A Geospatial Analysis of Arctic Marine Traffic

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A Geospatial Analysis of Arctic Marine Traffic

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Declaration

In accordance with the University of Cambridge regulations, I declare that this thesis, *A Geospatial Analysis of Arctic Marine Traffic*, represents my own work and conforms to the accepted standards of citation in those instances in which I have availed myself of the works of others. This dissertation does not exceed the regulations on length (225 pages) and has not been submitted to any other university or institution for any degree, diploma, or similar qualification.

William Eucker IV

Denver, December 2011

Dedication

Though I never had the opportunity to meet him, Dr Terrance Edward Armstrong inspired me with his published word and the stories fondly retold by those who knew him. RIP TEA.

Summary

Recent changes in Arctic Ocean climate dynamics and marine activity in the region require re-evaluation of physical operating conditions, ship traffic patterns, and policy requirements. This study used (1) government surveys, (2) vessel reports, and (3) Automatic Identification System (AIS) messages to characterize the spatial and temporal variability of surface vessel traffic in relation to various sea-ice conditions on the Arctic Ocean during a year-long study from 1 April 2010 to 31 March 2011. Data sources, methods of analysis, and errors were discussed. Three principal topics were examined.

First, sea-ice cover on the Arctic Ocean was analysed to determine the physical access for marine operations. Daily sea-ice concentration data based on satellite passive microwave measurements were used to calculate the extent of open water and duration of the sea-ice season.

Second, ship traffic on the Arctic Ocean was analysed to determine the present patterns of human activity. Time-stamped AIS messages encoded with Global Navigation Satellite System (GNSS) positions received by a commercial satellite constellation from north of the Arctic Circle (66·56°N) were used to calculate the distribution of vessels per unit area. Satellite AIS data from SpaceQuest, Limited, were compared with land-based vessel observations during the study period from the Marine Exchange of Alaska and the Port of Longyearbyen.

Third, the spatial and temporal relationship between sea ice and surface vessels on the Arctic Ocean was analysed to determine potential policy implications. Three groups of marine operations with distinct characteristics were determined from the analysis: operations in perennial open water, operations in the seasonal ice zone, and operations in the perennial ice zone. Throughout the study year, most ships north of 66·56°N operated in perennially ice-free areas, but year-round operations also occurred in ice-covered areas.

The results from this study identify new pathways of information to enable consistent pan-Arctic assessment of physical operating conditions and ship traffic patterns. This approach provides novel considerations to sustainably develop a safe, secure, and environmentally protected Arctic Ocean.

Судьбой дана, пройти покрыту льдами воду

«Петр Великий»
Михаил Васильевич Ломоносов, г. 1761

Their fate is given: pass the ice-covered water

Ode to Peter the Great
Mikhail Vasilevich Lomonosov, 1761

Acknowledgements

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List of Acronyms

AIS	Automatic Identification System
ASCII	American Standard Code for Information Interchange
ASI	Arctic Radiation and Turbulence Interaction Study (ARTIST) Sea-Ice concentration algorithm
AMAP	Arctic Monitoring and Assessment Programme
AMSA	Arctic Marine Shipping Assessment
AMSR-E	Advanced Microwave Scanning Radiometer - Earth Observing System
AMVER	Automated Mutual-Assistance Vessel Rescue Reporting System
CSV	Comma-Separated Values
DVD	Digital Video Disk
DMSP	United States Air Force Defense Meteorological Satellite Program
EOS	National Aeronautical Space Administration Earth Observing System
ESRI	Environmental Systems Research Institute
GIS	Geographic Information System
GNSS	Global Navigation Satellite System
IACS	International Association of Classification Societies
ICDC	Integrated Climate Data Center, University of Hamburg
IMO	International Maritime Organization
ITU	International Telecommunications Union
MID	Maritime Identification Digits
MMSI	Maritime Mobile Service Identity
NASA	National Aeronautics and Space Administration
NMEA	National Marine Electronics Association 0183 Interface Standard
NSIDC	National Snow and Ice Data Center, Boulder, Colorado
SSMIS	Special Sensor Microwave Imager / Sounder
TIFF	Tagged Image File Format
WGS 84	World Geodetic System 1984

1. Introduction

The changing spatial and temporal distribution of sea ice on the Arctic Ocean is redefining the physical constraints that limit access to globally important trade routes and resources. A replicable process to identify trends of human activity associated with various environmental conditions and consequences is needed to develop policy options that ensure sustainable development and environmental protection of the ice-diminishing Arctic Ocean. Based on advances in remote sensing, telecommunications, and information technology, this thesis develops a novel process to analyse surface vessel traffic on the Arctic Ocean in relation to sea ice using observations collected during a study year ending 1 April 2011.

1.1. The Transforming Arctic Ocean

Surface vessels operating on the Arctic Ocean may encounter hazardous atmospheric and oceanographic conditions including electromagnetic anomalies, mesoscale vortices, low air temperatures, blizzards, freezing rain, persistent fog, and sea ice with the complications of prolonged winter darkness. Such conditions sometimes cause interference with communication and navigational equipment, as well as icing that can affect vessel stability, and may lead to hypothermia and frostbite in mariners, or occasionally loss of the vessel. Many of these distinguishing and variable physical features of the maritime region are in part a consequence of its location north of the Arctic Circle.

The Arctic Circle (approximately 66·56º north latitude) is the astronomical boundary marking the southern extent of the polar day, a continuous period of illumination lasting more than 24 hours in summer, and the polar night, the converse period of darkness in winter. The extreme seasonal variations of exposure to solar radiation influence all elements of the Arctic Ocean environment, and as such, the Arctic Circle forms the southern boundary for this work.

The landmasses of North America and Eurasia, together with Greenland, Spitsbergen and other islands, comprise the land surface area north of the Arctic Circle. Continental shelves extend north, defining the characteristically shallow bathymetry of many Arctic Ocean marginal seas that restrict vessels with deeper drafts (United Kingdom Hydrographic Office, 2007; Norwegian Hydrographic Service, 1990). Particularly shallow water supersedes the wide Eurasian continental shelves of the Barents Sea, White Sea, Kara Sea, Laptev Sea, East Siberian Sea, and Chukchi Sea. In contrast, the narrower North American shelf is surrounded by deeper waters of the Greenland Sea, Lincoln Sea and Beaufort Sea. Beyond the marginal seas, the Lomonosov Ridge separates the Canada Basin and the Eurasian Basin in the central Arctic Ocean, each more than 4000 m deep. The seabed at the Geographic North Pole has a depth of 4179 m, and is approximately 600 km from the Northern Pole of Inaccessibility, the point furthest from land (Headland, 2009). The Arctic Ocean connects with the Atlantic via the Labrador Sea, Denmark Strait and Norwegian Sea, and to the Pacific through the much smaller Bering Strait (Zubov, 1963). The submarine and coastal limits of the Arctic marine operating environment are shown in the most recent International Bathymetric Chart of the Arctic Ocean, reprinted in Figure 1 (Jakobsson *et al.*, 2008).

In the maritime region north of the Arctic Circle, ice and snow cover a variable proportion of the surface throughout the year, impeding the manoeuvrability of surface vessels, resulting in delayed transits, and increasing the risk of accidents. Ice on the Arctic Ocean may form on land from fresh water, *e.g.* icebergs that calve from glaciers, or may form *in situ* from sea water. Sea ice forms in low atmospheric temperatures and is a combination of pure fresh water ice and brine (Untersteiner, 1990). Once formed, ice may increase in areal extent and thickness due to accumulation of snow, freezing vertically or laterally at the ice-ocean interface, and by dynamic rafting and ridging. A maximum average ice extent in the northern hemisphere during March is reduced by melting and mass transport to more southerly waters throughout spring and summer, reaching a minimum average ice extent in September. Figure 2 shows this annual pattern of sea ice growth and decay in the northern hemisphere from monthly average sea ice extent during 1979 to 2010.

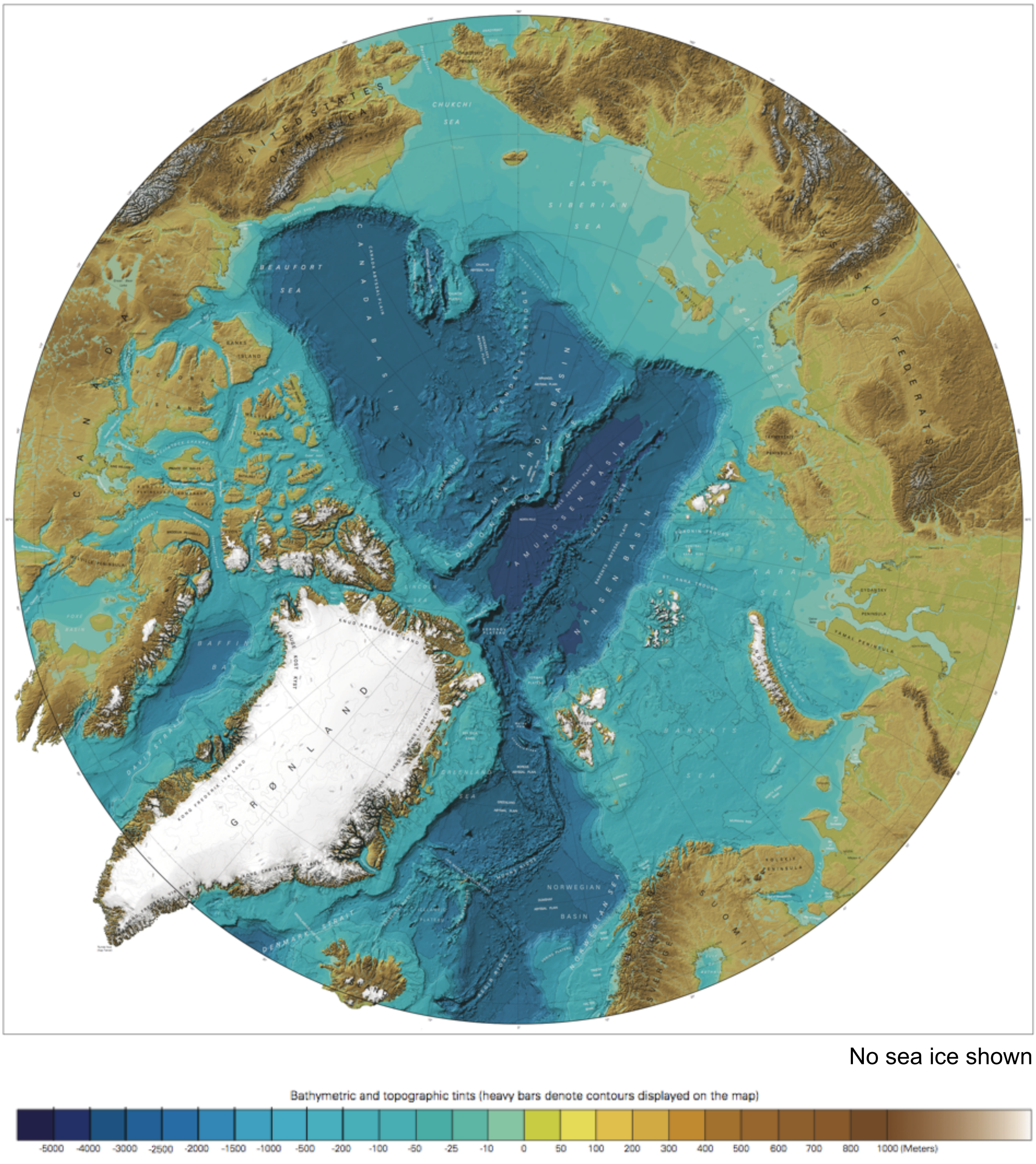


Figure 1. International Bathymetric Chart of the Arctic Ocean

The bathymetry of the Arctic Ocean is characterized by shallow marginal seas and a deep central basin. Shallow channels are found in the island archipelagos northeast of North America and north of Eurasia. The Arctic Ocean connects with the Atlantic via the Labrador Sea, Denmark Strait and Norwegian Sea, and to the Pacific through the much smaller Bering Strait. Depth measurements from multi-beam sonar and other echo-sounding instruments aboard icebreakers and submarines were interpolated to produce this digital chart with 2 × 2 km grid cell spacing using a polar stereographic projection with the World Geodetic System 1984 reference ellipsoid and the 75·00°N reference parallel (Jakobsson *et al.*, 2008).

Sea-ice cover can be separated into the 'perennial ice zone', where the sea ice endures throughout a year, and the 'seasonal ice zone', where sea ice cover exists only part of the year (Wadhams, 2000). As such, 'multi-year sea ice' that endures one or more melt season is predominantly located in the perennial ice zone, whereas 'first-year sea ice' that grows in a single year occupies the seasonal ice zone (Weeks and Ackley, 1986). Localized sea-ice conditions important for navigation include 'leads', a navigable passage through ice, 'polynyas', large areas of open water surrounded by sea ice, 'ice clusters' or 'ice massifs' [Russian: '*massiv*'], regular locations of concentrated ice, 'pressure ridges' of vertically deformed ice, and 'fast ice' that remains fixed along the coast—in contrast with drifting 'pack ice' (Armstrong, 1954; Armstrong and Roberts, 1956). Thermodynamic and mechanical forces influence the spatial and temporal distribution of three sea-ice parameters especially important for surface vessel navigation: concentration, thickness, and drift.

Sea-ice concentration measures the proportional amount of ice per unit area, and varies during the year throughout the Arctic maritime region. Sea-ice concentration is commonly reported in tenths, from open water to complete cover (Parkinson *et al.*, 1999). Explorers, whalers and sealers on shore stations or vessels in northern waters recorded encounters with ice and often reported the location of the sea-ice edge, the boundary between open water and a threshold of sea-ice concentration (Scoresby, 1820; Ackley *et al.*, 2003; Divine and Dick, 2006). Airships and aeroplanes of the 20th century enabled new methods for surveying sea ice, particularly in the North Atlantic where icebergs pose a hazard to navigation as far south as the Labrador Sea (Treasury Department, 1915; Ellsworth and Smith, 1932; Karelin et al., 1946). Many of these sea-ice measurements from shore stations, ships and aircraft have been consolidated in sub-regional and pan-Arctic ice atlases that note both disparate types of source observations and the sparsity of data (Hydrographic Office, 1922; Armstrong, 1958; Swithinbank, 1961; Treshnikov, 1985). Since 1978, a consistent pan-Arctic record of sea-ice concentration has been available from satellite-borne radiometry (Fetterer *et al.*, 2011). Passive microwave sensors on satellites can distinguish sea ice and snow from water by measuring surface brightness temperature, the temperature of the equivalent black body that would emit the identical radiance at a given frequency (Planck, 1914; Rees, 2009). This method is relatively insensitive to variability in cloud cover and daylight, however spatial and temporal differences in sea ice and snow morphology may influence the measurements (Spreen *et al.*, 2008). To account for these influences, various algorithms have been developed and are discussed in Chapter 2. Other methods based on visible- and infrared-band sensors and active microwave radiometry are often more accurate than passive radiometry, but inconsistencies in manual processing makes such techniques unsuitable for assessing long-term trends (Fetterer and Windnagel, 2010).

Sea-ice thickness measures the vertical distance between the ice-ocean interface and the ice-atmosphere interface and varies by season and location throughout the Arctic maritime region, ranging from newly formed 5 mm frazil ice to older paleocrystic 10 m ridged ice (Walker and Wadhams, 1979). The ice thickness distribution may be divided into three categories: open water, first-year sea ice, and multi-year sea ice (Wadhams, 2000). A consistent record of sea-ice thickness distribution has been provided by upward-directed sonar measurements recorded on undersea traverses of nuclear powered submarines (Rothrock *et al.*, 2007). The time delay and frequency shift between propagated and reflected sound waves indicate sea-ice draft, the depth below sea level which is equal to approximately 6/7ths of the total ice thickness (Wensnahan and Rothrock, 2005; Payne, 2006). Figure 3 shows the observed sea-ice draft from these submarine traverses (Rothrock *et al.*, 2008). The published sea-ice thickness measurements from undersea submarine traverses have sampled an area of the Arctic Ocean on the order of 1000 km^2, based on a 10 m sensor footprint and 122,000 km of total sample length from 1977 to 2000, representing only a small fraction of the 13.4 x 10^6 km^2 maritime region north of the Arctic Circle (Rothrock and Wensnahan, 2007). Further, satellite remote sensing measurements of sea-ice thickness are unable to distinguish melt water and snow at the ice-atmosphere interface or resolve ridging, roughness, and other local thickness variations (Kwok and Cunningham, 2008; European Space Agency, 2010).

Concentration, thickness, and other sea-ice parameters important for navigation are influenced by drifting of the pack ice primarily produced in the Eurasian marginal seas. In particular, the Laptev Sea has been labelled the sea-ice 'factory' of the Arctic Ocean (Ingólfsson, 2010). Pack ice movement has components of magnitude and direction which depend upon atmospheric pressure, wind, and ocean circulation (Johannessen *et al.*, 2007). Early scientific expeditions made observations of mesoscale sea-ice movements by penetrating the ice edge in ships which were frozen into and drifted with the pack (DeLong, 1884; Nansen, 1897). Similarly, Soviet and Russian polar drift stations were established atop ice floes to record sea-ice movements (Frolov *et al.*, 2005). These mesoscale ice drift records confirmed the existence of the Beaufort Gyre, a circulation pattern in the Beaufort Sea, and the Transpolar Drift Stream, a mechanism exporting an estimated 1 million km^2 of ice from the shallow marginal seas of the Eurasian Coast to North America (Johannessen *et al.*, 2007). Recent satellite remote sensing studies have provided additional data on the magnitude and direction of sea-ice drift (Alexandrov *et al.*, 2000; Sandven, *et al.*, 2001).

Consistent methods to measure sea ice over time enable assessment of inter-annual trends that are important for maritime operations. Figure 2 shows a decrease in sea-ice extent since 1978 based on monthly mean sea-ice concentration measurements using satellite passive microwave radiometry. These sea-ice concentration measurements, with spatial resolution on the order of 25 km, have sampled billions of square kilometres of the Arctic Ocean during the satellite record. According to this record, the September minimum sea-ice extent representing the amount of ice that will persist from one year to the next has been declining at an annual rate of 8%. This loss of multi-year ice is confirmed by the decreasing average thickness of the ice pack since 1976 based on upward-directed sonar measurements from declassified nuclear submarine traverses. Figure 3 shows this observed decrease in sea-ice thickness based on measurements with spatial resolution on the order of 10 m and total spatial coverage on the order of thousands of square kilometres during the submarine record. In addition, the sea-ice drift may be weakening, which in turn may result in greater spatial and temporal variability of concentration and thickness on local scales (Demchev, 2011). These consistent measurements of diminishing sea ice over various spatial scales and during the past thirty years signal a change to the Arctic Ocean operating environment. Reduced sea-ice cover in the 21s century is likely to result in an increase in marine transport and access to resources in the Arctic Ocean (Arctic Climate Impact Assessment, 2004). This likelihood raises questions about the implications for navigational access, marine use, and infrastructure requirements.

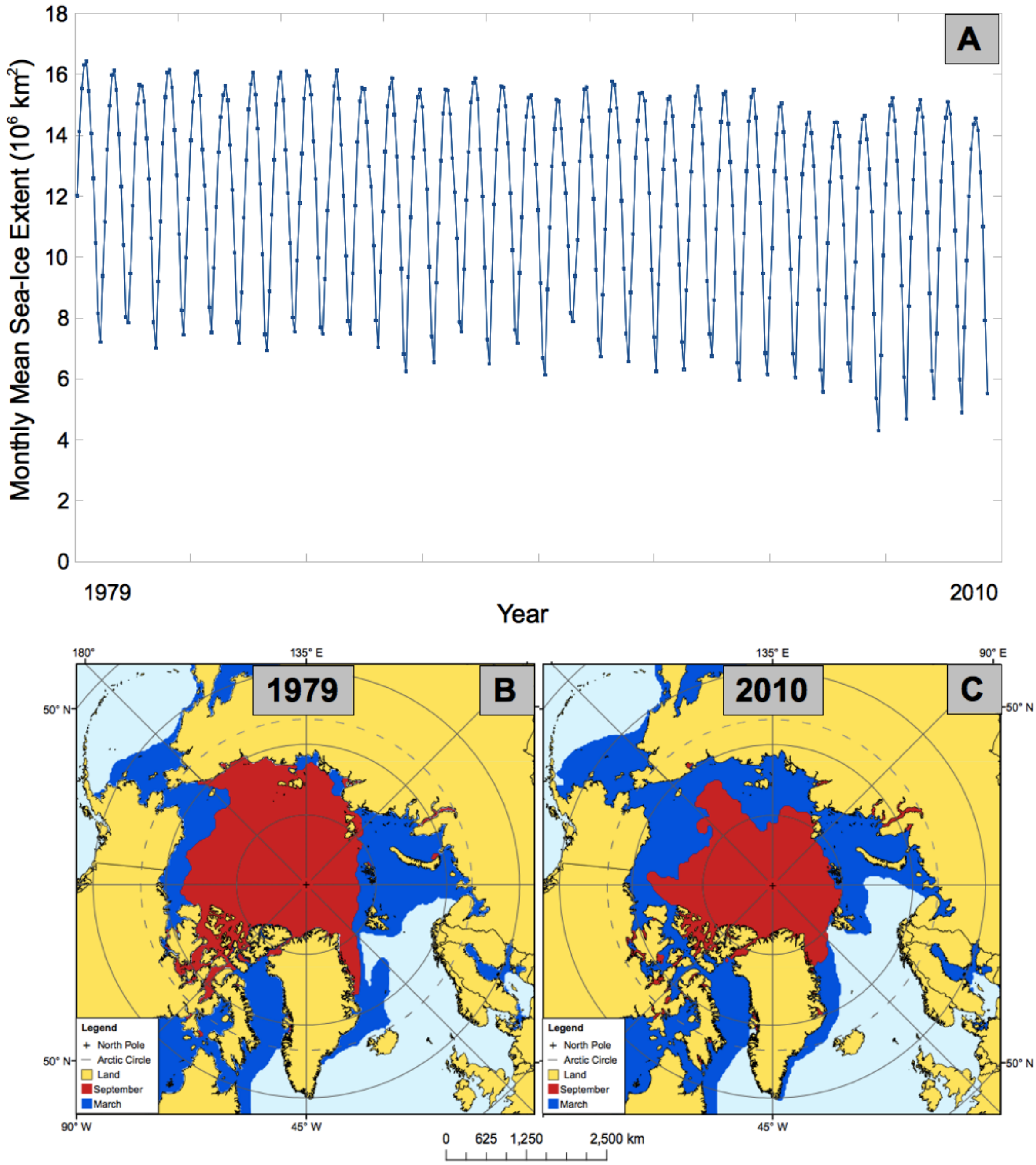


Figure 2. Decrease in Sea-Ice Extent

(A) Monthly mean sea-ice extent based on satellite passive microwave measurements of northern hemisphere sea-ice concentration. Annual sea-ice extent maxima and minima in March (blue) and September (red) have been decreasing during the satellite record, **(B)** 1979 to **(C)** 2010. (Fetterer *et al.*, 2011).

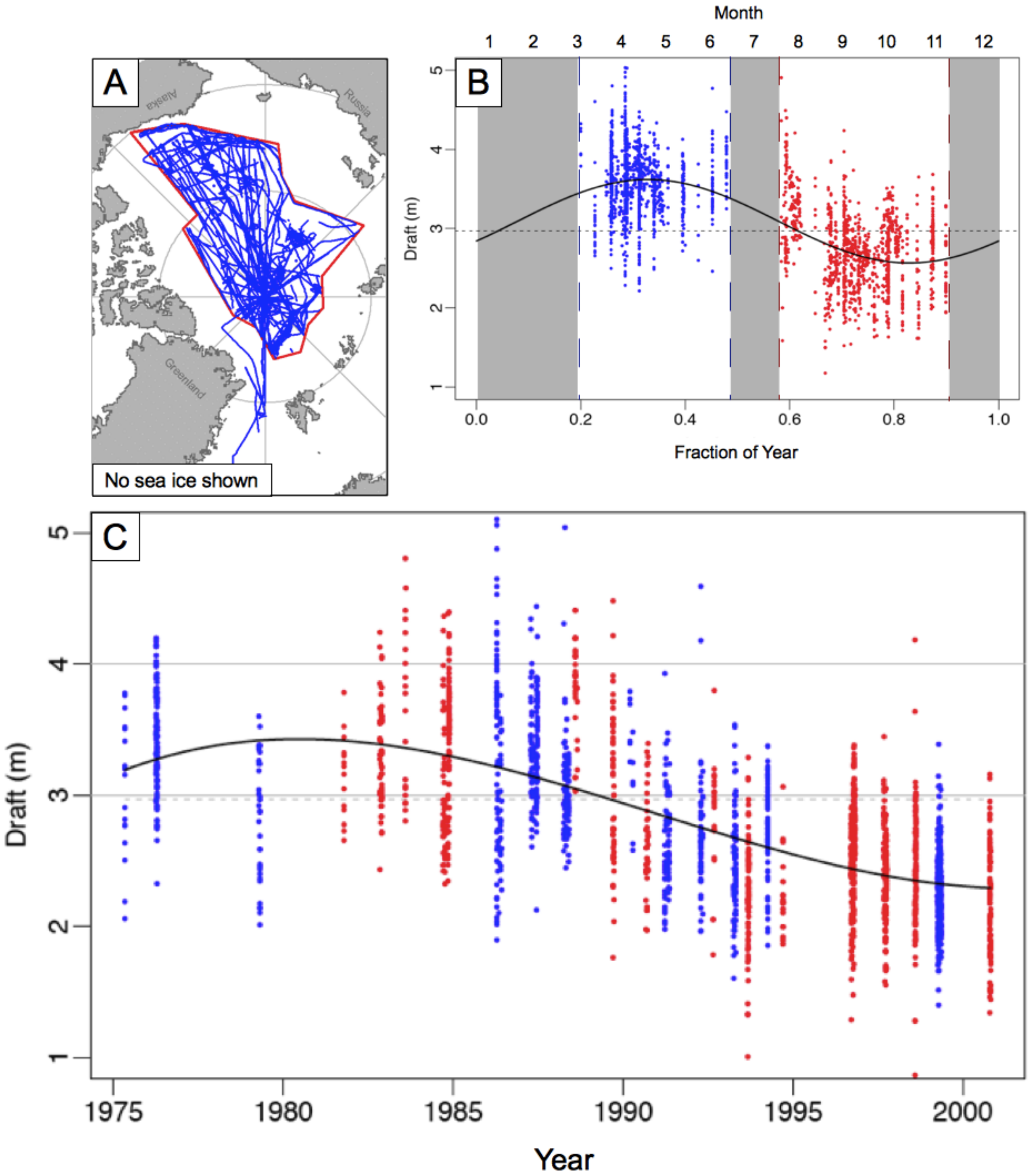


Figure 3. Decrease in Sea-Ice Thickness

A summary of upward-directed sonar measurements of Arctic sea ice draft thickness (Rothrock *et al.*, 2008): **(A)** Undersea traverses of United States Navy and Royal Navy nuclear submarines that conducted measurements within a polygon in the central Arctic Ocean; **(B)** Time of measurement, normalized into a year fraction, categorized into periods of thicker ice in winter (blue) and thinner ice in summer (red), and separated by seasons in which no data were released (grey); and **(C)** Decreasing trend of sea-ice draft from 1976 to 2006. The trend lines (black) guide the eye of the reader.

1.2. Previous Assessments of Arctic Marine Access

Changing climate dynamics and improving ship operation techniques prompt fundamental questions about the present and future possibilities to navigate the Arctic Ocean. Historically, sea ice studies, experimental voyage reports, and vessel classifications defined Arctic marine access based on single vessel transits of peripheral routes during the summer navigational season. Now, however, diminishing presence of sea ice, improving availability of environmental observations, and advancing capability of marine technologies are challenging the applicability of these constraints.

Theoretical navigating area and season describe Arctic marine access in the most universal terms. A surface vessel navigates toward a destination over the surface of the Earth, occupying a single geographic position at a given time. As such, the domain of possible ship position values spans a two-dimensional area that defines the spatial access for navigation, historically related to 'sea room' (Engeham, 2008). Defining navigational access in terms of a two-dimensional area is realistic in ice-covered waters because the optimal route is not necessarily a straight line—it may be prudent to deviate course to avoid pressure ridges or ice clusters and alternatively pursue a lead or polynya. In the maritime region north of the Arctic Circle, this theoretical navigating area is principally dependent on the physical operating environment, *i.e.* coastlines, bathymetry, and sea-ice conditions, as well as the physical capabilities of the vessel, *i.e.* structure and propulsion. Other considerations for surface vessel operations, such as safe operating speeds, safe distance in convoys, legal and political boundaries, operating limits specified in insurance arrangements, extent of communications networks, and search and rescue response ranges also merit review. Similarly, it is also beneficial to define the theoretical navigating season for a particular location, sometimes termed an 'operating window'. Ships not operating in the theoretical navigating area and season would be likely to encounter hazards which may cause a loss of manoeuvrability or structural damage. There are various examples, *e.g.* in October 1983 when more than fifty ships were caught in ice northeast of Siberia (Armstrong, 1984).

A number of sea ice atlases described Arctic marine access in terms of the ability of sea ice to impede the navigation of an 'ordinary' vessel, one that is not specifically designed to operate in ice, in the area and season historically important for marine traffic. One of these studies mapped the monthly average sea ice conditions in the Barents Sea for wartime Arctic convoys (Air Ministry, 1944). Two other studies described the spatial and temporal distribution of Arctic sea ice along two historic routes connecting Atlantic and Pacific: the Northeast Passage and the Northwest Passage (Armstrong, 1958; Swithinbank, 1961).

The Northeast Passage connects the Atlantic and the Pacific through the North Eurasian marginal seas: Barents Sea, Kara Sea, Laptev Sea, East Siberian Sea, and Chukchi Sea. Figure 4 depicts these seas their connecting straits. From 1878 to 1879, Adolf Erik Nordenskiöld first transited the Northeast Passage from Atlantic to Pacific north of Eurasia aboard *Vega* (Nordenskiöld, 1881). Subsequent investments by Russian, Soviet, and Russian governments have developed this maritime trade route into the 'Northern Sea Route', a formal administrative term that defines an area which extends between the Kara Gates Strait and Bering Strait, connecting many northern Russian settlements but excluding the Barents Sea (Northern Sea Route Administration, 1989). Figure 5 reprints a study that interpolated sea-ice conditions along a generalized route north of Eurasia according to a statistical compilation of a century of available sea-ice observations during the period from May to December (Armstrong, 1958). This geospatial analysis of Arctic marine access used a systematic approach, but characterized only one route, did not cover the period from January to April, and was based on sparse and inconsistent observations of sea ice.

The Northwest Passage connects the Atlantic and the Pacific through the waters surrounding the Canadian Arctic Archipelago north of North America, depicted in Figure 6. From 1903 to 1906, Roald Amundsen made the first transit of the Northwest Passage from Atlantic to Pacific north of the North America aboard *Gjøa* (Amundsen, 1908). In 1961, Swithinbank published a study that interpolated sea-ice conditions in Canadian Arctic waters based on a statistical compilation of sea-ice observations (Swithinbank, 1961). Based on similar analyses of historical sea-ice observations, the Canadian Government developed Canadian Shipping Safety Control Zones specifying dates of allowed transit for vessels based on their capability of navigating through ice (Transport Canada, 2010). These spatial, temporal, and structural categories defined in Figure 7 assess marine access north of North America.

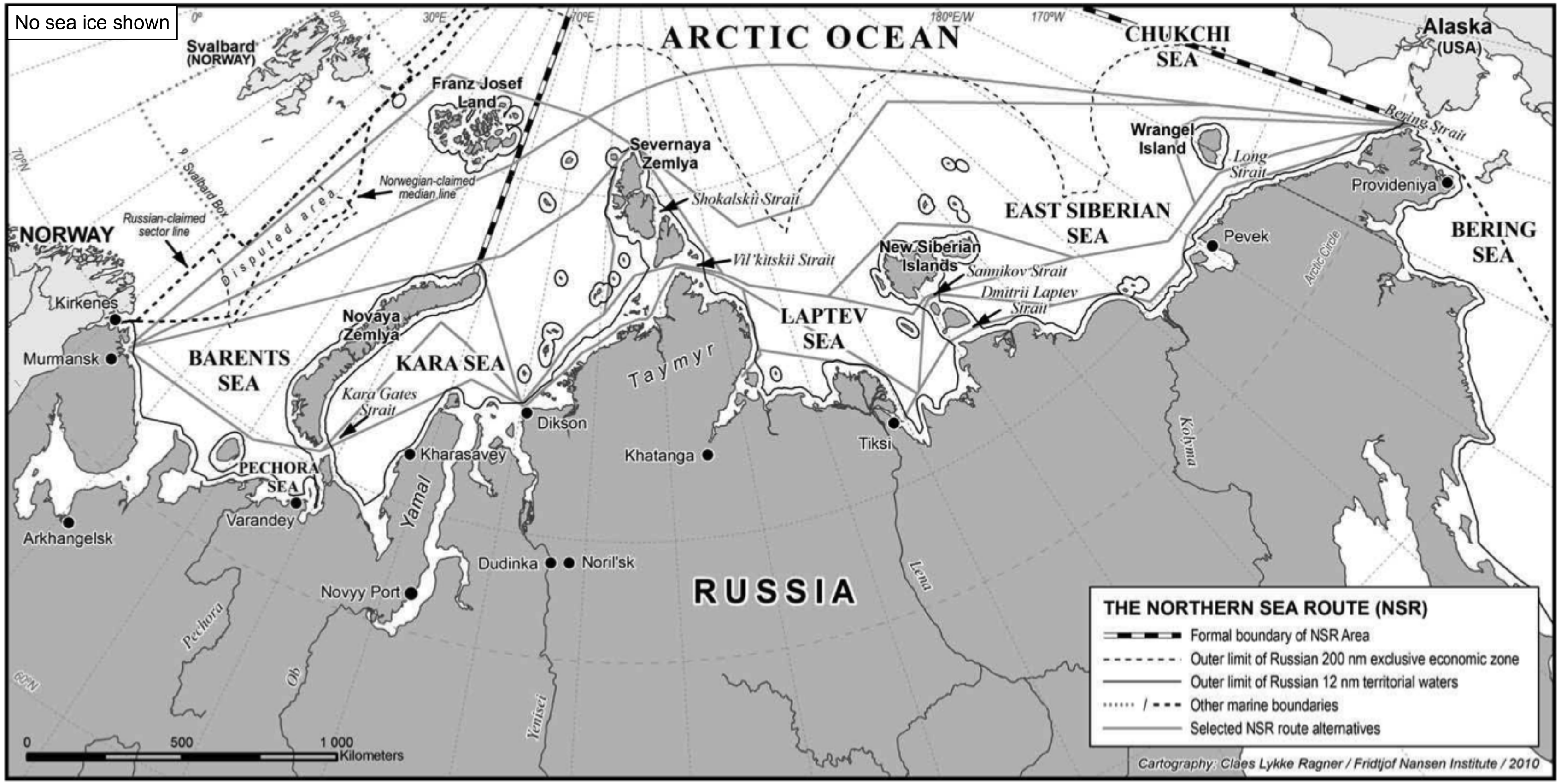


Figure 4. Seas and Straits North of Eurasia

Bathymetry and sea ice condition define marine access in the marginal seas north of Eurasia: Barents Sea, Kara Sea, Laptev Sea, East Siberian Sea, and Chuckchi Sea. These marginal seas are connected with a series of straits, including the Yugurskiy Shar Strait, Kara Gates Strait, Matochkin Shar Strait, Vil'kitskii Strait, Shokal'skii Strait, Red Army Strait, Yungshturm Strait, Dmitrii Laptev Strait, Sannikov Strait, Long Strait, and Bering Strait (Brubaker 2005; Brubaker and Ragner, 2010). The Northwest Passage connects the Atlantic Ocean with the Pacific Ocean, from Barents Sea to the Bering Sea, while the Russian 'Northern Sea Route' is bounded by the Kara Gates Strait and Bering Strait and, as such, does not include the Barents Sea. The 'Disputed area' was resolved by a maritime delimitation treaty signed 15 September 2010 (Norwegian Foreign Ministry, 2010).

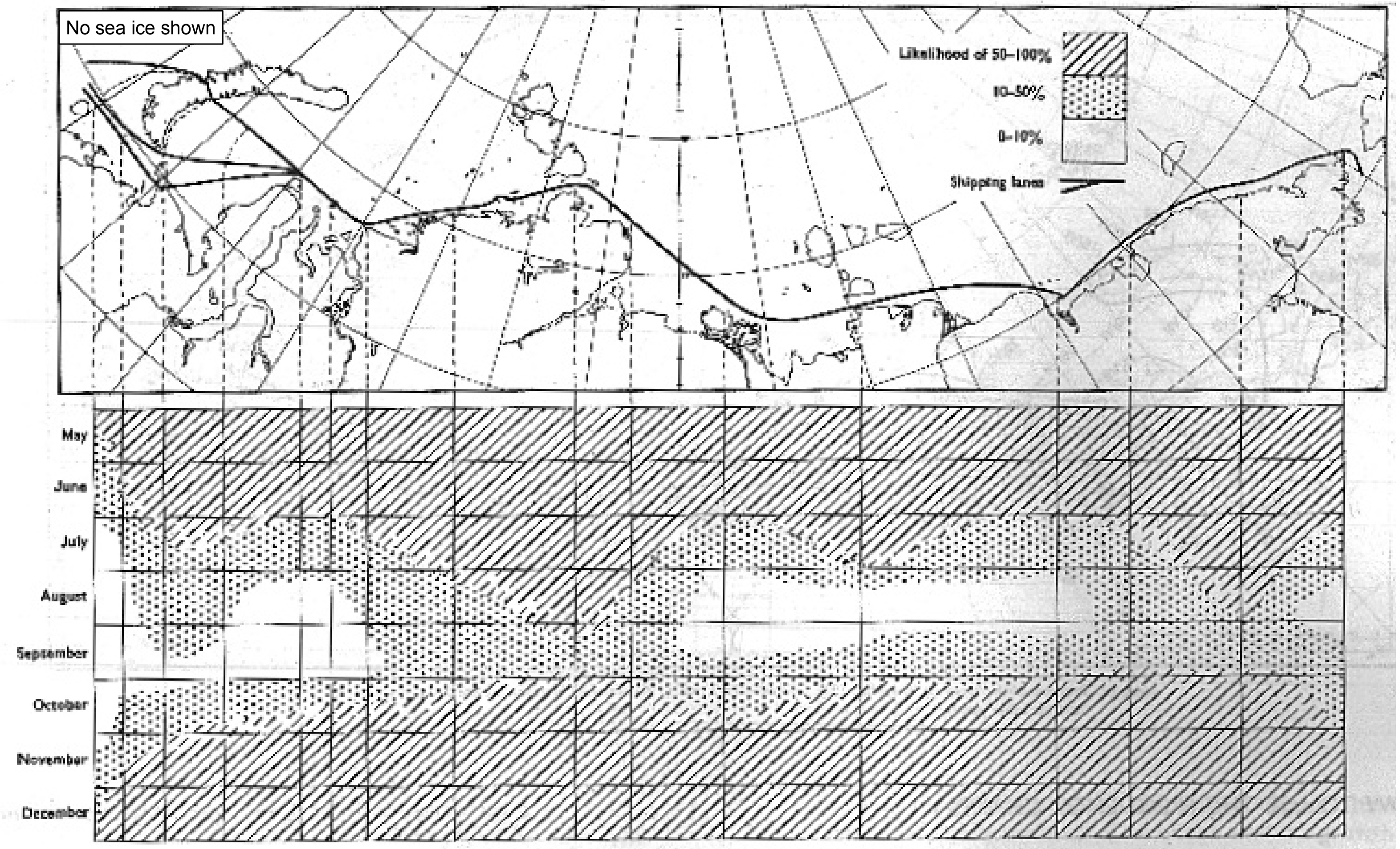


Figure 5. Assessment of Marine Access North of Eurasia from May to December

Likelihood of encountering sea ice that would stop an 'ordinary' ship along a principal marine route north of Eurasia during May through December. This assessment is based on a statistical compilation of available sea-ice observations from shipboard or from a point on shore during the period 1850 to 1952, aggregated into fifteen-day intervals. Sea ice was classified by degree of navigability for 'strongly built ships which are not afraid of meeting ice, but which have no icebreaker assistance' (Armstrong, 1958).

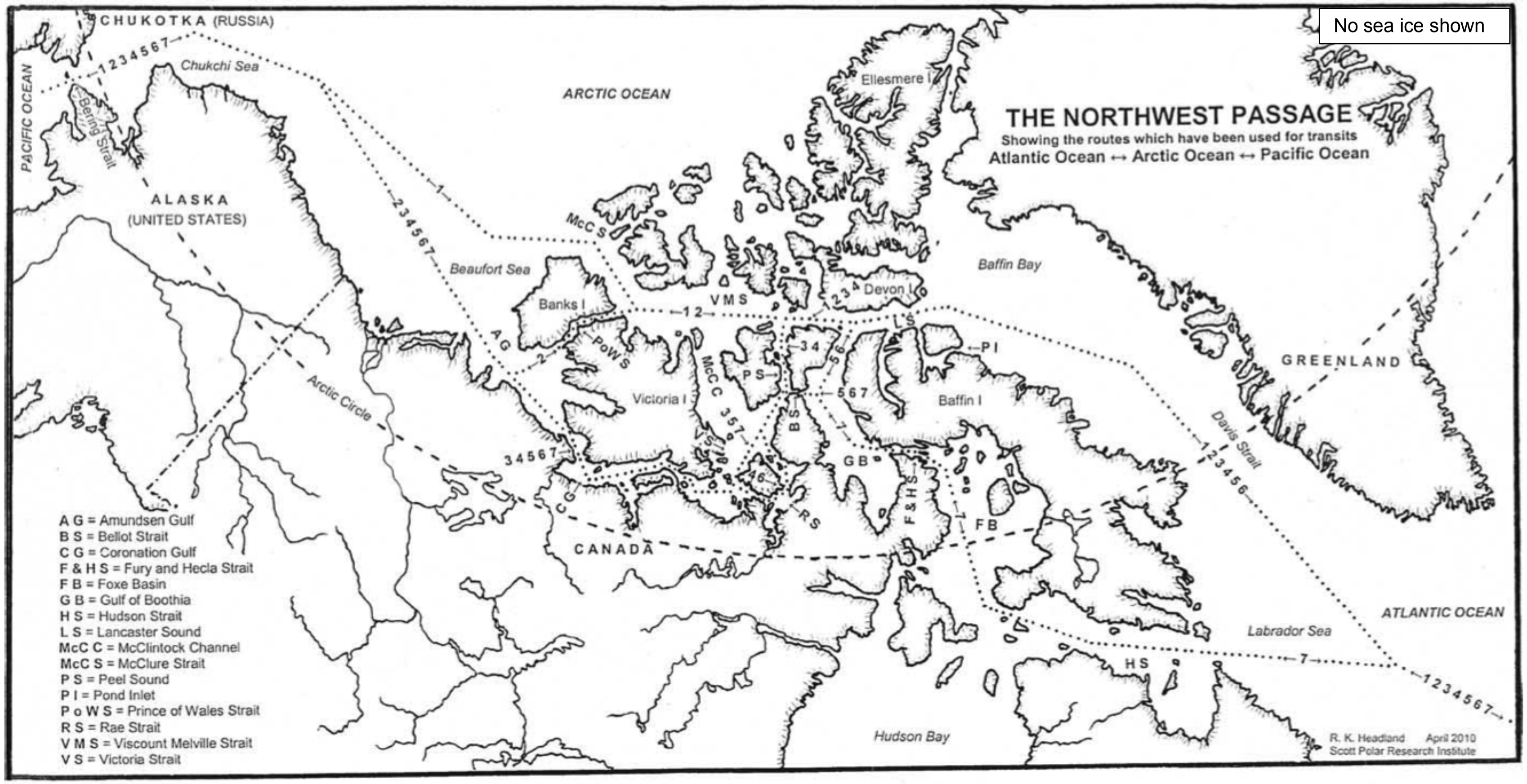
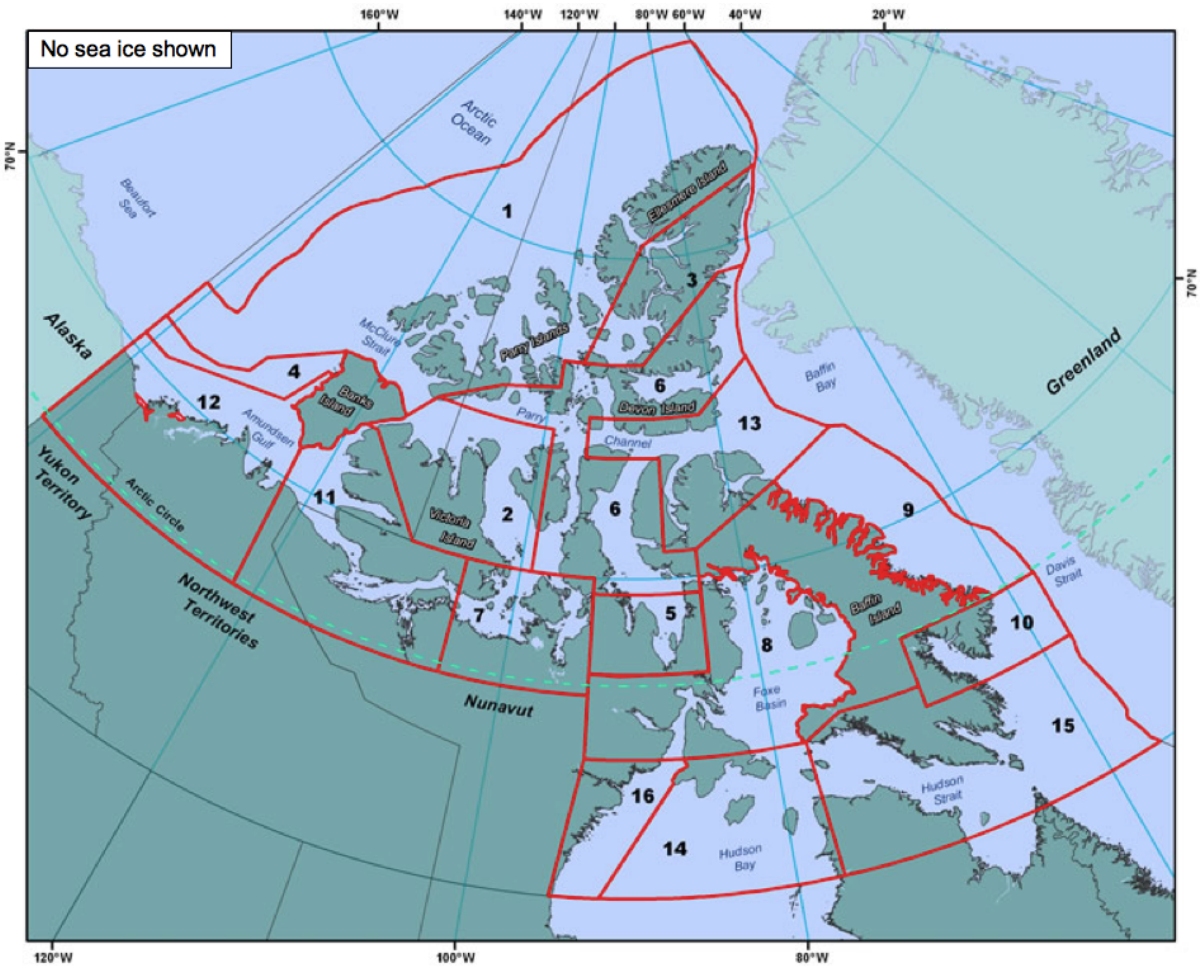


Figure 6. Seas and Straits North of North America

More than ninety islands larger than 130 km^2 comprise the Canadian Arctic Archipelago, through which seven routes of the Northwest Passage between the Atlantic Ocean and Pacific Ocean exist. Davis Strait, Hudson Strait, Barrow Strait, Rae Strait, Simpson Strait, Fury and Hecla Strait, Bellot Strait, McClure Strait, Franklin Strait, Victoria Strait, Prince of Wales Strait, and Bering Strait (Headland, 2011). In addition, Nares Strait between Ellesmere Island and Greenland connects Baffin Bay with the central Arctic Ocean.



Category	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Zone 7	Zone 8	Zone 9	Zone 10	Zone 11	Zone 12	Zone 13	Zone 14	Zone 15	Zone 16
Arctic Class 10	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year
Arctic Class 8	July 1 toOct.15	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year
Arctic Class 7	Aug.1 toSept.30	Aug.1 toNov.30	July 1 toDec.31	July 1 toDec.15	July 1 toDec.15	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year
Arctic Class 6	Aug.15 toSept.15	Aug.1 toOct.31	July 15 toNov.30	July 15 toNov.30	Aug.1 toOct.15	July 15 toFeb.28	July 1 toMar.31	July 1 toMar.31	All Year	All Year	July 1 toMar.31	All Year	All Year	All Year	All Year	All Year
Arctic Class 4	Aug.15 toSept.15	Aug.15 toOct.15	July 15 toOct.31	July 15 toNov.15	Aug.15 toSept.30	July 20 toDec.31	July 15 toJan.15	July 15 toJan.15	July 10 toMar.31	July 10 toFeb.28	July 5 toJan.15	June 1 toJan.31	June 1 toFeb.15	June 15 toFeb.15	June 15 toMar.15	June 1 toFeb.15
Arctic Class 3	Aug.20 toSept.15	Aug.20 toSept.30	July 25 toOct.15	July 20 toNov.5	Aug.20 toSept.25	Aug.1 toNov.30	July 20 toDec.15	July 20 toDec.31	July 20 toJan.20	July 15 toJan.25	July 5 toDec.15	June 10 toDec.31	June 10 toDec.31	June 20 toJan.10	June 20 toJan.31	June 5 toJan.10
Arctic Class 2	No Entry	No Entry	Aug.15 toSept.30	Aug.1 toOct.31	No Entry	Aug.15 toNov.20	Aug.1 toNov.20	Aug.1 toNov.30	Aug.1 toDec.20	July 25 toDec.20	July 10 toNov.20	June 15 toDec.5	June 25 toNov.22	June 25 toDec.10	June 25 toDec.20	June 10 toDec.10
Arctic Class 1A	No Entry	No Entry	Aug.20 toSept.15	Aug.20 toSept.30	No Entry	Aug.25 toOct.31	Aug.10 toNov.5	Aug.10 toNov.20	Aug.10 toDec.10	Aug.1 toDec.10	July 15 toNov.10	July 1 toNov.10	July 15 toOct.31	July 1 toNov.30	July 1 toDec.10	June 20 toNov.30
Arctic Class 1	No Entry	No Entry	No Entry	No Entry	No Entry	Aug.25 toSept.30	Aug.10 toOct.15	Aug.10 toOct.31	Aug.10 toOct.31	Aug.1 toOct.31	July 15 toOct.20	July 1 toOct.31	July 15 toOct.15	July 1 toNov.30	July 1 toNov.30	June 20 toNov.15
Type A	No Entry	No Entry	Aug.20 toSept.10	Aug.20 toSept.20	No Entry	Aug.15 toOct.15	Aug.1 toOct.25	Aug.1 toNov.10	Aug.1 toNov.20	July 25 toNov.20	July 10 toOct.31	June 15 toNov.10	June 25 toOct.22	June 25 toNov.30	June 25 toDec.5	June 20 toNov.20
Type B	No Entry	No Entry	Aug.20 toSept.5	Aug.20 toSept.15	No Entry	Aug.25 toSept.30	Aug.10 toOct.15	Aug.10 toOct.31	Aug.10 toOct.31	Aug.1 toOct.31	July 15 toOct.20	July 1 toOct.25	July 15 toOct.15	July 1 toNov.30	July 1 toNov.30	June 20 toNov.10
Type C	No Entry	No Entry	No Entry	No Entry	No Entry	Aug.25 toSept.25	Aug.10 toOct.10	Aug.10 toOct.25	Aug.10 toOct.25	Aug.1 toOct.25	July 15 toOct.15	July 1 toOct.25	July 15 toOct.10	July 1 toNov.25	July 1 toNov.25	June 25 toNov.10
Type D	No Entry	No Entry	No Entry	No Entry	No Entry	No Entry	Aug.10 toOct. 5	Aug.15 toOct.20	Aug.15 toOct.20	Aug.5 toOct.20	July 15 toOct.10	July 1 toOct.20	July 30 toSept.30	July 10 toNov.10	July 5 toNov.10	July 1 toOct.31
Type E	No Entry	No Entry	No Entry	No Entry	No Entry	No Entry	Aug.10 toSept.30	Aug.20 toOct.20	Aug.20 toOct.15	Aug.10 toOct.20	July 15 toSept.30	July 1 toOct.20	Aug.15 toSept.20	July 20 toOct.31	July 20 toNov.5	July 1 toOct.31

Figure 7. Assessment of Marine Access North of North America

Canadian Shipping Safety Control Zones 1-16 specify dates of allowed transit for vessels based on their capability of navigating through sea ice (Transport Canada, 2010).

