What New Knowledge MODIS 250m Imagery Brings About Summer Snow And Ice Climatology Over the Northern Landmass?

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Outline

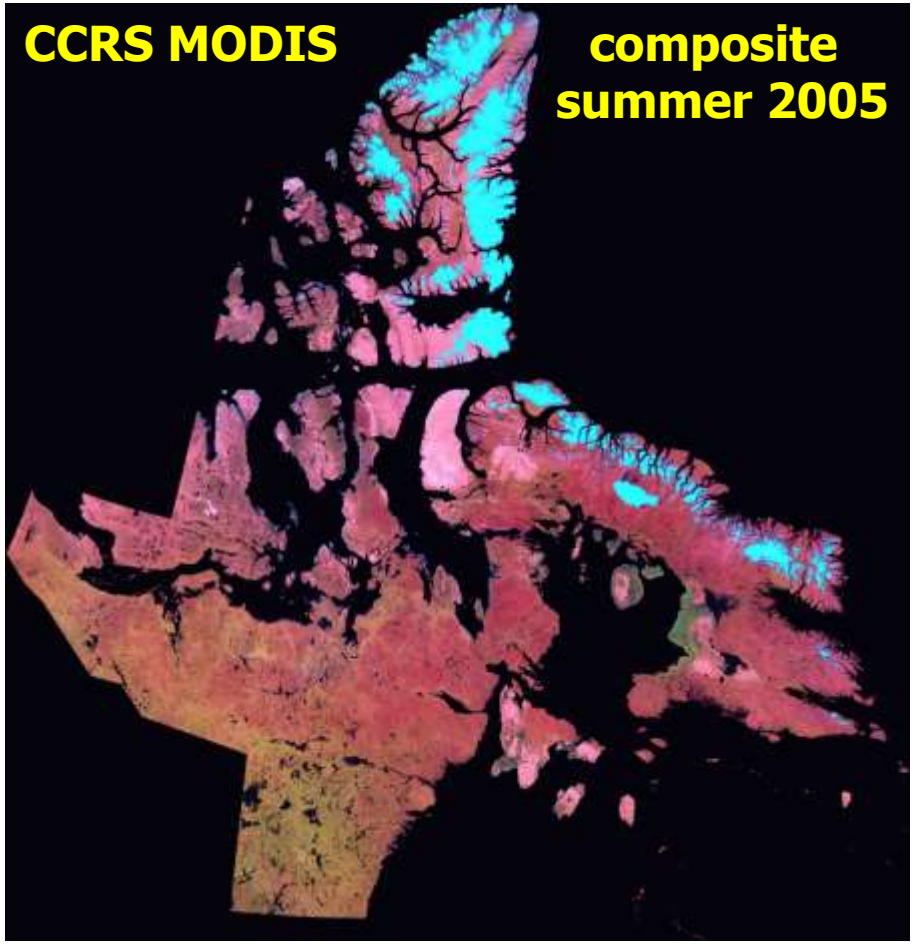
- Motivation
- Brief overview of CCRS MODIS processing features
- Summer snow/ice probability maps & Minimum Snow/Ice (MSI) extent
  - Circumpolar Arctic
  - Canadian Arctic
  - MSI and Climate Variations
  - Value of MODIS 250m results for RGI
  - Application for sea ice
- Continuing MODIS time series using VIIRS
- Conclusions
- Acknowledgements

CCRS MODIS processing results are discussed mostly in this talk. Not the standard MODIS products, except where it is mentioned. CCRS results are derived from L1 (swath) MODIS data MOD02/MOD03

Motivation

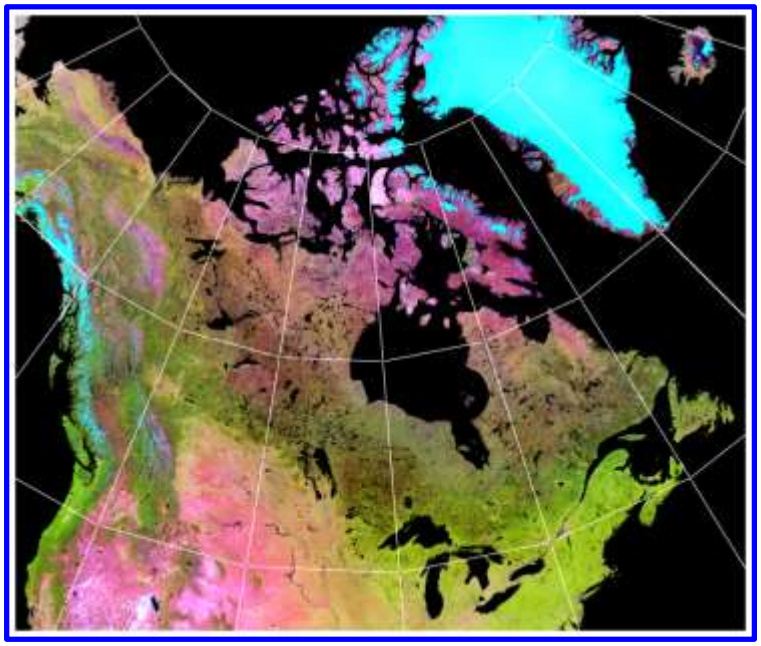
- In may respects, the MODIS data established a new standard of quality is global satellite observations;
  - What new knowledge and improvements this brought about the climate state and dynamics of the Northern cryosphere (over land) during the **warm season** ?
  - How consistent are these data with existing information from other available datasets ?
  - How useful are these data for land ice mapping (for example to RGI) ?
  - How useful are these data to quantify the snow extent during the summer season (is there anything indeed to quantify, i.e. does snow melt completely or not)?
  - What would be the best definition for summer snow (and ice) cover in **land cover legend**
    - Permanent snow/ice?
    - Perennial snow/ice ?
    - Semi-permanent snow/ice ?
    - Snow/ice ?
    - Annual **Minimum Snow/Ice (MSI**) extent
- **Why the warm season snow over land is important**?
  - Summer Arctic (Antarctic) ocean ice minimum is of great interest to climate community
  - Summer snow (and ice) extent over land is equally important for ecosystems, permafrost degradation, local communities, and as a climate change indicator
- We started thinking about these questions once we generated our initial MODIS Arctic composites at the start of IPY (2006-2007) and discovered some quite noticeable visual discrepancies over Canadian North between CCRS/MODIS and ESA GlobCover maps released in 2009.

Visual perception sometimes can be very insightful

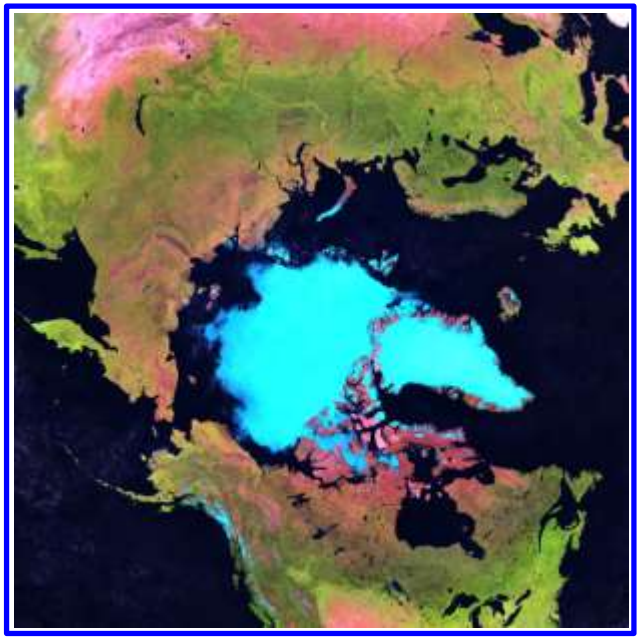


Our Study Regions: MODIS & VIIRS@ 250m

Regular Mapping Region - LCC
Lambert Conformal Conic Projection
22,800 pixels x 19,200 lines
Canada and neighbouring regions



Circumpolar Mapping Region - LAEA
Lambert Equal Area Azimuthal Projection
36,000 pixels x 36,000 lines
Circumpolar Arctic region

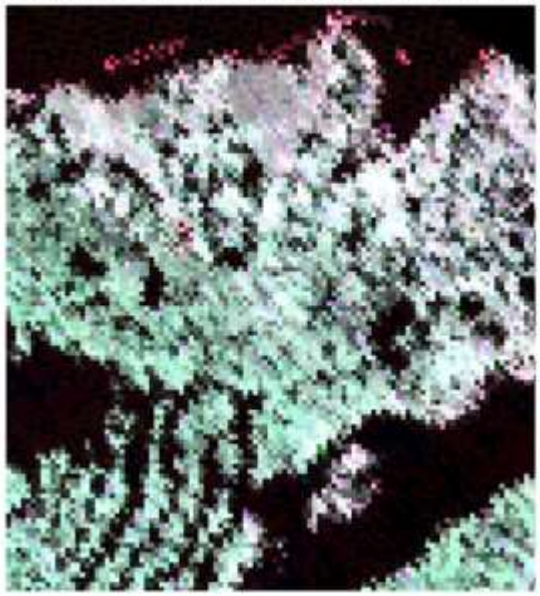


Trishchenko, A.P., et al., 2009. *Int. J. Rem. Sensing.* 30, 1635-1641
Luo, Trishchenko et al., 2008. *Rem. Sensing Environ*. 112 (12), 4167-4185

