Fine aeolian quartz flux in Cheju Island, Korea, during the last 6500 years and pathway change of the westerlies over East Asia

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Jaesoo Lim (Corresponding author)
Department of Earth and Environmental Sciences,
Graduate School of Environmental Studies, Nagoya University,
Nagoya 464-8601, Japan
E-mail: s020121d@mbox.nagoya-u.ac.jp
Tel.: +81-52-789-3471
Fax: +81-52-789-3436

Eiji Matsumoto
Department of Earth and Environmental Sciences,
Graduate School of Environmental Studies, Nagoya University,
Nagoya 464-8601, Japan

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Eiji Matsumoto
Department of Earth and Environmental Sciences,
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Abstract

We analyzed the fine aeolian quartz flux record of the last 6500 years obtained from a maar on Cheju Island, South Korea, to investigate variability of fine aeolian quartz and its main controlling factor. Results indicate that the time series of fine quartz flux (FQF) is sensitive to the position of the westerlies, which provide high-altitude and long-distance transport, and reveal centennial- to millennial-scale variability with periodicities of 1620, 810, 400, 325, and 210 years. Based on visual and spectral analyses, the high/low FQF corresponds to the warm/cold atmospheric temperature record from Greenland ice cores with significant coherent cycles at 325 and 200 years. This study suggests that the FQF variability on centennial timescales has been affected by pathway changes of the westerlies over East Asia. During the mid- to late Holocene, the pathway of the westerlies was probably controlled by a climatic response to initial solar activity and resulting atmospheric reorganization in polar and high-latitude regions.

1. Introduction

The atmosphere plays a major role in transporting heat and moisture around the world and is equal to the oceans in influencing and characterizing global climate changes. Numerous studies have provided vast information about the evolution of past atmospheric circulation and the link between atmospheric circulation and climatic systems. The most direct proxy indicator of past atmospheric circulation is aeolian mineral dust raised from the inner part of continents by dust storms and transported to downwind areas [*Pye and Zhou*, 1989; *Hovan et al., 1991*; *An et al.*, 1991; *O'Brien et al.*, 1995; *Porter and An*, 1995; *Xiao et al.*, 1995, 1997; *Sun*, 2004].

Recent grain-size analyses of aeolian sediments in northern and central China [*Sun et al.*, 2002; *Sun*, 2004] and downwind areas [*Lim and Matsumoto*, 2006] have indicated that aeolian sediments consist of a coarse component and an overlapping fine component with bimodal grain-size distribution. Different grain-size components have been attributed to two different types of transport–deposition processes in aeolian dust accumulation. Low-altitude winds of the East Asian winter monsoon are thought to have transported most of the coarse component, while high-altitude westerlies likely transported most of the fine component. These results are consistent with other studies showing that low-altitude (<5 km) winds of the winter monsoon are mainly responsible for aeolian dust transport to proximal areas including Central China and downwind areas including Korea and Japan, while high-altitude (>5 km) westerlies carry aeolian dust to remote regions such as the North Pacific and Greenland [*Sun et al.*, 2001; *Sun*, 2002]. Thus, downwind areas adjacent to dust sources under these two wind systems generally receive both coarse and fine aeolian dust particles, while areas far from dust sources such as the Northern Pacific and Greenland only receive fine particles. This suggests that past atmospheric circulation change or pathway change in the westerlies over East Asia, which are in need of clarification due to a lack of proper proxies, can be traced by studying the fine component of aeolian dust deposited in downwind areas.

In this study, we investigated the fine component of aeolian dust deposited on Cheju Island, Korea, a downwind area of the East Asia source area, to better understand atmospheric circulation over East Asia and its link to climate change during the last 6500 years. As a proxy for this study, we used the fine component of chemically isolated aeolian quartz from bulk sediments. The fine quartz flux (FQF) variation on centennial to millennial timescales is attributable to the pathway change of the westerlies over East Asia, based on comparison of the FQF record with the oxygen isotope record of Greenland ice cores and the viewpoint of global atmospheric–climatic teleconnections.

2. Sampling Site and Data

In a previous study, we reconstructed the past 6500-year flux variation of chemically isolated quartz in Tongsu maar (located at 692 m elevation on Cheju Island, Korea: 33°21'15.6"N, 126°37'32.4"E), which was transported by winds from the inner part of China [*Lim et al.*, 2005]. Further analysis of the grain size [*Lim and Matsumoto*, 2006] showed two components that could be partitioned into the fine component and coarse component using the Weibull function fitting method. The coarse component indicated a modal-size range of 10 to 20 μm and flux variation between 0.5 and 5.5 mg/cm^2/yr. The fine component showed a modal-size of 2 to 6 μm and 0.1 to 1.4 mg/cm^2/yr of flux. Changes in the coarse quartz flux transported by northwesterly winds of the winter monsoon are very similar to those in the overall quartz flux. In previous reports, the variations in the coarse/overall quartz flux have been discussed in detail and attributed to aridity changes in the dust-source areas of inner China [*Lim et al.*, 2005; *Lim and Matsumoto*, 2006]. Thus, we will focus our discussion here on the FQF and its relationship with the westerlies.

