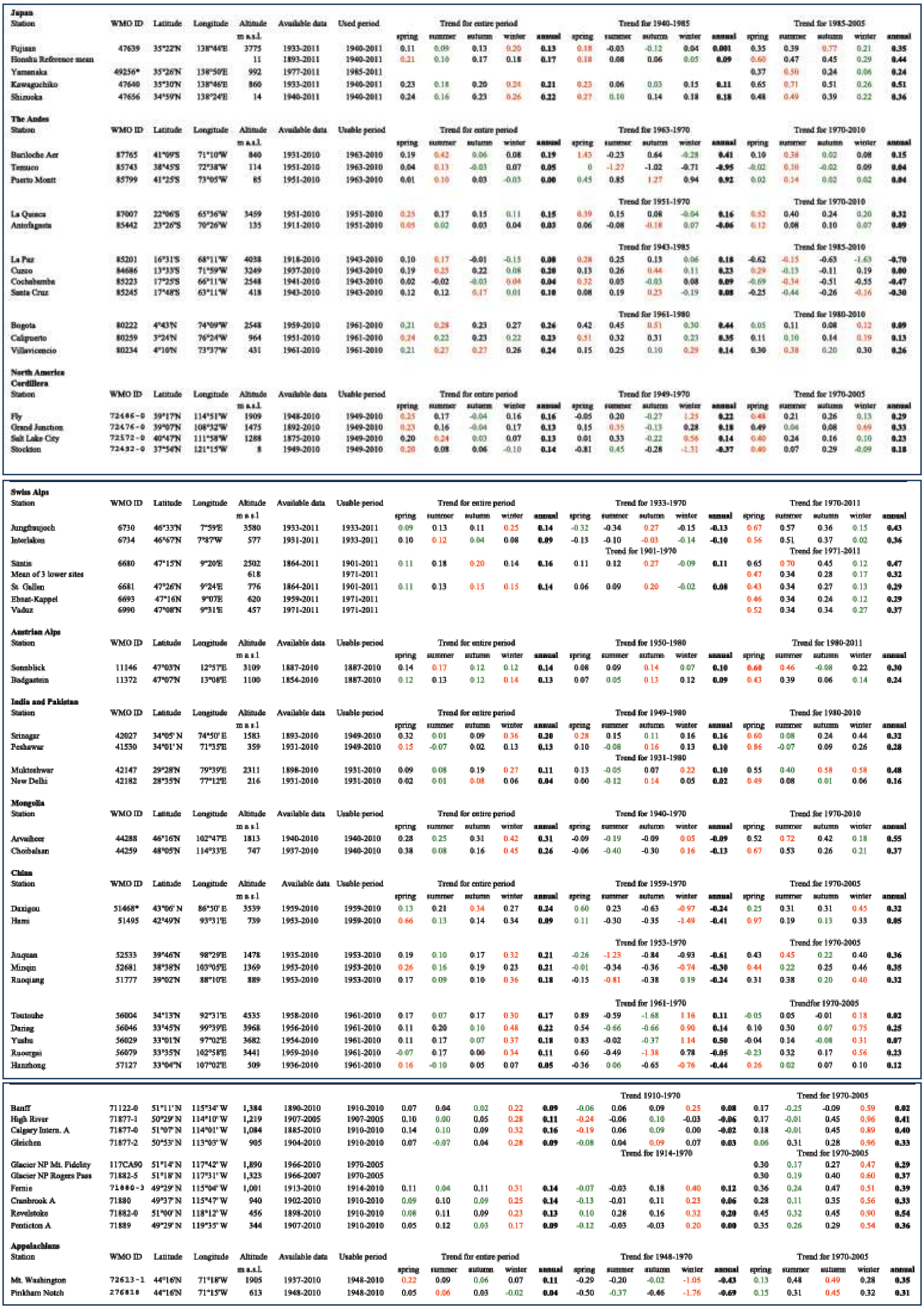
2.1 Data

The author searched globally for the availability of the air temperature observations for periods longer than 50 years at least at two locations in a pair within a short horizontal distance but separated by more than 800 m in altitude. The sources of the data are monthly mean air temperature stored in (1) Global Historical Climate Network Version 3 (Peterson and Vose 1997; Madu, Nosegbe, Orhorhoro, & Igbagbon, 2025; Okafor & Madu, 2025); (2) Climate Research Unit, University of East Anglia Temperature Station Data; and (3) on- and off-line supply of meteorological data from national meteorological services of the nations covered in the present work. The data from source 3 from meteorological services were especially important to replace doubtful entries in the first two databases and also to supplement the data of the most recent years. In the course of selecting stations, the sites with growing urban effect were avoided. To clarify the urban effect and the relocation history of the site, the author requested and received station meta-data from meteorological services of the relevant countries. The author visited 28 stations personally to evaluate the suitability of the sites and visually to reconstruct the history of the observation circumstances. If there were more than two stations within the area, additional stations were also taken into account, especially to fill the gap between the highest and lowest stations. For the present analysis, the data before 1901 were not used, except for the Austrian Alps, as the quality of homogeneity of older data for many stations was not the same as those of the subsequent years. The minimum length of the time series was set at 50 years. However, when slightly shorter data of high quality were available in the neighbourhood of the mountain stations, they were used only for the analysis of the current warming stage. The stations in the 18 groups from 10 regions presented in Table 1 fulfilled these conditions. Nevertheless, the quality of the time series may vary among the stations. Many stations, such as Sonnblick, Srinagar, New Delhi, Daxigou, Hushiki, Temuco, Calgary International Airport and Mt. Washington are full-scale synoptic meteorological stations manned by experienced observers, with other auxiliary observations such as radiation and evaporation