Precipitation chemistry of Lhasa and other remote towns, Tibet

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Abstract

Precipitation event samples during 1987-1988 field expedition periods and 1997, 1998, 1999 and 2000 have been collected at Lhasa, Dingri, Dangxiong and Amdo, Tibet. The sampling and analysis were based on WMO recommendations for a background network with some modifications according to local conditions and environmental characteristics, which include the following precipitation constituents and related parameters: pH, conductivity, CO_2 partial pressure, total suspended particles, and the content of K^+, Na^+, Ca^{2+}, Mg^{2+}, Fe, Mn, NH^+, Cl^-, NO^-_2, NO^-_3, SO^{-2}_4 Br^-, HCO^-_3 and HPO^{-2}_4. Some atmospheric dusts samples have also been collected. Over 300 hundred precipitation events have been measured for pH and conductivity. Among these, 60 have been analysed for their chemical components. The results show that Lhasa's precipitation events are constant alkaline with weighted averages of pH 8.36 in the 1987-1988 period, and 7.5 for 1997 to 1999. Only one event is weakly acidic during 1997-1999. Although CO_2 partial pressure, a major producer of acidity in natural water on the Plateau, reduces with rising elevation, the lowest measure CO_2 pressure can only raise pH value by 0.1 units in the sampling areas. Chemical analysis indicates that the major contributor to alkaline precipitation is the continental dust, which is rich in calcium. The analysis also shows that Tibet is still one of the cleanest areas in the world with little air pollution. However, the decline of pH value from the 80s to 90s, which was reflected by an increase of NO^-_3 and SO^{-2}_4 in precipitation, alert us the urgency of environmental protection in this fragile paradise.

Key words: Tibet, alkaline precipitation, pH and rainwater chemistry

Introduction

Tibet is located on the highest plateau in the world, which is a fascinating laboratory for environmental science studies. However, difficult access and the harsh physical conditions of the plateau, plus its political sensitivity, make modern scientific study very difficult. In the area covered by this research, the average annual temperature ranges from -1^{o}C to 5^{o}C and average precipitation from 250mm to 500mm. The precipitation falls in the forms of rain, snow and hail. Solar radiation receipt is very high, ranging from 170 to 200 kcal/cm^2, resulting in very strong evaporation. The average potential evaporation is 2000-2500 mm/y and the average relative humidity from 30-50% (Land Management Bureau of Tibetan Autonomous Region, 1994). The climate of Tibet is also characterized by distinct wet and dry seasons, and windy and calm seasons (TETCAS, 1984). Around 90% of its precipitation falls at night and in the wet season (June to September) in the sampling areas. The wet season is mainly controlled by the Indian monsoon. With an area over 1.2 million square kilometers, just two millions people live in this arid and cold place, most of them settled at places lower than 4000m.a.s.l. and concentrated in cities and towns along highways. However, in the last 15 years, fast economic development has resulted in a large number of immigrants moving to these cities and towns and population has doubled in its capital city, Lhasa.

Acid rain has been a serious concern of environmental scientists over the past four decades, and has become of political, scientific and popular interest. A global acid rain monitoring network has been established and many acid rain case studies have been reported (Brimblecombe, 2001). Since the 1990s, the Chinese government has set up many acid rain monitoring stations at the provincial level and in some heavy industrial areas. Many areas with acid rain have been identified. However, the rainwater of Tibet has never been monitored prior to this study even though it has a vast land surface. In 1987-1988 period, the first author measured rainfall pH and conductivity in his

Tibetan expedition trips that was supported by the Royal Society of Geography and Nanjing University, and found that rainwater was alkaline. In many scientific books and papers, natural rain is considered as being weakly acidic [e.g. Howells, 1990; Meszaros, 1992; Miller, 1998. Merritts et al, 1998, Baird, C. 1998; Nebel and Wright, 2000]. This is based on both measurements on remote oceanic islands and the theoretical calculation of potential acidity. The original acidity of natural rain calculated by either CO_2 partial pressure in the atmosphere at sea-level, or, by CO_2, plus other natural acids, is around 5.6 [Radojevic and Bashkin, 1999] or 5.0 [Golloway, et al. 1982] respectively. The contrast between the common concept of natural rainfall acidity and the 1987-1988 initial measurements on the Plateau stimulated our further monitoring and investigations in the 1997-2000 period.

