MASS BALANCE OF GREENLAND ICE SHEET: NEW TASK FOR CONCEPTUAL MODELING

Kirill Khvorostovsky,

Nansen Environmental and Remote Sensing Center, Bergen, Norway

Email kirill.khvorostovsky@nersc.no

Cyril Pshenichny,

Geognosis Project, ITMO University, St. Petersburg, Russian Federation

Email cpshenichny@yandex.ru

In the studies of present climate changes the mass balance of the Greenland ice sheets (GrIS) is of particular interest because its potential melting is critical for sea-level change and freshwater impact on ocean circulation. Wide range of satellite measurements during the last two decades allowed significant improving of our knowledge about such extreme polar environments as ice sheets. Various estimates show that the GrIS mass balance over this period is negative and mass loss is accelerating in time [AMAP, 2011].

Previously it was considered that mass changes of the ice sheets on the decadal time scale are primarily caused by surface mass balance, i.e. difference between snow accumulation and water runoff due to summer surface melting. Area extent of the surface melting varies significantly from year to year, but water runoff occurs only in the narrow zone over GrIS margins, while above the equilibrium line most water from surface melting refreezes in the firn. In this case variability of snow accumulation is the main parameter of the mass balance over most area of the ice sheet. At the same time water runoff from melting accounts for about half of the mass loss from the ice sheet. Another source of mass loss is the ice discharge through iceberg calving. Rate of the ice discharge depends on the ice flow velocity, which was considered to vary very slowly as a response on mass balance changes hundreds and thousands years ago and therefore may be assumed as constant.

However recent studies have shown that ice flow velocity may vary considerably on inter-decadal and even inter-annual time scales [e.g. Rignot et al., 2011; Moon et al., 2012]. Significant ice loss over the GrIS low-elevation areas occurred during the last decade is explained partly by the intense surface melting due to increased temperature and partly by the acceleration of the ice flow. This acceleration is observed not only over the ice streams and outlet glaciers, characterized by the high flow velocities of up to several kilometers per year, but also propagates inland of the ice sheet. These rapid changes in ice flow velocities were not predicted by the ice flow models, which were not able to resolve short time scale variations of the ice dynamics and did not account for the effect of all external forcing components.

Currently two mechanisms responsible for the increased ice flow velocities are considered. One of them is related to changes in basal lubrication and sliding of the ice following increased melting on the surface and drainage through moulins [Zwally et al., 2002; Joughin et al., 2008; Van de Wal et al., 2008; Bartholomew et al., 2010]. Another mechanism is connected with changes in buttressing of outlet glaciers caused by removal of their floating ice tongues due to warmer waters and allowing ice-flow speed-up [e.g. Thomas et al., 2004; Nick et al., 2009]. However although these processes may explain recent ice flow acceleration it is not obvious that they will remain dominant over longer-term scale. For example, it was shown [van de Wal et al., 2008] that rapid drainage of melt water significantly speeds-up ice flow over the period of only several days implying that the englacial hydraulic system adjusts constantly to the meltwater input. As for another mechanism, high sensitivity of tidewater outlet glaciers to changes in their terminus boundary conditions may reflect only short-term (of several years) dynamical adjustments but cannot be maintained in the long term [Nick et al., 2009].