measurements. Stations, such as Säntis and Fujisan had been full-scale synoptic meteorological stations until sometime in the past, when manned observations were replaced by automatic observation systems. The other stations, such as St. Gallen, Badgastein and Pinkham Notch are smaller stations with basic climatological observations carried out daily at fixed hours that are less frequent than the eight times required for the main synoptic observations. All these stations have the air temperature measurement as one of the main observations, and a considerable amount of work has been carried out to homogenize the data (e.g. Auer, et al. 2007; Böhm et al. 2009; MeteoSwiss 2010, Madu, Nwanze, Igbagbon & Emu, 2025).

2.2 The Data Analysis

The linear trend was calculated for the entire periods for which usable data exist at all stations in each group. The periods with usable data are determined by eliminating the data with frequently missing observations, or with serious relocations of the sites from the existing data series. The period finally adopted must also have simultaneous coverage for all stations in the group. The period of usable data contains for most regions three phases of temperature change: the initial warming phase during the early twentieth century, followed by the stagnating or even cooling phase starting between 1940 and 1960, which ended by 1970s to 1980s, followed by the present warming phase. The actual periods for these phases are different for the regions and also the groups. The trend analysis was made for each of the three periods for each station, that is, for the entire period of the used data, for the mid-century period of stagnating temperature change and for the last 30 to 40 years of prominent warming. The trend calculation was made for the annual means and for each season: spring (March–May; for the Southern Hemisphere September– November), summer (June–August), autumn (September– November) and winter (December–February). The main results are presented for each station of the 18 groups classified in 10 regions of the world as in Table 1.

Table 1: Decadal trends of annual and seasonal mean temperature for 10 major mountain regions of the world: trends are presented for the entire perios of the data availability, the mid-century cooling (or stagnating) period, and for the recent warming phase of the last 30 to 40 years.