Several experimental voyages tested Arctic marine access for a number of vessels along various routes during summer. In 1969, the *SS Manhatten* transited the Northwest Passage in August carrying one symbolic barrel of oil. During the journey, the ship encountered a pingo-like feature of melting submarine permafrost that rose 30 m from the sea bed (Bennett *et al.*, 2007). This type of dynamic hazard shows that Arctic marine access is variable in time and underlies the importance of repeated environmental observation to ensure safe navigation. In 1991, *L'Astrolabe* transited along the Northern Sea Route, receiving operational forecasts of the nearby sea-ice conditions based on satellite Synthetic Aperture Radar measurements analysed in St Petersburg and communicated to the vessel (Sandven, 1993). This successful test of a new pathway of information to the vessel enabled more informed ice navigation. Several other successful transits of commercial vessels subsequently tested the physical and economic viability of the Northern Sea Route. In 1994, an experimental northern sea route voyage occurred as a part of the European Arctic Development (ArcDev) project, a multinational effort designed to test the viability of the Northern Sea Route (European Commission, 1999). In 1995, the International Northern Sea Route Programme (INSROP), a longitudinal and trans-disciplinary study, sponsored the transit of *Kandalaksha* through the northern sea route (INSROP, 1999). These four Arctic transits successfully implemented experimental operating techniques, including *ad hoc* environmental monitoring over reduced space and time scales, but tested only a small part of what was theoretically possible for navigation north of the Arctic Circle.

There have also been efforts to classify the ice-navigation potential of a vessel based on its operating area, season, and activity type. The International Maritime Organization (IMO) defines ship operations in Arctic ice-covered waters based on a static area delineated to exclude the north Atlantic (IMO, 2009). The International Association of Classification Societies (IACS) categorized ice-strengthened vessels into seven Polar Classes by their operating season and structural reinforcements (IACS, 2007). In these systems, ice-strengthened vessels are distinguished from 'icebreakers', ice-breaking vessels with the appropriate structure and propulsion to enable 'aggressive' [sic] navigation through severe ice conditions for ice management and escort services (IACS, 2011). Recently, however, advances in naval engineering have led to the development of double-acting vessels capable moving ahead in open water and astern in ice, challenging the traditional definition of an icebreaker (Vocke *et al*., 2009). Classifications of ice navigation potential that include descriptions of operating area, operating season, and activity are prone to changes in climate and developments in ship design and operations.

Previous assessments of Arctic marine access limited the theoretical area and season for navigation to single routes and summer navigational seasons. These spatial and temporal constraints are being challenged by diminishing average sea-ice cover and improving capability for vessels operating in sea-ice. As a result, a fundamental re-assessment is required to define Arctic navigational possibilities in relation to sea-ice conditions.

1.3. Previous Assessments of Arctic Marine Traffic

Changing access for surface vessels prompt questions about the present and future marine use of the Arctic Ocean. As human use of the Arctic Ocean has evolved from stone-age subsistence (which persists in some forms) to industrialized nuclear-age exploitation, methods of observing marine traffic have become more timely, systematic, and comprehensive.

Original reports of Arctic marine activity were first-person observations recorded in messages left ashore or ships' logs. Eyewitness in settlements or on other vessels have directly observed and preserved accounts of Arctic voyages (Cook, 1791; Scoresby, 1820). As activity in the Arctic maritime region developed, economic interests, political conflict, and geographic historiography have motivated several comprehensive reviews of sub-regional marine traffic based on indirect observations. In particular, transits along the Northeast and Northwest Passages, and voyages to the Geographic North Pole have been the subject of previous assessments.

Since Adolf Erik Nordenskiöld first transited the Northeast Passage from Atlantic to Pacific north of Eurasia aboard *Vega* in 1879, records of the early expeditionary voyages along the Eurasian coast enabled scientific advancement and planning of subsequent Arctic marine operations (Nordenskiöld, 1881; Kotel'nekova, 1919; Zubov, 1948). Annual reviews of the marine traffic on the Northern Sea Route (NSR) were published in the years following 1945 using secondary sources counting number of vessels and total transported tonnage (Armstrong, 1991; Brigham, 1993; Michalichenko, 2010). Figure 8 shows the volume of marine traffic through the Northern Sea Route according to one of these sources (Michailichenko, 2010). After 1945, investment in icebreakers, Arctic ports, and marine infrastructure enabled increased traffic along the route. The operation of multiple nuclear icebreakers in the 1960s enabled even larger volumes of marine traffic. More than 6 million tonnes were transported via the Northern Sea Route at the peak of the marine traffic during 1986, representing approximately 1% of global transported cargo for that year (United Nations Conference on Trade and Development, 1986, Michailichenko, 2010). With *Perestroika* and collapse of the Soviet Union, Arctic settlements depopulated and the volume of marine traffic along the Northern Sea Route declined precipitously to the marine transport of the 1960s. While volume of transport in the Northern Sea Route has been slow to increase, a number of non-Russian ships have transited the Northeast Passage with Russian icebreaker escort since the 1990s (Brigham, 2010).

Since Roald Amundsen first transited the Northwest Passage from Atlantic to Pacific north of the North America aboard *Gjøa* from 1903 to 1906, there have been a number of individuals and organizations that have recorded subsequent voyages (Amundsen, 1908). A recent assessment of a century of Northwest Passage transits reported an increasing number of vessels transits, especially for tourism (Headland, 2010). Figure 9 shows the increase in number of Northwest Passage transits, especially the due to tourism and recreational sailing according to this published account (Headland, 2010). While the number of voyages have been increasing since the first transit, the volume of marine transport through the Northwest Passage was never as large as the marine traffic in the Northern Sea Route.

Since Yuriy Kuchiyev arrived at the Geographic North Pole by surface transit from Murmansk aboard Soviet nuclear icebreaker *Arktika* on 17 August 1977, there has been an account of the number of voyages to the central Arctic Ocean (Headland, 2011). According to this study, fourteen different nuclear and conventional surface vessels navigated to the Geographic North Pole (90·00°N) during eighty-eight voyages summarized in Figure 10 (Headland, 2011). All ships made the voyage during a summer period from 29 June to 12 September except for *Sibir*, which transited during May. Seven of these voyages transited between Atlantic and Pacific Oceans, beginning when Anatoly Gorshkovskiy crossed the Arctic Ocean from Atlantic to Pacific via the Geographic North Pole aboard Soviet nuclear icebreaker *Sovetskiy Soyuz* in 1991 (Headland, 2011).

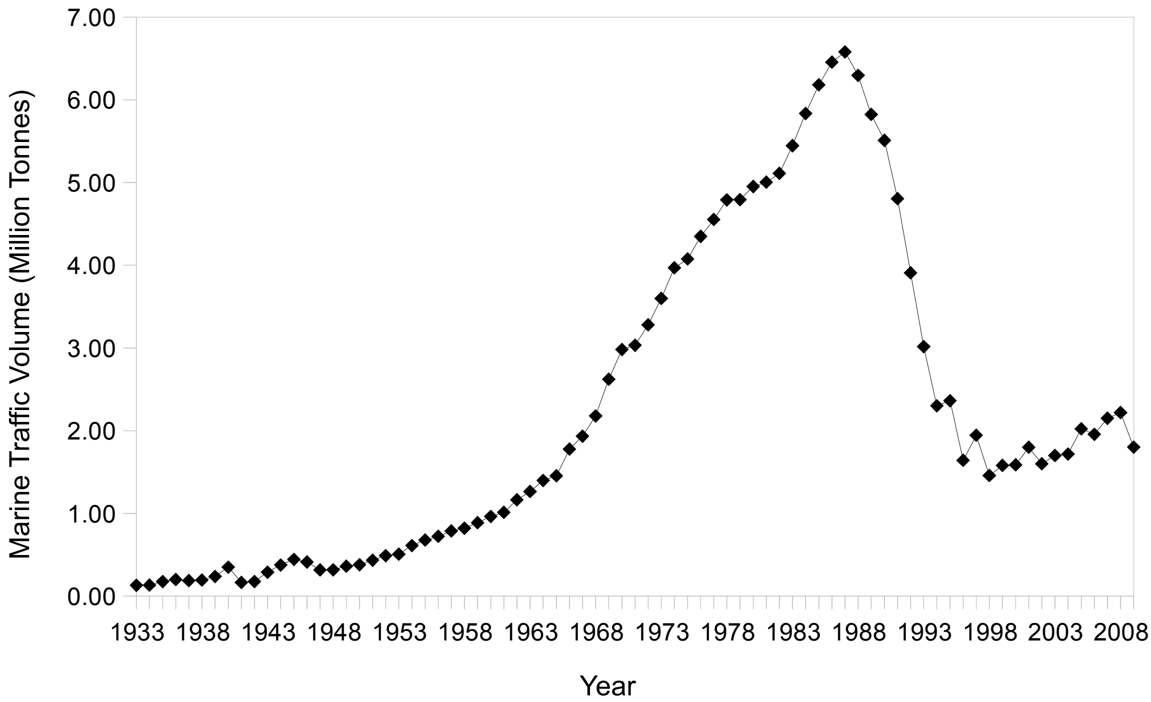
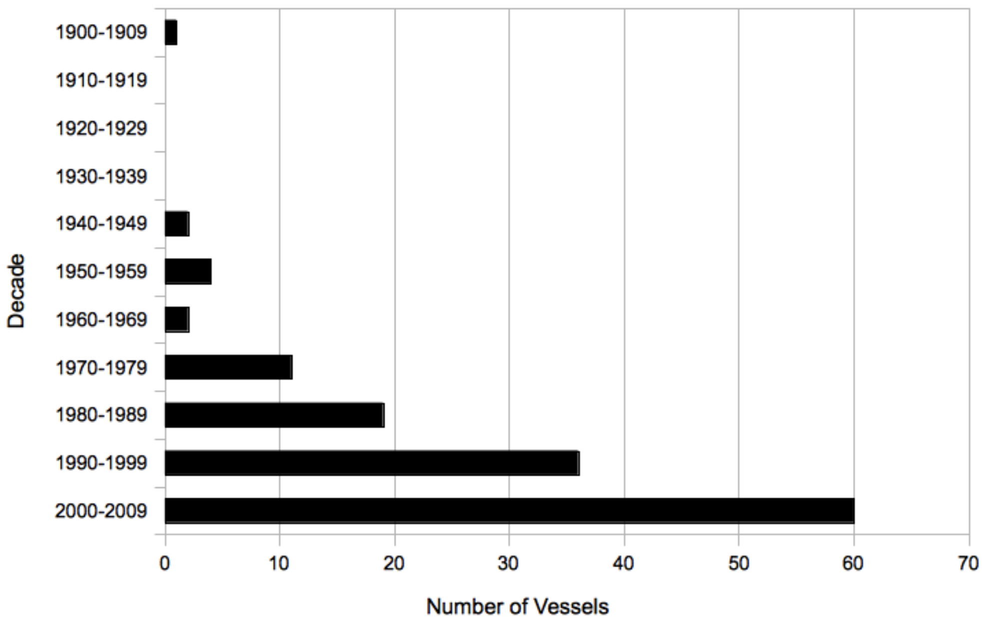


Figure 8. Marine Traffic on the Northern Sea Route

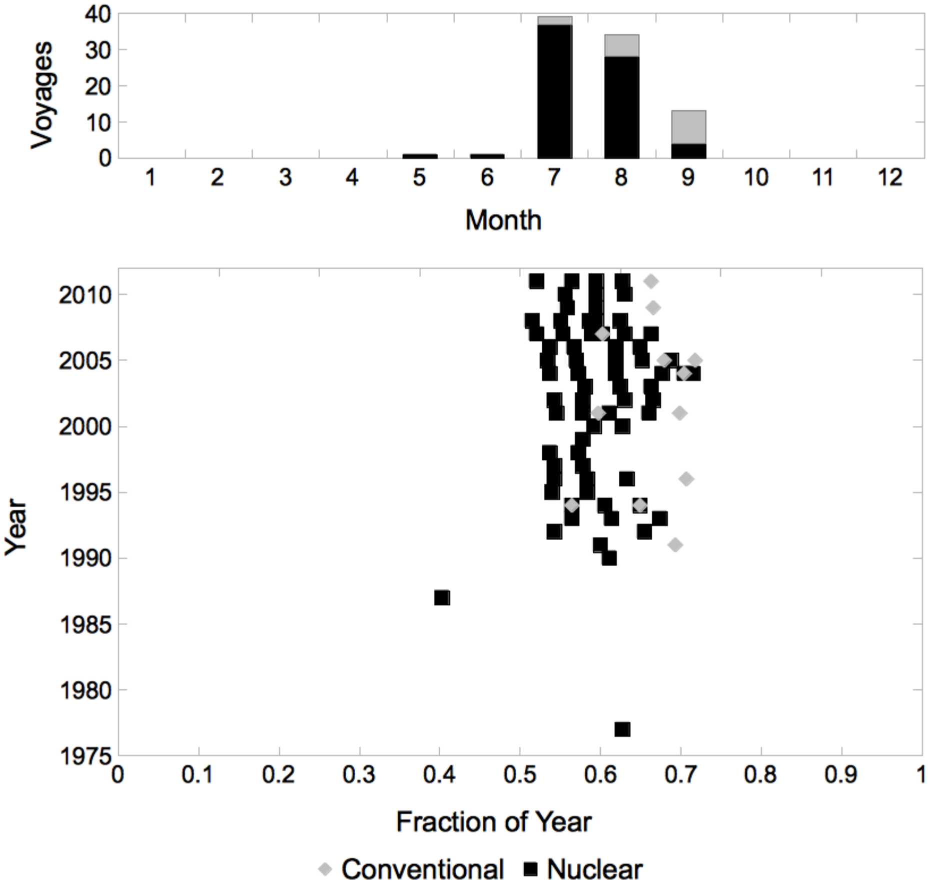
Marine traffic along the Northern Sea Route, the transport corridor between the Barents Sea and the Bering Strait (Mikhailichenko, 2011). The maximum volume transported was recorded in 1986, after which Peristroika saw the collapse of the trade infrastructure. This record shows that political and economic factors influence Arctic marine traffic.



	Small Craft	Passenger Vessel	Total
1900-1909	1		1
1910-1919			
1920-1929			
1930-1939			
1940-1949	2		2
1950-1959			4
1960-1969			2
1970-1979	2		11
1980-1989	5	3	19
1990-1999	4	15	36
2000-2009	38	16	60
	52	34	135

Figure 9. Surface Vessel Transits through the Northwest Passage

Marine traffic along the Northwest Passage from Atlantic to Pacific via the Arctic Ocean (Headland, 2010). Unlike the Northern Sea Route, marine traffic through the Northwest passage has increased since 1970. Tourism and recreation have comprised a growing proportion of marine traffic.



Surface Vessel	Fuel	First Voyage	Flag	Count
Arktika	Uranium	1977	Soviet Union	2
Sibir	Uranium	1987	Soviet Union	1
Rossiya	Uranium	1990	Soviet Union	2
Sovetskiy Soyuz	Uranium	1991	Soviet Union	8
Oden	Oil	1991	Sweden	6
Polarstern	Oil	1991	Germany	3
Yamal	Uranium	1993	Russian Federation	46
Kapitan Dranitsyn	Oil	1994	Russian Federation	1
Louis S. St Laurent	Oil	1994	Canada	1
Polar Sea	Oil	1994	United States	1
Vidar Viking	Oil	2004	Norway	1
Akedemik Federov	Oil	2005	Russian Federation	2
Healy	Oil	2001	United States	2
50 Let Pobedy	Uranium	2008	Russian Federation	12

Figure 10. Surface Vessel Voyages to the Geographic North Pole

Fourteen different nuclear and conventional surface vessels navigated to the Geographic North Pole (90·00°N) during eighty-eight voyages. *Sibir* was the only vessel that transited during May, all others made the voyage in a summer period from 29 June to 12 September. Seven of these voyages transited between Atlantic and Pacific Oceans (Headland, 2011).

While various assessments recorded surface vessel operations in localized Arctic areas, the earliest review of pan-Arctic marine operations was recorded in the 'Arctic Transport' section of the *Polar Regions Atlas* (Central Intelligence Agency, 1979). Figure 11 shows annual tonnage of marine traffic in selected ports and routes north of 55°N, including the dates approximating the annual limits of navigating season imposed by sea ice. In this report, the highest concentration of ship traffic in the Arctic at that time occurred in a section of the Northern Sea Route from Kara Strait to Murmansk and the Norwegian offshore region. Significant riverine transport volume was reported for the north Eurasian rivers, and to a lesser degree, the Mackenzie River in North America. The largest ports by transport volume were Valdez in Alaska, and Murmansk, Arkhangel'sk, and Dudinka/Noril'sk in the Soviet Union. The authors of this comprehensive circumpolar marine traffic review provided no references or discussion of study methods.

A recently completed Arctic Marine Shipping Assessment (AMSA) presented a comprehensive geospatial analysis of maritime activities on the Arctic Ocean for one year. Sponsored by the Arctic Council, the 2009 report was largely based on 2004 data collected independently from seven Arctic Council member states: Canada, Denmark, Iceland, Norway, Sweden, Russian Federation, United States of America. Military activities were excluded from the study. Each state authority defined vessel categories and geographic boundaries according to different national policies. For example, approximately 3,000 surface vessels of the 6,000 reported in AMSA transited the Great Circle Route through the Aleutian Islands, which is included in the Arctic maritime area as defined by the United States (United States Arctic Research and Policy Act, 1984). Further, each data set collected by the Arctic Council member states contained different types of observations of surface vessel transits, including visual observations, secondary sources, and received messages from Automatic Identification System. These heterogeneous data were consolidated into a common geographic information system and interpolated to produce an assessment of annual Arctic marine traffic. The study reported the number of fishing vessel days in each of the Large Marine Ecosystems of the Arctic and the number of transits by other types of vessels along selected shipping routes, shown in Figure 12 (AMSA, 2009). The assessment concluded that besides fishing, the principal categories of Arctic marine operations—resource extraction, supply of settlements, tourism, science, and government activities—were 'destinational' in character.

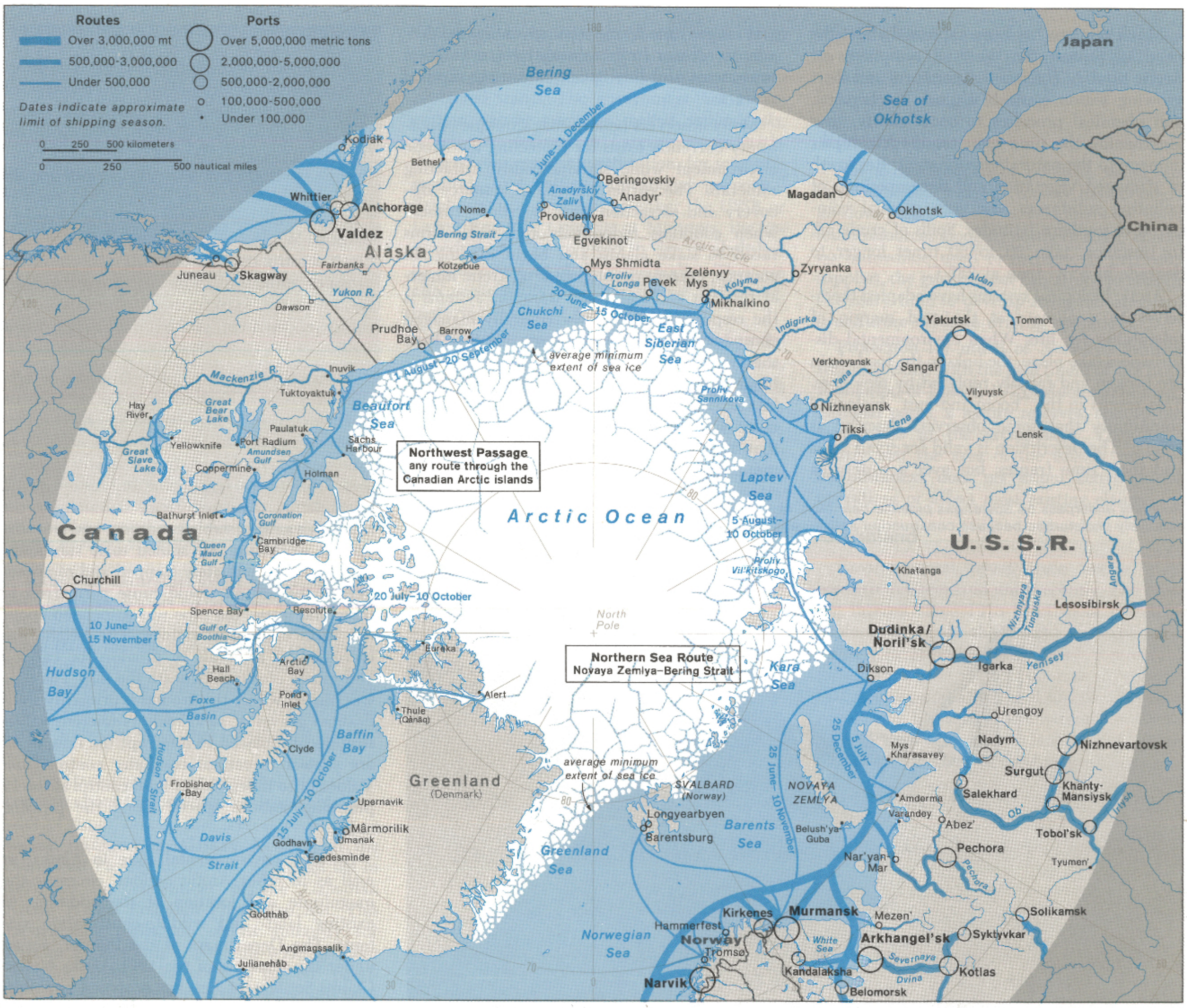


Figure 11. Earliest Assessment of Pan-Arctic Marine Traffic

Assessment of pan-Arctic marine traffic north of 55°N, excluding an area of the North Atlantic, in 1978 (Central Intelligence Agency, 1979). This report categorized ports and routes by annual tonnage in metric tons and attributed dates approximating the limits of the shipping season to various routes along the Northwest Passage and Northern Sea Route. In addition, the map labels Arctic coastal states, seas, and the average minimum extent of sea ice in 1978. At the time that this report was published, there had been one transit of a nuclear icebreaker, *Arktika*, to the Geographic North Pole in 1977.

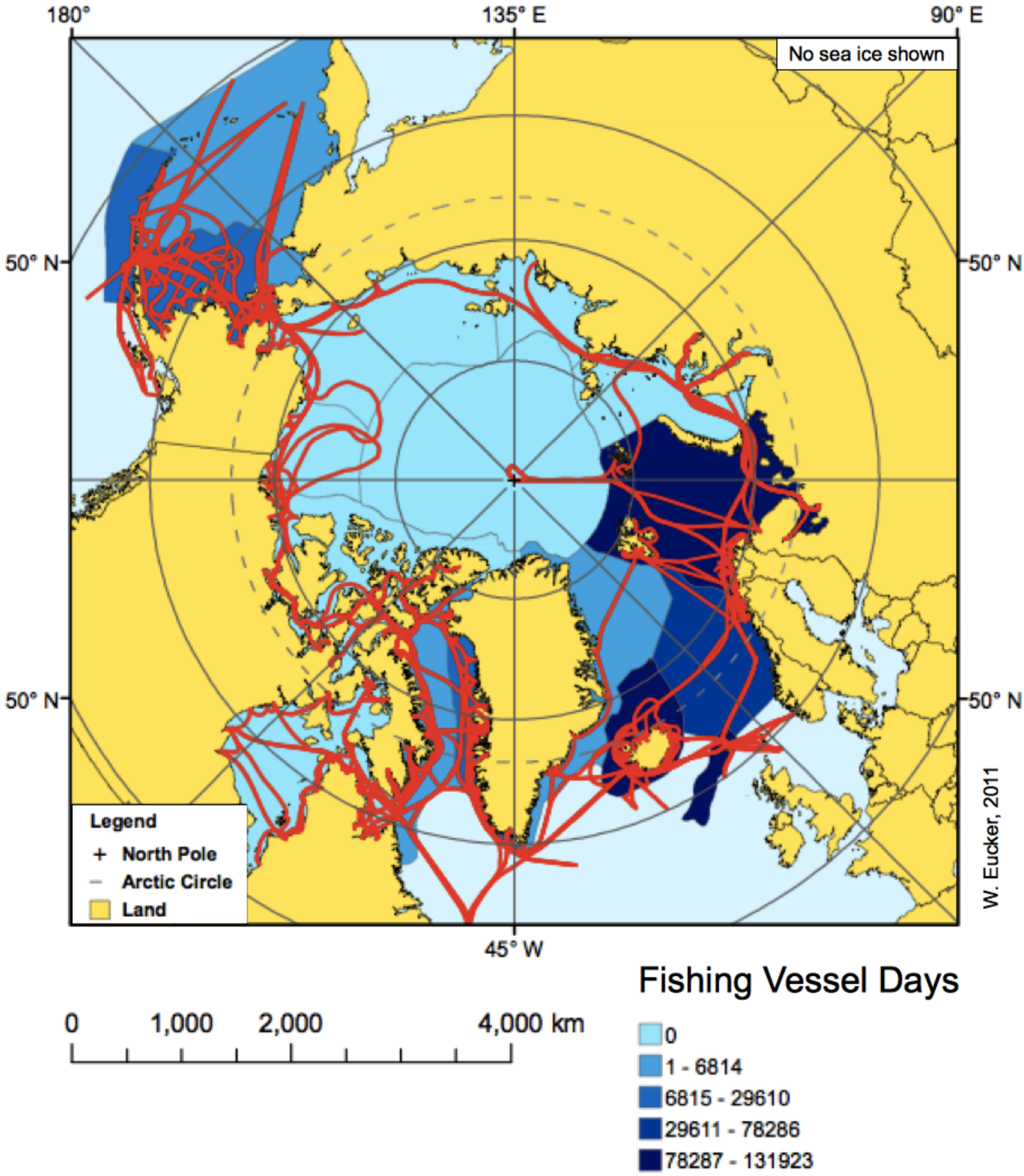


Figure 12. Most Recent Assessment of Pan-Arctic Marine Traffic

Number of surface vessels operating in the Arctic maritime region during 2004, reported in fishing vessel days per Large Marine Ecosystem (shades of blue) and number of transits along selected shipping routes (red). The majority of fishing occurred in the Atlantic Arctic and South of the Bering Strait in the Pacific, and no commercial fishing was reported in the Central Arctic Ocean. Other vessels navigated north of the Arctic Circle throughout the year, but the majority of reported surface vessels transited the Great Circle Route through the Aleutian Islands, south of the Arctic Circle. (Arctic Marine Shipping Assessment, 2009).

Various methods were used to observe, consolidate, and report surface vessels navigating along the Northern Sea Route, through Northwest Passage, to the geographic North Pole, and within the entire Arctic Ocean during the 20th and 21st centuries. These previous assessments show that Arctic marine traffic has varied spatially from route to region and temporally from season to year. Though there have been many different ways to report vessel activities, no method has yet been implemented that is suitable for timely, consistent, and comparative analysis of Arctic marine traffic across relevant spatial and temporal scales.

1.4. Requirements of Arctic Marine Information

Changing navigational possibilities and marine use prompt questions about the information required to enhance mariner safety, pollution prevention, and law enforcement in the Arctic Ocean. Surface vessel operations require information describing the operating environment, as information about the vessels is required to plan for infrastructure, respond to emergencies, and enforce laws. The dearth of timely and relevant information is at the centre of developing Arctic marine transport, and underlies the seventeen *Arctic Marine Shipping Assessment* policy recommendations listed in Table 1 (Arctic Council, 2009).

Table 1. Arctic Marine Shipping Assessment *Policy Recommendations*

I. Enhancing Arctic Marine Safety
Linking with International Organizations
IMO Measures for Arctic Shipping
Uniformity of Arctic Shipping Governance
Strengthening Passenger Ship Safety in Arctic Waters
Arctic Search and Rescue (SAR) Instrument
II. Protecting Arctic People and the Environment
Survey of Arctic Indigenous Marine Use
Engagement with Arctic Communities
Areas of Heigtened Ecological and Cultural Significance
Speially Designated Arctic Marine Areas
Protection from Invasive Species
Oil Spill Prevention
Addressing Impacts on Marine Mammals
Reducing Air Emissions
III. Building the Arctic Marine Infrastructure
Addressing the Infrastructure Deficit
Arctic Marine Traffic System
Circumpolar Environmental Response Capacity
Investing in Hydrographic, Meteorological and Oceanographic Data

These policy recommendations, the principal conclusions of the *Arctic Marine Shipping Assessment 2009 Report*, were grouped into three categories to promote safety, cultural and environmental awareness, and infrastructure development related to current and future Arctic marine traffic. With many questions ranging from the optimal spatial and temporal resolution of the observations, to time and effort needed for analysis, to the information delivery pathway, the three AMSA categories serve to organize the discussion related to formulating information requirements for Arctic marine traffic.

Enhancing marine safety has a philosophical foundation in perhaps the oldest and least-contested maritime custom: rendering aid to mariners in distress, regardless of nationality. After the *RMS Titanic* struck ice in the North Atlantic in 1912, a series of international conventions were signed to codify the ancient seafaring tradition:

> Every State shall require the master of a ship sailing under its flag, insofar as he can do so without serious danger to the ship, the crew or the passengers: (*a*) To render assistance to any person found at sea in danger of being lost; (*b*) To proceed with all possible speed to the rescue of persons in distress if informed of their need of assistance, insofar as such action may reasonably be expected of him (United Nations, 1958)

As such, the *International Convention for the Safety of Life at Sea (SOLAS), United Nations Convention on the High Seas*, and subsequent amendments provide for the safety of the individual mariner and ship (SOLAS, 1974).

The most comprehensive database on Arctic marine incidents, itself a part of the AMSA database, compiled a description of all accidents in Arctic waters as reported by Arctic coastal nations. Figure 13 shows a geospatial summary of these accidents which occurred aboard vessels north of the Arctic Circle during the 1995-2004 decade (AMSA, 2009). Of all the accidents reported north of the Arctic Circle, most occurred during the summer season, and only 20% involved ice damage. These incidents can be fatal, as a total of twelve lives were reported lost during the decade of reported accidents. However, with new maritime safety systems like the ones codified in the new *Agreement on Cooperation on Aeronautical and Maritime Search and Rescue in the Arct*ic (Arctic SAR Agreement), which delimited Search and Rescue Regions (SRR) of responsibility, these accidents may not increase in frequency as marine traffic increases in the region (Arctic SAR Agreement, 2011).

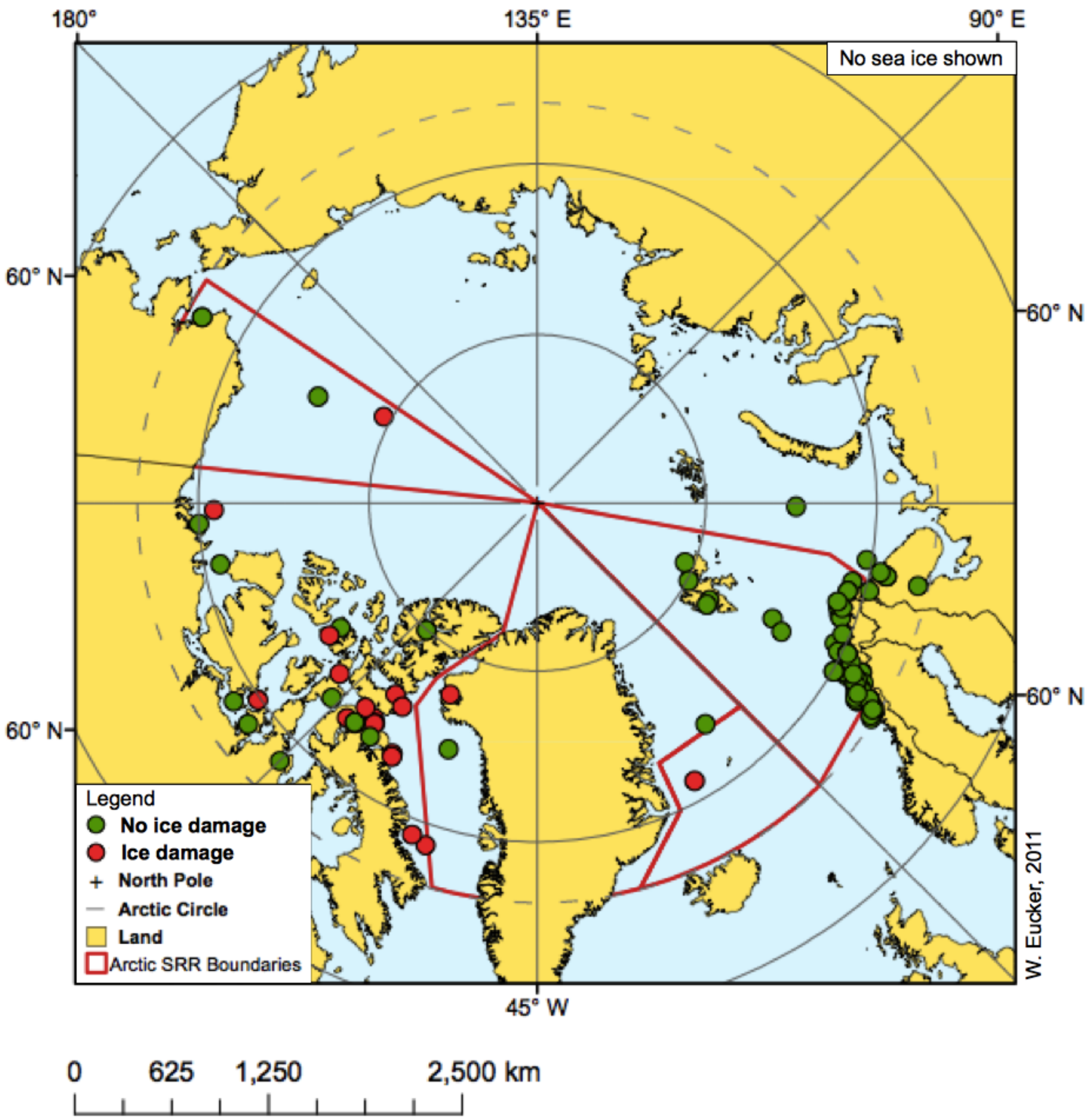


Figure 13. Marine Incidents in Arctic Search and Rescue Regions, 1995-2004

A decade of accidents due to various causes aboard surface vessels reported by national authorities in the Arctic Marine Shipping Assessment (AMSA, 2009). Of 109 accidents reported aboard vessels navigating north of the Arctic Circle from 1995 to 2004, nineteen (17%) involved ice damage and twenty-three (21%) were operating in ice. Thirteen incidents were reported during 2004, the AMSA study year, and a total of twelve lives were reported lost during the decade of reported accidents. The new Norwegian, Russian, United States, Canadian, Danish and Icelandic Search and Rescue Regions (SRR) of responsibility north of the Arctic Circle are shown, committing each Arctic Ocean coastal state to expand search and rescue capabilities in the region (Arctic SAR Agreement, 2011).

Chapter 1. Introduction

As a continued codification of the common desire to enhance maritime safety, the Arctic SAR Agreement is first legally binding accord of the Arctic Council, a high level forum for sustainable development and environmental protection composed of eight nations with territory north of the Arctic Circle, regional indigenous peoples, and observers (Ottawa Declaration, 1996; Arctic Council, 2011). The Agreement was drafted to improve the safety of mariners navigating the Arctic Ocean and tasked member states to assign national assets north of the Arctic Circle for international search and rescue efforts (Arctic SAR Agreement, 2011). Never before has a treaty obligated signatory participants to commit search and rescue infrastructure and expand search and rescue capabilities.

This same year, the Worldwide Navigation Warning Service (WWNWS) for promulgation of navigational and meteorological warnings has been extended to Arctic, the last place on Earth to be covered by the system. The promulgation of Maritime Safety Information (MSI), a principal capability of the Global Maritime Distress and Safety System (GMDSS), serves to identify specific hazards and notify ships of dangerous weather. Because the Inmarsat-C satellite footprint does not extend to the central Arctic Ocean, the Inmarsat SafteyNET system is augmented with safety equipment, protocol, and procedural standards for the high latitudes that includes Digital Selective Calling (DSC), Medium-, High-, and Very-High Frequency radio-communications, and Narrow Band Direct Printing (Maksimov, 2011; Bakker, 2011). The Canadian Coast Guard coordinates NAVAREAs XVII and XVIII, the Norwegian Coastal Administration coordinates NAVAREA XIX, and the Russian Federation coordinates NAVAREAs XX and XXI (WMO, 2009).

The promulgation of relevant, reliable, and timely maritime safety information for vessels and search and rescue responders relies upon a baseline understanding of pan-Arctic marine traffic. As such, expanding search and rescue capabilities and maritime safety information services in the international and multi-faceted Arctic maritime region requires investment decisions informed by the understanding of the physical environment and patterns of human use. Successful implementation of the Arctic SAR Regions, Arctic NAVAREAs/METAREAs, and future maritime safety systems requires the cooperation amongst states, International Governmental Organizations, and non-governmental organizations to invest in information architectures which universally enhance maritime safety.

Protecting Arctic people and the environment has its philosophical foundation in establishing equity for current and future generations. Understanding the complex physical environment and patterns of human use are fundamental to balance the stewardship of the natural environment and indigenous cultures on the one hand, and the pursuit of economic development on the other.

A precautionary approach has been taken by some Arctic authorities to constrain human use, at least until further information is collected. Examples of the precautionary approach include the *Arctic Waters Pollution Prevention Act* in the waters of the Canadian Arctic Archipelago and the moratorium on commercial fishing north of the Bering Strait (*Arctic Waters Pollution Prevention Act*, 1985; North Pacific Fishery Management Council, 2009). However, the precautionary approach is often not compatible with global economic demands for marine protein and geological resources, especially oil and gas. As such, more relevant information needs to be collected to better describe the extreme spatial and temporal variability of the natural environment and consequences of coincident biological and human marine activity.

One proposed approach for integrating the large quantity of complex information that would be required for marine spatial planning is the Large Marine Ecosystem. A Large Marine Ecosystem (LME) is a spatial area 200,000 km^2 or larger, with distinct bathymetry, hydrography, productivity and trophically dependent populations that were delimited for conservation purposes (Siron *et al.*, 2008). LMEs can span the sovereign jurisdictions of multiple states, and, as such, enable international ecosystem-based management (Wang, 2004). Figure 14 shows an Arctic Monitoring and Assessment Programme (AMAP) assessment in which petroleum development and biological activities spatially coincide in the twelve Large Marine Ecosystems with partial or entire area north of the Arctic Circle (AMAP, 2008).

The LME framework, or similar geospatial approaches, can be implemented to develop coordination in responding to oil in ice or to prevent whale-ship collisions (MacGillivary, 2010). Coordinated, consistent, and continuous quantitative assessments of the natural environment and surface vessel operations are required to provide sufficient information to inform policies that protect Arctic people and the environment.

Figure 14. Human and Biological Activities in the Arctic Large Marine Ecosystems

Pan-Arctic assessment of biological activities and petroleum development for Arctic Large Marine Ecosystems (AMAP, 2008). Understanding spatial and temporal patterns of use is important for sustainable development and environmental protection of the Arctic Ocean.

Law enforcement has its philosophical foundation in the responsibility of the state to ensure the continuity of political, economic, and cultural stability. As with any region where humans may be found, the Arctic requires the enforcement of laws which prohibit destructive and dangerous activities such as over-fishing, excessive pollution, and illegal transport of humans and controlled substances. The United Nations Convention on the Law of the Sea (UNCLOS) codifies the sovereign rights and jurisdiction of coastal states, including those in the Arctic (UNCLOS, 1982). This treaty provides the framework for coastal states to establish a 200 nautical mile Exclusive Economic Zone (EEZ) and to extend subsea jurisdiction to the outer limit of the respective continental shelf. North of the Arctic Circle, six states have established EEZ extending from their respective territories: Norway, Russian Federation, United States (Alaska), Canada, Denmark (Greenland), and Iceland. In addition, Norway has jurisdiction over the Jan Mayan Exclusive Economic Zone. Beyond the EEZ of these six Arctic coastal states are three regions of the High Seas: the largest one in the central Arctic Ocean, a smaller one in the North Atlantic, and the smallest in the Barents Sea. With six Arctic sovereigns in addition to the regions of High Seas, the Arctic Ocean is a region with challenges and opportunities for current and future law enforcement. Figure 15 summarizes the sovereignty and jurisdiction of the maritime region north of the Arctic Circle.

Relatively minimal human activity in the Arctic has limited the expansion of coastal state information architectures and infrastructure related to law enforcement. The prospect of economic development of the region motivates states to find common solutions that enable the rule of law, such as the Russian-Norwegian maritime boundary agreement (Norwegian Foreign Ministry, 2010). In addition, remote sensing observations and other novel approaches could enable a more distributed, and collaborative, system of enforcing laws in the Arctic.

Recent progress, such as the delimitation of Arctic Search and Rescue Regions, establishment of Arctic Large Marine Ecosystems, and the Russian-Norwegian maritime boundary agreement, has enhanced the mariner safety, pollution prevention, and law enforcement in the Arctic Ocean. However, the dearth of timely and relevant information still inhibits progress. Novel approaches integrating spatial and temporal information related to the marine operating environment and surface vessel operations can inform current and future policy.

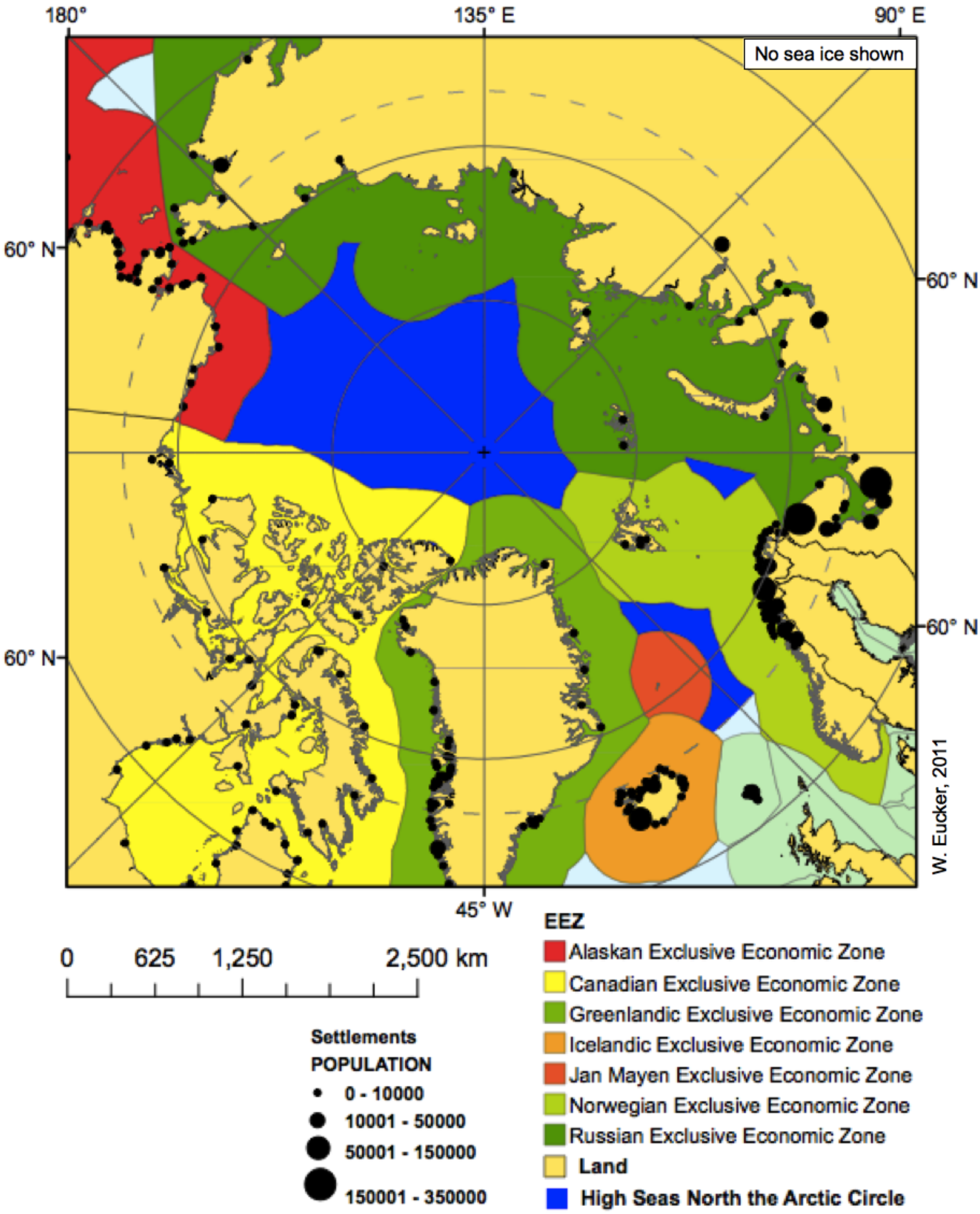


Figure 15. Populated Settlements and Arctic Exclusive Economic Zones

Exclusive Economic Zones (EEZs) and claimed continental shelves north of the Arctic Circle define spatial extent of coastal state rights and responsibilities. The high seas in the centre of the Arctic Ocean is an uncontested international space (International Boundaries Research Unit, 2011). Coastal settlements are the traditional centres of law enforcement for marine traffic.

1.5. Study Approach and Research Questions

This study seeks to characterize the spatial and temporal variability of Arctic marine traffic in relation to changing sea-ice conditions for emerging policies related to mariner safety, pollution prevention, and law enforcement in the Arctic Ocean. Three principal research questions were posed:

(1) What were the spatial and temporal navigating limits imposed by sea ice for surface vessel operations north of the Arctic Circle during the year beginning 1 April 2010?

(2) What were the spatial and temporal position distributions of surface vessel operations north of the Arctic Circle during the year beginning 1 April 2010?

(3) What were the spatial and temporal relationships between sea ice and surface vessel operations north of the Arctic Circle during the year beginning 1 April 2010?

A quantitative geospatial approach was employed to estimate sea-ice conditions, locate surface vessels, and relate the two using spatial statistics. This investigation was based primarily on daily satellite observations of sea-ice concentrations and surface vessel positions north of the Arctic Circle (66·56°N) for the year beginning 1 April 2010 and ending 31 March 2011. Data sources were selected for consistency, spatial and temporal resolution, and pan-Arctic coverage during the study period. The spatial and temporal features of sea ice and vessel traffic were examined using a Geographical Information System (GIS), and further validated with additional data for two representative sub-regions: the Bering Strait and Isfjorden, Spitsbergen. Finally, this thesis does not make recommendations based on these new assessments, but rather presents policy options for a transforming Arctic.

2. Data Sources and Analysis Methods

To investigate how surface vessel operations on the Arctic Ocean have varied over time and space in relation to sea ice for emerging policies related to mariner safety, law enforcement, and pollution prevention, a number of geospatial methods were employed to analyse satellite observations of sea ice concentrations and surface vessel positions north of 66·56°N during a study year beginning on 1 March 2010. The following sections discuss the sources of data and methods of analysis.

2.1. Sources of Data

Three principal research questions related to surface vessel operations were examined with a quantitative geospatial approach using a year of data. Various sea-ice concentration estimations based on radiometric measurements and surface vessel position observations based on Automatic Identification System (AIS) message reports available for the April 2010-March 2011 period were evaluated. A primary data set for analysis was selected from these sources based on consistency, spatial and temporal resolution, and pan-Arctic coverage.

2.1.1. Sea-Ice Concentrations

Since 1978, a consistent pan-Arctic record of sea-ice concentration has been available from satellite-borne passive microwave sensors that distinguish sea ice and snow from water by measuring surface brightness temperature, the relative thermal energy of an equivalent black body which emits the same radiance at the same frequency (Planck, 1914; Rees, 2009). Four sources of pan-Arctic and sea-ice concentration data based on daily satellite radiometry available for the study period are summarized in Table 2. These data are from the National Snow and Ice Data Center (NSIDC) and the Integrated Climate Data Center (ICDC), and differ in both the microwave sensor used to make the measurements and the process used to calculate and archive the sea-ice concentration estimates.

Table 2. Sea-Ice Concentration Data Sources

	1A	2A	2B	2C
Measurement				
Sensor	SSMIS	AMSR-E	AMSR-E	AMSR-E
Satellite	DMSP 5D-3/F17	EOS Aqua	EOS Aqua	EOS Aqua
Process				
Algorithm	NASA Team	NASA Team	NASA Team	ASI
Projection	NPS, 70°N	NPS, 70°N	NPS, 70°N	NPS, 70°N
Datum	Hughes 1980	Hughes 1980	Hughes 1980	WGS 84
Grid Size (km)	25	25	12.5	6.25
Format	BIN	HDF-EOS	HDF-EOS	TIFF

1A: Maslanik and Stroeve, 1999; **2A:** Cavalieri *et al*., 2004A; **2B:** Cavalieri *et al.*, 2004B; **2C:** Integrated Climate Data Center, Universität Hamburg; Kaleschke *et al.,* 2001; Spreen *et al.,* 2008.

Surface brightness temperatures in the maritime region north of 66·5°N during the study period were measured by two satellite-borne sensors: (1) the United States Air Force Defense Meteorological Satellite Program (DMSP) Special Sensor Microwave Imager/Sounder (SSMIS), and (2) the National Aeronautical Space Administration Earth Observing System (EOS) Advanced Microwave Scanning Radiometer - Earth Observing System (AMSR-E). Table 3 displays the characteristics for these sensors and satellites.

