Final Report

DEVELOPMENT OF AN INTEGRATED NORTHERN HEMISPHERE SNOW AND ICE OPERATIONAL CLIMATE DATA RECORD

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David A. Robinson, Principal Investigator
Center for Environmental Prediction
School of Environmental and Biological Sciences, Rutgers University

Mark R. Anderson, Co-Principal Investigator (NA08OAR4310677)
Department of Geosciences, University of Nebraska

&

Mark Tschudi Co-Principal Investigator (NA08OAR4310670)
Colorado Center for Astrodynamics Research, University of Colorado

With project consultants: Sheldon Drobot (NCAR), Chuck Fowler (U. Colorado, retired) and James Maslanik (U. Colorado, retired)

Project Overview

Our project was designed to: (1) develop mature Northern Hemisphere (NH) terrestrial snow and sea ice climate data records (CDRs) with known levels of uncertainty and with community-standard metadata; (2) assemble mature NH terrestrial snow and sea ice data products into an integrated snow and ice CDR; and (3) provide the snow and ice CDRs in multiple grids, on multiple time steps, and in multiple formats for the research community, decision-makers, and stakeholders.

Throughout the project, we sought community feedback via an advisory committee and through town hall meetings at American Geophysical Union fall meetings to ensure that our CDRs meet community needs. The CDRs will be provided via the Rutgers Global Snow Lab web site (http://snowcover.org/) on several time steps (daily through annual), in various grids (e.g., Equal-Area Scalable Earth, 1° x 1°), and in various formats (e.g., text, netCDF) for access by the community. The CDRs were also distributed to the National Climatic Data Center (NCDC). As a result of efforts under this grant, the CDRs are now being updated on a monthly basis and transferred to the National Climatic Data Center (NCDC). Period of record files will also be

stored at the National Snow and Ice Data Center (NSIDC). This first involved attaining production confidence and completing requisite data archives and metadata. This project dovetailed well with a related effort that has been funded by the NASA MEaSUREs initiative. The NOAA SDS project's major focus has been associated with operational and community aspects of our integrated snow-ice CDR. Meanwhile, the NASA effort has been geared more to the research side and concentrated on our developed products, their integration and how our research-quality CDR aligns with the principles expressed in a 2004 National Research Council report. In other words, within the SDS project, we developed the "framework for integrating the mature CDRs". For NASA, we mainly focused on putting together our own records, but for NOAA, we explicitly developed a framework that would permit linkages with other data records. Furthermore, within the SDS project we developed "known levels of uncertainty and community-standard metadata"; this did not appear in the NASA project as an objective.

Milestones for the project have been met successfully. These include: (1) collecting existing snow cover and melt onset data records, including metadata information; (2) combining the snowmelt onset with Dr. Walt Meier's (NSIDC) NOAA SDS sea ice concentration product; (3) an advisory committee was established and has met at the last four fall AGU meetings; and (4) special sessions on snow CDRs were held at the last four fall AGU meetings. The following discusses project products, the project web site, and the advisory committee.

During the course of the project, Chuck Fowler, the project co-investigator at the University of Colorado, retired. So too did project advisor Jim Maslanik at the U. Colorado. While they continued on in advisory capacities, Dr. Mark Tschudi took on the responsibilities of project co-investigator at Colorado. Dr. Tschudi has considerable experience working with satellite observations over Arctic sea ice, and generates monthly ice motion and ice age products used in this project.

Visible mapping of snow extent

Following multiple years of effort, mainly under NOAA support, a completed reanalysis of the NOAA satellite-derived snow cover extent product that dates back to late 1966 was completed. This CDR continues to be employed in national and international assessments of climate variability and change, and in investigations regarding the role of snow cover in the climate system (figure 1). Investigation of extremes within the annual cycle of Northern Hemisphere snow cover is underway using the new CDR.

A study was published (Brown and Robinson, 2011) that updated Northern Hemisphere (NH) spring (March, April) snow cover extent (SCE) over the 1922-2010 period incorporating the new CDR with station observations. Annual 95% confidence intervals were estimated from regression analysis and intercomparison of multiple datasets. The uncertainty analysis indicates a 95% confidence interval in NH spring SCE of ±5-10% over the pre-satellite period and ±3-5% over the satellite era (figure 2). The multi-dataset analysis shows larger uncertainties monitoring

