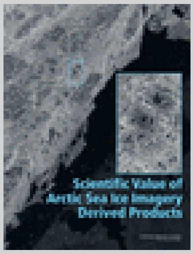

Scientific Value of Arctic Sea Ice Imagery Derived Products

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Polar Research Board

Division on Earth and Life Studies

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Preface

During the 1990s, a program called Medea brought together environmental scientists and members of the intelligence community to consider how classified assets and data could be applied to further the understanding of environmental change. As part of the Medea program, collection of overhead classified imagery of sea ice at four sites around the Arctic basin was initiated in 1999, and two additional sites were added in 2005. Collection of images during the summer months at these six locations has continued until the present day. Several hundred unclassified images with a nominal resolution of 1 meter have been derived from the classified images collected at the 6 Arctic sites. To assist in the process of making the unclassified derived imagery more widely useful, the National Research Council convened the Committee on the Scientific Value of Sea Ice Imagery Derived Products, which met in Seattle, Washington, December 11-12, 2008, to review the derived images and consider their potential uses for scientific research (see Statement of Task; Appendix A). In this report, we explore the importance of sea ice in the Arctic and illustrate the types of information – often unique in its detail – that the derived images could contribute to the scientific discussion.

The Committee based its scientific analysis of the dataset on our review of a representative subset of the derived images for each of the six sites. The images were displayed to us during the December 2008 meeting by Ron Kwok, Jet Propulsion Laboratory, who had been engaged by the NRC staff to preview and sort all available images prior to our meeting. We thank Dr. Kwok for facilitating our review of the dataset. We also thank the NRC staff for facilitating the committee process and the production of this report. We look forward to the release of the derived imagery dataset and the results of the scientific research it enables.

Sincerely,

Stephanie Pfirman, chair
Committee on the Scientific Value of Arctic Sea-Ice Imagery Derived Products

Acknowledgments

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's (NRC's) Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

Dr. Richard B. Alley, Pennsylvania State University, State College
Dr. Florence Fetterer, National Snow and Ice Data Center, Boulder, Colorado
Dr. Jacqueline M. Grebmeier, University of Maryland, College Park

Although the reviewers listed above have provided constructive comments and suggestions, they were not asked to endorse the report's conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Dr. Mary R. Albert, Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire. Appointed by the NRC, she was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring panel and the institution.

Contents

Summary

The loss of Arctic sea ice observed in recent years and the possibility that the Arctic Basin may become seasonally ice-free raise a number of environmental, economic, and national security issues. Sea ice is an important resource for coastal communities and ecosystems as a platform and a habitat, but it can also be a hazard for industrial activity. With increased periods of open water, industrial development and shipping are likely to increase to unprecedented levels. Destinational and trans-arctic shipping between the industrial centers of the Atlantic and Pacific will expand. Exploitation of natural resources will become more feasible as the ice recedes from continental shelves in summer. The Arctic will enter a new regime requiring international agreements and environmental regulation, with new policies for territorial waters, economic zones, search and rescue, and environmental protection.

To prepare for managing the transition to an Arctic that is nearly ice free in the summer, it is critical to have accurate projections of Arctic environmental changes over the next several decades. Forecasts of regional sea-ice conditions on seasonal timescales can help different stakeholders prepare for and adapt to the impacts of climate change and minimize environmental risks associated with development. Although the Intergovernmental Panel on Climate Change (IPCC) models provide meaningful projections of future global temperature and precipitation, projections of Arctic sea ice cover range widely, from almost no change to the end of the 21st century to a disappearance of the ice cover at the end of summer 20 years from now. In part, the models are hampered by the fact that many of the physical processes occurring in summer are poorly understood due to a lack of observations at appropriate times and scales. It is difficult and expensive to maintain manned drifting stations on the ice and conduct observational flights. In the history of U.S. Arctic research, there have been only four all-summer drifting stations. The spring melt and fall freeze-up periods are particularly challenging due to the rapidly changing environmental conditions and the weak platform offered by thin ice.

This report addresses a unique dataset that could facilitate significant advances in the scientific understanding of Arctic sea ice as we seek to address the myriad issues discussed above. During the 1990s, the Medea program brought together environmental scientists and members of the intelligence community to apply classified assets and data to further the understanding of environmental change. Under Medea auspices, the global "fiducials" program was established whereby participating scientists could request collection of classified images at environmentally sensitive locations around the globe. The term "fiducials" refers to the fact that the classified images were to be kept "in trust" in classified archives, with the eventual goal of declassification and release to the broader scientific community for research purposes. In 1999, Medea scientists requested that the intelligence community begin collecting images of Arctic sea ice at four different locations in the Arctic Basin during the summer months (the melt season). Two additional locations were added in 2005. Collection of images during the summer months at these six sites has continued until the present day.

In the latter years of the Medea program, procedures were established whereby Literal Imagery Derived Products (LIDPs) could be produced from the classified fiducials data at a resolution deemed suitable for declassification. Several hundred unclassified LIDPs with a nominal resolution of 1 meter have been produced from the images collected at the 6 Arctic sites. These images are unclassified but are not yet released to the public. These images, when released, could lend themselves to a wide range of studies leading to significant improvements in the way in which sea ice physical processes are represented in climate models, as well as understanding changes in ice habitat (Box S-1). Moreover, these data, which are derived from the unique capabilities provided by the classified imagery systems, provide a unique opportunity for scientists to leverage existing and publicly available data provided by unclassified civil and commercial satellite systems to maximum scientific benefit.

RECOMMENDATIONS

Recommendation: The Intelligence Community should release and disseminate all Arctic sea ice LIDPs that have been produced to date as soon as possible.

The Committee sees great value in releasing these sea ice images to the general public and scientific community. They provide information at scales, locations, and time periods that are extraordinarily important in advancing our knowledge of critical processes during this era of rapid loss and transformation of Arctic sea ice. There are no other data available that show the melting and freezing processes that we were able to observe in these images; their release will have a major impact on understanding effects of climate change on sea ice and ice habitat.

All of the Arctic sea ice LIDPs contain information that will be extremely valuable to scientific research. Three categories of LIDPs are of particularly high priority for dissemination and publicity efforts: (1) all six sites during 2007-2008, (2) all from the Barrow site, and (3) all from the Beaufort Sea site (Box S-2).

Recommendation: To maximize the utility of the images, the committee recommends that the metadata include: thumbnail (smaller size) copies of the images, exact information on the location of the images, calibration information, the time of acquisition, and information on the pointing angle.

The committee understands that the trustees of the fiducials archive, the U.S. Geological Survey's Civil Applications Program, are preparing a website to disseminate the derived Arctic sea-ice images. Inclusion of these metadata in the online archive would greatly facilitate the research of scientists who obtain and use the images.

BOX S-1

Processes Better Understood through the Medea Literal Imagery Derived Products (LIDPs)

Snow Depth: In the absence of any other method to observe the snow cover, the Medea data will provide valuable information about its morphology and interaction with the surface topography and will help to improve the interpretation of Ice, Clouds, Land Elevation Satellite (ICESat) laser altimeter records (a civilian data source) in terms of freeboard, ice thickness, and snow depth.

Lateral Melting: Sequential one-meter resolution images will enable scientists both to measure the kinematic shifts of ice floe assemblies and track the surface area of each individual piece of ice. Such observations are likely to help explain the contribution of lateral melting to the loss of multiyear ice.

Ice Topography and Albedo: There are virtually no sustained, systematic observations of the evolution of the spatial variability in ice albedo because neither radar nor passive microwave images have sufficient resolution. The LIDPs will provide an unprecedented view of how the surface topography affects the initial formation and subsequent evolution of melt ponds and their effect on the albedo and hence the short-wave radiative energy balance. Calibration information would make the images even more useful for albedo.

Ice Thickness Evolution: The designers of sea-ice models have no choice but to parameterize a relationship between albedo and ice thickness, which makes it a powerful tuning parameter. Ice thickness distributions from ICESat and albedo derived from Medea surface characterizations should be invaluable to improve these parameterizations.

Deformation: If it were possible to compare the 10-km ice velocity and deformation field with the high-resolution view of the Medea data, we could expect new insight on the relationship of stress and strain rate at the larger scales.

Shear and Crack Patterns: The 1-meter resolution Medea data would be of significant benefit to our understanding of ice failure and deformation processes as well as to calculations of the mass balance of the ice cover.

Melt Pond Recurrence: The ability to follow an individual piece of ice from freeze-up throughout the winter until the onset of melting in the following summer would shed light not only on the recurrence of melt ponds but also the seasonal evolution of albedo.

Habitat: The Medea data should significantly increase our ability to understand and track patterns that govern the evolution of mammal habitats, including polar bears, and the distribution of fisheries.

BOX S-2

Priorities for Dissemination and Publicity Efforts

All 2007-2008 Data: This window coincides with the International Polar Year (IPY). Images from all six sites during this time will greatly enhance the benefits and value of a broad range of intensive ground-based observations that were collected during the IPY. Furthermore, this subset includes images of the minimum in sea-ice coverage observed during the summer 2007, when the extent of summer melt far exceeded the previous record.

Barrow: Images from the Barrow site would support a range of high-profile research projects in the coastal region at Barrow (Norton, 2001). These data will serve as an important resource for questions revolving around adaptation of coastal communities and ecosystems to climate change.

Beaufort Sea: The Beaufort Sea, with imagery dating to 1999, exhibits the broadest range of different ice types and ice ages, greatly increasing the value of Arctic sea-ice LIDPs in improving our ability to monitor and forecast the movement and evolution of different ice age and thickness classes. Forecasts of regional sea-ice conditions on seasonal timescales can help different stakeholders prepare for and adapt to the impacts of climate change and minimize environmental risks associated with industrial activity. Converging economic activities (natural resource extraction and shipping) and indigenous interests (subsistence harvest of marine mammals) in the Beaufort region place great importance on the detection and tracking of multiyear ice. Offshore oil and gas exploration activities in this region will also benefit from more accurate determination of the ice edge and hazardous ice conditions.

CONSIDERATIONS FOR THE FUTURE

If data will be collected in the future and LIDPs produced for the purpose of public release, some modifications/additions would make the data even more useful for scientific research. Operators of classified assets could continue to collect ice images during suitable atmospheric conditions at the existing Beaufort Sea, Canada Basin, and Chukchi Sea sites. Assuming that the location and number of sites is not fixed, adding collection of imagery at the North Pole, where extended field observations are already underway, would be particularly valuable. *Dynamic* image collection that tracks how an individual ice feature evolves over time and a mechanism to communicate this information in near real-time for a given feature would complement the existing data, which are images at fixed locations in space through which different ice features pass over time. If available, any corresponding radar data would be particularly valuable.

