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Assimilation of Satellite Derived Snow Information in the Canadian Land Data Assimilation System

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Outline

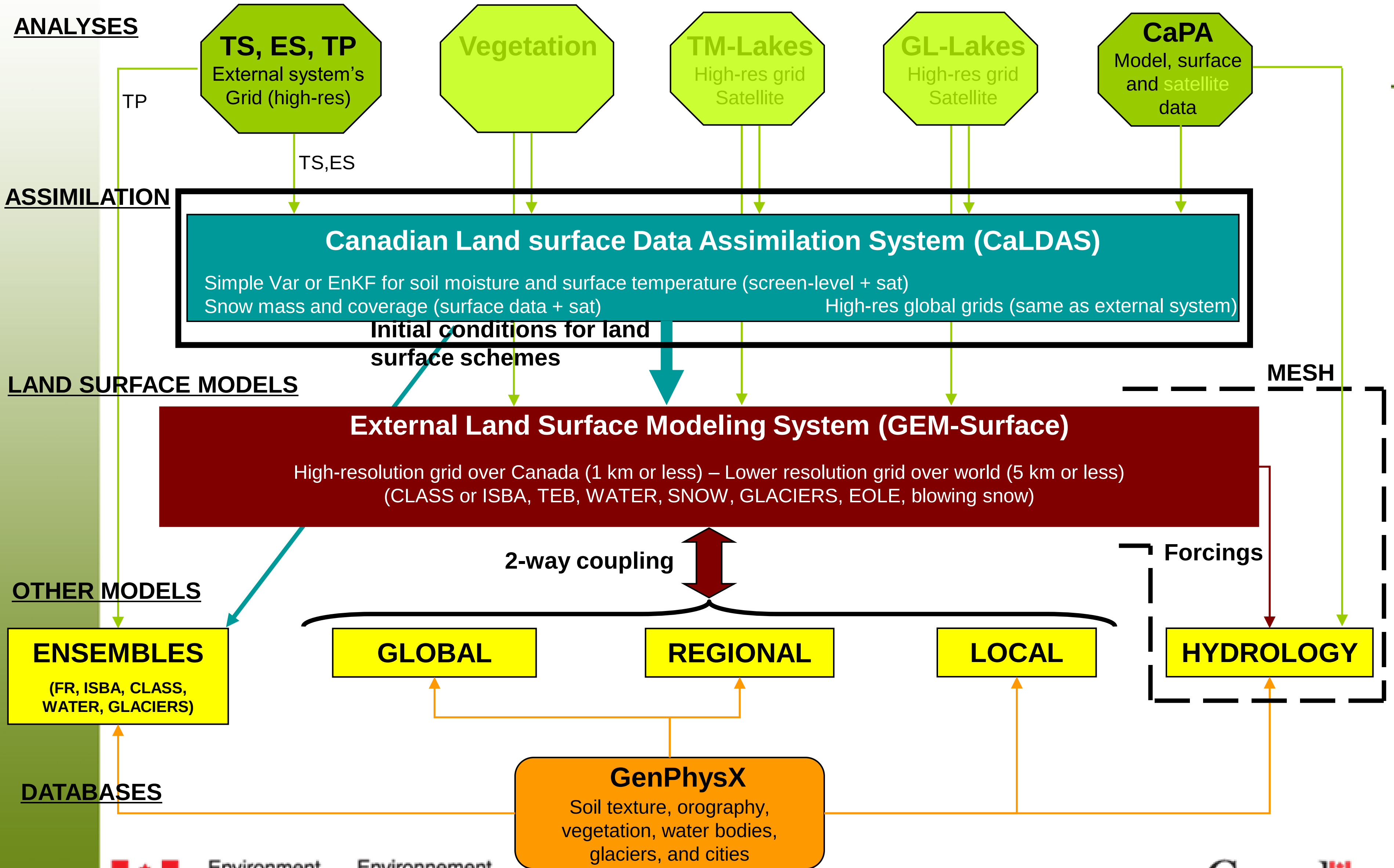
1. Overview: the Canadian Land Data Assimilation System (CaLDAS)
2. Uncertainty characterization for satellite derived snow datasets:
   - MODIS fractional snow cover (fSCA)
   - AMSR-E snow water equivalent (SWE)
3. Progress towards assimilating satellite snow datasets in CaLDAS
4. The potential impact of emerging datasets

Research Context

- Efforts are underway to improve treatment of the land surface, and include a hydrological component, to Environment Canada's (EC) numerical prediction systems.
- Emphasis on assimilation of space-based remote sensing data (for soil moisture, terrestrial snow, and vegetation).
- Single system for all NWP systems (deterministic and ensemble-based) + hydrology models.
- In EC's current prediction systems, snow is initialized using surface observations of snow depth (sparsely distributed in space; no information on the fractional coverage of snow on the ground).
- Satellite derived measurements can produce the spatially and temporally continuous observations necessary to systematically monitor snow cover, and characterize initial conditions.

A primary objective is to improve the representation of snow in Environment Canada's operational prediction systems by including space-based measurements in the Canadian Land Data Assimilation System (CaLDAS).

