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Observations of Impulsive Nitrate Enhancements Associated With Ground-Level Cosmic Ray Events 1-4 (1942-1949)

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Abstract: A direct comparison of impulsive nitrate enhancements observed in multiple polar ice cores from both hemispheres is presented for the years 1940-1950. During that time period, four ground-level solar cosmic ray events (GLEs) were recorded by ionization chambers. We show that large and sudden enhancements in the nitrate records from both hemispheres were observed within weeks of the dates of the GLEs. The observation of impulsive nitrate enhancements simultaneously in both hemispheres shortly after a large solar proton event is strong evidence in support of a causal connection and argues strongly for rapid gravitational sedimentation of atmospheric nitrates.

Introduction

We present a comparison of the impulsive nitrate deposition events found in high resolution measurements from polar ice cores obtained from the northern polar cap (Summit, Greenland) and the southern polar cap (Windless Bight, Antarctica) with known large solar proton events (SPEs), specifically the first four GLEs and strong polar cap absorption events.

Data Sources

The most comprehensive analysis to date examining the relationship between impulsive nitrate events NO_y[1] in Greenland and solar cosmic ray events relied on data from the GISP2-H core obtained from Summit, Greenland in the summer of 1992 [1-2]. McCracken et al. [2] also included data from previously drilled and analyzed ice cores from Windless Bight, Antarctica, in their initial nitrate deposition–solar proton event calibration, but did not associate individual events across both datasets. The nitrate analysis of the GISP2-H core was performed by hand and yielded a resolution of approximately 20 samples per year. For this analysis we utilize additional data from a 30-m core obtained from Summit, Greenland in the summer of 2004. This core has been analyzed for conductivity and nitrate concentration using a continuous flow analysis system[2]. This continuous flow analysis method provides a higher resolution of the nitrate record than the 1.5 cm core samples used in previous SPE/NO_y studies [1-3].

Ice cores collected from Summit, Greenland are particularly well-suited for high-resolution nitrate analysis since Summit has a persistent moderate precipitation accumulation rate. We focus on the period 1938-1950 to avoid the inherent increase in noise of the upper layers of the core arising from unconsolidated firn. This interval has the first four known ground-level enhancements

[1] NO_y is a generic term for the various nitrate compounds generated in the atmosphere as a result of the ionization, dissociations, dissociative ionizations and excitations caused by the solar proton interactions with the air molecules.

[2] In the last few years a technique known as continuous flow analysis has been developed that allows for the continuous analysis of a core segment providing a higher resolution profile than previously available [4]. In its simplest form a melter, consisting of an inner and an outer ring, is heated to just above freezing. The core is placed vertically on the melter, and the meltwater from the inner ring is continuously analyzed in a closed environment while the possibly contaminated melt from the outer ring is discarded.

(GLEs). Since space-based proton measurements are not available for this interval, we use the solar flare observations, the solar cosmic ray GLE events and strong polar cap blackout events as proxies for large solar proton events and show that there is a strong correlation of impulsive nitrate spikes in both hemispheres with the solar proton events.

Results

An overall analysis of the new 30-meter Summit 2004 core with a continuous flow system in the interval 1938-1950 is presented in the top section of Figure 1. We have dated the samples using the standard snow depth – time profile derived from the previous GISP ice core records. An additional unambiguous time marker is the eruption of the Hekla, Iceland volcano in 1947, easily identified as a large enhancement of conductivity near the depth of 25.9 m. We also identified the annual cycles in nitrate amplitude that are observed, and with the Hekla time marker have confidence in the dating during the time period 1940-1950. We further subdivided each year into months using an interpolation based upon the average monthly precipitation observed in central Greenland [5]. At this central Greenland location more precipitation falls during summer; the amount of core assigned to summer months is larger by nearly a factor of 2 compared to winter months. It is our opinion that this method of using the average annual accumulation to divide the annual cycle into months is more appropriate than the inter-year straight linear interpolation method employed in previous work [2].

