

5.2 EXTREME PRECIPITATION EVENTS OVER GREENLAND: CONSEQUENCES TO ICE SHEET MASS BALANCE

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1. INTRODUCTION

Greenland, Earth's largest island ($2.17 \times 10^6 \text{ km}^2$), is 81% covered by 3.2×10^6 cubic kilometers (km^3) of frozen precipitation. Of the $\sim 600 \text{ km}^3$ annual total mass input by precipitation, $\sim 500 \text{ km}^3$ remains after the wind consumes $\sim 100 \text{ km}^3$ by sublimation/evaporation (Box et al., 2004). The accumulated mass drives ice deformational flow resulting in $\sim 239 \text{ km}^3$ iceberg discharge with $\sim 32 \text{ km}^3$ basal melting (Reeh et al. 1999). Between 200-550 km^3 or approximately half of the annual mass input is lost by freshwater discharge (Zwally and Giovinetto, 2000; Box et al., 2004), making Greenland unique as compared to the other ice sheet in Antarctica, where runoff from surface melting is very small ($<1\%$) as compared to the other loss terms.

This study examines observational and modeled data related to the case of a persistent atmospheric circulation anomaly that led to large precipitation anomalies over the southeastern and southwestern slopes of the ice sheet. The impact of snow accumulation anomalies on melt rates are investigated in terms of snow depth on underlying relatively low albedo 'glacial ice'. We explore and describe this case in detail, seeking insight into major surface mass balance sensitivities.

2. DATA

We employ a variety of data sources in this study, including: mesoscale atmospheric model output at two horizontal resolutions, 12 km and 24 km; automated weather station observations from locations on the inland ice; visible satellite imagery from The Moderate Resolution Imaging Spectroradiometer (MODIS); MODIS-derived albedo based on an algorithm described in Stroeve et al. (2004); and NCEP/NCAR atmospheric Reanalysis Data (NNR) (Kalnay et al. 1996; Kistler et al. 2001) for a longer-term perspective. Regional model configuration, validation, and data description can be found in Box et al. (2004). The 24km data were updated after this publication which analyzed 1991-2000 data, to include three more years: 2001-2003.

3. THE ANOMALY

September 2002 – April 2003 was characterized by relatively high pressure over the Norwegian Sea and relatively low pressure southeast of the southern tip of Greenland (Figure 1). This blocking pattern promoted weather systems to impinge more often than normal along the southeast coast of Greenland, resulting in a circulation regime that delivered abnormally large and frequent storms to southeastern Greenland. Fewer west Greenland storms and precipitation shadow effects

caused relatively little precipitation along the southwest slope (Figure 2).

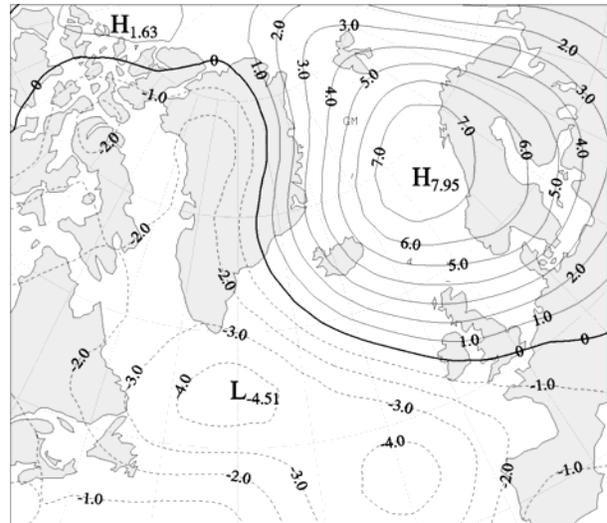


Figure 1. Mean sea level pressure anomaly: (September 2002 – April 2003) minus September – April 1972-2002 derived from NCEP/NCAR Reanalysis data. Units are hPa.

Climatologically, this event was unprecedented in the NNR record spanning 1948 – 2003, identified by mean pressure differences between a southern and a northern region. The southern area is defined by 52.5N to 60N latitude and 35°W to 50°W longitude. The northern box is 65-72.5°N and 5°W to 15°E longitude. Recorded as such, events nearly as strong occurred in 1954, 1960, and 1985. Use of a longer, historical SLP data set extending to 1900 (Trenberth and Paolino, 1980) also indicated that the 2003 event was the strongest on record although relative strong addition events also occurred in 1929 and 1940, in addition to 1954, 1960, and 1985 events.

