

The Snow Climate of Quebec

A compilation of data sources and information for
characterizing the snow cover of Québec

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Preamble:

The purpose of this slide deck is to provide a rapid overview of the main data sources available for snow cover studies in Quebec along with examples of previous or ongoing work based on these sources of information. This is not intended to be detailed or exhaustive and the reader is encouraged to consult the literature for further information on the applications and limitations of the various data sources.

Where possible, sample applications have been chosen that provide insights into the snow climate of Quebec.

If you wish to contribute to this deck, please provide me with slides that follow the general format presented here and I will be happy to include them.

Comments are always welcome - please send to ross.brown@ec.gc.ca

Ross Brown, November 27, 2007

Jargon... here is a list of definitions for some of the acronyms and abbreviations that inevitably crop-up when space is limited. Apologies if I've missed any.

AR4	4 th Scientific Assessment Report of the IPCC (2007)
CANGRD	Canadian gridded monthly temperature and precipitation dataset
CCRS	Canada Centre for Remote Sensing, Natural Resources Canada
CMC	Canadian Meteorological Centre
CRCM	Canadian Regional Climate Model
EASE	Equal-Area Scalable Earth map projection
ECMWF	European Centre for Medium-range Weather Forecasting
ERA-40	Atmospheric reanalysis dataset developed by ECMWF, 1958-2002
GSWP	Global Soil Wetness Project
IMS	Interactive Multisensor Snow and Ice Mapping System (NESDIS)
IPCC	Intergovernmental Panel on Climate Change
IREQ	Institut de Recherche d'Hydro-Québec
MDDEP	Ministère du Développement durable, de l'Environnement et des Parcs
NARR	North American Regional Reanalysis (NCEP)
NASA	National Aeronautics and Space Administration
NCEP	National Centers for Environmental Prediction
NESDIS	NOAA's National Environmental Satellite, Data, & Information Service
NOAA	National Oceanic and Atmospheric Administration
NSIDC	National Snow and Ice Data Center
PMW	passive microwave
PS	Polar Stereographic map projection
QCd	quality controlled
SCD	snow cover duration
SMMR	Scanning Multichannel Microwave Radiometer (1979-1987)
SSM/I	Special Sensor Microwave Imager (1987-)
SWE	Snow water equivalent

Data Sources:

Remotely Sensed:

- NOAA weekly snow cover extent, 1967-> (NOAA)
- IMS daily NH snow cover analysis, 1999 -> (IMS)
- CCRS merged daily snow cover datasets [TBC]
- Passive microwave, 1979->
- QuikSCAT, 1999->

In Situ:

- Daily Snow Depth observations, ~1950->
- Bi-weekly snow course observations, ~1940->

Analyzed and/or reconstructed:

- CMC daily operational snow depth analysis, 1998 ->
- Brown et al. (2003) daily snow depth and SWE analysis, 1979-1997 (B2003)
- Reconstructed daily snow depth and SWE, 1948-2006 (NCEP+CANGRD)
- High resolution (10-km) kriged SWE maps for Quebec and adjacent area
- North American Regional Analysis, 1979-2006
- ERA-40, 1958-2002

Modelled:

- GSWP-2 multi-land surface process model simulation, 1986-1995
- IPCC AR4 global climate model simulations
- Canadian Regional Climate Model

An aerial photograph of a desert landscape, likely a sand dune field. The terrain is characterized by numerous small, rounded dunes and larger, more elongated ridges. The lighting creates long, dark shadows that stretch across the sand, highlighting the undulating topography. The overall color palette is a range of light to medium tones, from pale beige to a soft, dusty blue-grey, suggesting a clear, bright day.

Remotely Sensed Data...

NOAA weekly snow cover extent, 1967-> (NOAA)

- weekly values of snow/no-snow on 190.5 km PS grid over Northern Hemisphere
- mainly derived from manual interpretation of visual satellite imagery (AVHRR, GOES, METEOSAT)
- snow/no-snow based on 50% snow cover threshold
- superseded by higher resolution daily IMS product in 1999 but continuity maintained by creating a pseudo-weekly product
- mainly suitable for continental-scale studies; high latitude summer snow cover is not considered reliable due to cloud cover, subjective interpretation of patchy snow and continuity issues with the IMS product (e.g. Wang et al., 2005; Brown et al., 2007; Dery and Brown, 2007)
- applications: monitoring snow cover extent, start/end dates of snow cover, snow-climate interactions, climate model evaluation
- QCd version of original data in weekly and monthly formats available from Dr. David Robinson, Rutgers U. (climate.rutgers.edu/snowcover/)
- NSIDC have a version of these data reinterpolated to 24 km EASE grid format (nsidc.org)

References:

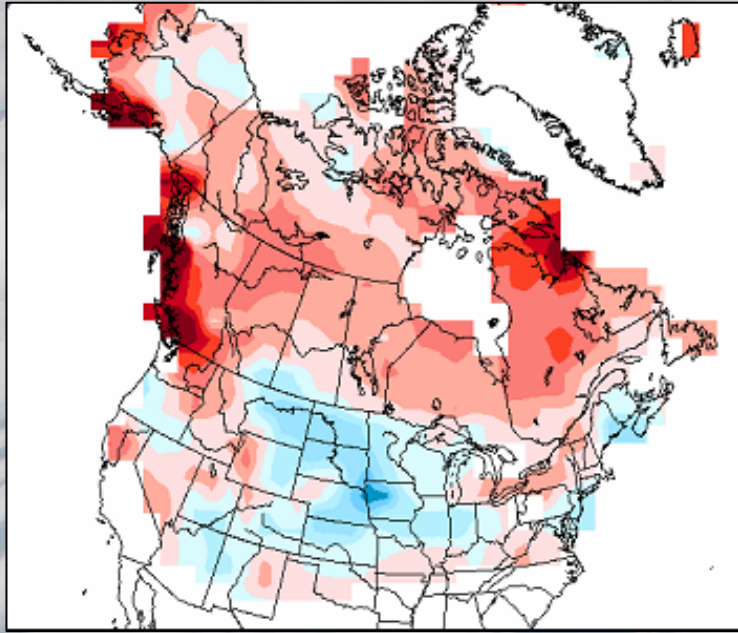
Brown, R., C. Derksen and L. Wang, 2007: Assessment of spring snow cover duration variability over northern Canada from satellite datasets. *Remote Sensing of Environment*, **111**, 367-381.

Dery, S.J. and R.D. Brown, 2007: Recent Northern Hemisphere snow cover extent trends and implications for the snow-albedo feedback. *Geophys. Res. Letters*, **34**, L22504, doi:10.1029/2007GL031474, 2007

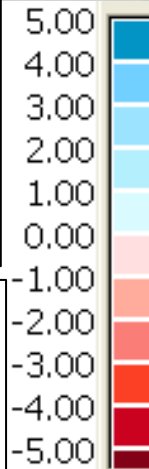
Robinson, D.A., K.F. Dewey and R.R. Heim. 1993. Global snow cover monitoring: an update. *Bull. Am. Meteorol. Soc.*, **74**, 1689-1696.

Wang, L., M. Sharp, R. Brown, C. Derksen and B. Rivard, 2005: Evaluation of spring snow covered area depletion in the Canadian Arctic from NOAA snow charts. *Remote Sensing of Environment*, **95**, 453-463.

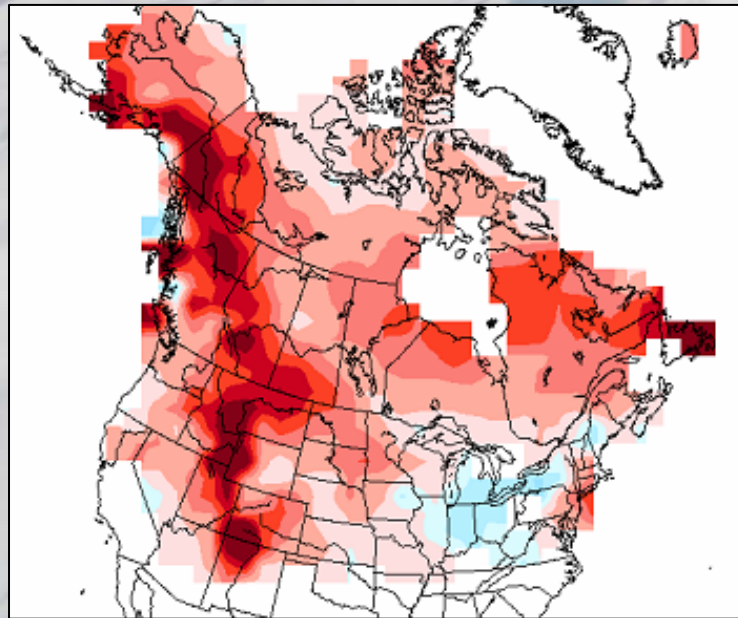
Application of NOAA dataset to document the temperature sensitivity of snow cover onset and disappearance. Monthly air temperatures from NCEP reanalysis.



Temperature sensitivity (days/C) for **snow cover onset** versus October mean air temperatures, 1970-2004

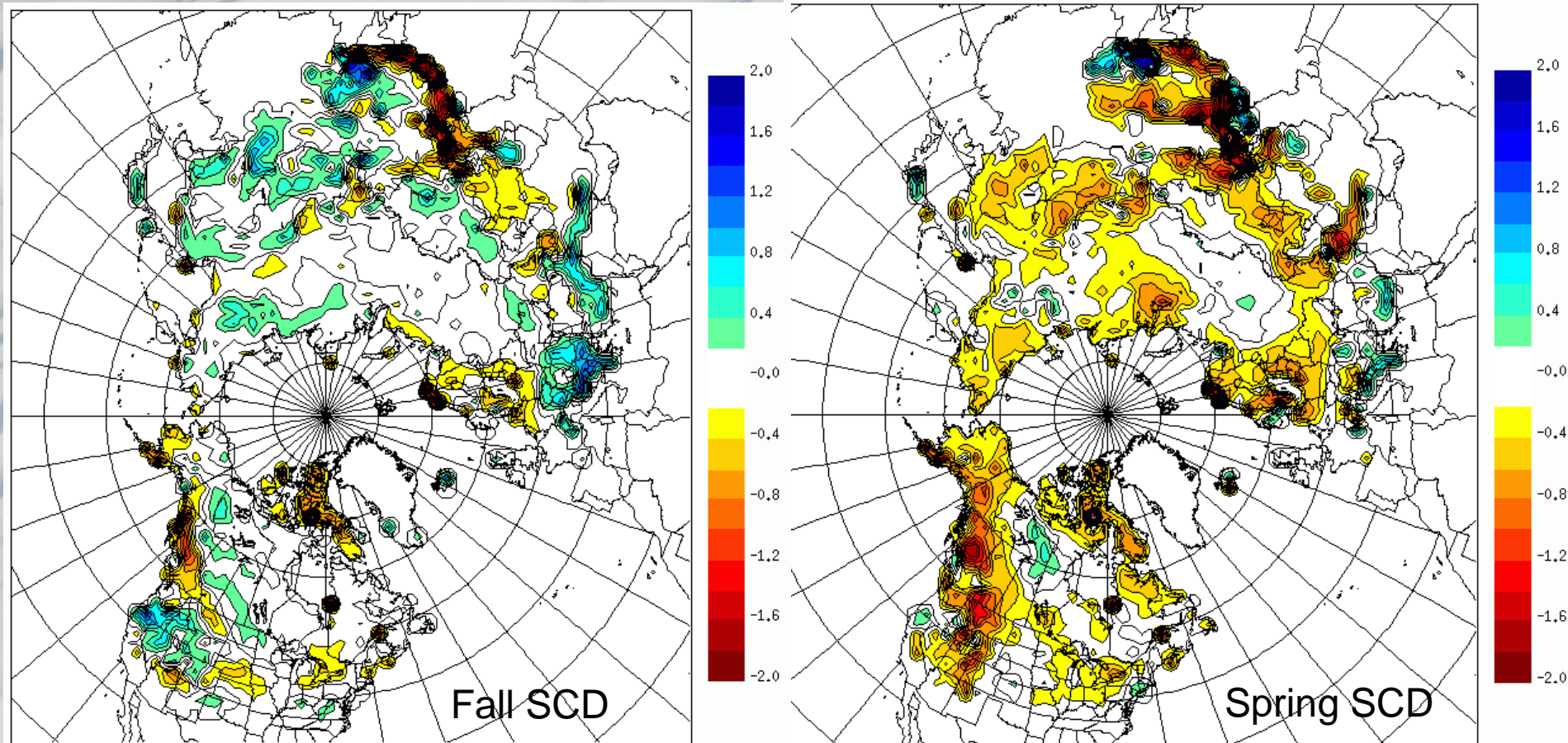


Results indicate snow cover onset/disappearance temperature sensitivities of -2 to -4 days/°C over Quebec



Temperature sensitivity (days/C) for **snow cover disappearance** versus May mean air temperatures, 1970-2004

Application of NOAA dataset to compute trends in snow cover onset and disappearance over 1970-2005 period



Trend in Fall (left) and Spring (right) snow cover duration (days/yr) from NOAA weekly satellite data set over 1970-2005 period. For Quebec the results suggest little change in onset date of snow cover but a significant trend toward earlier loss of spring snow cover in northern Quebec.

IMS daily NH snow cover analysis, 1999->

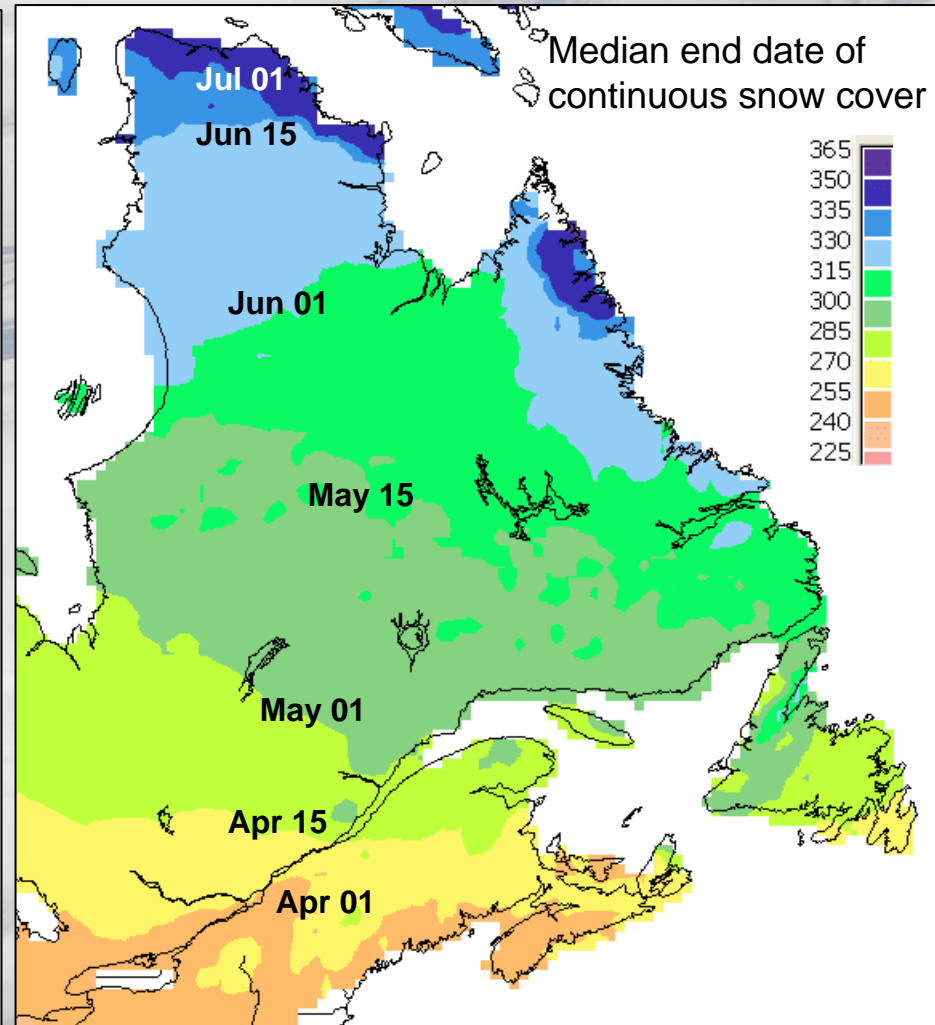
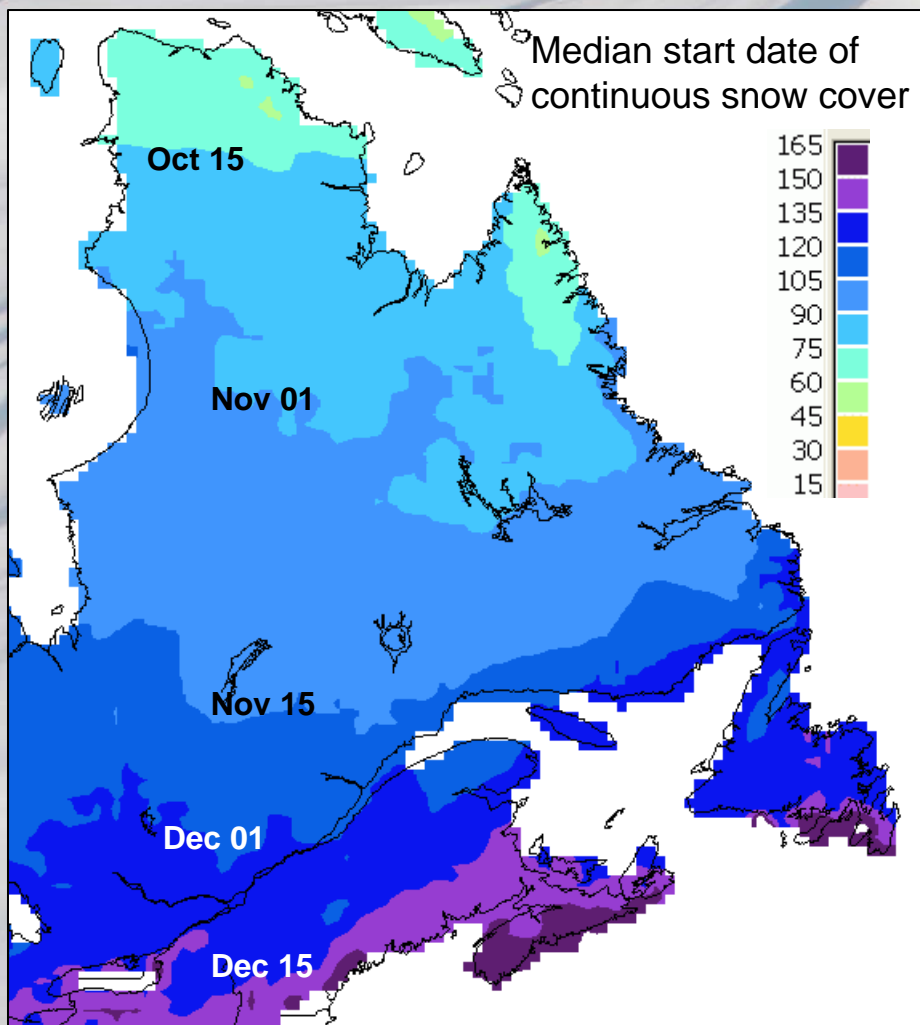
- IMS = Interactive Multisensor Snow and Ice Mapping System at NOAA NESDIS
- IMS became operational in 1997 providing satellite analysts improved access to imagery and drawing tools for identifying snow cover
- IMS maps produced daily at ~24 km resolution (1024 x 1024 grid) since 1997 (but only data from 1999 available for analysis)
- ~4 km resolution product (6144 x 6144 grid) available since February 2004
- snow cover extent identified from man-machine analysis of mainly visible satellite imagery
- incorporates some passive m/w information but not systematically
- applications: snow cover extent, start/end dates, climate model evaluation, snow-climate interactions
- data archived at National Snow and Ice Data Center (www.nisdc.org)