1

Sea Ice and the Global Climate System

THE IMPORTANCE OF SEA ICE

As an integral and interactive part of the global climate system, the presence or absence of sea ice has a number of important economic, societal, legal, and national security implications. If the current trend toward a loss of sea ice, especially during summer, continues, unimpeded shipping between the commercial centers of the Atlantic and the Pacific is bound to be an issue of enormous consequence (Stroeve et al., 2008). Such shipping will raise many questions regarding the Law of the Sea, territorial waters, and economic zones, as well as the monitoring and policing of international agreements, environmental pollution, and search and rescue (e.g. INSROP, 1999; AMSA, 2006).

Another important consequence of a diminished ice cover would be the greater access to areas with potential fossil fuel deposits and other mineral resources (Bird et al., 2008). All these activities will require the development of appropriate policies and infrastructures.

The diminishing amount of thick, multiyear ice poses a well-publicized threat to the survival of the polar bear (Figure 1.1; Durner et al., 2009). The survival of a dwindling population of bears in coastal sea ice areas is bound to induce additional shifts in the ecosystems, including potential threats to the basis of subsistence living of coastal native populations (Durner et al., 2005; USGS, 2007; FWS, 2008).

Another issue receiving increased attention is the possibility that the recent warming and the prolonged periods of open water during the Arctic summer are already having a significant impact on the marine ecosystem of the Bering Sea (Mueter and Lutzow, 2008). The Arctic Basin receives more continental runoff and nutrients per unit area than any other, and the very large and shallow Arctic shelf waters are well mixed. This holds the possibility that, in the future, the immigration of sub-arctic species into these areas may transform them into commercially significant fisheries.

The seasonal cycle of freezing and melting of sea ice imparts an annual cycle of salt injection (freezing) and dilution (melting) to the upper ocean layers. The amplitude of this cycle is small for thick, multiyear ice and much larger for seasonal ice. If the Arctic sea ice cycle were to evolve toward an ice-free summer, the increased amplitude of the upper ocean salinity variations may have profound consequences for the entire thermohaline regime of the Nordic Seas, including the properties and rate of production of North Atlantic Deep Water and the global thermohaline circulation (Wadhams, 2005).

ARCTIC SEA ICE IN INTERACTIVE CLIMATE MODELS

To prepare for managing the transition to an Arctic that may be nearly ice free during summer, it is critical to have accurate projections of Arctic environmental changes over the next several decades. Forecasts of regional sea-ice conditions on seasonal timescales can help different stakeholders prepare for and adapt to the impacts of climate change and minimize environmental risks associated with development. While the Intergovernmental Panel on Climate Change (IPCC) models provide meaningful projections of future global temperature and precipitation, projections of Arctic sea ice cover range widely, from almost no change to the end of the 21st century, to a disappearance of the ice cover at the end of summer 20 years from now.

Clouds (Figure 1.2, top figure) exert the strongest forcing on the surface heat balance, which controls the freezing and melting of ice (Kay et al., 2008; Curry et al., 2006). In view of several other uncertainties concerning sea ice physics, it is not surprising that the models show a huge variance in their predictions of the Arctic ice cover during the rest of our century.

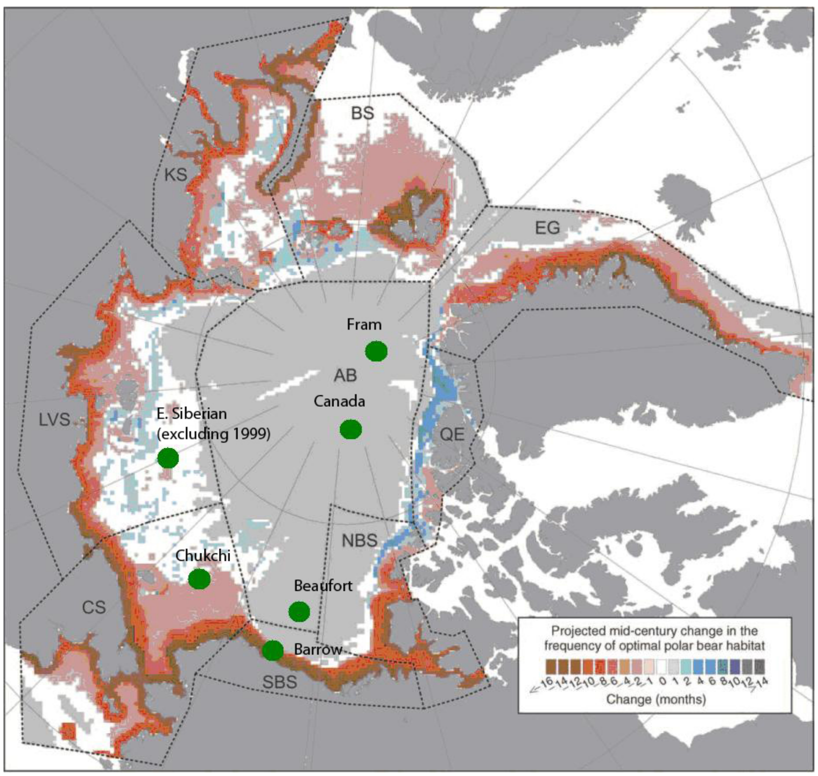

FIGURE 1.1 Projected changes in the spatial distribution and integrated annual area of optimal polar bear habitat for 2050. Map shows the cumulative number of months per decade where optimal polar bear habitat was either lost (red) or gained (blue). The green circles indicate the approximate locations of the Medea Fiducial Sites. SOURCE: Durner et al., 2009.

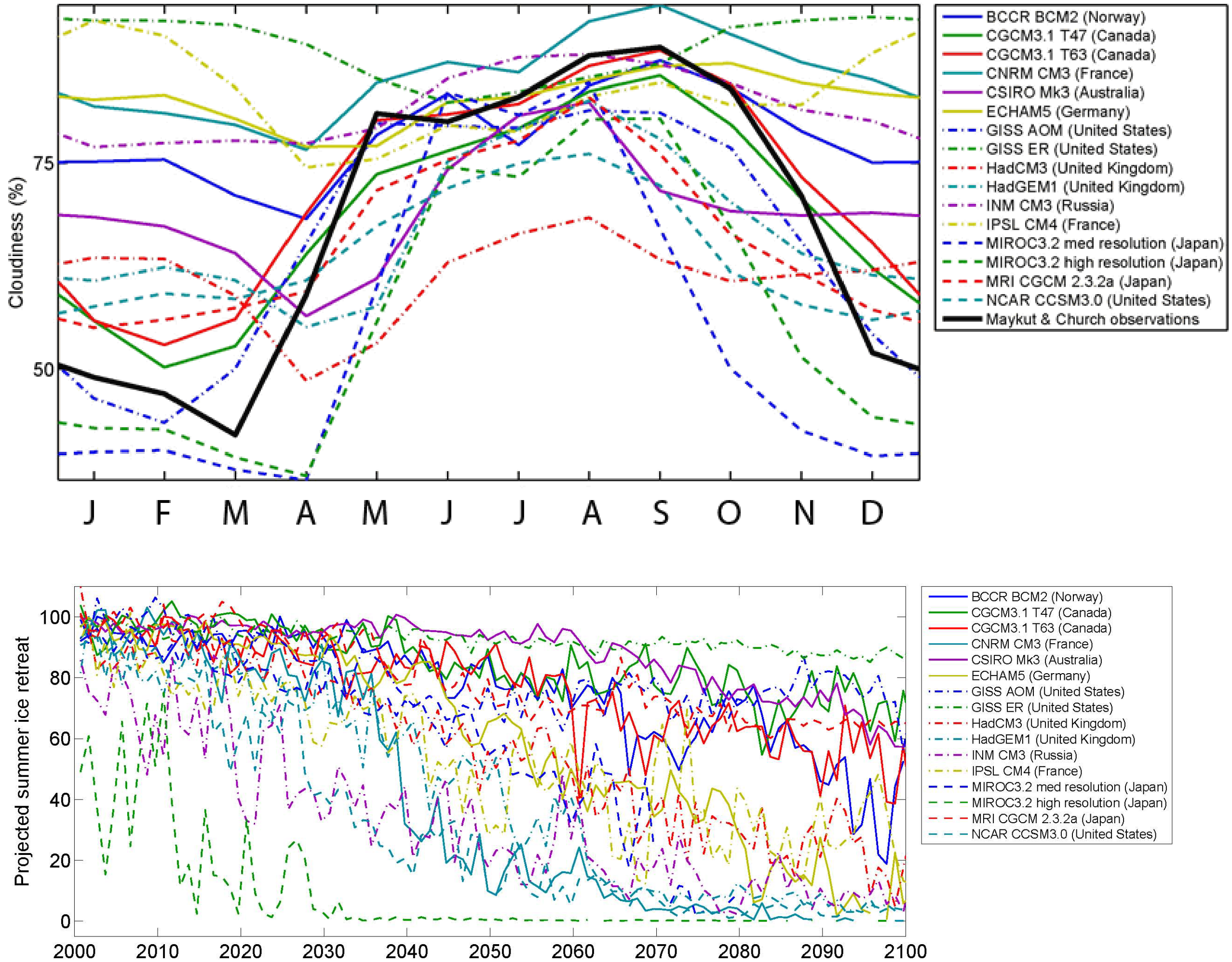

FIGURE 1.2 Selected results from 16 models used in the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC). Top figure: monthly contemporary mean cloud amount north of 66 degrees N from 16 climate models from IPCC-AR4. The black line shows the mean monthly cloud amount observed at the Russian drifting stations in the Arctic Basin (Lindsay, 1998). Bottom figure: Projected retreat of the summer ice extent from the same models. SOURCE: Reproduced with permission from Ian Eisenman, using data from the Program for Climate Model Diagnostics and Intercomparison at Lawrence Livermore National Laboratory.

The discrepancies in the total cloud amount alone (especially in winter) can make a major contribution to the vast range of the predicted ice cover shown in Figure 1.2. We cannot offer a discussion of the various parameterizations used in the different models and their effects on the outcome, but it seems clear that the vast range of results signifies a profound problem with model physics. Analyses of ice models with constant seasonal forcing suggest that the same applies to the ice models.