While satellite radiometry is relatively insensitive to variability in cloud cover and daylight, spatial and temporal differences in sea ice and snow morphology may influence the measurements (Spreen *et al.*, 2008). Various approaches have been developed to account for the variability in sea ice conditions, including the NASA-Team algorithm, the Comiso-Bootstrap algorithm, and the Arctic Radiation and Turbulence Interaction Study Sea Ice (ASI) concentration algorithm (Swift and Cavalieri, 1985; Comiso, 1986; Spreen *et al.*, 2008). These algorithms calculate sea-ice concentration from measured microwave brightness temperatures based on reference 'tie points' which are locations of validated sea-ice concentration. Sources of calculation error include variable sea-ice and snow morphology, atmospheric characteristics, and assumptions assigning tie points. Resulting uncertainty can be as much as 20% (Spreen *et al.*, 2008).

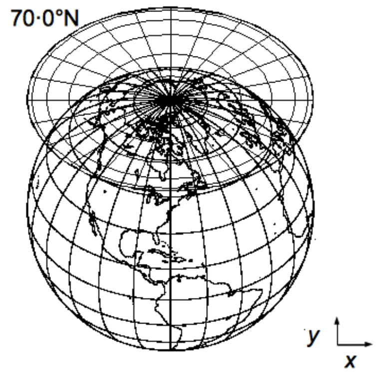
Table 3. Satellite Radiometers and Their Specifications

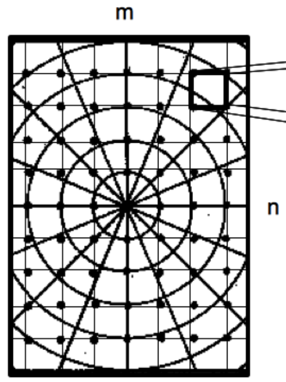
	SSMIS[1]	AMSR-E[2]
Satellite	DMSP 5D-3/F17	NASA EOS Aqua
Orbital Altitude (km)	833	705
Orbital Period (minutes)	102.0	98.4
Launch Year	2006	2002
Number of Channels	24	12
Frequency Range (GHz)	19·35 – 183·3	6·925 – 89·0
Swath Width (km)	1707	1445
Footprint[3] (km × km)	31 × 45	4 × 6
Northern Limit	87·6°N	89·24°N

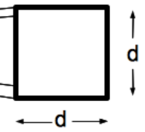
1: Northrup Grumman, 2002; NSIDC, 2011; **2**: NSIDC, No Date; **3**: There is no single value for the footprint of the satellite radiometer because the spatial sampling resolution is frequency dependent and sea-ice concentration estimations are based on measurements from multiple sensor channels on different frequencies. The values shown are based on the SSMIS 37·0 GHz channel and the AMSR-E 89·0 GHz channel (Rees, 2001; Northrup Grumman, 2002; NSIDC, No Date).

Sea-ice concentration estimates are calculated for square area 'grid cells' defined by a projected reference grid. The four sea-ice concentration data sources in Table 2 use the standard NSIDC reference grid for the Northern Hemisphere with various grid cell sizes and 'datum' reference ellipsoids. Figure 16 shows the projected reference grid and its parameters.

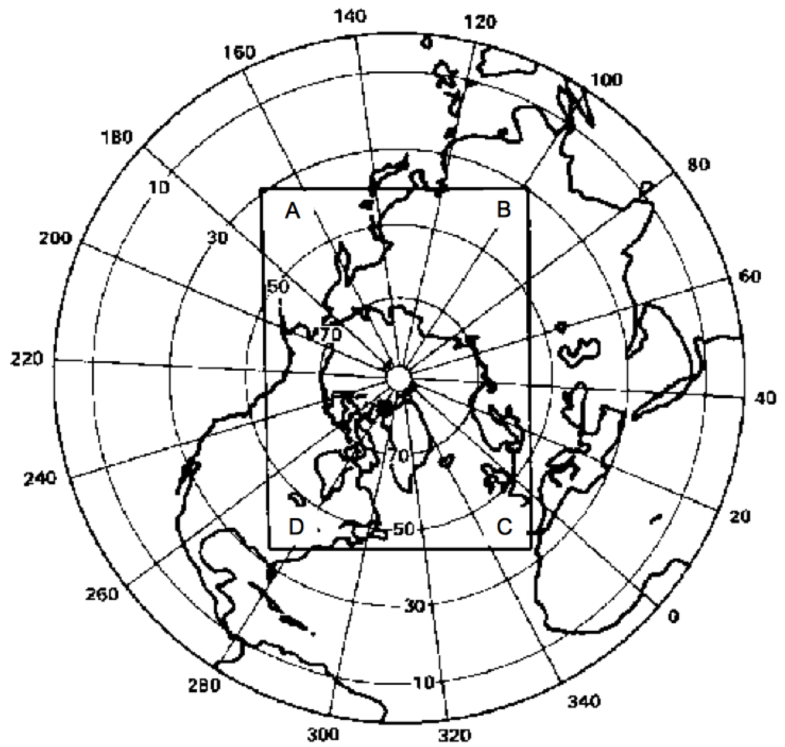
The surface of the Earth is projected onto a two-dimensional grid plane secant at 70·0°N using the north polar stereographic (NPS) projection (Maling, 1973). This projection was selected because it is conformal, accurately representing angles important for navigational applications. The particular geographic reference latitude was chosen to minimize distortion in the marginal ice zone (NSIDC, 2011). A Cartesian coördinate system defines the reference grid such that the origin is the geographic North Pole and the x and y axes orient along 45·0°E and 135·0°E meridians, respectively. The abscissa and ordinates of the corner points A to D define the area which includes most ice-covered seas in the Northern Hemisphere. The grid interval defines the way in which the data are sampled and is related to the spatial resolution of the radiometry measurements. The grid interval prescribes the nominal area of each square grid cell with side length d and corresponding number of columns m and rows n. The data sets implement two different reference ellipsoids, Hughes 1980 and the World Geodetic System 1984, which approximate the surface of the Earth (WGS 84). Table 4 presents the parameters for these reference surfaces which differ by approximately 100m at the Arctic Circle.







d	m	n
Grid Size (km)	**Columns**	**Rows**
6.25	1216	1792
12.50	608	896
25.00	304	448



Corner	*x* (km)	*y* (km)	Latitude	Longitude
A	-3850.0	5850.0	30.98°N	168.35°E
B	3750.0	5850.0	31.37°N	102.34°E
C	3750.0	-5350.0	34.35°N	9.97°W
D	-3850.0	-5350.0	33.92°N	80.74°W

Figure 16. North Polar Stereographic Grid

The reference grid produced by projecting the Earth's surface onto a plane secant at 70·0°N using a stereographic azimuthal projection such that the *x* and *y* axes align to 45·0°E and 135·0°E, respectively. Nominal grid cell size *d* determines the number of columns *m* and rows *n* between corner points *A* – *D* (Images adapted from NSIDC, 2011).

Table 4. Earth Surface Reference Parameters

	Hughes 1980	WGS 1984
Major Axis *a* $(10^6\ m)$	6.378273	6.378137
Flattening *f*	1/ 298.279411123064	1/ 298.257223563
Eccentricity *e*	0.081816153	0.08181919

(Maling, 1973; Pearson, 1990)

The sea-ice concentrations from dataset **2C** (ICSC) were chosen as the primary data set because they contained the greatest spatial resolution (nominal grid size 6·25 km). The ICSC sea-ice concentration data are stored in byte format (0 to 255), in which the value of the Tagged Image File Format (TIFF) byte data represents a range of 0·5% ice concentration such that the concentrations between 0% and 100% scale to values 0 to 200. A value of 251 corresponds to land, assigned by the ICSC team based on the International Bathymetric Chart of the Arctic Ocean, the Goddard Space Flight Center land mask provided by NSIDC, and the Generic Mapping Tools coastline (Jakobsson *et al*, 2008; NSIDC, 2011; Generic Mapping Tools, 2011). Similarly, a value of 255 corresponds to missing data for regions north of 89·24°N, the AMSR-E sensor limit. The ICSC dataset uses the WGS 84 reference surface.

2.1.2. Surface Vessel Positions

Remote reception of Automatic Identification System (AIS) messages can provide an automatic, consistent, and synoptic record of daily surface vessel locations on the Arctic Ocean. Various networks of ground stations and satellites receive AIS messages transmitted from surface vessels operating in the Arctic maritime region. In particular, the Port of Longyearbyen, the Marine Exchange of Alaska, and SpaceQuest, Limited, provided source data for this study based on AIS messages received by their networks from April 2010 to March 2011.

Originally developed to prevent ship collisions in the Swedish Archipelago where islands interfere with line-of-sight radar systems, AIS is a ship position reporting communication protocol and equipment integration standard required by the International Maritime Organization (IMO) since July 2008 for all ships larger than 300 Gross Tonnage and commercial passenger vessels of all sizes (SOLAS, 1974). AIS transponders broadcast messages encoded with static and dynamic information about the vessel in 2 second to 6 minute intervals using Time Division Multiple Access (TDMA) to avoid mutual interference on two dedicated very high frequency channels: (A) AIS1 at 161.975 MHz; and (B) AIS2 at 162.025 MHz (IMO, 2010). The International Telecommunications Union (ITU) has standardized the specifications of AIS, describing 27 message types of which types 1, 3 and 18 are position reports (ITU, 2010). Global Navigation Satellite System (GNSS) position and information from other electronic navigational sensors are automatically encoded into an ASCII bit vector according to the National Marine Electronics Association 'NMEA 0183' (NMEA) Interface Standard, in which each character represents six bits of data (Raymond, 2011). For example, a type 1 AIS message transmitted on Channel B contains an NMEA payload (in bold): !AIVDM,1,1,,B,**19NS93@02>ClhbHVH<O5gDaTIVr`**,0*68 (SpaceQuest, 2011). Table 5 describes the information encoded in each character field for type 1 AIS messages and decodes the above example. This information can be used to provide not only ship position but a variety of other information as well.

Table 5. Automatic Identification System Position Report Message

Field	Description	Abbreviation	Example
0-5	Message Type	type	1
6-7	Repeat Indicator	repeat	
8-37	Maritime Mobile Service Identity	MMSI	636012813
38-41	Navigation Status	status	0
42-49	Rate of Turn	ROT	0
50-59	Speed Over Ground	SOG	14.2
60-60	Position Accuracy	acc	0
61-88	Longitude	lon	-170.2275
89-115	Latitude	lat	67.0705
116-127	Course Over Ground	COG	147
128-136	True Heading	HDG	148
137-142	Time Stamp	ts	50
143-144	Manoeuvre Indicator	mi	0
145-147	Spare		0
148-148	RAIM flag	raim	0
149-167	Radio status	radio	0

Example AIS message received by the satellite constellation operated by SpaceQuest, Limited, and decoded with AIS Decoder (ITU, 2010; SpaceQuest, 2011; Arundale, 2011).

The vessel transmitting an AIS message is distinguished by its Maritime Mobile Service Identity (MMSI), a unique 9 digit code $M_1I_2D_3X_4X_5X_6X_7X_8X_9$ composed of integers from 0 to 9 of which the leading three Maritime Identification Digits (MID) represent nationality. Further information about the vessel is often available on the International Telecommunications Union online database of 'Particulars of Ship Stations' (ITU, 2011). In the above example, MMSI 636012813 is listed on the ITU database as vessel *SCF Baltica,* and the MID 636 correspond to Liberia, the country of vessel registration. Position is reported in decimal degrees of latitude and longitude referenced from the Equator and Greenwich Meridian, respectively, such that North and East are positive. Speed over ground is expressed in knots (nautical miles per hour), rate of turn is expressed in degrees per minute, and course over ground and true heading are expressed in degrees relative to North. The vessel operator may also declare the navigation status represented by eight standard integer values and a default setting: underway using engine (0), at anchor (1), not under command (2), restricted manoeuvrability (3), constrained by her draught (4), moored (5), aground (6), and engaged in fishing (7), underway sailing (8), and the default (15).

While the three source data sets were all based on AIS messages, they varied in the method of collection, range of the receiver network, and format of the data provided. These differences, summarized in Table 6, are described in the following paragraphs.

Table 6. Surface Vessel Position Data Sources

	Port of Longyearbyen	**Marine Exchange of Alaska**	**SpaceQuest, Limited**
Radio Receiver			
Number	1	13	20
Platform	Ground Station	Ground Stations	Aprize Satellites
Position	Stationary	Stationary	Low Earth Orbit
Nominal Range	100 km² [a]	1000 km² [b]	Global
Data			
Other Sources	*Sysselman* Reports, Visual Observations	None	None
Start Time	1 January 2004	1 January 2009	1 February 2010
End Time	31 December 2010	31 December 2010	31 March 2011
Position Constraint	Nonne	'Passageline' Position	North of 66·56°N
Format	CSV	CSV	NMEA
Use agreement	Free access	Official Agreement	Legal Agreement

Nominal range calculated for (a) the radio receiver in Isfjorden, Spitsbergen, and (b) a sum of the estimated range of the thirteen Marine Exchange of Alaska radio receivers with ranges extending to the Bering Strait region and North Slope of Alaska that were operational during the study period.

First, the Port of Longyearbyen provided a record of all vessels that arrived at the Bykaia International Ship and Port Facility in Longyearbyen from 1 January 2004 to 31 December 2010. The vessel observations from the Port of Longyearbyen consisted of time of arrival and time of departure from the Port, vessel name and International Maritime Organization (IMO) number, and vessel parameters. This dataset is based on AIS receiver information validated with radiocommunications and visual observations from the Bykaia facility, and records from the *Sysselman* (Norwegian: Governor of Svalbard). Vessels with other destinations in Isfjorden (*e.g.* Barentsburg and Pyramiden) are not included in the data set, but were frequently observed by the Port of Longyearbyen AIS ground station.

Second, the Marine Exchange of Alaska provided decoded AIS messages from vessels navigating in the Bering Strait region from 1 January 2009 and to 31 December 2010. The network of stationary radio receivers recorded time-stamped messages with latitude and longitude coincident with a Bering Strait 'passage-line' drawn from Cape Dezhnev, Chukotka (169·72°W, 66·00°N), and Cape Prince of Wales, Alaska (168·08°W, 66·00°N). Table 7 lists the thirteen Marine Exchange of Alaska ground stations with ranges extending to the Bering Strait region and North Slope of Alaska that were operational during the 1 January 2009 and to 31 December 2010 study period.

Table 7. Marine Exchange of Alaska AIS Network

Ground Station	**Position**
Barrow	71°17′N, 156°47′W
Wainwright	70°38′N, 160°00′W
Prudhoe Bay	70°29′N, 147°58′W
Kaktovik	70°08′N, 143°38′W
Point Lay	69°46′N, 163°03′W
Point Hope	68°21′N, 166°47′W
Kivalina*	67°35′N, 164°03′W
Kotzebue	66°54′N, 162°35′W
Wales	65°36′N, 168°05′W
Nome	64°30′N, 165°25′W
Gambell	63°46′N, 171°44′W
Savoonga	63°42′N, 170°27′W
Stebbins	63°31′N, 162°17′W

*The Kivalina AIS Station is located at the port that services Red Dog Mine

Third, SpaceQuest, Limited, provided time-referenced AIS position report messages from vessels operating north of 66·56°N that were received by two satellites during the period 1 February 2010 to 31 March 2011. Launched in 2009, AprizeSat-3 and AprizeSat-4 each contain ten radio receivers, two transmitters, and up to twelve megabytes of solid-state data storage. These Low Earth Orbit satellites circle the earth 14 times in a 24 hour period and regularly uplink data from shipboard AIS systems in the path of the orbit to User Terminals, such as the SvalSat downlink facility in Spitsbergen and other receiving stations (SpaceQuest, 2011; SvalSat, 2011). Time-referenced AIS messages received by the SpaceQuest satellite constellation were provided for this research in NMEA format under a data license agreement (Appendix 1).

The AIS messages from SpaceQuest, Limited, were chosen as the primary dataset because of the spatial and temporal coverage and data-rich format enabling more complete and detailed analysis.

2.2. Methods of Analysis

A number of geospatial methods were employed to analyse the satellite-derived records of sea ice concentration and surface vessel locations north of Arctic Circle during a study year beginning 1 March 2010. The Arctic Circle was selected as the principal boundary for this geospatial analysis of Arctic marine traffic because it is the southern boundary of the region in the Northern Hemisphere that experiences the Polar Day and Polar Night. While astronomically defined, the Arctic Circle fluctuates approximately 2° Latitude over a period of 40,000 years because lines of latitude are dependent on the 'obliquity of the ecliptic', the axial tilt of the Earth relative to the plane of its orbit around the sun (Wittman, 1979). In 2010, the Arctic Circle was coincident with the 66·56°N latitude (Gautier, 2008).

Much of the work was accomplished using a Geographic Information System (GIS) software suite uniquely suited to analyse geospatial data. The Environmental Systems Research Institute (ESRI) proprietary GIS ArcMap version 9.0, the legacy ArcView version 3.0, and ERDAS IMAGINE 9.3 were used to generate databases, maps, and spatial-temporal distributions of sea ice and surface vessel positions with a north polar stereographic projection with the World Geodetic System 1984 reference ellipsoid and the 70·00°N reference parallel and 6·25 km reference grid adapted from the NSIDC northern hemisphere projection and grid. This reference projection and datum were retained for all maps produced in this work. The calculations in this work were accomplished using the following open source codes: R Statistical Language version 2.13.1, OpenOffice version 3.3.0, and AIS Decoder version 3.1.0.66 (R Development Core Team, 2011; Oracle, 2011; Arundale, 2011).

2.2.1. Open Water Area and Sea-Ice Duration

The following methods of analysis were applied to the selected sea-ice concentration dataset **2C** (ICSC) to interpret a navigational area and season in the maritime region north of 66·56°N over day, month, and year timescales.

Environmental Systems Research Institute (ESRI) ArcMap version 9.0 was used to read daily TIFF raster images and georeference them with the reference projection and datum (ESRI, 2011). These files were converted to text files in the American Standard Code for Information Interchange (ASCII) using a batch conversion command and named according to the following convention: iceddd.txt where ddd represents the day in the period beginning 1 January 2010. In this manner, ice091.txt represents the first day of the study year, 1 April 2010, and ice455.txt represents the final day, 31 March 2011. The 365 ASCII text files were imported into R and converted into arrays of value 0-200 (sea ice concentration in 0·5%), 251 (land), and 255 (no data) with dimension 1216 × 1792 (R Development Core Team, 2011).

In order to spatially constrain the daily sea-ice concentration data to the study area north of the Arctic Circle, a process was implemented to mask the area south of 66·56°N. Erdas Imagine was used to build a vector 'polygon' coverage representing the area north of the Arctic Cricle by defining a point every 0·1° longitude along the 66·56°N latitude. (Erdas, 2011). Building vector layer topology in Erdas Imagine, a polygon encompassing all area north of the was created and imported into ArcView. ArcMap was used to project this coverage using the reference projection. A vector feature 'reference grid' with 1216 columns and 1792 rows of 6·25 km square polygons (over 2 million grid cells) was constructed to replicate the sea-ice concentration dataset **2C** reference grid using an extension to the ESRI software suite (Nicholas, 2003). A sequential spatial join with this reference grid, raster conversion, and ASCII conversion yielded an array with dimension 1216 × 1792, in which value of zero represents areas south of 66·56°N and a value of one represents those north. This Arctic Circle mask was imported to R and applied to all 365 sea-ice concentration arrays such that array elements corresponding to grid cells south of the 66.56°N were assigned a value of 211 (heretofore unassigned). A similar process was implemented to assign a value of 200 (100% sea-ice concentration) to areas north of 89·24°N, approximating the near-complete sea-ice cover beyond the AMSR-E radiometer limit (Parkinson, 1999). Table 8 shows the count of total, land, and maritime grid cells and their corresponding areas within the study boundaries.

Table 8. Grid Cell Counts and Areas

	Grid	Arctic Circle	AMSR-E Limit
Latitude (°N)	–	66.56	89.2
Cell Count			
Total	2179072	534501	766
Land	1106243	205420	0
Maritime	1072829	329081	766
Total Area (10^3 km^2)			
Total	85120.00	20878.95	29.92
Land	43212.62	8024.22	0.00
Maritime	41907.38	12854.73	29.92
Maritime Proportion (%)	49.2	61.6	100.0

*The area of each grid cell was approximated to be 39·069 km^2

The frequencies of sea-ice concentration values (0-200, 211, 251, 255) were calculated for each day across all cells in the reference grid. Daily sea-ice extent, the cumulative area covered with sea ice, was calculated for 15%, 30%, and 50% concentration thresholds by multiplying the nominal grid cell area, 39·069 km^2, with the number of grid cells with sea ice concentration at least equal to the concentration threshold. The three threshold values were selected to represent a wide range of sea ice conditions important for navigation, of which the 15% threshold has been cited as the most robust value for sea-ice extent calculations (Parkinson, 2002). Open water area A_w was calculated in the same manner using the number of grid cells with 0% sea-ice concentration.

The arithmetic mean of daily sea-ice concentration was calculated for each grid cell in each month. Mean monthly open water area and mean monthly sea-ice extent in the maritime area north of the Arctic Circle was calculated, the latter for 15%, 30%, and 50% concentration thresholds. Open water (value of zero) in the mean sea-ice concentration calculation signifies that no sea ice was measured in any day during the month. Table 9 shows the range of days for each month in the study period.

Table 9. Days and Months in Study Period

Month	Start Day	End Day
April	91	120
May	121	151
June	152	181
July	182	212
August	213	243
September	244	273
October	274	304
November	305	334
December	335	365
January	366	396
February	397	424
March	425	455

The duration of the sea-ice season counts the number of days that sea-ice concentration more than a certain threshold exists in a particular location (Parkinson, 1992). The sea-ice duration for each grid cell during the study period was calculated by counting the number of days in which the sea-ice cover met a certain concentration threshold (15%, 30%, 50%). Though the calculation loses the specific temporal location and precise sea ice concentration, the resulting sea-ice duration array summarizes a year of Arctic sea ice cover observations while retaining the original spatial location and daily resolution.

Chapter 3 presents the resulting databases, maps and spatial-temporal distributions that were constructed with the above calculations in the OpenOffice v. 3.3, ArcMap v. 9.0, and R v. 2.13.1 software suites (Oracle, 2010; ESRI, 2010; R Development Core Team, 2011).

2.2.2. Surface Vessel Locations

The following methods of analysis were applied to the SpaceQuest dataset to interpret patterns of surface vessel locations in the maritime region north of 66·56°N.

The 425 ASCII text files corresponding to original daily-consolidated AIS messages in NMEA format were aggregated by month, February 2010 to March 2011, using unix commands to facilitate batch processing. The resulting fourteen NMEA text files were converted into alphanumeric CSV files with AIS Decoder, an open source software suite that unpackages NMEA payloads (Arundale, 2011). Decoded messages were formatted post-processing to standardize time and position data for each distinct AIS message. MMSI and position were evaluated to exclude invalid messages. All messages with invalid MMSI were excluded, *e.g.* MMSI field beginning in digit 1. Further, remaining MMSI were cross-referenced on ITU database of ship stations (ITU, 2011) and open source databases (Marine Traffic.com, 2011). Similarly, AIS messages reporting invalid positions were excluded, e.g. longitude less than -180·00° or more than 180·00°. Reported positions corresponding to 90·00°N, a GNSS reference point, were further evaluated by looking for other reported positions from the vessel north of 80·00°N. In addition to position, the flag (MID) and engaged activity (Navigation Status) of the surface vessel was investigated.

Table 10. Arctic Coastal State Maritime Identification Digits

State	Allocated MID
Kingdom of Denmark	219, 220, 231[a], 331[b]
Kingdom of Norway	257, 258, 259
Iceland	251
Russian Federation	273
United States of America	303[c], 338, 366, 367, 368, 369
Canada	316

a) Faroe Islands, b) Greenland, c) Alaska

A similar process as with the sea ice concentration data was implemented to assign each AIS message a cell in the reference grid. The process is shown with a flow chart in Figure 17.

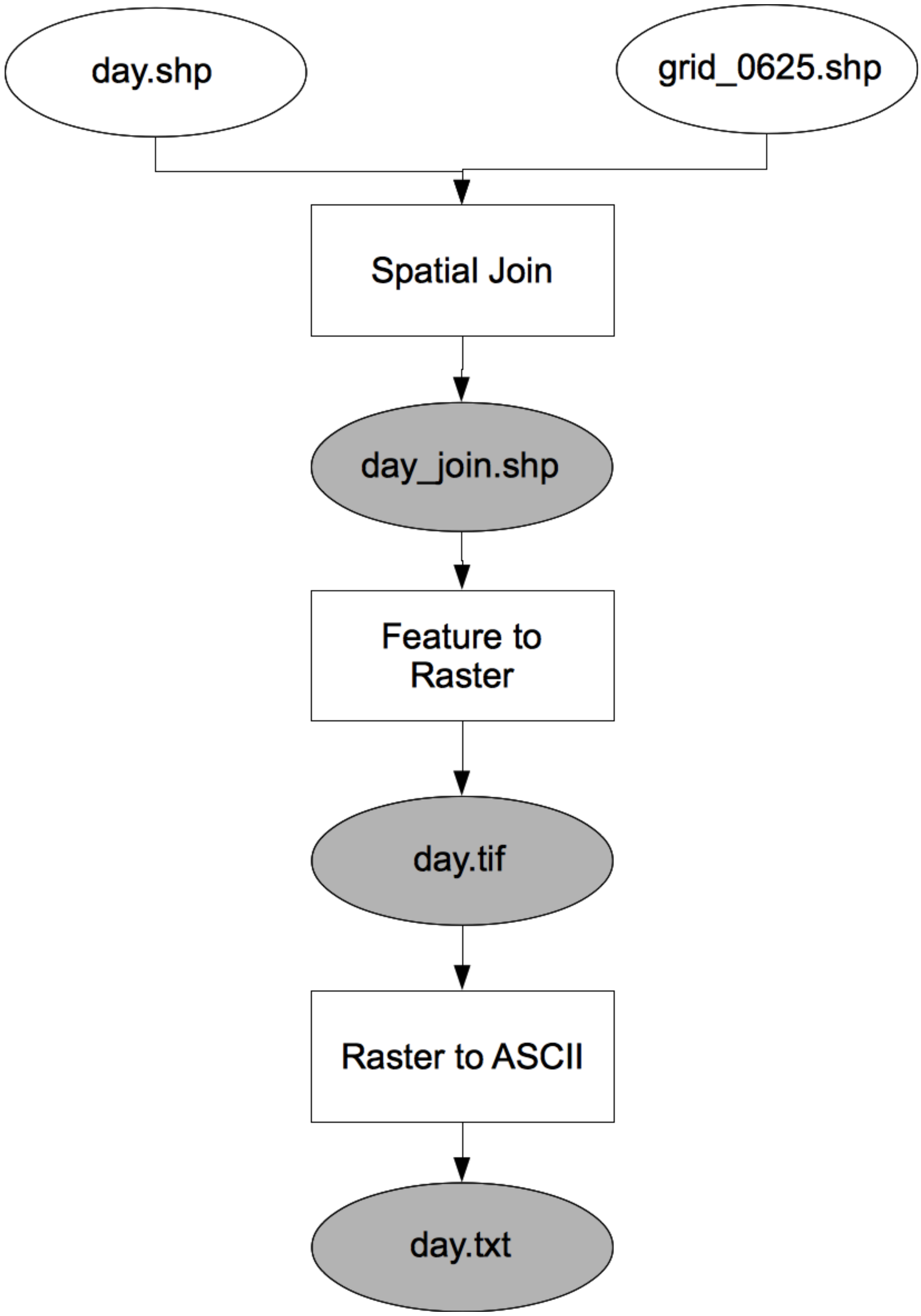


Figure 17. Geographic Information System Model

ESRI ArcMap model used to assign a grid cell to AIS position vector features (ESRI, 2011).

2.2.2. Sea Ice and Surface Vessel Relationship

The spatial and temporal patterns of sea ice conditions and surface vessel operations were compared using spatial statistics. Daily aggregations of sea-ice concentration measurements based on satellite radiometry and AIS position report messages received by the SpaceQuest satellite constellation were used to analyse the spatial and temporal relationship between sea ice and surface vessel operations north of the Arctic Circle during the study period.

Automatic Identification System messages received by the SpaceQuest satellite constellation from 1 April 2010 to 31 March 2011 were mapped alongside satellite observations of sea ice conditions. Daily ship identifications were attributed to areas with various ice conditions and aggregated for the study year to examine the relationship between Arctic marine access and Arctic marine traffic. Further, a quantitative method to compare the presence of surface vessels and sea ice for the maritime area north of the Arctic Circle was developed based on a comparison between daily aggregated satellite observations of sea-ice concentration and AIS message concentration per 6·25 km maritime reference grid cell north of the Arctic Circle. Figure 18 shows the method of comparison for 1 April 2010. The messages identified surface vessels located in 6·25 km grid cell areas associated with various sea ice conditions.

Similarly, a year aggregation of daily sea-ice concentration measurements based on satellite radiometry and AIS position report messages received by the SpaceQuest satellite constellation were used to analyse the spatial and temporal relationship between sea ice and surface vessel operations north of the Arctic Circle during the study period. Sea-ice duration and AIS message concentration per unit area were calculated to quantify the spatial and temporal components of marine access and marine traffic. A geographic information system was used to overlay AIS message concentration onto sea-ice duration per 6·25 km reference grid cells north of 66·56°N for the year from 1 April 2010 to 31 March 2011. This spatial analysis method enabled the attribution of observed marine traffic to sea ice conditions for the entire study period.

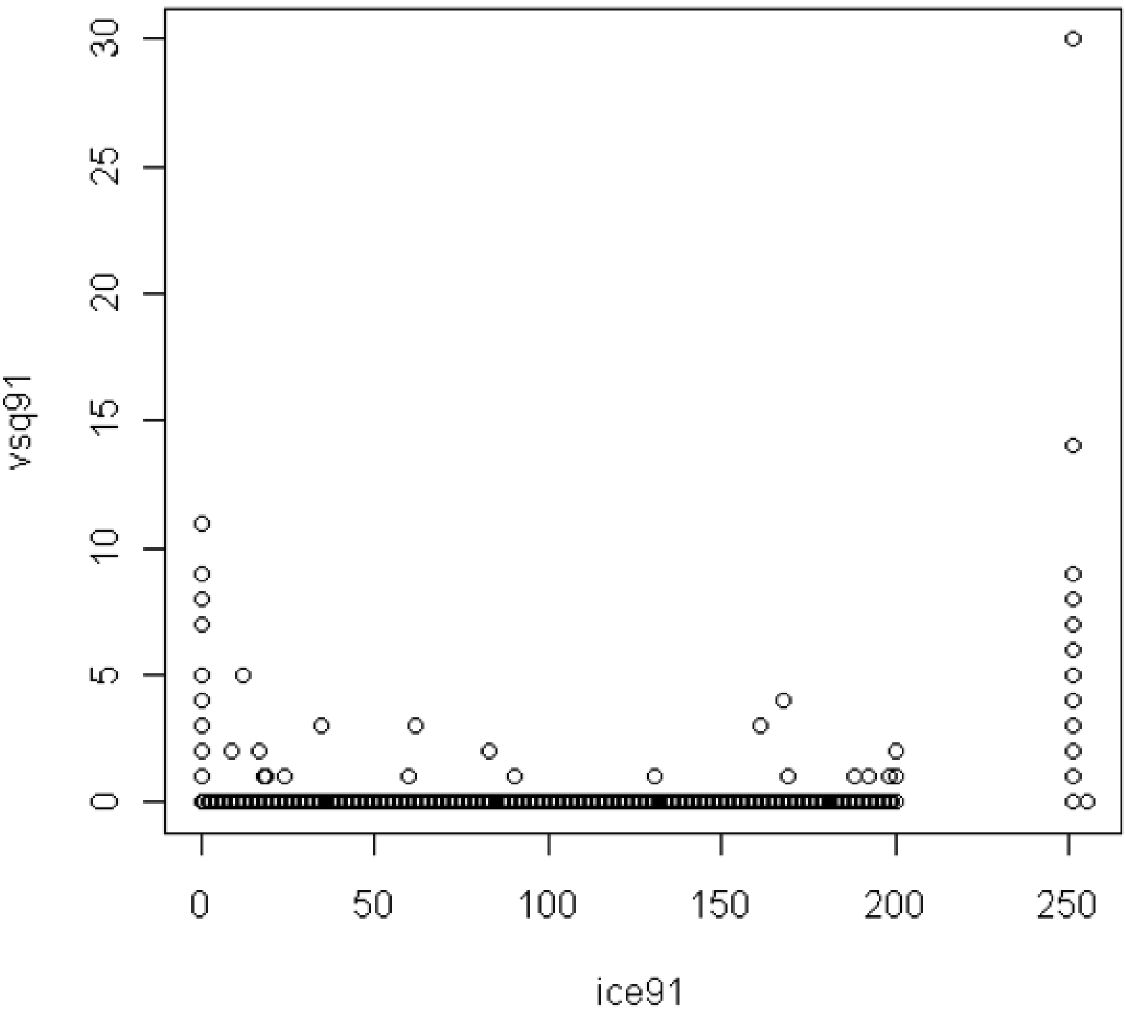


Figure 18. AIS Message Concentration vs Sea-Ice Concentration for 1 April 2010

Method to compare presence of surface vessels and sea ice for the maritime area north of the Arctic Circle. The example above compares satellite observations of sea-ice concentration and AIS message concentration per 6·25 km maritime reference grid cell north of the Arctic Circle for 1 April 2010. Sea-ice concentration is the abscissa, where 0 corresponds to 0%, 200 corresponds to 100%, 251 corresponds to land, and 255 corresponds to no data. AIS message concentration is the ordinate.

3. Results of the Analysis

Spatial and temporal features of sea ice and surface vessel operations north of 66·56°N during a study period from 1 March 2010 to 31 April 2011 were analysed. Satellite observations of sea-ice concentration and surface vessel position on the Arctic Ocean enabled a synoptic and daily assessment of operating conditions, marine use, and their relationship. The following sections discuss the results of the analysis.

3.1. Spatial and Temporal Patterns of Arctic Access

Sea-ice concentration measurements based on satellite radiometry were used to determine theoretical area and season for navigation of surface vessels on the Arctic Ocean. A database, maps, and spatial and temporal distributions were calculated based on the estimated presence or absence of sea ice north of the Arctic Circle during the period 1 April 2010 to 31 March 2011. Further, a number of parameters were calculated to quantify the theoretical area and season for navigation north of the Arctic circle during the study year, probing different time and space scales.

First, daily sea-ice extent was calculated by summing the area of 6·25 km reference grid cells with observed sea-ice concentration greater than 15%. Similarly, daily open water area was calculated by summing the area of 6·25 km reference grid cells with less than 0·5% sea-ice concentration. Figure 19 shows the calculated extent of sea ice and open water for 1 September 2010 and 1 March 2011. Similarly, calculation of sea-ice extent and open water area north of the Arctic Circle for each day in the study period yielded Figure 20, a year summary of the seasonal variability of Arctic navigation based on daily satellite observation.

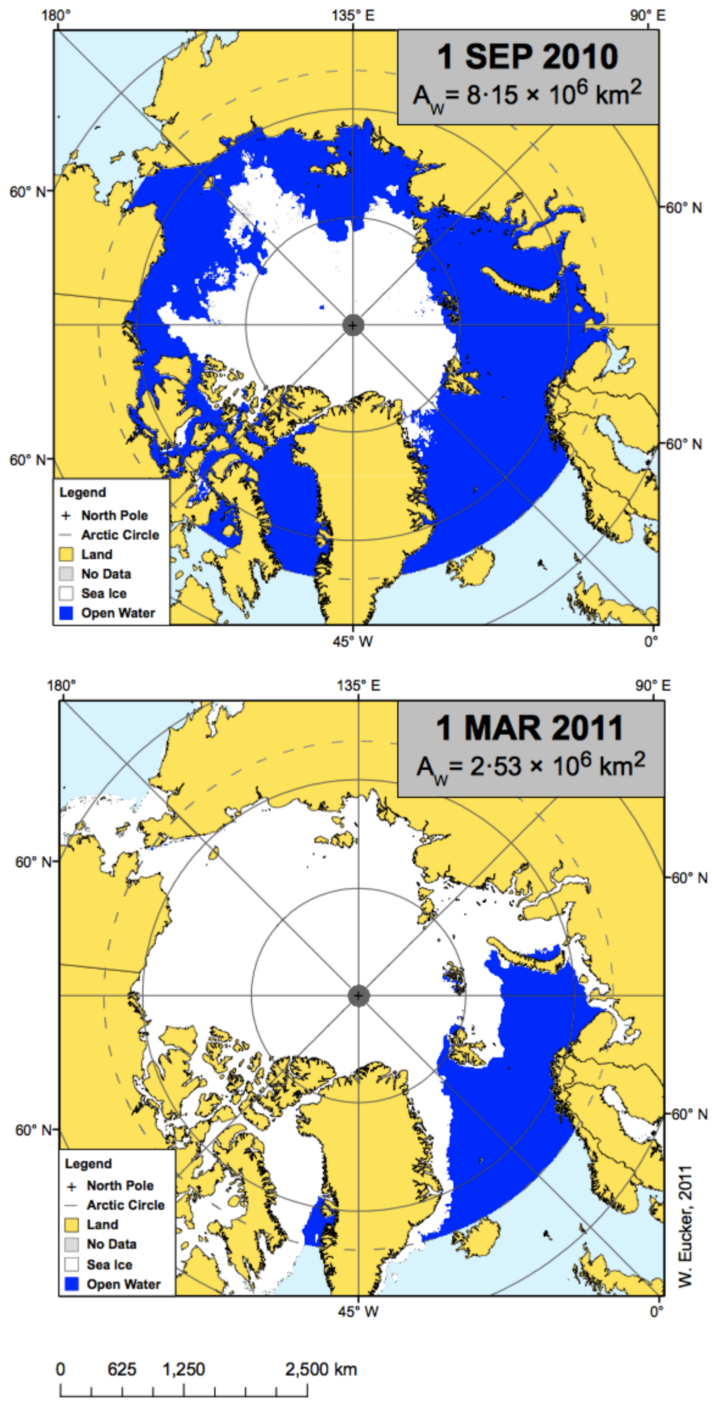


Figure 19. Daily Arctic Open Water on 1 September 2010 and 1 March 2011

Extent of open water (blue) and sea ice (white) north of the Arctic Circle was calculated by counting the number of 6·25 km maritime reference grid cells north of 66·56°N and south of 89·24°N in which sea ice was estimated to occupy less than 0·5% and greater than 15% of the total cell area, respectively. Open water area, A_w, quantifies navigational access for two days in the study period: 1 September 2010 and 1 March 2011.

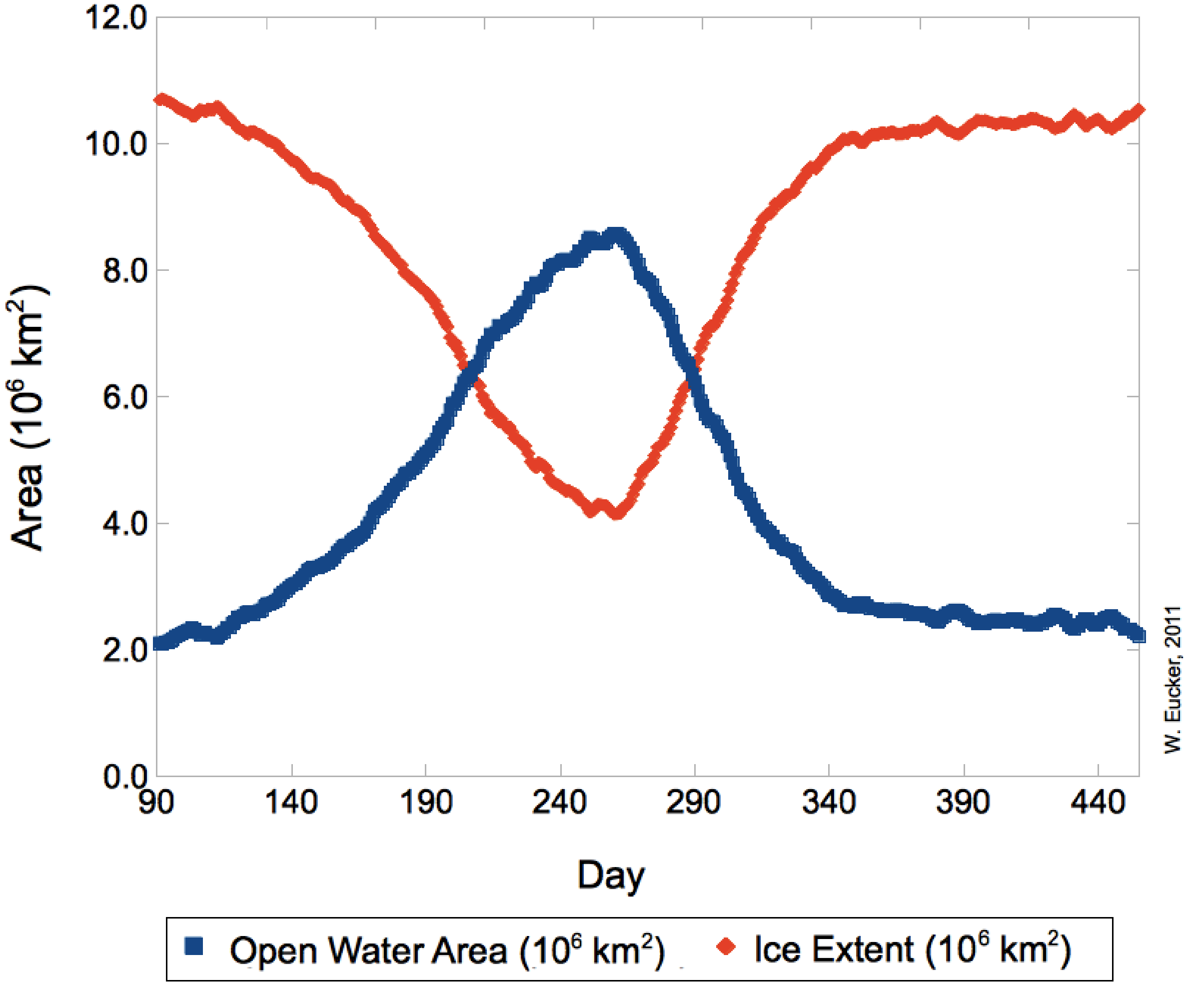


Figure 20. Arctic Open Water Area, 1 April 2010 to 31 March 2011

Open water varies throughout the study year from a minimum on 2 April 2010 to a maximum on 17 September 2010, defining the amplitude of an Arctic navigating area.

Second, daily satellite observations of sea-ice concentration were aggregated by month to determine the distribution of monthly mean sea-ice concentration in the maritime area north of the Arctic Circle. The monthly mean sea ice concentration was calculated for each maritime reference grid cell north of the Arctic Circle and south of the 89·24°N 'hole' corresponding to the AMSR-E radiometer limit. The frequency distribution of monthly mean sea-ice concentration for all maritime reference grid cells surveyed the navigational access for the entire maritime area north of the Arctic Circle. Histograms in Figure 21 show the number of maritime reference grid cells (each with nominal area 6·25 km × 6·25 km) in 5% monthly mean sea-ice concentration categories. The frequency of monthly mean sea-ice concentration less than 0·5% determines the area of open water, A_w. Similarly, the frequency of monthly mean sea-ice concentration greater than 15% determines the extent of sea ice. By applying these thresholds, extent of sea and open water may be calculated. Figure 22 shows the calculated monthly mean extent of sea ice and open water north of the Arctic Circle during the study year.

Third, using a method of mapping the 'length of season' of the sea ice developed by Parkinson, sea-ice duration was calculated by counting the number of days that sea-ice concentration was greater than a 15% threshold for each 6·25 km maritime reference grid cell (Parkinson, 1992). In this manner, sea-ice duration is a temporal parameter that surveys the degree of persistence of sea ice, and open water, in a geographic location. When mapped, this parameter enables the visualization and simultaneous analysis of geospatial and temporal patterns. Figure 23 shows daily satellite observations of sea ice integrated over the entire Northern Hemisphere (south of the 89·24°N AMSR-E radiometer limit) and over the 365 days of the study year. The assessment showed concentrated sea ice endured more than 360 days in the central Arctic Ocean and sea ice diminished below the 15% concentration threshold in the Arctic marginal seas for part of the year. Figures 24-27 show magnified quadrants of Figure 23 for the benefit of the reader. Perennial open water in the Atlantic Quadrant extended north to 80°N, and perennial sea ice in the central Arctic Ocean extended south to 73°N in the Pacific Quadrant. More localized variability was evident in the marginal ice zone, especially in the Chukchi Sea, Laptev Sea, and along the coast of northeastern Greenland.

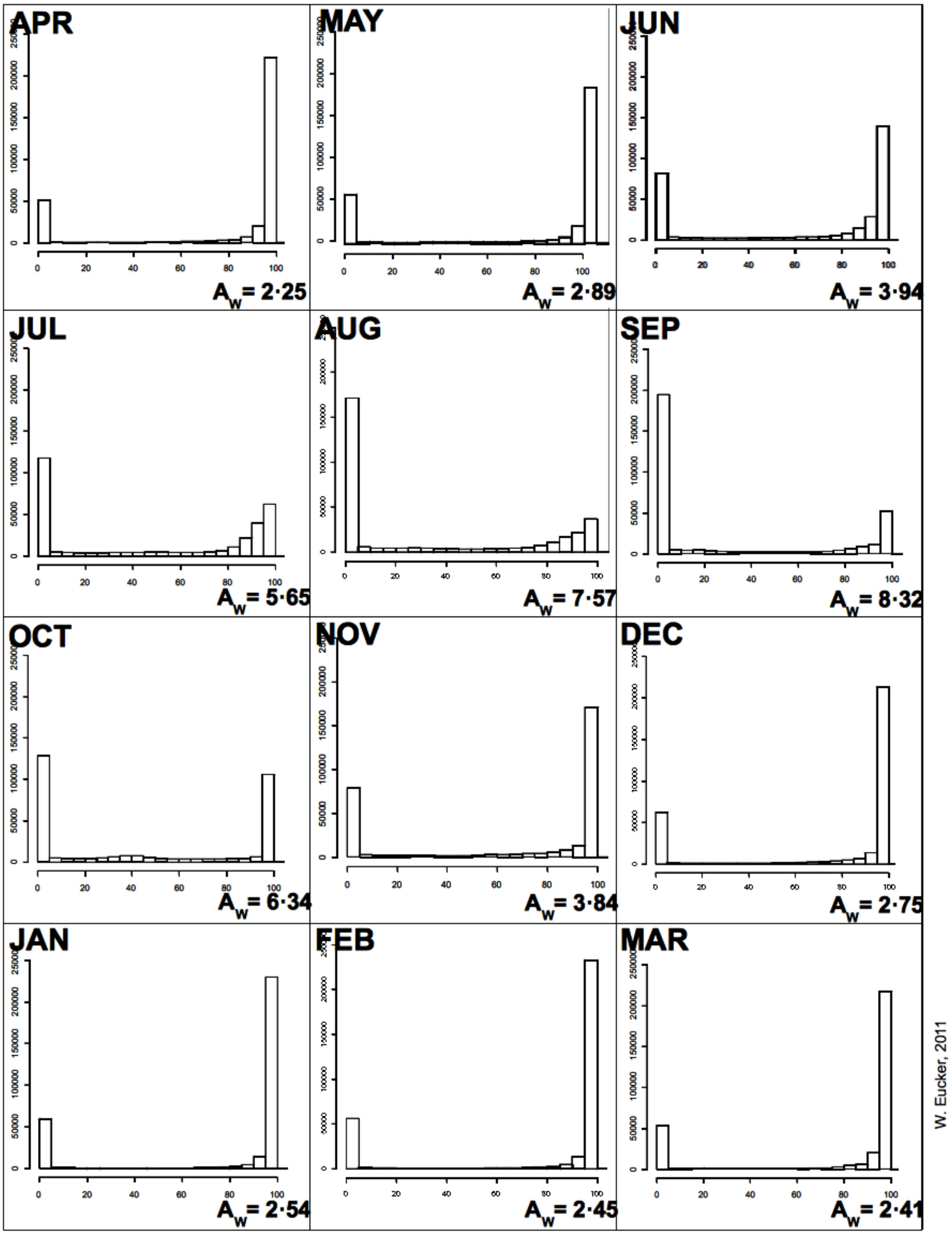


Figure 21. Monthly Mean Pan-Arctic Sea Ice Concentration, April 2010 to March 2011

Histograms of monthly mean sea-ice concentration for 6·25 km maritime reference grid cells north of 66·56°N. The relative frequency of open water (0%) and complete sea-ice cover (100%) vary throughout the study year, with the most open water in September 2010. The total area of reference grid cells with less than 0·5% sea-ice concentration determined the areal extent of open water, A_w, shown in units of 10^6 km^2.

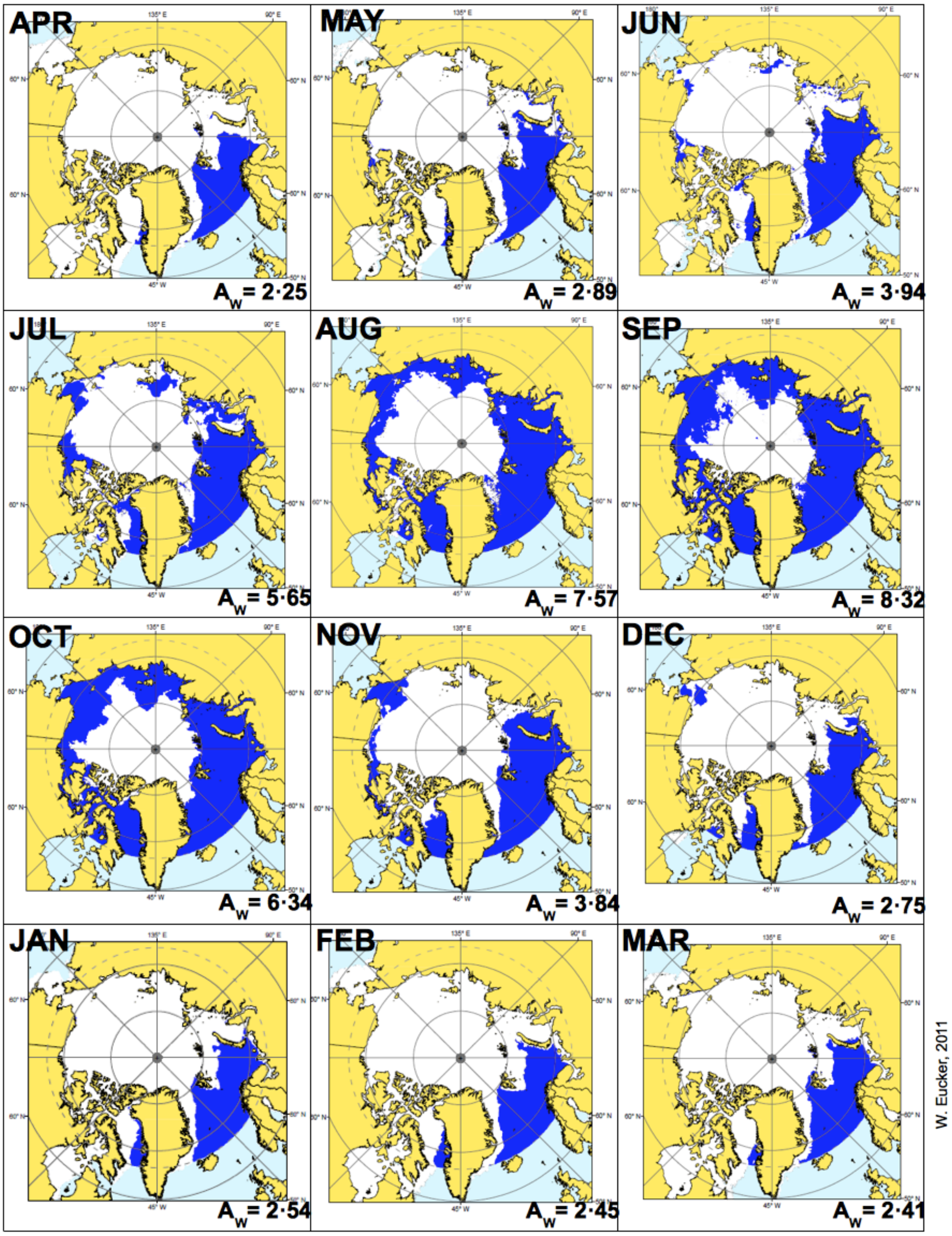


Figure 22. Monthly Mean Pan-Arctic Open Water, April 2010 to March 2011

The total area of reference grid cells with less 0·5% sea-ice concentration during the entire month determined the monthly mean area of open water, A_w, shown in units of 10^6 km^2. Monthly mean open water varies from 17% to 67% of total maritime area north of the Arctic Circle from the April minimum to the September maximum, respectively. See Appendix II for enlarged maps of Arctic sea ice.

