Evolution processes of the firn structure in polar ice sheets based on analyses of dielectric anisotropy - latest results of analyses for Greenland SE core as a central topic -

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1. Introduction

The authors and their collaborators have conducted multi-disciplinary studies of polar deep ice cores to better understand history of environmental change on the earth over time scales of 1 million years. Such ice in polar ice cores once experience a state of firn - an intermediate state between snow and ice - taking long periods of time from 10^1 to 10^3 years, without exceptions. Therefore, to better understand climate signals within ice cores, it is very important to understand physical processes of firn formation, metamorphism and deformation.

Metamorphism process from snow/firn to ice have been studied traditionally by measurement of density and observation of grain size and shape. Modern technologies include X-ray absorption computer tomography (X-ray CT). As one of modern methods, the authors have investigated firn through measurement of tensorial values of the dielectric permittivity at microwave and millimeter-wave frequencies. This method can show presence and strength of anisotropic structure in the geometry of pore spaces and ice matrix within polar firn.

2. Major points of understanding based on earlier studies

(i) Firn in inland of Antarctica and inland of Greenland have strong dielectric anisotropy thus geometrical anisotropy. At the near-surface-depth (immediately below the surface), vertically anisotropic structure is already developed and found. At much deeper depths of "bubble close off" where air bubbles are formed and isolated from the upper atmosphere, this vertical anisotropy gradually disappears.

(ii) In Antarctica and Greenland, the strength of such vertically anisotropic structures are determined depending on depositional environment. For example, at Dome Fuji in East Antarctica, strength of the anisotropic structure differed strongly between two sites that are apart only ~100 m.

(iii) Plastic deformation rate is influenced by presence of ions such as F^-, Cl^- or NH_4^+. These ions are known to be substituted to oxygen in the crystal lattice of ice. Ice containing F^- or Cl^- becomes softer whereas ice containing NH_4^+ becomes harder.

3. New knowledge from the Greenland SE (South-East) core

Greenland SE core was drilled from one of local dome at the south-eastern side of the Greenland ice sheet in 2015. PI was Dr. IIzuka at Low Temperature Science Institute at Hokkaido University. The accumulation rate at this site exceeds 1 meters per year water equivalent. Snow temperature at a depth of 20 m was -20.9 °C. Due to this high accumulation rate, a depth of firn-ice transition was deep, 83.4-86.8 meter. We found that at depths range generally shallower that about 20m, there was a tendency that horizontal components of the permittivity were often larger than the vertical components of the permittivity. In addition, despite this tendency at shallow (<20 m) depth zone, vertical anisotropy gradually develops as firn becomes deeper. Moreover, the strength of the vertical anisotropy is then preserved to much deeper depths of bubble close off. This was a surprising results for us, because generally in earlier studies, vertical anisotropy decreased with increasing depths. This time, the tendency was opposite.

4. Discussions

It seems that firn that have shorter residence time at the ice sheet surface does not form vertical anisotropy that was caused by vertical movement of moistures due to diurnal and seasonal cycles of temperature within firn. Geometry of firn is dominated by gravitational effects that are often found in snow in equi-temperature conditions. On the other hand, as progress of densification within firn, air within firn needs to "escape" to upward directions (as compared to sinking firn). In firn, porous structure tend to have vertically elongated structure because of this vertical "escape" movement of air. The observed phenomena of the growth of the vertical dielectric anisotropy can be understood by this vertical movement of the air within firn. It is not immediately clear if this growth of vertical "tubes" have some effects to understanding the ice core signals. However, this seems new information to better understand firn properties as a function of various conditions such as depositional environment and ambient temperatures.