Climate Models and Snow: Projections and Predictions, Decades to Days
Outline

Three Snow Lectures:

1. Why you should care about snow...
2. How we measure snow...
3. Snow and climate modeling...
   • The observational foundation: SnowPEx
   • Climate model analysis: historical simulations and multi-decadal projections
   • Seasonal prediction: initialization/verification
   • Numerical weather prediction
Simulated vs. Observed Arctic SCE

North America

Eurasia

May

June

Historical + projected (16 CMIP5 models; rcp85 scenario) and observed (NOAA snow chart CDR) snow cover extent for May and June.

SCE normalized by the maximum area simulated by each model.
Trends in Snow Cover

- Multi-dataset SCE (n=5) and SIE (n=3) anomaly time series, 1981-2010
- Multi-dataset consistency in SCE anomaly sign only emerges after 2005
Background

• Reliable information on terrestrial snow is required for studies of freshwater and energy budgets, the assessment of coupled climate model simulations, and the evaluation and initialization of land surface models for both short term weather and seasonal forecasts.

• Gridded snow extent and snow water equivalent datasets were assessed within the European Space Agency (ESA) Satellite Snow Product Inter-comparison and Evaluation Experiment (SnowPEx).

• Analysis was performed in order to quantify the spatial and temporal consistency of the products (spread); all datasets were also compared to independent in situ reference datasets (absolute uncertainty, bias).

• The goal is to develop ‘observational ensembles’ for comparison with model ensembles.
## SnowPEx SWE Datasets

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Abbreviation</th>
<th>Snow Scheme</th>
<th>Land Model</th>
<th>Forcing Data</th>
<th>Resolution</th>
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<tr>
<td>GlobSnow</td>
<td>GS</td>
<td>satellite passive microwave + \textit{in situ} \textsuperscript{1}</td>
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<td>25 km</td>
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<td>1/2° × 2/3°</td>
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Preliminary Dataset Evaluation

- Anomaly shift in MERRA-land SWE in 1998, consistent with shift in precipitation forcing

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¹ Satellite passive microwave + *in situ* data
² Simple + *in situ* data

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**Canada**

Environment and Climate Change Canada

Environnement et Changement climatique Canada
Snow Mass Climatology

Climatological NH snow water mass, 1981–2010

Multidataset SWE climatology, February–March, 1981–2010

Snow Mass Climatology - Spread

Spread among NH snow water mass climatologies by region, 1981–2010

Ratio of climatological SWE to spread, February–March 1981, 2010

Difference From Multi-Dataset Mean

Snow Mass Anomalies

Comparisons with in situ Data

Eurasian snow courses (n=517):
- 1 to 2 km snow transects
- data for 1979 – 2011
Comparisons with in situ Data

ERA-land: +42mm bias, 74.7 mm RMSE
GlobSnow: -4mm bias, 44.9 mm RMSE
MERRA: +15mm bias, 57.9 mm RMSE
CROCUS: +5mm bias, 48.0 mm RMSE
GLDAS: -11mm bias 49.5 mm RMSE
Comparisons with in situ Data

Monthly relative RMSE

Monthly bias
Conversion of SWE to SCE

- Reanalysis products very sensitive to low SWE thresholds
- Climatology and trends sensitive to SWE threshold although 0 mm can be ruled out as a reasonable threshold
Trend Spread, 1981-2010

SCF Trends
0mm-10mm Threshold

SCF Trends
4mm-10mm Threshold
Influence of Observational Uncertainty on Determination of Trends

Monthly surface temperature trends from CRU, NCDC, GISS and NCEP2m

Monthly snow cover trends from MERRA, ERA-I-Land, Crocus, GLDAS-2, Brown, and GlobSnow.
The October Snow Problem

Brown and Derksen, 2013
Challenges in Operational Snow Charting in October

- Higher cloud fraction in the snow cover onset period creates challenges for NOAA analysts

- Significant improvements in satellite data quality and quantity, and snow charting procedures over recent decades

Climatological cloud fraction from MODIS

Brown and Derksen, 2013
Influence of Observational Uncertainty on Climate Model Evaluation

Mean and spread (interquartile range) of Northern Hemisphere snow cover extent trends calculated over the 1981-2010 period

L. Mudryk
Relationship between spring SCE trends and NH extratropical land warming for the CMIP5 models during the historical period (1981-2010). Each model is represented by a letter.

Filled circles represent the CMIP5 mean (blue), CanESM-LE mean (black), and the observation-based mean (red).

