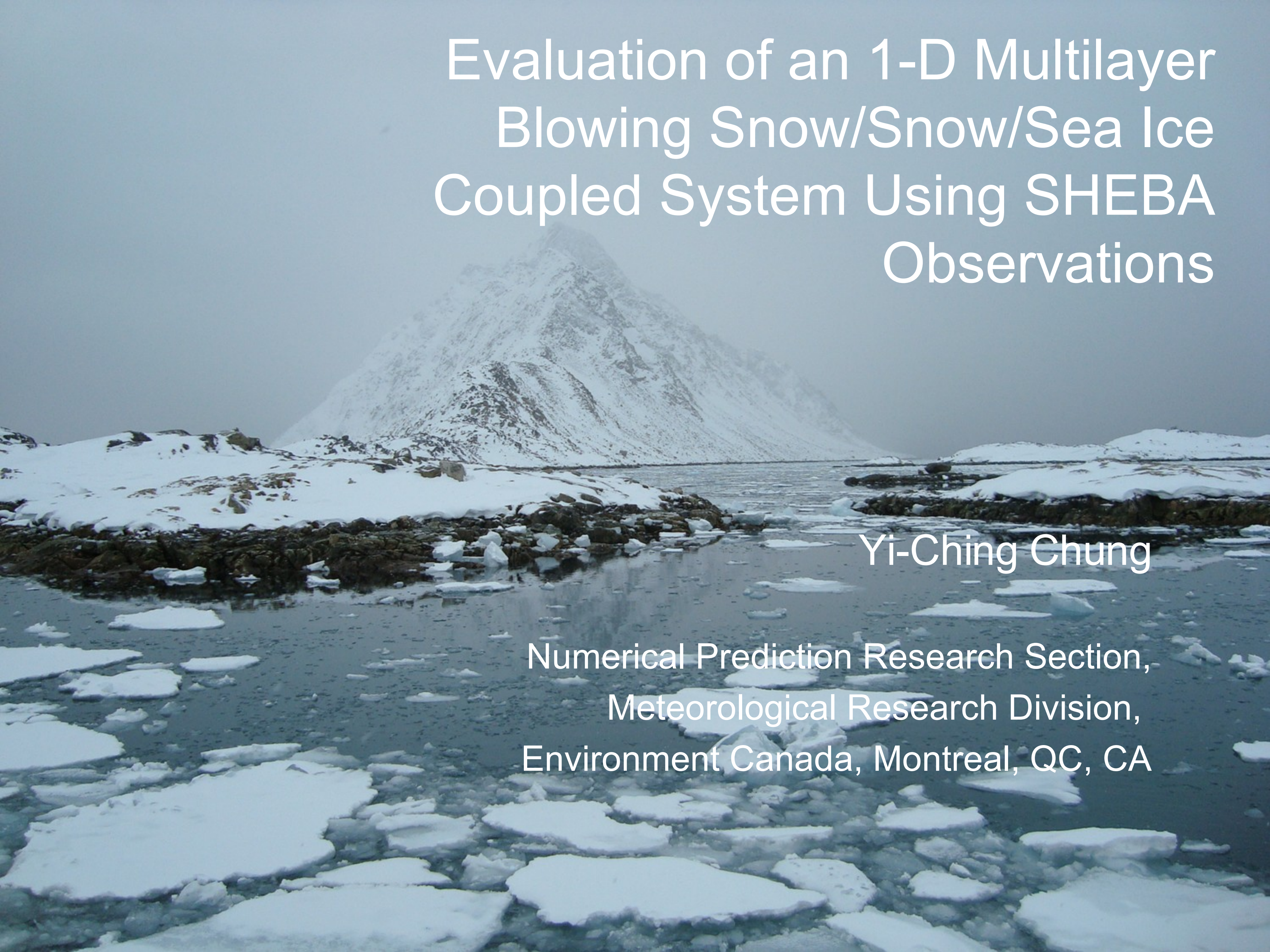

Evaluation of an 1-D Multilayer Blowing Snow/Snow/Sea Ice Coupled System Using SHEBA Observations

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Outline

- Snow/Sea ice system
  - NEW-RPN vs. RPN
- Inclusion of blowing snow
  - NEW-RPN-BS vs. NEW-RPN
- Photo
  - SHEBA
  - Field experiment (Oct. 2009)

Snow and Climate

- 46% of the northern hemisphere land surface
- Water for one-six of the world’s population
- Temperature: 18~52% in Europe
- Annual precipitation: 20±25% in semi-arid Great Plains of North America
- Development of anticyclonic conditions
- Accelerating local atmospheric heating
- 80% of the yearly discharge of some arctic streams and rivers
- Onset of the growing season
- Snow cover: ↓10% since the late 1960s

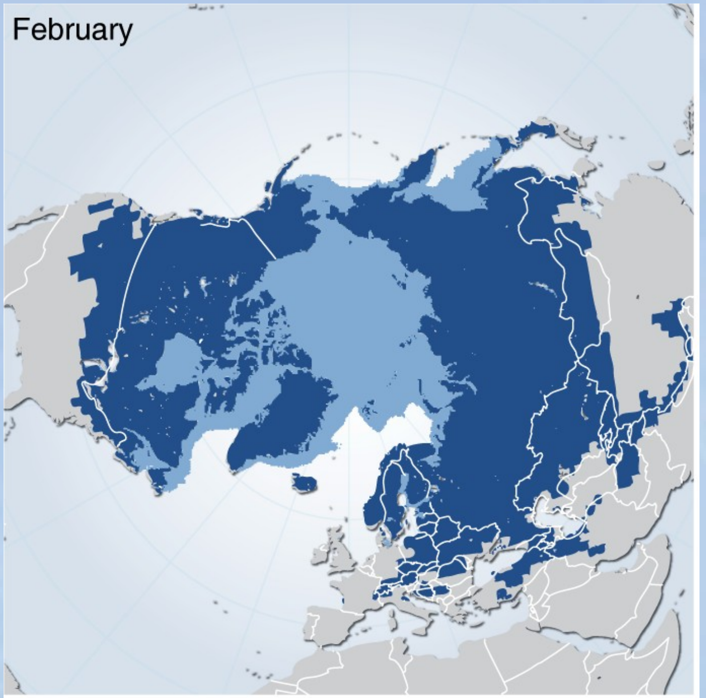


Fig: Mean snow-cover extent in the Northern Hemisphere 1966-2006

Impact of climate change on the Arctic snow/ice

- Hydrology
  - Runoff from western U.S. snowfall peaks several weeks earlier in spring than it did in the 1950's
  - Carbon dioxide and methane uptake of surface water from the ice
  - Ocean circulation and acidification
  - Increases of volatile contaminants evaporated during melting period
- Ecology
  - Seasonal phytoplankton growth
  - Mismatch between the availability of plant and hatching date of snow goose
  - Vulnerability of arctic predators like snow owls and polar bears

Motivation

- **Snow processes over sea ice are currently represented with a simple one-layer snow model in the Meteorological Service of Canada (MSC) operational forecasting systems**

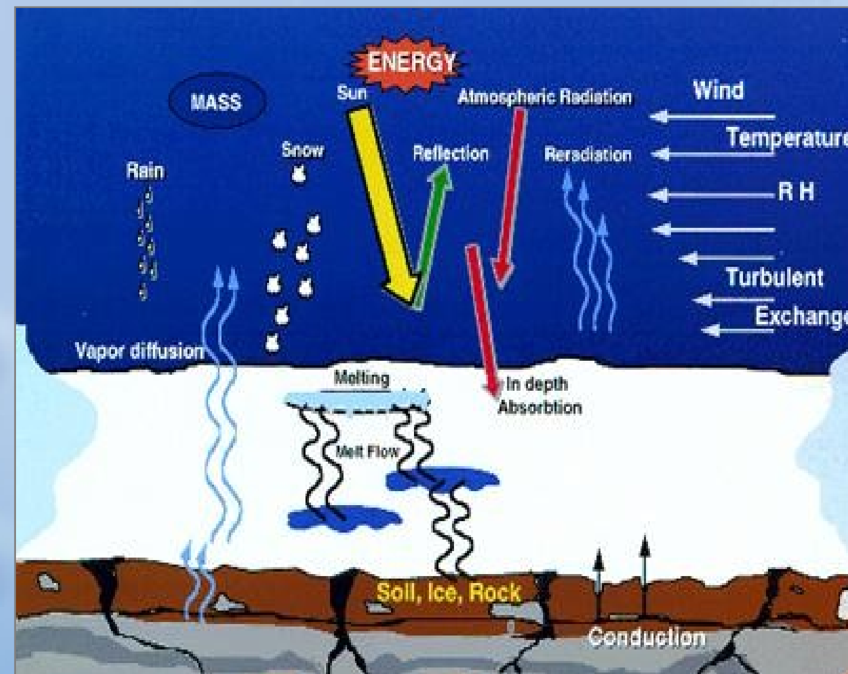
- **To more realistically describe interactions between snowpack and sea ice, while preserving reasonable computing efficiency, we intend to couple SNTHERM with a sea-ice model in MSC's physics package**

