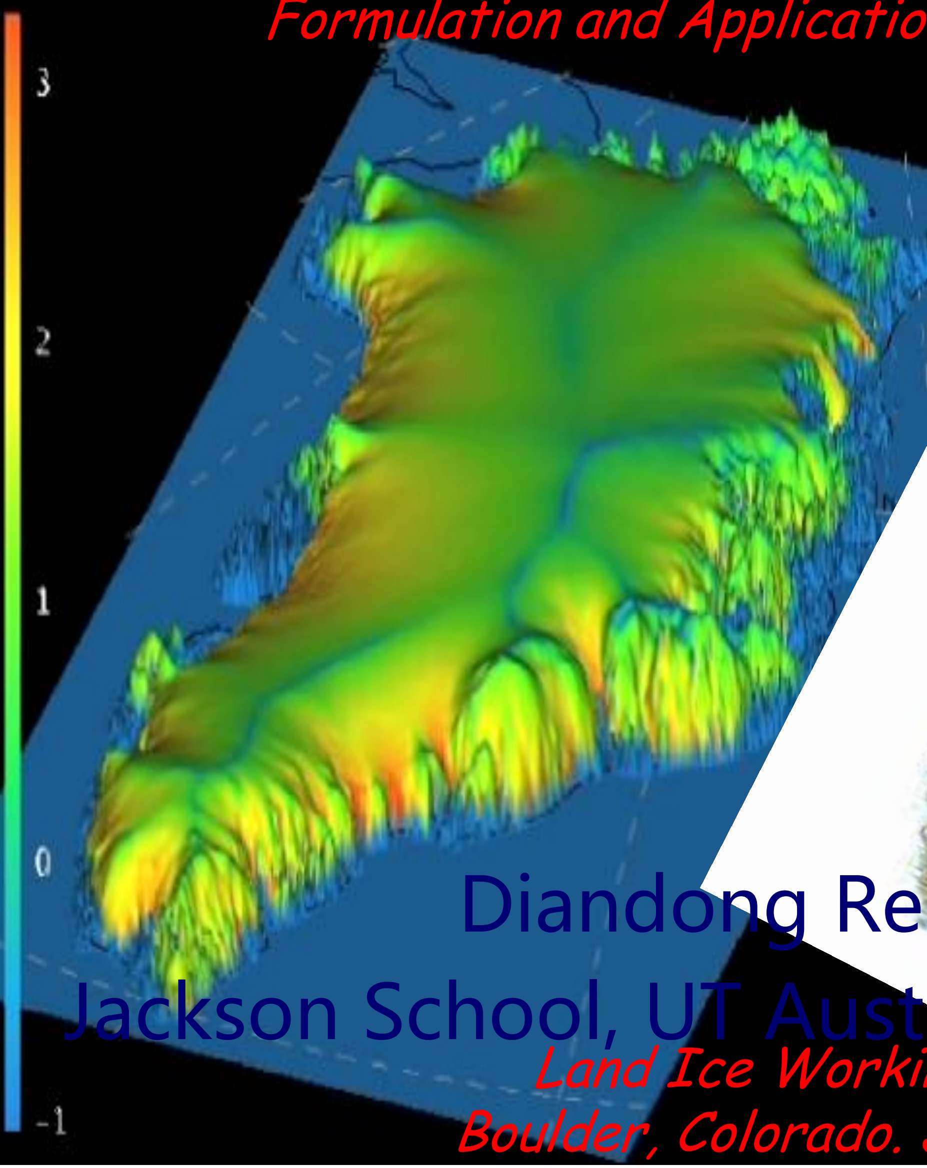
A Multi-Rheology Ice Model: SEGMENT-ice

Formulation and Application to the Greenland Ice Sheet



Diandong Ren, Rong Fu, Lance M. Leslie

Jackson School, UT Austin & ASDI, Curtin, Australia

Land Ice Working Group Meeting

Boulder, Colorado. January 12-13, 2001.

Pictures adapted from R.Bindschadler (NASA GSFC) (L) and Ginny Catania (UTIG) (R)

Review of previous studies

- Reactions of the Greenland ice sheet to climate changes have already been investigated by
  - Kuhn (1981) and Ambach (1985) as sensitivity studies
  - Huybrechts et al. (1991), van de Wal and Oerlemans (1997), and Greve (2000)
  - Ohmura et al. (1996) using a general circulation model (GCM) provided forcing series of temp. & precip. rate
  - van der Wal and Oerlemans (1994) suggests a net melting of 0.52 cm yr^{-1}. In contrast, Huybrechts (1994) gives a thickening at a rate of ~ 1cm yr^{-1}, while Ohmura et al. (1996) gives yet another picture. Although the latter's estimate of precipitation is about 25% above observational estimates, its conclusions are echoed recently by Meier et al. (2007)
  - Observational research: Zwally et al. (1990) , Douglas et al. (1990) ; Rignot & Kanagaratnam, 2006; Ashcraft and Long (2006); Mote (2007)
- It would be ideal to study this issue in a fully coupled modeling system. Unfortunately, few present coupled ocean-atmosphere climate models (CGCMs) include the interactive land ice flow dynamics (R. Binschandler, personal communication, 2006; M. Openheimer, personal communication, 2007)
- The IPCC AR4 (http://ipcc-wg1.ucar.edu/wg1/wg1-report.html) used only a surface-mass-balance estimation in sea-level predictions, stating that "quantitative projections of how much the accelerated ice flow would add (to sea level rise) cannot be made with confidence, owing to limited understanding of the relevant processes (FAQ 5.1)."

Sea level rise andGrIS related recent publications

Alley, R. (1993), In search of ice-stream sticky spots. *J. Glaciol.*, **39**, 447-454.

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Mernild, S., G. Liston, C. Hiemstra, J. Christensen (2010), Greenland Ice Sheet Surface Mass-Balance Modeling in a 131-Yr Perspective, 1950–2080. Journal of Hydrometeorology, 11, 3-25.

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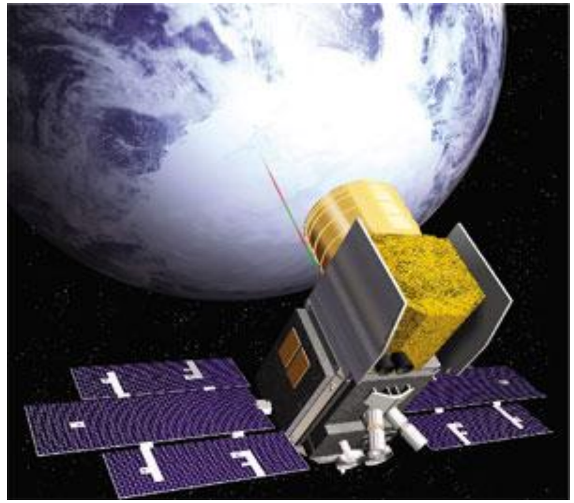
Wang, W., R. Warner (1999), Modelling of anisotropic ice flow in Law Dome, East Antarctica. Annals of Glaciology, 29, 184-190.

Yin, J., M. Schlesinger, and R. Stouffer (2009), Model projections of rapid sea-level rise on the northeast coast of the United States. Nature-geosciences, 2, 262-266.

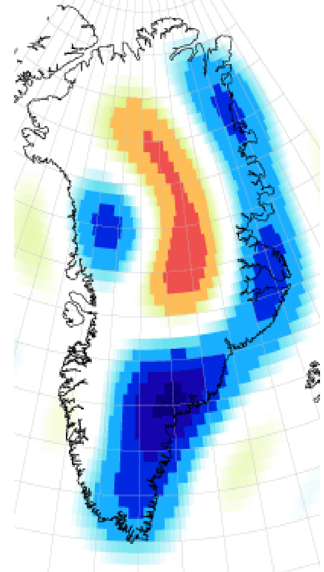
Zwally, H., and M. Giovinetto (2001), Balance mass flux and ice velocity across the equilibrium line in drainage systems of Greenland. *J. Geophys. Res.* **106**, 33717-33728.

Zwinger, T., R. Greve, O. Gagliardini, T. Shiraiwa, and M. Lyly (2007), A full Stokes flow thermo-mechanical model for firn and ice applied to Gorshkov crater glacier, Kamchatka, Ann. Glaciol., 45, 29 – 37.