Japan																					
Station	WMO ID	Latitude	Longitude	Altitude	Available data	Used period	Trend for entire period					Trend for 1940-1985					Trend for 1985-2005				
				m a.s.l.			spring	summer	autumn	winter	annual	spring	summer	autumn	winter	annual	spring	summer	autumn	winter	annual
Fujisan	47639	35°22'N	138°44'E	3775	1933-2011	1940-2011	0.11	0.09	0.13	0.20	0.13	0.18	-0.03	-0.12	0.04	0.001	0.35	0.39	0.77	0.21	0.35
Honshu Reference mean				11	1893-2011	1940-2011	0.21	0.10	0.17	0.18	0.17	0.18	0.08	0.06	0.05	0.09	0.60	0.47	0.45	0.29	0.44
Yamanaka	49256*	35°26'N	138°50'E	992	1977-2011	1985-2011											0.37	0.50	0.24	0.06	0.24
Kawaguchiko	47640	35°30'N	138°46'E	860	1933-2011	1940-2011	0.23	0.18	0.20	0.24	0.21	0.23	0.06	0.03	0.15	0.11	0.65	0.71	0.51	0.26	0.51
Shizuoka	47656	34°59'N	138°24'E	14	1940-2011	1940-2011	0.24	0.16	0.23	0.26	0.22	0.27	0.10	0.14	0.18	0.18	0.48	0.49	0.39	0.22	0.36
The Andes																					
Station	WMO ID	Latitude	Longitude	Altitude	Available data	Usable period	Trend for entire period					Trend for 1963-1970					Trend for 1970-2010				
				m a.s.l.			spring	summer	autumn	winter	annual	spring	summer	autumn	winter	annual	spring	summer	autumn	winter	annual
Bariloche Aer	87765	41°09'S	71°10'W	840	1931-2010	1963-2010	0.19	0.42	0.06	0.08	0.19	1.43	-0.23	0.64	-0.28	0.41	0.10	0.38	0.02	0.08	0.15
Temuco	85743	38°45'S	72°38'W	114	1951-2010	1963-2010	0.04	0.13	-0.03	0.07	0.05	0	-1.27	-1.02	-0.71	-0.95	-0.02	0.10	-0.02	0.09	0.04
Puerto Montt	85799	41°25'S	73°05'W	85	1951-2010	1963-2010	0.01	0.10	0.03	-0.03	0.00	0.45	0.85	1.27	0.94	0.92	0.02	0.14	0.02	0.02	0.04
												Trend for 1951-1970					Trend for 1970-2010				
La Quiaca	87007	22°06'S	65°36'W	3459	1951-2010	1951-2010	0.25	0.17	0.15	0.11	0.15	0.39	0.15	0.08	-0.04	0.16	0.52	0.40	0.24	0.20	0.32
Antofagasta	85442	23°26'S	70°26'W	135	1911-2010	1951-2010	0.05	0.02	0.03	0.04	0.03	0.06	-0.08	-0.18	0.07	-0.06	0.12	0.08	0.10	0.07	0.09
												Trend for 1943-1985					Trend for 1985-2010				
La Paz	85201	16°31'S	68°11'W	4038	1918-2010	1943-2010	0.10	0.17	-0.01	-0.13	0.08	0.28	0.25	0.13	0.06	0.18	-0.62	-0.15	-0.63	-1.63	-0.70
Cuzco	84686	13°33'S	71°59'W	3249	1937-2010	1943-2010	0.19	0.25	0.22	0.08	0.20	0.13	0.26	0.44	0.11	0.23	0.29	-0.13	-0.11	0.19	0.00
Cochabamba	85223	17°25'S	66°11'W	2548	1941-2010	1943-2010	0.02	-0.02	-0.03	0.04	0.04	0.32	0.03	-0.03	0.08	0.09	-0.69	-0.34	-0.51	-0.55	-0.47
Santa Cruz	85245	17°48'S	63°11'W	418	1943-2010	1943-2010	0.12	0.12	0.17	0.01	0.10	0.08	0.19	0.23	-0.19	0.08	-0.25	-0.44	-0.26	-0.16	-0.30
												Trend for 1961-1980					Trend for 1980-2010				
Bogota	80222	4°43'N	74°09'W	2548	1959-2010	1961-2010	0.21	0.28	0.23	0.27	0.26	0.42	0.45	0.51	0.30	0.44	0.05	0.11	0.08	0.12	0.09
Calipuerto	80259	3°24'N	76°24'W	964	1951-2010	1961-2010	0.24	0.22	0.23	0.22	0.23	0.51	0.32	0.31	0.23	0.35	0.11	0.10	0.14	0.19	0.13
Villavicencio	80234	4°10'N	73°37'W	431	1961-2010	1961-2010	0.21	0.27	0.27	0.26	0.24	0.15	0.25	0.10	0.29	0.14	0.30	0.38	0.20	0.30	0.26
North America Cordillera																					
Station	WMO ID	Latitude	Longitude	Altitude	Available data	Usable period	Trend for entire period					Trend for 1949-1970					Trend for 1970-2005				
				m a.s.l.			spring	summer	autumn	winter	annual	spring	summer	autumn	winter	annual	spring	summer	autumn	winter	annual
Fly	72486-0	39°17'N	114°51'W	1909	1948-2010	1949-2010	0.25	0.17	-0.04	0.16	0.16	-0.05	0.20	-0.27	1.25	0.22	0.48	0.21	0.26	0.13	0.29
Grand Junction	72476-0	39°07'N	108°32'W	1475	1892-2010	1949-2010	0.23	0.16	-0.04	0.17	0.13	0.15	0.35	-0.13	0.28	0.18	0.49	0.04	0.08	0.69	0.33