In part, the models are hampered by the fact that many of the physical processes are poorly understood due to a lack of observations at appropriate times and scales. Maintaining manned drifting stations on the ice and conducting observational flights is difficult and expensive. The spring melt and fall freeze-up periods are particularly challenging due to the rapidly changing environmental conditions and the weak platform offered by thin ice.

The essential ingredients of an ice model are shown in Figure 1.3. The external forcing consists of wind, ocean currents, short- and long-wave radiation, and turbulent fluxes in the atmospheric and oceanic boundary layer. A flow law describes the relationship of external stress and strain rate, and a thickness re-distribution function (psi) relates the ice strain to the formation of leads and pressure ridges (Thorndike et al., 1975).

The external forcing functions are the subject of interactive atmosphere/ocean models, and the prediction of their effect on the ice is only as realistic as they are. The thermodynamic processes are dominated by the radiation balance, i.e. by the amount of incoming radiation and by the reflectivity (albedo) of the surface. In summer, the surface albedo is strongly affected by the area of ice covered by low-albedo melt ponds, which in turn is affected by the surface topography, i.e. the thickness distribution. Currently available data on this relationship are sparse, to say the least. Hence the albedo assigned to the different thickness categories is a powerful tuning parameter in the models.

The amount of cloud cover exerts a strong control on the downwelling radiation that reaches the surface of the ice. In the absence of sunshine, the total downwelling radiation is composed only of the longwave component, whose magnitude is determined unilaterally by the presence or absence of cloud cover. In the presence of sunshine, the total downwelling radiation is the sum of longwave and shortwave components. Because cloud amount decreases downwelling shortwave but increases downwelling longwave radiation, the relative impact of clouds on the total downwelling radiation that is observed by the ice may be greater in winter than summer. The extremely high inter-model variance of cloudiness, particularly during the winter months (Figure 1.2, top panel) may well make a major contribution to the widely differing model results seen in the bottom panel of Figure 1.2.

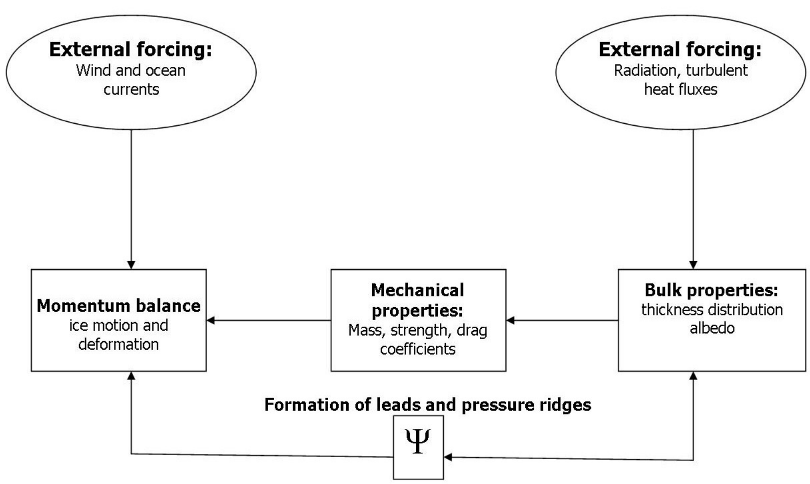

FIGURE 1.3 Schematic representation of sea ice in a climate model. SOURCE: Thorndike et al., 1975; Reprinted by permission of American Geophysical Union.

A half-century-long record shows a trend downward in sea ice extent. This trend is much steeper for the summer months and, until recent years, relatively insignificant for winter months (Meier et al., 2007; Figure 1.4). From the viewpoint of greenhouse gas (GHG) forcing, the opposite might be expected: during the warm season, variations in atmospheric water vapor dominate GHG forcing and are likely to overwhelm the effect of the other greenhouse gases. During the cold season, when the atmosphere is drier, the effect of the non-vapor GHG should dominate.

The stronger decline in the summer sea ice extent compared to the winter extent indicates that an increasing amount of multiyear ice either melts or is exported through Fram Strait, which is compensated to some extent by an increase in first-year (and thus thinner) sea ice (Figure 1.4). Kwok (2009, unpublished) reports that the export of multiyear ice has not increased during the past 5 years, hence the loss of multiyear ice must be ascribed to in situ melting (Figure 1.5). According to energy balance climatology, established mostly during the second half of the 20th century, multiyear ice is too thick to melt completely in one summer.

The preceding remarks are intended to illustrate that many unresolved problems exist regarding the processes occurring in sea ice. The Medea data set and future collections, described in the following chapter, will deepen our understanding of sea ice and help us cope with the consequences of a changing Arctic.

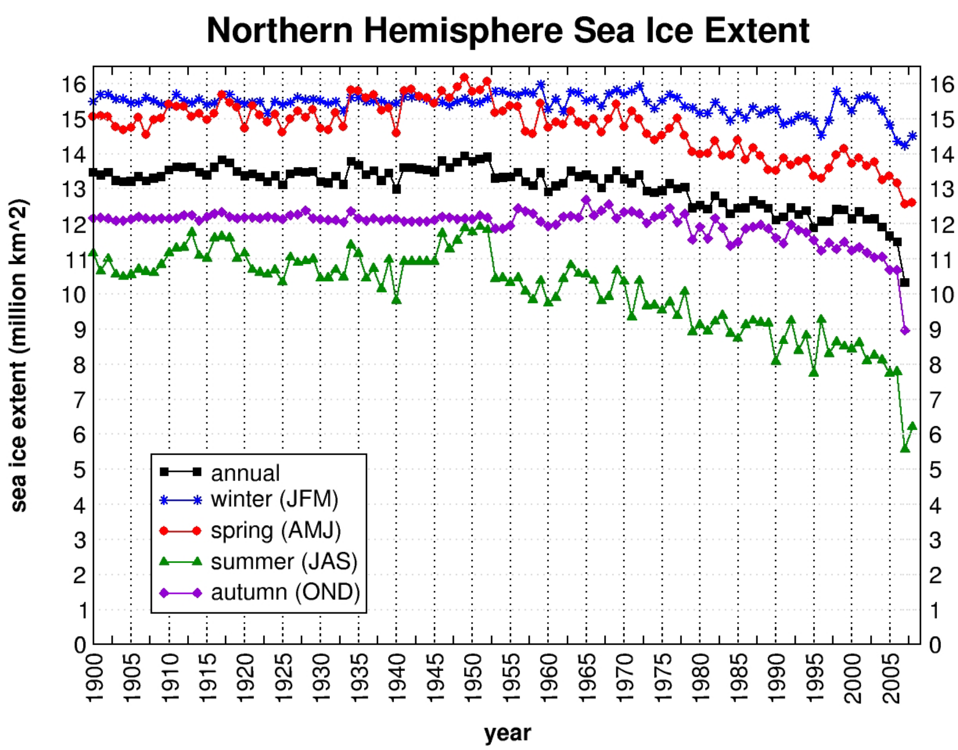

FIGURE 1.4 Three-monthly and annual means of the surface area of Arctic sea ice since the inception of observations by satellite. SOURCE: The Cryosphere Today, http://arctic.atmos.uiuc.edu/cryosphere/.

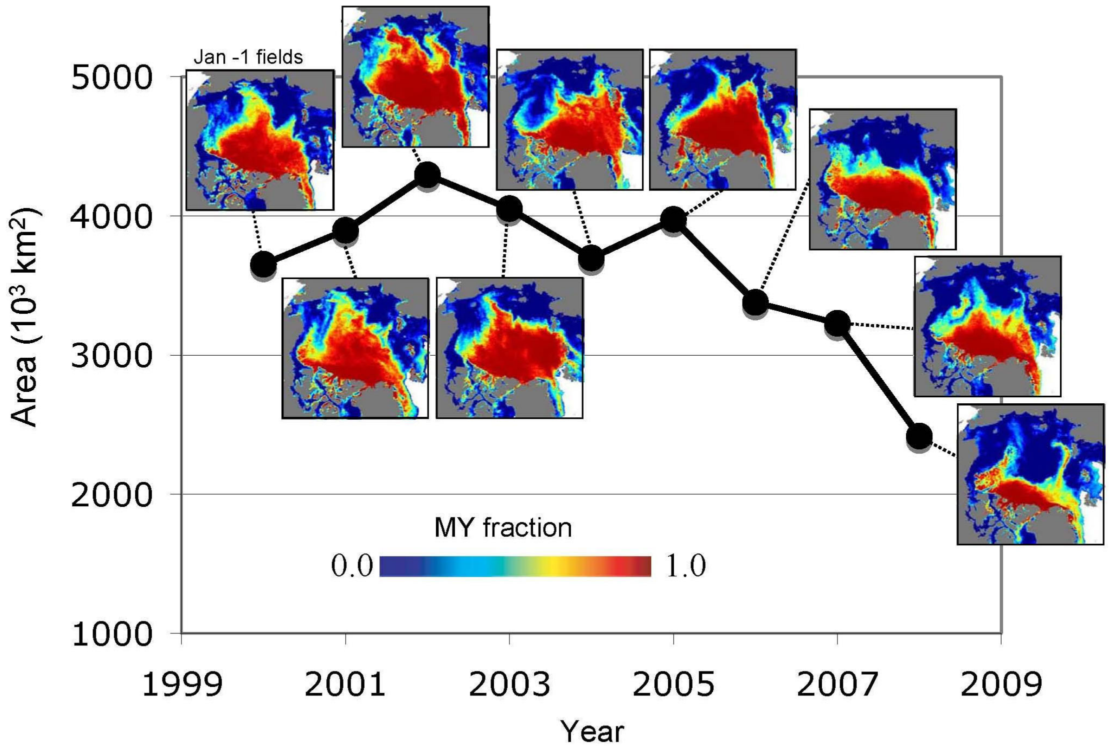

FIGURE 1.5 Decline in Arctic Ocean Multiyear Sea Ice Coverage. SOURCE: Figure courtesy of Ron Kwok, JPL.

