Modelling of Greenland summer 1991 with a coupled atmosphere -snow regional climate model in view of surface melt calculations

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The last IPCC report predicts more important snow falls in winter and an increase of the summer melting in Greenland. Without quantifying it, General Circulation Models (GCMs) predict that this last phenomenon will dominate. A subsequent mass loss of the Greenland ice sheet will occur, with an impact on sea level and possibly on the Atlantic Ocean circulation. A more precise estimate of this mass loss requires notably a fine spatial resolution, elaborated atmospheric physics (e.g., to simulate katabatic wind) and a detailed representation of the snow-ice surface, as in the coupled atmosphere-snow model MAR used at UCL-ASTR.

The ability of MAR to simulate the Greenland climate is assessed by simulating the 1991 melting season. MAR results compare favourably with observations from weather stations or satellite derived data, including local components as the melt parameters. The comparison to the ECMWF re-analysis highlights the interest of a regional model to study the Greenland climate and its mass balance.

MAR description

We use here the regional atmospheric climate model **MAR** (**M**odèle **A**tmosphérique **R**égional) coupled with a multi-layered energy balance one-dimensional snow model. The atmospheric part of MAR is fully described in Gallée and Schayes (1994) and Gallée (1995). MAR is a hydrostatic primitive equation model in which the vertical coordinate is the normalized pressure $\sigma = (p - p_t) / (p_s - p_t)$ where p, p_t and p_s are respectively the actual pressure, the constant model top pressure and the surface pressure. The solar radiation scheme is that of Fouquart and Bonnel (1980). The longwave radiation scheme follows a wide-band formulation of the radiative transfer equation (Morcrette 1984). The heat and moisture exchanges over land are represented with the surface model of Deardorff (1978). The hydrological cycle based on the Kessler (1969) parametrisation is fully described in Gallée (1995). The boundaries are treated according a dynamic relaxation that includes a Newtonian term and a diffusion term (Davies 1983; Marbaix et al. 2002). The parameterization scheme for the surface layer is based on Businger (1973) and Duynkerke (1991) formulations. In view of the complex structure of the Katabatic layer, the E-ε order closure form Duynkerle (1988) are used.

Sea surface temperatures from which is deduced the sea ice distribution are prescribed from the Reynolds SST's data (Reynolds and Smith, 1994). An albedo of 0.10 and 0.70 is respectively fixed for the open water and the sea ice. For the tundra around the Greenland ice sheet, the force-restore surface model of Deardorff (1978) represents the heat and moisture exchanges over land in case of snow-free surface (with an albedo of 0.20). In case of snow deposition, the snow model is used.

The snow-ice model, part of the model MAR as an interactive lower boundary rules the exchange between both sheet ice surface and snow covered tundra, and atmosphere. Its physics and validation are described in detail in Gallée and Duynkerle (1997) and Lefebre et al. (2002). In particular, the albedo is function (i) of the simulated snow grains forms and size represented by the CROCUS snow metamorphism laws (Brun et al., 1992), (ii) the snow depth, (iii) the cloudiness and (iv) in case of all snow has melted away in the ablation zone, the amount of meltwater accumulated upon the ice which reaches values lower than ice albedo fixed to 0.55. The percolated surface meltwater and internal meltwater can refreeze and form superimposed ice taken into account in the albedo computations.