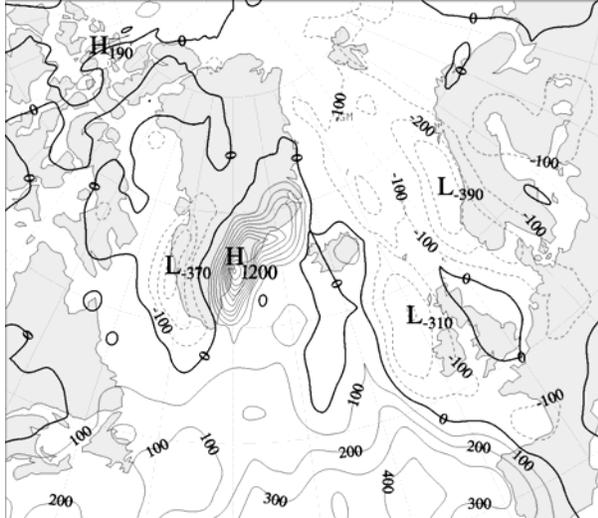


Figure 2. Precipitation anomaly (September 2002 – April 2003) minus September – April 1972-2002 average derived from NCEP/NCAR Reanalysis data.

3. PRECIPITATION AND ALBEDO

The negative precipitation anomaly along southwest Greenland had important implications for melt season potential for two reasons: 1) relatively low surface albedo resulted from little (or no) seasonal snow accumulation in the ablation zone (Figure 3) and 2) less seasonal snow would promote a larger than normal melt season given less snow to burn-off before the normal glacial ice ablation.

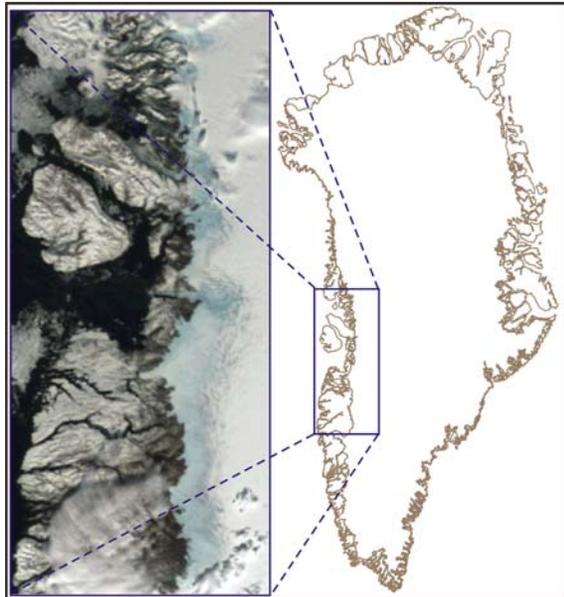


Figure 3. MODIS imagery over the Jakobshavn ablation region (R:CH1, G:CH4, B:CH3): 17 April 2003 of west Greenland showing blue ice, i.e. no seasonal snow accumulation.

4. ATMOSPHERIC DYNAMICS

We investigated the atmospheric dynamics of this event using the Polar MM5 model (Bromwich et al. 2001; Cassano et al. 2001) run at 12 km horizontal

resolution and an additional 6 vertical levels (35 total) were used.

Figure 4 shows an atmospheric cross section during a case of particularly intense atmospheric circulation, onshore flow, and precipitation. The orographic barrier imposed by the ice sheet promoted strong updrafts along the eastern slope which promoted non-convective precipitation rates of up to 9 mm h^{-1} , water equivalence (w e). Isentropes and wind vectors indicate wave-patterns, including strong up and downdrafts near the western ice sheet edge. These waves were experienced first hand, by passengers on Twin Otter and LC-130 flights forced to return from attempts to be delivered to camps from Kangerlussuaq to Swiss Camp and DYE-2 the western ice, respectively. Potential vorticity patterns indicate wind shear maxima at the transition of the atmospheric boundary layer with the outer synoptic layer.

