Department of Atmospheric and Oceanic Sciences McGill

Development of a coupled blowing snow-atmospheric model and its applications

a Ph.D. Defense by:

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Aug 2, 2010

So why study blowing snow?

a question I've been asking myself quite a lot lately…

It occurs frequently in high latitudes:

Often more than 90 days per year.

It has important impacts:

1. Reduces visibility

2. Plays an important role in surface water mass budgets:

through wind transport of snow

through increased sublimation

3. Can impact dynamics, e.g., through low level cooling associated with sublimation of blowing snow particles.

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Model Development

1. Developed a stand-alone triple-moment blowing snow model (PIEKTUK-T)
2. Coupled it to MC2 (as a two-way coupling system)

Applications:

1. Seasonal water mass budgets over the Northern Hemisphere
2. Study of blowing snow cooling effects on anticyclogenesis

Blowing snow

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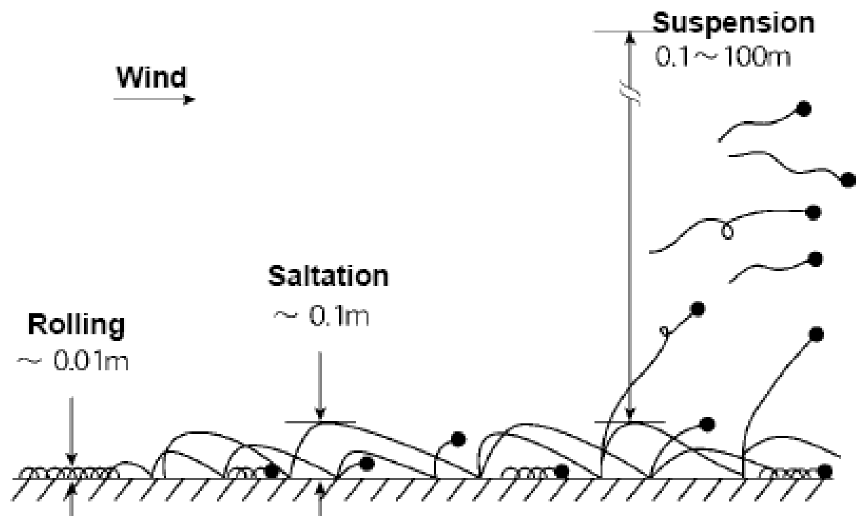

Schematic of blowing snow transport (Takeuchi 1984)

Saltation layer: a narrow layer where snow particles bounce (or dance) along the surface at heights of a few centimeters

Suspension layer: If turbulence is strong, saltating particles may be transported by turbulent eddies into suspension.

1-D Blowing Snow model

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$$\frac{\partial T_a}{\partial t} = \frac{\partial}{\partial z}(K_h \frac{\partial T_a}{\partial z}) + \frac{S_b L_s}{c_p}$$

$$\frac{\partial q_v}{\partial t} = \frac{\partial}{\partial z}(K_v \frac{\partial q_v}{\partial z}) - S_b$$

$$\frac{\partial N}{\partial t} = \frac{\partial}{\partial z}(K_N \frac{\partial N}{\partial z} + v_N N) + S_N$$

$$\frac{\partial q_b}{\partial t} = \frac{\partial}{\partial z}(K_b \frac{\partial q_b}{\partial z} + v_b q_b) + S_b$$

$$\frac{\partial Z}{\partial t} = \frac{\partial}{\partial z}(K_Z \frac{\partial Z}{\partial z} + v_Z Z) + S_Z$$

PIEKTUK-T (Yang and Yau, 2008, BLM)

Assumption:

Blowing snow particles follow a three-parameter Gamma size distribution $F(r) \propto (N, \alpha, \beta)$

N, q_b, Z are the 0th, 3rd and 6th moments of $F(r)$.

Physical processes:

Diffusion – subgridscale turbulence modelled by vertical diffusion.

Sedimentation- $v_{,N}$, v_b, v_Z are moment-weighted fall velocities for N, q_b, and Z.

Sublimation- S_N, S_b, S_Z represent changes in N, q_b, Z due to sublimation (integrated over all radii). Note that S_b is a source of moisture and sink of heat.

1-D Blowing Snow model: Verification

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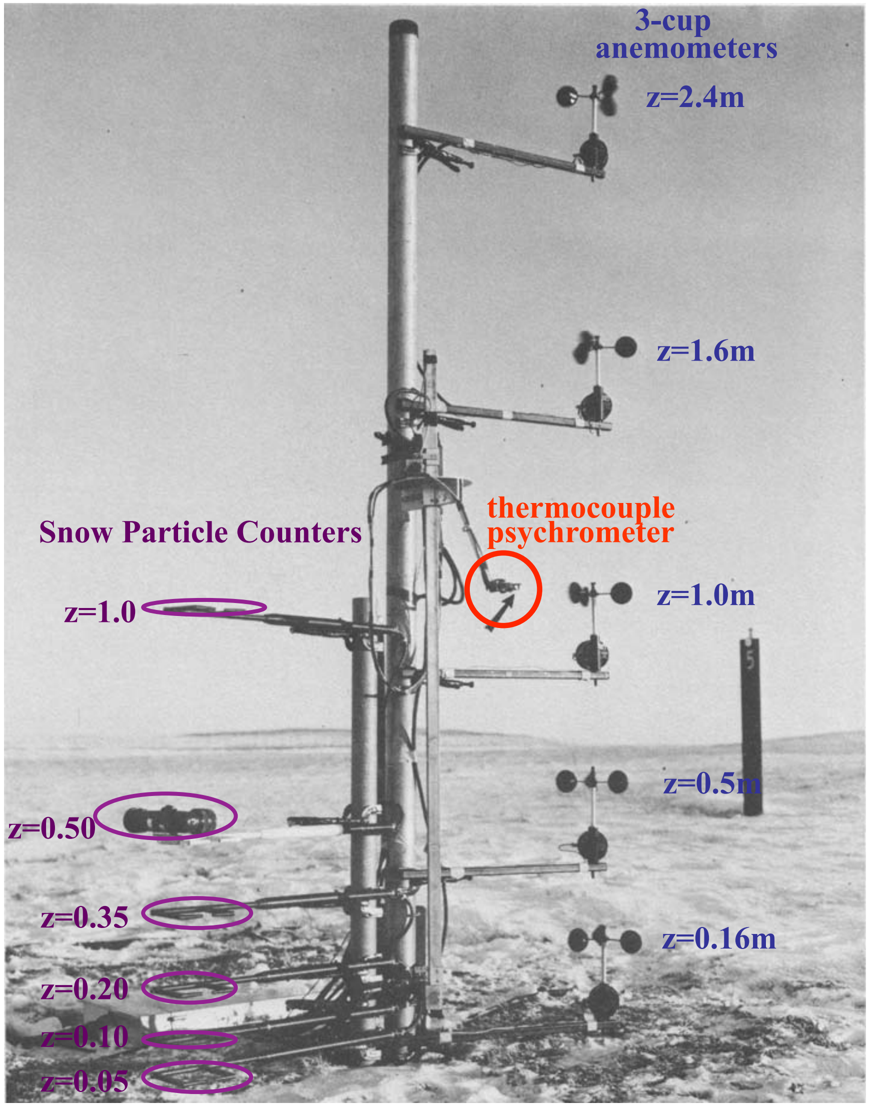


Schmidt R.A. (1982)

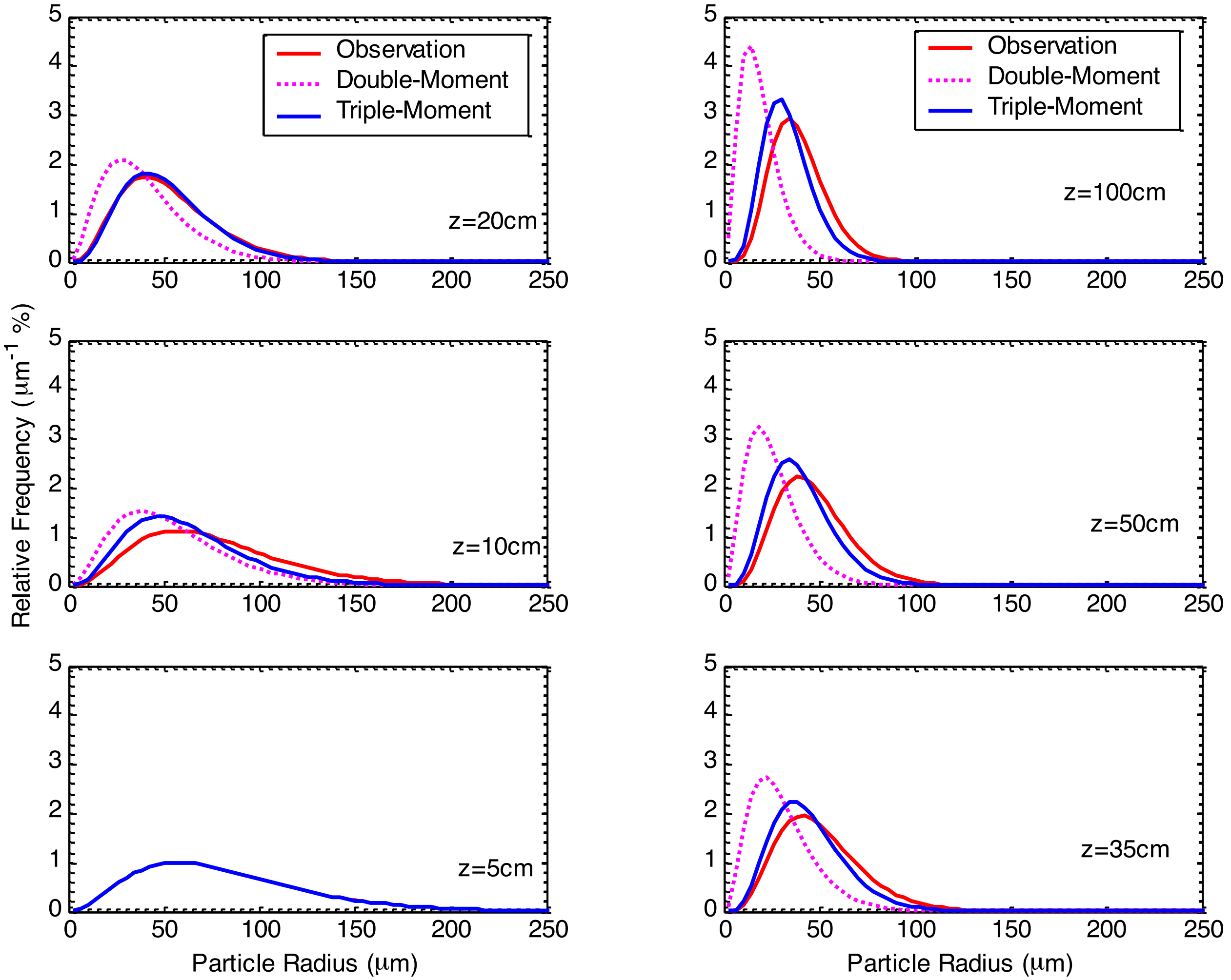
Location: Southeastern Wyoming, USA

Time : 4~5 April, 1974

Observed fields:

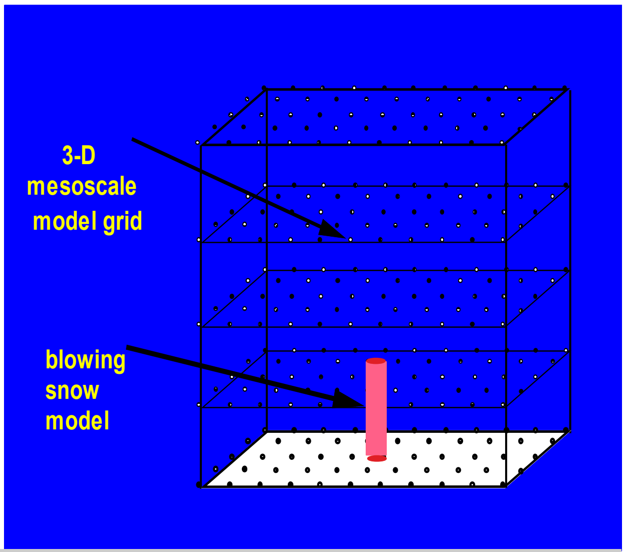
- wind speed profiles
- humidity
- blowing snow concentration
- particle size

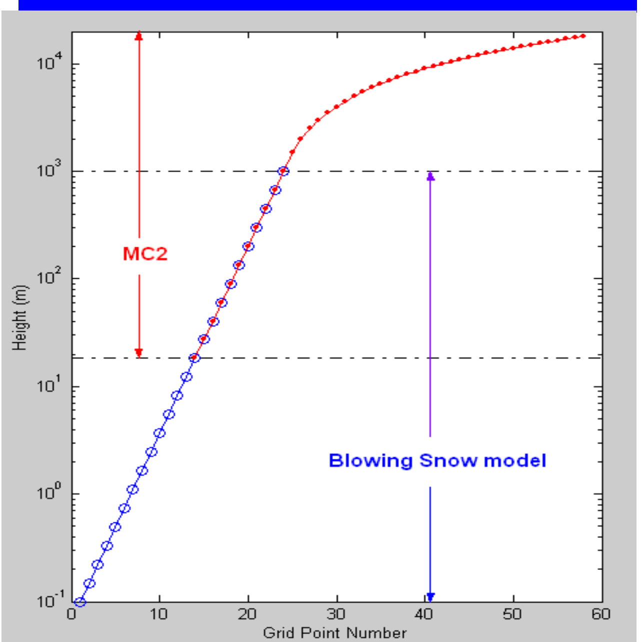
1-D Blowing Snow model: Verification



Particle size distributions: Red curve is observations; blue curve is triple moment; dashed curve is double moment (Déry and Yau, 2001).

Coupled model





Dynamics: Semi-Implicit and Semi-Lagrangian (SISL) numerical scheme

Physics: Physical processes computed on independent columns so parallel computation is possible.

- MC2: 46 levels from 12 m to 18 km.
- Blowing Snow model: 24 levels
  - 12 in the matching layer (12m-1km)
  - 12 below the lowest MC2 grid point

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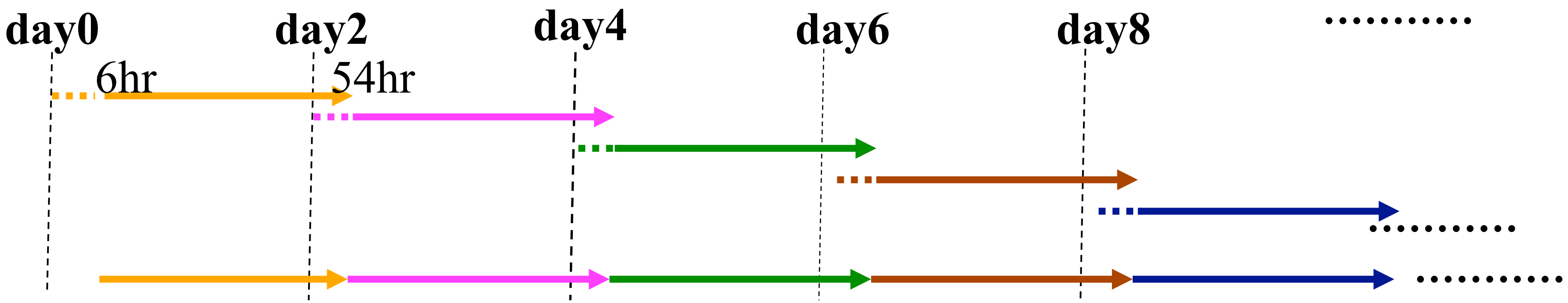
Application 1- Mass budget

E1. The coupled model is first verified against snow measurements over SDNWA in south-central Saskatchewan (180x180x46, 31 Oct 05 ~27 Mar 06)

E2. And then run over the Northern Hemisphere (640x640x46, 18km resolution, DJF 06/07)



Time series for an entire winter season constructed from multiple 54 hour simulations

- **First six hours considered spin-up**
- **Subsequent 48 hours used to construct the time series**

Yang et al., 2010, HESS, 14, 1063-1079

Calculations of terms in the model water mass budget

- **Blowing snow mass transport**

$$Q_{tx} = \int_0^{ta} \left(\rho \int_{zlb}^{zub} q_b U dz \right) dt \qquad Q_{ty} = \int_0^{ta} \left(\rho \int_{zlb}^{zub} q_b V dz \right) dt$$

- **Divergence of blowing snow transport**

$$D = \nabla \cdot \vec{Q}_t = \frac{\partial Q_{tx}}{\partial x} + \frac{\partial Q_{ty}}{\partial y}$$

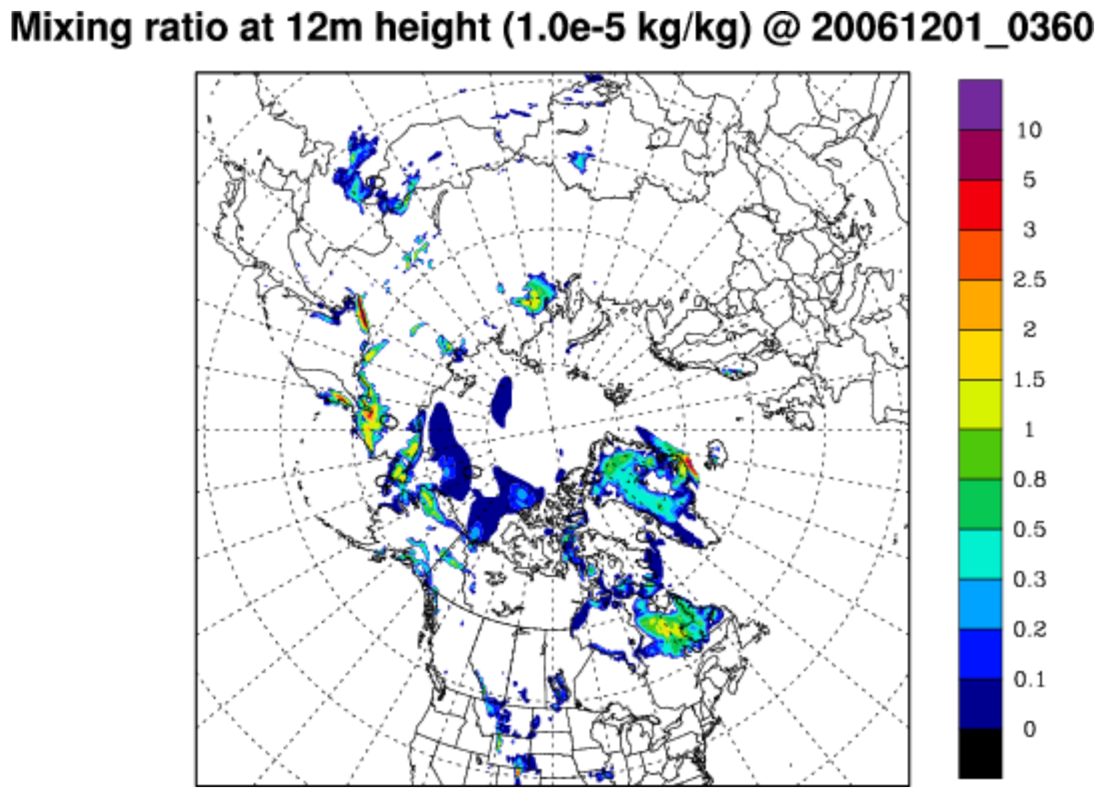
- **Blowing snow sublimation**

$$Q_{bs} = -\int_0^{ta} \left(\rho' \int_{zlb}^{zub} S_b dz \right) dt$$

- **Surface sublimation**

$$Q_{surf} = \int_0^{ta} \left(\rho \overline{w' q_s'} \right) dt = \int_0^{ta} \left(\rho C_D U^* (q_{surf} - q_a) \right) dt$$

