Arctic Perennial Sea Ice Crash of the 2000s and its Impacts

Son V. Nghiem and Gregory Neumann
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California, U.S.A.
Son.V.Nghiem@jpl.nasa.gov
Gregory.Neumann@jpl.nasa.gov

Pablo Clemente-Colón
National Ice Center
National Oceanic and Atmospheric Administration
Washington, District of Columbia, U.S.A.
Pablo.Clemente-Colon@noaa.gov

Ignatius G. Rigor
Applied Physics Laboratory
University of Washington
Seattle, Washington, U.S.A.
ignatius@apl.washington.edu

Donald K. Perovich
Cold Regions Research and Engineering Laboratory
US Army Corps of Engineers
Hanover, New Hampshire, U.S.A.
Donald.K.Perovich@usace.army.mil

***Abstract*—Satellite and surface observations show that half of the extent of perennial sea ice in the Arctic Ocean has been lost in the decade of 2000s. Perennial sea ice is the class of old and thick ice important for the stability of the Arctic environment. Perennial ice extent set the record low in 2008 and has remained low as seen in updated satellite scatterometer data and surface drifting buoy measurements in 2011. The drastic decline of Arctic sea ice is far exceeding the worst-case projections from climate models of the Intergovernmental Panel on Climate Change Fourth Assessment Report. The important role of the Polar Express phenomenon has been identified, indicating dynamic and thermodynamic effects are combined to expedite the loss of perennial sea ice. Consequently, major impacts include decreases in Arctic surface albedo, increases in absorbed insolation, facilitation of sea-route opening, and changes in tropospheric chemical processes such as bromine explosion, ozone depletion, and mercury deposition that impact the biosphere.**

Keywords—Perennial sea ice loss, Polar Express, albedo, insolation, Arctic passages, tropospheric chemical changes.

I. Introduction

The Arctic sea ice cover consists of two major synoptic ice classes: seasonal or first-year sea ice that grows and melts in a seasonal cycle, and perennial or multi-year sea ice that survives at least a summer melt season and can last for multiple years. At their boundary, these sea ice classes can be mixed together to form an area of mixed ice. Perennial sea ice is older, thicker, and more massive than seasonal sea ice, and its presence is critical to the stability of the Arctic environment. The total sea ice extent (S_T), encompassing both perennial and seasonal ice, typically reaches a minimum in late summer or early fall. Setting a record low in 2007, S_T has been reduced far beyond the worst-case projections from climate models of the Intergovernmental Panel on Climate Change Forth Assessment Report (IPCC-AR4) [1-2], which are in dire need for improvements in the next IPCC assessment. While the 2007 record minimum of S_T in summer has been widely reported [3-5], the partition between perennial and seasonal ice within the total ice extent in springtime is crucial to assess the overall change in sea ice and its resulting impacts. Much attention has been on increased heating as a thermodynamic cause of sea ice loss by melting within the Arctic Ocean [3-5]. In this paper, we review the extreme loss of Arctic perennial ice in the decade of 2000s with respect to a half-century record, present the latest update on the state of Arctic sea ice in 2011, highlight the role of the Polar Express phenomenon as an important dynamic mechanism for perennial ice loss by ice transport out of the Arctic Ocean, and discuss impacts of the precipitous loss of Arctic perennial ice. Observations of perennial sea ice are presented in Section II, impacts of perennial ice loss are discussed in Section III, and finally the conclusions and future perspectives are noted in Section IV.

II. Observations of Arctic Perennial Sea Ice

A decadal record of backscatter data has been obtained globally throughout the lifetime of the National Aeronautics and Space Administration (NASA) SeaWinds scatterometer, a stable and accurate radar aboard the QuikSCAT satellite from 1999 to 2009. QuikSCAT Ku-band backscatter (QS) is sensitive to different sea ice classes with a large dynamic range of signatures, providing an excellent capability to accurately delineate and map Arctic perennial and seasonal ice [6-8]. We review the recent state of Arctic sea ice including observations from QS data in the 2000s in a multi-decadal context.