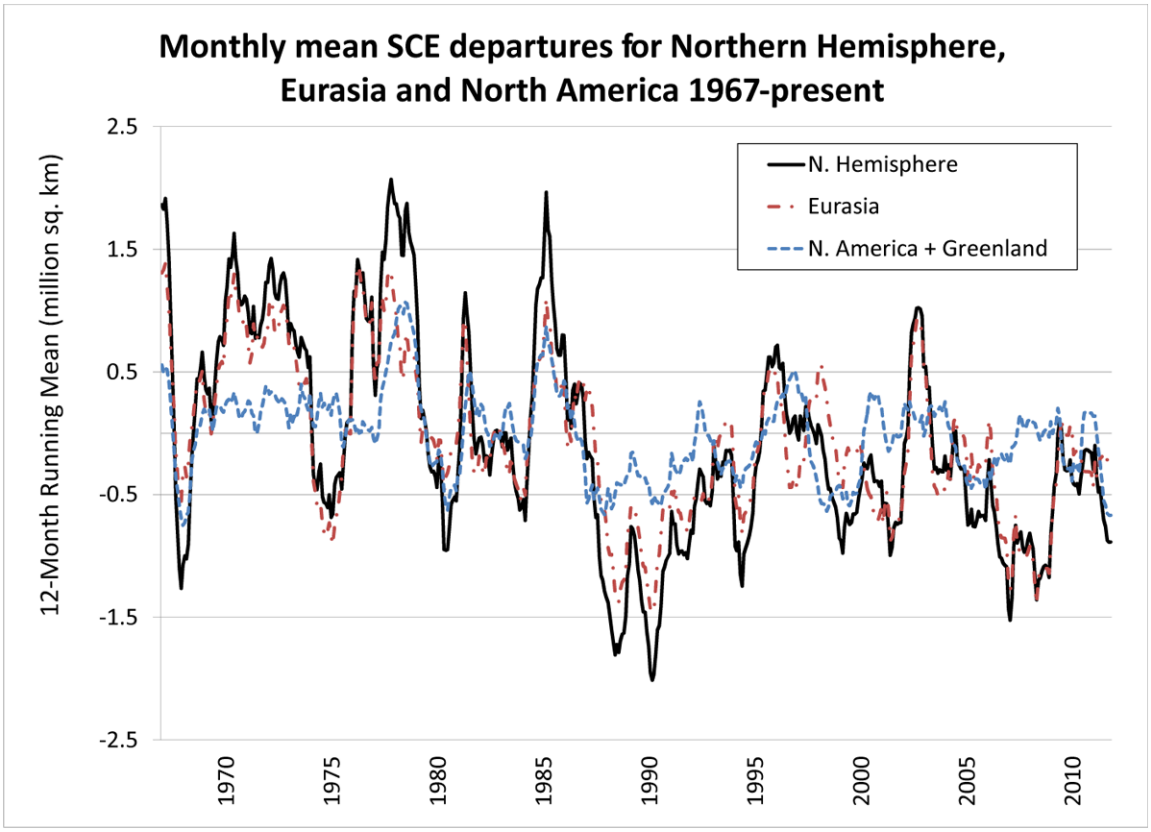

Figure 1. Twelve-month running anomalies of monthly snow cover extent over Northern Hemisphere lands (including Greenland) as a whole and Eurasia and North America separately between November 1966 and August 2012, plotted on the 7th month. Anomalies are calculated from NOAA snow maps. Mean hemispheric snow extent is 25.1 million sq. km. for the full period of record. Monthly means for the period of record are used for 9 missing months between 1968 and 1971 in order to create a continuous series of running means. Missing months fall between June and October, no winter months are missing.

spring SCE over Eurasia (EUR) than North America (NA) due to the more complex regional character of the snow cover variability and larger between-dataset variability over northern Europe and north-central Russia.

Trend analysis of the updated SCE series provides evidence that NH spring snow cover extent has undergone significant reductions over the past ~90 years and that the rate of decrease has accelerated over the past 40 years (figure 3). The rate of decrease in March and April NH SCE over the 1970-2010 period is ~0.8 million km^2 per decade corresponding to a 7% and 11% decrease in NH March and April SCE respectively from pre-1970 values. In March, most of the change is being driven by Eurasia (NA trends are not significant) but both continents exhibit significant SCE reductions in April.

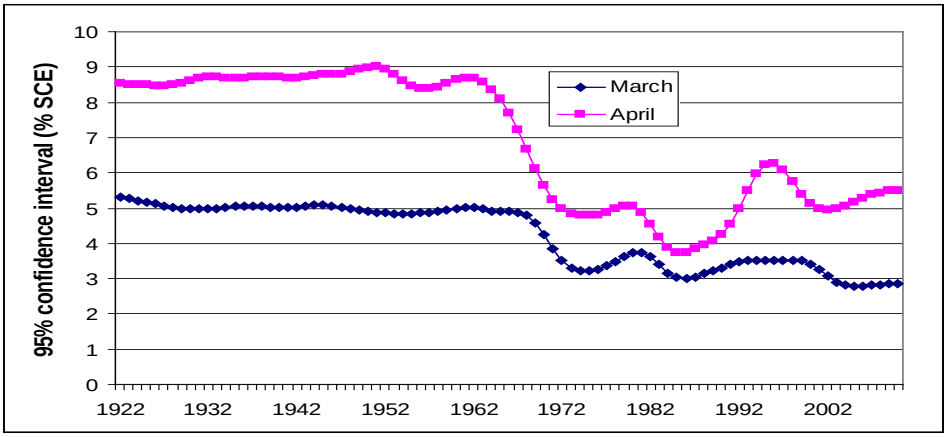

Figure 2 Smoothed (13-term binomial filter) 95% confidence intervals for NH March and April SCE expressed as a % of the corresponding mean SCE.

