**Chapter 1-Introduction**

**1.1 Overview**

Satellite geodesy is the measurement of the size and shape of the Earth as well as its gravity field by means of artificial satellites. Satellite geodesy is a powerful tool to monitor time variations in the Earth related to plate tectonics, post-glacial, ocean circulation, etc. … This dissertation focuses on the applications of satellite geodesy to studies of environment and global change. Three satellite geodesy techniques are used in this dissertation: high precision Global Positioning System (GPS), Interferometric Synthetic Aperture Radar (InSAR) and the Gravity Recovery and Climate Experiment (GRACE). This dissertation is divided into three research works. Research background of each work is presented below.

The first work (Chapter 3) focuses on using coastal vertical displacement observed by high precision GPS to study the mass loss of the Greenland ice sheet. High precision GPS has been used to study a number of Earth processes, including plate motion, fault-related crustal deformation, and coastal subsidence.  Many of these applications involve looking at secular (long-term) rates of surface deformation, where the displacement rate can be assumed constant over the measurement period, typically several years or longer. In a number of Earth processes, however, it is also useful to consider short term fluctuations. Many of these applications involve changes in Earth’s fluid envelope, for example annul loading and unloading of the crust associated with the hydrologic cycle. Accelerating uplift of the coastal regions of Greenland, where most of the current mass loss is concentrated [e.g., Zwally et al., 2005; Thomas et al., 2006; Luthcke et al., 2006; Rignot and Kanagaratnam, 2006; Wouters et al., 2008], is well recorded by a network of GPS stations emplaced on the rocky margins [Bevis et al., 2012]. The previous study of Jiang et al. [2010] focused on decadal scale trends and demonstrated that decadal time series of the vertical position component were well fit by a simple model of constant acceleration. Jiang et al. [2010] assumed constant amplitude of annual uplift each year, a common assumption in GPS time series analysis. However, the data show significant annual variation. More recent measurements suggest that accelerating melting of Greenland ice sheet is continuing, with the some melting seasons (for example 2010, 2012) experiencing significant ice mass loss [Bevis et al., 2012; Nghiem et al., 2012]. Thus, the short-term annual variation of coastal uplift measured by GPS can be very useful in studying variable and accelerating ice mass loss, which will be investigated in my dissertation.

One important aspect of the current retreat phase in Greenland is the role of climate forcing on melting costal areas of Greenland. In Greenland, ice mass change is regulated by two climate factors, atmospheric forcing [Zwally et al., 2002; Hall et al., 2008] and oceanic forcing [van de Wal et al., 2008; Holland et al., 2008; Hanna et al., 2009; Straneo et al., 2010, 2012, 2013; Seale et al., 2011]. Atmospheric forcing can affect surface mass balance (SMB) by changing either or both the snow accumulation rate and the ablation rate. Also, melt water can influence the basal sliding rate. Oceanic forcing can increase submarine melting of marine-terminating outlet glaciers, resulting in rapid changes in calving rate, and inducing dynamic changes upstream, including glacier acceleration and thinning [Straneo et al., 2013]. GRACE satellite data documents mass loss in Greenland over the last decade, and for West Greenland, clearly shows that loss is concentrated along the coast [Wouters et al., 2008]. Unfortunately these data lack the spatial resolution to investigate melting at the scale of individual drainage basins. However, coastal uplift as measured by GPS is sensitive to ice loss at this scale, which allows assessment of the influence of local climate conditions on melting. In my dissertation, both short term and long term surface deformation processes measured by GPS will be utilized to understand the climatic forcing on mass loss. What is the driving force for the recent accelerating phase of Greenland Ice Sheet? What is the relative contribution of oceanic versus atmospheric forcing on coastal melting at the scale of individual drainage basins? Those questions will be discussed in my dissertation by using GPS data combing with other oceanographic and meteorological data.

The second work (Chapter 4) focuses on using GRACE data to estimate the recent freshwater flux from Greenland and investigating its impact on the Atlantic Meridional Overturning Circulation (AMOC). The AMOC is a major ocean circulation driven by density differences in the Atlantic Ocean, which is a key component of the global climate system. Both theoretical and numerical studies show that the AMOC is sensitive to freshwater balance [Stommerl, 1961; Rooth, 1982, Rahmstorf, 1995, Stoufer et al., 2006]. There is significant evidence that the past abrupt climate changes were linked with changes in the AMOC in response to changes in the freshwater budget [Manabe and Souffer, 1993; 1995, Clack et al., 2002]. Recent anthropogenic warming and accelerated melting of the Greenland ice sheet leads to a general freshening of the North Atlantic, raising the concern that the AMOC may have been disrupted.

In this dissertation, we estimate Arctic freshwater flux from three sources that are undergoing rapid increases and can be estimated from remote observations: the Greenland ice sheet, CAA glaciers and Arctic sea ice. Among them, freshwater flux from Greenland is the largest component, which is estimated by using GRACE data and RACMO2.3 model [Ettema et al., 2009, Noel et al., 2015]. Since Labrador Sea Water is an important component of the dense southward return flow of the AMOC, changes in Labrador Sea Water can be an indicator of changes in the AMOC. In this dissertation, we compare our freshwater flux estimates to properties of Labrador Sea Water in order to investigate the possible impact of increased freshwater flux on AMOC.