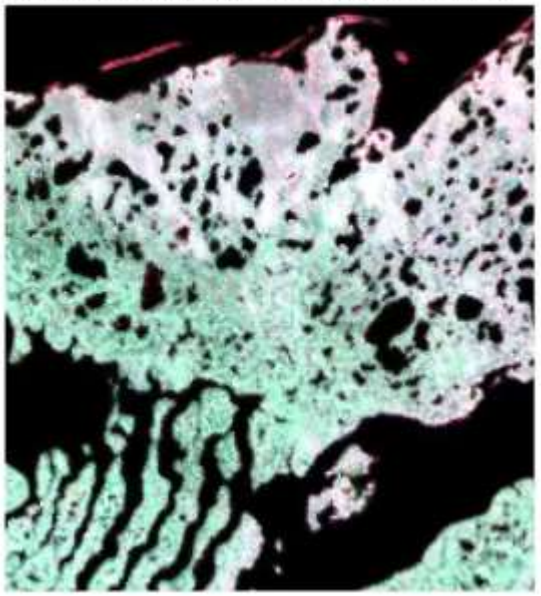
Key MODIS Processing Enhancements Implemented at CCRS

- Product is generated from original swath (L1B level) i.e. no multiple re-projection steps;
- Employs the correlation between 500m bands B3-B7 and B1,B2 and NDVI at 500m and applies it at **250m**;
- Generates bands B3-B7 at 250m resolution using B1, B2 and NDVI with **250m** using **Adaptive Regression and Normalization;**
- 10-day compositing intervals instead of 16-day;
- Two-value (Forward & Backward scattering geometry) composites;
  - Instead on MODIS SIN projection
    - Lambert Conic Conformal projection (LCC) for Canada
    - Lambert Azimuthal Equal Area (LAEA) projection for the circumpolar Arctic region
- Spatial resolution **250m** is required for several GCOS terrestrial products (fires, fPAR, LAI, wetlands ...) and close to a goal (100m) for snow extent

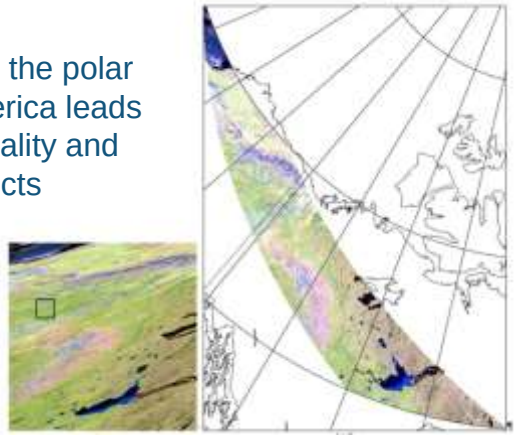
Standard NASA product
(c) MOD09A1 Composite (B5, B6, B7, 500m)



CCRS- developed product
(d) CCRS Composite (B5, B6, B7, 250m)



The application of SIN projection over the polar and mid-latitude regions of North America leads to large distortions, reduces image quality and spatial resolution of the MODIS products



Trishchenko et al., 2006. *SPIE, 6365. 35.*
Khlopenkov &Trishchenko, 2008. *IEEE TGRS, 46 (7), 2016-2027*

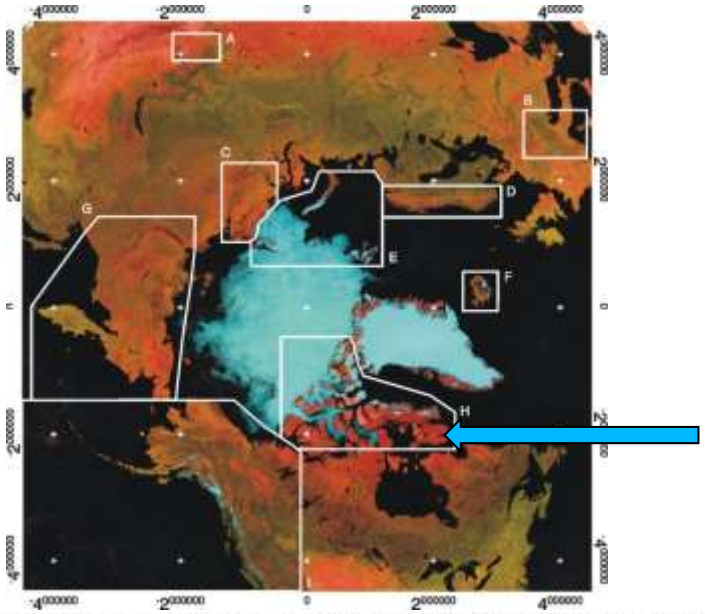
Creating 10-day Clear-Sky Composites over Canada
September 1-10, 2014

Single Granule

Accumulated Composite

Largest Biases in Canadian Arctic Archipelago

- Work was completed ~ 2009 and published in 2010, i.e. in pre-RGI era that started in 2012 after releasing first Randolph Glacier Inventory
- Analysis was based on the late summer CCRS MODIS composite imagery
- The largest absolute and relative biases were discovered between snow/ice land cover extent from several existing land cover schemes and CCRS MODIS product
- The discovered biases (~250,000 km^2) were equivalent to ~ 1/4 of province of Ontario territory!
- Is the any possibility that our results were wrong ?



Canadian Arctic Archipelago

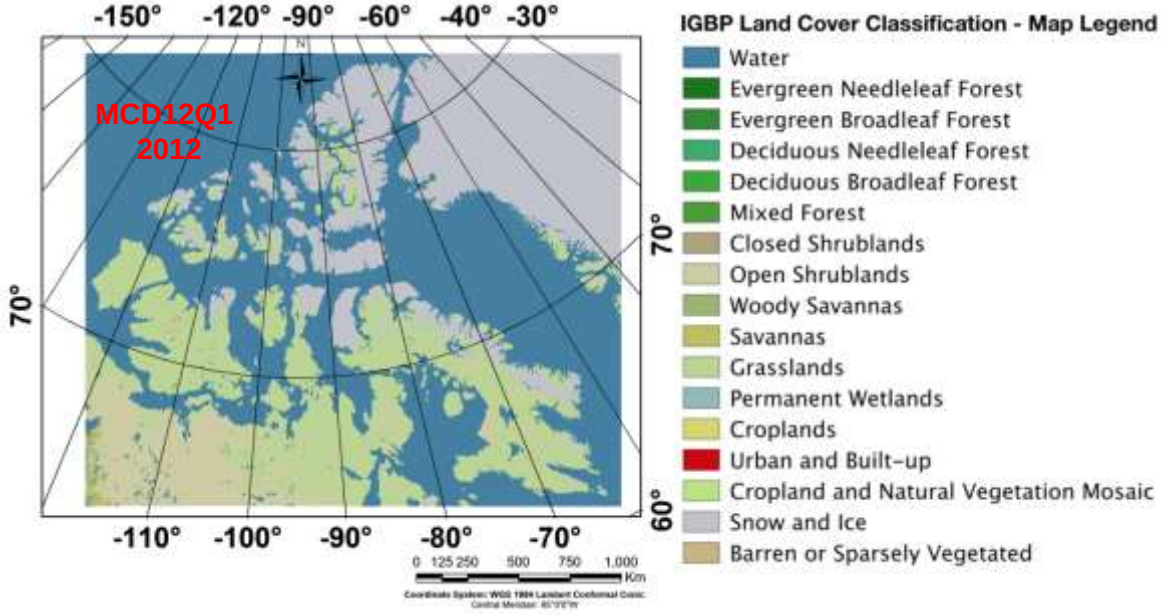
Table 4. Absolute and Relative Differences of PSI Extent as Extracted From the Global Land Cover (GLC-2000) as Well as Globcover Land Surface Classifications With Respect to PSI_{MODIS}[a]

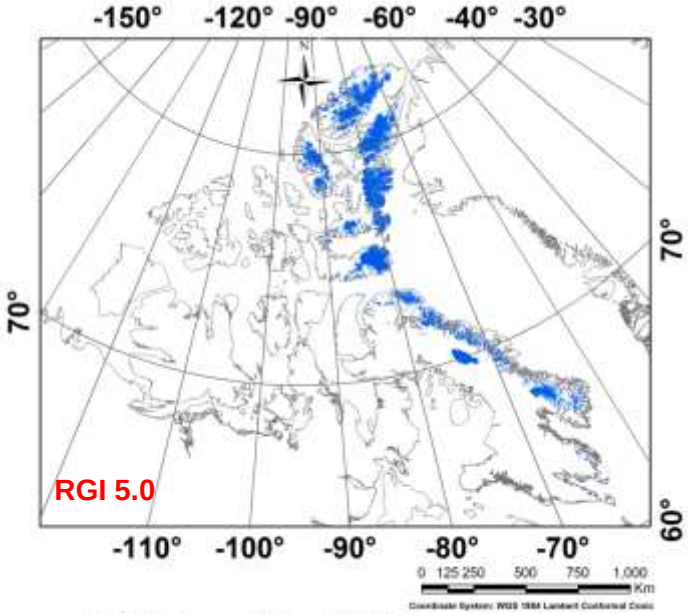
ROI	PSI_{MODIS} 2000 (km^2)	GLC-2000 Absolute (km^2)	GLC-2000 Relative (%)	PSI_{MODIS} 2005 (km^2)	Globcover 2005 Absolute (km^2)	Globcover 2005 Relative (%)
A	1.45×10^3	-1.06×10^3	−73	1.21×10^3	-6.85×10^2	−57
B	2.82×10^3	−5	0	2.25×10^3	3.15×10^2	14
C	4.96×10^2	3.31×10^2	67	1.66×10^3	-1.12×10^3	−68
D	1.08×10^4	-6.22×10^3	−57	5.66×10^3	-1.63×10^3	−29
E	1.11×10^5	-2.12×10^4	−19	1.03×10^5	8.25×10^4	80
F	1.12×10^4	4.77×10^2	4	1.06×10^4	1.22×10^4	115
G	9.94×10^3	-7.45×10^3	−75	2.72×10^3	5.55×10^2	20
H	2.12×10^5	2.71×10^5	128	1.80×10^5	2.32×10^5	129
I	1.67×10^5	1.42×10^4	8	1.16×10^5	3.98×10^4	34
All	5.26×10^5	2.50×10^5	47	4.23×10^5	3.64×10^5	86

[a]Differences indicated for GLC-2000 (Globcover) refer to PSI_{MODIS} in 2000 (2005). Positive (negative) values denote cases, where the land cover products overestimate (underestimate) PSI extent. Results are provided for all nine ROIs according to Table 1 and Figure 1.

