Uncertainties in satellite-derived sea ice extent estimates

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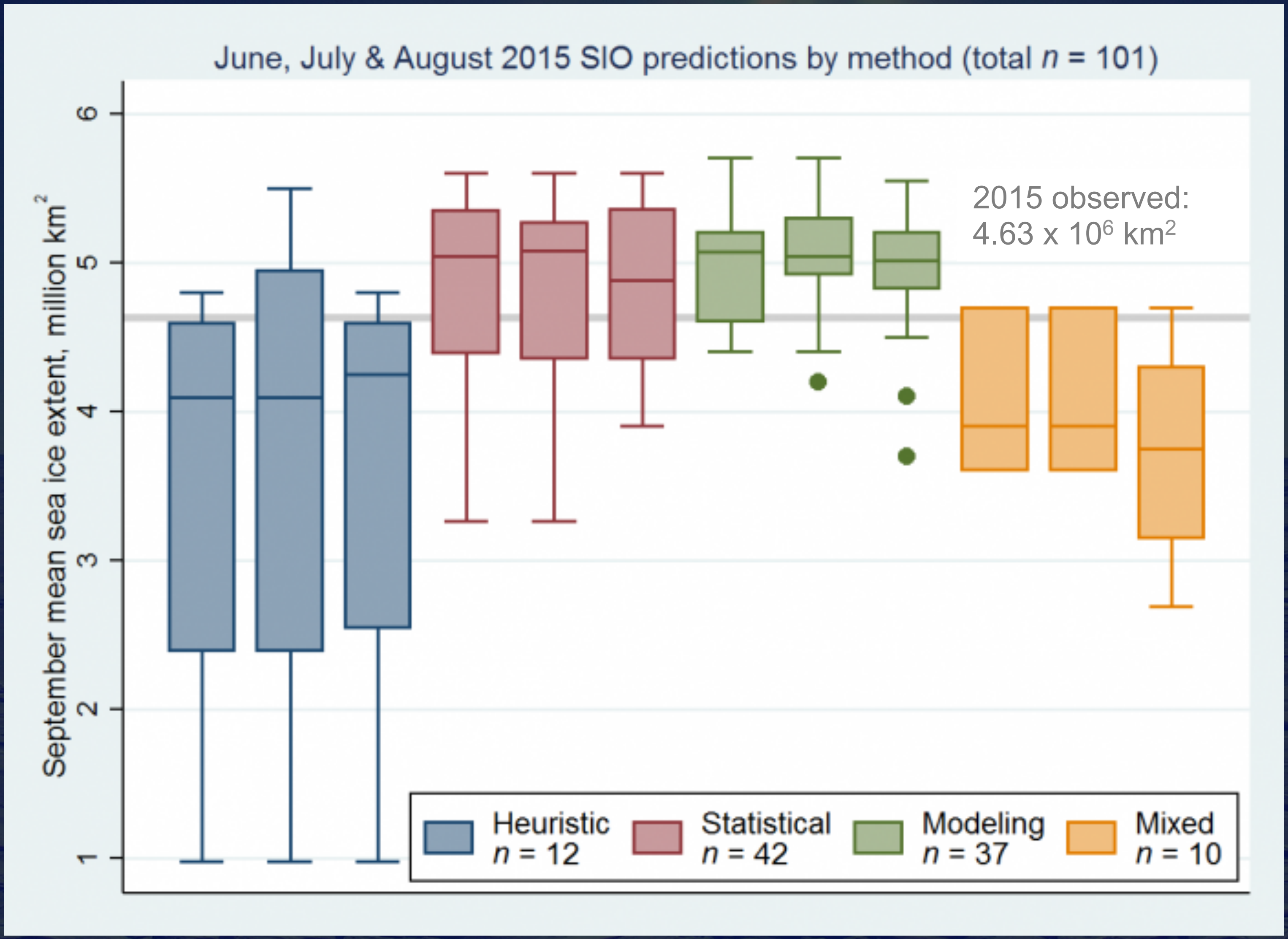
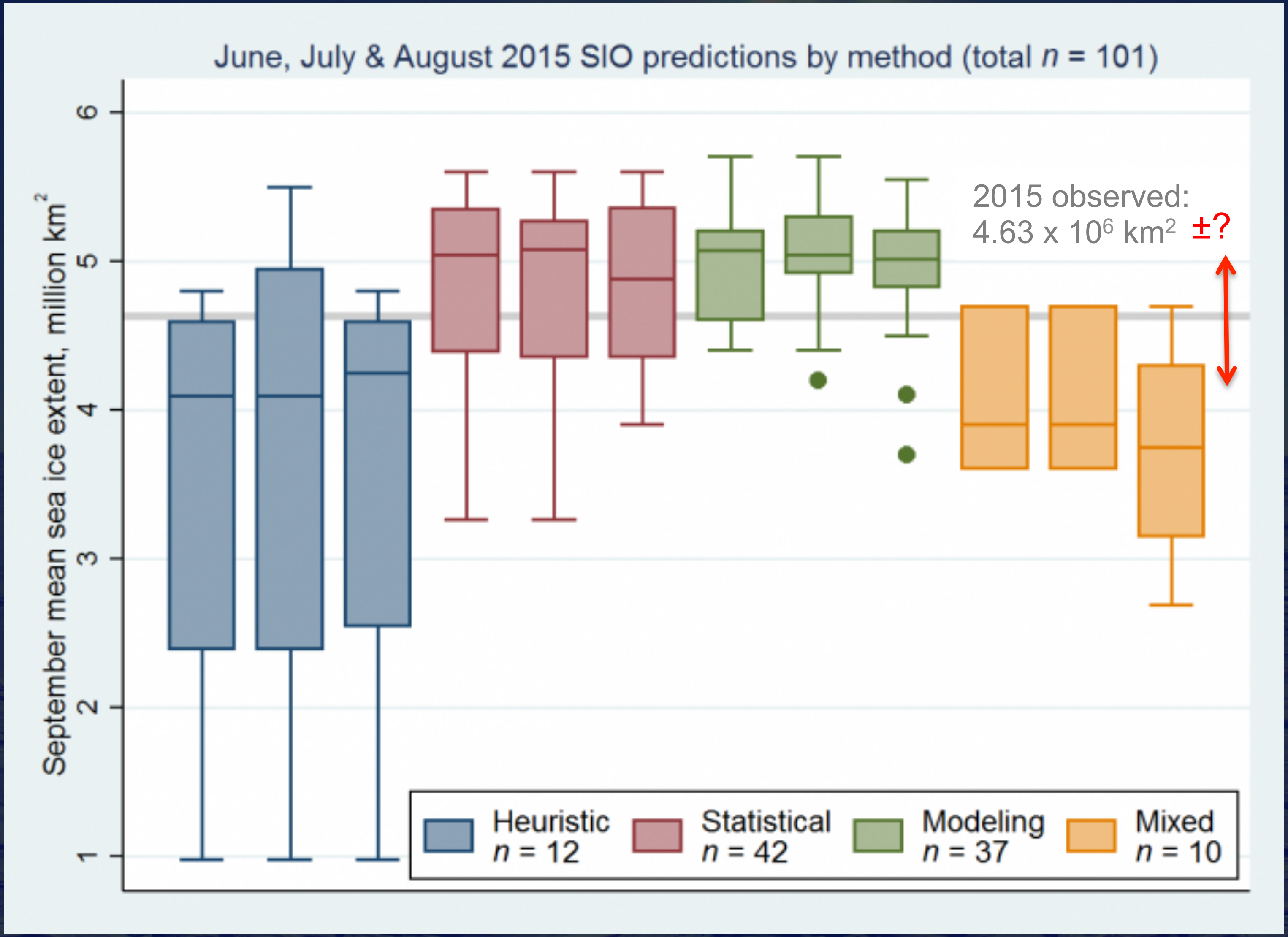
Sea Ice Prediction Network Webinar
23 August 2016