Model evaluation at ETH-Camp

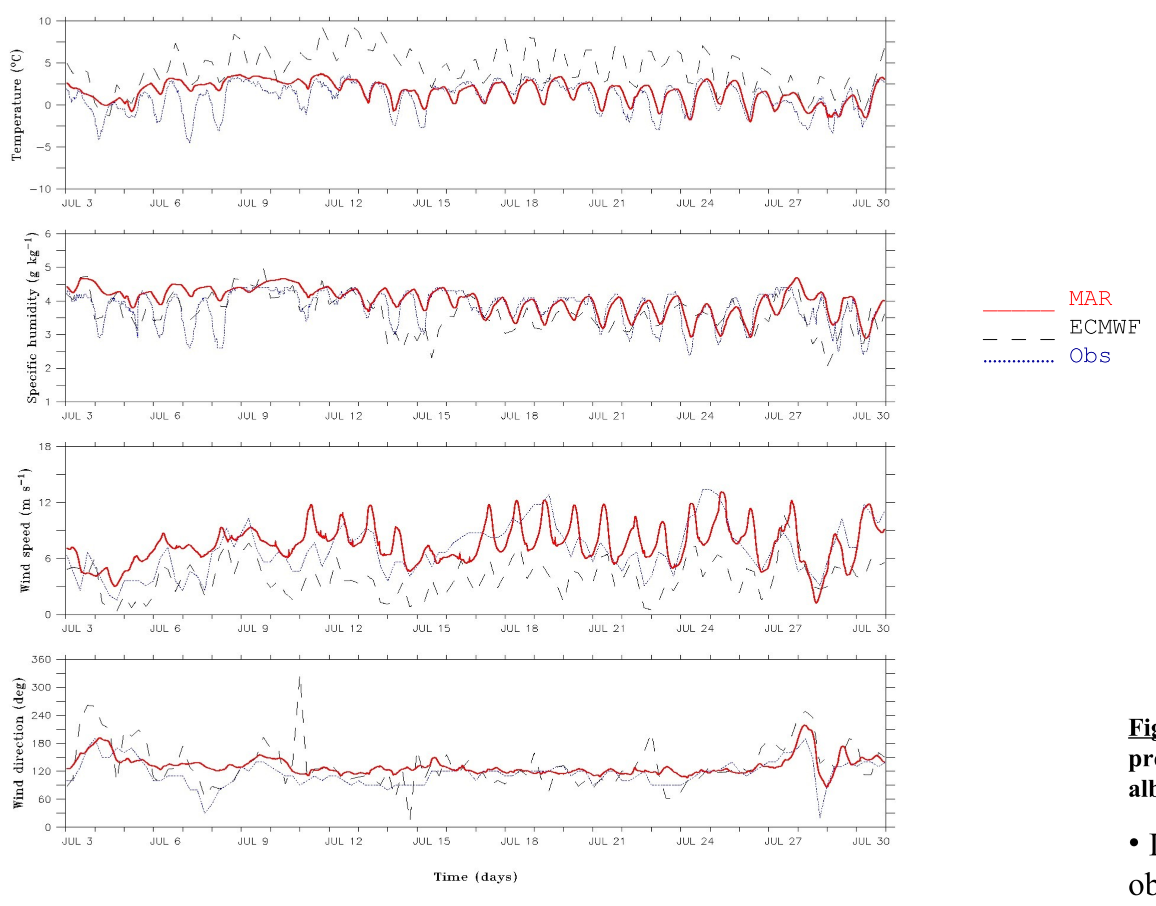

Fig1: Comparison between observed (dotted black), MAR (solid red) and ECMWF (dashed blue) modelled air temperature, specific humidity, wind speed and wind direction from half-hourly values during July 1991 at ETH-Camp (Ohmura et al., 1992).