Perennial sea ice extent (S_P) during the transition period between winter and spring (March) is an important parameter since it represents the amount of older and thicker ice that preconditions the summer melt of the Arctic sea ice cover and thus the minimum S_T. Furthermore, this transition period is the time of polar sunrise that affects chemical photolysis processes in the Arctic troposphere depending on the relative composition of perennial and seasonal sea ice. A new record has been set in the reduction of March S_P in 2008, while the total sea ice extent has been stable compared to the average over the previous nine years as observed in QS data. In March 2008, QS-measured S_P was reduced by one million km^2 compared to that in March 2007.

 ISBN: 978-1-61208-138-0

Beyond the QS satellite data time-series, the perennial sea ice pattern change has been deduced by using surface observations from buoys and manned ice camps to track sea ice movement around the Arctic Ocean beginning in 1955. The surface-based S_P is obtained from the Drift-Age Model (DM) [9]. The combination of the satellite and surface data records confirms that the reduction of winter perennial ice extent broke the record in 2008 compared to data over the last half century. Another historical fact is that the boundary of perennial sea ice already crossed the North Pole (NP) in February 2008, leaving the area around the NP occupied by seasonal sea ice. This is the first time, not only from the satellite data record but also in the history of sea ice charting at the National Ice Center since the 1970's, that observations indicate the seasonal ice migration into the NP area so early in winter.

In the context of a half century change, perennial sea ice has been declining precipitously in this decade. Perennial ice extent declines at rate of 0.5 million km^2 per decade in the 1970s-1990s while there is no discernable trend in the 1950s-1960s. Abruptly, the rate of decrease has tripled to 1.5 million km^2 per decade in the 2000s. This crashing rate of S_P is cross-validated by both satellite sensor and surface buoy measurements [10-11].

In November 2009, QS antenna was stuck in one azimuth direction due to a malfunction in the antenna rotary joint after more than 10 years in orbit. Nevertheless, the scatterometer is still working to collect good global backscatter data albeit a much reduced swath and a longer time for a full Arctic coverage. New results from QS show that S_P remained low in March 2010. Thus, the climatic data record of Arctic perennial ice extent in the 2000s (2000-2009) can be continued if QS is kept in continuous operation.

While QS can still map perennial sea ice well, the rotary problem reduces the capability of QS to delineate seasonal sea ice. To supplement this deficiency, we utilized a new daily sea ice analysis product called the Multisensor Analyzed Sea Ice Extent – Northern Hemisphere (MASIE-NH) [12], which is an Arctic-wide sea ice extent analysis produced by the National Ice Center (NIC) using a multitude of data sources. Different formats of MASIE-NH are derived and distributed by the National Snow and Ice Data Center. Since QS can detect perennial sea ice, the remainder of the total sea ice extent identified by MASIE-NH consists of seasonal as well as a mixed ice class. Thus, the QS/MASIE-NH composite product can map both perennial and non-perennial sea ice (seasonal and mixed ice) [13]. Moreover, DM results are used in conjunction with QS/MASIE-NH observations of ice to explain ice dynamics. To illustrate the drastic reduction of S_P, Figure 1 compares the extensive extent of perennial sea ice in 2001 with the much smaller perennial ice cover in 2011.

Although considerable efforts were made to investigate thermodynamics effects on sea ice melt in the last several decades, the importance of dynamic effects as a significant sea ice reduction mechanism was noted in recent years [9, 10, 14]. In the 2000s, a record low of S_T first occurred in summer 2005, which was broken again in 2007. While the ice extent had been decreasing throughout the summer 2005 significantly by melting, an important contribution to this minimum extent was from dynamic effects due to wind forcing. Data from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis in July-September 2005 reveal a dipole anomaly pattern (DAP) of the surface level pressure (SLP) with a coexistence of a pronounced atmospheric low pressure over the Barents Sea together with a strong high pressure over the Canadian Basin. Clockwise winds around the high SLP merged together with counterclockwise winds around the low SLP to set up the strong wind anomaly along the Transpolar Drift Stream (TDS) that enhanced the ice transport out of the Arctic via the Fram Strait [15].

