Late Quaternary Climate Fluctuations and Their Causes: A Brief Review

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1. Introduction

The Vostock ice cores from Antarctica records roughly four glacial/interglacial cycles during the past 0.4 million years, showing 100 K year cyclicity (Fig. 1). Ice core records from Greenland show finer and larger climate fluctuations within short time periods, which is believed to be associated with the fluctuation of ice sheet melting (Fig. 1 middle). After the last glacial maximum (LGM), the Bollign-Alleroid warm period leads to a melting of the Laurentide ice sheet and provides freshwater to the North Atlantic, where deep ocean overturning circulation is produced, and eventually shutting down the overturning circulation. This leads to a sharp cooling period, called 'Younger Dryas' (YD) cold event at about 11,000 years ago. The YD cold event is probably limited to northern hemisphere. Towards present, surface temperature increases gradually up to 10,000 years BP and shows a climatic optimum at about 6,000 years BP associated with the increase in solar radiation due to the shift of perihelion. At about 1,000 years AD a climatic optimum, called medieval warm period is shown and since then the climate gradually become colder up to about 1,900 year and this period is called Little Ice Age. After industrialization the earth's temperature become skyrocketing associated with the increase in greenhouse gas concentration. This paper reviews climate fluctuations for the late quaternary and describes their causes.

2. Late Quaternary Climate Fluctuations

The LGM extended from about 22,000 to 14,000 BP. The most dramatic feature of the LGM is the presence of hue ice sheets, over North America (Laurentide Ice Sheet) and northwestern Europe (Fennoscandian Ice Sheet), and smaller in the western North America (Cordillerian Ice Sheet), and west Antarctica. The formation of ice sheets required evaporation of about 50-60 x 10^6 km^3 and the best estimate of the compatible sea level is about 121 m (Fairbanks, 1989). CLIMAP (1976, 1981) reconstruction shows that in the LGM sea surface temperature (SST) is reduced in most ocean areas. In particular, in regions affected by the migration of sea ice and oceanic polar fronts, SST decreased by 6-10°C. Recent reconstruction suggests that the SST was underestimated in the North Atlantic and Norwegian Sea (Sarnthein et al., 1995; De Vernal and Hillaire-Marcel, 2000). Over large parts of the tropical ocean, SST changes were much smaller and in some subtropical oceans an anomalous warming was recorded, but more recent reconstructions suggest a range of glacial ocean cooling from 2 to 5°C (Guilderson et al., 1994; Hostetler and Mix, 1999; Mix et al., 1999).

Oceanic polar front and sea ice migrated equatorward in both hemispheres. At present the northeastern Atlantic is seasonally ice free as far north as 78°N in the Norwegian Sea. This is due to the advection of the warm North Atlantic Current (i.e. Gulf Stream) water into this region. During the LGM, the oceanic polar front migrated to about 45°N. There were also large changes in Antarctic sea ice cover. At present winter sea ice cover in the Southern Ocean is approximately equal to the amount of ice on Antarctica (~ 15 x 10^6 km^2

Cavalieri et al., 2003). At 18,000 BP, sea ice was approximately twice the area of Antarctic ice cover.

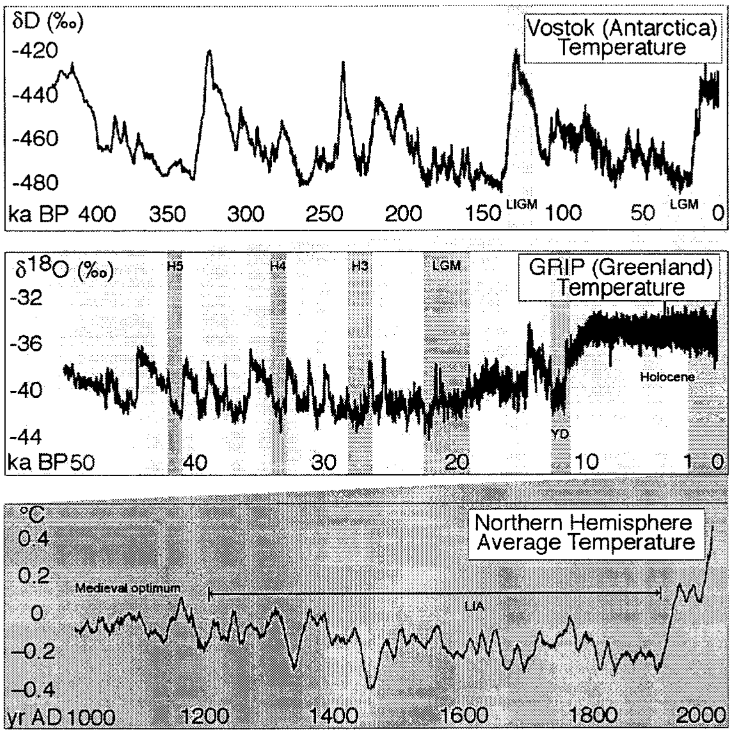

Fig. 1 Late Quaternary temperature variability on different time scales. The upper panel is from Petit et al. (1999), middle panel from Dansgaard et al. (1993), and lower panel from Mann et al. (1999).

