SPECIAL PROJECT PROGRESS REPORT

Progress Reports should be 2 to 10 pages in length, depending on importance of the project. All the following mandatory information needs to be provided.

Reporting year	July 2010 – June 2011
Project Title:	Regional modelling of the Greenland surface mass balance for key episodes in past and future
Computer Project Account:	SPNLGSMB
Principal Investigator(s):	Dr. E. van Meijgaard
Affiliation:	Royal Netherlands Meteorological Institute (KNMI)
Name of ECMWF scientist(s) collaborating to the project (if applicable)	
Start date of the project:	1 January 2008
Expected end date:	31 December 2011

Computer resources allocated/used for the current year and the previous one
(if applicable)
Please answer for all project resources

		Previous year		**Current year**	
		Allocated	Used	Allocated	Used
High Performance Computing Facility	(units)	500 kSBU	623	499 kSBU	365
Data storage capacity	(Gbytes)	500		500	

Summary of project objectives

(10 lines max)

In this project, the surface mass balance of the GrIS will be modelled for the present-day climate and for key periods in the past and future. By using a regional atmospheric climate model (RACMO2), driven at the boundaries by state-of-the-art atmospheric general circulation models, this can be done at unprecedented high resolution (11 km) to match the typical resolution of ice dynamical models. Another big advantage of using a meteorological model is the availability of spatially and temporally realistic melt fluxes to study the interaction with ice dynamics. With results from this research we will be able to hindcast and predict the changes in the volume of the GrIS with much improved accuracy and with that its contribution to past and future changes in global sea level.

Summary of problems encountered (if any)

(20 lines max)

No problems were encountered.

Summary of results of the current year (from July of previous year to June of current year)

See paragraph APPENDED at bottom of this document

List of publications/reports from the project with complete references

Ettema J., M.R. van den Broeke, E. van Meijgaard, J. Bamber, R. Gladstone, 2008: Greenland surface mass balance using a regional atmospheric climate model, In proceedings of *The dynamics and mass budget of Arctic glaciers*, Workshop on the dynamics and mass budget of Arctic glaciers, 28 January - 1 February 2008, Obergurgl, Austria. Ed.: J. Oerlemans and C.H. Tijm-Reijmer

Ettema, J., M. R. van den Broeke, E. van Meijgaard, W. J. van de Berg, J. L. Bamber, J. E. Box, and R. C. Bales, 2009, Higher surface mass balance of the Greenland ice sheet revealed by high-resolution climate modeling, Geophys. Res. Lett., 36, L12501, doi:10.1029/2009GL038110.

Broeke, M.R. van den, J. Bamber, J. Ettema, E. Rignot, E. Schrama, W.J. van den Berg, E. van Meijgaard, I. Velicogna en B. Wouters, Partitioning Recent Greenland Mass Loss, Science, 2009, **326**, 5955, 984-986, doi:10.1126/science.1178176.

Ettema J., 2010: The present-day climate of Greenland – a study with a regional climate model, Ph.D. Thesis, University of Utrecht

Ettema, J., van den Broeke, M. R., Van Meijgaard, E., and Van de Berg, W. (2010a). Climate of the Greenland ice sheet using a high-resolution climate model, part 1: Evaluation. The Cryosphere, 4, 561–602.

Summary of plans for the continuation of the project

(10 lines max)

The project will NOT be continued beyond 2011.

Summary of results of the current year

Introduction

As part of the RAPID Climate Change program we aim to investigate the potential effects of rapid climate changes on the surface mass balance and freshwater contributions of the Greenland ice sheet, as well on the climate conditions in the Greenland region. In the past year, output of the well evaluated multi-annual integration with the regional climate model RACMO2.1/GRN (Ettema et al., 2010a) is used to study the momentum budget of the Atmospheric Boundary Layer over the Greenland Ice Sheet.

Model setup

RACMO2.1/GRN is adapted from the KNMI regional climate model RACMO2.1 (van Meijgaard et al., 2008). It consists of the atmospheric dynamics of the High-Resolution Limited Area Model (HIRLAM) and the physical processes package from the European Centre for Medium-Range Weather Forecasts (ECMWF), cycle 23r4. The horizontal resolution of RACMO2.1/GRN is about 11 km. The model employs 40 hybrid levels in the vertical, of which the lowest is about 10 m above the surface. ERA-40 fields force the model at lateral boundaries complemented with ERA-Interim fields from 1989 onwards.