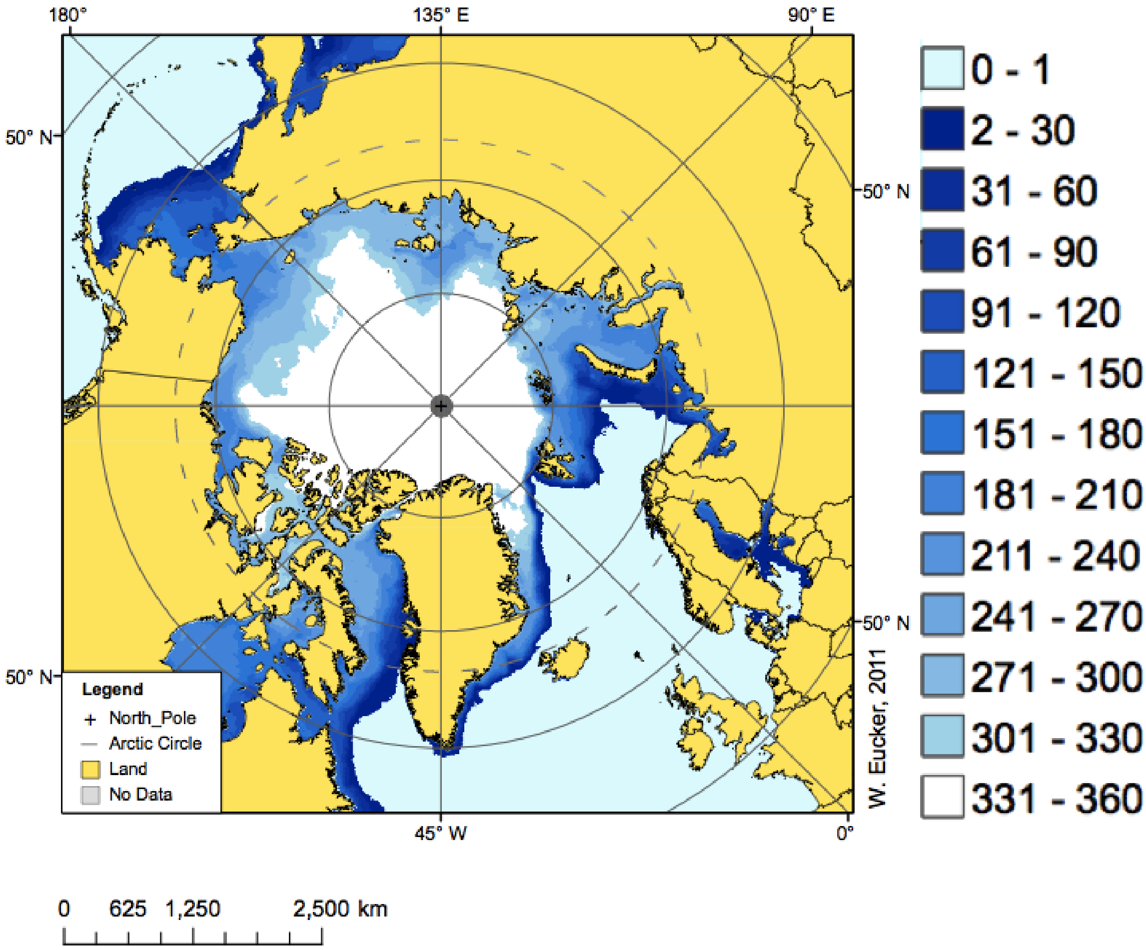


Figure 23. Pan-Arctic Sea-Ice Duration, 1 April 2010 to 31 March 2011

Sea-ice duration was calculated by counting the number of days that sea-ice concentration was greater than a 15% threshold for each 6·25 km reference grid cell. Sea-ice concentration was based on satellite radiometric measurements of the northern hemisphere during the study period. Concentrated sea ice endured more than 360 days in the central Arctic Ocean. However, sea ice diminished below the 15% threshold in the Arctic marginal seas for part of the year, defining a minimal navigating area and season for surface vessels during the 1 April 2010-31 March 2011 study year.

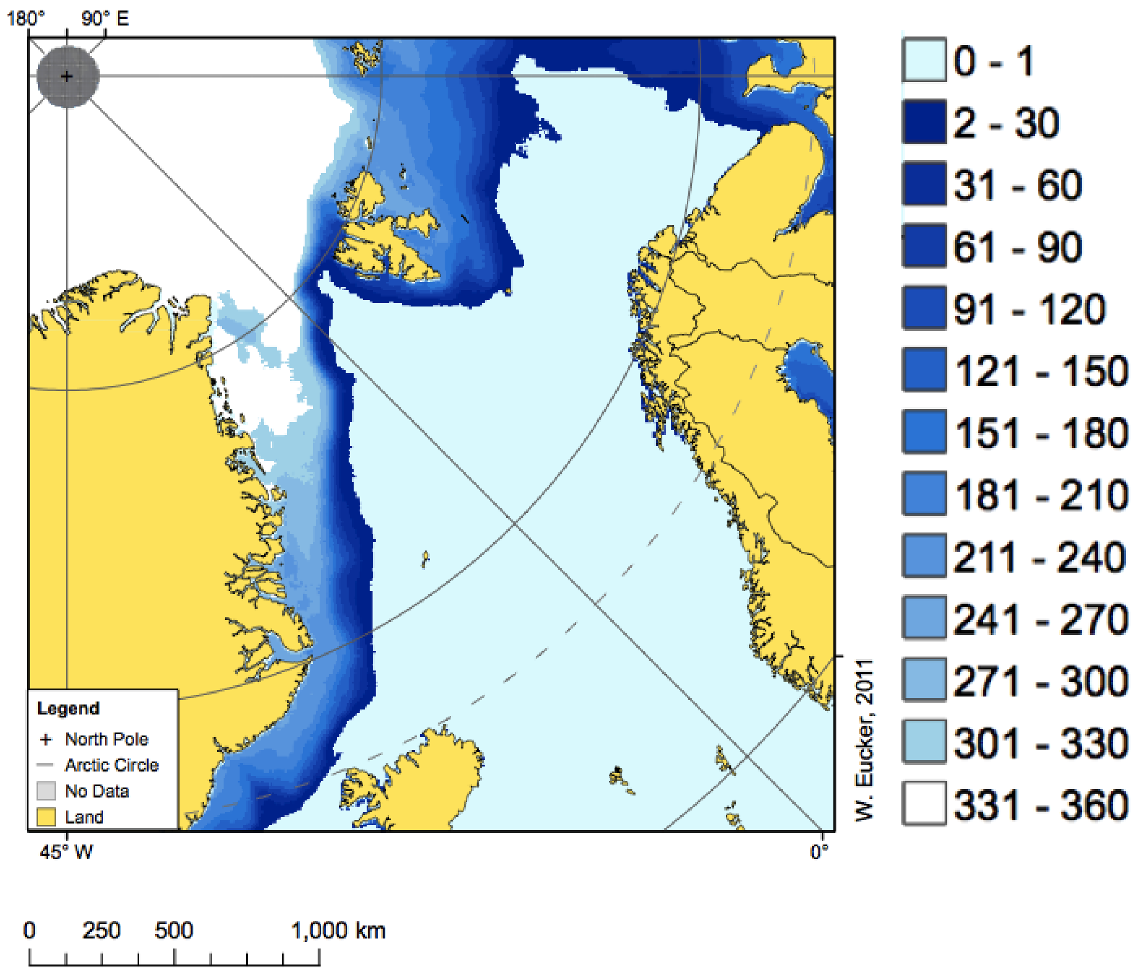


Figure 24. Arctic Sea-Ice Duration, 45·00°W to 45·00°E, 1 April 2010 to 31 March 2011

Sea-ice duration in the Atlantic Arctic quadrant, 45·00°W to 45·00°E, describes the number of days that the sea-ice concentration was greater than a 15% threshold for each 6·25 km reference grid cell during the 1 April 2010-31 March 2011 study year. In this quadrant, continuous, perennial sea ice extends south from the Geographic North Pole to 82°N and along Northeastern Greenland. Continuous perennial open water extends North from the Arctic Circle into the Barents Sea, to the east and west of Spitsbergen.

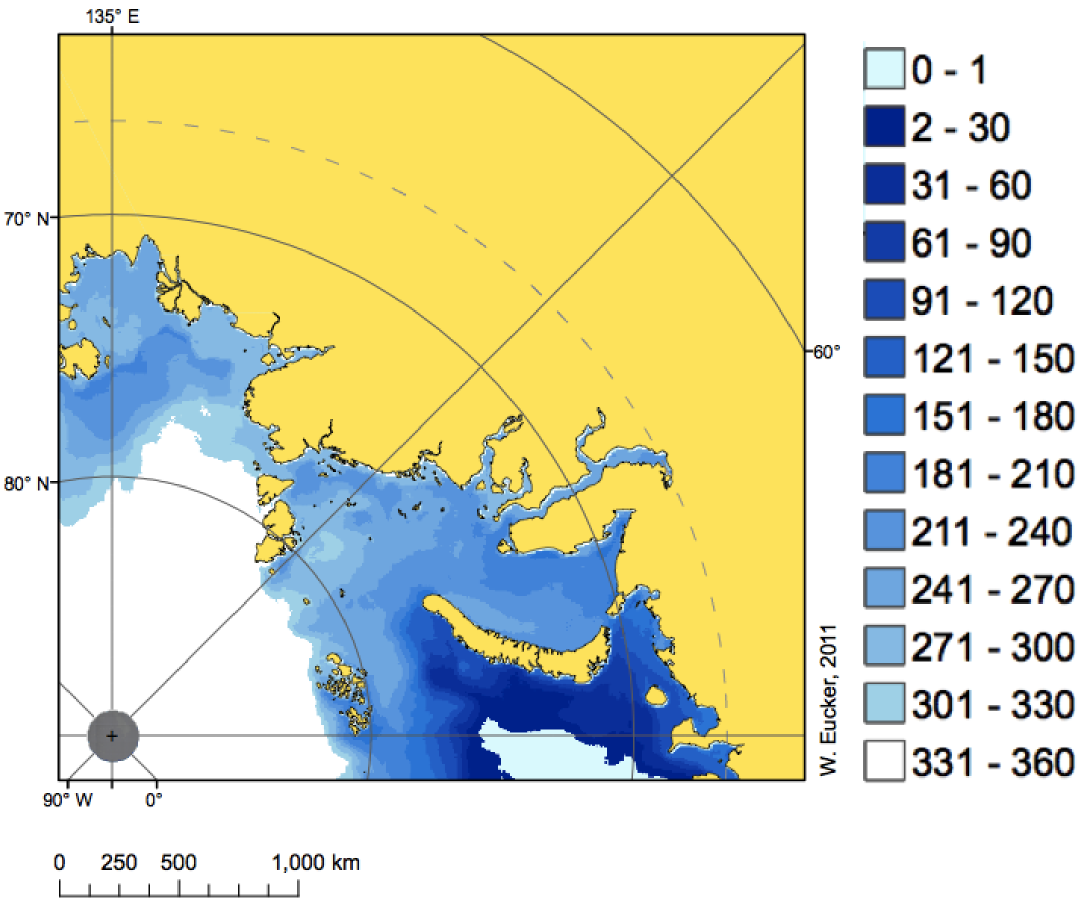


Figure 25. Arctic Sea-Ice Duration, 45·00°E to 135·00°E, 1 April 2010 to 31 March 2011

Sea-ice duration in the Eurasian Arctic quadrant, 45·00°E to 135·00°E, describes the number of days that the sea-ice concentration was greater than a 15% threshold for each 6·25 km reference grid cell during the 1 April 2010-31 March 2011 study year. Continuous, near-perennial sea ice extended south to 77°N in the Laptev Sea and to the northern extent of the New Siberian Islands and Franz Josef Land. Continuous open water did not extend north of 75°N in this quadrant, and perennial and near-perennial open water in the Barents Sea did not extend east of Novaya Zemlya.

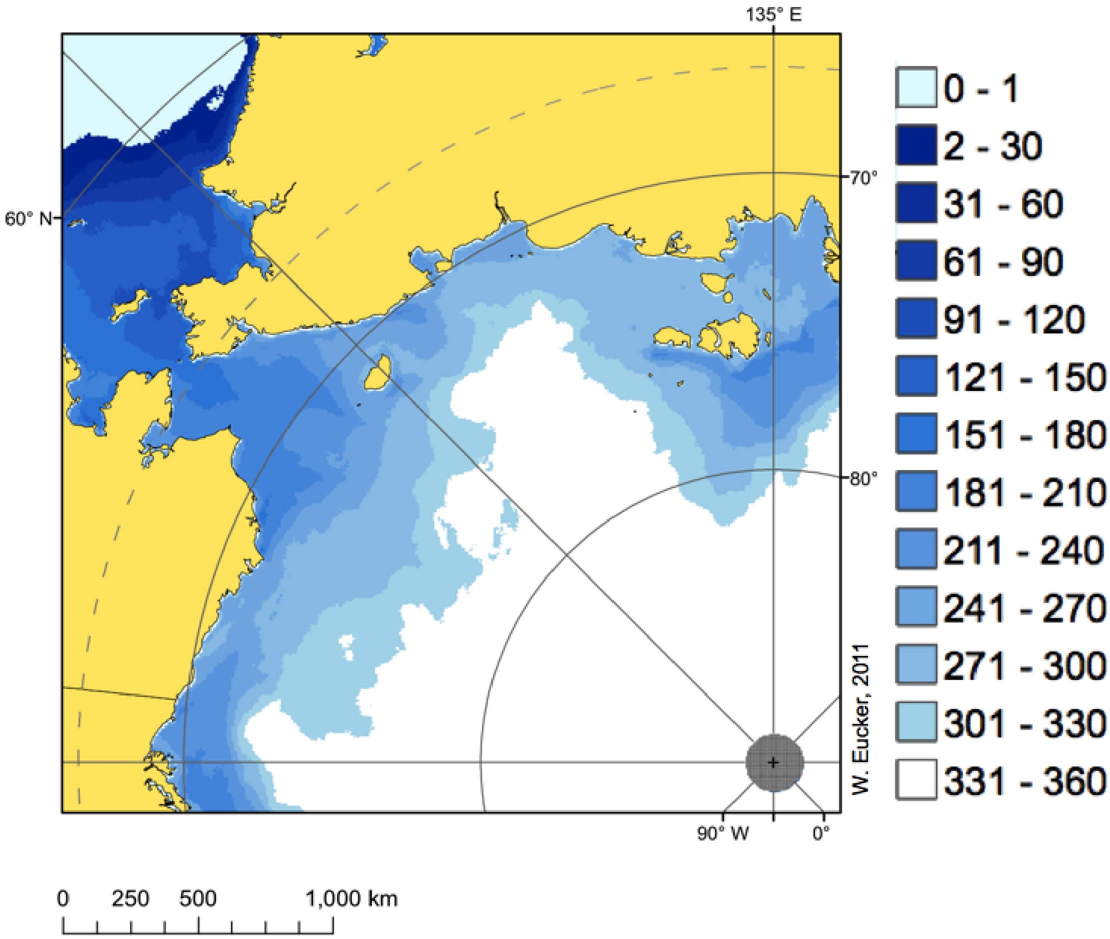


Figure 26. Arctic Sea-Ice Duration, 135·00°E to 135·00°W, 1 April 2010 to 31 March 2011

Sea-ice duration in the Pacific Arctic quadrant, 135·00°E to 135·00°W, describes the number of days that the sea-ice concentration was greater than a 15% threshold for each 6·25 km reference grid cell during the 1 April 2010-31 March 2011 study year. The maritime area north of the 82°N in this quadrant was dominated by near-perennial sea ice with duration greater than 330 days. In addition, an arm of near-perennial sea ice extended westward into the Beaufort Sea. The maritime area in the East Siberian Sea was dominated with an arm of near-perennial sea ice that extended south from the Geographic North Pole to 73°N. Calculations showed perennial open water did not extend north of the Arctic Circle in this quadrant.

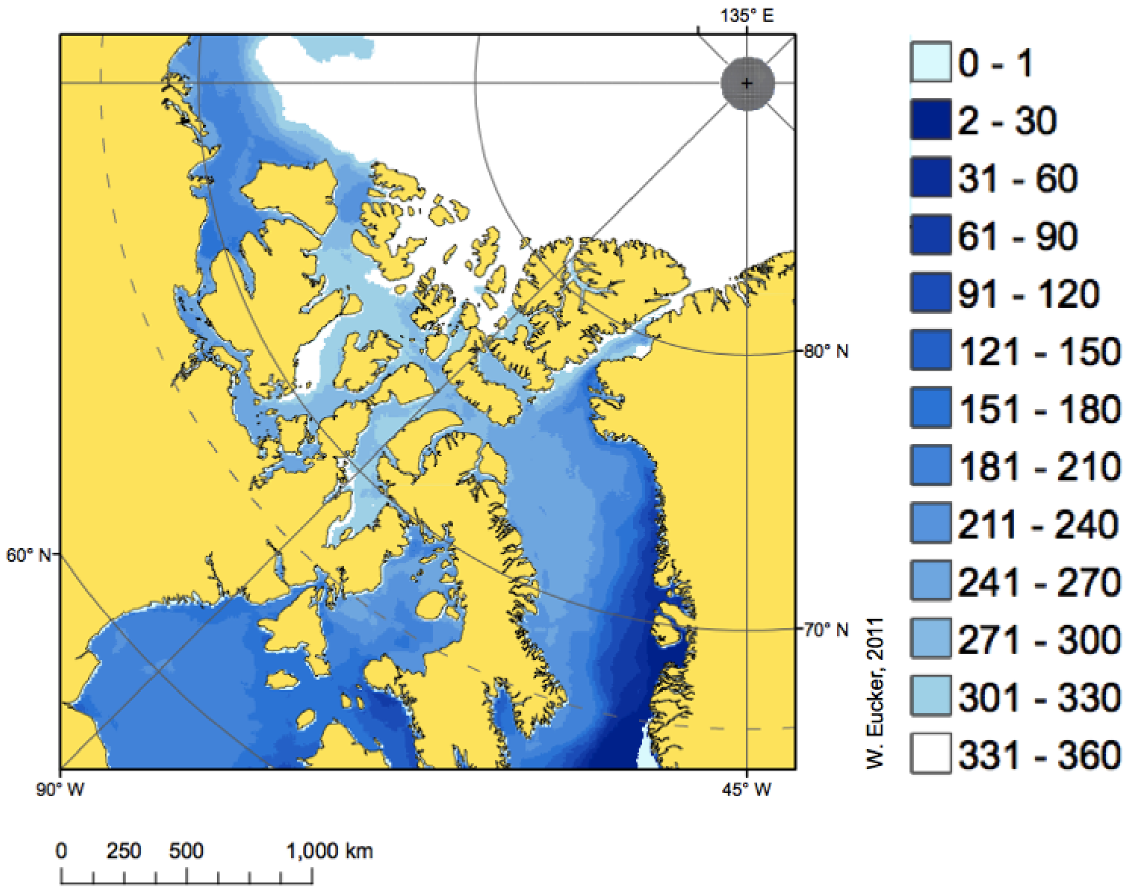


Figure 27. Arctic Sea-Ice Duration, 135·00°W to 45·00°W, 1 April 2010 to 31 March 2011

Sea-ice duration in the American Arctic quadrant, 135·00°W to 45·00°W, describes the number of days that the sea-ice concentration was greater than a 15% threshold for each 6·25 km reference grid cell during the 1 April 2010-31 March 2011 study year. The maritime area north of the Canadian Arctic Archipelago and western Greenland was dominated by near-perennial sea ice with duration greater than 330 days. In addition, an arm of near-perennial sea ice extended westward into the Beaufort Sea. The maritime area west of Greenland showed the longest duration of open water in the American quadrant north of the Arctic Circle. Calculations showed perennial open water did not extend north of the Arctic Circle in this quadrant.

The year study of Arctic sea ice for navigational possibilities yielded five principal results. First, total open water area varied from 17% to 67% of the maritime area north of the Arctic Circle during the study period, representing the amplitude of a theoretical navigating area for non-ice capable surface vessels. A total 2·08 million km^2 of open water on 2 April 2010 corresponded to the maximum area covered by sea-ice with concentration greater than 0·5% per 6·25 km^2. The total open water area increased to 8·58 million km^2 of open water on 17 September 2010—the maximum navigating area during the study period. The minimum total open water area corresponds approximately to the maximum seasonal extent of sea ice (a difference may exist because sea-ice extent and open water are calculated using different sea-ice concentration thresholds). Open water may not be ice free, however, as icebergs calve from glaciers of peri-Arctic islands and drift southward.

Second, the only perennial open water north of the Arctic Circle during the study period was an approximate 2 million km^2 area located in the Atlantic Arctic, signifying a year-round navigating area for all vessels. The surface of the Norwegian and Barents Seas is warmed by the North Atlantic Current, elevating the temperature and preventing freezing. In contrast with the Atlantic quadrant, perennial open water did not extend north of the Arctic Circle in any other quadrant (except for a small area in the Barents Sea East of 45·00°E. Compared with the beginning of the satellite record, the open water area Paleorecords suggest that the Eocene Epoch, 55·8 to 33·9 million years ago, was the most recent time when the entire Arctic was perennially ice free (Polyak *et al.*, 2010).

Third, most of the continuous sea-ice duration north of the Arctic Circle during the study period was located in an approximate 4 million km^2 area located in the central Arctic Ocean, signifying a year-round navigation exclusion area for most surface vessels. This perennial area of sea ice is located around the geographic north pole, which receives little incident solar radiation during winter. Further, there was the most continuous perennial sea ice in the Pacific quadrant and the least in the Atlantic quadrant. While sea-ice concentration measurements do not explicitly measure age or thickness, areas where satellite radiometry has continuously observed sea ice during an entire year are likely covered with thick, multi-year sea ice. The estimated area north of the Arctic Circle in which sea ice duration was greater than 360 days is 4 million km^2. This area compares to 3.5 million km^2 of multi-year ice estimation based on IceSat for 2009 (Kwok, 2009).

Fourth, mesoscale variations of sea-ice duration in the seasonal ice zone north of the Arctic Circle during the study period signify spatial and temporal variability of navigational access for surface vessels. The sea ice duration map for the study year shows localized maxima and minima in the seasonal ice zone which correspond to areas where sea ice may persist more or less than the surrounding area. While most areas that sea ice covers for more than 300 days were located in the centre of the pack, several 'sea-ice clusters' congregated in the Arctic periphery due to atmospheric and ocean circulation patterns. The sea-ice duration associated with the area west of Severnaya Zemlya was on the order of 100 km and 300 days. Another sea-ice 'cluster' was visible southwest of Wrangel Island, on the order of 100 km and 250 days. Still another was visible south of the New Siberian Islands, on the order of 200 km and 200 days. Other areas with longer sea-ice duration included a 300 km-wide area offshore northeast Greenland and the Canadian Arctic Archipelago that is the location of most ice export through the Fram Strait. The Canadian Arctic Archipelago has perennial sea ice in much of its northern area from Banks Island to Ellsmere Island, and a local maximum of sea ice duration east of Victoria Island.

Fifth, the maximum rates of increasing and decreasing total open water area north of the Arctic Circle during the study period occurred in July and October, on the order of 100 thousand km^2 day^{-1}, characterizing the beginning and end of the theoretical navigating season for non-ice capable surface vessels. These hazardous 'shoulder seasons' occur before and after the time of greatest change in open water area.

Calculation of open water area and sea ice duration for a study year identified a theoretical navigating season and the amplitude, rate of change, and spatial and temporal variations of the theoretical navigating area north of the Arctic Circle. These five findings are the results of automated processes that analysed sea-ice concentration based on satellite measurements with spatial and temporal resolutions on the order of kilometres and 24 hours.

3.2. Spatial and Temporal Patterns of Arctic Marine Traffic

Observations of ship position based on satellite reception of AIS messages were used to determine the spatial and temporal distribution of surface vessels on the Arctic Ocean. A database, maps, and spatial and temporal distributions were calculated based on the estimated presence or absence of surface vessels north of the Arctic Circle during the year from 1 April 2010 to 31 March 2011. Further, a number of parameters were calculated to quantify marine traffic north of the Arctic circle during the study year, probing different temporal and spatial scales.

First, daily aggregations of AIS position report messages received by the SpaceQuest satellite constellation were used to analyse the spatial and temporal patterns of surface vessel operations north of the Arctic Circle during the study period. Locations of surface vessels were mapped for each day in the study year based on the latitude and longitude encoded in daily-aggregated AIS position report messages received by the SpaceQuest satellite constellation. Figure 28 shows the surface vessel locations for a day in Arctic summer, 1 September 2010, and a day in Arctic winter, 1 March 2011. On 1 September 2010, 725 distinct vessels operated north of the Arctic Circle based on the number of unique Maritime Mobile Service Identity (MMSI) encoded in 941 received AIS messages aggregated for the day. Similarly, 604 distinct vessels operated north of the Arctic Circle on 1 March 2011, based on the 812 validated AIS messages received during that day.

Second, monthly aggregations of AIS position report messages received by the SpaceQuest satellite constellation were used to analyse spatial and temporal patterns of surface vessel operations north of the Arctic Circle during the study period. Locations of surface vessels were mapped for each month in the study year based on the latitude and longitude encoded in monthly-aggregated AIS position report messages received by the SpaceQuest satellite constellation. Figure 29 and Appendix III show the surface vessel locations for the twelve months throughout the study year. In September 2010, 1439 distinct vessels operated north of the Arctic Circle based on the number of MMSI encoded in the 28264 validated AIS messages received during the month. Similarly, 1383 distinct vessels operated north of the Arctic Circle in March 2011, based on the 23065 validated AIS messages received during the month.

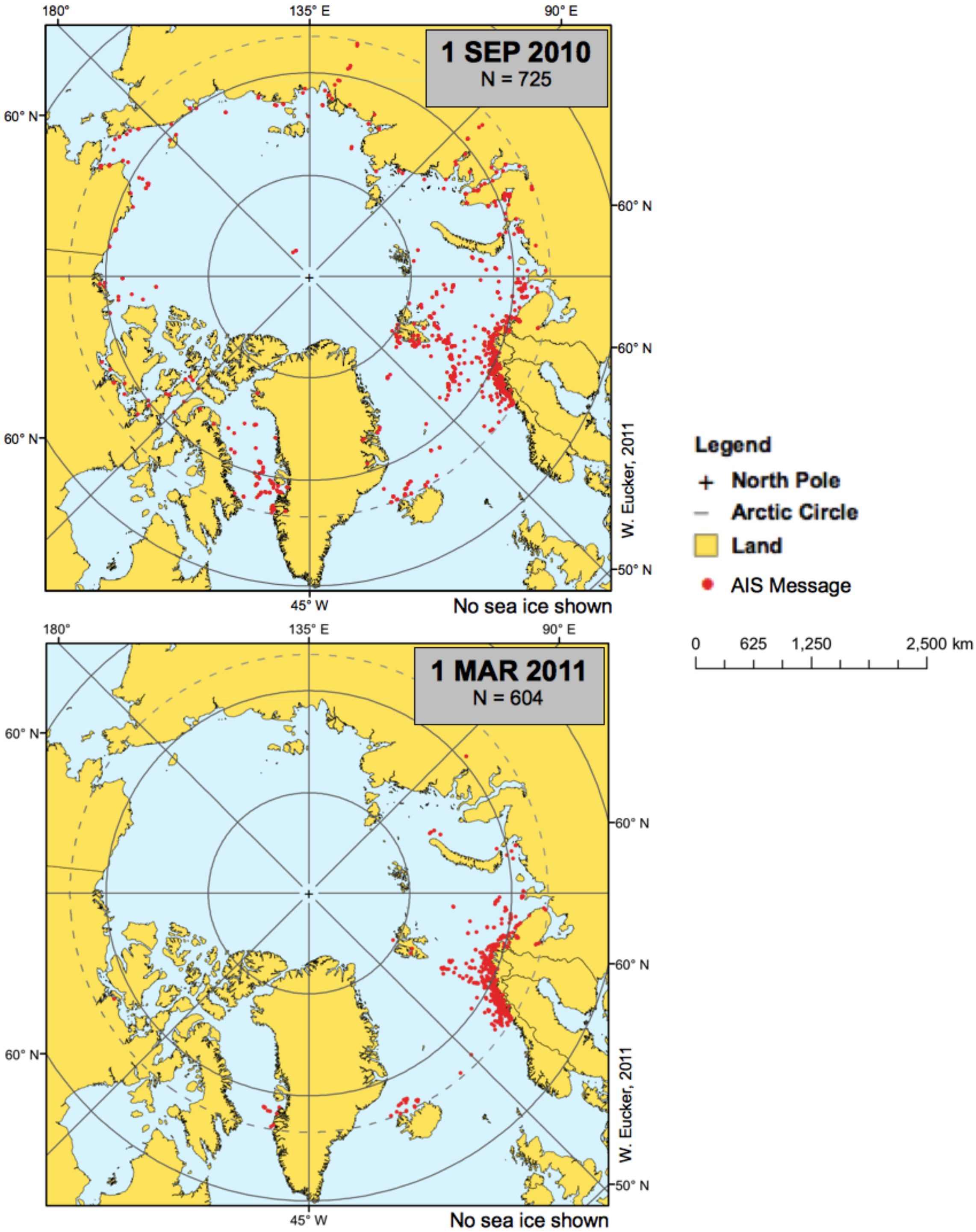


Figure 28. Daily Pan-Arctic Marine Traffic on 1 September 2010 and 1 March 2011

Surface vessel locations (red) north of the Arctic Circle based on AIS position report messages received by the SpaceQuest satellite constellation during two days in the study period: 1 September 2010 and 1 March 2011. The number of distinct vessels, N, was calculated based on the number of unique Maritime Mobile Service Identity (MMSI) encoded in the received AIS messages aggregated for the day.

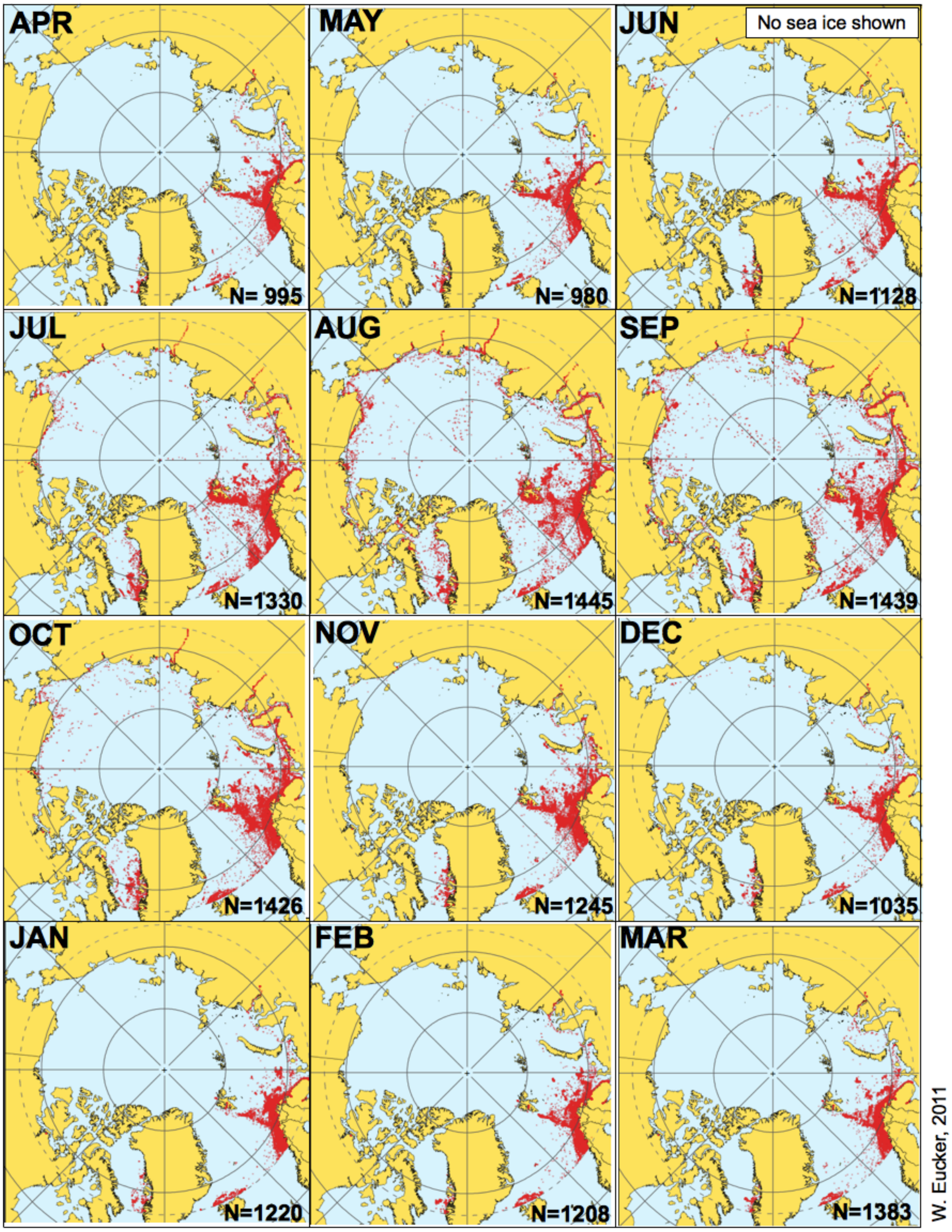


Figure 29. Monthly Pan-Arctic Marine Traffic, April 2010 to March 2011

Surface vessel locations (red) north of the Arctic Circle based on AIS position report messages received by the SpaceQuest satellite constellation aggregated by month. Number of distinct vessels, N, quantifies the observed marine traffic north of 66·56°N for each month during the 1 April 2010 to 31 March 2011 study year. See Appendix III for enlarged maps of Arctic marine traffic.

Third, a year of aggregated AIS position report messages received by the SpaceQuest satellite constellation was used to analyse the spatial and temporal patterns of surface vessel operations north of the Arctic Circle during the study period. Locations of surface vessels were mapped for the entire study year based on the latitude and longitude encoded in AIS position report messages received by the SpaceQuest satellite constellation. Figure 30 and Appendix III show the surface vessel locations for the study year. Figures 31-34 magnify the four quadrants of Figure 30 for the benefit of the reader. The SpaceQuest satellite constellation received more than 280,000 validated AIS messages from more than 3200 distinct vessels operating north of the Arctic Circle from 1 April 2010 to 31 March 2011.

There were several spatial and temporal patterns of Arctic marine traffic observed in the analyses based on AIS messages aggregated by day, by month, and by year. Aggregation over longer timescales increased the number of surface vessel observations and as a result, enabled the visualization of more localized patterns of Arctic marine traffic. Landmasses of North America, Eurasia, Greenland, Severnaya Zemlya, and other circum-Arctic islands excluded vessels. However, vessels were observed navigating the principal Eurasian rivers including the Lena River, Yenisei River, Ob River, Indigirka River, and Kolyma River, as well as the Mackenzie River in North America. A strong year-round signal of marine traffic is evident in the Atlantic Arctic quadrant, particularly in the Barents Sea and in the waters north of Iceland. Other year-round marine traffic was observed in the Kara Sea and southeastern Baffin Bay. In addition, surface vessel operations in summer were observed in northwest Russian waters, the Russian Far East, north of the Alaskan North Slope, and Baffin Bay. Surface vessel locations based on monthly aggregations of AIS messages indicated central Arctic Ocean operations from May to October. The monthly distribution of messages from vessels at longitudes changes throughout the year. The distribution is centred in Atlantic meridians for all twelve months, but there were limited numbers of vessels operating more than 60·00° east or west of Greenwich from November to May. Further, there was less spatial dispersion in surface vessel locations in April, when most marine traffic north of the Arctic Circle is localized to the Kara Sea, southeastern Baffin Bay, and North Atlantic/Barents Sea, as compared with September, when marine traffic was observed in every Arctic quadrant north of the Arctic Circle.

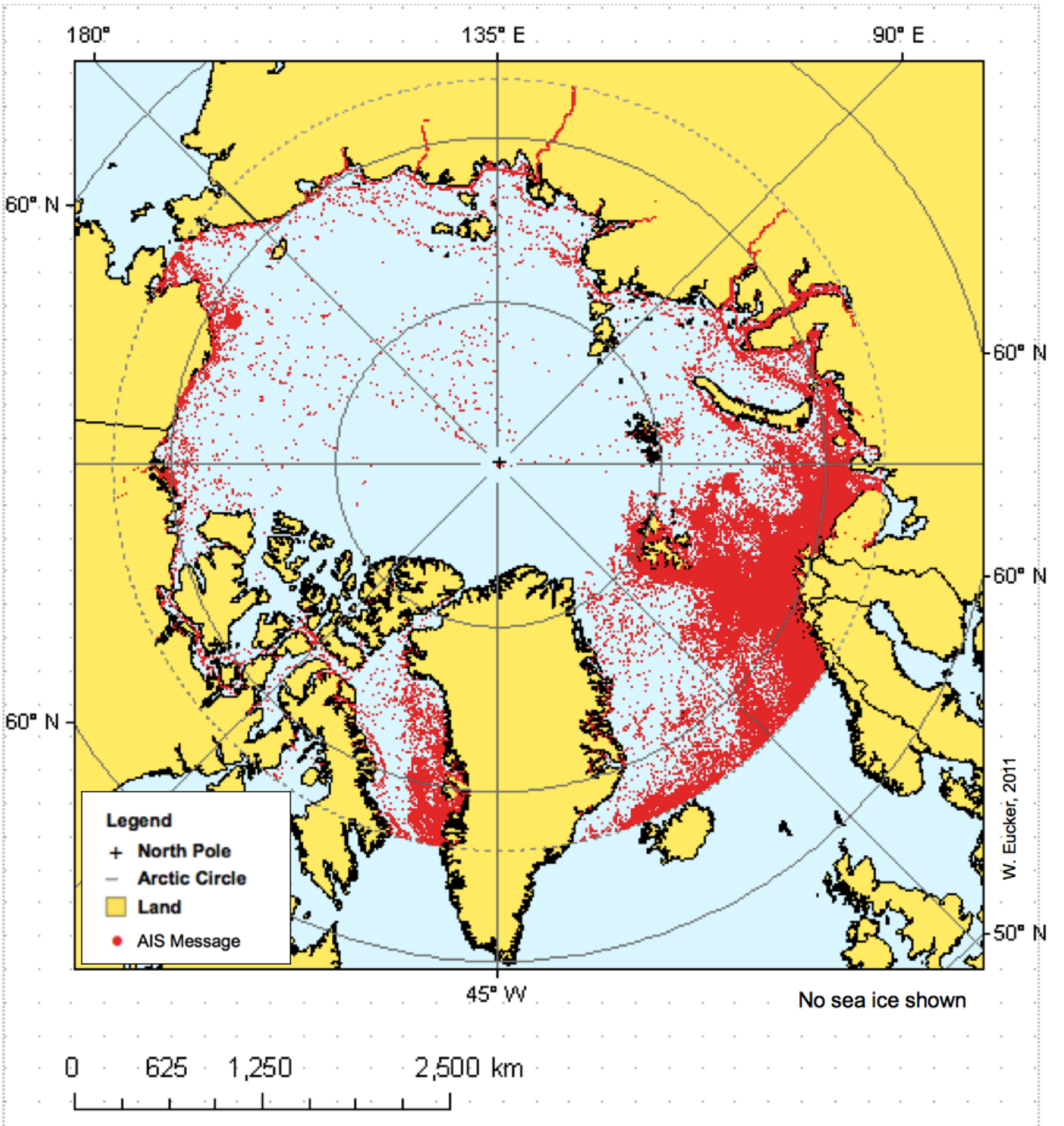


Figure 30. Pan-Arctic Marine Traffic, 1 April 2010 to 31 March 2011

Surface vessel locations (red) north of the Arctic Circle based on AIS position report messages received by the SpaceQuest satellite constellation aggregated for the study year. In the maritime area north of the Arctic Circle during the study year, most of the aggregated AIS position report messages indicated surface vessels were operating in the Barents Sea whereas relatively few messages indicated central Arctic Ocean surface vessel operations. In addition, messages reported surface vessel positions coincident with rivers in Eurasia as well as the Mackenzie River in North America.

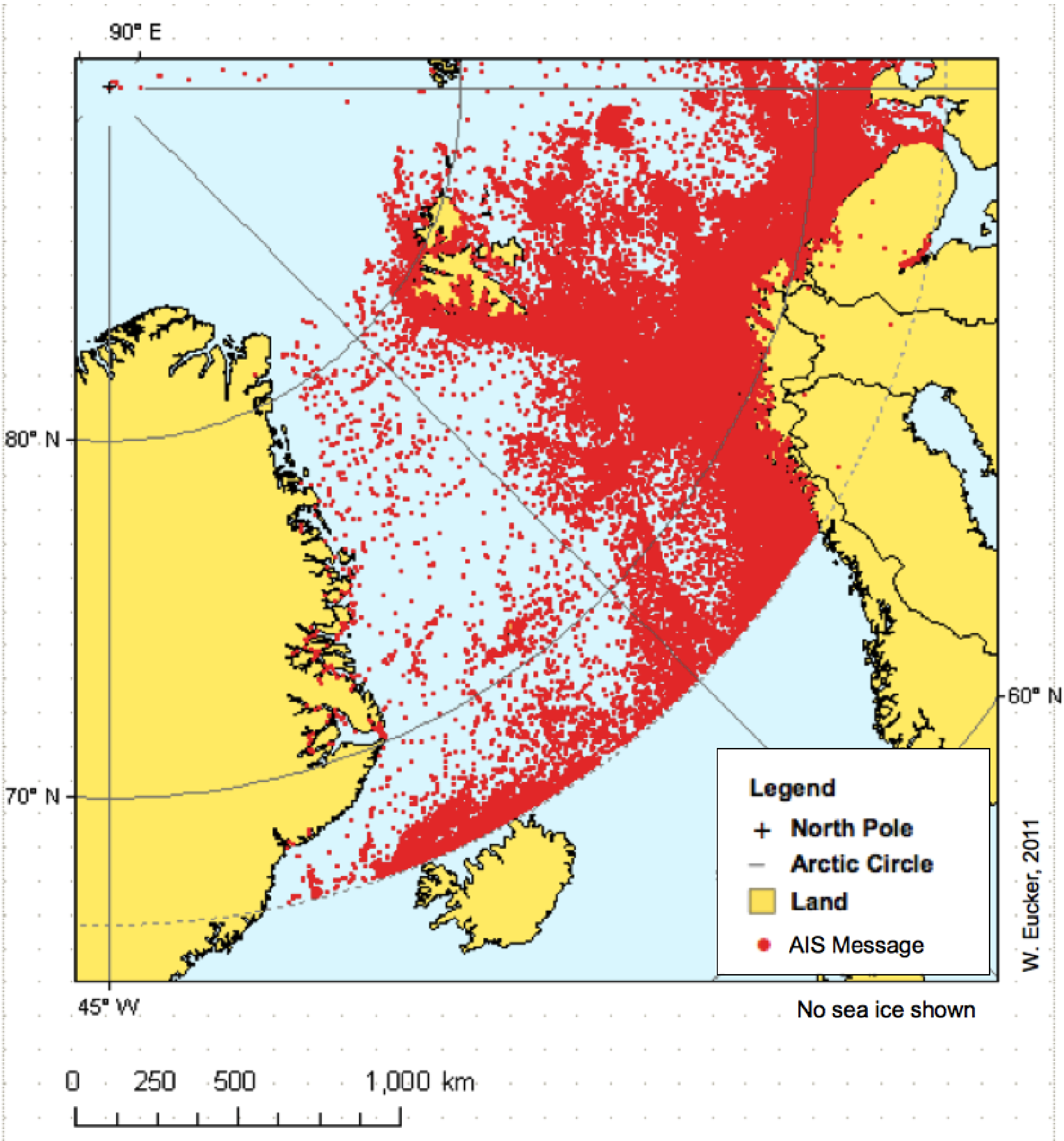


Figure 31. Arctic Marine Traffic, 45·00 °W to 45·00 °E, 1 April 2010 to 31 March 2011

Surface vessel locations (red) north of 66·56°N in the Atlantic Arctic quadrant, 45·00°W to 45·00°E, based on AIS position report messages received by the SpaceQuest satellite constellation aggregated during the 1 April 2010-31 March 2011 study year. In this quadrant, fewer than ten messages were received from vessels in the maritime area that extends south from the Geographic North Pole to 82°N. By contrast, thousands of messages were received from vessels in the Norwegian Sea and Barents Sea. In addition, numerous vessels were observed in the small area of the White Sea south of the Kola Peninsula that is not physically contiguous with the principal maritime area north of 66·56°N. Further, several messages reported surface vessel positions coincident with land, mostly near the coastline in Svalbard, Greenland and Northern Europe.

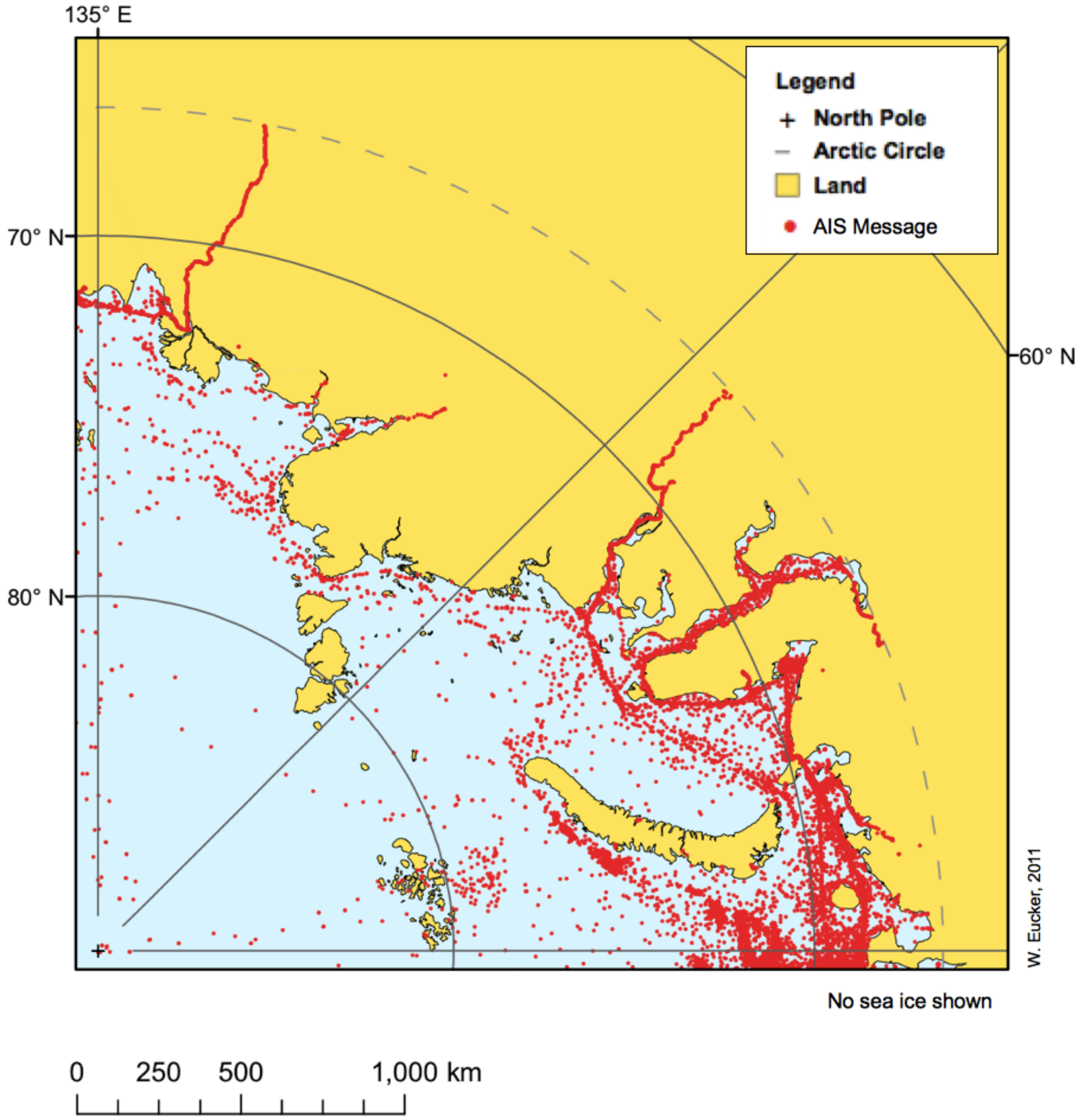


Figure 32. Arctic Marine Traffic, 45·00°E to 135·00°E, 1 April 2010 to 31 March 2011

Surface vessel locations (red) north of 66·56°N in the Eurasian Arctic quadrant, 45·00°E to 135·00°E, based on AIS position report messages received by the SpaceQuest satellite constellation aggregated during the 1 April 2010-31 March 2011 study year. In this quadrant, the majority of messages were received from thousands of vessels operating in the Barents Sea and Kara Sea. By contrast, two distinct vessels were observed in the central Arctic Ocean north of 82°N. Localized areas of marine traffic may be identified from linear spatial patterns coincident with components of the Northern Sea Route and other trade routes, including passages through the Yugorskiy Shar Strait, Kara Gates Strait, Malygina Striat, Vil'kitskii Strait. In addition, messages reported vessel locations coincident with the Lena River, Yenisei River, and the Ob River north of the Arctic Circle.