Thanks to Scott Stewart, Matt Savoie, and others at NSIDC


June, July & August 2015 SIO predictions by method (total n = 101)
September mean sea ice extent, million km2
1
2
3
4
5
6
2015 observed:
4.63 x 10⁶ km²
Heuristic
n = 12
Statistical
n = 42
Modeling
n = 37
Mixed
n = 10


June, July & August 2015 SIO predictions by method (total n = 101)
September mean sea ice extent, million km²
1
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2015 observed:
4.63 x 10⁶ km² ±?
Heuristic n = 12
Statistical n = 42
Modeling n = 37
Mixed n = 10

Passive microwave (PM) sea ice estimates

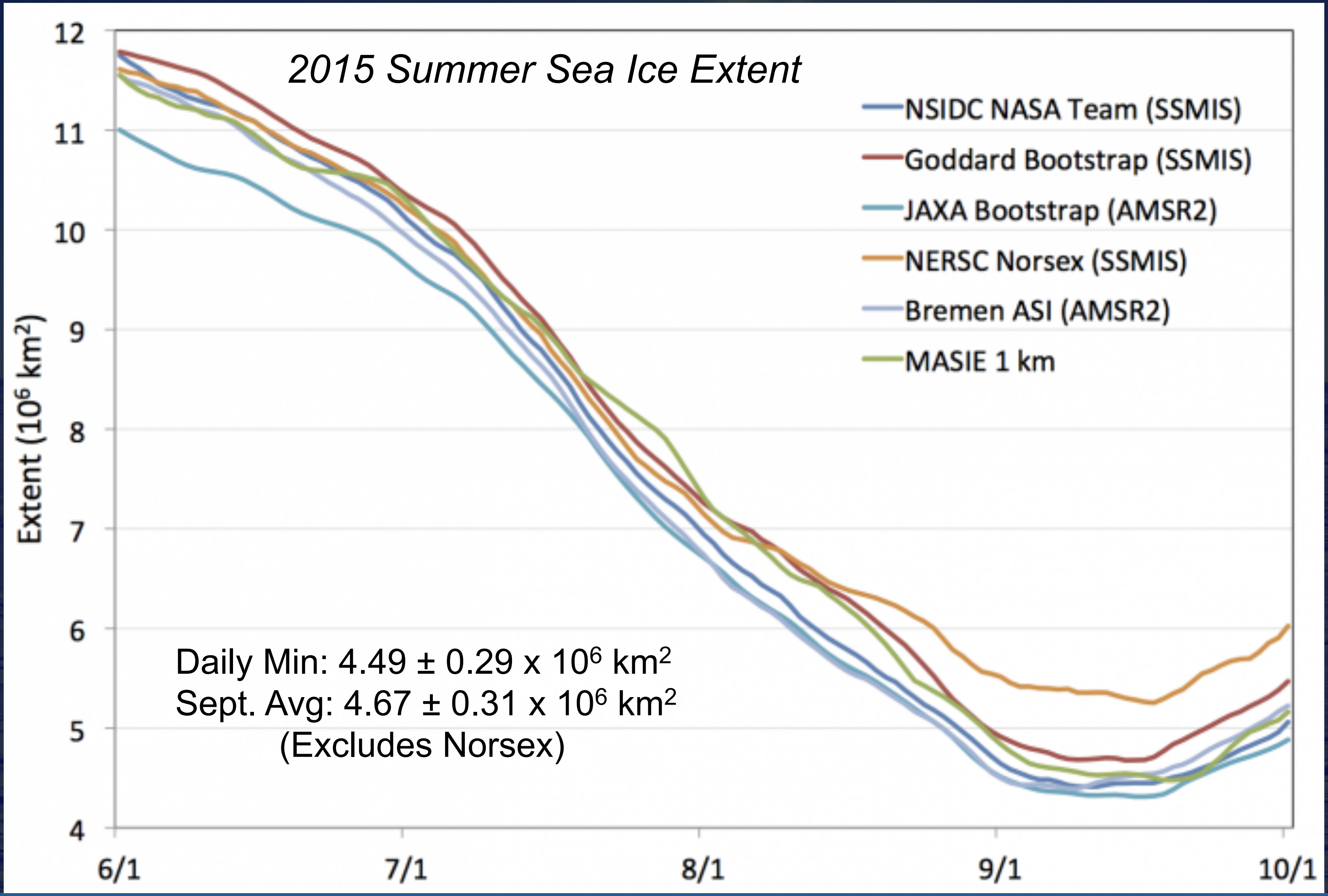
- PM sensors measure emitted energy in the microwave range, conveyed in units of “brightness temperature” (TB)
- Several algorithms have been developed to convert TB into sea ice concentration using combinations of sensor channels
- “Extent” is a binary ice/no-ice indicator
  - Defined by a minimum concentration threshold (typically 15%)
- “Total extent” is the areal sum of all “ice” grid cells
- The focus here is on NSIDC Sea Ice Index extent estimates – used in Sea Ice Outlook
  - NASA Team algorithm (NT)
  - SSMI and SSMIS sensors on U.S. Dept. of Defense DMSP satellites