Dataset: H3 RIP: H3-cross Init: 0000 UTC Tue 15 Apr 03
 Pct: 28.00 Valid: 0400 UTC Wed 16 Apr 03 (2200 MDT Tue 15 Apr 03)
 Potential vorticity XY= 19.3, 73.7 to 101.0, 90.9
 Potential temperature XY= 19.3, 73.7 to 101.0, 90.9
 Circulation vectors XY= 19.3, 73.7 to 101.0, 90.9

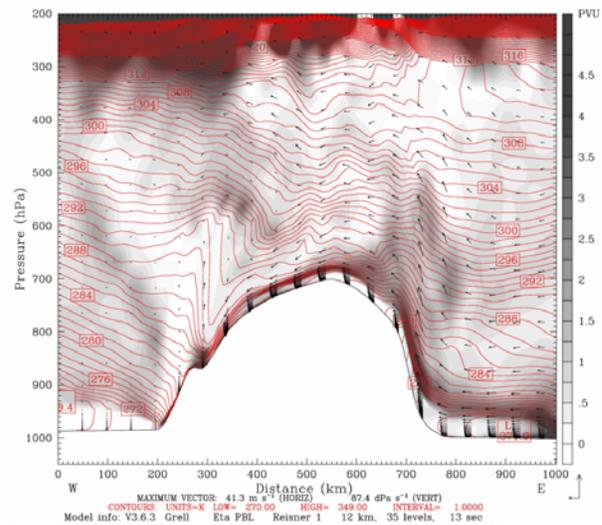


Figure 4. W-E cross section 16 April 2003 0400 UTC, showing: isentropic surfaces (red lines); atmospheric motion vectors (arrows); and potential vorticity (grey shading).

Figure 5 illustrates Polar MM5 forecast precipitation for the day with largest precipitation rates, i.e. April 16, 2003. For this day, forecast 24h maximum precipitation of 21 cm near 1100 m elevation at grid location 64.9° N , 41.4° W on the southeastern slope of the ice sheet, west of Jens Munk Is. There is notable precipitation intensification offshore, apparently from upstream effects. However, by far, most of the precipitation intensification occurs over land. Extremely large spatial gradients are apparent near the precipitation maxima, denoted by yellow and black colored grid cells in Figure 5.

Average maximum total (solid + liquid) precipitation based on 11 years of 24 km Polar MM5 output (1991-2001) is 2100 mm y^{-1} . Maximum precipitation for 2002 was 4097 mm y^{-1} and 3721 mm y^{-1} for 2003.

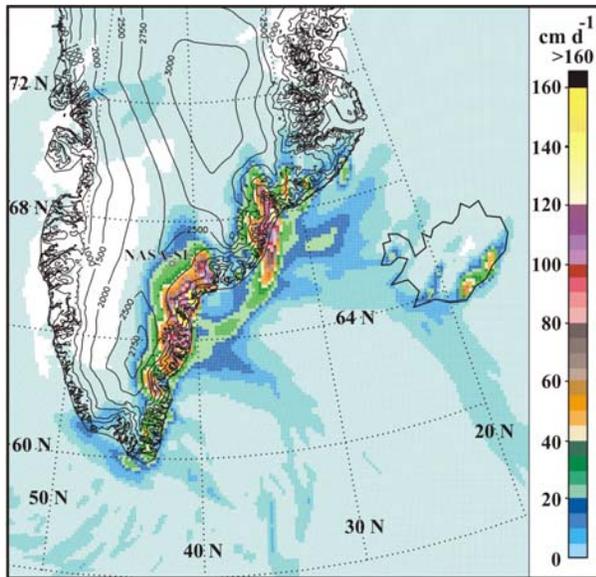


Figure 5. Accumulated precipitation from 24h Polar MM5 forecast at 12 km horizontal resolution, 16 April 2003.

Observations from the NASA-SE automatic weather station indicate a large single accumulation event, i.e. 65 cm in 7 hours on 15 April, 2003 (Figure 6A). This snow accumulation was then drifted and compacted to a thickness of 40 cm by very strong winds ($>25 \text{ m s}^{-1}$ hourly means) (Figure 6B). Modeled cumulative precipitation does not capture this high frequency signal, however, but rather simulates a more gradual precipitation accumulation.

