

1. Objectives

- Better understand the processes controlling the spatial variability in surface energy fluxes, snow water equivalent, snowmelt, soil moisture, and frozen soil, and use this to further develop our predictive ability

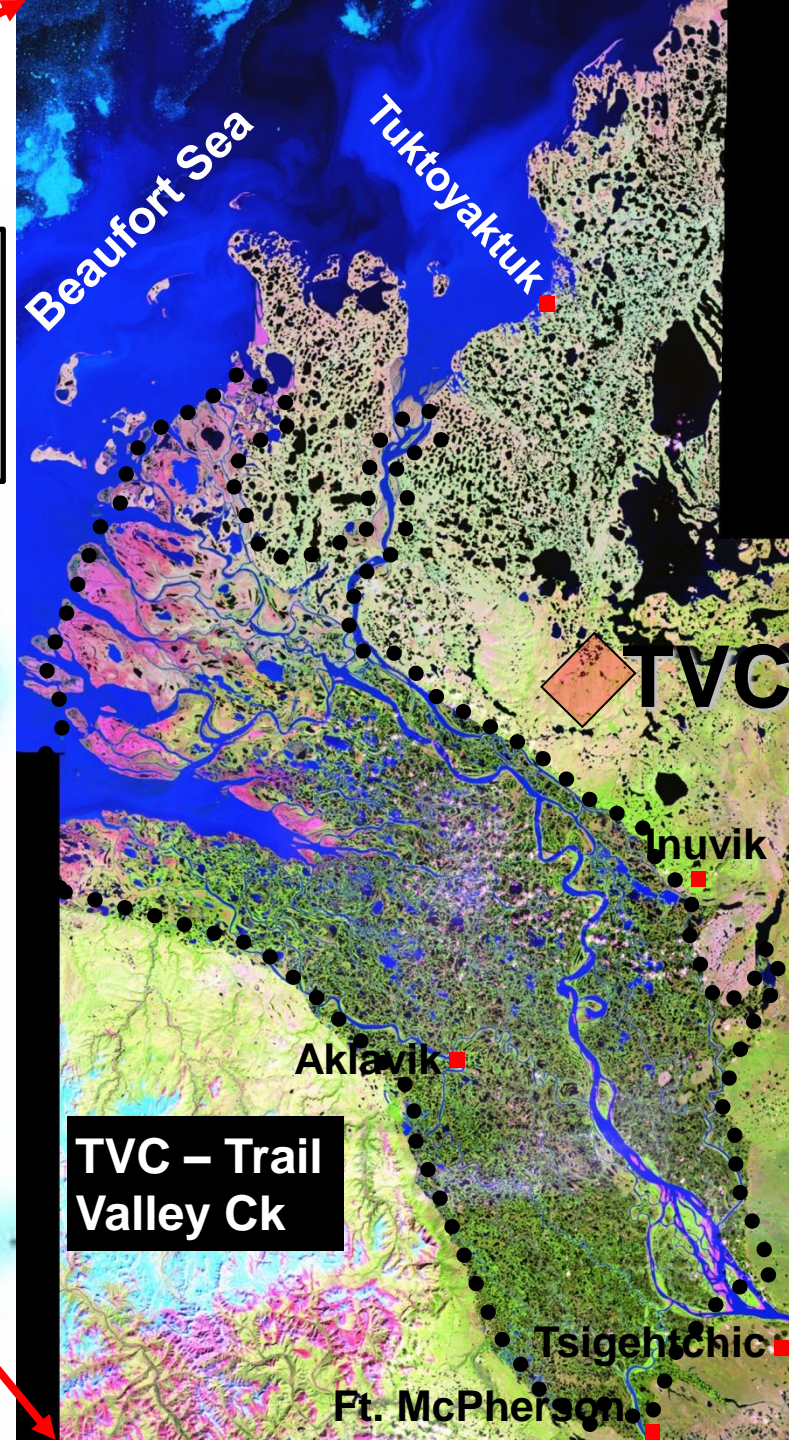
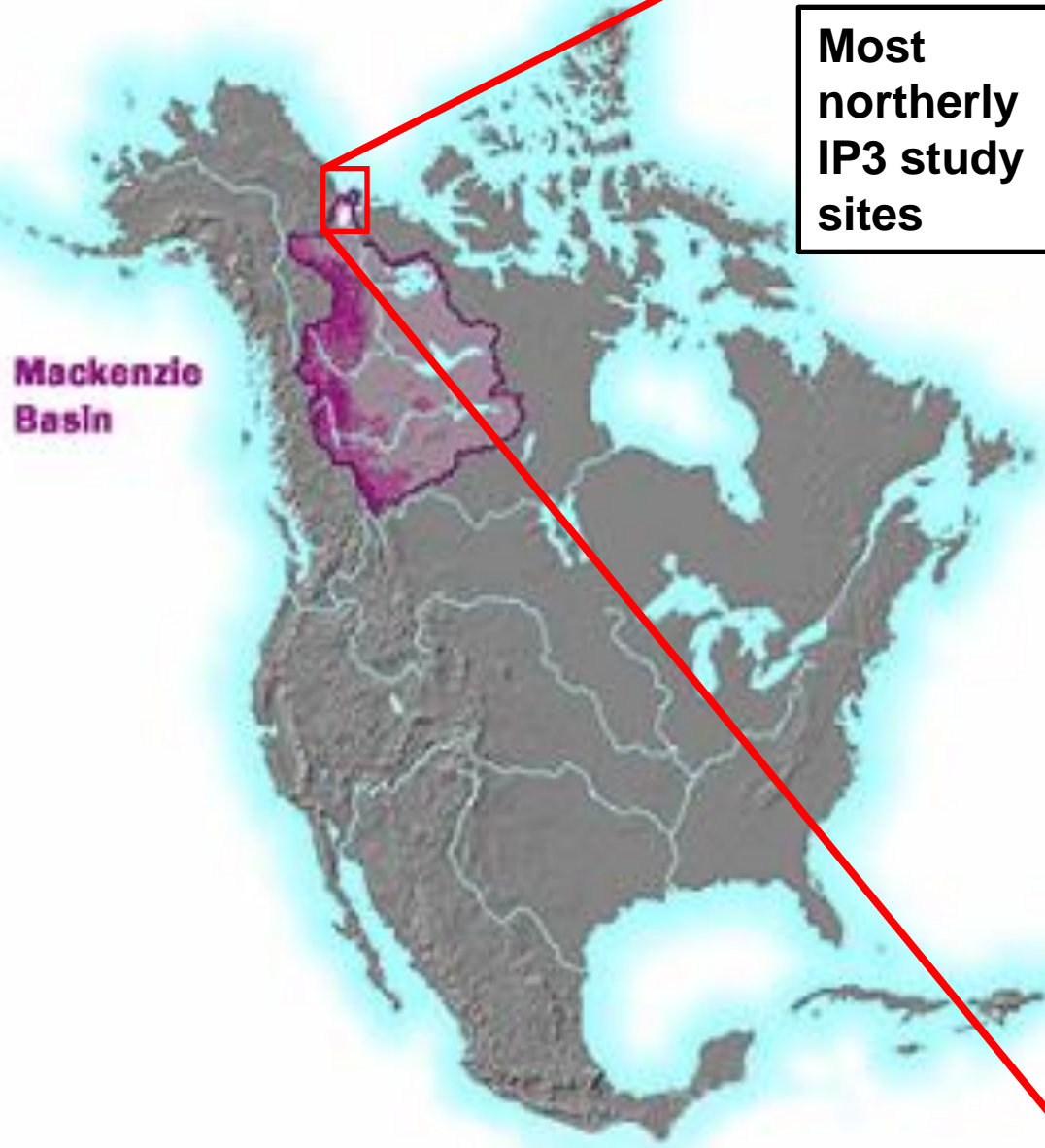
- Processes:

- end of winter snow accumulation (influence of terrain and vegetation);
- heat fluxes over dominate vegetation types (shrub tundra, tundra);
- spatial variability in radiation and turbulent fluxes over an area of 100 km²;
- **energy-based framework of runoff generation and spatial variation of ground thaw in permafrost areas**

- Parameterization and Prediction

- Test and improve a suite of models, including
 - CRHM,
 - **CLASS, and**
 - **MESH will be tested.**

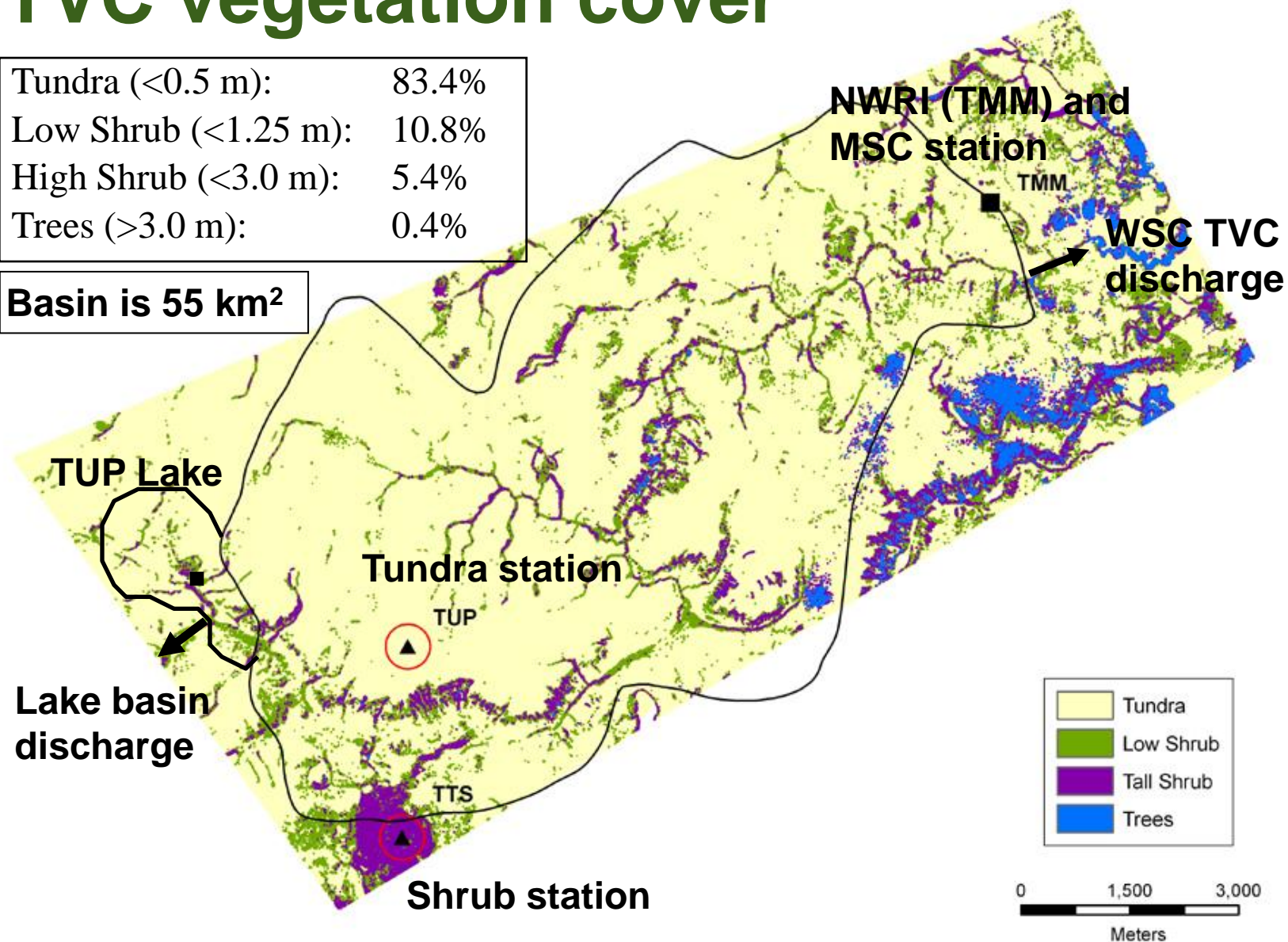
2. Study area and Env. Canada field observations