3. Results and Discussion

3.1. Past pathway changes in the westerlies over East Asia

Regarding pathway changes in the westerlies on a millennial timescale, a few studies using proxies for the summer and winter monsoons tentatively suggested that the pathway changes in the westerlies were atmospheric responses to glacial boundary conditions (e.g., ice volume, sea surface temperature, albedo, and atmospheric trace-gas concentrations) correlated with climate changes in higher latitude regions including subpolar Greenland during the glacial–interglacial cycles [*Fang et al.*, 1999; *Ijiri et al.*, 2005]. Periods of intensified summer/winter monsoons in East Asia during the last glaciation corresponded to warm/cold periods in Greenland known as Dansgaard/Oeschger (D/O) cycles; these cycles are characterized by climatic warming periods (D/O interstadials) and cooling periods (D/O stadials) represented by higher/lower $\delta^{18}O$ values in Greenland ice cores [*Dansgaard et al.*, 1993]. Such climatic teleconnections have been attributed to the northward/southward shifts of the westerlies [*Fang et al.*, 1999; *Ijiri et al.*, 2005]. These D/O cycles have been closely correlated with the North Atlantic sea surface temperature and North Atlantic Deep Water (NADW) formations [*Bond et al.*, 1997; *Grootes and Stuiver*, 1997]. According to *Rohling et al.* (2003), the atmospheric response to the D/O oscillations in the Northern Hemisphere consisted of two modes. A polar/westerly mode dominated winter-type conditions during the D/O stadials, which showed intensification and expansion of the polar vortex in higher latitudes with enhanced winter monsoon intensities, and a tropical/monsoon mode dominated summer-type conditions during the D/O interstadials, which showed weakening and contraction of the polar vortex and enhanced summer monsoon intensities. These studies [*Grootes and Stuiver*, 1997; *Fang et al.*, 1999; *Rohling et al.*, 2003; *Ijiri et al.*, 2005] have suggested that millennial-scale southward/northward shift in the westerlies might have been correlated with D/O cycles, NADW formations, and the polar vortex conditions in higher latitudes.

Unlike glacial times, the Holocene has been considered to be stable with little change in glacial boundary conditions. Therefore, the pathway changes in the westerlies during the Holocene may have been more stable and different from the significant southward/northward shifts on the millennial timescale during glacial times. However, little is known of their decadal to centennial variations.

3.2. The meaning of the strong correlation between the FQF and $\delta^{18}O$ values in Greenland ice cores

If the FQF at Cheju Island has been influenced by the seasonal pathway of the westerlies over East Asia, variation in the FQF would be correlated with atmospheric/climatic conditions in Greenland, based on the teleconnection mentioned above. We have compared the time series of FQF with the $\delta^{18}O$ values in Greenland Ice Sheet Project 2 (GISP2) ice cores [*Stuiver et al.*, 1995; *Grootes and Stuiver*, 1997]. The similarity between the time series of FQF and $\delta^{18}O$ values in Greenland ice cores, both in their general patterns and in the number of peaks, is extremely strong (Figure 3). Even the long-term trends and relative amplitudes correspond. When FQF was lower (higher), colder (warmer) temperature in Greenland prevailed, as shown by lower (higher) $\delta^{18}O$ values in Greenland ice cores.

Furthermore, to assess the high-frequency component of variability, we performed spectral analysis and identified apparent millennial- to centennial-scale cycles in the fine flux record from Cheju Island (1620, 810, 400, 325, and 210 years) and in the $\delta^{18}O$ record from Greenland ice cores (2085, 810, 520, 405, 330, 240, and 200 years) (Figure 4). The coherent cycles in both records are 325 and 200 years. This result confirms the close link between fluctuations of the westerlies over East Asia and atmospheric temperature changes in Greenland during the last 6500 years.

Fine quartz found at Cheju Island may have been mainly transported by the westerlies from dust-source areas in China (e.g., the Taklimakan Desert) and deposited at Cheju Island [*Lim and Matsumoto*, 2006]. The $\delta^{18}O$ values in Greenland ice cores are affected by local Greenland temperatures as well as regional climate changes around the North Atlantic [*White et al.*, 1997]. *Rogers et al.* (1998) attributed the $\delta^{18}O$ values to changes in atmospheric circulation, indicating enhanced northerly (southerly) flow over the ice cap in isotopically cold (warm) winters, which were linked to sea-level pressure and 500-hPa variations around Greenland, the northernmost Atlantic, and parts of Europe. Considered the distance between the Greenland area and East Asia and their different production mechanisms, a connecting media would be needed to explain the same variation in the FQF and the $\delta^{18}O$ values in Greenland ice cores during the last 6500 years. Thus, the similarity in the two datasets can be understood in terms of global atmospheric/climatic teleconnection through the westerlies.