SSMI(S) = Special Sensor Microwave Imager (and Sounder)
DMSP = Defense Meteorological Satellite Program

Estimating extent uncertainty

- Concentration uncertainty and ice edge location uncertainty estimated by case-study comparisons with other imagery
- However, it is challenging to estimate total extent uncertainty – the integral of the ice edge location uncertainty around the entire perimeter of the ice pack
- One approach is to inter-compare different extent products
  - e.g., Ivanova et al., IEEE TGRS, 2014

Absolute uncertainty can be inferred from different extent products



Thanks to G. Heygster (Bremen) and J. Comiso (Goddard Bootstrap) for providing total extent estimates. Extent values from other sources were obtained from their product web sites.

Why do extent products differ?

- Source data – which satellite(s)?
- Algorithm differences – which channels?
  - Sensitivity to thin ice, melt
- Quality-control methods (weather/coastal filters)
- Land masks
- Definition of ice edge (15% threshold)
- *Spatial resolution of sources*

Products and sources

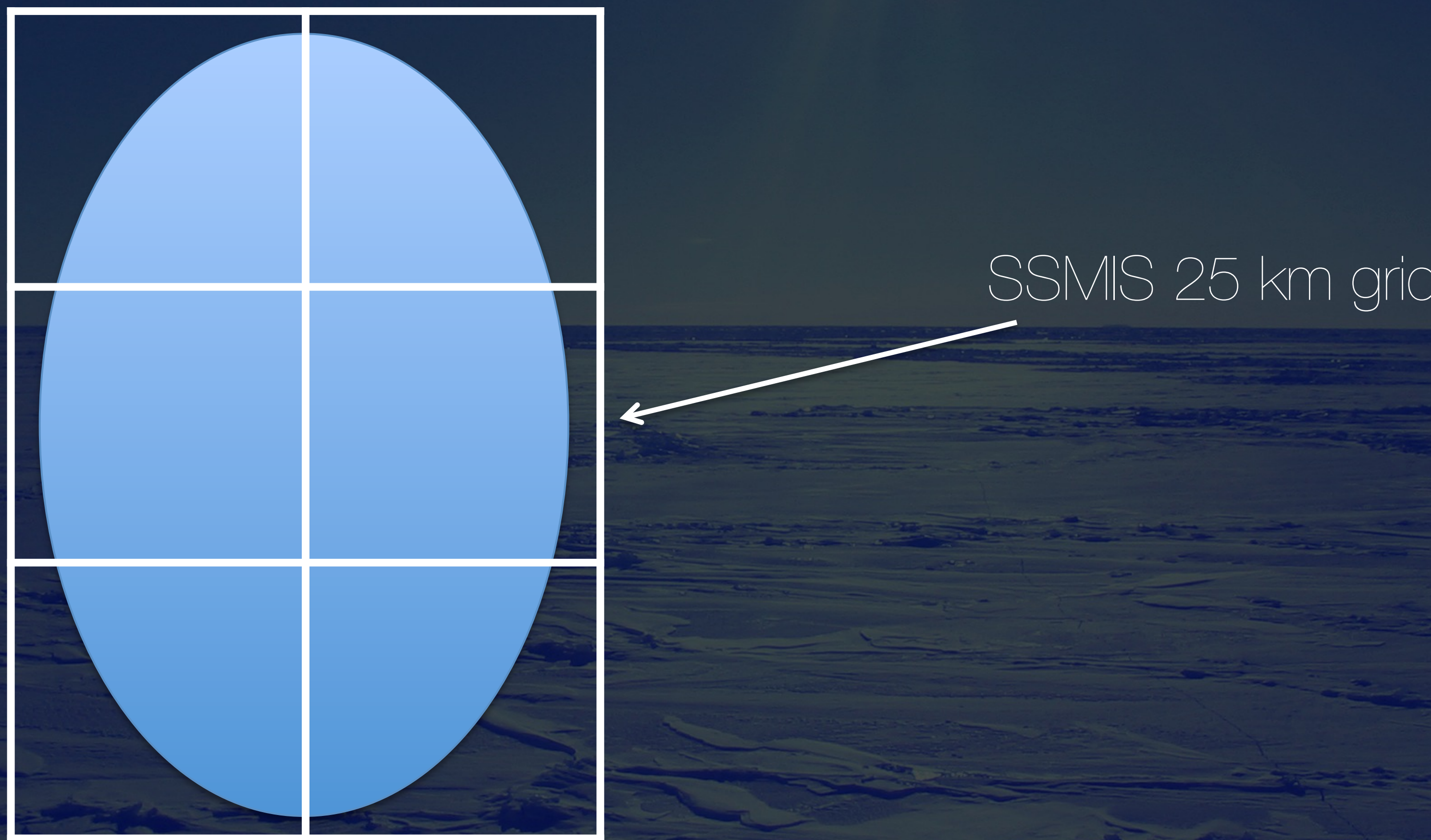
- Bremen ASI – AMSR2, 6.25 km grid
- Goddard Bootstrap – SSMIS, 25 km grid
- Goddard NASA Team – SSMIS, 25 km grid

  (NSIDC Sea Ice Index)
- NERSC Norsex – SSMIS, 25 km gird
- MASIE – 1 km grid; operational analyzed product using multiple image sources and human interpretation. From U.S. National Ice Center and NSIDC.