Impulsive Nitrate Deposition Events Associated With GLEs

The first four GLEs were identified by Forbush [6-7] who made the first association between solar flare activity and GLEs. The early GLEs were observed by cosmic ray ionization chambers whose primary response was to the secondary muons generated by the interaction of the incident high-energy particles (>4 GeV protons) with the atmosphere. Examination of the nitrate data in Figure 1 shows that the first four GLEs identified by Forbush are associated with impulsive nitrate enhancements in both the Summit, Greenland and Windless Bight, Antarctica ice cores. The delay between the date of the observed ground-level event and impulsive nitrate enhancement in the higher resolution Summit, Greenland data appears to be ~1 month. In the case of the first two GLEs, the occurrence sequence of two GLE events within a one week interval means that the accumulated NO_y from both events will be within the atmospheric integration time and will appear as one consolidated increase in the nitrate record.

We find evidence for the third GLE at an ice core depth of 26.2-26.5 meters in the 2004 ice core; this is the largest nitrate enhancement in this entire 30-meter core. The Windless Bight nitrate record also shows a similar very large enhancement. These impulsive nitrate enhancements were closely associated in time with the 25 July 1946 GLE followed by a 10-day polar cap blackout. A careful examination of the 2004 Summit ice core record shows an apparent delay of ~3 months, compared with other events in this paper. The Windless Bight data show an approximate one-month delay. We believe this discrepancy is a result of an error in assigning the break between the year 1945 and 1946 in the 2004 Summit ice core. This possible misalignment alters the apparent time-depth profile. Despite this timing discrepancy, the close temporal proximity of the largest nitrate enhancements in our polar ice core records with one of the largest GLEs on record suggests a causal connection.

The fourth GLE in this interval occurred on 19 November 1949, associated with a 3+ flare. This GLE was followed by a 52-hour polar cap blackout. Again the delay between the observed solar proton event and the impulsive nitrate enhancement is less than one month.

Impulsive Nitrate Depositions Associated With Polar Cap Blackout Events

There are additional impulsive nitrate enhancements beside those associated with the known GLEs. We find good association between these additional impulsive nitrate enhancements and the dates of strong long-duration polar cap blackouts [8]. It is now known that polar cap blackout events are intervals of enhanced D-region ionization caused by a large influx of energetic protons into the polar cap. The D-region ionization becomes so intense that the signals from the vertically incident ionospheric sounding are completely absorbed, and there is no return from the standard ionosphere layers (hence blackout). These intervals of enhanced ionization are now called polar cap absorption (PCA) events. Therefore, the polar cap blackout and the polar cap absorption data are particularly useful as proxies for identifying probable solar proton events. For the events identified by Švestka [8] the primary polar observatory was Tikhaya Bay, Russia.

These smaller amplitude impulsive nitrate enhancements found in the 2004 Summit ice core are summarized in table 1. The Windless Bight data show a similar nitrate profile, although not as finely resolved as in the Summit data. In previous work Shea et al. [9] determined that a >30 MeV proton omnidirectional fluence of 5×10^8 cm^{-2} is necessary to generate an impulsive nitrate event that is detectable above the terrestrial background in the Greenland ice. We note that there is an association with importance 3 or 3+ solar flares, but some events do not generate enough proton fluence to produce a detectable impulsive NO_y event.

Conclusions

During the period of 1940-1950, four solar cosmic ray ground-level events were recorded by cosmic ray ionization chambers. All four GLEs were closely associated with significant impulsive nitrate enhancements in both the Greenland and Antarctic ice core data within about one month after the GLE. Additional impulsive nitrate enhancements in the high-resolution Greenland core are temporally associated with significant large solar flares (importance 3 and 3+) and strong long-duration polar cap blackouts.

Acknowledgments

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Table 1: Impulsive nitrate events, important proton flares, and strong polar cap blackouts between 1939 and 1949 identified by Svestka [8]. Flares that are associated with a clearly identified spike in the Summit nitrate data are shown in boldface. The delays between the flare and the impulsive nitrate enhancement are in months.