TVC vegetation cover

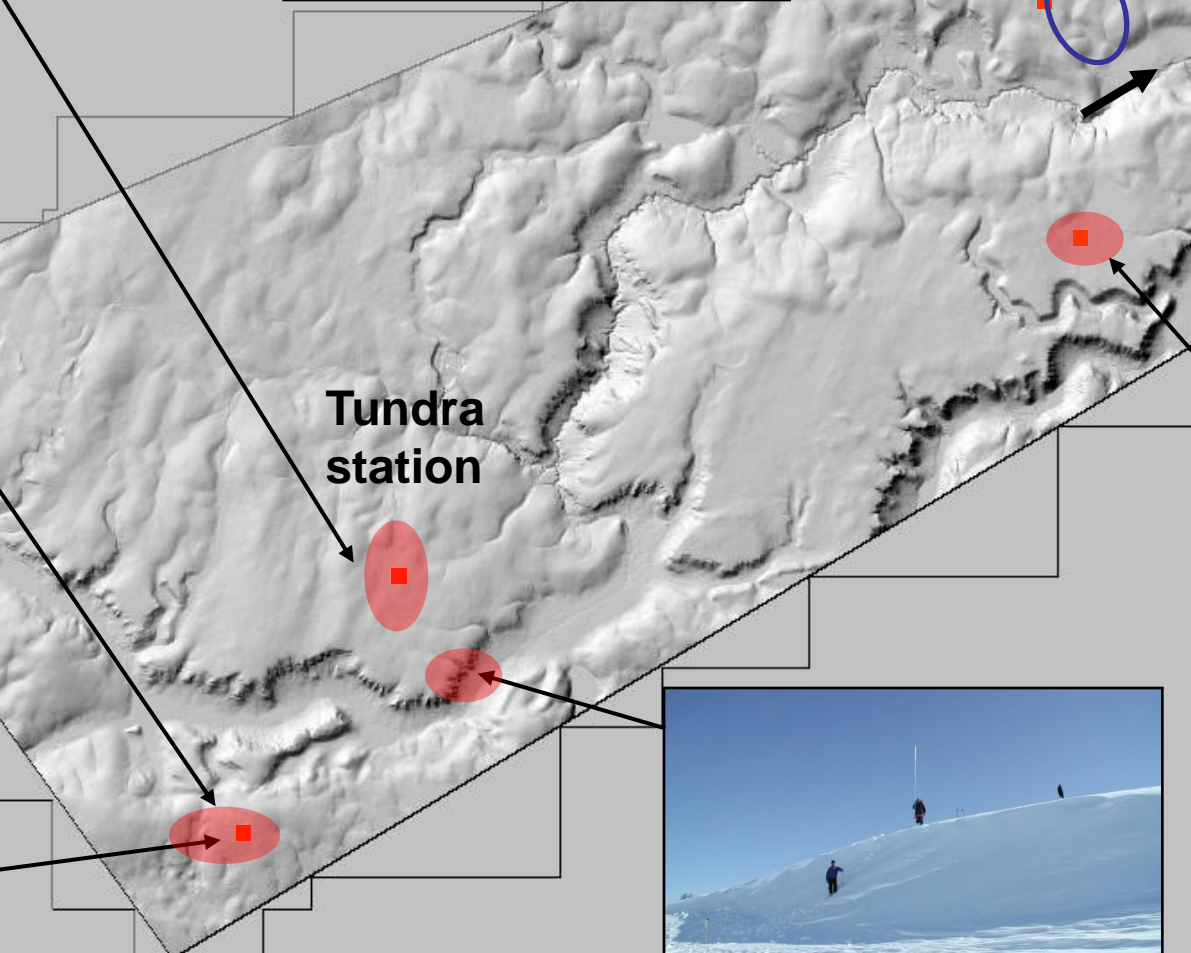
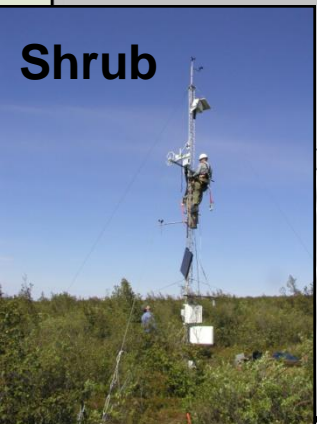
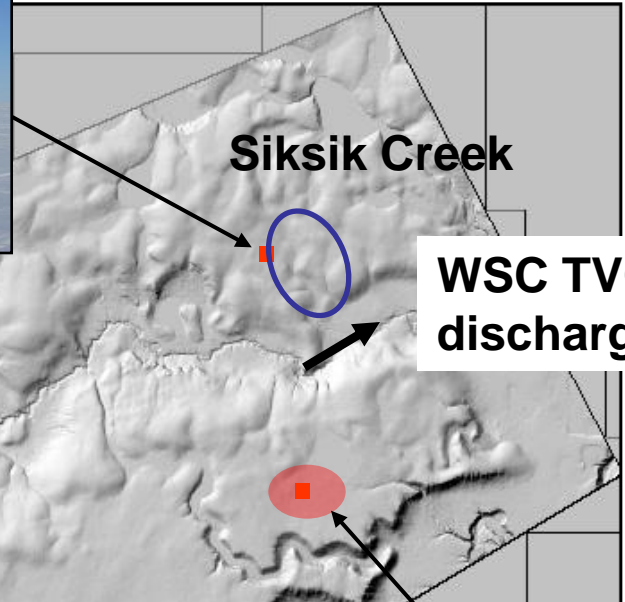
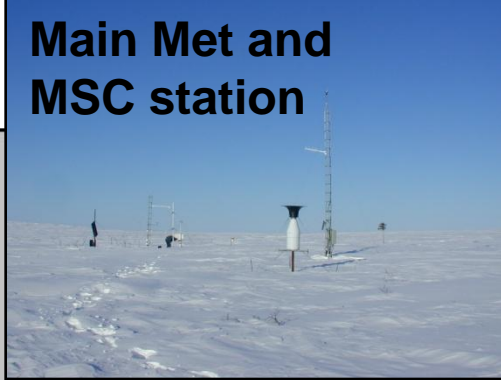
Tundra (<0.5 m):	83.4%
Low Shrub (<1.25 m):	10.8%
High Shrub (<3.0 m):	5.4%
Trees (>3.0 m):	0.4%

Basin is 55 km²

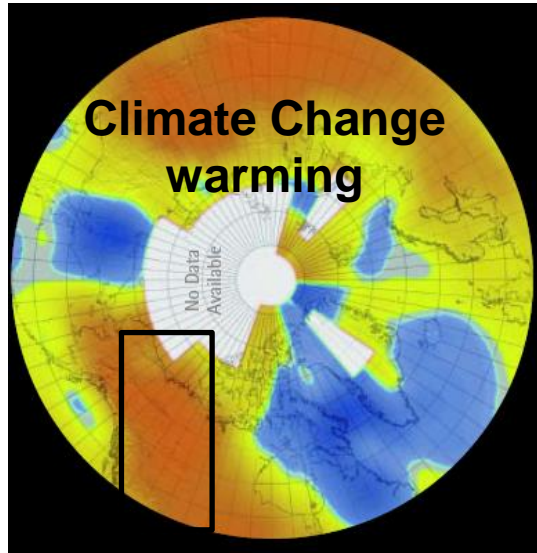


(vegetation height from high resolution LiDAR data)

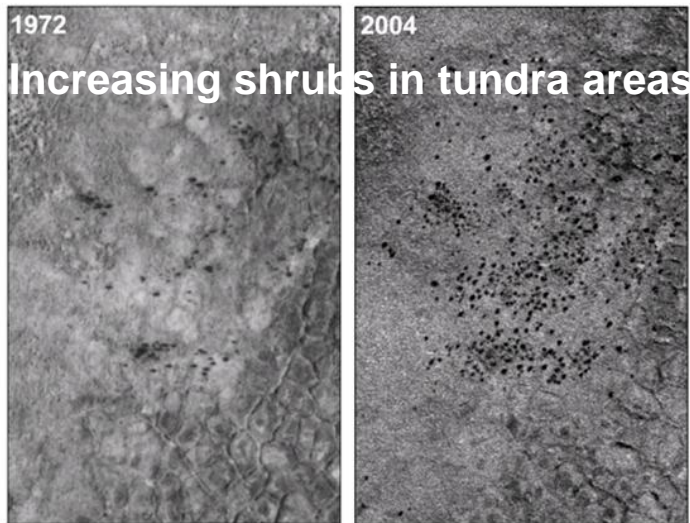
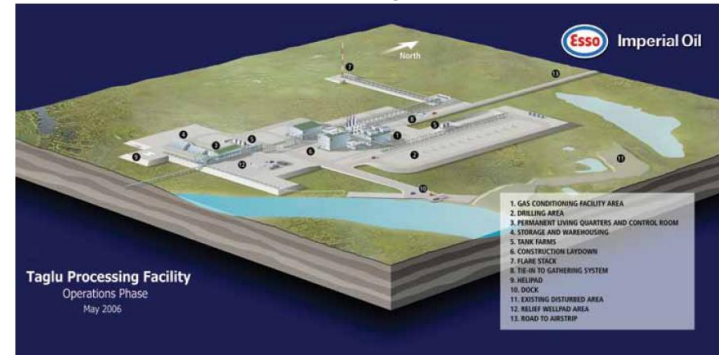
Trail Valley Creek



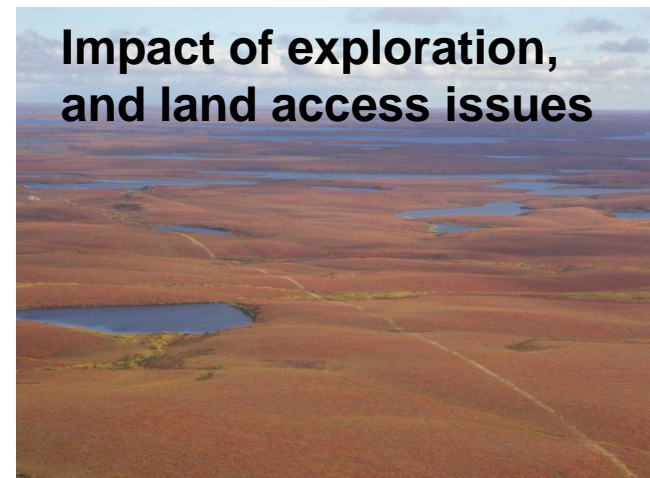
3. Issues requiring an increase in hydrologic knowledge and modelling capacity



Proposed natural gas development Mackenzie Gas Project and others



Trevor Lantz,
Marsh,
Kokelj. 2011.
Submitted.

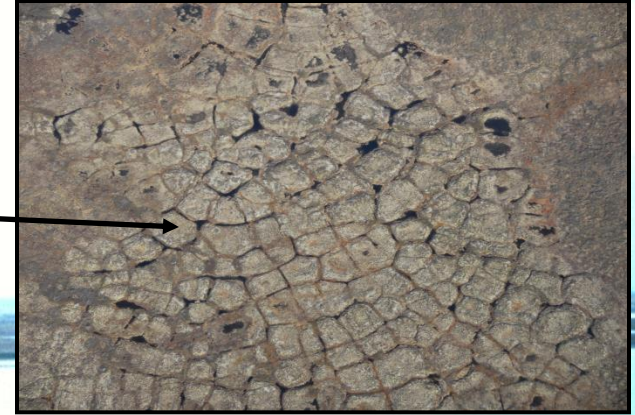


Existence of ice rich permafrost complicates prediction, and results in greater impacts

Pingo

Ice wedge

Tabular ice



North of Inuvik there are many areas with very high volumes of ground ice in the upper portions of the permafrost. Average is greater than 20% by volume in upper 10-20 m.