(a) Photograph of "Pittsburgh" site taken in spring (Perovich et al., 1999)

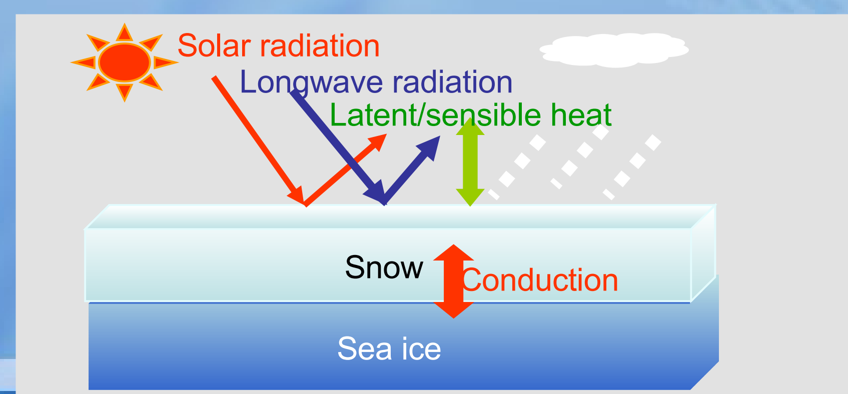
(b) Aerial photograph of Pittsburgh taken in summer (Perovich et al., 1999)

Models

- CRREL SNTHERM Model (Jordan, 1991)
  - One dimensional
  - Unlimited snow layers
  - Mass: retention/percolation, refreezing, snowfall, rainfall, compaction, vapor diffusion & grain metamorphism
  - Heat: thermal conduction, vapor diffusion, water convection & precipitation advection



- One-layer snow in the sea ice model
  - Mass: snowfall only
  - Heat: thermal conduction



- Improving understanding of the Arctic's climate in the present day and future
- Station on a multi-year ice floe, drifted more than 1400 km in the Beaufort and Chukchi Seas
- Measurements at "Pittsburgh" site from October, 1997 to October 1998

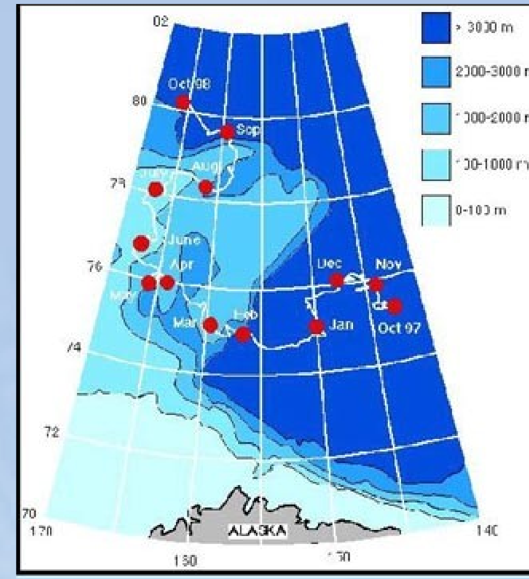


Fig 2 Drifted course of SHEBA (Perovich et al., 1999).

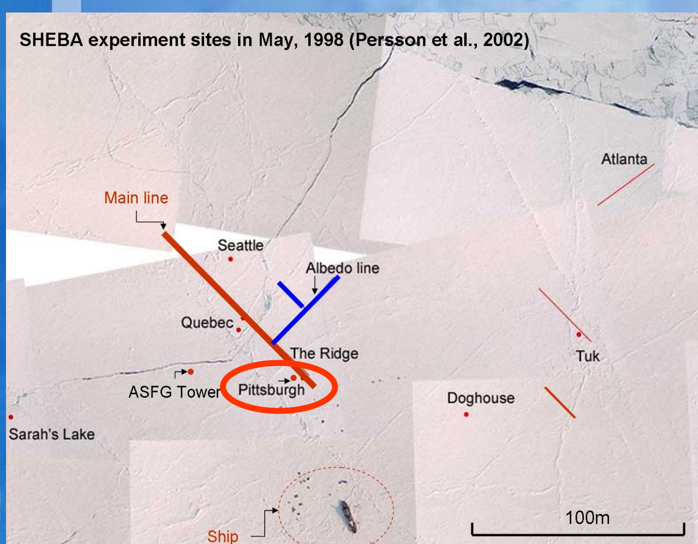


Fig 4 SHEBA campaign site.

Fig 3 Location of SHEBA in the Arctic (Perovich et al., 1999).

Snow depth

- Results from RPN better during the frozen period
  - an unrealistic calibration of the density of fresh snow (274 kg m^{-3})
  - 20 to 200 kg m^{-3} (Jordan 1991), or from 10 to 257 kg m^{-3} (Judson and Doesken 2000)
- Overestimation from New-RPN (by ~17 cm) in late winter
  - overestimation by 15 cm (Jordan et al. 1999)
- Blowing snow sublimation
  - effect of wind transport incorporated (Jordan et al. 1999)

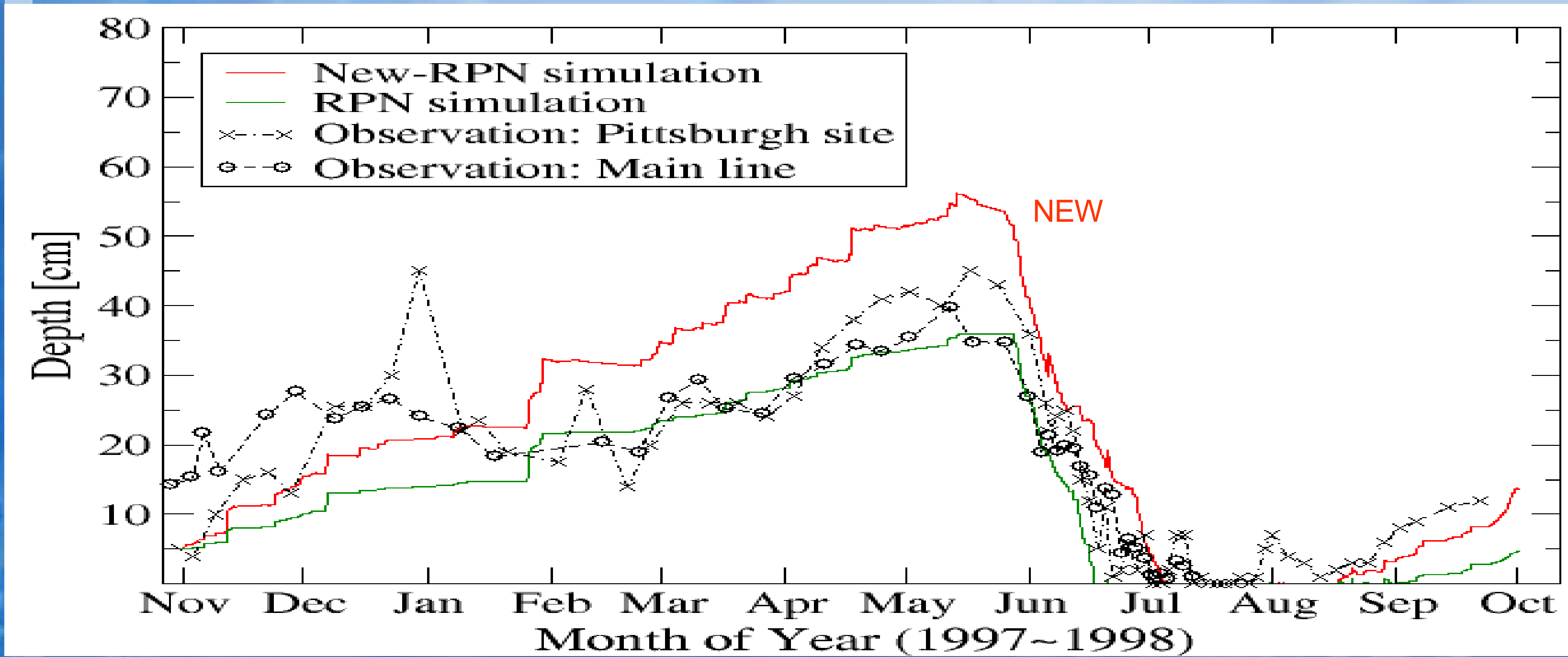


Fig. Evaluation of snow depth [cm] for RPN and NEW-RPN and for two sets of measurements.

