A Product Development Team for Snow and Ice Climate Data Records

YEAR 3 REPORT

Principal Investigator: Jeffrey Key
NOAA/NESDIS, Center for Satellite Applications and Research
1225 W. Dayton St., Madison, WI, 53706; 608-263-2605; jkey@ssec.wisc.edu

Co-Investigators: William Emery[1], James Maslanik[1], Charles Fowler[1], Julienne Stroeve[2], Walter Meier[2], Xuanji Wang[3], Yinghui Liu[3], Dorothy Hall[4], Mark Tschudi[1]

[1]Colorado Center for Astrodynamics Research (CCAR), University of Colorado, Boulder, CO
[2]National Snow and Ice Data Center (NSIDC) and the Cooperative Institute for Research in the Environmental Sciences (CIRES), University of Colorado, Boulder, CO
[3]Cooperative Institute for Meteorological Satellite Studies (CIMSS), University of Wisconsin
[4]Cryospheric Sciences Laboratory, Code 615, NASA Goddard Space Flight Center, Greenbelt, MD

July 31, 2012

SUMMARY

The availability, consistency and accuracy of cryospheric products are critical for applications such as climate change detection, weather and climate modeling, shipping, and hazard mitigation. In turn, full exploitation of cryospheric products can benefit greatly from the support provided by a coordinated group of data and applications experts. The Cryosphere Product Development Team created under this project is providing such coordination for the generation, validation, and archival of fundamental and thematic snow and ice climate data records (CDR) that the scientific community can use to help answer questions about a changing climate. The Team developing new products, establishing "best practices", and updating heritage products. Our focus is on products that can be derived from optical (visible, near-IR, and thermal IR) and passive microwave imagers. Fundamental CDRs (FCDR) are being created and used in the production of thematic CDRs (TCDR).

This report describes activities during the third year of this three-year project. A no-cost extention has been requested by some members of the team, so a final project report will be submitted at the end of that period. Accomplishments during the third year include:

- Daily and monthly concentration CDR fields have been produced in NetCDF4_CF format for 1987-2007 and delivered to NOAA with accompanying C-ATBD, software, metadata fields, and other documentation. NASA Goddard produced fields are provided for 1978-2007.
- Final coefficients for the newest DMSP sensor, the F17 SSMIS were obtained from NASA Goddard.
- The NASA Team passive microwave sea ice concentration product provides the basis for regular scientific analysis of conditions at the NASA and NOAA funded "NSIDC Arctic Sea Ice News and Analysis" (ASINA) website. The passive microwave sea ice products also provide input and a baseline for evaluation for the ARCUS/SEARCH Sea Ice Outlook.
- Based on comparisons to other data sets, the complete times series of the Lagrangian tracking ice age product has been reprocessed using a revised procedure that is more effective at representing the extent of ice cover with multiyear ice present. The resulting time series has been updated through December 2011 and delivered to NSIDC as a research level product. The ice age product has been used multiple times in the ASINA website and have also been incorporated into the Sea Ice Outlook.
- The process of extending the AVHRR Polar Pathfinder (APP) products through December 2011 has been completed. A number of changes and updates to the compositing and calibration procedures were made.
- A comparison of surface temperature over Greenland from AVHRR and MODIS has shown that APP-x underestimates the temperature relative to MODIS, with a lower bias observed during the summer months. In contrast, comparisons of the APP-x temperature

data with drifting buoy temperatures show good agreement during the non-melt period, with a slight bias during melt.

- An ESDR of the surface temperature of the Greenland Ice Sheet has been developed and is available online: http://modis-snow-ice.gsfc.nasa.gov/index.php?c=greenland.
- Comparisons between Northern Hemisphere snow cover using NOAA and Rutgers snow maps from 1966 through the MODIS era (2000 – present) have begun.
- A number of papers have been published on the use of snow and ice CDR products for climate studies. One important study employed a method to quantitatively determine the effect of changes in sea ice on changes in cloud cover.

This is a multi-institutional project led by the NOAA National Environmental Satellite, Data, and Information Service (NESDIS), including its Cooperative Institute for Meteorological Satellite Studies (CIMSS)/University of Wisconsin, NASA Goddard Space Flight Center (GSFC), the University of Colorado at Boulder (CU), and the National Snow and Ice Data Center at the CU/NOAA Cooperative Institute for Research in Environmental Sciences (CIRES).

TABLE OF CONTENTS

Summary ii
Table of Contents iv
Introduction 1
The Cryosphere Product Development Team 2
Visible and Infrared Products 3
  AVHRR Polar Pathfinder extended (APP-x) 3
  Ice Surface Temperature of the Greenland Ice Sheet 7
Passive Microwave Ice Products 10
  Sea Ice Concentration and Melt State 10
  Sea Ice Motion and Age 11
Snow Cover 13
Product Maturity 14
Scientific Discovery 14
Outreach 18
Linkages with International Programs 19
Deliverables 19
Plans for the Remainder of the Project 21
Publications Supported In Whole or in Part By this Grant 21
References 22

INTRODUCTION

The cryosphere collectively describes elements of the earth system containing water in its frozen state and includes sea ice, lake and river ice, snow cover, solid precipitation, glaciers, ice caps, ice sheets, permafrost, and seasonally frozen ground (Figure 1). The presence of frozen water in the atmosphere, on land, and on the ocean surface affects energy, moisture, gas and particle fluxes, clouds, precipitation, hydrological conditions, and atmospheric and oceanic circulation. Elements of the cryosphere are key indicators of climate variability and also contain important records of past climate providing benchmarks for interpreting modern climate change. The cryosphere exists at all latitudes and in about one hundred countries.

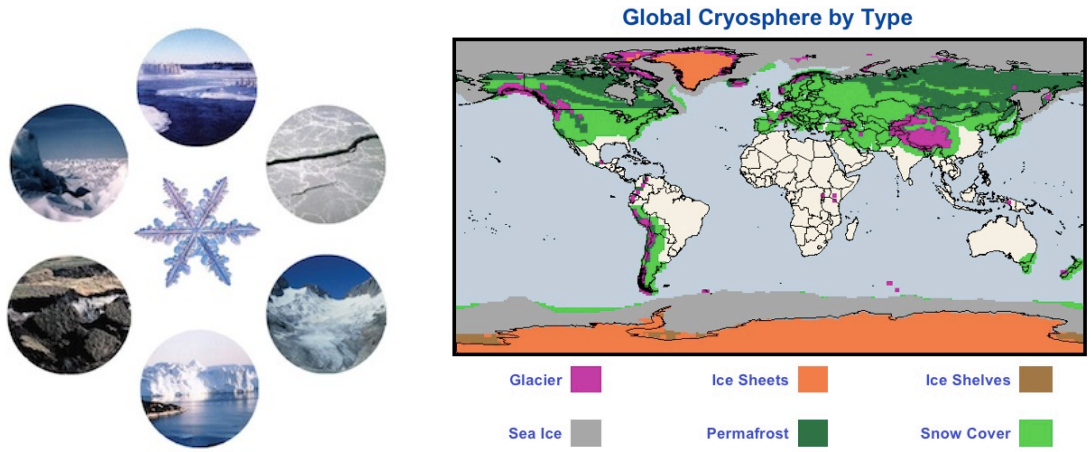

Fig. 1. Examples of the cryosphere (left) and its global distribution (right).

Adequate knowledge of the cryosphere is important for weather and climate prediction, assessment and prediction of sea level rise, availability of fresh water resources, navigation, shipping, fishing, and in many other practical applications. The cryosphere provides indicators of climate change, yet it may be the most under-sampled domain in the climate system.

In this project we have created a Cryosphere Product Development Team that is coordinating the generation, validation, and archival of fundamental and thematic snow and ice climate data records (FCDR and TCDR). The Team is coordinating existing and new products and updating heritage products. We are establishing "best practices" within the Team and for the broader cryosphere community, evaluating gridding options, consistency within and between similar products, and metadata.

Our focus is on products that can be derived from optical (visible, near-IR, and thermal IR) and passive microwave imagers as these encompass the longest and most consistent CDRs available for the cryosphere. We are evaluating existing FCDRs and creating new ones when necessary. The FCDRs are being used in the production of TCDRs. Our goal is to refine, extend, validate, document, and archive visible, infrared, and passive microwave cryosphere products. Snow and

ice products exist for both heritage (AVHRR, SSM/I) and newer (MODIS, AMSR-E) instruments. We are building on existing efforts, coordinating with other funded products, as appropriate. The Team is uniquely qualified for this effort. The following CDRs are being generated:

- Ice/snow surface temperature (AVHRR, MODIS)
- Ice/snow surface broadband albedo (AVHRR)
- Sea ice motion (AVHRR, SSM/I, AMSR-E)
- Sea ice concentration and extent (SSM/I, AMSR-E, AVHRR)
- Sea ice age (AVHRR, SSM/I, AMSR-E)
- Snow cover/extent (AVHRR, SSM/I, AMSR-E)
- Sea ice melt onset and freeze-up (SMMR, SSM/I, AMSR-E)
- Surface shortwave and longwave radiation (AVHRR)

Collectively, these CDRs provide information on the most important snow and ice characteristics for climate research, including the primary component of the surface energy budget: radiation. Snow and ice products exist for both heritage (AVHRR, SSM/I) and newer (MODIS, AMSR-E) instruments. Our goal is to continue to extend these products and merge them into consistent time series. A key point is that these data continue the AVHRR Polar Pathfinder (APP) philosophy of providing a suite of coordinated products mapped to a common map projection. Such a suite greatly facilitates investigations of the complex processes, interactions and feedbacks inherent in the cryosphere (cf, Fernandes et al., 2009; Francis and Hunter, 2007).

While a CDR is ideally a single authoritative product for a given parameter, e.g., sea ice concentration, in practice there are limitations to the use of any single sensor. In some cases, the same parameter can be estimated from different sensors, each having its strengths and weaknesses. For example, having passive microwave (PM) and visible/IR sea ice concentration products makes sense because (1) PM provides the complete all-sky coverage and consistent long-term record, while (2) visible/IR data provides improved spatial resolution useful for process studies and ice hazard observations, and potentially offers better performance under certain conditions (e.g., melt). In such cases we are developing both products.