Potential changes in northern environments with a warming climate



Modelling the impact on the hydrologic system is extremely challenging



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Environnement
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4. Improved Processes and Parameterizations

- Utilizing:

- Field observations

- Small scale, physically based modelling using GEOtop

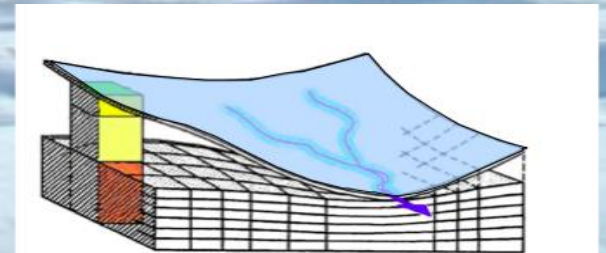


Figure adapted from SHE model (Abbot et al., 1986)

4.1 Field observations

Snow surveys

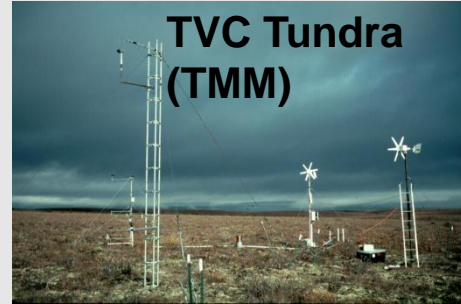


Flux measurements, Soil temp + moisture

TVC Tundra (TMM)



TVC Tundra (TMM)



TVC Shrub (TTS)

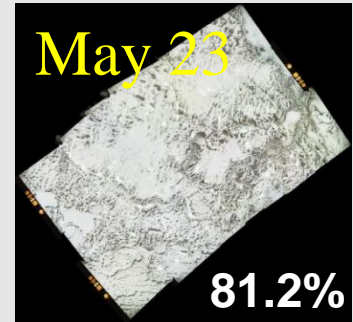


TVC Shrub (TTS)



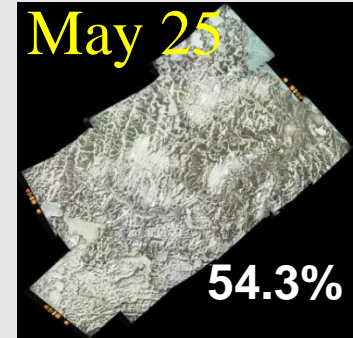
SCA

May 23



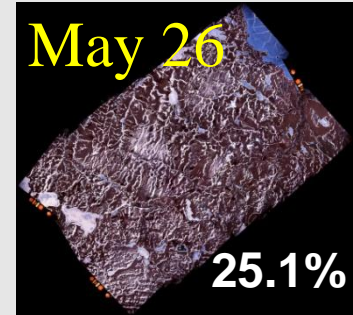
81.2%

May 25

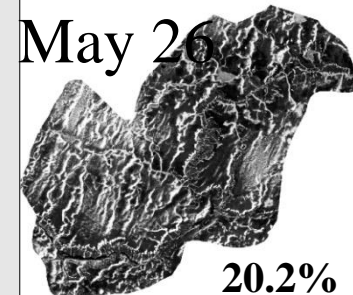


54.3%

May 26



25.1%



20.2%



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NRC Twin
Otter flux
aircraft

4.2 GEOtop

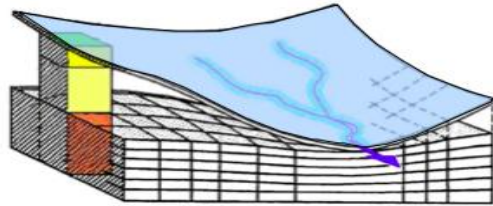
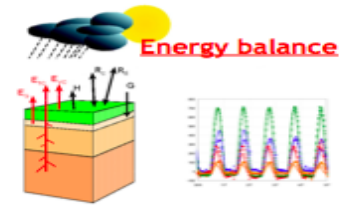


Figure adapted from SHE model (Abbot et al., 1986)

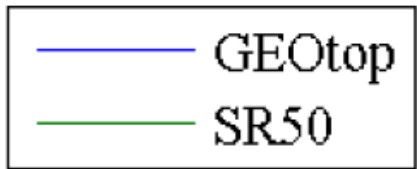
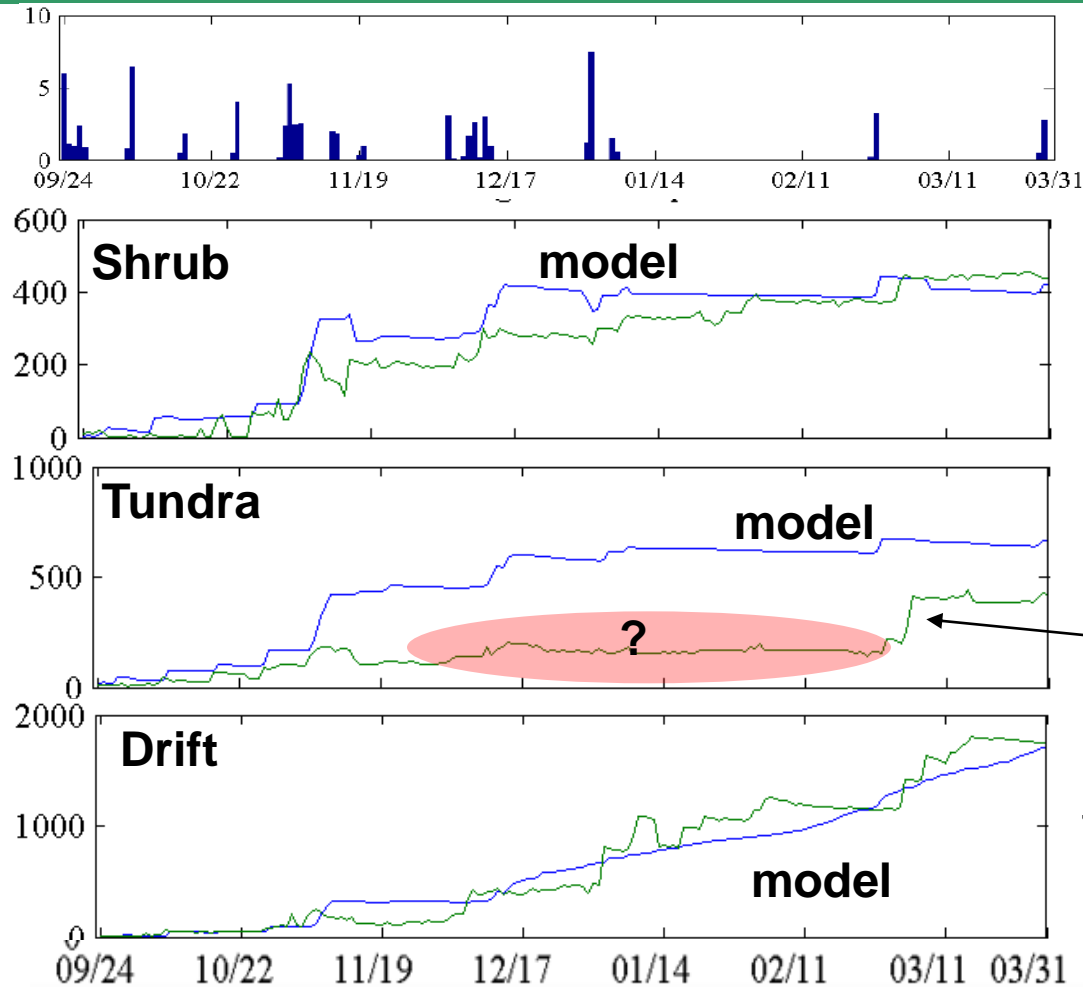


Figures adapted from VIC model (Liang et al., 1994)

- spatially distributed model, using a **coupled numerical solution** of the subsurface flow (3D Richards equation) and energy budget (1D heat equation with phase change). This applies for soil and snow cover
- model is **fully distributed** and can be run at grid sizes from metres to hundreds of metres
- **coupled to PBSM** (Pomeroy et al., 1993) to find snow wind transport rate and sublimation, and **Liston wind model**

4.3 End of Winter Snow accumulation

Snow Depth (mm)



SR50s offset reset by field staff

- In general the SWE of drifts are still under predicted and continuing work is needed

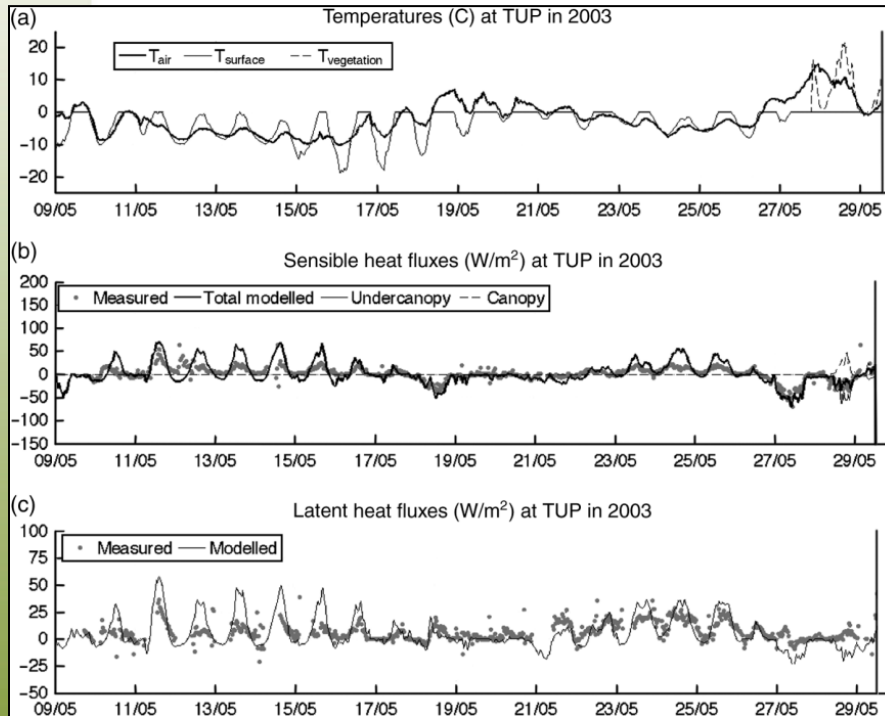
- Observations are the avg. of 5 measurements
- model is avg. of small domain



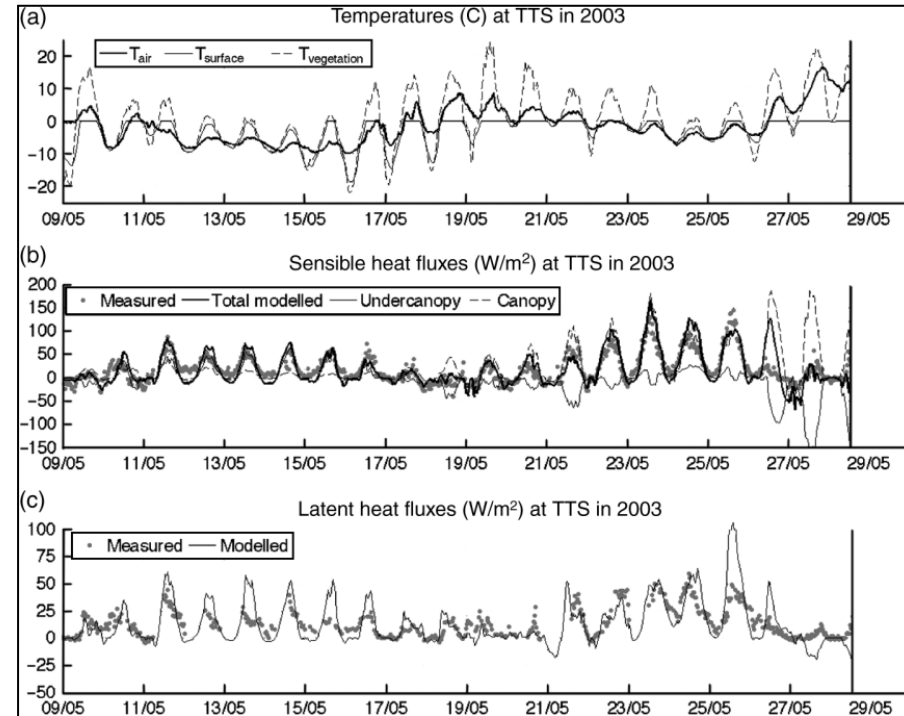
4.4 Sensible and latent heat fluxes at a point

