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Excerpt
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1

Introduction

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1.1 Overview

Sea ice is most popularly recognized as an important indicator of climate change due to media reports of recent record low amounts of Arctic sea ice and future ice climate scenarios that include the complete loss of summer ice in the Arctic. Perhaps less widely appreciated is the day-to-day importance of sea ice to those involved in marine activities. Whether it's considered an essential platform for either transportation or research or it represents a serious hazard to shipping or resource extraction, up-to-date information about current and future sea ice conditions is essential to many different components of society.

While sea ice information is still largely produced manually, ongoing advances in the development of automated computer-based prediction systems for sea ice provide opportunities for new or alternative types of ice information. Such systems are complex and consist of a number of essential components. They are quite distinct from sea ice models used purely for research purposes since an automated prediction system (APS) is required to produce high-quality information for clients reliably, often in near-real time. In this sense, an APS for sea ice is, in many ways, similar to other environmental prediction systems, such as those for numerical weather prediction (NWP). And as with NWP, the term "prediction" is used here to refer to all of the required components of the system. Principally, this consists of collecting and processing sea ice observations that are then used, through data assimilation, to obtain a complete and accurate estimate of the current sea ice conditions. This estimate is then used to initialize a sea ice forecast model to produce the forecast of future sea ice conditions. Thus, the outline of this book bears strong similarities to an equivalent book on weather prediction, and lessons learned from the introduction of NWP would also echo the discussions here.

Sea ice models have been in development for many years but have mainly been used in climate models and process studies. To adapt these models for the shorter forecast periods and higher spatial resolution forecasts that are needed to support a national ice information service (NIIS), model initialization and certain physical processes take on greater importance. Examples include land-fast ice formation and short-timescale ocean processes such as tides and wave–ice interactions. The conservation of mass and heat that is crucial for climate modelling is not essential for operational forecasting where the model state is repeatedly reinitialized by the data assimilation system. Chapter 2 reviews relevant sea ice physics and numerical modelling techniques.

One might expect that the automated use of satellite observations within an APS should be straightforward, since they are routinely used in current NIIS operations. However, humans have sophisticated pattern recognition ability, and analysts generally have to undergo lengthy training before they are able to prepare operational products of sufficiently high quality. The appearance of sea ice features depends not only on quantities such as concentration and thickness but may also be affected by snow cover, surface melting, surface temperature, salinity content, roughness, surface emissivity, etc. In addition, observations from a particular sensor may depend on the surface footprint, solar illumination, incidence angle and atmospheric interference. Unlike the analyst, who has knowledge and experience, automated systems must rely on a sometimes ambiguous mathematical relationship between the observation and the desired ice feature as well as the related uncertainty in both the observation and the mathematical relationship. Chapter 3 provides a review of sea ice observations and their utility.

Sea ice data assimilation systems should use as many independent observations as possible for computing an estimate of the current sea ice conditions. The complexity of data assimilation systems can span a wide range. The simplest approach uses data insertion to replace values predicted by the forecast model with those obtained directly from a single type of observation. More sophisticated methods, similar to those currently used for NWP, account for the spatial–temporal and multivariate statistical relationships of the errors in a short-term model forecast and observations when assimilating a wide range of diverse observation types. The choice of which data assimilation approach to employ by a particular NIIS can depend on the computational and scientific resources available and the final use of the APS output. Chapter 4 reviews data assimilation techniques and some specific challenges when applying them to sea ice prediction.

The integration of advances in forecast models, observations and data assimilation within a sea ice APS is taking place to varying degrees at a number of centres. The output from these systems may have NIIS as clients while others may provide a direct service to the marine community. Chapter 5 reviews key characteristics of a number of existing operational sea ice APS.

The objective evaluation of both manually generated products and products generated from the output of an APS to provide a measure of accuracy is crucial to their optimal use. Consistency has not yet been achieved in either evaluation methodology or the data used for evaluation for both types of products available from a single NIIS, let alone from different NIISs. Different approaches are required to evaluate various types of predicted variables, whether they are categorical, scalar or vector. Chapter 6 provides a review of objective evaluation techniques including examples used to measure the value of APS outputs.

The concept of using output from an APS, either exclusively or in combination with other data sources, when generating ice products will often be referred to as numerical guidance. Chapter 7 focuses on current ice services and how the integration of numerical guidance can lead to effective improvements in operational procedures and new products.