In recent years, RACMO2.1/GRN has been equipped with a multilevel snow scheme (Ettema et al., 2009), while a new snow albedo scheme that follows the evolution of snow grain sizes in the snow pack (Kuipers Munneke et al., 2011) has been installed and tested during the reporting year. Moreover, a snowdrift routine that takes into account the two-way interactions between snowdrift and the overlying atmosphere and underlying snow surface, has been developed and applied to the Antarctic ice sheet (Lenaerts et al., 2010) and will now also be used in RACMO2.1/GRN.

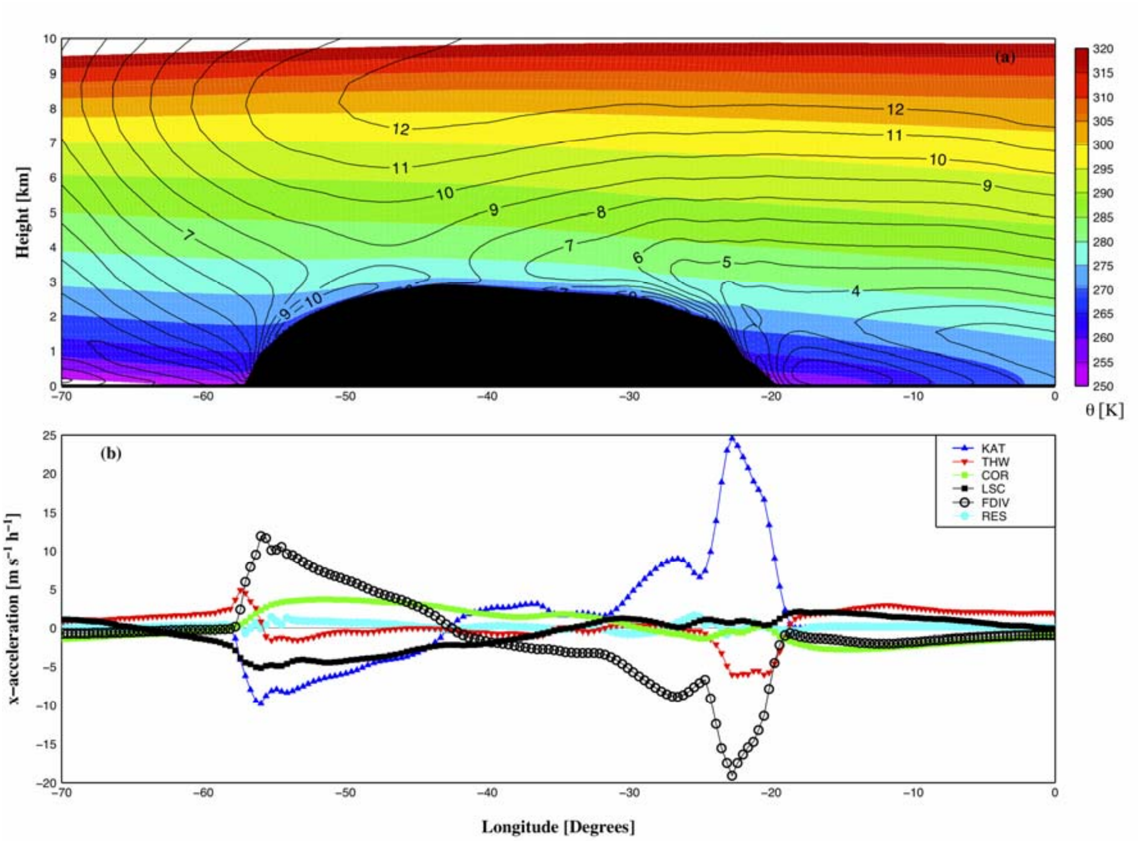

Figure 1*: A*verages for the winter months (1958-2007) for a transect through North Greenland; a: potential temperature and wind speed, b: momentum budget components in the lowest model layer (~7 m).

Momentum budget of the Atmospheric Boundary Layer over the Greenland Ice Sheet and its surrounding oceans.