Source: Fontana, Trishchenko, … Wunderle, 2010.
JGR Surface. VOL. 115, doi:10.1029/2010JF001664.

CCRS MODIS Snow/Ice in Canadian Archipelago vs MOD12 Land Cover during RGI Era

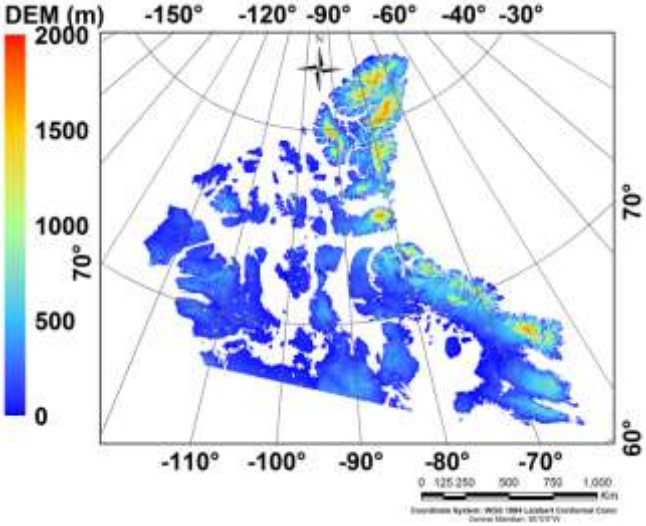




Standard MODIS land cover product

Channan, S., K. Collins, and W. R. Emanuel. 2014. Global mosaics of the standard MODIS land cover type data. U. of Maryland and the Pacific Northwest National Laboratory, College Park, Maryland, USA. **http://glcf.umd.edu/data/lc/**

Visual discrepancies over Canadian North between CCRS/MODIS and the standard MODIS product MCD12Q1 still can be noticed



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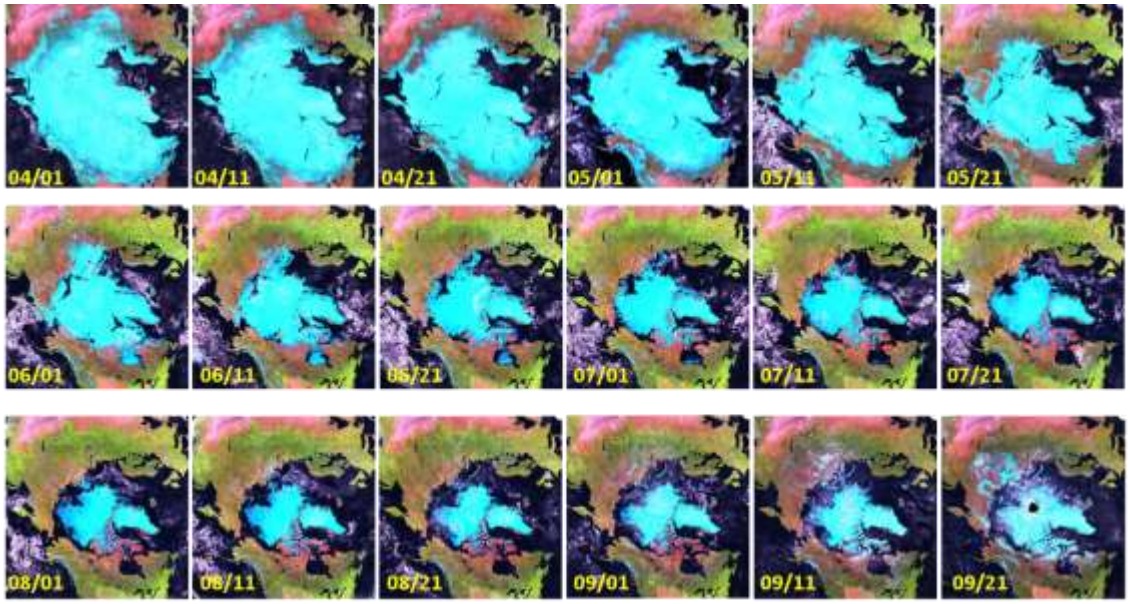
New Approach for Snow/Ice Mapping: From Sequence of Clear-Sky Composites to Probability Map

2014



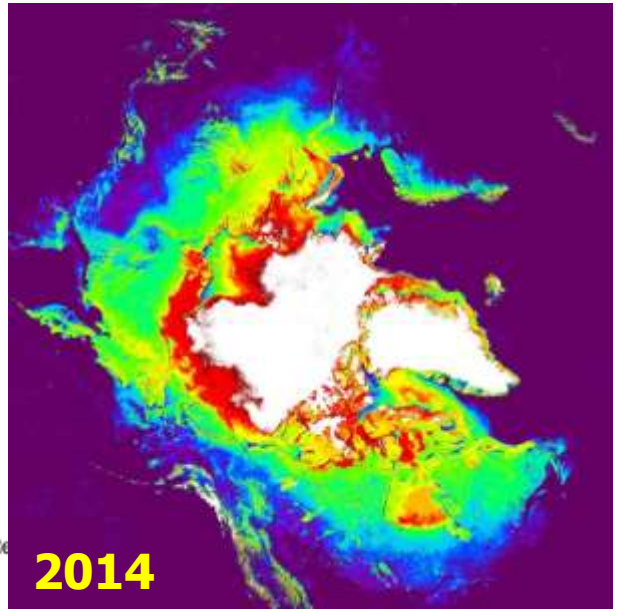
Probability P=
(Nsnow&ice)/MaxNumber

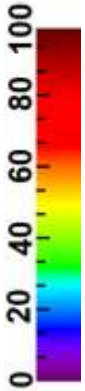
The Idea is

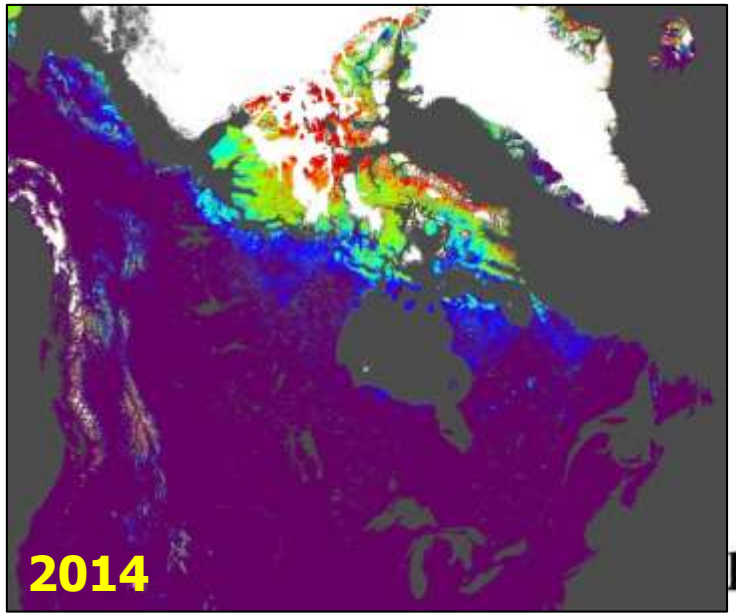
100% (or high enough value) probability ensures that snow/ice is present during the entire melt season and is not a result of ephemeral snow falls or scene ID artefacts.

Annual Minimum Snow/Ice (**MSI**) Extent is derived as area with P=100% (or above threshold P_0)

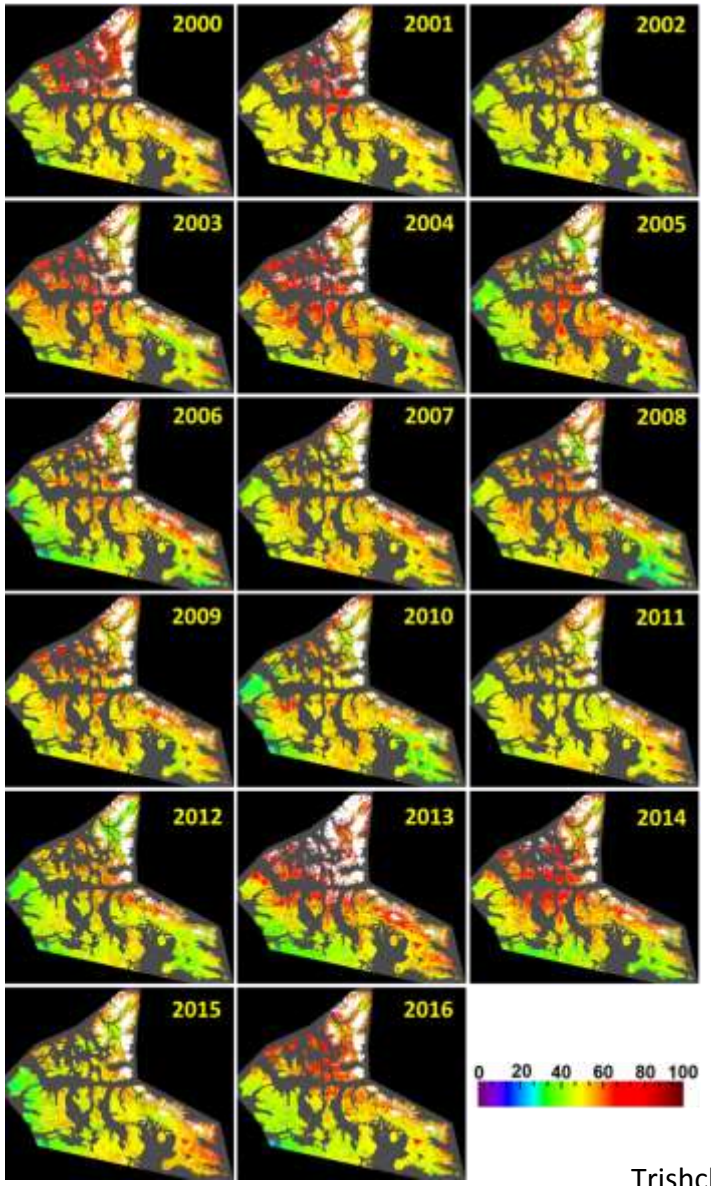
Trishchenko, A.P., et al 2016. *Can J Remote Sens*. 2016. 42(3), 214-242