1.2 A Brief Overview of Ice Services

Every day, a large volume of highly detailed ice information is provided to a wide variety of clients ranging from resource planners to ship crews navigating their vessels through extremely hazardous ice conditions. This information is considered operational because it must be reliably available in near-real time, seven days per week. Operational sea ice products are a crucial data source for safe and efficient operations in ice-covered waters. A suite of observations, numerical modelling systems and dedicated infrastructure and personnel working within specialized centres in numerous countries supports the generation of operational products. Highly trained ice analysts (IA) prepare these products using an essentially manual process that may not always be well documented, especially in scientific literature. To help understand how this operational production might evolve in the future, it is useful to begin with a background on operational ice services.

Ice occurring in the marine environment either forms in situ, referred to here as sea ice, or originates from land to form icebergs. While the focus of this book is on sea ice, it was an iceberg that sank the RMS Titanic in 1912, resulting in heightened general awareness of the threats posed by ice at sea. Monitoring of marine ice at that time was limited to ship and shore reports, with little or no information being widely distributed. By the 1950s and 1960s, visual aerial reconnaissance and radio facsimile communications made it feasible to provide near-real-time ice information in support of icebreaking, marine transportation and fishing operations.

Since the monitoring and reporting of sea ice conditions requires very specialized expertise and infrastructure, a number of countries have set up their own operational ice services. Some of the currently operational NIIS and organizations that provide similar services are: Argentine Naval Hydrographic Service; Canadian Ice Service (CIS); Danish Meteorological Institute (DMI); Finnish Meteorological Institute (FMI); German Federal Maritime and Hydrographic Agency; Japan Hydrographic and Oceanographic Department; Norwegian Meteorological Institute; Polish Hydrological Forecasting Office; Russian Arctic and Antarctic Research Institute (AARI); Swedish Meteorological and Hydrological Institute (SMHI); and, the US National Ice Centre (NIC). Other countries prepare sea ice information products as required, including Australia, Chile and Kazakhstan. Each NIIS provides information about past, present and future ice conditions, usually in the form of spatial information superimposed on maps or as text bulletins. In areas of geographic overlap, many of the NIIS coordinate their products to ensure consistent information is provided to clients. Coordination of ice services is facilitated by the World Meteorological Organization (WMO) and more detailed information on NIIS of the world may be found in the publication ‘Sea-Ice Information Services in the World’ (WMO, 2010).

To date, many of the NIIS innovations have been due to improvements in sea ice observations and information technology. Aircraft equipped with side-looking airborne radar (SLAR) went into operation in the 1970s and 1980s. Meanwhile, the NIISs were early adopters of using imagery from weather satellites for sea ice interpretation, starting in the 1970s. The widespread availability of operational satellites equipped with synthetic aperture radar (SAR) instruments in the 1990s has greatly improved the reliability and also the affordability of existing ice services, since it greatly reduced the need for observations from aircraft. These and other satellite observations combined with tailored analysis workstations incorporating geographic information systems (GIS), have allowed ice analysts to produce more accurate sea ice charts along with a large variety of derived products.

NIIS products may be categorized according to their use: (1) tactical products that are prepared in near-real time; and (2) strategic ice products that are more relevant to longer time periods. This book generally focuses on the first type of product but both are described briefly below.

1.2.1 Tactical Ice Products

Tactical ice products are provided to clients in near-real time and include mainly graphical charts and text bulletins. The preparation of these products involves manually interpreting and reconciling a wide variety of mainly satellite observations, while taking into account expected ice, weather and oceanographic conditions. Satellite observations do not provide ice information directly. Therefore, expert interpretation plays a significant role in their effective use. Similarly, forecasting ice conditions involves expert use of weather and oceanographic information along with an advanced knowledge of sea ice physics.

Clients typically use the resulting ice products to guide their daily activities such as navigating through or around ice-covered waters or identifying optimum locations for fishing. All of these products must adhere to operational deadlines, often resulting in a limited amount of time for the analysts to synthesize available data. In general, ice charts follow the guidance provided by WMO (2015), although regional adaptations are common. Ice charts depict areas of uniform ice conditions that are described in terms of the total ice concentration and partial concentrations of various ice types and corresponding predominant floe sizes. An example of an ice chart is shown in Figure 1.1 while a description of the WMO ‘egg’ code used in the chart is shown in Figure 1.2. Daily charts are prepared for operationally active marine areas whether or not current observations cover all areas. Since observations are rarely made at the valid time of the chart, the analysts at some centres simply stitch together the most recent observations and adjust areas of intersection for spatial continuity. At other centres, the more difficult procedure of predicting the evolution of ice conditions between the observation time and the valid time of the chart is used when producing the chart. Additional information may also be provided on the chart related to ice thickness measurements, sea surface temperatures and a description of the data sources used for a given area.

