INTERPRETATION OF THE CHEMICAL AND PHYSICAL TIME-SERIES RETRIEVED FROM SENTIK GLACIER, LADAKH HIMALAYA, INDIA

By Paul A. Mayewski, W. Berry Lyons,
(Department of Earth Sciences, Glacier Research Group, University of New Hampshire, Durham, New Hampshire 03824, U.S.A.)
N. Ahmad, (Aligarh Muslim University, Aligarh, India)
Gordon Smith, (Department of Earth Sciences, University of New Hampshire, Durham, New Hampshire 03824, U.S.A.)
and M. Pouriacht (Laboratoire de Glaciologie du CNRS, Grenoble, France)

ABSTRACT. Spectral analysis of time series of a c. 17 ± 0.3 year core, calibrated for total activity recovered from Sentik Glacier (4908 m) Ladakh, Himalaya, yields several recognizeable periodicities including sub-annual, annual, and multi-annual. The time-series, include both chemical data (chloride, sodium, reactive iron, reactive silicate, reactive phosphate, ammonium, δD, δ18O and pH) and physical data (density, debris and ice-band locations, and microparticles in size grades 0.50 to 12.70 μm). Source areas for chemical species investigated and general air-mass circulation defined from chemical and physical time-series are discussed to demonstrate the potential of such studies in the development of palaeo-meteorological data sets from remote high-alpine glaciated sites such as the Himalaya.

RESUME. Interpretation des séries de variations chimiques et physiques reconstituées au Sentik Glacier, Ladakh Himalaya, Inde. L’analyse spectrale de l’activité β totale d’une série temporelle de glace 17 ± 0.3 a issue du Sentik Glacier (4908 m) Ladakh Himalaya, a permis de reconnaître plusieurs périodicités, subannuelles, annuelles et multi-annuelles. Cette série comprend à la fois des résultats chimiques (chlorures, sodium, fer actif, silicate actif, phosphates actifs, ammonium, δD, δ18O) et pH et de données physiques (densité, localisation des bandes de glace et de sédiments et microparticules dans les plages de dimension de 0.50 à 12.70 μm). On discute les zones des sources pour les espèces chimiques trouvées et la circulation générale des masses d’air impliquée par les glaciers des Himalayas et des possiblités de ce type d’étude pour le développement des connaissances paléométéorologiques dans les sites de haute montagne alpine englacées tels que l’Himalaya.

ZUSAMMENFASSUNG. Interpretation einer chemischen und physikalischen Zeitreihe, gewonnen am Sentik-Gletscher, Ladakh-Himalaya, Indien. Die Spectralanalyse einer c. 17 ± 0.3 a, mit Gesamt-β-Aktivitäten kalibrierten Zeitreihe aus dem Sentik-Gletscher (4908 m) im Ladakh-Himalaya liefert einige erkennbare Periodizitäten, darunter solche von weniger als einem Jahr Dauer sowie ein- und vielfältige. Die Zeitreihe enthält sowohl chemische (Chloride, Sodim, aktives Eisen, Silikat und Phosphat, Ammonium, δD, δ18O) und pH wie physikalische Daten (Dichte, Lage von Schutt und Eisbändern sowie Mikropartikel in Größen von 0.50 bis 12.70 μm). Um die Bedeutung solcher Studien für die Aufstellung paläometeorologischer Datensätze aus vergleichbaren Gebieten von Hochgebirgen wie dem Himalaya zu zeigen, werden die Herkunftsgeschichte der untersuchten chemischen Stoffe und die allgemeine Luftzirkulation, die sich aus chemischen und physikalischen Zeitreihen ableiten lassen, diskutiert.

INTRODUCTION

Advances in climate prediction depend on a knowledge of historical and climatic sequences ranging in scale from seasons to millennia. Proxy data provided by glaciers can be used to construct these sequences when direct observations of the atmosphere are either spatially or temporally lacking. The glaciers of high Asia provide a unique tool for retrieving proxy data concerning atmospheric circulation because of their geography and elevation. Yet, although these glaciers comprise by area 50 % of all glaciers outside of the polar regions and contain approximately 33 times the areal cover of the glaciers in the European Alps (Wissman, 1960) they are perhaps the least understood and least intensively studied glacier system in the world.

The importance of glaciers as proxy indicators of climate in Asia is substantiated when one considers that the monsoonal circulation system that interacts with these glaciers is of great concern for the socio-economic stability of the Indian subcontinent. Mukherjee and others (1981) estimate that approximately 75-90% of the annual rainfall reaching the Indian subcontinent comes during the summer monsoon and Bahadur (personal communication in 1982) suggests that as much as 25-40% of the runoff in India could come from melting glaciers. Furthermore, the Asian monsoon circulation system may even have links to the severity of snow cover over Eurasia (Hahn and Shukla, 1976) which may in turn interact through the jet stream to exert influence on the weather and climate of North America (Reiter, 1981). The Himalayan ice mass also has interhemispheric teleconnections since 75% of the air mass entering western India comes from the Southern Hemisphere (Rangarajan and Eapen, 1981).