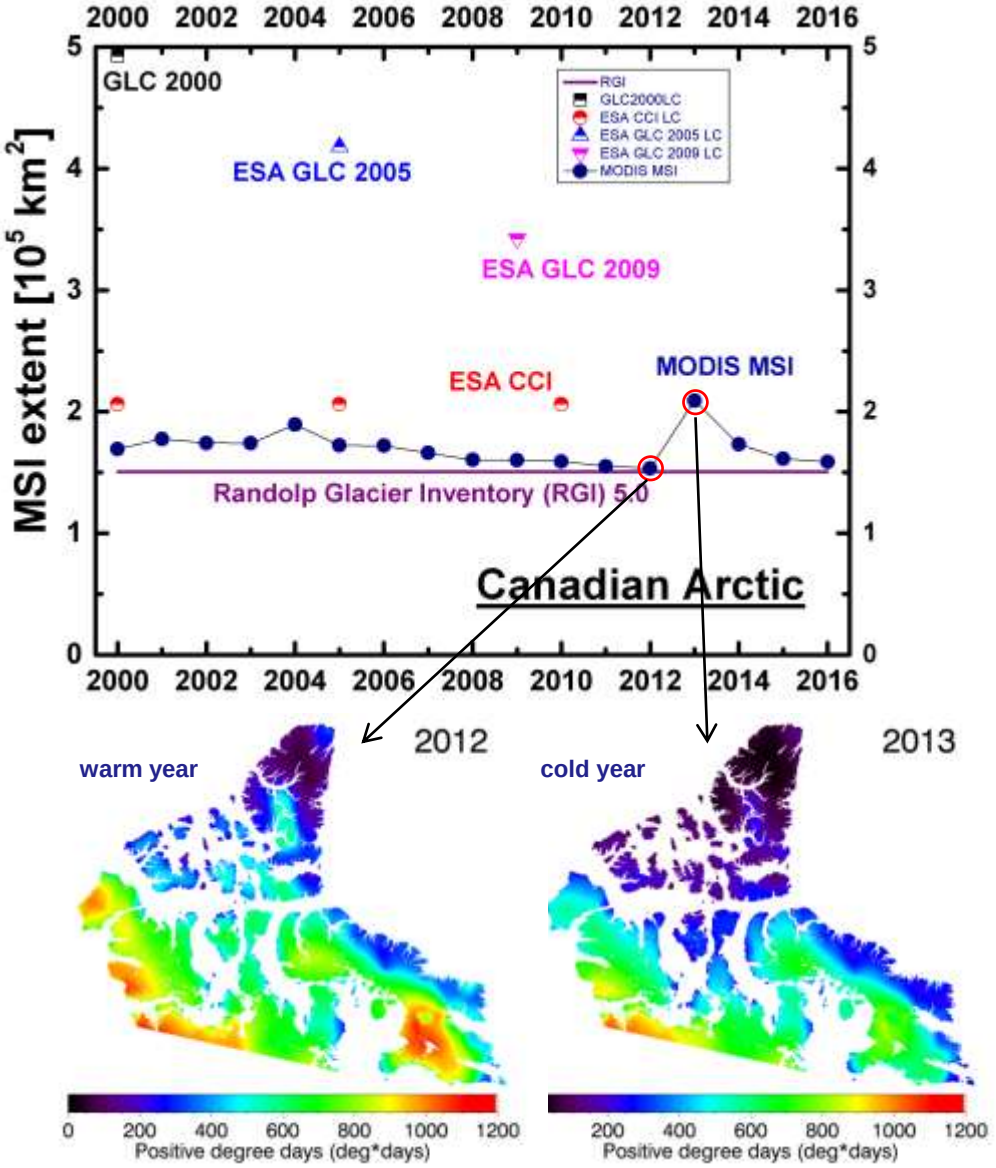






MSI Dynamics over Canadian Arctic Archipelago





Trishchenko, A.P., et al., *Can J Remote Sens*. 2016. 42(3), 214-242
Trishchenko and Wang, 2017 To be submitted *J.Clim*

CCRS MODIS MSI vs GLC 2000, ESA GlobCover and ESA CCI

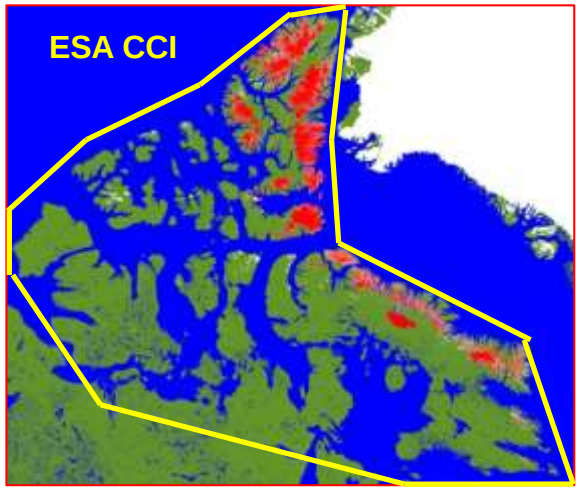
Significant differences were found between CCRS MODIS MSI and several global **LC maps**

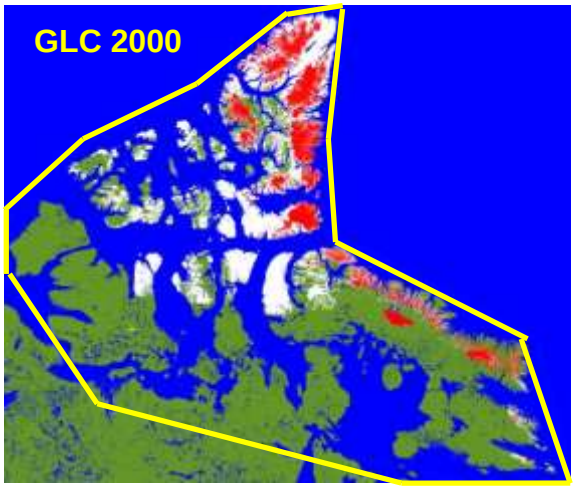
6 LC maps were compared with our results over the Canadian Arctic region