Greenland Ice Sheet Mass Balance

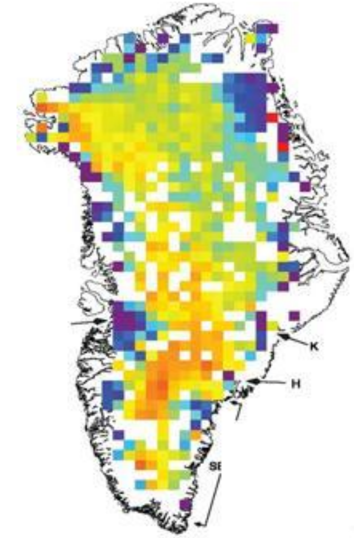


GRACE

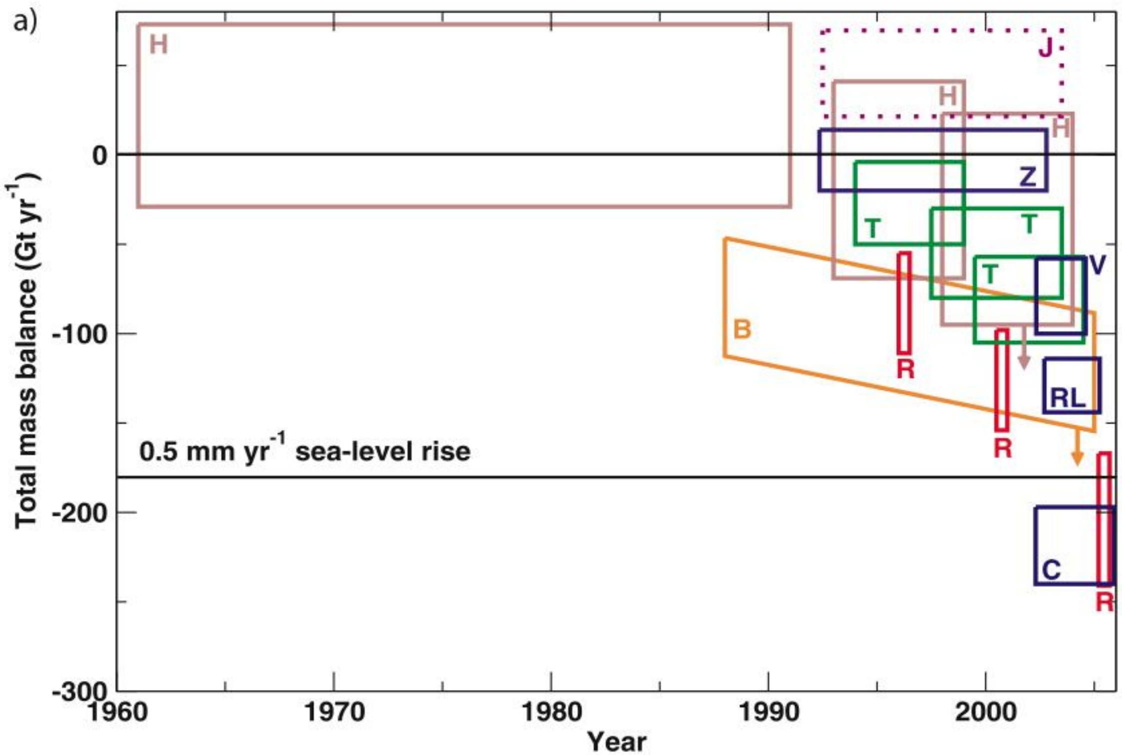


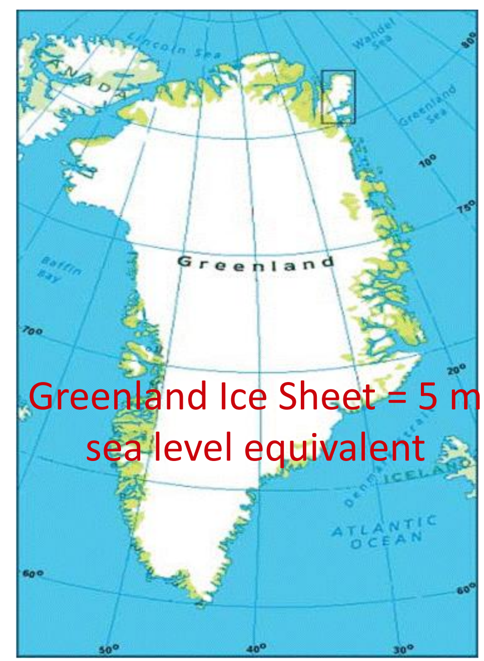
-100 Gt per year

ICESat

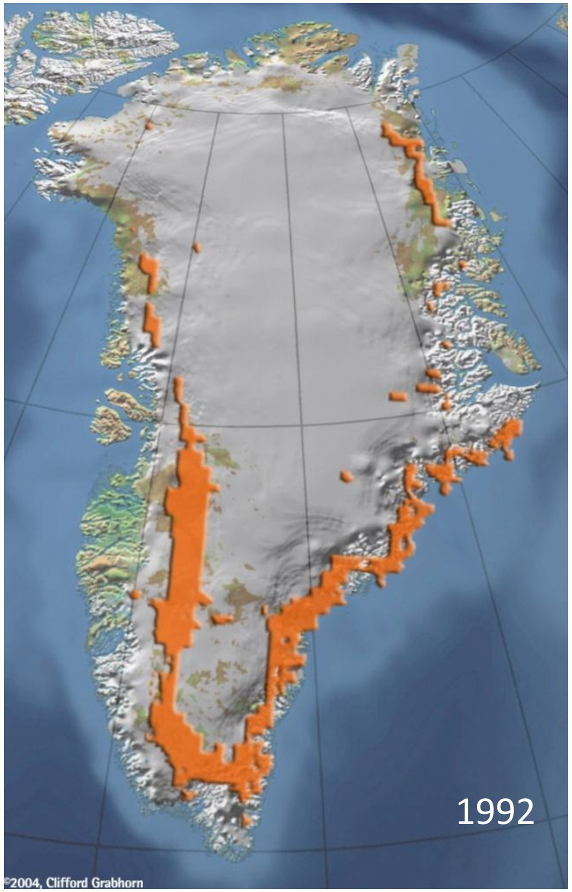


-80 Gt per year





Increased surface melt



Arctic Climate Impact Assessment

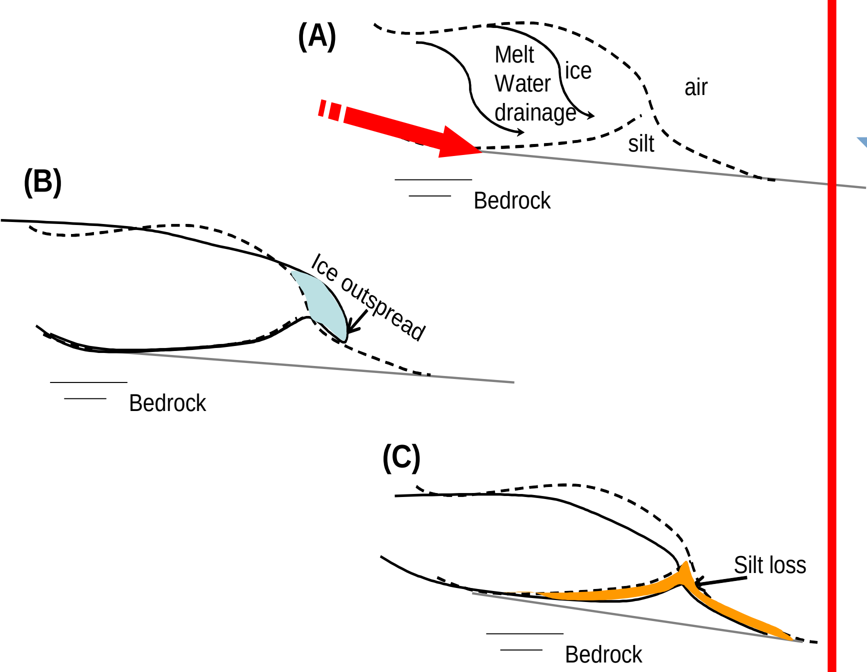
News Front Page > Environment

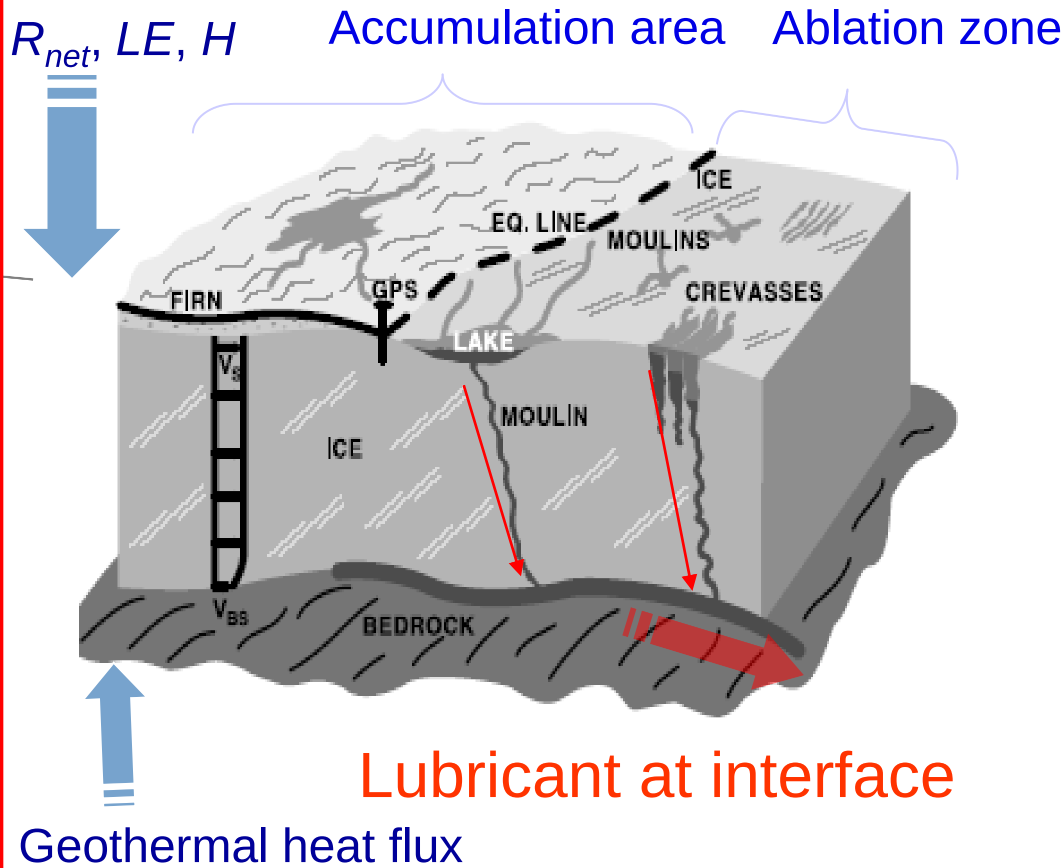
Greenland Melt May Swamp LA, Other Cities, Study Says

Stefan Lovgren
for National Geographic News
April 8, 2004

Flow in the Greenland ice sheet

Three stages of a mountain glacier snout movement

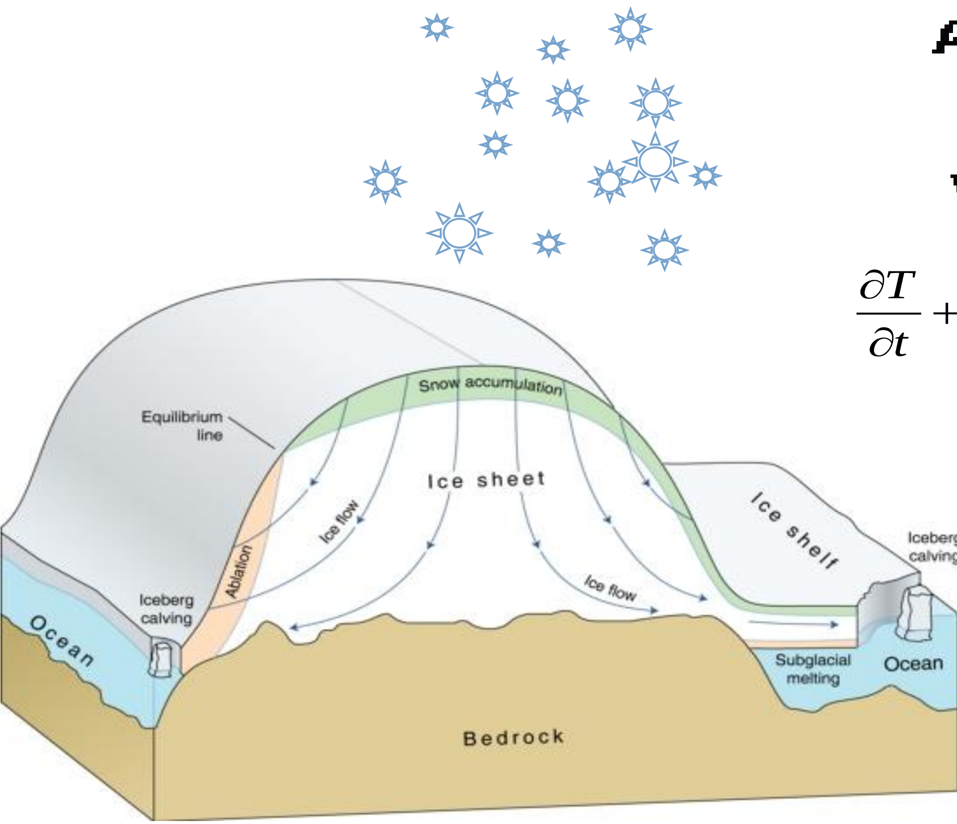




- Granular (basal tillage) basal sliding effect —“graded glacier” concept (R. Alley 2005)

- Surface melt water lubricating effect (H. Zwally et al., 2002)

Governing equations for ice flow



$$\rho\left[\frac{\partial \vec{V}}{\partial t} + \nabla \cdot \left(\vec{V} \otimes \vec{V}\right)\right] = \nabla \cdot \sigma + F \quad (1)$$

$$\nabla \cdot \vec{V} = 0 \quad (2)$$

$$\frac{\partial T}{\partial t} + \left(\vec{V} \cdot \nabla\right) T = \frac{1}{\rho C_p}\left[\nabla \cdot (\kappa \nabla T) + 2E\frac{\sigma_{eff}^2}{\nu}\right] \quad (3)$$

$$\begin{cases} \eta(T, P, \dot{\varepsilon}) = A^{\frac{1}{n}}(\dot{\varepsilon}_e)^{\frac{1}{n}-1} \\ \nu = \left(\mu_0 + \frac{\mu_1 - \mu_0}{I_0 / I + 1}\right)\frac{S}{|\dot{\varepsilon}_e|} \end{cases} \quad (4)$$

$$\dot{\varepsilon}_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right), i, j = r, \theta, \phi \quad (5)$$

$$\dot{\varepsilon}_e = \sqrt{\frac{1}{2} tr(\dot{\varepsilon})^2} \quad (6)$$

$$2 \bullet_{eff}^2 = \bullet_{xx}^2 + \bullet_{yy}^2 + \bullet_{zz}^2 + 2(\bullet_{xy}^2 + \bullet_{xz}^2 + \bullet_{yz}^2) \quad (7)$$

Ren et al. 2010a: A Multi-Rheology Ice Model: Formulation and Application to the Greenland Ice Sheet. JGR. In Press.

Ren et al. 2010b: The Greenland Ice Sheet Response to Transient Climate Change. J. Climate. Under Review.