The research hypothesis initially suggested by the first author is that the lower CO_2 partial pressure in air caused by high altitude and the existence of alkaline dust in this arid area have brought about the formation of alkaline rain on the Plateau. In order to test this hypothesis, the following research objectives have been identified. The first objective was to monitor the long-term changes of precipitation pH in Tibet in order to confirm that alkaline rain is a long-term phenomenon in Tibet. Secondly, to measure CO_2 content in air and evaluate whether the CO_2 content in Tibet could increase the pH of precipitation. Finally, to find out what are the cause or causes of alkaline rain by examining relationships between pH value and other environmental factors, such as dusts, climatic factors and human activity. Precipitation chemistry is used as the most important evidence to evaluate the controls upon pH.

Methodology

In order to carry out the research, several cities and towns with meteorological stations were chosen in northern, central and southern Tibet in the 1987-1988 period, including Lhasa, Amdo, Dingri and Dangxiong (Fig. 1). The pH, conductivity and other parameters of bulk precipitation were measured in the field during the field trip seasons. Bulk samples of the rainwater were brought

to the University of Manchester for chemical analysis because of a lack of laboratory facilities on the Plateau.

A precipitation monitoring station has been established by the Meteorological Bureau of Lhasa since 1997 with support from the Japanese Government and well-trained technicians operate the station. They follow the Chinese guidelines that are based the WMO recommendations for background networks. Our research grant also contributed to the operation of the station. The station runs on a 24-hour basis and the bulk precipitation samples were immediately measured in laboratory after each precipitation event finished. Furthermore, the Amdo, Dingri and Dangxiong stations were reused during the field seasons in the 1997-1999 period.

In order to investigate the relationship between rainfall pH and environmental factors, a few parameters, that are not commonly examined in the WMO recommendations, have been studied, such as CO_2 partial pressure, TSP, and HCO^-_3 in rainwater. The reason for measuring these parameters is based on the fact that Tibet with its high altitude, arid climate and less pollution may cause a rather low pCO_2 in the atmosphere, result in a lot of dust in the atmosphere and a dominance of HCO^-_3 in the anion species.

Field measurements

For each precipitation event the following parameters were recorded and analysed in the field and field laboratories following Standard Methods (APHA, 1980) with some additional items:

a. precipitation---- mm (volumetric)
b. pH--- pH units at 20^{o}C (glass electrode)
c. CO_2 ---- atmospheric partial pressure (air quality monitor)
d. TSP---- mg/m^3 (airborne particulates monitor)
e. conductivity---- μS cm^{-1} at 25^{o}C (conductivity cell)
f. temperature (air and water)----^{o}C (thermometer)

Every sample had three readings taken for each of pH, CO_2, TSP and conductivity with mean value being recorded. Other meteorological factors were also measured. In addition, air-borne dusts were

collected on a plastic sheet laid on the ground surface in Lhasa, Dingri, and Amdo. The purpose of this collection was to determine dust pH in order to test for an association between precipitation pH and dust pH. CO_2 partial pressure was measured along the expedition routes which started from Kathmandu and Chengdu respectively.

Laboratory analysis

Bulk precipitation samples were collected manually with a simple collector and stored in a refrigerator. The samples were well sealed in the local laboratories in order to keep the plateau's CO_2 partial pressure and brought to the University of Manchester, the Chinese State Key Laboratory of Environmental Geochemistry at Guiyang and Hong Kong University for chemical analysis. The parameters measured are:

a. K^+, Na^+, Ca^{2+}, Mg^{2+}, Fe, and Mn ---- mg/L (inductively coupled plasma and flame atomic emission spectroscopy)
b. F^-, Cl^-, NO^-_2, NO^-_3, SO^{-2}_4 Br^- and HPO^{-2}_4 ----mg/L (ion chromatography)
c. NH^+_4----mg/L (colorimetric and ICP)
d. HCO^-_3---mg/L (titration)

Conductivity and pH of the precipitation samples were re-measured in the laboratories.
pH values of air dust collected on the plastic sheet was measured in the laboratory at University of Hong Kong.