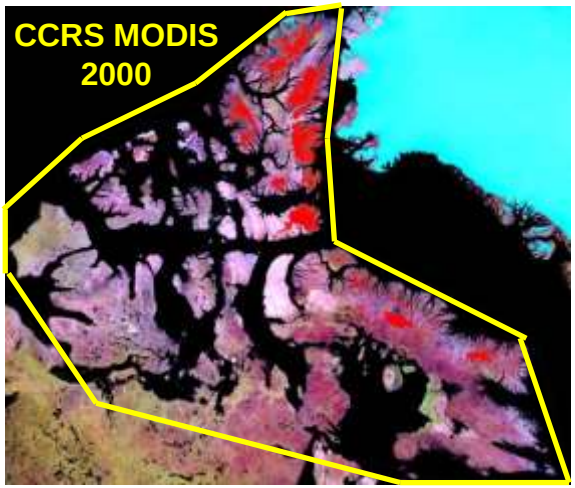
Minimum area - ESA CCI 2.06×10^5 km^2

Maximum area - GLC 2000 4.93×10^5 km^2 =====➔ CCRS MODIS - 1.69×10^5 km^2

RGI 5.0 area (in red) 1.51×10^5 km^2



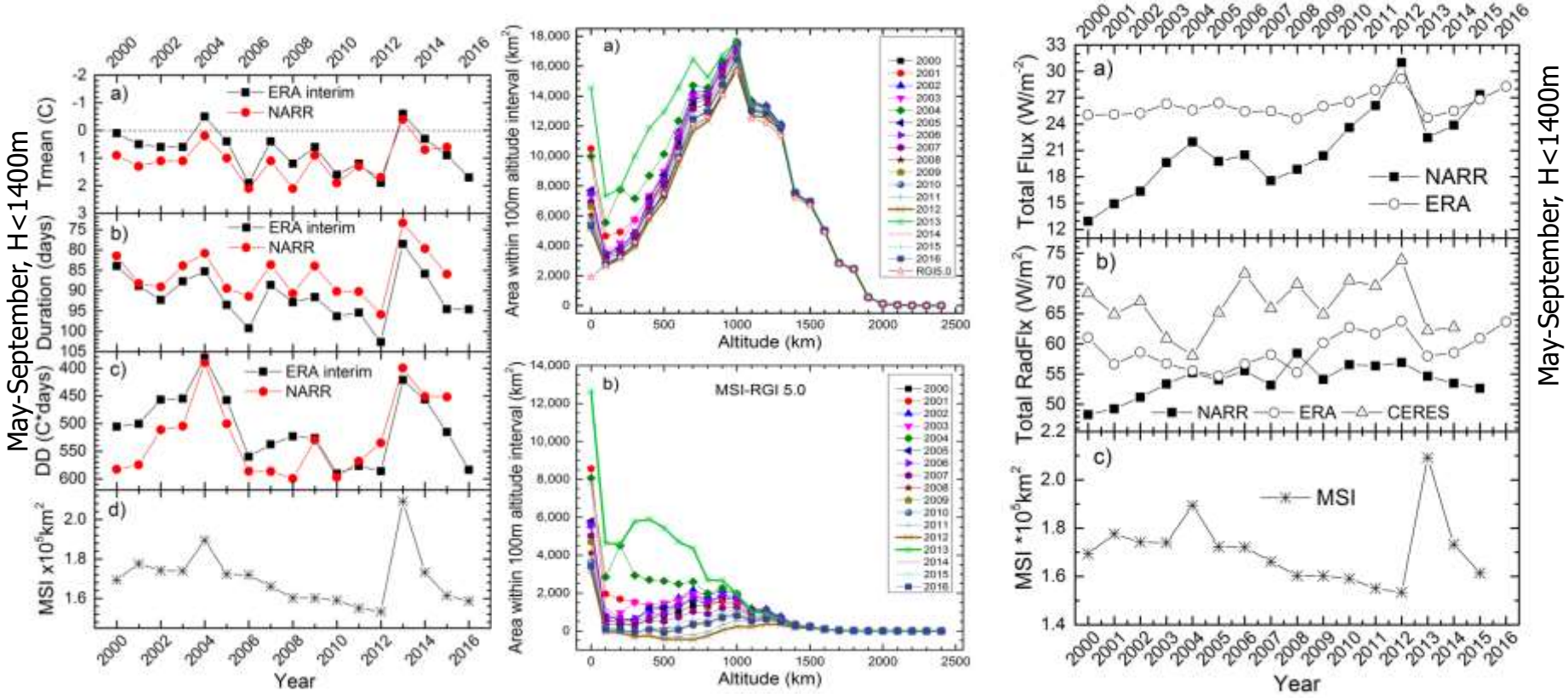




- GLC-2000 overestimated snow/ice extent by **194% (325,400 km^2)** for the Canadian Arctic. This bias is equivalent to ~ 1/3 of province of Ontario territory.
- The biases over the entire Canadian landmass (excluding Greenland) relative to our results are
  - **135% (3.7×10^5 km^2) - GLC-2000**
  - **113% (3.0×10^5 km^2) - ESA Globcover 2005**
  - **89% (2.2×10^5 km^2) - ESA Globcover 2009**
  - **28% (0.8×10^5 km^2) - ESA CCI datasets**

Trishchenko, A.P., et al., *Can J Remote Sens*. 2016. 42(3), 214-242

MSI and Climate Variations

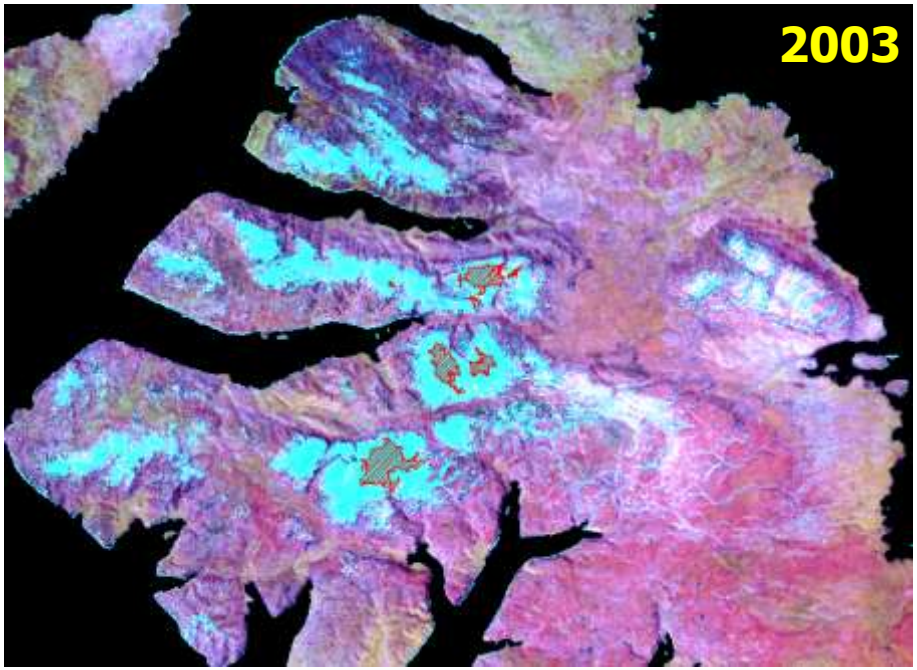


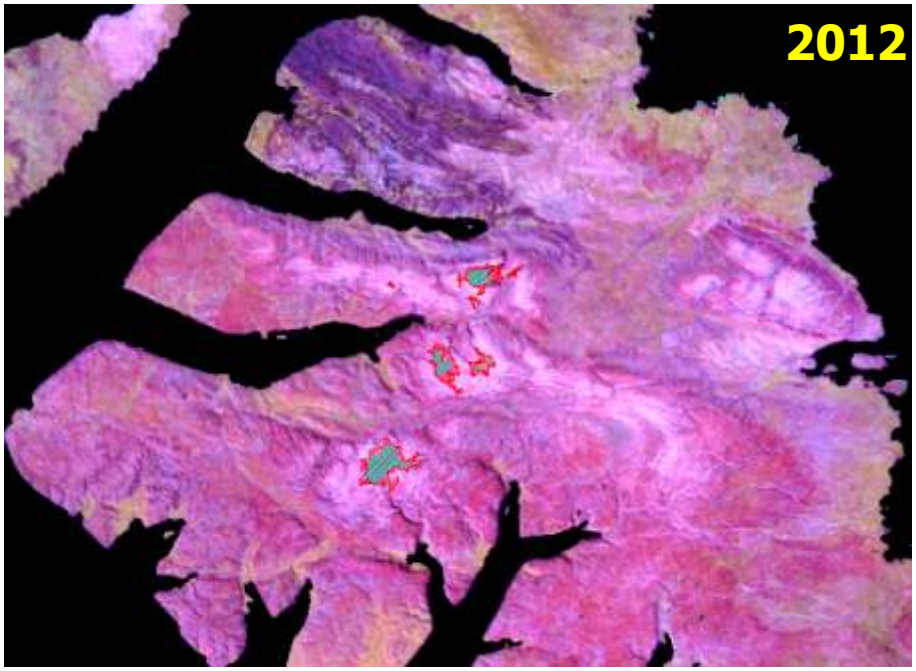
	Parameter									
	Taver		L		P		Total nets flx		Total net srf rad flx	
Dataset	corr r	p-value	corr	p-value	corr r	p-value	corr r	p-value	corr r	p-value
NARR	-0.70	0.0024	-0.65	0.006	-0.74	0.0012	-0.28	0.30	-0.24	0.37
ERA interim	-0.77	0.0003	-0.77	0.0003	-0.81	0.0001	-0.61	0.01	-0.55	0.023
CERES	-	-	-	-	-	-	-	-	-0.69	0.0046

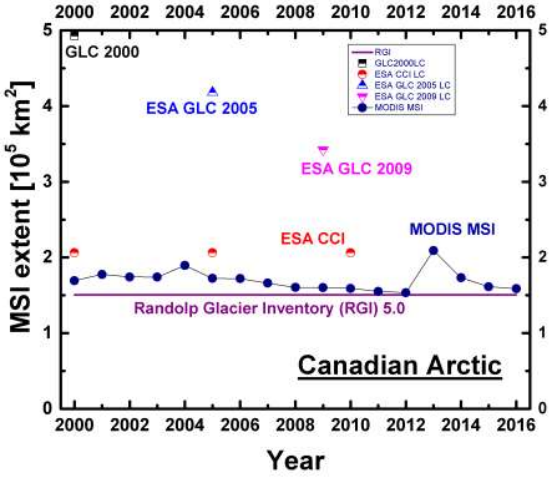
There is a good general (negative) correlation between summer Minimum Snow/Ice (MSI) extent in the Arctic and the warm season temperature, radiative and net fluxes distributions.