The most direct glacier proxy monitoring of monsoonal circulation is gained by the determination of the net mass balance, source area, and timing of precipitation using time-series derived from chemical and physical studies of ice cores. This paper presents the first of a series of such approaches which stem from prior investigations of Himalayan glacier fluctuation records (Mayewski and Jeschke, 1979) and examination of the feasibility of glaciochemical sampling in the Himalaya (Mayewski and others, 1981).

GEOGRAPHY AND METEOROLOGY OF NUN KUN

Nun Kun (long. 75°71’ to 76°08’E.; lat. 35°57’ to 35°02’N., Fig. 1) is commonly used as the name for the rectangular massif (25 km x 13 km) at the northwestern end of the Zaskar Range in Ladakh, India. It was chosen as a study site because in addition to containing several glaciers that radiate off its central snow-covered plateau it is a relatively arid portion of the Himalaya, close to the northern limit of the summer monsoon and is, therefore, potentially an area sensitive to monsoonal fluctuations.

Meteorological conditions in the Himalaya are dominated by the activity of the monsoonal system. During the winter months air flow in the general region of the study area is approximately north-west

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1. Loc a ti o n o f co r e site fro m a por ti on o f NASA Lan ds at Ima ge E -3053 -0449 -1 C d is play i ng the Nun Kun mas si f in the lower cen ter of the photograph. Pea ks in mas si f cen ter attai n el evati ons as high as 7135 m (Nun) and 7077 m (Kun). Gl ac ier with banded mor ai ne flo ws di rectly no rth of the mas si f. Mor ai ne bands as seen on the photograph are approxi mately 8 km in length. The Suru River meanders past the snout of this glacier. S marks the core site (4908 m) on Sentik Glacier.

Fig. 1. Location of core site from a portion of NASA Land sat Image E-3053-04491-C displaying the Nun Kun mas si f in the lower cen ter of the photograph. Pea ks in mas si f cen ter attai n el evati ons as high as 7135 m (Nun) and 7077 m (Kun). Gl acier with banded mor ai ne flo ws di rectly no rth of the mas si f. Mor ai ne bands as seen on the photograph are approxi mately 8 km in length. The Suru River meanders past the snout of this glacier. S marks the core site (4908 m) on Sentik Glacier.

to south-east near the ground surface and west to east at the 500 mbar level (Boucher, 1975). Summer air-mass circulation includes south-west to north-east to north-west flow near the ground surface and at the 500 mbar level air flow is eastward along the northern portion of the Himalaya and westward along the southern portion of the range (Boucher, 1975). An anticyclone rests for a portion of the summer season over the Himalaya and divides the eastward­ and westward-flowing 500 mbar level air system (Boucher, 1975). The lower air mass is believed to be relatively thin (<2 km) and overlain by an arid continental air mass (Sequerra and Kelkar, 1978).

Primary maximum precipitation comes to the region of the study site during the period July to August (Boucher, 1975). Estimated total rainfall for valley bottoms in the Nun Kun area is 0.80 m a-l water equivalent (Qazi, 1973). Rainfall records are available from several stations in the region, however the data are scant and contain numerous inconsistencies. Discharge rec­ords for the Suru River (Fig. 1), which flows in the valley directly north of the core site, suggest that the warmest time of the year is June to August (Qazi, 1973). The main core site was chosen at an elevation of 4908 m on a relatively flat, single-flow portion of a 3 km long alpine glacier, Sentik Glacier (Son Fig. 1), that flows north-east off the Nun Kun massif. Several other core sites were investigated in the massif area, at elevations as high as 5512 m, but these were either affected by avalanches or as in the case of the Nun Kun plateau itself primarily composed of wind-blown snow.

Interpretation of down-hole glaciochemistry re­covered from the Sentik Glacier core is based on the assumption that neither melting nor percolation, to depths significantly less than seasonal accumulation levels, is present at the core site. Although, as already noted, few meteorological data are available from the region, radiosonde measurements from Srinagar (1700 m a.s.l. 120 km east of Nun Kun) re­veal that even during the warmest months of the year, June-August, at only 500-600 m above Srinagar, mean monthly temperatures barely rise to 0°C. Furthermore, a set of down-hole temperatures made at the study site in July suggest that although the upper few centimeters of the glacier are close to 0°C, immediately beneath the surface, temperatures drop until finally at a depth of 3 m the core attains and maintains a temperature of -3.0°C to a depth of at least 16.6m.