Ice thickness

- Shallower snowpack leads to a thicker ice pack
  - NEW-RPN's onset of melt later than observations (by about 6 days)
  - RPN-estimations improved if a value (100 kg m^{-3}) of density used
- Overestimation after July occurs because of
  - inaccuracies in the sea ice model and a constant ocean heat flux forcing
- Basal ocean heat flux is crucial for ice evolution (especially summer)
  - e.g. decreases by 36 cm if annual mean values of 2 W m^{-2} replaced by

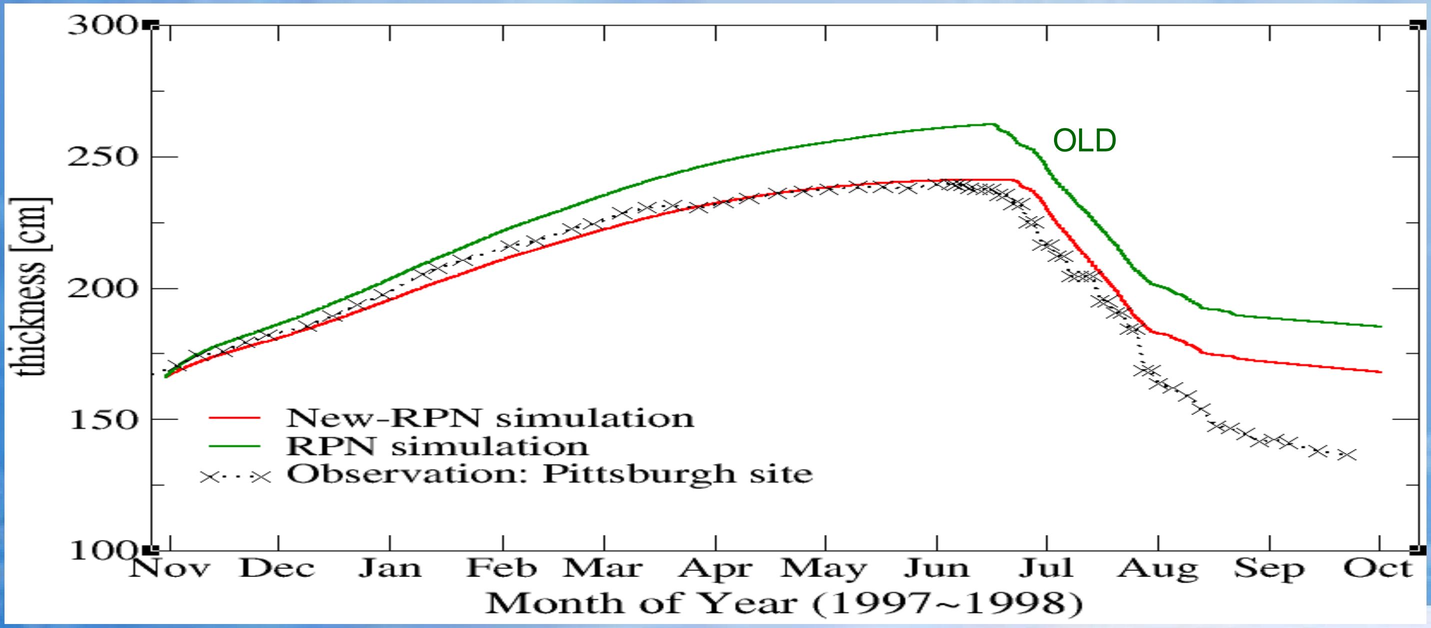
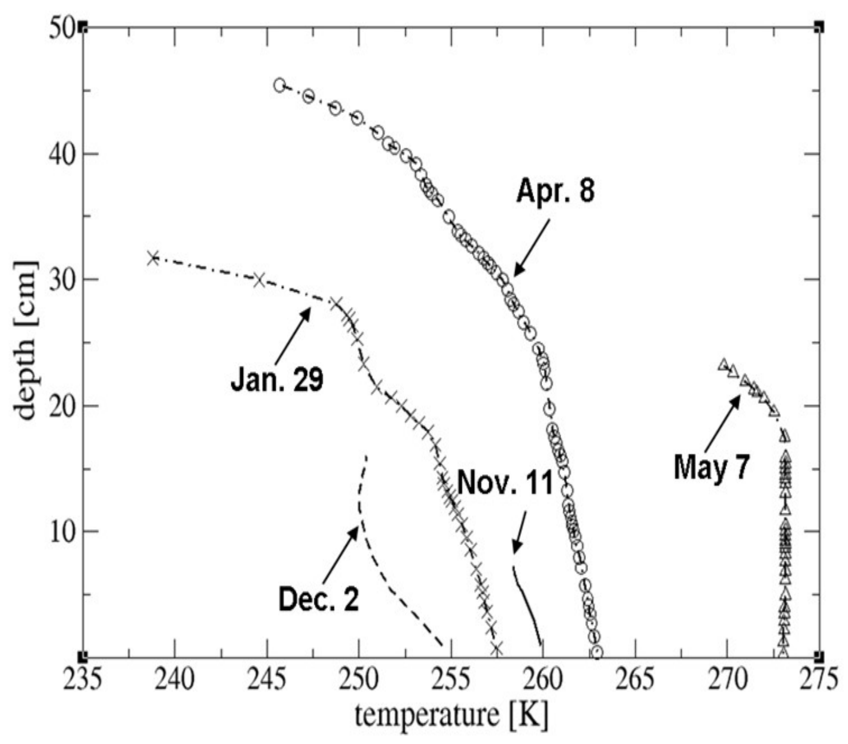


Fig. Evaluation of ice thickness [cm] for RPN and NEW-RPN and for measurements

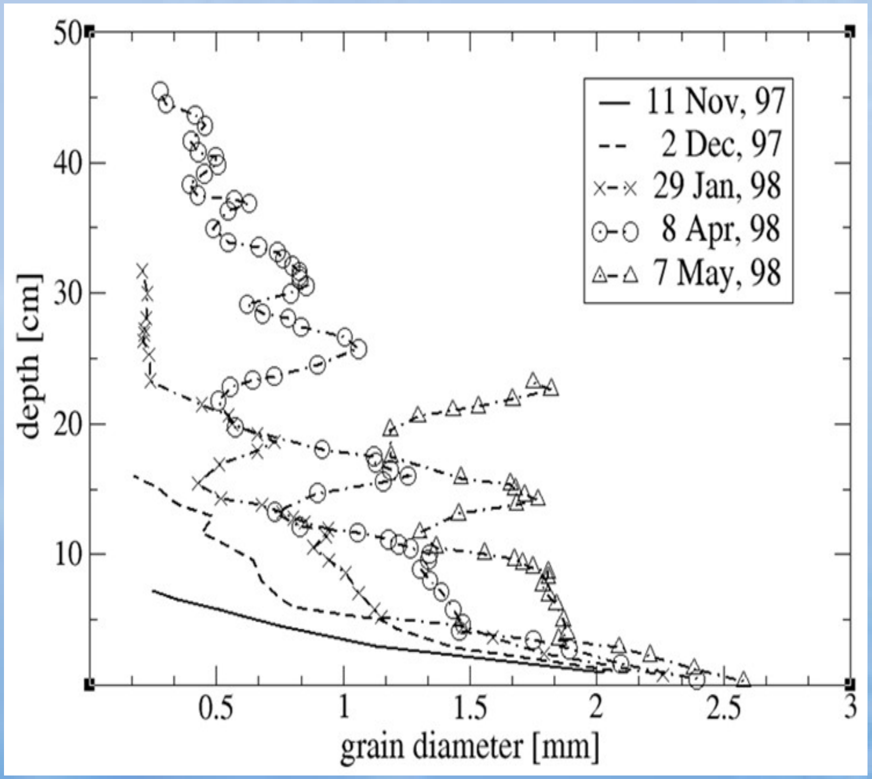
Vertical structure: Snow temperature

- Strongly stratified
  - with the exception of isothermal conditions on May 7
  - temperature gradients as large as 40 K m^{-1} on January 29
- Spatial inconsistency
  - mean snow depth at reference mass balance site deeper by 11 cm than estimation from temperatures measured at gauge sites (Huwald et al. 2005a)
- Single-layer snow models like the one used in the RPN configuration are not able to simulate grain growth and water convective fluxes, which in turn influence phase changes and the rate of refreezing