Salt Lake City	72572-0	40°47'N	111°58'W	1288	1875-2010	1949-2010	0.20	0.24	0.03	0.07	0.13	0.01	0.33	-0.22	0.56	0.14	0.40	0.24	0.16	0.10	0.23
Stockton	72492-0	37°54'N	121°15'W	8	1949-2010	1949-2010	0.20	0.08	0.06	-0.10	0.14	-0.81	0.45	-0.28	-1.31	-0.37	0.40	0.07	0.29	-0.09	0.18
Swiss Alps																					
Station	WMO ID	Latitude	Longitude	Altitude	Available data	Usable period	Trend for entire period					Trend for 1933-1970					Trend for 1970-2011				
				m a s l			spring	summer	autumn	winter	annual	spring	summer	autumn	winter	annual	spring	summer	autumn	winter	annual
Jungfraujoch	6730	46°33'N	7°59'E	3580	1933-2011	1933-2011	0.09	0.13	0.11	0.25	0.14	-0.32	-0.34	0.27	-0.15	-0.13	0.67	0.57	0.36	0.15	0.43
Interlaken	6734	46°67'N	7°87'W	577	1931-2011	1933-2011	0.10	0.12	0.04	0.08	0.09	-0.13	-0.10	-0.03	-0.14	-0.10	0.56	0.51	0.37	0.02	0.36
												Trend for 1901-1970					Trend for 1971-2011				
Säntis	6680	47°15'N	9°20'E	2502	1864-2011	1901-2011	0.11	0.18	0.20	0.14	0.16	0.11	0.12	0.27	-0.09	0.11	0.65	0.70	0.45	0.12	0.47
Mean of 3 lower sites				618		1971-2011											0.47	0.34	0.28	0.17	0.32
St. Gallen	6681	47°26'N	9°24'E	776	1864-2011	1901-2011	0.11	0.13	0.15	0.15	0.14	0.06	0.09	0.20	-0.02	0.08	0.43	0.34	0.27	0.13	0.29
Ebnat-Kappel	6693	47°16'N	9°07'E	620	1959-2011	1971-2011											0.46	0.34	0.24	0.12	0.29
Vaduz	6990	47°08'N	9°31'E	457	1971-2011	1971-2011											0.52	0.34	0.34	0.27	0.37
Austrian Alps																					
Station	WMO ID	Latitude	Longitude	Altitude	Available data	Usable period	Trend for entire period					Trend for 1950-1980					Trend for 1980-2011				
				m a s l			spring	summer	autumn	winter	annual	spring	summer	autumn	winter	annual	spring	summer	autumn	winter	annual
Sonnblick	11146	47°03'N	12°57'E	3109	1887-2010	1887-2010	0.14	0.17	0.12	0.12	0.14	0.08	0.09	0.14	0.07	0.10	0.60	0.46	-0.08	0.22	0.30
Badgastein	11372	47°07'N	13°08'E	1100	1854-2010	1887-2010	0.12	0.13	0.12	0.14	0.13	0.07	0.05	0.13	0.12	0.09	0.43	0.39	0.06	0.14	0.24
India and Pakistan																					
Station	WMO ID	Latitude	Longitude	Altitude	Available data	Usable period	Trend for entire period					Trend for 1949-1980					Trend for 1980-2010				
				m a s l			spring	summer	autumn	winter	annual	spring	summer	autumn	winter	annual	spring	summer	autumn	winter	annual
Srinagar	42027	34°05' N	74°50' E	1583	1893-2010	1949-2010	0.32	0.01	0.09	0.36	0.20	0.28	0.15	0.11	0.16	0.16	0.60	0.08	0.24	0.44	0.32
Peshawar	41530	34°01' N	71°35'E	359	1931-2010	1949-2010	0.15	-0.07	0.02	0.13	0.13	0.10	-0.08	0.16	0.13	0.10	0.86	-0.07	0.09	0.26	0.28
												Trend for 1931-1980									
Mukteshwar	42147	29°28'N	79°39'E	2311	1898-2010	1931-2010	0.09	0.08	0.19	0.27	0.11	0.13	-0.05	0.07	0.22	0.10	0.55	0.40	0.58	0.58	0.48
New Delhi	42182	28°35'N	77°12'E	216	1931-2010	1931-2010	0.02	0.01	0.08	0.06	0.04	0.00	-0.12	0.14	0.05	0.02	0.49	0.08	0.01	0.06	0.16
Mongolia																					
Station	WMO ID	Latitude	Longitude	Altitude	Available data	Usable period	Trend for entire period					Trend for 1940-1970					Trend for 1970-2010				
				m a s l			spring	summer	autumn	winter	annual	spring	summer	autumn	winter	annual	spring	summer	autumn	winter	annual
Arvaiheer	44288	46°16'N	102°47'E	1813	1940-2010	1940-2010	0.28	0.25	0.31	0.42	0.31	-0.09	-0.19	-0.09	0.05	-0.09	0.52	0.72	0.42	0.18	0.55
Choibalsan	44259	48°05'N	114°33'E	747	1937-2010	1940-2010	0.38	0.08	0.16	0.45	0.26	-0.06	-0.40	-0.30	0.16	-0.13	0.67	0.53	0.26	0.21	0.37
China																					
Station	WMO ID	Latitude	Longitude	Altitude	Available data	Usable period	Trend for entire period					Trend for 1959-1970					Trend for 1970-2005				