Results and analyses

CO_2 content

Atmospheric CO_2 partial pressure is a very important parameter in determining the acidity of natural rain and has been used to calculate the acidity of precipitation in many textbooks. The relationships between CO_2 partial pressure and pH can be reflected in the following equilibra:

$CO_2 + H_2O \rightarrow H_2CO_3$ $\quad K_H=[H_2CO_3]/pCO_2$ (1)

$H2CO3 \rightarrow H^+ + HCO^-_3$ $\quad K_1=[HCO^-_3][H^+]/[H_2CO_3]$ (2)

$HCO^-_3 \rightarrow CO^{-2}_3 + H^+$ $K_2=[CO^{-2}_3][H^+]/[HCO^-_3]$ (3)

At the global background level of atmospheric pCO_2 at sea level (0.00037 atm), pure water should have a pH value of 5.6 from the calculation of H^+ after absorption of the CO_2. However, CO_2 partial pressure changes with altitude and Tibet is the highest place in the world. Decrease of pCO_2 with increase of altitude certainly influences pH of rainwater. Measurements of CO_2 were made along the expedition routes from Kathmandu to Tibet and Chengdu to Tibet, and CO_2 concentration changes with elevation (Fig. 2). The measured atmospheric CO_2 partial pressures range from 0.0004 to 0.00009 atm. And, using Henry's Law, dissolved CO_2 can be calculated. Based on the electroneutrality balance of the above equilibria, the H^+ content of pure water in the atmosphere should be:

$[H^+]= [OH^-]+[HCO^-_3]+2[CO^{-2}_3]$ (4)

$[H^+]$ and $[CO^{-2}_3]$ can be eliminated because their contents are too small in natural rainwater. Then we have:

$[H^+]= (K_H \text{ x } K_1 \text{ x } pCO_2)1/2$ (5)

If we use the CO_2 range of values (0.00024-0.00015 atm) that were determined at the elevation of 2500-4000 m.a.s.l. of Tibet to calculate pH value based on $pH = -\log10\ [H^+]$, the pH of pure water in the elevations should be 5.7, which is just 0.1 unit higher than that calculated at sea level. Therefore, the low CO_2 partial pressure on the Tibetan Plateau is not a major contributor to the comparatively high pH value of its precipitation.

Precipitation pH and conductivity

The monthly weighted means of precipitation pH are calculated from measurements made during the 1987-88 field trip periods and the continuous measurement for 1997-99 in Lhasa and the data are presented in Fig. 3 and 4 respectively. At Lhasa during the 1987-88 the volume weighted mean pH was 8.36, but for 1997-99 the volume weighted mean pH was 7.5. Measurements of precipitation pH during the field trip periods for other remote towns are given in Table 1. These

results indicated that Tibetan precipitation is constantly alkaline. Such a long-term record of constant alkaline precipitation has rarely been reported in the scientific literature. Short-term, seasonal and occasional alkaline rain events are recorded around the world, such as Israel, India, western part of USA, Africa, Spain [Subramanian and Saxena 1980; Felly and Liljestrand, 1983; Khemani et al. 1985; Mamane et al.1987; Avila and Alarcon 1999, Goni et al, 2001]. These areas are located in arid or semiarid zones of the Earth. The origins of the alkaline rains have been explained as being associated with African trajectories bringing Saharan dusts and local dusts.

In order to find out the possible atmospheric causes of the alkaline rain on the Plateau, several lines of enquiry have been adopted. The first approach was to carry out a statistical test for association between the mean pH values and various climatic factors. There is no obvious correlation between pH and conductivity of the rainwater (r= 0.12), pH value and rainfall amount (r= - 0.018), with pH and rainwater temperature (r=0.17), and for pH and wind speed in the day (r=-0.023). There is also little correlation between rainfall amount and conductivity of the rainwater (r=-0.01). The second approach was a study of the influence of season on the pH value of rainfall. According to a classification of samples into wet season (May-September) and dry season (October-April), Fig. 2 and 3 reveal that there is no regularity in pH value change. If we divide the years into a windy season (December to May), which has 75% of annual gales, and calm season (June to November), pH values do not follow a seasonal pattern (Table 2). However, the data in Table 2 reveals that the conductivities of rainwater in the windy season are at least 30% higher than those of the calm season. *It has also been noted that Tibetan rainwater is less mineralized and quite a few samples of the rainwater only have the conductivity ranging from 5 to 10 $\mu s/cm^2$.* The third approach has been to examine the pH of the dust collected at the three locations, the results of which are given in Table 3. Table 3 reveals that the dusts in Lhasa, Dingri and Amdo are all alkaline and their pH values are similar to those of the precipitation from the 1987-88 measurements. The three lines of enquiry have two implications: air dust content may influence the total chemical concentration of the rainwater but not its pH value and that the air-borne dust has a pH value similar to that of

rainwater. However, the similarity of the pH values of dust and rainwater, whilst suggestive, may not be conclusive evidence that atmospheric dust is the cause of alkaline rain. During the windy season, surface vegetation in Tibet is poor, and strong winds may generate plenty of dust in the atmosphere which would enable precipitation to dissolve more minerals. This is reflected by the conductivities in the different seasons. Nevertheless, the relationship between dust content and pH of precipitation needs to be examined further by an examination of the chemical constituents of the rainwater.