The purpose of this document is to report on accomplishments for the third year of the three-year project. The project period for this report is July 2011 through June 2012.

THE CRYOSPHERE PRODUCT DEVELOPMENT TEAM

This is a multi-institutional project that includes personnel from the NOAA National Environmental Satellite, Data, and Information Service (NESDIS) Center for Satellite Applications and Research (STAR), including its Cooperative Institute for Meteorological Satellite Studies (CIMSS)/University of Wisconsin, the University of Colorado's (CU) Cooperative Institute for Research in Environmental Sciences (CIRES), the National Snow and

Ice Data Center (housed in CIRES), and NASA's Goddard Space Flight Center (GSFC). The Cryosphere Product Development Team is comprised of

- **Jeff Key** (PI), NOAA/NESDIS
- **Xuanji Wang**, University of Wisconsin
- **Yinghui Liu**, University of Wisconsin
- **James Maslanik**, University of Colorado
- **Walt Meier**, University of Colorado
- **Charles Fowler**, University of Colorado
- **Julienne Stroeve**, University of Colorado
- **William Emery**, University of Colorado
- **Dorothy Hall**, NASA/GSFC
- **Mark Tschudi**, University of Colorado

The Team has expertise in the remote sensing of snow and ice from visible, near-infrared, thermal infrared, and microwave sensors, and has extensive experience in the development and distribution of snow and ice climate data records.

VISIBLE AND INFRARED PRODUCTS

AVHRR Polar Pathfinder extended (APP-x)

As part of the NOAA/NASA Pathfinder Program in the 1990's, NASA provided funding for the generation of CDR-quality data products for the polar regions from AVHRR data. Co-investigators on the project, including Fowler, Emery, Maslanik, and Key, developed the Advanced Very High Resolution Radiometer (AVHRR) Polar Pathfinder (APP) product. APP includes FCDRs as well as TCDRs for clear-sky snow/ice temperature and albedo, cloud amount, and ice motion over both polar regions. In addition to the products derived solely from AVHRR, we have also generated multisensor products that include sea ice motion and ice age for the full record. Some years ago we extended APP (APP-x) to include all-sky surface albedo and temperature, cloud properties, and radiative fluxes, which we continue to improve and extend. These data represent one of the longest suites of satellite products available for climate research. The APP and APP-x products are widely used within the research community, and have also proven useful for operational purposes such as prediction of sea ice conditions in shipping routes.

The original APP product development funding covered the period from fall of 1981 through 1997. Subsequent NASA funding allowed extension of the dataset through 2004. More recently NASA funded another extension of the data set through 2010 by Fowler and Stroeve. During Year 3, the extension of the AVHRR Polar Pathfinder products to December 2011 was completed with funds from this project. During the reprocessing, the composition algorithm package was refined, including an update of the calibration coefficients, a correction to the

method that converts Universal Coordinated Time to Solar Local Time, and a refinement of the compositing process. The current updated data include twice-daily calibrated and gridded satellite channel data (five channels), solar zenith angle, satellite elevation angle, sun-satellite relative azimuth angle, surface type mask, and Universal Coordinated Time (UTC) of acquisition. An example is given in Figure 2.

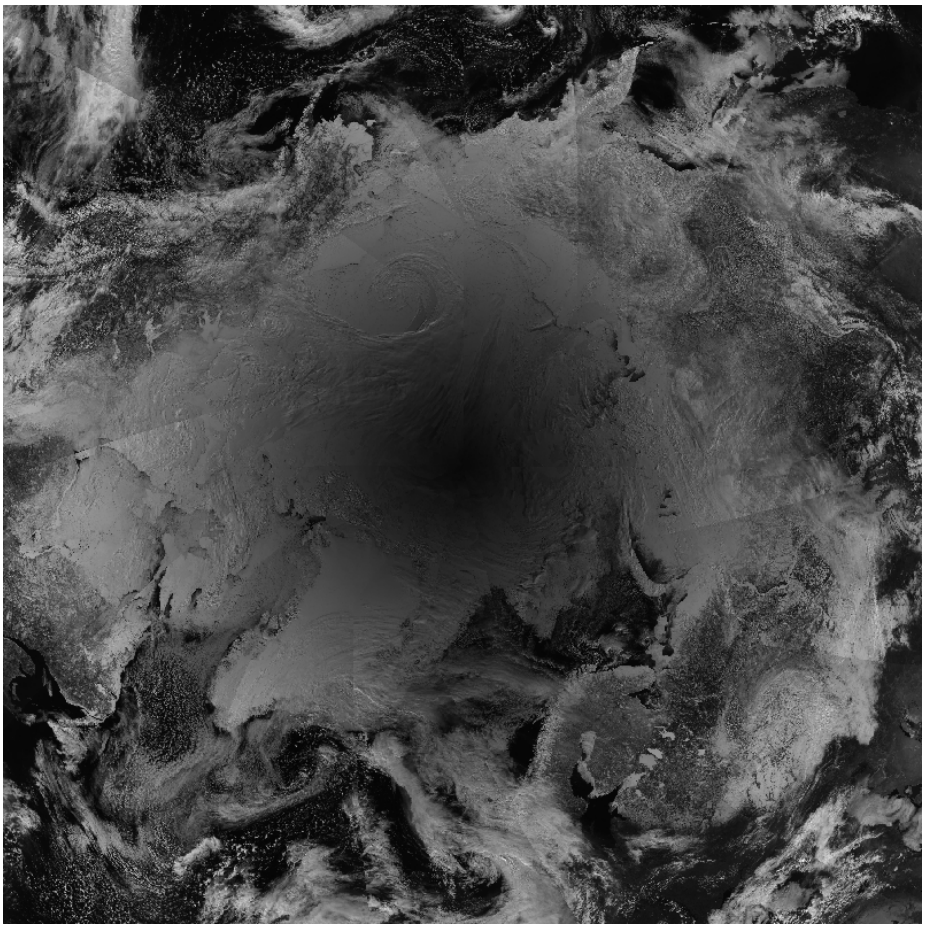

Fig. 2. Example of APP composite of channel 1 reflectance at 1400 Solar Local Time in the Arctic on Julian day 90, 2011.

APP-x has been further extended to include ice concentration and ice thickness. Ice age and thickness is being produced using two approaches that are each unique yet mutually beneficial and independent of each other. For the APP-x product suite, ice thickness and age are estimated with an energy balance approach. The other approach is based on Lagrangian tracking, described in the next section. The full suite of APP-x variables is given in Table 1. Examples of APP-x products are given in Figure 3.

Table 1. Summary of geophysical variables currently part of, or being developed for, APP-x.

Surface	***Clouds***	***Radiation***
Surface temperature, clear or all-sky	Cloud particle effective radius	Surface downwelling/ shortwave flux
Broadband albedo, clear or all-sky	Cloud optical depth	Surface downwelling/upwelling longwave flux
Surface type mask	Cloud particle phase	TOA downwelling/upwelling shortwave flux
Precipitable water	Cloud top temperature	Surface shortwave/longwave cloud forcing
Ice thickness and age	Cloud top pressure	
Ice extent & concentration	Cloud type	

There have been numerous updates to our core APP-x algorithm code, including the addition of ice concentration and thickness/age algorithms, sunglint to improve cloud detection, and surface type change tracking.

The extended products have been validated with the data collected during the Surface Heat Balance of the Arctic Ocean (SHEBA) field experiment in the western Arctic (Maslanik et al., 2001; Stroeve et al., 2001), with the data from two Antarctic meteorological stations: South Pole and Neumayer (Pavolonis et al., 2002) and to a lesser extent using data from individual field studies (Key et al., 1994). The APP-x data set was primarily compared with SHEBA ship measurements for the purpose of error estimation by averaging APP-x 5 x 5 pixel boxes (25 x 25 km^2) centered on the SHEBA ship site (Wang and Key, 2005). Key et al. (1997) investigated uncertainties in satellite-derived surface and cloud properties and surface radiation budget at the high latitudes, and arrived at the conclusion that the accuracy in estimating radiation budgets from satellite is appropriate for a wide range of process studies at monthly timescales. The consistency of the products from different satellites over the period of 1982 to 1999 was investigated and found no observable bias by Wang and Key (2003). The sea ice thickness product has been validated with the data from submarine cruises, meteorological stations, and moored upward looking sonar in the Arctic Ocean (Wang et al., 2010), and found the accuracy to be higher than 80%.

The visible/IR ice concentration has been compared to the Advanced Microwave Scanning Radiometer - Earth Observing System (AMSR-E) Level-3 gridded product. Daily sea ice concentration on July 1 and October 1, 2007 from MODIS and AMSR-E are shown in Figure 4. Both products show similar sea ice concentration values, but the higher-resolution MODIS ice concentration is more detailed in the central Arctic and the sea ice edge areas. Comparison of both products in 2007 shows that the MODIS product has a positive bias of 4% and standard deviation of 15% compared with AMSR-E. A similar algorithm has been implemented for AVHRR, and sea ice concentration will be generated in APP-x from 1982 to the present. This product in APP-x will be extensively compared with sea ice concentration retrievals from

microwave observations.