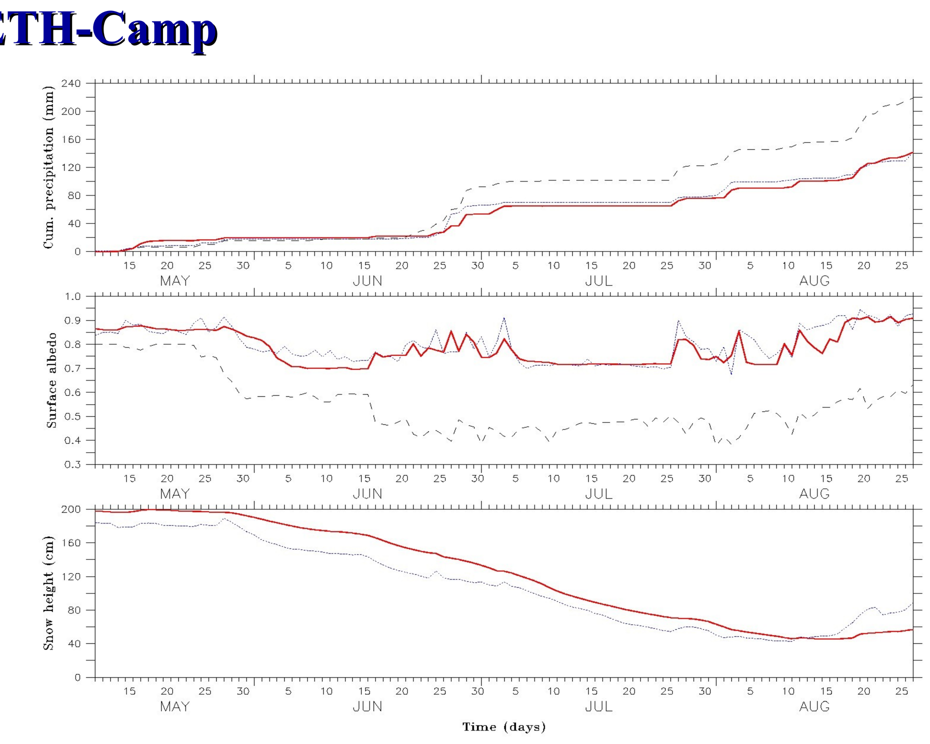

Fig2: Top: Observed (dotted blue), MAR (solid red) and ECMWF (dashed black) cumulative precipitation at ETH-Camp (Ohmura et al., 1993); Middle: same as above but for the surface albedo; below: same as top graph but for the snow pack height.

- Figure 1 demonstrates MAR ability to simulate correctly the daily cycle for the most important near-surface atmospheric parameters. The refreezing during night and diurnal melting characterized by a surface temperature of 0°C are good simulated by MAR. Similarly for the direction and wind speed which are in agreement with katabatic observed wind.
- Globally, ECMWF overestimates surface temperature and underestimates katabatic winds speed. Although interpolated values close to the ERA-15 ice sheet margin may be influenced by the presence of the tundra area, the error is certainly also due to the underestimated surface height in ECMWF model and the poor vertical resolution since the lowest ECMWF level is situated at 40 m above the surface. At 70° North, the west-east ERA-15 resolution is 2.8125 degrees (~106 km).
- During the whole simulation, MAR modelled snow albedo closely follows the observed snow albedo variations, i.e. the lowering of the albedo due to growing snow grains when melt takes place and the abrupt increases due to snow falls, very well simulated in frequency and intensity by the atmospheric model component. The simulated snow height above the ice is also in good agreement with observations.
- The use of a surface temperature dependent snow albedo in the ERA-15 re-analysis project clearly induces too low albedo values from the moment melt occurs (at the end of May). It can be seen too that ECMWF overestimates precipitation at ETH-Camp during 1991 summer.
- Previous experiments in which the ECMWF simulated 1990-1991 winter snow fall was used to determine the snow pack mass balance at the start of the simulation lead to worse model results because ECMWF winter precipitation is lower than the Bromwich et al. (2001) estimate. This resulted in a too rapid clearing of the snow pack which lowered the surface albedo and lead to an underestimated surface mass balance.

