quently involved in the targeting fusion of the vesicle (see the figure). As Allan *et al.* put it, budding "programs" the vesicle for subsequent targeting/fusion.

The discovery of a Rab-dependent step in the assembly of a targeting complex during budding raises a number of interesting questions. For example, does assembly of analogous complexes occur during other budding events in the cell? How does this p115-SNARE complex relate to the well-studied role of p115 in tethering mitotic Golgi fragments together during reassembly of the Golgi apparatus after mitosis (*9*)? Does the COPII coat participate in Rab-dependent formation of this p115-SNARE complex (see the figure)? In this regard, it is notable that COPII interacts with some SNAREs in yeast (*10*), and depletion of Rab1 inhibits budding from the ER in mammalian cells (*11*).

New questions about the events after vesicle budding are also raised by the Allan study. If most of the components required for targeting/fusion are already on the vesicle, what does the target membrane contribute to the reaction (see the figure)? One possibility is provided by recent work that analyzes ER-to-Golgi trafficking of proteins in yeast. In this model system, targeting requires two additional protein complexes: TRAPP and the Sec34/35p complex (*12*). TRAPP is particularly notable because it is statically localized to the Golgi, whereas SNAREs are mobile, moving back and forth between the ER and Golgi. Thus, TRAPP may be the marker protein that dictates vesicle targeting, a job originally postulated for the SNAREs attached to target membranes. Nevertheless, this still leaves open the question of whether the Golgi contributes SNAREs to the fusion process. The vesicle complex described by Allan *et al.* contains three SNAREs, each of which could contribute one α helix to the four–α-helix SNARE bundle. Thus, a SNARE contributing the fourth helix may reside on the Golgi membrane, providing targeting specificity and acting in the fusion process.

An alternative possibility is that a complex similar to the one found by Allan *et al.* on ER-derived vesicles is present on the Golgi apparatus (see the figure). Interaction of these complexes as the vesicle and Golgi membranes approach one another might allow fusion of the membranes. Symmetrical biochemical requirements are the norm for the targeting and fusion of similar membranes. However, this cannot be the whole story for ER-to-Golgi trafficking of vesicles because the dissimilar vesicle and Golgi membranes have different biochemical requirements for targeting and fusion (*13, 14*).

Thus, the Allan *et al.* study suggests that vesicle budding from the ER involves Rab-dependent assembly of a protein complex, including a p115 tether and several SNAREs. The important implication of this work is that during budding from the ER the vesicle is given a molecular program that will direct its subsequent targeting and fusion with the Golgi apparatus. Therefore, budding and targeting/fusion, which are separated in time and space, may be more interconnected than we previously thought.


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PERSPECTIVES: CLIMATE CHANGE

# The Greenland Ice Sheet Reacts

**Dorthe Dahl-Jensen**

The Greenland Ice Sheet contains a substantial part of Earth's fresh water. Because it lies on land above sea level, a change in its volume will directly cause a change in sea level: If the whole ice sheet were to melt, sea level would rise by 7 m (*1*). Two reports in this issue assess changes in the Greenland Ice Sheet. On page 428, Krabill *et al.* (*2*) analyze repeated airborne laser altimetry measurements of the surface elevation. They show that the low-elevation areas of the Greenland Ice Sheet are melting but detect no substantial elevation changes in the high-elevation areas. The resulting reduction in the ice sheet's volume corresponds to a sea level rise of 0.13 mm/year, or 7% of the observed rise. On page 426, Thomas *et al.* (*3*) present an independent estimate of the high-elevation balance. They compare the amount of ice that each year passes the 2000-m contour line of the Greenland Ice Sheet with the amount of ice deposited on the surface over the course of a year. They conclude that as a whole, the high-elevation area is showing no net reduction in ice volume, with a substantial thickening in the southwest balanced by thinning in the southeast. Knowledge of the balance of the Greenland Ice Sheet has been sought for decades, and varying estimates have been presented (*1, 4*). The two reports show that modern techniques now allow sufficiently precise measurements for a reliable estimate to be made.

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Even small sea level changes can have a severe impact on coastal populations living with the threat of flooding. It is thus important to be able to monitor ice volume change. But it is even more important to be able to predict future changes. The future contribution to sea level change from ice sheets is composed of two terms: A long-term trend determined by the climatic and dynamic history of the ice sheet on centennial to millennial time scales and short-term sea level rise or fall directly related to annual to decadal climate variations (*4*).

The long-term trend arises from several mechanisms. The ice in an ice sheet is in constant flow. If the balance of the mass supplied to the ice sheet by precipitation and the mass lost by melting or production of icebergs shift, the flow will change, thereby influencing the shape of the ice sheet (*5, 6*). In addition, the flow of ice strongly depends on temperature. During a glacial-interglacial cycle, surface temperatures on the ice sheet will vary by around 20°C (*5–7*). The time scale over which the volume of ice reacts to these variations spans centuries to millennia, because the flow is slow and the temperature changes take thousands of years to penetrate the ice. To complicate matters further, ice from different climatic periods may have different flow properties because impurity concentrations in the ice vary (*8*). Modeling of these long-term changes has shown that the Greenland Ice Sheet is still adjusting to the climate changes reaching back to the last glacial-interglacial transition (*6, 8*).