This phenomenon, called the Polar Express (PE) [10], forces the ice extent loss by these processes: (1) compressing sea ice from both sides of the TDS, (2) pushing sea ice from the Russian Arctic toward Greenland while accelerating the TDS, (3) transporting of sea ice by the TDS out of the Arctic, and (4) melting of the exported sea ice in the Greenland Sea by warm Atlantic waters originated from the south [10, 15]. It was not until 2007 that the PE occurred again. The 2007 PE was strong, and together with feedback effects on the lighter sea ice cover due to the loss of massive perennial ice in 2005, leading to another record low of S_T after the 2007 summer melt, and subsequently contributing to the record low of S_P in 2008.

III. IMPACTS OF PERENNIAL ICE LOSS

The crash of perennial sea ice extent in the 2000s has profound impacts on the Arctic environment. Here, we review several results including changes in surface albedo, absorbed radiation, Arctic sea routes, and troposheric chemical processes.

The different classes of sea ice partition solar energy differently, with the perennial ice having a larger albedo and thereby transmitting less solar radiation to the ocean [16]. The shift in the Arctic Ocean from perennial to thinner seasonal ice thus suggests a coincident decrease in surface albedo and more solar energy absorbed in the ice ocean system during summer melt [16-17]. To investigate changes in albedo and insolation, a synthetic approach was used to combine satellite-derived ice concentrations, incident irradiances determined from reanalysis products, and field observations of ocean albedo over the Arctic Ocean and the adjacent seas. Results show an increase in the solar energy deposited in the upper ocean over the past few decades in 89% of the studied region spanning across Chukchi Sea, Beaufort Sea, and East Siberian Sea, and the largest anomaly of solar heat input occurred in the 2000s [18]. As the Arctic becomes more dominated by seasonal sea ice with a lower overall albedo and lower ice mass, melting will become much more effective in causing sea ice loss.

Less perennial sea ice and more seasonal ice, which is thinner and requires less energy to melt, may facilitate the summer opening of Arctic sea routes such as the Northwest Passage (NWP) along the North American side or the Northern Sea Route (NSR) along the Siberian side. In winter 2007 and 2008, S_P loss was driven by winds that compressed the ice and transported it out of Fram Strait (east of