The third work (Chapter 5) focuses on using surface deformation observed by InSAR to study reservoir pressure change caused by fluid injection and production at an enhanced oil recovery field. Similar to GPS, InSAR has been used to study a number of Earth processes. Particularly, it has been used to monitor ground subsidence associated with oil and gas extraction for a long time [Tomas et al., 2005]. At present, as much of the easy-to-produce oil has already been recovered from many on-land oil fields, especially in the US, producers have applied enhanced oil recovery (EOR) techniques that offer prospects for increasing the amount of oil that can be extracted from an oil field. Pumping of CO2 or saline water into the reservoir is one of those practical EOR methods. Presently, there is increasing interest in pumping CO2 from industrial plants into deep geological formations for large-scale Geological Carbon Sequestration (GCS), thereby reducing CO2 emissions to the atmosphere. Much research is carried out to study the geomechanical impact of GCS, including microseismicity, fault reactivation, fracturing and ground deformation [e.g., Jurgen and Richard, 2004; Zhou et al., 2010; Mazzoldi et al., 2012; Antonio and Rutqvist, 2012; Vasco et al., 2010]. Here, ground deformation associated with fluid injection and production is the focus of Chapter 5. To understand the observed surface deformation, a numerical model is constructed to relate surface deformation to pressure changes at depth. Our method offers an inexpensive way to monitor deep reservoir pressure change based on low cost commercial satellite imagery.

Here is the outline for this dissertation. Chapter 1 is the introduction of this dissertation. Chapter 2 introduces the essential of three satellite geodesy techniques (GPS, InSAR and GRACE) used in this dissertation. Chapter 3 presents a study of annual crustal uplift in Greenland caused by ice mass loss. Temporal and spatial relationships between crustal uplift/ice mass loss and climatic forcing are investigated. Chapter 4 presents a new estimate of freshwater flux from the Greenland, Canadian Arctic Archipelago and Arctic sea ice. A link between recent increased freshwater flux and recent changes in Labrador Sea Water is presented. Chapter 5 presents a study of short-term surface movement in an enhance oil recovery field associated with CO2 injection. An analytical model to predict reservoir pressure change and surface displacement is also included in this chapter. Chapter 6 is the conclusion of my research and future studies.

**1.2 Reference**

Bevis, M., Wahr, J., Khan, S. A., Madsen, F. B., Brown, A., Willis, M., Kendrick,

E., Knudsen, P., Box, J. E., van Dam, T., et al. (2012). Bedrock displacements in

greenland manifest ice mass variations, climate cycles and climate change. Proceedings of the National Academy of Sciences, 109(30):11944–11948.

Clark, P. U., Pisias, N. G., Stocker, T. F., and Weaver, A. J. (2002). The role of the

thermohaline circulation in abrupt climate change. Nature, 415(6874):863–869.

Ettema, J., van den Broeke, M. R., van Meijgaard, E., van de Berg, W. J., Bamber,

J. L., Box, J. E., and Bales, R. C. (2009). Higher surface mass balance of the Greenland ice sheet revealed by high-resolution climate modeling. Geophysical Research Letters, 36(12).

Hall, D. K., Williams, R. S., Luthcke, S. B., and Digirolamo, N. E. (2008). Greenland

ice sheet surface temperature, melt and mass loss: 2000–06. Journal of Glaciology,

54(184):81–93.

Hanna, E., Cappelen, J., Fettweis, X., Huybrechts, P., Luckman, A., and Ribergaard,

M. (2009). Hydrologic response of the greenland ice sheet: the role of oceanographic

warming. Hydrological Processes, 23(1):7–30.

Holland, D. M., Thomas, R. H., De Young, B., Ribergaard, M. H., and Lyberth, B.

(2008). Acceleration of jakobshavn isbrae triggered by warm subsurface ocean waters. Nature Geoscience, 1(10):659–664.

Jiang, Y., Dixon, T. H., and Wdowinski, S. (2010). Accelerating uplift in the north

atlantic region as an indicator of ice loss. Nature Geoscience, 3(6):404–407.

Luthcke, S. B., Zwally, H., Abdalati, W., Rowlands, D., Ray, R., Nerem, R., Lemoine, F., McCarthy, J., and Chinn, D. (2006). Recent greenland ice mass loss by drainage system from satellite gravity observations. Science, 314(5803):1286–1289.

Manabe, S. and Stouffer, R. J. (1993). Century-scale effects of increased atmospheric co2 on the ocean-atmosphere system. Nature, 364(6434):215–218.

Manabe, S. and Stouffer, R. J. (1995). Simulation of abrupt climate change induced by freshwater input to the north atlantic ocean. Nature, 378(6553):165–167.

Mazzoldi, A., Rinaldi, A. P., Borgia, A., and Rutqvist, J. (2012). Induced seismicity

within geological carbon sequestration projects: maximum earthquake magnitude and

leakage potential from undetected faults. International Journal of Greenhouse Gas

Control, 10:434–442.