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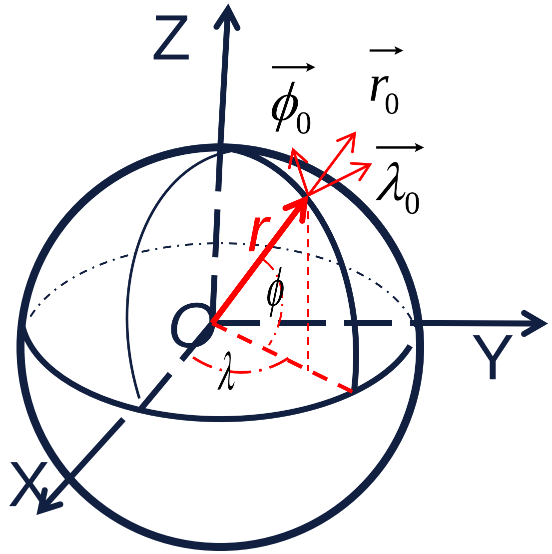
Selection of coordinate system (always in rotating earth ref. sys.)



➢Lame operators:

$$H_r = 1; \quad H_\phi = r; \quad H_\lambda = r\cos\phi$$

$$\frac{\partial \vec{\lambda}_0}{\partial \lambda} = \sin\phi\, \vec{\phi}_0; \quad \frac{\partial \vec{\phi}_0}{\partial \phi} = -\vec{r}_0; \quad \frac{\partial \vec{r}_0}{\partial \phi} = \vec{\phi}_0;$$

$$\frac{\partial \vec{r}_0}{\partial \lambda} = \cos\phi\, \vec{\lambda}_0; \quad \frac{\partial \vec{\phi}_0}{\partial \lambda} = -\sin\phi\, \vec{\lambda}_0$$

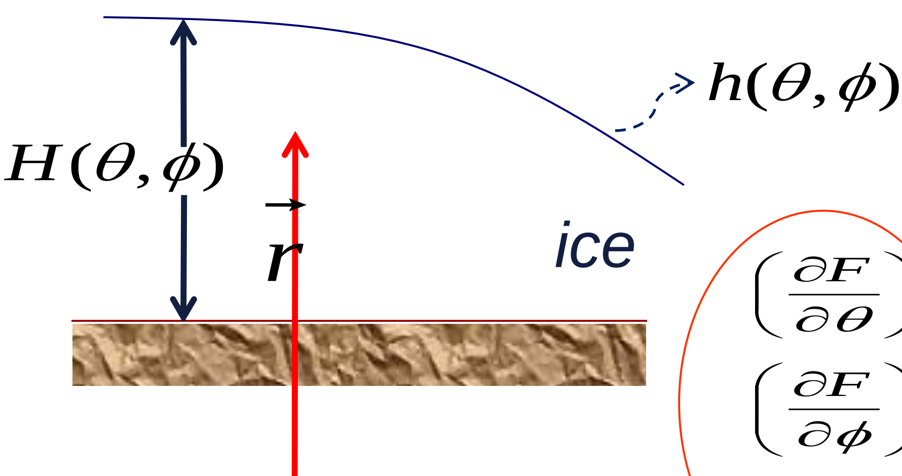
➢General curvilinear system:

Sacrifying the orthogonality in r-direction, introduce the terrain following system:

$$s = \frac{h - r}{H}$$

Where h is surface topography, *H* is local thickness, and r is vertical coordinate

The old (spherical) to new (terrain following, calculation space) coordinates transformation Ja (1st order) and He (2nd and higher order) are:



$$\left(\frac{\partial F}{\partial \theta}\right)_{s,\phi} = \left(\frac{\partial F}{\partial \theta}\right)_{r,\phi} - \frac{1}{H}\left(\frac{\partial F}{\partial s}\right)_{\theta,\phi} \Delta s_\theta$$

$$\left(\frac{\partial F}{\partial \phi}\right)_{s,\theta} = \left(\frac{\partial F}{\partial \phi}\right)_{r,\theta} - \frac{1}{H}\left(\frac{\partial F}{\partial s}\right)_{\theta,\phi} \Delta s_\phi$$

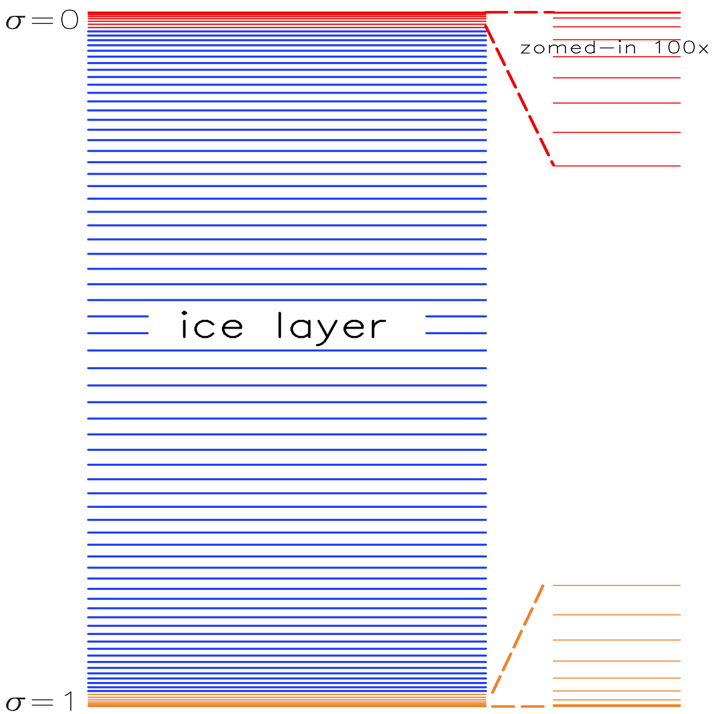
$$\left(\frac{\partial F}{\partial s}\right)_{\theta,\phi} = -H\left(\frac{\partial F}{\partial r}\right)_{\theta,\phi}$$

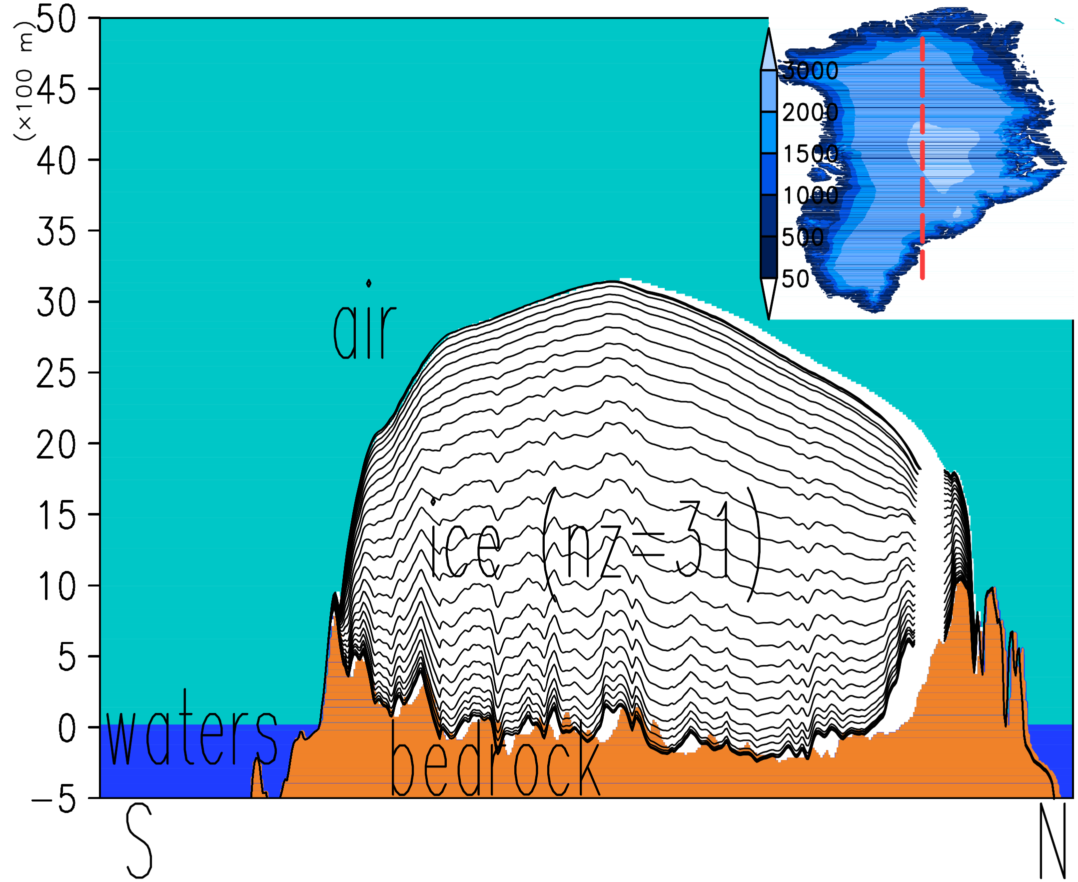
Specific to Greenland ice sheet

Vertical stretching using hyperbolic tangent function:

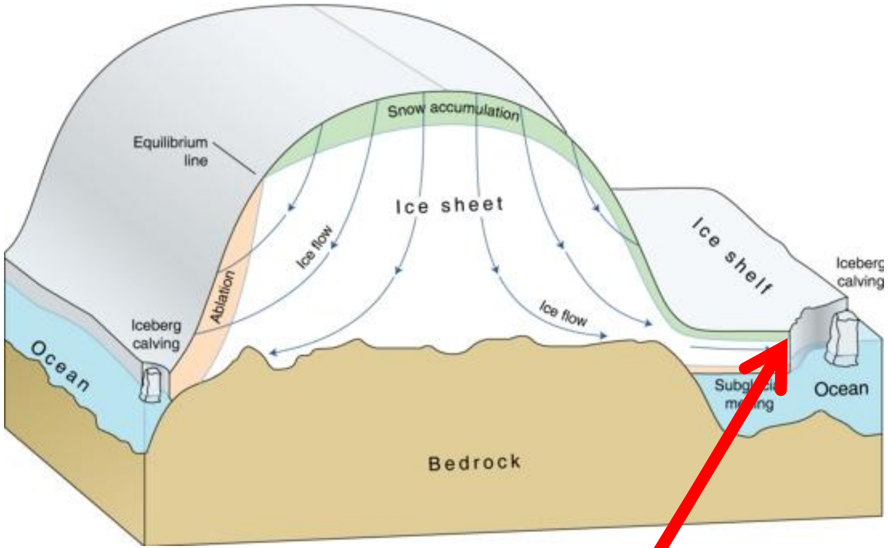
$$\Delta\mu_i = \Delta\mu_m + \frac{\Delta\mu_{\min} - \Delta\mu_m}{\tanh(2\alpha)} \tanh\left[\frac{2\alpha}{1-a}(1-a)\right] \text{ for i} = 1,2,\ldots \text{nz}/2,$$

$$\text{where a} = (1+\text{nz})/2$$





Basal treatment for water terminated glaciers (ice shelf/ocean interaction)



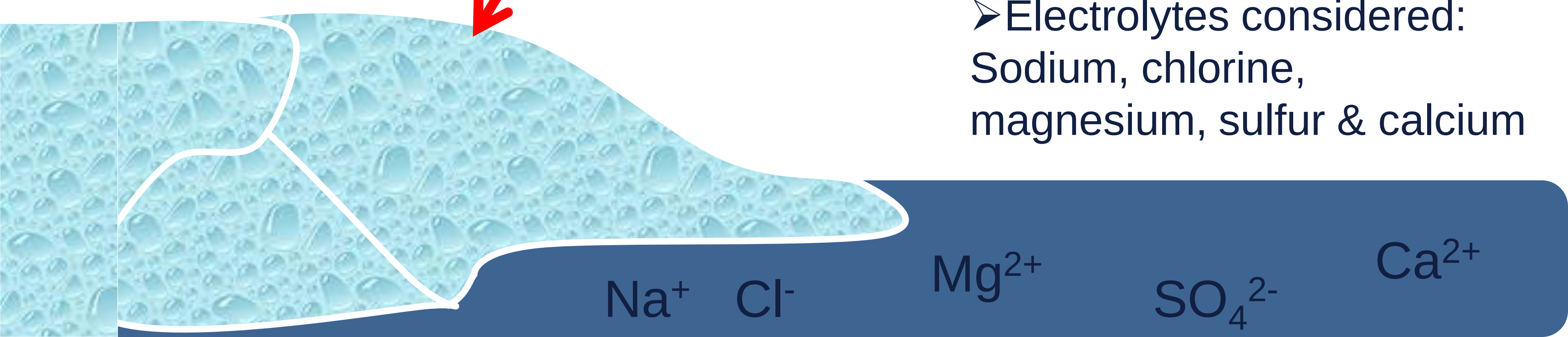
- Elevated thermal forcing:

$$\Delta T_{freeze} = \frac{R^* T \ln(1-s)}{c_p \ln T + S_0}$$

- Turbulent heat transfer:

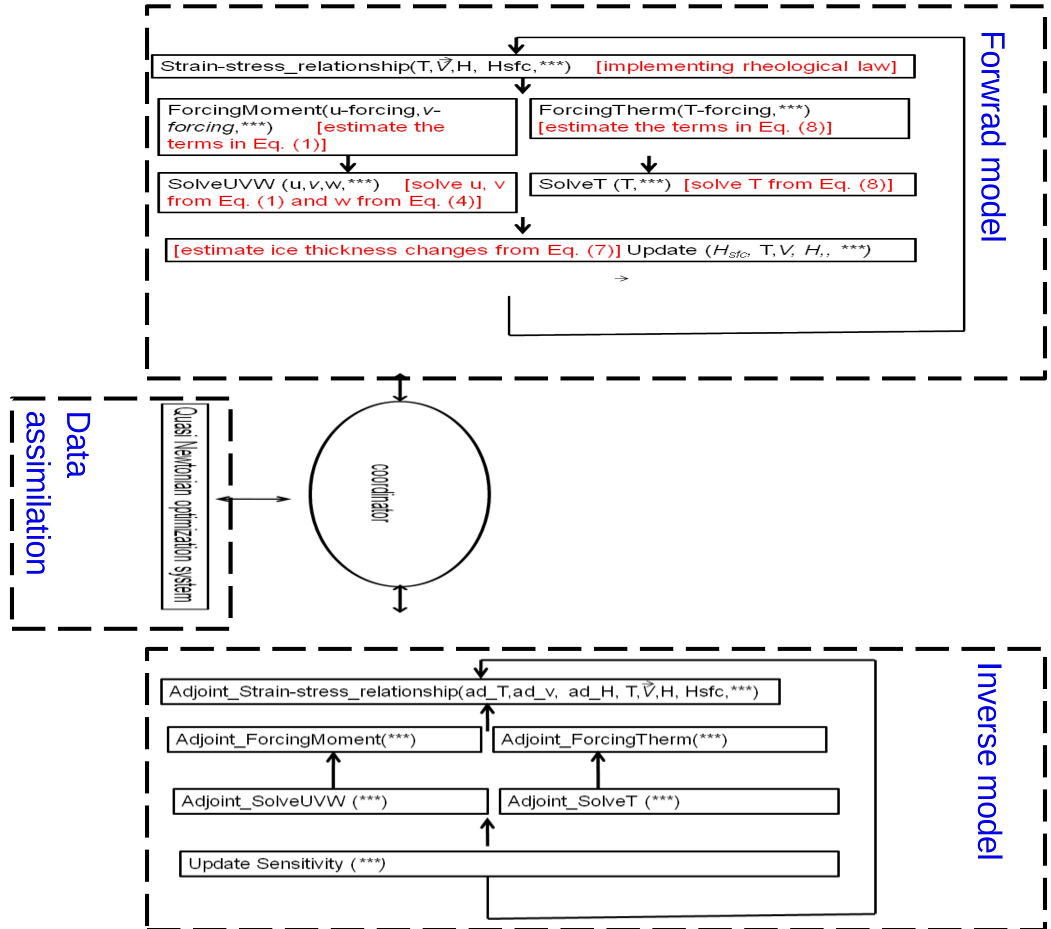
$\rho = 1028 kg/m^3$;
$c_p = 3986 J/K/kg$;
kinematic viscosity
$\nu = 1.8 \times 10^{-7} m^2 s^{-1}$; and
stability dependent eddy transfer coef. C_{DH}

- Electrolytes considered: Sodium, chlorine, magnesium, sulfur & calcium



Inverse modeling of SEGMENT-ice:adjoint based optimization

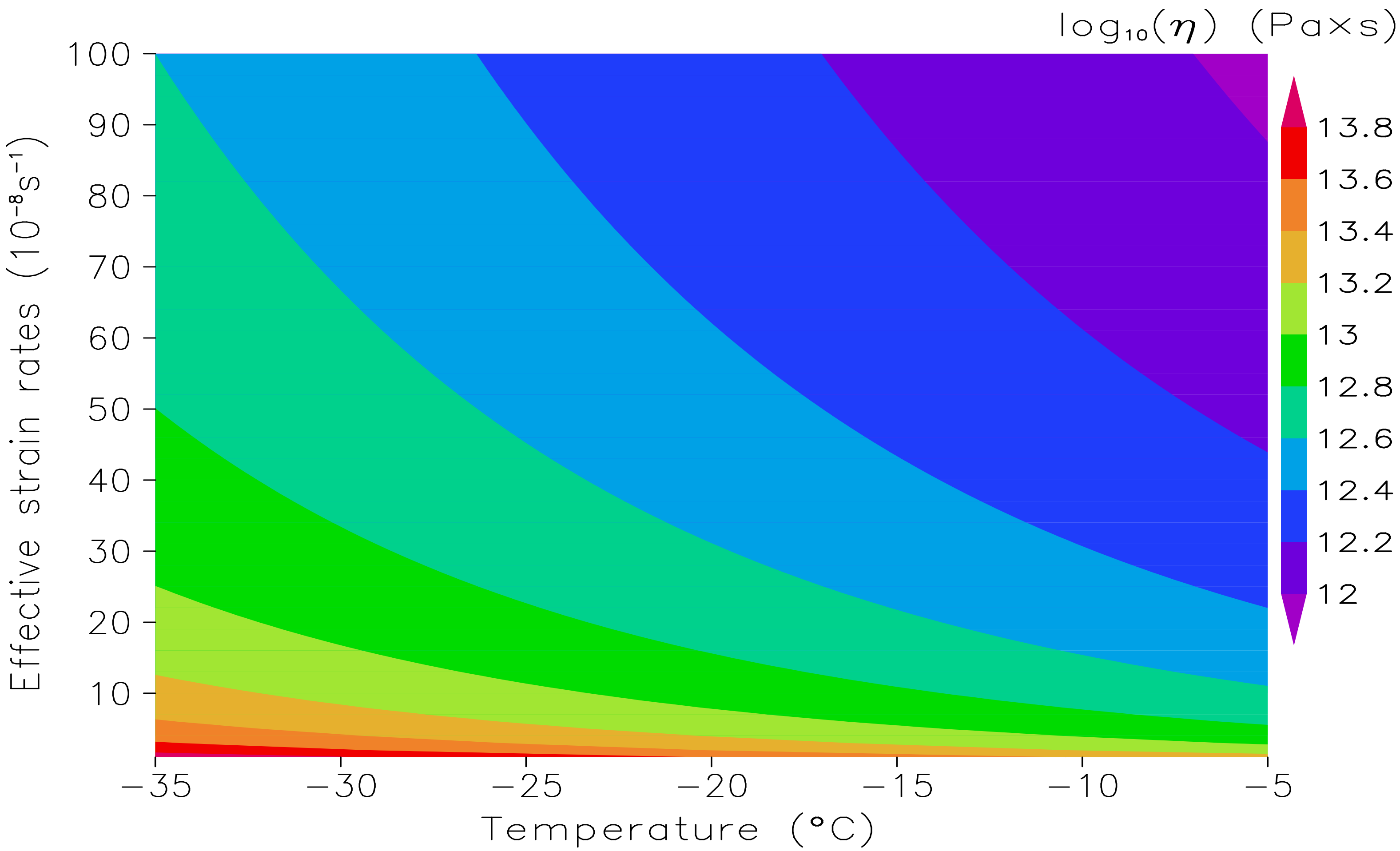
$$\delta x = 0$$
$$\delta y = 0$$
$$\delta z = 0$$
$$\ldots$$
$$z = a * x + b * y$$
$$\delta x = \delta x + a * \delta z$$
$$\delta y = \delta y + b * \delta z$$
$$\delta z = 0$$
$$\ldots\ldots$$



➢Usages: uncertain parameter retrieval; initial states (historical residual effects); and sensitivity experiments

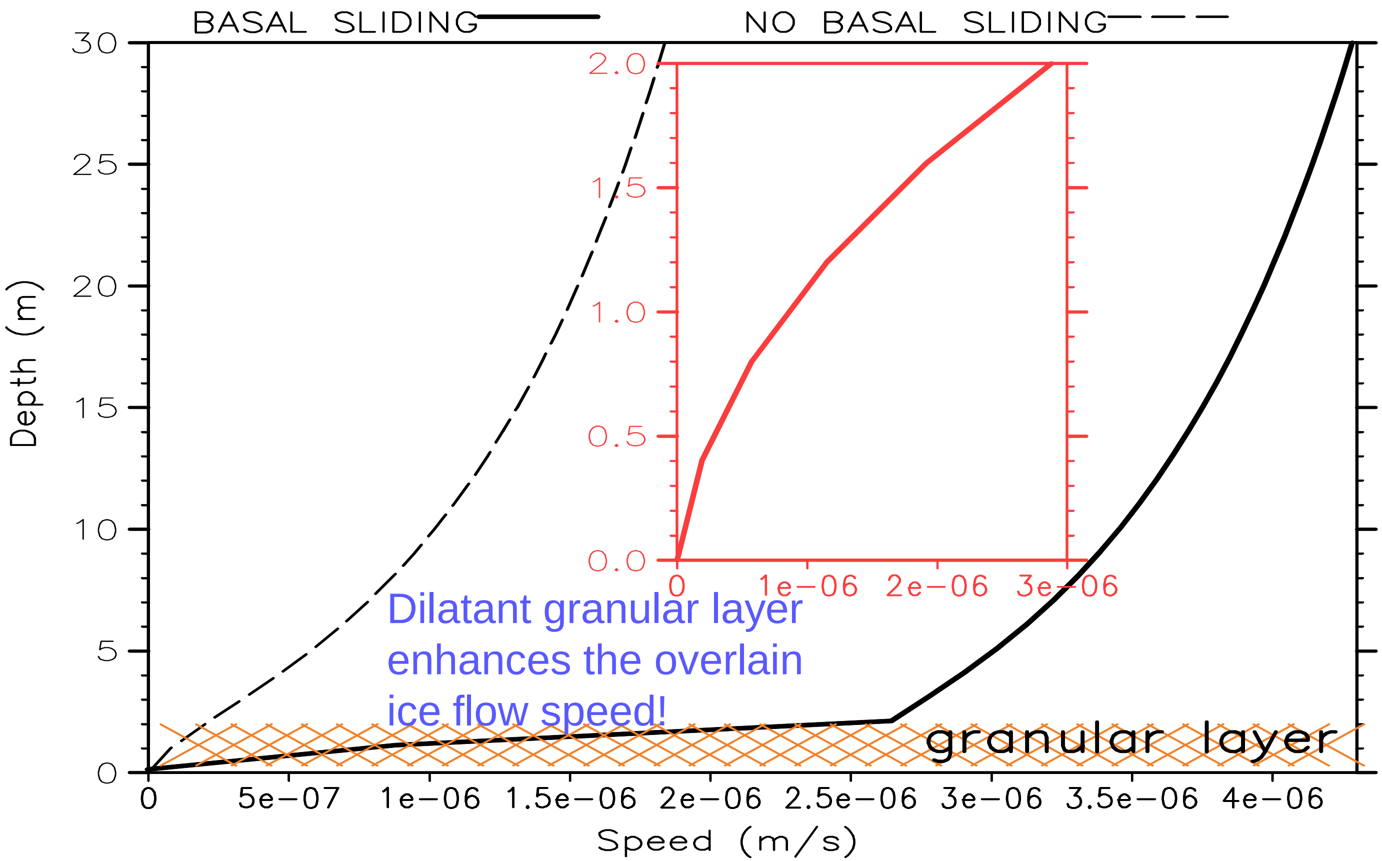
Ice Physics in SEGMENT-ice

Effects of temperature and strainstage



➢Further, in SEGMENT-ice, flow-induced anisotropy also is considered, following Wang and Werner (1999)