Application 1- Mass budget: evolution of q_b (E2)



Animation of blowing snow mixing ratio q_b at z=12 m

Application 1- Mass budget: B.S. Transport (E2)

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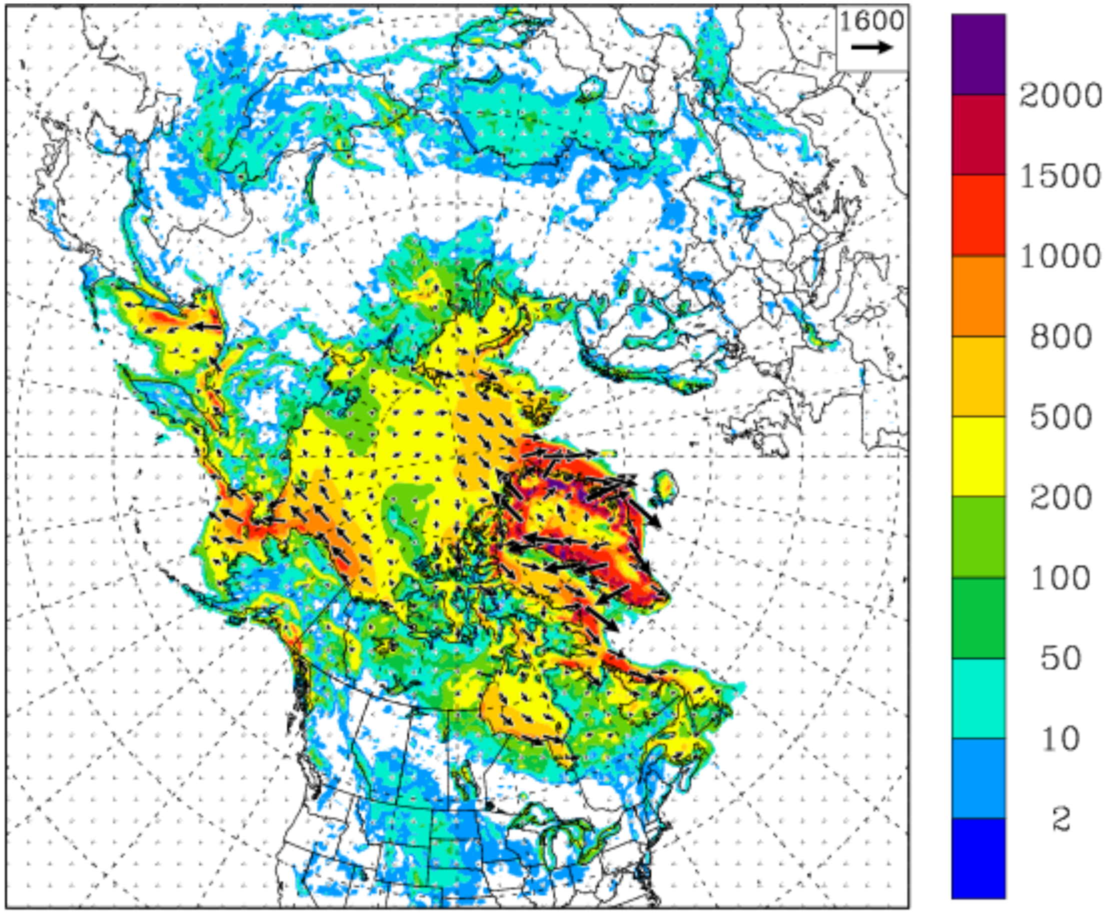
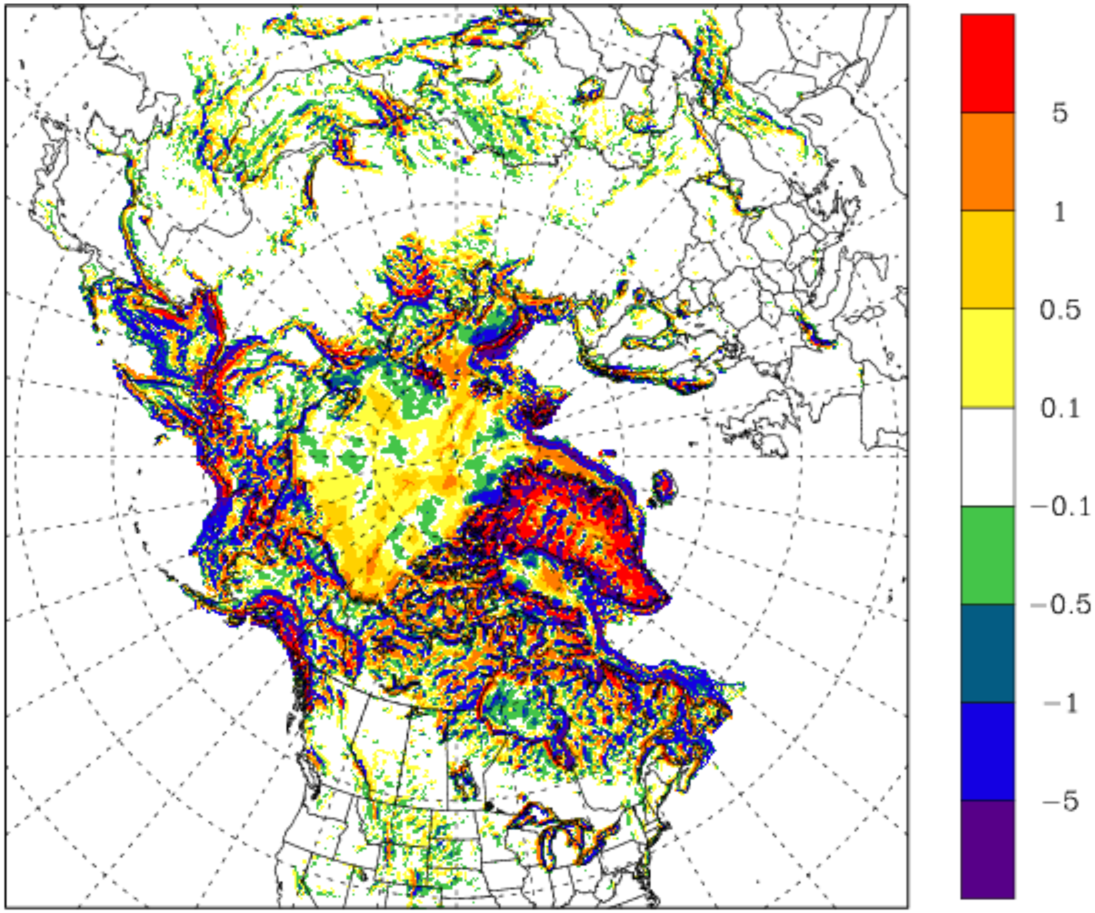


seasonal accumulated blowing snow mass transport $\vec{Q}_t$ (Mg m^{-1})

Application 1- Mass budget: B.S. Divergence (E2)



seasonal blowing snow divergence rate *D* (mm SWE)

Application 1- Mass budget: B.S. Sublimation (E2)