Today, the seasonal shift of the westerlies can be simply described by the annual cycle of the axis location [*Kuang and Zhang*, 2005]. The first period is from January to

March, showing a steady location over the Far East (Figure 1-(a)). The second period is from April to August, when northward migration occurs. The westerlies begin their seasonal shift northward in April, and those westerlies north of the Tibetan Plateau intensify and extend across central China and into Japan from April to June, passing over Cheju Island. As shown in Figure 1-(b), during this time, westerly depressions are most frequent, and the northern flow of the westerlies develops a stronger meridional component [*Pye and Zhou*, 1989]. The last period of the annual shift of the westerlies is from September to December, with the southward withdrawal of the westerlies (Figure 1-(c)). Researchers have suggested that for short cold events, such as at times when cold-air surges in the polar and high latitudes burst (e.g., a decrease of $\delta^{18}O$ values in the Greenland ice core), the Siberian–Mongolian High (East Asian winter monsoon) would have been intensified by the inflow of colder and drier air masses from the polar and high-latitude regions, and the westerlies would have been displaced southward so that they remained fixed on the south side of the Tibetan Plateau [*Fang et al.*, 1999; *Ijiri et al.*, 2005]. Under these circumstances, winter monsoonal winds would have prevailed over the northern part of China during the spring and early summer, as well as in winter, and would have delayed the northward shift in the westerlies. Considering that the main sources of fine aeolian dust are located in the northern part of China (Figure 1), the southward shift in the westerlies in times of stronger winter may have shortened the time they passed over dust source areas and decreased the frequency of aeolian dust lifting to the westerlies above ~5 km altitude for long-distance transport during the spring and summer. This longer stay of the westerlies on the south side of the Tibetan Plateau may have occurred between 2500 and 3100 cal. yr B.P. and between 4200 and 4800 cal. yr B.P. These two intervals are characterized by smaller median size and lower

FQF and seem to be parts of millennial-timescale variability with a periodicity of 1620 years. It is not clear whether these two intervals can be considered to be parts of mini-D/O cycles, which *Bond et al.* [1997, 2001] suggested were significant millennial-scale variability in the Holocene, although the intervals are generally consistent with the suggested mini-D/O stadials at 2800 and 4200 cal. yr B.P. To test this hypothesis, a longer FQF record covering at least the entire Holocene must be reconstructed. Consequently, the fluctuations in FQF transported by the westerlies to Cheju Island can be considered to mainly reflect changes in the latitudinal position of the westerlies, and the seasonal shifting of the westerlies seems to be linked to the climatic and atmospheric conditions in the polar and high latitudes.

In addition to the southward/northward shifts in the westerlies on a millennial timescale, the pathway pattern of the westerlies in East Asia could be an important factor controlling the variation of FQF at Cheju Island. The present pathway pattern of the westerlies can be classified as zonal and meridional atmospheric circulation patterns (ZACP, MACP) according to the feature of the major long-wave pattern and particular distribution of depressions and anticyclones at the surface (Figure 2) [*Barry and Perry*, 1973; *Aizen et al.*, 2001]. ZACP refers to a pattern with zonal movement of small-amplitude waves from the west to the east and the major long wave pattern is formed at high latitudes and gradually moves to the south. With MACP there are large-amplitude stationary waves. This pattern consists of two types of meridional patterns ($M_{1,2}$ACP). During M_1ACP, the sub-polar lows are shallow, there is a well-developed high, and the sub-tropical anticyclone cells are split and displaced northward. M_2ACP is comparable with M_1ACP, but troughs are in different locations. The sub-polar lows are well developed and the Siberian High is weaker and further west than with M_1ACP. These long-wave patterns vary throughout the year, and the major long-wave pattern is determined by which types of atmospheric circulation pattern prevails [*Barry and Perry*, 1973; *Aizen et al.*, 2001]. Given that the Taklimakan Desert is a main dust-source region in East Asia where dust can be entrained over 5000 m and transported by the westerlies [*Sun et al.*, 2001; *Sun*, 2002] and M_2ACP has a significant meridional component passing the Taklimakan Desert and Cheju Island, M_2ACP may be suitable for transporting fine dust from the Taklimakan Desert to Cheju Island among the present zonal and meridional atmospheric circulation patterns. Thus, the FQF might have been affected by the frequency of M_2ACP during the period of southward or northward shift in the westerlies. If we assume that the present hemispheric circulation patterns shown in Figure 2 are valid for the last 6500 years, based on the similarity between the time series of FQF at Cheju Island and $\delta^{18}O$ values in Greenland ice cores, it seems that these two sites were linked by the atmospheric circulation and that FQF at downstream Cheju Island was affected by the frequency of the M_2ACP over the upstream North Atlantic region. The relationship between aeolian dust activity and atmospheric circulation patterns over East Asia and the North Atlantic on decadal to centennial timescales has received little study, and at present it is difficult to specify the pathway changes of the westerlies based on the FQF record.