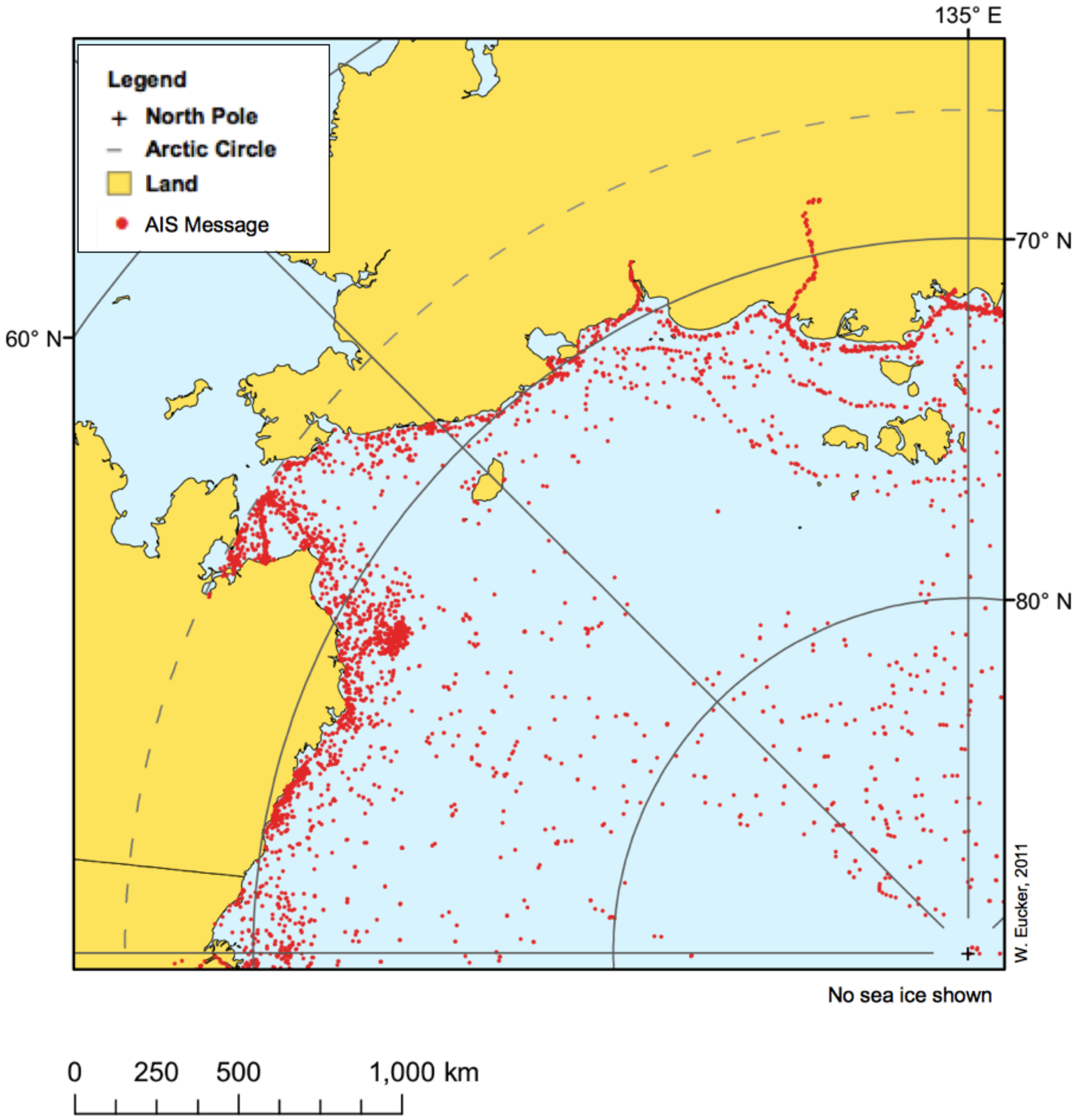


Figure 33. Arctic Marine Traffic, 135·00°E to 135·00°W, 1 April 2010 to 31 March 2011

Surface vessel locations (red) north of 66·56°N in the Pacific Arctic quadrant, 135·00°E to 135·00°W, based on AIS position report messages received by the SpaceQuest satellite constellation aggregated during the 1 April 2010-31 March 2011 study year. Localized areas of marine traffic may be identified from linear spatial patterns coincident with components of the Northern Sea Route north of Eurasia from the Bering Strait to the straits of the New Siberian Islands and the western section of the Northwest Passage north of North America. Compared with other quadrants, this quadrant had the greatest number of messages and distinct vessels in the central Arctic Ocean north of 82°N. In addition, messages reported vessel locations coincident with the Indigirka River and Kolyma River in Eurasia north of 68°N.

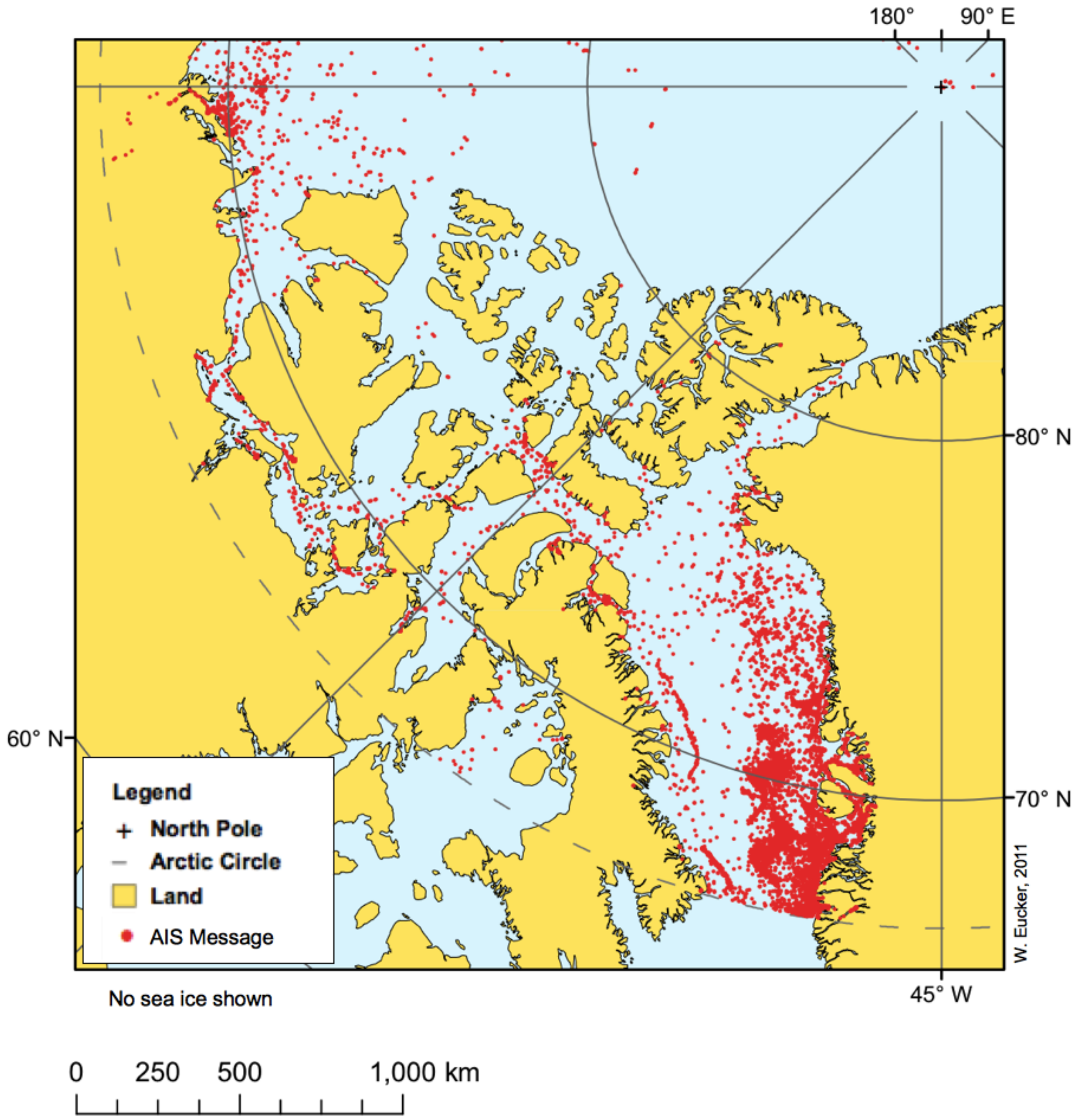


Figure 34. Arctic Marine Traffic, 135·00°W to 45·00°W, 1 April 2010 to 31 March 2011

Surface vessel locations (red) north of 66·56°N in the American Arctic quadrant, 135·00°W to 45·00°W, based on the number of AIS position report messages received by the SpaceQuest satellite constellation aggregated during the 1 April 2010-31 March 2011 study year. Localized areas of marine traffic may be identified as linear spatial patterns coincident with routes of the eastern section of the Northwest Passage through the Canadian Arctic Archipelago. Most vessels in this quadrant were observed in the eastern half of Baffin Bay and the Mackenzie River delta, and no AIS messages were received from vessels north of 82°N. In addition, messages reported vessels coincident with the Mackenzie River north of the Arctic Circle.

In addition to mapping the location of surface vessels based on received AIS messages, AIS message concentration per unit area was calculated. Message concentration quantifies magnitude of marine use in addition to the presence or absence of surface vessels. Figure 35 and Appendix III shows the AIS message concentration per 6·25 km reference grid cells north of 66·56°N for the year from 1 April 2010 to 31 March 2011. Localized areas of marine traffic may be identified from patterns of high message concentration near landmasses and along linear 'routes'.

Finally, AIS messages temporally aggregated for the entire study year were spatially aggregated by Exclusive Economic Zone (EEZ) and complementary High Seas region. A variety of parameters were calculated for each Exclusive Economic Zone or international space north of the Arctic Circle during the study year, including the number of distinct vessels, number of distinct flags, and frequency of common navigation status indicators. Table 11 shows a summary of these marine traffic parameters based on received AIS messages from each region north of the Arctic Circle during the study year.

Table 11. Arctic Marine Traffic by EEZ, 1 April 2010 to 31 March 2011

	AIS Messages	Distinct Vessels	Distinct Flags	Navigation Status		
				Engine (0)	Fishing (7)	Sail (8)
Norway						
Russian Federation	53198	1071	90	951	83	52
Greenland	13717	172	46	138	16	17
Iceland	9418	307	46	177	32	14
United States	3554	100	27	91	0	4
Canada	3422	81	25	70	5	7
International Space 2	3379	298	61	237	48	16
International Space 3	2218	43	9	27	13	4
Jan Mayen	543	125	36	86	19	7
International Space 1	409	10	6	8	0	0
Finland	3	2	1	1	0	0
Sweden	1	1	1	0	0	0

International Spaces were named in order of area: 1 - Central Arctic Ocean, 2 – Norwegian Sea, 3 – Barents Sea.

Geographic information system can probe multiple dimensions of information encoded in AIS messages on different temporal and spatial scales. For example, Figure 36 shows the concentration of marine traffic in the Norwegian EEZ from 1 April 2010 to 31 March 2011. This graphical approach can be used to quantitatively attribute specific marine activities, *e.g.* fishing or transport, to observations to improve the understanding of marine use of a region.

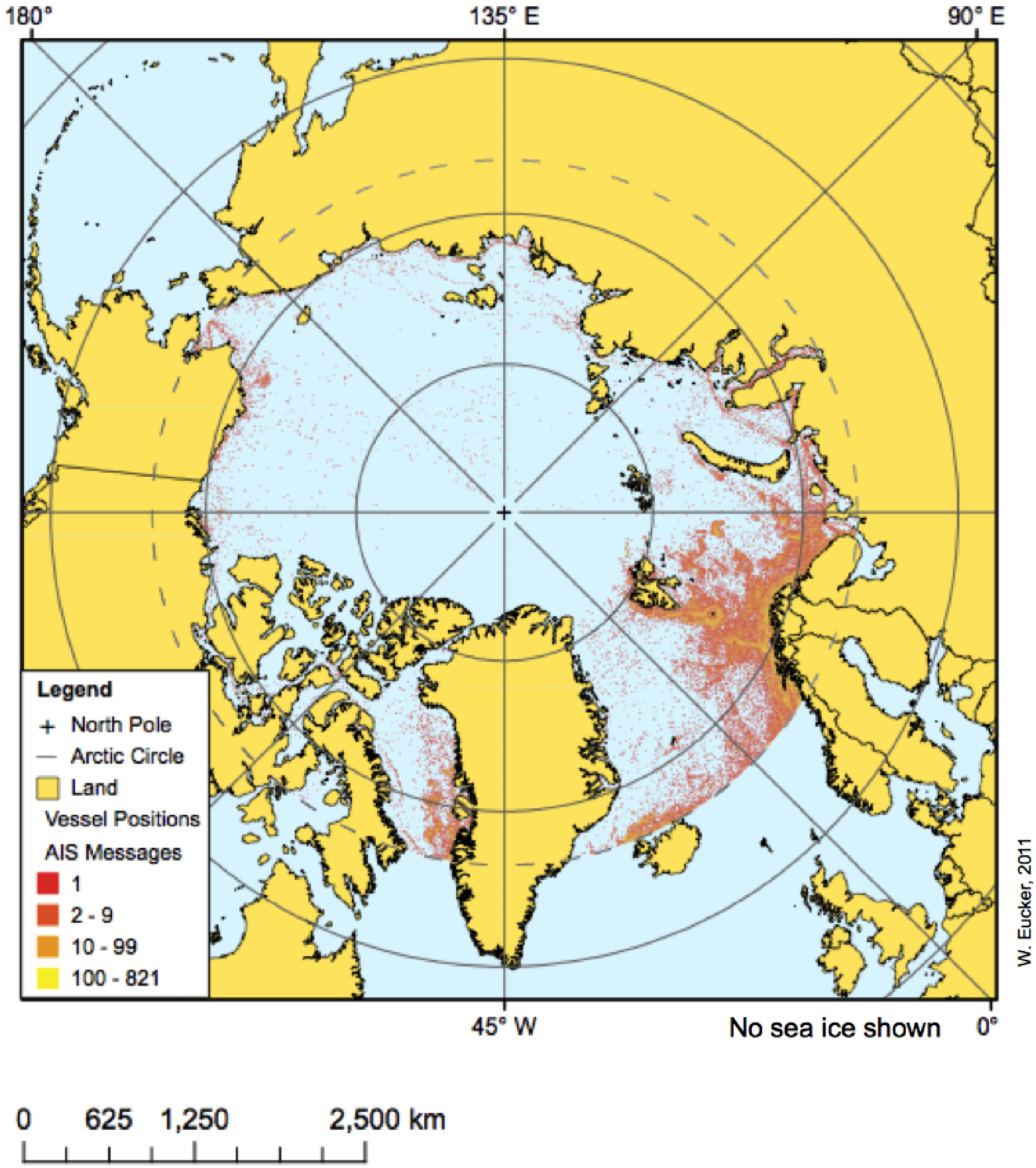


Figure 35. Pan-Arctic Marine Traffic Concentration, 1 April 2010 to 31 March 2011

Surface vessel concentration per unit area based on the number of AIS position report messages received by the SpaceQuest satellite constellation in 6·25 km reference grid cells north of 66·56°N for the year from 1 April 2010 to 31 March 2011. As compared with Figure 30 which shows the presence or absence of surface vessels, this AIS message concentration map estimates the magnitude of marine traffic north of the Arctic Circle during the study year. The Barents Sea and Norwegian Sea showed the highest concentration of received AIS messages per unit area. Further, localized areas of marine traffic may be identified from patterns of high message concentration near landmasses and along linear 'routes'.

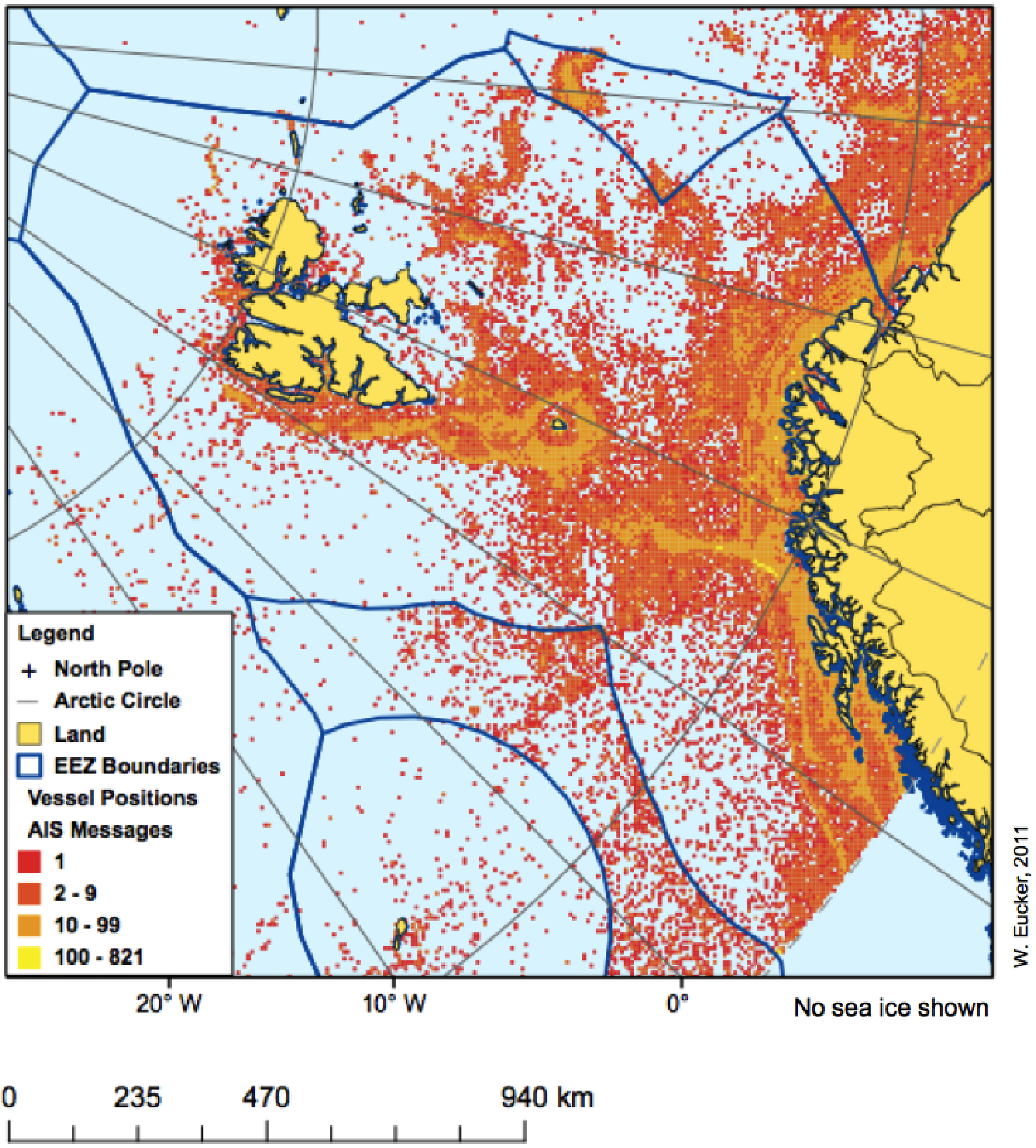


Figure 36. Marine Traffic Concentration, Norwegian EEZ, 1 April 2010 to 31 March 2011

Concentration of AIS position report messages received by the SpaceQuest satellite constellation per 6·25 km reference grid cells in the Norwegian Exclusive Economic Zone (EEZ) north of 66·56°N for the year from 1 April 2010 to 31 March 2011. The most concentrated areas of vessel location are the traffic separation scheme offshore mainland Norway, around Bjornøya, and north of Iceland. Vessels are more concentrated in the traffic separation zone offshore mainland Norway, in a 10 km perimeter around Bjornøya, and in the high seas region west of the Norwegian EEZ.

3.3. Spatial and Temporal Relationships between Arctic Marine Access and Use

Presence of sea ice and surface vessels based on satellite observations was used to determine spatial and temporal patterns of Arctic marine access and Arctic marine traffic. Databases, maps, and spatial and temporal distributions were calculated for sea ice concentration and surface vessel positions north of 66·56°N during the year from 1 April 2010 to 31 March 2011. Further, satellite observations were integrated over the entire study year to determine sea-ice duration and marine traffic concentration per 6·25 km reference grid cell.

Daily aggregations of sea-ice concentration measurements based on satellite radiometry and AIS position report messages received by the SpaceQuest satellite constellation were used to analyse the spatial and temporal relationship between sea ice and surface vessel operations north of the Arctic Circle during the study period. Extent of open water based on the number of 6·25 km maritime reference grid cells north of 66·56°N and south of 89·24°N in which sea ice was estimated to occupy less than 0·5% of the total cell area. Locations of surface vessels were mapped for each day in the study year based on the latitude and longitude encoded in daily-aggregated AIS position report messages received by the SpaceQuest satellite constellation. Figure 28 shows the open water area and surface vessel locations for a day in Arctic summer, 1 September 2010, and a day in Arctic winter, 1 March 2011. On 1 September 2010, 725 distinct vessels operated north of the Arctic Circle based on the number of unique Maritime Mobile Service Identity (MMSI) encoded in 941 received AIS messages aggregated for the day. Of these 941 messages, 660 identified surface vessels located in 6·25 km grid cell areas associated with open water. Further, 250 messages identified vessels on land, 31 in sea ice with concentration greater than 0.5%, and 25 in sea ice with concentration greater than 15%. On 1 March 2011, 604 distinct vessels operated north of the Arctic Circle based on the 812 validated AIS messages received during that day. Of these 812 messages, 427 identified surface vessels located in 6·25 km grid cell areas associated with open water, 294 messages identified vessels on land, 91 in sea ice with concentration greater than 0.5%, and 80 in sea ice with concentration greater than 15%.

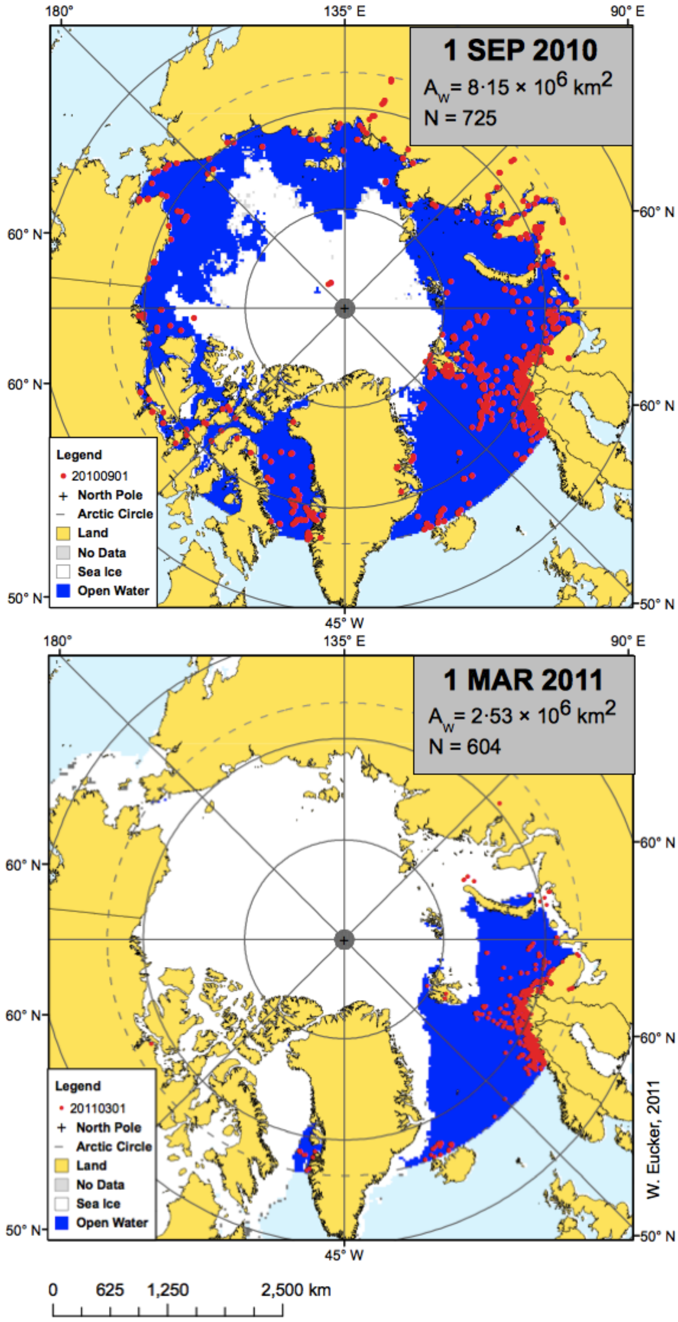


Figure 37. Daily Pan-Arctic Observations, 1 September 2010 and 1 March 2011

Open water area and surface vessels locations based on satellite observations for two days during the study period: 1 September 2010 and 1 March 2011. Extent of open water (blue) and sea ice (white) north of the Arctic Circle based on the number of 6·25 km maritime reference grid cells north of 66·56°N and south of 89·24°N in which sea ice was estimated to occupy less than 0·5% and greater than 15% of the total cell area, respectively. Surface vessel locations (red) north of the Arctic Circle based on AIS position report messages received by the SpaceQuest satellite constellation. Open water area, A_w, quantifies Arctic marine access and the number of distinct vessels, N, quantifies Arctic marine traffic.

A year aggregation of daily sea-ice concentration measurements based on satellite radiometry and AIS position report messages received by the SpaceQuest satellite constellation were used to analyse the spatial and temporal relationship between sea ice and surface vessel operations north of the Arctic Circle during the study period. Sea-ice duration and AIS message concentration per unit area were calculated to quantify the spatial and temporal components of marine access and marine traffic. Figure 38 overlays AIS message concentration onto sea-ice duration per 6·25 km reference grid cells north of 66·56°N in the Atlantic Arctic for the year from 1 April 2010 to 31 March 2011. Localized areas of marine traffic may be identified in areas of perennial open water of the North Atlantic and Barents Sea. In addition, areas with greater concentrations of AIS messages may be observed in the seasonal ice zone along the west coast of Spitsbergen, north of Bjornøya, and north of Iceland. However, the higher concentrations of AIS messages in these areas are due to pronounced seasonal traffic in summer open water. Finally, messages were also received indicating surface vessel operations in the perennial ice zone in the Greenland Sea and Central Arctic Ocean.

Automatic Identification System transmissions received by the SpaceQuest satellite constellation from 1 April 2010 to 31 March 2011 show surface vessels navigate north of the Arctic Circle throughout the year in various sea ice conditions. Daily ship identifications reveal more than 3200 distinct vessels with the largest densities in perennially ice-free areas as well as year-round operations in ice-covered areas. Three groups of marine operations with distinct characteristics were determined from the analysis: operations in perennial open water, operations in the seasonal ice zone, and operations in the perennial ice zone. Throughout the study year, most ships north of 66·56°N operated in perennially ice-free areas, but year-round operations also occurred in ice-covered areas.

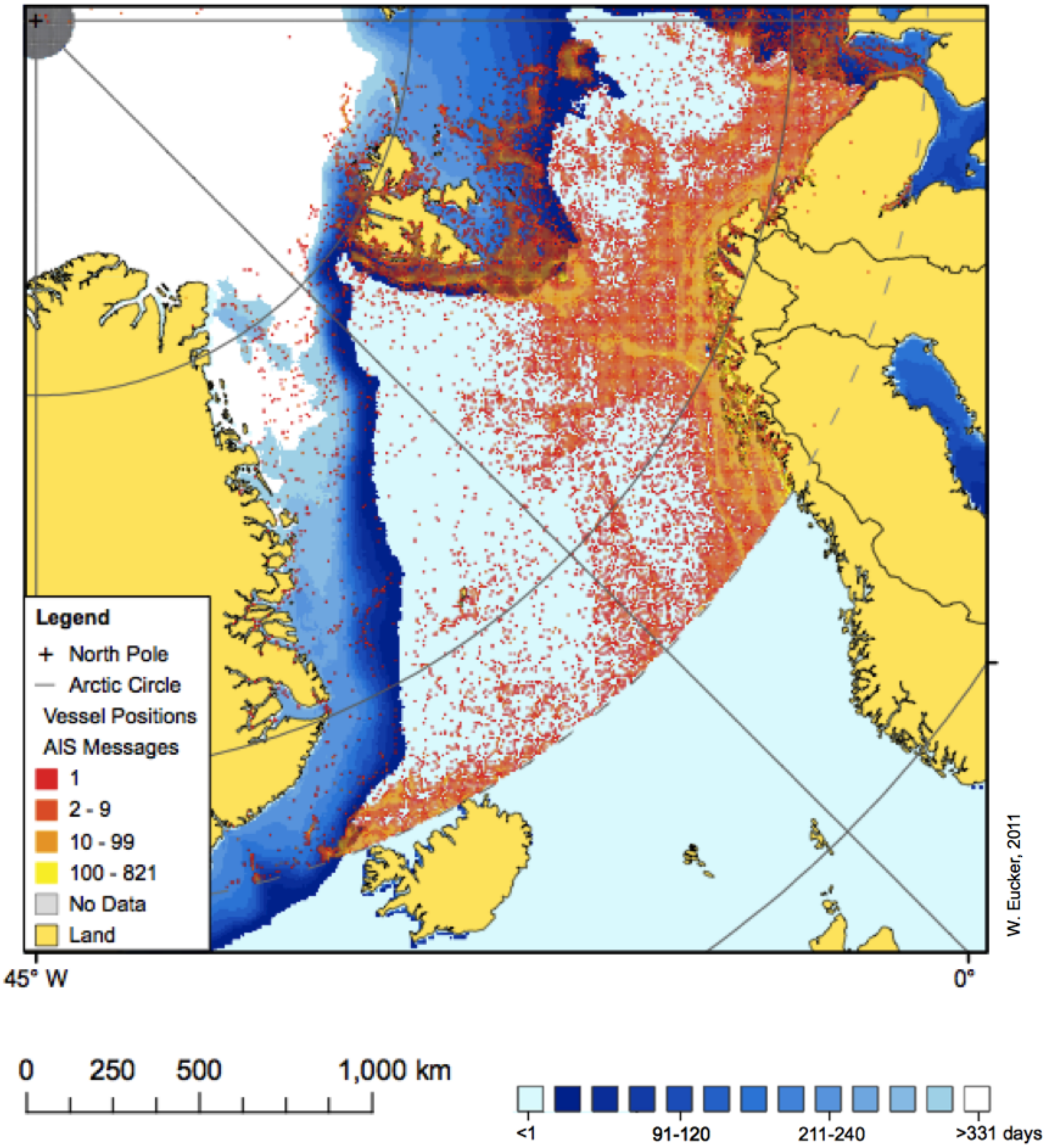


Figure 38. Access and Traffic, 45·00°W to 45·00°E, 1 April 2010 to 31 March 2011

Concentration of AIS position report messages from north of 66·56°N between the 45·00°W and 45·00°E meridians received by the SpaceQuest satellite constellation during the year from 1 April 2010 to 31 March 2011 were overlaid on a calculation of sea-ice duration during the same period. Both parameters were calculated using 6·25 km maritime reference grid cells. Marine access and marine use for the Atlantic Arctic.

3.4. Validation and Errors

The geospatial analysis of Arctic marine traffic based on AIS messages received by the SpaceQuest satellite constellation during the study year from 1 April 2010 to 31 March 2011 was further examined in two regions where independent observations of surface vessel operations were available. Spatial subsets of the SpaceQuest data set in the Bering Strait region and Isfjorden, Spitsbergen were validated with the Marine Exchange of Alaska ground-based AIS network and a database from the Port of Longyearbyen.

In addition to the availability of independent observations of surface vessel traffic with a temporal overlap with the SpaceQuest AIS dataset, the two seasonally-variable validation regions were selected to represent different spatial scales, different hemispheres, and different geographical features from each other to test the approach. First, the Bering Strait region was selected as one of the areas for validation because it provides an example of 1) an area with spatial scale: 10^2- 10^3 m, 2) a location in the Pacific Arctic, and 3) an Arctic strait. Second, Isfjorden, Spitsbergen, provides an example of 1) an area with spatial scale: 10^1- 10^2 m, 2) a location in the Atlantic Arctic, and 3) an Arctic port.

The Bering Strait region is the sole avenue between the Arctic Ocean and the Pacific Ocean, and as such includes all transit traffic through the Northeast Passage and Northwest Passage. Figure 39 summarizes the spatial and temporal distribution of marine traffic across a Bering Strait passage line based on AIS messages received by the Marine Exchange of Alaska ground-based network. Because marine traffic does not transit north of the Bering Strait between December and May, the temporal coverage of the data from the Marine Exchange of Alaska is comparable with the observations from SpaceQuest during the period 1 April 2010 to 31 December 2010. Figure 40 compares the geographic locations encoded in AIS messages received by the Marine Exchange of Alaska ground network with those from a subset of AIS position reports received by the SpaceQuest satellite constellation. The surface vessels observed by the Marine Exchange of Alaska navigated south of the Arctic Circle while those observed by SpaceQuest were operating in region bounded by the 66·56ºN and 72·00ºN parallels and the 160·00ºW and 180·00º meridians. On the spatial scale of the Bering Strait region, sea-ice duration and AIS message concentration accurately represented reality. Figure 41 shows the examination of sea ice and marine traffic for the Bering Strait region.

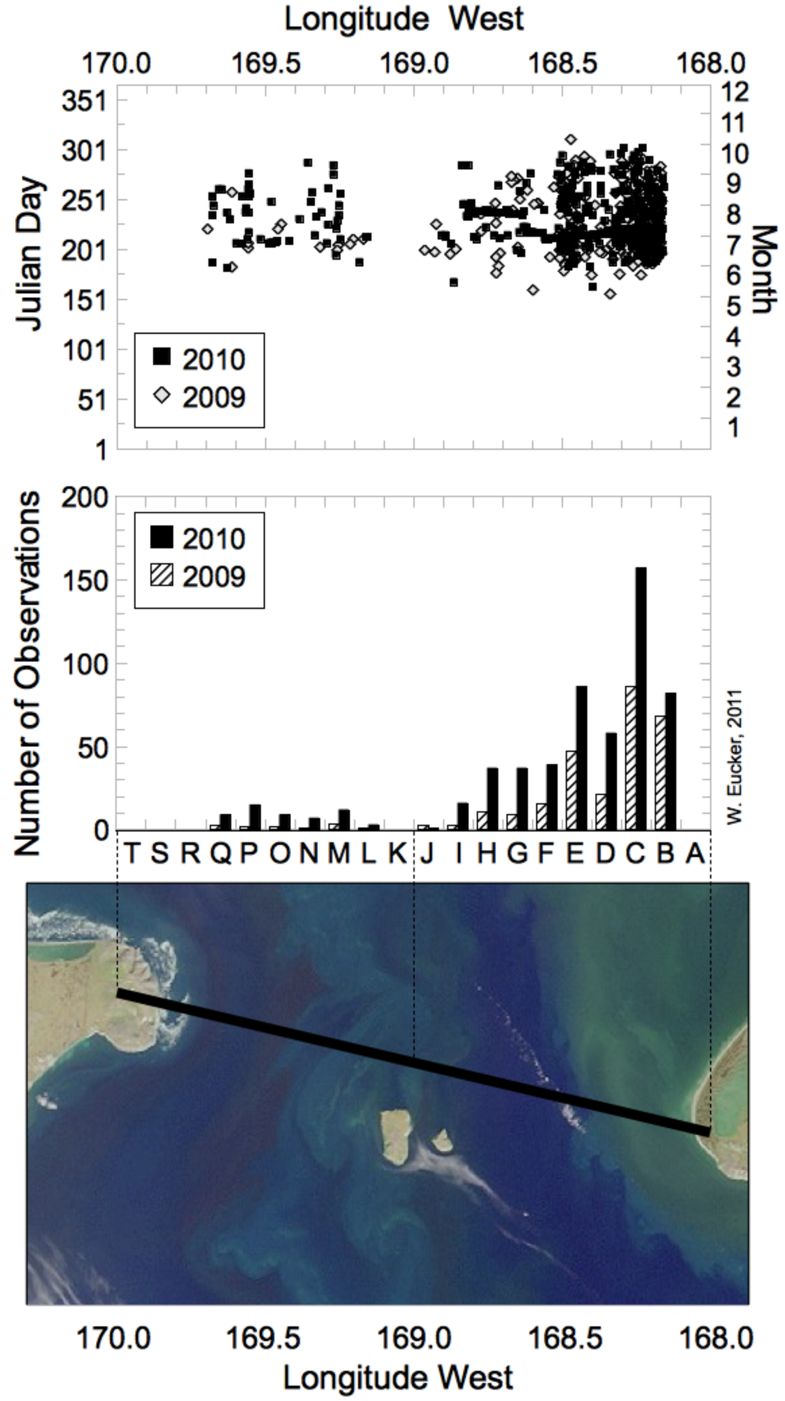


Figure 39. Spatial and Temporal Patterns of Marine Traffic in the Bering Strait

Spatial and temporal distribution of surface vessels crossing the Bering Strait in 2009 and 2010 based on Automatic Identification System messages received by the Marine Exchange of Alaska ground station network. Observations along a Bering Strait passage line were aggregated into segments of one tenth of a degree of longitude (approximately 4·5 km) from North America (A) to Eurasia (T). Inset is adapted from the Multi-angle Imaging SpectroRadiometer, 18 August 2000 (NASA, 2010).

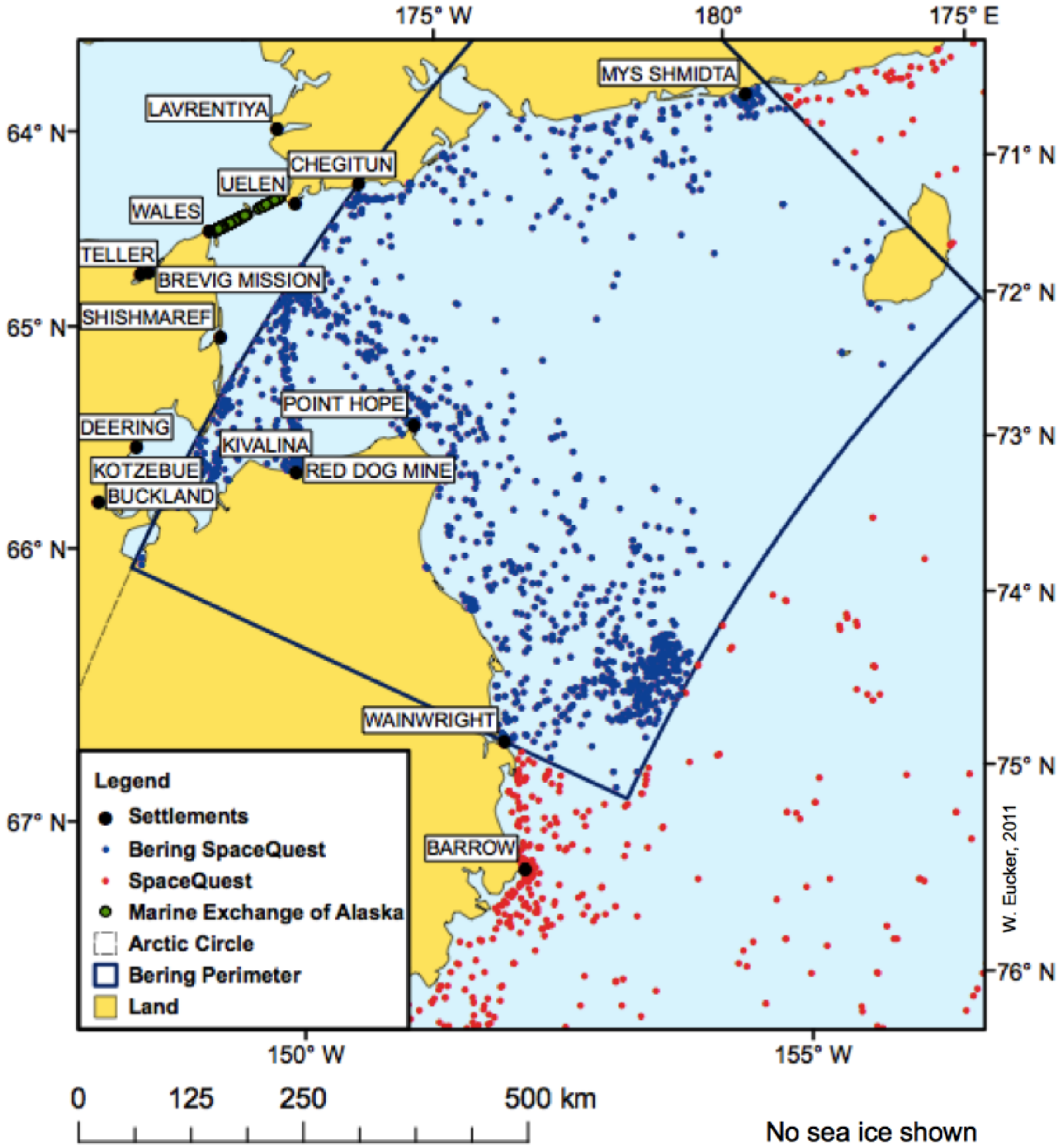


Figure 40. Marine Traffic in the Bering Strait Region, 1 April 2010 to 31 December 2010

The geographic locations encoded in AIS position reports received by the Marine Exchange of Alaska ground network (green) were compared with those from a subset of AIS position reports received by the SpaceQuest satellite constellation (blue). The surface vessels observed by the Marine Exchange of Alaska navigated south of the Arctic Circle while those observed by SpaceQuest were operating in region bounded by a 'Bering Perimeter', demarcated by the 66·56ºN and 72·00ºN parallels and the 160·00ºW and 180·00º meridians. While the two sets of observations did not coincide spatially, they overlapped in time during the period 1 April 2010 to 31 December 2010. The Bering Strait region includes all transit traffic through the Northeast and Northwest Passages.

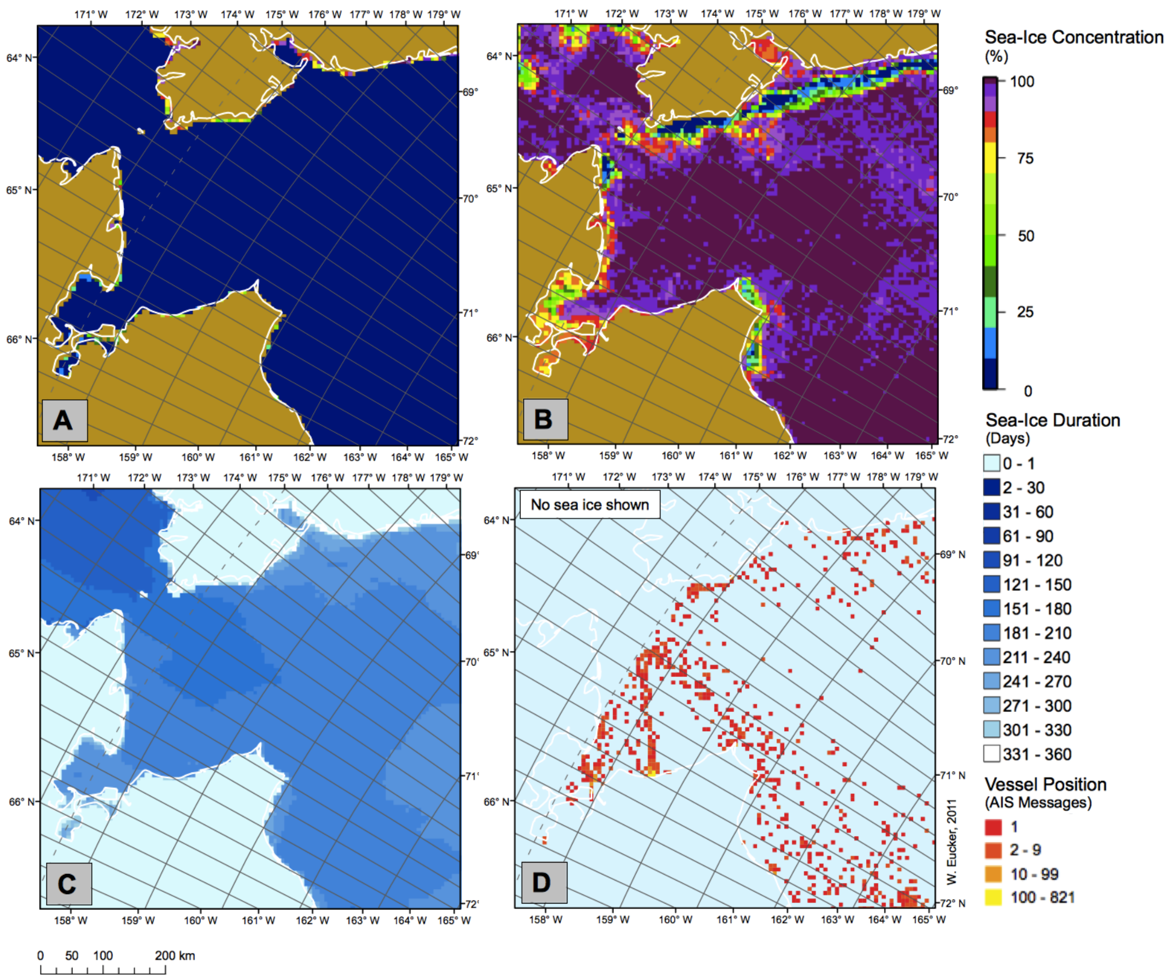


Figure 41. Sea Ice and Surface Vessels in the Bering Strait

(A) Sea-ice concentration per 6·25 km reference grid cell for 1 September 2010 shows near-complete open water. (B) Sea-ice concentration per 6·25 km reference grid cell for 1 March 2011 shows near-complete sea-ice cover. In both (A) and (B), the 6·25 km grid interval does not adequately distinguish sea ice and land proximate to the coastline, and a large sea-ice concentration gradient exists near shore of Alaska and Chukotka. (C) Sea-ice duration calculated by integrating sea ice concentration over the study year probes a different temporal scale and removes many of the effects caused by the proximity of land. (D) AIS message concentration per 6·25 km reference grid cell resolves local and regional marine use, including seasonal transport from Red Dog Mine (67·5ºN, 164·0ºW).

Isfjorden, Spitsbergen is an example of a seasonal Arctic port that supports mining, science, and tourism. The Port of Longyearbyen provided a record of all vessels that arrived at the Bykaia International Ship and Port Facility in Longyearbyen from 1 January 2004 to 31 December 2010. The vessel observations from the Port of Longyearbyen consisted of time of arrival and time of departure from the Port, vessel name and International Maritime Organization (IMO) number, and vessel parameters. This dataset is based on AIS receiver information validated with radiocommunications and visual observations from the Bykaia facility, and records from the *Sysselman* (Norwegian: Governor of Svalbard). Vessels with other destinations in Isfjorden (*e.g.* Barentsburg and Pyramiden) are not included in the data set, but were frequently observed by the Port of Longyearbyen AIS ground station. Figure 42 summarizes the spatial and temporal distribution of marine traffic in Isfjorden, Spitsbergen based on a subset of AIS messages received by SpaceQuest during the year from 1 April 2010 to 31 December 2010 (the temporal coverage of the data from the Port of Longyearbyen is comparable with the observations from SpaceQuest during this period). The observations from the Port of Longyearbyen were not mapped in Figure 42 because all vessel locations were coincident with the Port of Longyearbyen (78·22ºN, 15·55ºE). Figure 40 compares the geographic locations encoded in AIS messages received by the Marine Exchange of Alaska ground network with those from a subset of AIS position reports received by the SpaceQuest satellite constellation.

On the spatial scale of Isfjorden, an order of magnitude smaller than the previous Bering Strait case study, the 6·25 km reference grid cell fails to accurately represent the maritime area near land. However, sea-ice duration calculated by integrating daily sea-ice concentration measurements over the study year more accurately represents physical reality. Similarly, the map of vessel traffic concentration calculated using 6·25 km reference grid cells appears pixelated. However, the three cells of highest AIS message concentration coincide with the Port of Longyearbyen, the port servicing Svea mine (Sveagruva), and the face of the calving glacier in Tempelfjorden (a common tourist destination). Figure 43 shows the examination of sea ice and marine traffic for Isfjorden.

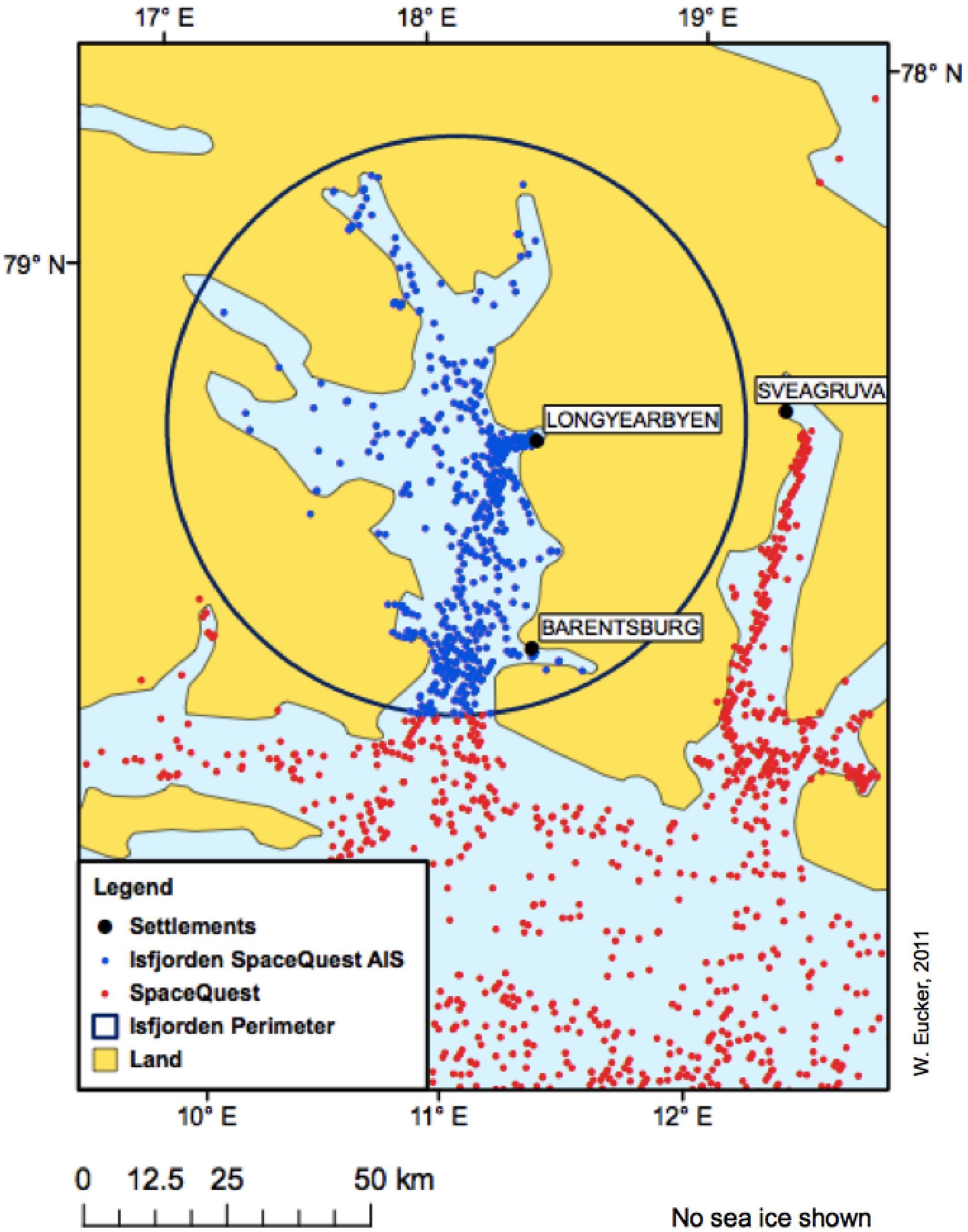


Figure 42. Marine Traffic in Isfjorden, 1 April 2010 to 31 March 2011

Reported surface vessel positions north of the Arctic Circle (red) and within Isfjorden, Spitsbergen (blue) based on AIS messages received by the SpaceQuest satellite constellation during the study period. Satellite observations of vessels in Isfjorden were compared with reports from the Port of Longyearbyen.

