Model-Data Comparison for the Arctic Using CICE, CASIE and IceBridge Data

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Talk dedicated to the memory of John Heinrichs

who observed the Arctic Sea Ice

and loved to think about its physics and complexity

Thanks to my collaborators and students ...

Geomath Team and former Geomath Team: Aris Sheiner, Jeff Jennings, Katherine Schneider, Phil Chen, Bruce Wallin (now NMTech), Ian Crocker (now NEON), Maciej Stachura, Alex Weltman, Lance Bradbury, Alex Yearsley, Griffin Hale, SeanOGrady, Steve Sucht, Scott Williams (now google)
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... and for support through

- Los Alamos Institute for Geophysics and Planetary Physics
- NASA Cryospheric Sciences
- University of Colorado UROP Program

APPROACH

Using Geomathematics

- to Connect Science and Engineering
- to Connect Data Analysis and Numerical Modeling

→ Applying Spatial Statistics to Design Cryospheric Observations, Instrumentation, Satellite, Airborne and Field Campaigns

← Understanding Environmental Change through Geomathematical Analysis of Remote-Sensing Data

Models and Observations

- Comparison between model results and observations
  $\rightarrow$ Validation of physical concepts
- History
  - physical understanding of sea-ice processes was ahead of observation technology for decades
  - new remote-sensing technology now yields data which facilitate insight in sea-ice processes ("now" - in the last few years)
- Bridging the data world and the modeling world is not trivial:
  - requires parameterizations from data that match models
  - scale matching: high-resolution observations — models run on relatively low-scale grids
  - spatial coverage and generalization: models cover entire ocean or hemisphere — observation campaigns often localized
  - time scale: observations happen at a short, specific time frame — models cover decades or centuries
- Comparison can lead to
  - either validation of physical concepts
  - or need to include different physical concepts in sea-ice models
  - sometimes different parameterizations in models are sufficient

Topics

- Arctic sea ice coverage continues to decrease
- Change from a perennial sea-ice cover to a seasonal sea-ice cover? (ice-free summers in the Arctic)
  $\rightarrow$ Consequences for Arctic ecology and human living, for weather and climate everywhere
- Loss of old ice
- Need to study the more complicated processes and properties of Arctic sea ice:
  - Deformation processes
  - Ridged ice (and rafted ice)
  - Melt-pond formation and localization
  - Relationships and interactions of the above processes

– Results from a collaborative project *Parameterization of Ridges and Other Spatial Sea-Ice Properties From Geomathematical Analysis of Recent Observations for Improvement of the Los Alamos Sea Ice Model, CICE*

Project Components

(1) Los Alamos Sea Ice Model, CICE (also: the Sea-Ice Component of CESM)
(2) Observations from UAS over Fram Strait (CASIE)
(3) Observations from NASA Operation IceBridge
(4) Mathematical parameterizations of observations that facilitate data-model comparison

Analysis Outline

(1) Data section
(2) How can we measure the area of deformed ice?
(3) Model - Data Comparison
(4) Definition revisited: What really is deformed ice?
(5) CASIE Image Analysis
(6) Melt ponds: Do ponds occur mostly on level ice, or do they occur on ridged ice as well?
(7) IceBridge Data Analysis

Survey campaigns and satellite missions
→ tiers of observations
SCALE

CASIE Experiment 2009
Fram Strait

CASIE – Characterization of Arctic Sea Ice Experiment

July/ August 2009 from a base in Nye Alesund, Svalbard

Objective: Collection of high-resolution microtopographic and roughness data

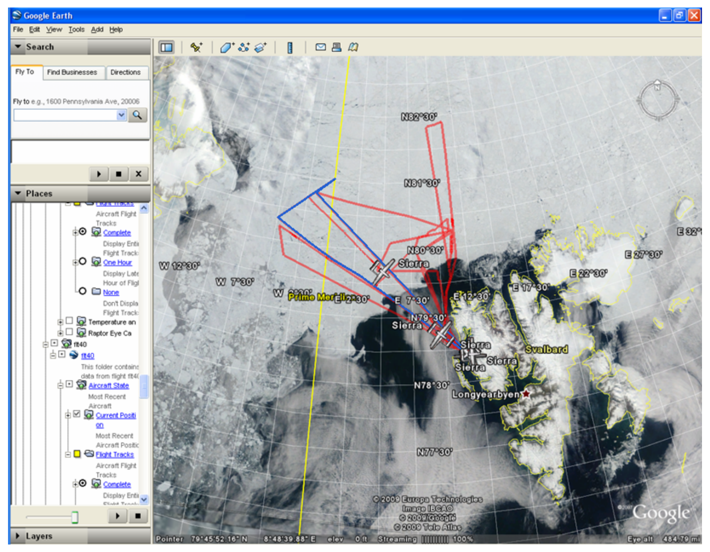
SIERRA UAV, NASA AMES Research Center: Matthew Fladeland and collaborators

Experiment science: Jim Maslanik (P.I.), Ute Herzfeld (Co-I.), David Long (Co-I.), R. Kwok (Co-I.), Ian Crocker, K. Wegrezyn

NASA IPY sea-ice roughness project: J. Maslanik, U. Herzfeld, J. Heinrichs, D. Long, R. Kwok

NASA AMES SIERRA: Ny Alesund, Svalbard

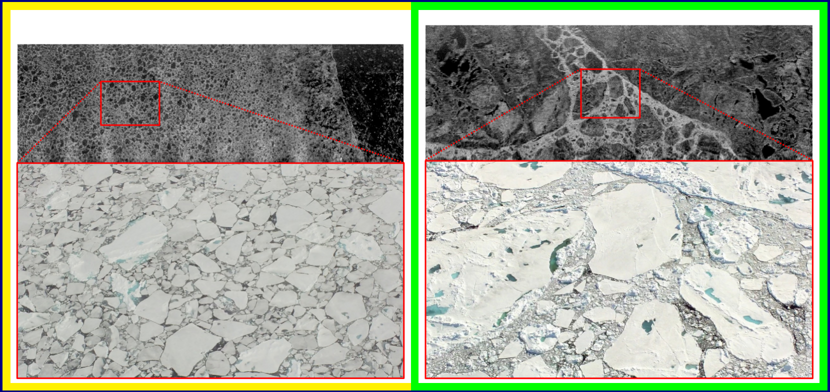
photograph by Ian Crocker



Flight tracks of the CASIE Experiment July/August 2009.

Data used here stem from flight 9 (marked blue).