Model Setup

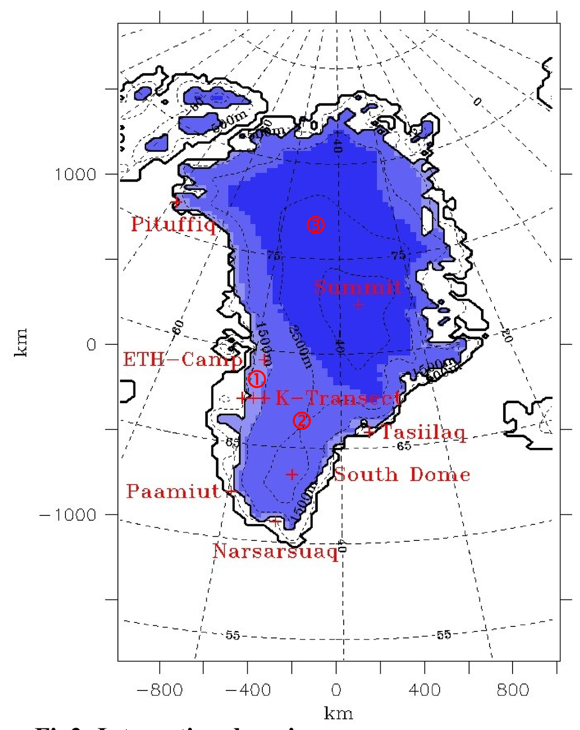

Fig3: Integration domain.

MAR coupled with a snow model		
Begin	01/05/1991	
End	31/08/1991	
Size of domain	2000 km x 3750 km	
Resolution	25 km	
MAR time step	1 min	
Snow model time step	5 min	
1st level	2 m	
Boundary forcing	Every 6h by ERA15	
Ablation Zone ①	20 m ice	+ 1990-1991 snow pack from Bromwich et al.
Percolation Zone ②	20 m snow	
Snow dry Zone③	20 m snow	

Precipitation

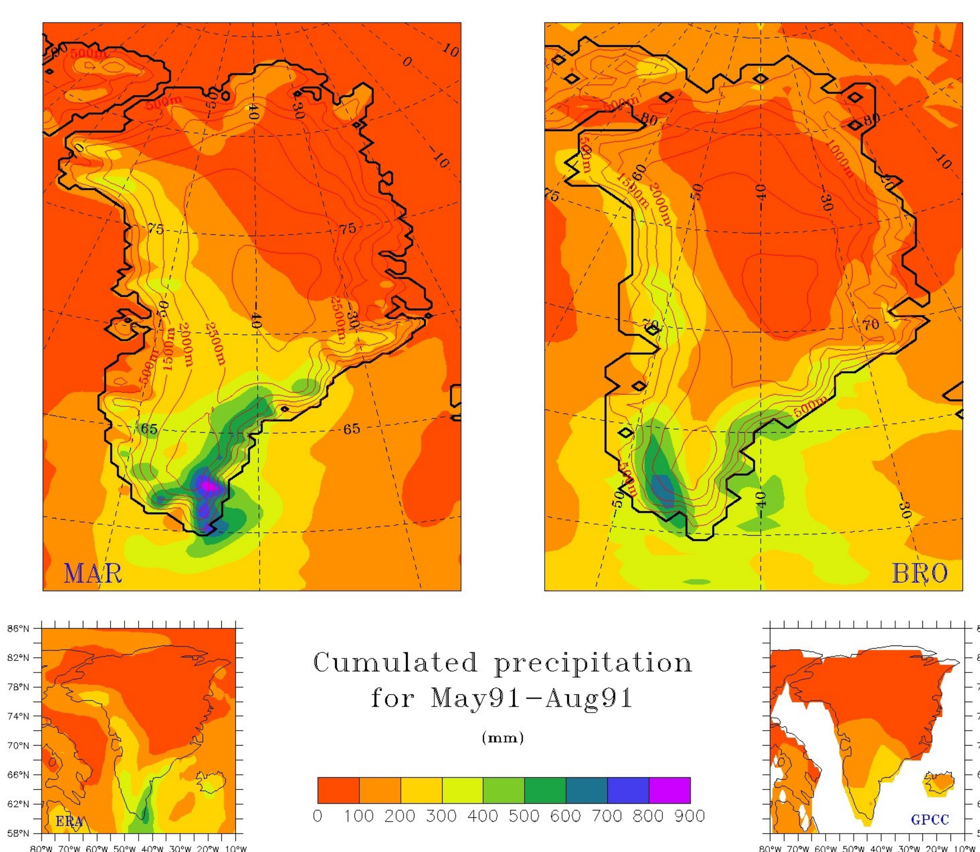

Fig4: Cumulated precipitation from May 1991 to Augustus 1991 a) simulated by MAR (top left), b) by Bromwich et al. (2001) (top right), c) from the ERA-15 re-analysis (below left) and d) from the GPCC climatology (below right).