As an additional test for the investigation of melt-water potential, plexiglass trays designed to capture melt water were inserted in snow-pits close to the sample site. Although this monitoring was conducted in late July, close to the peak of the summer season and at several depths (5, 10, 20, 30, 40 and 50 cm) no melt water was found in the trays. The presence of several thin ice bands, comprising <5% of the total core, suggests that melt events, although not common, do occur at certain times. Hastenrath (1978) has demonstrated that high-altitude areas,
such as the summit of Quelccaya ice cap, Peru, may absorb too little net radiation to allow melting. Although we do not have radiation data to compare to Hastenrath’s, the same situation may have existed at the Sentik Glacier core site for much of the time period represented by the core.

**METHODOLOGY**

Samples collected from a 16.6 m core on Sentik Glacier were analyzed for density, microparticles, and chemical properties (chloride, sodium, reactive iron, reactive silicate, reactive phosphate, ammonium, $\delta^18O$, total $\beta$-activity, and pH). Although the collection interval was continuous at 8 cm, most analyses were performed at 16 cm intervals due to sample volume constraints. Extreme care was taken at all times during sample collection, handling, and analyses to prevent sample contamination as required by the nature of the chemical studies. Cores were taken using a manually operated pre-cleaned teflon-coated SIPRE-type auger. Plastic suits, plastic gloves, and particle masks were worn by all members of the party who came in direct contact with the exposed core.

Each sample had its outer 1-2 cm scraped immediately after sectioning from the cores using pre-cleaned plexiglass scrapers, and the scrapings were discarded to reduce possible contamination by the auger. Once scraped, samples were placed in pre-cleaned plastic bags, and the auger involved a soap and water wash with rinsing several times in distilled-deionized water. After melting in the plastic bags each sample was transferred to two 30 ml and one 125 ml (LPE) container, pre-cleaned as described above, and one 125 ml (LPE) container that was pre-cleaned by acid-washing in concentrated hydrochloric acid followed by rinsing several times in distilled-deionized water. The portion of the sample in the soap-and-water cleaned 125 ml container was used for analysis of chloride (Zall and others, 1956) and of reactive phosphate employing AutoAnalyzer techniques (Gilbert and Loder, 1977). The portion of each sample in the acid-cleaned 125 ml container was used for analysis of reactive silicate and reactive iron by AutoAnalyzer using the techniques of Gilbert and Loder (1977) and Stookey (1970), respectively. These samples were acidified with ultrapure HNO$_3$ and allowed to sit at room temperature for at least two weeks prior to analysis. Sodium was analyzed via atomic absorption spectrophotometry. All of the aforementioned were analyzed at the University of New Hampshire. Duplicate analyses of standards were used to determine the precision of analysis for chloride, reactive iron, reactive silicate, reactive phosphate and sodium. Analytical precision of the replicate analyses of standards was ±1% at 7.0 $\mu$M, ±1% at 4.5 $\mu$M, ±1% at 4 $\mu$M, ±4% at 0.5 $\mu$M, and ±3% at 15.0 $\mu$M, respectively.

The two 30 ml (LPE) containers mentioned previously were used for collecting portions of the melted samples that were analyzed for $\delta^18O$, and total $\beta$-activity measurements were made in the CNRS Laboratoire de Glaciologie, France, on one set of 30 ml containers that were sealed with wax to prevent diffusion. Volumes required for total $\beta$-activity measurement required lumping of samples. pH was analyzed in the field on the other set of 30 ml samples using an Orion ion analyzer T.M. model 399A portable pH meter with an Orion 91-06 combination pH electrode standardized using NBS buffers of pH = 4.01 and pH = 7.00. pH analyses were made without stirring. Microparticles were analyzed at The Ohio State University using the 30 ml sample set from pH. The technique employed a Coulter

<table>
<thead>
<tr>
<th>Time-series set</th>
<th>Mean</th>
<th>Sample number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chloride</td>
<td>2.94 $\mu$M</td>
<td>114</td>
</tr>
<tr>
<td>Sodium</td>
<td>3.14 $\mu$M</td>
<td>114</td>
</tr>
<tr>
<td>Reactive iron</td>
<td>13.91 $\mu$M</td>
<td>228</td>
</tr>
<tr>
<td>Reactive silicate</td>
<td>8.35 $\mu$M</td>
<td>228</td>
</tr>
<tr>
<td>Reactive phosphate</td>
<td>0.39 $\mu$M</td>
<td>228</td>
</tr>
<tr>
<td>Ammonium</td>
<td>1.07 $\mu$M</td>
<td>114</td>
</tr>
<tr>
<td>$\delta^18O$</td>
<td>-97.90 $^\circ$/oo</td>
<td>114</td>
</tr>
<tr>
<td>pH</td>
<td>4.12-5.85 pH units*</td>
<td>19</td>
</tr>
<tr>
<td>Total $\beta$-activity</td>
<td>224.76 dph kg$^{-1}$</td>
<td>21</td>
</tr>
<tr>
<td>Density</td>
<td>570 kg m$^{-3}$</td>
<td>209</td>
</tr>
</tbody>
</table>