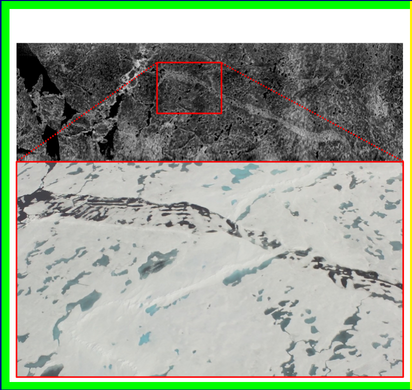
Sea Ice Types — Fram Strait, from CASIE 2009



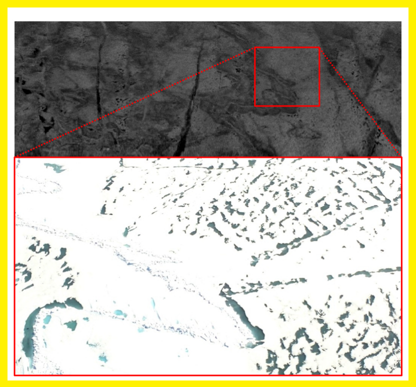
(a) near ice edge

(b) rubble – lead – floes

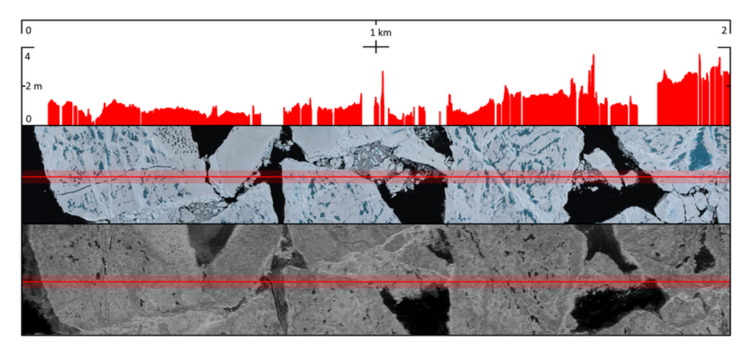
Sea Ice Types — Fram Strait, from CASIE 2009



(c) refrozen lead



(d) flooded floes – ridging



Laser altimeter data, videographic data and microASAR data from CASIE

(2) How can we measure the area of deformed ice?

Objectives of Ice Classification

(1) Characterization of ice provinces: Establish a unique quantitative description of each ice type

(2) Classification: Assign a given object to a surface class, using the characterization

(3) Segmentation: Create a thematic map by applying the classification operator in a moving window

Transfer to Modeling

(1) Parameterization of spatial sea-ice properties, based on characterization

(2) Summarize properties of ice types, based on classification

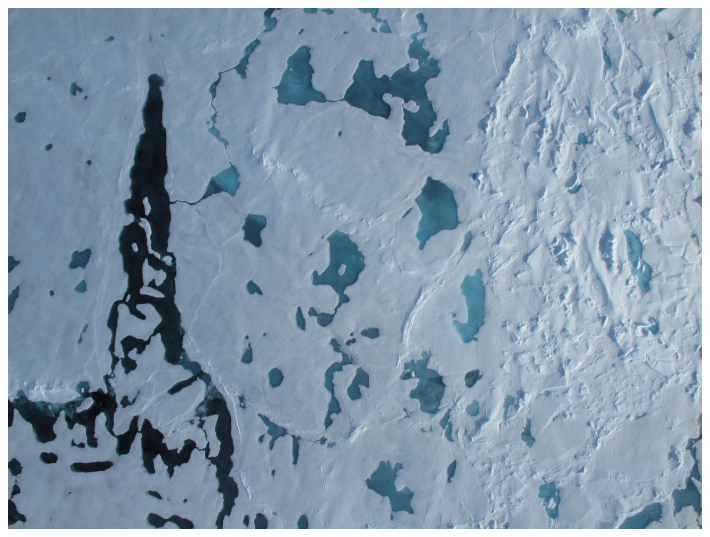
(3) Simplify regional ice-type distributions for model input at larger/ regional scale, based on segmentation

What is spatial surface roughness?

– a derivative of (micro)topography
  → characterization of spatial behavior

Why do we need spatial surface roughness?

– sub-scale information for satellite measurements
– indicator variable for other, harder to observe processes
– parameterization of sub-scale features or processes



CASIE image 20090725-15.36.22-IMG-9080.jpeg

(4.) How do we analyze surface roughness?

The analytically defined spatial derivative needs to be calculated numerically from a data set.

One way to do this:

$$\lim_{x \to x_0} \frac{z(x_0) - z(x)}{x_0 - x}$$

surface slope in a given location x_0

To characterize morphology, better use averages...

Definition of Vario Functions

$$V = \{(x, z) \text{ with } x = (x_1, x_2)\epsilon\mathcal{D} \text{ and } z = z(x)\} \subseteq \mathcal{R}^3$$

discrete-surface case or

$$V = \{(x, z) \text{ with } x\epsilon\mathcal{D} \text{ and } z = z(x)\} \subseteq \mathcal{R}^2$$

discrete-profile case

Define the first-order vario function v_1

$$v_1(h) = \frac{1}{2n} \sum_{i=1}^{n} [z(x_i) - z(x_i + h)]^2$$

with $(x_i, z(x_i)), (x_i + h, z(x_i + h))\epsilon\mathcal{D}$ and n the number of pairs separated by h.

Higher-Order Vario Functions

The first-order vario-function set is

$$V_1 = \{(h, v_1(h))\} = \underline{v}(V_0)$$

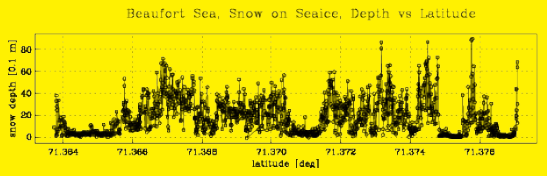
Then: get V_2 from V_1 in the same way you get V_1 from V_0. The second-order vario function is also called varvar function.

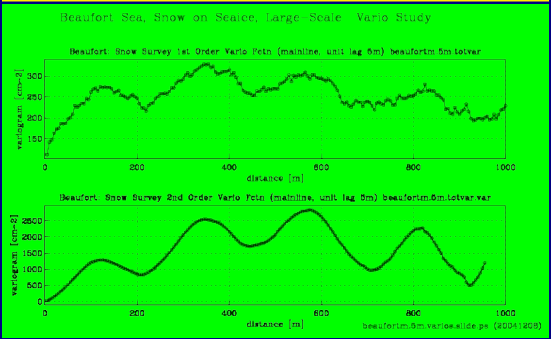
Recursively, the vario function set of order $i+1$ is defined by

$$V_{i+1} = \underline{v}(V_i)$$

for $i \epsilon \mathcal{N}_0$.