Most paleo data suggest that the climate was drier in the LGM. In high latitudes precipitation decreased by about 50% (Beer et al., 1983; Herron and Langway, 1985; Lorius et al., 1985). In low to mid latitudes, there are regions of moist due to equatorially displaced westerlies. The wetter regions are western North America, northern Africa, around Mediterranean, northwestern China, southern Africa, and southeastern Australia. These regions, presently on the poleward margins of subtropical arid belts, benefited from the equatorward displacements of midlatitude low-pressure system. On the other hand, the tropical low lands were drier during the LGM.

Many lines of geochemical evidence suggest that North Atlantic Deep Water (NADW) production was decreased in the LGM (Boyle and Keigwin, 1982, 1987; Curry and Lohmann, 1983; Oppo and Fairbanks, 1987; Duplessy et al., 1988; Curry et al., 1988). Observations indicate that production rates of NADW decreased by perhaps one-third to one-half during the last glacial maximum. Deep water may be produced in the northeastern Atlantic as a result of brine formation and sea ice freezing (Duplessy et al., 1980). Glacial NADW was located above modern Antarctic Intermediate Water. A similar inversion of water masses with ventilated nutrient-poor waters above 2,000 m, and generally poorly ventilated waters below was present in both the Indian (Kallel et al., 1988) and Pacific oceans (Dupplessy et al., 1988).

The deglaciation began about 14,000 BP rather abruptly, followed by a climate reversal at about 12,000 BP (termed "Younger Dryas" (YD)), and then another abrupt warming at about 11,000 BP. The rapid termination of glacial accompanied a huge melting of continental ice by 54 x 10^6 km^3 (Yokohama et al., 2000). In the tropics and Antarctica, deglaciation is initiated much earlier from about 18,000 BP and warmed up gradually up to about 12,000 BP without a clear climate reversal. The increase in atmospheric greenhouse gasses, CO_2, CH_4, δD, etc., occur quasi synchronously during each of the last four terminations in the Vostok ice record (Petit et al., 1999). The YD event is due to melt water induced changes in the atmosphere-ocean circulation. Discharge from ice age lakes was sometimes catastrophic and by about 11,000 BP the ice margin retreated to open up the St. Lawrence River and eventually to the subpolar North Atlantic. The outflow of low-salinity water into the subpolar North Atlantic affected the deep-sea mixing because the low-salinity water would not be dense enough to sink through the pycnocline. The lack of overturn might result in greatly diminishing the production of NADW as also found in geologic evidence (Boyle and Keigwin, 1987). Reduction in NADW production rate at the YD might be expected to result in decreased flow of cross equatorial current from the South Atlantic, cooling water north of the equator.

Since the LGM, the solar insolation gradually increases toward the early Holocene in the northern hemisphere and reaches its maximum at about 10,000 BP (~10% increase from present), while in the southern hemisphere it gradually decreases toward the early Holocene by about 4% and then increases towards the present. Due to the increase in incoming solar radiation, the early Holocene (about 4,500-10,000 BP) is suggested to be warmer than the last 4,500 years in northern hemisphere and this feature is recorded in the ice core isotopic and summer melt layer data from Greenland and Canadian Arctic ice caps (Fisher and Koerner, 2002). Many lines of evidence suggest that the onset of the "neoglaciation" occurred ~4000-5000 years BP.

The increase in surface temperature ranges from 1 to 4°C. In the Midwestern USA temperatures are about 2°C warmer than present (Webb, 1985), probably due to increased summer warming. In Europe, summer temperature also increased by about 2°C (Huntley and Prentice, 1988). The mid-Holocene warming is about 2°C in New Guinea (Hope et al., 1976), and 4°C in the Alps (Huntley and Prentice, 1988), and about 1°C in the western USA. Temperatures were 0.5-1.0°C warmer than present on Antarctica. During the mid-Holocene, many parts of the world were wetter. Other proxy records of marine and terrestrial data from Asia and Africa indicate that the monsoon was much stronger than present during the early to mid-Holocene, and weaker up to the present-day (Sirocko et al., 1991; An et al., 1993; Jarvis, 1993; Winklerand Wang, 1993; Overpeck et al., 1996; Wang et al., 2005).

"Little Ice Age", which is now considered to have occurred during the interval ~A.D. 1,250-1,880, with the main phase after AD 1550. An overall decline in temperature of ~0.2°C from AD 1,000 years to early 1900 is recorded (Briffa et al., 2001; Mann et al., 1998; Crowley and Lowery, 2000).

3. Concluding remarks

This paper attempted to summarize some discovered features of the late Quaternary climate fluctuations and their causes, especially for the LGM, glacial terminations, and the Holocene. Even though the causes of glacial/interglacial climate fluctuations are paced by the earth's orbital parameters, the climate for the LGM is largely modified by other factors such as the presence of ice sheets, expansion of sea ice, reduced CO_2 concentration, and ocean thermohaline circulation, etc. The increase in solar insolation initiated the deglaciation and climate had warmed toward the Holocene climatic optimum. The interaction between atmosphere and ocean is particularly important during the glacial termination, especially in the northern hemisphere. Proxy records suggest that the early to mid-Holocene was warmer than the present. Even though tons of information is available, there are many features uncovered on the late Quaternary climate change. A tenuous effort to understand a climate change mechanism is needed to predict what would happen in foreseeable future.

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