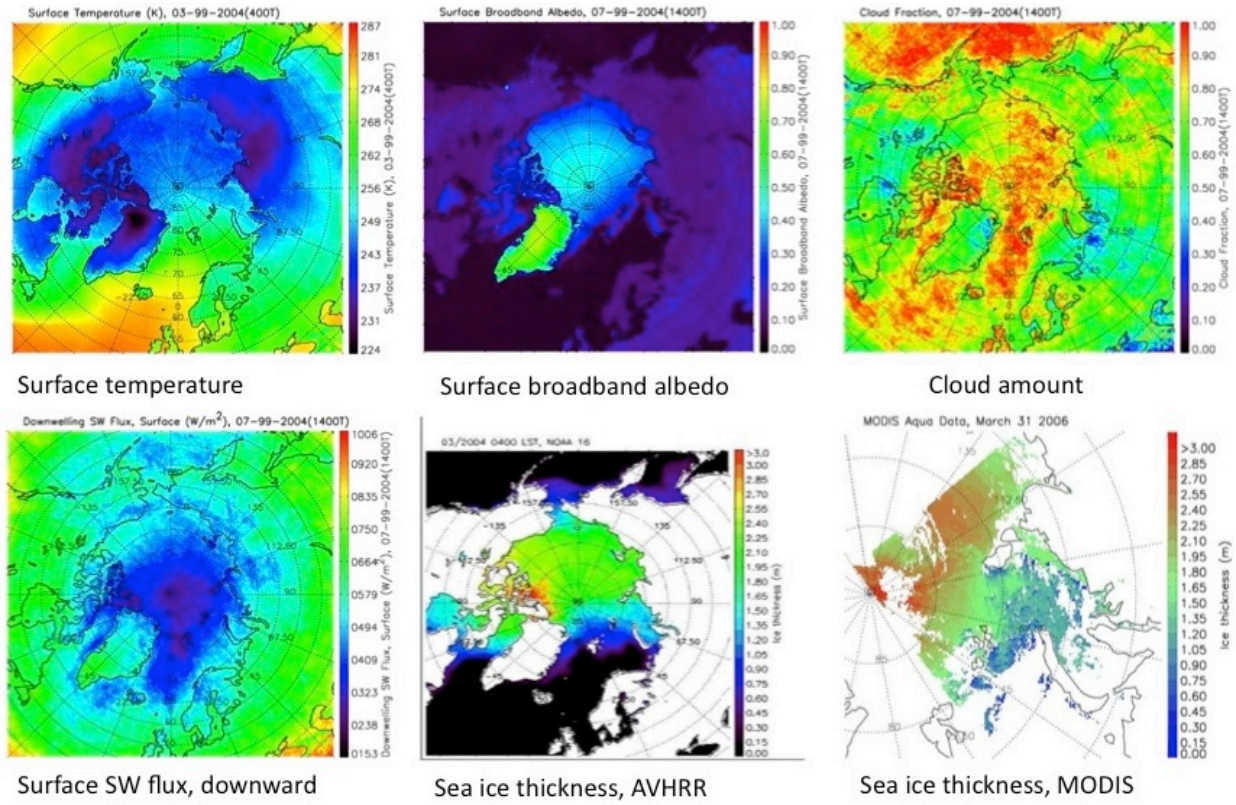

Fig. 3. Examples of APP-x products. Clockwise from upper left: surface temperature, surface albedo, cloud fraction, sea ice thickness from MODIS, sea ice thickness from AVHRR, and surface downwelling shortwave flux.

Many of the APP-x products have been adapted for use with MODIS data, and are being tested against algorithms developed by private industry for use with the NPP VIIRS instrument. The APP and APP-x algorithms provide valuable comparison data for VIIRS. They also represent potential improvement paths for VIIRS and can help address the lack of an NPP/JPSS passive microwave sensor. Several of the Team members are involved with VIIRS algorithm and processing assessment teams, and are thus well positioned to mesh the work proposed here with NPP and JPSS. Our algorithms also form the basis for snow and ice products that we are developing with NOAA funding for operational use with the Geostationary Operational Environmental Satellite-R (GOES-R) Advanced Baseline Imager (ABI). These projects are ongoing and contribute directly to the improvement of snow and ice CDRs.

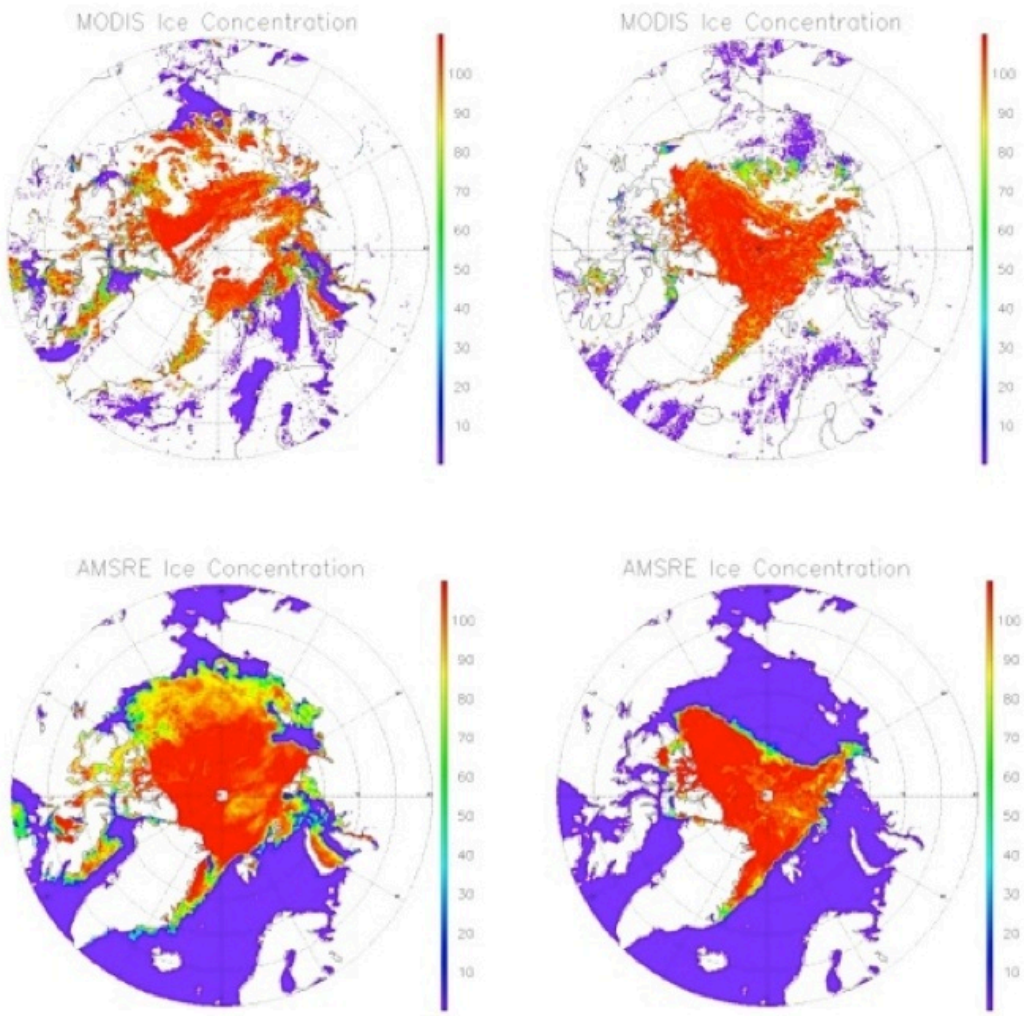

Fig. 4. Daily sea ice concentration on July 1 and October 1 from MODIS (first row), and from AMSR-E (second row). The white color over the Arctic Ocean represents cloud cover.

Ice Surface Temperature of the Greenland Ice Sheet

We have developed a climate-quality data record of the surface temperature of the Greenland Ice Sheet http://modis-snow-ice.gsfc.nasa.gov/index.php?c=greenland for a NASA-funded project (D. Hall, PI) through the Cryosphere Program, and the NASA MEaSUREs project (D. Robinson, PI). The original objective was to use APP or APP-x, MODIS, and future VIIRS data, so that the CDR would begin in 1982 with the APP or APP-x data and continue through the MODIS and VIIRS eras. Extensive comparisons between the APP IST and MODIS IST during an overlap period (2000 – 2004) were conducted. Results show that it is not feasible at this time to merge the APP and MODIS IST records of the Greenland Ice Sheet (Hall et al., 2012). The APP and MODIS IST records could not be merged because of the differences in the cloud masks inherent

in the two products. The MODIS instrument has more bands available with which to create a cloud mask. It is especially difficult, even with multiple bands, to create an accurate cloud mask over ice and snow surfaces during polar darkness. However, the APP data are currently being reprocessed and additional comparisons will be made between the reprocessed APP dataset and the MODIS IST dataset.

Therefore, a "climate-quality" data record was developed using MODIS data alone, spanning the time period from 1 March 2000 through 31 December 2011, at 6.25-km spatial resolution on a polar stereographic grid (see sample of monthly maps from 2010 in Figure 5). Both binary and color-coded daily and monthly IST maps are available.

Preliminary validation has been undertaken with the MODIS IST data record using in-situ data acquired during the 2008-09 winter at Summit Camp, Greenland (Figure 6). Under windy conditions, the 2-m air temperature is similar to the surface temperature, and under those conditions, results can be compared. Results show a ~3°C cold bias with the MODIS IST data. This conclusion is consistent with results from other investigators also using MODIS surface-temperature data. Reasons for the cold bias are currently being explored. It is thought that some atmospheric correction may be required to account for ice fog in the winter and water vapor in the melt season. In addition, new results show that, when the cloud mask fails to mask clouds, the algorithm will make a temperature decision on the cloud top, often causing a large dip (30 K or more) in IST during the June, July & August summer melt season. This contributes to the cold bias but can easily be removed now that the problem has been identified.

Since the MODIS IST algorithm is based on the AVHRR IST algorithm of Key and Haefliger (1992), the entire MODIS dataset (both from Terra and from Aqua) over Greenland had to be reprocessed using the IST algorithm (vs. the LST algorithm of Wan et al. (2002)). This was completed in the last year. Consistency of the IST algorithm (from AVHRR to MODIS to VIIRS) is needed to create a CDR.

