CGMS-44 IOC-WP-01
9 June 2016

IOC-UNESCO
Agenda Item: C.8
Discussed in Plenary

SATELLITE SEA ICE MEASUREMENTS IN THE ARCTIC OCEAN

In response to CGMS action A43.08
HLPP reference: 1.1

Executive Summary

Satellite observations sustained since 1979 have been the primary source of information to reveal Arctic Ocean sea ice extent is diminishing rapidly. Sea ice is also thinning based on historical surface and near-surface records and more recent satellite retrievals. There is a new “normal” environment in the Arctic environment with substantial socio-economic impacts. A key question is: What are the spatial and temporal characteristics of the sea ice thickness distribution throughout the annual cycle, and what is the evolving inter-annual trend? Arctic Ocean sea ice conditions have been determined with passive microwave radiometer, active scatterometer and other satellite instrument measurements recorded by a continuing series of satellites. An important feature of the continuous time series measurements has been the overlap of each new satellite dataset with ongoing measurements so as to provide adequate time intervals for calibration and validation. Satellite instrument diversity has provided both coarse spatial resolution measurements over the entire Arctic Ocean for long-period time series and limited-duration fine spatial resolution data over selected regions for navigation and other applications. Satellite observations of Arctic Ocean sea ice will continue to increase in importance because predictability of sea ice is poor and societal interest is great. Unfortunately, however the sustainability of some critical elements of the current Arctic Ocean satellite measurement suite beyond 2020 remains uncertain, e.g., after the CryoSat-2 and ICESat-2 missions have concluded.

Recommendations proposed: (1) Enable sustainability of satellite passive microwave sea ice extent measurements begun in 1978. (2) Promote the implementation of sustained satellite sea ice observations with scatterometer to provide an independent source of information concerning climate change impacts on the marine cryosphere. (3) Enable sustainability of satellite frequent high-spatial resolution marginal ice zone measurements for navigation and other near-real time applications. (4) Promote the implementation of sustained satellite measurements of Arctic Ocean sea ice thickness. (5) Encourage joint CEOS/CGMS Working Group on Climate to establish a CEOS Virtual Constellation on GCOS ECV Sea Ice Measurements.

SATELLITE SEA ICE MEASUREMENTS IN THE ARCTIC OCEAN

David Halpern[1]
NASA / California Institute of Technology Jet Propulsion Laboratory
Pasadena, California 91109, UNITED STATES

Mark R. Drinkwater
European Space Agency European Space Research and Technology Centre
2201 AZ Noordwijk, NETHERLANDS

Walter N. Meier
NASA Goddard Space Flight Center
Greenbelt, Maryland 20771, UNITED STATES

Humfrey Melling
Fisheries and Oceans Canada, Institute of Ocean Sciences
Sidney, British Columbia, CANADA V8L 4B2

1 INTRODUCTION

The first satellite images of sea ice, along with clouds and land cover, occurred early in the space age before the twentieth anniversary of Sputnik. These early satellite measurements and the 7 December 1972 "Blue Marble" image of Earth inspired the scientific community to embrace the concept of improving observations and understanding of the global integrated Earth system so as to enhance its predictability. It was quickly realized that the complexity of natural environments, including the Arctic Ocean with its huge spatial and temporal ranges of 10^9 m and 10^9 s, dictated a requirement for multiple in-situ and satellite observing systems. CGMS has critically important functions in coordinating a myriad of sustained Earth observations for climate and weather and in ensuring their continuous utility.

The Arctic Ocean and the Southern Ocean around Antarctica are the geographical regions with the largest amplitude annual cycles in incident solar radiation linked to the 4-month dark and light seasons. In recent years, climate warming has significantly altered annual cycles, especially across the Arctic Ocean where atmospheric warming has been strong (IPCC, 2013). The areal extent or coverage of

[1] For this paper, David Halpern represents the Intergovernmental Oceanographic Commission (IOC) of the United Nations Educational, Scientific, Cultural Organization (UNESCO), which is a member of the Coordination Group for Meteorological Satellites (CGMS). The World Meteorological Organization (WMO) – IOC Joint Commission on Oceanography and Marine Meteorology (JCOMM) supports IOC to accomplish CGMS Plenary Action 43.08, which invited IOC to provide a paper on guidance to CGMS members on sea ice observations.

sea ice at the end of summer diminished at the statistically significant average rate of 13.4% per decade from 1981 to 2010 with a higher rate during the last half of the record (Figure 1). Sea ice is an influential variable of the global integrated Earth system because sea ice can reflect as much as 80% of incident solar radiation whereas ice-free sea water can absorb as much as 90%. Sea ice volume has dramatically decreased during the same period (Figure 2), which suggests that summertime ice cover will continue to shrink. As a consequence of changing sea ice conditions, large environmental and socio-economic impacts are occurring (Meier et al., 2014), including altered weather patterns in the Northern Hemisphere (Overland, 2016); increased ease of Arctic shipping (CMTS, 2013; Christopher and Fast, 2008), more opportunities for oil spills (NRC, 2014a) and more tourism (Gordon, 2014) in Arctic coastal regions; increased coastal erosion (Hardwerk, 2011; Parry, 2011); displacements of communities (Colarossi, 2015; Gibbs and Lautsen, 2015); displacements of marine mammal habitats (ACIA, 2004); increased abundance of marine phytoplankton in some areas (Arrigo et al., 2012); and increased opportunities for naval operations (Bowes, 2009).

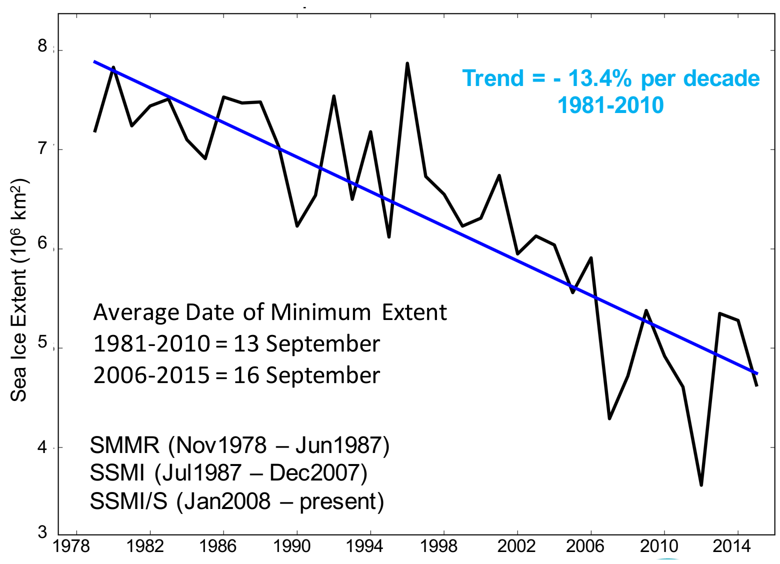

Figure 1. Annual minimum sea ice extent in September. Chart and information placed as insets in the diagram were extracted from https://nsidc.org/arcticseaicenews/2015/10/2015-melt-season-in-review/.

During the last decade, the observed changes in Arctic Ocean sea ice have been appreciably greater than those predicted by climate models (Figure 3), indicating that our knowledge of the Arctic marine environment is inadequate and that new knowledge and new sustained observations are warranted. It is necessary to improve predictions over large areas and also, because of the dynamic character of sea ice, to improve them over intervals as short as a day. In-situ measurements, including those by submarine, are inadequate to determine sea ice conditions at daily or even monthly intervals across the vastness of the Arctic Ocean. Likewise, measurements from fleets of aircraft, drones, gliders and ships, which are critically important to improve understanding of sea ice dynamics, are unsuitable to determine Arctic Ocean sea ice extent. A polar-orbiting satellite has the highly prized capability for daily, relatively high-spatial-resolution sea ice measurements across the entire marine cryosphere.