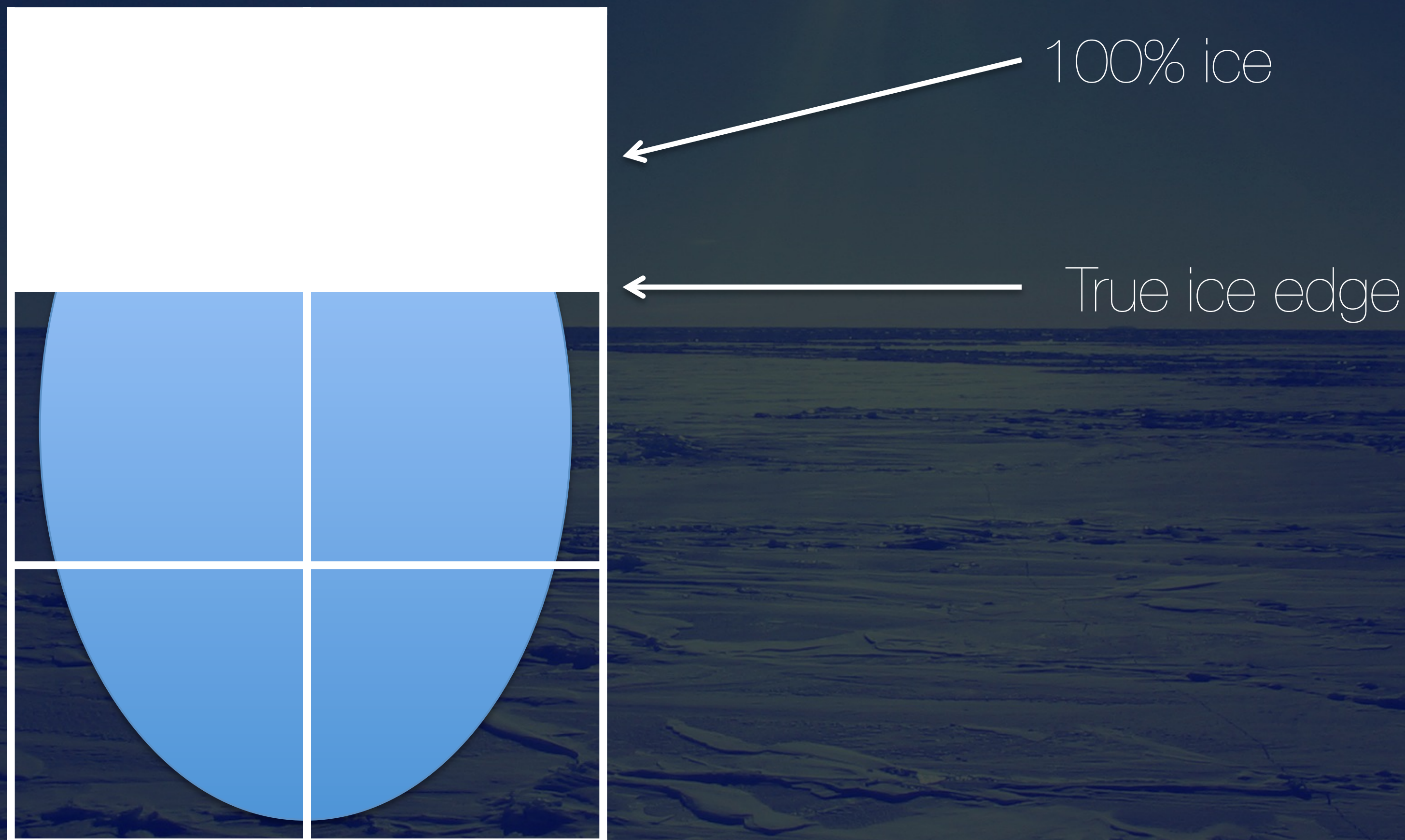
Passive microwave resolution

SSMIS 19 GHz field of view
~45 x 70 km

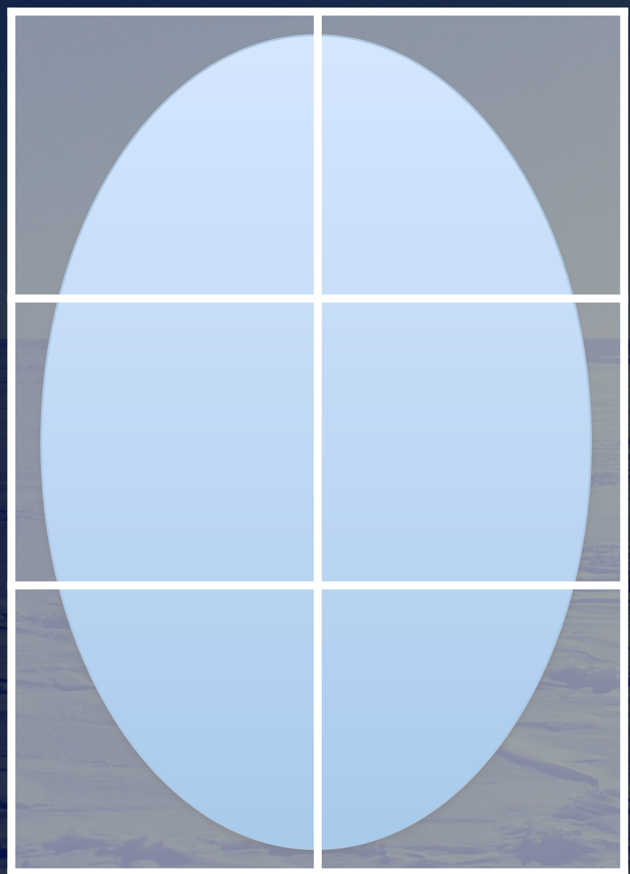
Passive microwave resolution



Reality



What the satellite "sees"