Trishchenko and Wang, 2017 To be submitted to *J.Clim*

Year-to-Year Variability in MSI: Melville Island







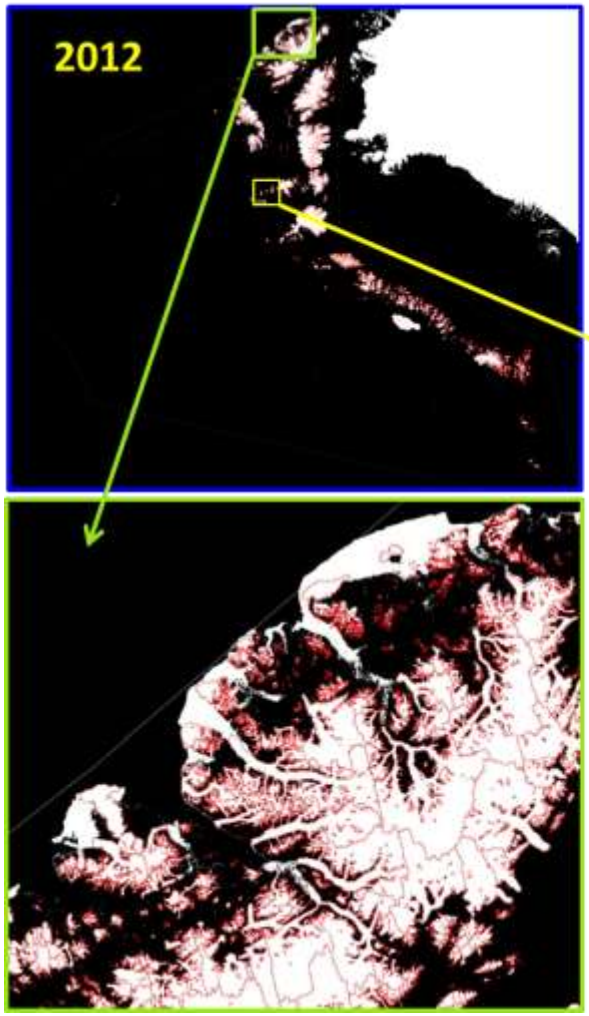
The interannual variations in the MSI extent in the Canadian Arctic Archipelago and comparison with the latest Randolph Glacier Inventory RGI 5.0 showed two important facts:

1) semi-permanent snow which persists through the entire melting season is a significant component relative to the ice caps and glacier-covered areas;
2) MSI anomalies over Canadian Arctic correlate well with the local climate dynamics such as monthly and seasonal temperature and energy flux anomalies.

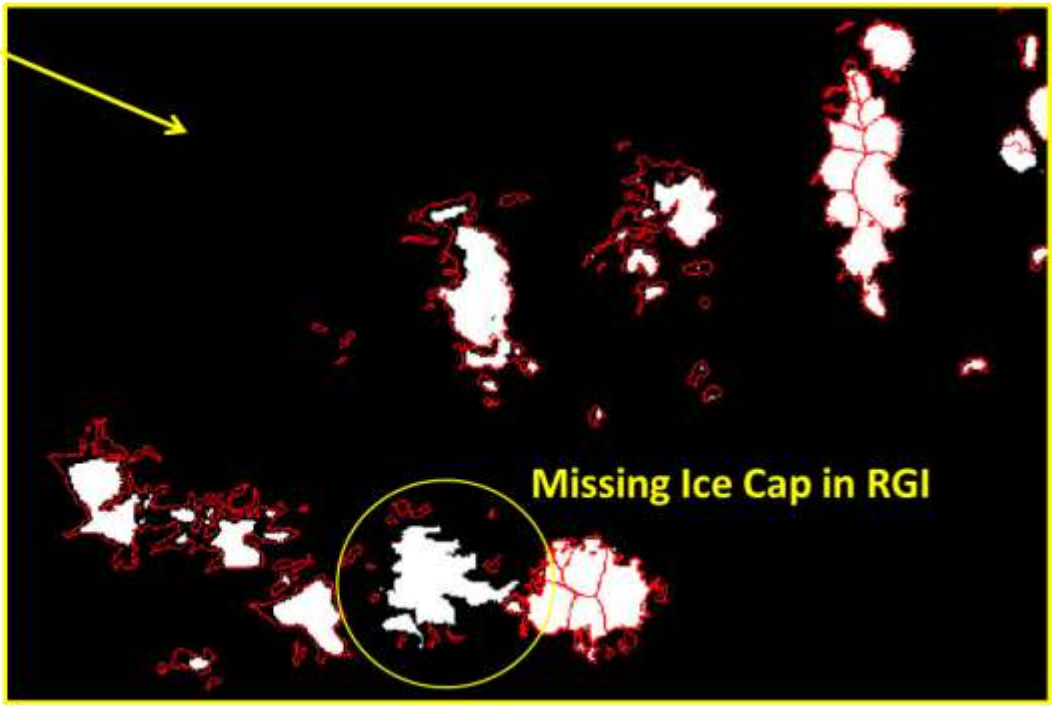
Trishchenko, A.P., et al., *Can J Remote Sens*. 2016. 42(3), 214-242

Canada

Value of 250m CCRS MODIS MSI results for RGI



- Missing ice cap has been identified in the IPCC AR5 glacier inventory RGI 4.0 ~ 126 km^2
- Reported to RGI chairs
- Corrected in new release RGI 5.0
- **Additional analysis is ongoing : Anna Regan et al.**



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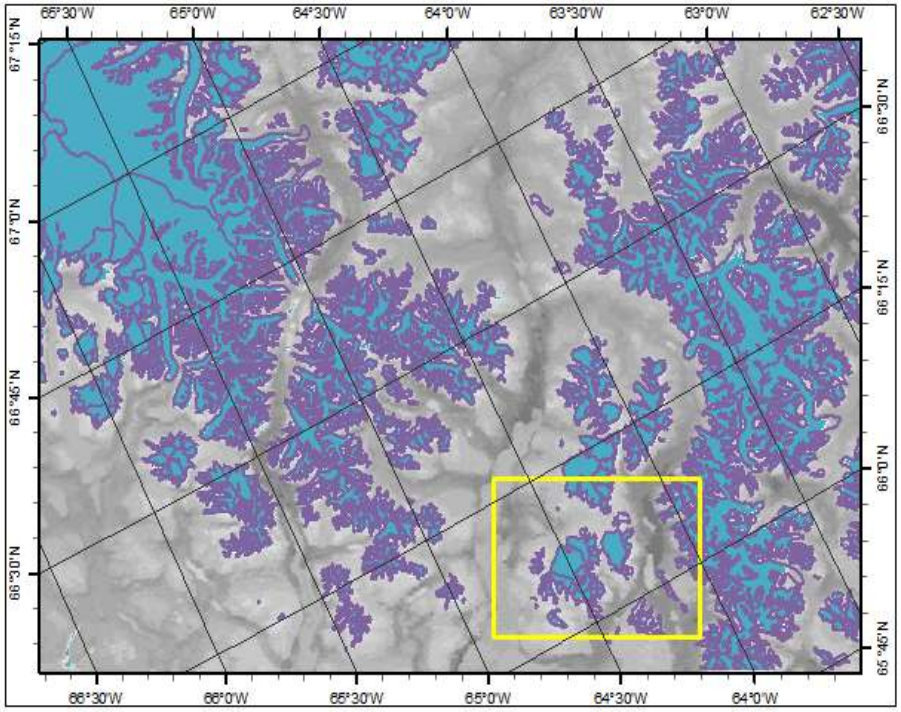
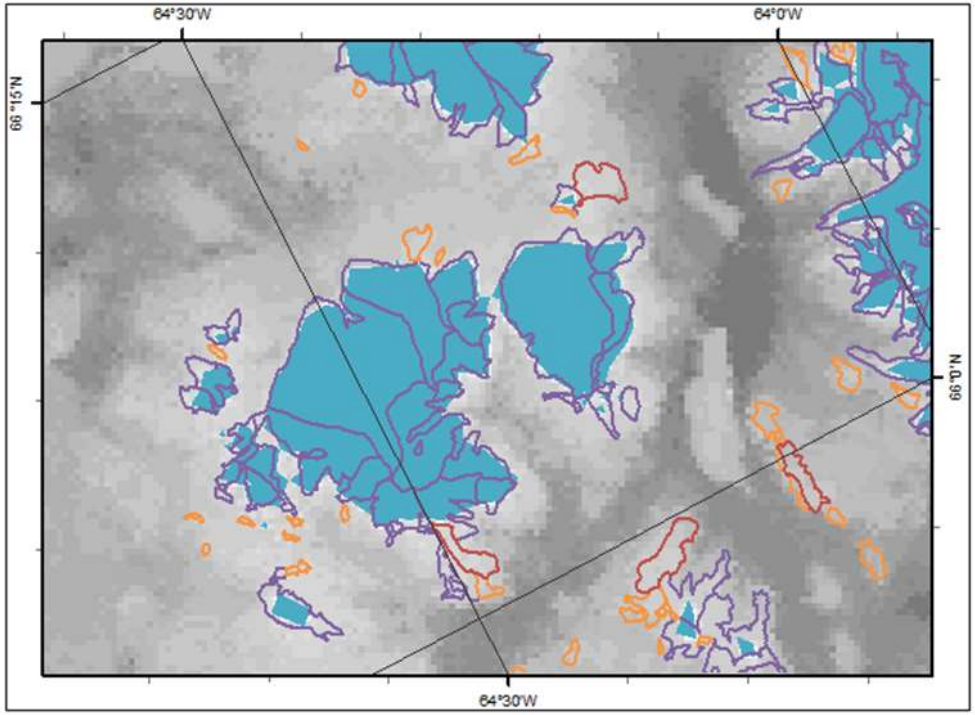
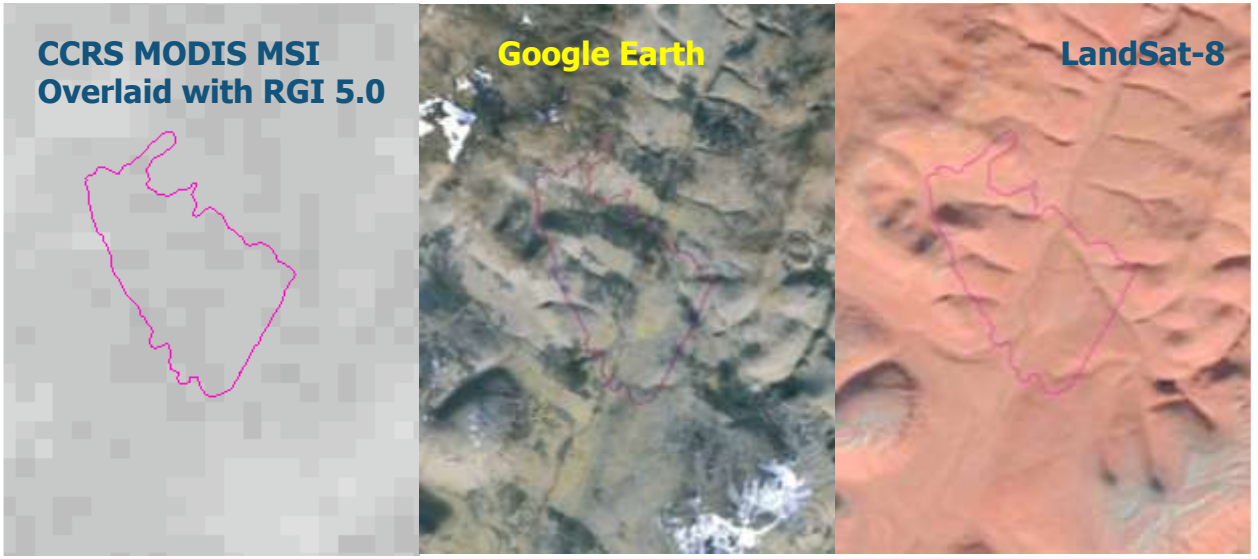
Vectorized CCRS MODIS MSI vs RGI 5.0