				m a s l			spring	summer	autumn	winter	annual	spring	summer	autumn	winter	annual	spring	summer	autumn	winter	annual
Daxigou	51468*	43°06' N	86°50' E	3539	1959-2010	1959-2010	0.13	0.21	0.34	0.27	0.24	0.60	0.23	-0.63	-0.97	-0.24	0.25	0.31	0.31	0.45	0.32
Hami	51495	42°49'N	93°31'E	739	1953-2010	1959-2010	0.66	0.13	0.14	0.34	0.09	0.11	-0.30	-0.35	-1.49	-0.41	0.97	0.19	0.13	0.33	0.05
												Trend for 1953-1970					Trend for 1970-2005				
Jiuquan	52533	39°46'N	98°29'E	1478	1935-2010	1953-2010	0.19	0.10	0.17	0.32	0.21	-0.26	-1.23	-0.84	-0.93	-0.61	0.43	0.45	0.22	0.40	0.36
Minqin	52681	38°38'N	103°05'E	1369	1953-2010	1953-2010	0.26	0.16	0.19	0.23	0.21	-0.01	-0.34	-0.36	-0.74	-0.30	0.44	0.22	0.25	0.46	0.35
Ruoqiang	51777	39°02'N	88°10'E	889	1953-2010	1953-2010	0.17	0.09	0.10	0.36	0.18	-0.15	-0.81	-0.38	0.19	-0.24	0.31	0.38	0.20	0.40	0.32
												Trend for 1961-1970					Trendfor 1970-2005				
Tuotouhe	56004	34°13'N	92°31'E	4535	1958-2010	1961-2010	0.17	0.07	0.17	0.30	0.17	0.89	-0.59	-1.68	1.16	0.11	-0.05	0.05	-0.01	0.18	0.02
Darlag	56046	33°45'N	99°39'E	3968	1956-2010	1961-2010	0.11	0.20	0.10	0.48	0.22	0.54	-0.66	-0.66	0.90	0.14	0.10	0.30	0.07	0.75	0.25
Yushu	56029	33°01'N	97°02'E	3682	1954-2010	1961-2010	0.11	0.17	0.07	0.37	0.18	0.83	-0.02	-0.37	1.14	0.50	-0.04	0.14	-0.08	0.31	0.07
Ruoergai	56079	33°35'N	102°58'E	3441	1959-2010	1961-2010	-0.07	0.17	0.00	0.34	0.11	0.60	-0.49	-1.38	0.78	-0.05	-0.23	0.32	0.17	0.56	0.23
Hanzhong	57127	33°04'N	107°02'E	509	1936-2010	1961-2010	0.16	-0.10	0.05	0.07	0.05	-0.36	0.06	-0.65	-0.76	-0.44	0.26	0.02	0.07	0.10	0.12
												Trend 1910-1970					Trend for 1970-2005				
Banff	71122-0	51°11'N	115°34'W	1,384	1890-2010	1910-2010	0.07	0.04	0.02	0.22	0.09	-0.06	0.06	0.09	0.25	0.08	0.17	-0.25	-0.09	0.59	0.02
High River	71877-1	50°29'N	114°10'W	1,219	1907-2005	1907-2005	0.10	0.00	0.05	0.28	0.11	-0.24	-0.06	0.10	-0.03	-0.06	0.17	-0.01	0.45	0.96	0.41
Calgary Intern. A	71877-0	51°07'N	114°01'W	1,084	1885-2010	1910-2010	0.14	0.10	0.09	0.32	0.16	-0.19	0.06	0.09	0.00	-0.02	0.18	-0.01	0.45	0.89	0.40
Gleichen	71877-2	50°53'N	113°03'W	905	1904-2010	1910-2010	0.07	-0.07	0.04	0.28	0.09	-0.08	0.04	0.09	0.07	0.03	0.06	0.31	0.28	0.96	0.33
												Trend for 1914-1970					Trend for 1970-2005				
Glacier NP Mt. Fidelity	117CA90	51°14'N	117°42'W	1,890	1966-2010	1970-2005											0.30	0.17	0.27	0.47	0.29
Glacier NP Rogers Pass	71882-5	51°18'N	117°31'W	1,323	1966-2007	1970-2005											0.30	0.19	0.40	0.60	0.37
Fernie	71880-3	49°29'N	115°04'W	1,001	1913-2010	1914-2010	0.11	0.04	0.11	0.31	0.14	-0.07	-0.03	0.18	0.40	0.12	0.36	0.24	0.47	0.51	0.39
Cranbrook A	71880	49°37'N	115°47'W	940	1902-2010	1910-2010	0.09	0.10	0.09	0.25	0.14	-0.13	-0.01	0.11	0.23	0.06	0.28	0.11	0.35	0.56	0.33
Revelstoke	71882-0	51°00'N	118°12'W	456	1898-2010	1910-2010	0.08	0.11	0.09	0.23	0.13	0.10	0.28	0.16	0.32	0.20	0.45	0.32	0.45	0.90	0.54
Penticton A	71889	49°29'N	119°35'W	344	1907-2010	1910-2010	0.05	0.12	0.03	0.17	0.09	-0.12	-0.03	-0.03	0.20	0.00	0.35	0.26	0.29	0.54	0.36
Appalachians																					
Station	WMO ID	Latitude	Longitude	Altitude	Available data	Usable period	Trend for entire period					Trend for 1948-1970					Trend for 1970-2005				
				m a.s.l.			spring	summer	autumn	winter	annual	spring	summer	autumn	winter	annual	spring	summer	autumn	winter	annual
Mt. Washington	72613-1	44°16'N	71°18'W	1905	1937-2010	1948-2010	0.22	0.09	0.06	0.07	0.11	-0.29	-0.20	-0.02	-1.05	-0.43	0.13	0.48	0.49	0.28	0.35
Pinkham Notch	276818	44°16'N	71°15'W	613	1948-2010	1948-2010	0.05	0.06	0.03	-0.02	0.04	-0.50	-0.37	-0.46	-1.76	-0.69	0.15	0.31	0.45	0.32	0.31