2

Potential Uses of the Medea Data Set

During the 1990s, the Medea program brought together environmental scientists and members of the intelligence community to apply classified assets and data to further the understanding of environmental change (Richelson 1998). Under Medea auspices, the global "fiducials" program was established whereby participating scientists could request collection of classified images at environmentally sensitive locations around the globe. The term "fiducials" refers to the fact that the classified images were to be kept "in trust" in classified archives, with the eventual goal of declassification and release to the broader scientific community for research purposes. In 1999, Medea scientists requested that the intelligence community begin collecting images of Arctic sea ice at four different locations in the Arctic Basin during the summer months (the melt season). Two additional locations were added in 2005. The request forwarded by Medea scientists included collections starting in May and ending in September at the approximate locations shown in Figure 2.1. Collection of images during the summer months at these six sites has continued until the present day

The rationale for selecting these sites was as follows:

Beaufort - The Beaufort Sea has been the site of many field studies since the International Geophysical Year 1957/58. The ice in this region is the most studied and best known. It was a focal point for the automatic data buoy program and many studies of the surface heat budget, as well as submarine sonar cross sections.

Canada - This region typically contains the oldest and thickest ice with the longest residence time in the Arctic Basin.

Fram - Fram Strait between Greenland and Spitsbergen is the dominant exit route of sea ice from the Arctic Basin into the Greenland Sea. The amount of low-salinity ice exported is an important component of the basin-wide ice balance and potentially impacts the global ocean circulation.

Siberia - this oceanic region produces most of the first-year ice and was judged to be most sensitive to interannual changes of oceanic and atmospheric forcing. This has been borne out by the extreme negative anomaly of ice extent in the autumn of 2007.

Two additional sites were added after 2005; they are:

Chukchi - While the other sites are in areas with generally thicker perennial ice (with the exception of 2007, when the East Siberian site was ice free in September), the Chukchi site was chosen to sample ice that is seasonal.

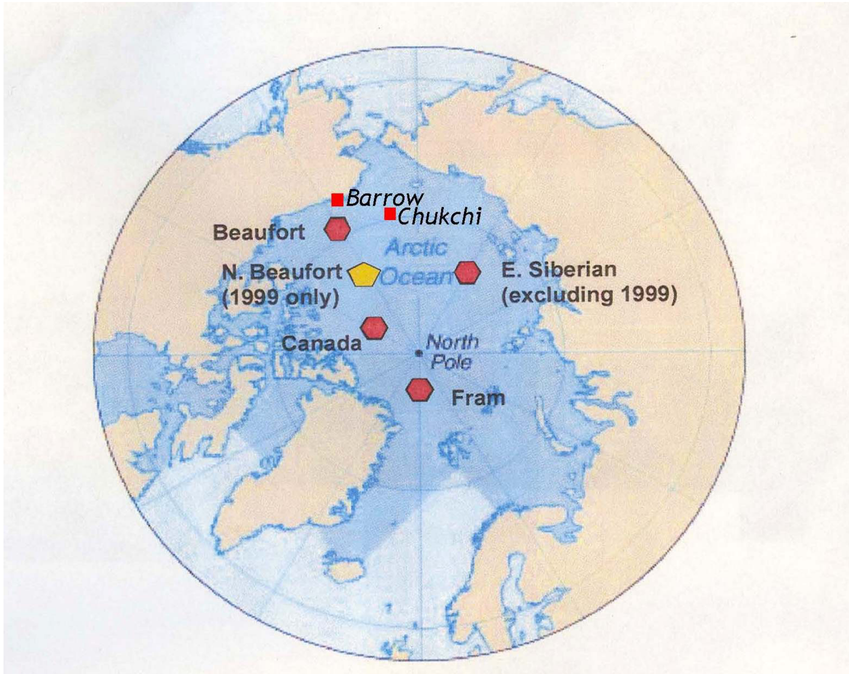

FIGURE 2.1 Approximate locations of the image collections requested by Medea scientists in 1999 (red hexagons). The Barrow and Chukchi sites (red squares) were added in 2005. Images were collected at the North Beaufort site (yellow pentagon) only during 1999 and are not part of the dataset considered in this report. SOURCE: Figure courtesy of USGS National Civil Applications Program.

Barrow – Barrow is the site of extensive real time monitoring of fast ice by investigators at the University of Alaska and elsewhere; imagery acquired here complements these and other in situ data.

Some products have already been derived from these data sets, in particular statistics and maps of melt pond distributions in the Arctic, disseminated by the National Snow and Ice Data Center (NSIDC, 2000; Fetterer et al., 2008) and used by the Arctic research community. However, these products are based only on images taken during 1999-2001. Furthermore, only surface type (e.g., ice or water) maps based on the imagery have been released. The literal imagery itself or a lower-resolution version of it has not been released. In the latter years of the Medea program, procedures were established whereby Literal Imagery Derived Products (LIDPs) could be produced from the classified fiducials data at a resolution deemed suitable for declassification. Several hundred LIDPs with a nominal resolution of 1 meter have been produced from the images collected at the six Arctic sites from 1999 to present. Below we discuss the many potential scientific uses of these LIDPs.

USES OF THE LIDPs: SEA ICE PHYSICAL PROCESSES

The derived images will lend themselves to a wide range of studies, leading to significant improvements in how sea ice physical processes are represented in climate models. These images will also enable scientists to understand changes in ice habitat. In particular, the images are useful for studying snow distribution and its relationship to surface topography, the initiation and development of meltwater ponds and their profound effect on the surface energy balance and the melting of ice in summer, the relationship of stress and strain rate and its reflection in the pattern of cracks and other discontinuities in the ice, lateral oblation, and thickness evolution. The LIDPs will help scientists better understand these specific physical processes, especially if used in conjunction with data from operational civil satellite systems.

The utility of data acquired by remote sensing depends on our ability to interpret them in terms of the actual state of the observed object, i.e. the ground truth. In many cases, understanding the effects of calibrations, and complex radiative properties of the observed object and the properties of the intervening medium, require a plethora of ancillary data sets and ground truth studies. These are particularly difficult to obtain in areas where field (ground-borne) measurements are logistically difficult or sometimes impossible.

The one-meter resolution, panchromatic LIDPs are not precisely ground truth. Nevertheless, they offer exceptional details of the surface features compared to images derived from widely available passive and active microwave, and infrared sensors. Such details are exemplified by Figure 2.2, which is a sequence of LIDPs (500 m on a side) showing the transition of melt ponds to open water during the summer of 2006. This committee believes that the great value of the Medea data are their potential to augment the meaning and interpretation of data obtained by other, unclassified, lower-resolution sensors. Below we describe in more detail the physical processes governing the evolution of Arctic sea ice that will be better understood through the LIDPs

Snow Distribution

Snow depth is an important ingredient in all thermodynamic models of sea ice. Most of the snow on Arctic sea ice falls during the autumn. Redistribution by wind produces an extremely variable snow cover. Smooth ice in frozen leads is often swept bare, while a large fraction of the snow collects in drifts behind aerodynamic obstacles, such as pressure ridges and hummocks. During periods of clear, cold weather, which typically follow precipitation events, the steep temperature gradient in the snow causes an upward diffusion of water vapor that hardens the snow surface and often makes the drifts survive for the whole winter. In the returning daylight of spring, drifts can be identified in 1-meter resolution images. In the absence of any other method to observe the snow cover, the Medea data collection will provide valuable information about the morphology of the snow cover and its interaction with the surface topography and help to improve the interpretation of Ice, Clouds, Land Elevation Satellite (ICESat) laser altimeter records in terms of freeboard, ice thickness, and snow depth. This issue was addressed in a recent paper by Kwok and Cunningham (2008).

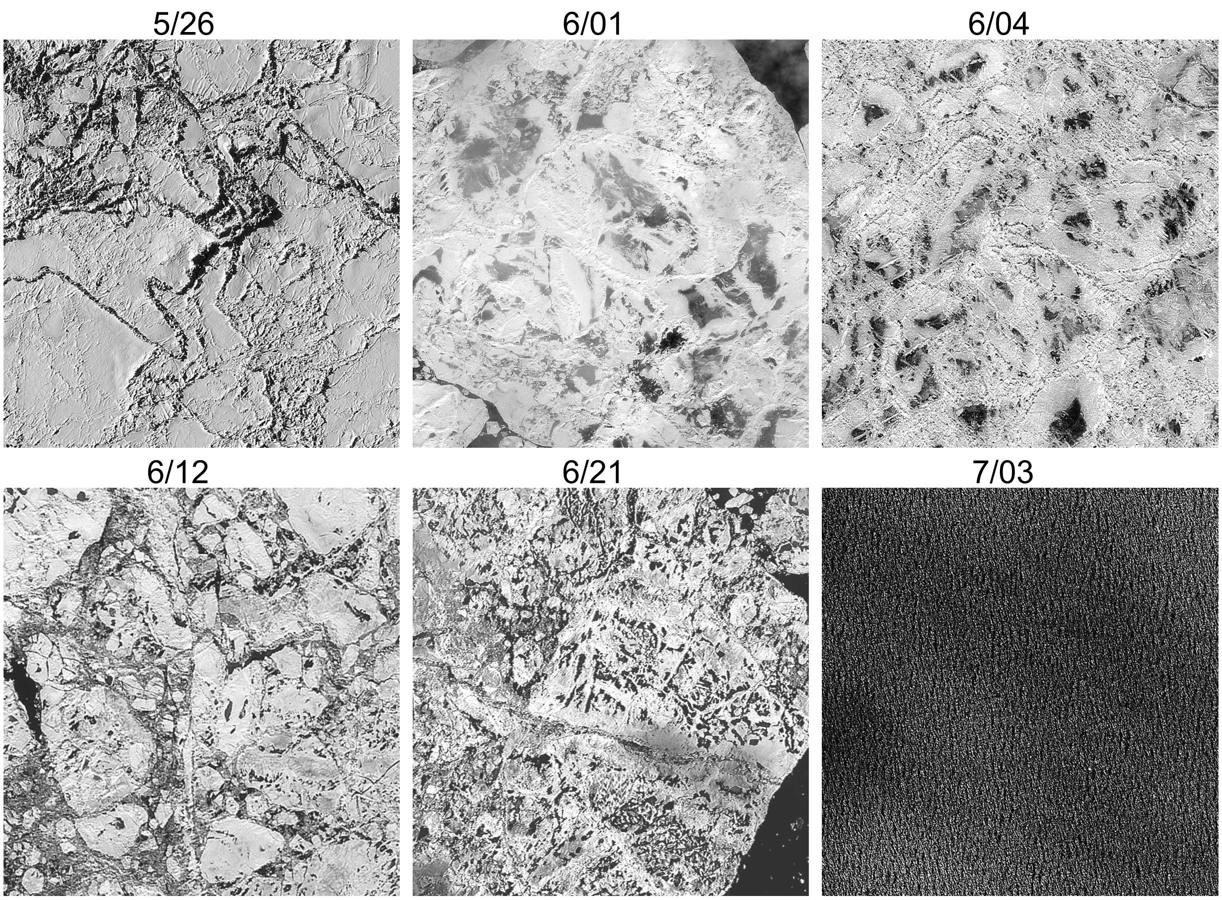

FIGURE 2.2 Development of melt ponds at the Chukchi Site during the summer of 2006 as seen in the 1-m resolution LIDP imagery. Each image in this sequence covers an area of ~500 m by 500 m. The last panel is of open water. SOURCE: Figure courtesy of USGS National Civil Applications Program).