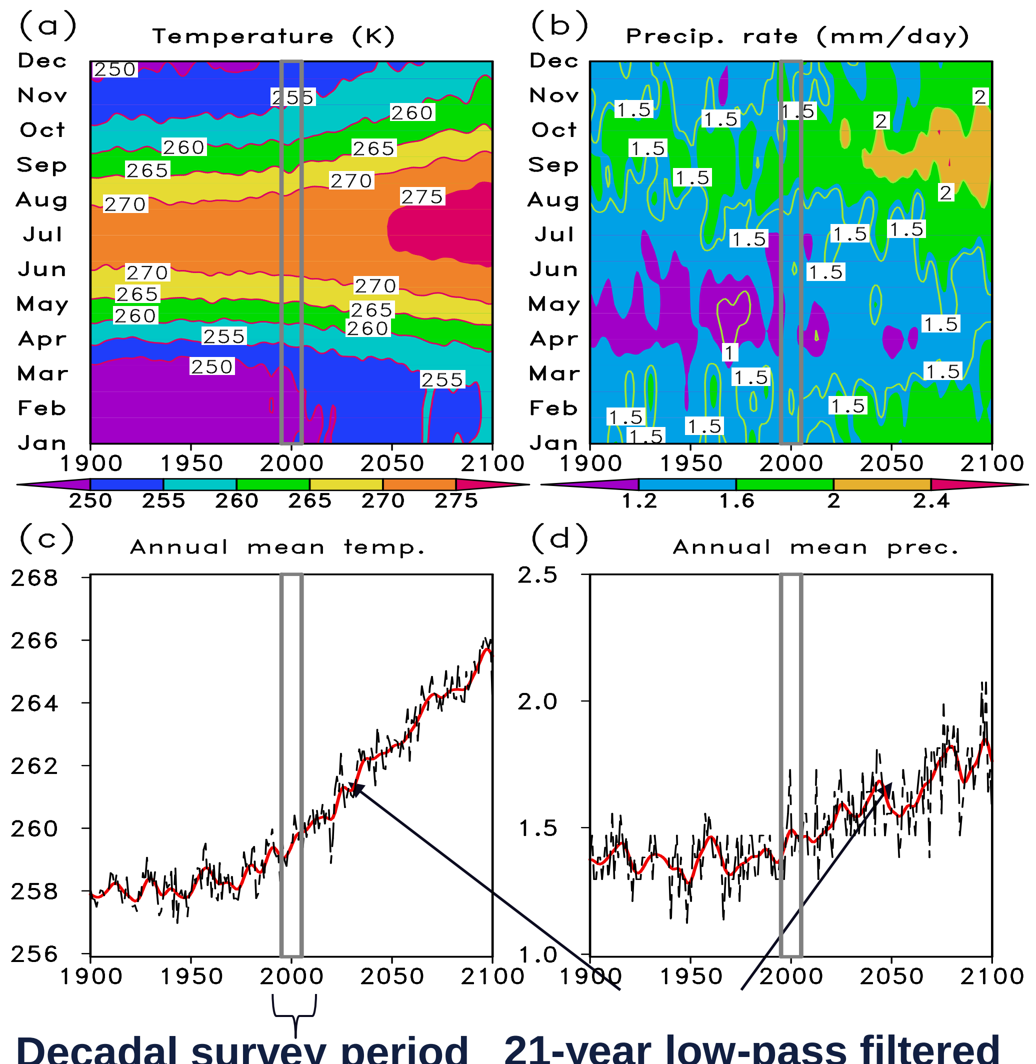
Effects of granular layer



Flow speed profile for an idealized geometry: -10 ° C ice of uniform 30 m thickness resting on a slope of 2 degrees steepness, 45 degree aspect (facing due northeast), and infinite length and width. Comparison between the case with an underlain granular layer of 2 m deep, with grain effective radius 10 cm, density of 2.7×10^3 kg m^{-3}, and 30 degree dry repose angle (hatched) and the case without such a granular base. Free-of-stress upper boundary condition is applied. The inset is a zoomed-in of the velocity profile within the granular basal layer.

Climate is warming up

- **MIROC-hires♣ simulated spatially averaged surface air temperature (*a* & *c*) and precipitation rate (*b* & *d*) trends over GRL**
- **The annual mean temperature (*c*) increases by ~4 ° C over the next century. Mean while, the annual mean precipitation (*d*) increases by 0.3 mm/day**
- **Without robust long-term modeling estimations, it thus is unclear whether GRL loses mass due to climate warming**
- **During the surveyed period (confined by the vertical grey lines), both temperature and precipitation trends are large within the 20th century but are modest when compared with the future ~100 years**



♣ Center for Climate System research, University of Tokyo; NIES; Frontier Research Center for Global Change

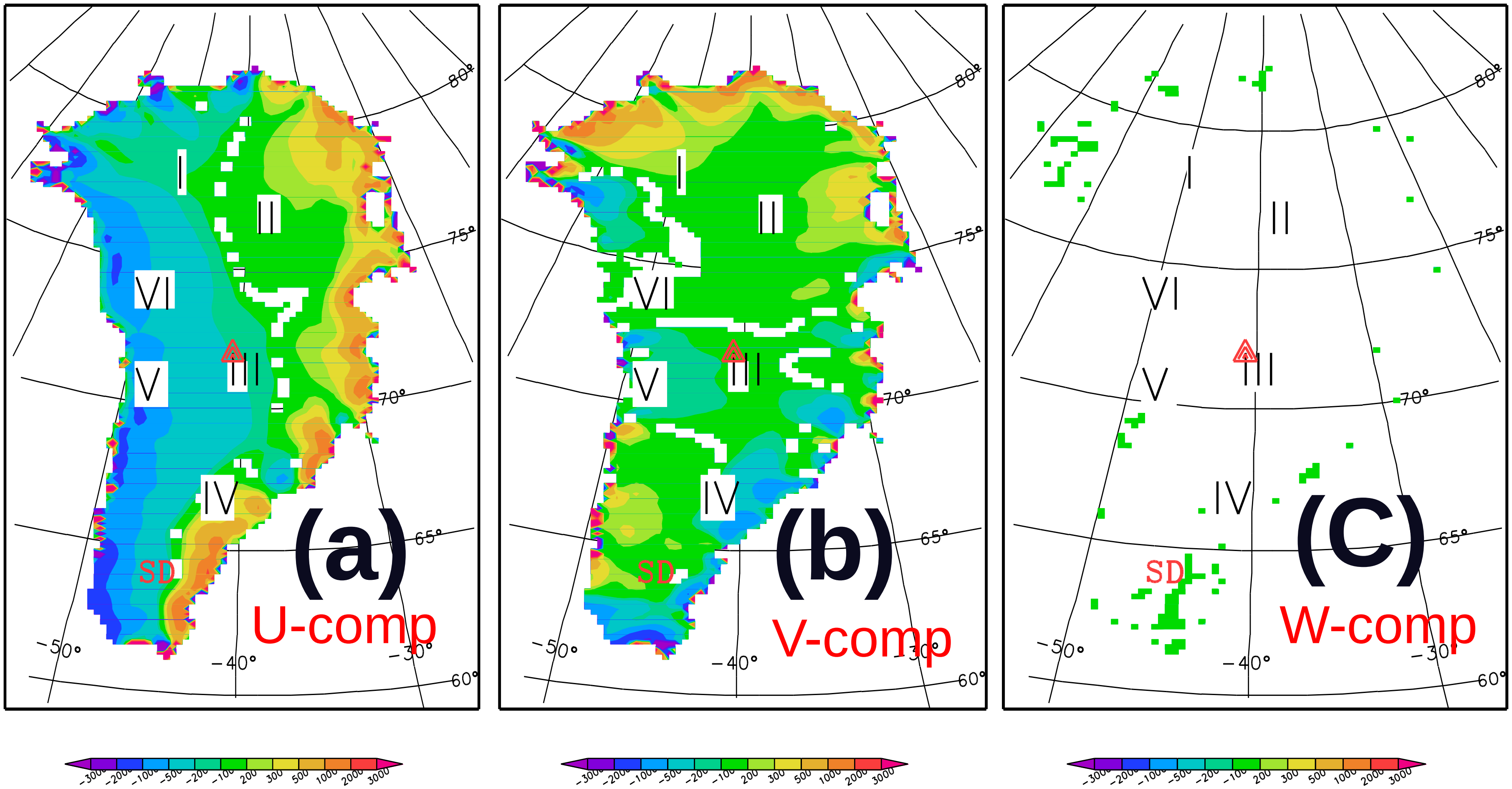
Modeling of Greenland Ice Sheet

- In2010, the Greenland Ice Sheet already is contributing 0.7-0.8 mm/yr sea level rise (E. Rignot, personal communication), to estimate the future contribution of GrIS to sea level under a constant warming climate, we need models that have the ability to reproduce/explain its recent observed dramatic behaviour

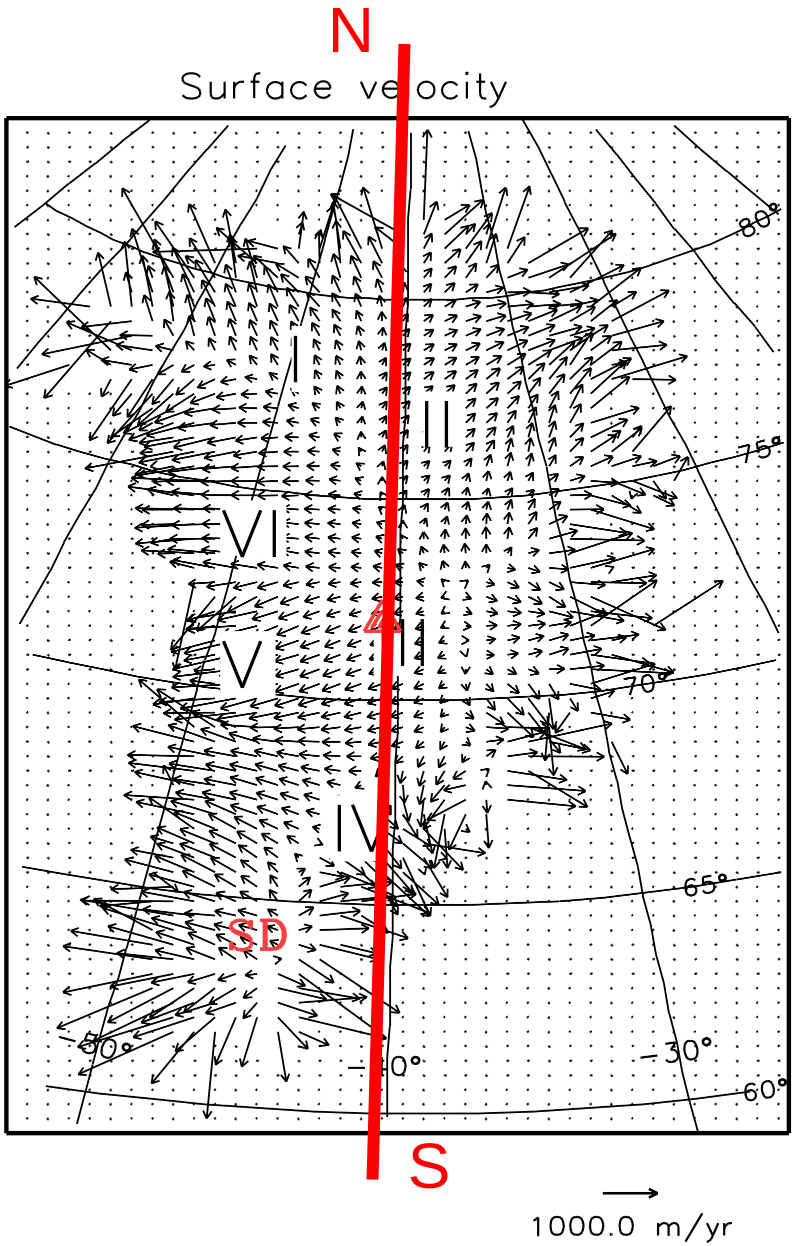
- This study presents a new multi-phase, multiple-rheology, scalable and extensible geofluid model of the Greenland ice sheet that shows the credential of successful reproducing the mass loss rate derived from the Gravity Recovery and Climate Experiment (GRACE), InSAR observed surface ice flow speed, and the microwave remote sensed surface melt area over the past decade