However not only understanding of the current GrIS mass changes, but also assessment of the mass balance still remains uncertain because various studies give different estimates. Three different methods are used for estimation of the GrIS (as well as the Antarctic ice sheet) mass balance [Alley et al., 2007; AMAP, 2011]. One is based on using radar or laser altimeter measurements from satellite or aircraft [e.g. Krabil et al., 2004; Johannessen et al., 2005; Zwally et al., 2005; Thomas et al., 2006; Zwally et al., 2011; Sørensen et al., 2011 Khvorostovsky, 2012]. This method gives direct assessment of the mass balance through estimating of ice volume changes from measured changes in the elevation. The mass budget method calculates input and output ice fluxes separately. Surface mass balance is determined from models and reanalysis, while survey of the ice discharge can be made from measurements of ice flow velocities along the coastline using satellite images [e.g. Rignot and Kanagnaratnam 2006; van den Broeke et al., 2009]. The third method is the use of satellite gravimetric measurements such as the Gravity Recovery and Climate Experiment (GRACE) that measure directly the difference between mass input and output [e.g. Luthke et al. 2006; Chen et al., 2006; Velicogna, 2009; Ramilen et al., 2006; Wouters et al., 2008, Wu et al., 2010]. The results obtained by different methods are in general agreement showing that the GrIS was near in balanced in 1990th, while from 2000th significant mass loss has began, and this loss accelerates gradually. As it was noted above current negative mass balance is primarily caused by the mass loss over the GrIS low-elevation areas due to increased surface melting and accelerating of the ice flow. In the interior regions the observed changes are comparatively small, although in some of these areas ice loss propagates inland that may be caused by the decrease of accumulation as well as by the effects of ice flow speed-up over margins. At the same time different mass balance estimates vary in a wide range even when obtained by the same method, and further studies are needed to come to an agreement.

To do this, in our opinion, the glacier dynamics should be better conceptualized, including its mass gain and mass loss by different mechanisms and their interplay. This will allow us to fix the list of “players” (i.e, portions of water coming to the glacier, portions of ice and firn and others), the external conditions and the rules of the “game” based on general glaciological, meteorological, hydrological and other related knowledge, trace the scenarios of glacier evolution under various conditions and their change, consider all possible relations between the real-world entities and physical parameters and, finally, link physical models and assumptions to the qualitatively outlined scenarios more or less in the way it was done in seismology for the site effects by the method of event bush [Carniel et al., 2011]. The obtained conceptual model is expected to put reasonable qualitative constraints on the physical and numerical modeling and decrease the uncertainty in interpretation of the observation data.

References

Alley, R. B., Spencer, M. K., and Anandakrishnan, S. 2007. Ice-sheet mass balance: Assessment, attribution and prognosis, Ann. Glaciol., vol. 46, no. 1, pp. 1–7, Oct. 2007.

AMAP, 2011. Snow, Water, Ice and Permafrost in the Arctic (SWIPA): Climate Change and the Cryosphere. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway. xii + 538 pp. (http://amap.no/swipa)

Bartholomew, I., P. Nienow, D. Mair, A. Hubbard, M.A. King and A. Sole. 2010. Seasonal evolution of subglacial drainage and acceleration in a Greenland outlet glacier. Nature Geosci., 3(6), 408–411.

Carniel, R., Pshenichny, C., Khrabrykh, Z., Shterkhun, V., Pascolo, P., 2011. Modeling Models: Understanding of Structure of Geophysical Knowledge by Means of the Event Bush Method, in: IAMG Proceedings, Mathematical geosciences at the crossroads of theory and practice, Marschallinger, R., and Zobl, F. (Eds.), Salzburg, September 2011, pp. 1336-1350; doi 10.5242/iamg.2011.0074.

Chen, J. L., C. R. Wilson, and B. D. Tapley (2006a), Satellite gravity measurements confirm accelerated melting of Greenland ice sheet, Science, 313, 1958–1960, doi:10.1126/science.1129007.

Johannessen, O. M., Khvorostovsky, K., Miles, M. W., and Bobylev, L. P., 2005. Recent ice-sheet growth in the interior of Greenland, Science, vol. 310, no. 5750, pp. 1013–1016, Nov. 2005.

Joughin, I., S.B. Das, M.A. King, B.E. Smith, I.M. Howat and T. Moon. 2008b. Seasonal speedup along the western flank of the Greenland Ice Sheet. Science, 320(5877), 781–783.

Khvorostovsky K. Merging and analysis of elevation time series over Greenland ice sheet from satellite radar altimetry. 2012, IEEE Trans. Geosc. Remote Sens., vol., 50, 1.