 ISBN: 978-1-61208-138-0

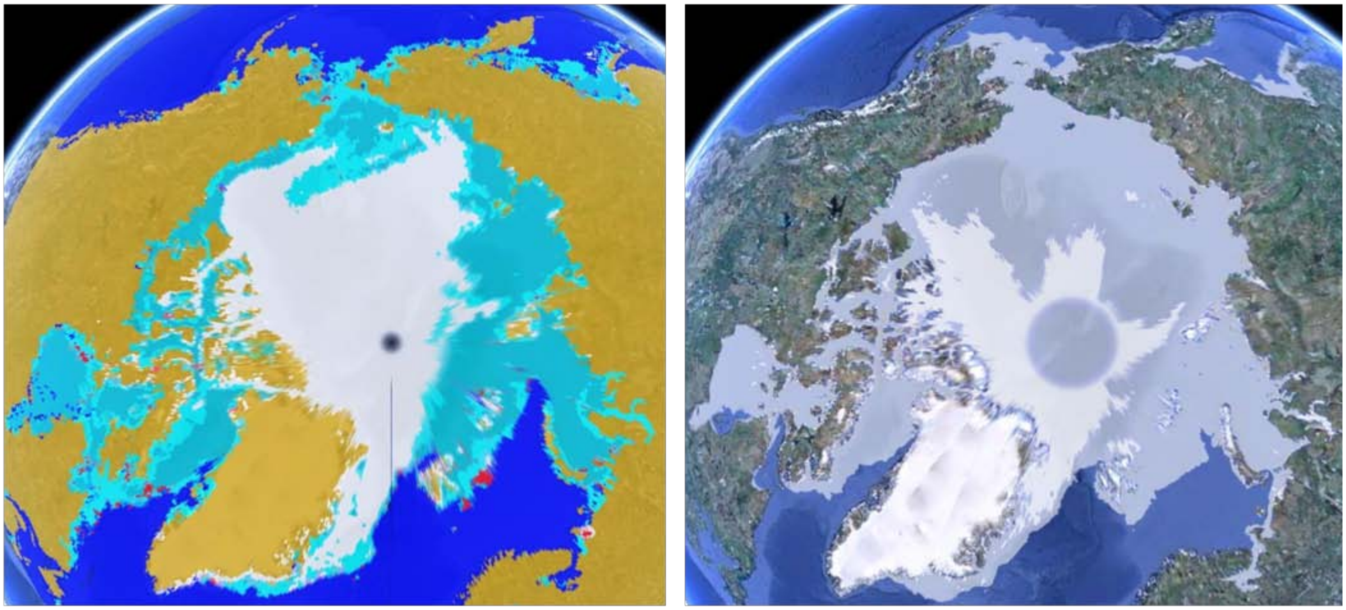

Figure 1. Comparison of Arctic sea ice maps showing the loss of half of perennial ice extent. Left panel is QS sea ice map for 6 January 2001: grayish white for perennial sea ice, aqua for seasonal ice, cyan for mixed ice, blue for open water, brown for land, and a dark disc around the North Pole for QS missing data. Right panel is QS/MASIE-NH composite sea ice map with bluish white for perennial sea ice from 3 weeks of QS data ending on 6 January 2011, light blue for non-perennial sea ice consisting of mixed ice and seasonal ice from MASIE-NH on 6 January 2011, and a large blue disc around the North Pole for QS missing data. The QS/MASIE-NH sea ice map is translucently overlaid on a bathymetric chart of the Arctic Ocean.

Greenland) and Nares Strait (west of Greenland) as observed by QS [19]. By March 2008, QS sea ice maps revealed that seasonal ice occupied the NSR, a vast region from Kara Sea and Laptev Sea to the North Pole, and most of two branches of the NWP north and south of Victoria Island [19]. In a news release in October 2008 [20], the International Ice Charting Working Group (IICWG) issued the statement "For the first time in recorded history, national ice charts showed that both the Northwest Passage and the Northern Sea Route were simultaneously open water for a brief period in September 2008" and also warned that "At lower concentrations, hazardous ice floes and icebergs are more mobile and less easily detected by mariners. Sustained monitoring with high resolution satellite sensors combined with surface and aerial reports is essential for safe navigation." In 2009, perennial ice remained low [21], and the IICWG reported a record number of pleasure craft transited the NWP although ice conditions were more difficult for shipping than in the three previous years [22]. In January 2011, little perennial ice was seen in the NWP and seasonal ice dominated the NSR (right panel in Figure 1).

As perennial sea ice diminished, the Arctic Ocean becomes dominated by seasonal ice, consisting of salty ice together with more leads, polynyas, and frost flowers. The high salinity in these ice conditions affects the release of bromine monoxide (BrO), a catalyst for depletions of ozone (O_3) [23] and gaseous element mercury (GEM) [24]. These changes may have significant implications on chemical fluxes in the Arctic biosphere [25-26], where ozone and mercury are toxic to people and wildlife. During polar sunrise, oxidation from bromide activates photochemically reactive forms, which are photo-disassociated into Br atoms that destroy O_3 and oxidize GEM. The Br atoms are regenerated to repeat this autocatalytic process. Subsequent reactions further multiply available bromine, which is called "bromine explosion" [27]. In 2007, the acceleration of the Transpolar Drift (TD), due to the Polar Express phenomenon excessively transported sea ice toward the Atlantic sector and finally out of the Arctic across Fram Strait. The 2007 TD acceleration was actually verified by a vessel drift during the TARA expedition [28]. Consequently, from QS observations, a polynya as large as the country of Austria was created with an extensive frost flower cover near the Taymyr Peninsula, and ozone depletion events were observed far down wind [29]. While S_P was low during the 2008 spring transition, bromine enhancement was observed across the Beaufort Sea to the Amundsen Gulf [30]. In March-May of 2009 and 2010 with low S_P, strong bromine explosion events were detected by satellite sensors [31].