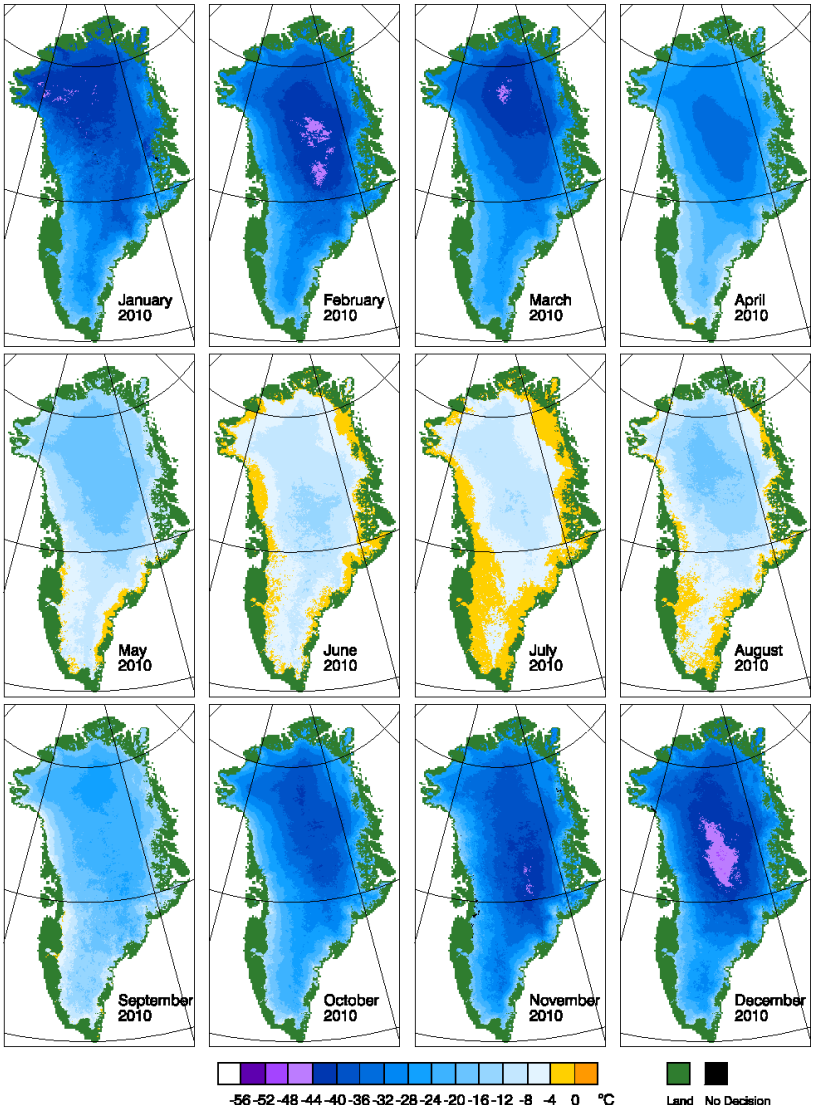

Fig. 5. Mean-monthly ice-surface temperature (IST) color-coded maps for 2010.

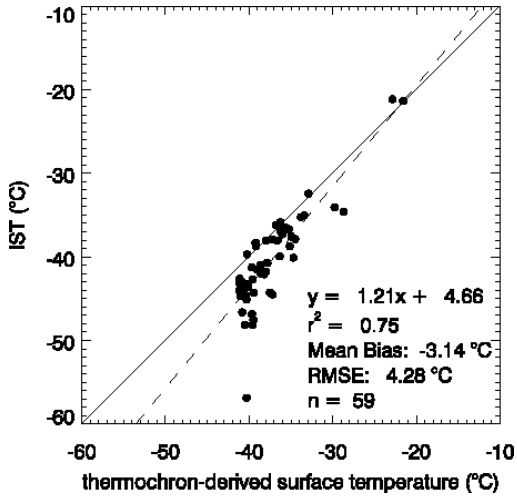

Fig. 6. Relationship between IST and in-situ derived snow/ice surface temperature (from thermochron data) at Summit Camp, Greenland, 17 November 2008 – 12 February 2009 (see Hall et al., 2012).

PASSIVE MICROWAVE ICE PRODUCTS

Sea Ice Concentration and Melt State

Implementation of the passive microwave sea ice concentration CDR was completed in the last year. This was primarily supported under an earlier project, "Creation and Preservation of a Sea Ice Climate Data Record" (NOAA Grant #NA07OAR4310056, W. Meier, PI), but the product will feed into this product development team project. A new concentration estimate is derived from current products along with data quality information. A sample of the product is shown in Figure 7. The product is based on the NASA Team and Bootstrap algorithm originally developed at NASA Goddard. The two algorithms are run independently and the higher concentration value between the two is used for the CDR concentration. A standard deviation field is created to provide an indication of uncertainty and a quality assessment field is produced to indicate regions (such as melt) of potentially high errors. The implemented product includes daily and monthly CDR-quality fields for 1987-2007, including metadata information, netCDF4 format with Climate and Forecasting (CF) extensions, processing documentation, and a CDR ATBD. Also included in the NetCDF files are analogous concentration fields from NASA-produced algorithm products. These fields include manual (albeit untracked) quality control to remove erroneous data as well as spatial and temporal interpolation to fill in regions of missing data. These fields also effectively extent the CDR timeseries to November 1978.

The sea ice concentration CDR is currently produced through the end of December 2007, which roughly marks the end of the high quality F13 SSM/I sensor lifetime. A near-real-time implementation of the NASA Team algorithm was developed at NSIDC to continue regular updated concentration information. However, for the highest quality within the CDR, it was deemed best to wait until final coefficient adjustments were made for the F17 SSMIS sensor to provide a consistent timeseries with the earlier SSM/I record. Coefficients were delivered by NASA Goddard and will be implemented at NSIDC in the coming year.

Collaboration also continued with other climate data record projects, including a NASA-sponsored snow and ice Earth Science Data Record (ESDR) being developed by researchers at Rutgers University, University of Nebraska, NASA Goddard, and the University of Colorado. Collaboration is also underway for consistency with the upcoming JAXA Global Change Observation Mission (GCOM-W) AMSR2 products. A co-investigator on this project is PI on a NESDIS-funded project to implement an operational AMSR2 sea ice product.

<u>Melt State</u>

Melt state has been implemented in the sea ice concentration product as a quality assessment flag (Figure 7), based on the Drobot and Anderson (2001) algorithm. We are working with M. Anderson (Univ. Nebraska) to coordinate our product with current NASA MEASURES and NOAA CDR projects to produce a melt onset CDR. Our products will be integrated together in the future to provide consistent and complementary products.

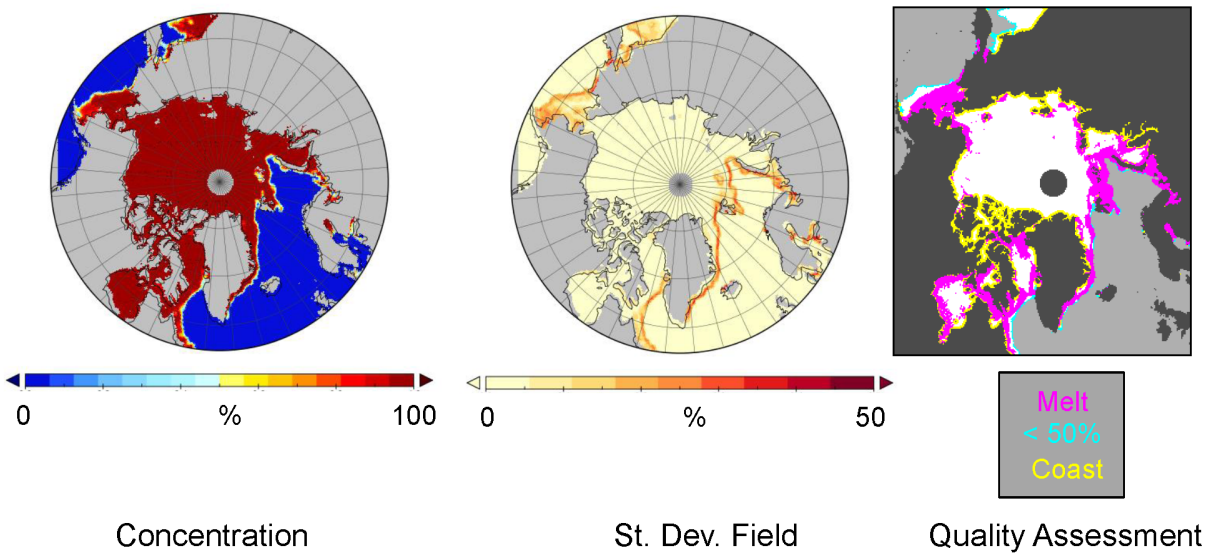

Fig. 7. Sample Arctic sea ice concentration climate data record field for 15 March 2007. The fields are: (left) CDR concentration field, (middle) concentration standard deviation field, and (right) data quality field.

For potential future work, we are also investigating another passive microwave melt product (Smith, 1998; Markus et al., 2009), produced at NASA Goddard (T. Markus and J. Miller). We have obtained their processing code and are reviewing it for potential implementation. This product will have two benefits. First, it provides an independent secondary screening for melt state, yielding confidence information on the true state of melt (i.e., if both products indicate melt, there is higher confidence than if only one did). Also, the Goddard product includes a freeze-up parameter, which it useful for indicating when freeze-up begins.

Sea Ice Motion and Age

Daily ice motion vectors are computed from AVHRR, SMMR, SSM/I, and International Arctic Buoy Programme (IABP) buoy data. Daily gridded fields combine data from all sensors. The vector time series has been updated through December 2011. These are being provided to NSIDC for public release as an update to the "Polar Pathfinder Daily 25 km EASE-Grid Sea Ice Motion Vectors" (http://nsidc.org/data/nsidc-0116.html). Based on analyses of a preliminary set of motion vectors calculated from AMSR-E data done during this project, the decision was made to use AMSR-E vectors in the operational time series for 2002 onward (i.e., the full period of the AMSR-E record). Vectors have now been calculated for the full AMSR-E series and were used to produce a new version of the complete time series of motion vectors from 1979 onward.

We have re-processed these data to incorporate Arctic Ocean Buoy Program buoy drift through 2011 (previously buoy data was only incorporated through 2009) and continue to work with the buoy PI (I. Rigor, Univ. Washington) to get more recent buoys and update further. Including the buoy data makes a substantial difference to the ice age fields generated from the vectors. This is more so for the eastern Arctic north of Greenland than for the western Arctic.