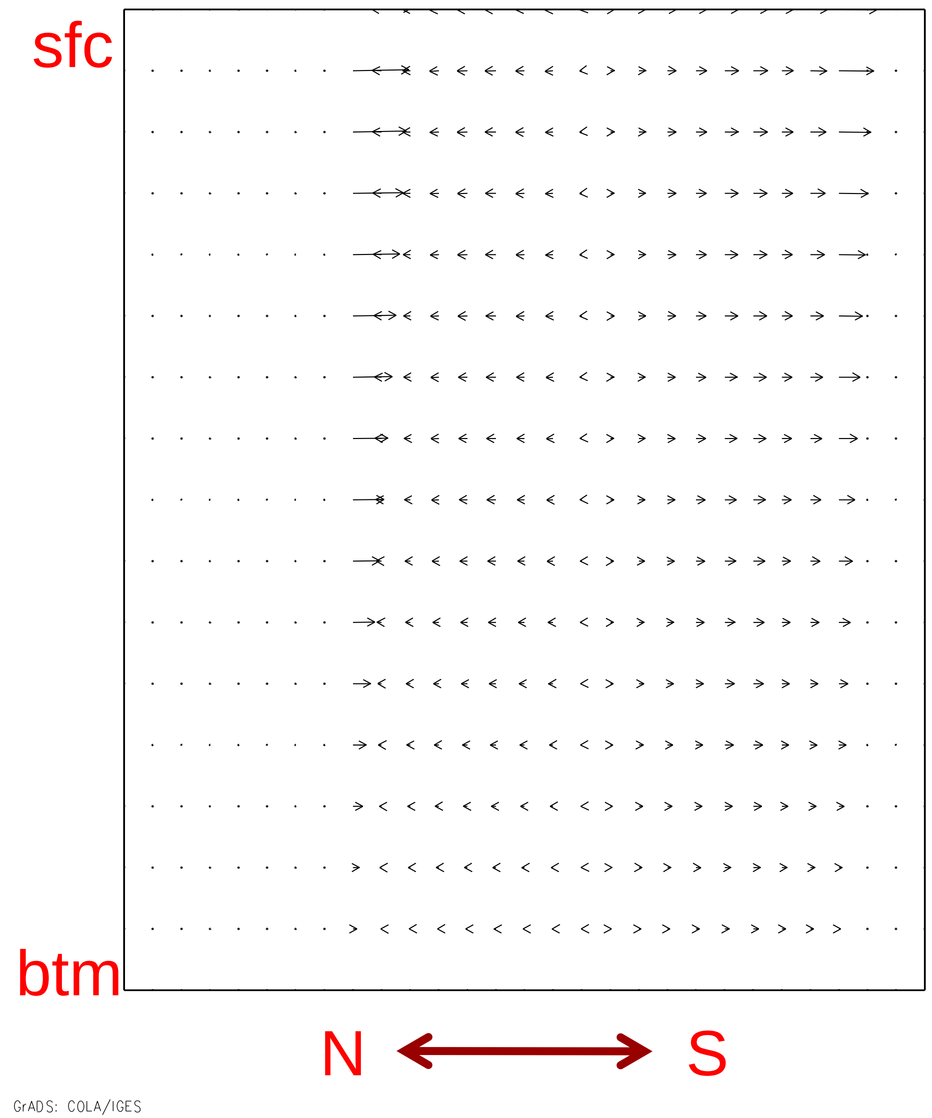
- Projections for the upcoming 50/100 years are made for each metric discused

Modeling of flow fields

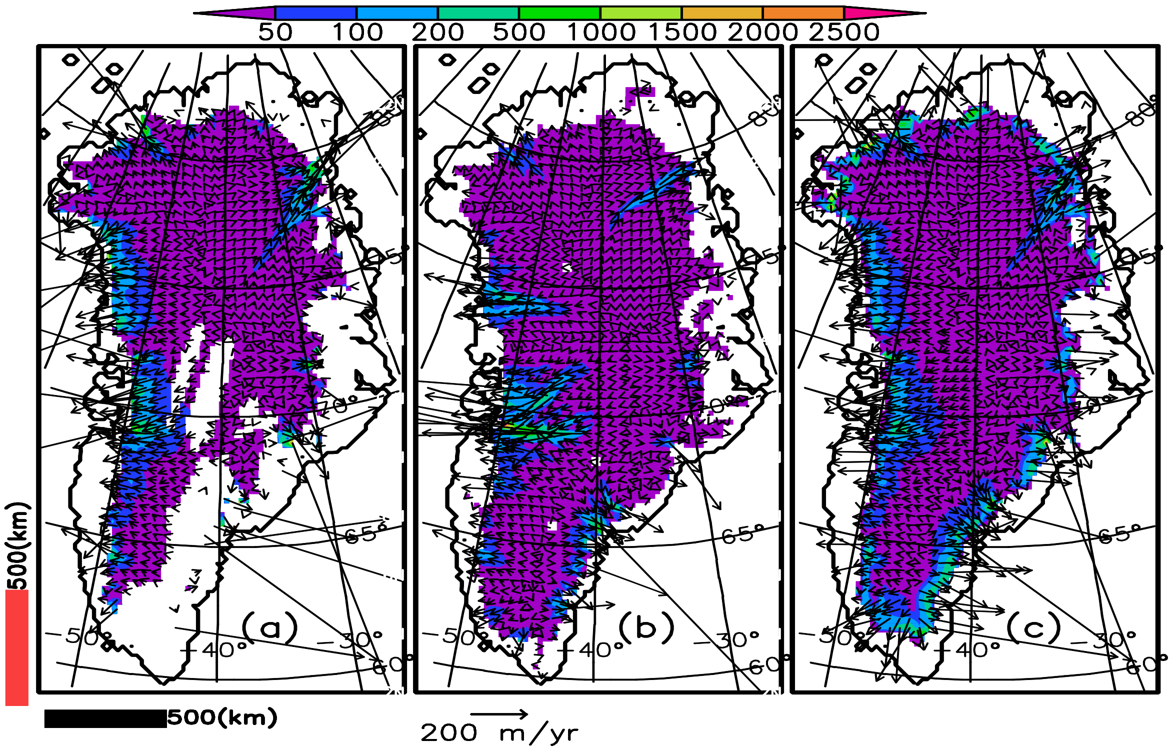


Modeling of flow fields



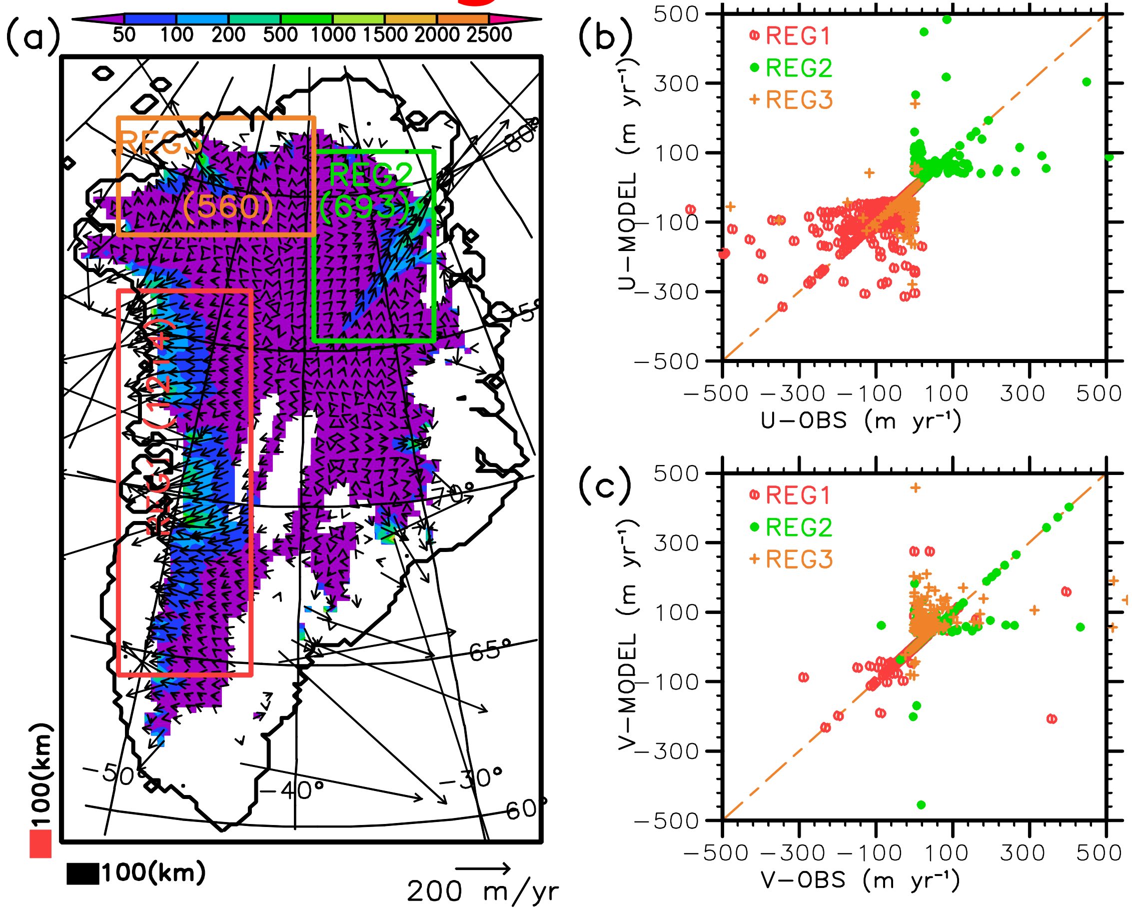


Modeling of flow fields



The surface velocity fields at present as measured by InSAR (a) (http://websrv.cs.umt.edu/isis/index.php/Present_Day_Greenland), simulated by PISM (b) and SEGMENT-ice (c). Ice sectors are clearly identifiable from flow patterns. In plotting the vector field, the data have been thinned for clarity by displaying one in every twenty grids