IV. Conclusions and Future Perspectives

As observed from decadal satellite and surface data across the Arctic, half of the perennial sea ice extent was lost in the decade of 2000s when the ice-loss rate was the most precipitous in the last half century. The role of dynamic mechanisms, such as the PE, has been identified as an important factor in causing the drastic sea ice loss, which is accelerated by the combination of dynamic and thermodynamic effects. Without appropriately accounting for these effects, many projections from IPCC-AR4 climate models underestimated the Arctic sea ice loss by far. Recently, Zhang et al. [32] conducted a model study to show that preconditioning, anomalous wind forcing, and ice-albedo feedback are the main contributors responsible for sea ice loss in 2007, and that the Arctic has become vulnerable to the anomalous atmospheric forcing. Later, Wang et al. [33]

 ISBN: 978-1-61208-138-0

examined the DAP and used a coupled ice-ocean model to explain the low extents of sea ice including the records in 2005 and in 2007. What causes the change between the typical Arctic Oscillation pattern and the anomalous DAP, how such change can be related to global temperature change, and whether the impacts can be amplified or suppressed by positive or negative feedbacks remain to be investigated in future research.

Given the 2000s crash of perennial sea ice, it is critical to closely monitor the sea ice change with both surface and satellite measurements. For surface measurements, the International Arctic Buoy Programme has been enhanced with a larger number of buoys during the International Polar Years 2007-2008. The need for the buoy program to sustain ocean observations has been articulated [34]. Regarding satellite scatterometer observations, QS unfortunately suffered from the rotary malfunction that has reduced its capability for sea ice mapping. Sea ice maps derived from the limited QS data after the rotary incident still need to be improved with better calibration and geolocation efforts. Launched in September 2009, the Indian Oceansat-2 satellite [35], carrying a sensor similar to QS, is currently operating and collecting global Ku-band backscatter data. Access to fully calibrated and validated data will be useful. Planned for a launch later in 2011, the Chinese Haiyan-2 satellite [36] will also have a Ku-band scatterometer. The U.S. National Research Council Decadal Survey recommends the development of another advanced satellite scatterometer [37]. All of these international satellite missions will potentially contribute to sea ice monitoring in the long term.

While important advances have been made for understanding sea ice changes and environmental impacts, many science questions as well as practically issues still need to be addressed. Sea ice-albedo feedback processes are complex, which demands interdisciplinary research involving all components including air, ice, ocean, and land to determine various inter-related positive and negative mechanisms in the overall feedback process of the Earth system. Either from satellite and surface observations or from model estimates, diverse and extensive temporal and spatial scales should be considered since results for a given area or a time period will likely lead to inconclusive or even erroneous projections from a series of non-physical numerical correlations, interpolations, and extrapolations. In any case, reducing potential causes, which would further decrease the albedo such as dust or black carbon deposition in the Arctic, may help to mitigate albedo feedback effects.

With the prospect of a more navigable Arctic, new issues have emerged and necessitated the need for high-resolution operational satellite sensors to monitor ice in polar sea routes, more accurate and complete bathymetry measurements, and consensus on international agreements such as the United Nations Convention on the Law of the Sea or the Arctic Council Memorandum on Search and Rescue. New bathymetry data are critical to avoid or reduce the threat of navigation hazards that may lead to environmental disasters such as oil spills. Although much attention has been paid to Arctic sea-route shortcuts and resource exploitation, it is important to consider the impact to the Arctic biosphere by changes in chemical processes, transport, and distribution that may adversely affect the well being of people and wildlife. There is a general understanding that a saltier snow and ice cover may exacerbate bromine explosions, ozone depletions, and mercury depositions. Reducing mercury emission into the atmosphere, under the auspices of the United Nations Environment Programme (UNEP) [38], may diminish the mercury source and thus decrease the mercury deposition in the Arctic environment. Nevertheless, exact contributions from different components such as seasonal ice, snow on sea ice, frost flowers in leads and polynyas, high salinity expulsion on ice surface, aerosols in the atmosphere, and chemical composition and exchange in the troposphere and stratosphere are not well understood. In this respect, more intensive interdisciplinary research is underway [31].