References:

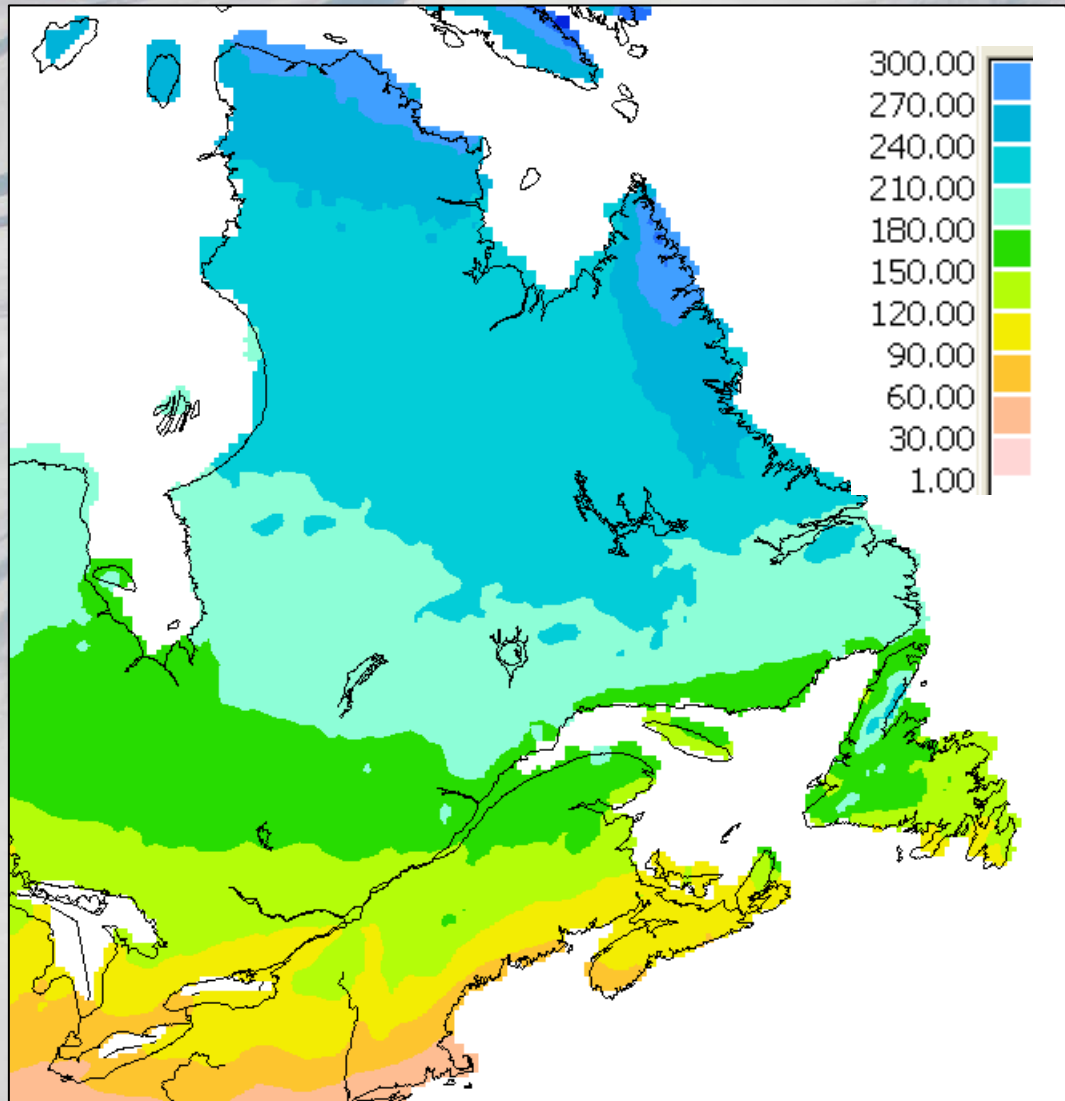
Ramsay, B., 1998: The interactive multisensor snow and ice mapping system. *Hydrological Processes*, **12**, 1537-1546.

Helfrich, SR; McNamara, D; Ramsay, BH; Baldwin, T; Kasheta, T., 2007: Enhancements to, and forthcoming developments in the Interactive Multisensor Snow and Ice Mapping System (IMS). *Hydrological Processes*, **21** (12): 1576-1586.

Median start and end dates of continuous snow cover from daily IMS product 2000-2006. Start (end) dates defined as first (last) period with 30 consecutive days of snow cover. Julian date of snow start/end defined with respect to start date of August 01.



Mean annual number of days with snow cover, IMS daily snow cover product, 2000-2006



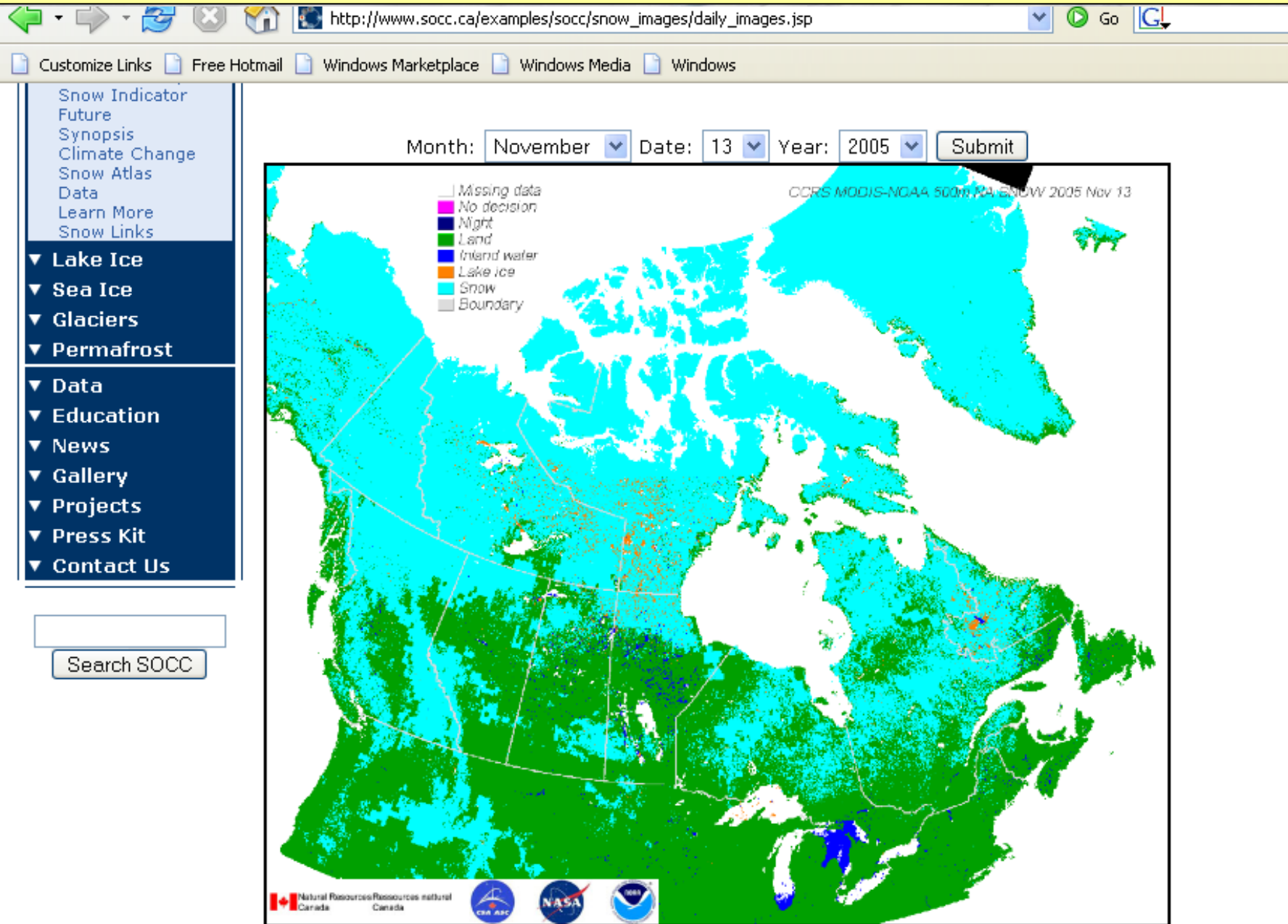
CCRS merged daily snow cover datasets:

- binary classification of snow cover presence at 1-km and 500 m resolution over Canada from fusion of multiple sources of visible satellite data (mostly AVHRR, MODIS and VGT)
- satellite data are rigorously recalibrated, corrected for various errors, georeferenced and resampled
- 1-km resolution daily snow cover maps available from 1985-2005 in GEOTiff format
- the data set also includes information on the presence of fresh water ice and open water
- 500-m resolution daily maps are available from 2005 in GEOTiff format based on MODIS, VGT and the IMS product
- the algorithms are based on the results of extensive verification with surface observations (e.g. Simic et al., 2004)
- contact richard.fernandes@ccrs.nrcan.gc.ca for further information on these datasets

References:

Simic, A., R. Fernandes, R. Brown, P. Romanov, and William Park, 2004: Validation of VEGETATION, MODIS, and GOES + SSM/I snow-cover products over Canada based on surface snow depth observations. *Hydrological Processes*, **18**, 1089-1104.

Example of CCRS 500 m resolution daily snow cover map derived from MODIS and NOAA IMS daily product (available online at www.socc.ca)



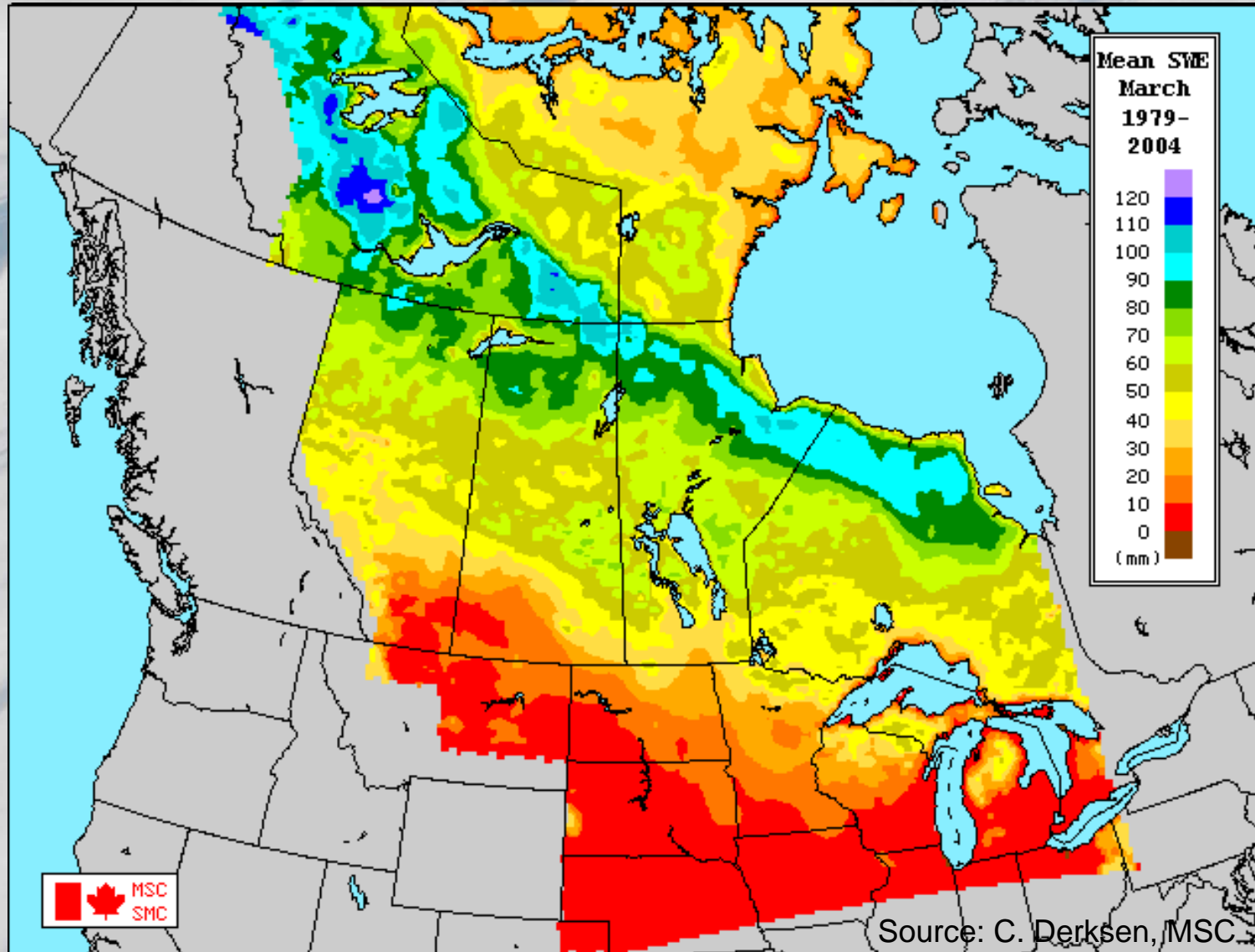
Passive microwave SWE data, 1979->

- provides all-weather potential for mapping daily SWE at a resolution of ~24 km based on the principle that dry snow is a very effective scatterer of microwave radiation; SWE usually estimated from the difference in brightness temperatures between 37 and 19 GHz channels
- a correction must be applied to the earlier (1979-1987) SMMR data stream to maintain continuity with the more recent (1987-) SMM/I data (Derksen and Walker, 2003)
- large uncertainties in SWE retrievals in tundra regions because of the complex sub-grid scale distribution of snow cover, large vertical gradients in snowpack properties (e.g. density and grain size), and strong microwave emission differences between tundra lakes and land (Derksen et al., 2005).
- wet snow not seen by passive microwave -> underestimates SWE compared to visible satellite data; SWE underestimated for deep snowpacks (> ~1 m) and the retrievals are less reliable over densely forested and mountainous terrain
- EC (Derksen), U. Sherbrooke (Royer, Goita) and INRS-ETE (Bernier) are collaborating on developing regional-specific algorithms for application in Quebec landcover regions as part of IPY; “beta-version” SWE maps are planned for winter 2008/09
- contact Chris.Derksen@ec.gc.ca for information on Canadian SWE products from passive m/w

References:

- Derksen, C. and Walker, A. (2003), Identification of systematic bias in the cross-platform (SMMR and SSM/I) EASE-Grid brightness temperature time series. *IEEE Transactions on Geoscience and Remote Sensing*, **41**, 910-915.
- Derksen, C., Walker, A. Goodison, B. (2005), Evaluation of passive microwave snow water equivalent retrievals across the boreal forest/tundra transition of western Canada. *Remote Sensing of Environment*, **96**, 315-327.