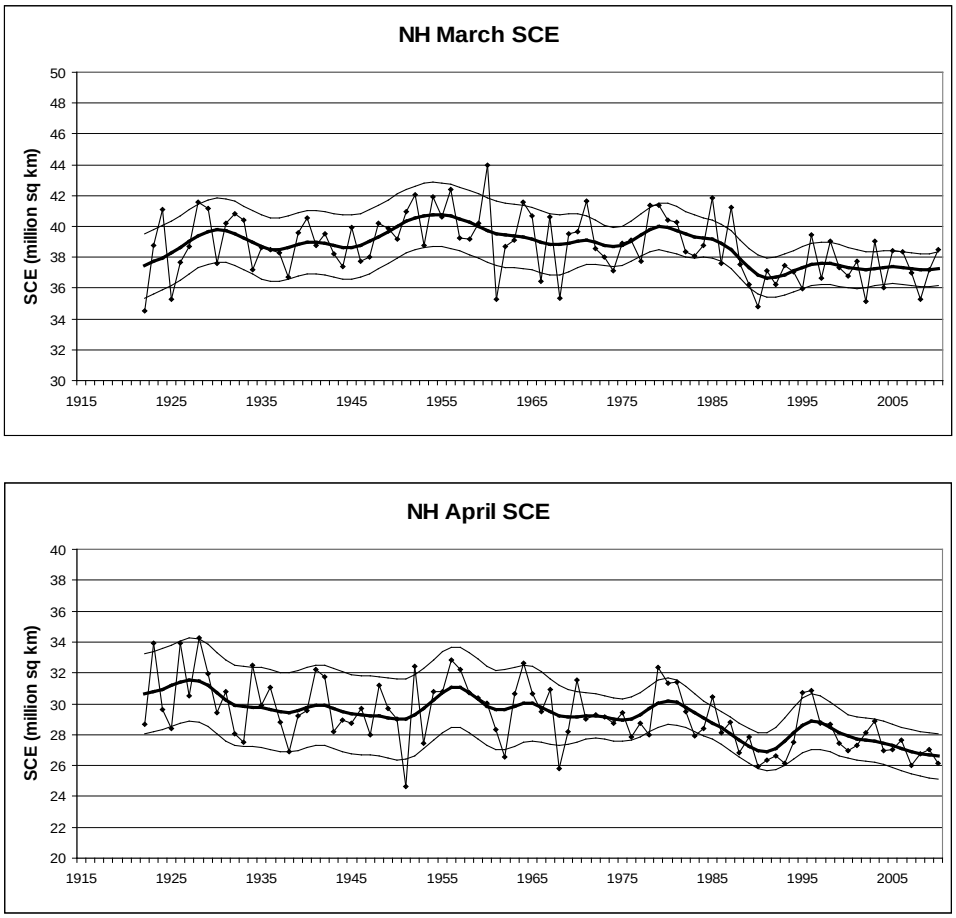

Figure 3. Variability in NH March (top) and April (bottom) SCE between 1922 and 2010 with 13-term filtered values of the mean and 95% confidence interval. NH SCE estimated from the anomaly series using the NOAA 1979-2002 reference period mean and standard deviation (excludes Greenland which averages 2.16 x 10^6 km^2). The width of the smoothed confidence interval is also influenced by the interannual variability in SCE.

The observed trends in SCE are being mainly driven by warmer air temperatures with NH mid-latitude air temperatures explaining ~50% of the variance in NH spring snow cover over the 89-year period analyzed. However, there is also evidence that changes in atmospheric circulation around 1980 involving the North Atlantic Oscillation and Scandinavian pattern have contributed to reductions in March SCE over Eurasia.

Additionally, comparison between MODIS Cloud Gap Filled and NOAA IMS daily snow maps has continued with the aim of assessing the error associated with both products. Initial results show significant differences in certain regions in snow extent reporting, however this could be due to a combination of the MODIS detection algorithm being particularly conservative, the temporal gap-filling technique used by the MODIS product, and the human element in IMS snow detection. So too have we continued working with colleagues in Canada and Finland to compare IMS daily maps with GlobSnow visible and microwave maps.

Snow melt onset over sea ice

An operational melt onset algorithm has been developed to determine the start of melt on sea ice surfaces in the Arctic, a valuable CDR variable. The melt onset algorithm uses the brightness temperature difference between the 19H Ghz and 37H Ghz channels from the NASA SMMR and DMSP SSM/I platforms for the years 1979-2007. When the brightness difference is greater than 2K, melt onset is considered to have taken place. Figure 4 provides an example of the melt onset dates for 2000. The operational melt onset algorithm (the NOAA algorithm, 4a) has also been compared with previous melt dates derived from the AHRA algorithm (Anderson and Drobot 2001) and the newly determined NASA MEaSUREs ESDR melt onset dates. It should be noted that these methods use a ten-day moving window to determine the melt onset occurrence and are not considered an operational algorithm. These algorithms were compared to the NOAA operation algorithm for comparison. Figure 4b shows the MEaSUREs melt onset dates for 2000. In most locations, there were very small differences between the two different algorithm approaches (Figures 5 and 6). When differences between the melt onset algorithms are indicated, the slight variations between the algorithm methodologies are due to the ten-day window approach and because of the land/ocean masks used with the algorithms. Difference maps were calculated for each year, with 2000 shown here as it was a representative year showing some of the larger differences, albeit small ones, between the products.

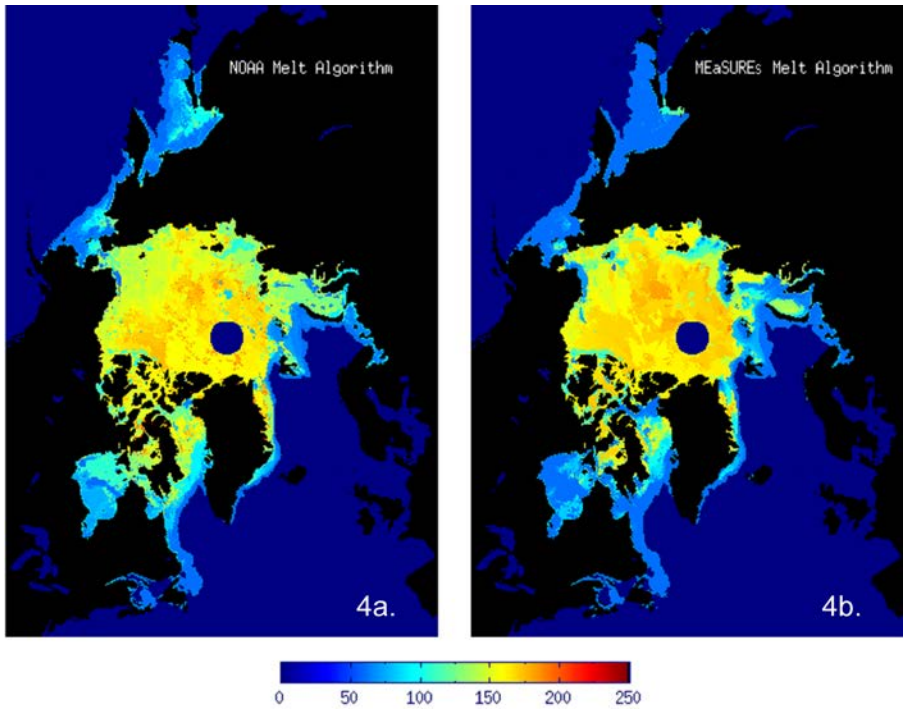

Figure 4. Comparison of the 2000 melt onset dates in days of the year from the NOAA melt algorithm (a) and the MEaSUREs melt algorithm (b).