Chemical composition of rainwater

The chemical analysis of precipitation from the 1987-88 period and 1998-2000 period given in Table 4 and 5 for Lhasa and three other towns respectively demonstrates the background atmospheric chemistry on the Tibetan Autonomous Region. Fe, Mn, HPO^{-2}_4 and Br^- for the 1998-2000 samples were either present in trace quantities (within the range of a few $\mu g\ L^{-1}$) or undetectable and hence their contents have not been reported here. Among all species, Ca^{2+} is the dominant cation and HCO^-_3 is the major anion species in the rainwater samples. There were small amounts of SO^{-2}_4 and NO^-_3 in the samples of the rainfall of Lhasa and the other three towns compared with other areas around the world. About one half of the samples were SO^{-2}_4 free or NO^-_3 free. The average concentrations of these two anions in the two monitoring periods are similar to those measured at the world's remote islands (Galloway et al. 1982). However, these two anions demonstrate an increase in the 1998-2000 period compared to 1987-88 possibly because of an increase of population and vehicles and industrial development. During the period from 1988 to 2000, Lhasa has doubled its population and its vehicle number has tripled (Zhang, personal communication). Its SO_2 emission has also increased as shown in Table 6 from 1,800 tones in 1991 to 3,000 tones in 1995. Because air pollution is not a problem in this area and no government pollution control measures to reduce the emission have been carried out since 1995, SO_2 emission

might currently be expected to be at least doubled that of 1995 if its increase rate from 1991 to 1995 is extrapolated. Therefore SO^{-2}_4 and NO^{-}_3 in the samples of rainfalls have increased whilst the pH value has declined during 1997-99 as noted previously, compared with the 1987-88 period. It should be noted that NO^{-}_3 has increased quicker than SO^{-2}_4. This might be because vehicles and domestic energy are mainly dependent on oil. A few precipitation samples taken in 1998 and 1999 from Dingri, Amdo and Dangxiong show that the rainfall chemistry did not change much compared with their earlier measurements (Table 5), although SO^{-2}_4 may be an exception. This may be due to slow industrial development in these remote areas as compared to Lhasa.

The preceding results suggest that the causes of the long-term occurrence of alkaline rain in Tibet have only two possibilities: the influence of sea salt and continental dusts. The average ratios of Na^+ to Mg^{2+}, Ca^{2+}, K^+ and SO^{-2}_4 in the Tibetan rainfall are not similar to those of seawater (Table 7). Therefore, the Tibetan rainfall is not derived from seawater. The concentration of Ca^{2+} and the ion ratios (Tables 4, 5 and 7) of the Tibetan rains are typical of continental precipitation. Therefore, the high pH on the plateau may originate from the air-borne dusts that are derived from the surface soils. These soils are commonly of saline and alkaline types, with a typical pH range of 6-10 in the Tibetan area [Land and Resource Bureau of Tibetan Government, 1994]. Such soils commonly contain base-forming cations, CO^{-2}_3 , HCO_{-3}, SO^{-2}_4 and free soluble salts, which could contribute alkaline particulates to the atmosphere. In addition, calcification is a dominant soil formation process in semiarid and arid regions, which produces abundant calcite ($CaCO_3$) that can form dust in the air. The wind-blown dusts mobilzed from these soils are usually >2.5 μm in diameter, that is mainly of the coarse aerosol type that can be effectively and rapidly scavenged by the rainfall washout process. Measurement of suspended particles reveals that the amounts of dust in the air change greatly, ranging from undetectable to 3mg/m^3 during the field seasons. There are dust storm days and very calm days on the plateau. However, because of the lack of acids in the rainwater, very small amounts of the dust on the calm days can easily buffer the rainwater and make it alkaline. According to the calculation of Charlson and Rodle (1982), only 0.38-1.12 mg of $CaCO_3$

can buffer a litre of "natural rainwater" with pH 4.4-6.2 to alkaline rain. It is common knowledge that such concentration of $CaCO_3$ in the rainfall of arid and semiarid areas is a minimum content. This analysis suggests that a minimum amount of alkaline dust in Lhasa rainfall is enough to neutralize rainwater and makes it alkaline, no matter whether it be the windy or calm season, wet or dry season. Even intensive rainfall cannot dilute the chemical concentration of rainwater because it only needs a small amount of $CaCO_3$ to buffer rainwater with a low acid content. This explains why seasonal change, wind speed, and rainfall amount have little influence on pH value of Tibetan rainfall. It also explains the poor association between rainfall and conductance.