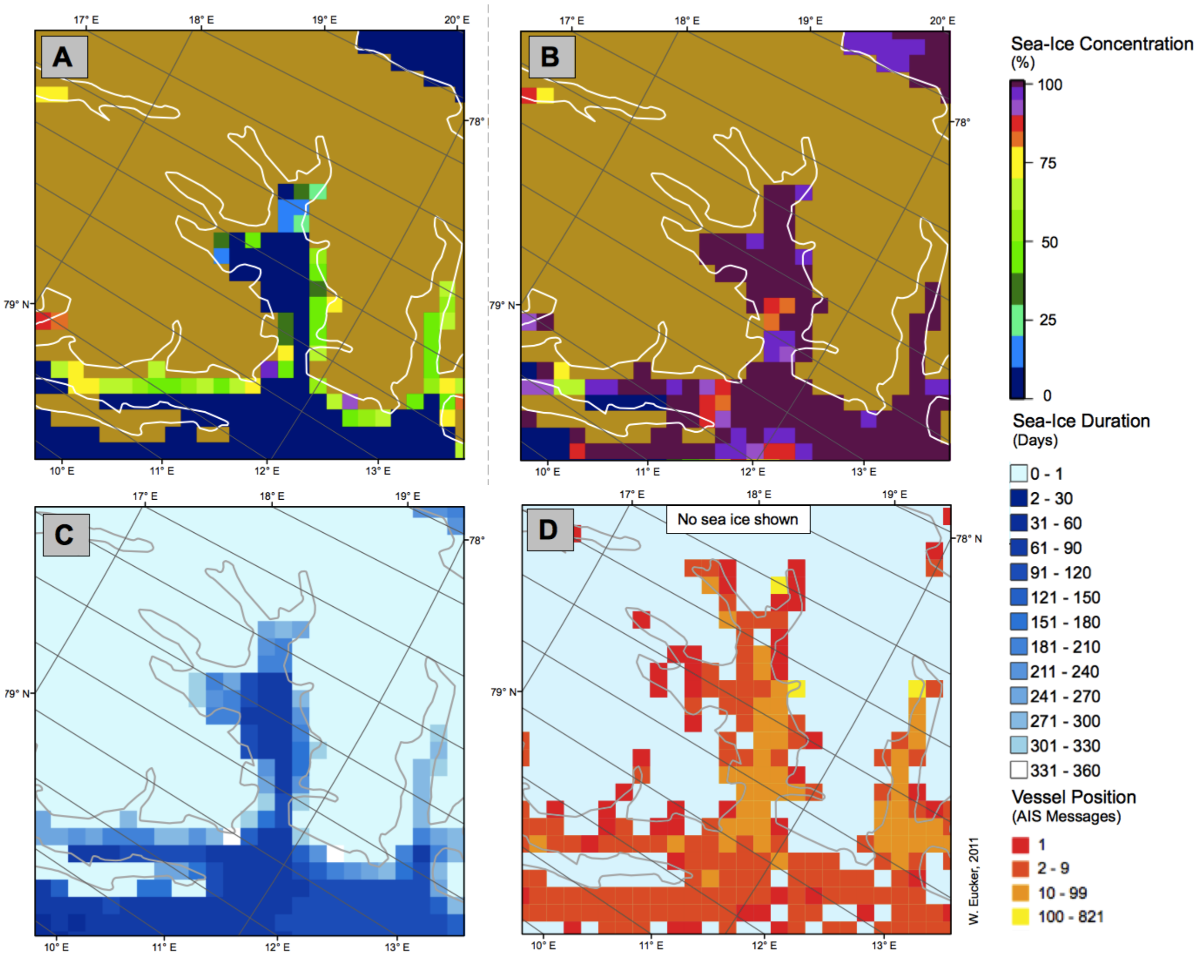


Figure 43. Sea Ice and Surface Vessels in Isfjorden, Spitsbergen

(A) Sea-ice concentration for 1 September 2010 shows near-complete open water. (B) Sea-ice concentration for 1 March 2011 shows near-complete sea-ice cover. In both (A) and (B), the 6·25 km grid interval does not adequately distinguish sea ice and land proximate to the coastline, and a large sea-ice concentration gradient exists near shore. (C) However, the year integration to calculate sea-ice duration effectively probes a different temporal scale and removes many of the effects caused by the proximity of land. (D) AIS message concentration per 6·25 km reference grid cell resolves a general pattern of localized marine use with highest concentration coincident with Longyearbyen and Barentsburg.

4. Discussion of Results

The Arctic maritime region is on the brink of a transformation due to changes in the sea-ice cover and growing global interests in its trade routes and resources. New pathways of information are needed to characterize the relationships amongst the physical and anthropogenic components of the Arctic Ocean in the 'Anthropocene', a proposed geological epoch that describes the present and future Earth climate in which human activities have unprecedented consequences in the physical environment (Crutzen, 2002). The analysis results present revised assessments of the transforming Arctic Ocean related to navigational possibilities and marine use realities. In addition, a new methodology was developed that integrates multiple sources of information.

4.1. Revised Arctic Marine Access Assessment

This work developed a reproducible approach to examine a navigating area and season for surface vessels in the Arctic Ocean. Compared with previous work, this study expanded the spatial and temporal scope from peripheral routes during summer to a pan-Arctic maritime area during an entire year. Daily sea-ice concentration measurements from satellite radiometry were used to estimate the presence or absence of sea ice greater than 15% concentration in 6·25 km square reference grid cells north of the Arctic Circle during the study period. An approach incorporating a Geographic Information System and computational spatial and temporal integration was used to construct databases, maps, and spatial and temporal distributions of sea-ice area and duration.

This year study of Arctic sea ice for navigational possibilities yielded five principal results. Calculation of open water area and sea ice duration for a study year identified a theoretical navigating season and the amplitude, rate of change, and localized variations of the theoretical navigating area north of the Arctic Circle. These five findings are the result of an automated process that examined sea-ice concentration measurements with spatial and temporal resolutions on the order of kilometres and 24 hours.

Other hazards in the Arctic Ocean physical operating environment exist in addition to sea ice concentration on spatial and temporal scales measured in this work. Pressure ridges, multi-year ice inclusions, and frequency and intensity of storms are hazards to navigation, but may not be explicitly resolved by passive microwave measurements. However, there are no reliable data that includes this information in a pan-Arctic or longitudinal context, and as a result was not included in this assessment. Ridging is presumably more likely in the perennial ice zone and sea ice clusters, but ridge frequency is not known. Other further studies include frequency and intensity of storms and multi-year ice in open water. Figure 43 shows various oceanographic and atmospheric processes distributed over space and time. Geophysical measurements enable the ability to probe temporal and spatial scales important for surface vessel operations. A challenge for the future will be to combine observations of large scale climate variability and small scale dynamic conditions for the physical operating environment. Drift and thickness are important characteristics of sea ice for surface vessel operations that could be included in future navigational assessments provided improved observation.

While sea-ice concentration is only one parameter that describes the Arctic Ocean physical operating environment, its analysis in space and time informs strategic planning for surface vessel operations. The results develop a process to analyse synoptic daily measurements of the Arctic Ocean physical operating environment that define navigational possibilities. Operational and tactical decisions for surface vessels require information on smaller temporal and spatial scales, but the geospatial analysis process developed herein may be applied to measurements of other sea-ice parameters on different spatial and temporal scales.

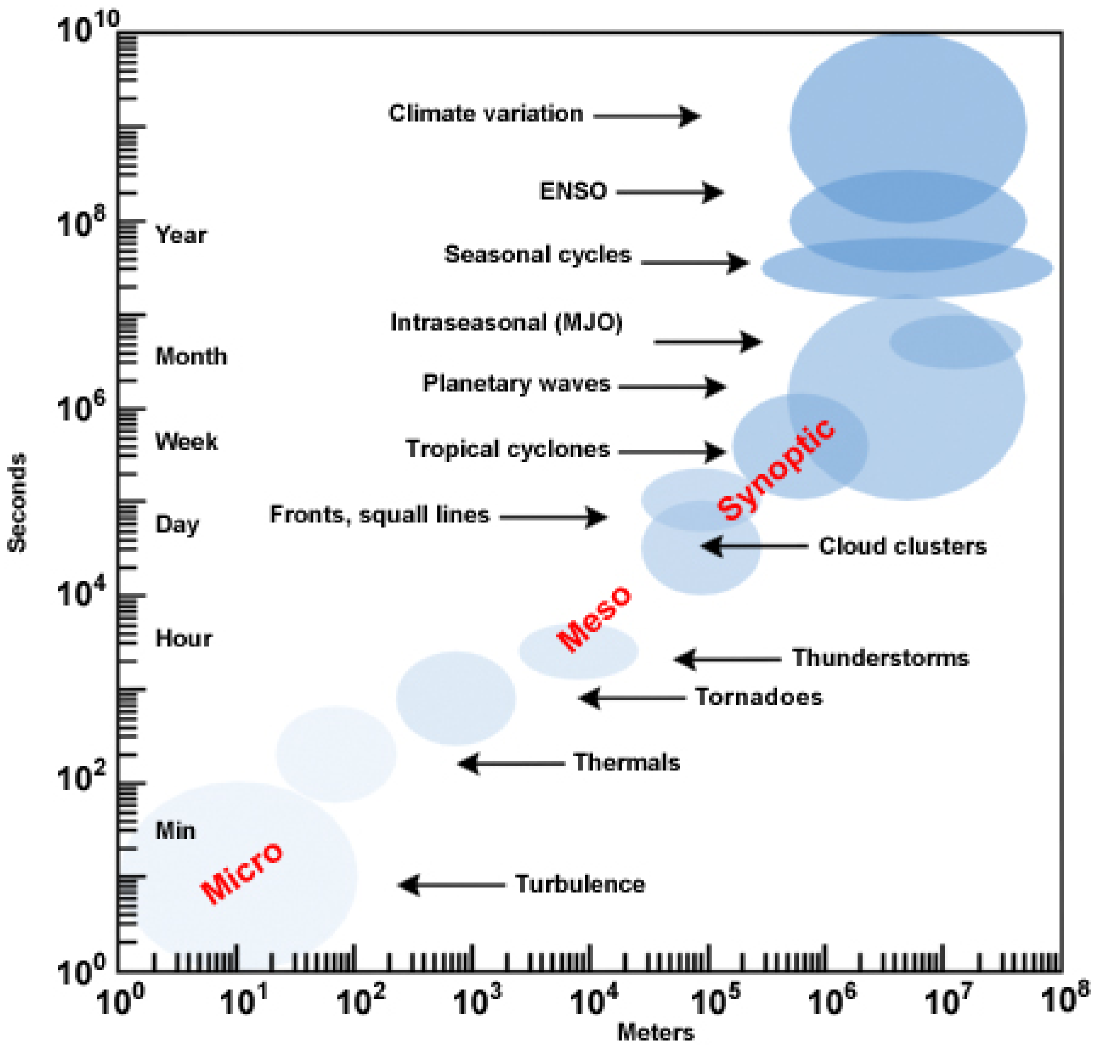


Figure 44. Spatial and Temporal Scales of Physical Operating Conditions

A challenge for the future will be to integrate understanding of large scale climate variability and small scale dynamic conditions for assessing navigational possibilities (University Corporation for Atmospheric Research, 2010).

4.2. Revised Arctic Marine Traffic Assessment

This work developed a reproducible approach to examine marine traffic in the Arctic Ocean. The analysis results presented revised assessments of the transforming Arctic Ocean related to the reality of marine use. In addition, a new methodology was developed that enables the integration of multiple sources of information. This revised arctic marine traffic assessment was an incremental improvement on previous assessments.

The Arctic Marine Shipping Assessment (AMSA) included the most comprehensive geospatial analysis of Arctic marine traffic for a study year, but the 2009 report was largely based on 2004 data collected by independent authorities who applied varying vessel definitions and marine boundaries defined by the internal policies of the Arctic states. The original sub-annual observations of surface vessel operations north of the Arctic Circle in 2004 were re-analysed to include all vessels reported within a consistent boundary. The original government surveys from the Russian Federation excluded fishing vessels and those from Norway contained observations of surface vessel observations from 2006, consolidated by quarter. Figure 45 presents the results from the reassessment of data collected for AMSA combined with synoptic observations of sea ice based on satellite passive microwave radiometry. Daily vessel traffic, quantified by tonnage, showed variability across the year, from minima in the dark months of January and December to maxima in August and September. A daily count of number of vessels aggregated by month (excluding data from Norway) showed that Arctic marine traffic was at a maximum in August 2004, preceding the September minimum in sea-ice extent. In both the daily and monthly aggregated re-assessments, there was a year-round baseline of marine traffic upon which a seasonal signal was added in summer (June to October).

The number of vessels operating north of the Arctic Circle in the AMSA study year (2004) was compared with the analysis of marine traffic based on the AIS messages received by SpaceQuest satellite constellation during the study year from 1 April 2010 to 31 March 2011. Since AMSA presented fishing activity separately from other marine traffic, the comparison between the AMSA reassessment and SpaceQuest analysis is similarly separated into two parts.

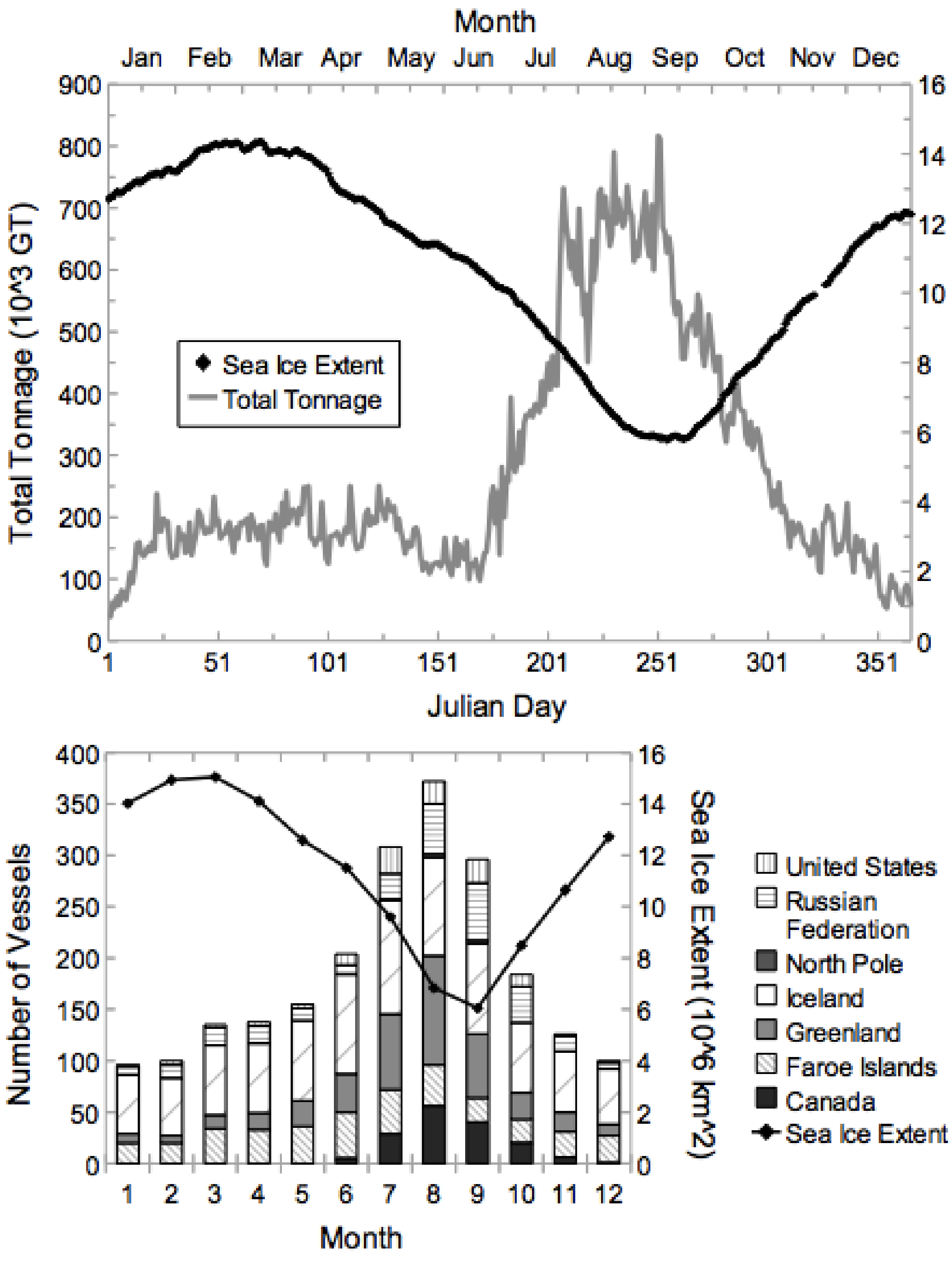


Figure 45. Re-analysis of Arctic Marine Shipping Assessment Surveys

Consolidated sub-annual observations of vessels operating north of the Arctic Circle in 2004 based on original responses to AMSA government surveys: (A) tonnage operating in the Arctic Ocean per day and daily observed sea ice extent for the northern hemisphere [malfunction in the Special Sensor Microwave/Imager (SSM/I) caused the gap in sea ice extent for Julian days 323-326], and (B) number of vessels per month and monthly mean sea ice extent for the northern hemisphere (AMSA, 2009; NSIDC, 2011). Quarterly data from 2006 provided by Norway was not included.

More than 280,000 time-stamped AIS messages were received by the SpaceQuest satellite constellation from 3200 distinct vessels operating north of 66·56°N during 1 April 2010 to 31 March 2011. Table 12 compares Arctic marine traffic based on AMSA and SpaceQuest observations.

Table 12. Marine Traffic Comparison Between AMSA and SpaceQuest

	AMSA			SpaceQuest		
Region	Voyages	Vessels	Flags	AIS Messages	Vessels	Flags
Norway	1356	1157	N/A	190795	1583	114
Russian Federation	152	42	6	53198	1071	90
Greenland	368	68	29	13717	172	46
Iceland	833	177	46	9418	307	46
United States	68	37	10	3554	100	27
Canada	85	46	16	3422	81	25
International Space 2	0	0	0	3379	298	61
International Space 3	0	0	0	2218	43	9
International Space 1	4	4	3	409	10	6
Finland	0	0	0	3	2	1
Sweden	0	0	0	1	1	1
Total	**3241**	**1575**	**64**	**280114**	**3203**	**312**

Fishing vessel days per Large Marine Ecosystem (LME) reported in AMSA were compared with number of days a position report AIS message was received that indicated the vessel was engaged in fishing (Navstatus 7). Table 13 and Figure 46 show the comparison.

Table 13. Fishing Activity Comparison Between AMSA and SpaceQuest

	AMSA	SpaceQuest		
Large Marine Ecosystem	Fishing Vessel Days	AIS Messages	Distinct Vessels	Distinct Days
Iceland Shelf/Sea	127 638	1 432	38	297
Barents Sea*	115 784	32 924	275	364
Norwegian Sea*	78 286	7 770	216	361
West Greenland Shelf/Sea	18 820	1 647	9	332
East Greenland Shelf/Sea	6 814	392	39	124
Baffin Bay/Davis Strait	2 577	668	13	194
Chukchi Sea	0	18	1	10
Kara Sea	0	0	0	0
East Siberian Sea	0	0	0	0
Laptev Sea	0	0	0	0
Beaufort Sea	0	0	0	0
Arctic Archipelago	0	0	0	0
Central Arctic Ocean	0	0	0	0
Total	0	47 134	344	364

*2,263 AIS messages were received that reported vessel positions on or near land in the Barents Sea and Norwegian Sea LME.

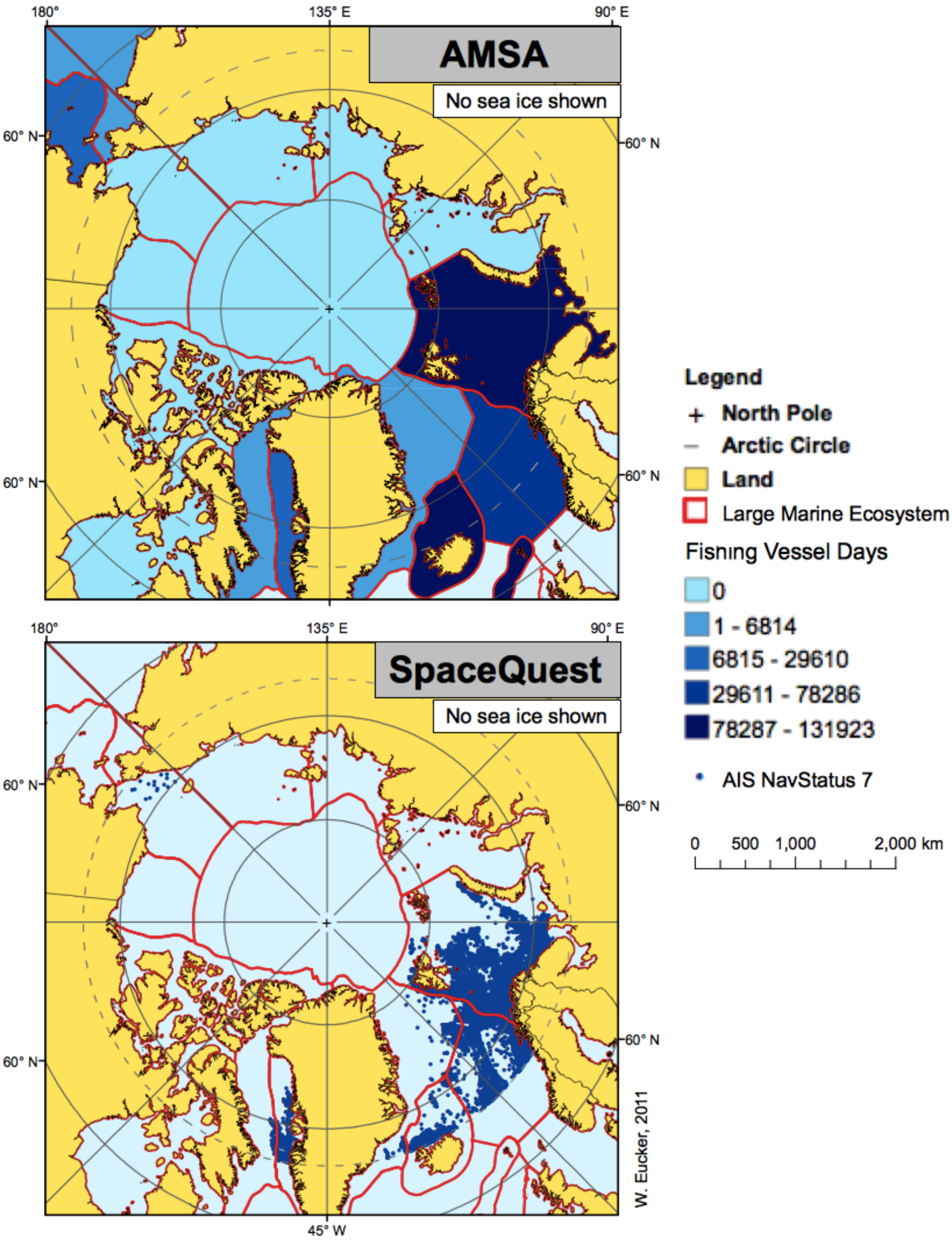


Figure 46. Comparison of Arctic Fishing Activities, 2004 and 2010-2011

Fishing in the Arctic Large Marine Ecosystems in 2004 as reported in the Arctic Marine Shipping Assessment 2009 Report is comparable to a revised assessment based on satellite reception of AIS messages from vessels engaged in fishing (Navigation Status 7). According to the SpaceQuest dataset, one vessel, *Tinro*, a Russian fisheries science vessel operated in the Chuckchi Sea LME from 7 to 16 September 2010 (10 days) north of 66·56°N.

With the launch of the Aprize satellites in 2008, SpaceQuest, Limited, receives and records real-time, universal position reports transmitted by vessels operating an Automatic Identification System (AIS). More than 280,000 time-stamped AIS messages were received by the SpaceQuest satellite constellation from vessels operating north of 66·56°N during 1 April 2010 to 31 March 2011. Daily ship identifications reveal more than 3200 distinct vessels. This study did not examine inter-annual variation marine traffic, but it provides a consistent process and baseline for future analysis of trends.

This marine traffic assessment underestimates the total number of vessels that operate north of the Arctic Circle because not all AIS message reports were received by the satellite constellation and not all vessels operate AIS. AIS messages received by the Marine Exchange of Alaska ground station network in the Bering Strait region were compared with those received by the SpaceQuest satellite constellation from a comparable region. While individual messages differed, the individual vessels corresponded. All ships larger than 300 Gross Tonnage and commercial passenger vessels are required by international law to operate AIS (SOLAS, 1974). From the validation with the Port of Longyearbyen observations of surface vessel in Isfjorden, it is estimated that the sample of vessels recorded in the SpaceQuest dataset represents approximately 80% of the total population of vessels that operated north of the Arctic Circle during the study year. Further, this marine traffic assessment is also based on AIS messages that encode navigational information from ship instruments and is an indirect method of observing vessel position and speed, as opposed to a direct satellite observation of the vessel using electromagnetic detection. As such, the location from which the AIS message was transmitted may not have been the reported position of the vessel.

Future analysis of the SpaceQuest dataset is possible, incorporating vessel size, destination, speed, and navigational status. Field tests could also be attempted to validate the message deconfliction software, and determine transmission range based on various meteorological conditions.

Since AMSA, the United States Coast Guard Automated Mutual-Assistance Vessel Rescue (AMVER) Reporting System has continued to record anonymous vessel positions in the Arctic Ocean. Originating after the *RMS Titanic* tragedy, the AMVER system collects and analyses daily position reports of participating vessels for the purpose of facilitating rescue response in case of accident. Commercial vessels over 1,000 Gross Tonnage and making a voyage of more than 24 hours volunteer to participate in the system. While the total participation in AMVER is growing, with more than 3500 vessel locations recorded globally per day, many vessels that operate in the Arctic do not participate in the AMVER system: the maximum number of vessels recorded north of the Arctic Circle recorded in 2010 was 50 (AMVER, 2011).

Systems of observing surface vessels in the Arctic Ocean has increased in automation and rapidness from the government surveys collected by the Arctic Marine Shipping Assessment, to the position reports received by the Automated Mutual-Assistance Vessel Rescue Reporting System, to the AIS messages received by SpaceQuest, Limited. The satellite passive remote sensing of AIS messages enables the ability to have an continuous assessment of marine use of the Arctic Ocean with resolution on the order of metres (dependent on GNSS) and hours (dependent on orbital and downlink periods). Remote-sensing data have advantages of being geo-referenced, real-time, objective and accessible. In addition to the revised assessment of Arctic marine traffic, the combination of synoptic daily satellite coverage and the universal AIS message protocol has implications for marine policy.

4.3. Toward an Arctic Marine Information Infrastructure

Transforming physical operating conditions and ship traffic patterns in the Arctic Ocean require a new set of rules for marine safety, security, and environmental protection. These rules and associated infrastructure require an assessment of the natural and anthropogenic consequences across the Arctic Ocean informed by consistent and timely observations. Satellite remote-sensing data paired with geographic information systems are uniquely suited to enable geo-referenced, real-time, and accessible analysis of individual or multiple surface vessels in relation to the physical environment.

The combination of synoptic daily satellite coverage and the universal AIS message protocol has enabled the geospatial analysis of individual vessels. This capability has implications for mariner safety, law enforcement, and environmental protection. Four notable voyages of *Monchegorsk, Nordic Barents, SCF Baltica,* and *Tor Viking* in 2010 are shown in relation to sea ice conditions Figure 47. Similarly, Figure 48 shows the positions of *Xue Long*.

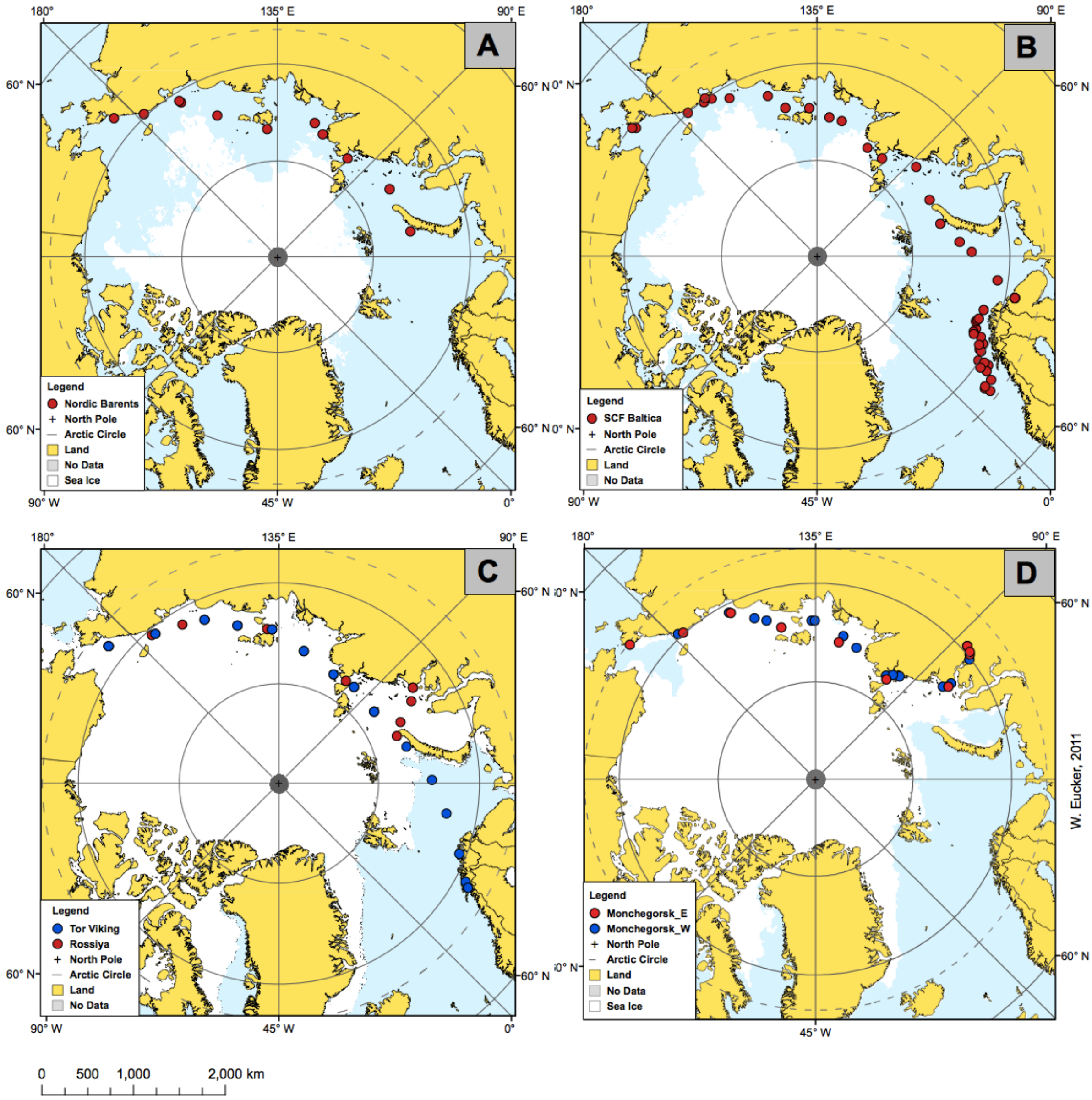


Figure 47. Satellite Observation of Four Notable Arctic Voyages

Location of four ships north of 66·56ºN based on AIS position report messages received by the SpaceQuest satellite constellation during the year from 1 April 2010 to 31 March 2011: (A) *Nordic Barents*, the first non-Russian flag vessel to transport cargo from one non-Russian port to a non-Russian destination through Russian Arctic Waters; (B) *SCF Baltica*, the first tanker greater than 100,000 deadweight tons to transit Russian Arctic Waters; (C) *Tor Viking* (escorted by Russian nuclear icebreaker *Rossiya*), the first vessel to transit Russian Arctic Waters in late December; and (D) *Monchegorsk*, the first commercial vessel to sail the Northern Sea Route East and West, from Murmansk to Shanghai to Dudinka, without icebreaker escort.

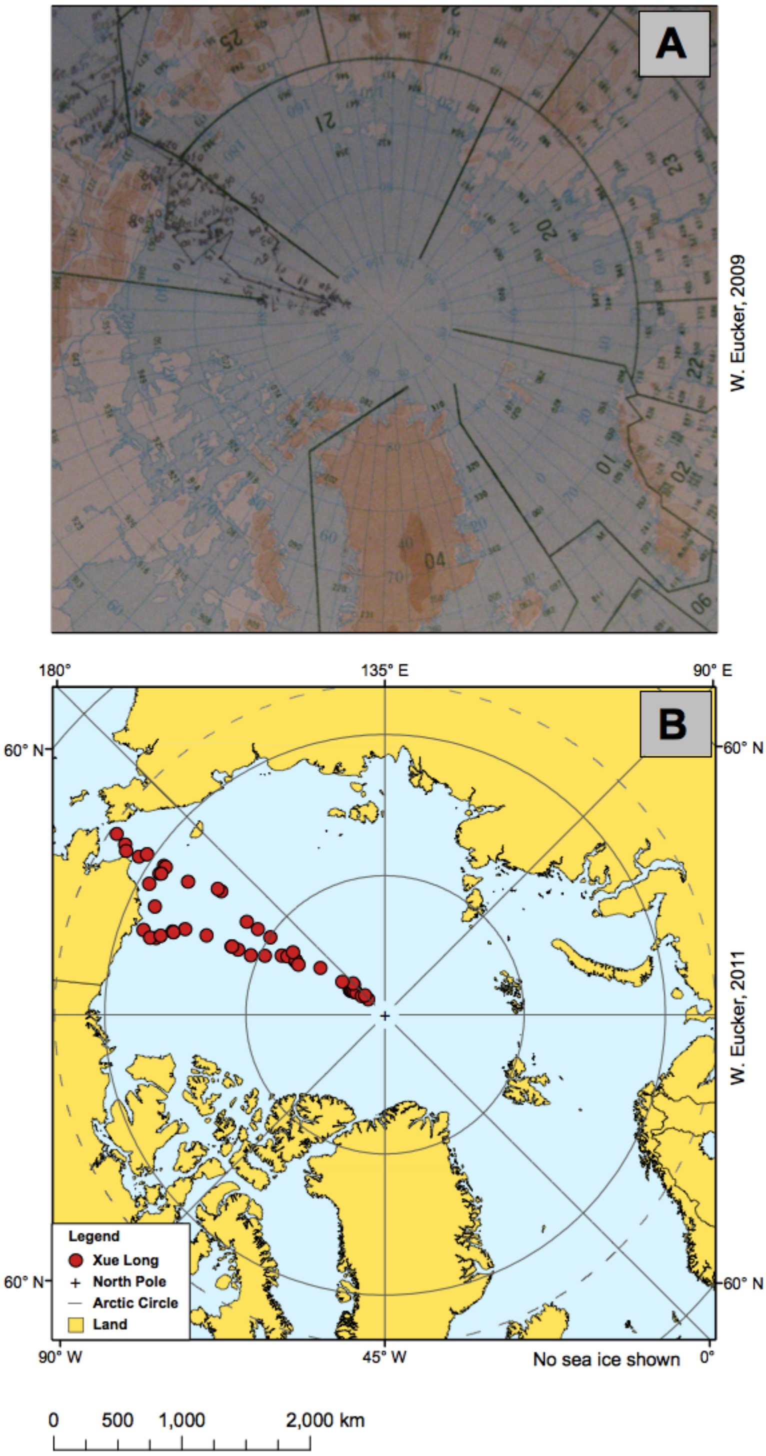


Figure 48. Voyage of the Xue Long *to the Central Arctic Ocean*

The voyage of Chinese icebreaker *Xue Long* from the Pacific Ocean through the Bering Strait north to 88·38°N and return during summer 2010. (A) Photograph of navigational chart used for voyage planning (W. Eucker, 2009). (B) Location of *Xue Long* north of 66·56ºN based on AIS position report messages received by the SpaceQuest satellite constellation from 20 June 2010 to 30 August 2010.

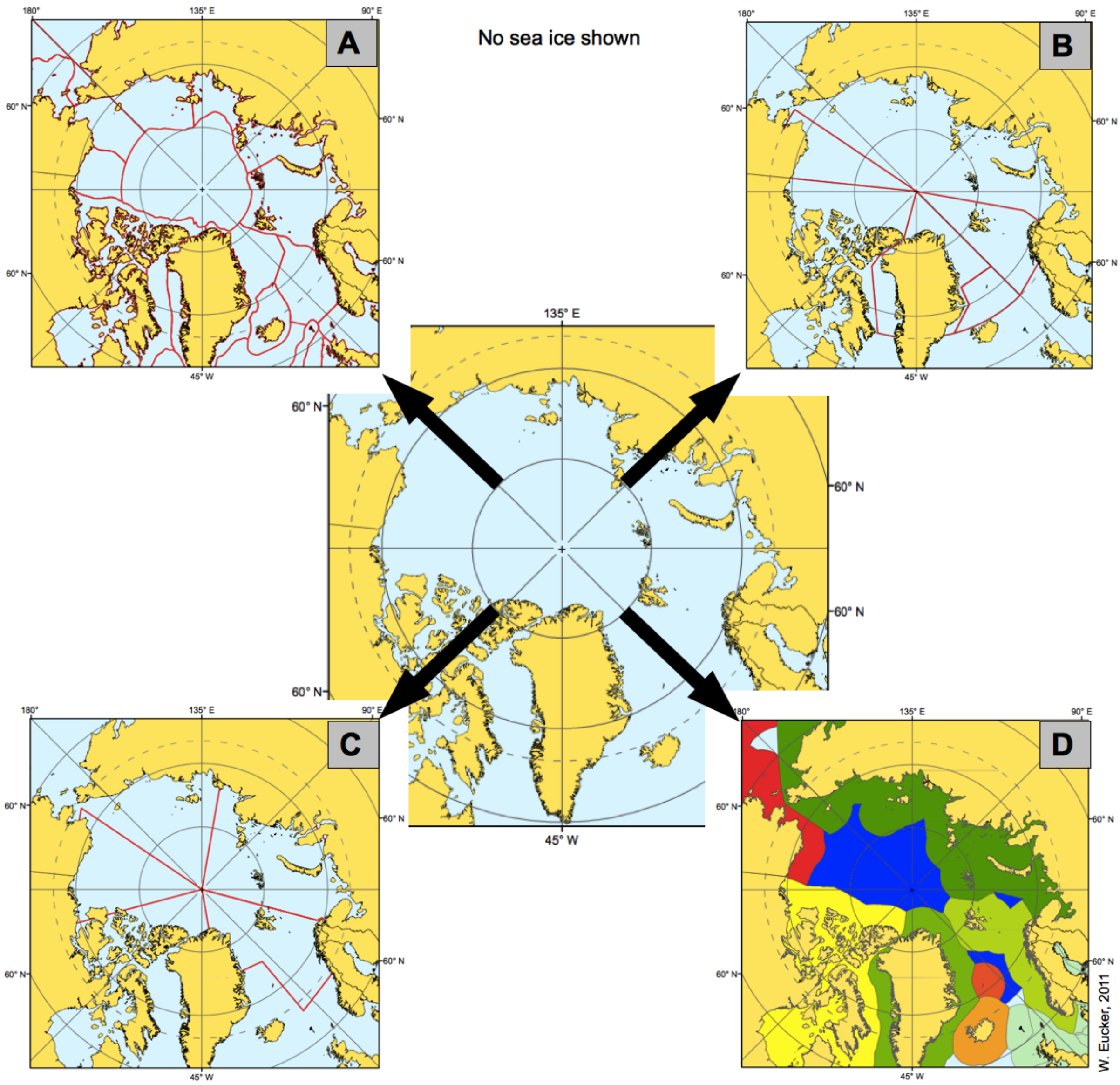


Figure 49. Boundaries Superimposed on the Geophysical Arctic Ocean

(A) Arctic Large Marine Ecosystems, (B) Arctic Search and Rescue Regions, (C) Arctic NAVAREAs/METAREAs, and (D) Arctic Exclusive Economic Zones overlay the eophysical Arctic Ocean. Remote-sensing observations are referenced to universal geophysical coordinates and may be used for various applications.

However, the ability to observe individual vessel voyages identifies an ethical dilemma related to privacy. There have been concerns raised that identify reporting the name of a vessel infringes on the privacy of the mariners aboard and ship owner. As a compromise, the name of the vessel may be removed for public documents.

The combination of synoptic daily satellite coverage and the universal AIS message protocol has enabled a geospatial analysis of multiple vessels in relation to the physical environment and relevant marine policy. Geopolitical boundaries for various application of policy may be superimposed on maps, as shown in Figure 49. This method enables new pathways of information, depicted in Figure 50. This process may help revise policy to enhance mariner safety, protect Arctic people and the environment, and develop Arctic marine infrastructure.

New pathways of information protect Arctic people and the environment. Advances in observing systems challenge the traditional paradigm of a dialectic between exploitation and protection. Environmentally adaptive policy, ecosystem-based management, and marine spatial planning are approaches that enable coordination of industrial resource development, indigenous subsistence, military activities, and scientific research using the best available understanding of human and biological activities. For example, policy related to fisheries management may require assessment of fish population and vessel traffic in a region of responsibility.

New pathways of information are essential for developing Arctic marine infrastructure. Growing globalization and the rise of multinational corporations and non-governmental organizations are enabling new, common approaches for the development of the Arctic region. The European Space Agency is assessing the need for high-latitude communications infrastructure (ESA, 2011). Similarly, the United States Coast Guard Cutter *Healy* and the Canadian Coast Guard *Louis S. Saint-Laurent* have operated as a pair to measure bathymetry in the Beaufort Sea, possibly to substantiate claims to the outer continental shelf. Regardless of who is responsible, investment decisions require information. There is a feedback mechanism between Arctic marine infrastructure and Arctic marine access: with more access, there will be a demand for more infrastructure, and increased infrastructure will invite greater access. This feedback mechanism can be tested with the consistent observations of vessel traffic.

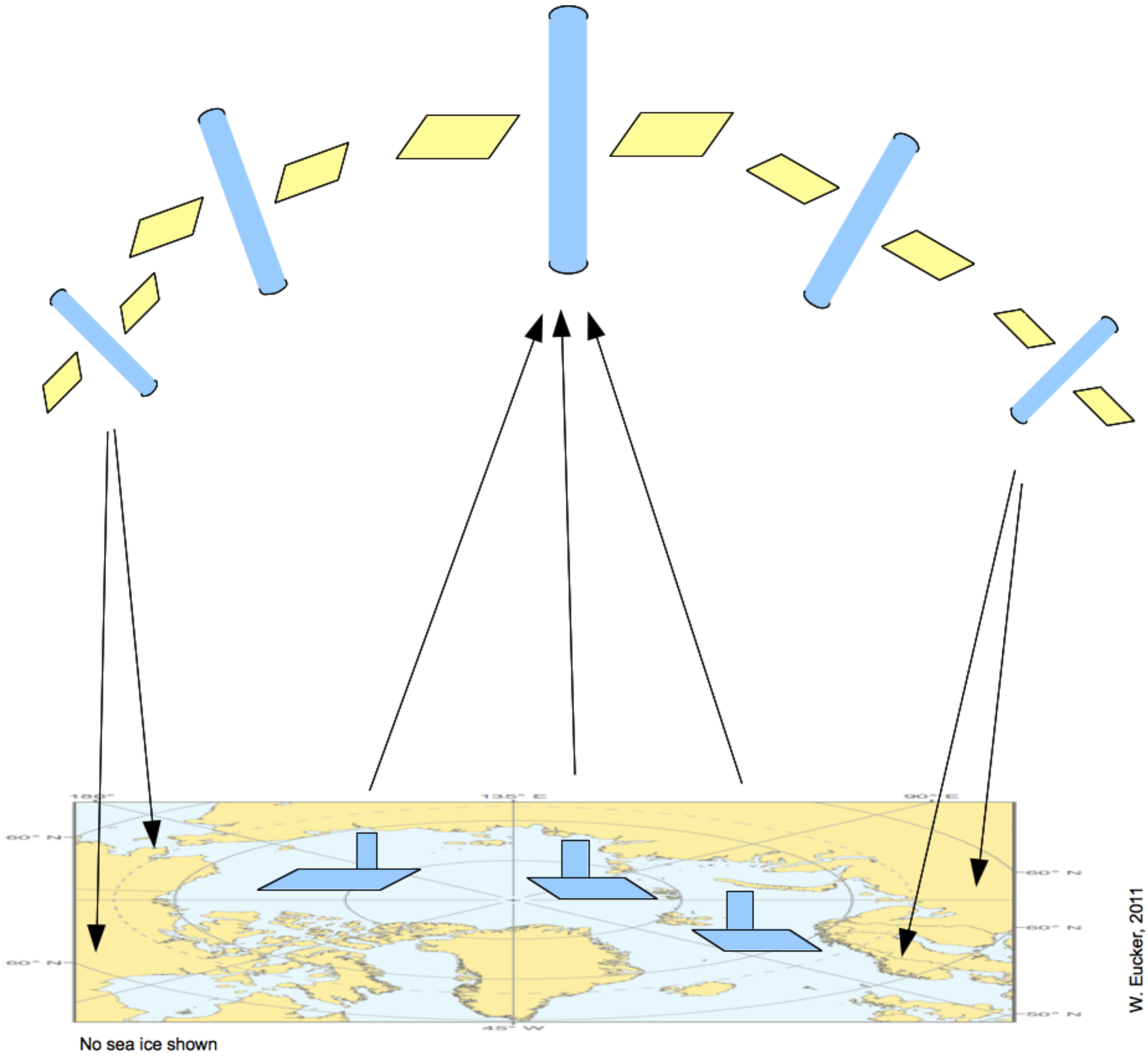


Figure 50. New Pathways of Information for the Arctic Ocean

Satellite remote-sensing and geographic information systems are uniquely suited to enable continuous pan-Arctic assessments of the Arctic Ocean that are real-time and accessible.

Chapter 4. Discussion of Results

Geographic information systems (GIS) are uniquely suited to compile, quantify, and display vessel traffic to identify and explain the relationship between the activities and the natural environment. This GIS-based process analyses observed surface ship movement based on consistent and comparable parameters (continuous variables) within consistent boundaries. The cartographic representation may be refined further to include spatial and temporal variations in physical, economic, and administrative conditions. This multi-layered and dynamic representation recalls the living 'Last Map' envisaged by the nineteenth century Prussian geographer Carl Ritter (Kaplan, 2000). Further, GIS is well suited to promote safe, secure and reliable Arctic shipping by presenting spatially-referenced data that are easily understood and easily distributed amongst various interested parties, users, and operators. In this manner, GIS can produce and display temporal and geographic trajectories that can aid Arctic coastal states in planning management infrastructure.

Good governance requires maintenance of, and regular updates to, an internally consistent database that catalogues marine traffic on the Arctic Ocean. The changing physical geography of the Arctic Ocean will influence the diverse human activities occurring in its maritime space. As sea ice diminishes, the dynamic relationship between humans and the physical environment needs to be continuously observed. The marine activity in the Arctic could change drastically, making baseline studies essential for calculating trends. Even with advancements in the spatial and temporal resolution of recording and reporting sea ice using satellite-borne sensors and geographic information systems (GIS), sea ice remains a formidable hazard that limits the operation of surface vessels to particular routes and a navigation season. There are multiple operators in the Arctic, and understanding traffic patterns is the first step to avoid conflict and enable sustainable use.

Despite the seeming availability of AIS as a new pathway of information to contribute to scientific understanding of the transforming Arctic Ocean, there are several factors that may constrain its development and implementation. First, there are legitimate privacy concerns about the ability to passively receive, record, and disseminate information about a vessel. Surveillance is a powerful method of regulating behaviour, especially in remote areas, but ethical considerations should be further examined. Second, many of these architectures are considered essential to national security, and as a result, safeguarded. For example, the AIS satellites, AISSAT-1 and AISSAT-2, launched by the Norwegian government are managed by their military. Third, the influence of environmental factors on the satellite reception of AIS messages is a lingering question. For example, atmospheric water vapour content is seasonally variable and may increase with increasing open water. Fourth, there are competing networks of ground stations, different satellite systems, and deconfliction software. A thoughtful investment assessment would require field tests and reliability studies further to this analysis.

This analysis developed a pathway of information based on satellite remote sensing and a geographic information system enables the formulation of new ways of thinking about navigational possibilities, marine use realities, and the establishment of infrastructure for responsible management and sustainable development. This universal monitoring approach is broad to consider changes to the natural environment and robust to observe for the purpose of comparison with previous measurements. Unlike the past, where over the horizon sailing did not lend itself to natural coordination, the satellite-era is inherently international, interdisciplinary and inclusive, enabling cooperation and trust-building.

In the Anthropocene, where human activities have unparalleled influence on the physical environment, coordination of observation and management are global challenges with generational consequences. In this context, new pathways of information enable multi-dimensional understandings of the transforming Arctic Ocean on various spatial and temporal scales.

5. Conclusion

Recent changes in Arctic Ocean climate dynamics motivated a re-evaluation of physical operating conditions, ship traffic patterns, and policy options. Based on advances in remote sensing, telecommunications, and information technology, this thesis develops a novel process to analyse surface vessel traffic on the Arctic Ocean in relation to sea ice and marine policy using a year of data ending 1 April 2011. The results from this study identify new pathways of information to enable timely pan-Arctic assessments of the physical operating conditions and ship traffic patterns.

First, sea-ice cover on the Arctic Ocean was analysed to determine the physical access for marine operations. Daily sea-ice concentration data based on satellite passive microwave measurements were used to calculate the extent of open water and duration of the sea-ice season.

Second, ship traffic on the Arctic Ocean was analysed to determine the present patterns of human activity. Time-stamped AIS messages encoded with Global Navigation Satellite System (GNSS) positions received by a commercial satellite constellation from north of the Arctic Circle (66·56°N) were used to calculate the distribution of vessels per unit area. Satellite AIS data from SpaceQuest, Limited, were compared with land-based vessel observations during the study period from the Marine Exchange of Alaska and the Port of Longyearbyen.

Third, the spatial and temporal relationship between sea ice and surface vessels on the Arctic Ocean was analysed to determine potential policy implications. Three groups of marine operations with distinct characteristics were determined from the analysis: operations in perennial open water, operations in the seasonal ice zone, and operations in the perennial ice zone. Throughout the study year, most ships north of 66·56°N operated in perennially ice-free areas, but year-round operations also occurred in ice-covered areas.

A consistent and timely pathway of information based on synoptic daily observations can relate the changing physical environment with marine use to inform international, interdisciplinary, and inclusive policy. This approach provides policy options to sustainably develop a safe, secure, and environmentally protected Arctic Ocean.

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Appendix I: Data Use Agreement

The following two page document is the Data Use Agreement between Dr Dino Lorenzini and Mr William Eucker signed 13 April 2011.

Appendix I: Data Use Agreement

DATA USE AGREEMENT

SpaceQuest, Ltd., located at 3554 Chain Bridge Road, Suite 103, Fairfax, VA 22030 ("SpaceQuest' or "Data Provider') will provide the investigator ("Recipient") with Data as further described below, in accordance with the terms and conditions of this Data Use Agreement ("Agreement).