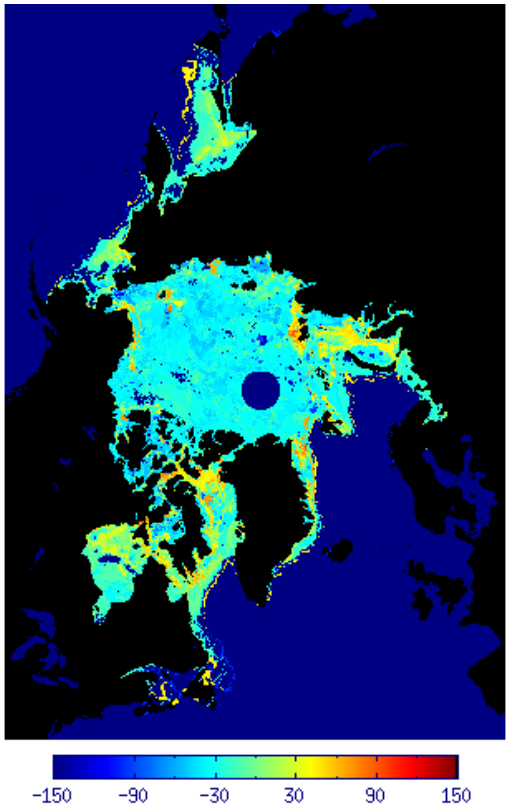

Figure 5. Differences between the NOAA operational algorithm and the MEaSUREs algorithm for 2000.

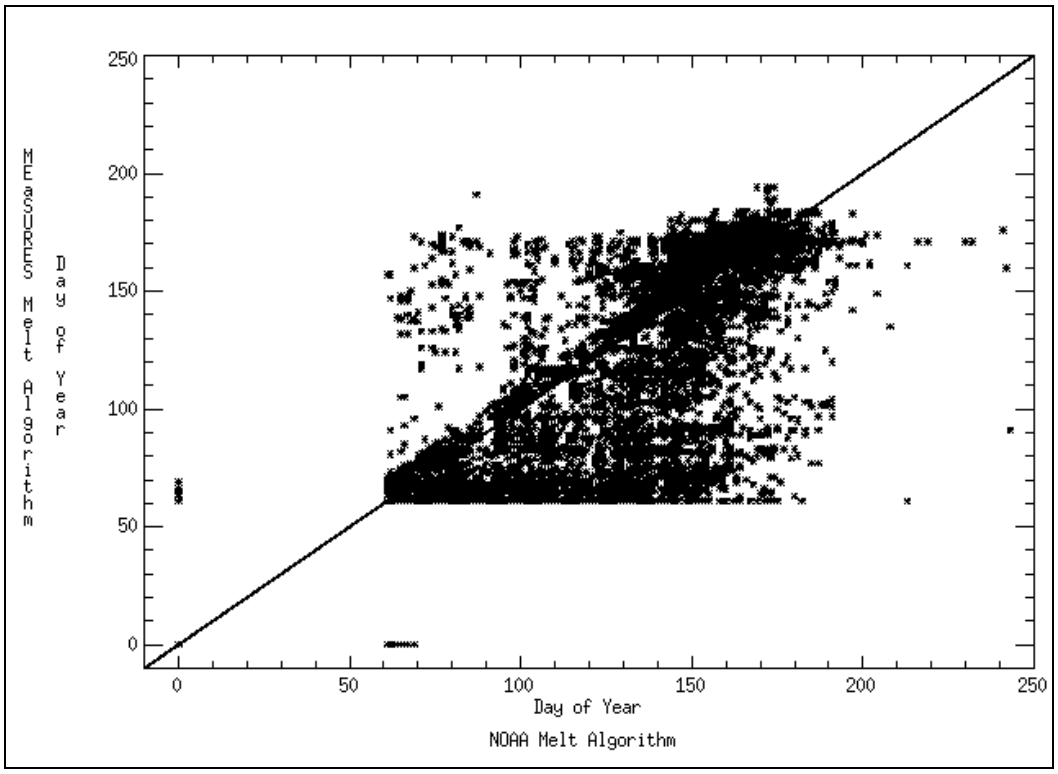

Figure 6. Scatterplot differences between the NOAA operational algorithm and the MEaSUREs algorithm for 2000.

The melt onset dates are calculated daily, permitting daily changes in melt to be determined. Figure 7 provides an example of such a daily melt map for Day 136 in 1993 derived from SMMR. Red shades indicate pixels where the AHRA identifies the melt onset as having started on Day 136. Light blue shades indicate regions where melt onset began prior to Day 136. However it is important to note that light blue shades do not necessarily indicate persistent melting on Day 136, as refreeze or new snowfall may have occurred. White shades are regions that have yet to begin melt.