Work has also been carried out to investigate other ways of improving the motion vector fields during summer melt periods, when uncertainties in the microwave-derived vectors increase substantially (e.g., Kwok, 2008). Toward this end, an approach has been developed that makes use of winds from the National Centers for Environmental Prediction (NCEP) within the optimal interpolation process (wherein the drift vectors obtained separately from passive microwave, AVHRR and buoy data are blended) to provide additional information on likely ice drift direction and speed. The overall approach is similar to that developed previously by Kwok et al. (1998). Testing of this new approach was completed during the reporting period, and the new motion product, blended with winds through 2011, has been delivered to NSIDC.

As noted above, an approach that is unique to our data sets is the use of the microwave-derived ice motion data to follow the drift tracks of ice “parcels” over time, and then using these positions to extract corresponding parameters from our APP-x and passive microwave data sets and to calculate the age of the ice cover. In contrast to the surface energy budget modeling approach to determining ice thickness and age described earlier, another ice age method makes use of the APP ice motion fields to track the transport of ice, and thus its life cycle (Fowler et al., 2003). In brief, using satellite data and drifting buoys, it is possible to observe the formation, movement, persistence, and disappearance of sea ice. This history can then be used to estimate age (Rigor and Wallace, 2004). In the Fowler et al. (2003) approach, ice movement is calculated using gridded satellite-derived ice motion vector fields for 1979 onward. Ice age is estimated by treating each grid cell that contains ice as a discrete, independent Lagrangian parcel, and then transporting the parcels at weekly time steps. In cases where particles of different ages fall within a single grid cell, the cell's age is assigned that of the oldest particle. If ice concentration at the corresponding grid cell, as estimated using the NASA Team Algorithm (Cavalieri et al., 1984) applied to SMMR and SSM/I passive microwave data, remains at or above a prescribed threshold value throughout the melt season, then that particle is assumed to have survived the summer, and the particle's age is incremented by one year. For example, first-year ice is ice that has yet to survive a melt period, while fifth-year ice is ice that has survived four melt cycles. This also has the effect of "re-setting" the multiyear ice extent each summer, thereby minimizing any cumulative errors in multiyear ice extent over the time series.

As summarized is the previous annual report, we updated the ice age product to utilize a minimum concentration threshold of 15%, replacing the previous 40% threshold. A characteristic of the product, which becomes accentuated when switching from the 40% to 15% threshold, is that because the grid cell is assigned the age of the oldest ice present, a cell with a total concentration as low as 15% at the end of the melt period is coded as multiyear ice even though

the majority of ice present after freeze-up is first-year ice. Also, since each grid cell is considered to be a single, discrete age category and is not assigned an ice concentration value, the maps are best considered as extent maps that indicate areas where ice of different ages exists. Using statistical relationships between age and thickness, the resulting age data can be converted to approximate thicknesses (Maslanik et al., 2007). The 15% concentration is now applied to all ice motion and age data for the processing period of 1979-present.

SNOW COVER

In conjunction with the NASA-funded EOS snow project (D. Hall, PI) and the NASA-funded MEaSUREs project (D. Robinson, PI), we are creating a CDR of Northern Hemisphere snow cover using NOAA and Rutgers snow maps from 1966 through the MODIS era (2000 – present) and into the VIIRS era. It has been very difficult to compare the MODIS and Rutgers AVHRR snow maps during the overlap period (2000 – present). Initial results were poor. The difficulty in comparing the maps was mainly due to cloud cover that is shown on the MODIS snow maps and not on the Rutgers maps. However, we have now developed a cloud-gap-filled (CGF) daily MODIS snow-cover map algorithm (Hall et al., 2010), as reported last year. This facilitates comparisons of daily data using the Rutgers and MODIS snow maps.

The CGF MODIS snow-cover algorithm provides a global, cloud-free snow map each day. For each pixel, if the current day is cloudy, then the snow result from the previous day is used; if that day was cloudy then the snow result from two days prior to the current day is used, and so on. While this CGF product is useful during times of the year and at latitudes when the snowpack is not changing much, it is not a good choice for studying ephemeral snow, or for studying rapidly changing snow cover at the continental snowline. For each pixel or cell, the CGF product provides a "confidence index" to the user to enable him/her to assess whether or not to use the value.

The MODIS snow-cover maps using the CGF algorithm will be available in Collection 6 (C6) of the MODIS processing. However that data will not be available until sometime in 2013, as C6 processing will not even begin until late 2012. We are in the process of producing daily, global CGF products from MODIS in advance of the C6 MODIS processing.

In discussions with the rest of the cryosphere team, and as a possible outcome of the upcoming NOAA CDR Team meeting on 31 Jul - 2 August 2012 in Asheville, we can collectively decide if we want to produce these data products for the current cryosphere CDR project. At a minimum, the CGF data can be used for intercomparison and perhaps validation of other satellite-derived snow-cover datasets for this project. This discussion is ongoing and should be resolved in the next year.

PRODUCT MATURITY

The average product maturity, based on the Bates and Barkstrom index (1 is least mature; 6 is most mature), is as follows:

- Sea ice concentration and extent: 5
- Sea ice motion: 5
- Sea ice age – Lagrangian: 3
- Sea ice thickness/age – energy budget: 4
- Ice/snow surface temperature: 4.5
- Ice/snow surface broadband albedo: 4.5
- Surface shortwave/longwave radiation: 4.5
- Snow cover/extent: 5
- Surface ice melt onset/freeze-up: 4

Complete maturity matrices for each product are available on request.

SCIENTIFIC DISCOVERY

The investigators are engaged not only in algorithm development, product generation, and validation; they also use the products for scientific discovery. The data have proven to be critical in the evaluation of trends and anomalies in sea ice extent and cloud cover, and have been instrumental in quantifying feedback processes and interactions within the climate system. Some examples are given here. For completeness, we include the research reported last year.

The ice age product continues to be used to study changes in Arctic sea ice thickness over time. (The analysis was supported by NASA.) Analysis of the record for 1980 through March 2011 (Maslanik et al., 2011) and continuing through June 2012 shows continued net decrease in multiyear ice coverage in the Arctic Ocean, with particularly extensive loss of the oldest ice types. The fraction of total ice extent made up of multiyear sea ice in March decreased from about 75% in the mid 1980s to 47% in 2012, while the proportion of the oldest ice declined from 50% of the multiyear ice pack to 10%. These losses in the oldest ice now extend into the central Arctic Ocean and adjacent to the Canadian Archipelago; areas where the ice cover was relatively stable prior to 2007 and where long-term survival of sea ice through summer is considered to be most likely. Following record-minimum multiyear ice coverage in summer 2008, the total multiyear ice extent has increased to amounts consistent with the negative trend from 2001-2006, with an increasing proportion of older ice types. This implies some ability of the ice pack to recover from extreme conditions. This recovery has been weakest in the Beaufort Sea and Canada Basin though, with multiyear ice coverage decreasing by 83% from 2002 to 2009 in the Canada Basin, and with more multiyear ice extent now lost in the Pacific sector than elsewhere in the Arctic Ocean. The age product continues to be used in other ways as well.

R. Sombrato of Lamont-Doherty Earth Observatory is now looking at our ice motion data to compare the presence of ice to prominent biological features. The basic idea here is that the source or provenance of the ice plays a significant role in the resulting productivity at the ice Edge [R. Sombrato, personal comm.]. The full ice age dataset and related images were also provided to P. Schaefer of the NGA Support Team to NORAD and USNORTHCOM, as well as J. Davies of the Pew Environment Group. Figure 8 is being usedas part of the NSF-sponsored "Sea Ice Outlook" forecasting summary for June 2012, and ice age figures were supplied to NASA aircraft mission planners to assist in flight line determination as part of the IceBridge project. The ice age product will also be used in a funded ONR project to track "source" and "sink" regions of multiyear ice and implications of changes in these locations for climate and ecosystems.

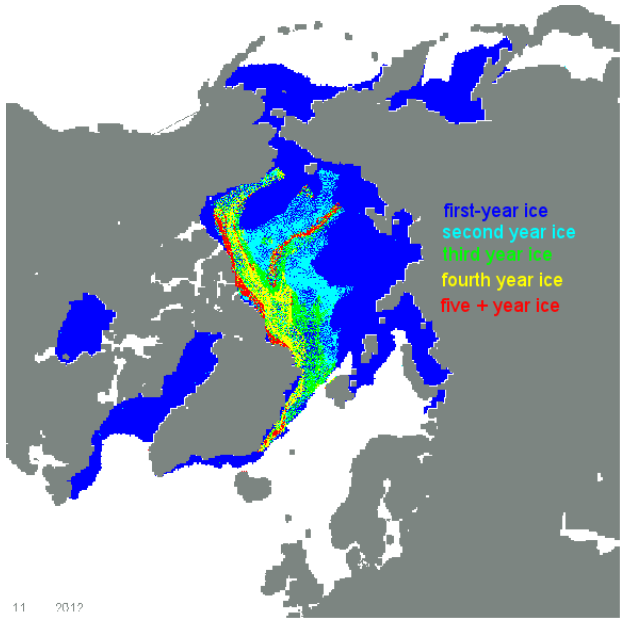

Fig. 8: Ice age from week 11 (March) 2012.

The APP-x product suite has been used extensively to determine trends in cloud cover and to quantify the relationships between clouds, sea ice, and surface temperature. The influence of trends in sea ice concentration (SIC) and cloud cover on trends in surface temperature over the Arctic Ocean from 1982 to 2004 was investigated analytically, and evaluated empirically with APP-x data. It was found that changes in SIC and cloud cover played major roles in the magnitude of recent Arctic surface temperature trends. Significant surface warming associated with sea ice loss was found over the Chukchi and Beaufort Seas in autumn, accounting for most of the observed warming trend. In winter, surface temperature trends associated with changes in cloud cover are negative over most of the Arctic Ocean, and with cloud cover trends explaining most of the surface temperature cooling. After eliminating the effects of changes in SIC and cloud cover on surface temperature trends, the residual surface temperature trends can be used in

a more robust diagnosis of surface warming or cooling in the Arctic.