Discussion

The difference between our measurements in Tibet and the commonly cited pH values for natural acidity of rainwater raises the question: has alkaline rain been paid enough attention? Despite the fact that short and occasion alkaline rains were reported in several papers (Subramanian and Saxena 1980; Felly and Liljestrand, 1983; Khemani et al. 1985; Mamane et al.1987; Avila and Alarcon 1999, Goni et al, 2001), natural rain is still considered as weakly acidic. The authors believe that the lack of attention given to alkaline precipitation can be explained by several reasons. The first one is that acid rain monitoring started after the Earth's industrialization and, generally carried out in urban areas, and the results from the monitoring therefore only indicate the polluted state of the atmosphere. Many areas with alkaline precipitation may have disappeared. The second is that the theoretical calculation of 'natural' rainfall pH did not consider atmospheric particles. Dust particles of natural origin could buffer weakly acidic precipitation leading to pH values higher than 5.6 in many places, especially in arid and semi-arid areas where there are plenty of air-borne dusts [Berner and Berner 1987; Sequeira 1993]. Hedin and Likens [1996] have pointed out the importance of atmospheric dusts in neutralizing acidic air pollutants and the reduction of atmospheric dust release has aggravated the acid rain problem. In the high-elevation, dry and minimally industrialized areas of the Tibetan Plateau, the original state of the atmosphere may have

been largely preserved, although the global baseline of atmospheric chemistry has already been changed. The third reason is that the measurements of "natural rain" were made at remote oceanic islands which is wet and humid and consequently lack dust in atmosphere. The final reason is that even if alkaline rain has been observed, further examination and reporting cannot be carried out because there is no acid rain problem, or lack of funding. Therefore, the fact that alkaline rain is a common natural phenomenon in arid and semiarid areas has not been noticed and therefore has not received the attention it deserves.

Another issue that needs to be discussed is how long this alkaline rain can be sustained on the plateau. In the western part of the USA, the calculated mean pH values of rainfall were alkaline during the 50s and 60s [Liljestrand and Morgan, 1979], when there was a lack of direct measurement of pH subsequently it has become more acidic. In India, the natural rain should be alkaline, although the rainfall pH of many areas is below 7 (Kulshrestha et al, 2001). Our measurements at a permanent monitoring station, Lhasa, also show a dangerous trend in rainfall acidification for Tibet. The VWM of pH for the 1987-88 field period was 8.36 and it had declined to 7.5 by the 1997-1999. This change was caused by only a few $equl^{-1}$ of SO^{-2}_4 and NO^{-}_3 increase in the water. We also notice that there are sometimes very small amounts of air-borne dusts in this place, which will reduce the atmospheric buffering capacity during that period. Based on these facts, if the emission of pollutants increases further, the rainfall in Lhasa would become weakly acidic, just like India and the United States.

The chemical examination of the rainfall of Tibet also raises another issue on acid rain monitoring. Generally the measurement of HCO^{-}_3 has not been recommended in the guidelines. It may be that HCO^{-}_3 is not an important anion in the rainwater of seriously-polluted areas, however, we found that HCO^{-}_3 is a dominant anion in the Tibetan rainwaters. This is not only due to the small amount of other anions from air pollution, but also the contribution of soil HCO^{-}_3 in this arid and semiarid area. If HCO^{-}_3 were ignored, it is would have been difficult to establish an ionic balance for the rainfall chemistry. It is suggested the HCO^{-}_3 should be included in background monitoring.