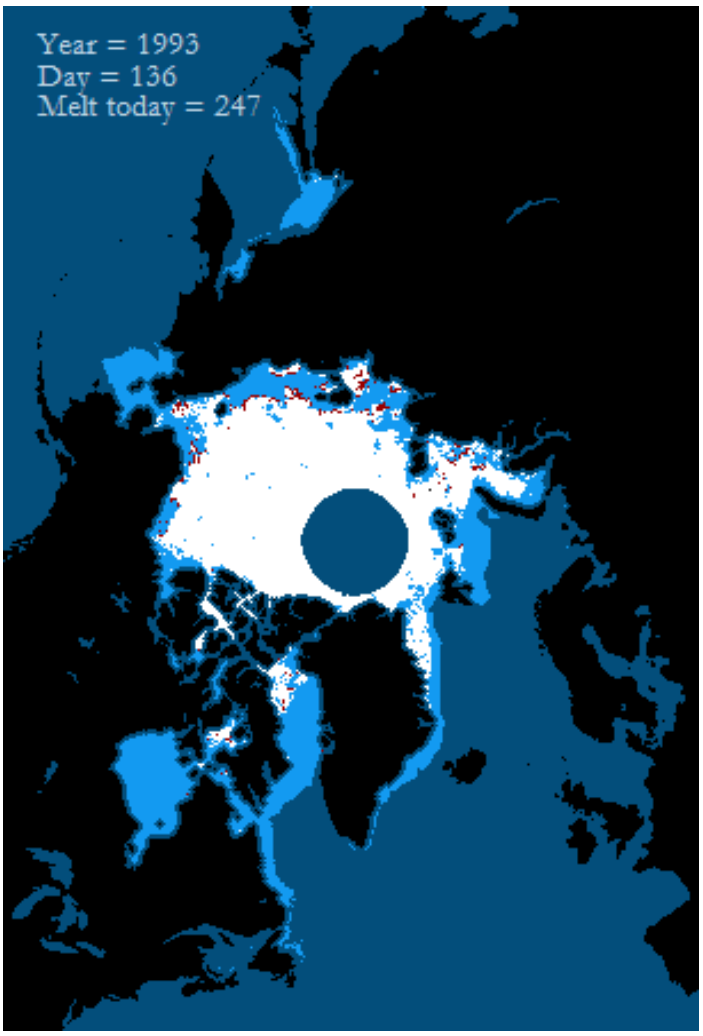

Figure 7. Locations of melt onset on Day 136, 1993. Red shades indicate pixels where the AHRA identifies current melt; light blue shades indicate regions where melt onset began prior to Day 136 and white shades are regions where melt has yet to begin.

Average melt onset dates over Arctic sea ice were calculated annually (Figure 8). More recent years, (2005-2010) have earlier melt onsets than the early SMMR years (1979-1987). The earliest melt onset date is 2005. The linear trend in melt dates produces an eight-day per decade earlier melt onset date. To further illustrate the shift in onset, the melt area on an individual date was accumulated for each year of the microwave era to show variations throughout the year (Figure 9). The SMMR years are for the most part later than the 32 year mean. The SSM/I beginning years occur more around the mean of the period and the later SSM/I years' accumulated melt areas occur earlier than the mean.

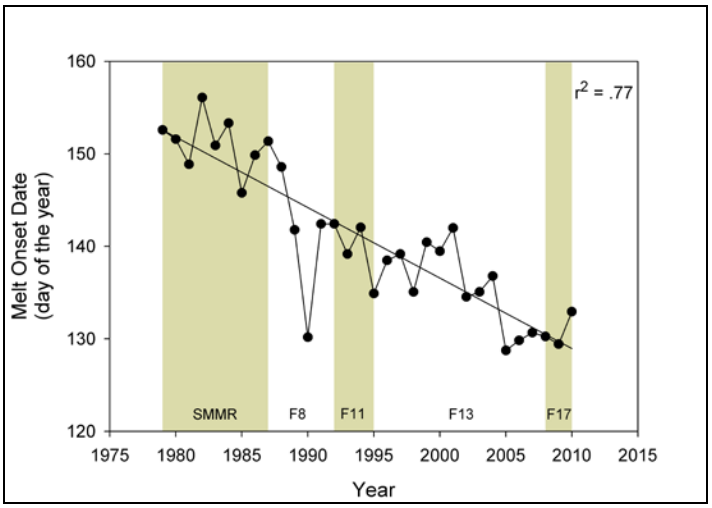

Figure 8. Annual average melt onset dates for the Arctic region and the representative sensors which collect the brightness temperatures for the calculation of the melt dates.