Output of the RACMO2.1/GRN run are used to study the circulation patterns over the Greenland Ice Sheet (GrIS) and its surrounding seas by explicitly calculating the momentum budget components (Van Angelen et al., 2011a). In winter (DJF), the katabatic pressure gradient force (PGF) dominates the momentum budget of the atmospheric boundary layer (ABL) over the ice sheet. Over the western slopes of the ice sheet, the large scale PGF acts in the same direction as the katabatic PGF, resulting in a strong southerly jet of up to 12 m s^{-1} (Figure 1). In winter, the accumulation of cold air over the sea ice along the northeast coast leads to a thermally induced northerly flow. This flow is defined as the 'Greenland Sea Jet' (GSJ) and is strongly related to sea ice export through Fram Strait (Van Angelen et al., 2011b). Although the thermal wind forcing is dominant, the inter-annual variability of the GSJ and thus sea ice export is caused by variations in the large scale forcing (Figure 2). Along the west coast, a similar west-east temperature gradient also forces a northerly flow. In the summer months, sea ice is absent and thermal wind forcing is largely reduced over the ocean. Summer insolation also reduces katabatic forcing, the large scale forcing dominates the ABL momentum budget over the ice sheet. Heating of the ABL over the snow free tundra induces thermal contrasts with the ice sheet and ocean, forcing barrier winds in the coastal regions.

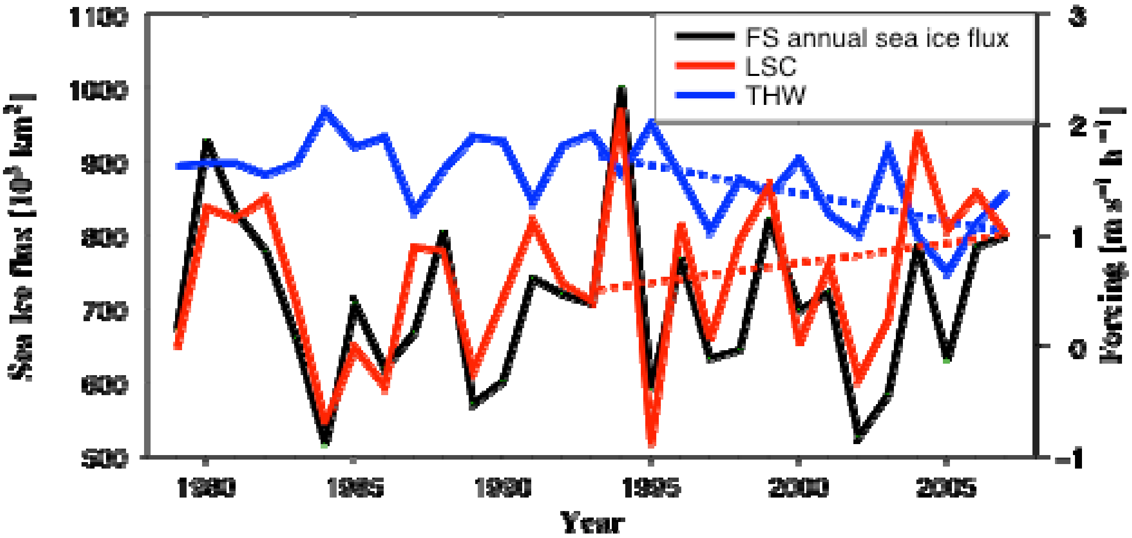

***Figure 2.** Yearly averaged values for sea ice flux through Fram Strait (black), averaged large scale forcing, LSC (red) and thermal wind forcing, THW(blue) in the Fram Strait region.*

Present day work

Currently, a new albedo scheme, based on snow grain size evolution, cloud optical thickness, and solar zenith angle is implemented in RACMO2.1/GRN (adapted from Kuipers Munneke et al., 2011). First test results are promising with a better representation of the ablation area and length of the melt season. Furthermore a background ice albedo based on MODIS satellite data for the period 2002-2010 will be implemented, since spatial variations in ice albedo are large.

In addition, we include snowdrift physics in RACMO2.1/GRN. We expect snowdrift to form a significant contribution to the surface mass balance (SMB, the balance of incoming mass (precipitation) and removed mass (meltwater runoff, sublimation and snow erosion at the ice sheet surface) in the dry and windy regions of the Greenland ice sheet. We will also investigate feedbacks between snowdrift and the atmosphere and snow surface, and seasonality and interannual variability of the different SMB components. Figure 3 illustrates the mean annual accumulated amount of snowdrift sublimation (left) and snow erosion (right) for the period 1995-2008, as modeled by RACMO2.1/GRN. Snowdrift sublimation equals 50-100 mm in most coastal regions, whereas snow erosion is more locally important (> 20 mm).

Outlook

With the major changes in the model physics a new integration for the period ERA-40/ERA-Interim era (1958-2011) will be performed in the coming months, followed by a scenario run in the framework of the Ice2Sea project (1980-2100). Results will become available throughout the year 2012 and will be published in the new IPCC report (AR5, 2013).