Example of passive microwave-derived SWE climatology for western Canada. In open prairie terrain the accuracy of the SWE retrieval is $\sim \pm 10$ mm. The high SWE band corresponds to a preferred storm track and has been verified in ground surveys and in regional climate model simulations (Derksen and MacKay, *Atmos.-Ocean.* **44**, 305-320)



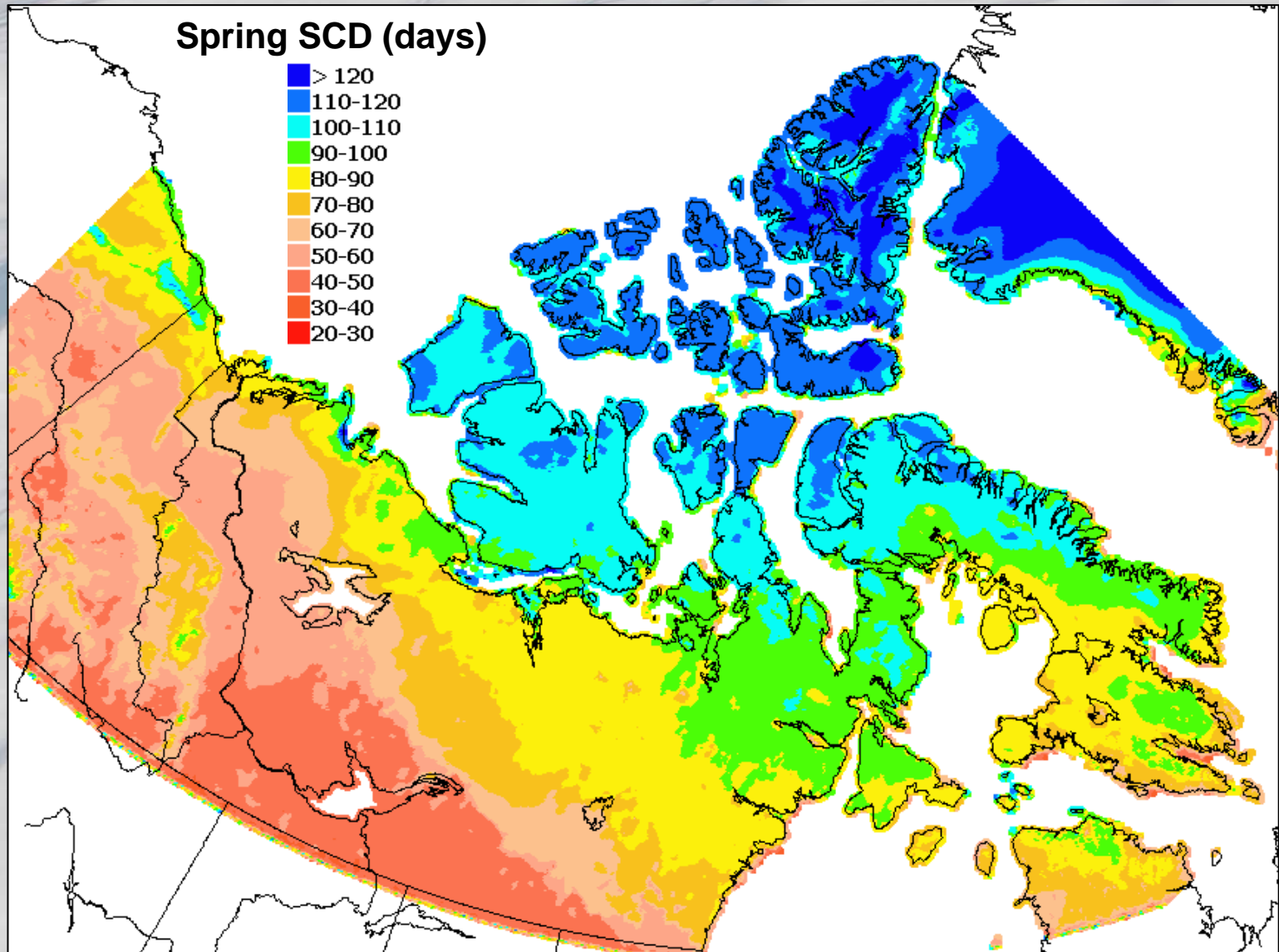
9. QuikSCAT 1999->

- satellite-borne active radar operating in Ku band (13.4GHz); data available twice daily from July 1999 over polar regions; the frequency of data coverage decreases with latitude (the limit to once daily coverage when combining ascending and descending passes is $\sim 45^{\circ}\text{N}$)
- enhanced resolution (4.45 by 4.45 km) QuikSCAT products from the NASA Scatterometer Climate Record Pathfinder Database are developed and maintained at Brigham Young University (<http://www.scp.byu.edu/>)
- applications: Ku band (13.4GHz) is sensitive to liquid water which means it can be used to monitor melt onset and duration over ice (Wang et al., 2005) and snow, as well as the end date of snow (Brown et al., 2007) and ice cover

References:

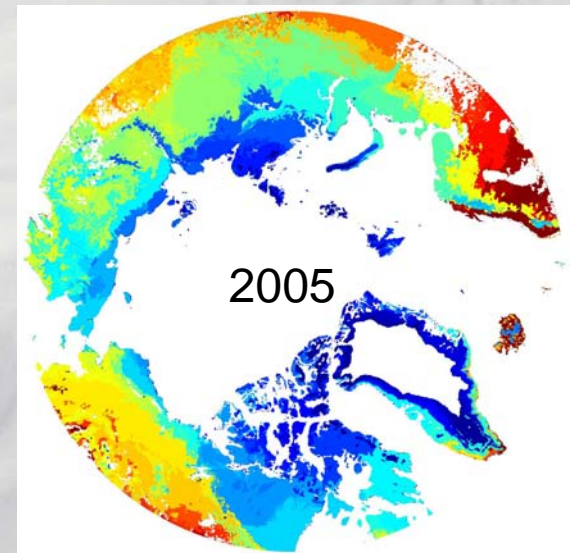
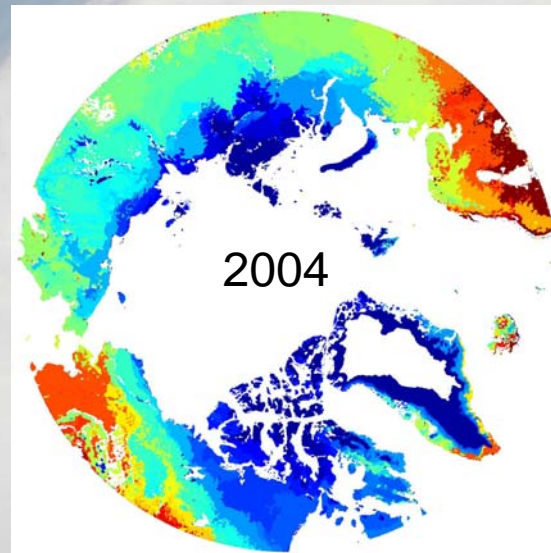
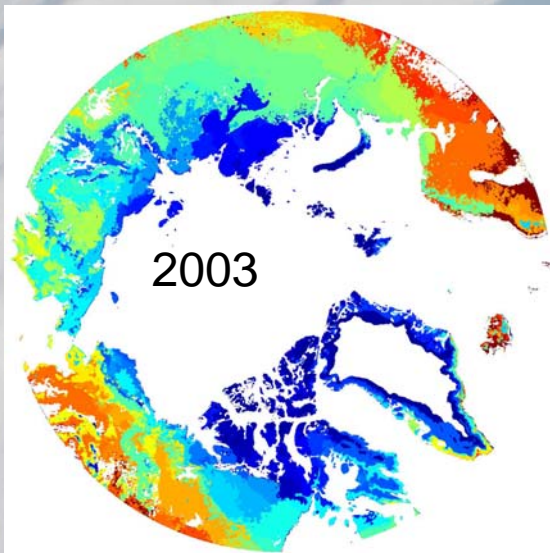
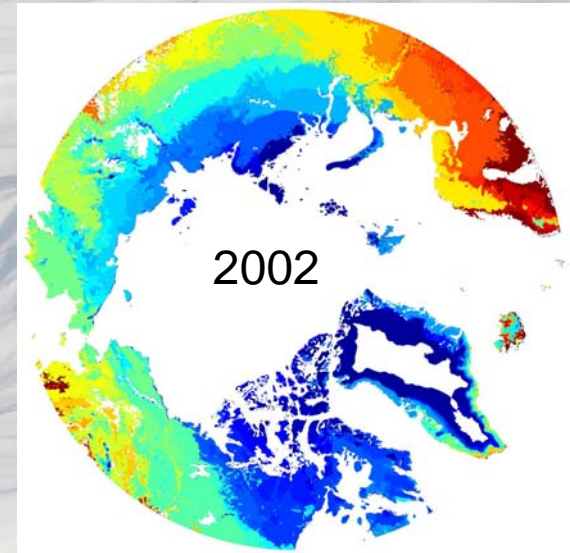
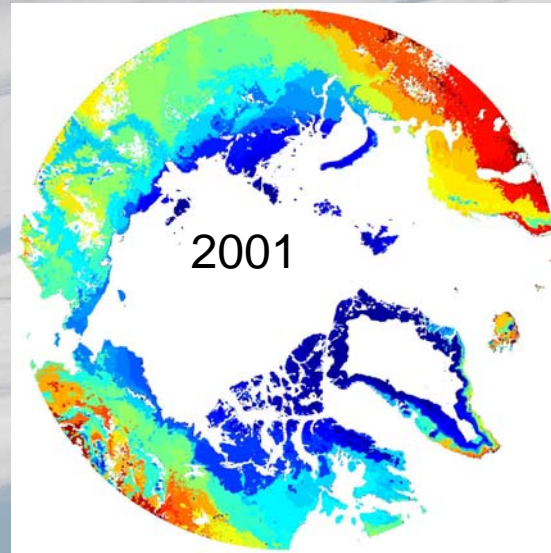
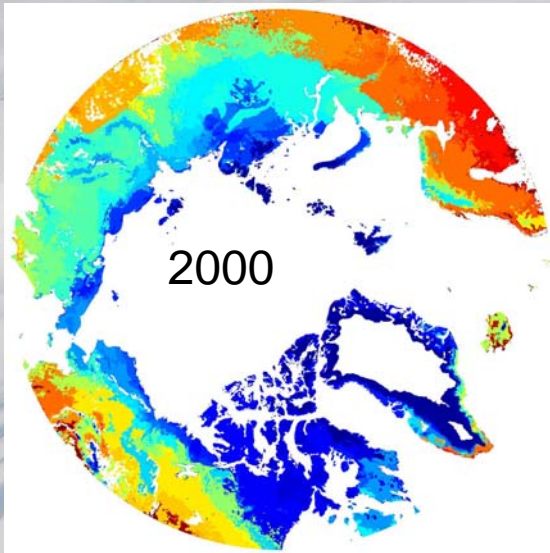
- Brown, R., C. Derksen and L. Wang, 2007: Assessment of spring snow cover duration variability over northern Canada from satellite datasets. *Remote Sensing of Environment*, **111**, 367-381.
- Wang, L. Sharp, M. Rivard, B. Marshall, S. and Burgess, D., 2005: Melt season duration on Canadian Arctic ice caps, 2000-2004. *Geophysical Research Letters*, **32**, doi:10.1029/2005GL023962.
- Wang, L., C. Derksen and R. Brown, 2007: Detection of Pan-Arctic Terrestrial Snowmelt from QuikSCAT, 2000 – 2005. *Remote Sensing of Environment* (submitted)

Application of QuikSCAT for mapping spring snow cover – mean spring (MAMJJ) snow cover duration, 2000-2004.

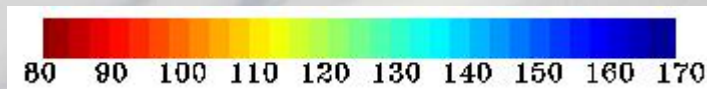


Source: Brown et al., 2007

Application of QuikSCAT for monitoring pan-Arctic melt onset, 2000 - 2005



Julian Day



Source: L. Wang, EC

An aerial photograph of a vast desert landscape featuring numerous sand dunes. The dunes are characterized by their smooth, undulating surfaces and distinct, dark shadows cast by the wind, creating a rhythmic pattern of light and dark across the terrain. The overall color palette is a range of light to medium beige and tan. Centered over the middle of the image is the text "In Situ Data..." in a bold, black, sans-serif font.

In Situ Data...

Daily Snow Depth observations, ~1950->

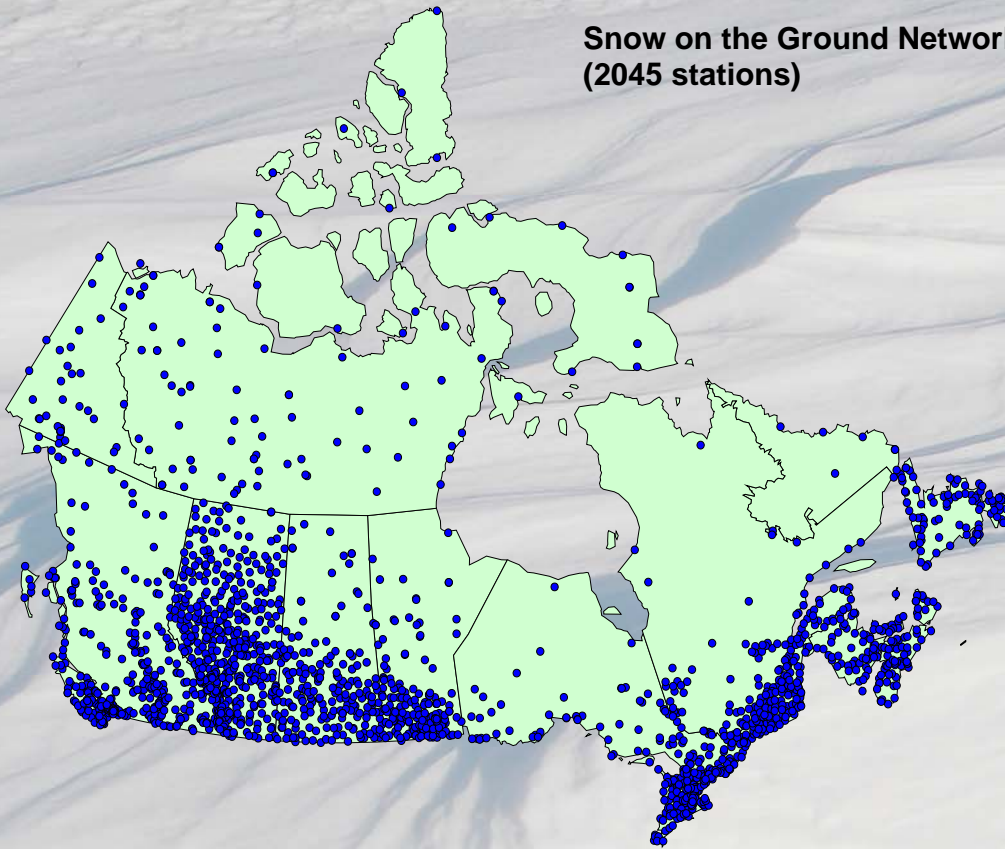
- daily ruler measurements of snow depth have been made at synoptic stations since ~1950; program expanded to climate stations in 1980 (see network map next page); daily snow depths prior to 1950 largely reconstructed from daily temperature and precipitation observations by Brown and Braaten (1998)
- only 14 stations in Quebec have consistent observed daily snow depth observations over the 1960-2006 period for investigating variability and change in snow depth (see over)
- 9 stations in southern Quebec have more-or-less complete reconstructed data from 1915 to assess variability and change in snow cover duration
- applications: climate monitoring, model evaluation, ecological studies, forest fire risk, permafrost studies...
- data up to 2003-04 are available from the latest update of the Canadian Snow CD (www.ccin.ca); after 1997 the Quebec MDDEP daily snow depth archive contains additional data not included in the Environment Canada national climate archive (eric.larrivee@mddep.gouv.qc.ca)

References:

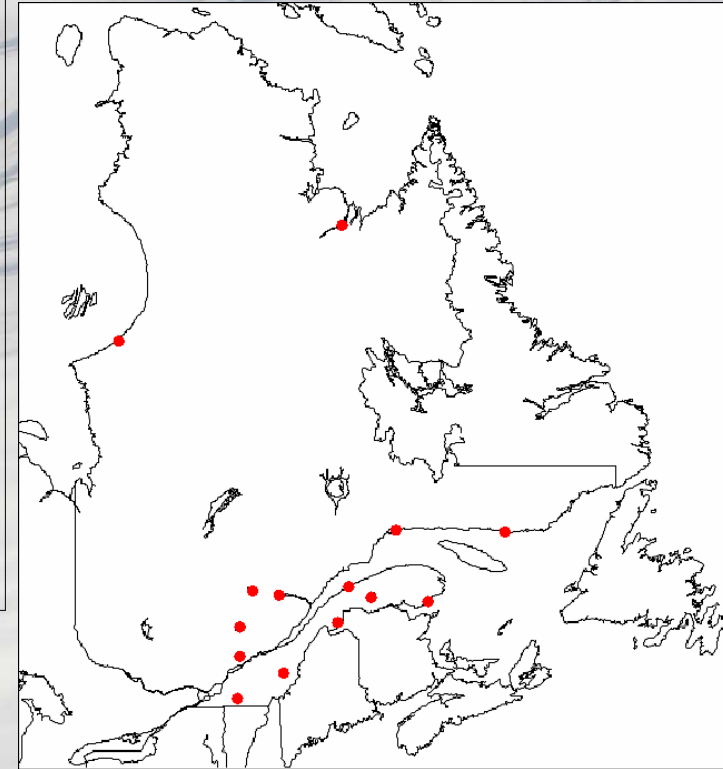
Brown, R.D. and R.O. Braaten, 1998: Spatial and temporal variability of Canadian monthly snow depths, 1946-1995. *Atmosphere-Ocean*, **36**: 37-45.

Meteorological Service of Canada (2000), Canadian Snow Data CD-ROM. CRYSYS Project, Climate Processes and Earth Observation Division, Meteorological Service of Canada, Downsview, Ontario.

**Snow on the Ground Network
(2045 stations)**

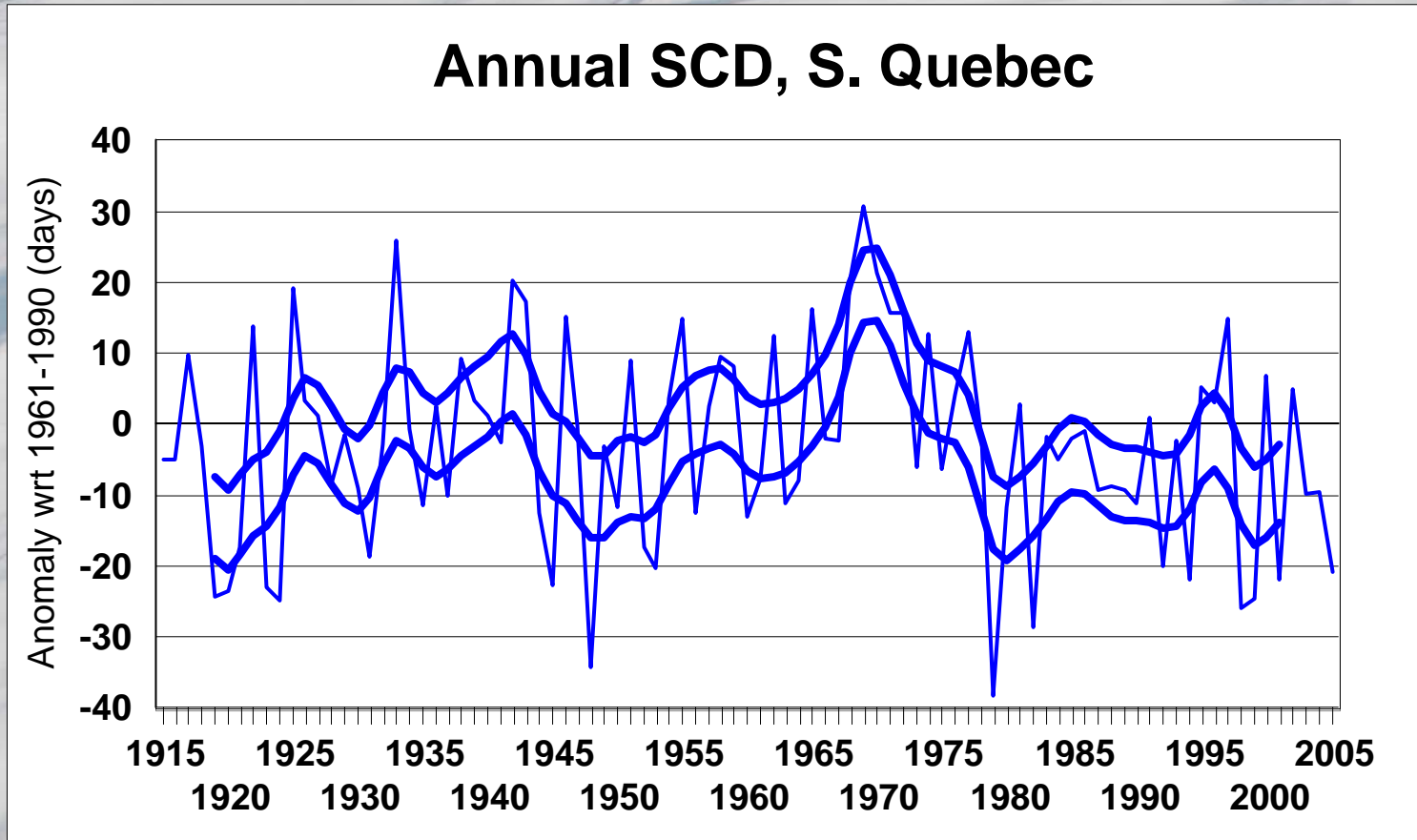


Daily snow depth observing network ~2002.