Summary and conclusion

The first systematic monitoring on rainfall chemistry in Tibet indicates that its precipitation is alkaline. Alkaline precipitation in the Tibetan area is mainly a consequence of its semi-arid environment and the less polluted air with the rainfall chemistry being mainly controlled by continental dust with little pollutants. There is scant contribution from marine aerosols. Such low concentrations of air pollutants leads to Tibet becoming one of the cleanest areas in the world. Lower atmospheric pCO_2 on the plateau, due to its altitude, plays a very minor role in the development of its high pH values. Long-term and constant alkaline precipitations in Lhasa can be regarded as being close to the original state of precipitation acidity on this plateau, because of slow industrialization, low population density and the high altitude of the plateau. However, the absolute original state of rainfall cannot be ascertained because global and regional atmospheric circulations have resulted in the air pollutants being transported into even this remote and high area. The decrease in pH values from the 1987-88 period to the 1997-99 period is coincides with its population and vehicle growth. Both SO^{-2}_4 and NO^{-}_3 in bulk deposition also reflect such growth in this period.

Based on the above analysis and evidence from other areas, we believe that the current concept for baseline rainfall pH of the world should be modified. Alkaline rain is an important natural phenomenon in the arid and semiarid areas of the world. For such area natural rainfall may not be acidic. Current rainfall pH in the Plateau depends on the magnitude of pollution and the natural buffering capacity of local dusts. Therefore, the pH value of precipitation in the areas cannot be used as a sole indictor of air pollution.

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Captions:
Table 1. The weighted mean of rainfall pH in three remote towns of Tibet
Table 2. pH and conductivity and season (December-May, windy; June-November, calm)
Table 3. pH values of dust deposits in different seasons of three locations
Table 4. Ionic concentrations ($equl^{-1}$) of precipitation in Lhasa
Table 5 Ionic concentrations (equl-1) of precipitation in the three towns of the Tibetan Autonomic Region
Table 6. SO_2 emission (T) of the Tibetan Autonomic Region
Table 7 Ratios of Na^+ to Cl^-, SO^{-2}_4, K^+, Ca^{2+} and Mg^{2+} in Tibetan rainfall

Fig. 1. Monitoring stations around the Tibetan Autonomic Region

Fig. 2. Atmospheric CO_2 contents at different elevations of Tibet

Fig. 3. Monthly volume-weighted mean of pH and conductivity for Lhasa precipitation during the 1997-99 period.

Fig. 4. Monthly volume-weighted mean of pH and conductivity for Tibetan precipitation during the fieldwork seasons of 1987-88

Table 1. The weighted mean of rainfall pH in three remote towns of Tibet

Locations	*Sample Number*	*1987-1988 pH*	*Conductivity*	*Sample number*	*1997-1999 pH*	*Conductivity*

Dangxiong	7	8.78	36	5	7.45	20.6
Amdo	3	7.96	24.4	6	7.89	28.4
Dingri	3	7.64	26.7	2	8.01	29.1

Table 2. pH and conductivity and season (December-May, windy; June-November, calm)

	1997		*1998*		*1999*	
	pH	*Conductivity*	*pH*	*Conductivity*	*pH*	*Conductivity*
Windy	7.03	44.88	7.44	51.55	7.52	30.81
Calm	7.82	29.56	7.96	24.00	7.03	21.11

Table 3 pH values of dust deposits in different seasons of three locations

Location	*Season*	*PH*
Lhasa	Windy	8.3
	Calm	8.5
Amdo	Windy	8.1
	Calm	8.7
Dingri	Windy	7.9
	Calm	7.5

Table 4. Ionic concentrations ($equl^{-1}$) of precipitation in Lhasa

	1987-88			1998-2000		
	Range	V.W.Mean	S.D.	Range	V.W.Mean	S.D.
K^+	0-79.87	14.8	25.47	0-26.34	5.14	7.66
Na^+	21.3-176.6	88.96	53.0	0-52.6	11.2	14.6
Ca^{2+}	84.3-242.5	150.3	53.66	37.4-327.2	197.4	87.9
Mg^{2+}	0-18.9	5.66	20.4	3.4-33.8	10.9	8.27
NH^+_4	1.1-39.3	21.92	14.2	0.7-68.1	14.3	19.2
F^-	*			0-11.1	0.4	2.7
Cl^-	4.2-33.6	21.7	9.17	0-25.1	9.7	8.3
NO^-_3	0-4.0	1.96	1.66	0-41.3	6.9	10.6
SO^{-2}_4	0-6.7	2.47	2.13	0-48.7	5.2	13.8
HCO^-_3	141.5-534	288.9	103.1	52.6-380.7	231.7	101.2

* no examination

Table 5 Ionic concentrations (equl-1) of precipitation in the three towns of the Tibetan Autonomic Region