LAND DATA ASSIMILATION at ENVIRONMENT CANADA In DEVELOPMENT



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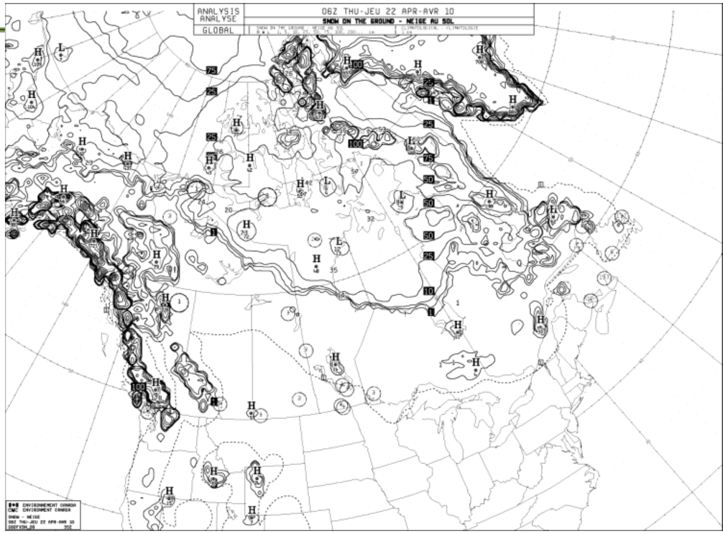
Current Treatment of Snow in CaLDAS: Canadian Meterological Centre Daily Gridded Global Snow Depth



• All available snow depth observations (from synops, meteorological aviation reports, and special aviation reports) are ingested into the analysis.

• Updated every 6 hours using optimum interpolation with an initial guess field provided by a simple snow accumulation and melt model using analyzed temperatures and forecast (6 hour) precipitation from the CMC global forecast model.

• The analysis includes an estimate of the density of the snowpack.

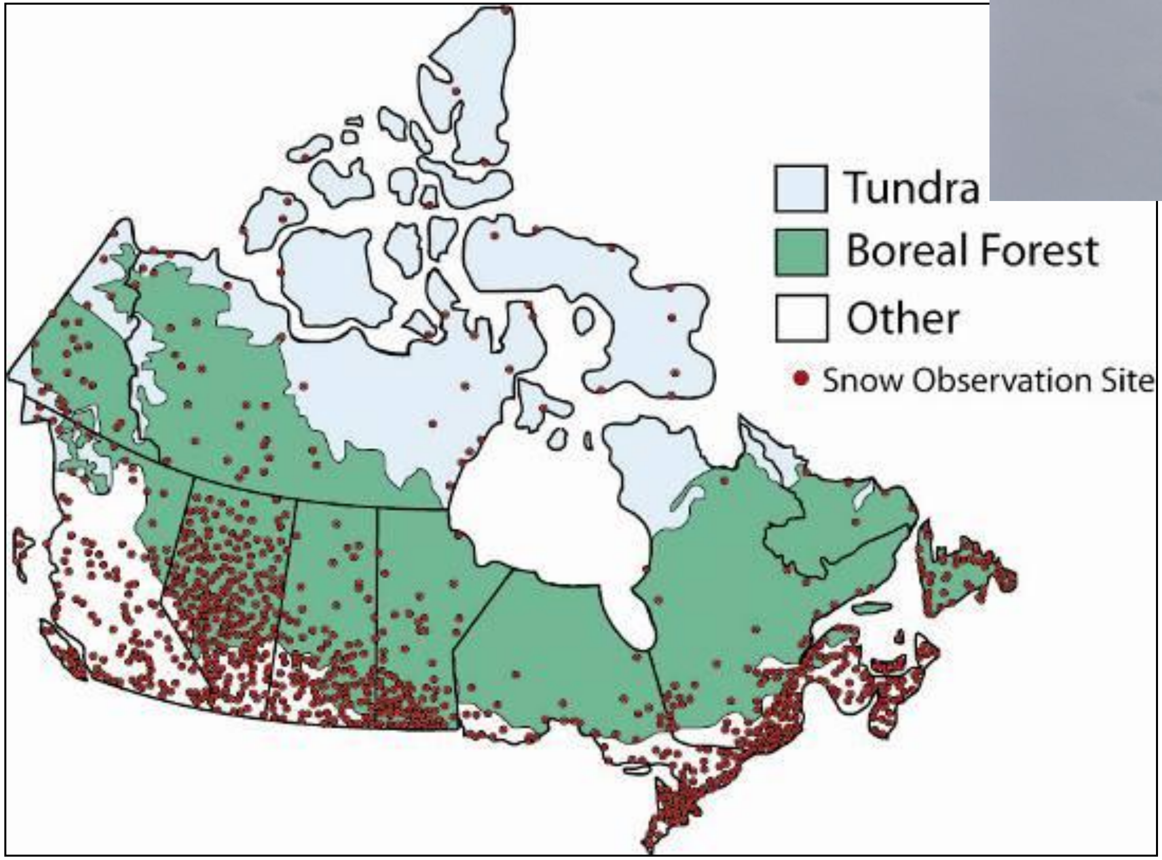
• Now archived at NSIDC.

Start Date	12-Mar-1998
End Date	Ongoing
Domain	Global
Temporal Resolution	Daily
Spatial Resolution	1/3 degree
Variables	Depth; Density

Known sources of uncertainty:
• Low depth bias and early melt bias due to climate station observing locations.
• Data sparse regions: snow depth corresponds to the initial guess field
• Density derived from very simple time decay function (can be replaced by climatology in post processing).