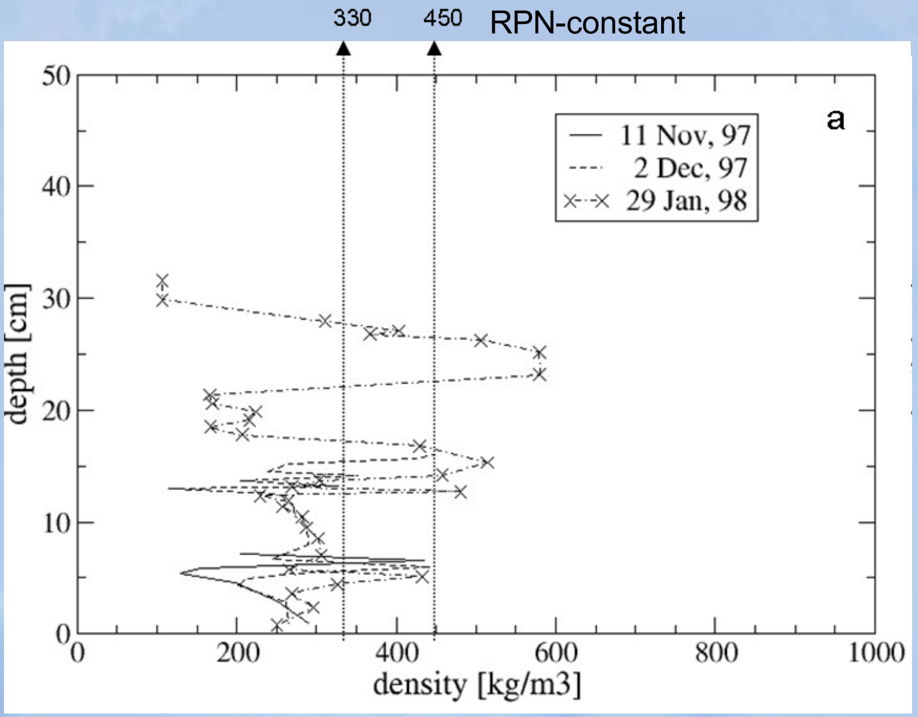
Vertical structure: Grain size

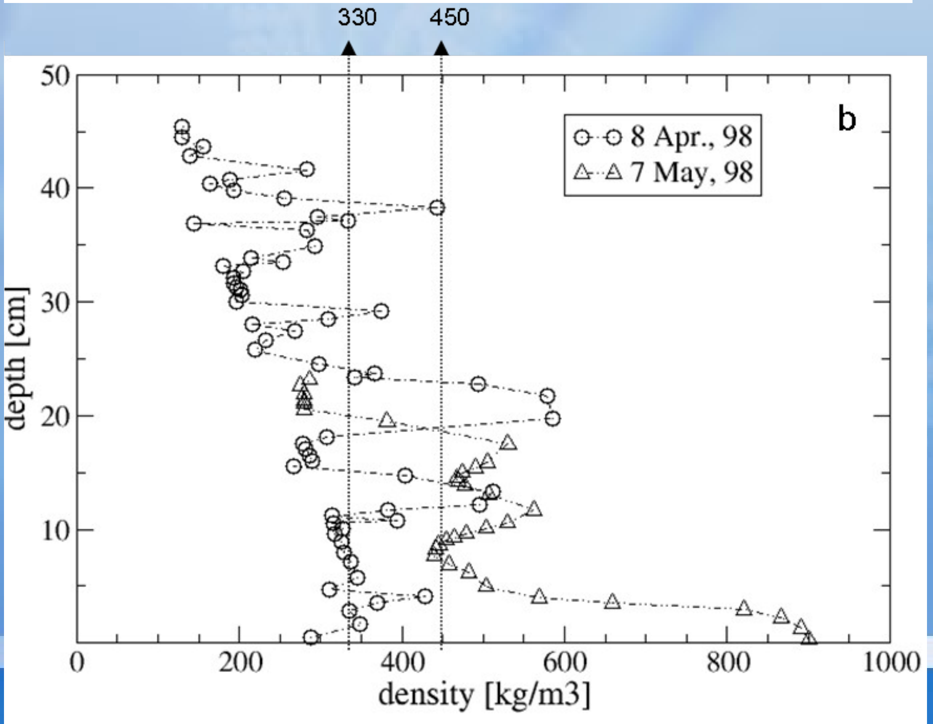
- Consistent with observations of upper snowpack
  - small grains of 0.5 mm near snow surface between December 1997 and April 1998, probably faceted depth hoar-like crystals (Sturm et al. 2002)
  - simulated fine grain sizes between 0.3 to 0.8 mm, due to wind slab effect, related to strong winds which could break the snow grains into smaller grains, pack them together, and sinter them into dense and well bonded layers (Seligman 1980)



Vertical structure: Snow bulk density

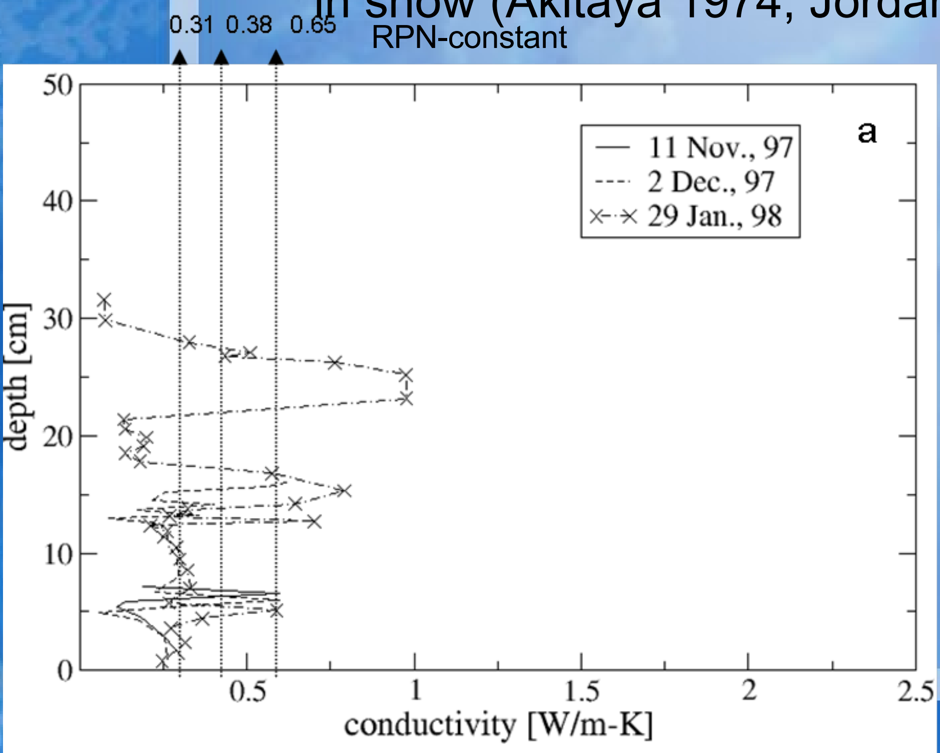
- Snow density did not change much in winter
  - similar from November to January (between 200 and 300 kg m^{-3})
  - limited impact from recent snow on total snow water equivalent (SWE) and mean density
  - no significant densification from wind slabs (Sturm and Holmgren 1998) and depth hoars (Armstrong 1980; Sturm and Benson 1997)
- There is a more rapid temporal variability in snow base in spring
  - on April 8, density evolving especially in the middle of snowpack due to snow compaction
  - on May 7, values as large as 900 kg m^{-3} at bottom due to ice formation
  - High-density snow layers near surface associated with wind slab due to intense winds
  - low-density, fine-grained layers under a reduced wind speed with snowfall (Sturm et al. 2002)

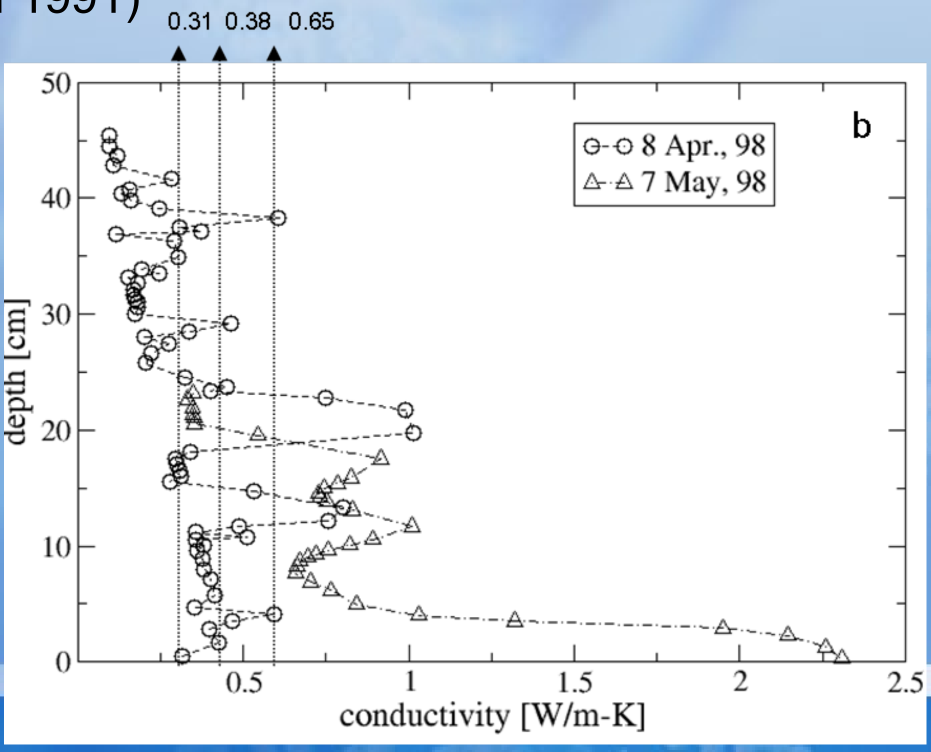




Vertical structure: Conductivity

- Many snow modules incorporated in atmospheric models use a value of 0.31 W $m^{-1}K^{-1}$
- There is considerable vertical variability
  - depth hoars (0.07 W $m^{-1}K^{-1}$) and wind slabs (1 W $m^{-1}K^{-1}$) near the surface (Sturm et al. 2002)
  - no depth hoar in the base (all greater than 0.25 W $m^{-1}K^{-1}$ before April) but ice layers simulated (about 2.3 W $m^{-1}K^{-1}$) at the base on May 7
  - spatial variability (Huwald et al. 2005a), difficulty of measuring fluxes (Huwald et al. 2005b), and variations of air fraction & natural convection in snow (Akitaya 1974; Jordan 1991)