Recipient:	LTJG William Eucker, USN Gates Cambridge Scholar We217@cam.ac.uk +44 7525151505
Sponsoring Institution:	Scott Polar Research Institute University of Cambridge Peterhouse, Cambridge, CB2 1RD
Data:	shall mean AIS datasets in NMEA format consisting of daily snapshots of all the vessels in the Arctic Region from Febr4uary 2010 through March 2011.
Research Purpose:	as described in Attachment A, "Redefining Arctic Navigating Limits"
Grant of License:	Data Provider hereby grants to Recipient a license to use the Data solely for the research purpose described in Attachment A.

The Recipient acknowledges, agrees, and represents that, unless otherwise expressly permitted in writing by SpaceQuest:

1. Recipient shall use the Data solely for bona fide university research/analysis described in the Research Purpose, and specifically shall not use the Data for any commercial purpose.
2. The Recipient shall not distribute or release raw data to anyone not involved in the research project outlined in Attachment A. Only those individuals who have a "need to know" shall access the Data, and all such individuals shall be advised of the terms of this Agreement and the restrictions upon use and disclosure.
3. Recipient shall keep an accurate written account of all authorized distribution of the Data.
4. Recipient shall report immediately to SpaceQuest any use or disclosure of the Data other than as permitted by this Agreement. Recipient shall take all reasonable steps to mitigate the effects of such improper use or disclosure, including cooperating with all reasonable requests of SpaceQuest.
5. The Recipient acknowledges that it has in place, and shall maintain throughout the proposed study, administrative, technical, procedural, and physical safeguards sufficient to protect the confidentiality of the Data and to prevent unauthorized access and use.
6. At the completion of the project, or after two years, unless explicitly given an extension by SpaceQuest, Recipient shall return the Data, or shall certify in writing the deletion and destruction of all copies of the Data.
7. Recipient shall submit any publications, presentations or other forms of research dissemination (e.g. working papers, conference presentations, journal article submissions) arising from any research that incorporates the Data to SpaceQuest for review before submission to a publication or presentation at a conference or seminar. SpaceQuest may withhold approval to publish the results of research only if it reasonably determines that the format of the Data presentation is such that it does not meet the terms and conditions for the use of the Data as reflected in this Agreement.

1

8. Published or disseminated reports will only include research results, not source Data.
9. Recipient will acknowledge SpaceQuest as the provider of the Data in any scholarly work, written or oral, arising from the datasets.
10. Recipient will send SpaceQuest a copy of the final report.

Additional Terms:

11. **DISCLAIMER OF WARRANTY**: THE SPACEQUEST AIS DATA AND INFORMATION PROVIDED BY SPACEQUEST, OR ANY OF ITS AFFILIATES, THEIR MEMBERS, DIRECTORS, OFFICERS, EMPLOYEES, AGENTS, AND CONTRACTORS ARE PROVIDED BY SPACEQUEST ON AN "AS IS" BASIS, AND SPACEQUEST EXPRESSLY DISCLAIMS ANY AND ALL WARRANTIES, EXPRESS OR IMPLIED, INCLUDING WITHOUT LIMITATION WARRANTIES OF MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE. SPACEQUEST DOES NOT WARRANT THAT THE SPACEQUEST AIS DATA WILL BE UNINTERRUPTED OR ERROR-FREE, THAT DEFECTS WILL BE CORRECTED, OR THAT THE SPACEQUEST AIS DATA IS FREE OF VIRUSES OR OTHER HARMFUL COMPONENTS. SPACEQUEST DOES NOT WARRANT OR REPRESENT THE USE OF THE SPACEQUEST AIS DATA IN TERMS OF ITS CORRECTNESS, ACCURACY, RELIABILITY, OR OTHERWISE. LICENSEE ACKNOWLEDGES AND AGREES THAT RELIANCE UPON OR USE OR DISTRIBUTION OF SUCH MESSAGES SHALL BE AT RECIPIENTS RISK.

12. This Agreement shall be governed by and construed in accordance with the laws of the Commonwealth of Virginia (U.S.A.).

13. Nothing in this Agreement shall, or shall be deemed to, create a partnership, joint venture or agency between SpaceQuest and Recipient.

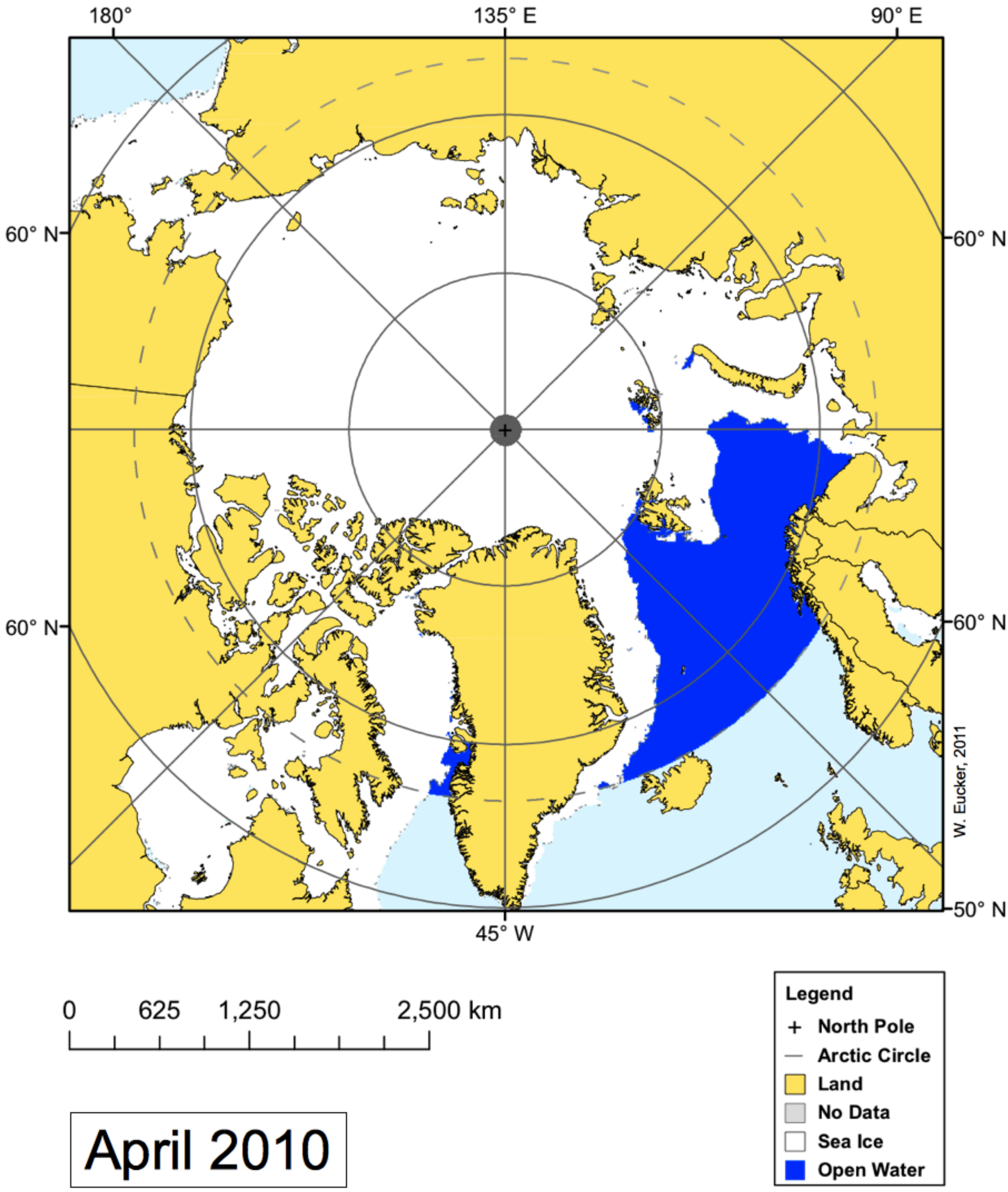
14. This Agreement may be terminated (i) for failure to cure a breach with 15 days of receipt of written notice of such breach; or (ii) by either party upon thirty (30) days written notice to the other party.

15. This Agreement may not be assigned by Recipient without express written consent of SpaceQuest.

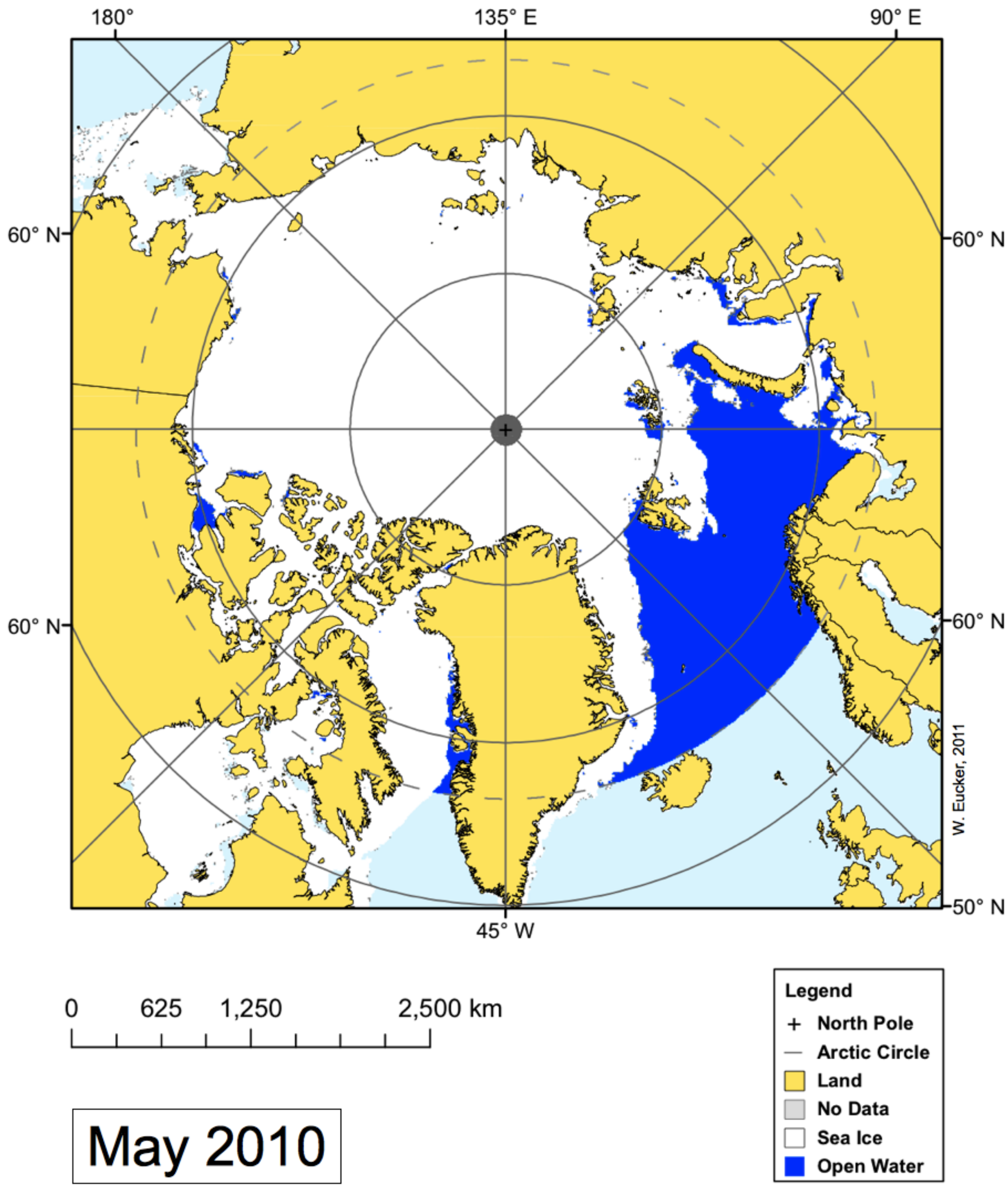
The parties have caused this Agreement to be executed on the date last written below:

Data Provider: SpaceQuest, Ltd.	Recipient: LTJG William Eucker, USN
Signed:	Signed: William Eucker
Name: Dino A. Lorenzini	Name: William Eucker
Title: President	Title: PhD student
Date:	Date: 13.04.2011

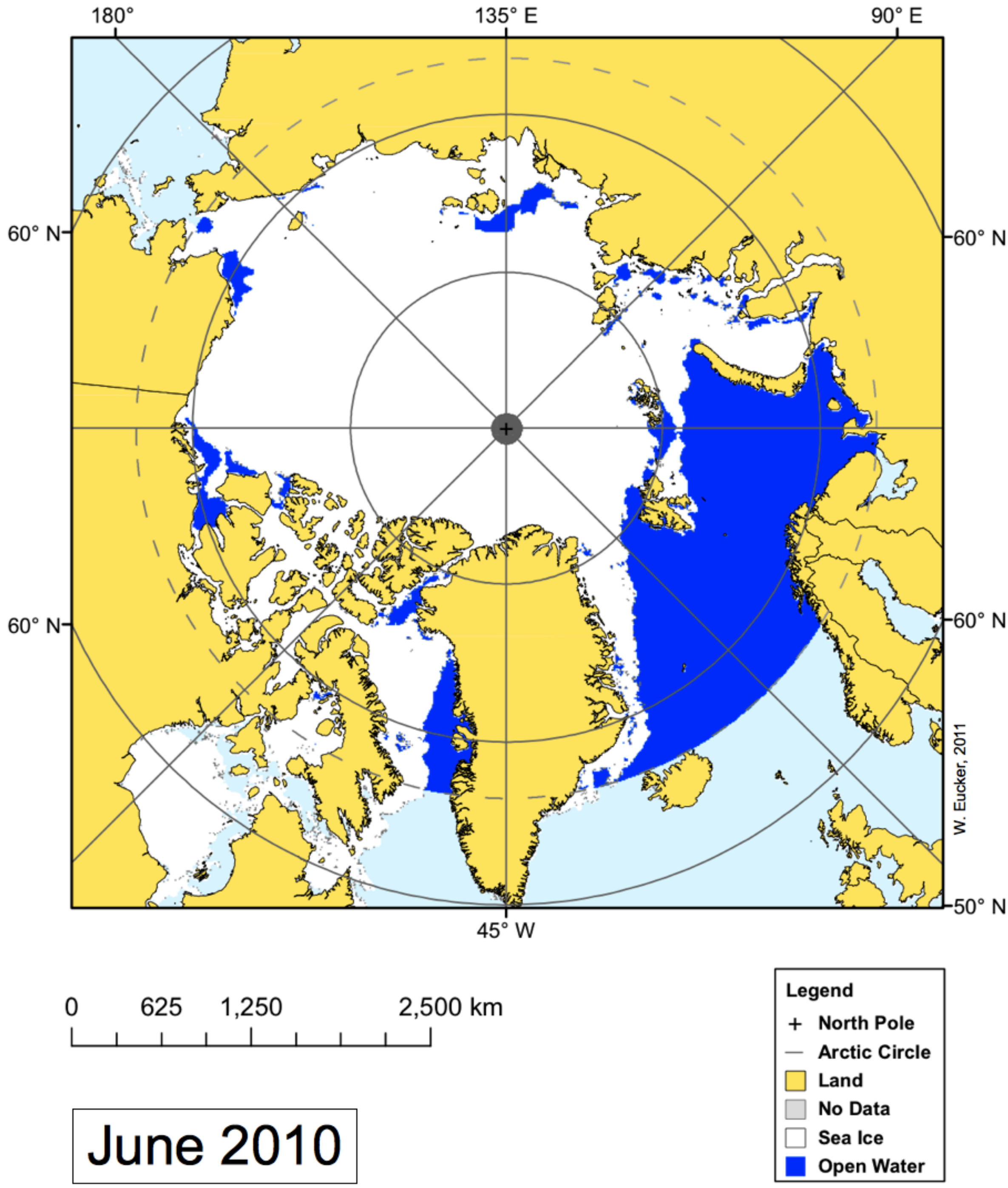
Appendix II: Maps of Arctic Sea Ice



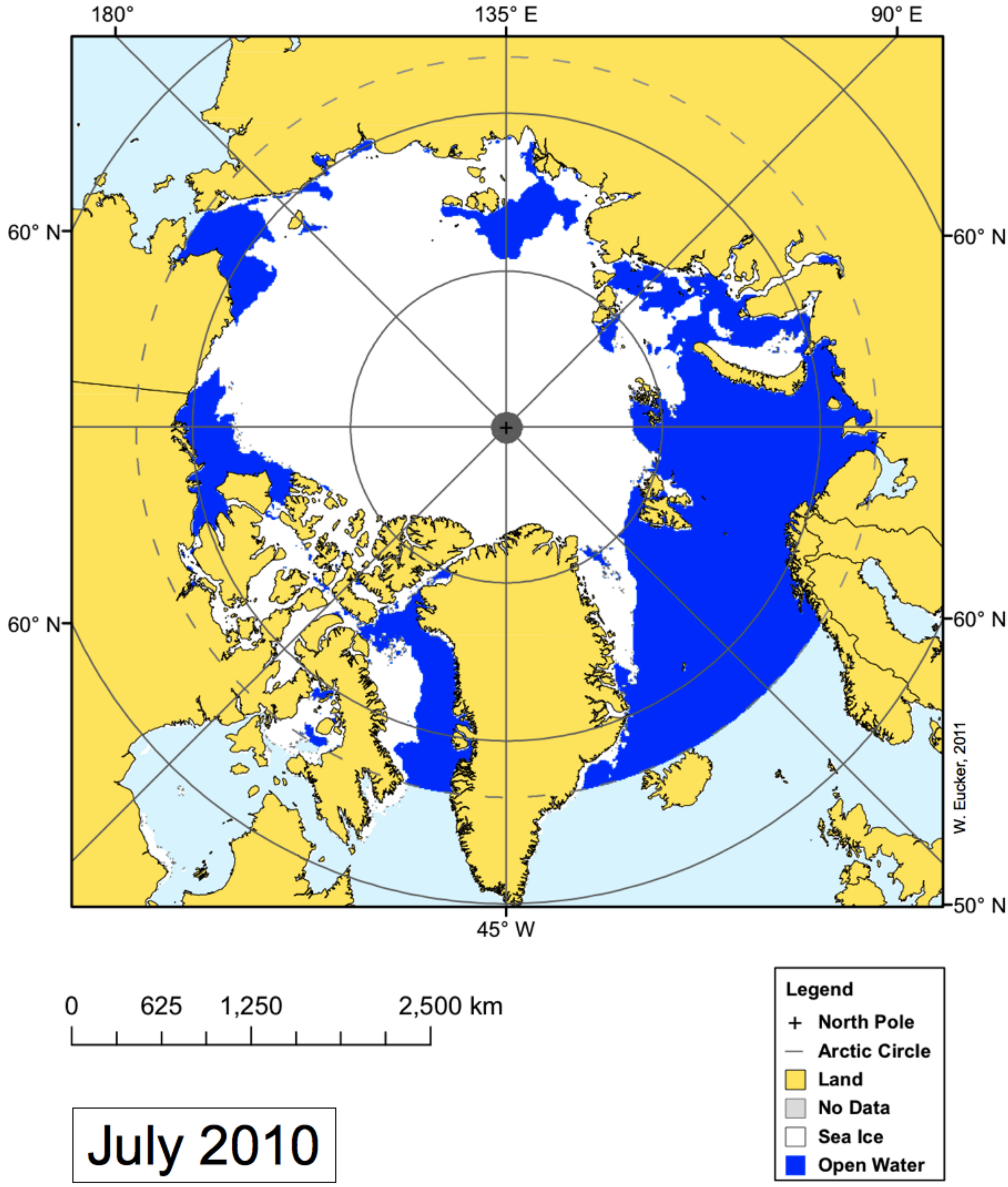
Monthly mean open water and sea ice extent north of the Arctic Circle during April 2010 calculated for each 6·25 km reference grid cell by averaging daily AMSR-E sea-ice concentration measurements interpreted using the ASI algorithm.



Monthly mean open water and sea ice extent north of the Arctic Circle during May 2010 calculated for each 6·25 km reference grid cell by averaging daily AMSR-E sea-ice concentration measurements interpreted using the ASI algorithm.

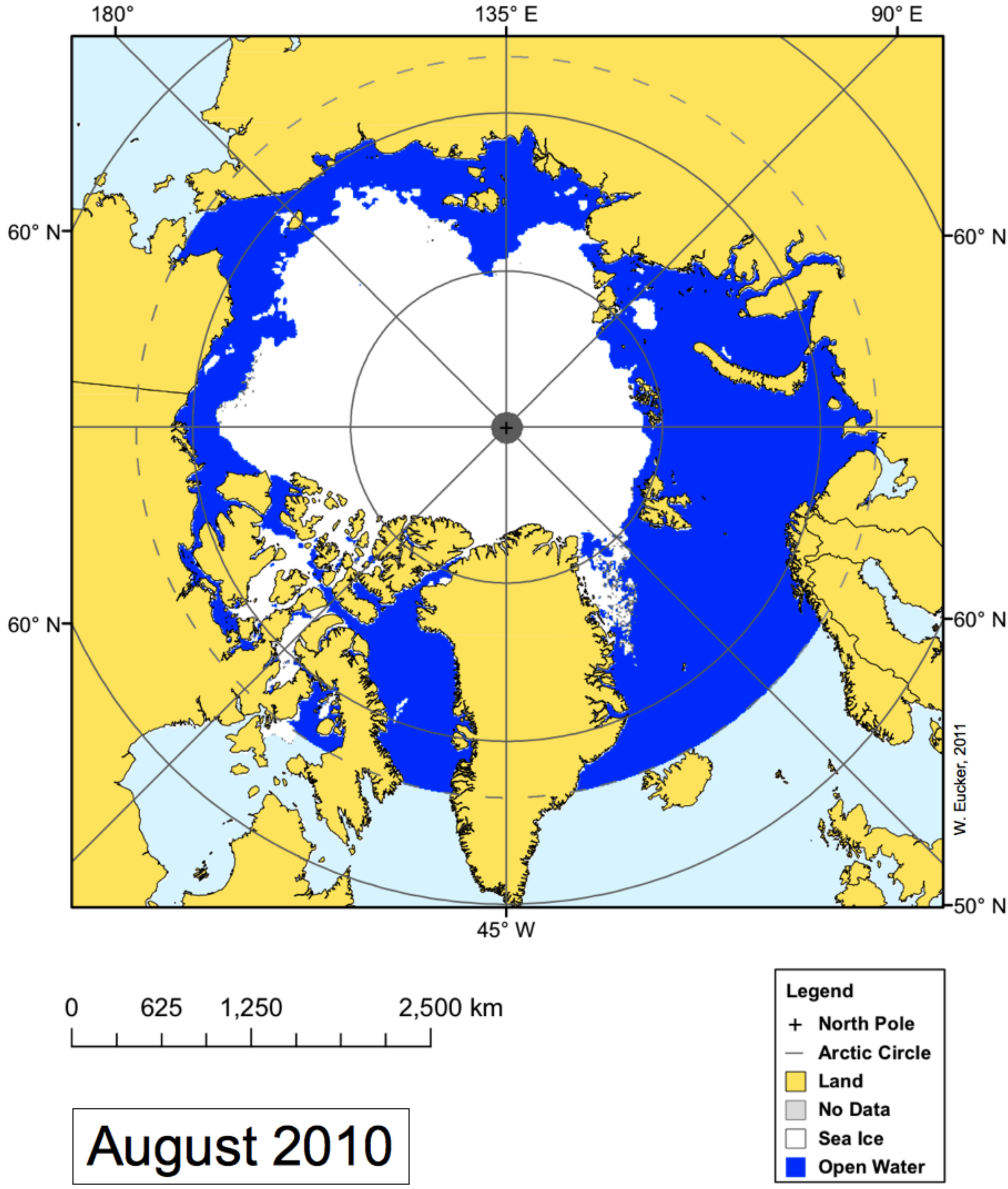


Monthly mean open water and sea ice extent north of the Arctic Circle during June 2010 calculated for each 6·25 km reference grid cell by averaging daily AMSR-E sea-ice concentration measurements interpreted using the ASI algorithm.

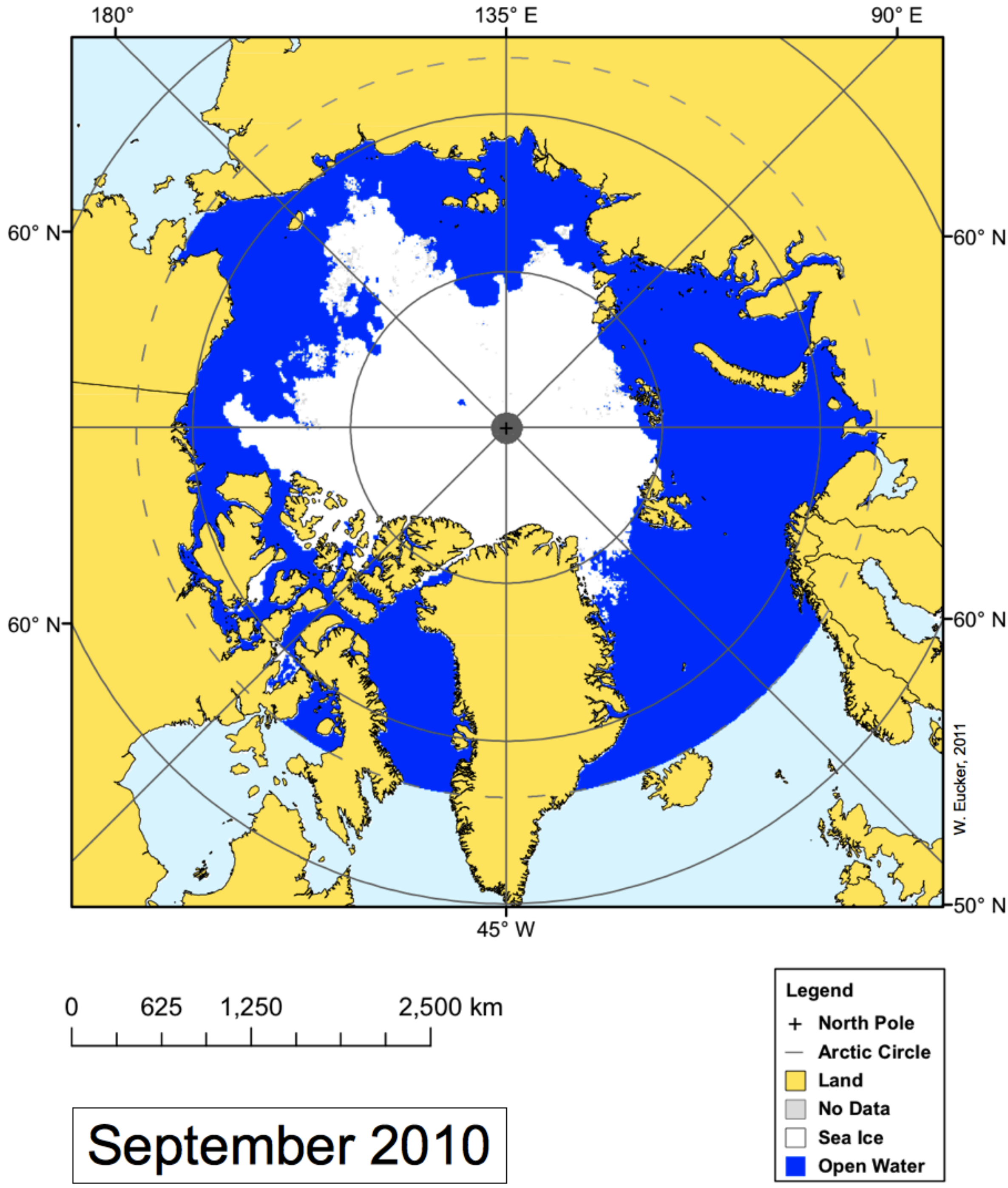


July 2010

Monthly mean open water and sea ice extent north of the Arctic Circle during July 2010 calculated for each 6·25 km reference grid cell by averaging daily AMSR-E sea-ice concentration measurements interpreted using the ASI algorithm.

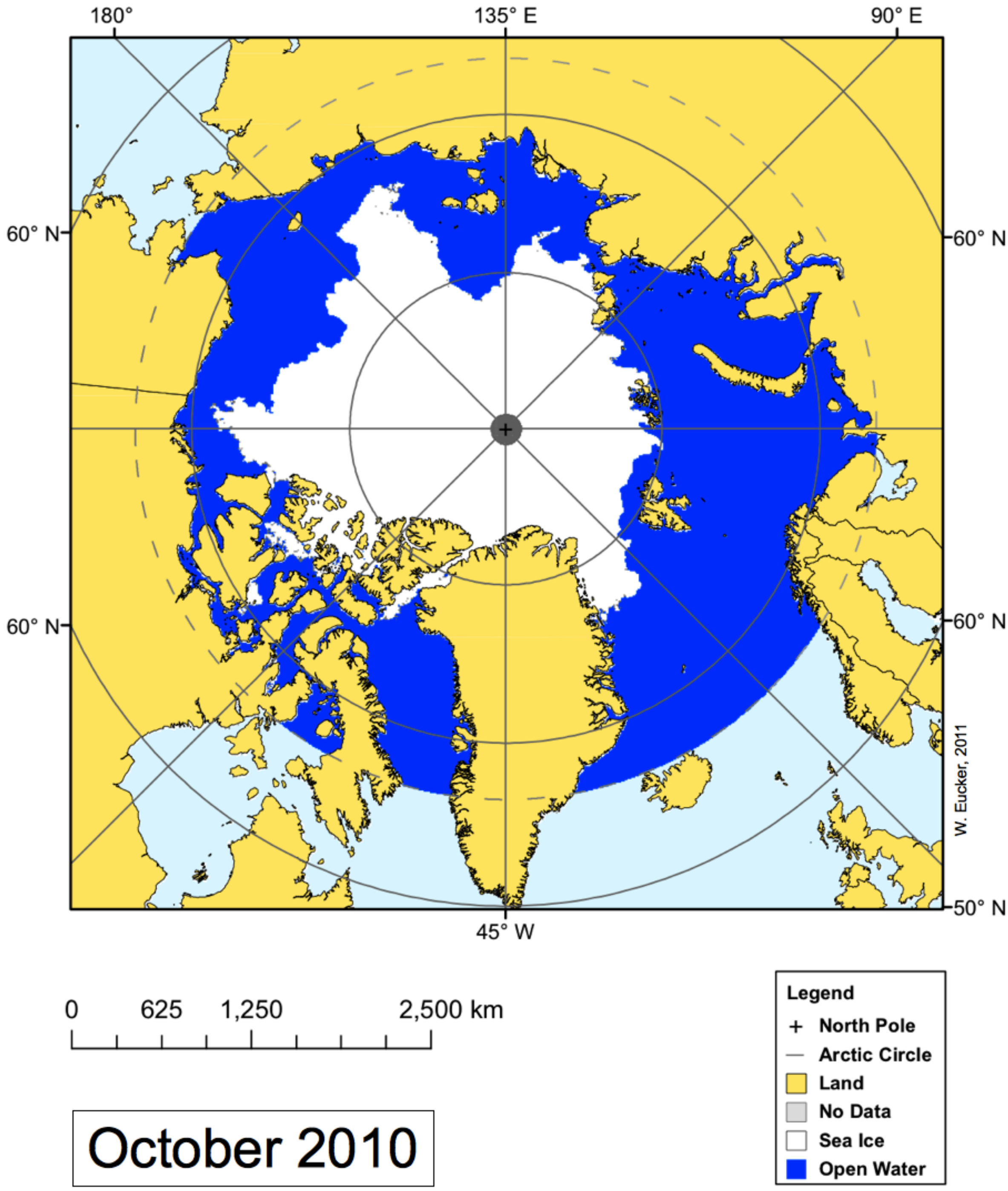


Monthly mean open water and sea ice extent north of the Arctic Circle during August 2010 calculated for each 6·25 km reference grid cell by averaging daily AMSR-E sea-ice concentration measurements interpreted using the ASI algorithm.

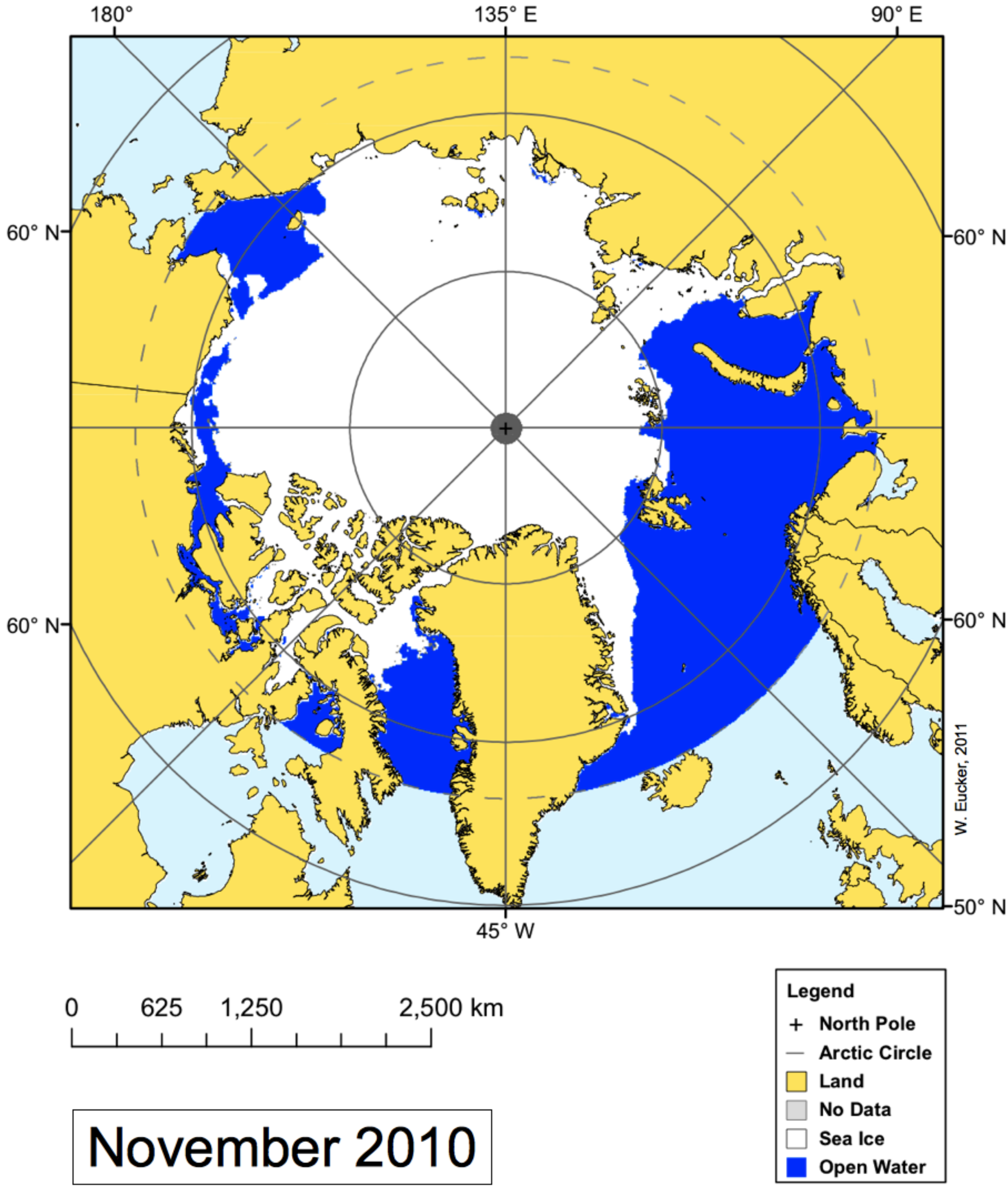


Monthly mean open water and sea ice extent north of the Arctic Circle during September 2010 calculated for each 6·25 km reference grid cell by averaging daily AMSR-E sea-ice concentration measurements interpreted using the ASI algorithm.

Appendix II: Maps of Arctic Sea Ice

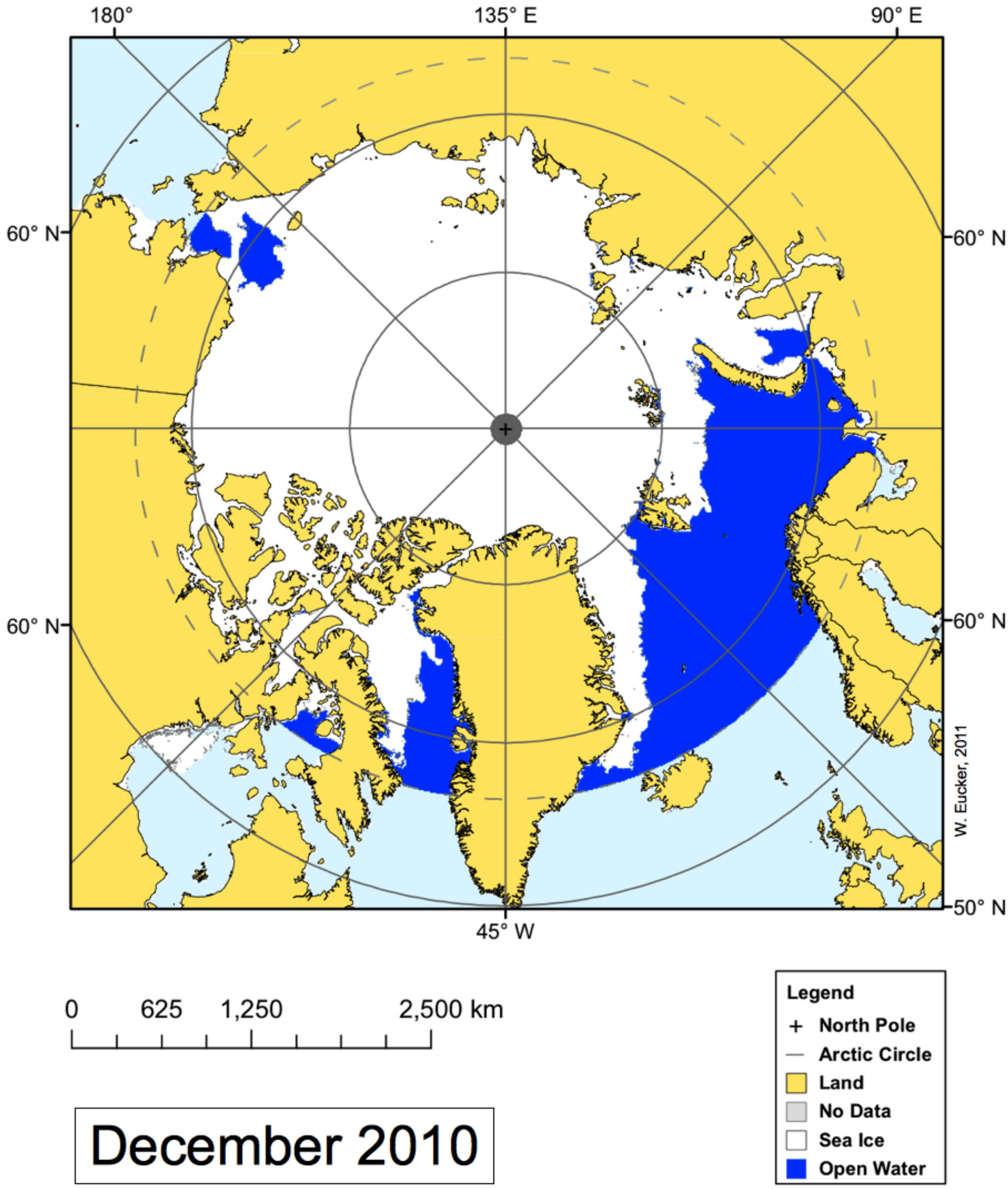


Monthly mean open water and sea ice extent north of the Arctic Circle during October 2010 calculated for each 6·25 km reference grid cell by averaging daily AMSR-E sea-ice concentration measurements interpreted using the ASI algorithm.

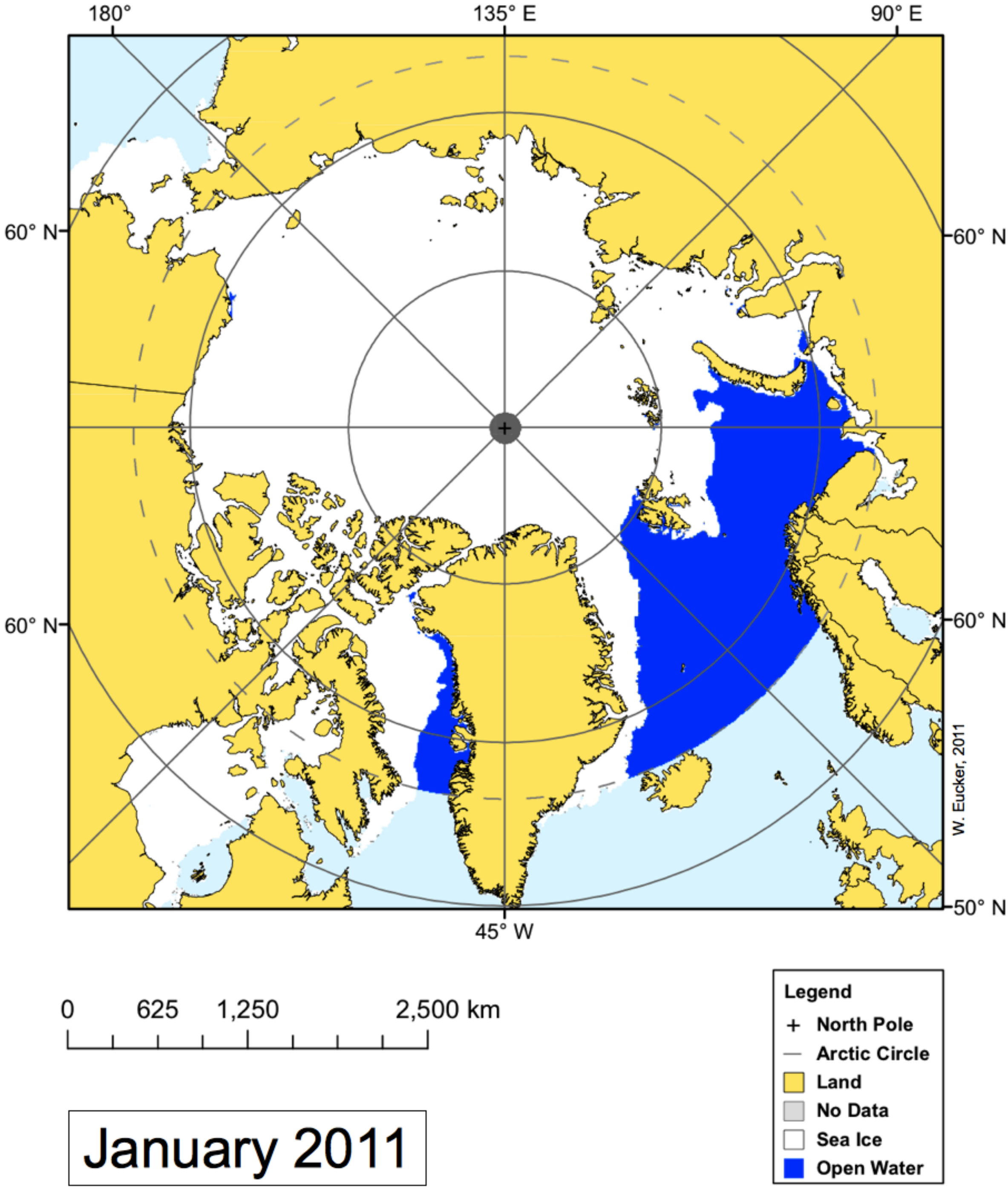


Monthly mean open water and sea ice extent north of the Arctic Circle during November 2010 calculated for each 6·25 km reference grid cell by averaging daily AMSR-E sea-ice concentration measurements interpreted using the ASI algorithm.

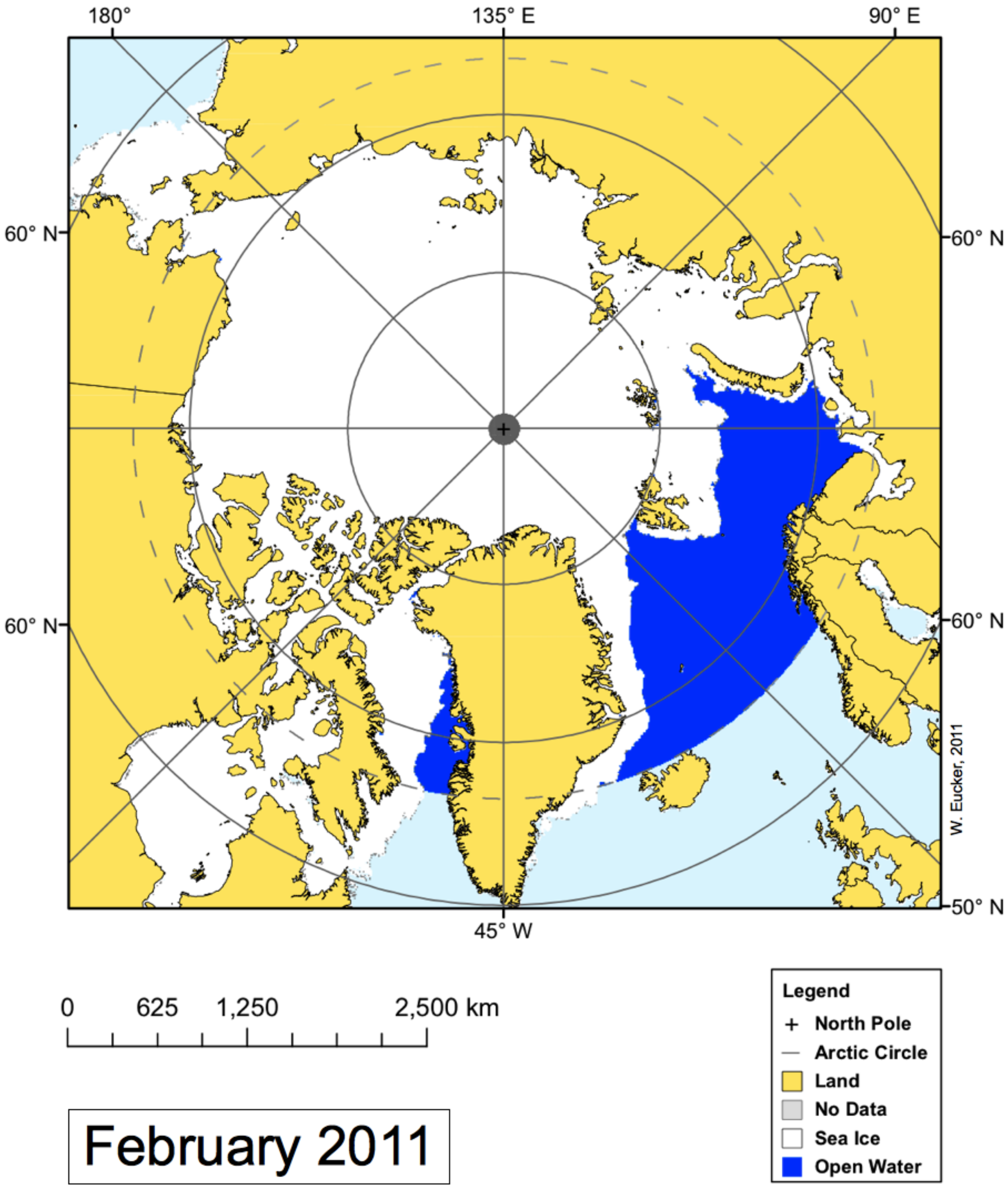
Appendix II: Maps of Arctic Sea Ice



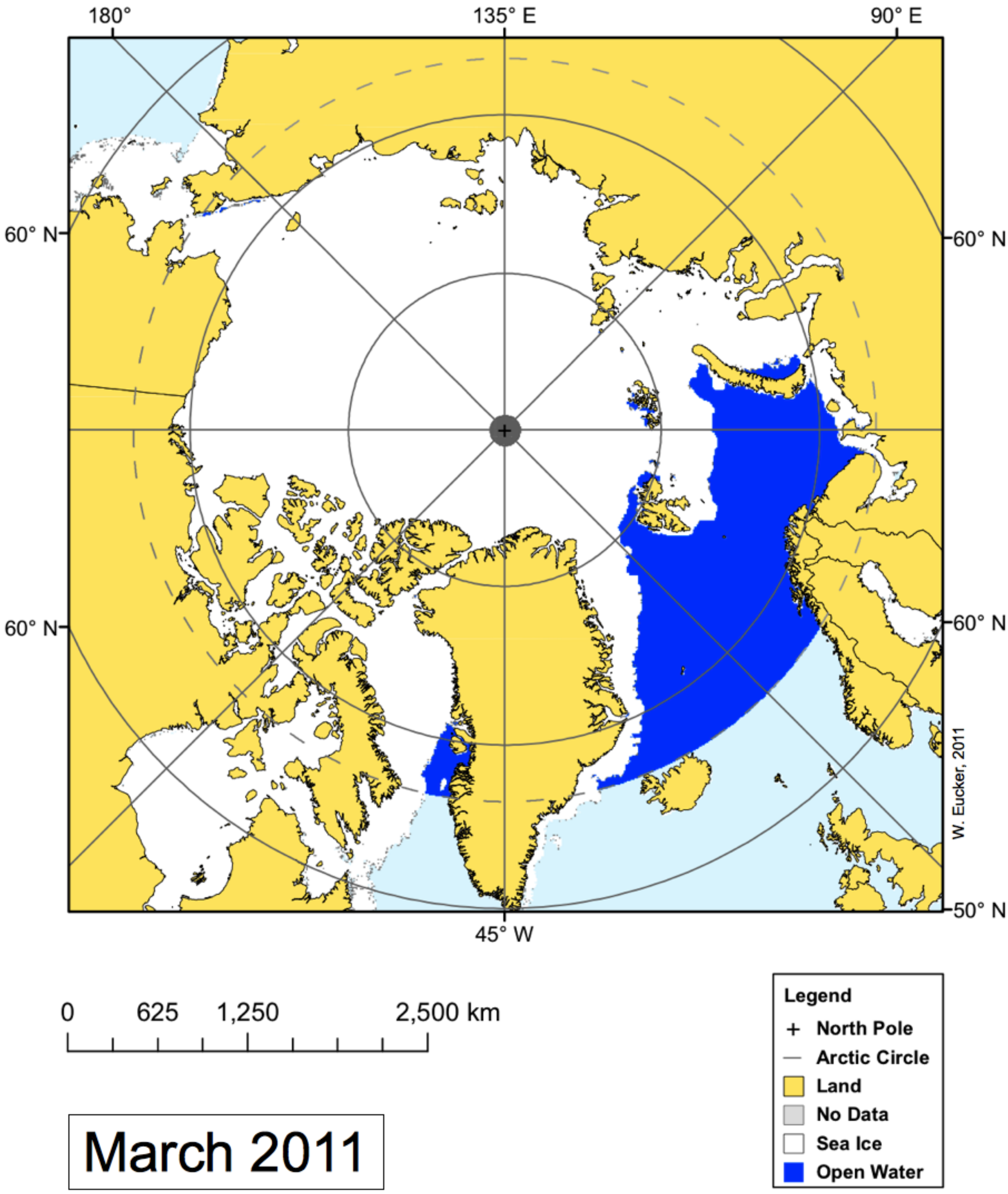
Monthly mean open water and sea ice extent north of the Arctic Circle during December 2010 calculated for each 6·25 km reference grid cell by averaging daily AMSR-E sea-ice concentration measurements interpreted using the ASI algorithm.