33% ice in all 6 cells

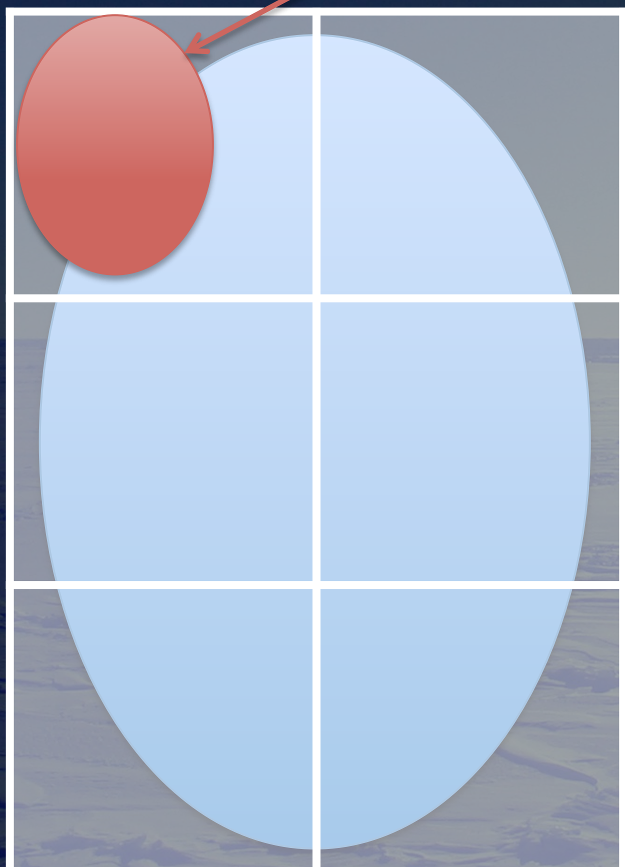
Sea ice is "smeared out" due to low resolution

In other cases, ice may be "missed" due to low resolution

Retrieved ice edge

Effect of higher spatial resolution

AMSR2 footprint (14 X 22 km)



AMSR2 retrieved ice edge

Higher resolution obtains a finer ice edge, more precision

SSMIS retrieved ice edge

Idealized sea ice extent

Circumference = 7540 km
≈ 302 grid cells
(25 x 25 km)

Extent = 4.52 million km^2

Note that most products use polar stereographic projection, which is not equal area

Idealized sea ice extent

Circumference = 7697 km
≈ 309 grid cells
(25 x 25 km)

Extent = 4.71 million km^2

Circumference = 7697 km
≈ 309 grid cells
(25 x 25 km)

A 25 km bias in ice edge results in ~190,000 km^2 difference in extent

Note that most products use polar stereographic projection, which is not equal area

Relative uncertainty

- Different products provide an inference of uncertainty about a "true" extent value
- In many cases, what is most relevant is relative uncertainty within a given product
- How discretely can we differentiate ice extent estimates from a given product at different times?
  - Initialized time vs. forecast time
  - Comparison between years

NSIDC minimum extent rankings

Rank	Extent (10^6 km^2)	Δextent between ranks	Year
1	3.39		2012
2	4.15	0.76	2007
3	4.34	0.19	2011
4	4.43	0.09	2015
5	4.59	0.16	2008
6	4.62	0.03	2010
7	5.03	0.41	2014
8	5.06	0.03	2013
9	5.12	0.06	2009
10	5.32	0.20	2005

Approaches to infer NSIDC uncertainty

- Near-real-time (NRT) vs. final processing
- Simultaneous observation by different sensors
- Sensitivity to concentration threshold
- Consistency over time (satellite drift, sensor intercalibration)

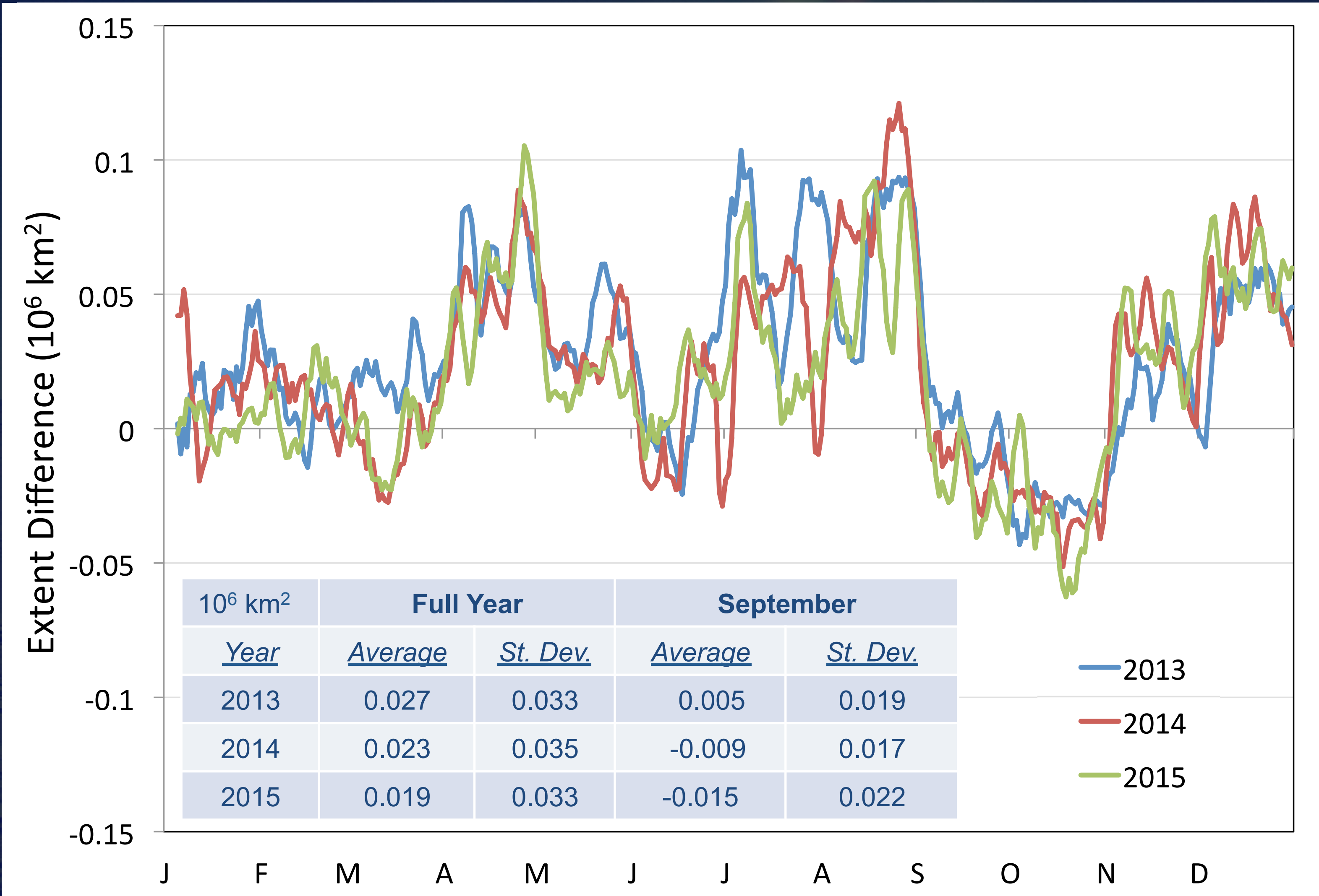
Near-real-time (NRT) vs. Final sea ice extent