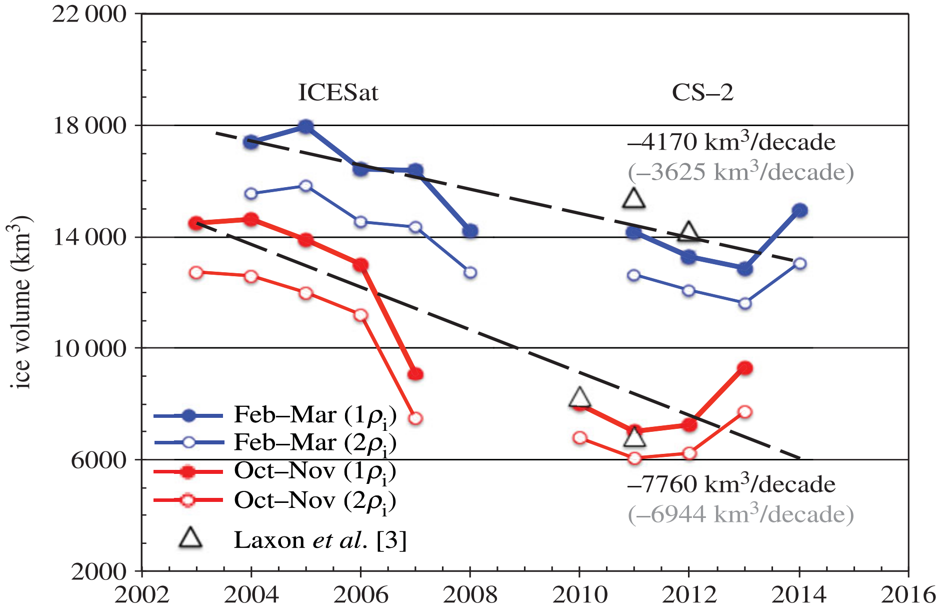

Figure 2. Volume of sea ice in the Arctic Ocean in February-March and October-November with ICESat and CryoSat-2 data. Two values of sea ice bulk density with "1" and "2" representing upper and lower estimates, respectively. Diagram extracted from Kwok et al. (2015).

This working paper will describe satellite sea ice observing systems and present guidance for their improvement. A variety of satellite instruments provide measurements of sea ice, including: active microwave scatterometer; active microwave altimeter; passive visible and infrared multispectral radiometer; passive microwave radiometer; and microwave synthetic aperture radar (SAR). Sensors operating with microwave frequencies provide data during day and night in all-weather conditions. In contrast, sensors using visible and infrared frequencies are useful only in daytime (visible sensors only) and in areas without clouds. A passive sensor observes natural emissions from seawater and sea ice; active sensors observe the electromagnetic energy reflected from a transmitted pulse.

2 SEA ICE EXTENT

2.1 Low-Spatial Resolution (~ 25 km) Observations

2.1.1 Passive Microwave Measurements

The United States (U.S.) National Aeronautics and Space Administration (NASA) Nimbus-5 (12 April 1972 – 29 March 1983) polar-orbiting satellite recorded the first sea ice measurements from space with the single-frequency (19 GHz) Electrically

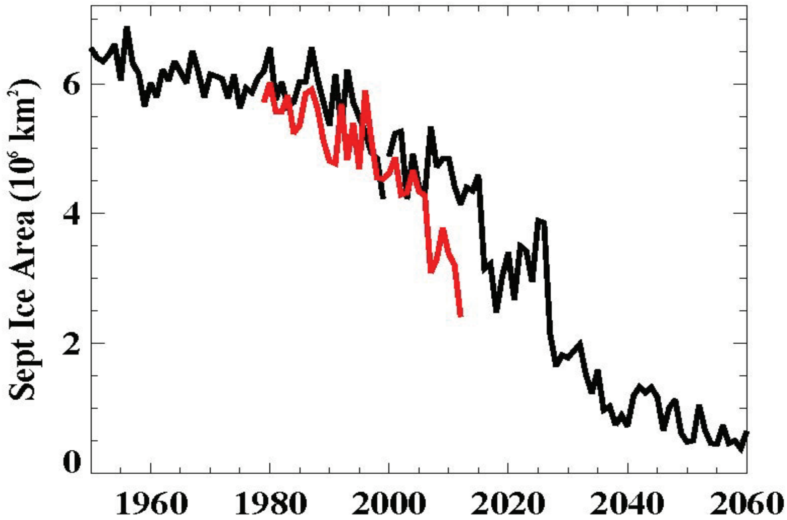

Figure 3. September Arctic Ocean sea ice extent determined with observations (red line) and from the National Center for Atmospheric Research (NCAR) Community Climate System Model (CCSM) version 3. Diagram extracted from NRC (2012).

Scanning Microwave Radiometer (ESMR) instrument from December 1972 to May 1977. ESMR yielded data on sea ice coverage and age at 25-km horizontal resolution. First-year and multi-year sea ice ages were discriminated on the basis of surface emissivity, which are 0.92 and 0.84, respectively. The emissivity of sea water is 0.44.

The ESMR instrument was the precursor to the Scanning Multichannel Microwave Radiometer (SMMR) instrument flown on SeaSat (26 June – 8 October 1978) and Nimbus-7 (24 October 1978 – 14 February 1995) and the Special Sensor Microwave Imager (SSMI) instrument flown on a continuous series of U.S. Defense Meteorological Satellite Program (DMSP) satellites (18 June 1987 – present). However, ESMR's relative simplicity (e.g., single frequency, horizontal polarization, along-track data acquisition, wide range of incident angles) prevented inter-comparison tests with the multi-channel SMMR and SSMI instruments (see Meier and Markus (2015) for description of channels). ESMR data are not consistent enough with the later multi-channel instruments to extend the time series of sea ice concentration to an earlier date. Multiple channels resolve ambiguities in brightness temperature and improve the algorithm to determine sea ice concentration and the designation of first-year and multi-year sea ice (Meier and Markus, 2015).

The SMMR instrument began the modern era of satellite sea ice observations (Gloersen and Barath, 1977), recording precise all-weather estimates of global sea ice concentrations and indications of sea ice age: first-year (ice formed since the previous summer) or multi-year (ice that has survived at least one summer melt season). In addition, it provided data to estimate snow cover, soil moisture, rainfall, cloud water content, atmospheric water vapor, and sea surface wind speed. The SMMR follow-on instrument is the SSMI instrument. The next-generation SSMI instrument is the 24-channel Special Sensor Microwave Imager/Sounder (SSMIS) instrument.

NASA continues to support the National Snow and Ice Data Center (NSIDC) in the sustained generation of internally consistent well-documented, quality-controlled, 25-km x 25-km resolution Arctic Ocean (and Antarctic Ocean) sea ice extent datasets (Cavalieri et al., 1996; Comiso, 2000). The sea ice extent data product with SMMR data had a time resolution of 2 days from November 1978 to June 1987; since that time, the interval between charts of Arctic Ocean sea ice extent has been 1 day using SSMI data from July 1987 to December 2007 and using SSMIS data from January 2008 to the present. As instruments became more advanced, the data hole around the North Pole became smaller: the radii of the holes associated with the SMMR, SSMI and SSMIS instruments were 611, 311 and 94 km, respectively (Cavalieri et al., 1996).

Regression analyses of total extents of the northern marine Cryosphere derived by different satellites during periods of overlap indicated that SMMR (SSMI) and SSMI (SSMIS) derived extents were in agreement to 1% (0.5%) (Cavalieri et al., 1996). The excellent statistical consistency among different satellite systems has allowed SMMR, SSMI and SSMIS datasets to be combined to provide the longest satellite climate-quality data record in the Arctic (Figure 1). The NSIDC sustained sea ice dataset provides the opportunity to determine decadal trends for a variety of sea ice extent parameters such as the day of the year when Arctic sea ice extent reaches its annual minimum and maximum.

The sea ice edge derived from passive microwave emissions can be as close as 10 km to the ice edge observed by optical and synthetic aperture radar sensors in the winter (Heinrichs et al., 2006), but correspondence is degraded where the ice is warm and wet and thin, as near open ocean boundaries in winter and throughout the Arctic in summer (Agnew and Howell, 2003). Passive microwave sensors have several limitations that can yield considerable uncertainties in sea ice concentration and total sea ice extent (total areal coverage, usually above a concentration threshold criterion). Even under optimal conditions, such as mid-winter in the middle of the ice pack, passive microwave sensors can only provide concentration estimates to within about ±5% accuracy. In less optimal conditions during the summer melt, near the ice edge and over thin ice regions, the uncertainty might reach values of more than ±20% (Cavalieri et al, 1996; Meier et al., 2015; https://www.wmo.int/pages/prog/www/OSY/Meetings/GCW-IM1/GCW_CliC_Sea_ice_Reliability.pdf). Current sea ice extent estimates do not meet the 5% Global Climate Observing System (GCOS) accuracy (WMO, 2011).