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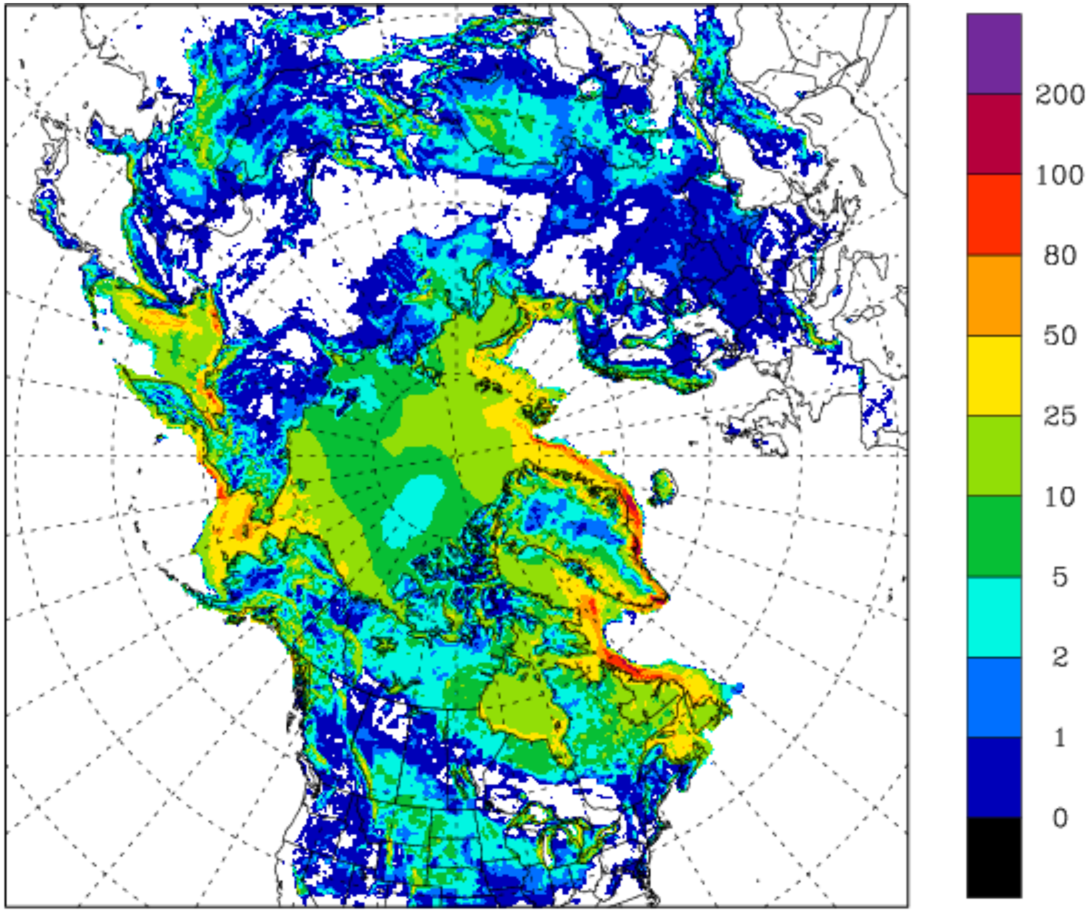
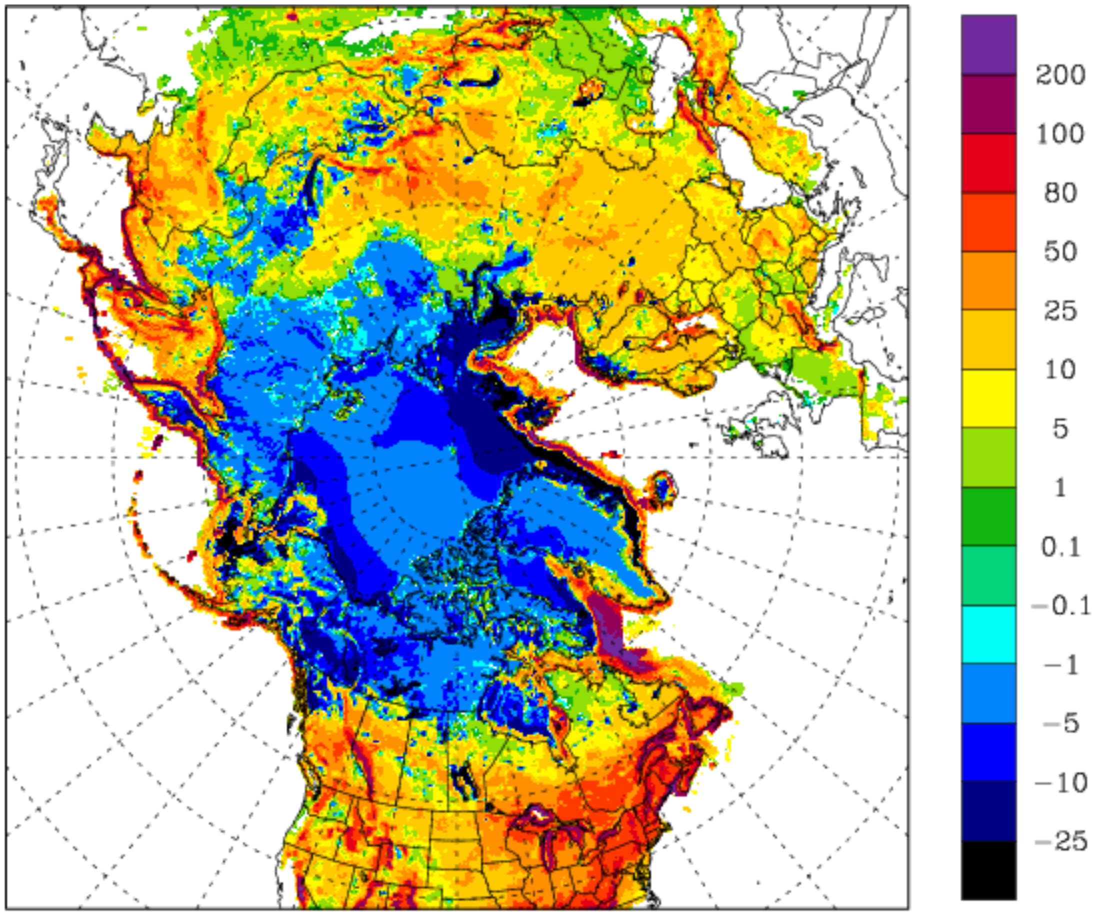


seasonal blowing snow sublimation rate Q_{bs} (mm SWE)

Application 1- Mass budget: Surface sublimation (E2)



seasonal surface sublimation rate Q_{surf}(mm SWE)

Application 1- Mass budget: Band-average values (E2)

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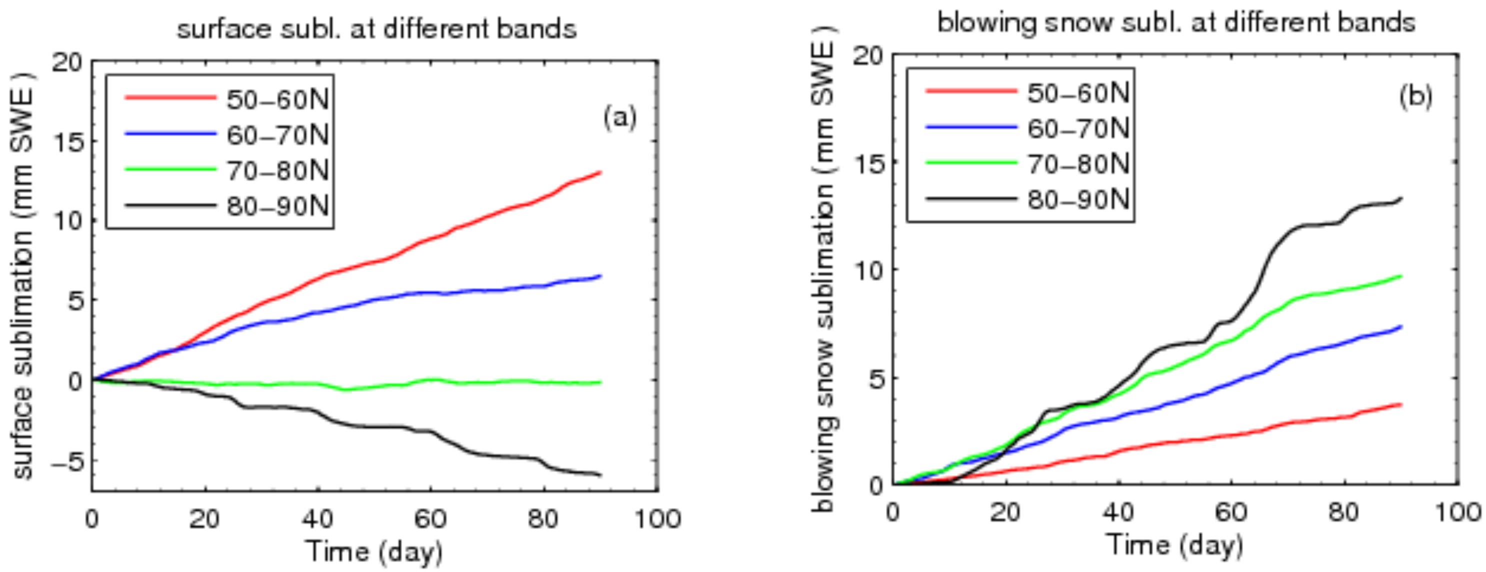

Integrated surface sublimation (left) and blowing snow sublimation (right), averaged over 10 degree latitude bands (DJF 2006/07)

Region	Q_{surf}	Q_{bs}	D	Sum	Precip.	Percent.
50º-60º	13.0	3.7	0.044	16.8	66.5	25%
60º-70º	6.5	7.4	-0.057	13.8	59.5	23%
70º-80º	-0.15	9.7	0.001	9.5	36.1	26%
80º-90º	-6.0	13.3	-0.12	7.2	13.9	52%

Outline of Presentation

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Model Development

1. Developed a stand-alone triple-moment blowing snow model (PIEKTUK-T)
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Mechanisms of anticyclonegenesis

- **Advection of negative relative vorticity at upper levels and/or differential thermal advection in the vertical.**

- **Cooling of the lower atmospheric levels**

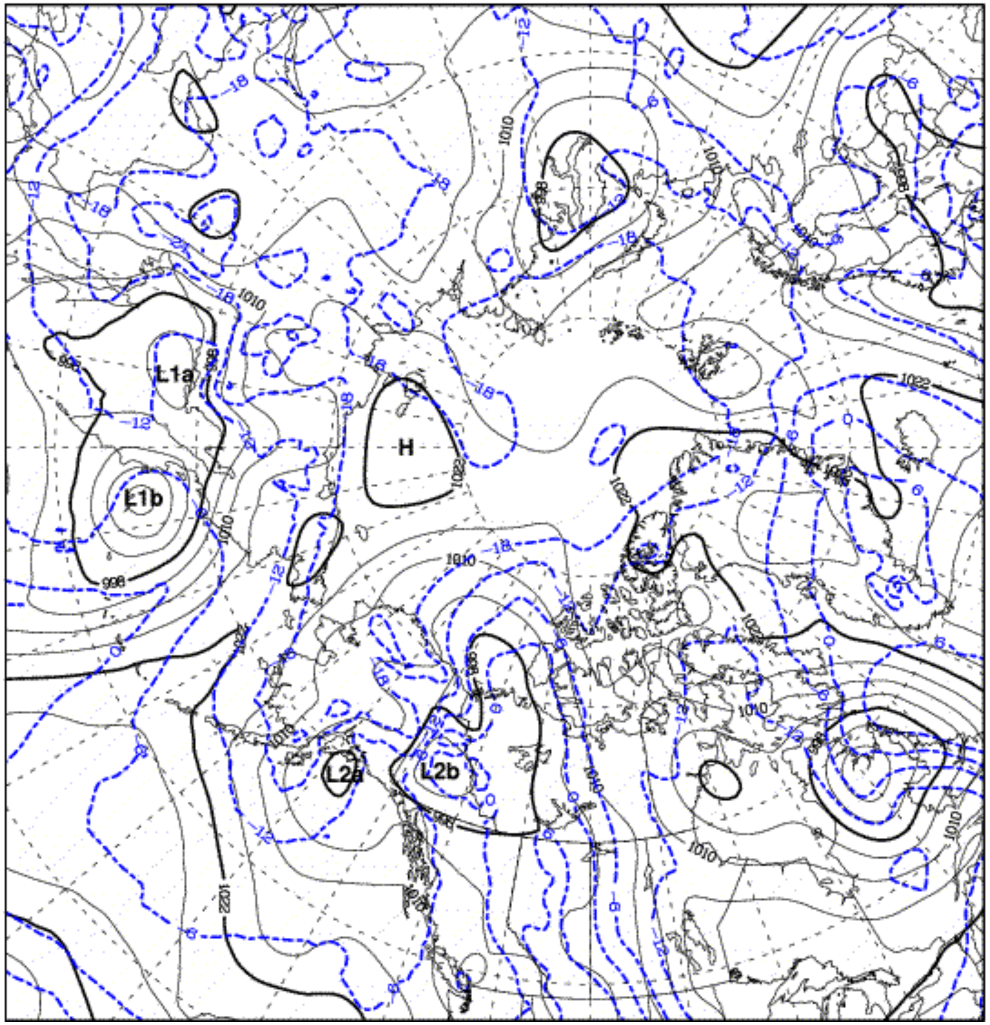
  - **Radiative cooling from the snow covered surface and/or from condensate in the PBL. (Curry 1983, 1987)**