Sensitivity Analysis

- During the ablation period, surface albedo has an impact on vertical temperature distribution and grain size, thus delaying or accelerating spring snow melt
- During the frozen period, wind speed and new snow density of greater concern
- Snow compaction may have the most influence on snow
  - snow metamorphism, overburden pressure, melting, and wind packing (Jordan 1991)
- Vapor diffusion has a limited effect on snow depth
  - unnecessary for snow schemes in atmospheric modeling systems (for NWP or for climate prediction)

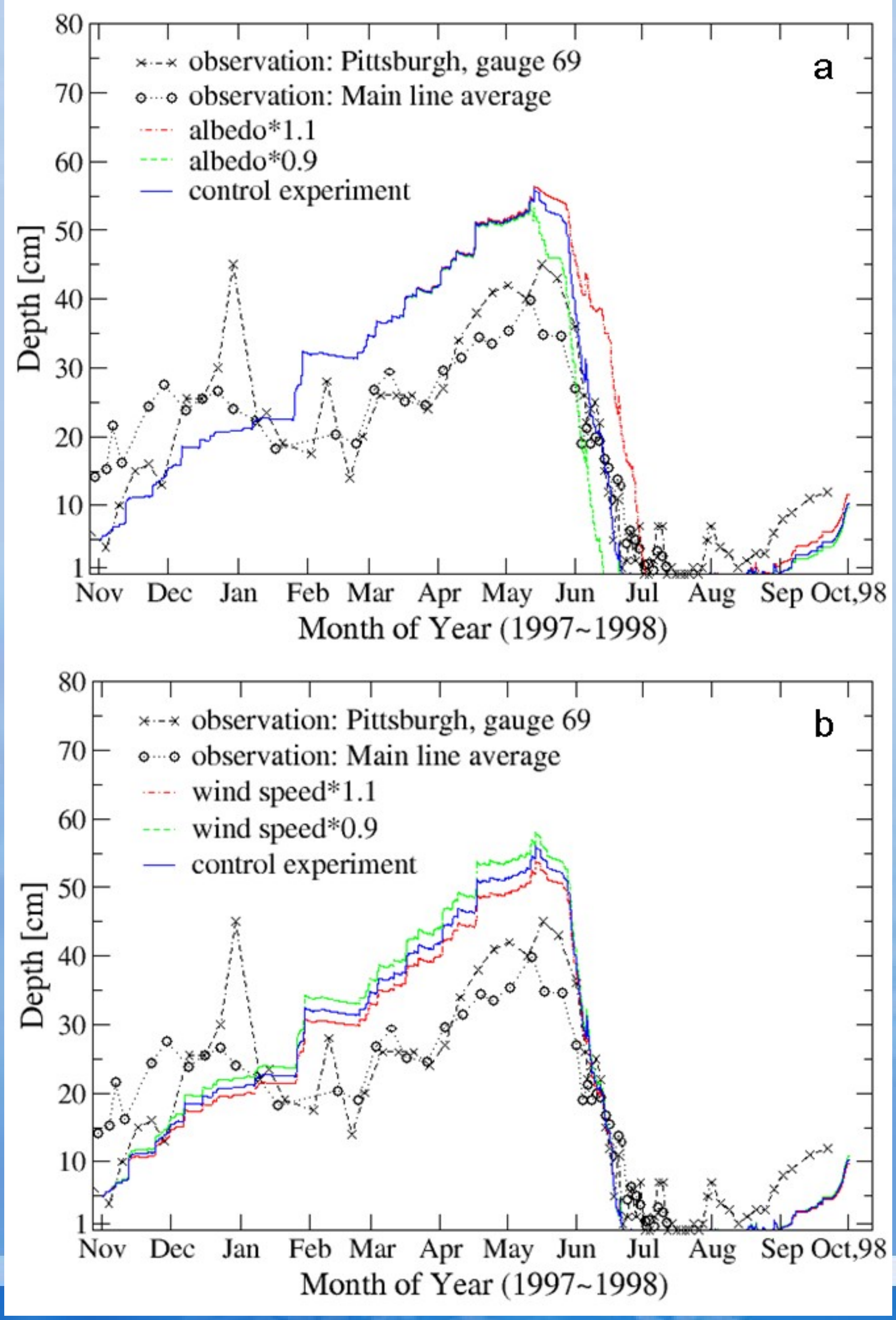


Fig Sensitivity analysis of simulated snow depth [cm] on (a) albedo and (b) wind speed, along with two sets of measurements

Conclusion

- Timing of snow depletion simulated by NEW-RPN is more accurate than that simulated by RPN
  - NEW-RPN's snowpack deeper than observed (by 17 cm) in winter
- NEW-RPN is able to more realistically simulate ice thickness, with a slower ice growth rate related to increased insulation by the deeper snowpack
- NEW-RPN may catch the formation of ice slabs in the bottom of snowpacks in spring but does not simulate full depth hoar conditions yet
  - Limited change of the snow density profiles during the winter (Sturm et al. 2002)
  - The averaged snow thermal conductivity (0.39 W m-1K^{-1}) within the range of values of 0.14 W m^{-1}K^{-1} (Sturm et al. 2002) and 0.5 W m^{-1}K^{-1} (Huwald et al. 2005a, 2005b) and larger than the typical value of 0.31 W m^{-1}K^{-1} used in single-layer snow models
- Spring snow evolution is highly sensitive to uncertainties in the surface albedo whereas the winter snow evolution is significantly affected by uncertainties in wind speed and new snow density

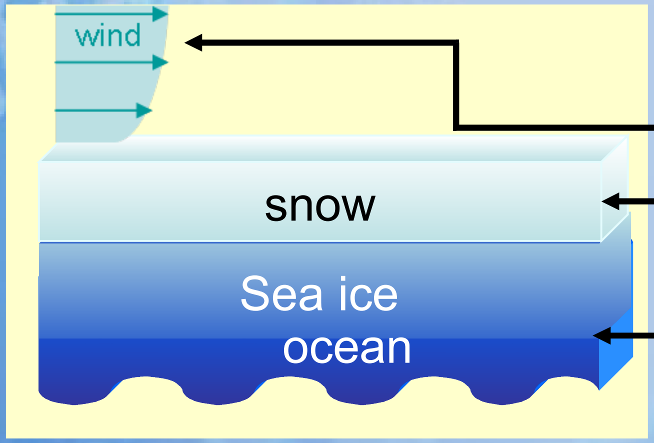
Perovich, D.K., T.C. Grenfell, B. Light, J.A. Richter-Menge, M. Sturm, W.B. Tucker III, H. Eicken, G.A. Maykut, B. Elder, SHEBA: Snow and Ice Studies CD-ROM, October, 1999.