The NSIDC sea ice extent datasets (Cavalieri et al., 1996; Comiso, 2000) are not the only such long-term records of sea ice extent. Tonboe et al. (2016) generated a SMMR-SSMI-SSMIS sea ice extent dataset with a different methodology compared to that used by NSIDC. The Arctic Regional Ocean Observing System (ROOS) (http://www.arctic-roos.org/observations/total-icearea-from-1978-2007) produces a SMMR-SSMI-SSMIS sea ice extent with algorithms different from than those used at NSIDC. The Arctic ROOS value for the decrease of the annual daily minimum sea ice extent in the Arctic Ocean was 10.5% per decade compared to 13.4% determined by NSIDC and displayed in Figure 1. The Japan Aerospace Exploration Agency (JAXA) National Institute of Polar Research (NIPR) Arctic Data archive

System (ADS) (https://ads.nipr.ac.jp) produces a passive microwave radiometer sea ice extent dataset over the past thirty-five years (Figure 4) with SMMR, SSMI, Advanced Microwave Scanning Radiometer – Earth Observing System (AMSR-E), WindSat (a polarimetric microwave radiometer instrument on the Coriolis satellite), and AMSR2 measurements. The Nansen Environmental and Remote Sensing Center (NERSC), through the ESA Sea Ice Climate Change Initiative (CCI), distributes SSMI and AMSR-E measurements of sea ice concentration. NERSC also hosts the Secretariat for the Arctic ROOS. Under the auspices of the CCI, Ivanova et al. (2015) evaluated 13 of 30 sea ice concentration passive-microwave-related algorithms and concluded that a hybrid approach would be appropriate to retrieve sea ice concentration globally for climate monitoring purposes.

Despite limitations that are reasonably well documented, the ice-extent record from passive microwave sensors has continuing high value because it is internally consistent, well studied and already quite long (37 years).

Recommendation 1: Enable sustainability of satellite passive microwave sea ice extent measurements begun in 1978.

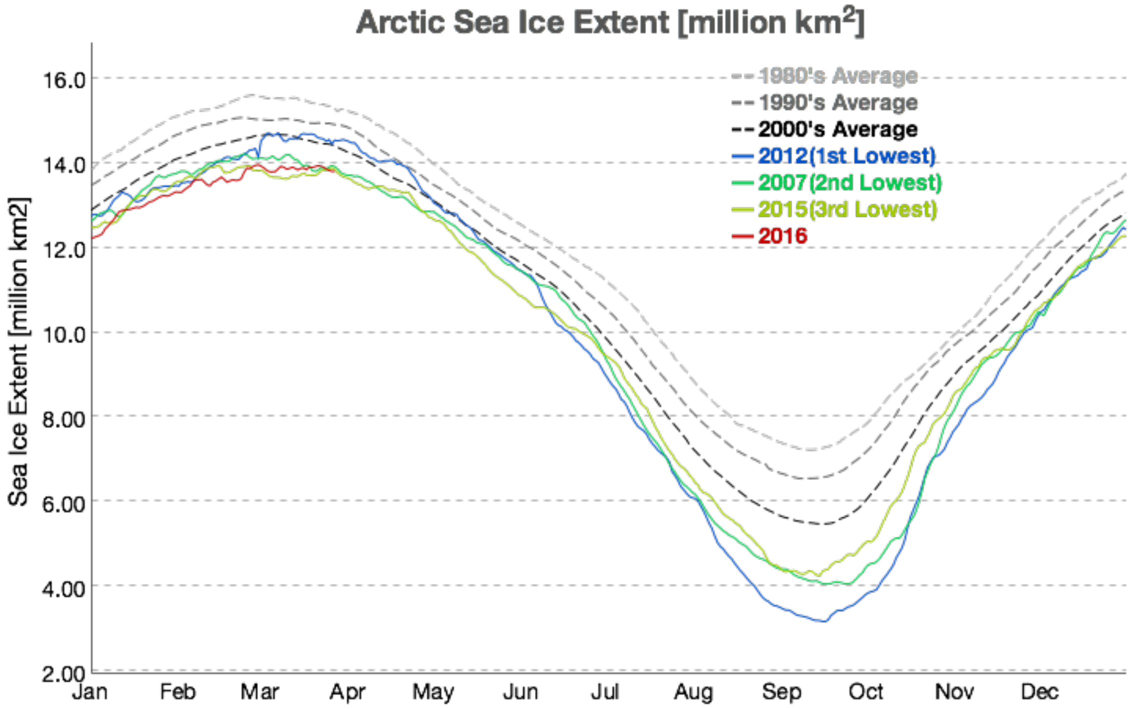

Figure 4. Annual cycle of daily Arctic Ocean sea ice extent for several time periods (see inset), including 27 March 2016 when diagram was extracted. The data product is produced by JAXA Arctic Data archive System (ADS) with the following satellite measurements: SMMR, January 1980 – July 1987; SSMI, July 1987 – June 2002; AMSR-E, June 2002 – October 2011; WindSat (a polarimetric microwave radiometer instrument on the Coriolis satellite), October 2011 – July 2012; and AMSR2, July 2012 – present. Diagram extracted from https://ads.nipr.ac.jp/vishop/vishop-extent.html?N.

2.1.2 Active Microwave Scatterometer Measurements

The large difference in dielectric permittivity between seawater and sea ice aids in discriminating between open water and sea ice using scatterometer backscatter measurements. Important at high wind speeds, wind-generated waves roughen the ocean surface and increase its backscatter, sometimes leading to confusion between ocean and newly formed sea ice, which tends to be thin and often saline. As sea ice ages, it becomes thicker, rougher and less saline, which tend to increase its backscatter. The resulting backscatter contrast between first-year and multi-year ice enables accurate scatterometer classification of sea ice by age, especially at Ku-band where the contrast is much more pronounced than at C-band. Melting conditions during the summer increase the liquid water content of sea ice and thereby increase its dielectric permittivity. This tends to suppress the contrast between first-year and multi-year ice, and between sea ice and wind-roughened open water. During the period of advanced surface melt in late summer (August and September in the Arctic), scatterometer ice age discrimination becomes impractical. However, sea ice coverage mapping is still possible, especially since the variability of ocean winds creates variable backscatter over the ocean in contrast to the more stable backscatter from sea ice. Due to their active radar processing, the spatial resolution of scatterometer sea ice maps is much higher than that of passive radiometer sensors, particularly when coupled with advanced resolution enhancement techniques.

It is reassuring to note that a 15-year sea ice age dataset produced from Ku-band Quick Scatterometer (QuikSCAT) and Indian Space Research Organization (ISRO) OceanSat Scatterometer (23 September 2009 – February 2014) instruments has independently confirmed the finding from passive microwave sea ice measurements that the area of first-year has increased and that of multi-year ice decreased (Lindell and Long, 2016).

Rivas et al. (2012) demonstrated that the European Space Agency (ESA) C-band Advanced Scatterometer (ASCAT) instrument on the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) Meteorological Operational (MetOp) satellite (15 May 2007 – present) and the NASA Ku-band SeaWinds instrument on the NASA QuikSCAT (19 June 1999 – 23 November 2009) satellite produced comparable measurements of Arctic Ocean sea ice extent throughout 2008. However, Rivas et al. (2012) noted that daily sea ice extents recorded with ASCAT and AMSR-E differed by 5-10% during summer months when mixed sea ice and sea water conditions occurred; AMSR-E estimates were lower (Figure 5). Should this bias also appear with SSMIS data and if it is consistent year to year, then the QuikSCAT-ASCAT series of scatterometer measurements have the potential to provide an independent estimate of the decadal trends of sea ice extent shown in Figure 1.