Extending the work described above, passive microwave sea ice concentration and MODIS (Moderate-resolution Imaging Spectroradiometer) cloud amount were combined to investigate Arctic cloud-sea ice feedbacks. The Arctic has been experiencing dramatic changes in both cloud characteristics and in sea ice extent and concentration, and one would expect the changes in the two may be related to some degree, given that clouds influence the surface energy budget, the presence of sea ice influences lower tropospheric moisture, and large scale horizontal fluxes of heat and moisture affect both ice and clouds. However, it is unclear how the changes in Arctic sea ice feedback on the clouds. An equilibrium feedback assessment is employed to quantify the relationship between changes in sea ice and clouds, using satellite-derived sea ice concentration and cloud cover over the period 2000–2010. Study shows one percent decrease in sea ice there is around a 0.4-0.5% increase in cloud cover during the July – December period. Increased cloud amount constitute a positive climate feedback, by trapping longwave radiation which leads to greater warming further accentuating sea ice melt. 22-34% of cloud variability is linked to variability of sea ice. These findings indicate that further warming and sea ice melt in coming years could lead to cloudier skies in the Arctic.

Observation based estimates of controls on the snow albedo feedback (SAF) are needed to constrain the snow and albedo parameterizations in general circulation model (GCM) projections of air temperature over the Northern Hemisphere (NH) landmass. Snow albedo and snow cover from APP-x were used to study controls on the NH SAF. The total SAF is the sum of the effect of temperature on surface albedo over snow covered surfaces ('metamorphism') and over surfaces transitioning from snow covered to snow free conditions ('snow cover'). The North American spatial pattern of SAF is chiefly explained by the snow cover component but there is evidence that both snow cover and metamorphosis components contribute to the pattern of SAF over Eurasia. Anthropogenic deposition of impurities on central Eurasia snow covered surfaces may explain the distinction between the two continents.

The passive microwave sea ice concentration products are one of the primary indicators of the seasonal and interannual evolution of the ice cover. The data provide the basis for regular scientific analysis of conditions at the NASA and NOAA funded "NSIDC Arctic Sea Ice News and Analysis" (ASINA) website (http://nsidc.org/arcticseaicenews/). Data and imagery are provided by the NSIDC Sea Ice Index (http://nsidc.org/data/seaice_index/), originally developed through NOAA funding and now maintained by NOAA and NASA funding (Figure 9). The passive microwave sea ice products also provide input and a baseline for evaluation for the ARCUS/SEARCH Sea Ice Outlook (http://www.arcus.org/search/seaiceoutlook/). This project informally brings together several science groups to assess and project summer sea ice conditions. Several researchers on this product development team (Maslanik and Fowler, Meier, Stroeve) contributed projections based on passive microwave sea ice concentration and age data.

The Outlook and ASINA analyses, as well as research by other groups, suggest that the ice extent decline and thinning due to loss of older ice types are changing the character of the ice

cover. The thinner ice cover is responding more dramatically to synoptic-scale variation both in the winter (i.e., late ice growth and a record late seasonal ice extent maximum during March 2010) and summer (more broken ice pack capable of being more easily compacted or dispersed).

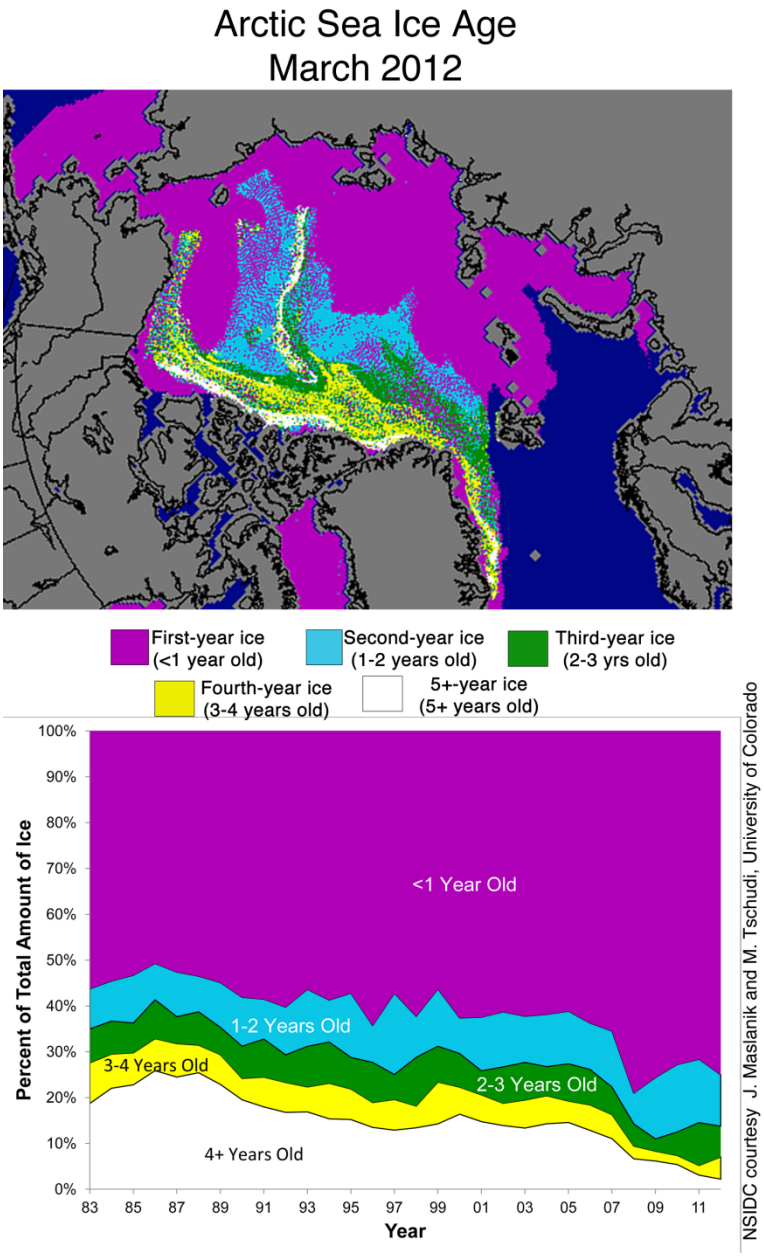

Fig. 9: Ice age data show that first-year ice made up 75% of the Arctic sea ice cover this March. Thicker multiyear ice used to make up around a quarter of the Arctic sea ice cover. Now it constitutes only 2%.

The combination of several of the CDR time series documents the time evolution of albedo and ice melt ponds as a function of sea ice type. One outcome from this work is that albedo – its evolution throughout the melt season as well as the albedo values themselves – vary as a function of ice type (first-year vs. multiyear ice, and between different ages of multiyear ice). As noted earlier, this is significant given the shift in the Arctic ice cover toward a greater fraction of first-year ice. A second outcome is that the proportion of surface melt ponds (which appear as open water to passive microwave ice concentration algorithms) does not translate into an equivalent fractional error in the microwave concentrations. This is counter-intuitive, perhaps arising from the use of daily averaged brightness temperatures for concentration vs. orbit-specific APP-x data.

OUTREACH

In partial fulfillment of the requirement that each product development team conduct a community workshop during the first project year, the cryosphere team held a public forum at the State of the Arctic (SoA) Conference (Miami, March 2010) to solicit feedback from the scientific community on the proposed snow and ice climate data records. Our first annual report provides more information on the SoA forum.

A project web site has (been established that includes an online forum (http://stratus.ssec.wisc.edu/cdrcryo).

Examples of data sets in various forms have been distributed to a range of users for outreach purposes. For example, movie animations of the CCAR/CU ice age product have been prepared for distribution and provided to requesters. One of these animations currently appears in Vice President Gore's climate presentation. Several of the CDRs, including concentration and age data, were used to provide contributions to the ongoing "Sea Ice Outlook" ice extent forecasts.

At the Fall 2011 AGU conference, co-investigators Hall and Meier organized and chaired a session on cryospheric CDRs. The session, including eight oral presentations and several posters, was well-attended and generated a lot of interest and feedback.

Several of the products have been featured in the Arctic Sea Ice News and Analysis website (http://nsidc.org/arcticseaice_news/), NSIDC's most visited website. Imagery and animations from the project have been used by NOAA's Climate Watch website (http://www.climatewatch.noaa.gov/video/2011/old-ice-becoming-rare-in-arctic). In addition, imagery from the project was highlighted in talks (including by co-investigators Meier and Stroeve) on the NASA Hyperwall at the International Polar Year Conference in Montreal in April 2012. Finally, imagery was included in NOAA's presentation at the UNFCC COP 17 meeting in Durban, South Africa in December 2011.

LINKAGES WITH INTERNATIONAL PROGRAMS

The work that goes into the assessment and development of CDRs, as well as the CDRs themselves, has broad applicability in the international community. In particular, the snow and ice CDRs could become standard products in the World Meteorological Organization (WMO) Global Cryosphere Watch (GCW). Discussions with the GCW development group have indicated the need to identify appropriate satellite datasets. The investigators on this project are engaged in that task and will work with GCW. Potential satellite datasets for GCW will also be considered by the WMO Polar Science Space Task Group. GCW was recently approved by the 16th WMO Congress (May 2011, Geneva). J. Key is co-leading the development of GCW.

During the second project year, a WCRP workshop that focused on essential climate variables (ECV), including sea ice, was held in Frascati, Italy (May 2011). J. Key was a co-organizer of the workshop; W. Meier attended and discussed sea ice CDRs. The broad aim of the workshop was to promote the implementation of the "Guideline for the Generation of Datasets and Products Meeting GCOS (Global Climate Observing System) Requirements". It focused on international assessment and review processes for quality control. It was decided that an inventory of ECV data sets will be developed. It is likely that the inventory will be established at the NOAA Global Observing Systems Information Center (GOSIC), and the admission of new datasets into the inventory will be managed by the GCOS Panels.

W. Meier is now part of the CliC Sea Ice Working Group. He will provide guidance on recommendations for remote sensing sea ice data products, including algorithms, data quality, and data formats. Serving on this working group will allow this CDR project to have wider impact and greater acceptance within the international community. Meier attended the working group meeting in Tromso, Norway, 4-5 June 2010 and discussed sea ice CDRs. W. Meier has also been selected as a member of the WCRP Data Advisory Council (WDAC) and will attend the first WDAC meeting in Beijing, China on 16 July 2012.