3.3. The westerlies as a propagator in the climatic system

As discussed above, the pathway change of the westerlies over East Asia may have mainly controlled FQF variation during the last 6500 years. This means that the variability in the FQF on centennial to millennial timescales would be correlated with factors controlling the pathway of the westerlies. The pathway of the westerlies over

East Asia can be controlled by a combination of the climatic–atmospheric conditions in its upstream areas, here the North Atlantic region, and regional climatic–atmospheric features at that time.

The similarity found between the time series of FQF at Cheju Island and $\delta^{18}O$ values of Greenland ice cores from visual and spectral analyses suggest a strong influence of the upstream regions. The present isotope record in Greenland may be affected by the winter North Atlantic oscillation, solar irradiance (as recorded by sunspot numbers), average Greenland coastal temperature, and the annual temperature seesaw between Jakobshaven and Oslo [*White et al.*, 1997; *Rogers et al.*, 1998]. *Stuiver et al.* (1995) mainly attributed the isotope record in Greenland ice cores during the Holocene to solar activity and atmospheric–oceanic circulations in the North Atlantic region. Furthermore, climate changes in the North Atlantic region during the Holocene have mainly been attributed to solar activity and an additional amplifying mechanism, which may be solar-triggered reductions in North Atlantic thermohaline overturning [*Stuiver et al.*, 1997; *Bond et al.*, 2001; *Hu et al.*, 2003; *Jiang et al.*, 2005]. Therefore, it seems that FQF variability is coupled with climate changes in the North Atlantic region. Moreover, this relationship suggests that the westerlies could be one of the main propagators spreading the impacts of the atmospheric and oceanic reorganization as a response to initial solar forcing in the North Atlantic region to downwind areas.

In addition, the coherent ~200-year cycle shown in Figure 4 corresponds with statistical significance to the solar cycle at the 205-year de Vries cycle. Thus, simultaneous responses in East Asia and Greenland to solar activity may occur. Modeling studies on the response of atmospheric dynamics to solar forcing [*Haigh*, 1999; *Shindell et al.*, 2001] have suggested that at times of reduced solar activity, the downward-propagating effects triggered by changes in stratospheric ozone lead to cooling of the high northern latitude atmosphere, a slight southward shift of the northern subtropical jet, and a decrease in the northern Hadley circulation. Those atmospheric responses to reduced irradiance could perhaps cause the coincident intensification of Siberian high and southward shift in the westerlies, decreasing fine aeolian dust to downwind regions, and the atmospheric cooling above Greenland. These initial responses may be amplified and rearranged by regional boundary conditions such as oceanic circulation and the continental snow cover ratio, probably resulting in regional difference as shown in Figure 3. These regional responses would be propagated by the hemispheric-scale atmospheric circulation, which transports heat and moisture, probably feeding back to enhance the climate changes occurring in mid- and high-latitude regions.

4. Conclusion

Our findings suggest that the FQF at Cheju Island, Korea, a downwind area from China during the last 6500 years, has mainly been controlled by the special and temporal features of the westerlies over East Asia. The long-term low FQF is attributable to the westerlies staying longer on the south side of the Tibetan Plateau during times of long-lasting cold, resulting in a shorter duration of passing over dust source areas and a decreased frequency of aeolian dust lifting to the westerlies above ~5 km altitude for long-distance transport in the spring and summer. On decadal to centennial timescales, FQF may have been controlled mainly by pathway changes of the westerlies resulting from a combination of climatic responses to initial solar activity and atmospheric–oceanic reorganization in polar and high-latitude regions.

As a final note, this study demonstrates that aeolian mineral dust raised from the continents by dust storms and transported by the westerlies can be used to elucidate past regional and global atmospheric circulations on decadal to centennial timescales. Further study is needed to specify pathway changes in detail and their links to the climatic system.

