USING GPS AND GRAVITY TO INFER ICE MASS CHANGES IN GREENLAND

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مقدمة:

إن الأبحاث المناخية تظهر أن ارتفاع درجة الحرارة على مستوى كوكب الأرض هو حاصل و لاشك أنه سيستمر في العقود الآتية من بين نتائج هذا الارتفاع في درجة الحرارة على مستوى كوكب الأرض ، ارتفاع منسوب البحار المنتظر من جراء 1/ التمدد الحراري لمياه المحيطات القريبة من السطح 2/ ذوبان الطبقات الجليدية للغروإلند ، القطب الجنوبي والمجلدات الإقليمية .

إن تحديد ميكانيزمات العلاقة و رد الفعل فيما بين المناخ، منسوب البحار، وتغيرات الكتل الجليدية قد كان صعبا بسبب نقص المعطيات المناسبة . فعلى سبيل المثال، لا يزال غير ممكن معرفة ما إذا كانت التغيرات في الطبقات الجليدية لغرويلند والقطب الجنوبي قد تسببت في ارتفاع منسوب البحار أو قد تسببت في انخفاضه .

نحن نقوم في هذا المخطوط بوصف لمشروع جيوديزي ساري المفعول من أجل قياس التغيرات الحاصلة في الوضعية الأفقية و جاذبية السطح على مستوي المواقع القاعدية على طول الجهة الجنوبية من الطبقة الجليدية للغرويلند . إن الهدف المسطر على المدى الطويل ، هو استعمال هذه القياسات للضغط على تغيرات الكتل الجليدية في الثلث الجنوبي من الطبقات الجادية واحتماليا إسهام المعطيات التي تفيد في فهم التغيرية المناخية و علاقتها مع اتجاهات منسوب البحار و الكتل الجليدية على المدى الطويل .

نحن على مدى خمسة سنوات فقط مما نعتبره قد سيكون عشرية ذات سلسلة طويلة من الملاحظات ، فإذن ليس بوسعنا بعد التعليق على تغيرات الكتل الجليدية في الغروإلند. إلا أن قياساتنا إلى الآن تظهر تحركات للقشرة أكبر بكثير مما كان مقدر ، مبينة أن تاريخ الكتلة الجليدية البلستوسينية في الغروإلند ليست ممثلة جيدا في النماذج الحالية .

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INTRODUCTION :

Les recherches climatiques indiquent que le réchauffement planétaire est en train de se produire et continuera probablement à se faire les quelques décennies à venir .

L'une des conséquences du scénario de réchauffement planétaire est l'élévation du niveau des mers de la planète prévue : 1) de l'expansion thermique des eaux de la surface des océans et 2) la fonte des nappes de glace de l'antarctique et du Groenland et les glaciers des continents .

Déterminer les mécanismes relationnels et réactionnels entre le climat, le niveau de la mer et les masses de glace a été difficile à cause de l'insuffisance des données appropriées .Il n'est pas encore clair, par exemple, si les changements dans les nappes de glace de l'antarctique et du Groenland ont causé, les siècles derniers, l'élévation du niveau des mers ou bien s'ils ont causé sa baisse .

Dans ce papier, nous décrivons un projet géodésique en cours pour mesurer les changements dans la position verticale et la pesanteur de surface au niveau des sites de soubassement tout au long du coté sud des nappes de glace du Groenland . L'objectif recherché à long terme est d'utiliser ces mesures pour contraindre les changements des masses de glaces dans le tiers sud des nappes de glace , et éventuellement, faire contribuer les données qui sont utiles à la compréhension de la variabilité climatique et son rapport avec les tendances à long terme du niveau de la mer et des changements des masses de glace .

Nous nous trouvons seulement à 5 ans de ce que nous espérons va être une décennie d'une longue série d'observations .Donc, il ne nous est pas possible de commenter à ce stade du travail les changements des masses de glace en Groenland. Néanmoins, nos mesures à ce jour révèlent des mouvements de la croûte qui sont considérablement plus grands qu'il n'était prévu, indiquant que l'histoire de la masse de glace notamment celle d'âge pléistocène du Groenland n'est pas bien représentée dans les modèles courants .

INTRODUCTION :

Climate research indicates that global warming is occurring and will probably continue to occur for the next several decades. One consequence of a global warming scenario is a global sea level rise that would be expected from 1) the thermal expansion of the near surface ocean water and 2) the melting of the Antarctic and Greenland ice sheets and continental glaciers.