Having redundancy in observational estimates of Arctic Ocean sea ice extent is critically important in enhancing the reliability of satellite-derived trends linked to climate warming. Declining sea ice extent is considered an important indicator of climate warming, analogous to the canary in the coal mine whose death warns

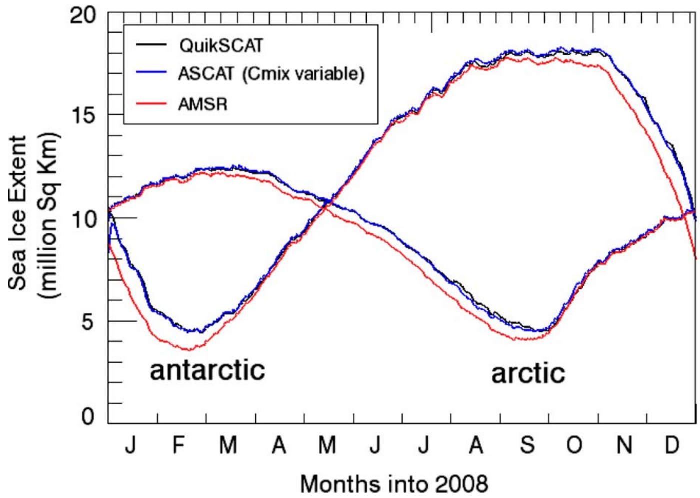

Figure 5. Daily Arctic and Antarctic sea ice extents from January - December 2008 from QuikSCAT (black line), ASCAT (blue lines) and AMSR-E (red lines). Extracted from Rivas et al. (2012).

miners of carbon monoxide. Redundancy is best achieved through independent observations and independent methodologies. Moreover, integration of passive microwave measurements (see Section 2.1.1) and scatterometer measurements could provide a single improved dataset (Meier and Stroeve, 2008). EUMETSAT intends to provide both scatterometer and passive microwave sea ice measurements for many years beyond 2020 (EUMETSAT, 2016). The sea ice Essential Climate Variable[2] (ECV) (GCOS, 2015) captures the need for passive microwave and scatterometer measurements, in addition to synthetic aperture radar and altimeter measurements (Drinkwater et al., 2008).

Recommendation 2: Promote the implementation of sustained satellite sea ice observations with scatterometer to provide an independent source of information concerning climate change impacts on the marine cryosphere.

2.2 High-Spatial Resolution (< 1 km) Observations

Sea ice observations at high-spatial resolution are important to day-to-day human concerns such as ship navigation and coastal safety. Satellite sea ice extent measurements with spatial resolutions of 1000 m and less are available from a variety of instruments, such as: the Advanced Very High Resolution Radiometer (AVHRR) on U.S. National Oceanic and Atmospheric Administration (NOAA) satellites (1981 – present) with 1000-m resolution; the DMSP (1976-present) visible/infrared Operational Linescan System (OLS) instrument, the Aqua (4 May 2002 – present) Moderate Resolution Imaging Spectroradiometer (MODIS)

[2] The sea-ice ECV covers concentration (fraction of the sea covered by ice), extent, area of coverage, motion, deformation, age, thickness, freeboard height of ice above the ocean surface and the timing of ice melt and creation. Snow depth on sea ice is also a crucial parameter

instrument, and the Suomi National Polar-orbiting Partnership (NPP) (28 October 2011 – present) Visible Infrared Imaging Radiometer Suite (VIIRS) instrument, each with about 500-m resolution; the synthetic aperture radar (SAR) on European Remote Sensing (ERS) satellites (July 1991 – July 2011) with 30-m resolution; and the SAR on RadarSat[3] satellites (November 1995 – present) with horizontal resolution as small as 3 m and typically 10-25 m. Although SAR data reveal the sea ice edge at high-spatial resolution, they have limited spatial coverage, i.e., SAR data are not recorded in a wide area on a specific day and not every day at the same location. Wide-swath SAR would have the capability to yield 1000-km coverage at 1- to 3-day intervals and complete coverage of the Arctic Ocean at 1-week interval (Drinkwater, 2012). Currently, the ESA Sentinel-1A (3 April 2014 – present) and -1B (25 April 2016) satellites, each with a SAR instrument, greatly increased SAR coverage of the Arctic. The Sentinel missions are elements of the European Union's Integrated Arctic Observing System.

Since the 1960s, local estimates of sea ice extent at 1-day time intervals during the navigation season have been produced by the U.S. National Ice Center (NIC) (http://www.natice.noaa.gov) and the Canadian Ice Service (https://www.ec.gc.ca/glaces-ice/). Ice analysts or forecasters have utilized various combinations of satellite data, as described in the previous paragraph and in Section 2.1, with a variety of in-situ observations from buoys, people on the ice, and aircraft and drone flights over the ice. In addition, analysts have incorporated subjective judgement based on experience and knowledge of the local region, similar to the local weather forecaster. Human-assisted ice analyses yield more spatial detail and ice-edge locations of higher accuracy that are excellent for navigation. However, the likelihood of uneven day-to-day and region-to-region data quality has compromised their application for climate research.

Efforts are now underway to minimize subjectivity in regional ice analyses and to improve short-term forecasts by assimilating satellite derived ice maps into dynamical atmosphere-ice-ocean models. Posey et al. (2015) described an improved initial state for the NIC operational sea ice forecast product. The daily initial sea ice extent is determined with AMSR-E (or AMSR1) and Global Change Observation Mission – Water (GCOM-W1) AMSR2 measurements, which have spatial resolutions of 12.5 km and 10 km, respectively, and which are considerably smaller than the 25 km of SSMIS data. When NIC used the new method, the skill of the daily ice-edge forecast (average separation of predicted and observed ice edges around the Arctic in summer 2012, formerly 30-60 km) improved by 40% (Posey et al., 2015)

NSIDC now produces a daily Arctic Ocean sea ice edge boundary at 1-km (available from 2 December 2014) and 4-km (available from 1 October 2006) grid cell sizes. NIC analysts integrate additional satellite measurements, including those recorded with visible/infrared, SAR, scatterometer and passive microwave instruments, and in-

[3] The Canadian Space Agency uses "RADARSAT" (http://www.asc-csa.gc.ca/eng/satellites/radarsat2/) whereas we follow the nomenclature in the World Meteorological Organization (WMO) Observing Systems Capability Analysis and Review (OSCAR) (http://www.wmo-sat.info/oscar/), which uses "RadarSat."

situ observations, including those recorded from aircraft, to produce daily sea ice extent at 4-km resolution.

The data assimilation approach shows great promise. It is the way of the future provided that the availability of high-resolution ice imagery can be sustained.

Recommendation 3: Enable sustainability of satellite frequent high-spatial marginal ice zone measurements for navigation and other near-real time applications.

3 SEA ICE THICKNESS

Space-based microwave sensors used to estimate sea-ice extent also provide a simple age classification, whether ice is first- or multi-year sea ice. This distinction can be a proxy for thickness since multi-year is often thicker, but this is not always true. In areas where sea ice drifts over warm water and loses mass from below, the top looks the same as multi-year ice but reality is different (Barber et al., 2009). The top surface of sea ice that has survived a summer changes its dielectric properties through normal weathering; surface roughness, salinity, air content, and the relative strength of volume and surface scattering are modified. Microwave backscatter from the surface by a scatterometer can also be a proxy for age through the distinction of first-year and multi-year ice (Nghiem et al., 2007; Lindell and Long, 2015). However, without actual thickness information, little was quantitatively known about sea ice volume, which is required to predict seasonal-to-interannual variations of sea ice extent.

Laxon et al. (2003) first demonstrated the utility of satellite radar altimeter data to directly determine sea ice thickness; they used ERS data. A more accurate method to determine ice thickness became available with the NASA Ice, Cloud, and land Elevation (ICESat-1; 12 January 2003 – 14 August 2010) satellite. Its active laser altimeter instrument showed that sea ice was thinning dramatically (Kwok et al., 2009). When ICESat-1 was no longer operational, NASA continued some ICESat-1 types of measurements over the Arctic Ocean with aircraft-based lidar under its Operation IceBridge annual March – May campaigns beginning in 2010 (http://www.nasa.gov/mission_pages/icebridge/index.html). Operation IceBridge measurements are expected to continue until 2019.