  - **Any other low level cooling process (like blowing snow sublimation)**

    Sublimation increases RH_i and decreases T during phase changes. It is a function of wind speed, temperature, relative humidity and the blowing snow size distribution.

Application 2- Cooling effects: Arctic anticyclone

0000UTC 26 Nov



Center SLP: 1032, 1040, 1048mb at 12Z 26, 27, 28 Nov

Arctic Anticyclone:

25 Nov ~ 29 Nov, 2006
Timestep: 60 s
Domain: 380 x 380
CMC analysis data used for initial and boundary conditions

Simulation 1 (STD)

Run without blowing snow

Simulation 2 (CPL)

Run with blowing snow

Simulation 3 (CPL2)

Same as CPL except that supersaturated water vapor was kept in PIEKTUK-T module

Application 2- Cooling effects: Simulation results

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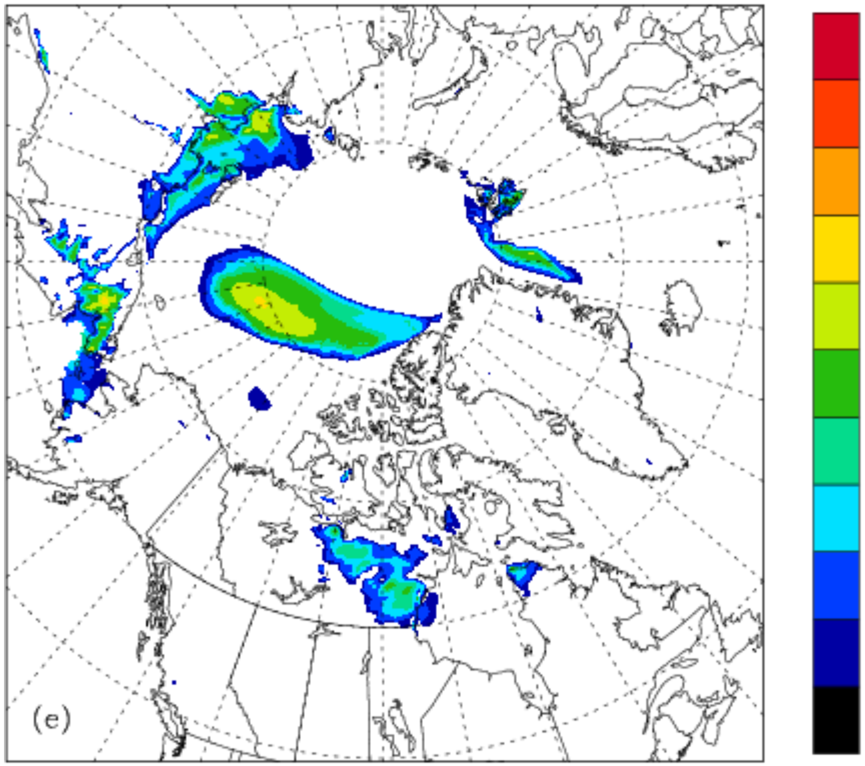
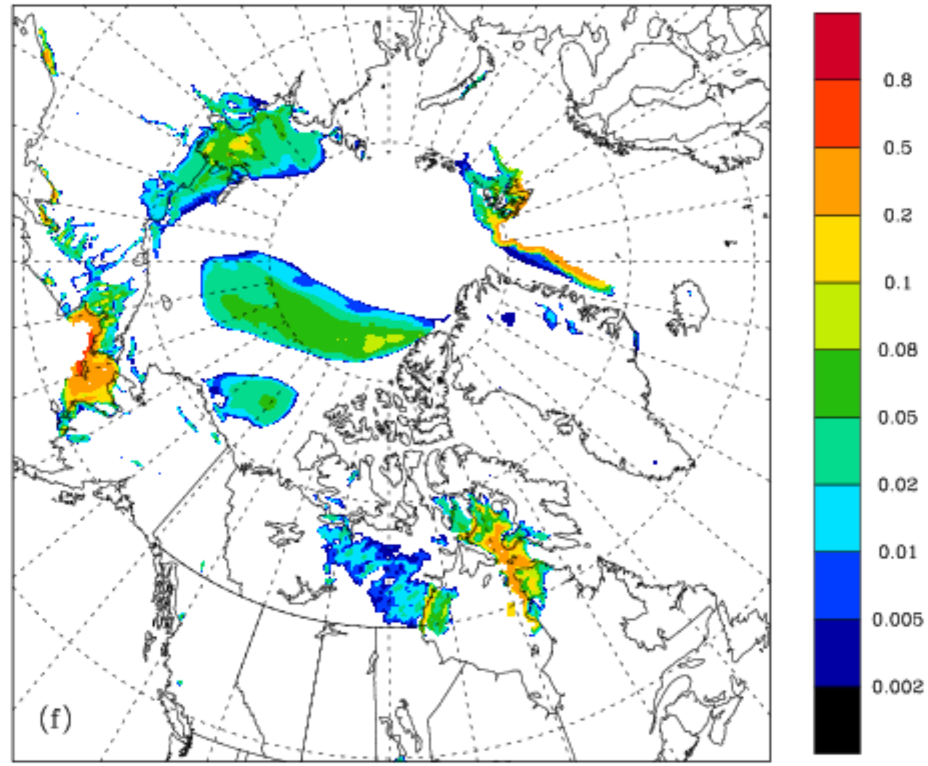
***t*=72 hr**