Determining the relationship and feedback mechanisms between climate, sea level, and ice mass changes has been difficult because of the lack of appropriate data. It is not even clear, for example, whether changes in the Greenland and Antarctic ice sheets over the last century have caused sea level to rise or have caused it to fall.

In this manuscript we describe an ongoing geodetic project to measure changes in the vertical position and surface gravity at bedrock sites along the southern edge of the Greenland ice sheet. The long term goal is to use these measurements to constrain ice mass changes in the southern third of the ice sheet and to eventually contribute useful data to understanding climate variability and its relationship to long-term sea level trends and ice mass changes.

We are only 5 years into what we expect to be a decade long set of observations. So we cannot yet comment on present day changes in the ice mass in Greenland. However our measurements to date reveal crustal motions that are substantially larger than anticipated indicating that the ice load history for the Pleistocene ice in Greenland is not well represented in current models.

Background

The principle of using geodesy to measure present day ice mass changes (or any surface load for that matter) is relatively straightforward. First, imagine that you have a positioning instrument or a gravimeter on bedrock at the edge of the Greenland ice sheet. If the ice sheet undergoes significant melting, the earth's crust in the vicinity of the ice sheet will experience an immediate uplift. If the uplift is large enough, it can be measured by a positioning instrument or a gravimeter. Three millimeters of uplift without associated mass changes causes a gravity change of 1 µgal (=10 nm/s**2). The gravity signal also has direct contributions from changes in the mass distribution of the underlying earth and the nearby ice.

The first question then is "Are the crustal motions expected from the ice sheet large enough to be observed with contemporary geodetic techniques?" Results from satellite radar altimeter observations of ice surface elevations indicate that the ice in the southern third of Greenland, has been thickening at a rate of several tens of millimeters per year [*Krabill et al*., 1999] of equivalent water thickness. If we assume that the ice is changing uniformly within, say, a 500 km radius of our bedrock location, we find that for an elastic earth model, crustal displacements would be about 1-2 % of the ice mass change or on the order of -1 mm/yr. Contemporary geodetic techniques can certainly measure crustal deformation rates of this magnitude within a few years.

The experiment, then, seems simple enough. We deploy positioning or gravity instruments to bedrock locations around the Greenland ice sheet, we collect data for a few years, analyze those data to determine long-period trends, and then interpret those trends as constraints on the ice mass variability. Unfortunately, there is a catch in this seemingly simple experiment. The interpretation of the vertical deformation signal will be complicated by the fact that in addition to the elastic crustal motions caused by present day changes in ice mass, the observed deformation signal will also contain a viscoelastic contribution caused by past changes in ice load. The viscoelastic deformations are called the Glacial Isostatic Adjustment (GIA).

Viscoelastic deformations in this region are likely to be relatively large. Using a viscoelastic earth model [*Han and Wahr*, 1994] and the Ice-3G ice load history [*Tushinham and Peltier*, 1991], the viscoelastic crustal uplift predicted at the southwestern edge of the ice sheet is estimated to be about 3.5 ± 2.5 mm/yr. However this signal can easily be a factor of two smaller or larger depending on our choice of earth model, lithospheric thickness or ice load history. Hence, the viscoelastic crustal motions from past melting might be significantly larger than the elastic crustal motions due to present day melting and must be accurately determined and removed from the data before the observed signal can be interpreted in terms of a present day ice-mass change.

In ice free regions, absolute gravity observations have been proposed as a way for testing different postglacial rebound models.

But in regions covered with ice, gravity measurements and positioning measurements alone are incapable of distinguishing between the elastic deformations caused by present day changes in ice mass and the earth's viscous response to any changes in ice that might have occurred over the last several thousand years.

The issue of separating the elastic crustal motions due to present day melting from the GIA was first addressed by *Wahr et al*. [1995]. In that publication the authors demonstrated that by making measurements of both gravity and vertical crustal motion at a bedrock site, the elastic and viscoelastic signals could be separated. The viscoelastic crustal motions are related to the viscoelastic changes in gravity via a proportionality constant that is independent of the choice of earth or ice model. Hence collocated observations of crustal motions and gravity changes can be linearly combined to provide information on present day changes in ice mass, independent of GIA.

In principle, any positioning technique could be used to measure vertical crustal motions in Greenland. We chose to use GPS because of its cost-effectiveness, precision, and portability. The gravity changes that we expect to observe are approximately 1 µgal/yr. To observe changes of this order of magnitude, a very precise instrument with long-term stability is required. We have chosen the FG5 absolute gravimeters for our gravity observations. The instrument has a footprint of about 2 m x 2 m and weighs approximately 500 kg, including accessories such as a tent for outdoor measurements.