The ESA CryoSat-2 satellite (8 April 2010 - present) measures sea ice thickness (Kwok et al., 2015) with a SAR Interferometric Altimeter (SIRAL) instrument with an along-track resolution of 250 m (Tilling et al., 2015). Wind-driven transport in winter months produced thick sea ice bordering the Canadian archipelago. This sea ice is expected to continue for decades after sea ice diminishes elsewhere in the Arctic Ocean, which would provide a supportive habitat for polar bears, ringed seals and other species dependent on sea ice (NRC, 2014b).

CryoSat-2's orbit has an unusually high inclination of 92°, reaching to 88°N and 88°S, thereby providing unique data on sea ice thickness close to the North Pole. CryoSat-2 calibration and validation activities (Ricker et al., 2015) involve NASA's annual Operation IceBridge and ESA's annual CryoSat-2 Validation Experiment

(CryoVEx) with in-situ ground measurements (http://www.esa.int/Our_Activities/Observing_the_Earth/The_Living_Planet_Programme/Campaigns/Cryovex). The Russian launch vehicle carrying Cryosat-1 had a catastrophic failure on launch on 8 October 2005.

Additional satellite datasets are available to determine the thickness of thin (<0.5 m) ice, which is important because ICESat-1 and CryoSat-2 have a weak capability to determine sea ice thickness when sea ice is thin. Thin sea ice allows air-sea fluxes of heat, momentum and other variables. Yu and Rothrock (1996) and Su and Wang (2012) described sea ice thickness methods with thermal imagery from AVHRR and MODIS data, respectively, in which the occurrence of clouds limited daily coverage. Kaleschke et al. (2012) demonstrated that Soil Moisture and Ocean Salinity (SMOS) (2 November 2009-present) data could provide estimates of sea ice thickness in the range 0- to 0.5 m. De Matthaeis et al. (2014) found that Aquarius sea ice thicknesses had a similar trend compared with SMOS data, with Aquarius-derived thicknesses being larger and with higher variability.

Satellite-derived ice thickness is calculated from measurements of ice freeboard, corrected for snow depth (which is not measured). Since 90% of ice thickness is submerged, accurate estimates are elusive. Much work remains in the validation of satellite-derived ice thickness (Ricker et al., 2014), although much work has been done. For example, measurements recorded by the CNES-ISRO AltiKa (25 February 2013-present) and CryoSat-2 missions along collocated ground tracks will provide estimates of uncertainties due to snow loading because the AltiKa altimeter would penetrate less through the snow compared to CryoSat-2 altimeter. Results from inter-comparison of upward-looking sonar and laser derived sea ice thickness averaged over 25-km tracks indicate indicate mean ensemble differences in the ± 0.3-m range with the 95% bounds on individual estimates being ± 1 m (Kwok et al., 2009). The accuracy of an individual sonar-derived ice draft measurement was ± 0.1 m with 95% confidence (Melling et al., 1995). An integrated in-situ and satellite observing system is warranted.

Recommendation 4: Promote the implementation of sustained satellite measurements of Arctic Ocean sea ice thickness.

4 SEA ICE PREDICTABILITY

Forecasting in advance by 2-3 months the areal extent of Arctic Ocean sea ice for September is very challenging because late summer ice conditions depend very strongly on cumulative atmospheric forcing for which predictability is also very challenging on this time scale. Since 2008, the Study of Environmental Arctic Change (SEARCH) Program conducted an annual informal contest to examine the Arctic sea ice community's accuracy in forecasting the sea ice extent at its minimum in September. Research groups in Canada, Europe and the United States participate in the SEARCH Sea Ice Outlook (https://www.arcus.org/sipn/sea-ice-outlook). We highlight forecasts for 2012 when the sea ice extent reached its minimum value since the beginning of the satellite era in 1978 (Figure 1). Forecasts were based on a range of methods: statistical, numerical models, comparison with previous rates of sea ice loss, composites of several approaches, estimates based on various non-sea ice datasets and trends, and subjective information. On 11 July 2012, the median of 21 sea ice extent forecasts for September 2012 was 4.6×10^6 km^2 (Figure 6). The observed value, 3.6×10^6 km^2, indicates that we have a long way to go in achieving seasonal ice extent forecasts of useful accuracy. All July 2012 forecast estimates were above the observed value; none were below. In the following year 2013, all July 2013 forecasts, but one, were below the observed value (https://www.arcus.org/search-program/seaiceoutlook/2013/summary). A study of Outlook submissions for 2008-2013 found that skill was good when the observed September value was near the long-term trend, but there was very little skill in capturing an extreme event (Stroeve et al., 2014). It is interesting to note that all estimates in July 2012 and July 2013 were well below the 1981-2010 September mean of 6.5×10^6 km^2.

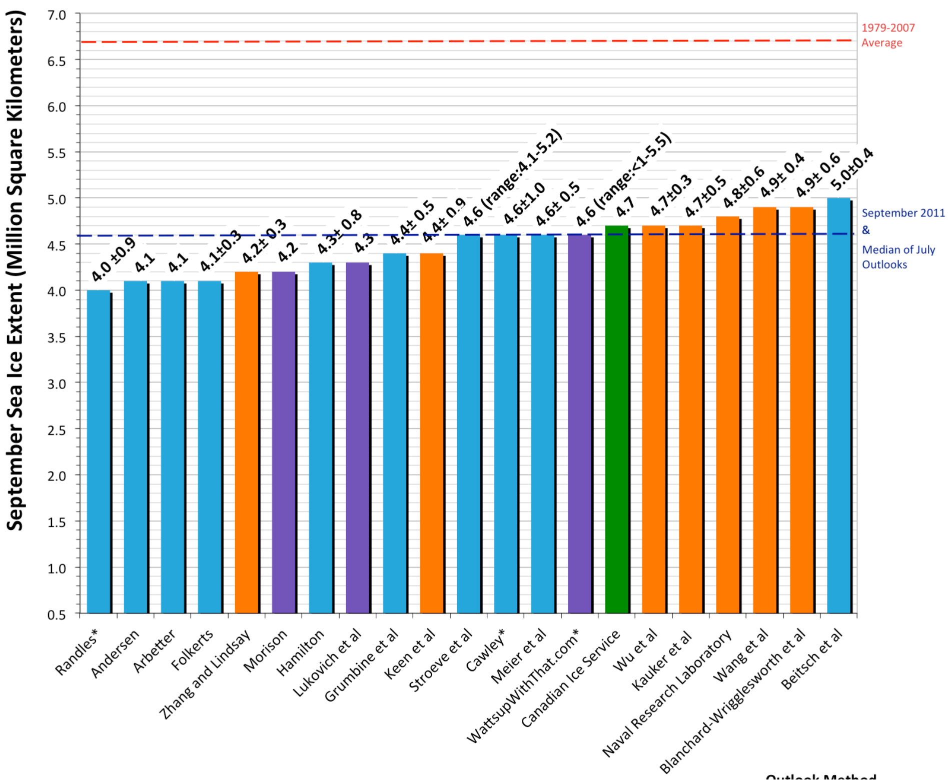

Figure 6. Twenty-one volunteer forecasts of the monthly mean Arctic Ocean sea ice extent in September 2012, which were provided to the SEARCH Program by 11 July 2012. Blue, orange, purple and green colors represent statistical, dynamical, heuristic and a combination of statistical and dynamical models, respectively. Horizontal dashed red and blue lines represent the average value from 1979-2007 and the September 2011 value, respectively; the September 2011 value was equal to the median value of the 21 forecasts. Diagram was extracted from https://www.arcus.org/search-program/seaiceoutlook/2012/july.

Statistical models based on past behavior of Arctic Ocean sea ice extent and thickness may not be reliable in the future when much more thin ice is expected. In an Arctic Ocean undergoing rapid changes with large year-to-year variations, accurate knowledge of initial ice-ocean conditions is critically important for dynamical prediction. Whereas improved sea ice extent, sea ice age (first year or multi-year) and sea ice thickness observations are necessary to improve seasonal predictions, limited seasonal predictability of the atmosphere is also a key factor.