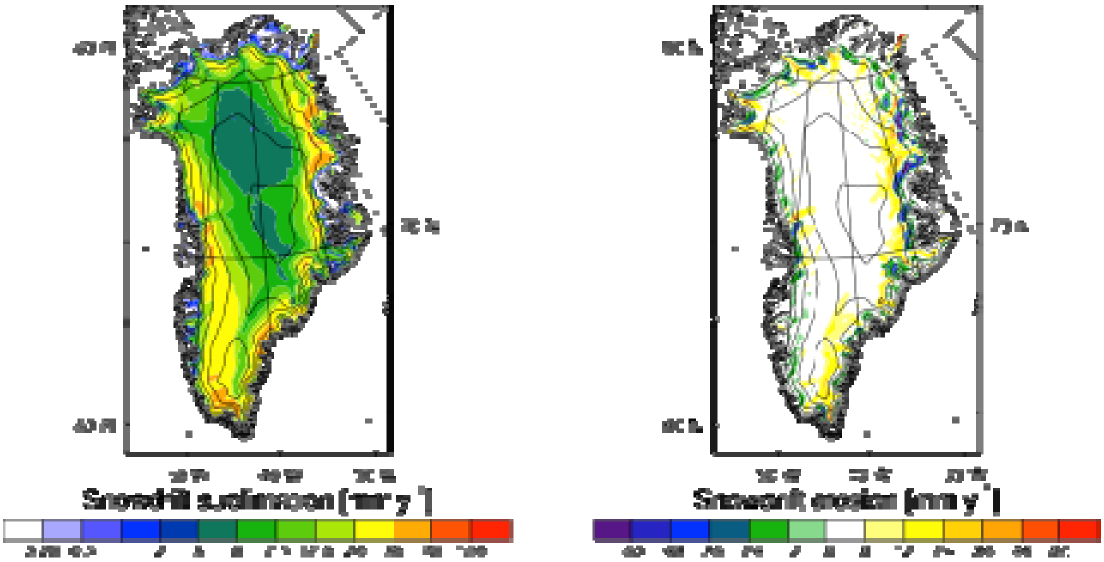

Figure 3. *Annual mean (1995-2008, mm y^{-1}) snowdrift sublimation (left) and snow erosion (right) from RACMO2.1/GRN.*

References

Ettema, J., M.R. van den Broeke, E. van Meijgaard, W.J. van de Berg, J.L. Bamber, J.E. Box, and R.C. Bales (2009), Higher surface mass balance of the Greenland ice sheet revealed by high-resolution climate modeling, *Geophys. Res. Lett.*, *36* (L12501), doi:10.1029/2009GL038110.

Ettema, J., van den Broeke, M., Van Meijgaard, E., and Van de Berg, W. (2010a). Climate of the Greenland ice sheet using a high-resolution climate model, part 1: Evaluation. The Cryosphere, 4, 561–602.

Kuipers Munneke, P, M. R. van den Broeke, J. T. M. Lenaerts, M. G. Flanner, A. S. Gardner, and W. J. van de Berg (2011), A new albedo parameterization for use in climate models over the Antarctic ice sheet, *J. Geophys. Res.*, 116, D05114, doi:10.1029/2010JD015113.

Lenaerts, J.T.M., M. R. van den Broeke, S. J. Déry, G. König-Langlo, J. Ettema, and P. Kuipers Munneke, (2010): Modelling snowdrift sublimation on an Antarctic ice shelf. The Cryosphere, 4, 179-190, doi:10.5194/tc-4-179-2010

Meijgaard, E. van, L.H. van Ulft, W.J. van den Berg, F.C. Bosveld, B.J.J.M. van den Hurk, G. Lenderink, A.P.Siebesma, 2008: The KNMI regional atmospheric climate model RACMO, version 2.1. KNMI Technical Report **302**, 43 pp. Available from KNMI, Postbus 201, 3730 AE, De Bilt, The Netherlands.

Van Angelen, J.H., M. R. van den Broeke, and W. J. van de Berg (2011a), Momentum budget of the atmospheric boundary layer over the Greenland ice sheet and its surrounding seas, *J. Geophys. Res.*, 116, D10101, doi:10.1029/2010JD015485

Van Angelen, J. H., M. R. van den Broeke, and R. Kwok (2011), The Greenland Sea Jet: A mechanism for wind-driven sea ice export through Fram Strait, *Geophys. Res. Lett.*, 38, L12805, doi:10.1029/2011GL047837.