Krabill, W. and 12 others. 2004. Greenland Ice Sheet: increased coastal thinning. Geophys. Res. Lett., 31(2), L24402. (10.1029/2004GL021533.)

Luthcke, S.B. and 8 others. 2006. Recent Greenland ice mass loss by drainage system from satellite gravity observations. Science, 314(5803), 1286–1289.

Moon T., I. Joughin, B. Smith, I. Howat, 21st-Century Evolution of Greenland Outlet Glacier Velocities2012, Science 336, 576.

Nick, F.M., A. Vieli, I.M. Howat and I. Joughin. 2009. Large-scale changes in Greenland outlet glacier dynamics triggered at the terminus. Nature Geosci., 2(2), 110–114.

Ramillien, G., A. Lombart, A. Cazenave, E. R. Ivins, M. Llubes, F. Remy, and R. Biancale (2006), Interannual variations of the mass balance of the Antarctica and Greenland ice sheets from GRACE, Global Planet. Change, 53, 198– 208, doi:10.1016/j.gloplacha.2006.06.003.

Rignot, E. and P. Kanagaratnam. 2006. Changes in the velocity structure of the Greenland Ice Sheet. Science, 311(5673), 986–990.

Rignot, E., et. al., 2011, Geophys. Res. Lett., 38, L05503.

Sørensen, L.S., S.B. Simonsen, K. Nielsen, P. Lucas-Picher, G. Spada, G. Adalgeirsdottir, R. Forsberg and C.S. Hvidberg. Mass balance of the Greenland ice sheet (2003–2008) from ICESat data – the impact of interpolation, sampling and firn density. The Cryosphere, 5(1), 173-186, 2011.

Thomas, R., E. Frederick, W. Krabill, S. Manizade and C. Martin. 2006. Progressive increase in ice loss from Greenland. Geophys. Res. Lett., 33(10), L10503. (10.1029/2006GL026075.)

Thomas, R.H., E.J. Rignot, K. Kanagaratnam, W.B. Krabill and G. Casassa. 2004. Force-perturbation analysis of Pine Glacier, Antarctica, suggests cause for recent acceleration. Ann. Glaciol., 39, 133–138.

Van de Wal, R.S.W. and 6 others. 2008. Large and rapid meltinduced velocity changes in the ablation zone of the Greenland Ice Sheet. Science, 321(5885), 111–113.

Van den Broeke, M. R., Bamber, J., Ettema, J., Rignot, E., Schrama, E., van de Berg, W. J., van Meijgaard, E., Velicogna, I., and Wouters, B.: Partitioning recent Greenland mass loss, Science, 326, 984–986, 2009. 2434

Velicogna, 2009; Geophys. Res. Lett.,. 36, L19503, doi:10.1029/2009GL040222. Increasing rates of ice mass loss from the Greenland and Antarctic ice sheets revealed by GRACE

Wouters, B., D. Chambers, and E. J. O. Schrama (2008), GRACE observes small-scale mass loss in Greenland, Geophys. Res. Lett., 35, L20501, doi:10.1029/2008GL034816.

Wu et al.,. Simultaneous estimation of global present-day water transport and glacial isostatic adjustment 2010. Nature Geoscience, 3, 642-646.

Zwally et al., 2005. J. Glaciol.51, 509-527.

Zwally, H.J., J. Li, A.C. Brenner, M. Beckley, H.G. Cornejo, J. DiMarzio, M.B. Giovinetto, T. Neumann, J. Robbins, J.L. Saba, D. Yi & W. Wang Greenland ice sheet mass balance: distribution of increased mass loss with climate warming; 2003-07 versus 1992–2002, J. Glaciol. 57, 201, 88–102 (2011).

Zwally, H.J., W. Abdalati, T. Herring, K. Larson, J. Saba and K. Steffen. 2002. Surface melt-induced acceleration of Greenland ice-sheet flow. Science, 297(5579), 218–222.