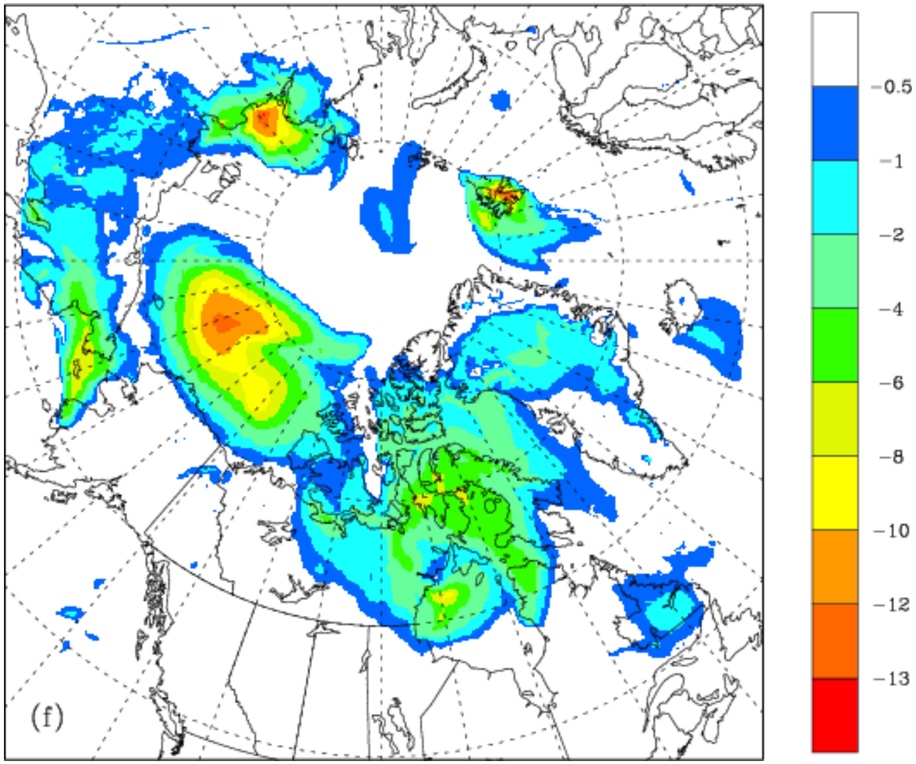
Blowing snow mixing ratio at z=12 m



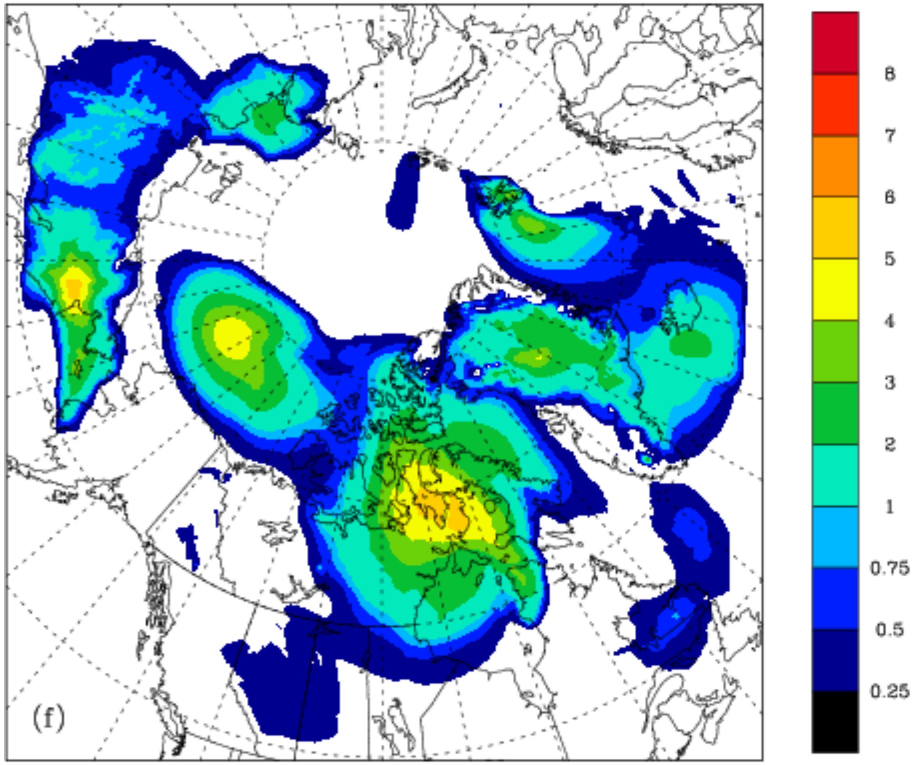
3-hour accumulated blowing snow sublimation (mm SWE)

Application 2- Cooling effects: Dif. btw CPL and CTL

t=72 hr



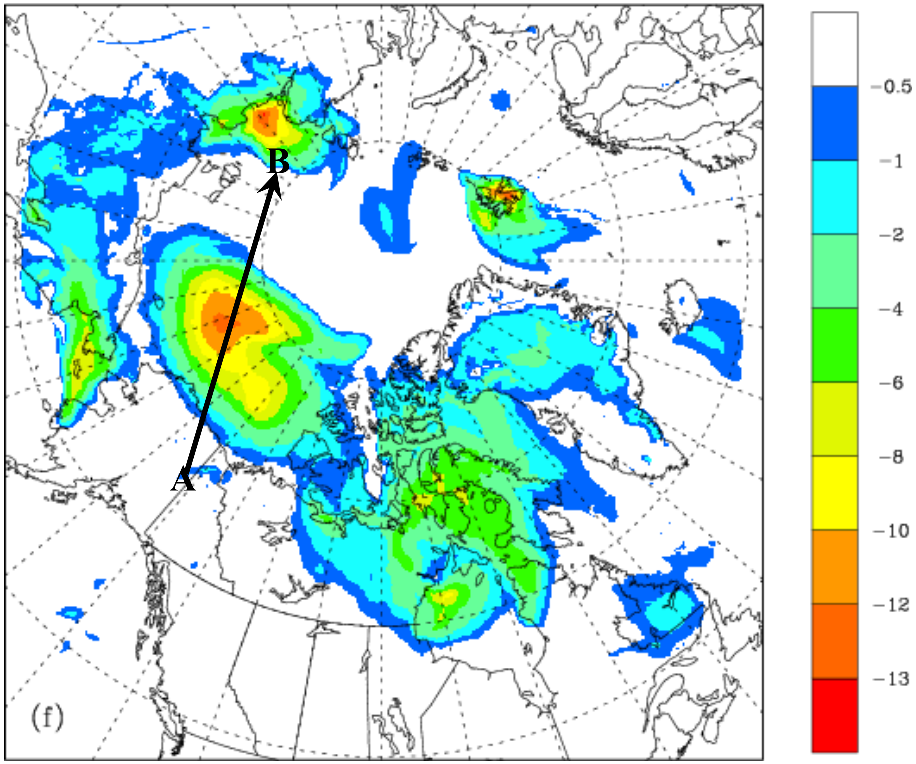
T difference at *z*=12 m btw CPL and STD



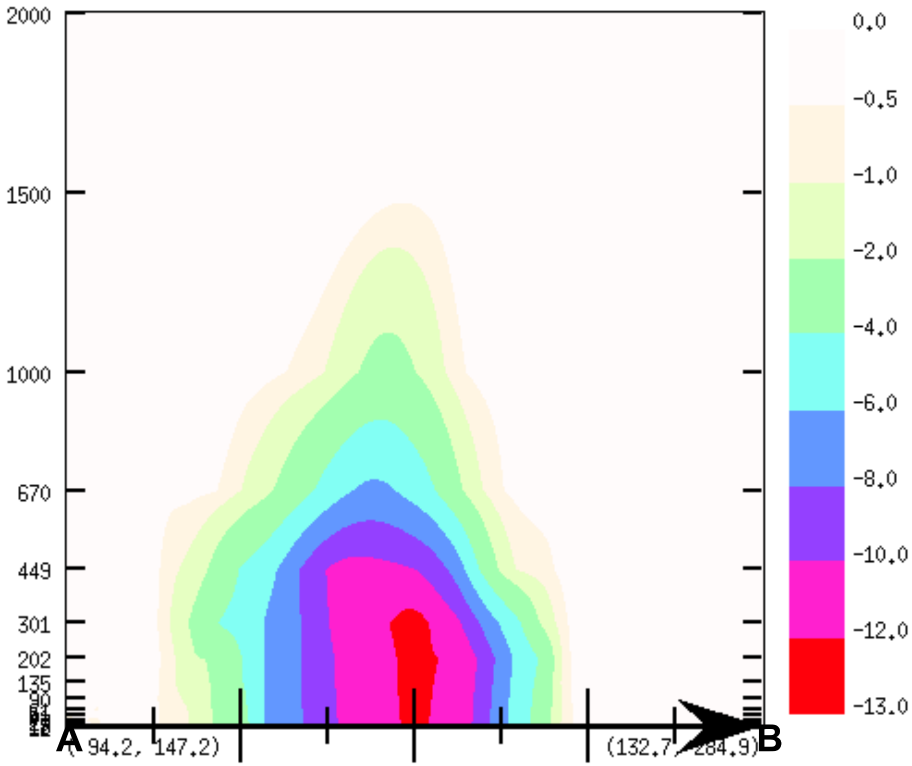
SLP (mb) differences btw CPL and STD

Application 2- Cooling effects: Dif. btw CPL and CTL

***t*=72 hr**



T difference at *z*=12 m btw CPL and STD



Vertical cross section of cooling effects

Application 2: Cooling effects-PV inversion

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Potential Vorticity: $q = \frac{1}{\rho}\vec{\eta}\cdot\nabla\theta$

- **Surface θ differences between CPL and CTL are treated as PV anomalies.**
- **Successive over-relaxation iterative numerical method is used to invert these to get geopotential height and streamfunction anomalies resulting from the blowing snow cooling effects.**

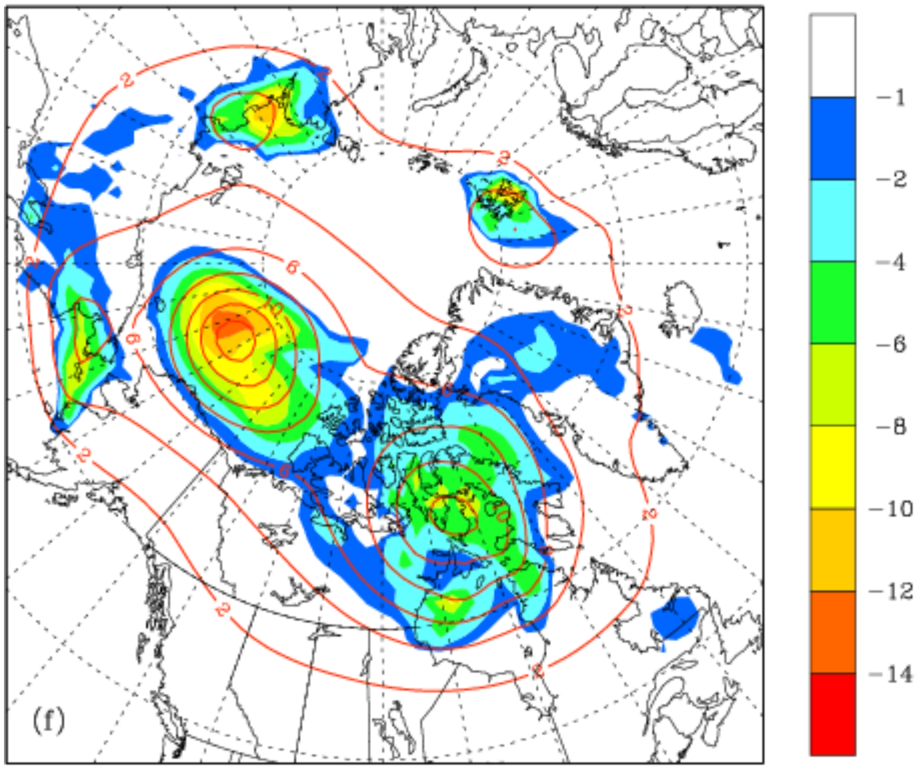
PV inversion diagnostics system (Davis 1991):

$$\nabla^2\phi = \nabla\cdot f\nabla\psi + 2m^2\left[\frac{\partial^2\psi}{\partial x^2}\frac{\partial^2\psi}{\partial y^2} - \left(\frac{\partial^2\psi}{\partial x\partial y}\right)^2\right] \quad ; \quad \pi = C_p\left(\frac{p}{p_0}\right)^k$$