ACKNOWLEDGMENT

The research carried out at the Jet Propulsion Laboratory (JPL), California Institute of Technology, was supported by the National Aeronautics and Space Administration (NASA) Cryospheric Sciences Program. The statements, findings, conclusions, and recommendations in this paper are those of the author(s) and do not necessarily reflect the views of the National Oceanic and Atmospheric Administration or the Department of Commerce.

REFERENCES

[1] I. N. Allison, L. Bindoff, R. A. Bindschadler, P. M. Cox, N. de Noblet, M. H. England, J. E. Francis, N. Gruber, A. M. Haywood, D. J. Karoly, G. Kaser, C. Le Quéré, T. M. Lenton, M. E. Mann, B. I. McNeil, A. J. Pitman, S. Rahmstorf, E. Rignot, H. J. Schellnhuber, S. H. Schneider, S. C. Sherwood, R. C. J. Somerville, K. Steffen, E. J. Steig, M. Visbeck, and A. J. Weaver, The Copenhagen Diagnosis, 2009: Updating the World on the Latest Climate Science, The University of New South Wales Climate Change Research Centre (CCRC), Sydney, Australia, 60 pp., 2009.

[2] J. Stroeve, M. M. Holland, W. Meier, T. Scambos, and M. Serreze, “Arctic sea ice decline: Faster than forecast,” Geophys. Res. Lett., vol. 34, L09501, doi:10.1029/2007/GL029703, 2007.

[3] J. A. Maslanik, C. Fowler, J. Stroeve, S. Drobot, J. Zwally, D. Yi, and W. Emery, “A younger, thinner Arctic ice cover: Increase potential for rapid, extensive sea-ice loss,” Geophys. Res. Lett., vol. 34, no. 24, L24501, doi:10.1029/2007GL032043, 2007.

[4] D. K. Perovich, J. Richter-Menge, K. F. Jones, and B. Light, “Sunlight, water, and ice: Extreme Arctic sea ice melt during summer 2007,” Geophys. Res. Lett., vol. 35, no. 11, L11501, doi:10.1029/2008GL034007, 2008.

[5] J. Richter-Menge, J. Comiso, W. Meier, S. Nghiem, and D. Perovich, “Sea Ice Cover,” in State of the Climate in 2007, Bull. Amer. Meteorol. Soc., vol. 89, no. 7, pp. S1-S179, 2008.

[6] S. V. Nghiem, M. L. Van Woert, and G. Neumann, Rapid formation of a sea ice barrier east of Svalbard, J. Geophys. Res., vol. 110, doi:10.1029/2004JC002654, 2005.

[7] S. V. Nghiem and G. Neumann, “Arctic Sea-Ice Monitoring,” in 2007 McGraw-Hill Yearbook of Science and Technology, pp. 12-15, McGraw-Hill, New York, 2007.

[8] F. Girard-Ardhuin, R. Ezraty, D. Croizé-Fillon, “ASCAT/MetOp scatterometer data: First results for sea ice study,” Acte Coll., Archimer, Arch. Inst. Ifremer, Plouzané, France, 2009.

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

 ISBN: 978-1-61208-138-0

[10] S. V. Nghiem, I. G. Rigor, D. K. Perovich, P. Clemente-Colon, J. W. Weatherly, and G. Neumann, "Rapid reduction of Arctic perennial sea ice," Geophys. Res. Lett., vol. 34, L19504, doi:10.1029/2007GL031138, 2007.

[11] S. V. Nghiem, I. G. Rigor, P. Clemente-Colón, D. K. Perovich, and J. E. Overland, "Triple Loss Rate of Arctic Perennial Sea Ice Extent in the Decade of 2000s," International Polar Year Oslo Science Conference, Oslo, Norway, 8-12 June 2010.

[12] P. Clemente-Colón, S. R. Helfrich, M. Vancas, F. Fetterer, and M. Savoie, "A New Role for a NIC Product: the Multisensor Analyzed Sea Ice Extent (MASIE)," submitted to IEEE Int. Geosci. and Remote Sens. Symp. (IGARSS), 2011.