**Location of stations in Quebec with
at least 41 years of observed daily
snow depth data in the 1960-2006
period for analyzing variability and
change in snow depth**

Application of daily snow depth data for climate monitoring...



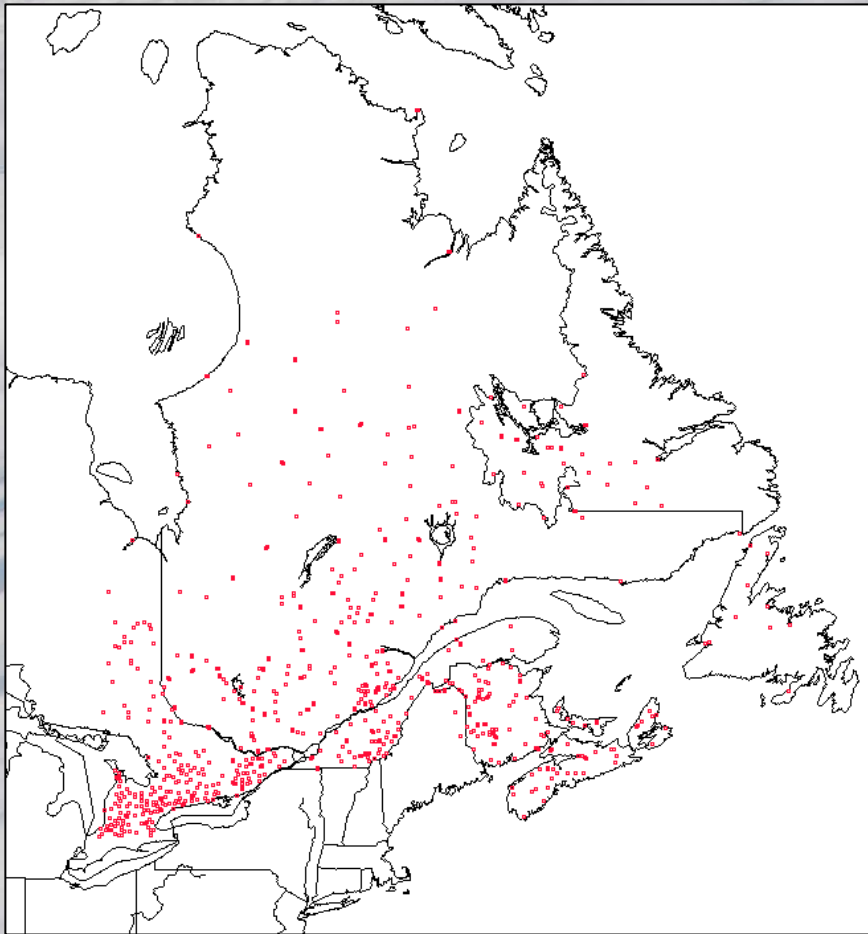
Regionally-averaged series of annual snow cover duration (SCD) for southern Quebec. The smoothed curves are 9-term binomial filtered values of the 95% confidence interval for the regional mean following Wigley et al. (1984). There is no trend in these data over the period 1915-2005.

Bi-weekly snow course observations, ~1940->

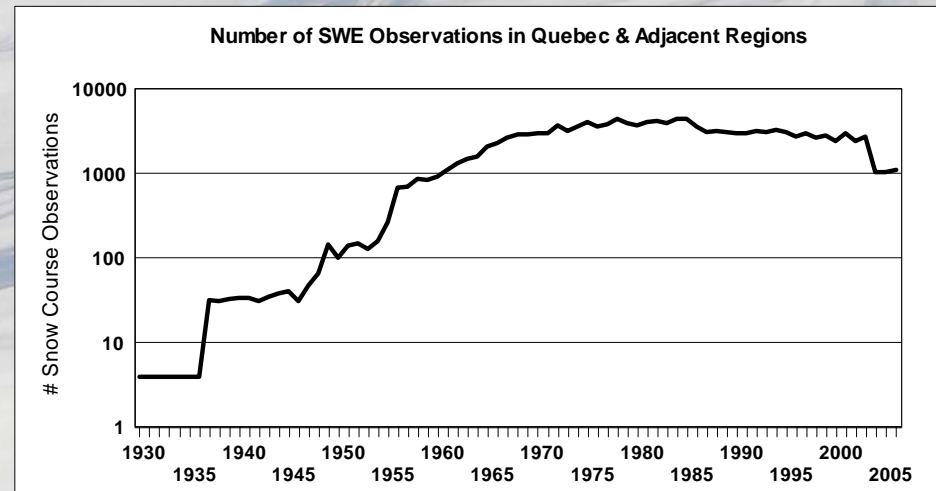
- Bi-weekly snow course observations are made in Quebec and surrounding provinces by provincial water resource agencies and hydroelectric companies for water resource operations and planning
- the two variables archived are mean SWE (mm) and depth (cm) taken over 5-10 survey points
- the number of snow course observations reached a peak in the 1970s and 1980s; the network has a southern bias with major data gaps over northern Quebec and the North Shore (see over)
- a national compilation of historical snow course data was provided by Environment Canada in 2000 (update available online at www.ccin.ca)
- this dataset is incomplete for Quebec and must be supplemented with the Quebec snow course dataset maintained by the MDDEP (contact: eric.larrivee@mddep.gouv.qc.ca)

References:

Meteorological Service of Canada (2000), Canadian Snow Data CD-ROM. CRYSYS Project, Climate Processes and Earth Observation Division, Meteorological Service of Canada, Downsview, Ontario.

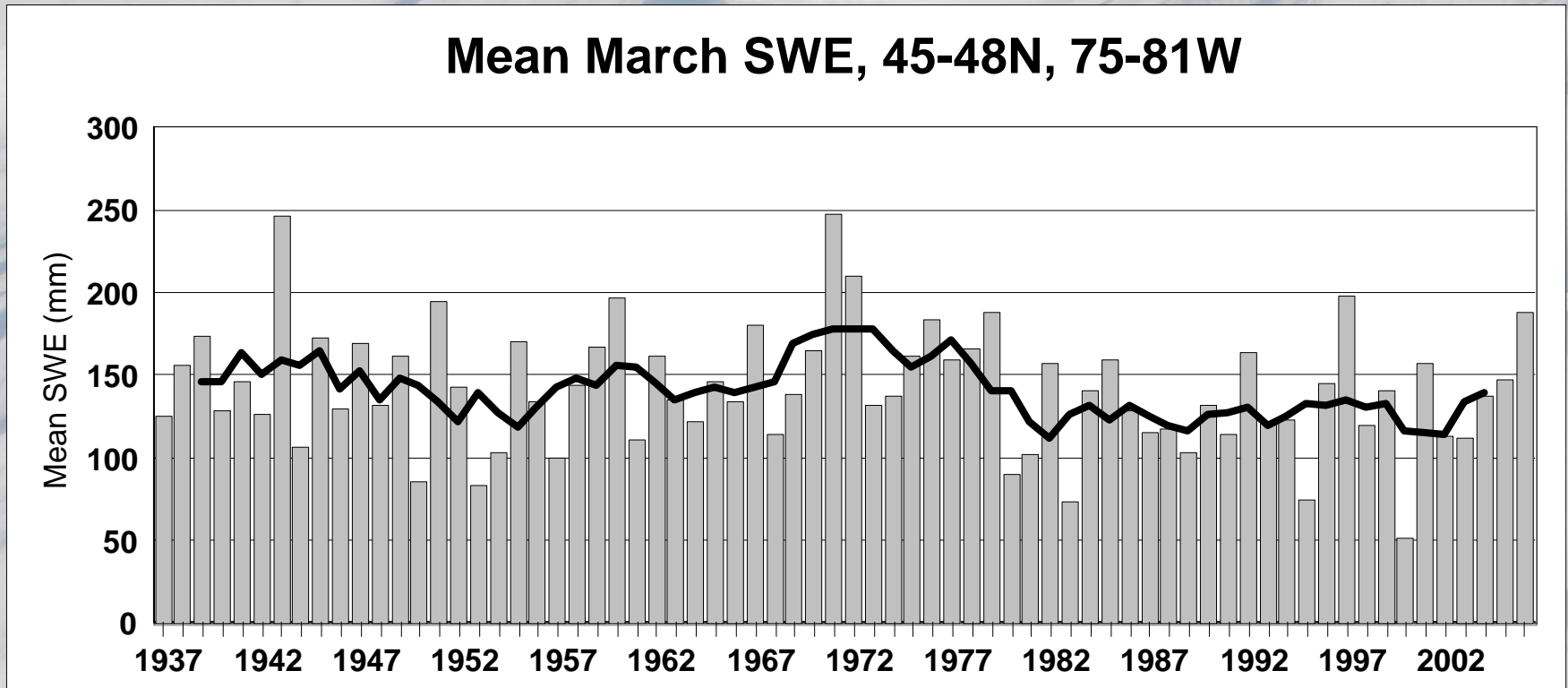


Location of snow courses with complete observations of March 01 SWE during the decade of the 1970s.



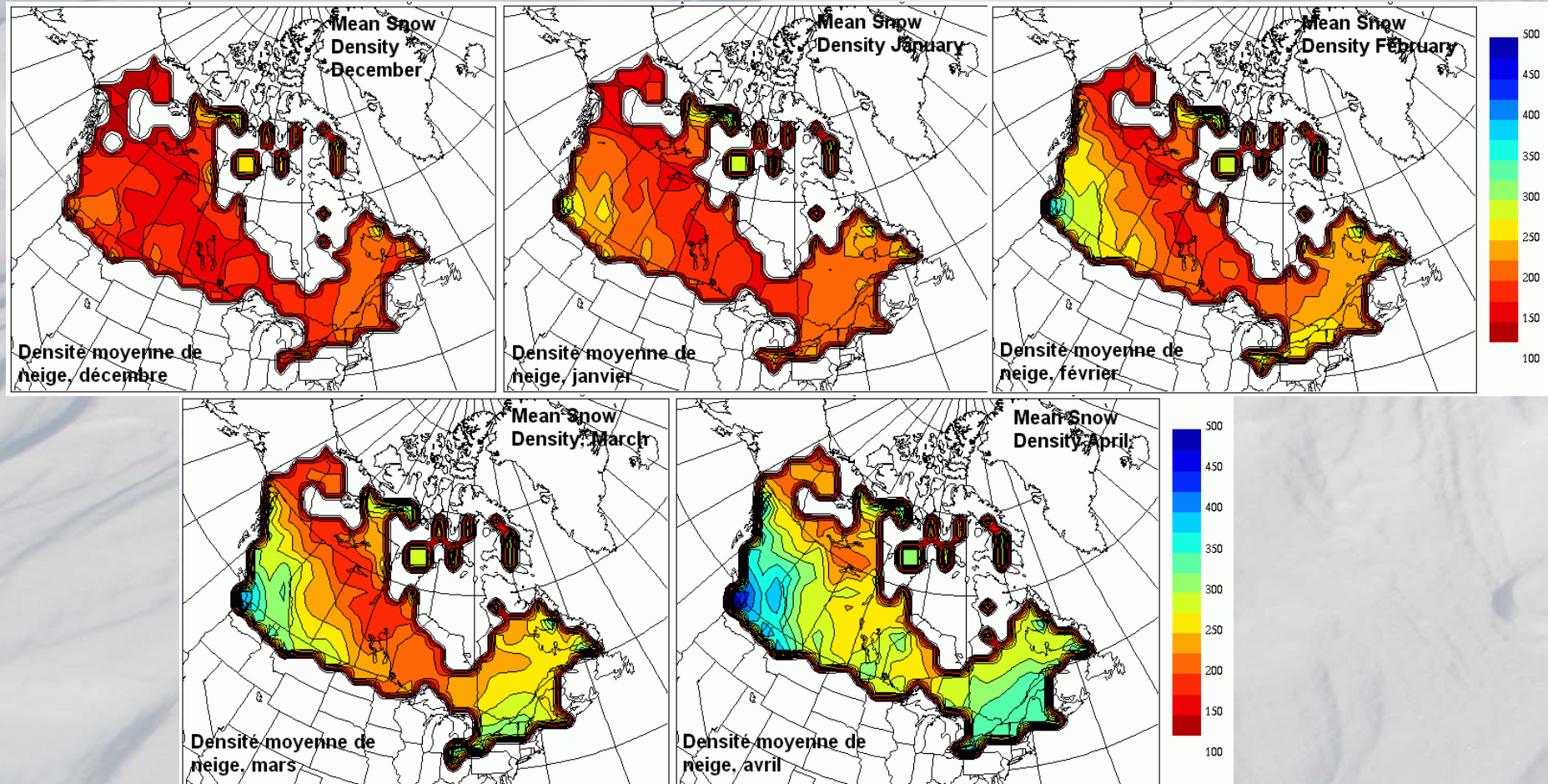
Annual number of snow course observations in Quebec and adjacent regions. Note the logarithmic scale on the y-axis.

Application of the snow course data set for climate monitoring...



Historical variability in regionally-averaged March SWE over southern Ontario and Quebec from 1937 to 2006. SWE values decreased after ~1980 but the trend is **not significant** over the 70-yr period.

Application of snow course data set to generate maps of monthly mean snow density ($\text{kg}\cdot\text{m}^{-3}$) over the 1966-1985 period



Spatially-averaged snow density from Canadian snow course observations, 1961-2000 for the snow-climate classes defined by Sturm et al (1995)

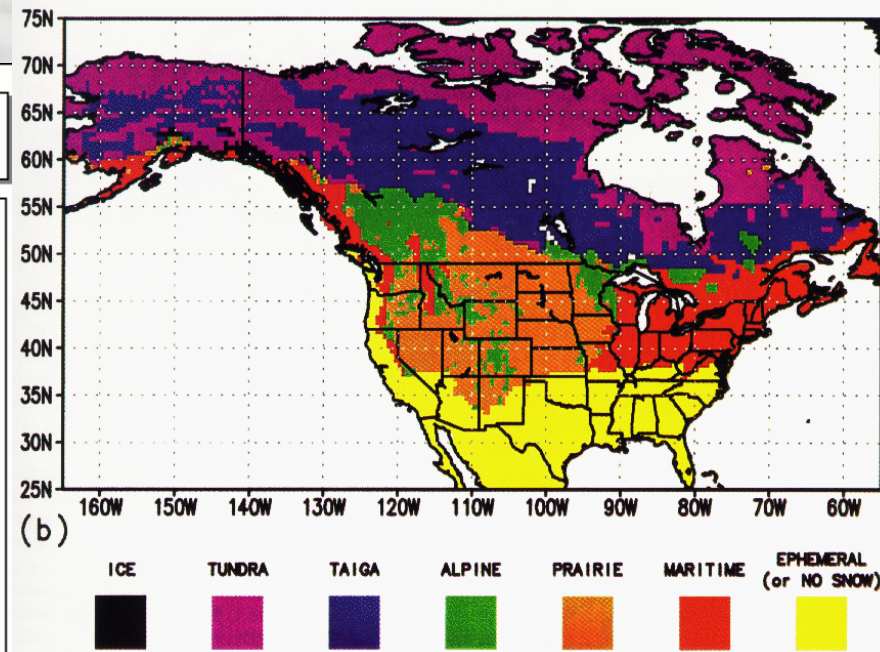
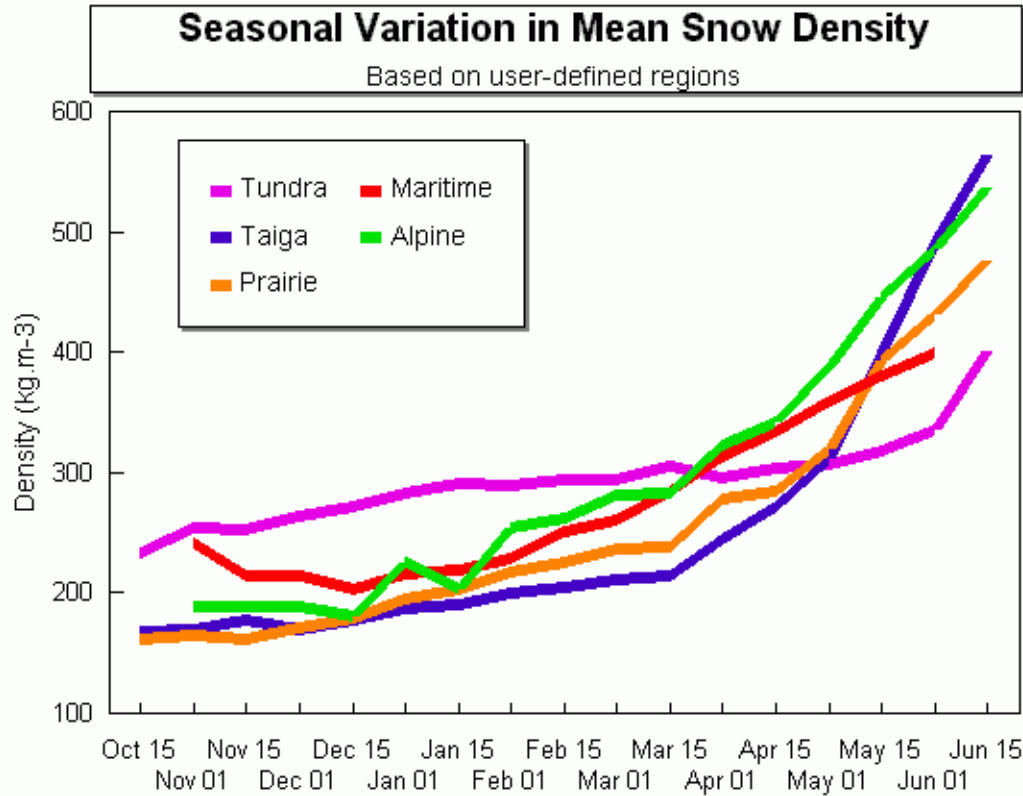


FIG. 10. Snow class distribution based on climate variables in (a) Eurasia and (b) North America.