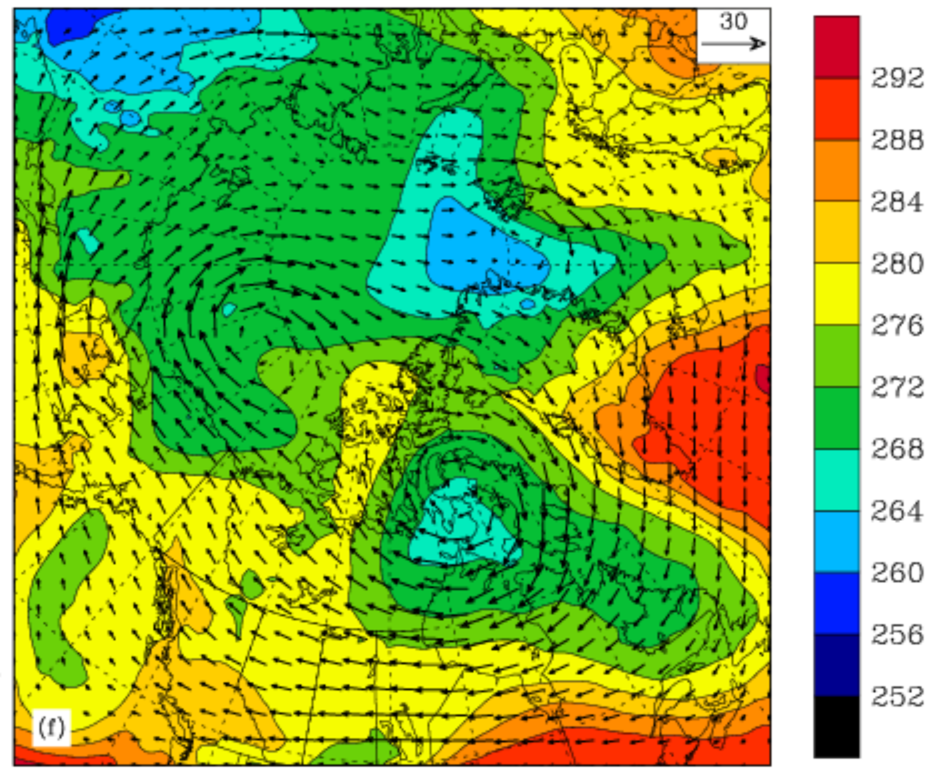
$$q = \frac{gk\pi}{p}\left[\left(m^2\nabla^2\psi + f\right)\frac{\partial^2\phi}{\partial\pi^2} - m^2\frac{\partial^2\psi}{\partial x\partial\pi}\frac{\partial^2\phi}{\partial x\partial\pi} - m^2\frac{\partial^2\psi}{\partial y\partial\pi}\frac{\partial^2\phi}{\partial y\partial\pi}\right]$$

Boundary Conditions: $\frac{\partial\phi}{\partial\pi} = f\frac{\partial\psi}{\partial\pi} = -\theta$

t=72 hr



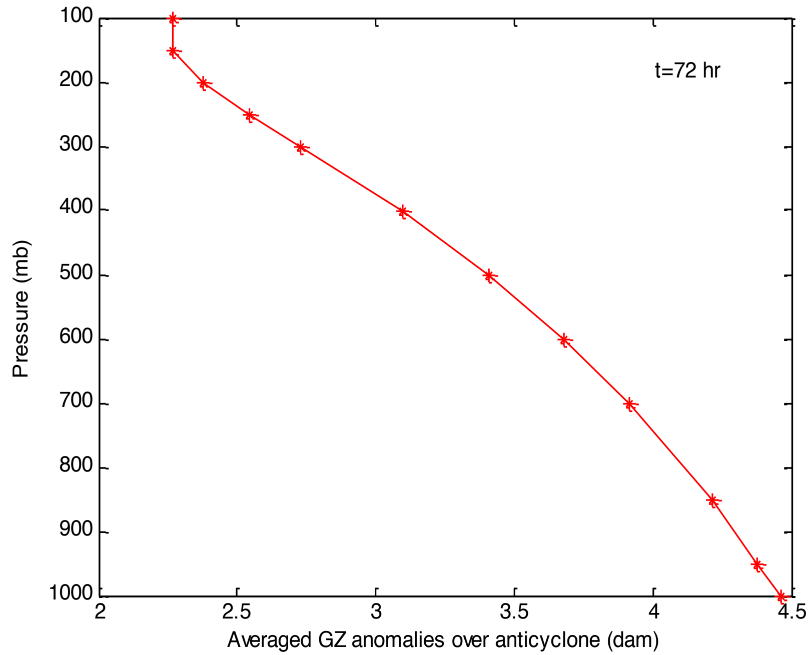
Surface θ anomalies & inverted Gepotential Height (dam) at 850 mb



850-mb θand the balanced wind vector (knots)

Application 2: Cooling effects-PV inversion results

t=72 hr



Vertical Profiles of inverted geopotential height averaged over the areal extent of the anticyclone.

Summary and Conclusions

1. Extended the double moment blowing snow model to a triple moment scheme, validated it with field observation data, and coupled it to MC2

2. Computed water mass budgets over the Northern Hemisphere, and quantified the contribution of blowing snow on the seasonal water mass budget.

   • Over the Arctic Ocean, blowing snow sublimation returned up to 50mm SWE back to the air; surface deposition occurred with average values of 30mm SWE; divergence is negligible

   • Surface sublimation decreases and blowing snow sublimation increases with latitude

   • Surface and blowing snow sublimation together can distribute 23% to 52% of winter precipitation over winter season.

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3. Carried out sensitivity experiments with and without blowing snow to isolate its cooling effect.

- Blowing snow cooling extended throughout the boundary and contributes to the Sea Level Pressure rise.

- Effect of blowing snow cooling on anticyclogenesis was determined using a PV inversion method.

- Surface cooling can induce positive geopotential height fall and anticyclonic flow up to 500 mb

- After 72 hours, the averaged geopotential height anomaly at 1000 mb over the anticyclone can be 4.5 dam (This should be considered as an upper bound).

Thanks to

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Prof. M.K.(Peter) Yau

Dr. Badrinath Nagarajan and everyone in the group

Dr. Lei Wen

Michael Havas

Colleagues and Friends

Backup slides

Application 1- Mass budget: Surface fields (E2)

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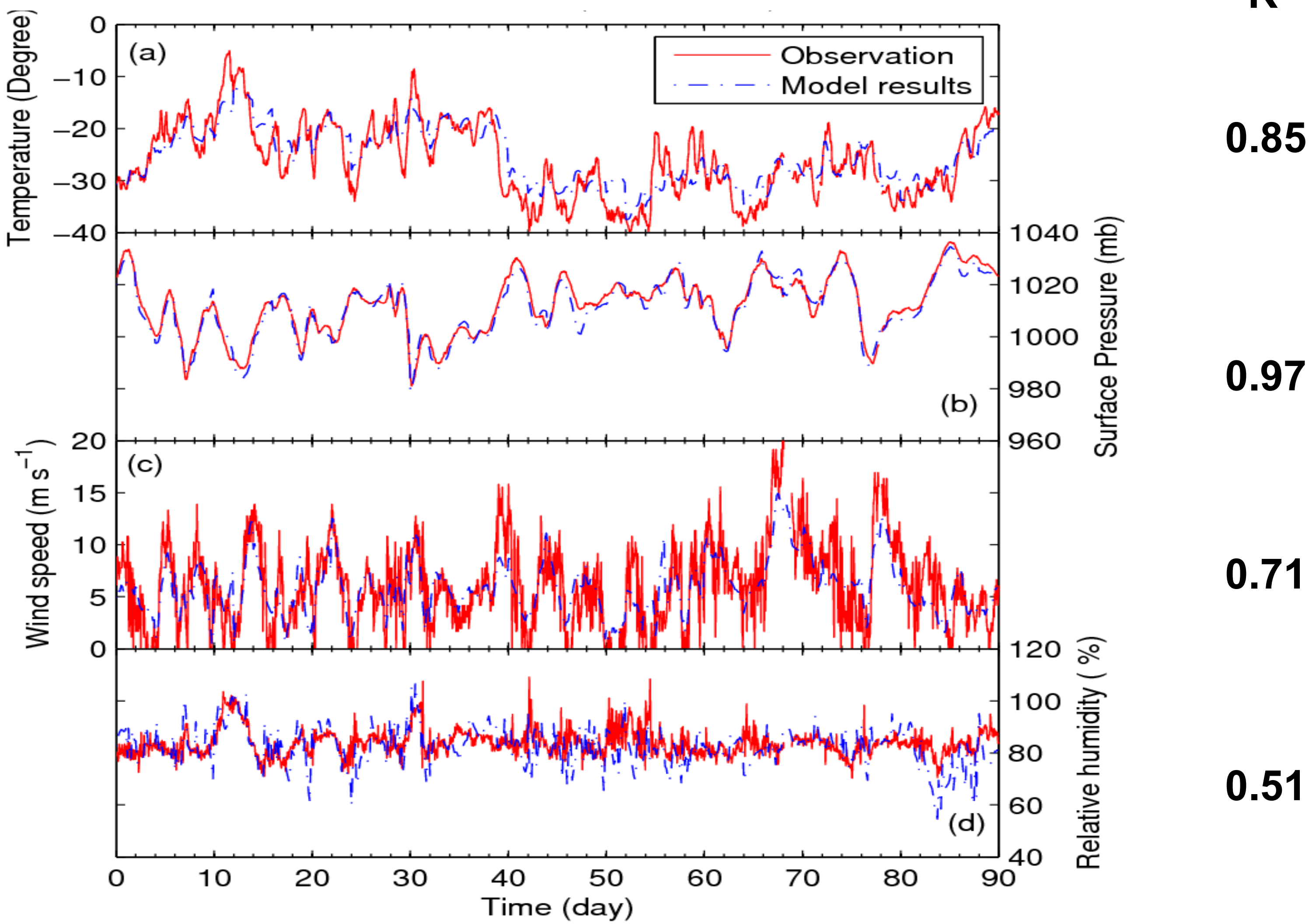
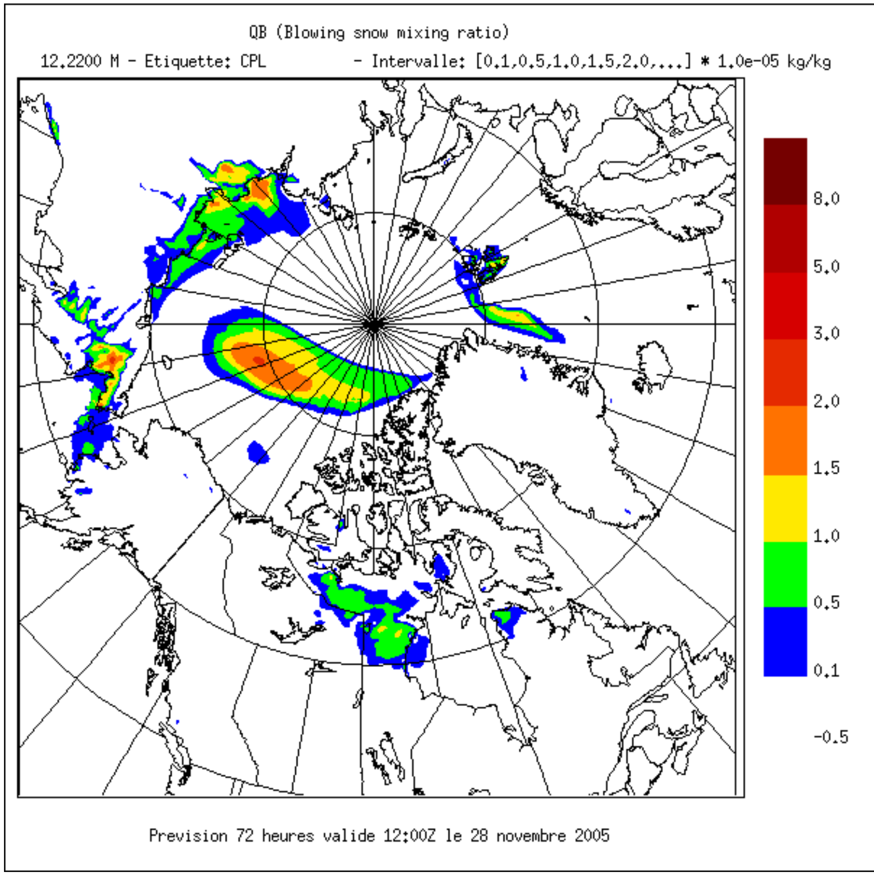