Each member of the CanESM-LE is shown as a small black square.

The shaded red rectangle illustrates the range of observation-based trends.

Thackeray et al., in review
Northern Hemisphere March (a) April (b) May (c) and June (d) SCE trends over the 21st century under the RCP8.5 emissions scenario amongst three ensembles: CMIP5, CanESM-LE, and observation-based (OBS).

The CMIP5 box uses the mean for each model (averaged over all available realizations).

Projected trends are shown in millions of km² per decade and split into four thirty-year climatological periods (1981-2010, 2011-2040, 2041-2070, and 2071-2100).

Thackeray et al., in review
Projected Spring Snow Cover Extent Reductions

Percentage of climatological Northern Hemisphere SCE (1981-2010 mean) lost over the 21st century in CMIP5 and CanESM-LE for (a) early-spring (b) late-spring.

Ensemble mean shown with ±1 standard deviation shading.

Note that the decreasing CanESM-LE variability in Fig. 6b is caused by June SCE falling closer to zero.

Thackeray et al., in review
## Evaluation of Snow Initial Conditions in Canadian Seasonal to Interannual Prediction System (CanSIPS)

### How close are initial conditions to observations of SWE?

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<tr>
<th>Assimilation Runs</th>
<th>Hindcasts</th>
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<tr>
<td>serve as initial conditions for hindcasts</td>
<td>1 year duration</td>
</tr>
<tr>
<td>assimilate observed T, u, v, q, SST, sea ice</td>
<td>begin on 1st of month</td>
</tr>
</tbody>
</table>

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<th>Historical Runs</th>
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<tr>
<td>freely running CanCM3\CanCM4</td>
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Springtime Bias in SWE Initial Conditions


SWE biases in the Canadian Seasonal to Interannual Prediction System (CanSIPS; Sospedra et al 2015)

Sospedra-Alfonso et al., 2016
Temporal correlations of interannual SWE anomalies in 1981–2010 for (a)–(c) CanCM3 and (d)–(f) CanCM4 relative to MERRA during (left) October, (middle) January, and (right) April.

Sospedra-Alfonso et al., 2016
Spatial averages of anomaly correlation coefficient (ACC; top) and mean square skill score (MSSS; bottom) in the Northern Hemisphere for CanSIPS (Sospedra et al., 2016)
The Canada Land Data Assimilation System (CaLDAS)

**IN**
- Ancillary land surface data
  - Orography, vegetation, soils, water fraction, ...
- Atmospheric forcing
  - T, q, U, V, Pr, SW, LW
- Observations
  - Screen-level (T, Td)
  - Surface stations snow depth
  - L-band passive (SMOS, SMAP)
  - Microwave SWE (AMSR-E)
  - *Optical / IR (MODIS, VIIRS)
  - Combined products (GlobSnow)

**CaLDAS**

**LAND MODEL (SPS)**

**ASSIMILATION**
EnKF + EnOI

**OUT**
- Analyses of...
  - Surface Temperature
  - Soil moisture
  - Snow depth or SWE
  - Vegetation*

\[
x^a = x^b + K \{ y - H(x^b) \}
\]

\[
K = BH^T (HBH^T + R)^{-1}
\]

Stephane Belair
Benefits of 100-m downscaled snow analyses for the 2010 Vancouver Games

Large decrease of T2m bias

Bernier et al. 2011
Bernier et al. 2012
OSSE – Observation System Simulation Experiment

Nature Run → Upscaled and perturbed → Synthetic Observations

CaLDAS

Initial conditions → 24 members → Analysis with “Obs”

Camille Garnaud
Summary

• Historical climate model simulations agree reasonably well with an ensemble of ‘observed’ snow analyses

• Projected spring snow cover extent (and snow mass) reductions are dramatic in the coming decades

• Improvements in terrestrial snow products impacts seasonal prediction initialization and verification

• Land surface data assimilation schemes used for numerical weather prediction require advancement with respect to snow for operational purposes, but are already very useful experimental tools
Final Thoughts

- Snow is layered; Arctic snow is unlike snow found in other land cover/climate zones
- Arctic spring snow cover is changing rapidly, consistent with other elements of the cryosphere
- Conventional snow observations are fraught with uncertainties
- Satellite remote sensing plays an important role in building an observational snow ensemble:
  - conventional obs needed for retrievals
  - campaigns (including aircraft) still required
  - new mission concepts needed to meet emerging needs
- Snow is an important variable with respect NH land surface temperature trends, seasonal prediction