Nghiem, S., Hall, D., Mote, T., Tedesco, M., Albert, M., Keegan, K., Shuman, C.,

DiGirolamo, N., and Neumann, G. (2012). The extreme melt across the greenland ice

sheet in 2012. Geophysical Research Letters, 39(20).

Noël, B., van de Berg, W., Meijgaard, E. v., Kuipers Munneke, P., van de Wal, R., and van den Broeke, M. (2015). Summer snowfall on the greenland ice sheet: a study

with the updated regional climate model racmo2. 3. The Cryosphere Discussions,

9(1):1177–1208.

Rahmstorf, S. (1995). Bifurcations of the atlantic thermohaline circulation in response

to changes in the hydrological cycle. Nature, 378(6553):145–149.

Rignot, E. and Kanagaratnam, P. (2006). Changes in the velocity structure of the Greenland ice sheet. Science, 311(5763):986–990.

Rinaldi, A. P. and Rutqvist, J. (2013). Modeling of deep fracture zone opening and transient ground surface uplift at kb-502 co 2 injection well, in salah, algeria. International Journal of Greenhouse Gas Control, 12:155–167.

Rooth, C. (1982). Hydrology and ocean circulation. Progress in Oceanography, 11(2):131–149.

Seale, A., Christoffersen, P., Mugford, R. I., and O’Leary, M. (2011). Ocean forcing of the greenland ice sheet: Calving fronts and patterns of retreat identified by automatic satellite monitoring of eastern outlet glaciers. Journal of Geophysical Research: Earth Surface (2003–2012), 116(F3).

Stommel, H. (1961). Thermohaline convection with two stable regimes of flow. Tellus, 13(2):224–230.

Stouffer, R. J., Yin, J., Gregory, J., Dixon, K., Spelman, M., Hurlin, W., Weaver, A.,

Eby, M., Flato, G., Hasumi, H., et al. (2006). Investigating the causes of the response

of the thermohaline circulation to past and future climate changes. Journal of Climate,

19(8):1365–1387.

Straneo, F., Hamilton, G. S., Sutherland, D. A., Stearns, L. A., Davidson, F., Hammill, M. O., Stenson, G. B., and Rosing-Asvid, A. (2010). Rapid circulation of warm subtropical waters in a major glacial fjord in east greenland. Nature Geoscience, 3(3):182–186.

Straneo, F. and Heimbach, P. (2013). North atlantic warming and the retreat of greenland’s outlet glaciers. Nature, 504(7478):36–43.

Straneo, F., Sutherland, D. A., Holland, D., Gladish, C., Hamilton, G. S., Johnson, H. L., Rignot, E., Xu, Y., and Koppes, M. (2012). Characteristics of ocean waters reaching greenland’s glaciers. Annals of Glaciology, 53(60):202–210.

Streit, J. E. and Hillis, R. R. (2004). Estimating fault stability and sustainable fluid

pressures for underground storage of co 2 in porous rock. Energy, 29(9):1445–1456.

Thomas, R., Frederick, E., Krabill, W., Manizade, S., and Martin, C. (2006). Progressive increase in ice loss from greenland. Geophysical Research Letters, 33(10).

Tomás, R., Márquez, Y., Lopez-Sanchez, J. M., Delgado, J., Blanco, P., Mallorquí, J. J., Martínez, M., Herrera, G., and Mulas, J. (2005). Mapping ground subsidence induced by aquifer overexploitation using advanced differential sar interferometry: Vega media of the segura river (se spain) case study. Remote Sensing of Environment, 98(2):269–283.

Van de Wal, R., Boot, W., Van den Broeke, M., Smeets, C., Reijmer, C., Donker, J., and Oerlemans, J. (2008). Large and rapid melt-induced velocity changes in the ablation zone of the greenland ice sheet. science, 321(5885):111–113.

Vasco, D., Rucci, A., Ferretti, A., Novali, F., Bissell, R., Ringrose, P., Mathieson, A.,

and Wright, I. (2010). Satellite-based measurements of surface deformation reveal fluid flow associated with the geological storage of carbon dioxide. Geophysical Research Letters, 37(3).

Wouters, B., Chambers, D., and Schrama, E. (2008). Grace observes small-scale mass

loss in greenland. Geophysical Research Letters, 35(20).

Zhou, R., Huang, L., and Rutledge, J. (2010). Microseismic event location for monitoring co 2 injection using double-difference tomography. The Leading Edge, 29(2):208–214.

Zwally, H. J., Abdalati, W., Herring, T., Larson, K., Saba, J., and Steffen, K. (2002).

Surface melt-induced acceleration of greenland ice-sheet flow. Science, 297(5579):218– 222.

Zwally, H. J., Giovinetto, M. B., Li, J., Cornejo, H. G., Beckley, M. A., Brenner, A. C., Saba, J. L., and Yi, D. (2005). Mass changes of the greenland and antarctic ice sheets and shelves and contributions to sea-level rise: 1992–2002. Journal of Glaciology, 51(175):509–527.