	1987-88	1998-2000

	Range	*V.W.Mean*	*S.D.*	*Range*	*V.W.Mean*	*S.D.*
K^+	1.54-18	9.5	5.7	4.6-18.2	10.3	5.1
Na^+	13.9-35.2	23.2	8.2	4.4-18.4	12.1	5.6
Ca^{2+}	75.9-169.2	139.7	34.8	40.6-235.0	93.2	79.3
Mg^{2+}	0-18.9	5.7	7.1	3.8-27.2	10.4	9.5
NH^+_4	1.1-39.3	21.9	15.5	0.7-21.1	14.9	7.4
F^-				0-0.5	0.1	0.2
Cl^-	10.4-46.3	21.2	13.1	1.4-7.1	2.9	2.3
NO^-_3	0-9.4	2.71	3.5	1.1-2.7	1.7	0.7
SO-24	0-4.4	1.6	1.5	5.3-66.6	6.0	2.9
HCO^-_3	122.4-252.3	199.5	45.9	85.9-282.6	137.0	81.7

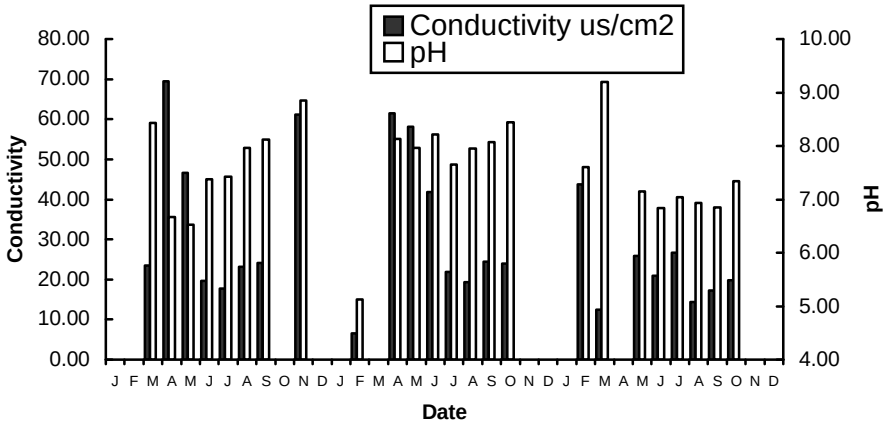
Table 6. SO_2 emission (T) of the Tibetan Autonomic Region

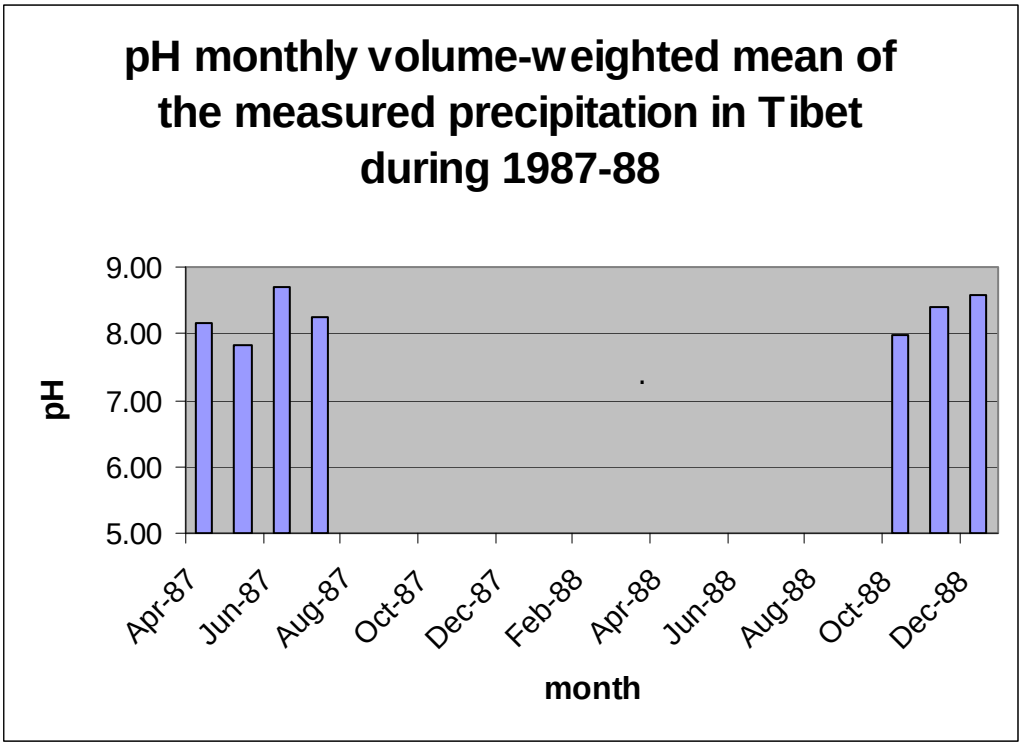
1991	1992	1993	1994	1995
1800	1900	2200	2200	3000

