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

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ABSTRACT. Spectral analysis of time series of a c. 17 ± 0.5 year core, calibrated for total β activity recovered from Sentik Glacier (4908 m) Ladakh, Himalaya, yields several recognizable periodicities including sub-annual, annual, and multi-annual. The time-series include both chemical data (chloride, sodium, reactive iron, reactive silicate, reactive phosphate, ammonium, δ13C, δ18O and pH) and physical data (density, debris and ice-bound locations, and microparticles in size grades 0.05 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 palaeomeeteorological data sets from remote high-alpine glacierized sites such as the Himalaya.

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 (Wissmann, 1960) they are perhaps the least understood and least intensely 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 other (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).

GEOPGRAPHY AND METEOROLOGY OF NUN KUN

Nun Kun (long. 75°71' to 76°08'E.; lat. 35°57' to 36°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 monsoon system. During the winter months air flow in the general region of the study area is approximately north-west

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1. Location of core site from a portion of NASA LandSat Image E-50831-94491-0 displaying the Nun Kun massif in the lower center of the photograph. Peaks in massif center attain elevations as high as 7165 m (Nun) and 7077 m (Kun). Glacier with banded moraine flows directly north off the massif. Moraine bands as seen on the photograph are approximately 8 km in length. The Suru River meanders past the snout of this glacier. S marks the core site (4908 m) on Sentaik Glacier.

Fig. 1. Location of core site from a portion of NASA Landsat Image E-50831-94491-0 displaying the Nun Kun massif in the lower center of the photograph. Peaks in massif center attain elevations as high as 7165 m (Nun) and 7077 m (Kun). Glacier with banded moraine flows directly north off the massif. Moraine bands as seen on the photograph are approximately 8 km in length. The Suru River meanders past the snout of this glacier. S marks the core site (4908 m) on Sentaik Glacier.

Interpretation of down-hole glaciochemistry recovered from the Sentaik 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 9 m the core attains and maintains a temperature of -3.0°C to a depth of at least 16.6 m. 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, $\delta D$, $\delta^{18}O$), 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. Pre-cleaning of bags, scrapers, 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 $\delta D$ and $\delta^{18}O$ by 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>$\delta D$</td>
<td>-97.90 $\delta$/oo</td>
<td>114</td>
</tr>
<tr>
<td>$\delta^{18}O$</td>
<td>-15.07 $\delta$/oo</td>
<td>19</td>
</tr>
<tr>
<td>pH</td>
<td>4.12-5.85 pH units*</td>
<td>114</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)

<table>
<thead>
<tr>
<th>Size grade</th>
<th>Count rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.50-0.63 $\mu$m</td>
<td>34 x 10$^2$</td>
</tr>
<tr>
<td>1.00-1.25 $\mu$m</td>
<td>20 x 10$^2$</td>
</tr>
<tr>
<td>8.00-10.00 $\mu$m</td>
<td>3 $\mu$m particles</td>
</tr>
</tbody>
</table>

* 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, 60, 6(180), pH, and total α-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 α-activity measurements although integrated over more than one sample are available for the entire length of the core. The resultant total α-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 α-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.

Periodicity events

With the exception of total α-activity, 6(180), 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-
2b. - includes time-series sets displaying annual and subannual power peaks at 20 lags (n = 228).

2c. - includes time-series sets at 10 lags displaying just subannual power.

Fig. 8. Power (unit²/yr m⁻¹), period (m) and frequency (cy m⁻¹) for time-series sets. Units equal to µM for chemical species, °/oo for δD, pH units for pH, kg m⁻³ for density and particles/600 µl of sample for specified µm microparticle size grades. Vertical bar represents 50% 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 be classified as a peak. Note that confidence interval is valid only at frequency (period) specified. Confidence interval for period = ± 0.16 m using a 20 sampling interval.

General runs. These peaks occur at periodicities of: ≥3.22 m, <1.22 to >0.32 m and ≤0.32 m. Using the chronology provided by the total β-activity measurements and the resultant average net mass balance, 0.92 m a⁻¹, a depth to time conversion yields power peaks at ≥3.5 a, <3.5 to <0.35 a, and ≤0.35 a. Power peaks with periodicity ≥3.5 a (≥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 ≥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 ≥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 a⁻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 total record in this study, need to be examined on an individual basis. The most apparent non-periodic anomaly in concentration is a technique yields a smoothed display of the data. Non-periodic elements in a time-series assemblage this density, debris bands, and the time-series for chlor-Note 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 absence of a major density transition at this depth suggests that denitification and/or ablation may exert some control on the concentration distribution of concentrations down core. Alternatively, relatively high concentrations of chemical species may simply deposit 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-synchroneity of the spectral signature (Fig. 2c) of this time-series assemblage 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.