The Need for Satellite Derived Snow Information

Sparse conventional observation network:
A challenge for data assimilation strategies and algorithm evaluation.



Satellite-Derived Snow Cover Dataset Development at Environment Canada

Objective is to develop validated, temporally consistent datasets:

1.	Fractional snow covered area:	MODIS
2.	Snow water equivalent:	Passive microwave (AMSR-E; SSM/I)
3.	Snow melt onset/duration:	QuikSCAT

Collectively, these datasets tell us what fraction of the surface is snow covered, how much water is stored in the snowpack, when and for how long it melts.

These snow cover parameters are then utilized for:

- Determining cryosphere/climate interactions
- Evaluation of historical data records
- Climate model evaluation
- **Initial conditions for land surface data assimilation**

MODIS Derived Fractional Snow Covered Area (fSCA)

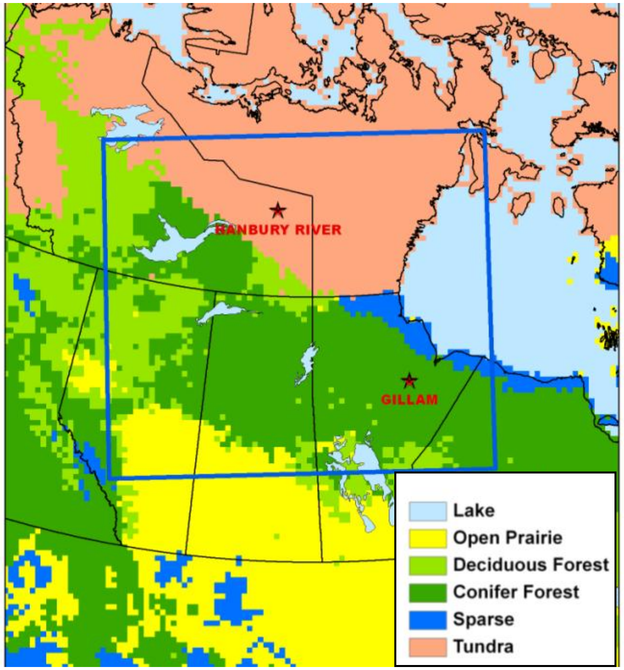
Based on Metsamaki et al. (2005), reflectance of the target area described as a function of:

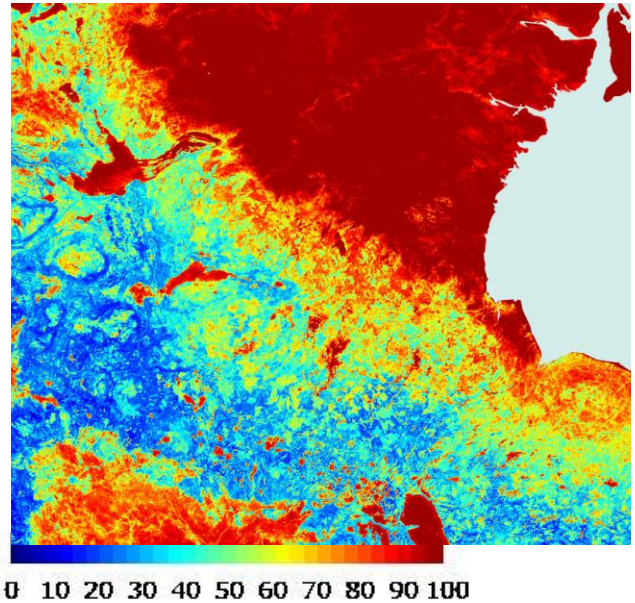
-canopy transmissivity (tλ),
-snow covered area (SCA),
-dry snow reflectance (ρλ,snow),
-snow-free ground reflectance (ρλ,ground)
-forest canopy reflectance (ρλ,forest)):

$$\rho_{\lambda,obs}(SCA) = (1 - t_\lambda^{\ 2}) * \rho_{\lambda,forest} + t_\lambda^{\ 2}\left[SCA * \rho_{\lambda,snow} + (1 - SCA) * \rho_{\lambda,ground}\right]$$

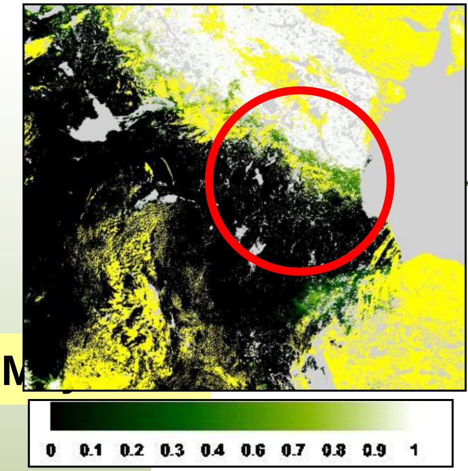
The effective transmissivity estimated from MODIS reflectance data at full dry snow cover conditions (SCA=1):

$$t_\lambda^{\ 2} = \frac{\rho_{\lambda,obs}(SCA=1) - \rho_{\lambda,forest}}{\rho_{\lambda,drysnow} - \rho_{\lambda,forest}}$$