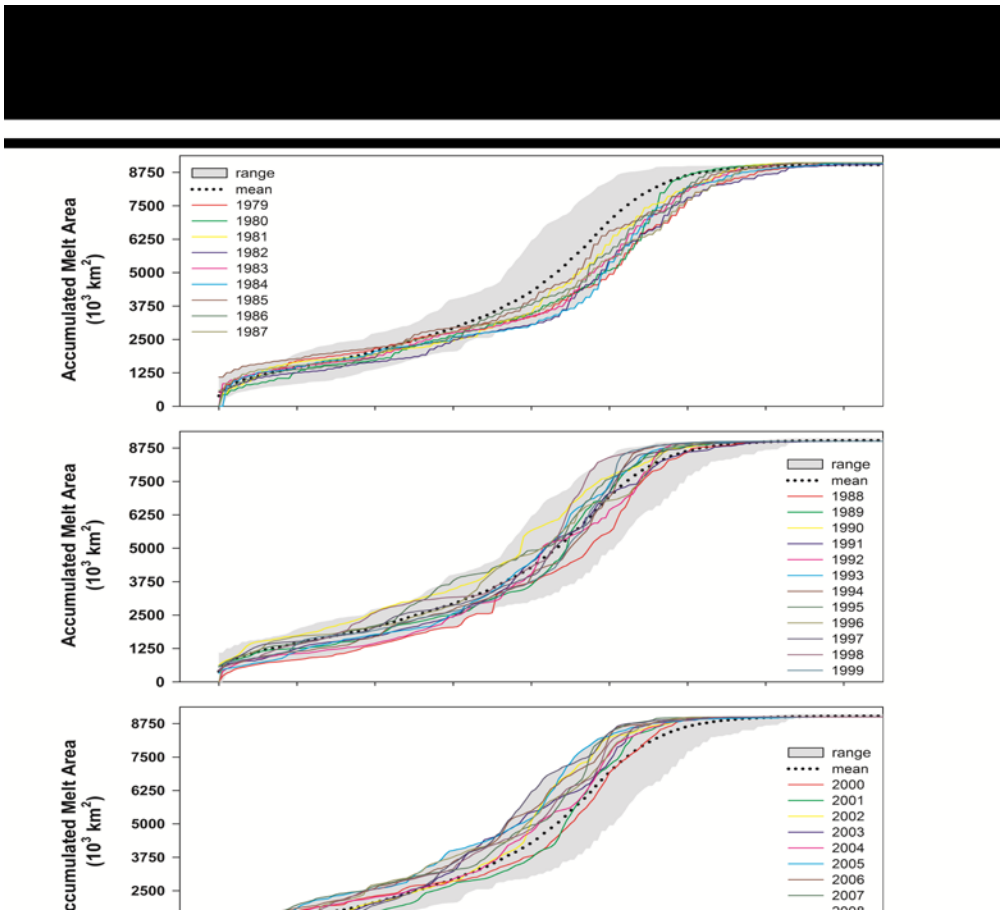

Figure 9. Daily melt onset accumulation areas (10^3 km^2) for the Arctic region, SMMR data 1979-1987 (top), early SSM/I years 1988-1999 (middle), and late SSM/I years 2000-2010 (bottom). The 32-year time period range (gray shaded) and mean (black dashed line) are given for comparison.

Sea ice age and motion

University of Colorado daily sea ice motion vector fields and the derived weekly Lagrangian sea ice age product continue to be updated through the end of each month, and are now available through September 2012 (Figure 10). These data, which provide an overview of basic changes in Arctic ice conditions, have been distributed to a variety of users. AMSR data from 2002 to the present has been added to improve the accuracy of the ice motion vectors, which also improves the iceage product. The AMSR data were used for as long as they were available (2003-2009). NCEP wind data are also now used to help compute the ice motion fields, which are used as a basis for the ice age product.

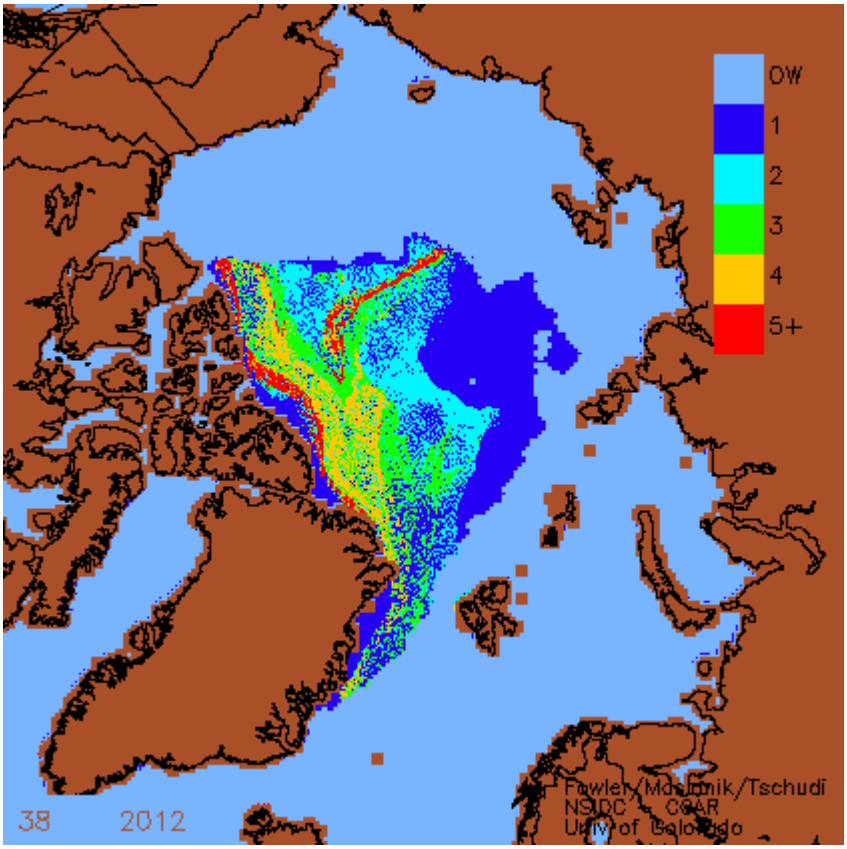

Figure 10. Ice age product for week 38 (September 16-22, 2012). "OW" is open water. Ice of age "1" is first-year ice (has not yet survived a melt season), age "2"has survived one melt season, etc.

Dataset archiving

The Research to Operations (R2O) transition of the weekly snow cover extent CDR to NCDC has been successfully completed. The product has met CDR Program Office requirements for transition to Initial Operating Capability (IOC). Documents including a Climate Algorithm Theoretical Basis Document (C-ATBD), Data Flow Diagram, and Submission Agreement (SA) have been developed, transferred to NCDC and archived.

The weekly snow product has been converted to netCDF file format according to IOC metadata guidelines, and source code conforms to CDR Program General Programming Standards. Now that the CDR submission package has been archived, monthly updates to the snow product will be delivered following the terms of the SA. The snow product netCDF and metadata files are currently available for download on the NCDC THREDDS Data Server (TDS) and via the CDR program's FTP server.

Discussions with Dr. Walter Meier at NSIDC have led to the incorporation of the NOAA operational melt onset algorithm into his NOAA CDR sea ice product (Meier's work was done under a different SDS contract). This was done to two reasons: first the melt onset algorithm uses the same brightness temperatures as in the ice product, and second, the melt onset dates are a quality flag for the sea ice calculations. Therefore anyone using the sea ice calculations would also have the melt onset data in the same files. The files generated by Dr. Meier have the melt onsets dates in each daily record. During melt onset, there is an increase in the crystal structures within the snowpack above the sea ice surface that causes a change in the brightness temperatures. The changes in the brightness temperatures have been shown to lead to false reports of declining sea ice concentrations. Therefore by incorporating a flag for melt onset into the sea ice concentrations, a confidence level is established during melt. These melt onset dates have already been incorporated in to the sea ice CDR and are written in the sea ice ATBD.