Background

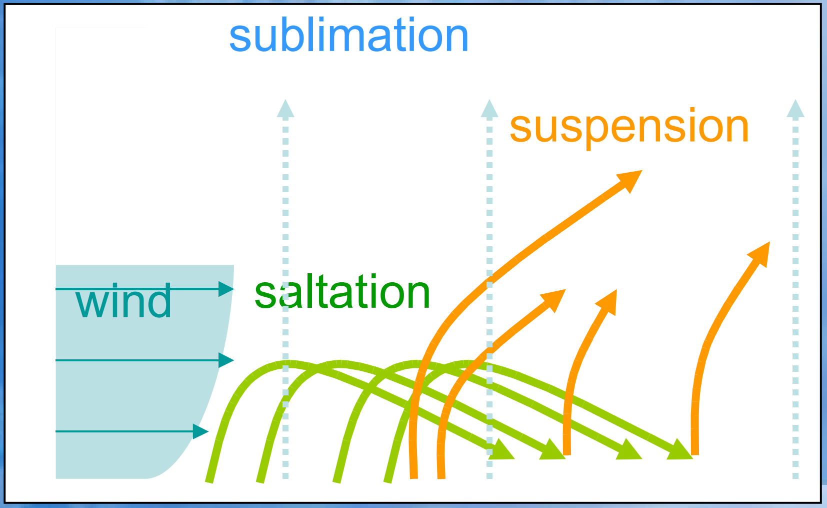
- **Introduction**
  - Strong low-level winds can occur very frequently in the Arctic Ocean & Antarctica
  - Estimates in snow depth may be improved if including wind blowing parameterization (Déry and Yau, 1999; Chung et al., 2008)
- **Objectives**
  - Examine the effect of blowing snow on the simulation of snow and sea ice in the Arctic Ocean

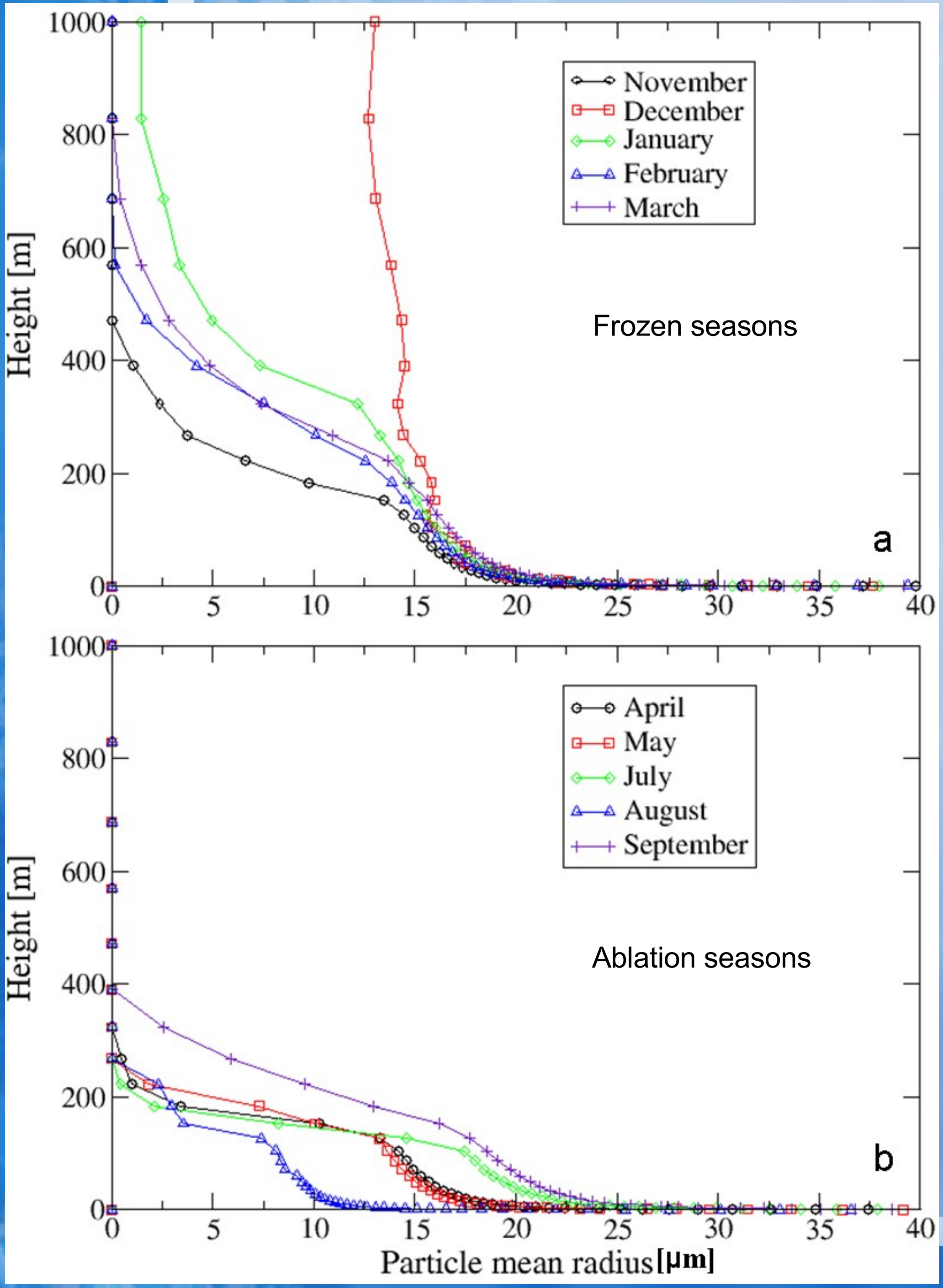
Blowing snow on the ice shelf edge near Rampen (72S, 16W), Antarctica, from Dr. R. Bintanja
Institute for Marine and Atmospheric research Utrecht (IMAU), Utrecht University, The Netherlands

Models in coupled system



- 1-D, **blowing snow model**, PIEKTUK (Déry, 2001)
- 1-D, **multi-layer snow model** SNTHERM (Jordan, 1991)
- **Multi-layer, thermodynamic sea ice model** from Meteorological Service of Canada (MSC) operational forecasting system run 1-D, offline model