The comparison between modeled precipitation and in-situ surface height observations is complicated by factors that affect the in-situ surface height signal, i.e., snow compaction; blowing snow transport divergence; and surface water vapor fluxes. Modeled wind speed magnitude is accurate on average, but also does not correspond well in terms of high frequency variability. Further model experimentation is needed. It is probably unreasonable to expect a model to capture the high frequency wind variability as this is a highly localized variable.

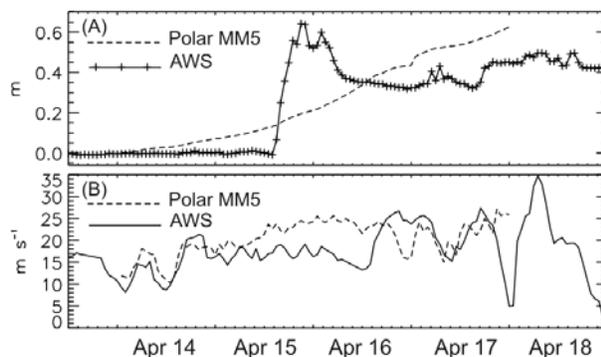


Figure 6. Comparison of automatic weather station and Polar MM5 values. (A) in-situ surface snow height observations and modeled water equivalent precipitation (cm). The lower figure (B) indicates modeled and observed wind speed.

5. ICE SHEET MASS BALANCE SENSITIVITY

In a sensitivity experiment, 19-year mean daily albedos (1982-1999) from Key et al. (2001) were used in place of the 2003 daily MODIS albedo data to determine the impact of the western-slope negative precipitation anomaly on surface albedo and melt rates. The result suggests that the negative albedo anomaly produced a surface melt and freshwater discharge anomaly of $+40 \text{ km}^3$ for the southwestern sector of the ice sheet. As a whole, 2003 freshwater discharge as 71 km^3 above that determined from the climatological albedo.

Though there was some snow accumulation in the southwest ablation zone starting April 17, it was apparently insufficient to produce a normal melt season. Roughly 1 m of seasonal snow is normal for equilibrium line altitude in the Jakobshavn glacier basin. Despite only modest positive spring (MAM) and autumn (SON) positive temperature anomalies ($<1 \text{ K}$) and a -0.4 K summer temperature anomaly, the 2003 melt season ranked 3rd, i.e. among 2001 (1st), 2002 (2nd).

With 13-years of 24 km Polar MM5 output, i.e. 1991-2003, and catchment basins defined by topography, it is possible to assess the regional surface mass balance impacts of the atmospheric circulation anomaly. For the 2002 calendar year, the anomaly contributed to 45% (74 km^3) increased precipitation rate over the southeastern slope and an 16% (24 km^3) decrease in mass input along the southwest. For the ice sheet as a whole, calendar year 2003 precipitation was 18% (116 km^3) above the 13-year mean and 9% (57 km^3) above normal for 2002.

6. CONCLUSIONS

Data from Polar MM5 mesoscale atmospheric simulations, satellite imagery, and automatic weather stations, have shed light on complexities of Greenland ice sheet mass balance variability and sensitivity.

West Greenland mass balance is highly sensitive to precipitation variability. Western melt zone melt rates are sensitive to negative precipitation anomalies. Despite relatively low summer temperatures, a negative albedo anomaly dominated ablation rates, producing approximately 71 km^3 more melting and freshwater discharge than normal from the Greenland ice sheet as a whole. The majority of the freshwater discharge originated from the southwest sector, where the negative albedo anomaly was pronounced. Western slope surface mass balance variability is more sensitive, in terms of melt rates, than the eastern slope. The southeastern slope accumulation rates dominate the surface mass balance.

Both precipitation and freshwater discharge were above average for 2002 and 2003. According to our calculations, the net effect of these opposing anomalies for the ice sheet as a whole was dominated by ablation. The 2003 freshwater discharge anomaly was 31 km^3 larger than that for precipitation.

ACKNOWLEDGMENTS

This research was supported by NASA grant IDS/03-0143-0058.

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