Notably although 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 unstable 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.

Sources

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 appropriate, for the chemical and physical constituents analyzed are discussed in the following order: chloride, sodium, reactive iron, reactive silicate, reactive phosphate, and reactive amionic particles. 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 Gulmarag (Sen Gupta and Kelkar, 1970), suggest progressive depletion of chloride as air travels off the Arabian Sea to the core site (Mayewski and others, 1993). 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 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 inflow 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. The Na peak may be derived 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 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, in general, from a relatively low-elevation mass direct-ed off either 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 seasonal 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 mean reactive phosphate value of samples having no visible debris bands is lower than that of rain from remote northern hemispheric areas <0.06 μm (Graham and Duee, 1979) and (2) similarities in distribution of reactive phosphate and reactive iron concentrations in fresh summer snow collected at several elevations on Nun Kun (Mayewski and others, 1983). The foregoing are suggestive of phosphate influx due to deposition onto wind-blown materials such as iron oxide coatings as might be expected from an agricultural site where exposed terrain has been subjected to fertilizer usage (Mayewski and others, 1983). Aerosol loading from eroded soil material is a notable component in the aerosols 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 mean seasonal values 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 periods as might be expected considering potential multiple sources and multiple timing of inputs. No unique sources can be determined for this species and the high core values may not be useful as a stratigraphic marker. However, analysis of ammonium from freshly fallen summer snow collected in the study area reveals that the relatively high values, >0.5 μm, are found at elevations below 5300 m (Mayewski and others, 1983). Examination of Nepalese aerosols by Ikegami and others (1980) reveals a similar distribution in ammonium concentrations with ammonium sulfate peaks at elevations <3000 m and sulfate particles at 5000 m. pH has similar spectral power in both annual and subannual periods 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 (Mayewski 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 a number of workers (Schlamminger and Berner, 1978; Stauffer and Berner, 1978; Oeschger and others, 1982) have shown that even polar ice and snow are easily "contaminated" with CO₂.

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 transport in 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: Aitken (<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 this study (<0.50 to 0.80, 0.80 to 2.00, and 2.00 to 12.70 μm), do not provide sufficient detail to differentiate Junge's (1963) finer grades, Aitken 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 the 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).

This distribution has been noted by Lamb (1970) and Shaw (1979), microparticles ≤0.1 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 differentiation of source types 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 proportion of these microparticles consist of iron and silicate. This is substantiated in our study by the similarity in spectral signatures of the time-series for reactive silicate and the <0.50 to 0.80 μm size group microparticles.

The 2.00 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 core 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 δ0 were measured regularly every 0.16 m down core whereas δ18O was only measured at selected depths. To test δ0 to δ18O relationships down-core values and summer snowfall samples collected in the elevation range 5130 to 5512 m (Meyewski and others, 1983) were examined. Best-fit linear regressions for δ0 and δ18O down-hole and surface snowfall collections were 0.69 = 1.2 (0.18) + 0.3 (1.1) and 8.85 (13.2), respectively. By comparison the best fit for northern hemisphere continental stations is 0.69 = 8.60 (10) + 10 (Dansgaard, 1964) and for suites of samples relative close to Nun Kun in the central Hindukush and Karakoramdd 0.69 = 12 (18) + 10 and 8.80 (10) + 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 δ0 values it has not affected the distribution of chemical 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 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 δ0 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 δ0 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 δ0 distributions.

**Synchonocity of selected time-series data**

Time-dependent relationships between two time-series sets can be expressed using cross-spectral analysis in terms of phase shift and the strength of their dependence at various frequencies (Edwards and Thorndes, 1973). Coherence between base and cross sets as close to unity as possible are sought although phase shift for the chemical-species time series chloride, sodium, and reactive phosphate (Table II) suggest that all three species enter the core site in-phase annually. Since the annual pulse of high chloride concentration enters the core site in summer, the cross-spectral analysis demonstrates that the annual power peaks of sodium and reactive phosphate correspond to summer events.