Snowmelt period

Tundra Site



Tall Shrub Site



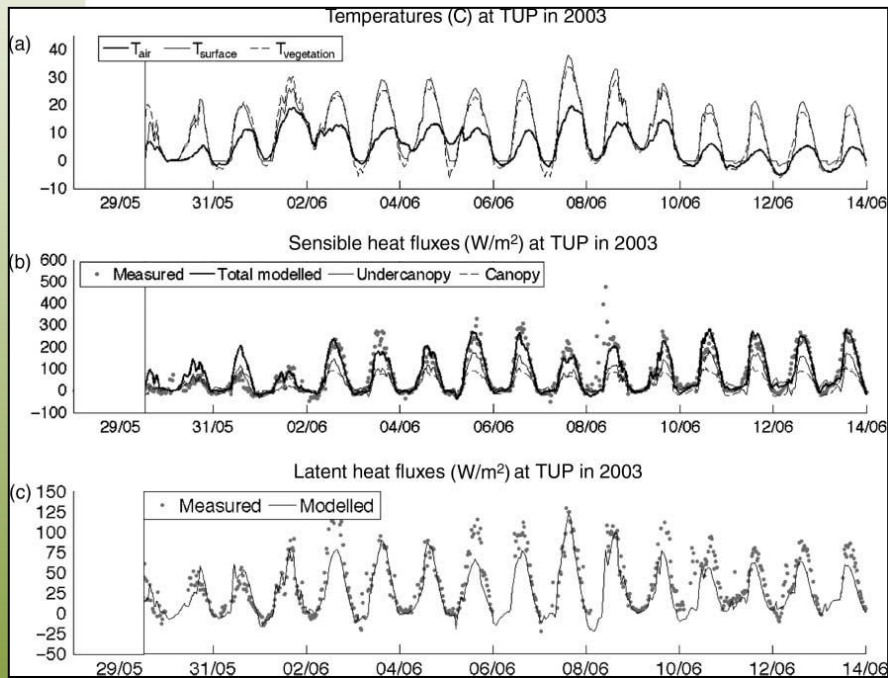
- general pattern of fluxes are properly modelled
- peaks during melt are often over estimated
- the effect of shrub bending over, burial and exposure is still not fully understood and predictive ability is still limited



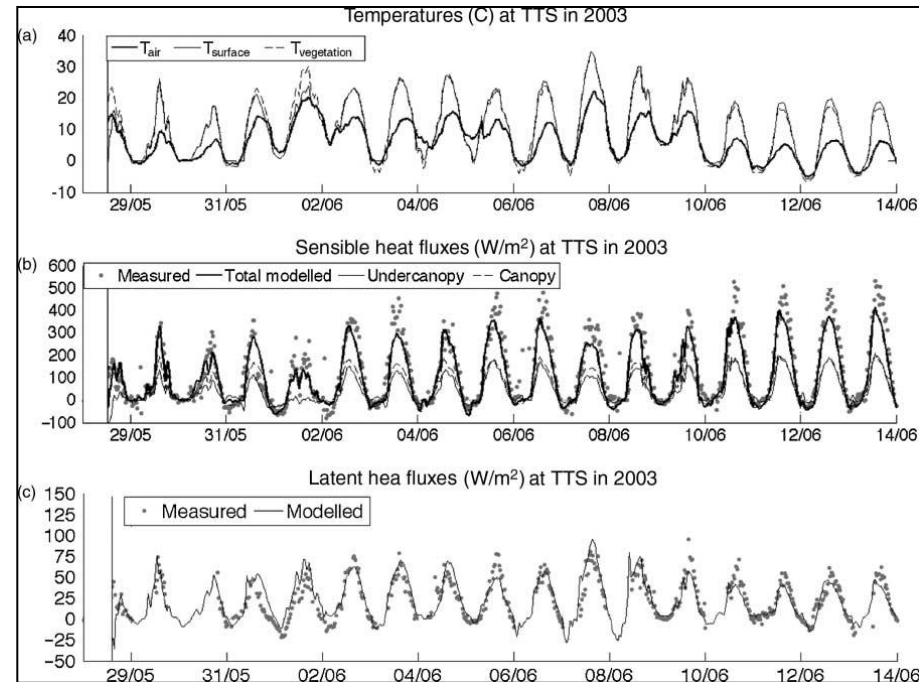
4.5 Sensible and latent heat fluxes at a point

Snow-free period

Tundra Site



Tall Shrub Site



- Model generally better captures the fluxes during the snow-free period

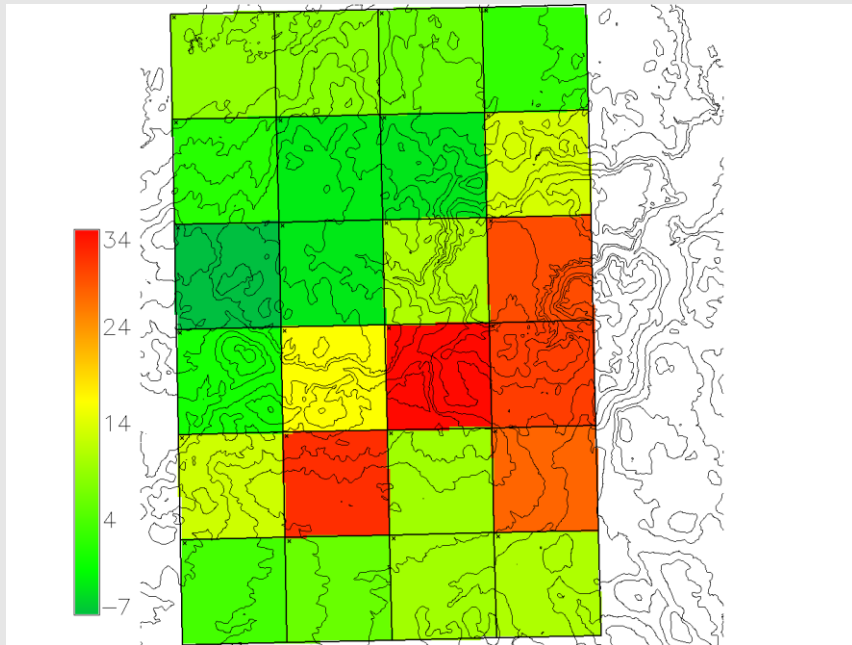


4.6 Spatially variable fluxes

MAGS Aircraft Flux data

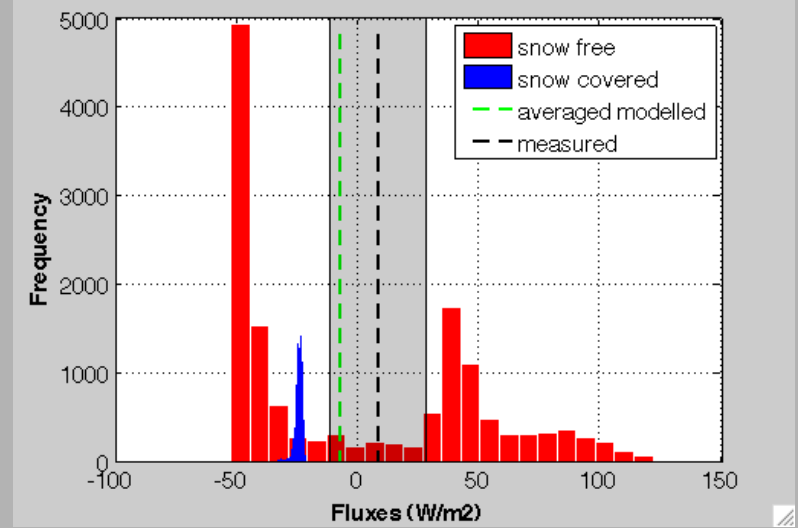
Sensible heat (W/m^2): 3km x 3km grids from aircraft flux measurements

May 27, 1999

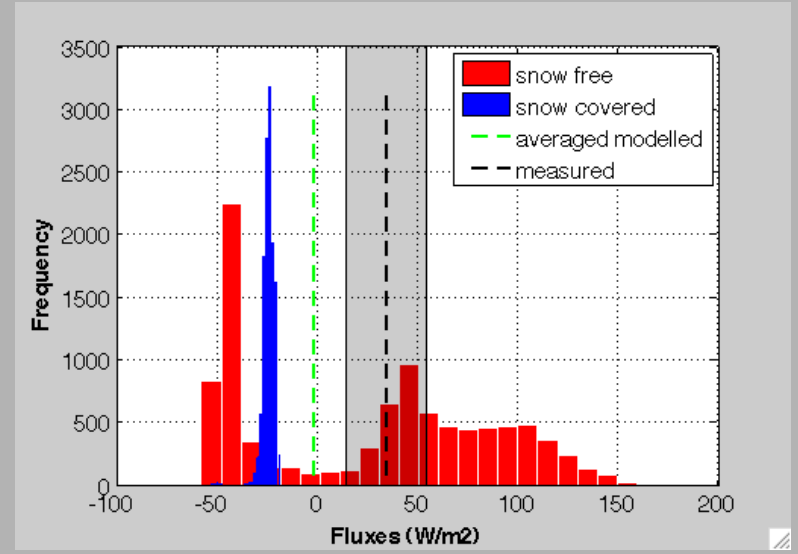


We also have surface temperature data from the aircraft and are comparing this to model estimates

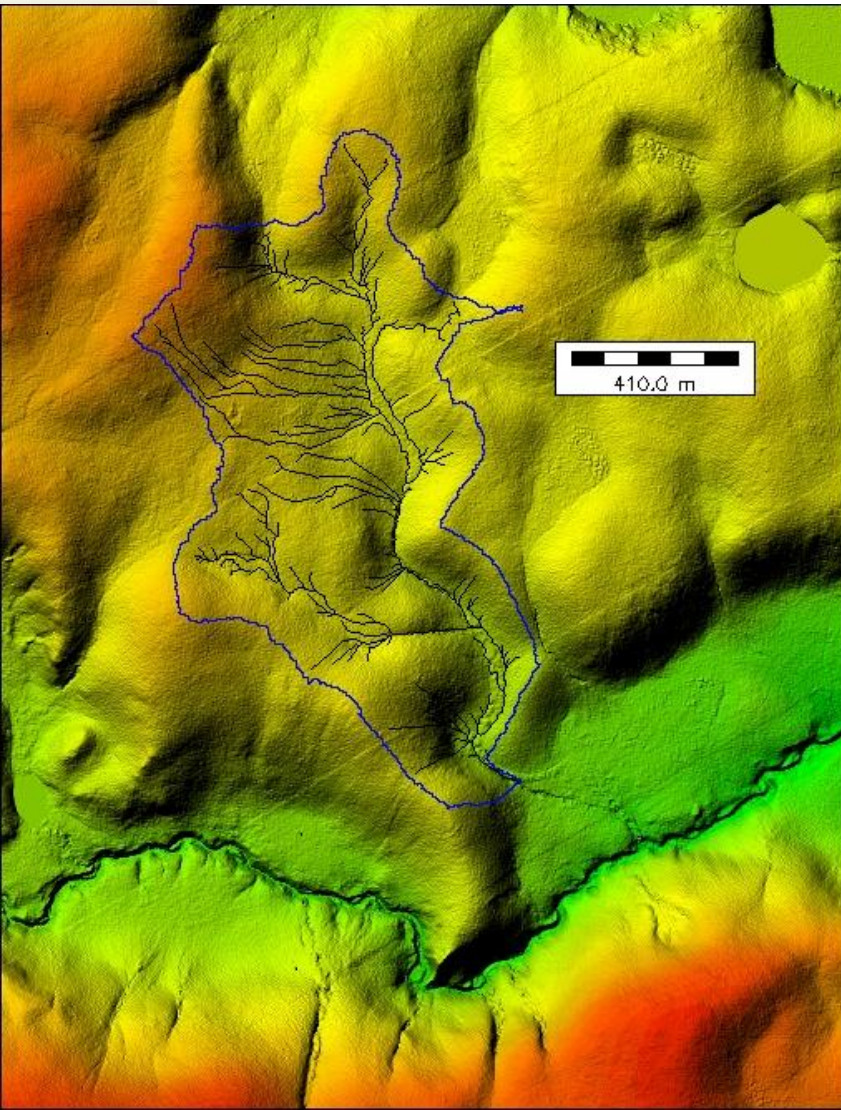
Modelled Sensible heat: 100 m grids



- For 15 of the 24 grids the modelled grid average is within the error bars of the aircraft data



4.7 Spatial variation of ground thaw in permafrost areas



Siksik Ck., a 1 km² sub-basin of Trail Valley Creek

- Frost table depth is critical to predicting runoff from organic-covered permafrost terrain
- integrated process studies to date (snow, radiation, turbulent fluxes) to consider active layer melt over the summer
- Consider the factors controlling the spatial variability in frost table melt, and therefore runoff

Factors controlling thaw depth

- depth of thaw is often closely related:
 - **cumulated heat flux** (radiation plus turbulent fluxes) y et al.,1978)
- Carey and Woo (2001) showed that thaw depths were related to **slope aspect**, with north facing slopes in sub-arctic mountain sites characterized by greater near-surface wetness as a result of shallow thaw depths, while deeper subsurface pathways due to deeper thaw were more evident on south-facing slopes
- pattern of soil thaw is also influenced by the **spatial pattern of snow disappearance** which, in turn, is determined by the spatial distribution of the snow mass and melt energy at the snow surface (Quinton and Carey, 2008),
- **Subsurface water flow** can also affect the thermal regime of the seasonally thawed or active, layer.
 - converging flow where water accumulates, the soil thermal conductivity, which increases with soil water content is raised, producing greater thawing, even if the rate of energy transfer into the ground is offset by the energy loss due to enhanced evaporation of the relatively wet ground surface (Kane et al., 2001)
- Due to these complex interactions, it is difficult to consider the relative importance of various processes. The GEOtop model was used to better understand these interactions, and then to use these results to improve predictive models where appropriate.