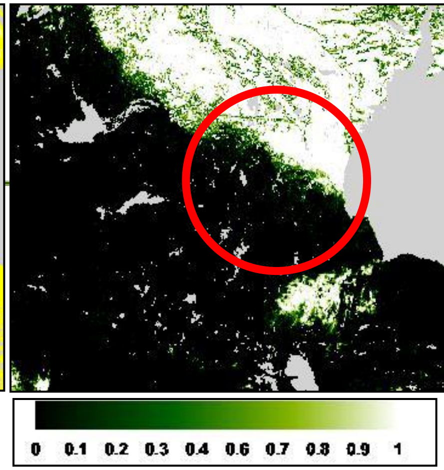




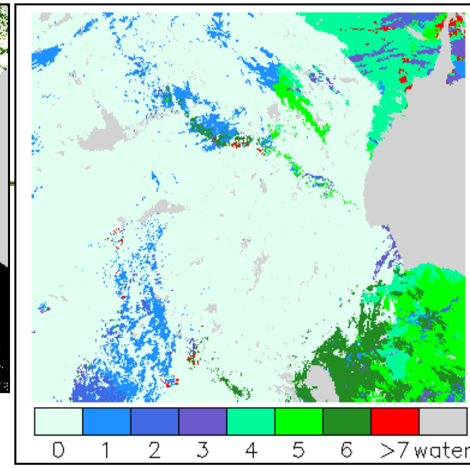
Assessment: MODIS fSCA



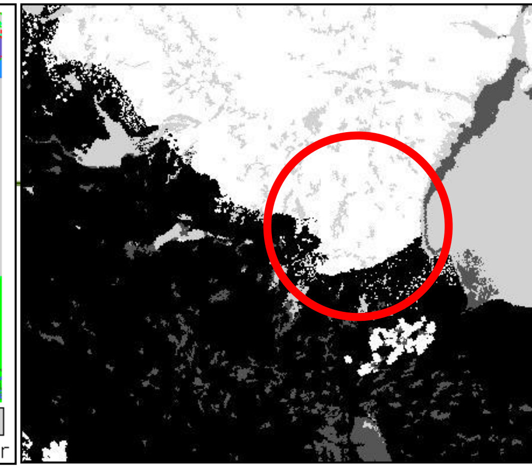
MODIS fSCA



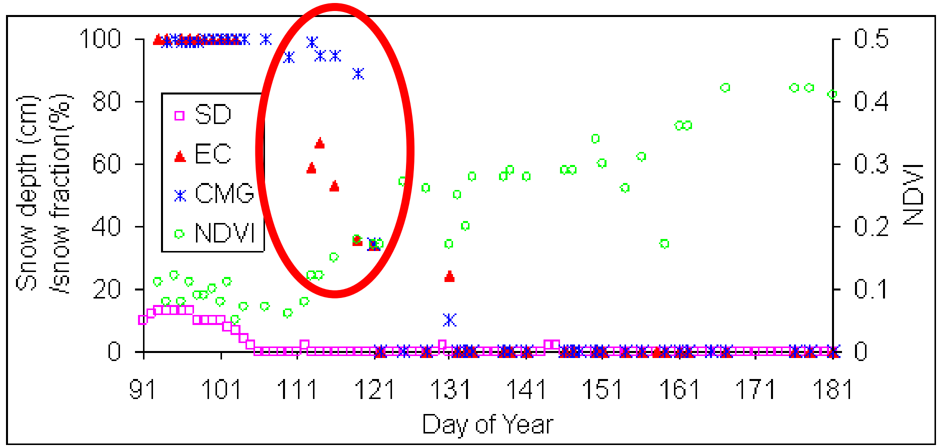
NASA MODIS CGF



CGF Cloud Persistence

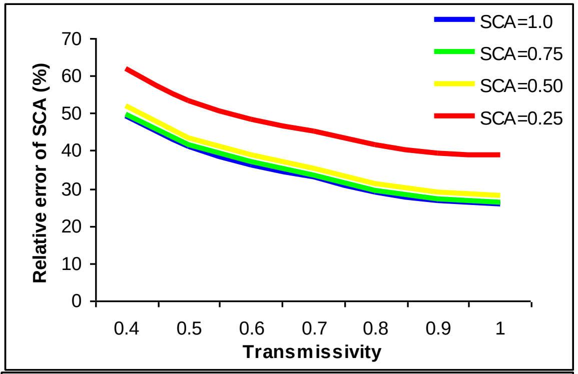


NOAA IMS



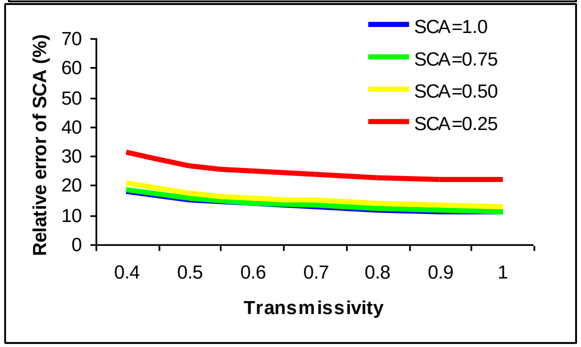
Dataset	Resolution	Snow Parameter	Retrieval Basis	Clouds	Uncertainty Determination
NOAA IMS	4 km	Snow Extent (snow/no-snow)	Subjective	No	Agreement with model first guess
MODIS CGF	5 km	fSCA	Statistical	No	Time lag since cloud free look
MODIS fSCA	1 km	fSCA	Spectral	Yes	Variance in reference reflectance used in retrieval equations