Sturm et al, (1995) snow climate classes (*J. Clim.*, **8**, 1261-1283)

Mean seasonal variation in Canadian snow density for Sturm et al., (1995) snow climate classes, 1961-2000

An aerial photograph of a vast desert landscape, likely a sand dune field. The terrain is characterized by numerous small, rounded dunes and larger, more prominent ridges. The lighting creates long, dark shadows that stretch across the sand, highlighting the undulating topography. The overall color palette is a range of light to medium beige and tan tones.

Analyzed and/or reconstructed...

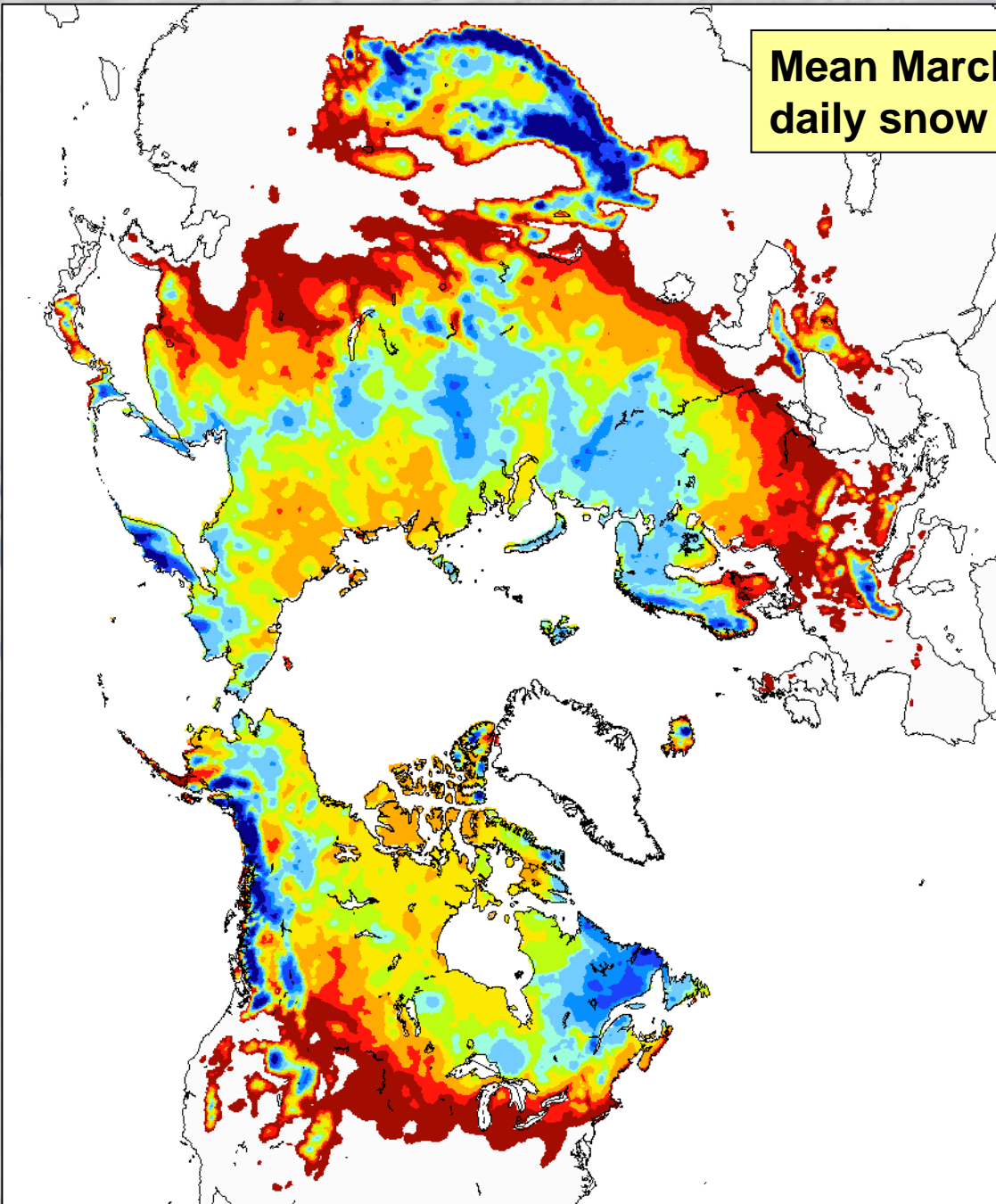
CMC daily operational global snow depth analysis, 1998->

- objectively analyzed values of daily snow depth on an $\sim 1/3^\circ$ grid over the globe based on the method of optimal interpolation (Brasnett, 1999)
- uses all available real-time snow depth reports i.e. synoptic reports, meteorological aviation reports and special aviation reports
- analysis updated every 6 hours using the method of optimum interpolation
- a background field is generated by a simple snow accumulation and melt (degree-day) routine using forecast precipitation and temperature from the CMC forecast model; precipitation is assumed to be snow if the analyzed screen-level temperature is $< 0^\circ\text{C}$
- the error correlations used in analysis have e-folding distances of about 120 km horizontally and 800 m vertically; the vertical correlation is taken into account in the interpolation of screen-temperatures to the $1/3^\circ$ grid.
- data archived at CMC; R. Brown has extracted all the daily files from 1998 to 2006 and has computed the monthly means and monthly climatology over the NH from 1999-2006 (see over ross.brown@ec.gc.ca)
- estimated SWE values are also available based on a density look-up table derived from snow course observations for the Sturm et al. (1995) snow-climate classes

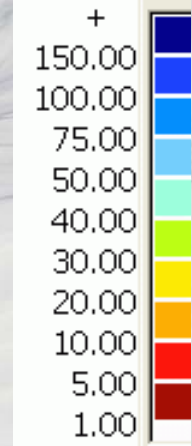
References:

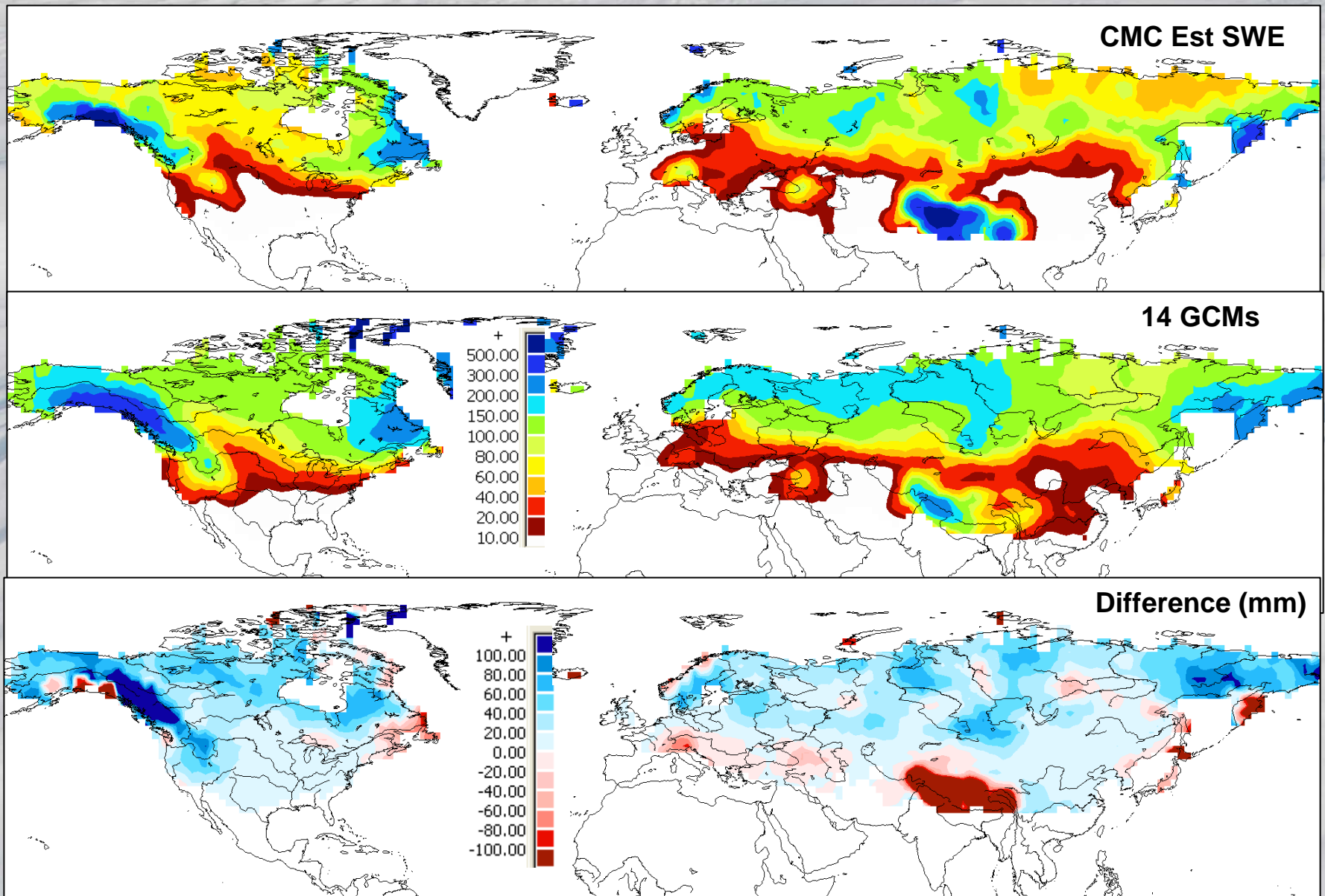
Brasnett, B., 1999: A global analysis of snow depth for numerical weather prediction. *J. Appl. Meteorol.*, **38**, 726-740.

**Mean March snow depth from CMC
daily snow depth analyses, 1999-2006**



Snow
Depth (cm)





Comparison of CMC estimated mean monthly max SWE for 1999-2006 with the average from 14 GCMs used in IPCC AR4 for the 1970-1999 reference period. On average the models overestimate annual maximum monthly SWE by 16 mm over NH land areas north of 30N.

Brown et al. (2003) daily snow depth and SWE analysis, 1979-1997

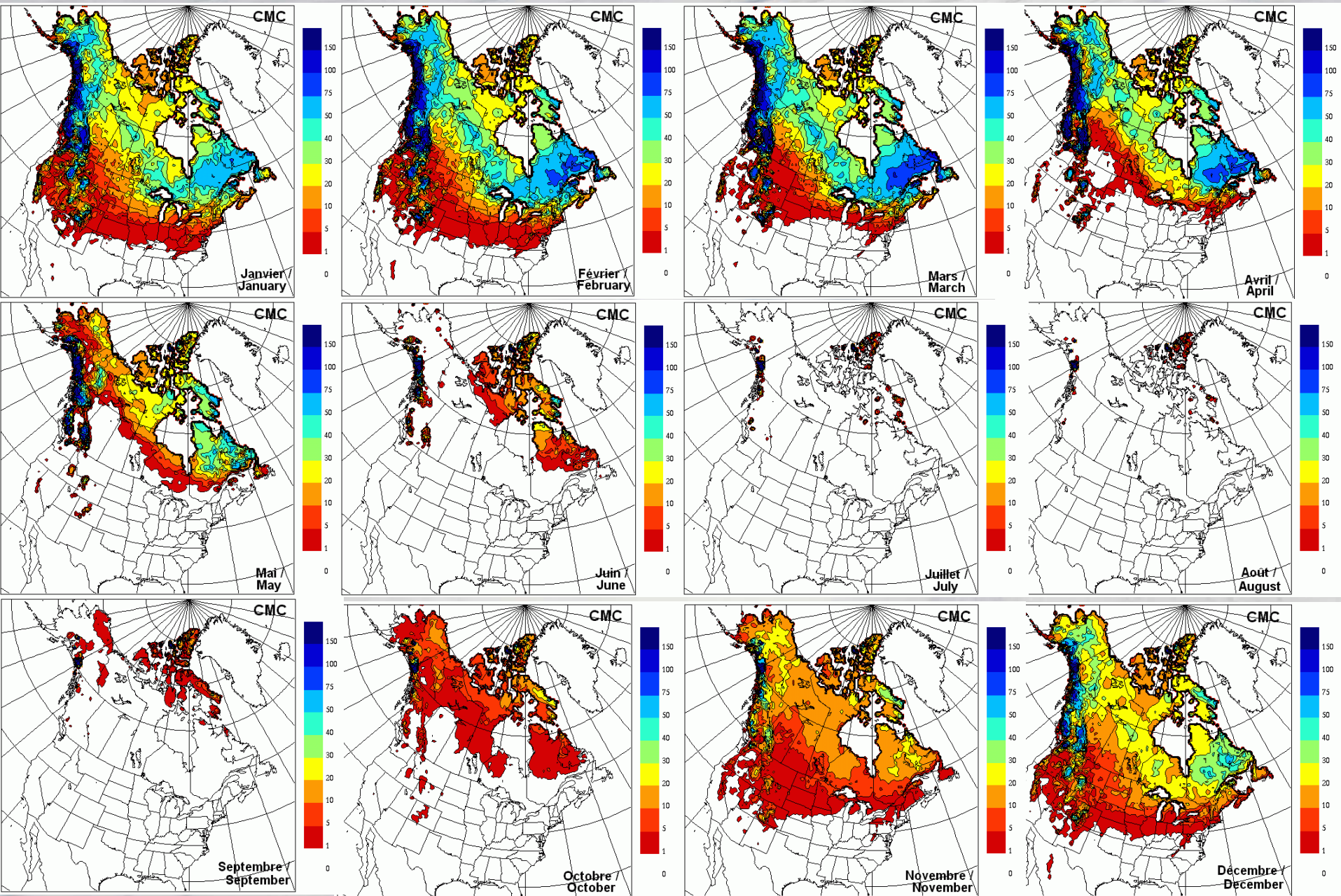
- objectively analyzed values of daily snow depth on ~25 km grid over North America based on the snow depth analysis scheme used at CMC (Brasnett, 1999)
- historical daily snow depth observations from Canada and US as input
- background field generated by simplified snowpack model driven by 6-hourly temperature and precipitation from ERA-15
- SWE values estimated using snow density simulated from empirical snow aging expressions in the snowpack model
- product agreed well with independent observations in data rich areas; less confidence over more data sparse regions north of ~55°N
- applications: evaluation of climate and hydrological models, lake ice and permafrost modelling, snow cover-climate interactions
- data archived as daily values, monthly means and climatological means for both depth and SWE; available from ross.brown@ec.gc.ca

References:

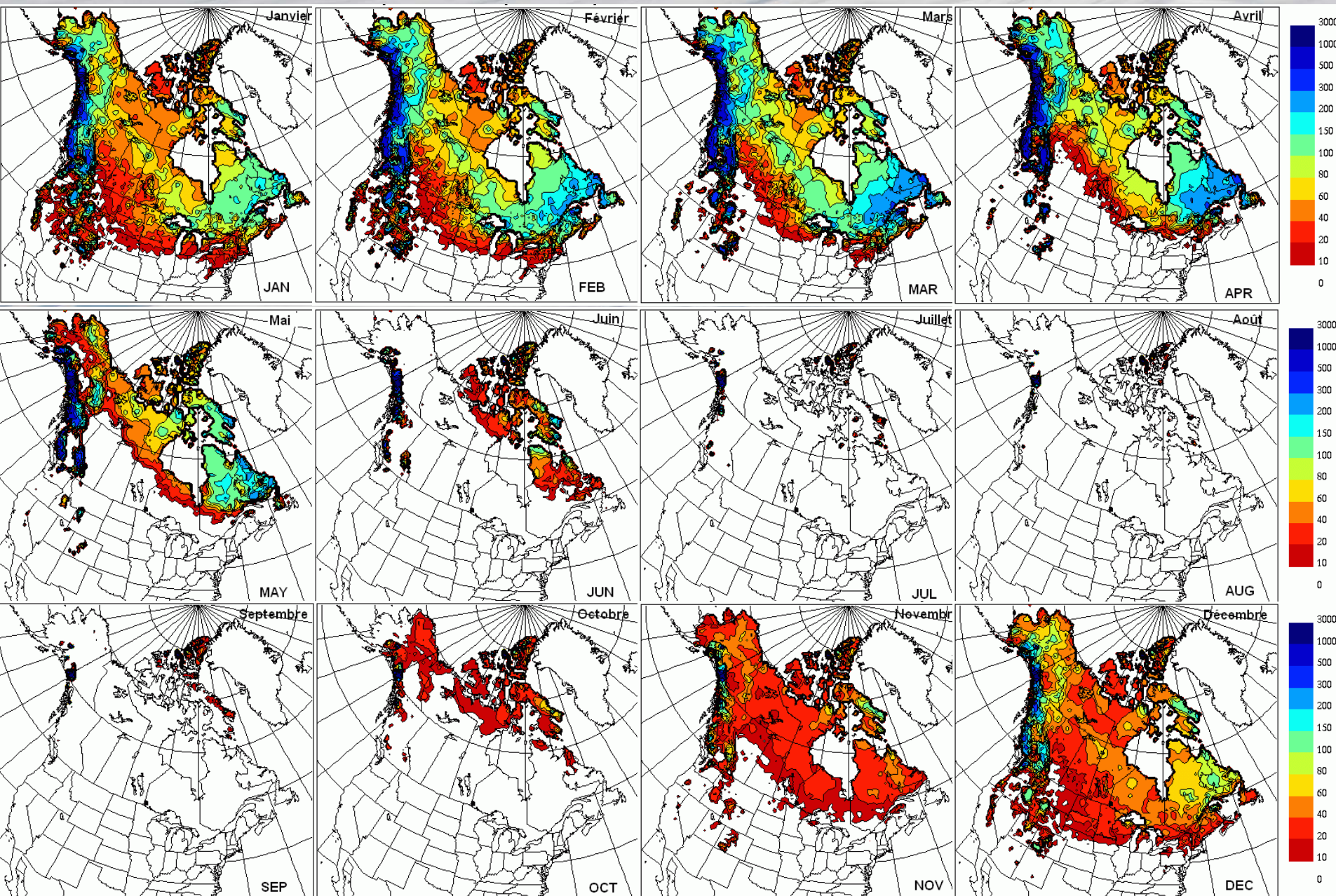
Brasnett, B., 1999: A global analysis of snow depth for numerical weather prediction. *J. Appl. Meteorol.*, **38**, 726-740.