- Except in South Greenland, MAR approaches relatively well in quantity and distribution the modelled precipitation from Bromwich et al. (2001). The figures 5a and 5b both show a maximum of precipitation situated along the western and south-eastern coast, and a minimum in north central Greenland. The topography influence on the simulated precipitation appears more clearly in MAR than in precipitation of Bromwich et al. (2001) who use a coarser resolution of 50 km.
- The MAR overpredicted precipitation, in the South Greenland along the coast and steep windward margins, is very probably associated to the "topography barrier effect". It modifies the horizontal flow, or contributes to raise air masses and to produce condensation and precipitation during their forced ascent. This overestimation is too present in the Polar MM5 model simulations (Cassano et al. (2001)).
- Clearly, the GPCC climatology (resol. 1 degree) based on extrapolated weather station measurements appears much less reliable in Greenland, in view of the lack of weather stations. A direct comparison with the ERA-15 re-analysis is less significant because of the great differences between topography and resolutions used by both models (Bromwich et al., 2001).

Surface melt

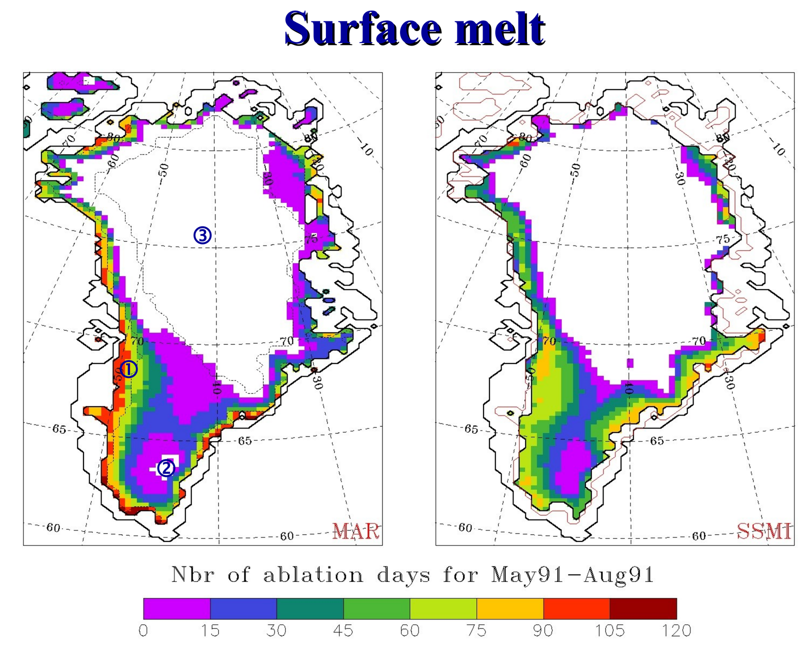

Fig5: Total number of ablation days from May 1991 to Augustus 1991 a) simulated by MAR (left) and b) from melt field of Abdalati et Steffen (1997) based on data of the Special Sensor Microwave/Imager (SSM/I). As mentioned in Abdalati and Steffen (1997), a mean liquid water content (LWC) of 1 % by volume in the top meter of snow is used as threshold value to distinguish melt from non-melt points in the simulation.

- Despite the differences between both ice sheet masks, the different snow areas on the ice sheet (ablation, percolation and dry snow zone) clearly appear on both figures and are in very good agreement. MAR ice sheet is comparatively longer and slopes down lower, which explains a more significant melt in the lower ablation zone.