Beaufort Sea





Geostatistical Classification Parameters

significance parameters:

slope parameter:

$$p1 = \frac{\gamma_{max_1} - \gamma_{min_1}}{h_{min_1} - h_{max_1}}$$

relative significance parameter:

$$p2 = \frac{\gamma_{max_1} - \gamma_{min_1}}{\gamma_{max_1}}$$

pond – maximum vario value

mindist – distance to first min after first max

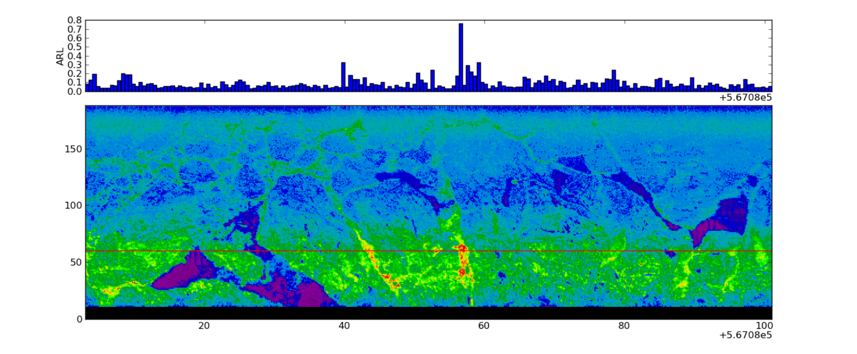
$$avgspac = \frac{1}{n} \sum_{i=1}^{n} \frac{1}{i} \; h_{min_i}$$

typically for $n = 3$ or $n = 4$

Roughness length approximation:

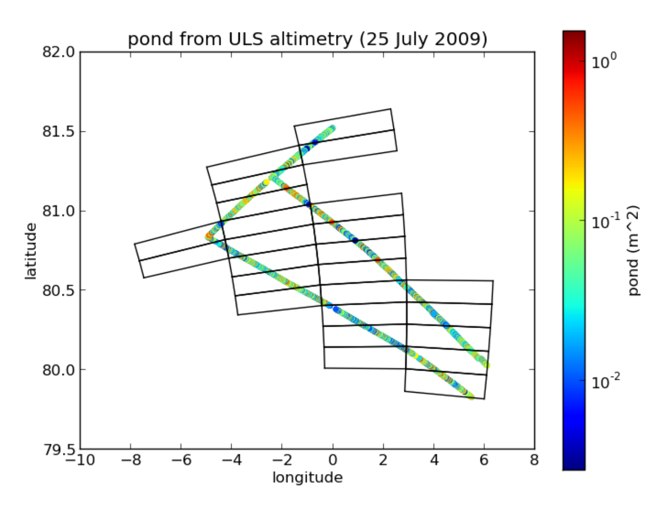
$$arl = \frac{1}{2}\sqrt{2pond}$$

ARL from altimetry and matching microASAR data



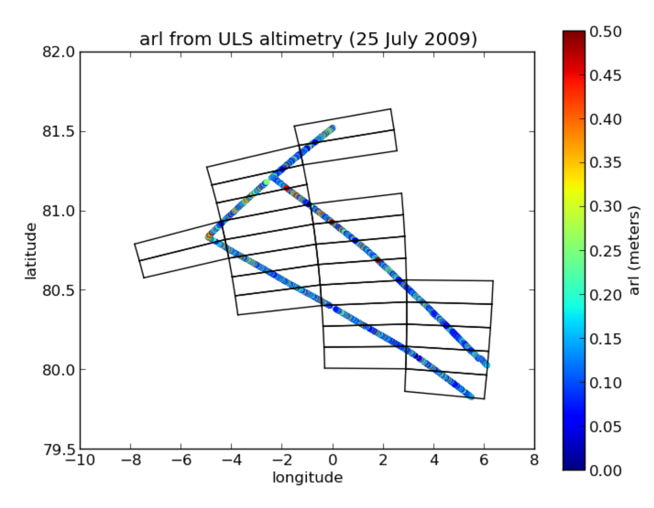
Segment 1 (msar104), Flight 9, 2009-07-25, CASIE 2009

CICE- CASIE Comparison: Ice-Surface Roughness (*pond*)



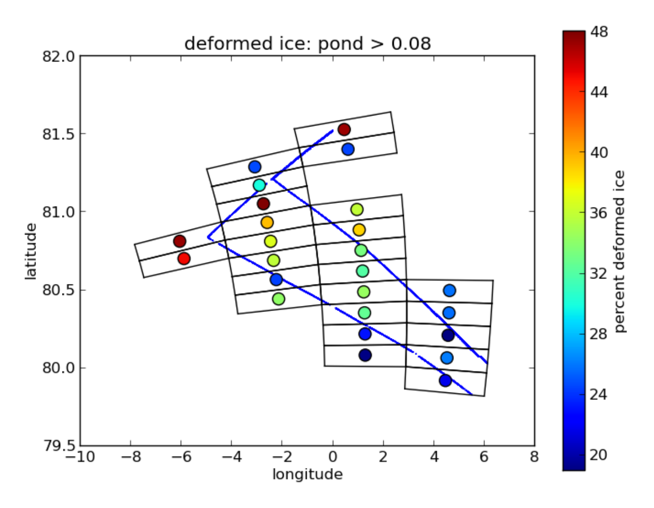
25 CICE grid nodes over sea ice; sea-ice water boundary determined using returned-signal counts

CICE- CASIE Comparison: Ice-Surface Roughness (arl)