NRT	Final
Processed at NSIDC	Processed at NASA Goddard
Input NRT TBs from NOAA CLASS	Input TBs from Remote Sensing Systems, Inc.
Ocean mask from U.S. National Ice Center ice chart climatology	Ocean mask from sea surface temperature (SST) climatology
Only automated quality control (QC)	Manual QC to remove spurious data

Final data replaces NRT data in archive

TB = passive microwave brightness temperature

NRT vs. Final sea ice extent

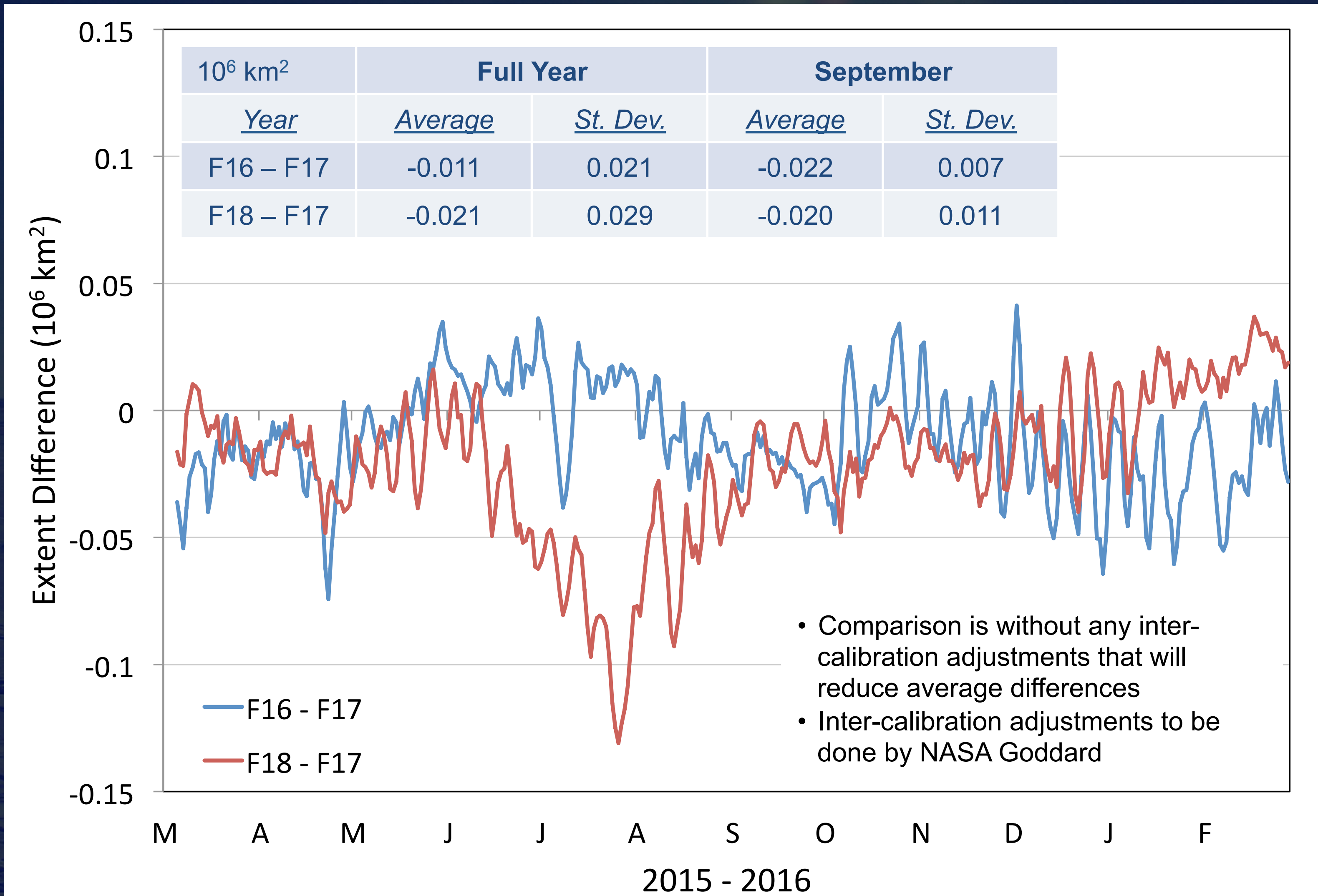


10^6 km^2	Full Year		September	
Year	*Average*	*St. Dev.*	*Average*	*St. Dev.*
2013	0.027	0.033	0.005	0.019
2014	0.023	0.035	-0.009	0.017
2015	0.019	0.033	-0.015	0.022

Sensor intercomparison

- Generally, extent estimates from only one sensor at a time provided
- Sensor inter-calibration done during operational overlap periods to match extents
- Multiple sensors available for much of the record
- Currently, DMSP F16, F17, and F18 operating
  - F17 limited capability starting in April 2016
  - NSIDC now using F18
  - Goddard will do in-depth calibration of F18 for final product

Extent differences: F16, F17, F18



10^6 km^2	**Full Year**		**September**	
Year	*Average*	*St. Dev.*	*Average*	*St. Dev.*
F16 – F17	-0.011	0.021	-0.022	0.007
F18 – F17	-0.021	0.029	-0.020	0.011

Origin of the 15% threshold?