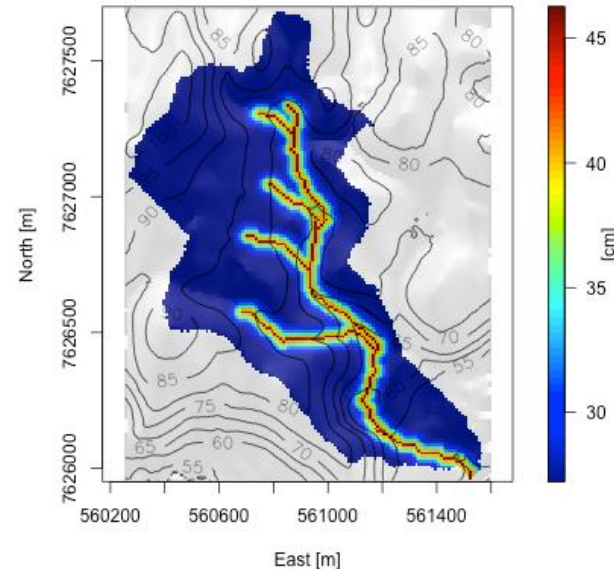
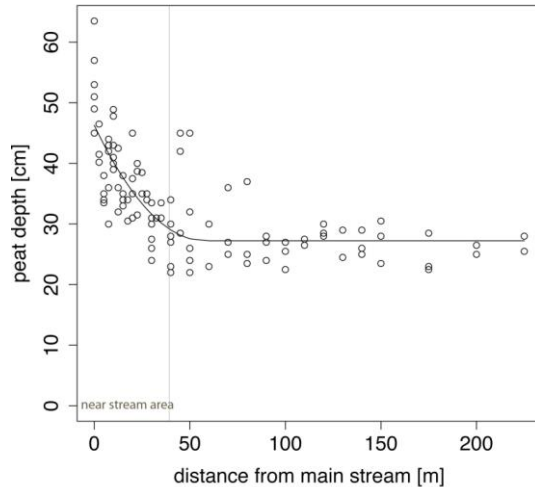
GEOtop

- GEOtop includes:
 - Surface energy balance and blowing snow
 - Numerical solution of both heat and subsurface flow equations in soil
 - Equations are solved at a small grid size (metres to tens of metres)
 - 30 soil layers with variable thickness to a depth of 3.5m
- Appropriate field information on:
 - DEM and vegetation height from Lidar
 - Spatial variability in surface organic layer
- Recent GEOtop improvements include:
 - Representation of surface energy balance (Endrizzi and Marsh, 2010)
 - Soil freezing and thawing processes (Dall'Amico et al., 2010), and
 - The numerical algorithms

GEOTop

- domain is discretized in a finite regular grid (10 m in this case), given by the intersection of the DEM cells.
- heat and subsurface water flow equations are solved with finite differences schemes.
- heat equation is solved in a one-dimensional form in the grid cell columns normal to the surface,
- equation describing the water flow in the soil (Richards equation) is solved in a fully three-dimensional way, which allows a complete coupled description of vertical and lateral flows.
- Hydraulic properties of the peat follow Carey et al. (2007), Quinton et al. (2005), Quinton et al. (2008), Quinton and Gray (2003). Mineral earth hummocks are represented as sub-grid variability.
- surface water flow over land is also described, with a solution of a simplified version of the shallow water equations that neglects the inertia terms.
- integration time step ranges from a few minutes to a few hours.
- determination of the heat flux exchanged from the atmosphere to the ground surface (hereafter referred to as ground heat flux) is crucial, since it constitutes the upper boundary condition of the heat equation.
- The ground heat flux is given by the algebraic sum of net shortwave (solar) radiation, net longwave (terrestrial) radiation, and turbulent fluxes of sensible and latent heat.

Peat thickness (fig 2)

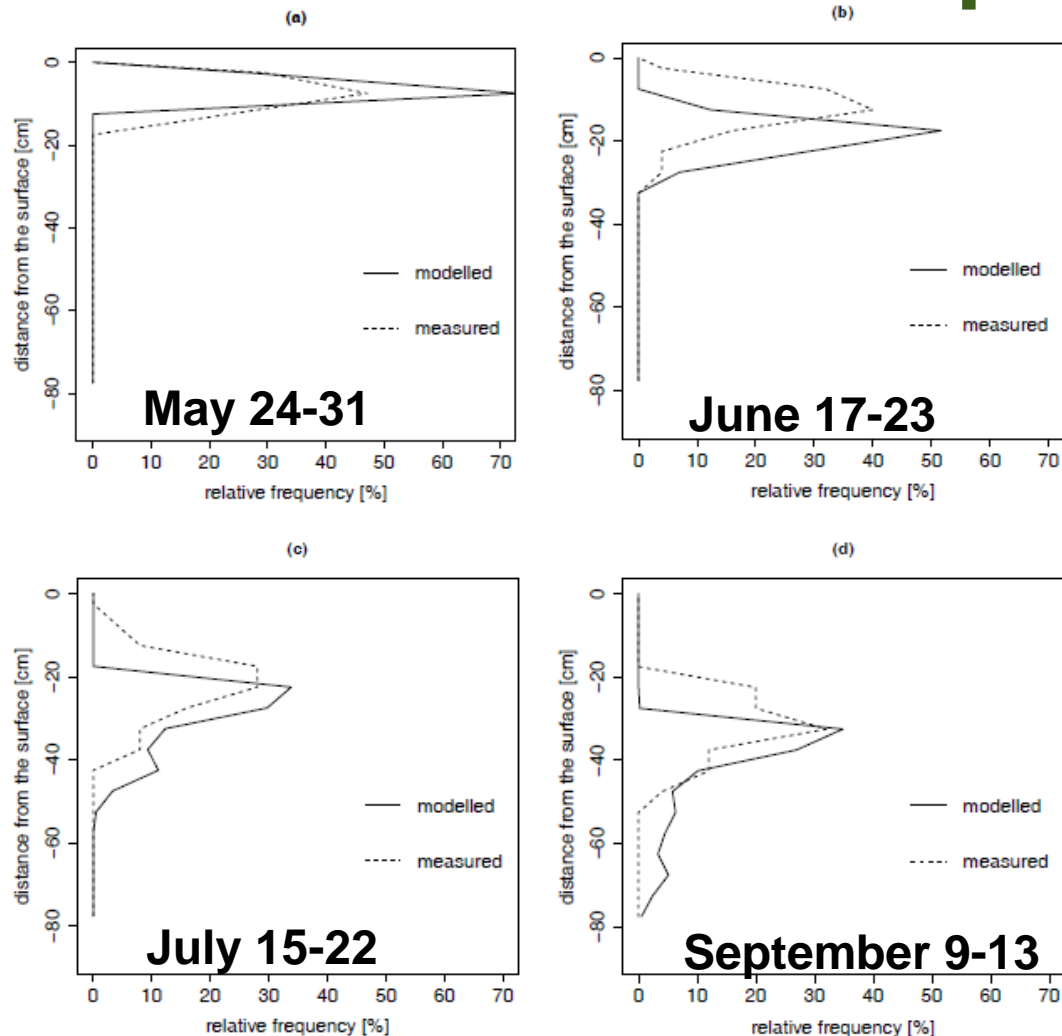


-Peat thickness is extremely important as it is highly permeable in the upper layers, with the hydraulic conductivity decreasing with depth by 2 orders of magnitude over a 20 cm depth, and it overlies less permeable mineral soil.

- position of the frost table, and its change over the summer, is important as it is the major control on hillslope drainage.

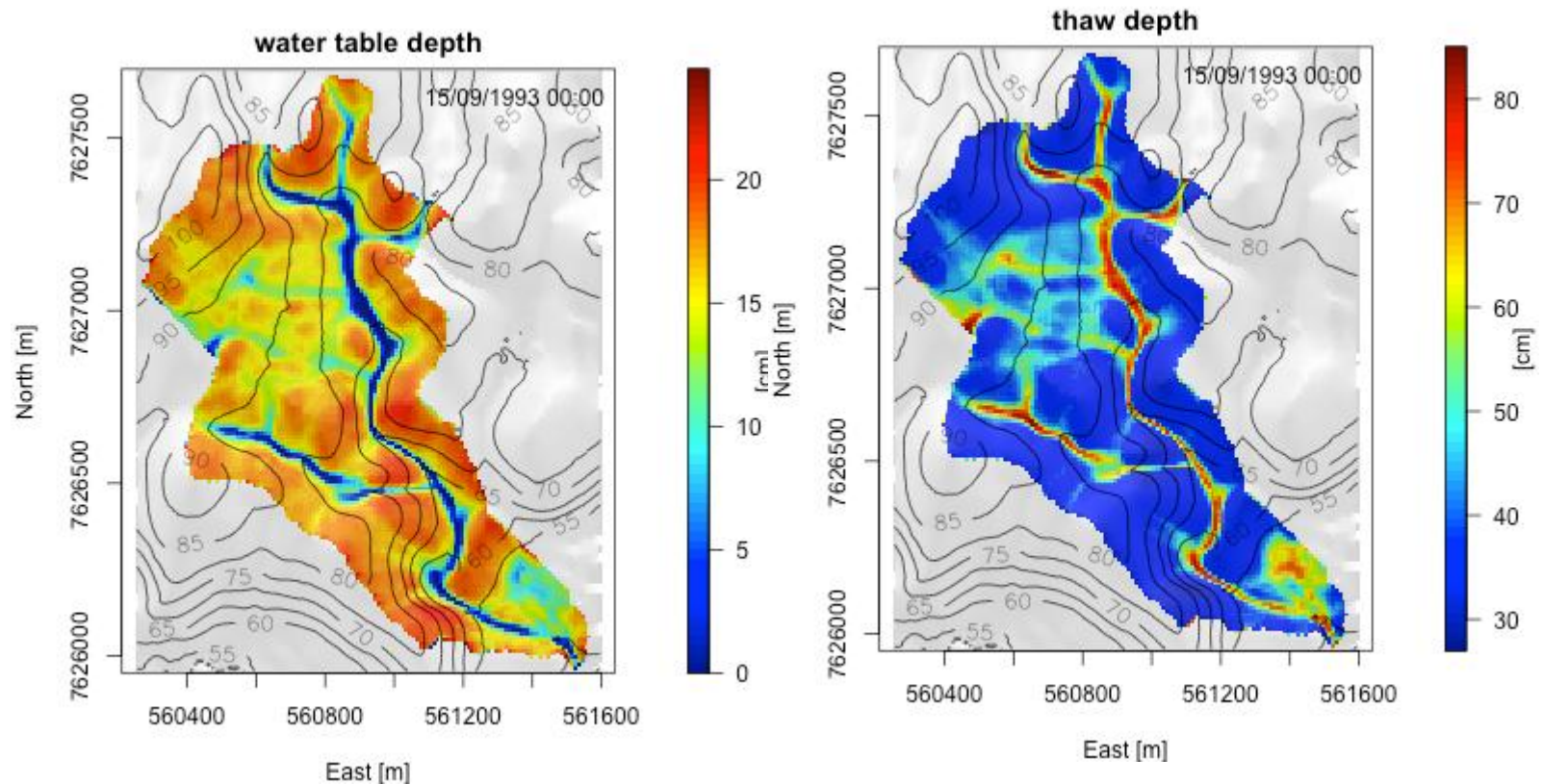


Weekly averaged frequency distributions of thaw depth (Fig 9)



End of Summer (Fig 3a,b)

Note that thaw depths are greatest in areas with the highest water table depth



Environment
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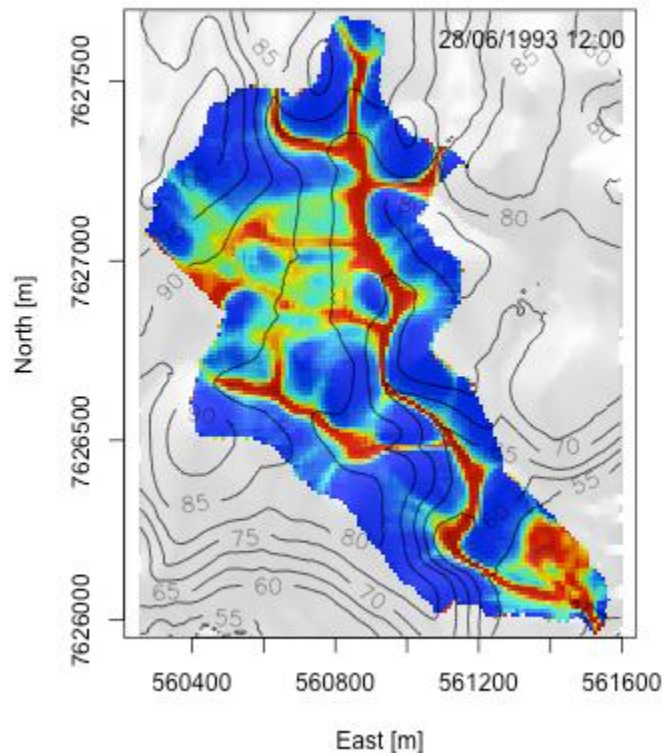
Environnement
Canada

Endrizzi, Quinton, Marsh. 2011.
Cryosphere Discussion.