Lateral Ablation

The loss of multiyear ice (Figure 2.3) may be governed, in part, by lateral melting of ice floes. Open leads with an albedo of less than 0.1 absorb 5-7 times as much solar energy as flat ice, and convection transfers this energy to the side wall of the floes. The possible importance of the process has long been recognized (Steele, 1992), but observations require a field party to spend an entire summer on the ice and make the technically difficult measurements of ablation in many places. In the history of U.S. Arctic research, there have been only four all-summer drifting stations.

Sequential one-meter-resolution LIDPs will be capable both of measuring the kinematic shifts of ice floe assemblies and at the same time tracking the surface area of each individual piece of ice. Such observations will help explain the contribution of lateral melting to the loss of multiyear ice.

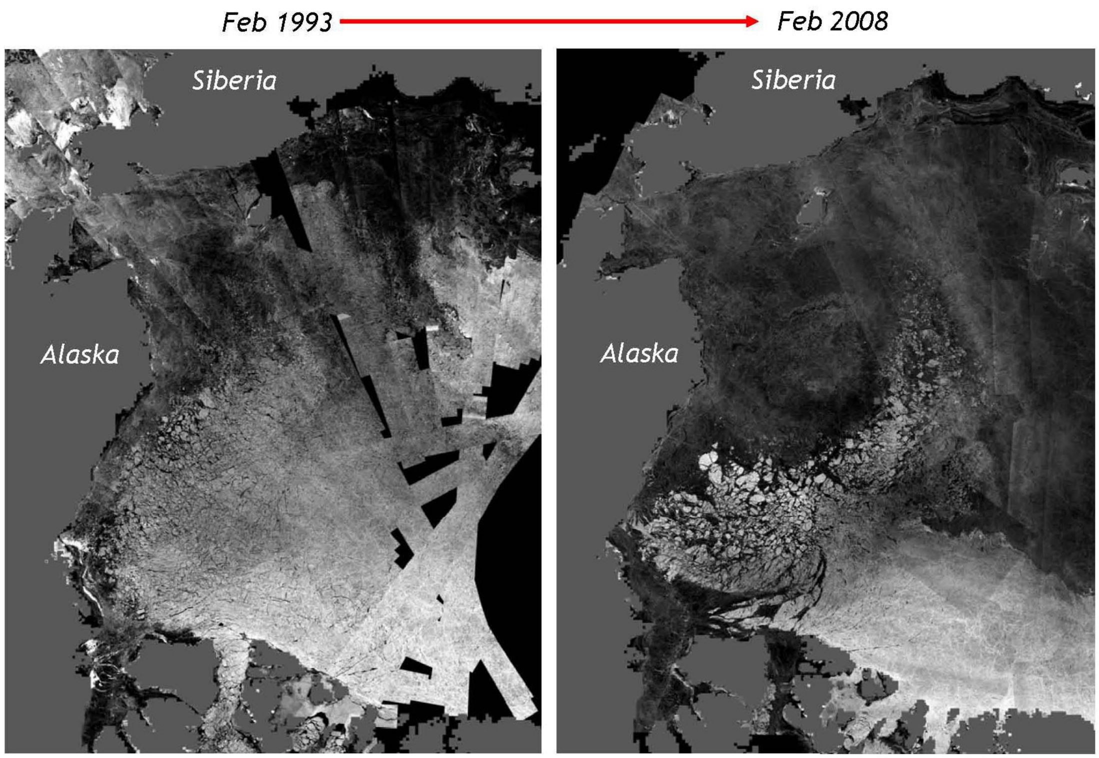

FIGURE 2.3 Imagery from the European Remote Sensing Synthetic Aperture Radar (ERS SAR; left) and the Canadian Space Agency (CSA) Radarsat (right) indicating the reduction in Arctic multiyear ice cover over 15 years. On the image, the thick multiyear ice is bright; the thinner first year ice is dark. The figure shows the great reduction in multiyear sea ice over a 15 year period. Alaska is to the upper left. SOURCE: Figure constructed by Ron Kwok, JPL.

Ice Topography and Albedo

In the Arctic summer, a strong positive feedback exists between the absorbed downwelling short-wave radiation and the state of the ice surface. The melting snow and ice produce melt ponds whose low albedo further enhances the rate of melting. The meltwater tends to collect on topographically low (i.e. thin) ice. Besides an average thinning of the ice, this process truncates the thickness distribution g(h) at the thin end and produces open water. The close linkages between meltwater pooling and ice surface topography are also key to deriving information about ice albedo from independent estimates of ice roughness or ice age (Eicken et al., 2004), with LIDP images providing a means to improve such indirect derivation of information about ice albedo.

There are virtually no sustained, systematic observations of the evolution of the spatial variability in ice albedo because Moderate Resolution Imaging (MODIS) does not have sufficient resolution and Landsat does not have sufficient spatial coverage. The Medea LIDP images will provide an unprecedented view of how the surface topography affects the initial formation and subsequent evolution of melt ponds and their effect on the albedo and hence the short-wave radiative energy balance. Thus the sequential high-resolution pictures will be instrumental in estimating the thermodynamic part of the changes in g(h) during summer. To obtain the maximum benefit from these images, however, calibration information is needed if it can be supplied.

Ice Thickness Evolution

Until recently, the only source of information on the thickness distribution has come from occasional transects by submarines with upward looking sonar (Rothrock et al., 2007). It was recently shown by Kwok and Cunningham (2008) that observations from the ICESat laser altimeter can be interpreted to produce ice thickness distributions in numerous places within the Arctic Basin (Figure 2.4). As shown in Figure 1.3, dynamic ice models carry the thickness distribution g(h) as an internal variable, controlled by the energy balance and by the mechanical deformation. In view of the large effect that the albedo has on the computed loss of ice during summer, the models have to assign a certain albedo to the different categories of ice thickness. There are no observational data documenting a relationship between different categories of ice thickness and their albedo throughout the summer. Hence, the designers of models have no choice but to parameterize a relationship between albedo and ice thickness, which makes it a powerful tuning parameter. Ice thickness distributions from ICESat and albedo from the Medea LIDPs should be invaluable to improve these parameterizations.

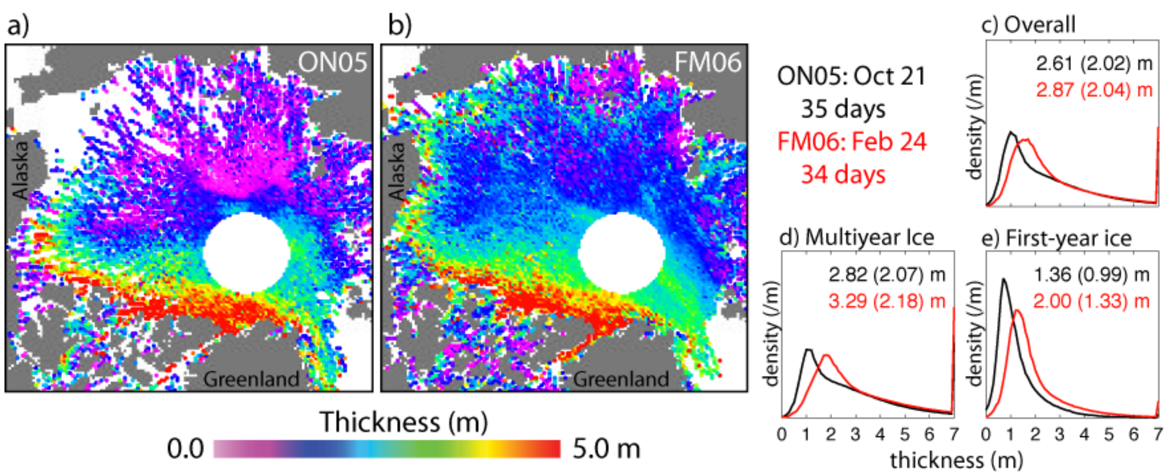

FIGURE 2.4 Sea ice thickness from ICESat. (a) Spatial field of ice thickness from ICESat data acquired over a 35-day period between October and November of 2005 (ON05). (b) Same as (a) but of data acquired in February and March of 2006 (FM06). The start day and duration of each campaign are shown above. (c) Overall ice thickness distributions of the Arctic basin in ON05 (black) and FM05 (red). The quantities in the plot are the mean and standard deviation (in brackets) of the thickness distributions. (d) Thickness distributions of the multiyear sea ice zone. (e) Thickness distributions of the first-year ice zone. SOURCE: Kwok and Cunningham, 2008; Modified by permission of American Geophysical Union.

Deformation

The realistic representation of the relationship of stress and strain rate of the ice has been a persistent and seemingly intractable problem in the design of dynamic sea ice models (Hibler, 2003). In a recent study, Kwok et al. (2008) use Radarsat to analyze the ice deformation fields on a 10 km scale (Figure 2.5), and compare them to the output of four different dynamic ice models. Given the different physics and forcing functions in the models, the authors cannot state the reasons for the differences between observed and modeled results, but they show that the model outputs are significantly in error, both in terms of the velocity field and ice production.

If it were possible to compare the 10-km ice velocity and deformation field with the high-resolution view of the Medea LIDP, we could expect new insight into the processes whose combined effect lead to the relationship of stress and strain rate at the larger scales.