Uncertainty Characterization: MODIS fSCA



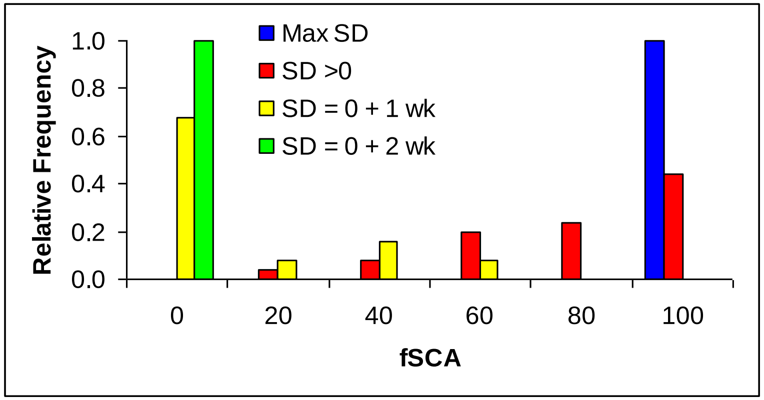
Relative error in SCA as a function of transmissivity.

- Reference reflectance and variance from **MODIS channel 3**.
- This approach allows use of the full MODIS swath.



Relative error in SCA as a function of transmissivity.

- Reference reflectance and variance from **ground-based spectral measurements**.
- This approach limited to near-nadir MODIS observations.
- Problematic for large regions and cloud mitigation.



Distribution of MODIS fSCA retrievals grouped by climate station snow depth (11 stations; 2006/07 snow season).

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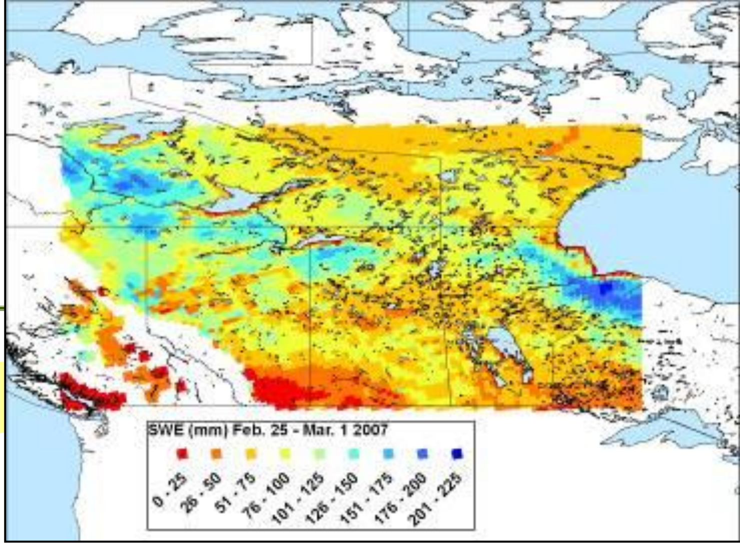
Environment Canada SWE Algorithm Summary



Suite of empirical, land cover specific algorithms

SWE Algorithm	Approach	Experiments	References
Open prairie with wet/patchy snow indicator	37V-19V	Saskatchewan 1982	Goodison and Walker, 1995 Walker and Goodison, 1993 (A. Glaciology)
Boreal forest: Shallow snow	37V-19V (Separate equations for deciduous, coniferous, and sparse forest)	BOREAS 1994; Saskatchewan 2003	Goita et al., 2003 (Int. J. Remote Sensing)
Boreal forest: Deep snow	19V-10V	Manitoba 2004-2007; NWT 2005-2007	Derksen, 2008 (Remote Sens. Environ.)
Lake rich sub-arctic tundra	37V	NWT 2005; SnowSTAR 2007; IPY 2008	Derksen et al., in press (Remote Sens. Environ.)

Assessment: AMSR-E SWE

<u>GlobSnow Validation Approach:</u>

- 3 algorithms
- 3 seasons:
  2004/05 – 2006/07
- 3 study regions:
  Canada; Finland; Russia
- Multiple independent ground datasets

<u>SWE Algorithms:</u>

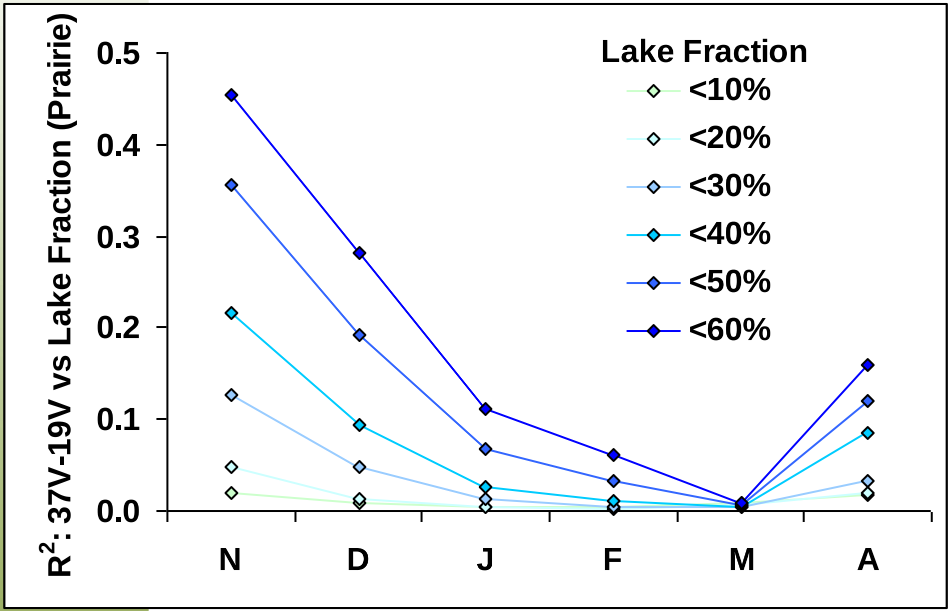
1. Environment Canada land cover specific suite (EC)
2. NASA AMSR-E global pentad (NASA)
3. Finnish Meteorological Institute assimilation approach (FMI)