The surface elevation changes measured in the laser altimetry surveys between 1993 and 1999 (*2*) are very sensitive to the natural annual to decadal fluctuations in snow accumulation and melt rates over the Greenland Ice Sheet. These fluctuations are believed to be nearly a factor of 10 larger than the long-term elevation changes (*4, 9*). These annual to decadal

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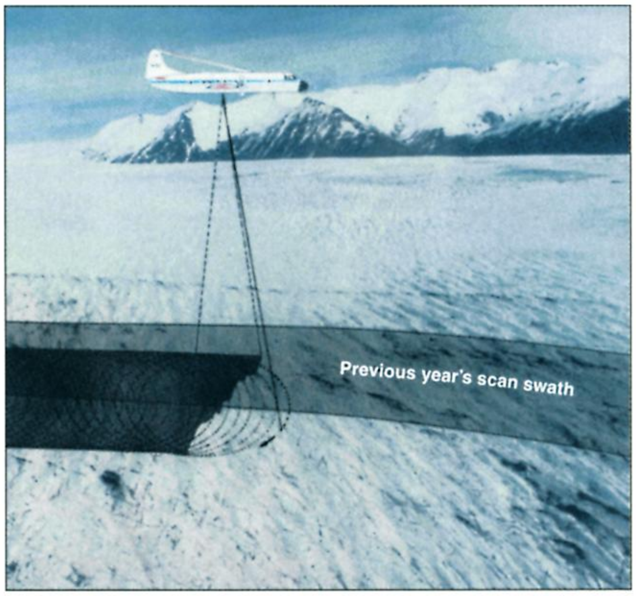
fluctuations are connected with present climate changes. General circulation models can be used to estimate temperature and precipitation variations and thus the sensitivity of ice sheet mass balance to these climate changes. Model results have indicated that in Greenland, climate warming would result in increased melt rates along the margin of the ice sheet but that this would be counteracted at least in part by increased precipitation rates in the high-elevation areas (*1*). A series of a few warm years is expected to produce a sea level rise. This is most likely what is being observed; the years from 1993 to 1999 have been warm years, although the long-term component is also present.

The mass balance budget considerations presented by Thomas *et al.* (*3*) are based on measurements of the amount of mass deposited on the high-elevation area and the amount of ice that flows out of this region. Surface velocities have been measured at stations 30-km apart along the 2000-m contour line by repeated measurements with the Global Positioning System (GPS). On the basis of these velocities, the discharge of mass is estimated. The measured discharge represents the response to the mass budget over a time scale of a century to a millennium. The total precipitation was estimated from a compilation of all available data (*10*) on time scales ranging from a few years to centuries. The authors conclude that there has been no substantial ice volume change over several decades in the high-elevation area of the Greenland Ice Sheet. The difficulty is that the imbalance is determined by subtracting two large figures: the total precipitation and the total discharge by flow across the 2000-m contour line. The uncertainty of the estimate is an ice thickness change of 7 mm/year, the same order of magnitude as the expected long-term trend from climate and dynamic history.

It is not surprising that slightly different results are reached in the two reports: They represent mass balances over different time scales. What is perhaps surprising is that they agree on the balance of the high-elevation regions.

How can we predict sea level changes from ice volume changes in the Greenland Ice Sheet in the future? In my opinion, we need to be able to detect both the long-term trend and the short-term signal. The ability to detect annual to decadal surface elevation changes by airborne and satellite observations (*2*, *9*) will be refined. Future satellites will provide additional information and hopefully decrease the uncertainty of the observations. But the records need to be extended to several decades before the long-term trend can be estimated. The "waiting time" can be reduced by using general circulation models to calculate the long-term impact of past climate change on the Greenland Ice Sheet and estimate the size of the fluctuations. The mass budget approach (*3*) may be able to provide a more reliable long-term trend if internal radio echo layers in the ice can be used to reconstruct the spatial and temporal distribution of ice deposition over a longer time period (*4*).

It should be noted that the Greenland Ice Sheet contains only 10% of the ice bound globally in ice sheets. The Antarctic Ice Sheet contains almost all of the remainder. Its area is an order of magnitude larger, accumulation is a factor of 10 less, and ice shelves and ice grounded below present sea level further complicate the picture. The balance of the Antarctic Ice Sheet thus represents another extremely important challenge for the coming generations of air- and spaceborne remote sensing methods.




**Airborne measurements of ice sheet elevation changes.** Surface elevation changes of the Greenland Ice Sheet are detected by repeated laser altimeter surveys. The entire region above 2000 m is in balance within ±5 mm/year, whereas thinning predominates along 70% of the region below 2000 m. The net loss over the Greenland Ice Sheet leads to a sea level rise of 0.13 mm/year (*2*).

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PERSPECTIVES: QUANTUM COMPUTING

# Quantum Entangled Bits Step Closer to IT

**Anton Zeilinger**

Today's computers and methods of communication are based on digital technology, where information is represented in bits that either take the value "0" or "1." From a fundamental point of view, these machines and procedures are equivalent to the glass beads and smoke signals of the past. But as elements in computers become smaller and smaller and communication technologies try to use less and less energy to send the same information, individual bits will ultimately be represented by individual quantum systems. Fundamentally new phenomena such as quantum superposition and quantum entanglement will result, bringing with them novel ways of communication and computation with no analog in today's information technology. Recent research provides a glimpse into the future by realizing entanglement-based quantum cryptography and by demonstrating entanglement of more than two quantum systems with methods that may allow scaling up to even more particles.

A quantum bit, or qubit, can not only

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