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Figure legends

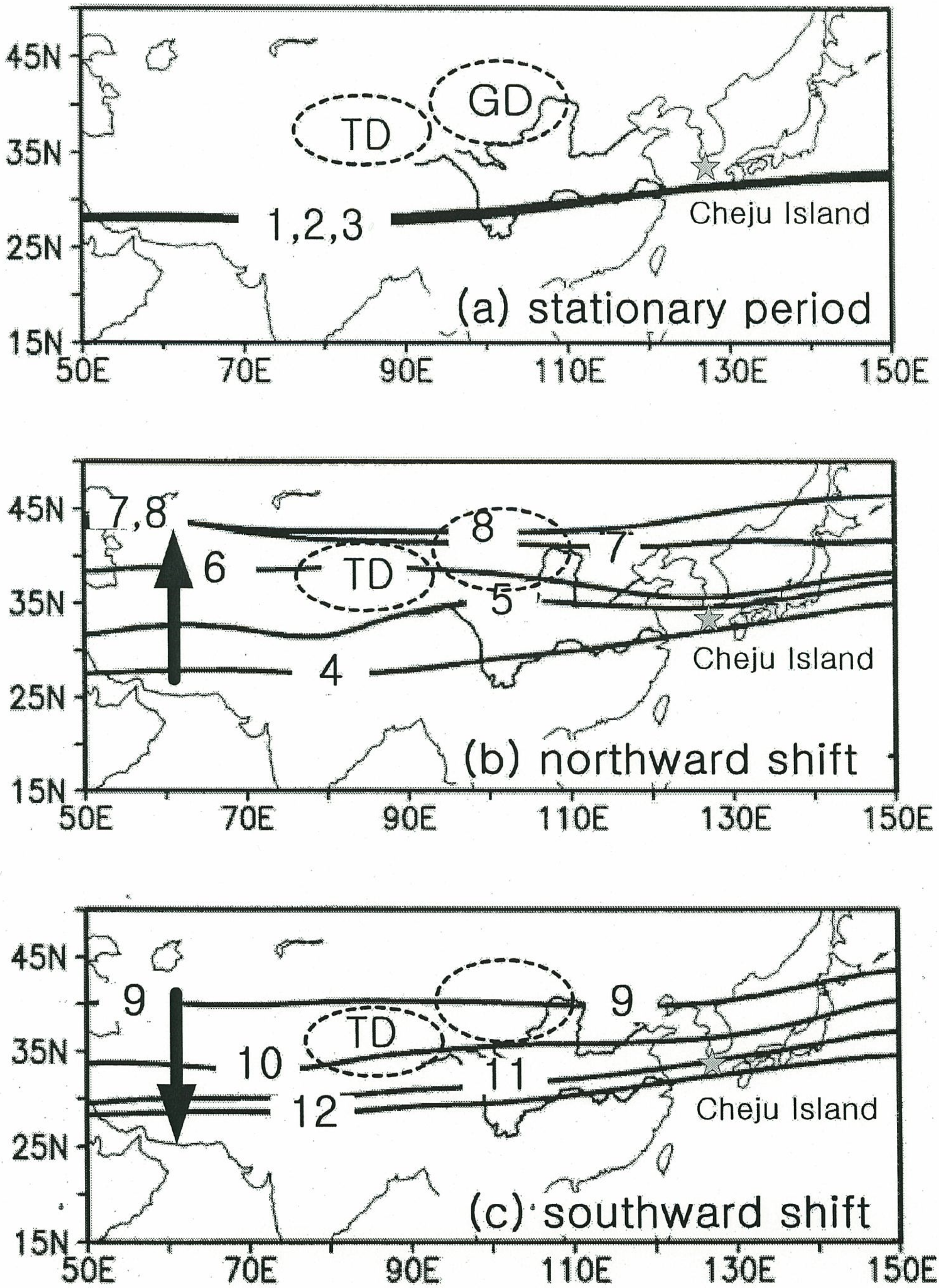
Figure 1. The annual cycle of the westerlies described by the axis shift [modified from *Kuang and Zhang*, 2005] and the main source regions of aeolian dust in East Asia (TD: Taklimakan Desert, GD: Gobi Desert including Gobi Desert portions in southern Mongolia as well as the adjoining Gobi and sand deserts in China [*Sun et al.*, 2001; *Sun*, 2002]. The numbers represent months.

Figure 2. The 500 hPa trough position for the zonal atmospheric circulation pattern (ZACP) and meridional atmospheric circulation pattern ($M_{1,2}$ACP) [modified from *Barry and Perry*, 1973 and *Aizen et al.*, 2001]. GISP2 represents the Greenland Ice Sheet Project 2 (GISP2) deep ice core from the central Greenland. TD represents the Taklimakan Desert as a main dust-source region in East Asia where dust can be entrained over 5000 m and transported by the westerlies [*Sun et al.*, 2001; *Sun*, 2002].