Shear and Crack Pattern

The Arctic pack ice is crisscrossed by countless cracks and leads with a wide range of sizes. They are related to the wind and water stress fields and their gradients, and sometimes to the land boundaries of the ocean. Synoptic weather systems, eddies in the ocean, and inertial and tidal motions produce discontinuities in the ice on a scale of 10^0 to 10^5 meters. When water at the freezing temperature in winter is exposed to a cold sky and cold air, rapid ice growth results. It was shown by Kwok et al. (2003) that the semidiurnal openings and closing caused by tidal and inertial motions could enhance ice production by 10 percent. In summer, the reverse is the case.

In either case, civilian satellite images cannot resolve the smaller scale of the spectrum of openings. The 1-meter resolution Medea LIDPs would be of significant benefit to the calculations of the mass balance of the ice cover.

Melt Pond Recurrence

An issue of importance for the thermodynamic modeling of multiyear ice is the question whether or not melt ponds have a tendency to recur in the same place in consecutive summers. As mentioned above, field observations in summer are sparse. In fact, only one station was maintained by a western country for two consecutive summers (during the IGY, 1957-1958), but the ice break-up in 1958 forced the team to move to a different ice floe nearby. When the surface of melt ponds freezes in autumn, liquid water remains for many weeks under the snow ice cover, acting as a source of latent heat and retarding the formation of new ice at the base. The ability to follow an individual piece of ice from freeze-up throughout the winter until the onset of melting in the following summer would shed light not only at the recurrence of melt ponds but several other processes addressed in the previous sections.

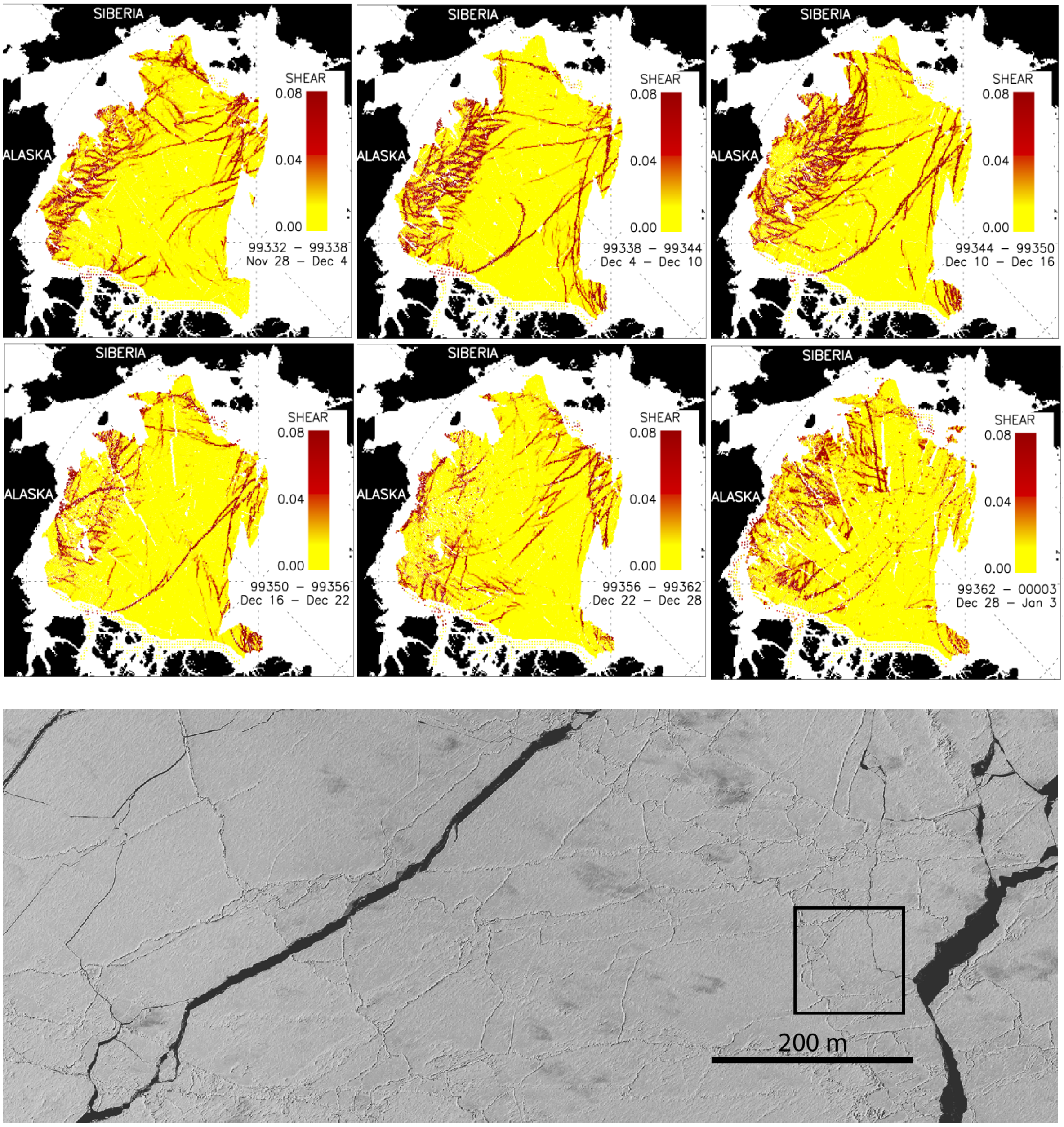

FIGURE 2.5 The top six figures show time-varying fields of ice deformation (magnitude of shear) from November 28, 1999 through January 3, 2000 derived from 100-m resolution RADARSAT Synthetic Aperture Radar (SAR) imagery. These fields cover a large part of the Arctic basin, but not all the details in the fracture patterns are resolved by the 100-m resolution data (Kwok et al., 2008; Modified by permission of American Geophysical Union). Bottom figure: A sample LIDP image (1 m spatial resolution) offers a significant improvement in the resolution of the open-water leads (their width and orientation), and surface morphology beyond that seen in widely available SAR imagery. The square shows the coverage of one SAR pixel. SOURCE: Figure courtesy of USGS National Civil Applications Program.

COMPLEMENTING CIVILIAN AND COMMERCIALLY AVAILABLE DATASETS

The more recent LIDPs would be extremely useful in assessing the performance of relatively new civilian satellite sensors, particularly the Advanced Microwave Scanning Radiometer for the Earth Observing System (AMSR-E), which began operation in 2002, and ICESat, which began operation in 2003. AMSR-E is a passive microwave sensor and thus suffers from limitations in sea ice retrieval due to surface melt, melt-ponding, and other sub-pixel processes. The effects on passive microwave emissivity from these processes are still not well understood. The LIDPs, with dimensions roughly 15 km x 15 km, are roughly the same scale as the AMSR-E sensor footprint (5-15 km, depending on sensor frequency channel; Figure 2.6). Previous validation campaigns with high-resolution imagery from satellites and aircraft as well as in situ data have helped resolved some of the ambiguities in the passive microwave signature (e.g. Cavalieri et al., 2006; Maslanik et al., 2006). However, the sea ice surface is highly variable in space and time, and these limited campaigns cannot capture that full variability. The numerous scenes that could be released here - covering several years, spanning the full range of the melt season, and encompassing several different geographic regions of different ice regimes (e.g., first-year vs. multiyear ice) - will encompass the full variability of the sea ice passive microwave characteristics. Passive microwave sea ice data are crucial for monitoring the long-term changes in Arctic sea ice because they have a continuous, consistent, and near-complete 30-year record. The released imagery would help improve this long-term record.

The imagery will also be very beneficial to ICESat freeboard estimates that are being developed (e.g., Kwok et al., 2007). The imagery will confirm visible surface features revealed in the ICESat freeboard data. For example, surface shadows in the imagery can allow calculation of sea ice ridge freeboard heights, which are generally below the resolution of ICESat. The imagery may also provide snow cover information, an important unknown in ICESat data.

The accurate interpretation of lower-resolution visible/infrared data from MODIS will also benefit from this imagery. MODIS, with 500-m resolution, provides a reasonably detailed picture of sea ice conditions. However, the resolution is not fine enough to explicitly capture most meltpond features. There has been some development in calculating meltpond statistics from MODIS imagery (Tschudi et al., 2008), but this high-resolution imagery would be a tremendous help in further refining these efforts.

One of the greatest values of the Arctic sea-ice imagery data set lies not only in its high resolution and image quality, but in the availability of imagery with very high repeat rates in all key regions. Given the high probability of cloud cover over summer Arctic sea ice (typically 80 percent or more, Beesley, 1999), any other type of comparable commercial or research-grade imagery would be available at time intervals of at best several weeks. Since these acquisition dates are constrained by the satellite, likely many such acquired images would be unusable due to cloud cover. In contrast, the Arctic IDPs are available at much higher time resolution, in some cases on a daily basis, allowing studies of seasonal progression at a scale hitherto extremely difficult or impossible to achieve. For example, in a previous study one of the committee members worked with specially acquired commercial (SPOT) imagery over a location at roughly 75° N between the months of May through September. Only one of the more than 100 scenes was not obscured by clouds and thus could be analyzed in the study. In contrast, on the order of two dozen scenes are available for a similar time period in a single year at a comparable Medea fiducial Site.