Sea ice is not stationary and does not remain at the location of formation. Information on atmospheric conditions, such as wind, incident solar radiation and clouds, and information on ocean conditions, such as current, salinity and water temperature, are required in dynamical sea ice prediction models. Furthermore, the delivery of information on upper ocean currents and temperature is often not available daily when satellite sea ice measurements are recorded.

5 SATELLITE SEA ICE MEASUREMENT CONSTELLATIONS

5.1 Current Outlook

The outstanding WMO OSCAR (http://www.wmo-sat.info/oscar/) database indicates a wide variety of satellite instruments record sea ice information. Satellite missions providing data related to sea ice thickness and sea ice extent on 1 May 2016 (at the time of preparation of the working paper) are discussed below.

5.1.1 Sea Ice Extent

Approximately 250 satellite instruments record the occurrence of sea ice. The number is reduced to about 130 if information from high Arctic latitude at the “fair” quality level or higher is demanded – “fair” is one level above “marginal.”

It is beyond the scope of the working paper to review the adequacy of each mission. This type of activity would be appropriate for a Committee on Earth Observation Satellites (CEOS) Virtual Constellation. Although CEOS Virtual Constellations exist for sea surface temperature, clouds, sea surface topography, ocean vector winds, atmospheric composition, land surface imaging, ocean color radiometry and precipitation, they do not for sea ice parameters. The CEOS Virtual Constellations coordinate space-based, ground-based, and/or data delivery systems that meet a common set of requirements within a specific domain. They leverage collaboration and partnerships to address observational gaps, sustain the routine collection of critical observations and minimize duplication/overlaps. CEOS had partnered with the former Integrated Global Observing System (IGOS) Cryosphere Theme (WMO, 2007).

The Polar Space Task Group (PSTG) of the WMO Global Cryosphere Watch represents community-wide sources of information on all natural ice domains, including sea ice. A primary objective of the PSTG is to make SAR measurements routinely available (Falkingham, 2014), similar to passive microwave, altimeter, scatterometer and optical data. PSTG reports to CGMS (WMO, 2015).

5.1.2 Sea Ice Thickness

For sea ice thickness, only two of twenty satellite missions in the WMO OSCAR database recorded sea ice thickness above the "marginal" level (http://www.wmo-sat.info/oscar/gapanalyses?view=138): (1) the SIRAL instrument on the ESA CryoSat-2 satellite and (2) the recently launched ESA synthetic aperture radar altimeter (SRAL) instrument on Copernicus Sentinel-3A satellite (16 February 2016 – present). The former was discussed in Section 3. The SRAL instrument is the follow-on instrument of the SIRAL instrument, and data are expected to be released in August 2016, after about a 6-month commissioning period.

Recommendation 5: Encourage joint CEOS/CGMS Working Group on Climate to establish a CEOS Virtual Constellation on GCOS ECV Sea Ice Measurements.

5.2 10- to 20-Year Outlook

5.2.1 Sea Ice Extent

The SMMR-SSMI-SSMIS time series measurements will cease in a few years when the last DMSP satellite in orbit fails from old age. The DMSP 5D3-F19 (3 April 2014 – 11 February 2016) suffered a communication failure on 11 February 2016 and was designated no longer operational on 24 March 2016. The backup DMSP 5D3-F17 (11 April 2006 – present) has been returned to service. The DMSP 5D3-F20 satellite, which would have been the final DMSP satellite since the first DMSP satellite was launched on 23 August 1962 (https://directory.eoportal.org/web/eoportal/satellite-missions/d/dmsp-block-5d), will not likely be launched (Gruss, 2015). In addition, the U.S. Defense Weather Satellite System (DWSS), which would have continued DMSP passive microwave sea ice measurements, is no longer an option (Ray, 2012). The AMSR-E and AMSR2 instruments have proven a reliable replacement for SSMI or SSMIS (see Sections 2.1.1 and 2.2). While many satellite passive microwave radiometers capable of measuring sea ice extent are anticipated in the next decade (http://www.wmo-sat.info/oscar/gapanalyses?view=135), the GCOM-W2 and GCOM-W3 satellite missions are only under consideration for launch (http://database.eohandbook.com/database/missionsummary.aspx?missionID542) so that the follow-on AMSR2 instruments, should they be built, may need to find satellite missions. The AMSR-E instrument lasted ~ 9 years; if AMSR2 on GCOM-W1 also last ~ 9 years, then a data gap would begin in ~ 2021. The EUMETSAT Polar System – Second Generation Program intends to continue passive microwave sea ice measurements beyond 2020 with the microwave imager (MWI) instrument (EUMETSAT, 2016, page 68).

A satellite scatterometer, which provides similar sea ice information to a passive microwave radiometer (see Section 2.1.2) is currently on MetOp-A (19 October 2006 – present) and MetOp-B (17 September 2012 – present) and is planned to be on MetOp-C (launch scheduled in 2018), and then on a 3-satellite series of MetOp Second Generation missions (http://www.wmo-sat.info/oscar/spacecapabilities). However, measurement gaps could threaten the critically important overlapping time and space intervals for calibration between sensors.

5.2.2 Sea Ice Thickness

The SRAL instrument on Sentinal-3A is expected to begin delivery of data in August 2016.

ICESat-2 (scheduled for launch in October 2017) will carry the Advanced Topographic Laser Altimeter System (ATLAS) that represents a quantum leap from ICESat-1. ATLAS is a six-beam, photon counting lidar that collects data at 10 kHz, in contrast to the 40-Hz single beam lidar on ICESat-1. ICESat-2 data will have 70-m footprints spaced along track at 170-m intervals. In addition, ICESat-2 will collect data continuously all the time, in contrast to ICESat-1 short-duration campaigns. However, these lasers do not resolve pressure ridge (30-m scale) where much of the sea ice volume is concentrated, particularly within a hundred kilometers of the coast.

The measurement gaps between ICESat-1 and CryoSat-2 and between ICESat-1 and ICESat-2 are unfortunate, despite Operation IceBridge’s heroic attempt to mitigate the measurement gaps. Overlap between CryoSat-2, ICESat-2 and Sentinel-3 would allow the biases between these measurement systems to be characterised.

6 CONCLUSIONS

The Arctic Ocean sea ice extent and volume are undergoing unprecedented changes and new “normal” conditions are being established (Jeffries et al., 2013), leading to substantial socio-economic impacts. Present predictions of sea ice extent and volume for 1-day and seasonal lead times are not good. Satellite observations coupled with in-situ observations are critically needed to initialize the forecast models and to validate their predictions.

Recommendations 1-5 are directed towards sustaining present capabilities for observing sea ice from satellites and towards initiating new observations. Improvements to in-situ observing systems are strongly warranted at least until the skill of model prediction improves significantly and likely thereafter for data assimilation. Continuity of instruments across multiple satellite missions is critical to observing and understanding the rapid changes occurring in the Arctic Ocean sea ice. Establishing and sustaining appropriate validation data series at selected sites in the Arctic Ocean and in marginal seas would improve interpretation of data and robustness of forecasts (NRC, 2014b).

The WMO-sponsored Year of Polar Prediction (YOPP) from mid-2017 to mid-2019 provides an opportunity for CGMS members to improve access to satellite observations over the Arctic marine and terrestrial environments, including intensive observation periods.

7 ACKNOWLEDGEMENTS

We are grateful to Dr. Mark Bourassa (Florida State University), Dr. Joël Dorandeu (Collecte Localisation Satellites) and Dr. Jean-Louis Fellous (Committee on Space Research) for perceptive comments, which improved the working paper. WM is supported by the NASA Cryospheric Sciences Program. HM acknowledges support for this effort through the Canadian Program of Energy Research and Development (PERD 1B00-004B) and the Environmental Studies Research Fund (ESRF 2014-02N). DH is indebted to Dr. Jack Kaye (NASA Headquarters) for his support for participation in CGMS. Part of this research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

8 REFERENCES

ACIA (2004) *Impacts of a Warming Arctic: Arctic Climate Impact Assessment*. Cambridge University Press, Cambridge, UK, 140 pp.