The annual trends are printed in bold types. The most sensitive seasonal trends are presented in red, while the trends of the least sensitive seasons are in green. Since the duration of the mid-century cooling and the recent warming periods depend on regions, the actual periods for each region is presented in the header line

Station ID numbers marked with an asteriks (*) are national ID numbers, as they lack in WMO ID numbers

3. Results Discussion: The altitude dependency of a climatic temperature

3.1 The Andes

The region in and around the Andes offers a unique opportunity to investigate the trend in temperature change. Firstly, this is about the only area in the Southern Hemisphere with climatic observations at high altitudes. Secondly, the north–south orientation of the mountain range allows sampling of the data from high latitudes to the equator. Thirdly, the effect of the altitude can be studied on the continental (east) as well as on the maritime (west) side of high mountains.

Vuille et al. (2003) analysed the temperature data of the tropical Andes for the latitude range between 1°N and 23°S and reported a trend of 0.15 °C/decade for the period 1950– 1994. The highest elevations reported a trend of approximately 0.05–0.20 °C/decade, with a slightly decreasing trend above 3,500 ma.s.l. These are similar to results found in the present study, although the temporal coverages of the study periods are different. Earlier, Vuille and Bradley (2000) reported a major warming on the coast and a decreasing trend with altitude (Nwanze, Iweka, Madu & Edafiadhe 2024). This conclusion contradicts the present analysis that shows an extremely small warming trend towards lower altitudes for all phases before and after 1970.

3.2 The Austrian Alps

In Austria, one of the best conditions exists to evaluate the difference in temperature change between high altitude and the low-level plains in the climatic time scale. Namely Sonnblick Observatory (3,105 ma.s.l.), one of the oldest high mountain observatories, is located only 10 km in horizontal distance from Badgastein (1,100 m) with more than 2,000 m altitude difference. The observation at Badgastein started in 1853, 33 years before the Sonnblick Observatory. The homogeneity of the time series for these stations allows the use of the data before 1901. When the entire 125-year temperature observations are compared, the trends in annual means are 0.14 and 0.13 °C/decade, for Sonnblick and Badgastein, respectively. The difference is at 95 % confidence level statistically not significant. Since the period of the last 125 years contains significant fluctuations, the periods with common trends were identified and the trend was computed for the individual phases.

3.3 The Appalachians

Near the northern end of the Appalachians there is a pair of stations with long meteorological records in State of New Hampshire. Mount Washington at 1,910 ma.s.l. has records from 1937 to the present. Only 4 km from the Mount Washington Observatory, there is another station, Pinkham Notch at 613 ma.s.l. with observations from 1948 to present. The annual mean temperature for the two sites for the entire period of 60 years shows a larger warming trend at Mount Washington. Both sites experienced a cooling phase until mid-1960s, which turned into warming at the end of 1970s. Vuille et al. (2003) analysed the temperature data of the tropical Andes for the latitude range between 1°N and 23°S and reported a trend of 0.15 °C/decade for the period 1950– 1994. The highest elevations reported a trend of approximately 0.05–0.20 °C/decade, with a slightly decreasing trend above 3,500 ma.s.l. These are similar to results found in the present study, although the temporal coverages of the study periods are different. Earlier, Vuille and Bradley (2000), and Madu, (2018) reported a major warming on the coast and a decreasing trend with altitude. This conclusion contradicts the present analysis that shows an extremely small warming trend towards lower altitudes for all phases before and after 1970.

3.4 China

In the Tienshan Mountains off the northern fringe of Taklimakan Desert, there is a high-altitude station, Daxigou (3,539 ma.s.l.) with more than 50 years of continuous observations in the high alpine tundra. Another station Hami is located 500 km east of Daxigou at an elevation of 739 m. During the mid-century decade from 1959 to 1970, the low-lying Hami showed a faster trend of cooling. Ten years however may be too short a period to evaluate a trend. In other mountainous regions of China, there are at least two localities with a high cluster of stations that are separated with large altitude differences. They are the areas around Jiuquan in the Qilianshan Mountain Range and the north-eastern corner of Tibet around Toutouhe. In the Qilianshan region, the trend is clearly correlated with altitude for all three periods.

3.5 Japan

Japan is a mountainous country and has many stations in high altitudes, which are accompanied by other stations on surrounding low lands. A meteorological observatory was established at the top of the nation's highest mountain, Fujisan in the summer of 1932, with the annual statistics starting in 1933. At the Fujisan Observatory (3,775 ma.s.l.), the temperature fluctuated greatly, although the mean trend was an increase. There was a warming period from 1930s to 1960, which was followed by 25 years of cooling. The recent fast warming started in 1985, but a new cooling phase set in after 2005. The diurnal range of air temperature however increased throughout the last 80 years, whereby the increase in the daily maximum temperature was stronger than that of the daily minimum. The trend of the annual mean temperature at the Fujisan Observatory for the entire period is about the same as that of the mean temperature at the low altitude of Honshu, the main island, which is calculated based on the observations made at three reference stations (Fushiki 12 m, Sakai 2 m and Hamada 19 m).