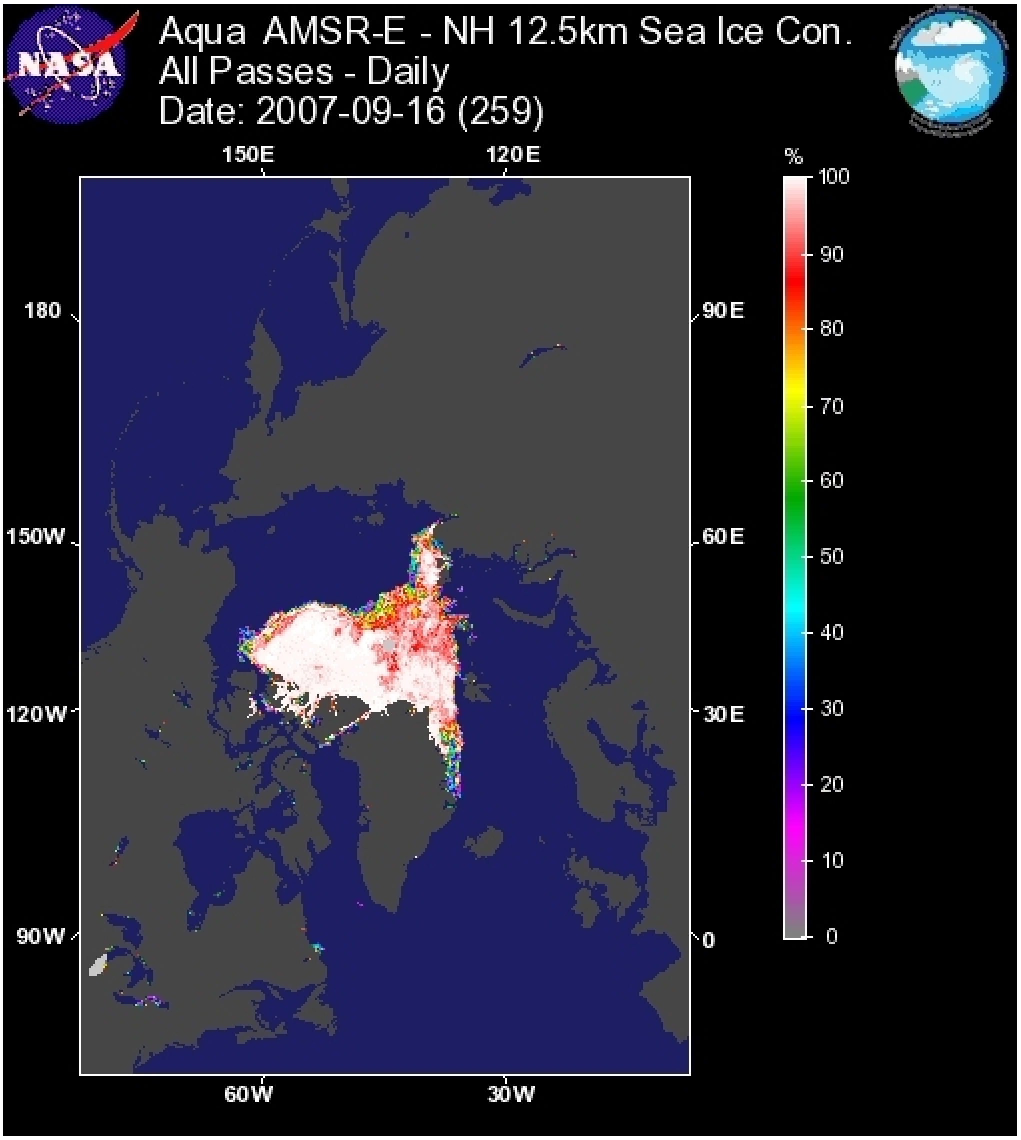

FIGURE 2.6 AMSR-E, which began operating in 2002, is a passive microwave sensor. Because the LIDPs are the same scale as AMSR-E, they would be extremely useful in assessing the performance of AMSR-E (Image courtesy of Matt Smith, Information Technology & Systems Center, University of Alabama at Huntsville).

3

Recommendations

Recommendation: The intelligence community should release and disseminate all Arctic sea ice Literal Imagery Products (LIDPs) that have been produced to date as soon as possible.

As detailed in the previous chapters, great immediate benefits can be derived from the release of all Arctic sea-ice LIDPs because they will help improve our understanding of important climate-system processes and add substantial value to other remote-sensing and modeling efforts. The images provide information at scales, locations, and time periods that are extraordinarily important in advancing our knowledge of critical processes during this period of rapid loss and transformation of Arctic sea ice. There are no other data available that show the melting and freezing processes that we were able to observe in these images. Their release will have a major impact on understanding effects of climate change on sea ice and ice habitat.

DISSEMINATION PRIORITIES

All of the Arctic sea ice LIDPs contain information that will be extremely valuable to scientific research. Three categories of LIDPs are of particularly high priority for dissemination and publicity efforts: (1) all six sites during 2007-2008, (2) all from the Barrow site, and (3) all from the Beaufort Sea site.

2007-2008 Images

Placing a high priority on the publicity of the availability of images from all six sites during 2007 and 2008 is critical, because this window coincides with the research programs undertaken during International Polar Year (IPY). The availability of 2007-2008 images will greatly enhance the benefits and value of a broad range of intensive ground-based observations that were collected during the Fourth IPY. Furthermore, this subset of the data includes images of the summer 2007 minimum in sea-ice coverage, a record low that was more than 20 percent below the previous low (in 2005) and nearly 40 percent below the 1979-2000 average minimum (Figure 1.4, Stroeve et al., 2008). This dramatic loss of sea ice will be investigated in more detail using this high-resolution imagery.

Barrow

Giving high priority to the dissemination of all LIDPs from the Barrow site would support a range of high-profile research projects in the coastal region at Barrow (Norton, 2001). These data will serve as an important resource for questions revolving around adaptation of coastal communities and ecosystems to climate change (see Figures 1.1, 3.1).

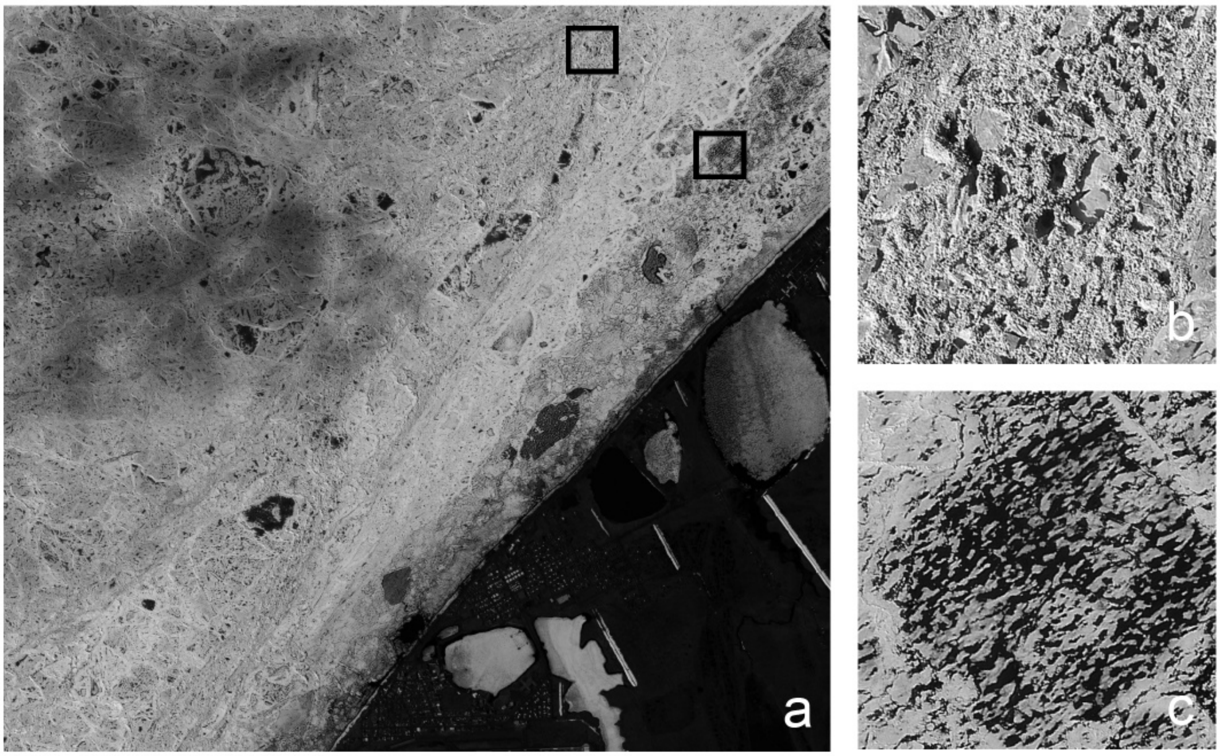

FIGURE 3.1 LIDP over Barrow Fiducial Site acquired on 18 June 2006. The two boxes shown in (a) are approximately 400 m to the side and are shown at a scale that approaches the limit of resolution at right. For the patch of highly deformed ice shown in (b) the approximately 1-m pixel dimensions are sufficient to partly resolve the block structure in the pressure ridges (broken ice piled to several meters thickness or more). Such deformed ice areas serve as important habitat for seals and polar bears. These deformed ice areas may help anchor the coastal landfast ice shown here, thereby creating a platform for animals and people. They can also represent a significant obstacle to subsistence hunters who construct seasonal trails on the landfast ice at Barrow. Note the contrast in the distribution of surface melt ponds in the deformed ice as opposed to flat ice shown in (c). The degree of ice deformation and its surface roughness are important in controlling the lateral extent and depth of melt ponds and hence ice albedo. SOURCE: Figure courtesy of USGS National Civil Applications Program.

Beaufort Sea

The Beaufort Sea, with imagery dating to 1999, has seen some of the most substantial rates of sea-ice thinning and retreat anywhere in the Arctic (Serreze et al., 2007). It also exhibits the broadest range of different ice types and ice ages, greatly increasing the value of Arctic sea-ice LIDPs in improving our ability to monitor the movement and evolution of different ice age and thickness classes. At the same time, converging economic activities (natural resource extraction and shipping) and indigenous interests (subsistence harvest of marine mammals) in the Beaufort region place great importance on the detection and tracking of multiyear ice. Such ice represents both an important resource for coastal communities and ecosystems (e.g., as a platform and habitat) as well as a potential hazard for industrial activity (Eicken et al., 2009).

Forecasts of regional sea-ice conditions on seasonal timescales can help different stakeholders prepare for and adapt to the impacts of climate change and minimize environmental risks associated with industrial activity. However, the most promising approaches for forecasts on these timescales (Drobot and Maslanik, 2002; Zhang et al., 2008) require much better information on relationships between ice age, thickness, and surface-melt than are currently available. Placing a high priority on the dissemination of LIDPs from the Beaufort site for all available years would be of great value. Increasing ship traffic and offshore oil and gas exploration activities in this region would also benefit from more accurate determination of the ice edge and hazardous ice conditions through validation of other satellite remote-sensing data sets such as the Special Sensor Microwave Imager (SSM/I) and Advanced Microwave Scanning Radiometer for the Earth Observing System (AMSR-E) with LIDPs.

Recommendation: To maximize the utility of the images, the committee recommends that the metadata include: thumbnail (smaller size) copies of the images, exact information on the location of the images, calibration information, the time of acquisition, and information on the pointing angle.