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 96, NO. C12, PAGES 21,989–22,008, DECEMBER 15, 1991

Aircraft Active and Passive Microwave Validation of Sea Ice Concentration From the Defense Meteorological Satellite Program Special Sensor Microwave Imager

D. J. CAVALIERI,[1] J. P. CRAWFORD,[2] M. R. DRINKWATER,[2] D. T. EPPLER,[3] L. D. FARMER,[3] R. R. JENTZ,[4] AND C. C. WACKERMAN[4]

During March 1988 a series of coordinated special sensor microwave imager (SSM/I) underflights were carried out with NASA and Navy aircraft over portions of the Bering, Beaufort, and Chukchi seas as part of the NASA Defense Meteorological Satellite Program SSM/I Sea Ice Validation Program. The two Navy research aircraft, a Naval Research Laboratory P-3 with the NOARL K_a band radiometric mapping system operating at 33.6 GHz and a Naval Air Development Center (NADC) P-3 with the NADC–Environmental Research Institute of Michigan (ERIM) C band synthetic aperture radar (SAR), provided wide-swath, high-resolution microwave imagery for direct comparison with sea ice concentrations calculated from SSM/I radiances using the NASA sea ice algorithm. Coincident measurements made with the Jet Propulsion Laboratory (JPL) C band SAR and the Goddard Space Flight Center (GSFC) aircraft multifrequency microwave radiometers (AMMR) on the NASA DC-8 airborne laboratory provided additional verification of the algorithm. NASA DC-8 AMMR data from Bering Sea ice edge crossings were used to verify that the ice edge location, defined as the position of the initial ice bands encountered by the aircraft, corresponds to an SSM/I ice concentration of 15%. Direct comparison of SSM/I and aircraft ice concentrations for regions having at least 80% aircraft coverage reveals that the SSM/I total ice concentration is lower on average by 2.4% ± 2.4%. For multiyear ice, NASA and Navy flights across the Beaufort and Chukchi seas show that the SSM/I algorithm correctly maps the large-scale distribution of multiyear ice: the zone of first-year ice off the Alaskan coast, the large areas of mixed first-year and multiyear ice, and the region of predominantly multiyear ice north of the Canadian archipelago. Quantitative comparisons show that the SSM/I algorithm overestimates multiyear ice concentration by 12% ± 11% on average in the Chukchi and Beaufort seas. Excluding data for a day which gave anomalously large positive biases, the multiyear ice concentration difference reduces to 5% ± 4%, also indicating a positive SSM/I bias. Anomalously low SSM/I concentrations were found in the coastal zone north of Ellesmere Island. Differences between multiyear ice concentrations estimated from the JPL C band SAR imagery and from the GSFC AMMR radiances using an SSM/I type algorithm show that the AMMR concentrations are smaller on average by 6% ± 14%. Sea ice conditions are described, and possible causes of the observed differences are discussed.

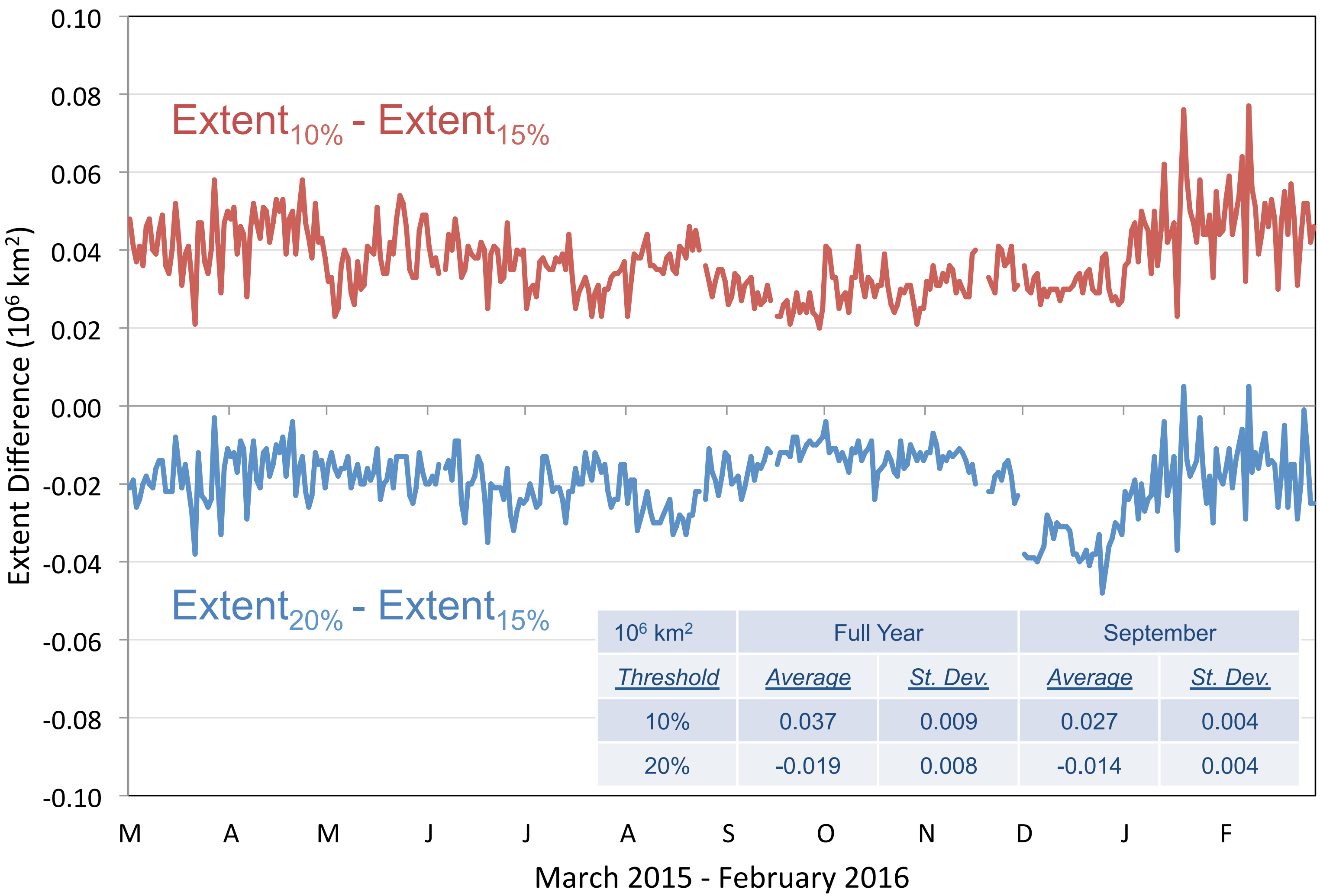
TABLE 8. Comparison of SSM/I Ice Concentrations Corresponding to Ice Edge Features as Determined From Aircraft Crossing

Date	Crossing	SSM/I C_T, % Ice Band	SSM/I C_T, % Main Pack
March 13	1	11	46
	2	20	32
	3	20	46
March 21	1	13	28
	2	15	61
	3	15	28
	4	13	25

Average = 15.3 %

"On average, the SSM/I ice concentration for the grid containing the initial ice band is about 15%....The importance of this result is that it establishes that the SSM/I 15% ice concentration contour on average locates the outer ice edge position..."