25 CICE grid nodes over sea ice; sea-ice water boundary determined using returned-signal counts

CICE- CASIE Comparison:
Percent Deformed Ice Area from Laser Altimetry



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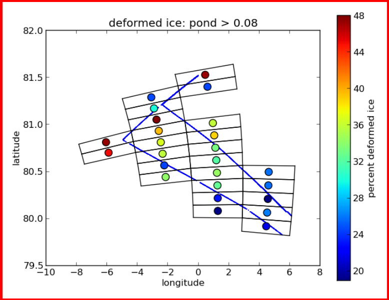
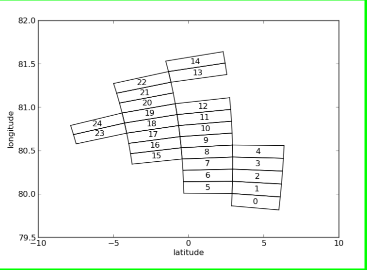
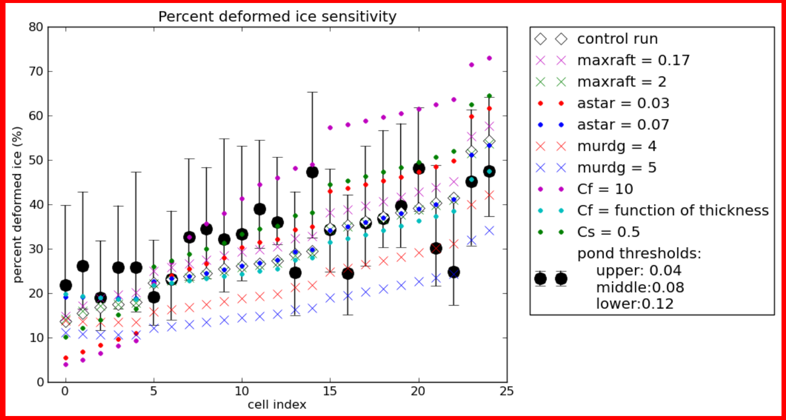




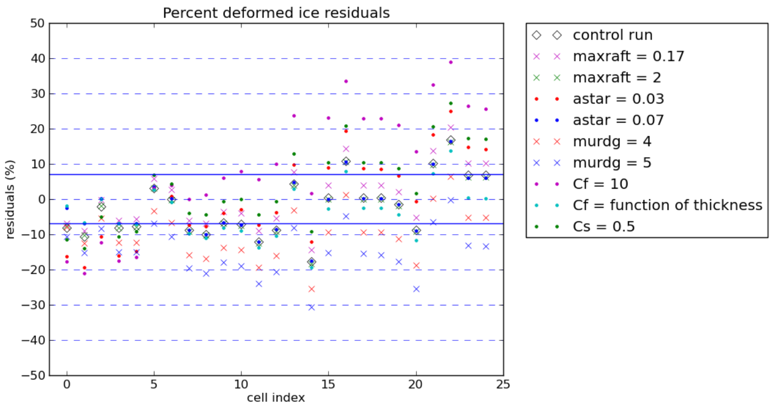
25 CICE grid nodes over sea ice; sea-ice water boundary determined using returned-signal counts

CICE-CASIE Comparison: Sensitivity Studies
Percent Deformed Ice Area from CICE and CASIE



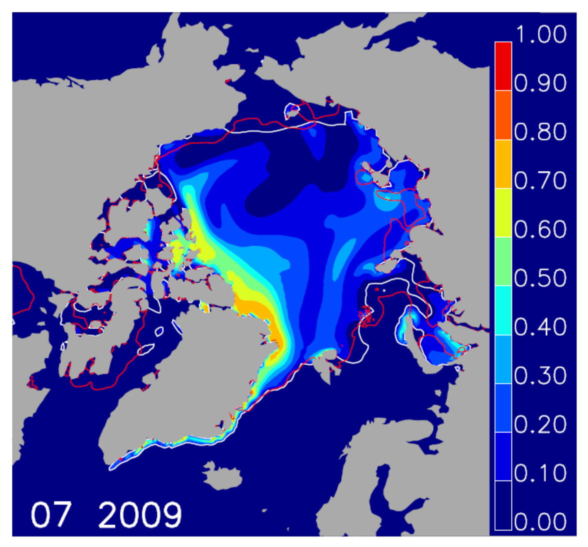
25 CICE grid nodes over sea ice

CICE-CASIE Comparison: Sensitivity Studies
Residuals of Percent Deformed Ice Area from CICE and CASIE

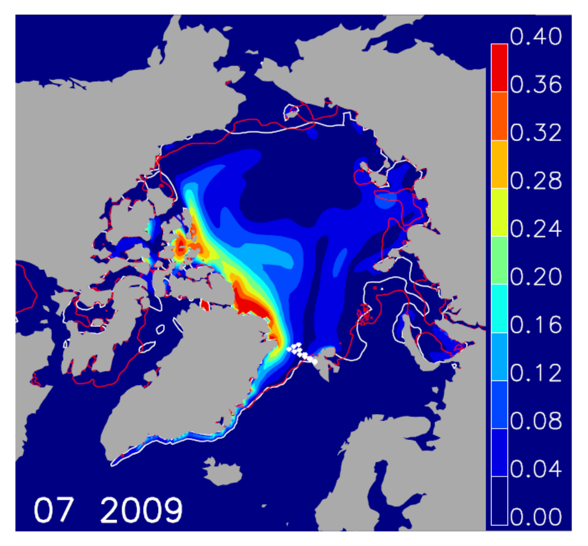


Results from model runs and data analysis match to within 7% of deformed ice area concentration when varying parameters in sensitivity studies (and to within 20% for control run)

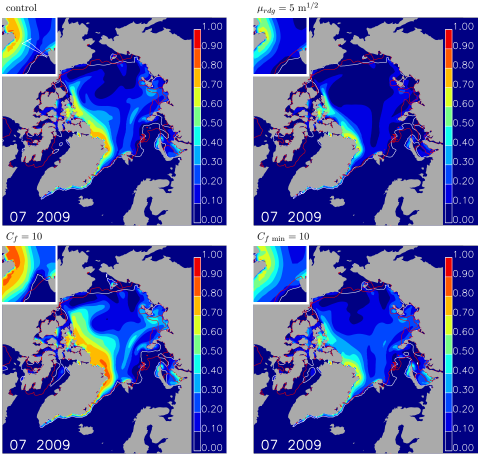
CICE Model Run For CASIE Flight 09 Time Deformed Ice Area Fraction – July 2009



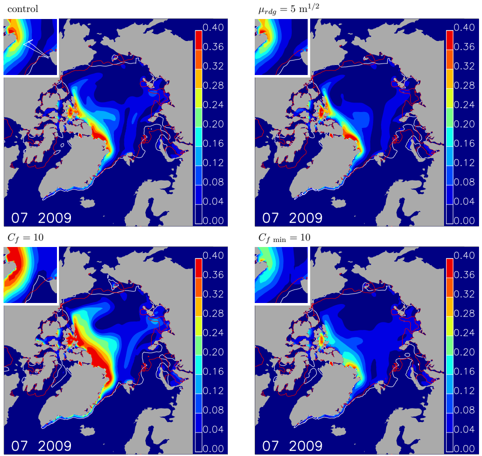
CICE Model Run For CASIE Flight 09 Time
Sail Height – July 2009