			Flare		PCA	NO_y Delay		
Date			Importance	Position	(hrs)	Summit	WB	Notes
1939	**Aug**	**10**	**3**	**13°N 43°W**	**62**	2	4	
1940	Mar	27	3	12°N 17°W	169			
1941	Jul	03	3	12°N 04°E	42	<1		
1942	**Feb**	**28**	**3**	**07°N 05°E**	**	<1	<1	GLE # 1
1942	**Mar**	**07**	**?**	**(07°N 90°W)**	**	<1	<1	GLE # 2
1946	Feb	06	3+	27°N 19°W	36			
1946	**Mar**	**27**	**3**	**20°N 05°E**	**52**	<3		
1946	**Jul**	**25**	**3+**	**21°N 16°E**	**211**	<2.5	1	GLE #3
1948	**May**	**21**	**3+**	**11°S 69°W**	**42**	1		
1949	Jan	23	3	23°N 01°E	34-		<1	
1949	May	10	3+	19°S 08°E	64			
1949	**Aug**	**05**	**3+**	**21°S 55°W**	**82**	1	<2	
1949	**Nov**	**19**	**3+**	**03°S 72°W**	**58**	1	<2	GLE #4

** World War II gap in Tikhaya Bay, Russia data.

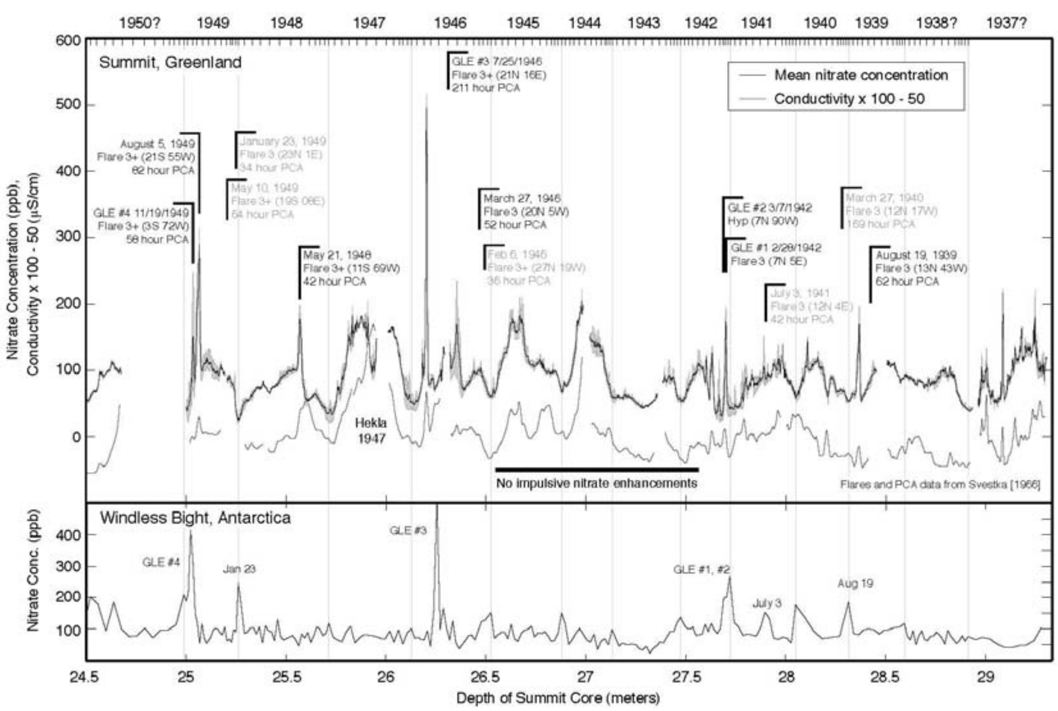

Figure 1: Top: High resolution nitrate deposition data from the 2004 Summit, Greenland core with annotated solar events. Bottom: Lower resolution nitrate deposition data from Windless Bight, Antarctica ice cores acquired in 1988 and 1989.