While along the south-eastern relief, MAR limits the melt in the ablation zone and underestimates the melt on the summits. On the one hand, MAR overestimates snow precipitation in this region which increases the albedo and then decreases the melt. On the other hand, the satellite derived melt values may constitute an overestimation in the high percolation area. The influence of crusts and ice layers on microwave derived melt extent should be investigated into more details by comparing in-situ data from a site located in the higher percolation area with the satellite corresponding data.

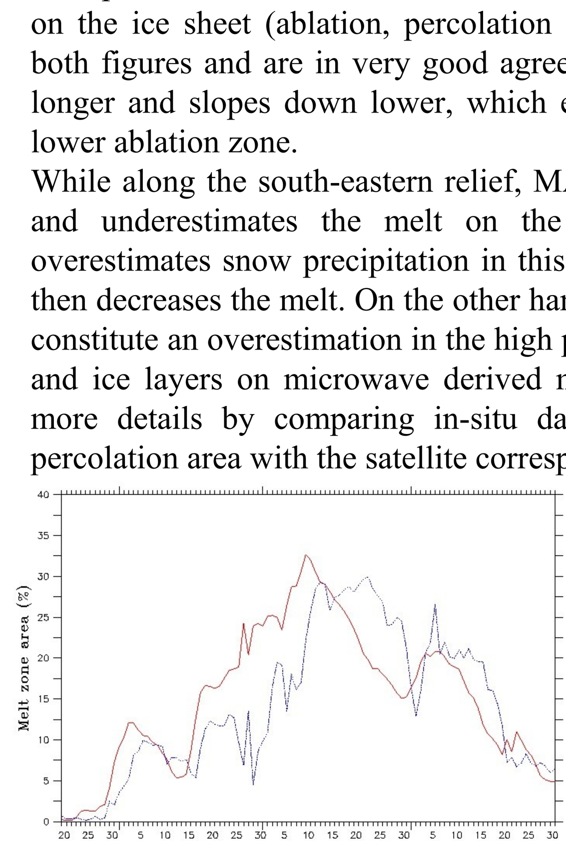

Fig6: Comparison between MAR modelled (red) and SSM/I satellite derived (blue) daily average melt extent. Melt is expressed in percentage of the part of the ice sheet that lies in the satellite derived melt grid and MAR domain respectively.

- The simulated timing and amplitude of melt onset and maximum melt compare very well to the satellite derived area. For example, the melt begins the first week of June 1991 followed by a decrease next week. Similarly, the first maximum melt occurs in early July and the second in early August are well represented by the model.

Conclusion:

The coupled atmosphere-snow model **MAR** has been applied over whole Greenland at a horizontal resolution of 25 km during 1991 ablation season with forcing from ECMWF re-analysis. The simulation is first validated successfully with observations from the ETH-Camp weather station situated on the equilibrium line. The comparison with the ECMWF re-analysis highlights the usefulness of a regional model to study the Greenland climate and its mass balance. Next, we compare with success the high resolution MAR precipitation with modelled 50km-precipitation from Bromwich et al. (2001), more significant and reliable in Greenland by comparison with precipitation from ERA-15 and classical climatologies (GPCC). Finally, we evaluate MAR simulated melt zone with satellite derived melt signal from Abdalati et Steffen (1997) based on data from SSM/I. Despite the differences between both ice sheet masks, the simulated timing and amplitude of melting, and the simulated melt zone distribution compare very well with the satellite derived data.

It appears that the accurate melt parameters (required for a good surface mass balance simulation) depend strongly on the state of the snow pack at the start of the ablation season. This means that modelling activities should also focus on the winter accumulation processes at high resolution (precipitation and snow drift). In a next step, simulations covering longer time periods should be foreseen in order to study for example the origins and mechanisms behind the inter-annual variability of the Greenland surface mass balance.

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