Microparticles (examples of 3 out of the 15 size grades available appear below)

- 0.50-0.63 $\mu$m: 34 x 10$^3$ $\mu$m size particles/500 $\mu$l of sample
- 1.00-1.25 $\mu$m: 20 x 10$^2$ $\mu$m size particles/500 $\mu$l of sample
- 8.00-10.00 $\mu$m: 3 $\mu$m size particles/500 $\mu$l of sample

* range rather than mean is specified due to the log scale used to measure pH.
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Counter (L.G. Thompson, 1977) and yielded 15 size grades in the range 0.50 to 12.70 μM.

**DATA ARRAY AND INTERPRETATION**

Time-series sets of down-hole chemical properties (chloride, sodium, reactive iron, reactive silicate, reactive phosphate, δ¹⁸O, δ¹⁸O, pH, and total β-activity) and physical properties (debris and ice band locations, density, and three selected microparticle size grades out of the 15 size grades analyzed) appear in Appendix A. Table I contains a list of mean values for all of the data sets appearing in Appendix A. Results stemming from the analysis of this data array follow.

**Core chronology**

Total β-activity measurements although integrated over more than one sample are available for the entire length of the core. The resultant total β-activity record has a built-in ±0.3 error in down-hole position due to the sampling interval required for this analysis. In the depth range 15.40-15.96 m a maximum total β-activity value for the core was encountered, 639 dph kg⁻¹, which is believed to coincide with the 1963 thermonuclear test level. The time period represented by the core is therefore ± 17 ± 0.3 years which is equivalent to an average net mass balance of ~ 0.92 m a⁻¹. Using an average core density of 570 kg m⁻³ this yields an average net mass balance of 0.62 m a⁻¹ water equivalent.

**Periodic events**

With the exception of total β-activity, δ¹⁸O, and debris and ice band locations all of the data sets in Appendix A are nearly regularly spaced. The latter yield an array of 23 time series sets each with a value every 0.16 m down core and some (reactive iron, reactive silicate, and reactive phosphate) with values every 0.08 m down core. The volume of data and potential combinations presented by these data require synthesis using a statistical technique capable of revealing trends such as periodicity. Spectral analysis involving the computation of spectral density (power) at chosen frequencies provides just such a statistical tool. Power at a given frequency is the measure of how much of the variance of a time-series, or in this case a depth-series exists at a particular frequency (period).

Power, frequency, period, and confidence interval, at specified frequencies, appear in Figure 2a-c. For most of these depth-series several power peaks are recognizable. Reliability of peaks was tested using simplified filtering and by varying lag number in sev-
Fig. 2. Power (unit$^2$/yr m$^{-1}$), period (yr) and frequency (yr$^{-1}$) for time-series sets. Units equal to $\mu$M for chemical species, °/oo for $\delta$D, pH units for $pH$, kg m$^{-3}$ for density and particles/600 $\mu$L of sample for specified $\mu$m microparticle size grades. Vertical bar represents 90% confidence interval for power peaks at 10 degrees of freedom for $n$ = 114 and 24 degrees of freedom for $n$ = 228 (after Koopmans, 1974). The lower limit of the vertical bar defines whether the peak departs significantly enough from baseline to the classified as a peak. Note that confidence interval is valid only at frequency (period) specified. Confidence interval for period $= \pm 0.16$ m using a 20 sampling interval.

5b - includes time-series sets displaying annual and subannual power peaks at 20 lags ($n$ = 228).

5c - includes time-series sets at 10 lags displaying just subannual power.

eral runs. These peaks occur at periodicities of: $\geq 3.22$ m, $< 1.22$ to $> 0.32$ m and $< 0.32$ m. Using the chronology provided by the total $\beta$-activity measurements and the resultant average net mass balance, 0.92 m yr$^{-1}$, a depth to time conversion yields power peaks at $\geq 3.5$ a, $< 3.5$ to $< 0.35$ a, and $< 0.35$ a. Power peaks with periodicity $\geq 3.5$ a ($\geq 3.22$ m) are displayed by all time-(depth-)series. These events cannot, however, be precisely constrained with the sample number and length of record available in this study. Power at $\geq 3.5$ a is both a product of the length of the time-series used in this study and of "real" trends in the data. The latter was tested by increasing the number of lags examined in the spectral study. The presence of power in the multi-annual period suggests that collection of longer time-series, i.e. deeper cores, may yield valuable information concerning events with periodicities $\geq 3.5$ a. Power peaks with periodicity $< 0.35$ a ($< 0.35$ m) are displayed by several time-series. However, events represented by power in this periodicity are almost indistinguishable from noise and thus at the sampling interval used in this study further resolution of these events is not statistically justifiable.