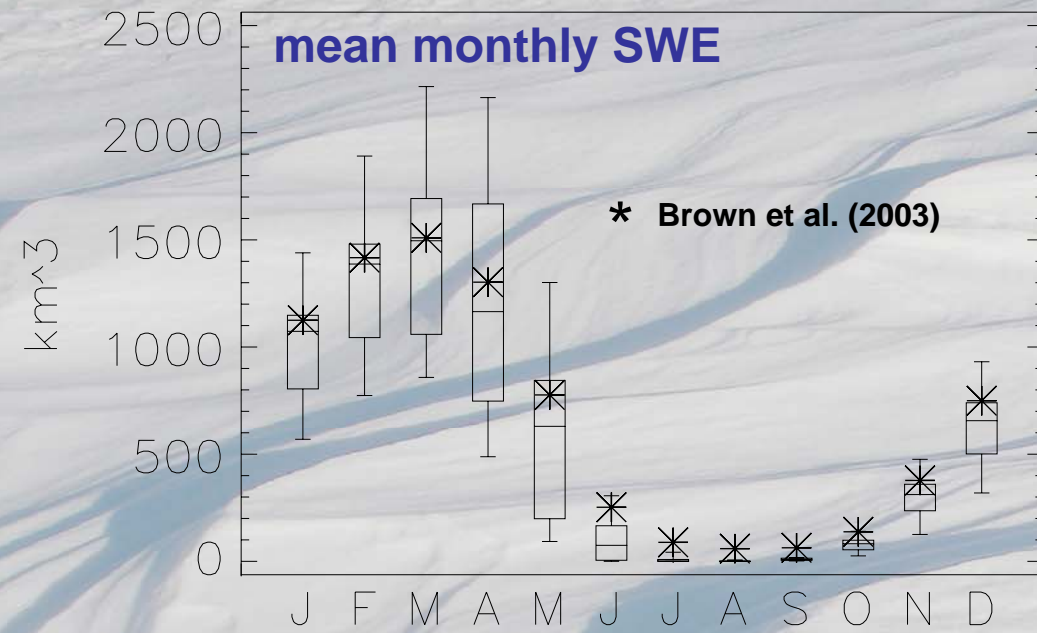
Brown, R.D., B. Brasnett and D. Robinson, 2003: Gridded North American monthly snow depth and snow water equivalent for GCM evaluation. *Atmosphere-Ocean*, **41**: 1-14.

Mean monthly snow depth (cm), 1979-1997 from Brown et al. (2003) analysis



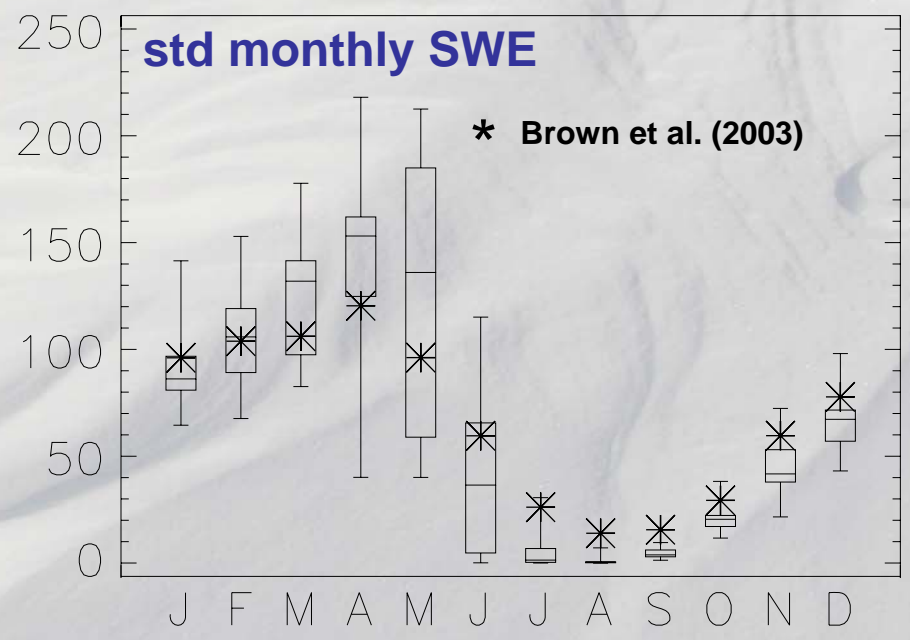
Mean monthly SWE (mm), 1979-1997 from Brown et al. (2003) analysis





Application of the B2003 dataset to evaluate the representation of SWE over North America by 18 GCMs in the AMIP2 experiment

Frei et al. (2003), *JGR Atmos.*, **108**(D12), 4369.



Reconstructed daily snow depth and SWE, 1948-2005 (NCEP+CANGRD)

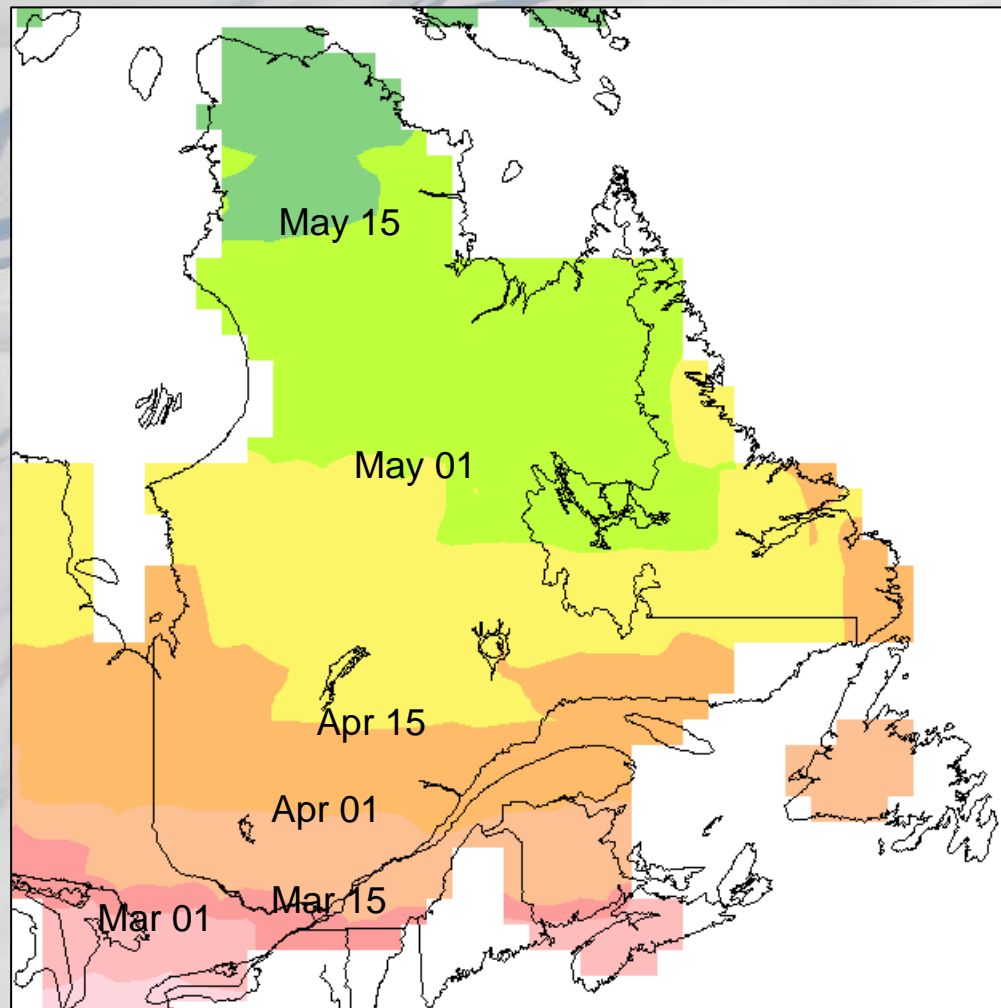
- daily snow depth and density simulated using temperature-index snowpack model of Brown et al. (2003)
- model driven with 6-hourly values of NCEP reanalysis temperature and daily total precipitation derived from CANGRD monthly totals (Milewska et al., 2005)
- model run at a resolution of 50 km over Quebec (there are some missing points along the North Shore where there are no precipitation data) for the period 1948-2005
- precipitation and melt were empirically adjusted to provide unbiased simulation of snow cover over the central SWE maximum zone of Quebec
- applications: spatial-temporal analysis of SWE over Quebec, SWE-climate interactions
- dataset archived as daily values of snow depth and density; available from ross.brown@ec.gc.ca at the end of 2007

References:

Brown, R.D., 2007: Snow cover variability and change in Quebec (in prep)

Milewska, E., R.F. Hopkinson and A. Niitsoo, 2005: Evaluation of Geo-Referenced Grids of 1961 – 1990 Canadian Temperature and Precipitation Normals. *Atmosphere-Ocean*, **43**(1): 49-75

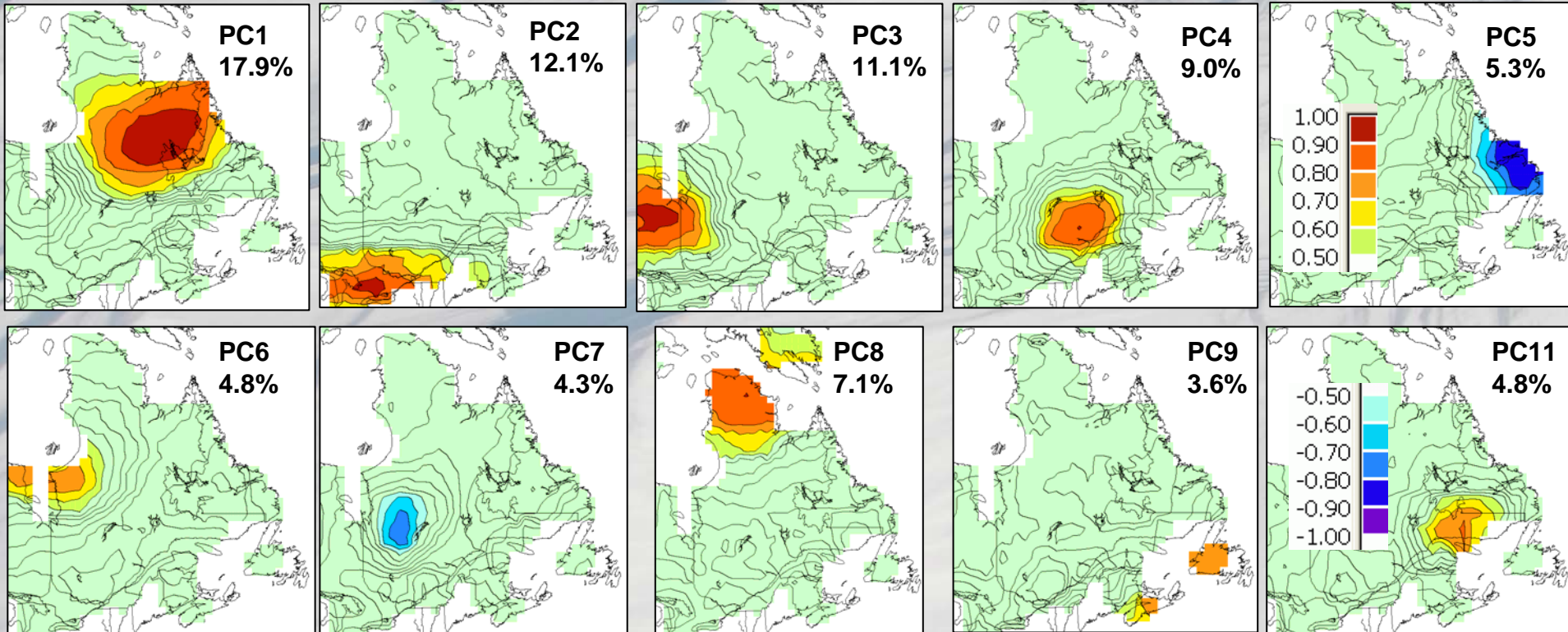
Application of the NCEP+CANGRD SWE reconstruction to estimate the mean date of annual maximum SWE (1948-2005)



PC Loadings for Annual Max SWE from NCEP+CANGRD SWE reconstruction, 1948-2005

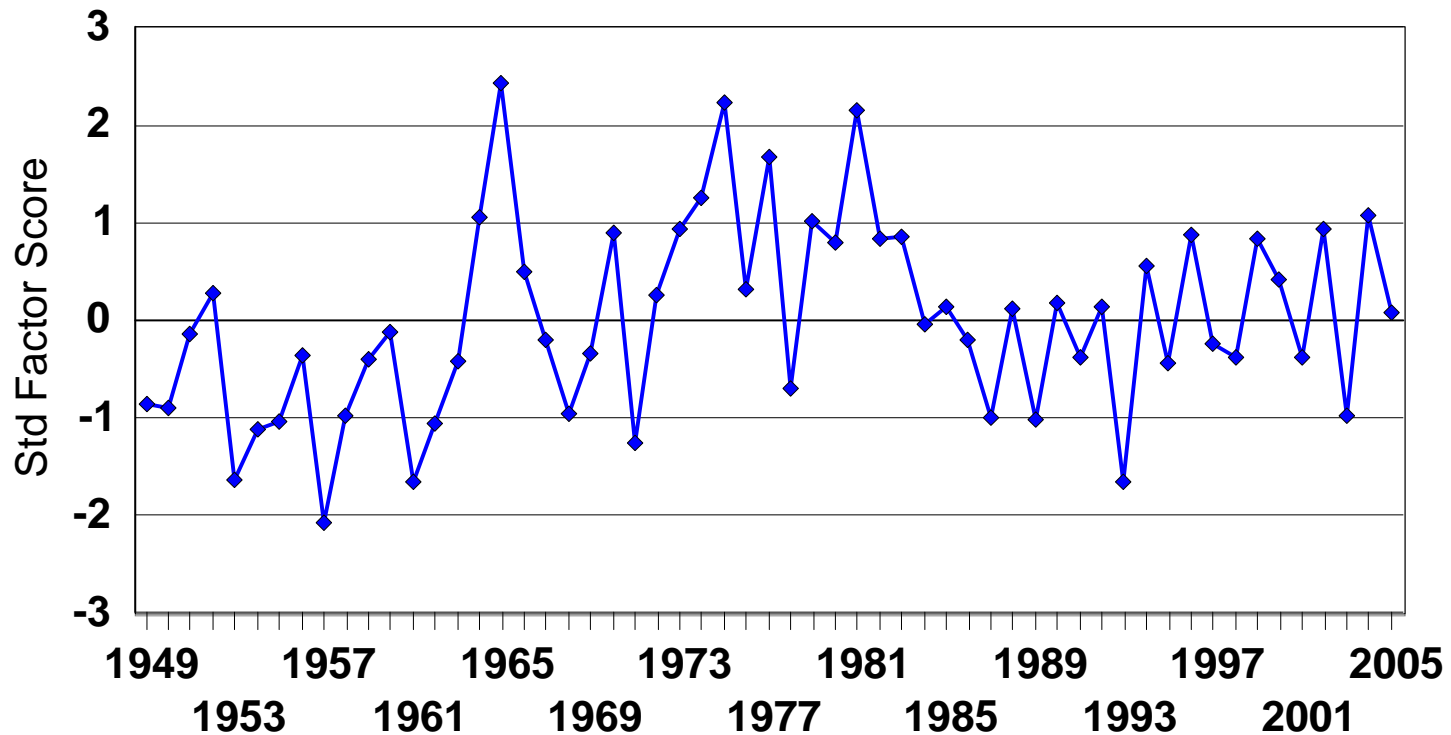
Components explaining > 3% variance

10 components explain 80% of the total variance



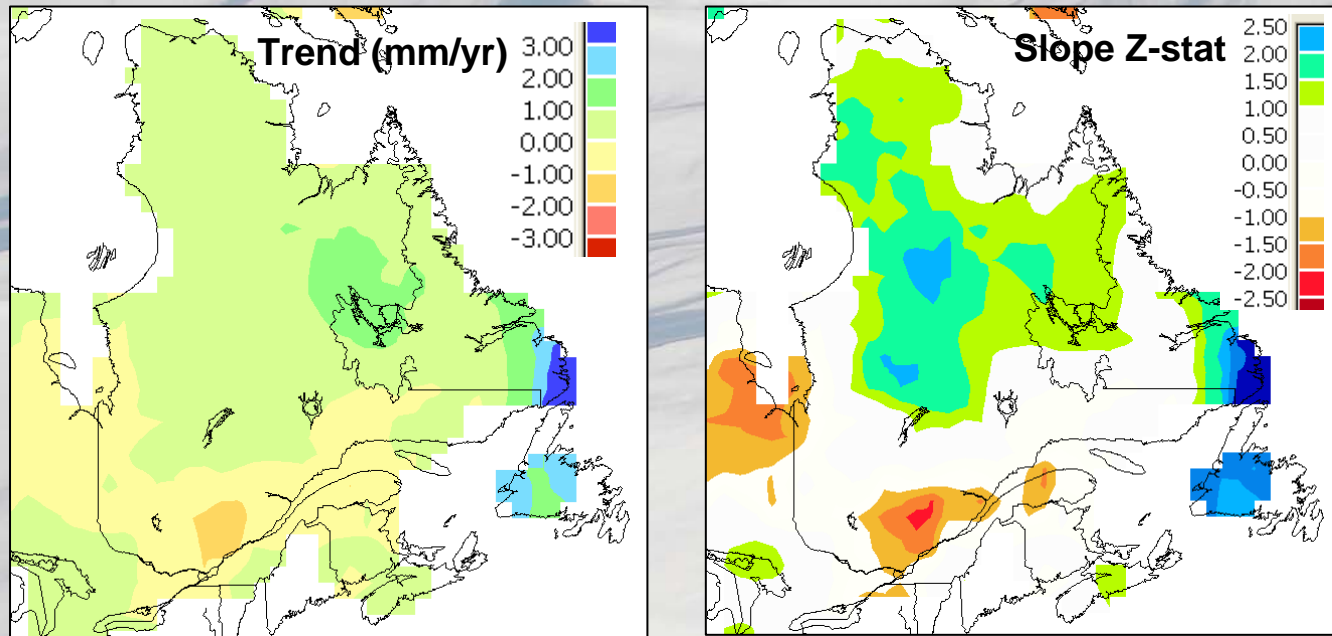
Results indicate that interannual variability in annual maximum SWE is quite regional in character with the largest variance (17.9%) explained by SWE fluctuations over north-central Quebec.