CICE Sensitivity Study
Ridged Ice – July 2009



CICE Sensitivity Study
Sail Height – July 2009



Deformed Ice Dependent on CICE Model Parameters

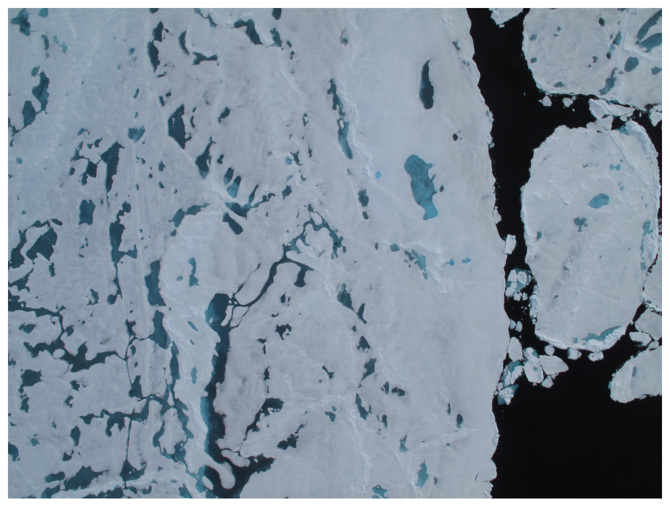
Parameter	Northern Hem.	Casie Mask (35 Nodes)
orginal	31.1634	38.1931
astar.03	32.4175	45.5128
astar.07	30.9051	39.2194
maxraft.17	33.0950	41.8181
maxraft2	30.7335	37.6406
murdg4	24.6877	27.6685
murdg5	20.2645	21.2877
Cf10	41.5542	63.9714
Cs.5	36.6809	50.2486

Deformed Ice Area for Entire Fram Strait Study Area Sensitivity to Roughness Thresholds

pond [m^2]	arl [m]	% ridged	% level
0.020	0.100	64.8	35.2
0.040	0.141	46.9	53.1
0.060	0.173	37.1	62.9
0.080	0.200	30.6	69.4
0.100	0.224	25.2	74.8
0.120	0.244	21.3	78.7
0.140	0.265	18.6	81.4

Definition revisited

What do we actually call "deformed sea ice"?

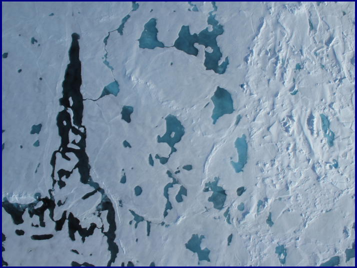


CASIE image 1-20090725-10-33-55-IMG-4580-R.jpg

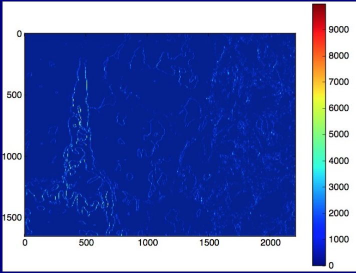
Approach for measuring deformed sea ice areas from imagery

- Use high-resolution CASIE imagery
- Geo-reference all images individually using GPS data
- Define a *pond*-filter that identifies ridge areas
- Apply this to images in all grid cells

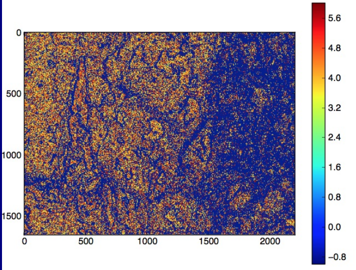
Geostatistical Classification Parameters Applied To Sea-Ice Image



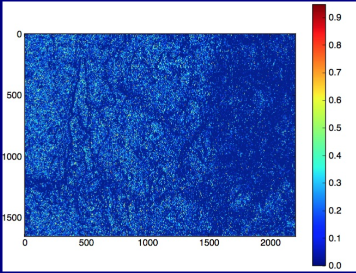
image



pond

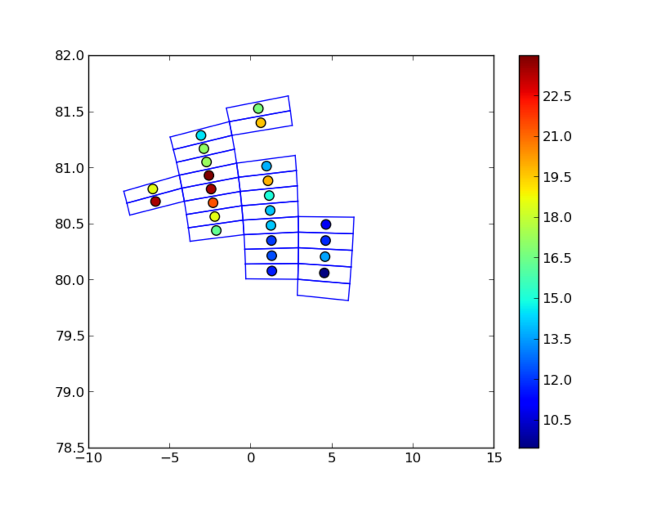


mindist



p2

CICE - CASIE Comparison: Percent Deformed Ice Area from Image Analysis



25 CICE grid nodes over sea ice

sea-ice water boundary determined using returned-signal counts

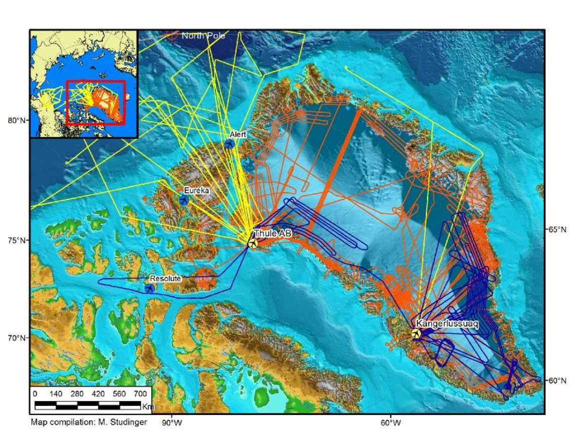
Deformed Ice from CASIE Images (*pond*)