Agnew, T. and S. Howell (2003) The use of operational ice charts for evaluating passive microwave ice concentration data. *Atmosphere Ocean*, *41*, 317–331, doi:10.3137/ao.410405.

Arrigo, K. R., D. K. Perovich, R. S. Pickart, Z. W. Brown, G. L. van Dijken, K. E. Lowry, M. M. Mills, M. A. Palmer, W. M. Balch, F. Bahr, N. R. Bates, C. Benitez-Nelson, B. Bowler, E. Brownlee, J. K. Ehn, K. E. Frey, R. Garley, S. R. Laney, L. Lubelczyk, J. Mathis, A. Matsuoka, B. G. Mitchell, G. W. K. Moore, E. Ortega-Retuerta, S. Pal, C. M. Polashenski, R. A. Reynolds, B. Schieber, H. M. Sosik, M. Stephens and J. H. Swift (2012) Massive phytoplankton blooms under Arctic sea ice. *Science*, *336*,1408, doi: 10.1126/science.1215065.

Barber, D. G., R. Galley, M. G. Asplin, R. De Abreu, K.-A. Warner, M. Pućko, M. Gupta, S. Prinsenberg and S. Julien (2009) Perennial pack ice in the southern Beaufort Sea was not as it appeared in the summer of 2009. *Geophysical Research Letters*, *36*, doi:10.1029/2009GL041434.

Bowes, M. D. (2009) Impact of climate change in naval operations in the Arctic. CNA, Alexandria, VA 22311, 48 pp.

Cavalieri, D., C. Parkinson, P. Gloersen and H. J. Zwally (1996, updated yearly) Sea ice concentrations from Nimbus-7 SMMR and DMSP SSM/I-SSMIS passive microwave data, version 1. National Snow and Ice Data Center, Boulder, Colorado. http://dx.doi.org/10.5067/8GQ8LZQVL0VL [assessed 9 March 2016].

Christopher, J. and E. Fast (2008) The Arctic: transportation, infrastructure, and communications. Publication 2008-08-E, Parliamentary Information and Research Service, Library of Parliament, Ottawa, 4 pp.

CMTS (2013) U.S. Arctic marine transportation system: Overview and priorities for action 2013. U.S. Committee on the Marine Transportation System, Washington, D.C., 114 pp.

Colarossi, J. (2015) This community in Alaska is relocating because of climate change. ClimateProgress, 6 October 2015.

Comiso, J. C. (2000) [updated 2015] Bootstrap Sea Ice Concentrations from Nimbus 7 SMMR and DMSP SSMI-SSMIS, Version 2. NASA National Snow and Ice Data center Distributed Active Archive, NSIDC, Boulder, CO, doi: http://dx.doi.org/10.5067/J6JQLS9EJ5HU.

de Matthaeis, P. C. Utku, D. M. Le Vine and A. Moyer (2014) Aquarius retrieval of sea ice thickness: Initial results. In, IEEE Microwave Radiometry Conference and Remote Sensing of the Environment, 24-27 March 2014, Pasadena, California, 69-71, 10.1109/MicroRad.2014.6878910

Drinkwater, M. R. (2012) Cryosphere and polar region observing system. In, Encyclopedia of Remote Sensing, edited E. Njoku, Springer-Verlag, Berlin, 91-97, doi:10.1007/SpringerReference_327089.

Drinkwater, M. R., K. C. Jezek and J. Key (2008) Coordinated satellite observations during the International Polar Year: Towards achieving a polar constellation. *Space Research Today*, No, 171 (April 2008), 6-17.

EUMETSAT (2016) EPS-SG End User Requirements Document [EURD], EUMETSAT Document EUM/PEPS/REQ/09/0151, EUMETSAT, Darmstadt, Germany, 173 pp.

Falkingham, J. (2014) Global satellite observation requirements for floating ice: Focusing on synthetic aperture radar. 71 pp., https://www.wmo.int/pages/prog/sat/meetings/documents/PSTG-4_Doc_08-04_GlobSatObsReq-FloatingIce.pdf.

Gibbs, A. and P. Lautsen (2015) Northern Alaska coastal erosion threatens habitat and infrastructure. USGS Press Release, 1 July 2015.

Gloersen, P. and F. T. Barath (1977) A Scanning Multichannel Microwave Radiometer for Nimbus-G and SeaSat-A. *IEEE Journal of Oceanic Engineering*, *2*, 172-178.

Gordon, S. (2014) Climate change will benefit tourism and cause a boom in Arctic cruises, claims leaked UN report. *DailyMail.com*, 28 March 2014.

Gruss, M. (2015) Senate spending bill echoes House call to shelve DMSP-F20. *Space News*, 12 June 2015.

Hardwerk, B. (2011) Some Arctic coasts eroding by a hundred feet a year. *National Geographic News*, 19 April 2011.

Heinrichs, J. F., D. J. Cavalieri and T. Markus (2006) Assessment of the AMSR sea ice concentration product at the ice edge using RadarSat-1 and MODIS imagery. *IEEE Transactions on GeoScience and Remote Sensing*, *44*, 3070-3080, 10.1109/TGRS.2006.880622.

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

Ivanove, N., L. T. Pedersen, R. T. Tonboe, S. Kern, G. Heygster, T. Lavergne, A. Sórensen, R. Saldo, G. Dybkjær, L. Brucker and M. Shokr (2015) Inter-comparison and evaluation of sea ice algorithms: Towards further identification of challenges and optimal approach using passive microwave observations. *The Cryosphere*, *9*, 1797-1817, doi:10.5194/tc-9-1797-2015.

Jeffries, M. O., J. E. Overland and D. K. Perovich (2013) The Arctic shifts to a new normal. *Physics Today*, *66*, 35-40, doi:10.1063/PT.3.2147.

Kaleschke, L., X. Tian-Kunze, N. Maaß, M. Mäkynen and M. Drusch (2012) Sea ice thickness retrieval from SMOS brightness temperatures during the Arctic freeze-up period. *Geophysical Research Letters*, *39*, L05501, doi:10.1029/2012GL050916.

Kwok, R. and G. F. Cunningham (2015) Variability of Arctic sea ice thickness and volume from CryoSat-2. *Philosophical Transactions of the Royal Society, A, Mathematical Physical Engineering Sciences*, *373*, doi:10.1098/rsta.2014.0157.
Kwok, R., G. F. Cunningham, M. Wensnaham, I. Rigor, H, J. Zwally and D. Yi (2009) Thinning and volume loss of the Arctic Ocean sea ice cover: 2003-2008. *Journal of Geophysical Research*, *114*, doi:10.1029/2009JC005312.

Laxon, S. W., K, A Giles, A. L. Ridout, D. J. Wingham, R. Willatt, R. Cullen, R. Kwok, A. Schweiger, J. Zhang, C. Haas, S. Hendricks, R. Krishfield, N. Kurtz, S. Farrell and M. Davidson (2013) CryoSat-2 estimates of Arctic sea ice thickness and volume. *Geophysical Research Letters, 40,* 732–737, doi:10.1002/grl.50193.

Laxon, S., N. Peacock and D. Smith (2003) High interannual variability of sea ice thickness in the Arctic region. *Nature, 425*, 947–950.

Lindell, D. B and D. G. Long (2016) Multiyear Arctic sea ice classification using OSCAT and QuikSCAT. *IEEE Transactions on Geoscience and Remote Sensing*, *54*, 167-175, doi:10.1109/TGRS.2015.2452215.

Meier, W. N. and T. Markus (2015) Remote sensing of sea ice. In *Remote Sensing of the Cryosphere*, editor M. Tedesco, John Wiley & Sons, New York, 248-272.

Meier, W. N. and J. Stroeve (2008) Comparison of sea-ice extent and ice-edge location estimates from passive microwave and enhanced-resolution scatterometer data. Annals of Glaciology, 48, 65- 70, doi:10.3189/172756408784700743.

Meier, W. N., F. Fetterer, J. S. Stewart and S. Helfrich (2015) How do sea-ice concentrations from operational data compare with passive microwave estimates? Implications for improved model evaluations and forecasting. *Annals of Glaciology*, *56*, 332-340, doi:10.3189/2015AoG69A694.