Since not all ships are equipped with the communications and reception equipment necessary to receive the graphical ice charts, ice bulletins made up of only text are often used. Ice bulletins contain at the very least a description of total ice concentration. They

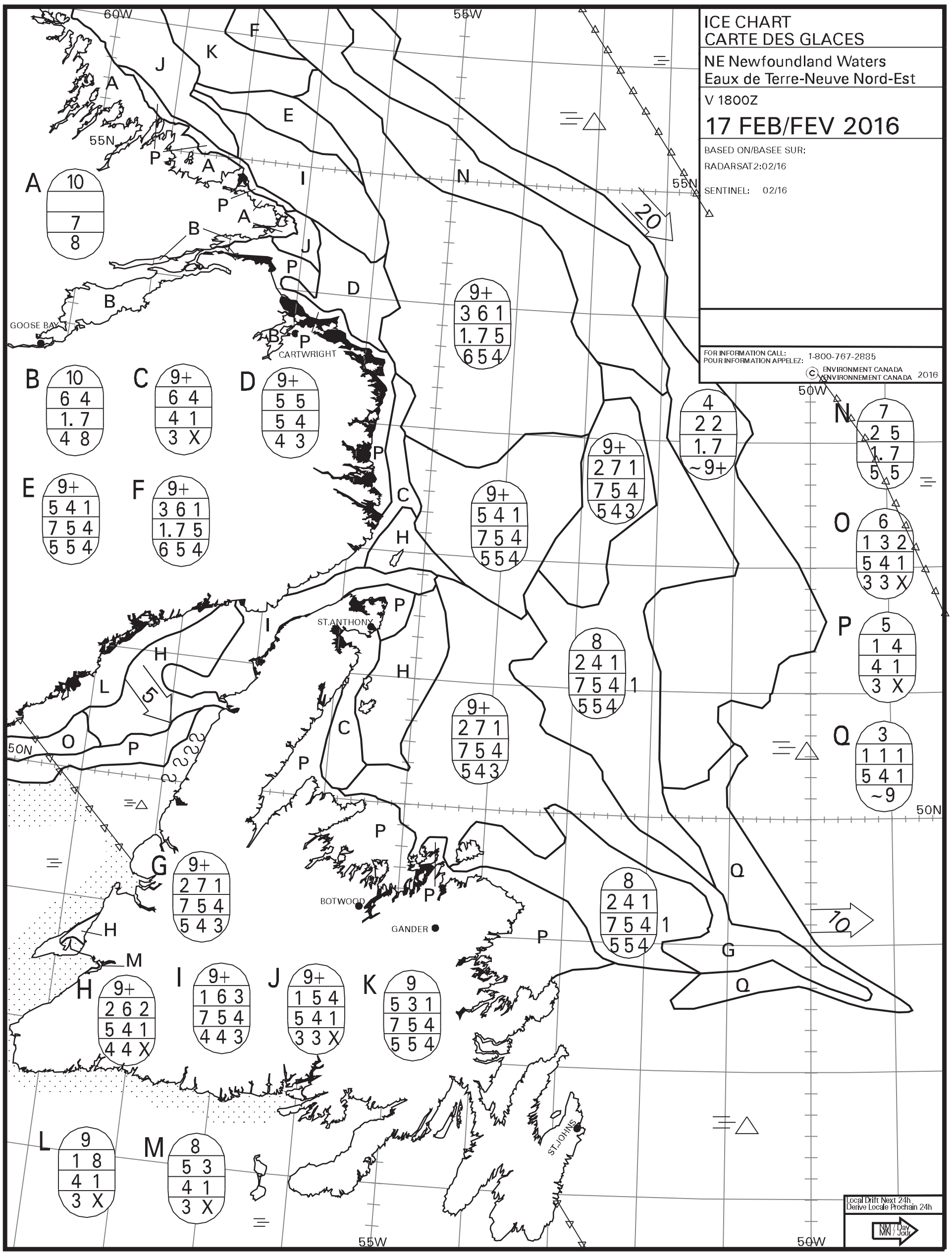

Figure 1.1: An example of a daily ice chart as prepared by the Canadian Ice Service. Conditions are those expected at the chart valid time and are presented as delineated areas of relatively uniform ice conditions described using the egg code format, described in Figure 1.2. The 24-hour forecast ice drift direction is shown as arrows with net drift distance inserted as a number with units of nautical miles. The iceberg limit is depicted as a line with overlaid triangles. Areas of ice free water are identified as (≡) and bergy water as (△). Open water areas (i.e. between 0 and 1 tenth of ice) are dotted. © Her Majesty the Queen in Right of Canada, as represented by the Minister of the Environment Canada, 2017.

