



Wet deposition at the base of Mt Everest: Seasonal evolution of the chemistry and isotopic composition



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HIGHLIGHTS

- The chemical and isotopic composition of precipitation showed differences between rain and snow.
- Combustion emission tracers increased during the pre-monsoon and during the summer monsoon onset.
- Volume-weighted mean concentrations of SO_4^{2-} and NO_3^- did not differ from those measured in the 1990's.
- Ion deposition from snow largely contributed to the wet deposition fluxes.

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ABSTRACT

The chemistry of wet deposition was investigated during 2012–2014 at the Pyramid International Laboratory in the Upper Khumbu Valley, Nepal, at 5050 m a.s.l., within the Global Atmosphere Watch (GAW) programme. The main hydro-chemical species and stable isotopes of the water molecule were determined for monsoon rain (July–September) and snow samples (October–June). To evaluate the synoptic-scale variability of air masses reaching the measurement site, 5 day back-trajectories were computed for the sampling period. Ion concentrations in precipitation during the monsoon were low suggesting that they represent global regional background concentrations. The associations between ions suggested that the principal sources of chemical species were marine aerosols, rock and soil dust, and fossil fuel combustion. Most chemical species exhibited a pattern during the monsoon, with maxima at the beginning and at the end of the season, partially correlated with the precipitation amount. Snow samples exhibited significantly higher concentrations of chemical species, compared to the monsoon rainfall observations. Particularly during 2013, elevated concentrations of NO_3^- , SO_4^{2-} and NH_4^+ were measured in the first winter snow event, and in May at the end of the pre-monsoon season. The analysis of large-scale circulation and wind regimes as well as atmospheric composition observations in the region indicates the transport of polluted air masses from the Himalayan foothills and Indian sub-continent up to the Himalaya region. During the summer monsoon onset period, the greater values of pollutants can be attributed to air-mass transport from the planetary boundary layer (PBL) of the Indo-Gangetic plains. Isotopic data confirm that during the monsoon period, precipitation occurred from water vapor that originated from the Indian Ocean and the Bay of Bengal; by contrast during the non-monsoon period, an isotopic signature of more continental origin appeared, indicating that the higher recorded NO_3^- and SO_4^{2-} concentrations could be ascribed to a change in air circulation patterns. A comparison of recent monsoon deposition chemistry with data from the 1990's shows similar levels of contaminants in the rainfall. However, non-monsoon deposition can be significant, as it largely contributed to the ion wet deposition fluxes for all analyzed species in 2013.

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1. Introduction

High-elevation environments are perceived to be among the most pristine regions on Earth owing to their remote location and distance from emissions sources. The Himalayas host a unique range of ecosystems with a high degree of biodiversity (Mittermeier et al., 2005), but they are characterized by a fragility that makes the region highly sensitive to environmental changes. The glaciers and snowpack of these mountains serve as “water towers” (Immerzeel et al., 2010), and their meltwaters are a major source of water for some of the largest rivers of Asia: the Indus, Ganga, and Brahmaputra.

Long-range aeolian transport of dust and pollution threaten the relatively pristine high-alpine ecosystems. They also jeopardize the stability of glaciers and snowpack by lowering albedo and making them more vulnerable to melt. A considerable amount of mineral dust is systematically transported toward the Himalaya from the Tibetan Plateau and the arid areas of the Indo-Gangetic Plains (Duchi et al., 2014). The southern Himalayas region is seasonally reached by high level of ozone (O₃), black carbon (BC), and other aerosol particles (Cristofanelli et al., 2014), which constitute the so-called atmospheric brown clouds (ABC).

Pollution from industrial emissions in neighboring China and India can alter the chemical composition of rain in the Himalayas. Between 2000 and 2008, emissions of nitrogen oxides (NO_x) increased more than 50% in India and sulfur dioxide (SO₂) emissions increased more than 50% in China (Kurokawa et al., 2013). There is evidence that emissions regulations in China have stabilized SO₂ emissions there since 2006, while SO₂ emissions in India have continued to increase (Klimont et al., 2013). Measurements of the quality of precipitation and dry deposition in the Himalayas are infrequent and geographically sparse, and there remain open questions regarding contribution of contaminants in the alpine environment. Data that do exist primarily come from the Tibetan Plateau (Li et al., 2007; Xu et al., 2009; Zhang et al., 2003), where desert dust dominates atmospheric deposition. Snow and ice core data for the Everest region demonstrate that monsoon air masses are the predominant sources of deposition on the southern slopes of the eastern Himalayas (Marinoni et al., 2001; Valsecchi et al., 1999; Shrestha et al., 2002). Some studies highlight differences in the wet deposition chemistry during different stages of the summer monsoon in high Nepali Himalayan valleys (Balestrini et al., 2014; Shrestha et al., 2002), indicating the transition phases of the monsoon season are critical periods for a full understanding of wet deposition behavior.