17 potentially melted RGI 5.0 glaciers with size >2 km² were identified based on CCRS MODIS MSI over Canadian Arctic RGI regions (S&N)

Regan, A.M., Trishchenko, A.P., Woulf, J., McClacherty, S., 2016. Initial validation of Randolph Glacier Inventory: Version 5.0 data over Canada using 250 m MODIS-derived Annual Minimum Snow/Ice extent; Geomatics Canada, Open File 28, 15 p. doi:10.4095/299351



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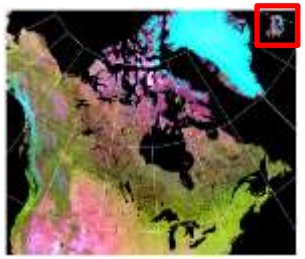
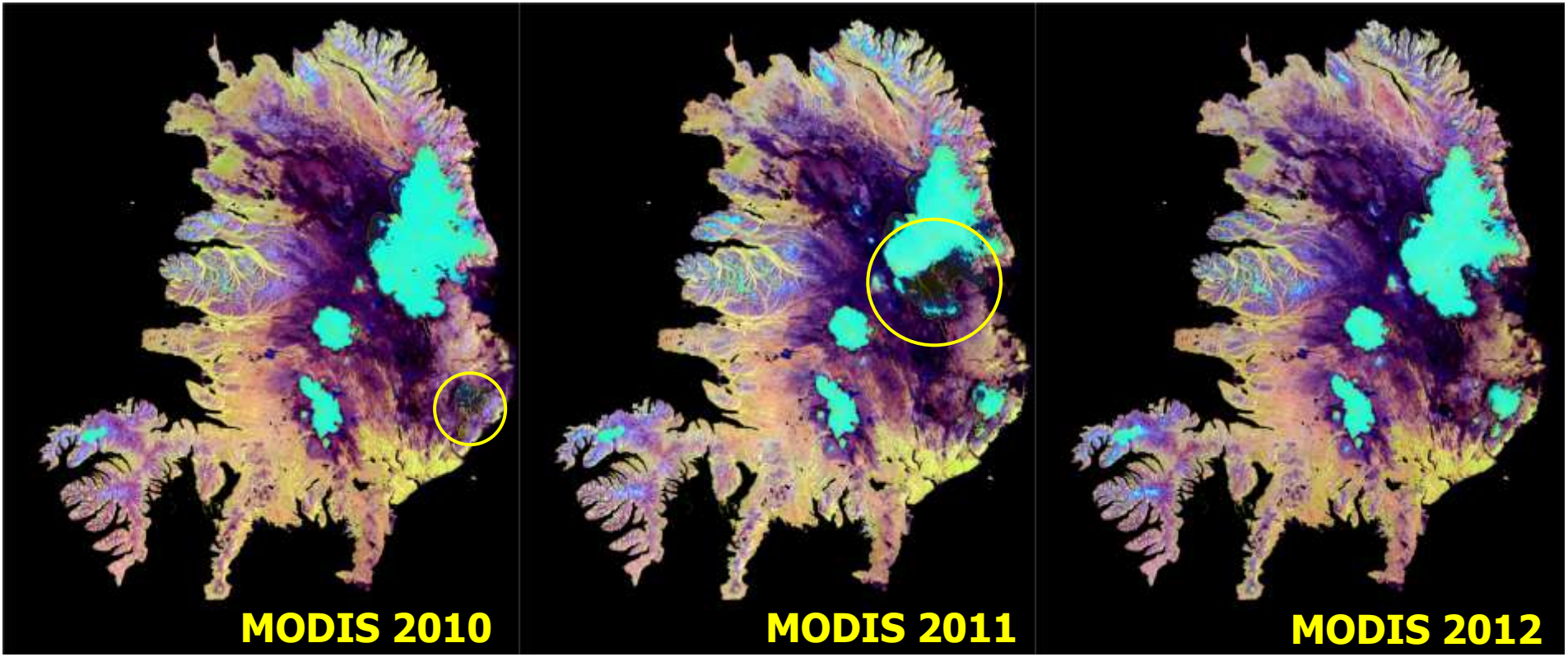
Optical Imagery Challenges: Iceland





2010 eruption of Eyjafjallajökull
2011 eruption of Grímsvötn

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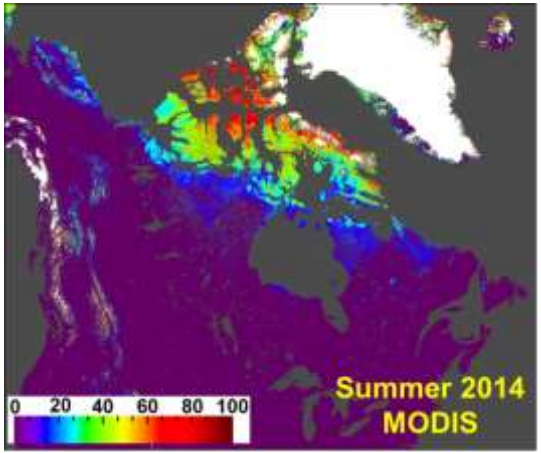
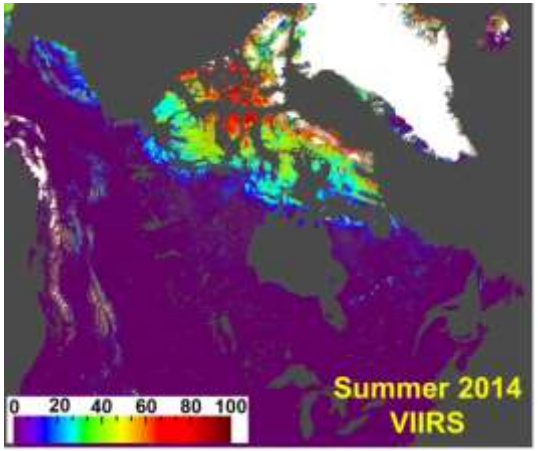
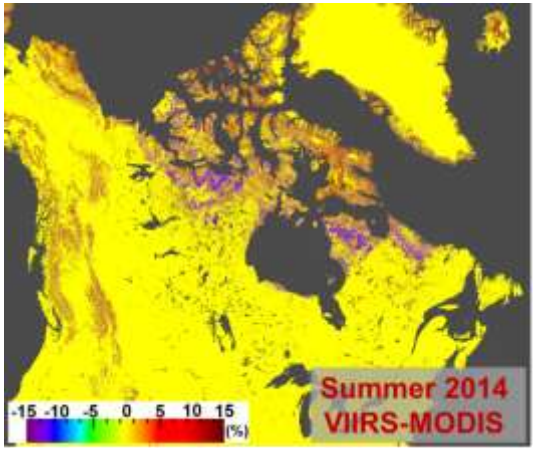
Continuing MODIS with VIIRS: Comparison







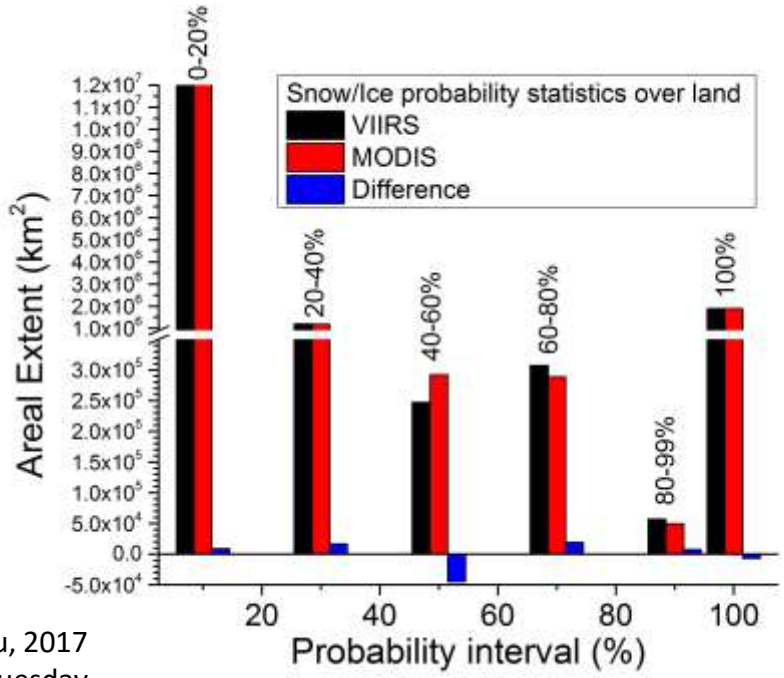
Visible Infrared Imaging Radiometer Suite (VIIRS) processing features at CCRSto compatibile to MODIS