Latitude	Longitude	% Ridged Ice
80.06551361	4.50762939	9.46214414035
80.08296967	1.27127075	11.6643353086
80.21040344	4.5546875	13.6099826824
80.2192688	1.26473999	12.3897421788
80.35453033	4.58929443	11.8910531342
80.35469818	1.24539185	12.0757602732
80.44387054	-2.15808105	16.299423827
80.48925018	1.21295166	14.1650751776
80.49788666	4.6111145	10.9840662275
80.56816101	-2.25061035	18.5388512147
80.62290192	1.16702271	14.1661271789
80.69143677	-2.35668945	21.4184618124
80.70297241	-5.90551758	23.4446026942
80.75563049	1.10736084	15.0469354395
80.81368256	-2.47665405	23.4854014599
80.81427002	-6.0753479	18.4906210044
80.88742828	1.03353882	19.9097706637
80.93487549	-2.61074829	23.9840593802
81.01826477	0.94525146	13.8140709211
81.05499268	-2.75927734	17.2569472543
81.17401123	-2.92260742	17.0840548983
81.29190826	-3.1010437	14.5342062246
81.40483093	0.58953857	19.6372618836
81.53162384	0.43930054	16.6952595206

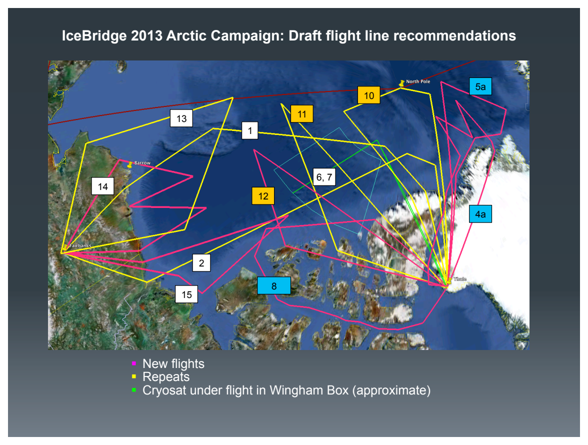
- from 25 nodes (ice-covered regions only)

- threshold for classification: $60 < pond < 200$ to determine ridged ice areas

NASA Operation Ice Bridge — Flight Tracks

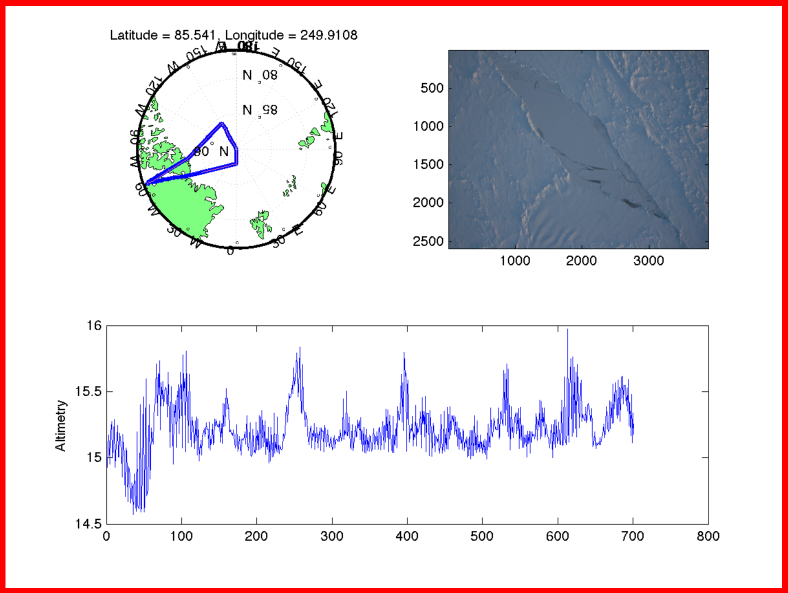


NASA Operation Ice Bridge — Flight Tracks

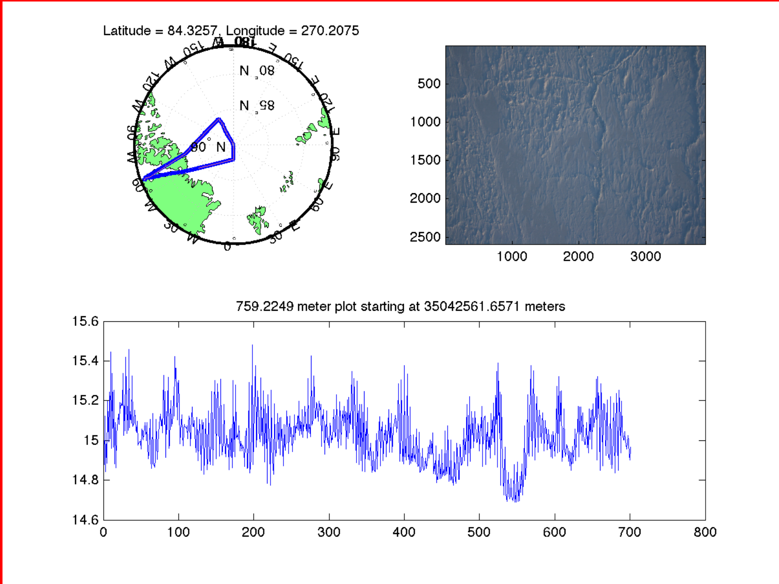


from Jackie Richter-Menge, Feb 11, 2013

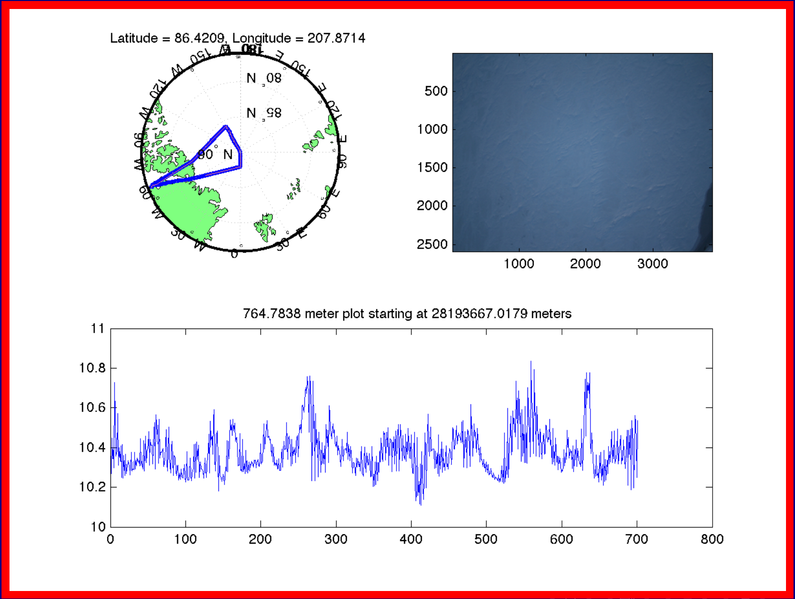
NASA Operation Ice Bridge — NorthPoleTrack 2013