In this context, the chemistry of wet deposition was investigated at the Pyramid International Laboratory (PIL) in the northernmost portion of the Khumbu Valley, at 5050 m asl, within the Global Atmosphere Watch (GAW) programme. The main hydro-chemical species and the stable isotopes of oxygen and deuterium were measured for summer monsoon precipitation (2012–2013) and winter snow (2013–2014). To evaluate the synoptic-scale variability of the air masses reaching the measurement site, 5-day back-trajectories were computed for the sampling period.

The aim of this study was to analyze daily, weekly, and seasonal variation in the concentration of wet deposition chemistry and to analyze depositional fluxes during the different seasons that characterize the Himalayan climate. The chemical analysis combined with isotope data and the description of large-scale circulation provide insights into both the long-range transport of man-made contamination and the different origins of the air masses.

Additionally, we compared these results to previous measurements collected in the early 1990's (Valsecchi et al., 1999) in order to evaluate potential for changes in the quality of wet deposition over time. Our analysis focus on solutes in precipitation and, to help

interpret these results, aerosols observations from our research site are discussed when available.

2. Methods

2.1. Study area

The rain and snow samples were collected at the Pyramid International Laboratory (PIL; 5050 m a.s.l.; 27.959°N; 86.813°E) located in the Khumbu Valley in the Sagarmatha (Mt. Everest) National Park of Nepal. The Khumbu Valley extends in elevation from 2845 m to 8848 m at the summit of Mt. Everest and lies in a geologically complex transition zone between Nepal and Tibet. Here, a large-scale and low-angle fault, called the South Tibetan detachment, places unmetamorphosed Paleozoic sediments, which make up the numerous peaks that exceed 8000 m (e.g., Mount Everest and Lhotse), above high-grade gneisses and leucogranites.

The Pyramid International Laboratory, located in the Upper Khumbu Valley, is a multi-disciplinary and high altitude research center, founded by the Ev-K2-CNR Committee and the Nepal Academy of Science and Technology in 1990 (Baudo et al., 2007).

The majority of rainfall (90%) in the sampling area occurs from June to September (Salerno et al., 2015) during the monsoon season, whereas the winter season is relatively dry. Land cover surroundings of the PIL are composed of typical upper alpine herbaceous vegetation (UNEP/WCMC, 2008) and rocks. About 75% of the surface area of glaciers in the valley is located between 5000 m and 6500 m a.s.l. (Salerno et al., 2015). An automatic weather station installed near the PIL allows for hourly recording of meteorological parameters (temperature, relative humidity, atmospheric pressure, wind speed and direction, global radiation, total precipitation) according to WMO standards (Bertolani et al., 2000). In addition, in 2006, a permanent station for aerosol, ozone and halocarbon measurements was established on the top of a hill near the PIL (the Nepal Climate Observatory-Pyramid — NCO-P) (Bonasoni et al., 2008).

2.2. Sampling and analyses

Precipitation was collected for chemical and isotopic analysis in 2012, 2013 and 2014. Rain water was sampled during the 2012 and 2013 monsoon seasons (June–September) by means of a wet-only sampler (MTX, Bologna, Italy) equipped with a polyethylene vessel (30 cm i.d.). Sampling was on a daily basis for the main part of the monsoon season, usually starting at 9.00 a.m., from July to mid-August. Sampling was on a weekly basis at the beginning and at the end of the rainy period (June; mid-August - September). During the non-monsoon period (from October to May) we sampled snow events by using a polyethylene vessel (30 cm i.d.) inserted in a plastic tank driven into the ground. This precaution was necessary because of the wind blowing at PIL site.

All the sample volumes were measured gravimetrically at the Pyramid laboratory. Depending on the amount of available volume, samples were poured in different plastic bottles for chemical or water molecule isotope analysis. Aliquots for chemical analyses were stabilized with chloroform (Galloway et al., 1989), used for its properties as a bactericide. Bottles were stored in plastic bags and refrigerated (4 °C) until shipment to Italy.

The amount of rain and snow were calculated using volumes and the area of the samplers. Weekly millimeters of rain compared with those measured by the automatic weather station showed good agreement. Some discrepancies were observed for snow due to the precipitation scarcity and the occurrence of strong wind. Therefore, the amount measured by means of the polyethylene vessel sometimes exceeded those measured by the automatic

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