3.6 Mongolia

A pair of high- and low-altitude stations in the continental climatic zone in the middle of the Eurasian Continent is Arvailkheer (1,813 ma.s.l.) at the eastern end of the Hangayn Nuruu Mountains and Choibalsan (747 m) near the country's lowest elevation in Mongolia. Based on the 70 years of records from 1940 to 2010 as parallel observations were made at both sites, the trend at

Arvaikheer is 0.31 °C/decade, while it is 0.26 °C/decade at Choibalsan. During the mid-century of 30 years from 1940 to 1970, the trend is mostly negative with a statistically insignificant difference. The temperature trend of the last 40 years shows rates of warming of 0.55 and 0.37 °C/decade for Arvaikheer and Choibalsan, respectively. The warming rate of 0.55 °C/ decade at Arvailkheer for the last 40 years is the fastest temperature increase obtained in the present study presented in Table 1. Therefore, here, also a steeper temperature rise was witnessed at a high-altitude site.

3.7 North American Cordillera

In North America, groups of stations with large altitude differences were located in the North American Cordillera on the west coast and in the Appalachians near the east coast. The lower middle latitude group centred around Fly (1,909 ma.s.l.) on Egan Ridge in the U.S.A. is made up of the stations between Rocky Mountains and Sierra Nevada. For evaluating the altitude dependency, an additional station at a low altitude had to be selected inevitably from the Pacific side. Stockton was chosen at the foot of Sierra Nevada, which is well shielded from the Pacific effect by the Coastal Range. In this group, also a clear altitude dependency of the temperature trend is seen in all periods as summarized in Table 1. Since the temperature course for Banff during the twentieth century is so peculiar compared with other stations, the status of homogeneity of this station should be investigated in the future. The group of stations around Glacier National Park Mt. Fidelity/Fernie also shows the largest trend at the highest site for the entire observation period. During the earlier period from 1914 to 1970, Revelstoke, one of the two lower sites showed the largest trend. For the recent 35 years from 1970 to 2005, there seems to be no altitude dependency in the trend. Seidel and Free (2003) obtained the largest trend at lower altitudes in the Rockies for the period 1979–2000. The stronger trends in the high latitude Cordillera sites are seen in winter.

3.8 Pakistan and India

There are at least two pairs of meteorological stations with adequate altitude differences, which have kept relatively long and continuous observation records in the high mountain regions of India and Pakistan. They are Srinagar (1,583 ma.s.l.) and Peshawar (359 m) in Kashmir, and Mukteshwar (2,311 m) and New Delhi (216 m) in the Pre- Himalayas. The main attributes for the four stations are presented in Table 1. Trends are calculated for three periods, for the longest period of the available temperature record of 1949–2010, for the first 30 years of slow changes from 1949 to 1980 and for the recent rapid warming period of 30 years from 1980 to 2010. In all periods, the sites at higher altitudes showed larger rates of temperature rise in terms of annual means. The trends for the entire 60 years are 0.20 and 0.13 °C/decade for the higher and lower sites in Kashmir and 0.11 and 0.04 °C/decade for the Pre-Himalayas. For the first 30 years, the trends are 0.16 °C/decade (higher site) and 0.10 °C/decade (lower site) for Kashmir, and 0.10 °C/ decade (higher site) and 0.02 °C/decade (lower site) for the Pre-Himalayas.

3.9 The Swiss Alps

To aid the interpretation of Table 1 that contains the basic material, a detailed illustration is presented for the first three groups. The Swiss Alps is made up of two groups, Jungfraujoch and Säntis. The Jungfraujoch group in Bernerober land is made up of two stations with available data for the period from 1933 to 2011 for Jungfraujoch and from 1931 to 2011 for Interlaken. The data of these stations were rigorously checked for their homogeneity by the Federal Office of Meteorology and Climatology (Swiss National Meteorological Service). They are 18 km apart from each other in horizontal distance with about 3,000-m-altitude difference. Since the trend calculation should be made based on the same period, the common period of 1933 to 2011 has been chosen as the entire period. The trend of the annual means for the entire period is 0.14 °C/decade for Jungfraujoch at 3,580 ma.s.l. and 0.09 °C/decade for Interlaken at 577 ma.s.l.

The course of the seasonal temperature difference, however, is not the same as the seasonal trend of each station. The temperature difference between the two sites decreases mainly in summer (0.05 C/decade) and autumn (0.02 C/decade), while in winter and spring the temperature difference between the two sites has remained virtually unchanged during the last 40 years.