Meier, W. N., G. Hovelsrud, B. E. H. van Oort, J. R. Key, K. M. Kovacs, C. Michel, C. Haas, M. A. Granskog, S. Gerland, D. K. Perovich, A. Makshtas and J. D. Reist (2014) Arctic sea ice in transformation: A review of recent observed changes and impacts on biology and human activity. *Reviews of Geophysics*, *51*, 185-217, doi:10.1002/2013RG000431.

Melling, H., P. H. Johnston and D. A. Riedel (1995) Measurement of the topography of sea ice by moored sub-sea sonar. *Journal of Atmospheric and Oceanic Technology*, *12*, 589–602.

Nghiem, S. V., I. G. Rigor, D. K. Perovich, P. Clemente-Colón, J. W. Weatherly and G. Neumann (2007) Rapid reduction of Arctic perennial sea ice. *Geophysical Research Letters*, *34*, doi:10.1029/2007GL031138.

NRC (2014a) Responding to oil spills in the U.S. Arctic marine environment. Ocean Studies Board, National Research Council, Washington, DC, 195 pp.

NRC (2014b) The Arctic in the Anthropocene: Emerging research questions. Polar Research Board, National Research Council, Washington, DC, 210 pp.

NRC (2012) Seasonal to decadal predictions of Arctic sea ice: Challenges and strategies. Polar Research Board, National Research Council, Washington, 92 pp.
Overland, J. E. (2016) Is the melting Arctic changing midlatitude weather? *Physics Today*, *69* (3), 38-43, doi:10.1063/PT.3.3107

Parry, W. (2011) Arctic's icy coastlines retreat as planet warms. *LiveScience.com*, 17 April 2011.

Posey, P. G., E. J. Metzger, A. J. Wallcraft, D. A. Hebert, R. A. Allard, O. M. Smedstad, M. W. Phelps, F. Fetterer, J. S. Stewart, W. N. Meier and S. R. Helfrich (2015) Improving Arctic sea ice edge forecasts by assimilating high horizontal resolution sea ice concentration data into the US Navy's ice forecast systems. *The Cryosphere*, *9*, 1735-1745, doi:10.5194/tc-9-1735-2015.

Ray, J. (2012) Proposed next-generation weather satellites get the ax. *Spaceflight Now*, 24 January 2012.

Ricker, R., S. Hendricks, V. Helm, H. Skourup and M. Davidson (2014) Sensitivity of

CryoSat-2 Arctic sea-ice freeboard and thickness on radar-waveform interpretation. *The Cryosphere*, *8*, 1607-1622, doi:10.5194/tc-8-1607-2014.

Rivas, B. M., J. Verspeek, A. Verhoef and A. Stofflen (2012) Bayesian sea ice detection with the advanced scatterometer ASCAT. *IEEE Transactions on Geoscience and Remote Sensing*, *50*, 2649-2657, doi:10.1109/TGRS.2011.2182356.

Stroeve, J., L. Hamilton, C. Bitz and E. Blanchard-Wrigglesworth (2014) Predicting September sea ice: Ensemble skill of the SEARCH Sea Ice Outlook 2008-2013. Geophysical Research Letters, 41, 2411-2418, doi: 1o.1002/2014GL059388.

Su, H. and Y. Wang (2012) Using MODIS data to estimate sea ice thickness in the Bohai Sea (China) in the 2009–2010 winter. *Journal of Geophysical Research*, *117*, C10018, doi:10.1029/2012JC008251.

Tilling, R. L., A. Ridout, A. Shepherd and D. J. Wingham (2015) Increased Arctic sea ice volume after anomalously low melting in 2013. *Nature Geoscience*, *8*, 643-646, doi:10.1038/ngeo2489.

Tonboe, R. T., S. Eastwood, T. Lavergne, A. M. Sørensen, N. Rathmann, G. Dybkjær, L. Toudal Pedersen, J. L. Høyer, and S. Kern (2016) The EUMETSAT sea ice climate record. *The Cryosphere Discussions*, doi:10.5194/tc-2016-34.

WMO (2015) PSTG strategic plan: 2015-2018. World Meteorological Organization, Geneva, Switzerland, 16 pp., http://www.wmo.int/pages/prog/sat/documents/SAT-GEN_PSTG-StratPlan2015-2018.pdf.

WMO (2011) Systematic observation requirements for satellite-based data products for climate, 2011 update. GCOS Report 154, World Meteorological Organization, Geneva, Switzerland, 127 pp. https://www.wmo.int/pages/prog/gcos/Publications/gcos-154.pdf.

WMO (2007) A cryosphere theme report for the IGOS partnership. WMO/TD-No.1405, World Meteorological Organization, Geneva, Switzerland, 114 pp. http://www.globsnow.info/docs/IGOS_cryos_theme_report.pdf

Yu, Y. and D. Rothrock (1996) Thin ice thickness from satellite thermal imagery, *Journal of Geophysical Research*, 101, 25753–25766.

APPENDIX A RECOMMENDATIONS FOR CONSIDERATION BY CGMS

Recommendation 1: Enable sustainability of satellite passive microwave sea ice extent measurements begun in 1978.

Recommendation 2: Promote the implementation of sustained satellite sea ice observations with scatterometer to provide an independent source of information concerning climate change impacts on the marine cryosphere.

Recommendation 3: Enable sustainability of satellite frequent high-spatial marginal ice zone measurements for navigation and other near-real time applications.

Recommendation 4: Promote the implementation of sustained satellite measurements of Arctic Ocean sea ice thickness.

Recommendation 5: Encourage joint CEOS/CGMS Working Group on Climate to establish a CEOS Virtual Constellation on GCOS ECV Sea Ice Measurements.

APPENDIX B LIST OF ACRONYMS

ACIA	Arctic Climate Impact Assessment
ADS	Arctic Data archive System
AltiKa	Ka-band Altimeter
AMSR-E	Advanced Microwave Scanning Radiometer – Earth Observing System
AMSR2	Advanced Microwave Scanning Radiometer 2
ASCAT	Advanced Scatterometer
ATLAS	Advanced Topographic Laser Altimeter System
AVHRR	Advanced Very High Resolution Radiometer
CCSM	Community Climate System Model
CEOS	Committee on Earth Observation Satellites
CGMS	Coordination Group for Meteorological Satellites
CMTS	Committee on Marine Transportation System
CryoVEx	CryoSat Validation Experiment
DMSP	Defense Meteorological Satellite Program
ECV	Essential Climate Variable
ERS	European Remote Sensing
ESA	European Space Agency
ESMR	Electrically Scanning Microwave Radiometer
EUMETSAT	European Organization for the Exploitation of Meteorological Satellites
GCOM-W	Global Change Observation Mission – Water
GCOS	Global Climate Observing System
ICESat	Ice, Cloud, and land Elevation Satellite
IOC	Intergovernmental Oceanographic Commission
IGOS	Integrated Global Observing System
IPCC	Intergovernmental Panel on Climate Change
ISRO	Indian Space Research Organization
JAXA	Japan Aerospace Exploration Agency
MetOp	Meteorological Operational
MODIS	Moderate Resolution Imaging Spectroradiometer
MWI	Microwave Imager
NERSC	Nansen Environmental and Remote Sensing Center
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NIC	National Ice Center
NIPR	National Institute of Polar Research
NOAA	National Oceanic and Atmospheric Administration
NPP	National Polar-orbiting partnership
NRC	National Research Council
NSIDC	National Snow and Ice Data Center
OLS	Operational Linescan System
OSCAR	Observing Systems Capability Analysis and Review
QuikSCAT	Quick Scatterometer
SAR	Synthetic Aperture Radar
SEARCH	Study of Environmental Arctic Change

SIRAL	SAR Interferometric Altimeter
SMOS	Soil Moisture and Ocean Salinity
SRAL	Synthetic Aperture Radar Altimeter
SSMI	Special Sensor Microwave Imager
SSMIS	Special Sensor Microwave Imager Sounder
SSMR	Scanning Multichannel Microwave Radiometer
US	United States
VIIRS	Visible Infrared Imaging Radiometer Suite
WMO	World Meteorological Organization
YOPP	Year of Polar Prediction