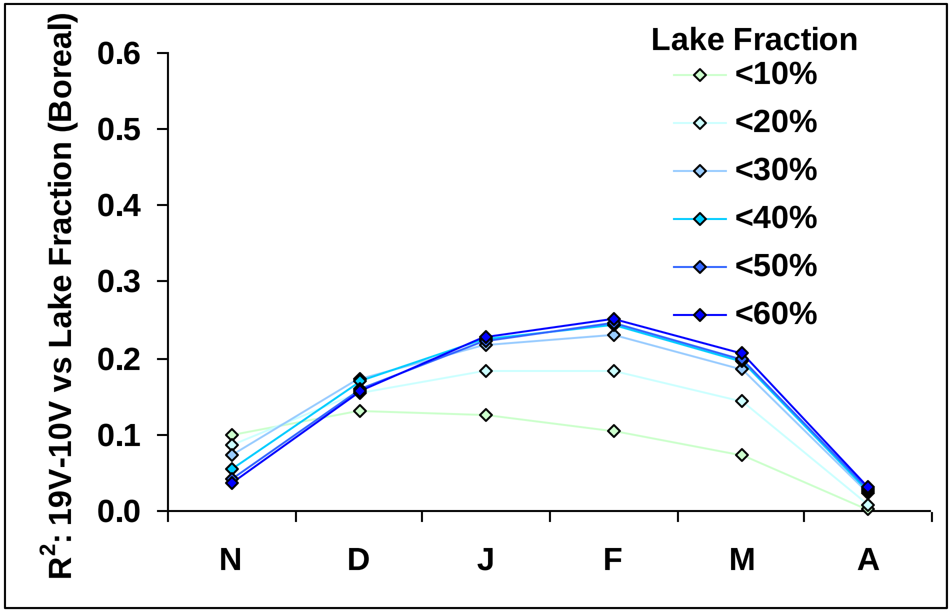
For full GlobSnow details: globsnow.fmi.fi

RMSE	EC	NASA	FMI
Tundra	20	65	50
Northern Boreal	50	74	77
Southern Boreal	32	33	24
Prairie	21	37	32
Correlation (r)	**EC**	**NASA**	**FMI**
Tundra	0.83	0.52	0.91
Northern Boreal	0.71	0.00	0.24
Southern Boreal	0.61	0.63	0.70
Prairie	0.59	0.41	0.23

Summary of algorithm validation over Canada separated by land cover.

Uncertainty Characterization: AMSR-E SWE



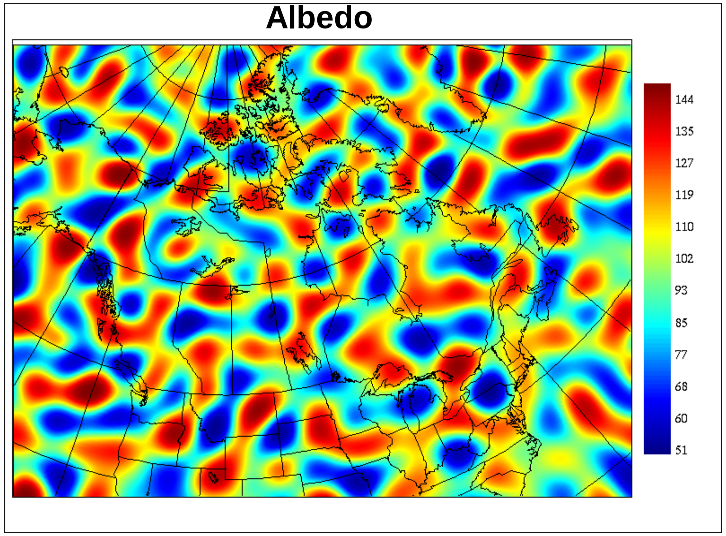


Example statistical uncertainty results for passive microwave SWE retrievals based on the variance explained in brightness temperature due to grid cell lake fraction.

Progress Towards Assimilation of Satellite Information:
Perturbation of Surface Fields

Surface characteristics forced with an ensemble of inputs by perturbing albedo, leaf area index, vegetation fraction and roughness length over the sphere.
This determines the first guess or model error covariance matrix B.

- Surface characteristics are perturbed using a Markov chain approach, thus producing random fields (between 20 to 60) which are used for ensemble data assimilation.
- The fields that are produced are space-time auto-correlated to get a smoother time evolution by avoiding the generation of noisy patterns.
- These fields are input to the GEM model which outputs 20 (to 60) model states at each time step.
- From this, the covariance between the different model states is used to estimate the model error (first guess error B).