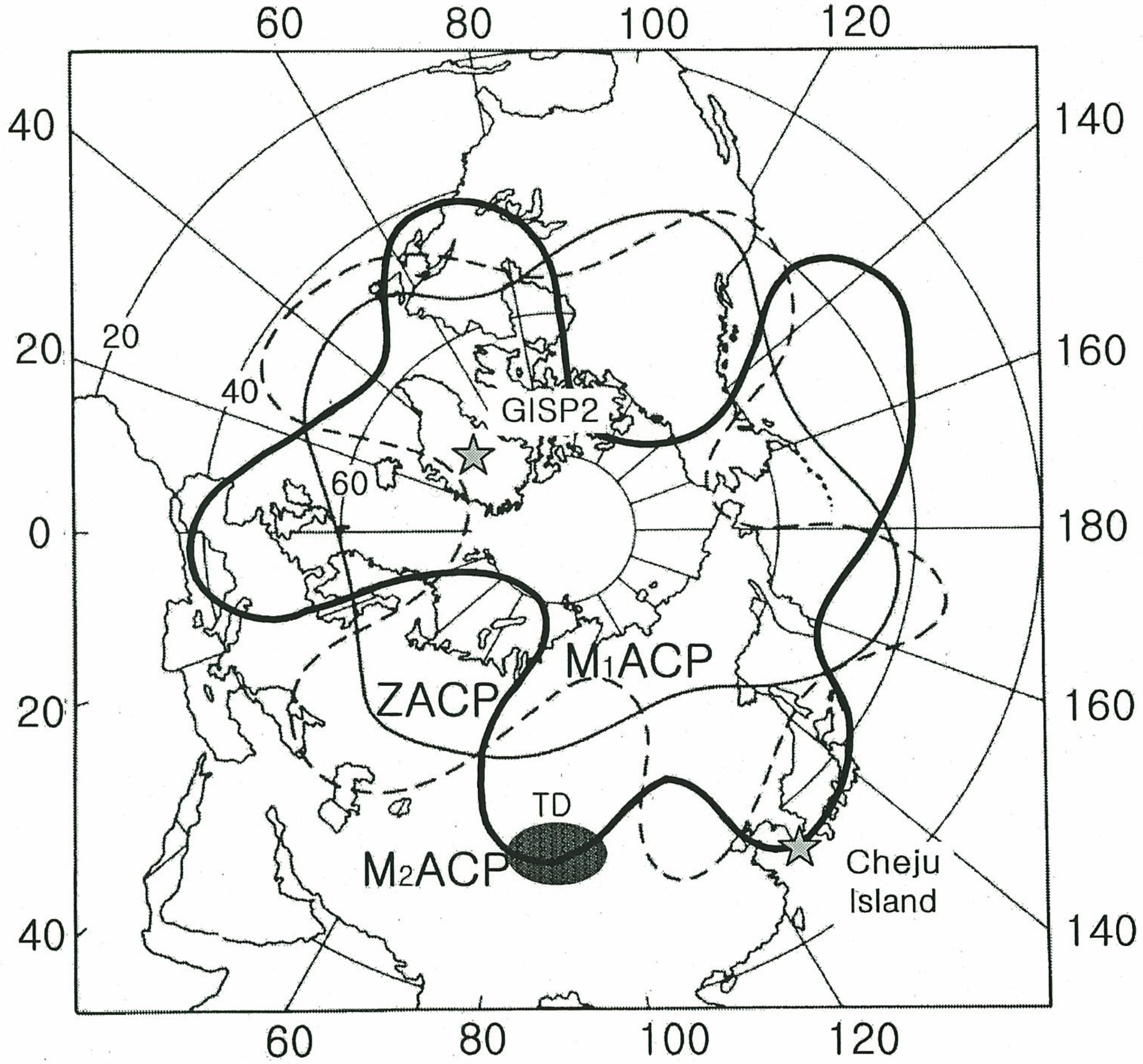
Figure 3. Comparison of the time series of FQF from Cheju Island, Korea, with $\delta^{18}O$ values from Greenland ice cores [*Stuiver et al.*, 1995; *Grootes and Stuiver*, 1997] during the mid- to late Holocene. (A) FQF from Cheju Island (the black bold line represents the 3-point running average). (B) $\delta^{18}O$ values from Greenland ice cores [*Stuiver et al.*, 1995; *Grootes and Stuiver*, 1997] (the black bold line represents the 7-point running average).