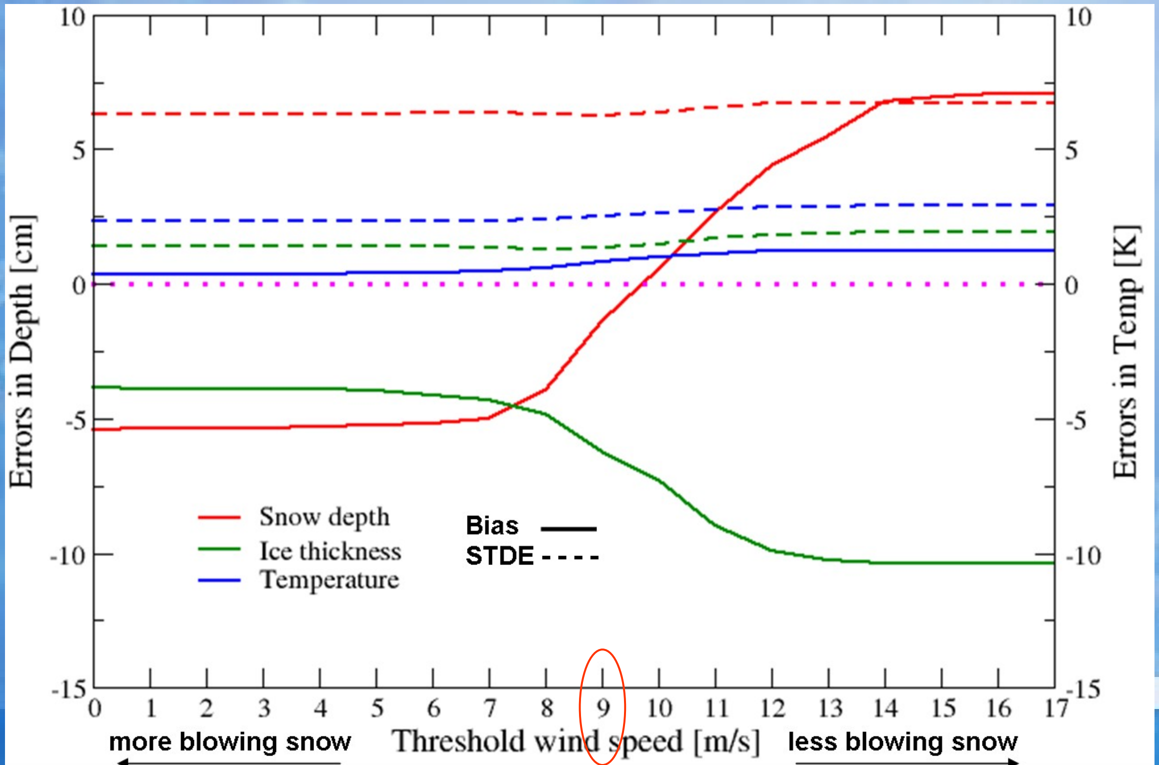


Particle size for drifting snow

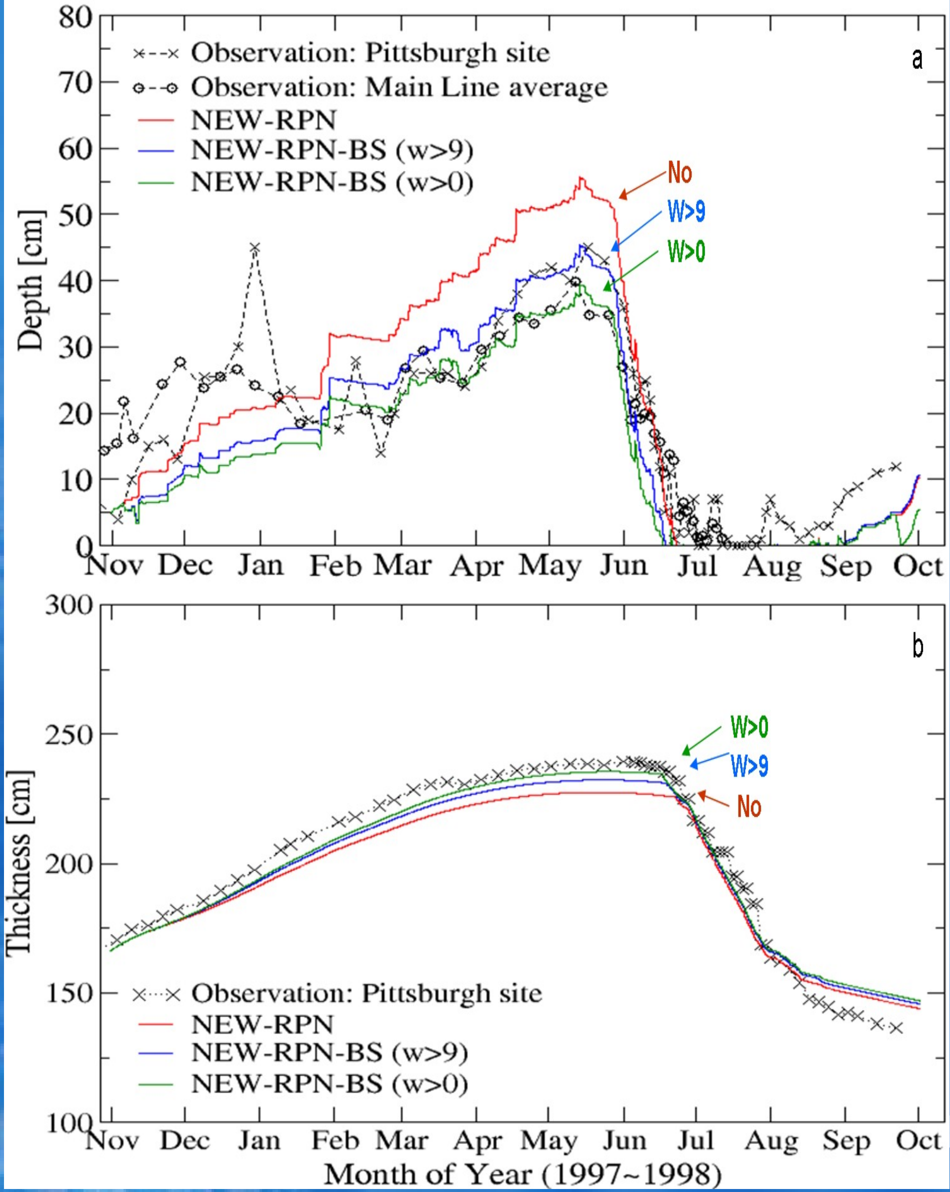
- The mean radius ranges between 0 μm and 40 μm
- Layer of suspended blowing snow extends to heights between 400 m (April to September) to beyond 1000 m (November to March)
- Drift particles are more predominant in winter
- These resulted from complex interactions between turbulent diffusive processes and relatively sophisticated microphysical processes

Sensitivity analysis

- Bias
  - overestimation of snow depth reduced by blowing snow sublimation
  - ice thickness increasing more rapidly by bottom accretion
  - lower temperature at the snow and ice interface
- STDE
  - STDEs do not depend much on the occurrence of blowing snow
  - ice thickness exhibits less temporal variability; opposite for temperature
- A wind speed threshold of 9 m s^{-1} is chosen
  - between the values of 7.7 m $^{-1}$ and 9.9 m s^{-1} (Li and Pomeroy 1997)



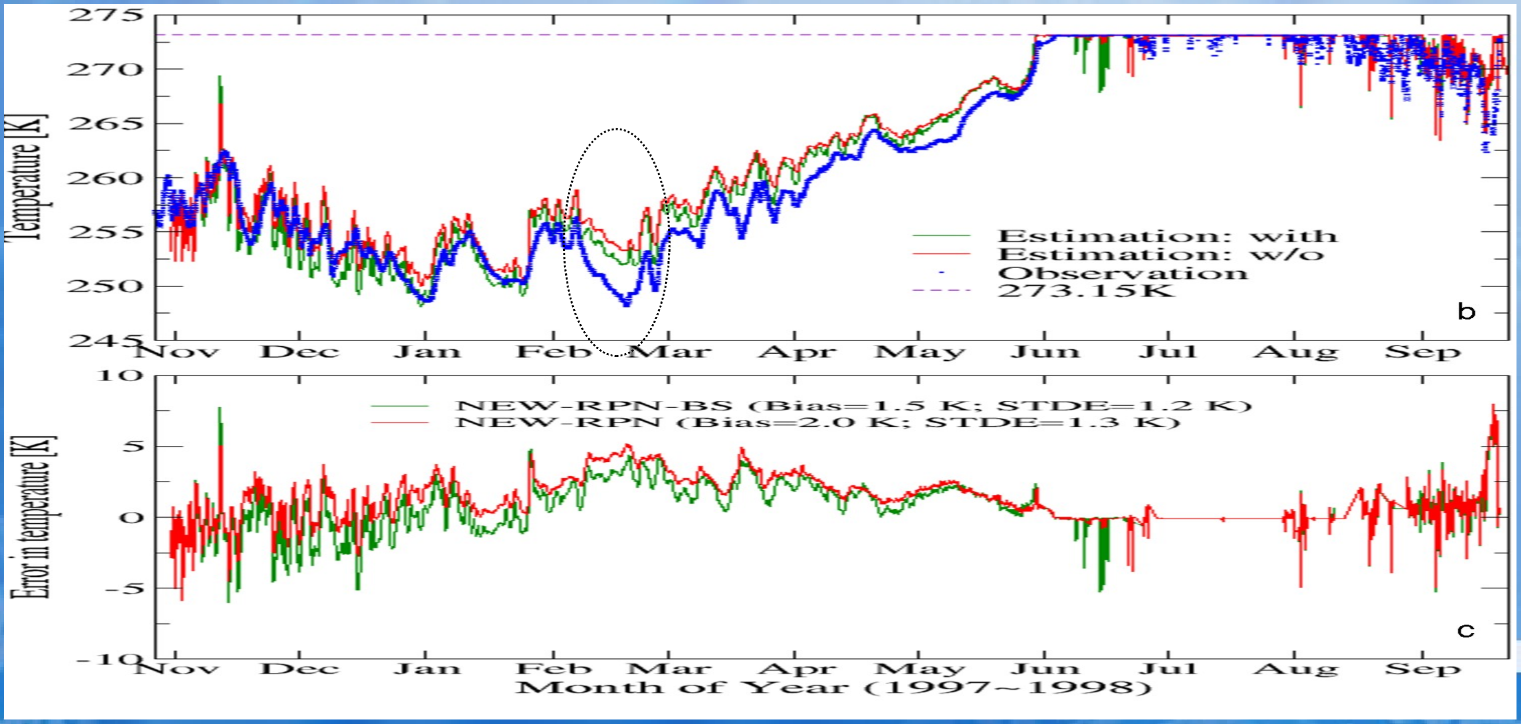
Impact of blowing snow on thickness



- Snow depth
  - A significant reduction (difference of 9 cm in average) in snow depth
  - Shortening of the snow cover duration by 4 days
  - Model performance greatly improved during snow accumulation
  - Less affected by horizontal wind transport from February to June (Sturm et al. 2002)
- Ice thickness
  - A slight increase for ice thickness, with a difference of about 4 cm in average
  - Accelerating the ice melt after the snow ablation by 6 days

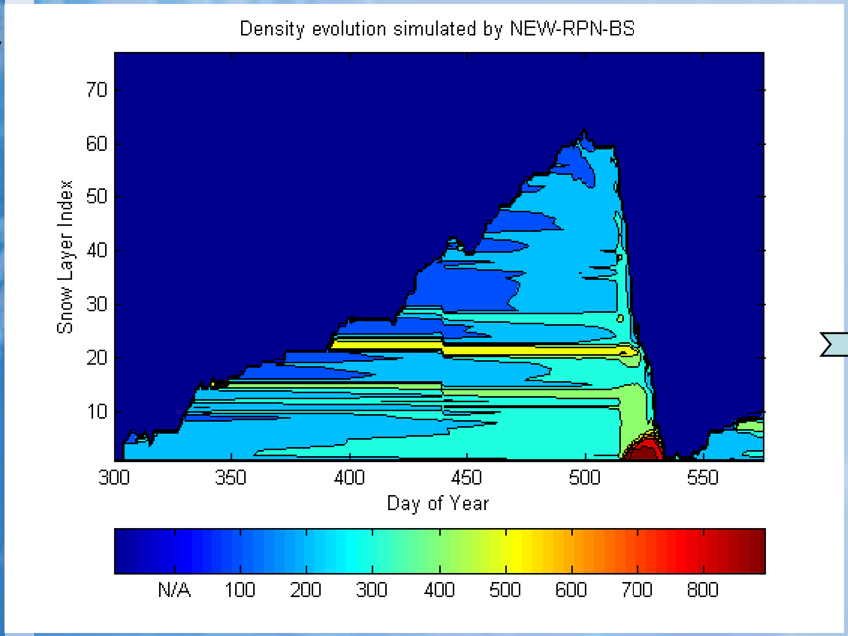
Impact of blowing snow at the snow/ice interface