[13] S. V. Nghiem, P. Clemente-Colón, I. G. Rigor, and G. Neumann, "Remote sensing of Arctic perennial sea ice reduction and its impact on tropopheric chemical processes," submitted to IEEE Int. Geosci. and Remote Sens. Symp. (IGARSS), 2011.

[14] S. V. Nghiem, Y. Chao, G. Neumann, P. Li, D. K. Perovich, T. Street, and P. Clemente-Colon, "Depletion of perennial sea ice in the East Arctic ocean," Geophys. Res. Lett., vol. 33, L17501, doi:10.1029/2006GL027198, 2006.

[15] S. V. Nghiem, Y. Chao, G. Neumann, P. Li, D. K. Perovich, T. Street, and P. Clemente-Colón, "Significant reduction in Arctic perennial sea ice," EOS Trans., AGU, vol. 87, no. 52, Fall Meet. Suppl., Abst. C33B-1265, 2006.

[16] D. K. Perovich, T. C. Grenfell, B. Light, and P.V. Hobbs, "The seasonal evolution of Arctic sea ice-albedo," J. Geophys. Res., doi:10.1029/2000JC000438, 2002.

[17] D. K. Perovich, S. V. Nghiem, T. Markus, and A. Schweiger, "Seasonal evolution and interannual variability of the solar energy absorbed by the Arctic sea ice-ocean system," J. Geophys. Res., vol. 112, C03005, doi:10.1029/2006JC003558, 2007.

[18] D. K. Perovich, B. Light, H. Eicken, K. F. Jones, K. Runciman, S. V. Nghiem, "Increasing solar heating of the Arctic Ocean and adjacent seas, 1979–2005: Attribution and role in the ice-albedo feedback," Geophys. Res. Lett., vol. 34, L19505, doi:10.1029/2007GL031480, 2007.

[19] S. V. Nghiem, I. G. Rigor, P. Clemente-colón, D. K. Perovich, and G. Neumann, "New record reduction of Arctic perennial sea ice in winter 2008," Sci. Res. Article, JPL D-44233, Jet Prop. Lab., California Institute of Technology, Mar. 13, 2008.

[20] International Ice Charting Working Group, "National Ice Services Advise of Continuing Navigation Hazards," news release, Luleå, Sweden, Oct. 24, 2008.

[21] S. V. Nghiem, I. G. Rigor, P. Clemente-Colón, D. K. Perovich, H. Eicken, J. E. Overland, T. Markus, D. G. Barber, and G. Neumann, "Observing the State of Arctic Sea Ice," *State of the Arctic Conference*, Miami, Florida, Mar. 16-19, 2010.

[22] International Ice Charting Working Group, "National Ice Services Advise of Continuing Navigation Hazards," news release, Geneva, Switzerland, Oct. 16, 2009.

[23] L. A. Barrie, J. W. Bottenheim, R. C. Schnell, P. J. Crutzen, and R. A. Rasmussen, "Ozone destruction and photo-chemical reactions at polar sunrise in the lower Arctic atmosphere," Nature, vol. 334, pp. 138-141, 1988.

[24] W. H. Schroeder, K. G. Anlauf, L. A. Barrie, J. Y. Lu, A. Steffen, D. R. Schneeberger, and T. Berg, "Arctic springtime depletion of mercury," Nature, vol. 394, pp. 331-332, 1998.

[25] J. Y. Lu, W. H. Schroeder, L. A. Barrie, A. Steffen, H. E. Welch, K. Martin, L. Lockhart, R. V. Hunt, G. Boila, and A. Richter, "Magnification of atmospheric mercury deposition to polar regions in springtime: the link to tropospheric ozone chemistry," Geophys. Res. Lett., vol. 28, no. 17, pp. 3219-3222, 2001.