3.10 Consideration on the altitude effect on climatic temperature change

Cold regions are often cited as the geographic region where a larger climatic temperature change happens. The reasons attributed for this tendency are (1) cryosphere/temperature feedback and (2) temperature amplification in an inversion layer. The cryosphere/temperature feedback certainly makes a contribution also in the case of high-altitude sites. This is responsible for a larger trend in colder seasons. The second cause through an inversion brings about the larger convergence (negative divergence) of vertical sensible heat flux, amplifying the temperature change within a thin lowest atmospheric layer. In high mountain regions, however, an inversion is difficult to maintain, as cooled air drains to a lower altitude. This process certainly contributes to the amplification of the temperature variation at lower altitudes at the foot of the mountain, in a basin or on a plain. Therefore, in some groups discussed above, those stations at lower altitudes showing the largest temperature change, such as Villavicencio in Colombia and Revelstoke, British Columbia in Canada may have a stronger inversion effect making the larger amplitude of temperature change.

There are at least two more reasons why a high-altitude site creates larger amplitude or trend in temperature change. Both processes are based on the energy balance at the surface of the earth. (3) The third reason for the high altitude amplification is a direct consequence of the energy balance at the surface and in the atmosphere. The mean state of the surface energy balance for the earth's surface can be written in the following manner:

$$S(1-a)+L\downarrow+LE+H=\sigma T^4$$
$$175(1-0.15)+340-85-20=385\ \mathrm{Wm^{-2}}$$

where S is global solar radiation, a is the mean surface albedo, L! is long-wave incoming radiation, LE is latent heat of evaporation, H is sensible heat flux and !T4 is the surface emission. Presently, known best estimates of the global mean energy balance terms are presented below the equation (Ohmura 2006). This global mean state of the surface energy balance suggests that 80 %, the majority of the energy concentration at the surface, is transferred into the atmosphere through evaporation and less than 20 % is transferred as enthalpy, which heats up the lower troposphere. The release of the majority of the surface heat production happens upon condensation in the middle troposphere. Newell et al. (1972) estimated the core of the latent heat release at 6 km above the sea level in the equatorial–tropical region and 3 to 4 km in the mid-latitudes. Since the release of latent heat is much more powerful than the other heat sources in the atmosphere, the altitudes at which most condensation occurs can be considered as the altitude where the temperature trend reaches maximum. Since most of the causes of known climate changes are the change in radiation, it is probably natural that the result of climate changes is felt as the temperature variation at higher elevations. If the atmosphere is chronically moist as in many maritime regions, the condensation level tends to be lower. In such cases, the maximum temperature change may happen well below the highest stations in the region. This tendency was observed through the present analysis. (4) The forth process causing the high-altitude temperature change is the natural consequence of the mathematical shape of the Stefan–Boltzmann equation, with which a surface reaches an equilibrium under given energy exchanges. Let the surface energy exchange and the effect of the flux variation on temperature change be expressed in the following manner:

$$\sum_i F_i = \sigma T^4,$$

$$4\sigma T^3 \frac{dT}{dx_j} = \frac{\sum_i dF_i}{dx_j},$$

$$\frac{dT}{dx_j} = \frac{1}{4\sigma T^3} \frac{\sum_i dF_i}{dx_j},$$

Where
Fi is an energy flux
T is temperature
σ is Stefan–Boltzmann constant
x_j is energy flux, or any climatic elements that can affect fluxes

Suppose a change in xj causes changes in energy fluxes exactly in the same manner in warmer and colder climates, so that is th $\sum_i dF_i/dx_j$ e same for both climates, but T is different. For the same energy flux changes $\sum_i dF_i/dx_j$ the temperature sensitivity dT/dx_j at 0 °C is 30 % larger than at 25 °C, as a result of T^3 in the denominator (Ohmura 1984).
This effect amplifies the temperature sensitivity of the energy balance change under lower temperature. All these processes contribute to cause a larger temperature variation in polar and high-altitude climate.

4. Conclusion

Based on the analysis of 50 to 125 years of time series of annual mean temperature at 56 stations in 18 groups selected from 10 mountainous regions of the world, the Alps, Kashmir, the Himalayas, Tibet, the Tienshans, the Qilianshans, the Japanese Archipelago, the Andes, the North American Cordillera and the Appalachians, 65 % of the groups showed the largest trend of temperature change at the highest locations, 20 % at an intermediate altitude between the summit and the foot of mountains, and the remaining 15% at the lowest altitude. The annual trend was most effectively influenced by the trends in colder seasons. The altitude is only one of many factors that influence the trend or amplitude of climate changes. The present analysis indicates, however, that the altitude is no doubt an important factor for causing a larger and faster temperature changes at high altitudes in many mountain regions. This tendency must be taken into account in high-altitude ecology, glaciology and permafrost research, when temperature data are available only at stations in lower altitudes. The present study shows the global importance of the observations at high altitudes. Especially for detecting and monitoring climate changes, high-altitude locations offer climatically sensitive sites, which are free from direct urban and industrial effects.

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