Do the techniques of GPS and absolute gravity currently have the precision required for this experiment? The vertical component is the least well-determined coordinate in GPS with reports of 10 mm in scatter over one week of data for sites in North America [*Zumberge* et al., 1997]. Using a statistical analysis and assuming randomly distributed errors, we determine that with one year of daily GPS observations we should be able to measure a rate of vertical crustal motion with an accuracy of 4 mm/yr which is the amplitude of the expected total crustal motion signal. However, GPS errors are not randomly distributed, which complicates our error estimates. With respect to the absolute gravimeter, the instrumental precision of the FG5 is approximately 1.0 µGal integrated over 12 hours of observations [*Francis et al.*, 1998]. Even though the FG5 is an absolute instrument, the calibration is checked before and after every field deployment by comparing FG5 observations of gravity at the National Oceanic and Atmospheric Administrations Table Mountain Gravity Observatory with continuous observations of gravity taken there with a superconducting gravimeter.

Like GPS observations, gravity observations are subject to non-random noise effects such as poorly modeled gravitational signals caused by changes in local air pressure, in ground water very near the instrument, and in non-tidal sea level fluctuations if the observations are taken near a coast.

For both GPS and gravity, the most effective way of determining a secular signal is to make continuous observations so that these non-secular terms can be identified and removed. This can be done with GPS, by installing a permanent receiver. It is not practical, however, to make continuous absolute gravity measurements over time periods longer than about a month or so. The wear and tear on the instrument is too great. Thus, we have installed two permanent GPS receivers in Greenland but only make gravity measurements over a period of 1-2 weeks once every year, and it is the accuracy of our gravity measurements, not that of the GPS vertical coordinate, that is the limiting factor in our ability to separate the elastic and viscoelastic crustal deformations (see above). From our estimates of the accuracy levels we can achieve with these instruments, we must make gravity observations every year for the better part of a decade.

Project Status

We began our project in the summer of 1995, installing one GPS receiver and making absolute gravity measurements at the Sondrestrom Radar Facility near Kangerlussuaq (Sondre Stromfjord) (KELY Figure 2). This site was chosen primarily because of the existing infrastructure support, which is helpful when establishing sites in remote regions. The Sondrestrom facility, funded by the NSF Upper Atmosphere Facilities Program is operated and managed by SRI International for a wide variety of university and government users.

In the summer of 1996 we established a second site on the eastern side of the ice sheet at the Kulusuk Airport (KULU Figure 2). (For completeness, we also show in Figure 2 the location of two other continuously operating sites in Greenland, Thule (THU1) and Scorsbysund (SCOB)). There is currently no internet connection at Kulusuk and we rely on a local site contact to periodically download and mail the data to the University Navstar Consortium (UNAVCO) Boulder Facility in Boulder, Colorado.

Absolute gravity measurements have been taken every summer since 1995 at Kangerlussuaq and every summer since 1996 at Kulusuk. The observations range in duration from 6 days to two weeks. Larger than expected scatter has been observed in the gravity data due to problems with controlling the temperature and the verticality of the instrument in the portable shelter where the measurements are taken.

The GPS observations are analyzed using the GIPSY/OASIS II software developed at the Jet Propulsion Laboratory (JPL) [*Zumberge* et al., 1997]. We use GPS orbits, earth orientation, and clock products produced by JPL. We estimate station position, tropospheric refraction, and the receiver clock behavior. Figure 3 shows the weekly averages of the daily GPS vertical positions at KELY and KULU. (The error bars are removed for clarity but have an average value of 9 mm.) Neither atmospheric pressure nor ocean loading effects have been removed from the GPS data. The data have a RMS scatter about the best-fitting straight line of approximately 12 mm at KELY and about 13 mm at KULU.

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The break in the KELY data beginning in November 1995 was the result of a bad antenna that was replaced in July 1996. Otherwise the site KELY has been essentially trouble free.

The sparse observations at Kulusuk present another story altogether. Strong winds, extreme cold, and excessive humidity resulted in instrument failures that without an internet connection were difficult to diagnose and subsequently repair.