Assimilation of Snow in CaLDAS
First Complete Strategy: Two Control Variables

Error covariances based on ensemble modeling

FIRST GUESS (MODEL)

From land surface scheme (*fSCA* is either prognostic or diagnostic)

Current Experiment: Simulation with rule based determination for passive microwave SWE based on fSCA for the time period Sept. 2006 - April 2007.

$$\underbrace{\begin{bmatrix} SWE \\ fSCA \end{bmatrix}^a} = \begin{bmatrix} SWE \\ fSCA \end{bmatrix}^b + K \left\{ \begin{bmatrix} SWE \\ fSCA \end{bmatrix}^o - H \begin{bmatrix} SWE \\ fSCA \end{bmatrix}^b \right\}$$

fSCA from MODIS (or IMS)

SWE from AMSR-E

Rule-based enforcement of coherency between *SWE*^{a} and *fSCA*^{a}

OBSERVATIONS

Error covariances based on transmissivity/cloud coverage (fSCA); pixel heterogeneity (SWE)

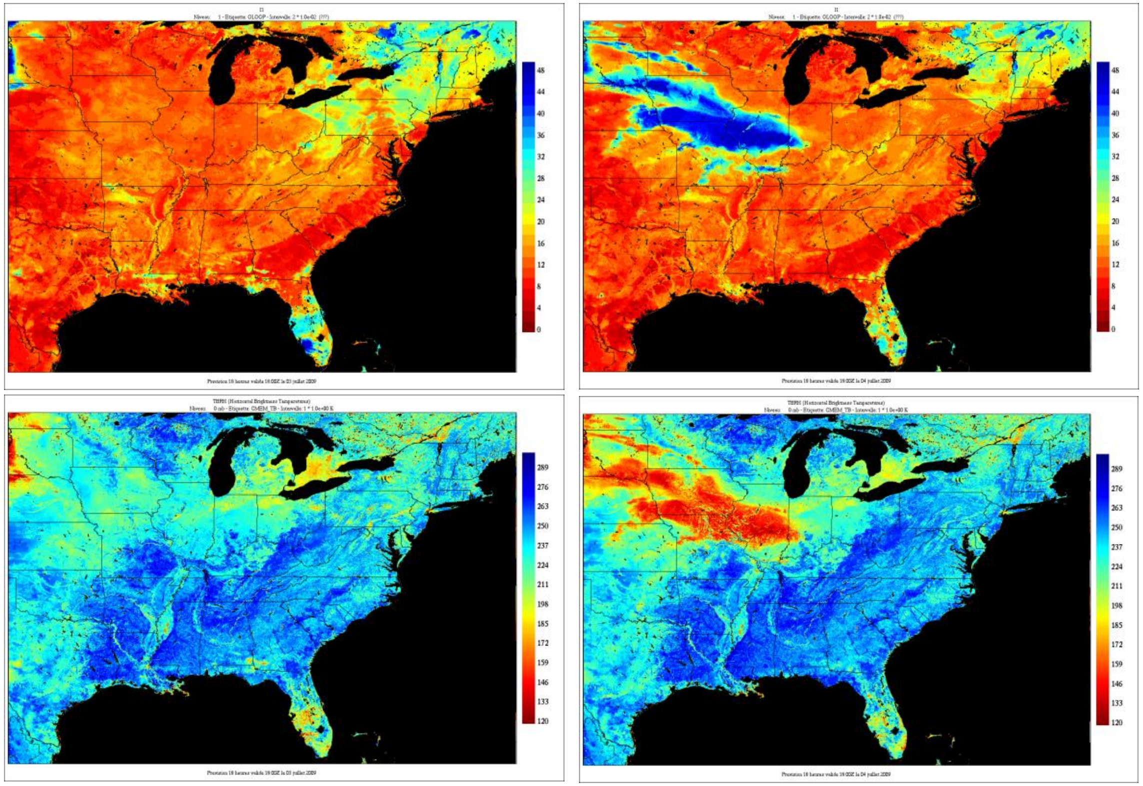
Progress Towards Assimilation of Satellite Information:
1 km Nature Run

Offline land-surface modeling system forced by 6-18 hour forecast provided by the Regional GEM atmospheric model.

Horizontal Resolution : 1km
Time Period : 30 March 2009 - 31 March 2010.
Land-Surface Model : ISBA
Open-Loop : No Assimilation

Soil moisture in the upper soil layer (10 cm; m^3/m^3). Significant increase in soil moisture across the upper Midwest from the 3 to the 4 July 2009.

Horizontal L-band brightness temperatures (Kelvin) calculated using CMEM (Community Microwave Emission Model).