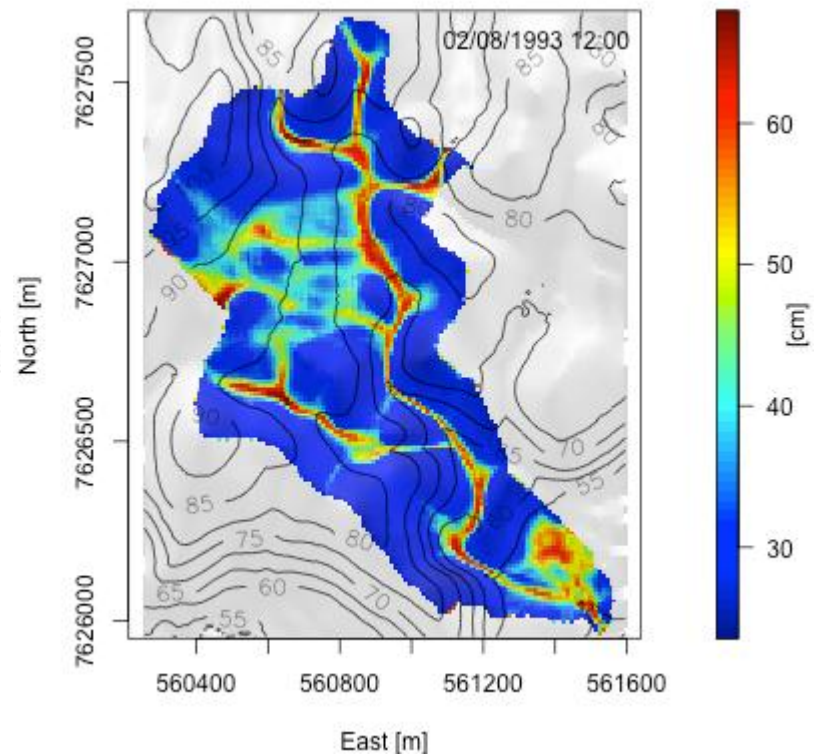
Canada

Similar patterns of thaw depth earlier in the summer (Fig 4 a, b)

June 28



Aug. 2



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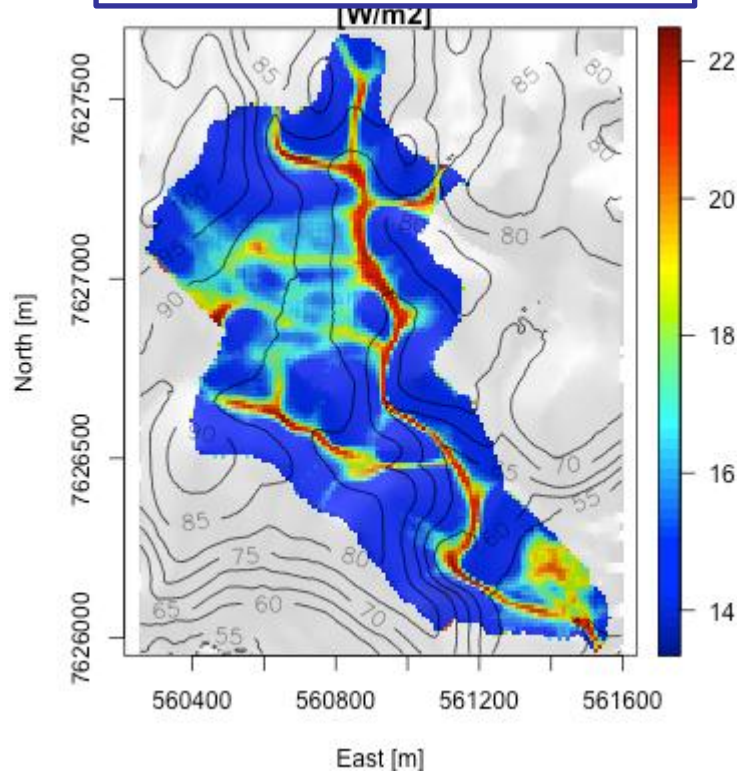
Environnement
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Endrizzi, Quinton, Marsh. 2011.
Cryosphere Discussion.

Canada

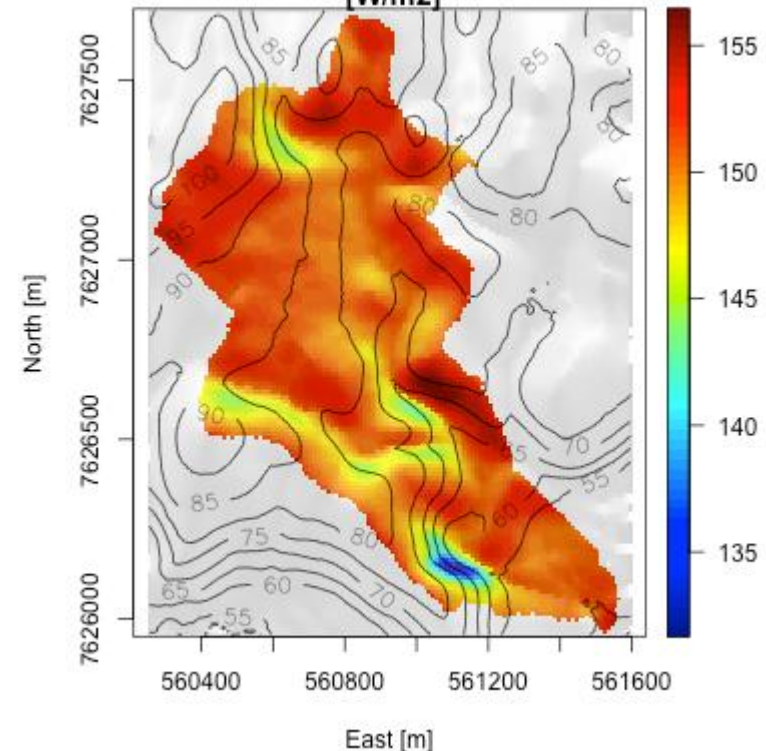
Role of ground heat flux vs shortwave radiation (Fig 5 a,b)

Sum of surface heat fluxes



Strongly related to thaw depth

net shortwave radiation
[W/m²]



No significant correlation with thaw

Average over simulation time

Endrizzi, Quinton, Marsh. 2011.
Cryosphere Discussion.

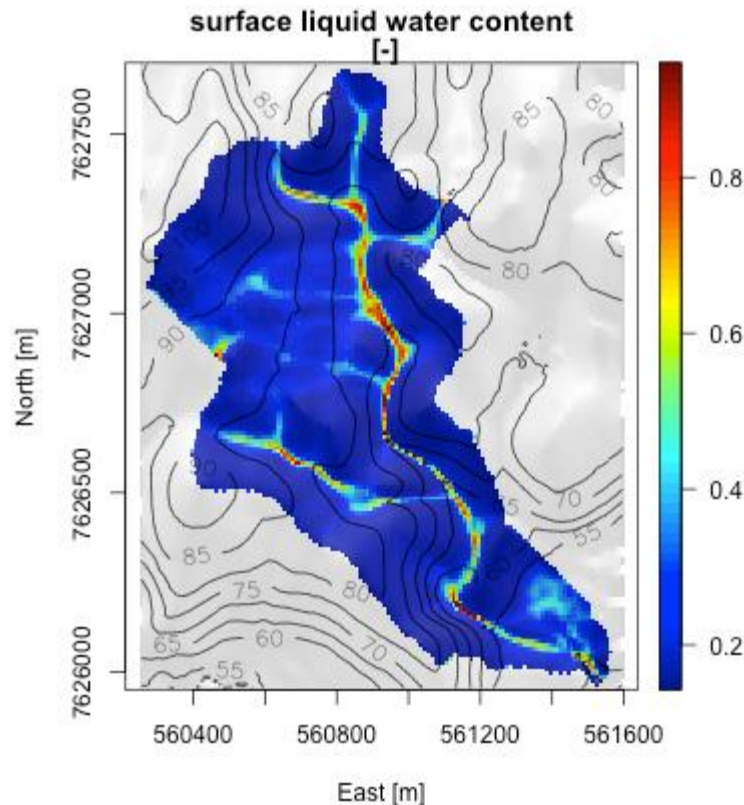


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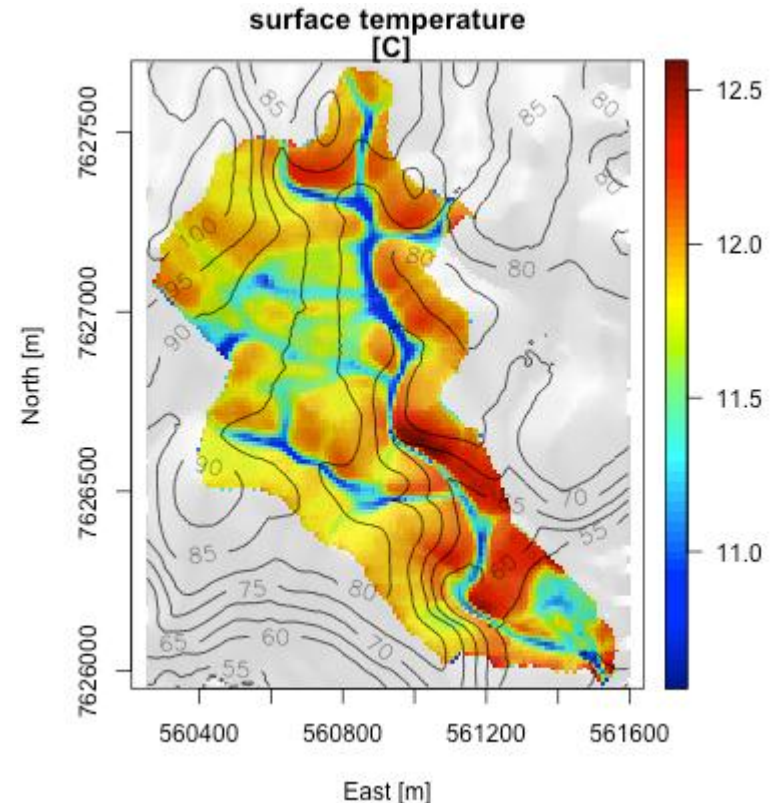
Environnement
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Surface water and temperature (Fig 6 a,b)