Assuming an average net mass balance for the core of 0.92 m yr$^{-1}$ and an error in sample position of
Non-periodic events

Since spectral analysis provides a view of the periodic elements in a time-series assemblage, this technique yields a smoothed display of the data. Non-periodic components of the time-series sets, although comprising a small portion of the record in this study, need to be examined on an individual basis. The most apparent non-periodic anomaly in concentration is found at the depth 3.0 to 3.5 m. It is displayed by density, debris bands, and the time-series for chloride, sodium, reactive iron, reactive silicate, reactive phosphate, ammonium, and microparticles in the range 0.50 to 0.80 μm and 3.17 to 10.00 μm as relatively high values. The presence of a major density transition at this depth suggests that deposition and/or ablation may exert some control on the distribution of concentrations down core. Alternatively, relatively high concentrations of chemical species may imply deposition during a period of intensified atmospheric circulation. The lack of spectral power in the annual period for the density time-series and the general non-synchronousity of the spectral signature (Fig. 2c) of this time-series in this study suggests that trends in the density time-series are not associated with trends in the chemical species and/or microparticle time-series.

Notwithstanding several of the chemical time-series record annual and subannual events, the number of debris bands encountered down core does not match the total p-activity of the core. The presence of debris bands is unusual as a stratigraphic marker but rather as an indication of events such as unusual ablation and/or intensified transport of debris to the core site.

Source

Chemical and physical constituents in the core are introduced from several source types, size source areas, and distances. Source input timing and atmospheric circulation interpretations, where applicable, for the chemical and physical constituents analyzed are discussed in the following order: chloride, sodium, reactive iron, reactive silicate, reactive phosphate, ammonium, and microparticles, 50, and 6160. Volcanism although a potential source for several of the preceding has been deleted from the discussion that follows since it is unlikely as a periodically occurring source at the study site. The primary source for the chloride in this core is marine and the closest marine source to Nun Kun during the period of the summer monsoon is the Arabian Sea, a distance of ~1250 km from the core site. Values of chloride from fresh surface snows analyzed at several sites in the Nun Kun area (Mayewski and others, 1983) compared to those of fresh rain samples collected 75 km downwind from Nun Kun at Gulkarg (Sequeria and Kolker, 1978), suggest progressive depletion of chloride as air travels off the Arabian Sea to the core site (Mayewski and others, 1983). The annual power peak derived from the spectral analysis of the chloride time-series is larger than the subannual peak which is consistent with the view that the major input of chloride comes once each year. Since concentrations of chloride in fresh summer snow [Mayewski and others, 1993] are very similar to those representing annual pulses in the time-series record, the high core values are assumed to be summer events. Subannual input of chloride probably results from the influx of oceanic air which to a varying degree enters this site throughout the year from sources more distant than the Arabian Sea.

Sodium is brought to the core site either in combination with chloride from a sea-salt source or independently from crustal weathering. Since sodium has a higher mean concentration than chloride it probably comes from an admixture of these sources. Sodium has a relatively strong subannual spectral power peak and a weak annual peak. It is a minor source from any wind direction and, therefore, any season thus explaining the stronger peak in the subannual period. The primary source for periodically occurring reactive iron and reactive silicate is crustal weathering. Reactive iron has the higher mean concentration and a dominant subannual power peak suggesting perhaps a more local and/or larger source. Annual power in the reactive silicate spectral signature is less prominent than subannual power suggesting that annual inputs of this species come from a source that is limited or long-travelled by comparison with the subannual input or inputs of reactive iron. Subannual input of the reactive silicate may come from the same local weathering source as the reactive iron while the annual reactive silicate pulse may be separate. Measurements of reactive iron and reactive silicate on fresh summer snow from Nun Kun (Mayewski and others, 1983) suggest that these species are derived, respectively, from the Indian subcontinent or the Tibetan Plateau.