[26] A. Steffen, T. Douglas, M. Amyot, P. Ariya, K. Aspmo, T. Berg, J. Bottenheim, S. Brooks, F. Cobbett, A. Dastoor, A. Dommergue, R. Ebinghaus, C. Ferrari, K. Gardfeldt, M. E. Goodsite, D. Lean, A. J. Poulain, C. Scherz, H. Skov, J. Sommar, and C. Temme, "A synthesis of atmospheric mercury depletion event chemistry in the atmosphere and snow," Atmos. Chem. Phys., vol. 8, pp. 1445-1482, 2008.

[27] P. Wennberg, "Atmospheric chemistry – Bromine explosion," Nature, vol. 397, pp. 299-301, 1999.

[28] J.-C. Gascard, Jean Festy, H. le Goff, M. Weber, B. Bruemmer, M. Offermann, M. Doble, P. Wadhams, R. Forsberg, S. Hanson, H. Skourup, S. Gerland, M. Nicolaus, J.-P. Metaxian, J. Grangeon, J. Haapala, E. Rinne, C. Haas, G. Heygster, E. Jakobson, T. Palo, J. Wilkinson, L. Kaleschke, K. Claffey, B. Elder, and J. Bottenheim, "Exploring Arctic transpolar drift during dramatic sea ice retreat," EOS Trans. AGU, vol. 89, no. 3, pp. 21-22, doi:10.1029/2008EO160002, 2008.

[29] J. W. Bottenheim, S. Netcheva, S. Morin, and S. V. Nghiem, "Ozone in the Boundary Layer Air over the Arctic Ocean: Measurements during the TARA Transpolar Drift 2006-2008," Atmos. Chem. Phys., vol. 9, pp. 4545-4557, 2009.

[30] S. V. Nghiem, "Implications of Arctic Sea Ice Reduction on Arctic Tropospheric Chemical Change," Eos Trans. AGU, vol. 90, no. 52, Fall Meet. Suppl., Abst. A24B-01, 29 December, 2009

[31] S. V. Nghiem, I. G. Rigor, P. Clemente-Colón, A. Freeman, A. Richter, J. P. Burrows, P. B. Shepson, J. Bottenheim, D. G. Barber, W. Simpson, D. K. Perovich, M. Sturm, A. Steffen, L. Kaleschke, D. K. Hall, T. Markus, H. Eicken, and G. Neumann, "Rejuvenation of Arctic sea ice and tropospheric chemical change," Abs. C43D-0580, AGU Fall Meeting, San Francisco, Calif., Dec. 13-17, 2010.

[32] Zhang, J., R. Lindsay, M. Steele, and A. Schweiger, "What drove the dramatic retreat of arctic sea ice during summer 2007?" Geophys. Res. Lett., vol. 35, L11505, doi:10.1029/2008GL034005, 2008.

[33] Wang, J., J. Zhang, E. Watanabe, M. Ikeda, K. Mizobata, J. E. Walsh, X. Bai, and B. Wu, "Is the Dipole Anomaly a major driver to record lows in Arctic summer sea ice extent?" Geophys. Res. Lett., vol. 36, L05706, doi:10.1029/2008GL036706, 2009.

[34] U.S. Commission on Ocean Policy, An Ocean Blueprint for the 21st Century, Final Rep., Washington, DC, 2004.

[35] V. Jayaraman, V. S. Hedge, M. Rao, and H. H. Gowda, "Future Earth observation missions for oceanographic applications: Indian perspectives," Acta Astronautica, vol. 44, no. 7-12, pp. 667-674, 1999.

[36] X. Dong, K. Xu, H. Liu, and J. Jiang, "The radar altimeter and scatterometer of China's HY-2 satellite," Proc. Geosci. Remote Sens. Symp., IGARSS, vol. 3, pp. 1703-1706, doi:10.1109/ IGARSS.2004.1370659, 2004.

[37] National Research Council, Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond, the National Academies Press, Washington, D.C., 2007.

[38] UNEP, *Report of the intergovernmental negotiation committee to prepare a global legally binding instrument on mercury on the work of its second session,* UNEP(DTIE)/Hg/INC.2/20, Chiba, Japan, 2011.

 ISBN: 978-1-61208-138-0