Phase shift 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, δ0, δ18O, total β-activity, pH) and physical properties (density, debris band and ice lens locations, and microparticles in 15 size grades from 0.50 to 12.70 μm) reveals details concerning the net mass balance, timing of precipitation events and source of precipitation for a core collected at 4908 m on Sentik Glacier. The core is believed to have experienced minimal post-depositional alter-
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$^1$ m</th>
<th>Amplitude of power peak$^2$</th>
<th>Coherence</th>
<th>Zero significance level for coherence$^3$</th>
<th>Phase$^4$ m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chloride</td>
<td>Sodium</td>
<td>0.81 ± 0.32</td>
<td>0.85 ± 0.05</td>
<td>0.66 ± 0.05</td>
<td>0.05 (0.01)</td>
<td>1.09 (1.09)</td>
</tr>
<tr>
<td>Chloride</td>
<td>Reactive Phosphate</td>
<td>0.81 ± 0.32</td>
<td>0.70 ± 0.04</td>
<td>0.44 ± 0.04</td>
<td>0.91 (0.74)</td>
<td></td>
</tr>
<tr>
<td>Chloride</td>
<td>Reactive Phosphate</td>
<td>1.08 ± 0.32</td>
<td>0.70 ± 0.04</td>
<td>0.44 ± 0.04</td>
<td>0.91 (0.99)</td>
<td></td>
</tr>
<tr>
<td>0.50 to 0.63 μm</td>
<td>0.80 μm</td>
<td>0.63 ± 0.32</td>
<td>0.45 ± 0.04</td>
<td>0.99 ± 0.04</td>
<td>0.09 (0.45)</td>
<td></td>
</tr>
<tr>
<td>Microparticles</td>
<td>Microparticles</td>
<td>0.45 ± 0.32</td>
<td>10 x 10$^6$</td>
<td>0.66 ± 0.04</td>
<td>1.00 (0.45)</td>
<td></td>
</tr>
</tbody>
</table>

$^1$ Chloride concentrations are highest in the summer and are derived at this time from a marine source, the Arabian Sea. Subannual chloride inputs probably come from distant marine sources. Sodium covaries with chloride since much of it is marine-derived. However, some sodium is probably brought into the core site from crustal weathering during both the summer and winter monsoon events. Reactive phosphate is probably carried to the core site during the summer adsorbed onto wind-blown materials derived from exposed agricultural sites. Subannual inputs of this species may come from combined biologic and anthropogenic sources. Ammonium has multiple sources which are not differentiable in this study. Reactive iron and reactive silicate are both derived from crustal weathering and are deposited at the core site during at least the summer and winter monsoons and silicate comes to the core site 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.

Microparticles have multiple sources and are spectrally divisible into two major groups with a "gray" intermediate group. The smaller Laskhakaricles at 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. Microparticle size grades 2.00 to 12.70 μm are probably of more local derivation than the 0.50 to 0.80 μm group. SD displays a weak subannual periodicity either due to damping 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-serial events. Events with periodicity >3.5 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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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 $\beta$-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 ($x 10^3$ kg m$^{-3}$)</td>
</tr>
<tr>
<td>CL</td>
<td>Chloride ($\mu$M); note scale change</td>
</tr>
<tr>
<td>NA</td>
<td>Sodium ($\mu$M); note scale change</td>
</tr>
<tr>
<td>FE</td>
<td>Reactive iron ($\mu$M); note two scales</td>
</tr>
<tr>
<td>SIO2</td>
<td>Reactive silicate ($\mu$M); note two scales</td>
</tr>
</tbody>
</table>

Po4 = Reactive phosphate ($\mu$M); note two scales
NH4 = Ammonium ($\mu$M)
DELTAD = $\delta D$ ($^\circ/oo$)
DELTAM = $\delta(^18)O$ ($^\circ/oo$)

pH = pH (pH units)

MICRO = $0.63 \times 10^3$

MICRO = $1.25 \times 10^2$

MICRO = $10.0$

"0.50-0.63 $x 10^3$ Micro particles 0.63 $\mu$m x $10^3$ (particles/500 µl of sample)"

"1.00-1.25 $x 10^2$ Micro particles 1.25 $\mu$m x $10^2$ (particles/500 µl of sample)"

"8.00-10.00 = Micro particles 10.0 $\mu$m (particles/500 µl of sample)"