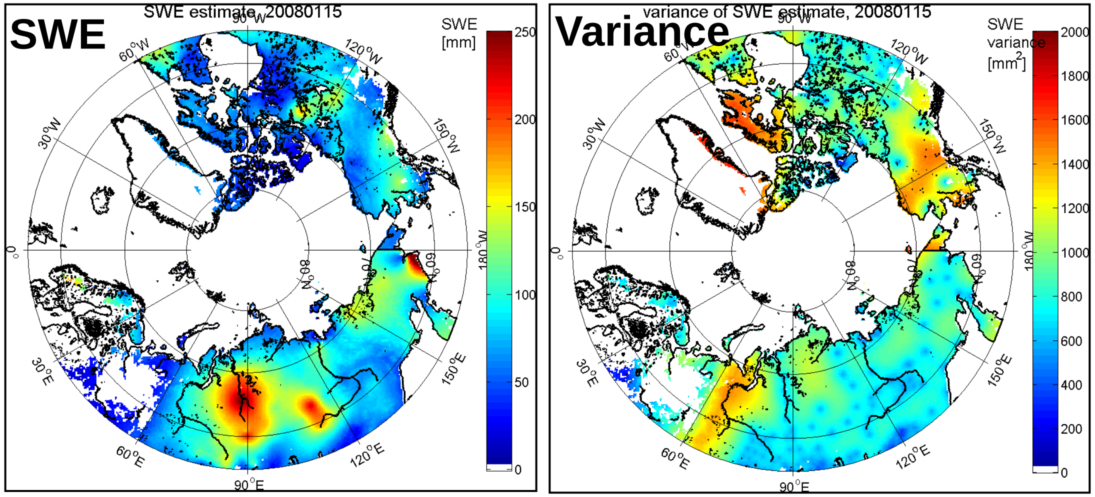


3 July 2009 **4 July 2009**

Potential Impacts of Emerging Datasets

GlobSnow

Global SE and SWE datasets available in NRT for NWP and climate applications (2012). Includes SWE retrieval + variance estimate.



CoReH20

High resolution measurements with sensitivity to deep snowpacks will produce datasets that address priority EC applications, including:

-Land surface initial conditions in CaLDAS (***1– 4 km***)
-Evaluation of hydrological models, i.e. CRHM; improved flood forecasting (**1 km**)
-Information for alpine snowpacks (**100 – 500 m**)

Conclusions

- The characterization of uncertainty in satellite-derived snow datasets is necessary to facilitate assimilation. This process now complete for 2 datasets over central Canada:
  -MODIS fSCA (SYKE algorithm)
  -AMSR-E SWE (EC algorithms)

- A new method was developed to produce an ensemble spread or variance based on realistic perturbations of both atmospheric forcing and surface characteristics.

- The framework for the assimilation of satellite snow observations in CaLDAS was developed using an Ensemble Kalman Filter approach.

- A one-year high-resolution (1 km) nature run coupled with CMEM simulations was performed over eastern North America. This approach will be utilized as a test bed for the assimilation of SWE information in CaLDAS.

- GlobSnow and CoReH20 datasets represent important new levels of information for assimilation.

Questions?

- AMSR-E data provided by the National Snow and Ice Data Center.
- Dorothy Hall, Jeff Miller and George Riggs provided the MODIS CGF dataset; Yi Luo, Alexander Trishchenko, and Konstantin Khlopenkov provided MODIS clear-sky compositing and reprojection software.
- Thanks to the Canadian Space Agency for support through the Government Research Initiatives Program

Progress Towards Assimilation of Satellite Information:
Perturbation of Surface Fields

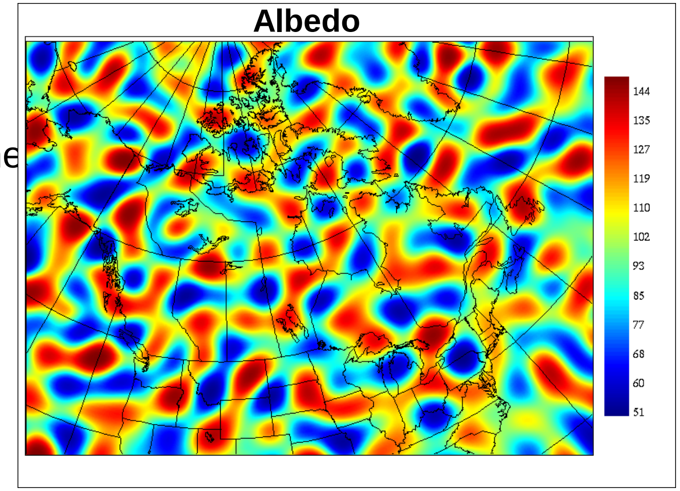
For determining the first guess or model error covariance matrix B, surface characteristics forced with an ensemble of inputs by perturbing albedo, leaf area index, vegetation fraction and roughness length over the sphere.

Space-time auto-correlated 2D random fields on sphere are generated using Markov's chain

$$\psi(\lambda,\varphi,t) = \mu + \sum_{Lmin}^{Lmax} a_{lm}(t) Y_{lm}(\lambda,\varphi)$$

ψ	perturbation factor
(λ,φ)	longitude and latitude
μ	mean perturbation
$L_{min};L_{max}$	min and max wavenumbers perturbed
Y_{lm}	spherical harmonics of degree l and order m
A_{lm}	spherical harmonics coefficient that evolves in time
Δt	time step

Perturbation time step: 6 hr
20 random fields/ensembles evolving in time for each variable



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Assimilation of Snow in CaLDAS
Simple Approach: SWE only

Error covariances based on ensemble modeling

FIRST GUESS (MODEL)

Experiment 1: Simulation with passive microwave SWE compared with an open loop (no assimilation run) run, Sept. 2006 - April 2007.

From land surface scheme (*only care here about SWE*)

Control variable:SD

Observation:SWE

$$[SWE]^a = [SWE]^b + K\,\{[SWE]^o - H\,[SWE]^b\}$$

SWE from AMSR-E/or synthetic data

OBSERVATIONS

Error covariances will be specified arbitrarily