NASA Operation Ice Bridge — NorthPoleTrack 2013



NASA Operation Ice Bridge — NorthPoleTrack 2013



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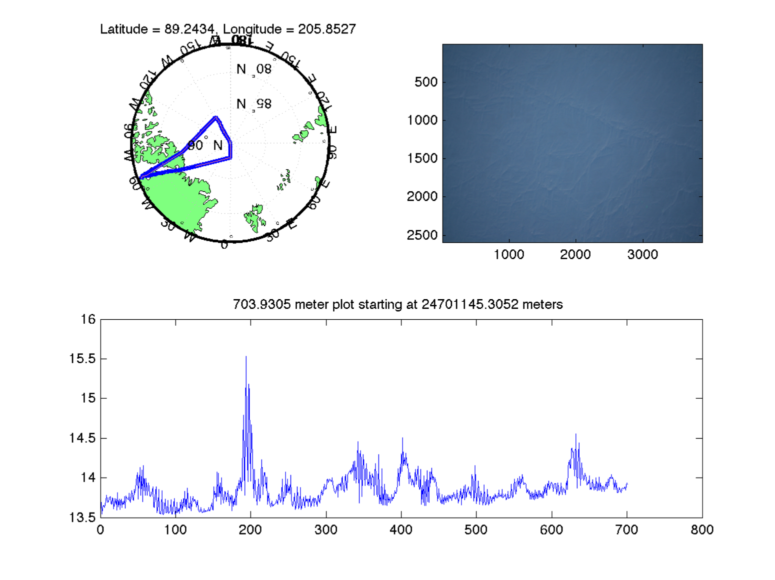
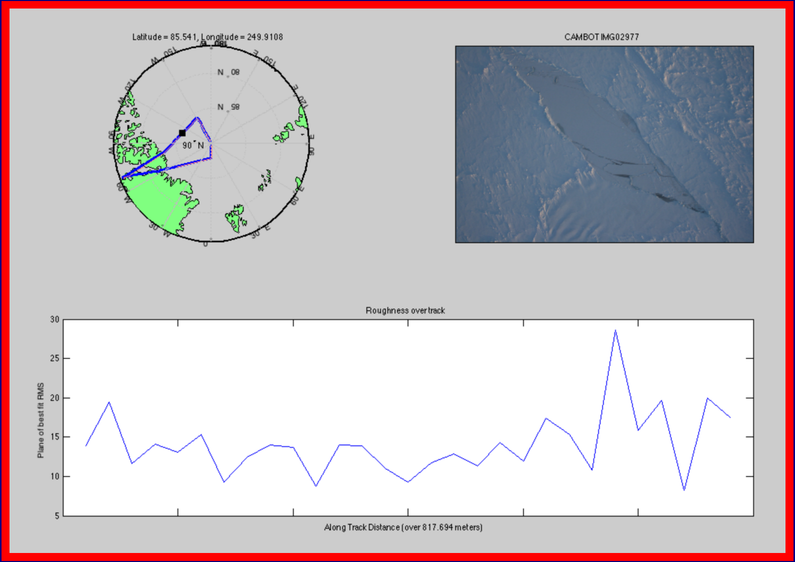
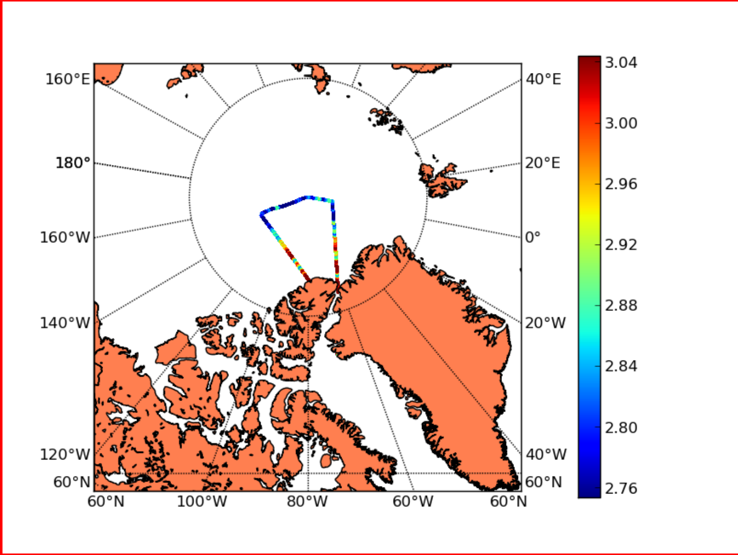


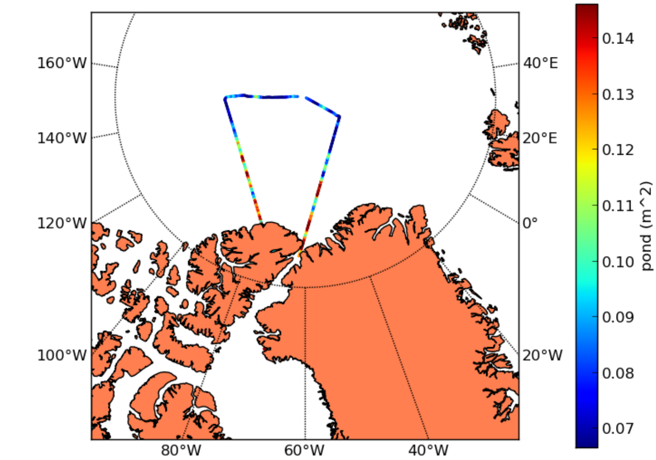
NASA Operation Ice Bridge — NorthPoleTrack 2013



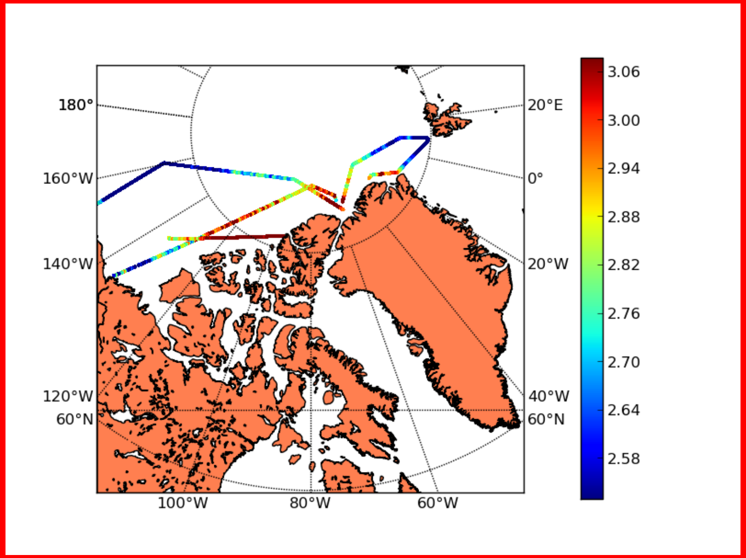
IceBridge – North Pole Track
2012-03-21 rms roughness to fitted ATM data