F18 extent sensitivity to % conc. threshold



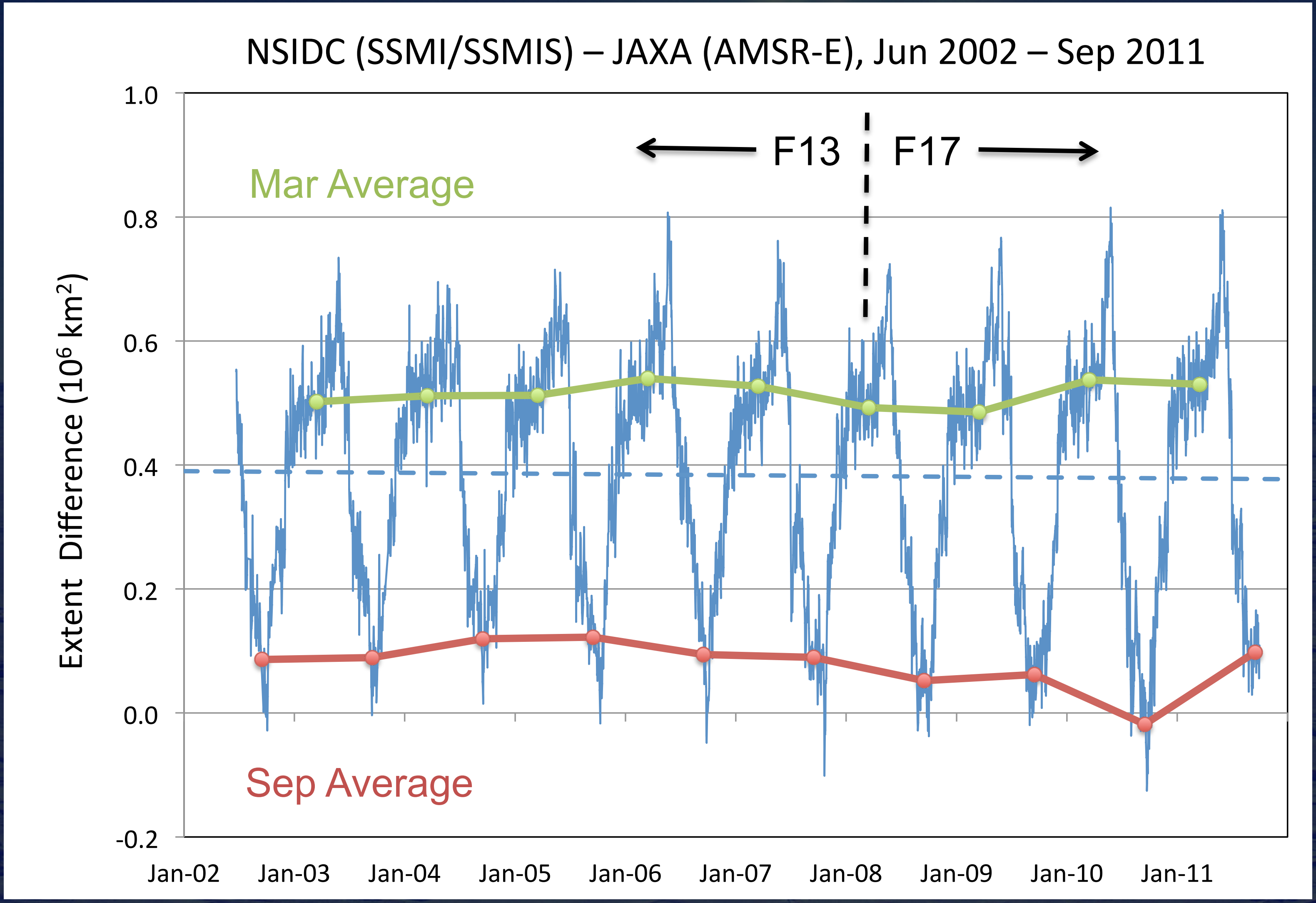
10^6 km^2	Full Year		September	
Threshold	*Average*	*St. Dev.*	*Average*	*St. Dev.*
10%	0.037	0.009	0.027	0.004
20%	-0.019	0.008	-0.014	0.004

Calculate difference between extent 10% or 20% threshold and standard 15% threshold.
St. dev. provides indication of stability of ice edge estimates under the differing criteria.

Consistency over time

- DMSP satellite orbits drift over time
  - Crossing time changes
  - Altitude changes
  - Does this affect extent retrievals?
- Transition between sensors potentially introduces bias (Eisenman et al., 2014)
- Compare with AMSR-E time series
  - AMSR-E part of "A-Train" constellation
  - Periodic burns to keep station (constant crossing-time and altitude)

Consistency of extent over time



Daily difference (blue) between NSIDC and JAXA extent, linear trend (dashed line), and monthly average differences for March and September

A stab at a total uncertainty estimate

$$\sigma^2_{total} = \sigma^2_{nrt} + \sigma^2_{sensor} + \sigma^2_{threshold} + \sigma^2_{drift/inter\text{-}calibration}$$

$$\sigma^2_{Year} = (0.034)^2 + (0.025)^2 + (0.009)^2 + {\sim}0^*$$
$$\sigma^2_{Sept} = (0.019)^2 + (0.009)^2 + (0.004)^2 + {\sim}0^*$$

$$\sigma_{Year} = 0.043 \times 10^6 \text{ km}^2$$
$$\sigma_{Sept} = 0.021 \times 10^6 \text{ km}^2$$

Caveats:

- assumes errors are independent and Gaussian
- doesn't account for potential biases (e.g., sensor intercalibration)
- may miss other sources of uncertainty

*may not be true over the long term, particularly the early part of the record (Eisenman et al., The Cryosphere, 2014)

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2016?

Rank based on 95% confidence level


Thanks!
Photo by Terry Haran, NSIDC