- LCC (and potentially Circumpolar Arctic) projections compatible with CCRS MODIS formats
- 10-day compositing intervals
- Spatial resolution (re-mapping) for output products
- 250m for I-bands (originally at 375m)
- 500m for M-bands (originally at 750m)
- In-house re-projection tool
- In-house scene ID-mask
- In-house corrections and compositing scheme

Initial testing results

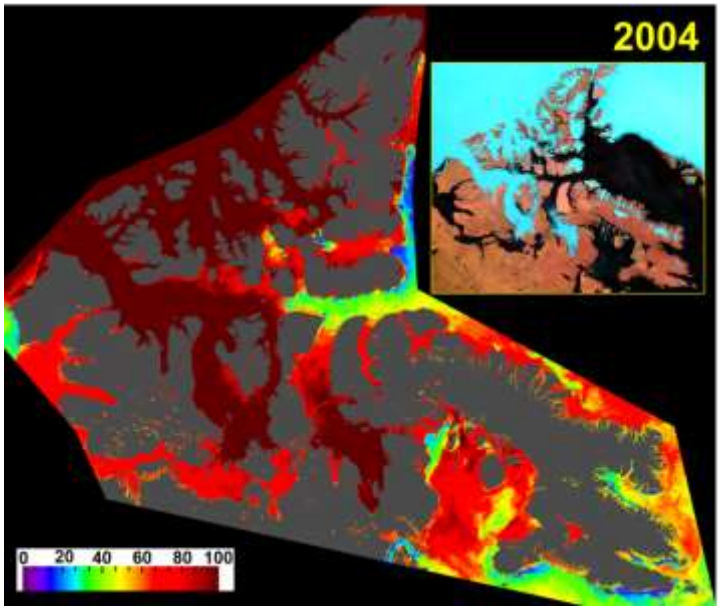
VIIRS cloud screening and compositing scheme also performs close to MODIS one;

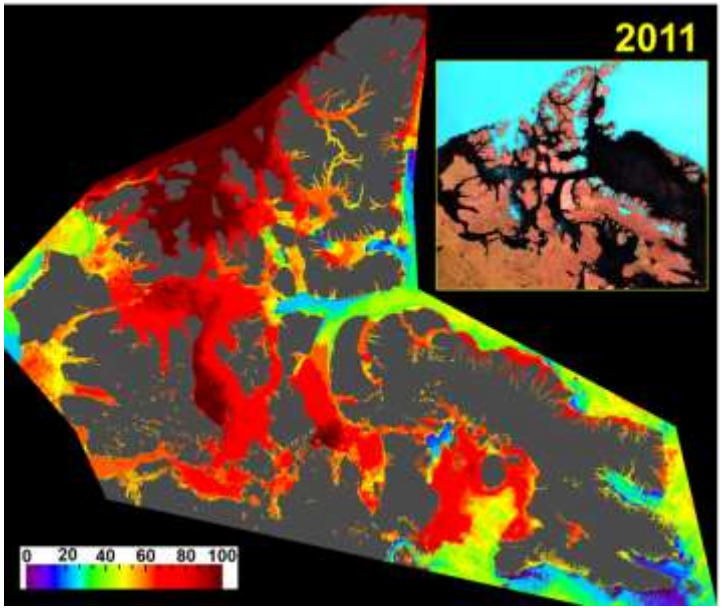
Difference in seasonal minimum snow/ice (MSI) extent between MODIS and VIIRS is less than 0.4%;



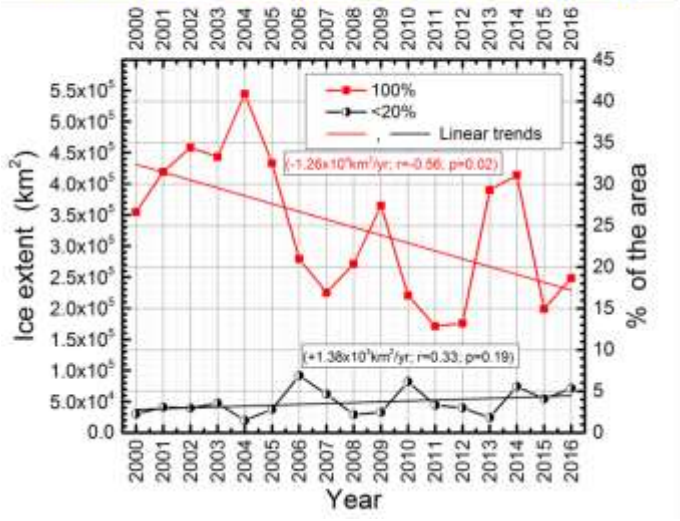
Trishchenko and Ungureanu, 2017
afternoon poster session, Tuesday

Probability Maps and MSI Extent: Application to Sea Ice in Arctic Archipelago





Interannual variations in landfast and sea ice extent in Canadian Arctic Archipelago



Developed method can be used to map the extent of Summer Minimum Ice (SMI) (i.e. landfast and sea ice that persists over the entre summer season from April to September) using warm season MODIS ice probability maps;

The average sea ice extent (100% probability) in the Canadian Arctic Archipelago region (as defined in this study) for 17-year period 2000-2016 was found to be 0.33×10^6 km^2 (24.8% of the water area) with minimum 0.17×10^6 km^2 (12.9%) in 2011 and maximum 0.544×10^6 km^2 (40.9%) in 2004. The open water (ice prob <20%) extent is on average 0.48×10^5 km^2 (or 3.6% of the total archipelago water area);

Analysis of sea ice probability over 17-year period revealed a significant (r=-0.56, p=0.02) negative trend (1.26×10^4 km^2 /yr decrease) for sea ice extent at 100% probability. A positive trend (increase 1.38×10^3 km^2 /yr) for areal ice extent with less than 20% probability was detected, although statistically less significant (r=0.33; p=0.19);

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Conclusions

- Probabilistic snow/ice mapping approach has been developed at the Canada Centre for Remote Sensing (CCRS) based clear-sky compositing of MODIS land bands imagery downscaled to 250m spatial resolution: Canada and Circumpolar Arctic region;
- Analysis uses the clear-sky composites for 6 months of warm season imagery (April-Sept) to produce snow/ice probability maps and to derive the **Minimum Snow/Ice (MSI) Extent** for each year;
- Substantial year-to-year variations in MSI from MODIS are observed;
    - Example of 17-yr statistics (since 2000) for Canadian Arctic region:
        - Mean MSI extent – 1.70×10^5 km^2
        - Minimum in 2012 – 1.53×10^5 km^2 close to RGI total glaciated area 1.51×10^5 km^2
        - Maximum in 2013 – 2.09×10^5 km^2
        - Std deviation – 0.14×10^5 km^2 (or **8%** of the mean)
        - Range (Max-Min) – 0.56×10^5 km^2 (or **33%** of the mean)
- CCRS MODIS MSI time series derived over 17-yr period (since 2000) established a baseline climatology that demonstrated consistency with variations of climate in the region;
- Several Land Cover maps were analyzed. Significant positive biases relative to our results and RGI maps in Canadian Arctic region were found in some cases (> 300,000 km^2);
- Developed methodology can be recommended to Glacier Scientific Community as a **source of annual updates and the first order validation data source for the RGI**;
- Preliminary analysis showed that properly processed imagery from VIIRS sensor on SNPP produced results that are consistent with MODIS and therefore can be used for continuing MODIS MSI time series into the future.

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MODIS and CERES data were acquired from NASA

VIIRS data were acquired from NOAA CLASS

NARR and ERA Interim Reanalysis data were used

Land Cover maps from ESA GlobeCover and ESA CCI projects were used

Land Cover map GLC-2000 from Joint Research Center were used

Vector layers from GSHHG - A Global Self-consistent, Hierarchical, High-resolution Geography Database were used

Glacier vector data from Randolph Glacier Inventory 4.0 and 5.0 were used

Work is currently conducted under the CCRS project on Long-Term Satellite Data Records (LTSDR) and the NRCan Climate Change Geoscience Program (CCGP)

250m Spatial Resolution

- GCOS Observation Requirements in WMO/CEOS Database (incl ECVs)

	Goal	BT	Max	Obs Cycle Required	OC BT	OC Min	Delay R/BT/Max	Acc R/BT/Max
Glacier	**30m**	**45m**	**100m**	**1yr**	**1.5yr**	**5yr**	**1 / 1.5 / 2 yr**	**5% / 7% / 10%**
Snow	**100m**	**450m**	**10km**	**24h**	**75h**	**1mon**	**30h / 70h / 15d**	**5% / 7% / 10%**

- The WMO requirements are good. Are they realistic and consistent ?
  - High-resolution sensors (LandSat etc) do not have sufficient frequency of observations to adequately observe glaciers under clear-sky conditions at the end of melt season, i.e. in snow-free conditions;
  - For example, Landsat revisit cycle is 16 days and swath width is ~ 185 km;
  - Cloud probability normally >60% or more in the polar and mountain regions.
- Moderate resolution sensors like MODIS and VIIRS have 250m &375m bands that can deliver multiple daily images globally;
- MODIS and VIIRS data streams have very significant potential to deliver good quality information about annual minimum snow&ice extent in the mountain regions.
- 250m resolution corresponds to ~ 1:500,000 - 1:1,000,000 map scale, or ~ 50 -100 DPI.