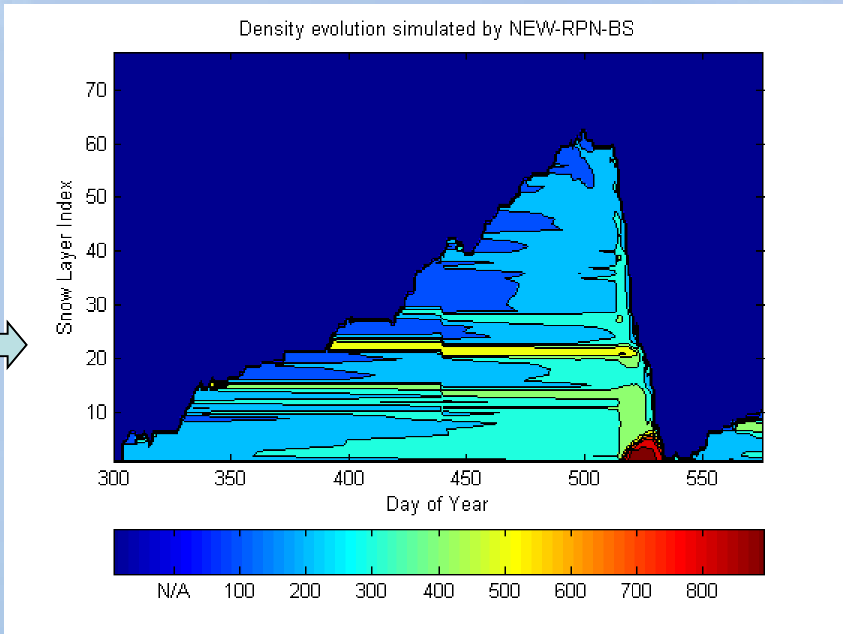
- Temperatures
  - Intense and prolonged cooling in February (7 K in two weeks)
  - Experiment with blowing snow exhibiting smaller errors
  - Effect of Wind transport, termination of polar night, and dramatic variations of atmospheric pressure and of relative humidity in late winter, then frequent melt and freeze cycles in early spring
- Blowing snow can decrease insulation of snow depth, leading to a decrease of temperatures at interface, forcing ice growth, and enhancing sensible heat fluxes from ocean (Huwald et al. 2005)



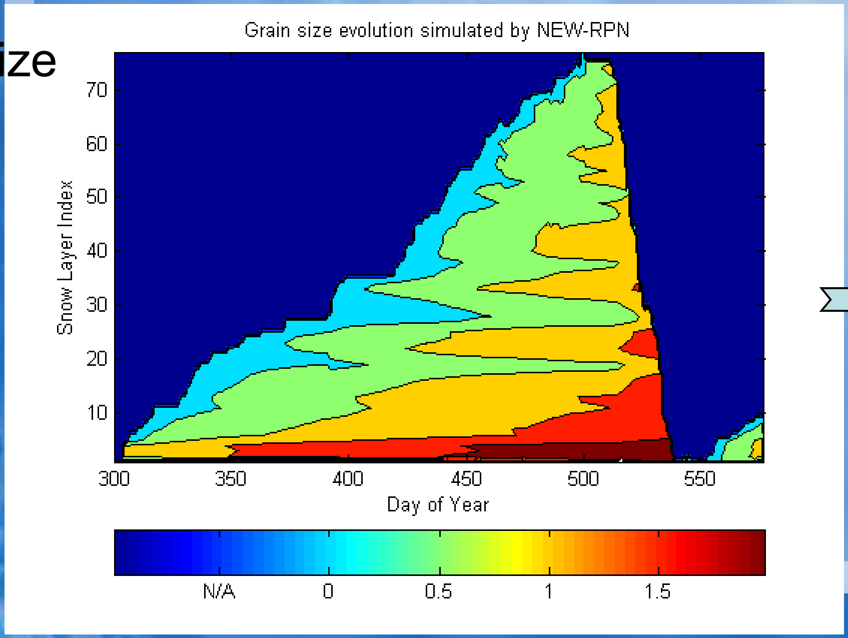
Simulated internal snow structure

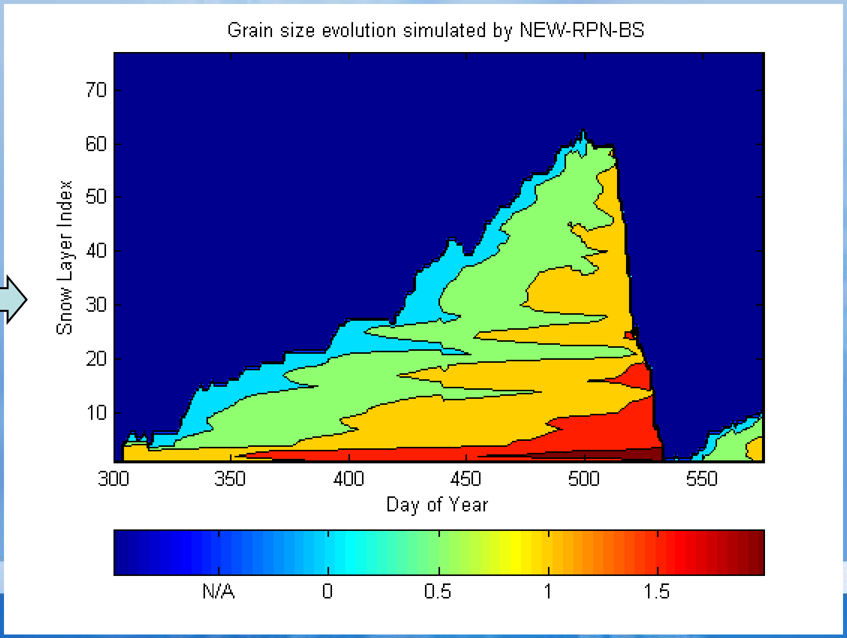
Density





Grain size





Simulated internal snow structure

- Density
  - a peak for values of 200-300 kg m^{-3} (40% for NEW-RPN; 46% for NEW-RPN-BS)
  - In NEW-RPN, 12% smaller than 200 kg m^{-3}; in NEW-RPN-BS, 15%
  - less wind slab layers (48% for NEW-RPN; 38% for NEW-RPN-BS for density greater than 300 kg m^{-3}), especially near the surface of the snowpack.
  - high-density snow layers in the middle or bottom
  - ice formations with densities as large as 900 kg m^{-3} at bottom in spring, with the same results (1%)
- Grain sizes
  - a peak for values of 1-1.5 mm (30% for NEW-RPN; 34% for NEW-RPN-BS).
  - much smaller values (42% by NEW-RPN and 46% by NEW-RPN-BS for grain size between 1 mm to 2 mm) than the observed profiles of 10 mm facets observed by Sturm et al. (2002).
- Even though blowing snow increases snow grain size and decreases snow density, leading to a weaker snowpack, its impact on the internal snowpack is small

Conclusion

- Blowing snow sublimation
  - Sublimation loss ranging from 0.1 and 0.26 SWE mm hr^{-1} during strong winds with a total accumulated sublimation of 56 mm SWE
  - Radius of blowing snow particle distribution between 0 µm and 40 µm, extending to heights of 400 m for spring and 1000 m for winter
- Snow
  - Blowing snow potential of improving model performance in late winter and early spring
  - A significant reduction (9 cm) in snow depth and for a shortening of the snow-covered period by 4 days
- Sea ice
  - A decrease of 0.4 K found for temperature at snow/ice interface
  - A slight increase of about 4 cm on for ice thickness found, with an improvement for the prediction of the onset of ice melt (by ~6 days)

Future work

- Simulation
  - Urban snow evolution with snow hydrology
  - 3-D atmospheric models
  - Effect of anthropogenic sources
    - Sulphate deposition (Wasiuta et al. 2009)
    - Mercury deposition
    - Black carbon
  - Avalanche

- Dataset
  - ESA CryoSat-2 mission
    - covers the entire Arctic region except for a small polar gap since 2009
    - with a corresponding airborne and in-situ campaigns in Greenland, Svalbard, Canada and the Arctic Ocean (Hanson et al. 2009)
  - SCLP satellite mission for snow and cold land processes launched in 2016-2020

Questions?