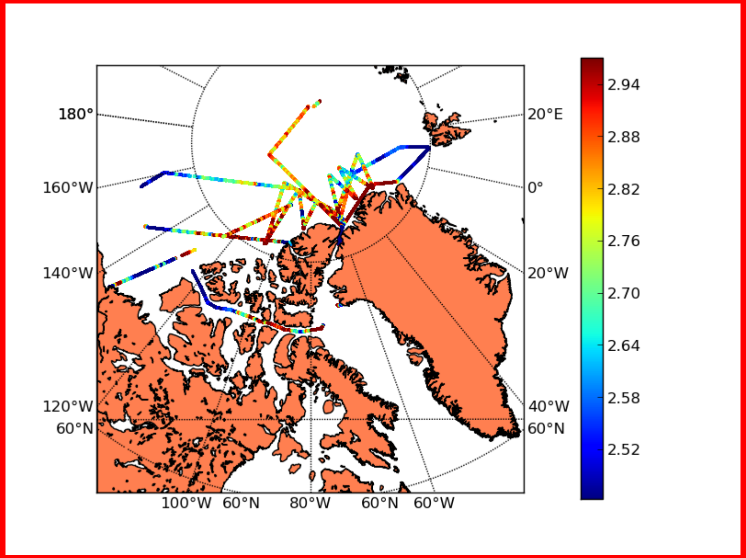
IceBridge – North Pole Track
2012-03-21 *pond* roughness (from full-res ATM data)



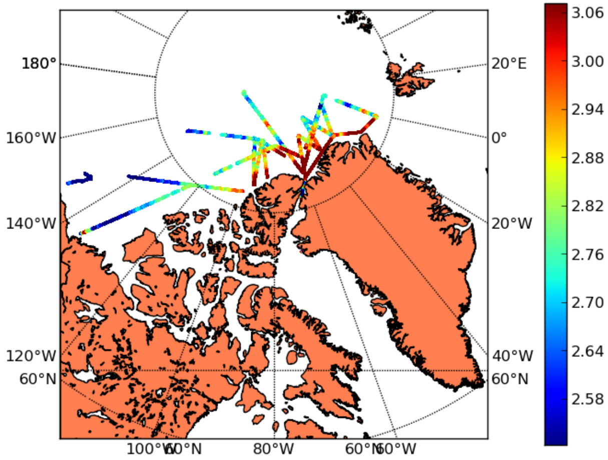
IceBridge – 2009 ATM data rms roughness



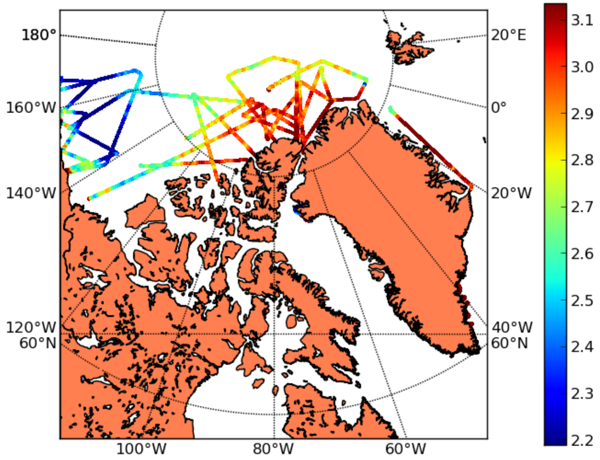
IceBridge – 2010 ATM data rms roughness



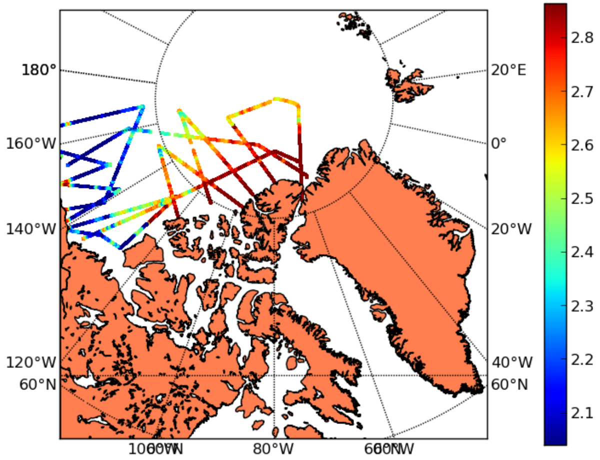
IceBridge – 2011 ATM data rms roughness



IceBridge – 2012 ATM data rms roughness



IceBridge – 2013 ATM data rms roughness



Results

- Prediction of an impeding transition from a perennial to a seasonal Arctic sea-ice cover is one of today's "big science" questions. The assessment of the future of the Arctic sea ice depends on the understanding of changes in old ice, which is typically morphologically complex and deformed. Our work addresses a key problem in sea-ice modeling, the correct representation of ridges and other deformation features.
- We have derived a novel approach for sea-ice model-data comparison and hence for evaluation of numerical models.
- The approach utilizes parameterization on both the data analysis and the modeling side.
- We perform a comparison of results from a sea-ice model, CICE, and geostatistical classification of remote sensing data, collected from unmanned aircraft over Fram Strait during the Characterization of Arctic Sea Ice Experiment (CASIE).
- Results from model and data analysis are in the same range, with deformed ice concentration within 20% and sea-ice freeboard matching very well (except for the 0.1-0.2 m thickness).
- Results of a sensitivity study, varying model parameters that control ridging, yield a match of better than 7% deformed ice area concentration (ridged areas) between model and data analysis. The winning parameter depends on geographic location and morphological province.

Herzfeld, Hunke, McDonald and Wallin, 2014, subm

Ongoing and future work

- Analysis of the situation for other areas of the Arctic, especially the Arctic basin, using data from IceBridge
- Generalization of model-data comparison metrics to include altimetry and imagery, ridging and melt ponding
- Sensitivity studies using parameter combinations (rather than single parameters).