Strongly related to water table depth

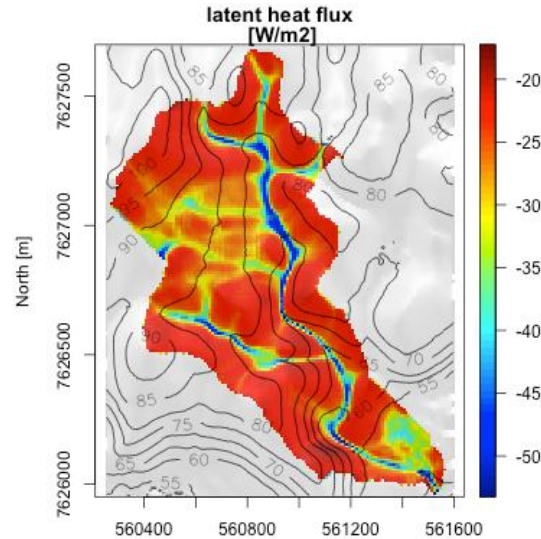
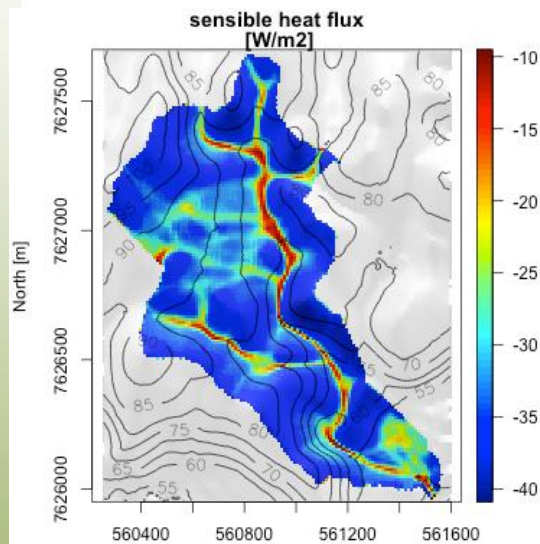


Soil temp. is negatively correlated to soil water. Wet areas are colder



Surface heat fluxes(FIG 7 a,b,c,d)

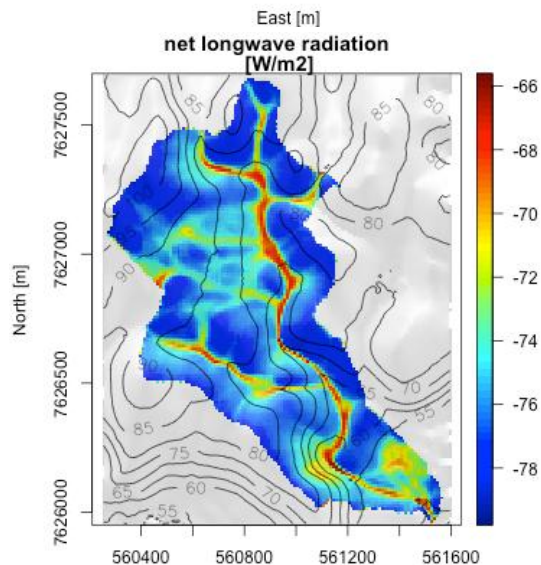
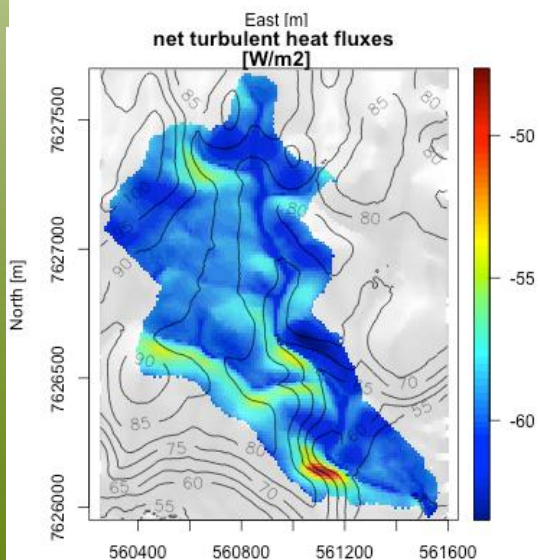
Negative values are fluxes directed towards the atmosphere



The net result:

-wetter areas have relatively low energy losses to the atmosphere,

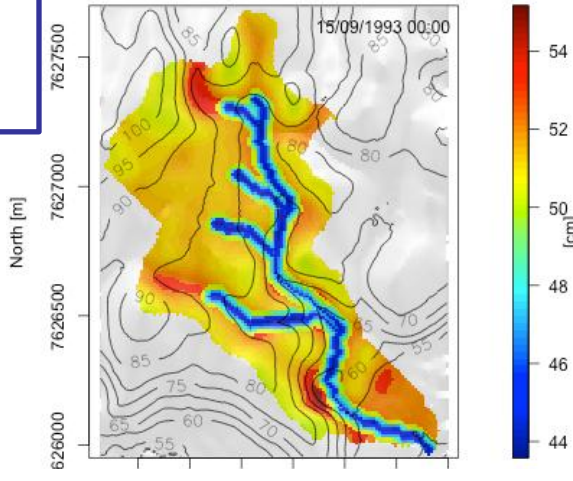
- this contributes to increase the rate of ground thaw.



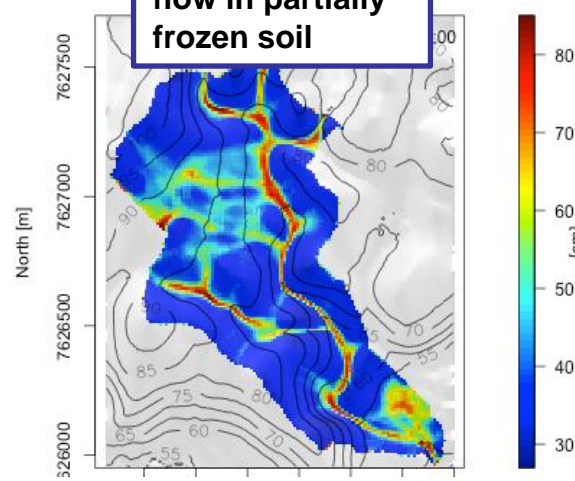
- Subsurface lateral water flow, therefore, seems to completely control the spatial patterns of the ground heat flux, which, in turn, affects the spatial variability of ground thaw

Relative importance of various processes in controlling end of summer thaw depth (Fig 8 a,b,c,d)

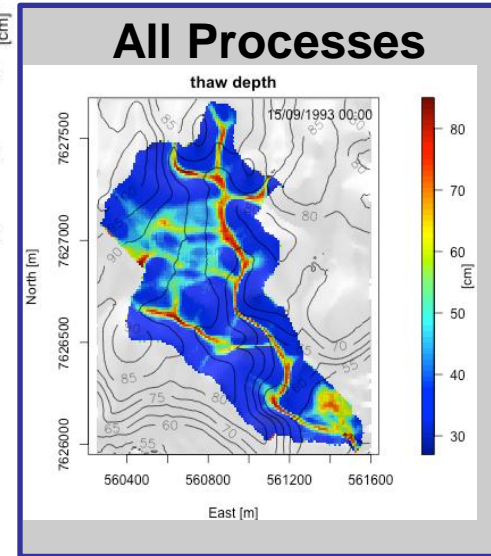
No lateral subsurface flow



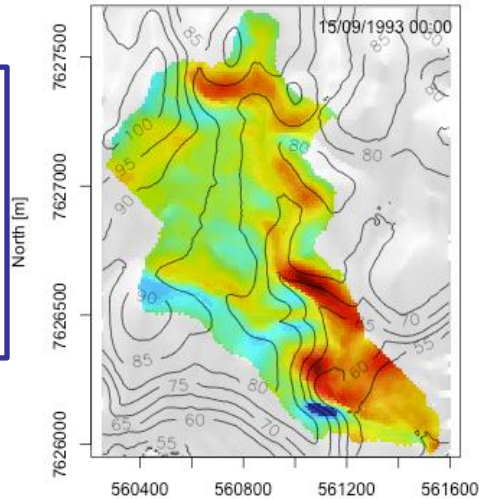
No subsurface flow in partially frozen soil



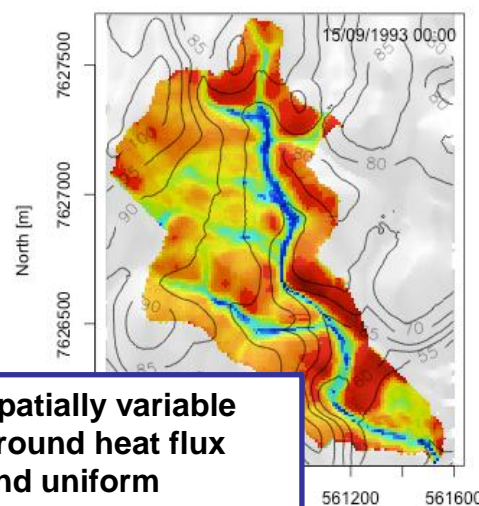
All Processes



Uniform ground heat flux and spatially variable thermal conductivity



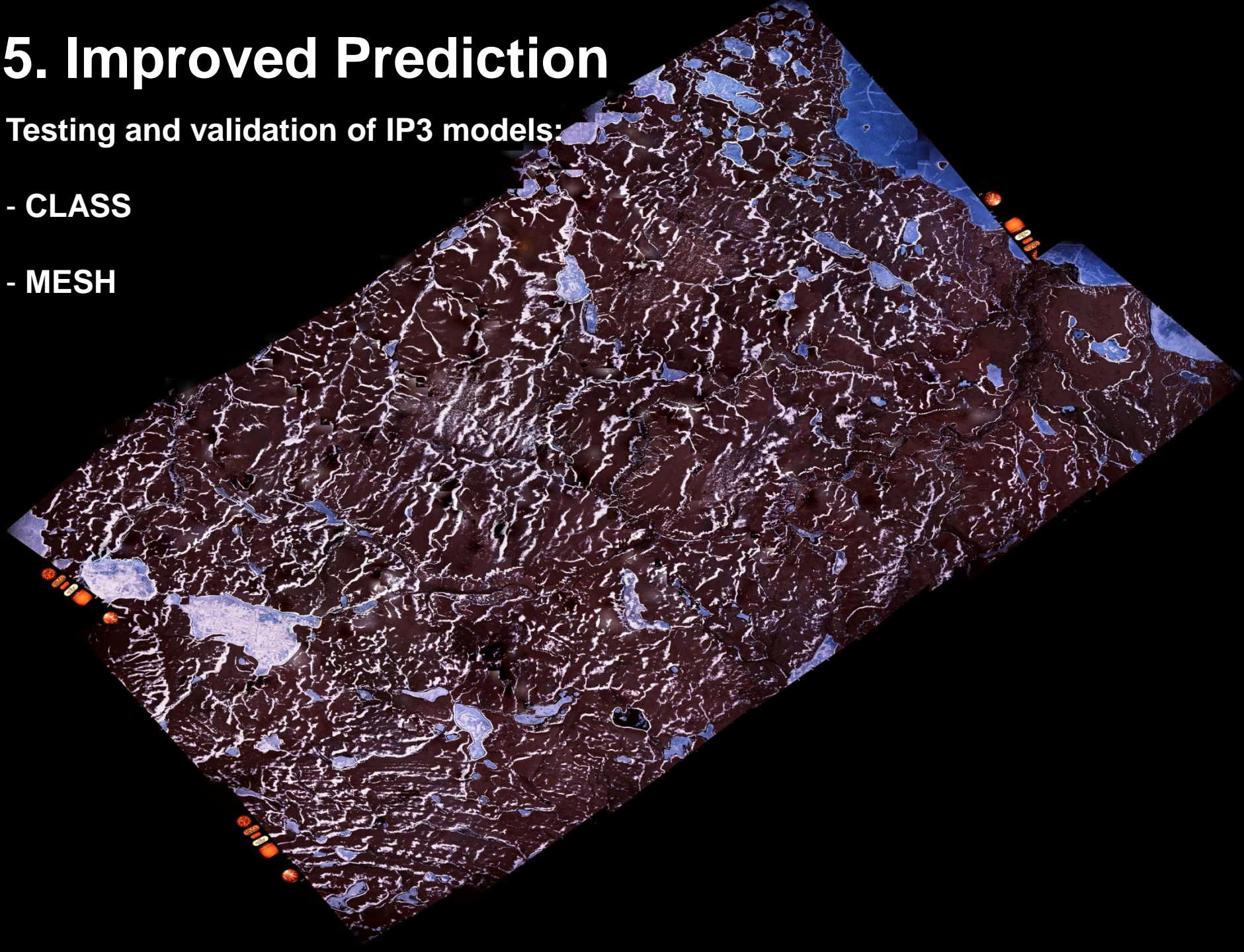
Spatially variable ground heat flux and uniform thermal conductivity



5. Improved Prediction

Testing and validation of IP3 models:

- CLASS
- MESH

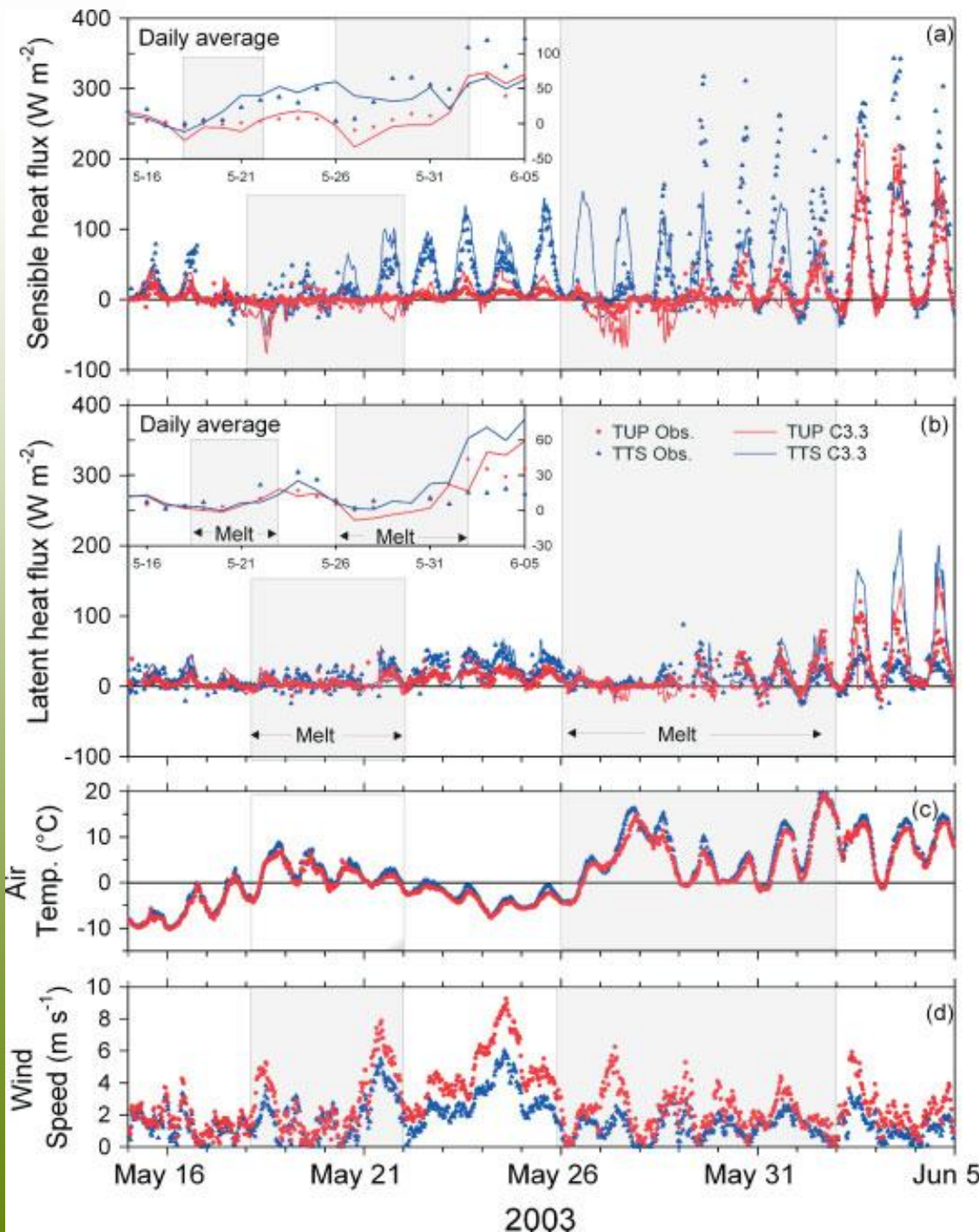


5.1 CLASS

Marsh, Paul Bartlett, Murray Mackay and Trevor Lantz. 2010. Hydrological Processes.

As with GEOtop, CLASS was able to reasonably model the fluxes of energy.

- One of the main problems is how to consider the bending/unbending of shrubs



5.2 MESH

- MESH version 1.3 was run for TVC from May 1st to Sep 30th for 1996 to 2006
- Model was run at resolution of 1 km
- Initial base case runs were carried out using “traditional” vegetation based land cover classes tundra, shrub tundra, forest, water
- Will not show calibration runs, or runs for all years as these have been shown previously.

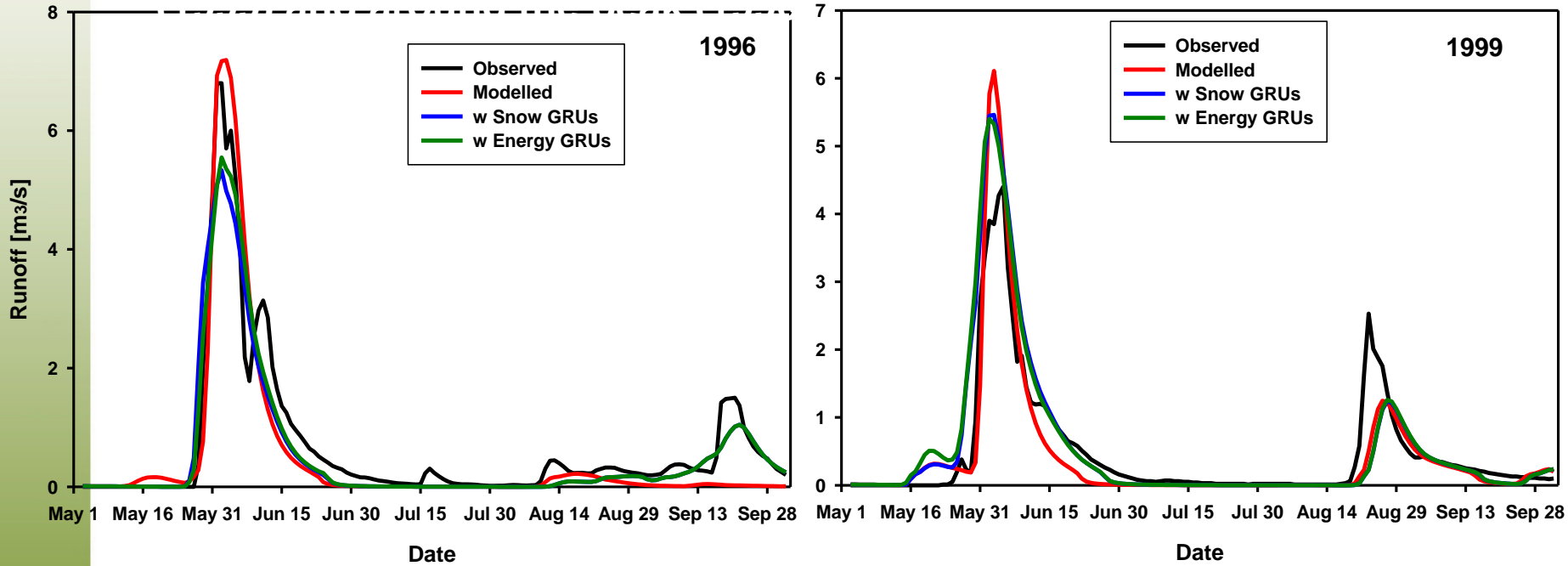
MESH Model Run “Snow GRUs”

- To better capture end of winter snow cover variability, topography based GRUs were added
- Added were:
 - windswept tundra and
 - snow drifts
- All GRUs receive the same energy inputs but have a different end of winter snow cover

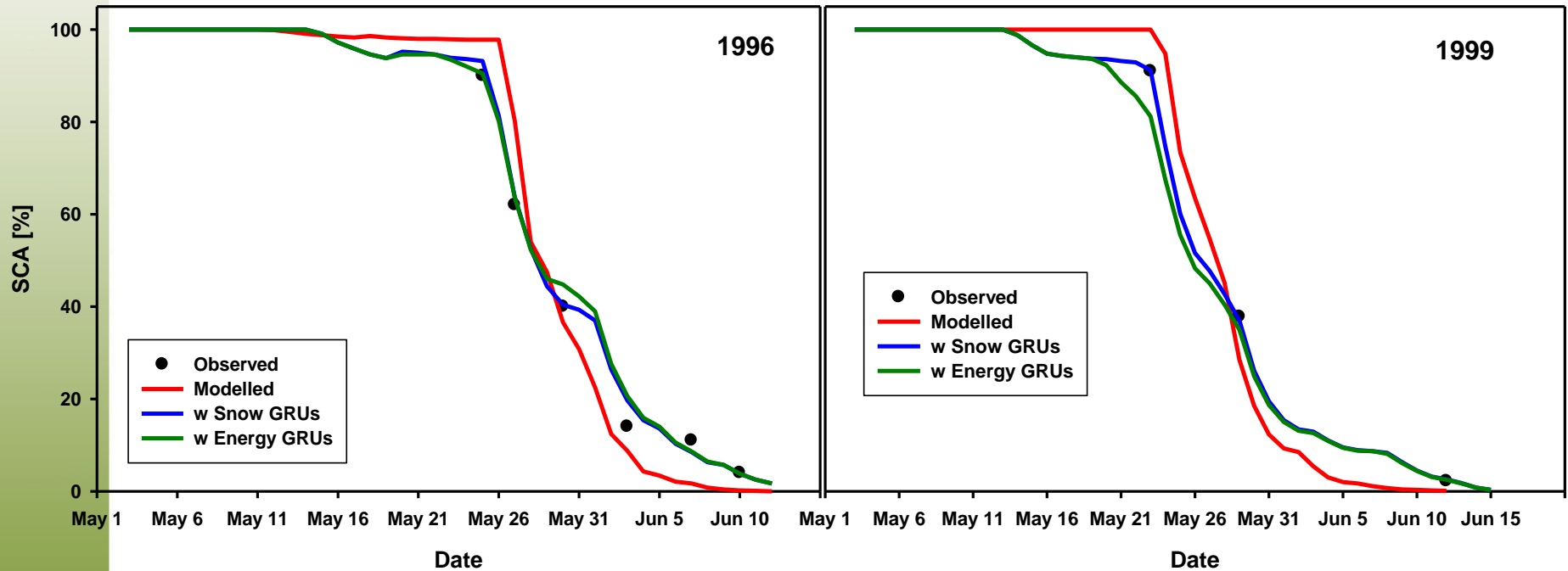
MESH Model Run “Energy GRUs”

- Finally, GRUs were chosen according to land cover type and slope orientation to improve the energy, especially solar radiation, input
- Added were:
 - north facing tundra slopes and
 - south facing tundra slopes
- The added GRUs receive the same end of winter snow cover inputs as the tundra GRU but different solar radiation inputs

Model Runs with Energy GRUs



Basin Average SCA with Energy GRUs



Spatial Variability (SCA) (1996)

Date	Observed SCA		Modelled SCA Base Case		Modelled SCA with Snow GRUs		Modelled SCA with Energy GRUs	
	AVG	Range	AVG	Range	AVG	Range	AVG	Range
	%	%	%	%	%	%	%	%
23-May	90	45	95	12	91	16	87	21
25-May	62	75	65	35	62	49	62	50
28-May	40	76	38	47	40	60	43	65
01. Jun	14	38	8	22	16	38	18	43
05. Jun	11	32	3	8	10	26	10	28
08. Jun	4	15	0	0	4	14	4	15



Results When Including Snow GRUs

- **MESH simulation results of basin runoff did not change significantly**
- **Basin wide average SCA improved considerably**
- **Prediction of spatial variability of SCA is greatly improved**

Results When Including Energy GRUs

- **MESH simulation results of basin runoff did not change significantly**
- **Basin wide average SCA were predicted to drop slightly more quickly in the early part of the melt as a result of the south facing slopes becoming snow free more quickly**
- **The impact of the slower melt on north facing slopes on the basin average SCA seems to be overshadowed by the drift areas, that dominate the late season SCA in TVC**
- **The range of SCAs increased slightly throughout the melt period**

6. Conclusions

Have made significant progress during IP3 and IPY on:

- Process understanding
- Improved parameterization in a range of models including GEOtop, CLASS and MESH
- But.... Still many areas where our knowledge needs improving
 - blowing snow and snow accumulation in drift areas is typically underpredicted
 - frost table simulations
 - shrub-snow-atmosphere interactions

7. Next steps

We are continuing this line of research at Trail Valley Creek

-Using funding from the Program for Energy R&D

- interested in improved hydrologic prediction for pipeline development in northern Canada (Mackenzie Pipeline, Yukon Pipeline, and High Arctic)

- However, no funding currently to work in a larger research group like we have had in MAGS, IP3 and IPY over the last 10+ years

- this will greatly hamper our continuing advance in understanding and predicting changes in northern hydrology due to climate change and resource development