Metadata (additional information that accompanies the actual data) is a critical part of a data set that can significantly enhance its general and broader usefulness. The committee understands that the trustees of the fiducials archive, the U.S. Geological Survey's Civil Applications Program, are preparing a website to disseminate the derived Arctic sea-ice images. Inclusion of these metadata in the online archive would greatly facilitate the research of scientists who obtain the images. For the data set in question the following would be the most useful:

- Thumbnail (smaller size) copies of the images. The raw images are rather large and copies of the images with reduced resolution will make browsing through the catalogue much easier.
- Exact information on the location of the images. The data are already mapped to a standard projection and resolution. As pixel size is known, only the latitude and longitude of the center are needed.
- If possible, calibration information would be very useful. This would allow the scientists to intercompare the data sets. For example, with increasing sea ice melt, the ice and snow gets darker (the albedo is decreasing). Calibration would

enable scientists to estimate the rate of this darkening which would lead to a better understanding the melt process.

- The time acquisition (the nearest hour should be sufficient). At this high resolution, ice drift within hours can make a difference. This needs to be accounted for when the data set is compared with other data sets, which could be data from civilian satellites, aircraft data, or in-situ measurements. The time is also important for the estimation of the sun angle.
- If possible, information on the pointing angle would be very valuable. Together with calibration information and the sun angle (determined from the time of the acquisition), we can then calculate an objective brightness of the sea ice, which makes it tremendously easier to intercompare the data and investigate the temporal evolution of the sea ice. The pointing angle would also be useful in accounting for any distortion in the data.

CONSIDERATIONS FOR THE FUTURE

If data will be collected in the future and LIDPs produced for the purpose of public release, some modifications/additions would make the data even more useful for scientific research. Operators of national assets could continue collecting ice images during suitable atmospheric conditions at the existing Beaufort Sea, Canada Basin, and Chukchi Sea sites. Assuming that the location and number of sites is not fixed, adding collection of imagery at the North Pole, where extended field observations are already underway, would be particularly valuable. Dynamic image collection that tracks how individual ice features evolve over time and a mechanism to communicate this information in near real-time for a given feature would complement the existing data, which are images at fixed locations in space through which different ice features pass over time.

In 1999, when Medea scientists requested the collections at the original four sites in the Arctic Ocean shown in Figure 2.1, it was known that viewing the ice repeatedly at fixed coordinates was not ideal because, due to the movement of the ice, the satellite would view different ensembles of floes every time a picture was taken. To derive most information about the physical processes occurring in the snow ice system—including meltpond evolution—will be necessary to view the SAME ensemble of floes as it drifts along under the influence of winds and ocean currents. This will require that these ensembles are identified by their surface characteristics, or marked by a data buoy that records its position via the Global Positioning Systems. When the Medea scientists made the initial request, it was not clear whether the unclassified systems would be able to provide the necessary continuous records and what agency would take responsibility to communicate daily coordinates of the ice to the intelligence community. However, near-real time locations of the selected ensembles of ice floes can be derived from unclassified SAR and Ice, Clouds, Land Elevation Satellite (ICESat) systems, or by the International Arctic Data Buoy Program. Those data could be used for location determination. Furthermore, several scientists calculate sea ice drift from satellite active and passive microwave data, which most likely could also be used to follow specific sea ice floes.

If corresponding radar data exist, it would be outstanding if those data could be made available as well. They would not only help us with the filling data gaps in times of cloudiness, but the different physical principle of radar remote sensing compared to visible remote sensing would yield additional information about the characteristics of the sea ice. For example, radar responds more strongly to wetness and sea ice roughness.

Because of the large contrast between open water and ice, visible images can at times be saturated for the generally white sea ice. Nevertheless, there is valuable information in those "different shades of white." For example, as snow and ice age they get slightly darker. Also variations in surface topography can be identified. Therefore, data with the full dynamic range in contrast would be preferable. Any Multi-spectral data, if available, would be particularly valuable to obtain more complete information on albedo and radiative surface fluxes.

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Appendix A

Statement of Task

The National Academy of Sciences is helping facilitate the increased involvement of scientists in answering questions related to climate, energy, and environmental change. The goal is both to advance scientific understanding of global climate and other environmental and disaster-related phenomena, and consider the implications for both fundamental scientific understanding and national security.

For this particular activity, The National Academy of Sciences/National Research Council will form a small ad hoc committee of experts to assess the scientific value and usefulness of Imagery Derived Products on Arctic sea ice and identify the images that would be most valuable to Arctic ice research if publicly released. The panel will carry out the following tasks:

- Evaluate the collection of Arctic Ice Imagery Derived Products, a subset of the Global Fiducial Program data from U.S. National Imagery Systems, and assess their scientific value and usefulness in furthering the understanding of important climate parameters and processes.
- Identify those images from the Arctic Ice fiducials (observation sites) that would be most valuable to arctic ice research if released for open use. The analysis should identify the high priority images, explain why they are important, and describe what could be done with the data if such images were openly available.

Appendix B

Acronyms and Initialisms

AIDJEX	Arctic Ice Dynamics Joint Experiment
AMSR-E	Advanced Microwave Scanning Radiometer for the Earth Observing System
AR4	Fourth Assessment Report
ERS SAR	European Space Agency Synthetic Aperture Radar
GHG	Greenhouse Gas
ICESat	Ice, Clouds, Land Elevation Satellite
IGY	International Geophysical Year
INSROP	International Northern Sea Route Program
IPCC	Intergovernmental Panel on Climate
LIDPs	Literal Imagery Products
MODIS	Moderate Resolution Imaging
MY	multi-year
NPOESS	National Polar-orbiting Environmental Satellite
SHEBA	Solution High-Energy Assembly
SSM/I	Special Sensor Microwave/Imager
USGS	United States Geological Survey

Appendix C

Committee and Staff Biosketches

Committee:

Dr. Stephanie Pfirman (Chair) is Alena Wels Hirschorn and Martin Hirschorn Professor in Environmental and Applied Sciences and Chair of the Department of Environmental Science at Barnard College, which she joined in 1993. Current interests include environmental aspects of sea ice in the Arctic, and the development of women scientists and interdisciplinary scholars. Dr. Pfirman is President of the Council of Environmental Deans and Directors, a member of the Polar Research Board of the NAS, and co-PI of the NSF-sponsored Advancing Women in the Sciences initiative of the Columbia Earth Institute.

Dr. Hajo Eicken's interests are in the field of sea-ice geophysics. In particular, he is interested in how small-scale properties and (micro)structure of sea ice impact processes on a larger scale as well as the role of sea ice in the climate system. As part of the International Polar Year (IPY) 2007-2009, Dr. Eicken is part of an international group that is studying the seasonal Arctic ice zone through an observing network. As Professor of Geophysics at the University of Alaska Fairbanks, he is leading a university-wide IPY initiative to promote exchange between scientists and stakeholders.

Dr. Thorsten Markus is the Branch Head of the Cryospheric Sciences Branch at NASA Goddard Space Flight Center, Greenbelt, MD. His interests include the remote sensing of the polar regions and the utilization of remote sensing data to study polar processes. He is a member of Aqua AMSR-E Science Team responsible for sea ice concentration and snow on sea ice products, and the ICESat Science Team. He participated in ship-borne and air-borne validation campaigns in both The Antarctic and The Arctic. Dr. Markus is working on utilization of satellite-derived geophysical parameters in data analysis efforts and in data assimilation schemes to explore the role of cryospheric processes in the polar and global climate system.

Dr. Walter Meier is an expert on sea ice remote sensing and data assimilation; Arctic climate and climate change. His areas of observational expertise include SSM/I passive microwave polar stereographic sea ice products; visible and infrared products; and field observations. He is currently focused on better understanding the decreasing Arctic summer sea ice cover and its impacts. Dr. Meier is a former professor at the US Naval Academy.

Dr. Norbert Untersteiner, originally from Austria, began his polar career during International Geophysical Year (IGY) as the Chief Scientist on Ice Station Alpha in the Arctic Ocean. In a scientific sense, it was one of the most successful science programs during the IGY. He was the organizer and director of Operation AIDJEX (Arctic Ice Dynamics Joint Experiment) the most comprehensive inter-scientific-disciplinary study of the Arctic Ocean ever attempted from the sea ice. AIDJEX was fielded from March 1975 to May 1976 and involved 125 people living on four ice floes in the central Beaufort Sea. It was extremely successful and became the model of later studies of the Arctic Ocean culminating with Operation SHEBA a follow-on to AIDJEX completed in 1998. He led numerous field operations, and directed numerous science divisions and directorates at the University of Washington, including the Polar Science Center in the Applied Physics Laboratory. He served as chairman of the Department of Atmospheric Science until his retirement in 1997. He was also a member of the Vice President's (of the USA) Medea Commission. From 1999-2005 was the Sydney Chapman Professor of Physical Science at the University of Alaska.

Staff:

Curtis H. Marshall is a senior program officer with the Board on Atmospheric Sciences and Climate (BASC). He received B.S. (1995) and M.S. (1998) degrees in meteorology from the University of Oklahoma, and a Ph.D. (2004) in atmospheric science from Colorado State University. His doctoral research, which examined the impact of anthropogenic land-use change on the mesoscale climate of the Florida peninsula, was featured in Nature and the New York Times. Prior to joining the staff of BASC in 2006, he was employed as a research scientist in the National Oceanic and Atmospheric Administration. Since joining the staff of BASC, he has directed peer reviews for the U.S. Climate Change Science Program and staffed studies on mesoscale meteorological observing systems, weather radar, the NPOESS spacecraft, and the impacts of climate change on human health.

Ms. Katie Weller is a Research Associate for the Board on Atmospheric Sciences and Climate (BASC). She has worked on National Research Council studies that produced the reports *Earth Observations from Space: The First 50 Years of Scientific Achievements*, *Evaluation of the Multifunction Phased Array Radar Planning Process*, and *Review of the US Climate Change Science Program's Synthesis and Assessment Product 3.3, Weather and Climate Extremes in a Changing Climate*, among others. In 2004, she received her B.S. from the University of Michigan in Biopsychology. Ms. Weller is currently working toward a master's degree in Environmental Science and Policy at Johns Hopkins University.

Ms. Shelly Freeland is a Program Assistant for the Board on Atmospheric Sciences and Climate (BASC). Since joining BASC in 2008, she has worked on studies and workshops involving climate change, climate, energy and national security, and uncertainty management in remote sensing of climate data. Ms. Freeland is interested in Environmental Science and Engineering, focusing on environmental policies.