Modeling of flow fields

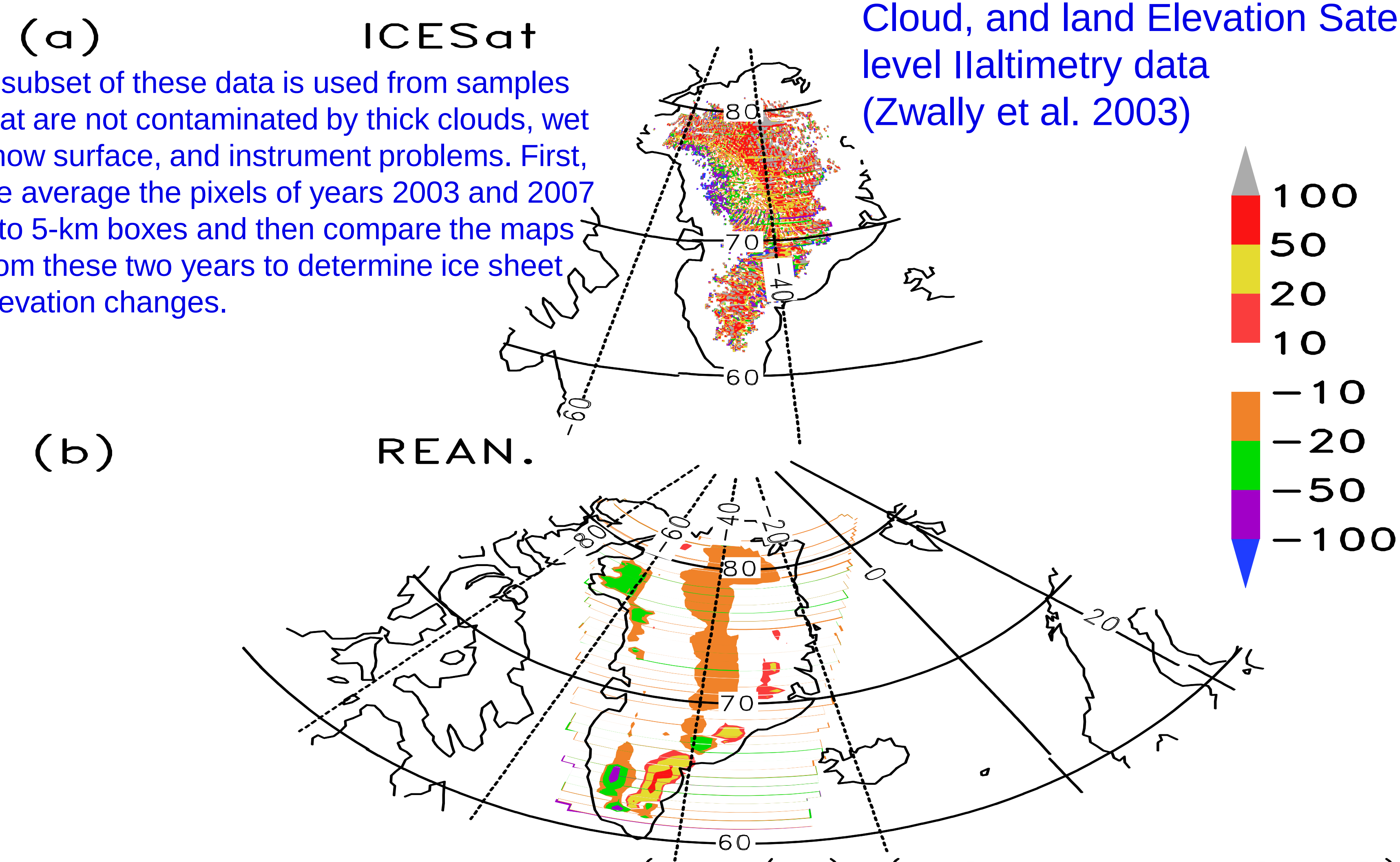


Region-by-region comparisons between SEGMENT-ice and InSAR observations of the present surface velocity fields. The observed velocity field (a) is representative of the early 21st century speeds. The SAR data were provided by the Canadian Space Agency and then processed by the NASA-funded Alaska SAR facility. (b) a region-by region scatter plot of the u-component; and (c) for the v-component.

Modeling of Greenland Ice Sheet Mass Loss

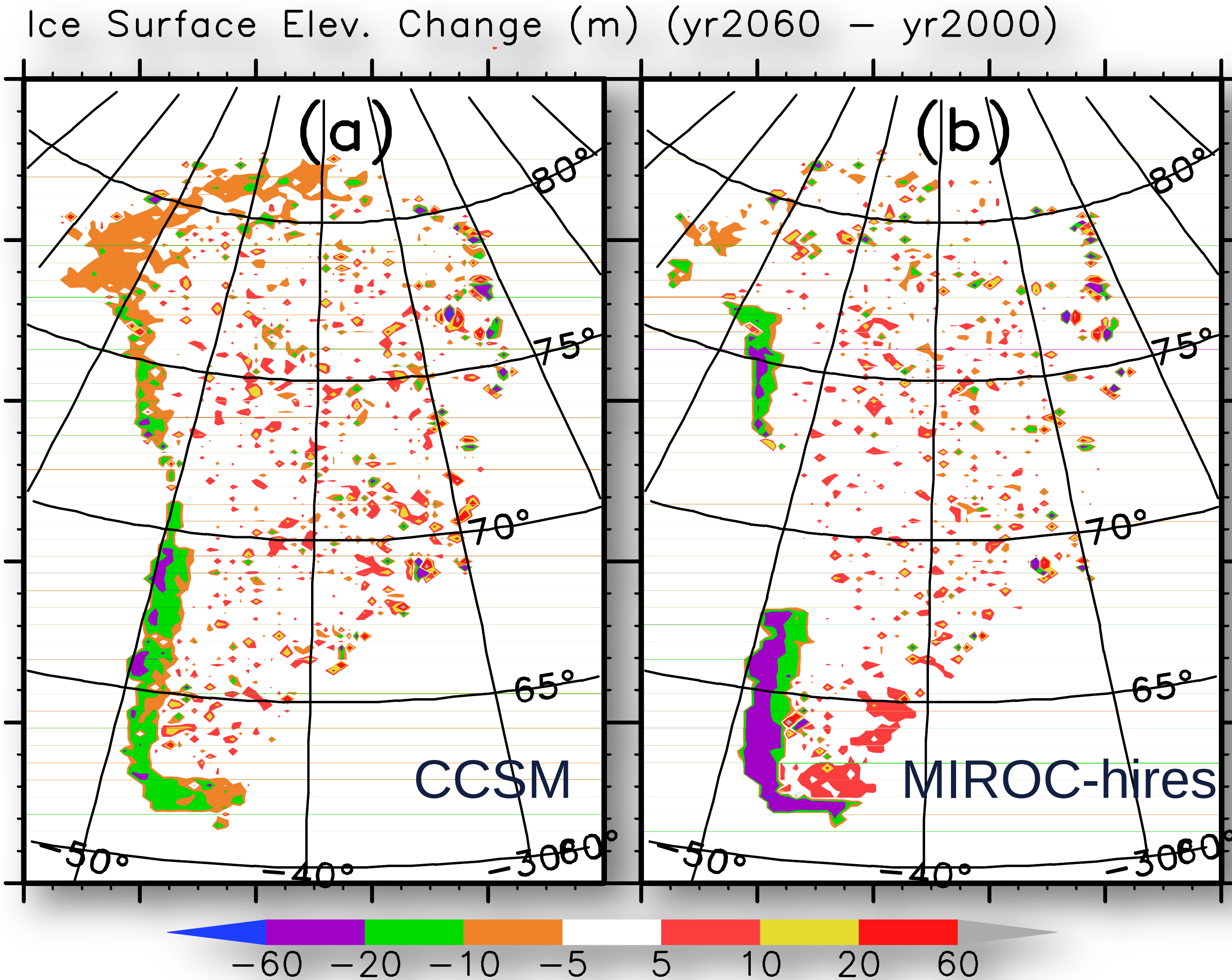
GLAS instrument on the Ice, Cloud, and land Elevation Satellite level IIaltimetry data (Zwally et al. 2003)

A subset of these data is used from samples that are not contaminated by thick clouds, wet snow surface, and instrument problems. First, we average the pixels of years 2003 and 2007 into 5-km boxes and then compare the maps from these two years to determine ice sheet elevation changes.

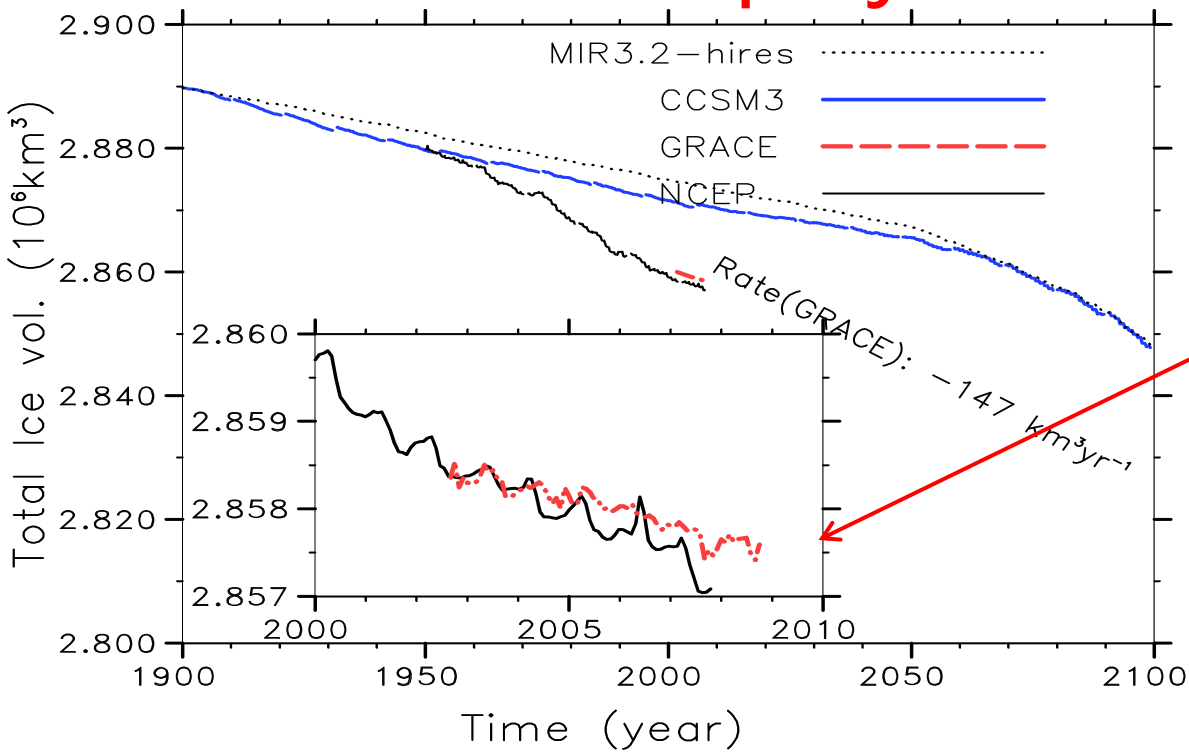


Surface Elev. Change (cm/yr) (yr2007 – yr2002)

Future projections



Future projections

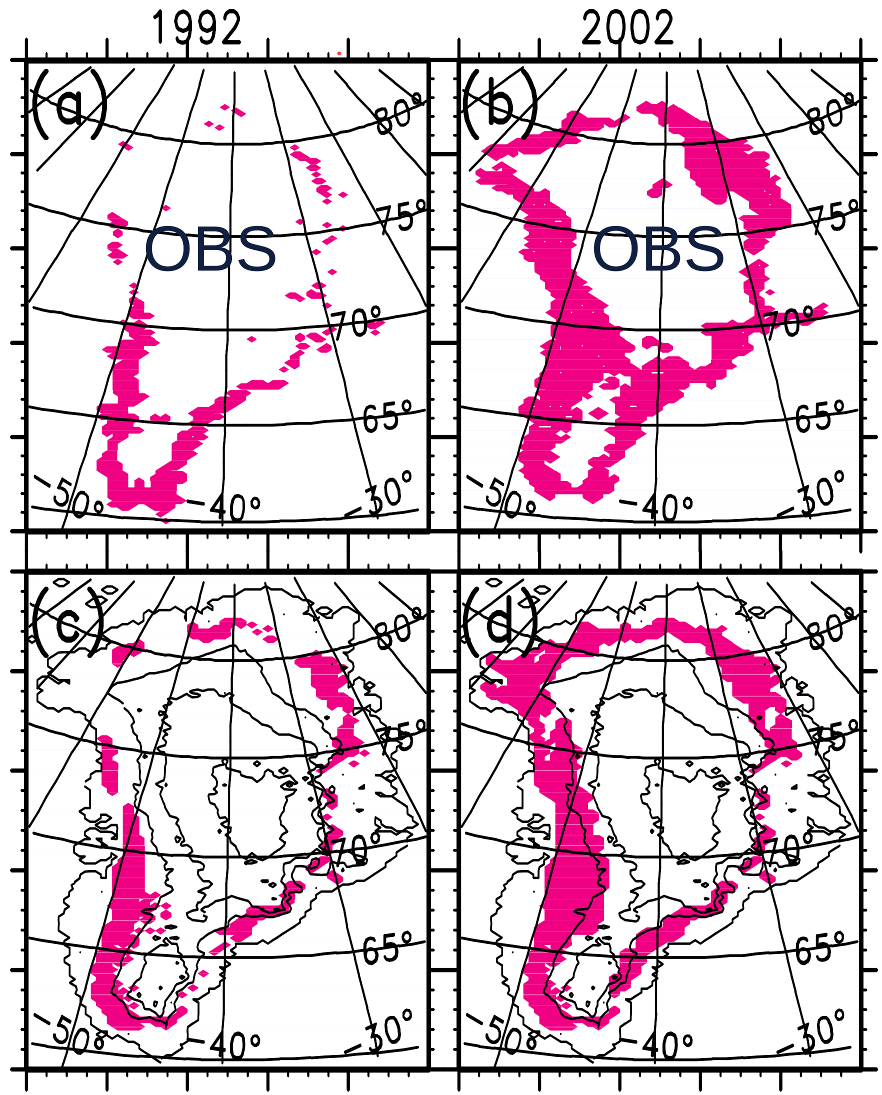


Mass loss rate: -160 km^3/yr
GRACE: -147 km^3/yr

- Net mass balance of the GrIS for the 20th and 21st centuries. Comparisons are among using two CGCM provided meteorological conditions: MIROC3.2-hires (dot line) and CCSM3 (blue solid line), NCEP reanalysis provided meteorological conditions, and GRACE observations (red dashed line).
- The inset is a zoom-in for the past decade. Comparisons are between model simulation using NCEP reanalysis provided meteorological conditions (black line) and GRACE measurements (red line).
- Because GRACE mts are only meaningful as relative values compared with the starting point, we shifted the curve so that the two curves have the same value at the first mts time.