Reactive phosphate has potentially both biogenic and anthropogenic sources, and for this study displays spectral power in both the annual and subannual ranges. Examination of temporal and spatial distributions measured in this study of reactive phosphate reveals: (1) that several of the high reactive phosphate values in the time-series correspond with debris band positions while the lowest phosphate value of samples having no visible debris bands is lower than that of rain from remote northern hemispheric areas (Graham and Duce, 1979) and (2) similarities in distributions measured in the subannual reactive phosphate time-series the annual power peak probably represents summer input. While transport of wind-blown material may be a likely source for summer inputs of reactive phosphate, subannual inputs may also be derived from this source as well as biogenic emissions and fuel-burning (Davidson and others, 1981). Ammonium present in the core samples has as its most probable sources in this area anthropogenic and biogenic activity. The ammonium time-series display the same relative power in both the annual and subannual period as might be expected considering potential multiple sources and multiple timing of inputs. No unique sources can be identified, however, this species may not be useful as a stratigraphic marker. While the peak of ammonium from freshly fallen summer snow collected in the study area reveals that the relative high pH has similar spectral power in both annual and subannual periods may be expected from an agricultural site where exposed terrain has been subjected to fertilizer usage (Mayewski and others, 1983). Ammonium loading from eroded soil material is a notable component of the atmosphere in north-west India (Bryson and Swain, 1981). Since summer reactive phosphate concentrations, determined from the fresh snow study (Mayewski and others, 1983) are similar to the maximum values displayed in the reactive phosphate time-series the annual power peak probably represents summer input. While transport of wind-blown material may be a likely source for summer inputs of reactive phosphate, subannual inputs may also be derived from this source as well as biogenic emissions and fuel-burning (Davidson and others, 1981). Ammonium present in the core samples has as its most probable sources in this area anthropogenic and biogenic activity. The ammonium time-series display the same relative power in both the annual and subannual period as might be expected considering potential multiple sources and multiple timing of inputs. No unique sources can be identified, however, this species may not be useful as a stratigraphic marker. While the peak of ammonium from freshly fallen summer snow collected in the study area reveals that the relative high pH has similar spectral power in both annual and subannual periods may be expected from an agricultural site where exposed terrain has been subjected to fertilizer usage (Mayewski and others, 1983). Ammonium loading from eroded soil material is a notable component of the atmosphere in north-west India (Bryson and Swain, 1981). Since summer reactive phosphate concentrations, determined from the fresh snow study (Mayewski and others, 1983) are similar to the maximum values displayed in the reactive phosphate time-series the annual power peak probably represents summer input. While transport of wind-blown material may be a likely source for summer inputs of reactive phosphate, subannual inputs may also be derived from this source as well as biogenic emissions and fuel-burning (Davidson and others, 1981). pH has similar spectral power in both annual and subannual period which is probably indicative of the fact that it is a composite measure (i.e., nitric and sulfuric) and weak acids (i.e., carbonic) from multiple sources. While pH measurements...
on fresh summer snow from Nun Kun in conjunction with other measurements have been used to help differentiate air masses (Neywski and others, 1983) their use as a climate reconstruction tool in areas such as the Himalaya is suspect not only because of potential multiple sources but also because of a number of workers (Schlosser and others, 1981; Bernoulli and others, 1978; Stauffer and Berner, 1978; Oeschger and others, 1982) have shown that even polar ice and snow are easily "contaminated" with CO$_2$.

The fifteen size grades of microparticles measured as part of this study display a regular decrease in concentration per size grade as expected from Junge (1963, p. 111-201). This relationship indicates that sorting in transport and source area exert control on the microparticle distributions measured in this study. Microparticle sources are not only varied but they can be additive and include, as summarized by E.M. Thompson (1980), chemical reactions (natural and anthropogenic) and incorporation of volcanic, extraterrestrial, terrestrial, and marine components.

Junge (1963, p. 111-201) divides microparticles up into: Atten (<0.1 µm), large (0.1 to 1.0 µm), and giant (>1.0 µm) sizes. Preservation of this grouping was investigated for the microparticle size grades in this study as a first approximation prior to interpretation of the data. The microparticle size grades used in the <0.50 to 0.80 µm, do not provide sufficient detail to differentiate Junge's (1963) finer grade, Atten size particles, but they are divisible by comparison of their spectral properties into three size-grade groups (Fig. 2a and b): <0.50 to 0.80 µm, 0.80 to 2.00 µm, and 2.00 to 12.70 µm. This division roughly spans Junge’s (1963) large and giant range with an intermediate “gray” group at 0.80 to 2.00 µm. The <0.50 to 0.80 µm microparticle size group displays power in both annual and subannual periods (Fig. 2a) while the 0.80 to 2.00 µm group has a spectral signature in which power in the subannual period dominates over power in the annual period (Fig. 2a). The 2.00 to 12.70 µm group displays power in the subannual period but none in the annual period (Fig. 2c).

As noted by Lamb (1970) and Shaw (1979), microparticles <1.00 µm are believed to have long residence times in the stratosphere and/or high troposphere. Residence time, transport distance, and potential multiple sources for these microparticles prevent the isolation of unique source and/or source areas. Although no elemental analysis of the microparticles in our study was undertaken, such studies at South Pole (E.M. Thompson, 1980) reveal that a high concentration of these microparticles contain iron and silica. This is substantiated in our study by the similarity in spectral signatures of the timeseries for reactive silicate and the <0.50 to 0.80 µm size grade microparticles.