Temporal variability in EOF1 from reconstructed SWE



- The dominant PC from the SWE reconstruction (north-central Quebec) shows evidence of a gradual increase with a probability of $p=0.056$ (almost statistically significant!)
- Only PC9 (NFLD + Nova Scotia) showed a significant ($p=0.05$) trend (increase in SWE)

Trend in annual maximum SWE 1949-2005 (mm/yr) from NCEP+CANGRD reconstruction



Results indicate significant reductions in SWE over parts of southern Quebec and significant increases over central-northern Quebec and NFLD

High resolution (10-km) kriged SWE maps for Quebec and adjacent area

- Ouranos-IREQ project in progress to generate 10-km gridded SWE values over Quebec based on the method of kriging with external drift (KED) (Tapsoba et al., 2005)
- uses observed snow course and snow depth data with surface elevation and estimated SWE (from NCEP+CANGRD reconstruction) as external drift variables
- KED maps of SWE on 10-km grid over eastern Canada have been generated from 1970-2005 for 1st and 15th of each month from December to June
- the gridded values will be used to evaluate snow in the CRCM and to study the spatial and temporal variability of in SWE over Quebec
- the approach also has operational applications (e.g. use real-time kriged SWE with SWE climatology to identify and monitor SWE anomalies)

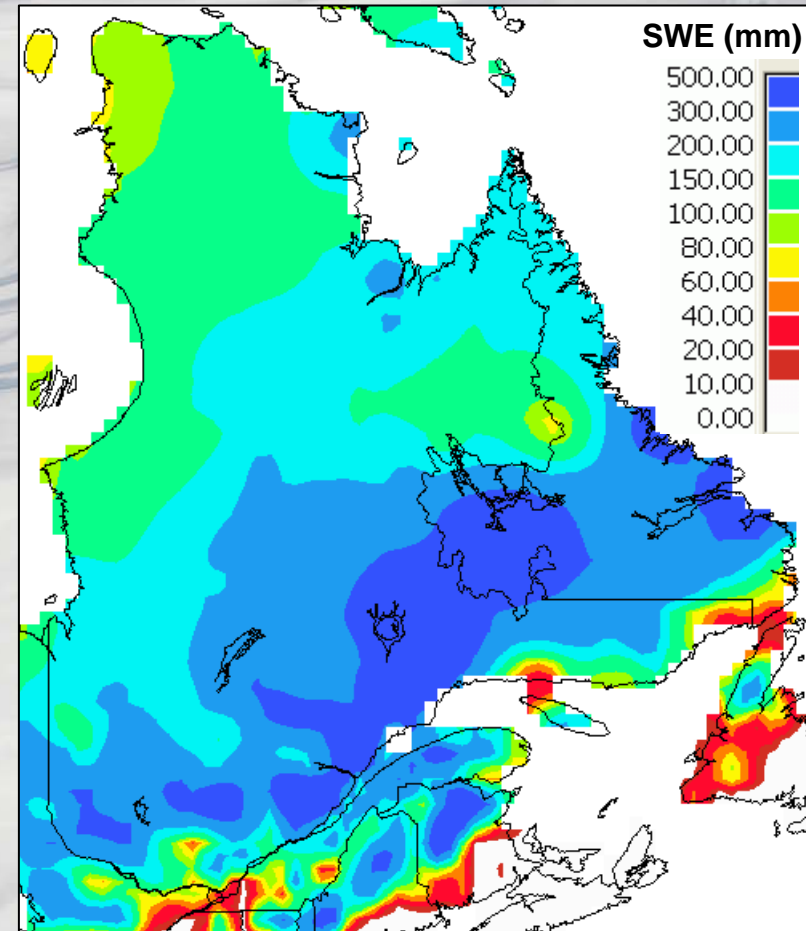
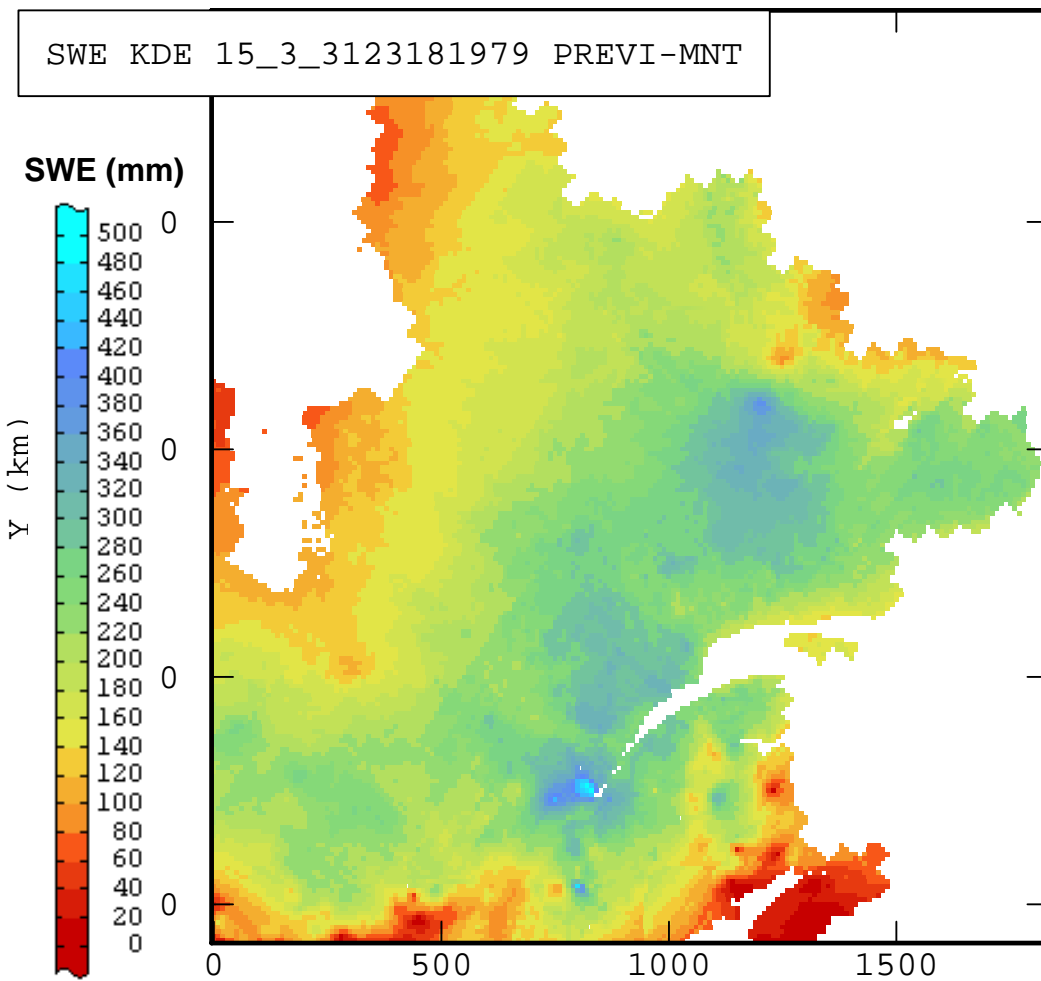
References:

Brown, R.D. and D. Tapsoba, 2007: Improved Mapping of Snow Water Equivalent over Quebec. Proc. 2007 Eastern Snow Conference, St. John's, NFLD, May 28 – June 01, 2007 (in press).

Tapsoba, D, Fortin V, Anctil F, Haché M. 2005. Apport de la technique du krigeage avec dérive externe pour une cartographie raisonnée de l'équivalent en eau de la neige : Application aux bassins de la rivière Gatineau. *Can. J. Civil Engineering* **32**, 289-297.

Tapsoba, D. and R.D. Brown, 2008: The spatio-temporal characteristics of SWE over northeastern North America – results from a new 10-km gridded SWE dataset. (in prep)

Preliminary results: Example of 10-km kriged SWE map for March 15, 1979 (D. Tapsoba)



- KED method does not smear obs SWE anomalies to the same extent as B2003
- improved detail in coastal regions and areas with complex topography

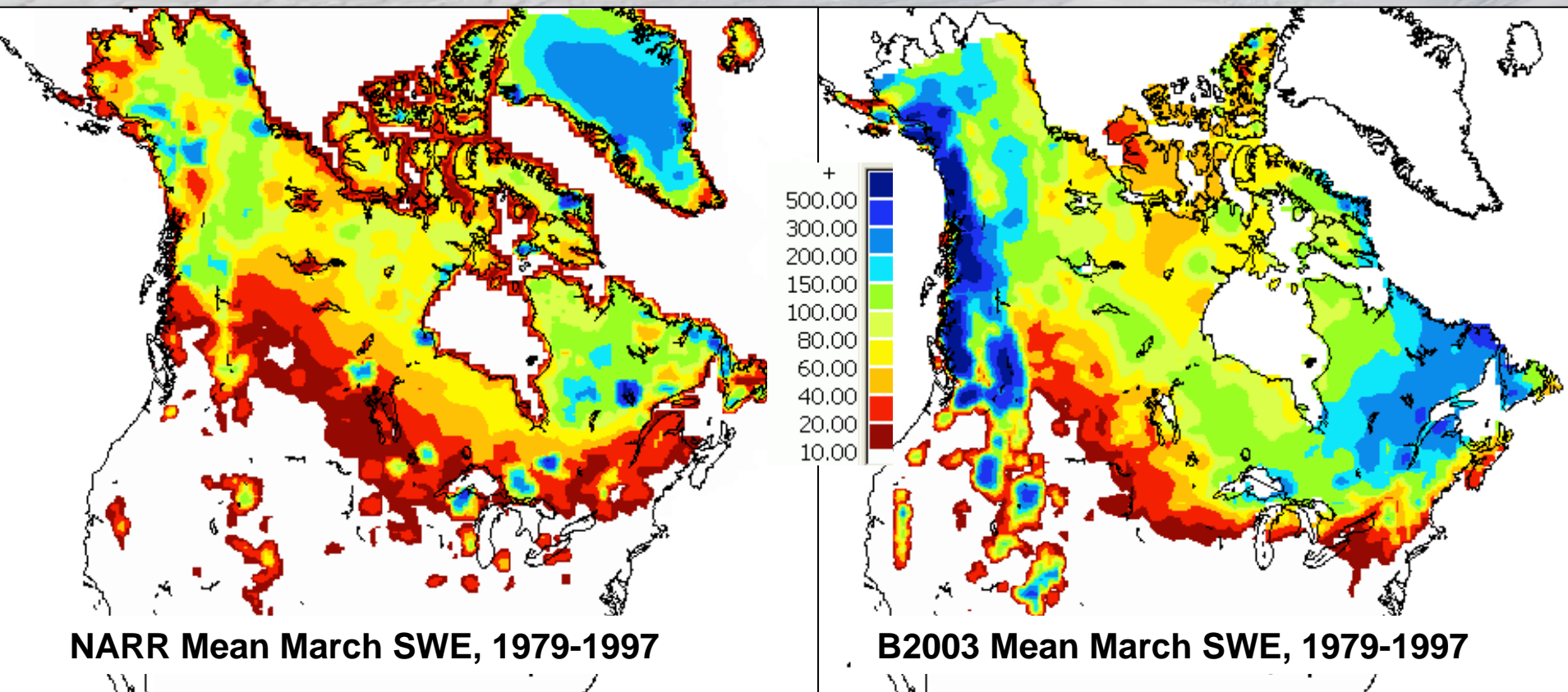
Comparison: SWE field for March 15, 1979 from Brown et al. (2003) (B2003)

North American Regional Reanalysis (NARR), 1979-2006

- Snow information (depth, SWE, snow cover fraction, albedo) are included in the NARR dataset based on the Noah land surface process model and assimilated snow depth information from the US Air Force daily snow depth analysis
- SWE is updated daily at the 0000 UTC analysis time from the US Air Force daily global snow depth analysis (47-km)
- The reanalysis is run at a resolution of ~32 km over North America
- Data are available at 3hr, daily, monthly and climatological (1979-2001) periods from <http://www.cdc.noaa.gov/cdc/data.narr.html#plot>
- These data have not yet undergone detailed evaluation over Quebec; the online documentation indicates the Noah model melts snow too quickly in the spring; a comparison of the March SWE climatology (over) suggests that NARR greatly underestimates SWE over the western Cordillera and Quebec.
- These data suffer from the same problem of sparse observations over northern latitudes noted by Brown et al. (2003)

References:

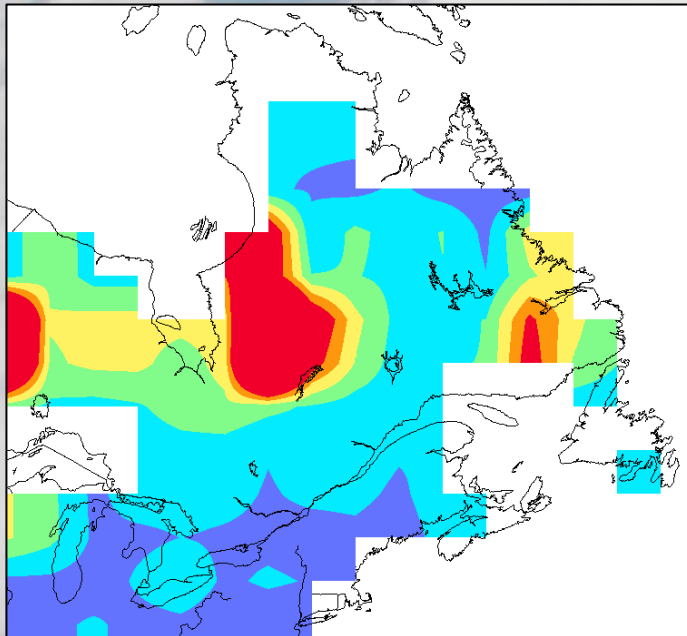
Mesinger, F., and coauthors, 2006: North American Regional Reanalysis. *BAMS*, **87**, 343-360



Comparison of mean March SWE (mm) for NARR (left) and Brown et al. 2003 (right). The two datasets have similar resolutions (~30 km) but the NARR greatly underestimates SWE over the western Cordillera and Quebec.

ERA-40 reanalysis, 1958-2002

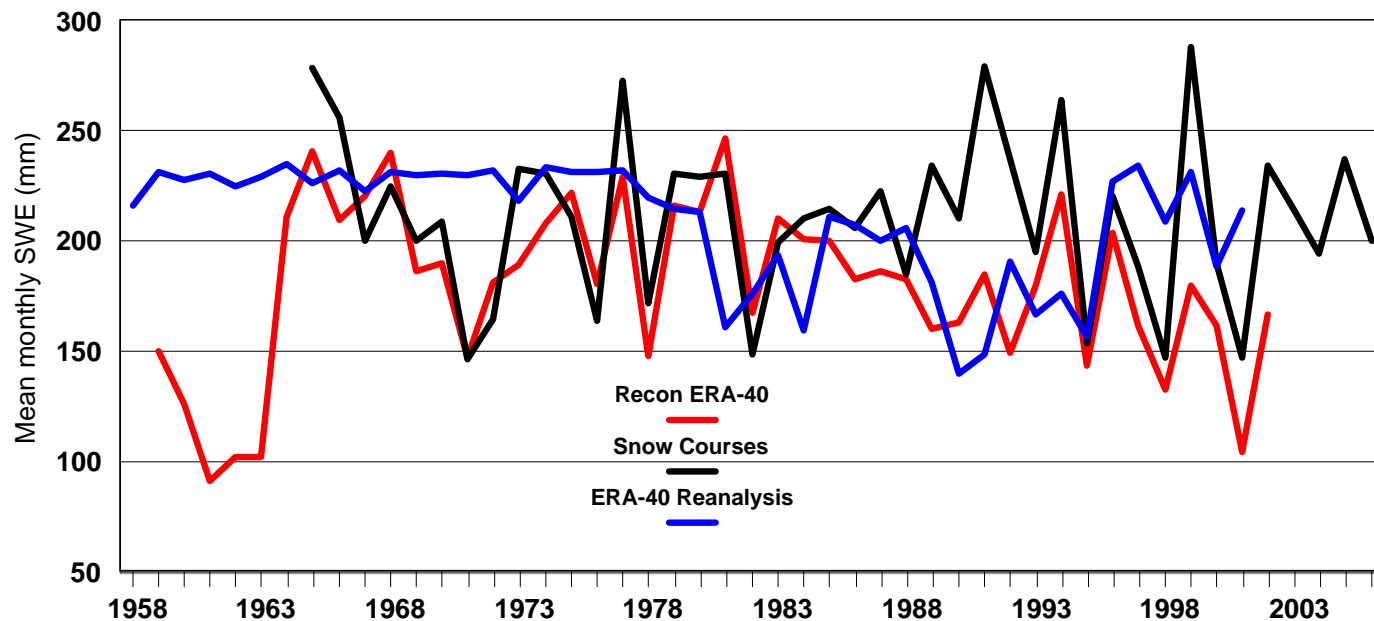
- SWE information is provided in the ECMWF ERA-40 reanalysis. This is based on assimilated snow depth information when and where this is available (highly variable in space and time)
- There are a number of documented bugs in the snow assimilation in ERA-40 and verification of the ERA-40 SWE data over Quebec revealed that SWE values are essentially constant at a number of gridpoints up to ~1980.
- The ERA-40 SWE climatology looks reasonable for Quebec but the user needs to be very careful if using the data to look at interannual variability in SWE.



Ratio of the standard deviation of March SWE in ERA40 for the periods before and after 1980. The area in red is affected by essentially constant SWE values prior to 1980.

Comparison of SWE values from ERA-40 (blue) with reconstructed values using 6-hourly temp and precip from ERA-40 (red) in the Brown et al. (2003) snow model, and observed values from snow course data (black). Values are spatial averages over an area that includes the La Grande Basin. The ERA-40 reanalysis SWE mean shows little agreement with the observations and there are major inconsistencies between it and the expected interannual variability of the ERA-40 snowpack (i.e. the reconstructed values)

Mean March SWE, La Grande Basin



An aerial photograph of a vast, snow-covered landscape. The terrain is characterized by a complex network of dark, winding shadows and ridges, suggesting a series of interconnected ridges and valleys. The overall appearance is that of a large-scale, natural or possibly human-made pattern in the snow. The text "Modelled snow cover information..." is overlaid in the upper left quadrant.

Modelled snow cover information...