The sea ice motion and iceage datasets will be archived at NSIDC. Currently, the sea ice motion dataset is archived through 2011. The iceage dataset continues to be produced at the University of Colorado by Dr. Tschudi. The iceage product will be transitioned to NSIDC later this year, accompanied by pertinent coding and proper ATBD documentation.

Project web site

The NOAA snow product has been the focus of our website (http://snowcover.org). We have also posted North American microwave-derived snow extent maps, North American station-derived snow extent maps, and some preliminary assessments of agreement/disagreement amongst the visible, microwave and station mapping of North American extent. An international array of individuals maintains an interest in the databases and derived information. For the vast majority, a visit to the project website suffices to meet their needs. As an example of yearly statistics over the course of the project, in 2011, 22,367 individuals visited the site at least once. Visitors clearly found the site useful, as there were 20,304 return visits over the course of the year. Visits in 2011 came from 115 countries, with the top ten from greatest to least including the U.S., Russia, United Kingdom, Netherlands, Canada, Germany, Italy, France, Finland and Sweden. 39% of the visitors came directly to the site, 39% arrived from a referring site,

indicating a number of other websites contain a link to our site. The remaining 22% found the site through search engines.

For those seeking further information concerning the data or wishing to obtain all or portions of the gridded databases, individual consultations occur primarily via email. Most often these involve making all or portions of a data product, including metadata, available for the customer to download. Follow up interactions often occur. In 2011 we provided data to 55 individuals, and 38 requests have already been satisfied in 2012. Recent contacts have been primarily from the international academic community, although the NOAA Climate Prediction Center, US Department of Agriculture, ESA GlobSnow, and the China Meteorological Administration from the government sector and several private firms received data in 2011. Several publications also requested data products in 2011 including the NOAA Climate Services Global Climate Dashboard, IPCC Fifth Assessment Report, KNMI Climate Explorer, and the BAMS State of the Climate Report.

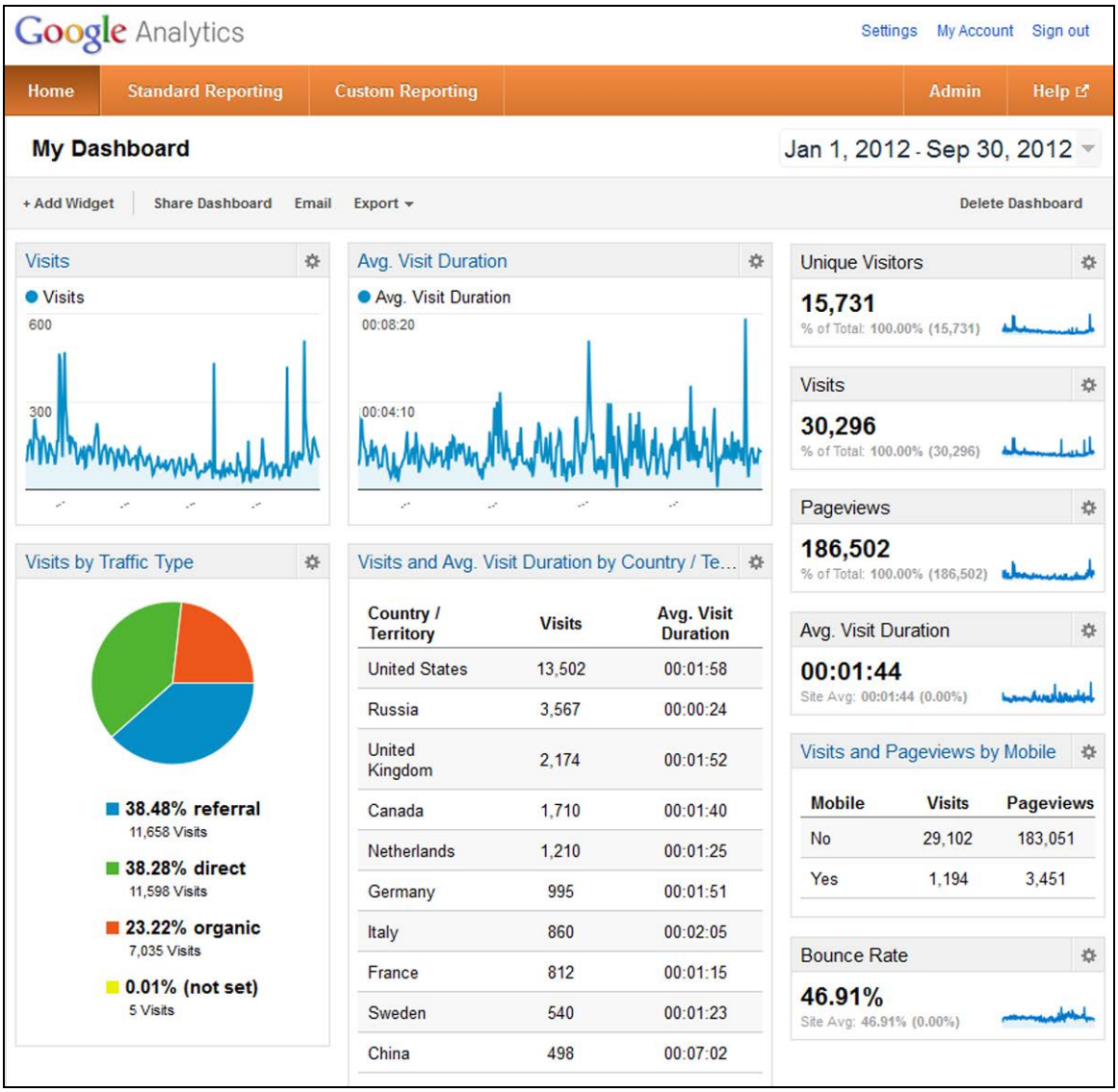

Figure 8. Google Analytics output for website access and traffic for the months of January 2012 – September 2012.