The 0.20 to 12.70 µm microparticle size group is probably derived from a more local source than the 0.50 to 0.80 µm group based purely on size. The site-specific local derivation of the 2.00 to 12.70 µm microparticles is further substantiated by their high concentration in the Nun Kun area relative to concentrations of microparticles in other high-altitude alpine areas such as Mt. Kenya (L.S. Thompson, 1981) and Quelccaya, Peru (Thompson and others, 1979).

Values of δ were measured regularly every 0.16 m down core whereas δ$^18$O was only measured at selected depths. To test δ$^18$O to δ$^18$O relationships down-core values and summer snowfall samples collected in the elevation range 5130 to 5652 m (Meyewski and others, 1983) were examined. Best-fit linear regressions for δ$^18$O and δ$^18$O down-hole and surface-air samples revealed a correlation coefficient of 0.91 and 0.82 and δ$^18$O and δ$^18$O + 13.4, respectively. By comparison the best fit for northern hemisphere continental stations is δ$^18$O = 8.4δ$^18$O + 10 (Dansgaard, 1964) and for suites of samples relatively close to Nun Kun in the central Indian Himalaya, δ$^18$O = 6δ$^18$O + 12 and δ$^18$O = 8.6δ$^18$O + 10, respectively (Niewodniczanski and others, 1981). Although it should be noted that the surface and down-hole samples in our study come from different elevations, comparison of these with fits from Dansgaard (1964) and Niewodniczanski and others (1981) suggest that our down-hole samples may have experienced some degree of post-depositional alteration perhaps due to slight diffusion and/or melting. Although post-depositional alteration may have had some effect on the distribution down core of δ$^18$O values it has not affected the distinction of the biological species and the microparticles. Glaciochemical analysis of a core collected from a low elevation Norwegian glacier (Davies and others, 1982) reveals that ions migrate down core by order of solubility. The coincidence of the core of reactive iron, reactive silicate, and microparticles all of low solubility, with higher solubility chloride, reactive phosphate, and ammonium suggests that post-depositional alteration by melting and/or diffusion if present is minimal at the core site.

Spectral power for the δ$^18$O values is apparent for the subannual period but not annually even though monsoonal circulation in the area results in major shifts in the temperature of the air masses entering this site. The study of the fresh surface snow reveals why a major annual δ$^18$O power peak may not exist since it can be used to demonstrate that during any single event two adjacent air masses may have quite different temperatures and thus individual storm events may be as effective as seasonal air mass shifts in creating δ$^18$O distributions.

Synchroneity of selected time-series data

Time-dependent relationships between two timeseries sets can be expressed using cross-spectral analysis in terms of phase lags and the strength of their dependence at various frequencies (Edwards and Thornes, 1973). Coherence between base and cross sets as close to unity as possible are sought although knowledge of the zero lag power is necessary to determine coherence values (Koopmans, 1974) provides information concerning the reliability of coherence values less than unity. Phase shift (lead or lag) of selected timeseries sets that are useful as annual and/or subannual indicators in this study, and that display power at statistically similar periods are examined (Table II). Since air mass circulation in the Himalayas is complicated, it cannot be assumed that all timeseries sets with finite phase lags or spectral power necessarily enter the core site simultaneously. However, several examples of time-series sets which do enter simultaneously are dealt with below.

Phase shits for examples of the spectrally defined groups equivalent to Junge's (1963) large and giant microparticles are also presented (Table II). Based on their cross-spectral relationships the large and giant particles enter the core site in phase annually.

SUMMARY AND DISCUSSION

Analysis of selected chemical properties (chloride, sodium, reactive iron, reactive silicate, reactive phosphate, δ$^18$O, δ$^18$O, total β-activity, δ$^18$O and δ$^18$O) and physical properties (density, debris band and ice lens locations, and microparticles in size grades from 0.50 to 12.70 µm) reveal detailed concerning the net mass balance, timing of precipitation events and source of precipitation for a core collected at 4908 m on Senitk Glacier. The core is believed to have experienced minimal post-depositional alter-
Mayewski and others: Chemical and physical time-series from Sentik Glacier