GSWP-2 Land Surface Process model output, 1986-1995

- SWE is included as an output variable from 15 land surface process models run under the GSWP-2 experiment (Global Soil Wetness Project, Dirmeyer et al., 2006)
- models were forced with “hybrid” data that combined reanalysis and observational data over the 10-year period 1986-1995
- individual model and model-averaged output is provided on a 1° grid and can be downloaded from

<http://haneda.tkl.iis.u-tokyo.ac.jp/gswp2/>

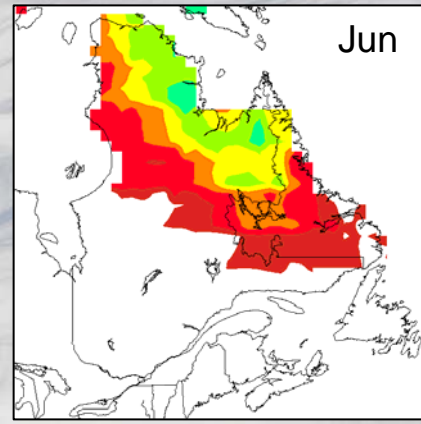
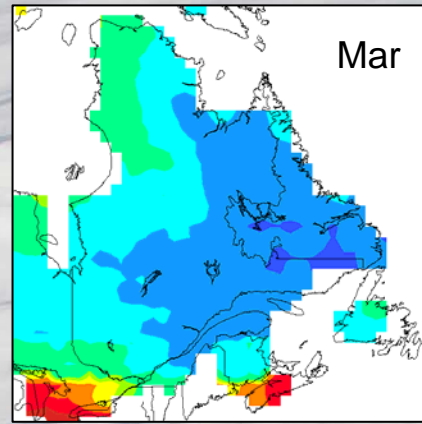
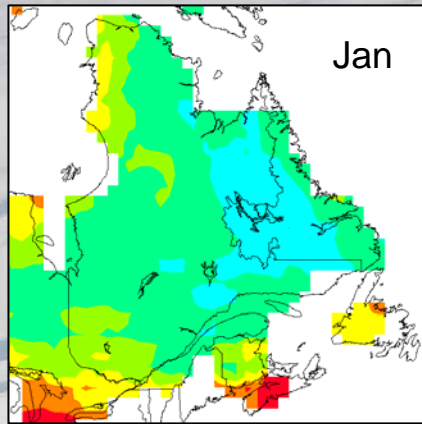
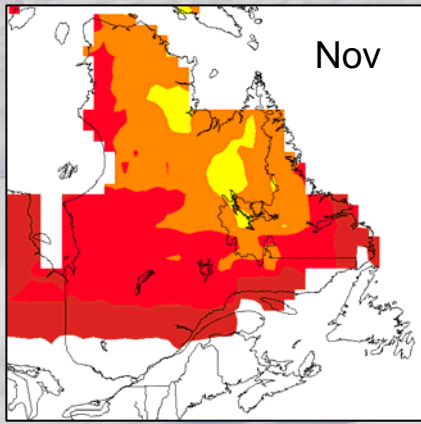
- a quick comparison of the model averaged SWE field over Quebec (see over) showed it agreed reasonably well with the Brown et al. (2003) and NCEP+CANGRD reconstructions although it appeared to melt snow off too quickly in the spring
- Dirmeyer et al. (2006) indicate there was only mediocre agreement between the models for most of the snow-related variables (SWE, snow fraction, snow albedo)

References:

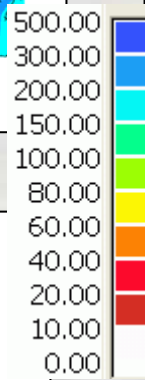
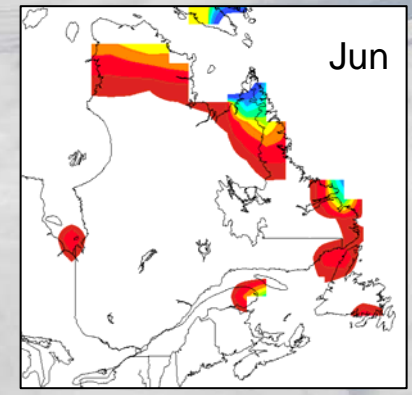
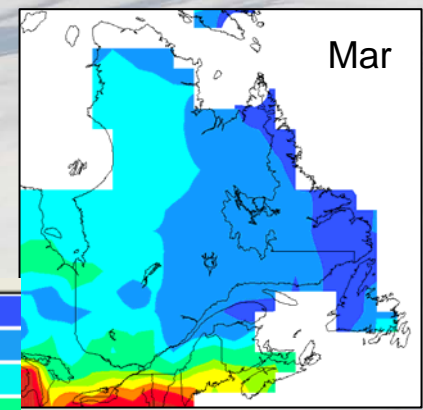
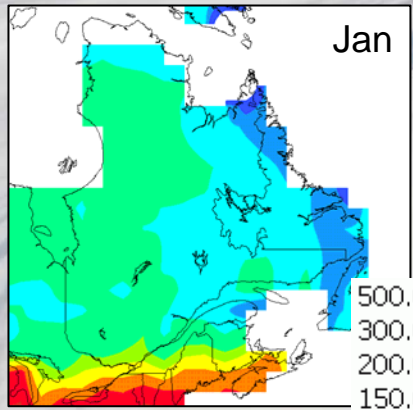
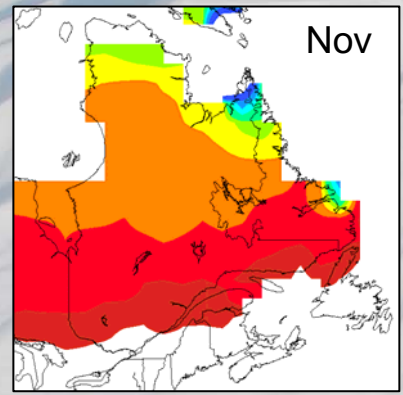
Dirmeyer et al., 2006: GSWP-2 multi-model analysis and implications for our perception of the land surface. *BAMS*, **87**, 1381-1397.

NCEP+CANGRD 1979-1997 50km

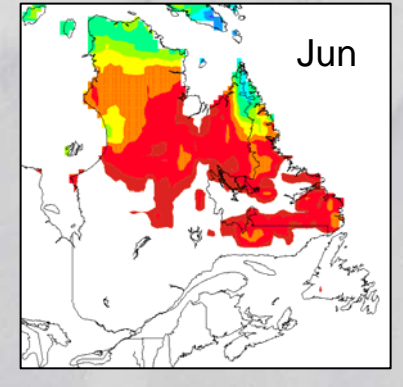
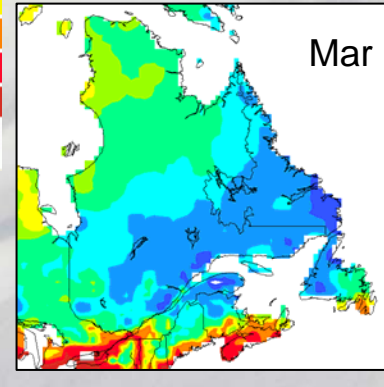
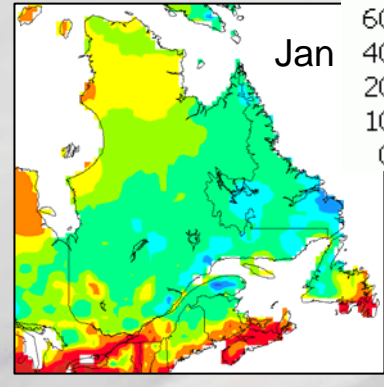
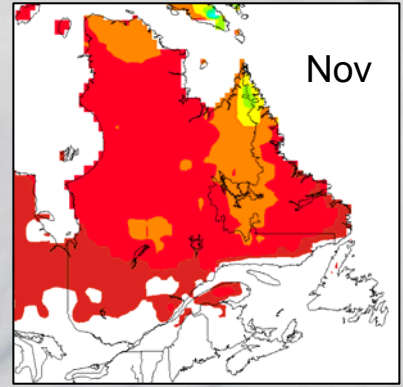
Comparison of Monthly Mean SWE Climatologies (mm)



GSWP-2 multi-model simulation 1986-1995 100km



Brown et al. (2003) 1979-1997 25km

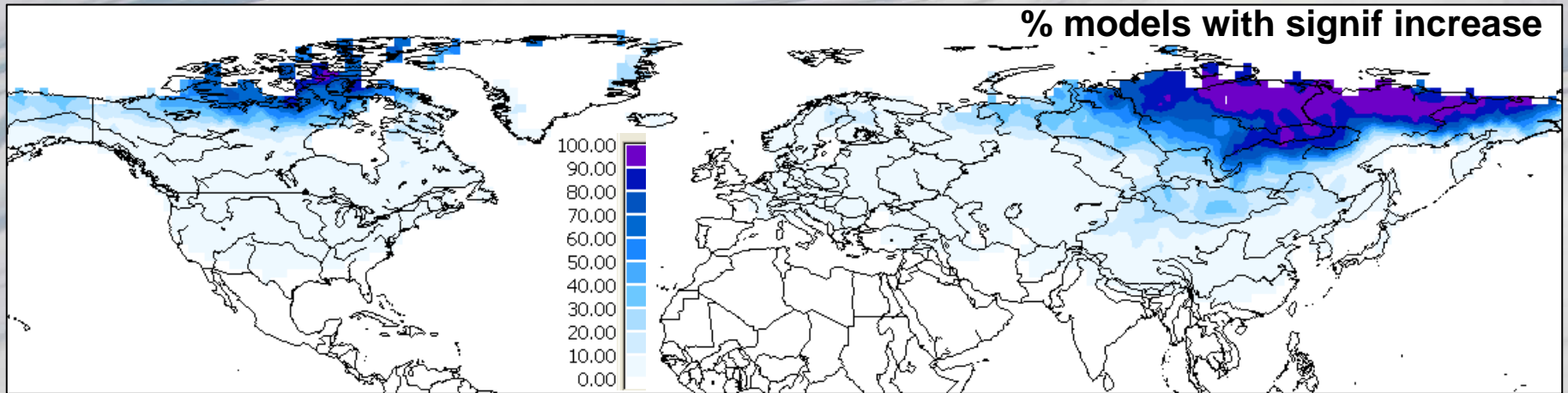
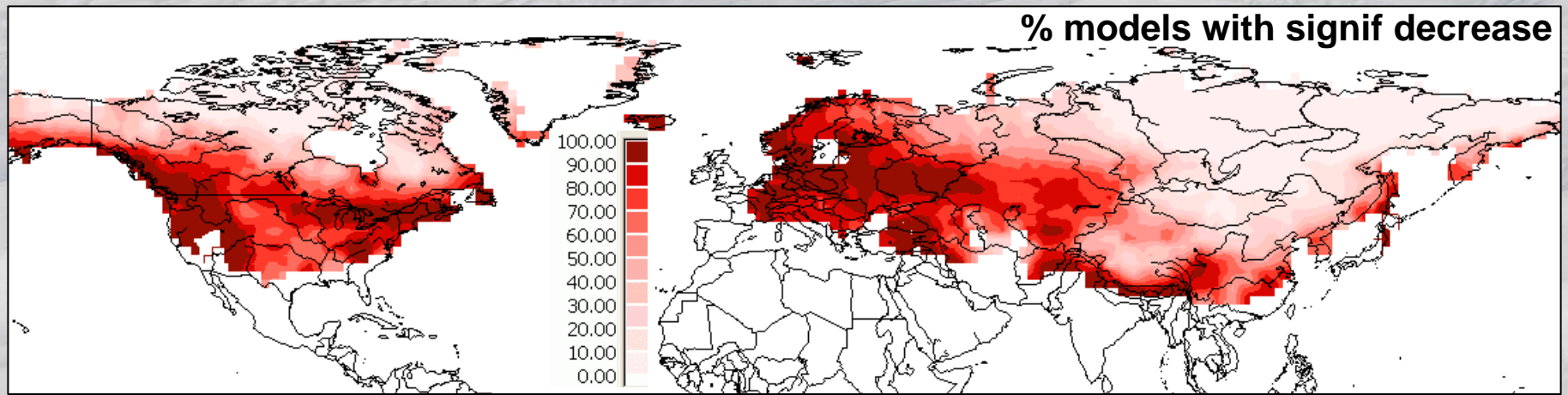


IPCC AR4 Global Climate Model (GCM) simulations

- Snow depth, SWE and snow cover fraction are available from the ~20 GCMs participating in the recent 4th IPCC Assessment but not for all runs or scenarios
- Based on the data available at the IPCC data gateway, there are a total of 14 GCMs with SWE information for both the 20th Century run and A2 and B1 scenarios
- Raisanen (2007) examined the changes in mean March SWE over the NH from the AR4 climate model runs and concluded that the location of the Nov-Mar -20°C isotherm determined whether SWE increased (cold side) or decreased (warm side).
- We are currently examining the projected changes in annual maximum monthly SWE over the NH and Quebec (see example over)
- **Note:** GCMs smooth the topography in mountainous regions and may miss the signal of increasing SWE at higher elevations in response to increasing precipitation (see CRCM next section)

References:

Raisanen, J, 2007: Warmer climate: less or more snow? *Climate Dynamics*, DOI 10.007/s00382-007-0289-y



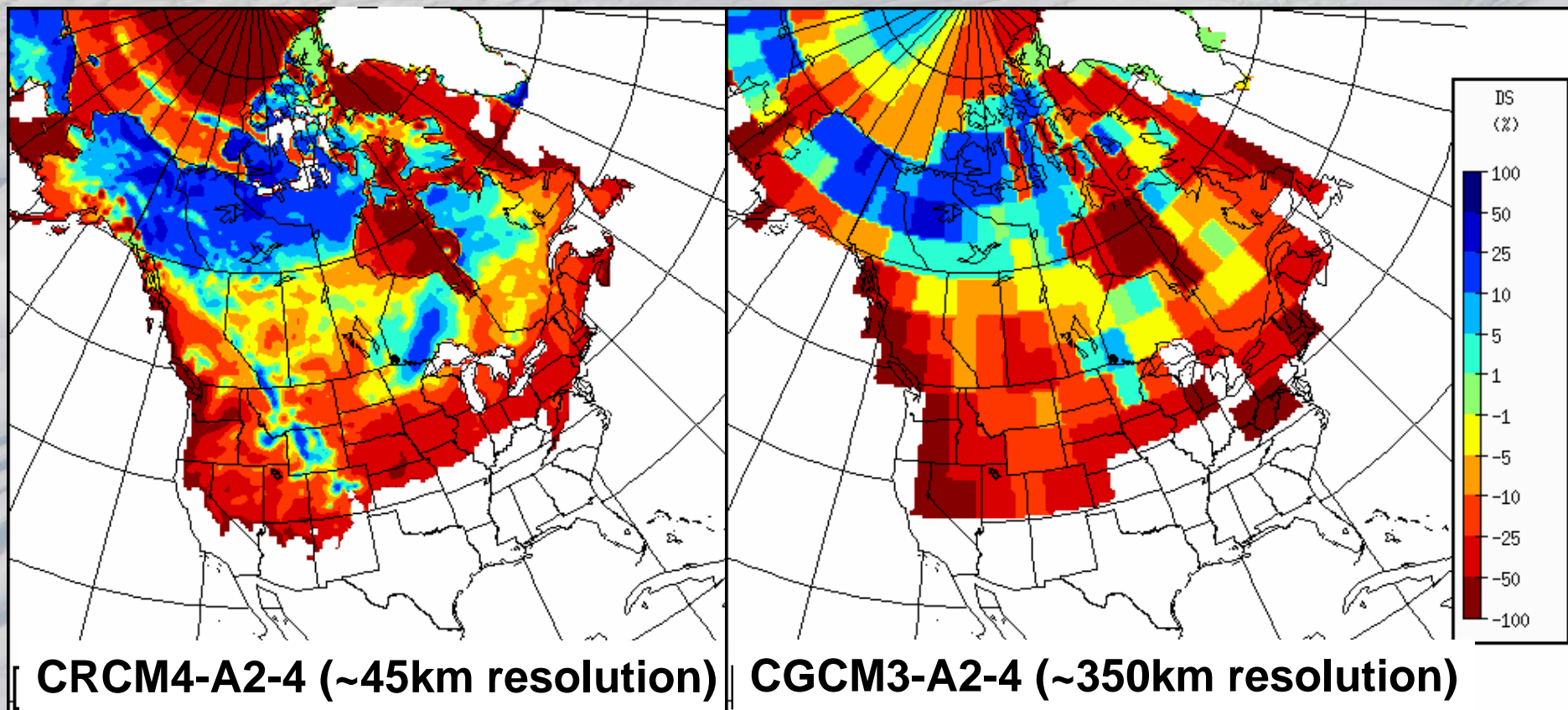
% of 14 GCMs showing significant increases or decreases in annual maximum monthly SWE between 1970-1999 and 2070-2099 for the SRES A2 scenario. More models show significant reductions over Quebec than significant increases. R. Brown 4/09/2007

Canadian Regional Climate Model (CRCM)

- SWE is one of many variables available from CRCM climate change simulations carried out at Ouranos
- A number of climate change simulations have been performed with CRCM (e.g. Caya and Laprise 1999; Plummer et al. 2006) for various configurations (model version, domain, driving data, etc.). The latest version, CRCM4 (Music and Caya, 2007), incorporates version 2.7 of the multi-layer Canadian Land Surface Scheme (CLASS)
- CRCM climate simulations for the North American or Quebec model domains can be obtained from chaumont.diane@ouranos.ca
- A qualitative comparison of CRCM4.1.1 monthly averaged SWE fields over Quebec showed acceptable agreement with the Brown et al. (2003) and NCEP+CANGRD reconstructions although it appeared to melt snow off too early in the spring
- The higher resolution offered by CRCM (~45 km) compared to most GCMs (~300 km) allows it to provide more detailed simulations of regional snow cover changes (see example over)

References

- Caya, D, and R Laprise, 1999: A semi-implicit semi-lagrangian regional climate model: The Canadian RCM, *Mon. Wea. Rev.*, **127**, 341-362.
- Music, B, and D Caya, 2007: Evaluation of the Hydrological Cycle over the Mississippi River Basin as Simulated by the Canadian Regional Climate Model (CRCM). *J. Hydromet.* (in press).
- Plummer, DA, D Caya, A Frigon, H Côté, M Giguère, D Paquin, S Biner, R Harvey, and R de Elia, 2006: Climate and Climate Change over North America as Simulated by the Canadian RCM, *J. Climate*, **19**, 3112-3132.



% change in mean winter (DJF) SWE between 1961-1990 and 2041-2070 for the SRES A2 scenario. The left panel shows results from a CRCM4.1.1 simulation driven at its lateral boundaries by the Canadian CGCM3 SRES A2 scenario, run4. The right panel presents SWE change simulated by CGCM3. CRCM provides more detailed information on regional changes in SWE especially over the Rockies and Quebec. Source: Ouranos Climate Simulation Team, 13/09/2007