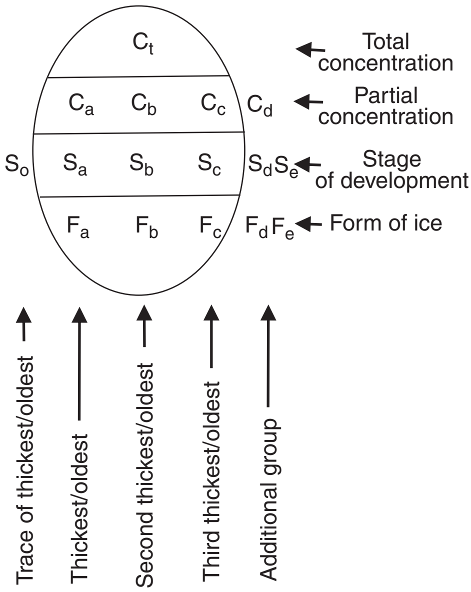

Figure 1.2: The WMO egg code format. Concentrations are given in tenths while the stage of development and form of ice are numerical codes related to the age or thickness of the ice and the size or form of the ice, respectively. © Her Majesty the Queen in Right of Canada, as represented by the Minister of the Environment Canada, 2017.

may also provide information on ice edge location, ice stage of development and a short-term forecast of expected changes.

Other tactical products are linked more closely to observations, including the satellite images themselves and image analysis charts. Image-based products are portions of satellite images or whole images that are often compressed to accommodate the limited communication bandwidth available in many areas at sea. Full resolution SAR and optical satellite image products may provide the high spatial resolution suitable for navigation purposes, although clients must have the expertise necessary to interpret the data. To assist in this area, expert analysts interpret the satellite imagery and provide image analysis charts. These charts are based on an analysis of a single satellite image or image swath and they are valid at the time of the satellite pass. Usually they are prepared using SAR or optical imagery, although other image sources and meteorological information can be used to assist in the image interpretation. Since ice conditions can evolve rapidly, every effort is made to prepare and transmit these products as quickly as possible.

Clients for tactical ice products include Coast Guard icebreaking and vessel routing, marine transportation, offshore oil and gas industry, national defence, fishing industry, aboriginal/local transportation, port authorities and tourists/adventurists.

1.2.2 Strategic Ice Products

Given its chaotic nature, the predictability of the atmosphere is about two weeks, resulting in a direct limitation on the predictability of sea ice. However, anomalies in the large-scale ocean and sea ice conditions relative to climatological averages (e.g. sea surface temperature, ice area, ice thickness) can provide longer-term predictability of large-scale characteristics. Hence, forecasts from beyond several days up to a season provide information more related to the general evolution of conditions or departures from normal.

Similar configurations of a physically-based APS could be used for short-term and seasonal forecasts. However, NIIS often rely on statistical or analogue techniques for predicting the evolution of the sea ice cover on monthly to seasonal timescales and sea ice APS are not yet widely used for guidance. Forecasts beyond the coming ice season are not normally issued by NIIS, although they may provide general trends in ice cover at very coarse scales.

Climate products are another type of strategic ice product. They are quite diverse and can include, for example, the normal extent of ice for a given area and time of year or extreme ice conditions at a point location. They are typically used as input to the design of structures and vessels, planning new ship routes or to help monitor climate change. They are usually based on a 30-year period as that is considered long enough to capture interannual variability while short enough to represent current normal conditions. Typical products include the frequency of occurrence of ice and each ice stage of development on a monthly basis. It is crucial that the source products used to generate such an ice climatology do not introduce artificial trends such as may result from a change in input data or a change in preparation techniques.

Clients for these products include long-range planners for marine transportation routing and vessel deployment, marine planners, naval architects, climate research scientists and policy makers.

1.3 The Components of an Automated Prediction System

In some cases, current daily ice chart and bulletin production may fall short of new and evolving client information requirements. In addition, climate change may result in year-round Arctic shipping being feasible, thus significantly increasing the demand for ice services. In other cases, new products, such as site-specific information and probabilistic information, are required to support local communities and risk-based decision makers. Opposing these expanding requirements is the financial pressure on governments to limit increases to the budgets of the centres that provide these services. While a large number of observations should lead to more accurate ice products, it takes considerable time and expertise to analyse and integrate the information. As a result, the most accurate products require the greatest amount of time to prepare. While the current, mostly manual procedures are becoming more efficient, the provision of a significant increase in ice information would still require a roughly proportional increase in the number of ice analysts.