Figure 4. Cross-spectral analysis of FQF and $\delta^{18}O$ values from Greenland ice cores [*Stuiver et al.*, 1995; *Grootes and Stuiver*, 1997] for the time interval of 1 to 6.5 10^3 cal. yr B.P. (Settings: OFAC = 4; HIFAC = 1; N_{seg} = 2; α = 0.2; Welch-window; see *Schulz*

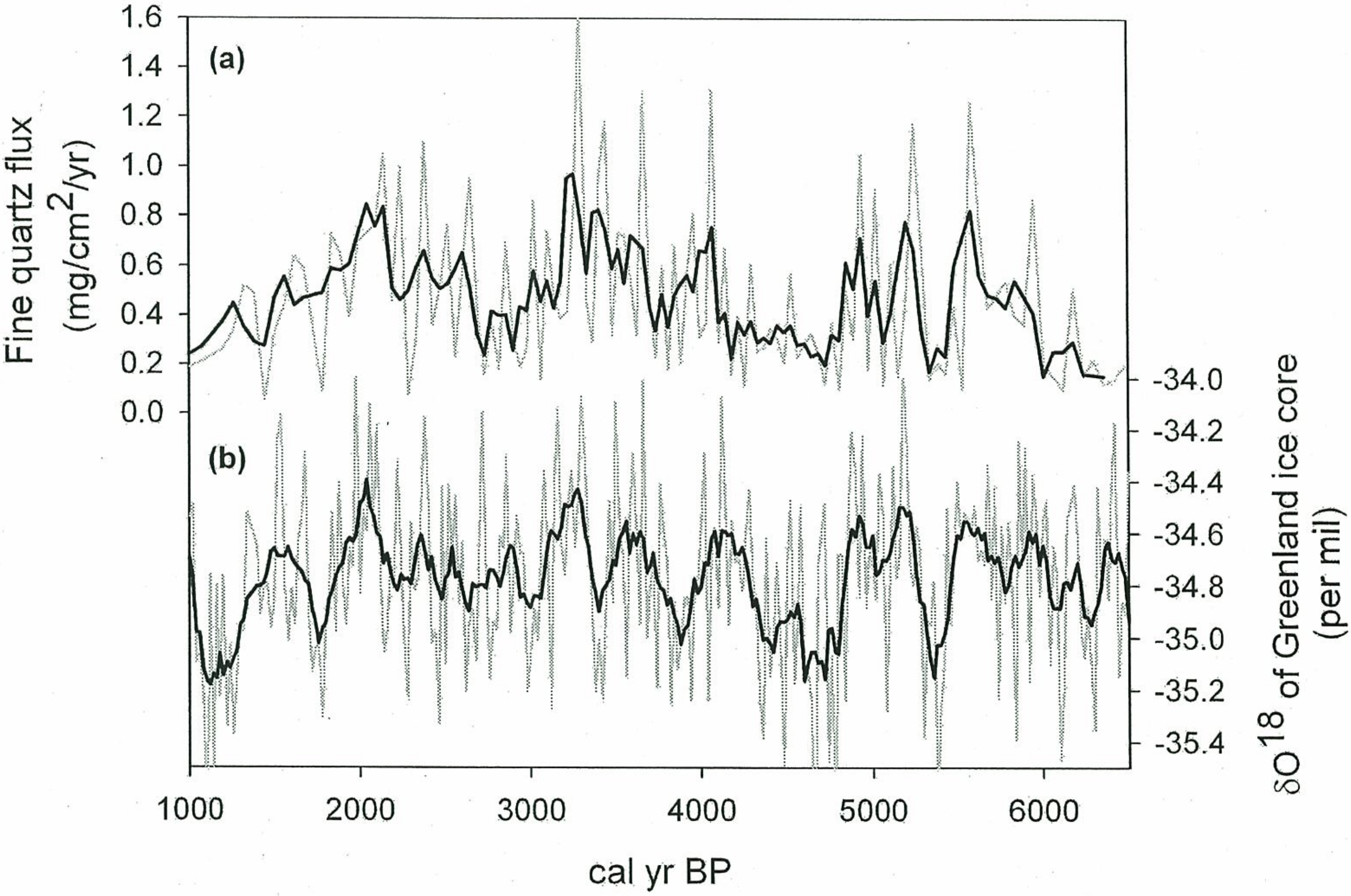
and Stattegger, 1997 for details) after resampling in a 50-year interval using the AnalySeries program (setting: simple interpolation-spline function) (This program is available free of charge at www.ngdc.noaa.gov/paleo/softlib.html or ftp://ftp.ngdc.noaa.gov/paleo/softlib). (A) Autospectrum of the FQF time series. Numbers above peaks indicate respective periods. The horizontal dashed line denotes the average value of the spectrum and is a rough estimate for a white noise component in the time series. Considering only those parts of spectral peaks above this level gives an estimation of their corresponding variance contribution. The cross in the right-hand corner marks the 6-dB bandwidth (horizontal) and 80% confidence interval (vertical). (B) As in A but for the $\delta^{18}O$ values from Greenland ice cores. (C) Coherency between two time series. The dashed horizontal line indicates the false alarm level ($\alpha = 0.2$).