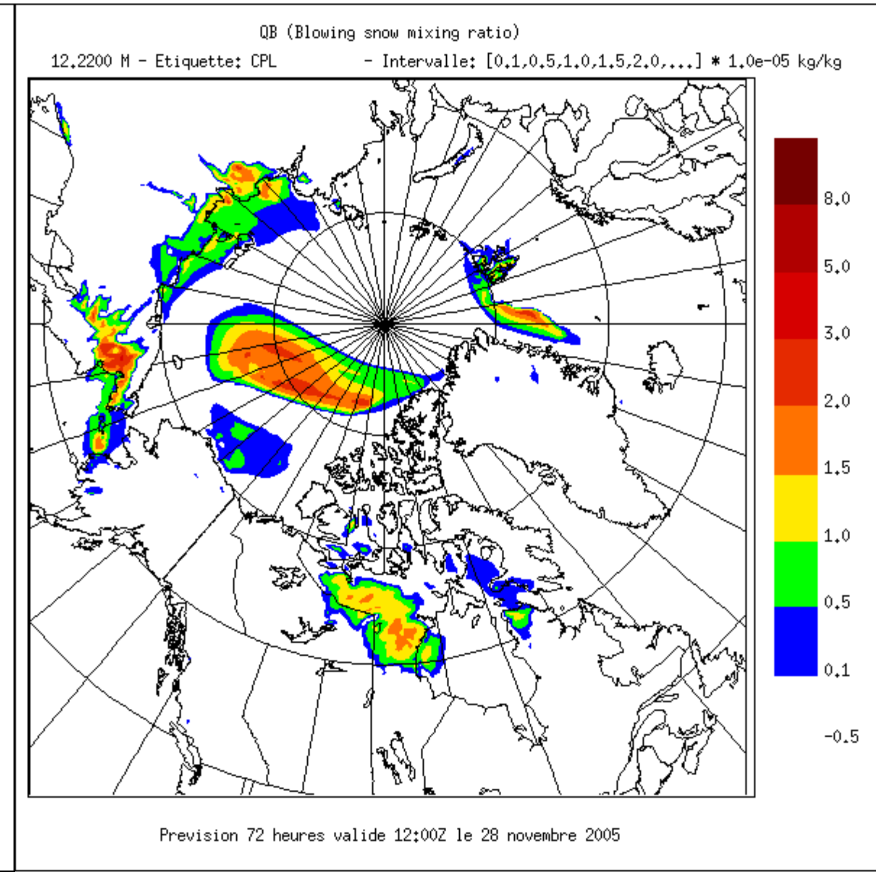
Time series of observed (hourly) and simulated (3 hourly) T, P_s, U and RH_i at Baker Lake Station (NVT, 64ºN, 96ºW)

Blowing snow mixing ratio q_b (10^{-5} kgkg^{-1}) at 12 m height from

CPL



CPL2



q_b for CPL < q_b for CPL2: In CPL2, there is supersaturation, blowing snow crystals can continue to grow by deposition.

Potential Vorticity: $q = \frac{1}{\rho}\vec{\eta}\cdot\nabla\theta$

PV is a conserved quantity on an isentropic surface in the absence of diabatic and dissipative processes

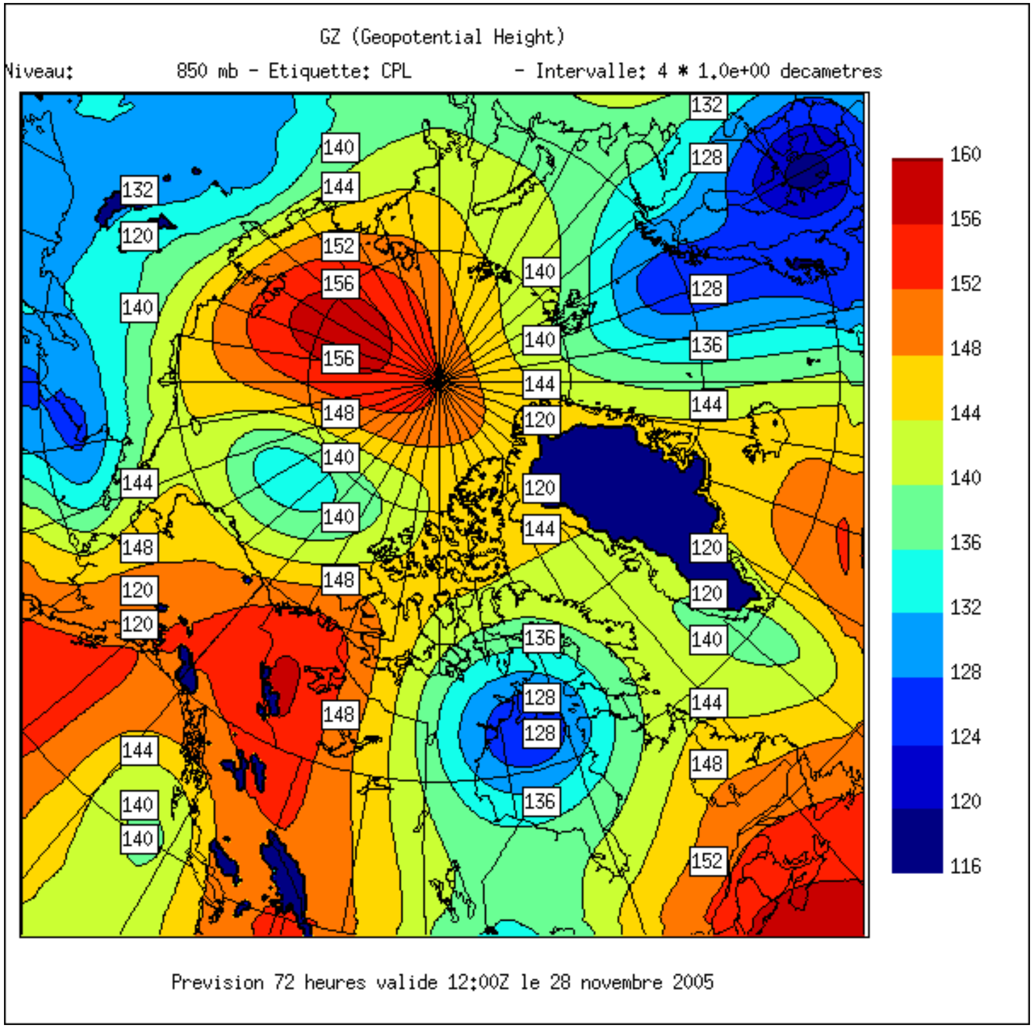
Invertibility allows the mass and wind fields associated with any particular PV to be determined.

***Piecewise PV inversion* (Davis and Emanuel, 1991) can quantify the contribution of upper-level and lower-level processes on cyclogenesis / anticyclogenesis.**

PV anomaly is partitioned to isolate the perturbations associated with: upper level dry PV anomaly; lower level moist PV anomaly; bottom potential temperature anomaly; residual PV anomaly.

The technique is also been applied to alter the initial conditions of a simulation to shed light on the effect of including or excluding a certain feature in the initial state.

Backup slides



Geopotential height at 850 mb

Backup slides