TABLE II. CROSS-SPECTRAL RELATIONSHIPS FOR SELECTED TIME-SERIES SETS

<table>
<thead>
<tr>
<th>Base set</th>
<th>Cross set</th>
<th>Period</th>
<th>Amplitude of power peak</th>
<th>Coherence</th>
<th>Zero significance level for coherence</th>
<th>Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chloride</td>
<td>Sodium</td>
<td>0.81 m</td>
<td>5.03</td>
<td>0.85</td>
<td>0.66</td>
<td>0.05 (&lt;0.01)</td>
</tr>
<tr>
<td>Chloride</td>
<td>Sodium</td>
<td>1.28 m</td>
<td>5.92</td>
<td>0.86</td>
<td>0.66</td>
<td>-</td>
</tr>
<tr>
<td>Chloride</td>
<td>Reactive Phosphate</td>
<td>0.81 m</td>
<td>1.73</td>
<td>0.70</td>
<td>0.44</td>
<td>0.91 (&lt;0.74)</td>
</tr>
<tr>
<td>Chloride</td>
<td>Reactive Phosphate</td>
<td>1.08 m</td>
<td>1.70</td>
<td>0.70</td>
<td>0.44</td>
<td>0.91 (&lt;0.99)</td>
</tr>
<tr>
<td>0.50 to 0.63 µm</td>
<td>0.50 to 0.80 µm</td>
<td>0.63 to 0.67 µm</td>
<td>0.45</td>
<td>40 x 10^6</td>
<td>0.87</td>
<td>0.66</td>
</tr>
<tr>
<td>Micro-particles</td>
<td>Micro-particles</td>
<td>0.45</td>
<td>23.90</td>
<td></td>
<td>0.98</td>
<td>0.66</td>
</tr>
</tbody>
</table>

1. 0.81 and 1.08 m are used to span the annual period.
2. Chemical species in (µm)^2/µm^2; Micro-particles in (µm)^2/µm^3.
3. From Koopmans (1974) at 90% confidence level.
4. In fractions of a circle.

ation and thus to be a true mirror of the combined wet and dry deposition reaching this site.

Based on a total g-activity core chronology the 16.8 m core represents an ~ 17 ± 0.3 year record. The average net mass balance computed from this chronology is 0.92 m a^-1 which using an average core density of 270 kg m^-3 is 0.62 m a^-1 water equivalent. The latter value is somewhat less than the precipitation rate of 0.90 m a^-1 water equivalent estimated for the valley bottom adjacent to the core site (Qazi, 1973) suggesting a decrease in precipitation with elevation in this area.

Spectral analysis of chemical and physical time-series sets developed from the core reveal recognizable periodic events at ~0.32 m (noise), <3.22 to >0.32 m, and ~0.50 to 0.80 µm. The periodicity <3.22 to >0.32 µm includes annual and subannual events. The existence of spectrally defined periodic events is of particular significance in this study since they help to prove that selected high-altitude temperate glaciers in the Himalaya can provide stratigraphic records for use in the delineation of former climate. Discussion of these periodic events and the source and atmospheric circulation implications of the chemical and physical time-series are summarized below.

Chloride concentrations are highest in the summer and are derived at this time from either a distinct limited source or over a long distance annually. pH distribution with time may be a composite monitor of strong and weak acid contributions to the site and interpretation of its distribution down core may be too complicated to allow development of a useful record. Micro-particles have multiple sources and are spectrally divisible into two major groups with a "gray" intermediate group. The smallest, 0.50 to 0.80 µm, have a strong annual input and a weaker subannual input, are believed to be long-travelled and derived from a relatively high-altitude air mass and composed of at least silicate. Micro-particle size grades 2.00 to 12.70 µm are probably of more local derivation than the <0.50 to 0.80 µm group. 60 displays a weak subannual periodicity either due to dampening by melting and/or diffusion or because temperature differences season to season are no greater than those found during subseasonal events.

Multianual periodicity is displayed by all time-series. Events with periodicity >0.5 years require far more investigation because of their potential value to monsoon studies. This information could be gained by deeper drilling.

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India and their cooperation and help in this program is very much appreciated.

REFERENCES


APPENDIX A. DOWN-HOLE DATA SETS

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Data set (units)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BETA</td>
<td>Total β-activity (dph kg⁻¹)</td>
</tr>
<tr>
<td>DEBRIS AND ICE BANDS</td>
<td>Debris bands (2 = diffuse; 4 = semi-concentrated) and ice bands (= 1)</td>
</tr>
<tr>
<td>DENSITY</td>
<td>Density (x 10³ kg m⁻³)</td>
</tr>
<tr>
<td>CL</td>
<td>Chloride (µM); note scale change</td>
</tr>
<tr>
<td>NA</td>
<td>Sodium (µM); note scale change</td>
</tr>
<tr>
<td>FE</td>
<td>Reactive iron (µM); note two scales</td>
</tr>
<tr>
<td>SI02</td>
<td>Reactive silicate (µM); note two scales</td>
</tr>
</tbody>
</table>

Po₄ = Reactive phosphate (µM); note two scales
NH₄ = Ammonium (µM)
DELTA D = δD (‰)
DELTA 0₁₈ = δ¹⁸O (‰)
pH = pH (pH units)
MICRO = 0.63 x 10⁻³ = 0.50-0.63 x 10⁻³ = Microparticles 0.63 µ x 10⁻³ (particles/500 µl of sample)
MICRO = 1.25 x 10⁻² = 1.00-1.25 x 10⁻² = Microparticles 1.25 µ x 10⁻² (particles/500 µl of sample)
MICRO = 10.0 = 8.00-10.00 = Microparticles 10.0 µm (particles/500 µl of sample)