Preliminary Observations

At KELY, we observe a significant subsidence during the first 4.5 years of 5.7 ± 0.9 mm/yr, but a slight uplift that started in the summer of 1998 indicates that our model of a trend plus an annually varying signal is probably not complete. Removing the predicted effects of atmospheric pressure loading does not affect the estimate of the subsidence rate. We find that atmospheric pressure loading is a zero mean process. It will add noise to the height time series but it does not affect the slope if the slope is calculated using continuous data that spans many years. The inferred elastic crustal subsidence (GPS vertical rate - GIA predicted uplift) is much larger than the 1 mm/yr value predicted from altimeter observations. This result begs the question “Could the subsidence at KELY be an artifact of our analysis products?”. Time series from other sites near KELY and at the same latitude, Reykjavik, Iceland and THU1, suggest not, as neither shows a similar subsidence over that time period.

The gravity data from both sites are shown in 40 4. The results at both KULU and KELY are corrected for ocean loading, polar motion, earth tides, and atmospheric pressure (loading and direct mass attraction is removed using the conversion -0.3 µgals /mbar). Each point on the plot represents the average of one to two weeks of actual observations. The error bars in most years are on the order of 2.5 µgals. This scatter is larger than the reported instrument precision because 1) we are making observations in the field and 2) we cannot model the environmental effects perfectly. The large error bars in 1997 are related to the fact that the instrument was malfunctioning that year.

A linear fit to the gravity data at KELY indicates that the gravity change has a slope of 1.6 µ 1.2 µgals /yr, which is not significantly different from zero. The gravity data from KULU cannot be interpreted. During the summers of 1997 and 1998 a large hotel was being constructed only 10 meters away from our absolute gravity site. We have modeled the gravity effects of the mass of the hotel and various geometries for the redistribution of top soil and bedrock associated with the construction. We find that gravity can change from 4 to 11 µgals depending on the soil distribution model we choose. We will try to more accurately measure the soil redistribution this field season in an attempt to reduce the errors from the hotel construction near the KULU gravity site.

Interpretation (or Going out on a Limb)

Recall that because of our short annual visits with the gravimeter, it is still too early to report definitive conclusions about ongoing changes in ice in the southern third of the Greenland ice sheet. However, the GPS subsidence rate at KELY is substantially larger than what we think is a reasonable upper bound for the crustal deformation, even given uncertainties in our estimate of the earth's viscous response to past ice changes. Hence, we may be able to use an earth model and an ice load history model to estimate the viscous effects, assign large error bars to the estimate and put an upper bound on the what the elastic signal might be.

As mentioned earlier, when we use the Ice-3G model for the melting of Pleistocene ice prior to 4000 years ago, and convolve these data with viscoelastic Green's functions, we estimate a viscoelastic uplift of 3.5 ± 2.5 mm/yr at KELY. The uncertainty on this value represents the range of possibilities in our estimate, given the uncertainty in the earth's viscosity profile. If we remove this rate of uplift from the GPS secular subsidence value (~ 5.7 ± 0.9 mm/yr), we obtain an effective elastic subsidence of 9.2 ± 2.7 mm/yr. If the Ice-3G model is correct, then this subsidence would have to be due to a combination of ongoing changes in ice and of the earth's viscous response to any changes in ice that might have occurred during the past 4000 years. (Ice-3G only attempts to model the deglaciation prior to 4000 years ago). We have little idea of what ice changes in Greenland in the last 4000 years might have been. However, there needs to be a substantial change in ice over the last 1000 years or so to produce a significant GIA. The 1995 Intergovernmental Panel on Climate Change report [*Warrick et al.*, 1995] concludes that Greenland's contribution to sea level rise over this past century has been somewhere in the range of ± 0. 4 mm/yr. This corresponds to an ± 80 mm/yr change in ice averaged over the Greenland ice sheet. As an upper bound, we accordingly assume that the average rate of change in ice thickness over the past 4000 years was somewhere in the interval ± 80 mm/yr and that this thickness change was uniformly distributed over the ice cap. Using this assumption, we calculate a present-day crustal subsidence at KELY caused by the changing ice over the past 4000 years, of ± 4 mm/yr, and we add this ± 4 mm/yr to the uncertainty of the elastic subsidence rate. We thus conclude that the subsidence at KELY due to ongoing changes in ice is 9.2 ± 4.8 mm/yr.

This result is almost certainly too large. For example, 9 mm/yr of subsidence at the edge of the ice sheet would imply that the ice is thickening at a rate of about 45-90 cm/yr averaged over the ice within a few hundred kilometers of KELY. This is at the far greater than the ice surface changes inferred from altimetric observations [*Krabill et al.*, 1999]. The lower bound of 9.2 - 4.8 = 4.4 mm/yr would imply the ice is thickening at a rate from 22 to 44 cm/yr, which is only marginallly within the extreme upper bounds of the existing altimeter solutions.