J. Maslanik supplied ice age and motion vector-derived products to the ESA Cryosat-2 validation effort.

DELIVERABLES

The complete list of products that will be generated, the instruments used, and data set characteristics is given in Table 2. Additional deliverables include data set summaries and assessment documents.

Table 2. Characteristics of snow and ice CDRs.

CDR Variable Name	Essential Climate Variable		Algorithm Name	Source Data Sensors	Spacecraft	Channels	Spatial Resolution		Temporal Resolution			Product Units	Projection	Output Format	Other Characteristics	Expected User Groups
	Domain	Variable					Horizontal	Vertical	Orbits	Start Date	End Date					
Ice/snow surface temperature	Oceanic	Sea ice	APP-x, MODIS IST	AVHRR, MODIS	NOAA-7 through NOAA-19, Terra and Aqua, and JPSS	AVHRR 4,5; MODIS 31,32	5 km	N/A	All POES orbits	1982	present	K	EASE grid (equal area)	netCDF	60-90N, S (Arctic and Antarctic)	Climate scientists; climate reanalysis verification
Ice/snow albedo	Oceanic	Sea ice	APP-x (none for MODIS)	AVHRR, MODIS	NOAA-7 through NOAA-19, Terra and Aqua, and JPSS	AVHRR 1,2; MODIS 1,2,6	5 km	N/A	All POES orbits	1982	present	Reflectance (unitless)	EASE grid (equal area)	netCDF	60-90N, S (Arctic and Antarctic)	Climate scientists; climate reanalysis verification
Surface radiative fluxes (downwelling and upwelling shortwave and longwave)	Oceanic	Sea ice	APP-x	AVHRR, MODIS	NOAA-7 through NOAA-19 and JPSS	AVHRR 1,2,3a/b,4,5; MODIS 1,2,6,20,31,32	5 km	N/A	All POES orbits	1982	present	W	EASE grid (equal area)	netCDF	60-90N, S (Arctic and Antarctic)	Climate scientists; climate reanalysis verification; Energy
Sea ice thickness	Oceanic	Sea ice	OTIM	AVHRR, MODIS	NOAA-7 through NOAA-19 and JPSS	AVHRR1,2,3a/b, 4,5; MODIS 1,2,6,20,31,32	5 km	N/A	All POES orbits	1982	present	m	EASE grid (equal area)	netCDF	60-90N, S (Arctic and Antarctic)	Climate scientists; climate reanalysis verification; cryosphere
Sea ice age (Lagrangian tracking)	Oceanic	Sea ice	Lagrangian Age	AVHRR, SMMR, SSM/I, AMSR-E, AOBP buoy trajectories	NOAA-7 through NOAA-19 and JPSS	AVHRR 4,5; MODIS 31,32	12.5 km	N/A	All POES orbits	1979	present	K, brightness temp. (Tb)	EASE grid (equal area)	binary and visualizations	All ocean (ice-covered) areas	environmental organizations, shipping operators, resource extraction and management organizations
Sea ice concentration	Oceanic	Sea ice	APP-x	AVHRR, MODIS	NOAA-7 through NOAA-19, Terra and Aqua, NPP, JPSS	AVHRR 1,2,4,5; MODIS 1,2,31,32	5 km	N/A	All POES orbits	1982	present	percentage (%)	EASE grid (equal area)	netCDF	60-90N, S (Arctic and Antarctic)	Climate scientists; climate reanalysis verification; environmental organizations, biologists, general public
Sea ice concentration	Oceanic	Sea ice	NASA Team, Bootstrap	SMMR, SSM/I, SSMIS	DMSP, JPSS, GCOM-W	19,22,37 GHz	25 km	N/A	Daily composites fromall POES orbits	1978	present	Concentration (0-100%)	EASE grid (equal area), possibly polar stereographic	binary	90N-90S	sea ice researchers, climate modelers, operational ice centers, SST groups, biologists, educators, journalists, general public
Sea ice motion	Oceanic	Sea ice	Cross-Correlation	AVHRR, MODIS, SMMR, SSM/I, SSMIS, AOBP buoys	NOAA-7 through NOAA-19, DMSP, Terra and Aqua, Nimbus-7, NPP, JPSS	AVHRR 4; MODIS 31	5-25 km	N/A	All POES orbits	1979	present	Velocity (direction and speed; cm/s)	EASE grid (equal area)	binary	All ocean (ice-covered) areas. Feasible over large inland water bodies but not currently implemented.	environmental organizations, wildlife/biology resaerch and monitoring, shipping operators, resource extraction and management organizations
Sea ice melt onset and freeze-up	Oceanic	Sea ice	Drobot and Anderson, Markus and Miller	SMMR, SSM/I, AMSR-E	DMSP, JPSS, GCOM-W	19, 37 GHz	12.5-25 km	N/A	Daily composites from all POES orbits	1979	present	Day of year, number of days	EASE grid (equal area)	netCDF	All ocean (ice-covered) areas	Climate scientists; climate reanalysis verification
Snow cover	Terrestrial	Snow cover	Snowmap	MODIS	Terra and Aqua, NPP, JPSS	MODIS 1,2,4,6,31 & 32	500 m to 0.05 deg	N/A	All orbits	2000	present	Unitless	sinusoidal	HDF-EOS	90N-90S - land only	Climate scientists; climate reanalysis verification
Greenland surface temperature	Terrestrial	Ice Surface Temperature	IST	MODIS	Terra and Aqua, NPP, JPSS	MODIS 31 & 32	5 km	N/A	All orbits	200	present	K	sinusoidal	HDF-EOS	Greenland only	Climate scientists; climate reanalysis verification

PLANS FOR THE REMAINDER OF THE PROJECT

Data products, documentation, and code will be delivered to NCDC and/or NSIDC, as appropriate and as agreed upon by the project investigators and NCDC program management. Additional funding might be required.

PUBLICATIONS SUPPORTED IN WHOLE OR IN PART BY THIS GRANT

Blazey, B.,, J.A. Maslanik, J. Cassano, M. Holland and D. Bailey, Arctic sea ice preconditioning and recovery potential in CCSM/CICE, submitted to J. Climate.

Calder, J., A. Proshutinsky, E. Carmack, I. Ashik, H. Loeng, J. Key, M. McCammon, H. Melling, D. Perovich, M. Johnson, and I. Rigor, 2009, Community White Paper: An integrated international approach to Arctic Ocean observations for Society (A legacy of the International Polar Year), Proceeding of OceanObs'09 (peer-reviewed white papers), Venice, Italy, September 21-25.

Fernandes, R., H. Zhao, X. Wang, J. Key, X. Qu, and A. Hall, Controls on Northern Hemisphere snow albedo feedback quantified using satellite Earth observations, Geophys. Res. Lett., 36, 21, doi:10.1029/2009GL040057, 2009.

Fetterer, F., W.N. Meier, J. Stroeve, C. Fowler, J. Maslanik, R. Duerr, 2011. Sea ice climate data records. Association of American Geographers, Seattle, WA, 12-16 April.

Gibbons, P., W. Meier, and D. Scott, 2010. Transition from DMSP SSM/I to SSMIS sensors for NSIDC near-real-time snow and ice climate records. American Geophysical Union Fall 2010 Meeting, San Francisco, CA, 13-17 December.

Hall, D.K., J.C. Comiso, N.E. DiGirolamo, C.A. Shuman, J.R. Key and L.S. Koenig, 2012: A Satellite-Derived Climate-Quality Data Record of the Clear-Sky Surface Temperature of the Greenland Ice Sheet, Journal of Climate, 25(14):4785-4798.

Hall, D.K., G.A. Riggs, J.L. Foster and S. Kumar, 2010: Development and validation of a cloud-gap filled MODIS daily snow-cover product, Remote Sensing of Environment, 114:496-503, doi:10.1016/j.rse.2009.10.007.

Liu, Y., J. R. Key, Z. Liu, X. Wang, and S. J. Vavrus, 2012, A cloudier Arctic expected with diminishing sea ice, Geophys. Res. Lett., 39, L05705, doi:10.1029/2012GL051251.

Liu, Y., S. Ackerman, B. Maddux, J. Key, and R. Frey, 2010, Errors in cloud detection over the Arctic using a satellite imager and implications for observing feedback mechanisms, J. Climate, 23(7), 1894-1907.

Liu, Y., J. Key, and X. Wang, 2009, Influence of changes in sea ice concentration and cloud cover on recent Arctic surface temperature trends, Geophys. Research Lett., 36, L20710, doi:10.1029/2009GL040708.

Liu Yinghui, Key R. Jeffrey, Wang Xuanji, Understanding the interactions and feedbacks between Arctic sea ice, clouds, and the atmosphere from satellite observations, (keynote talk), 2011 EUMESAT meteorological satellite conference, September 5-9, 2011, Oslo, Norway.

Ledley, T.S., B. Youngman, W. Meier, and E. Bardar, 2010. Enabling climate science

investigations using cryosphere climate data records. American Geophysical Union Fall 2010 Meeting, San Francisco, CA, 13-17 December.

Maslanik, J.A., 2010. Assessment of the quality and utility of the University of Colorado ice age product. Internal report, to be provided as an NSIDC technical note.

Maslanik, J.A., J. Stroeve, C. Fowler, and W. Emery, 2011. Distribution and trends in Arctic sea ice through spring 2011. Geophys. Res. Lett., Vol. 38, L13502, 6 pp., doi:10.1029/2011GL047735.

Meier, W.N., F. Fetterer, R. Duerr, D. Scott, M. Savoie, S. Mallory, 2011. A new sea ice climate data record for climate studies, WCRP Open Science Conference, Denver, CO, October.

Meier, W.N., S. Mallory, M. Savoie, D. Scott, R. Duerr, and F. Fetterer, 2011. A new sea ice concentration climate data record for tracking Arctic and Antarctic variability and change, C14A-03, AGU Fall Meeting, San Francisco, CA, December.