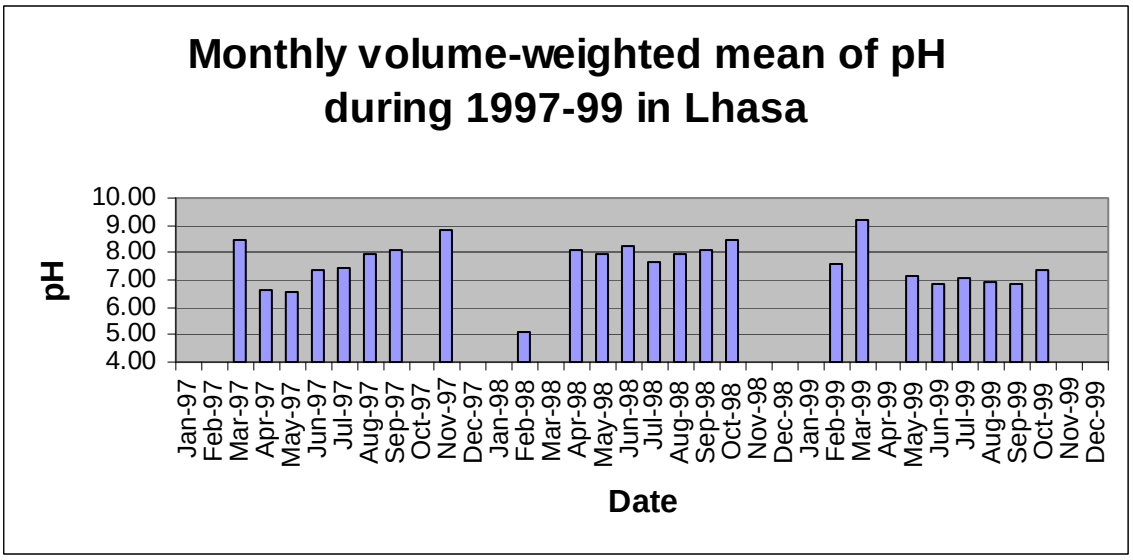
Source: Urban and Rural Construction and Environmental Protection Bureau of the Tibetan Autonomous Region, 1996,

Table 7 Ratios of Na^+ to Cl^-, SO^{-2}_4, K^+, Ca^{2+} and Mg^{2+} in Tibetan rainfall

	Cl^-/Na^+	SO^{-2}_4/Na^+	K^+/Na^+	Ca^{2+}/Na^+	Mg^{2+}/Na^+
Lhasa 1988	0.34	0.031	0.42	1.58	0.14
Lhasa 1997-1999	2.35	1.78	2.13	17.04	0.65
Other towns 1988	1.42	0.16	0.75	5.26	0.18
Other towns 1997-1999	0.38	1.00	1.34	7.31	0.52
Seawater	1.8	0.25	0.036	0.038	0.13


Conductivity us/cm2
pH
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
Conductivity
10.00
9.00
8.00
7.00
6.00
5.00
4.00
pH
J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D
Date


pH monthly volume-weighted mean of the measured precipitation in Tibet during 1987-88
9.00
8.00
7.00
6.00
5.00
pH
Apr-87
Jun-87
Aug-87
Oct-87
Dec-87
Feb-88
Apr-88
Jun-88
Aug-88
Oct-88
Dec-88
month


Monthly volume-weighted mean of pH during 1997-99 in Lhasa
pH
10.00
9.00
8.00
7.00
6.00
5.00
4.00
Jan-97
Feb-97
Mar-97
Apr-97
May-97
Jun-97
Jul-97
Aug-97
Sep-97
Oct-97
Nov-97
Dec-97
Jan-98
Feb-98
Mar-98
Apr-98
May-98
Jun-98
Jul-98
Aug-98
Sep-98
Oct-98
Nov-98
Dec-98
Jan-99
Feb-99
Mar-99
Apr-99
May-99
Jun-99
Jul-99
Aug-99
Sep-99
Oct-99
Nov-99
Dec-99
Date