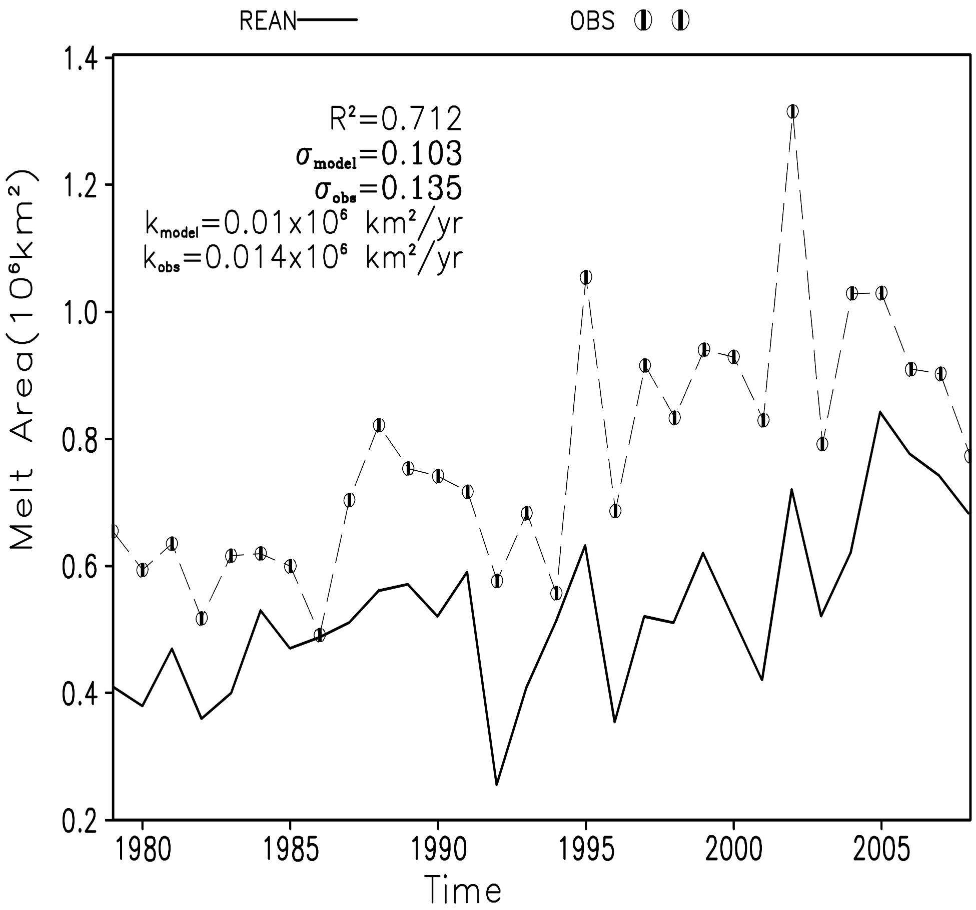
Summer maximum surface melt extent (SME)

- Microwave mts. obtain good estimation of the ice sheet sfc. melt extent and duration because T_b and σ_0 both are sensitive to liquid water present in snow (Ashcraft and Long 2006)
- Observed (upper panels) and simulated (lower panels) SME (melting areas are in red)
- 'near-surface forcing criteria' for surface melting is stipulated as a $T_{2m} > -5\,°C$ & $R_{net} > 170\ W\ m^{-2}$ (L.Thompson, May 2007, personal communication)
- The model simulated yr 2002 melting extent (*c*) is very close to that observed (*b*)
- Panels (a) and (b) are adapted from Chapter 6 in ACIA2005, and originally from K. Steffen, CIRES/U. Colorado at Boulder



MIROC-hires

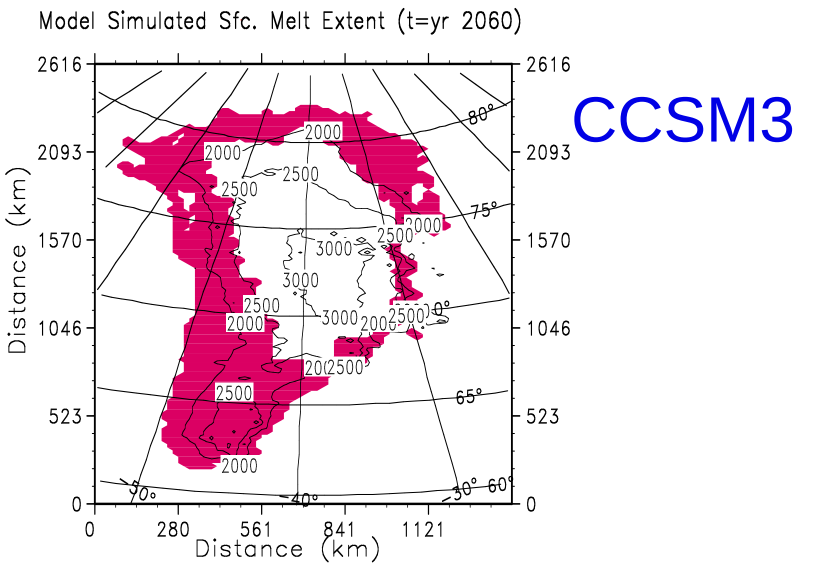
Total SME time series

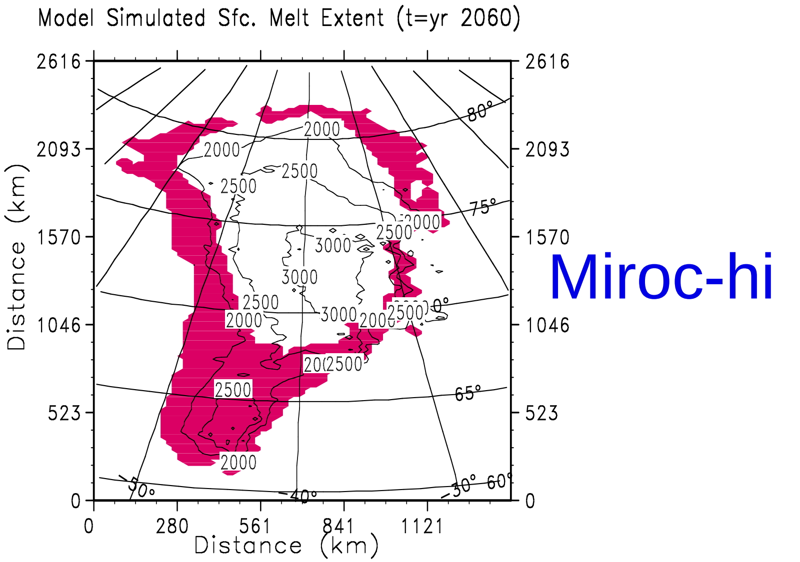


- ✓ The seasonal surface melt extent on the Greenland ice sheet has been observed by satellites since 1979 and shows an increasing trend
- ✓ Obs. re-procesed based on National Snow and Ice Data Center (NSIDC) archive of T_b at 25 km reso. on a NPS progection. See total ice cover of ~1.7 million km^2 close to what the model see
- ✓ Different definition of surface melt may account for the differences in magnitude

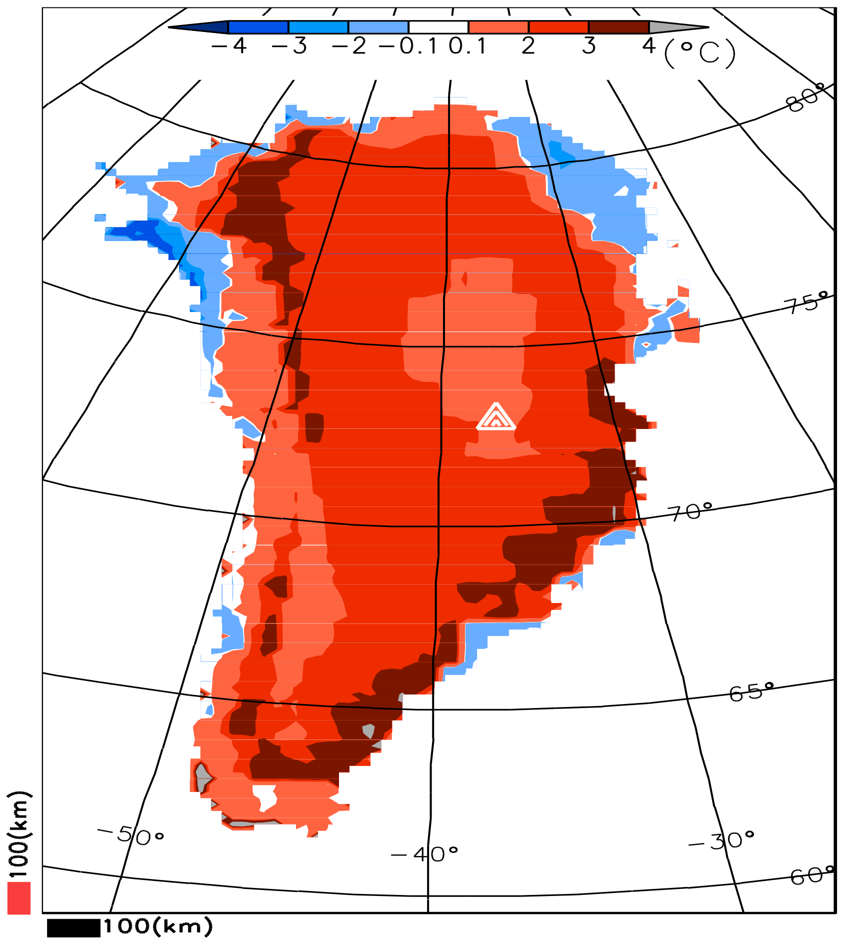
Maximum SME projection

- There are no permanently frozen surfaces south of 68° N
- South of 75° N, the melting expands inland and approaches the 2500 m elevation contour, while on the colder northern side it generally reaches the 2000 m contour
- Centred on the intersection of the 74° N and 38° W, the melt area increases steadily after 2020 and extends to ~1×10^6 km^2 by 2100, with the melting front surpassing the 2600 m elevation contour, leaving only ~7×10^5 km^2 of frozen surface area surrounding the Summit
- The two CGCMs project a very similar pattern for increased SME





Future projections



Ren et al., 2010: A new ice sheet model –formulation and verification

Surface ice temperature changes 2000-2100 simulated by SEGMENT-ice, driven by the NCAR-CCSM3 (B1) scenario for meteorological forcing.

➢Cooling areas at lower elevations exist, especially in the north; likely due to horizontal advection of inland, colder ice. Because ice temperatures are higher at these lower elevations, the ice flow is large and horizontal advection dominates other heating (e.g., sensible heat flux and precipitation).

➢In the vast central GrIS, horizontal advection (a cooling effect) is relatively small and sensible heat flux warming dominates.

➢In between is a ring with greatest warming, corresponding with strong precipitation input, which usually heats the ice.