Meier, W.N., S.J.S. Khalsa, and M.H.Savoie, 2011. Intersensor calibration between F-13 SSM/I and F-17 SSMIS near-real-time sea ice estimates, IEEE Trans. Geosci. Rem. Sens., 49(9), 3343-3349.

Meier, W.N., J. Maslanik, C. Fowler, and R. Duerr, J. Stroeve, 2010. Development of passive microwave cryospheric climate data records [invited]. American Geophysical Union Fall 2010 Meeting, San Francisco, CA, 13-17 December.

Meier, W.N., A. Leon, M.J. Brodzik, and R. Weaver, 2010. Cryospheric applications of GCOM-W AMSR2 data at NSIDC. JAXA GCOM-W AMSR2 Science Team Meeting, Tokyo, Japan, 6-9 December.

Persson, P. O. G., E. L Andreas, J-W. Bao, C. W. Fairall, A. A. Grachev, P. S. Guest, and J. Maslanik, 2010: Determining wintertime heterogeneous pack ice characteristics and their impact on the aggregate atmospheric surface flux. J. Geophys. Res. (in press).

Scott, D., B.W. Billingsley, J. Smith, and W.Meier. Revealing passive microwave data production at NSIDC. AGU Fall 2010 Meeting, San Francisco, CA, 13-17 December.

Stroeve, J.C., J.A. Maslanik, M.C. Serreze, I. Rigor, W. Meier, and C. Fowler, 2011. Sea ice response to an extreme negative phase of the Arctic Oscillation during winter 2009/2010. *Geophys. Res. Lett.,* 38, L02502, doi:10.1029/2010GL045662.

Tschudi, M.A., Fowler, C., Maslanik, J.A., Stroeve, J.C., 2011. Climate Data Records (CDRs) for Ice Motion and Ice Age. C14A-02, Amer. Geoph. Union Fall Mtg., San Francisco, CA.

Wang, X., J. Key, and Y. Liu, 2010, A thermodynamic model for estimating sea and lake ice thickness with optical satellite data, J. Geophys. Res.-Oceans, 115, C12035, doi:10.1029/2009JC005857.

REFERENCES

Anderson, M. 1997. Determination of a melt onset date for Arctic sea ice regions using passive microwave data. *Annals of Glaciology,* 25,382-387.

Cavalieri, D. J., P. Gloersen, and W. J. Campbell. 1984. Determination of sea ice parameters with the NIMBUS-7 SMMR. *J. Geophys. Res*., 89(D4):5355-5369.

Drobot, S. and M. Anderson. 2001. Comparison of interannual snowmelt onset dates with atmospheric conditions. *Annals of Glaciology,* 33, 79-84.

Francis, J.A. and E. Hunter, 2007. Changes in the fabric of the Arctic's greenhouse blanket. Environ. Res. Lett., 2, doi:10.1088/1748-9226/2/4/045011.

Fowler, C., W. Emery and J.A. Maslanik, 2003. Satellite derived arctic sea ice evolution Oct. 1978 to March 2003, *Trans. Geosci. and Remote Sensing Letters,* Vol. 1, No. 2, 71-74.

Hall, D.K., J.C. Comiso, N.E. DiGirolamo, C.A. Shuman, J.R. Key and L.S. Koenig, 2012: A Satellite-Derived Climate-Quality Data Record of the Clear-Sky Surface Temperature of the Greenland Ice Sheet, Journal of Climate, 25(14):4785-4798.

Hall, D.K., J.E. Box, K.A. Casey, S.J. Hook, C.A. Shuman and K. Steffen, 2008a. Comparison of satellite-derived ice and snow surface temperatures over Greenland from MODIS, ASTER, ETM+ and in-situ observations, *Remote Sensing of Environment*, 112(10):3739-3749, doi:10.1016/j.rse.2008.05.007.

Hall, D.K., R.S. Williams, Jr., S.B. Luthcke and N.E. DiGirolamo, 2008b. "Greenland Ice Sheet surface-temperature, melt and mass loss: 2000 – 2006," *Journal of Glaciology*, 54(184):81.

Key, J.R., 2002. Streamer User's Guide. Cooperative Institute for Meteorological Satellite Studies, University of Wisconsin, Madison, 107 pp.

Key, J. R., (2002) The cloud and surface parameter retrieval (CASPR) system for polar AVHRR. Cooperative Institute for Meteorological Satellite Studies, University of Wiscon- sin—Madison, 59 pp. [Available online at http://stratus.ssec. wisc.edu/caspr/documentation.html.]

Key. J.R. and A.J. Schweiger, 1998: Tools for atmospheric radiative transfer: Streamer and FluxNet. Computers and Geosciences, 24(5), 443-451.Markus, T., and D.J. Cavalieri, 2000. An enhancement of the NASA Team sea ice algorithm, IEEE Trans. Geosci. Remote Sens., 38(3), 1387-1398.

Key, J., A.J. Schweiger, and R.S. Stone, 1997: Expected uncertainty in satellite-derived estimates of the high-latitude surface radiation budget. *J. Geophys. Res*., 102(C7), 15837.

Key, J., J.A. Maslanik, T. Papakyriakou, M.C. Serreze, and A.J. Schweiger, 1994. On the validation of satellite-derived sea ice surface temperature. *Arctic*, 47(3), 280-287.

Key, J. and Haefliger, M.,1992: Arctic ice surface temperature retrieval from AVHRR thermal channels, Journal of Geophysical Research, 97(D5), 5885-5893.

Kwok, R., 2008. Summer sea ice motion from the 18 GHz channel of AMSR-E and the exchange of sea ice between the Pacific and Atlantic Sectors, Geophys. Res. Lett., 35, L03504, doi:10.1029/2007GL032692.

Kwok, R., A. Schweiger, D. A. Rothrock, S. Pang and C. Kottmeier, 1998. Sea ice motion from satellite passive microwave data assessed with ERS SAR and buoy data, J. Geophys. Res.,103(C4), 8191-8214.

Markus, T., J. C. Stroeve, and J. Miller, 2009. Recent changes in Arctic sea ice melt onset, freezeup, and melt season length, J. Geophys. Res., 114, C12024, doi:10.1029/2009JC005436.

Maslanik, J.A., J.R. Key, C.W. Fowler, T. Nguyen, and X.Wang, 2001. Spatial and Temporal Variability of Satellite-derived Cloud and Surface Characteristics during FIRE-ACE. *J. Geophys. Res.*, 106(D14), 15233-15249.

Maslanik, J.A., C. Fowler, J. Stroeve, S. Drobit, J. Zwally, D. Yi and W. Emery, 2007. A younger, thinner Arctic ice cover: Increased potential for rapid, extensive sea-ice loss. *Geophys. Res. Lett*., 34, L24501, doi:10.1029/2007GL032043.

Meier, W.N., 2005. Comparison of passive microwave ice concentration algorithm retrievals with AVHRR imagery in the Arctic peripheral seas, *IEEE Trans. Geosci. and Rem. Sens*., 43(6), 1324-1337.

Meier, W.N., J.A. Maslanik, J.R. Key, and C.W. W. Fowler, 1997. Multiparameter AVHRR-derived products for Arctic climate studies, *Earth Interactions*, Vol. 1.

Meier, W.N., 2005. Comparison of passive microwave ice concentration algorithm retrievals with AVHRR imagery in the Arctic peripheral seas, IEEE *Trans. Geosci. and Rem. Sens*., 43(6), 1324-1337.

Meier, W.N., J. Stroeve, and F. Fetterer, 2007. Whither Arctic sea ice?: A clear signal of decline regionally, seasonally, and extending beyond the satellite record, *Ann. Glaciol*., 46, 428-434.

Parkinson C. L., D. J. Cavalieri, 2008. Arctic sea ice variability and trends, 1979–2006, *J. Geophys. Res*., 113, C07003, doi:10.1029/2007JC004558.

Pavolonis, M.J., J. R. Key, and X. Wang, 2002. Antarctic cloud radiative forcing at the surface estimated from the ISCCP D2 and AVHRR polar pathfinder data sets, 1985-1993. Presented at International Geoscience and Remote Sensing Symposium, Toronto, Canada, June 23-28.

Rigor, I.G. and J.M. Wallace, 2004. Variations in the age of Arctic sea-ice and summer sea-ice extent, *Geophys. Res. Lett.*, Vol. 31, L09401, doi:10.1029/2004GL019492.

Smith, D.M., Observation of perennial Arctic sea ice melt and freeze-up using passive microwave data, *J. Geophys. Res.,* 103, 27,753-27,769, 1998.

Stroeve, J., J. Box, C. Fowler, T. Haran, and J.R. Key, 2001. Intercomparison Between in situ and AVHRR Polar Pathfinder-derived Surface Albedo over Greenland. *Remote Sensing of the Environment*, 75(3), 360-374.

Tschudi, M., C.Fowler, J. Maslanik, J. Stroeve, 2010. Tracking the movement and changing surface characteristics of Arctic sea ice, IEEE J. of Selected Topics in Applied Earth Observations and Remote Sensing, 5 pp.

Tschudi, M.A., J.A. Maslanik and D.K. Perovich, (2008), Derivation of melt pond coverage on Arctic sea ice using MODIS observations, Rem. Sens. Environ., 112, 2605-2614.

Wan, Z., Y. Zhang, Q. Zhang and Z.-L. Li, 2002: Validation of the land-surface temperature products retrieved from Terra Moderate Resolution Imaging Spectroradiometer data, Remote Sensing of Environment, 83, 163-180.

Wang, X. and Jeffrey R. Key, 2003. Recent Trends in Arctic Surface, Cloud, and Radiation Properties from Space. *Science*, 299, 1725-1728.

Wang, X. and Jeffrey R. Key, 2005, Arctic Surface, Cloud, and Radiation Properties Based on the AVHRR Polar Pathfinder Data Set. Part I: Spatial and Temporal Characteristics, *J. Climate*, Vol.18, No.14, 2558-2574, 2005.

Wang, X. and Jeffrey R. Key, 2005, Arctic Surface, Cloud, and Radiation Properties Based on the AVHRR Polar Pathfinder Data Set. Part II: Recent Trends, *J. Climate*, Vol.18, No.14, 2575-2593, 2005.