Of course, these issues have been faced by the much larger weather service community. Advances in NWP have allowed weather forecasters to focus on short-range, high-impact weather, while at the same time more accurate and longer-range forecasts are automated. This automation requires investments in forecast model and data assimilation research as well as the supporting information technology and communications. For the weather community, these investments are providing increasingly accurate and reliable weather forecasts.

The sea ice community is going through a similar transition, but with the confidence that longer-term benefits will be achieved, as experienced with NWP. The purpose of this book is to provide an advanced introduction to some of the scientific and technological advances in automated sea ice prediction systems that enable this transformation. It is also suggested that, as the accuracy of these systems improves, they can increasingly be used to provide input either to a manual or fully automated process for the generation of ice products. This will facilitate the expansion and increased tailoring of ice services while remaining financially affordable. It should also be noted that, to further improve the accuracy of weather forecasts, NWP systems are being developed that increasingly incorporate more components of the complete Earth system, including representations of the ice and ocean. This ongoing evolution can also benefit centres responsible for operational ice services, as it provides an excellent opportunity for coordinated development of coupled sea ice, ocean and weather prediction systems to ensure that the resulting systems meet the combined requirements of ice, ocean and weather information services. Hence, large investments in coupled prediction systems that only meet the needs of NIIS are not required. More modest investments into improving automated sea ice prediction, combined with close collaboration with weather and ocean APS developers, should result in significant ongoing benefits.

Figure 1.3 depicts the components of an APS. Some parts of this system emulate the manual ice analysis and forecasting process. One starts with an initial estimate of current conditions, also referred to as a background state, which in this case is provided by a short-term forecast from a numerical model. A correction to the background state is obtained by synthesizing observations from a large variety of sources using a data assimilation system. This corrected background state, referred to as the analysis state, then serves as the starting point to predict future conditions using the forecast model and information about other relevant environmental conditions. As the forecast model increases in complexity to include ocean and atmospheric components, less reliance on external forcing is required. Initially, manual intervention could be used to correct deficiencies in the system, although the goal would be to minimize or eliminate such intervention altogether. A crucial component of this system is routine objective evaluation in order to identify and correct problem areas as well as to quantify expected accuracy. Some systems could also include post-processing that would correct errors in APS outputs using a variety of statistical techniques.

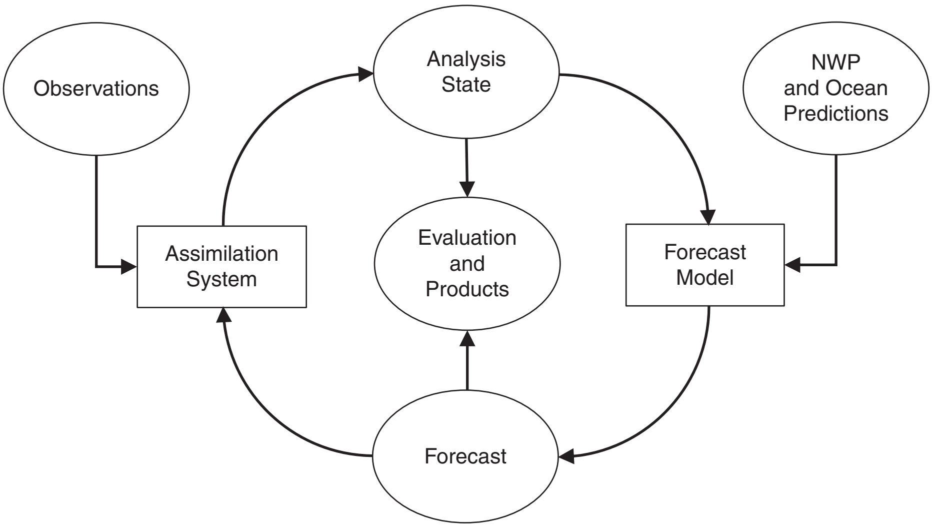

Figure 1.3: A schematic of the main components of an automated prediction system

1.4 Chapter Summary

A NIIS provides information about past, present and future ice conditions to a large variety of clients both in near-real time and for non-time-critical operations. Although these services rely on manual approaches, they will continue to adapt due to the availability of new technologies and evolving client requirements. With the availability of operational APS outputs and the ongoing developments to improve these systems, it is expected that ice services will rely more and more on APS products for guidance.

The components (described in the following chapters) of an ice APS include a sea ice model, observations, a data assimilation system and objective evaluation and post-processing, all aimed at providing new and improved ice information products.

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