The explanation for the large subsidence rate is most likely related to changes in ice that occurred since the end of the large, early Holocene deglaciation. In fact, archeological and historical observations along the west Greenland coast from several hundred km north to several hundred km south of KELY, indicate that there has been widespread subsidence throughout this region of up to several mm/yr averaged over the last 2000 years or so (see, e.g., *Weidick* [1996]). This suggests that the ice sheet margin in this area may actually have been advancing during the last 2,000-2,500 years [*Weidick*, 1993]. By using extreme but not unreasonable estimates for the rate of this readvance in our viscoelastic models, we find that 9-10 mm/yr of subsidence at KELY is quite plausible.

In the near future, we hope to use geologic data from Greenland to refine our models of the ice load history and hence to improve the viscoelastic models we are currently using. Until we are certain of our viscoelastic modeling however, we will continue to collect more gravity and GPS observations. This is the data that will ultimately allow us to accurately separate the viscoelastic part of the crustal motion signal from the elastic. From this data we will be able to infer present day changes in ice mass in the southern third of the Greenland ice sheet and perhaps contribute to understanding the relationship between climate, ice mass and sea level.

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Figure Captions:

Figure 1: View looking East from the Kulusuk GPS monument. The photo was taken in March of 2000 by Bjorn Johns.

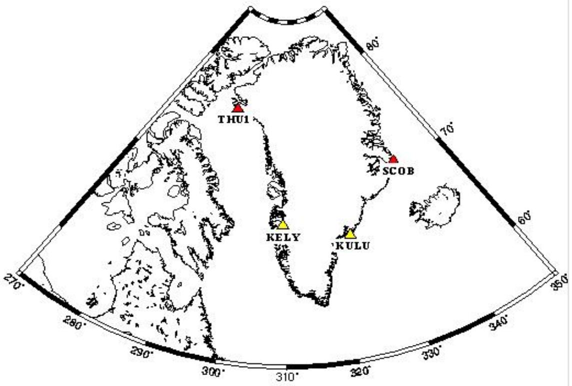

Figure 2: Map showing the relative locations of the continuous GPS sites in Greenland including: Kangerlussuaq (KELY) and Kulusuk (KULU) used in this project, the JPL site at Thule (THU1) and the Scorsbysund site (SCOB) maintained by the National Survey and Cadastre of Denmark.

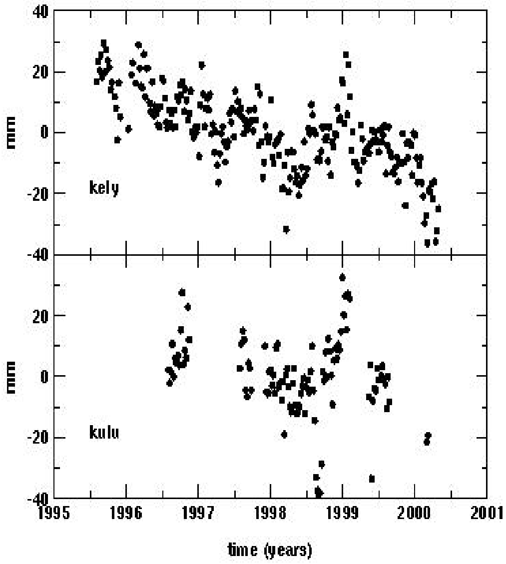

Figure 3: Weekly averages of GPS vertical position changes at KELY and KULU. Errors bars have been removed for clarity , with average value of 9mm.

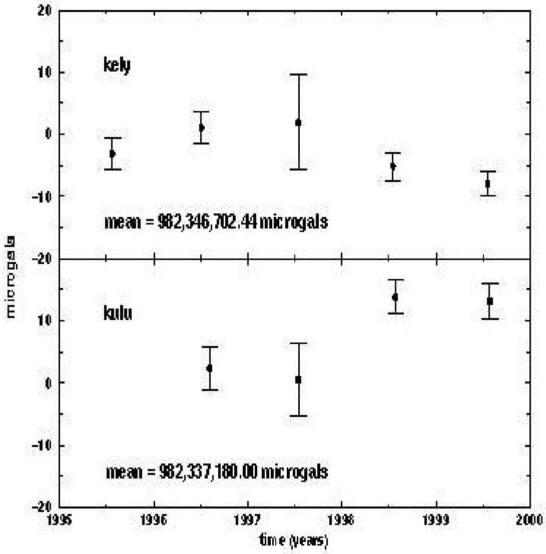

Figure 4: Gravity observation:s from KELY and KULU. A mean has been removed from the data.