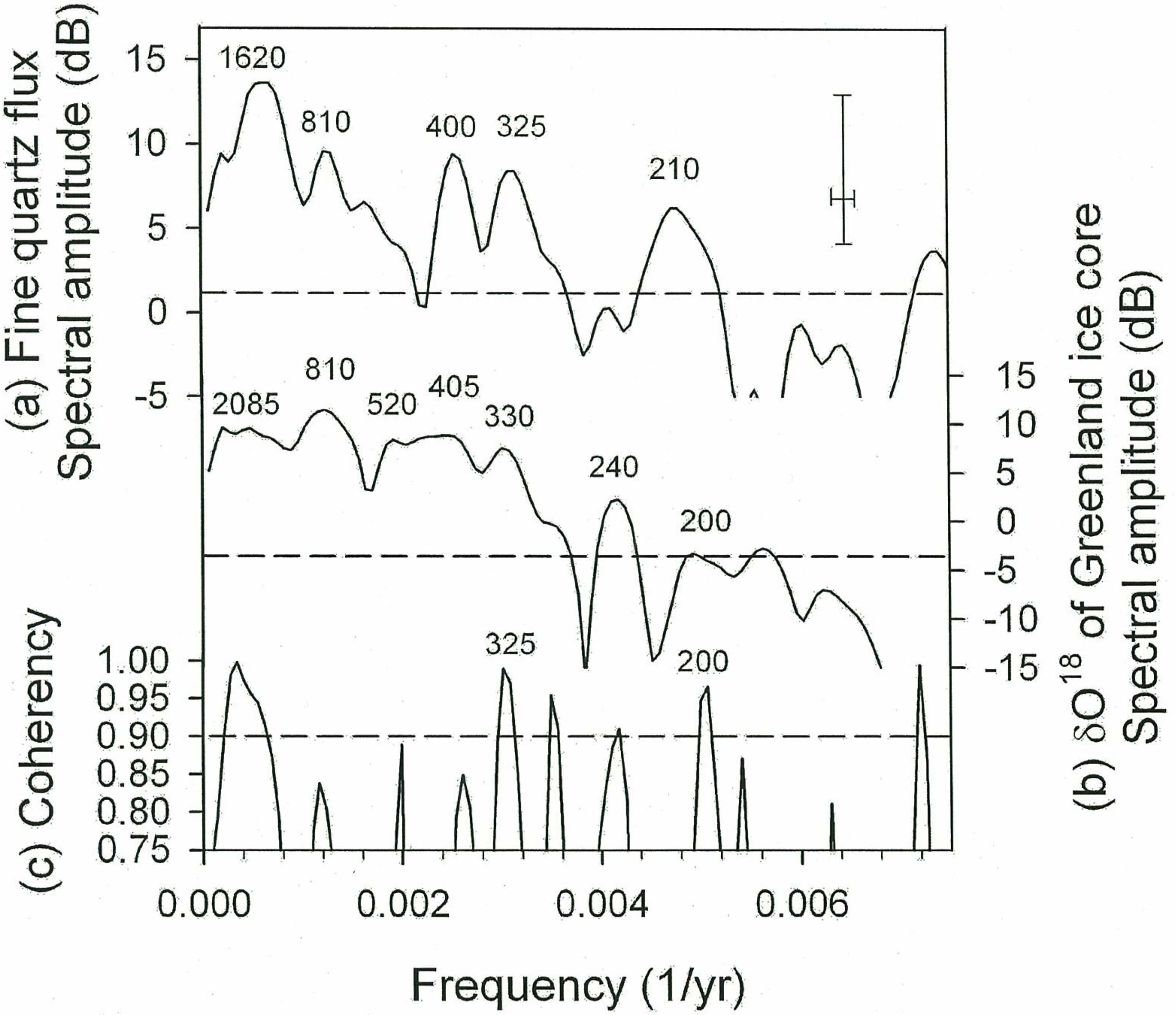
45N
35N
25N
15N
50E
70E
90E
110E
130E
150E
TD
GD
1,2,3
Cheju Island
(a) stationary period
7,8
8
7
6
TD
5
4
Cheju Island
(b) northward shift
9
9
TD
10
11
12
Cheju Island
(c) southward shift



60
80
100
120
40
20
0
20
40
140
160
180
160
140
20
40
60
GISP2
M1ACP
ZACP
TD
M2ACP
Cheju
Island



Fine quartz flux (mg/cm2/yr)
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
(a)
(b)
-34.0
-34.2
-34.4
-34.6
-34.8
-35.0
-35.2
-35.4
δO18 of Greenland ice core (per mil)
1000
2000
3000
4000
5000
6000
cal yr BP



(a) Fine quartz flux
Spectral amplitude (dB)
15
10
5
0
-5
1620
810
400
325
210
2085
810
520
405
330
240
200
(b) δO18 of Greenland ice core
Spectral amplitude (dB)
15
10
5
0
-5
-10
-15
(c) Coherency
1.00
0.95
0.90
0.85
0.80
0.75
325
200
0.000
0.002
0.004
0.006
Frequency (1/yr)