Project advisory committee

The following cryospheric scientists served on the project's advisory committee over the course of our efforts. They were an invaluable resource due to their cryospheric research focus and diverse knowledge. Each year of the project saw us meet with (most of) the committee in person during the AGU Fall Meeting. Those not at the meeting joined other committee members, project co-PIs, and the National Snow and Ice Data Center via a phone link.

Advisory committee members include:
Dr. Jesse Cherry, University of Alaska, Fairbanks
Dr. Chris Derksen, Environment Canada
Dr. Gavin Gong, Columbia University (inactive, has left Columbia)
Dr. Kari Luojus, Finnish Meteorological Institute

Dr. Walt Meier, National Snow and Ice Data Center, University of Colorado
Dr. Marc Stieglitz, Georgia Tech University
Dr. Daqing Yang, Atmosphere Environment Service, Saskatoon, Saskatchewan.

Other synergistic activities

Anderson chairs the PoDAG committee. In the process he is learning more about the process of submitting data sets into the NSIDC data archive from MEaSUREs projects. Gina Henderson, a post doc in Robinson's lab through the summer of 2011 and recently a new assistant professor at the US Naval Academy (while continuing to work on our project) also became a member of PoDAG in 2010.

Anderson and Henderson attended the October 2011 PoDAG working group meeting in Boulder. Robinson joined them at the 2010 meeting in Washington.

Anderson sits on the American Meteorological Society's committee on Data Stewardship.

Robinson contributed to the State of the Climate reports for 2007, 2008, 2009, 2010 and 2011 that are published in the *Bulletin of the American Meteorological Society*.

Fowler, Maslanik and Tschudi (April & Sept 2012) and Robinson (Jul. 18 2011) contributed to the NSIDC Arctic Sea Ice News & Analysis website.
http://nsidc.org/arcticseaicenews/2012/09/arctic-sea-ice-falls-below-4-million-square-kilometers/
http://nsidc.org/arcticseaicenews/2012/04/arctic-sea-ice-enters-the-spring-melt-season/

http://nsidc.org/arcticseaicenews/2011/071811.html
http://nsidc.org/arcticseaicenews/2011/100411.html

Fowler and Maslanik contributed to the NOAA Climate Services ClimateWatch Magazine (Apr. 14 2011 and Oct. 4 2011).
http://www.climatewatch.noaa.gov/video/2011/old-ice-becoming-rare-in-arctic
http://www.climatewatch.noaa.gov/2011/articles/march-2011-ice-extent-second-lowest-on-record

Maslanik, Fowler and Tschudi contributed to the Arctic Report Card in 2010, 2011 and 2012.

Robinson is a member of the National Academy of Sciences Board of Atmospheric Sciences and Climate advisory committee and NOAA's Climate Working Group (NOAA's lead climate advisory committee).

Publications and Presentations

Since the project's inception, there have been a number of papers published or submitted by team members that employ data from the SDS project datasets or are related to cryospheric data records. One master's thesis using project data has been completed. Numerous project-related presentations (most with accompanying abstracts) have been made as well.

Publications

Anderson, M.A., J.L. Busse and S. Drobot, 2011 A Comparison between SSM/I Passive Microwave Melt Onset Dates and Satellite Derived Albedo Melt Onset Dates in the Arctic, *International Journal of Remote Sensing*. 33, 517-533, DOI:10.1080/01431161.2010.542198.

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Bliss, A.C. and M.R. Anderson; Arctic snow and sea ice response to melt season atmospheric forcing across the land-ocean boundary, *Journal of Geophysical Research - Atmospheres*, (revised, currently under-review)

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Jahn, A., K. Sterling, M.M. Holland, J.E. Kay, J.A. Maslanik, C.M. Bitz, D.A. Bailey, J. Stroeve, E.C. Hunke, W.H. Lipscomb, and D.A. Pollak, (accepted for publication). Late 20th century simulation of Arctic sea ice and ocean properties in the CCSM4. *Journal of Climate*.

Ma, T., X. Xhang, H. Massam, F.W. Zwiers, G. Monette, and D.A. Robinson. Bayesian hierarchical models for climate change detection and attribution. *Journal of Climate*. (submitted for review)

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Perovich, D., W. Meier, J. Maslanik, and J. Richter-Menge, 2010. "Sea Ice Cover", in "Arctic Report Card 2010, Richter-Menge, J., and J.E. Overland, Eds., http://www.arctic.noaa.gov/reportcard.

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Abstracts/Presentations (all abstracts were presented at the meetings listed)

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Anderson, M.R., A.C. Bliss, and S Drobot, 2011. Arctic sea ice snowmelt onset dates climate data record derived from satellite passive microwave for 1979-2010, Fall Meeting of the American Geophysical Union, San Francisco, CA.

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Anderson, MR., J. Busse and S Drobot, 2009. A pilot study to compare SSM/I passive microwave derived melt onset dates to satellite derived albedo melt onset dates for select points throughout the Arctic. American Geophysical Union Fall Meeting, San Francisco, CA.

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Bliss, A.C., and M.R. Anderson, 2011. Response of arctic snow and sea ice extents to melt season atmospheric forcing across the land-ocean boundary. Fall Meeting of the American Geophysical Union, San Francisco, CA.

Bliss, A.C. and M.R. Anderson, 2011. Arctic snow and sea ice response to melt season atmospheric forcing across the land-ocean boundary, AMS 11th Conference on Polar Meteorology and Oceanography, Boston, MA.

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