Monthly mean open water and sea ice extent north of the Arctic Circle during January 2011 calculated for each 6·25 km reference grid cell by averaging daily AMSR-E sea-ice concentration measurements interpreted using the ASI algorithm.

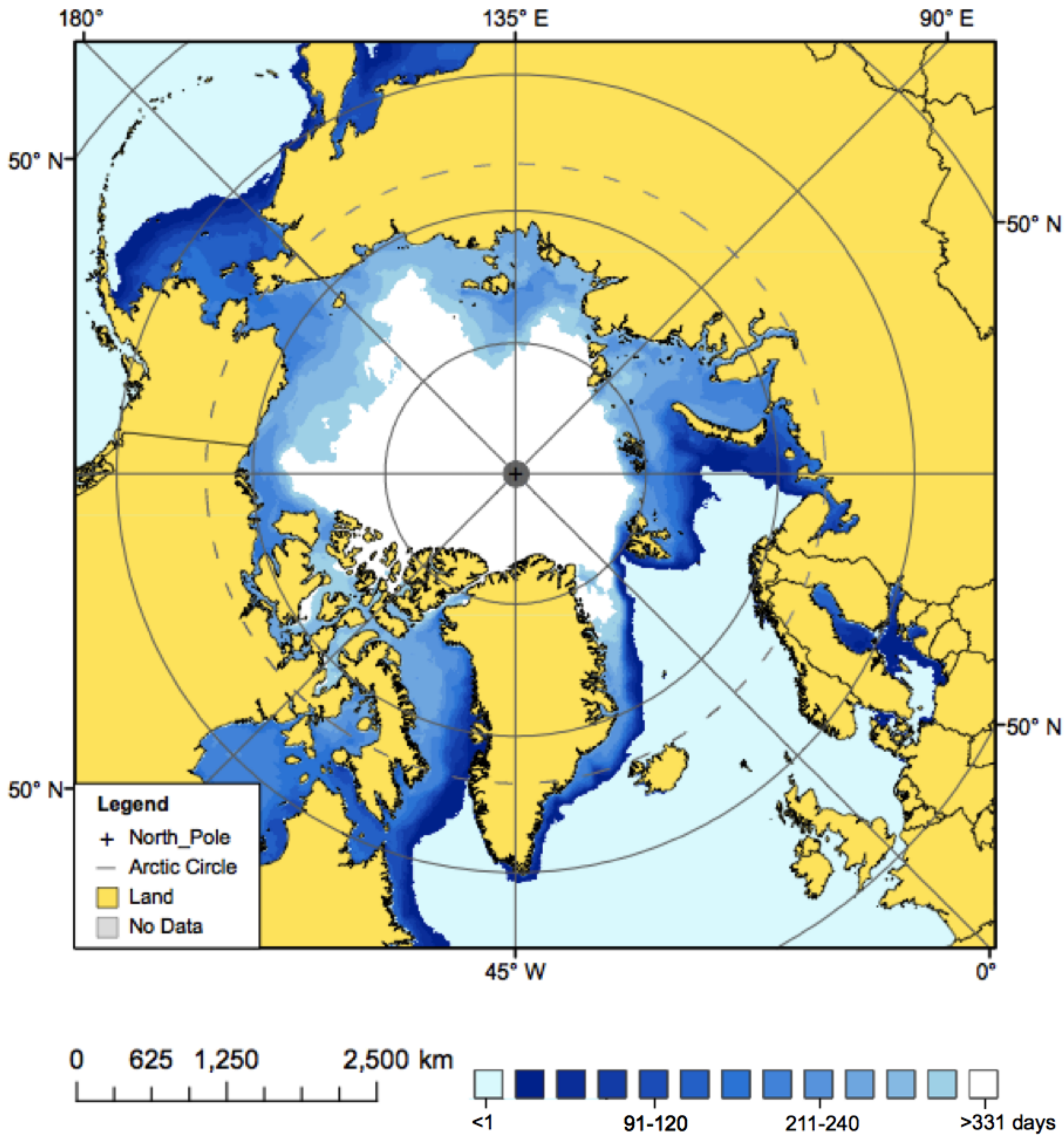


Monthly mean open water and sea ice extent north of the Arctic Circle during February 2011 calculated for each 6·25 km reference grid cell by averaging daily AMSR-E sea-ice concentration measurements interpreted using the ASI algorithm.



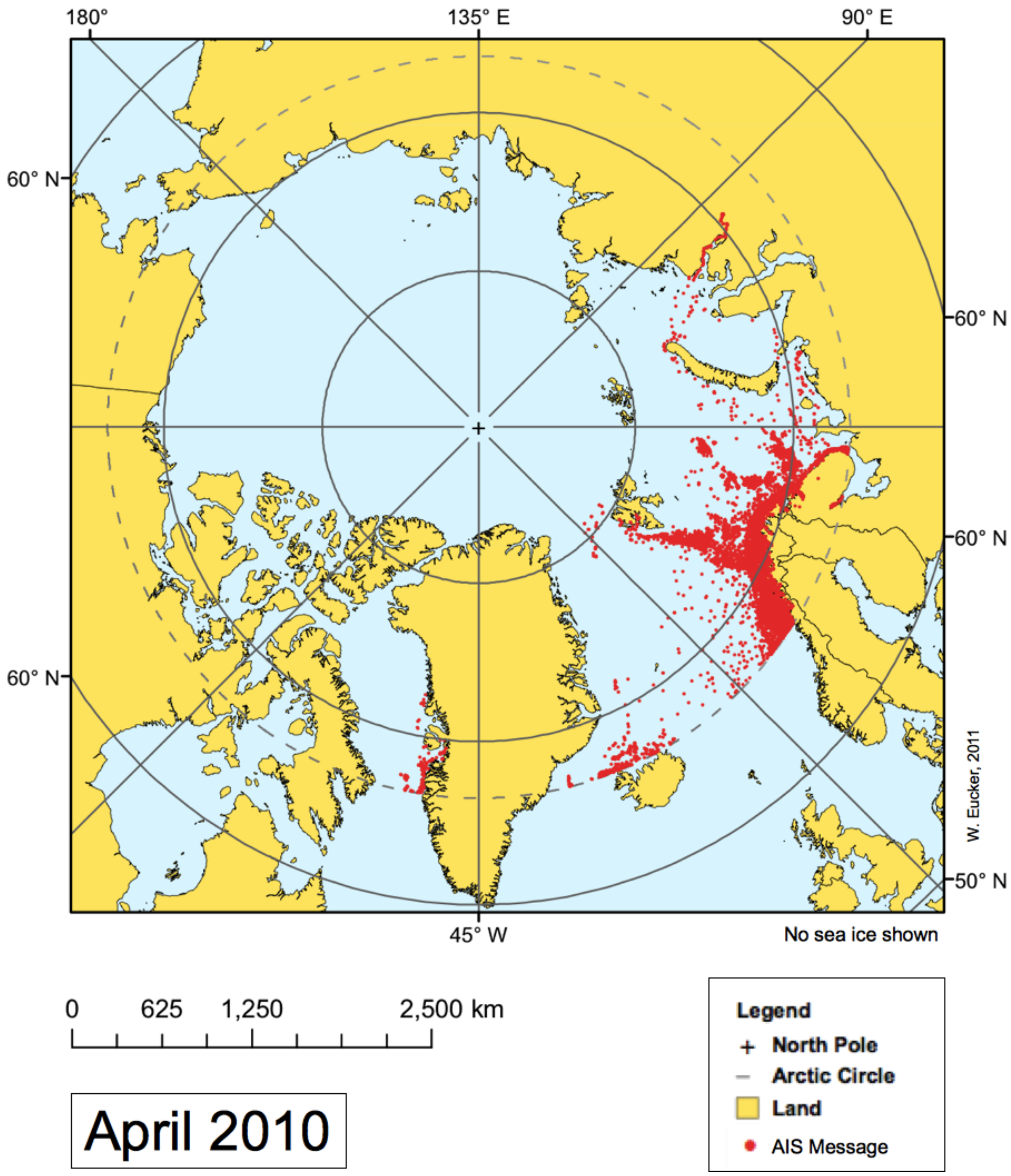
Monthly mean open water and sea ice extent north of the Arctic Circle during March 2011 calculated for each 6·25 km reference grid cell by averaging daily AMSR-E sea-ice concentration measurements interpreted using the ASI algorithm.

Appendix II: Maps of Arctic Sea Ice

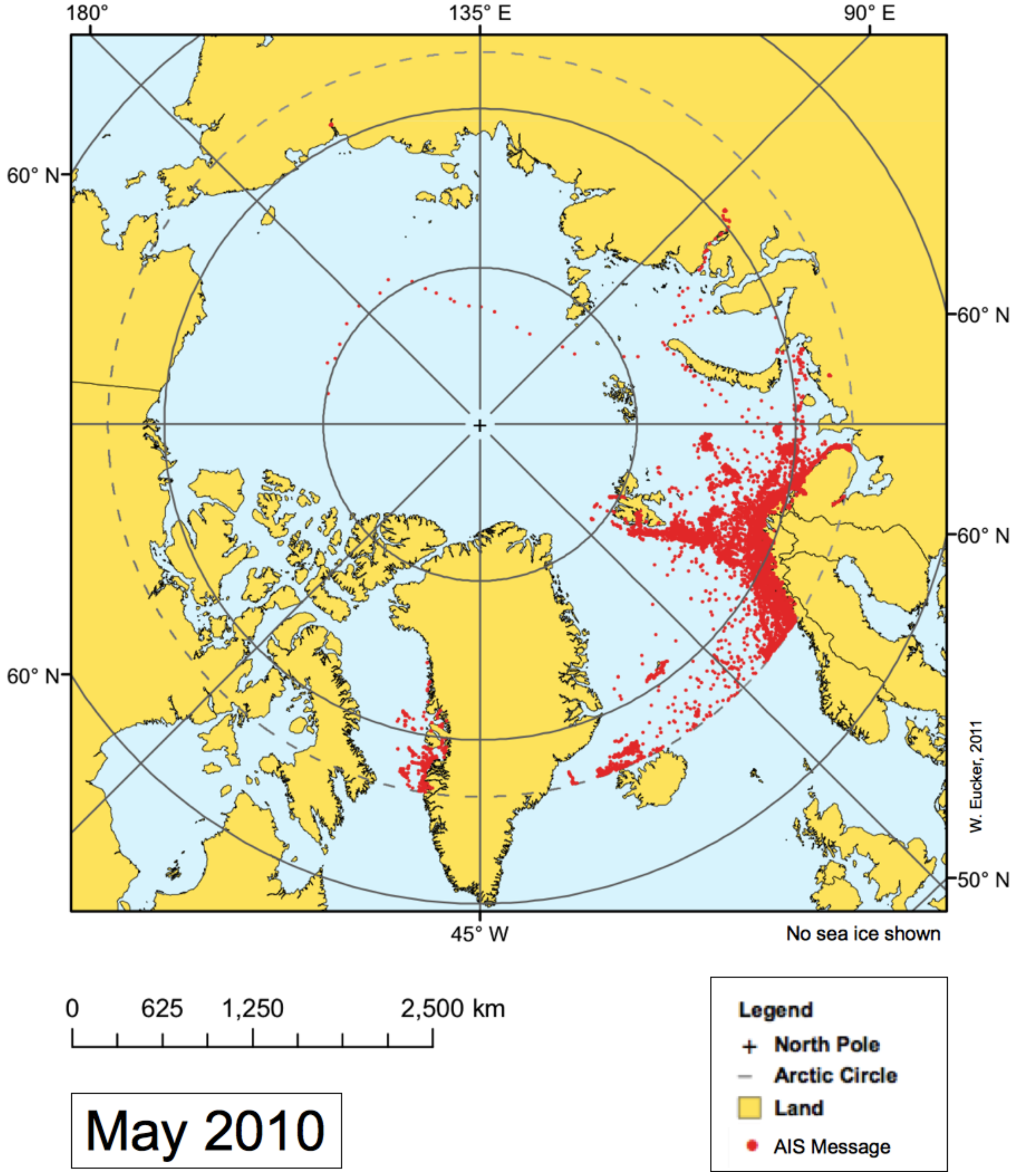


Sea-ice duration describes the number of days in which Arctic sea-ice concentration based on satellite radiometry was greater than a 15% threshold for each 6·25 km reference grid cell during the 1 April 2010-31 March 2011 study year.

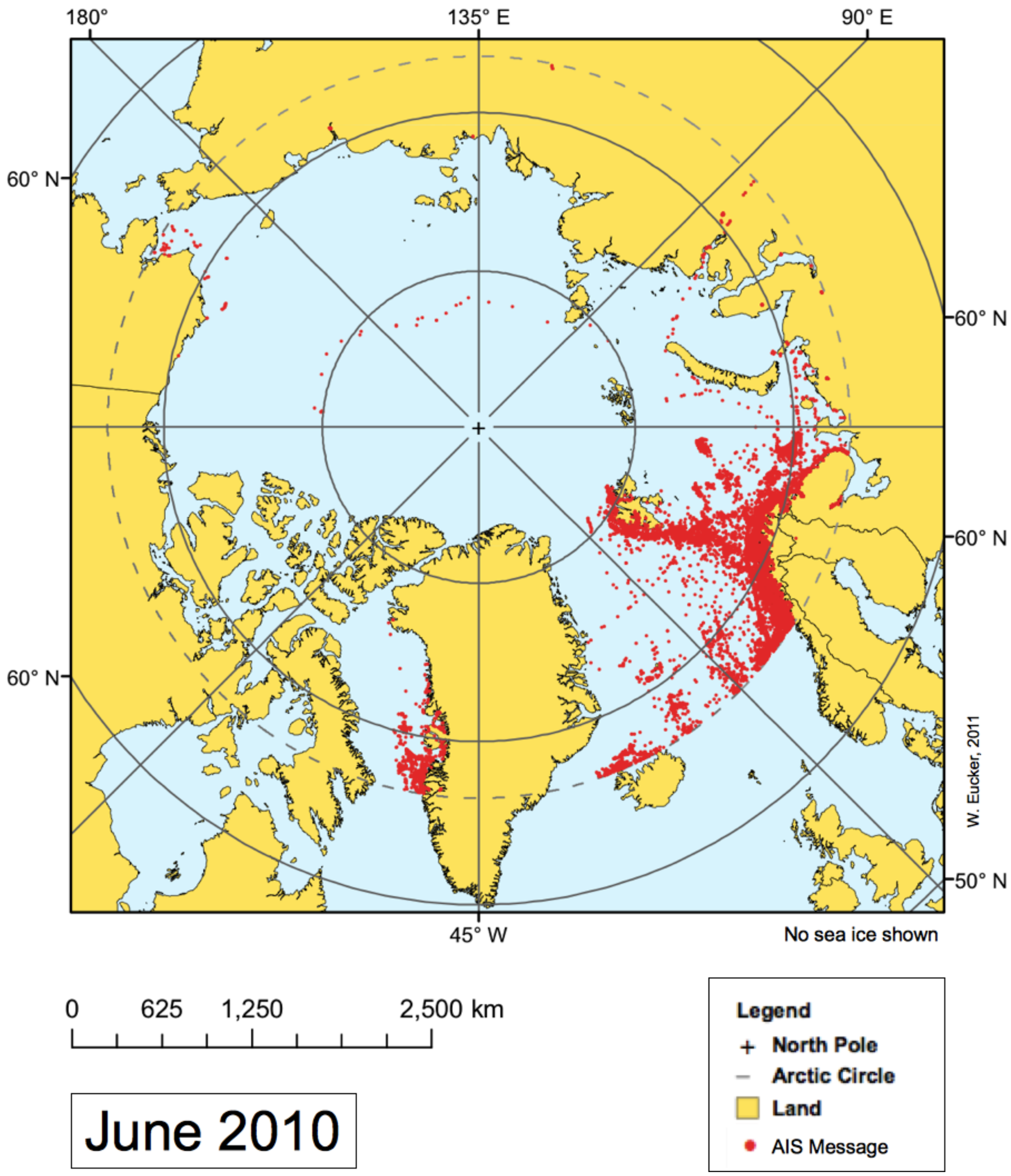
Appendix III: Maps of Arctic Marine Traffic



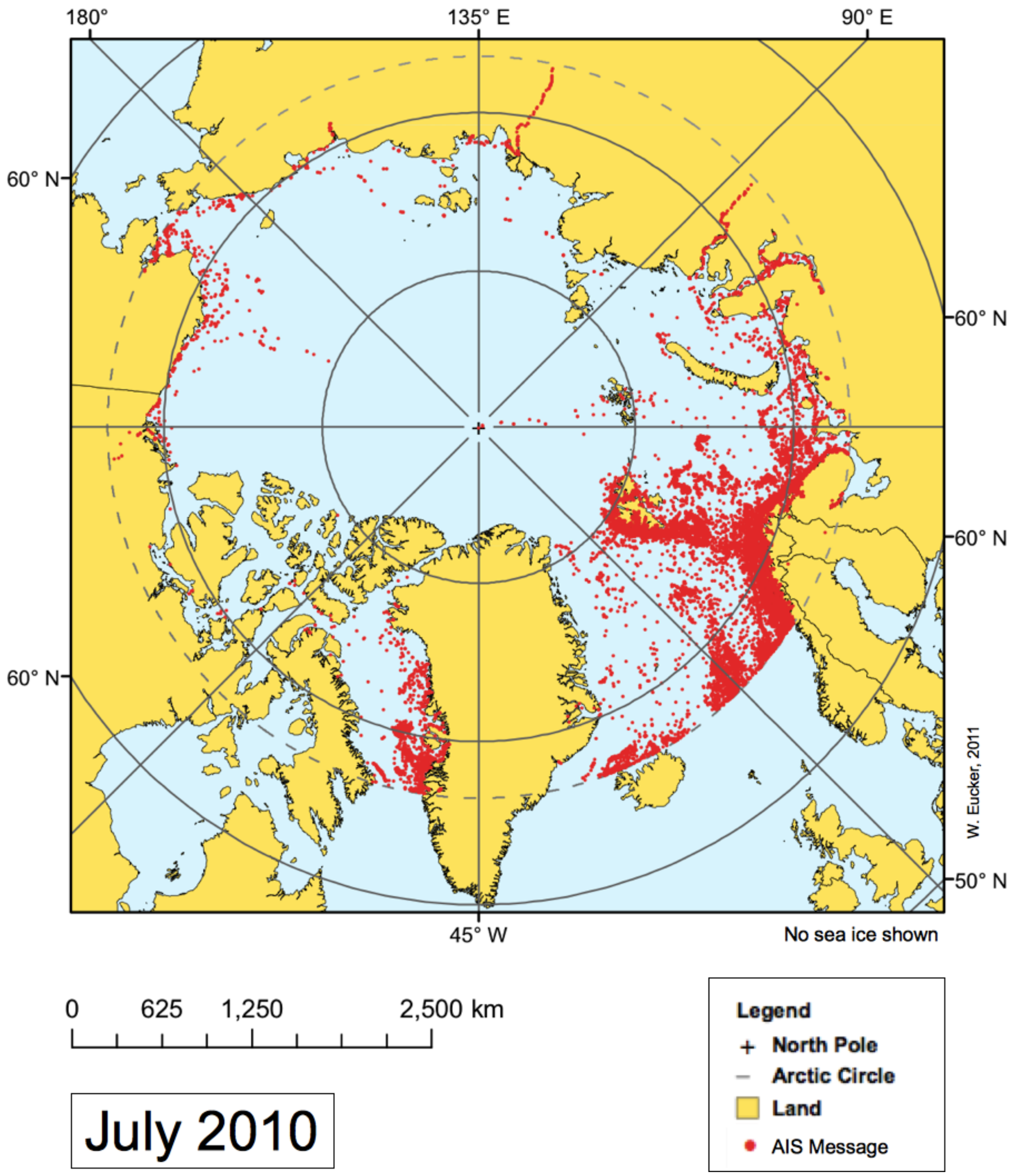
Locations of 995 distinct surface vessels north of the Arctic Circle during the month of April 2010 based on AIS position report messages received by the SpaceQuest satellite constellation.



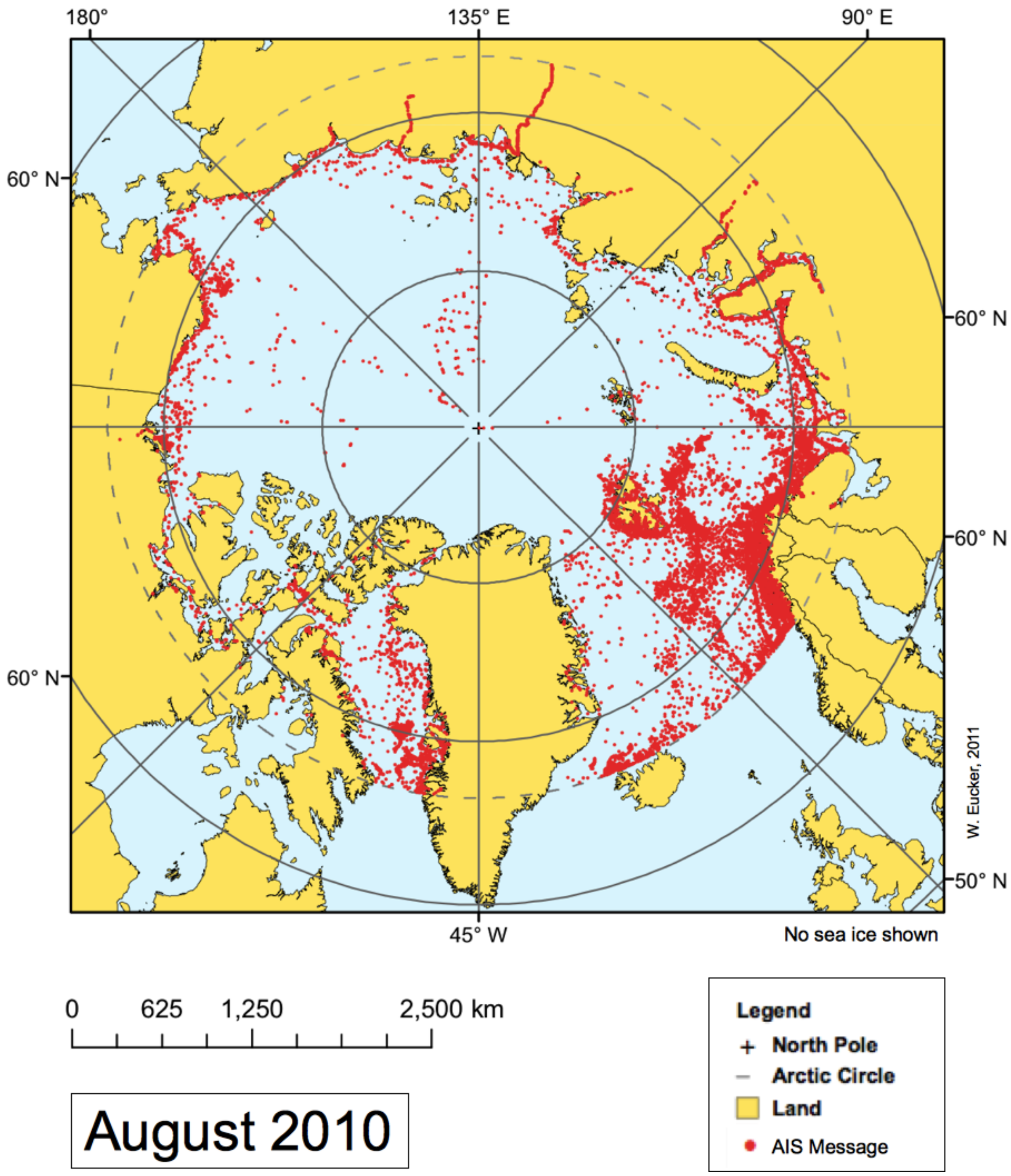
Locations of 980 distinct surface vessels north of the Arctic Circle during the month of May 2010 based on AIS position report messages received by the SpaceQuest satellite constellation.



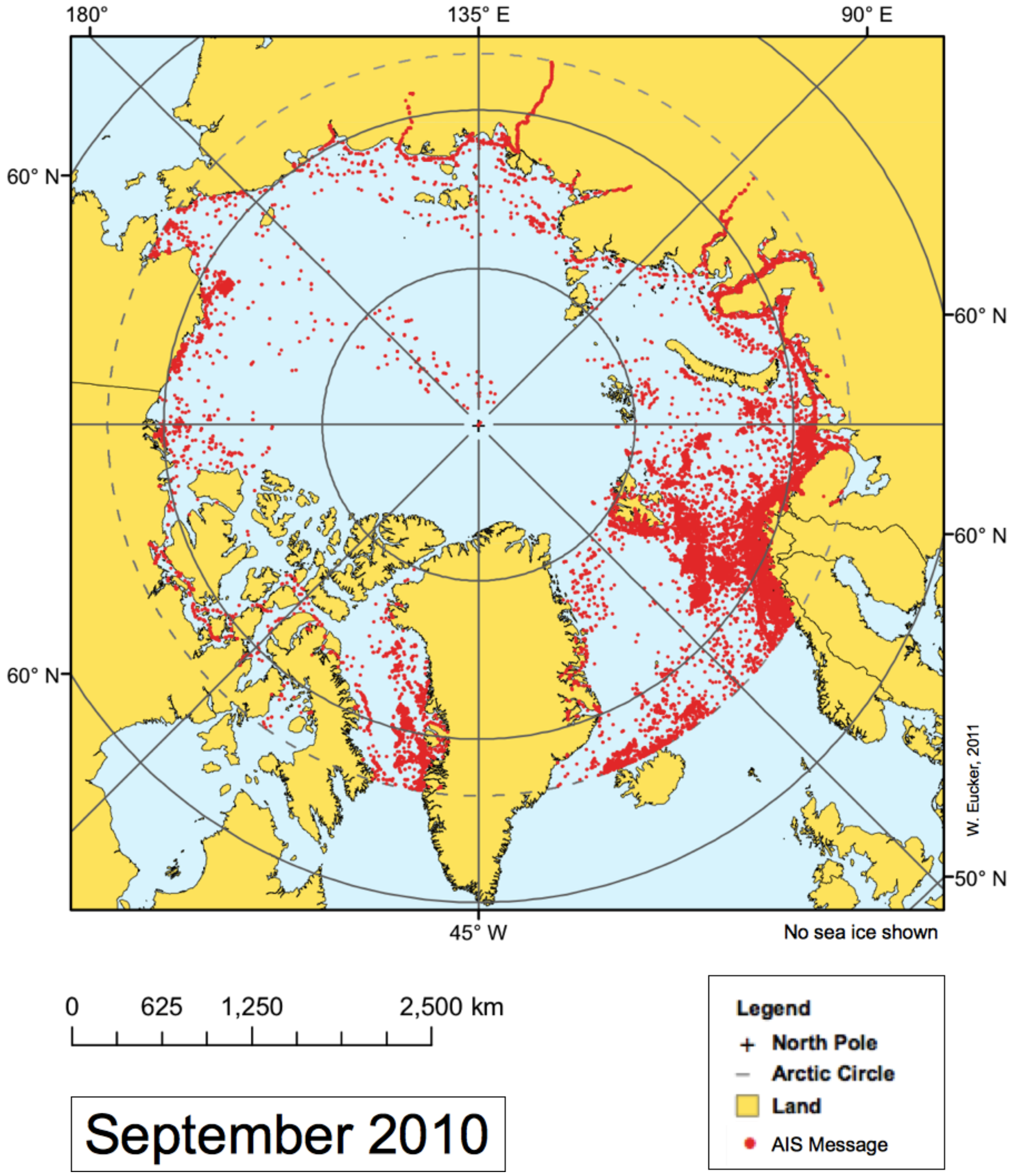
Locations of 1128 distinct surface vessels north of the Arctic Circle during the month of June 2010 based on AIS position report messages received by the SpaceQuest satellite constellation.



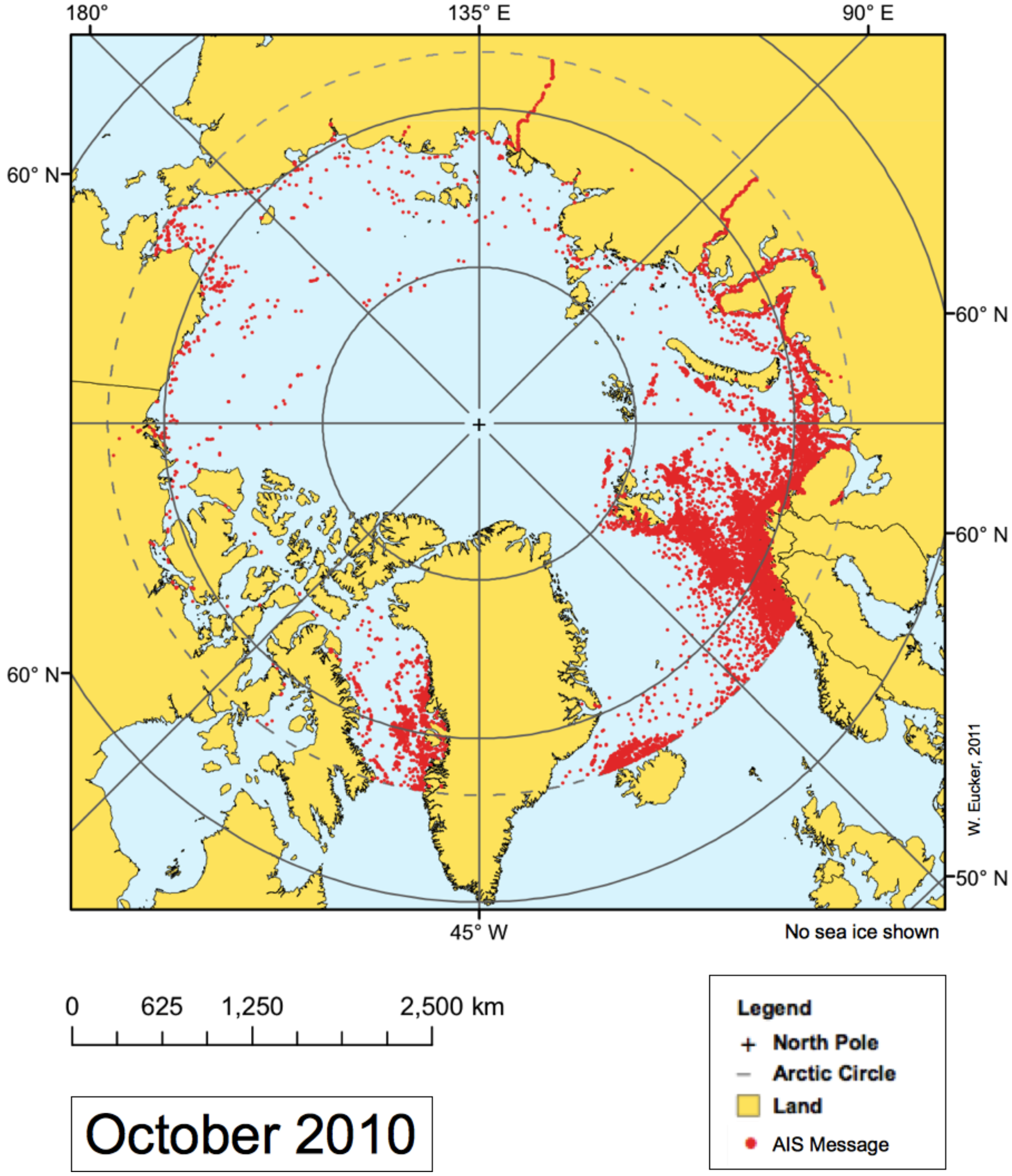
Locations of 1330 distinct surface vessels north of the Arctic Circle during the month of July 2010 based on AIS position report messages received by the SpaceQuest satellite constellation.



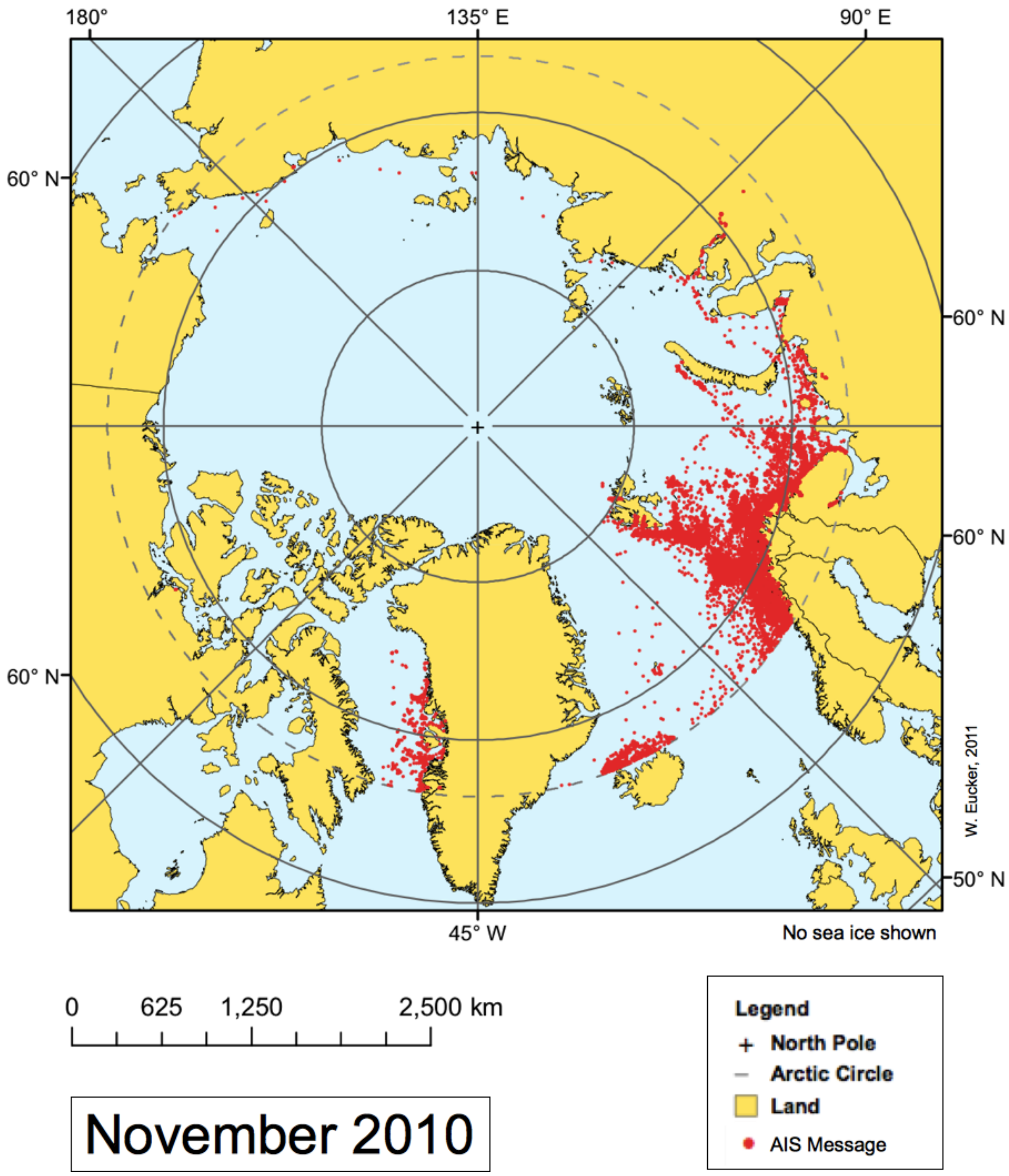
Locations of 1445 distinct surface vessels north of the Arctic Circle during the month of August 2010 based on AIS position report messages received by the SpaceQuest satellite constellation.



Locations of 1439 distinct surface vessels north of the Arctic Circle during the month of September 2010 based on AIS position report messages received by the SpaceQuest satellite constellation.

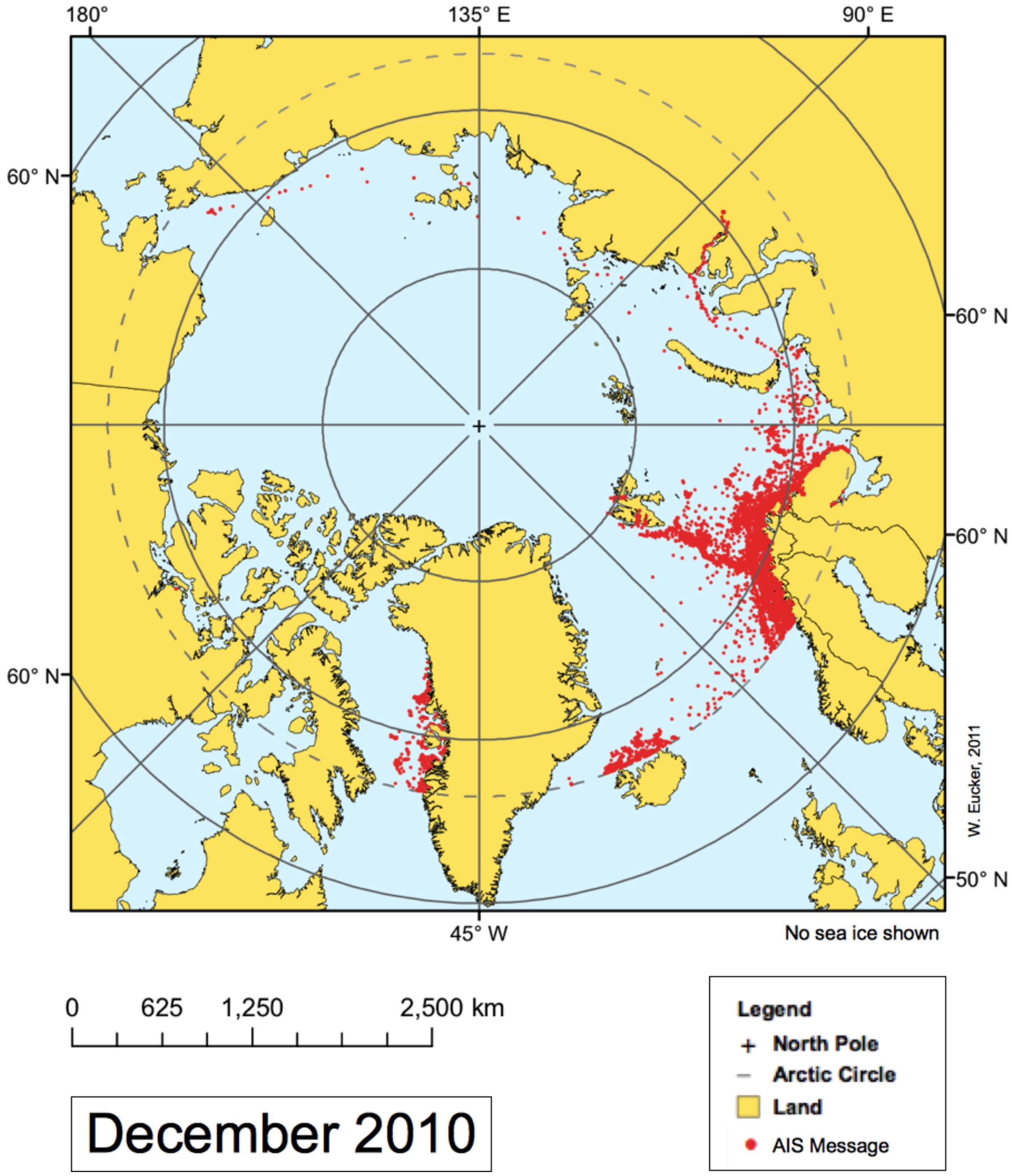


Locations of 1426 distinct surface vessels north of the Arctic Circle during the month of October 2010 based on AIS position report messages received by the SpaceQuest satellite constellation.

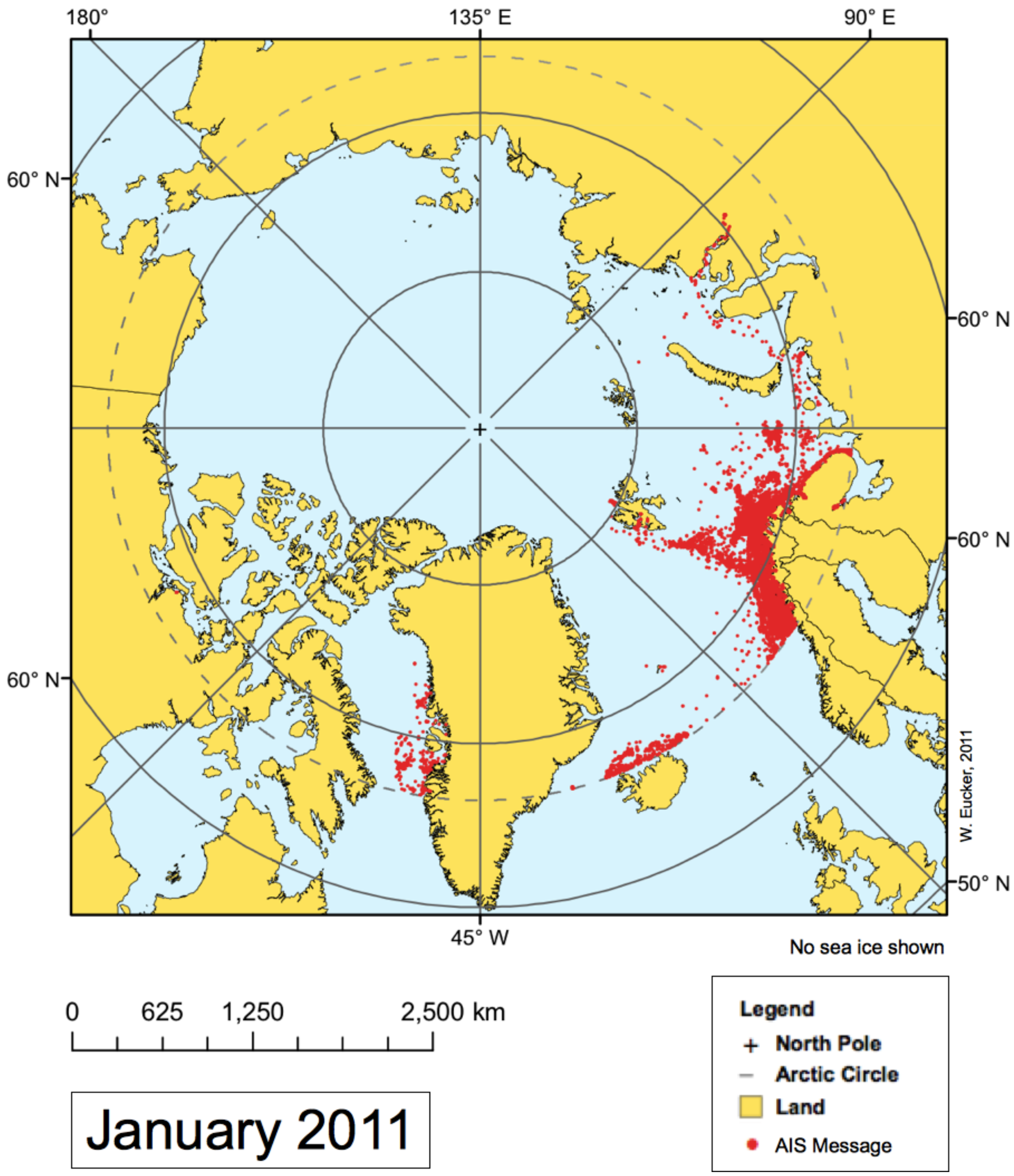


Locations of 1245 distinct surface vessels north of the Arctic Circle during the month of November 2010 based on AIS position report messages received by the SpaceQuest satellite constellation.

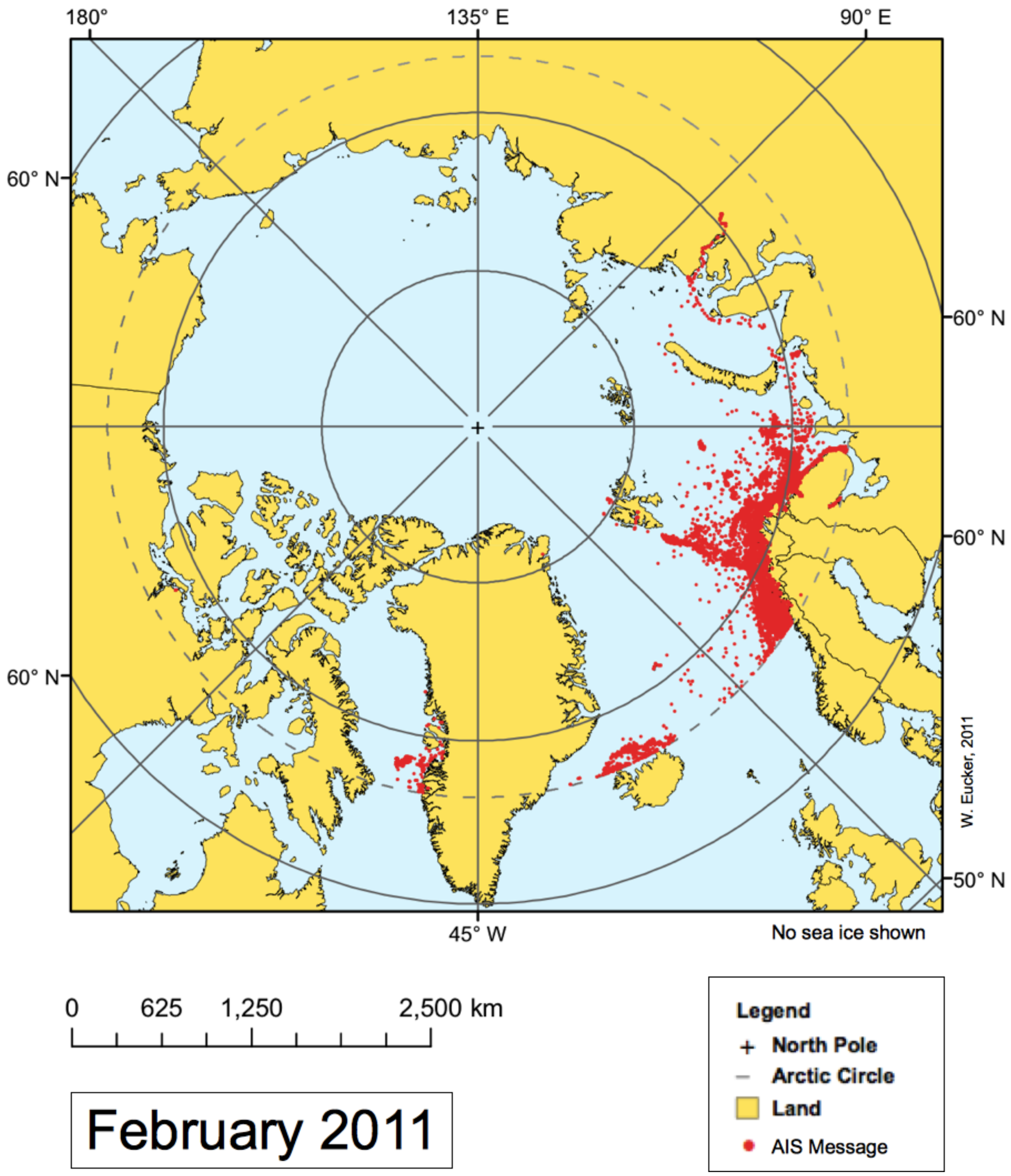
Appendix III: Maps of Arctic Marine Traffic



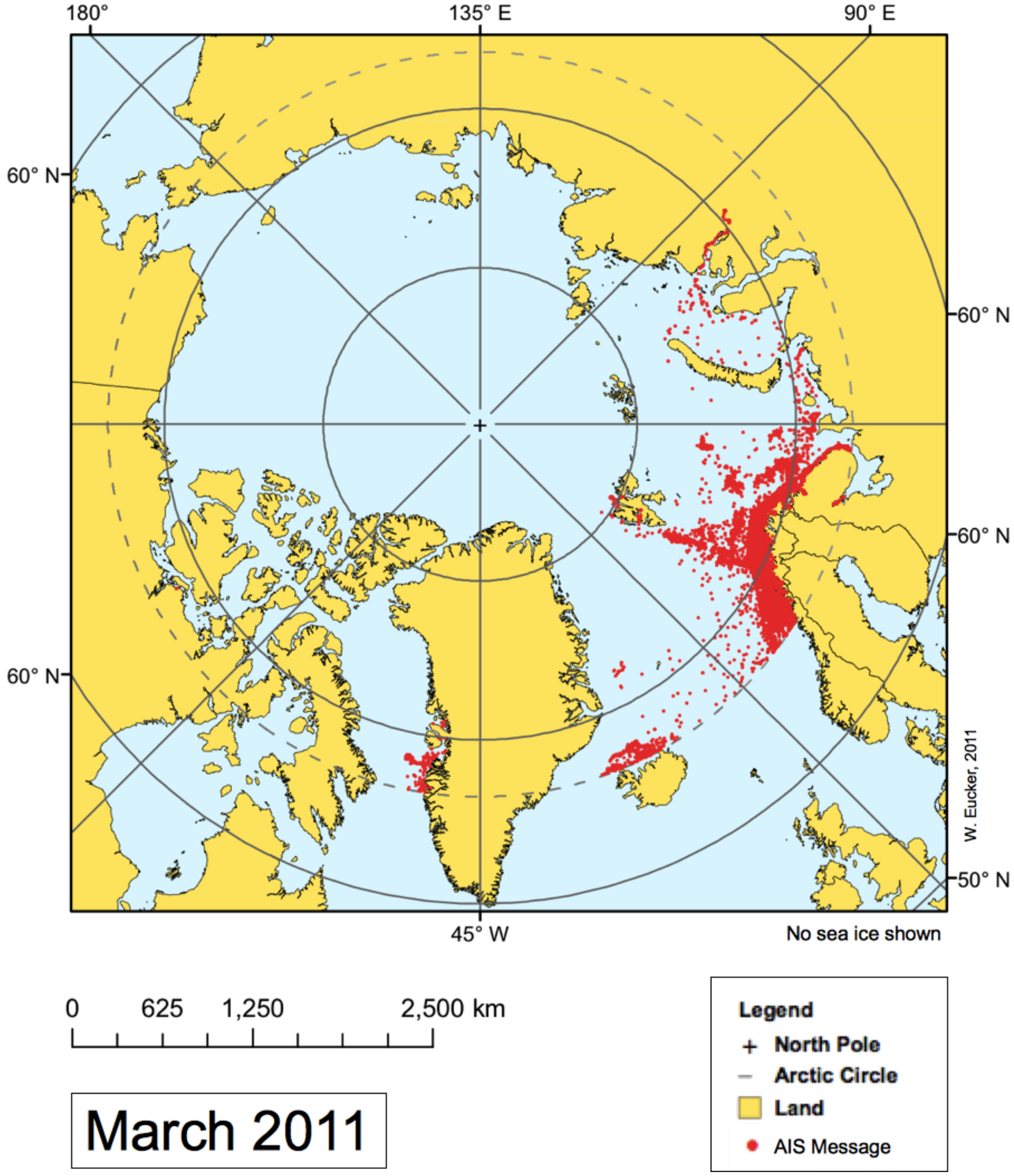
Locations of 1034 distinct surface vessels north of the Arctic Circle during the month of December 2010 based on AIS position report messages received by the SpaceQuest satellite constellation.



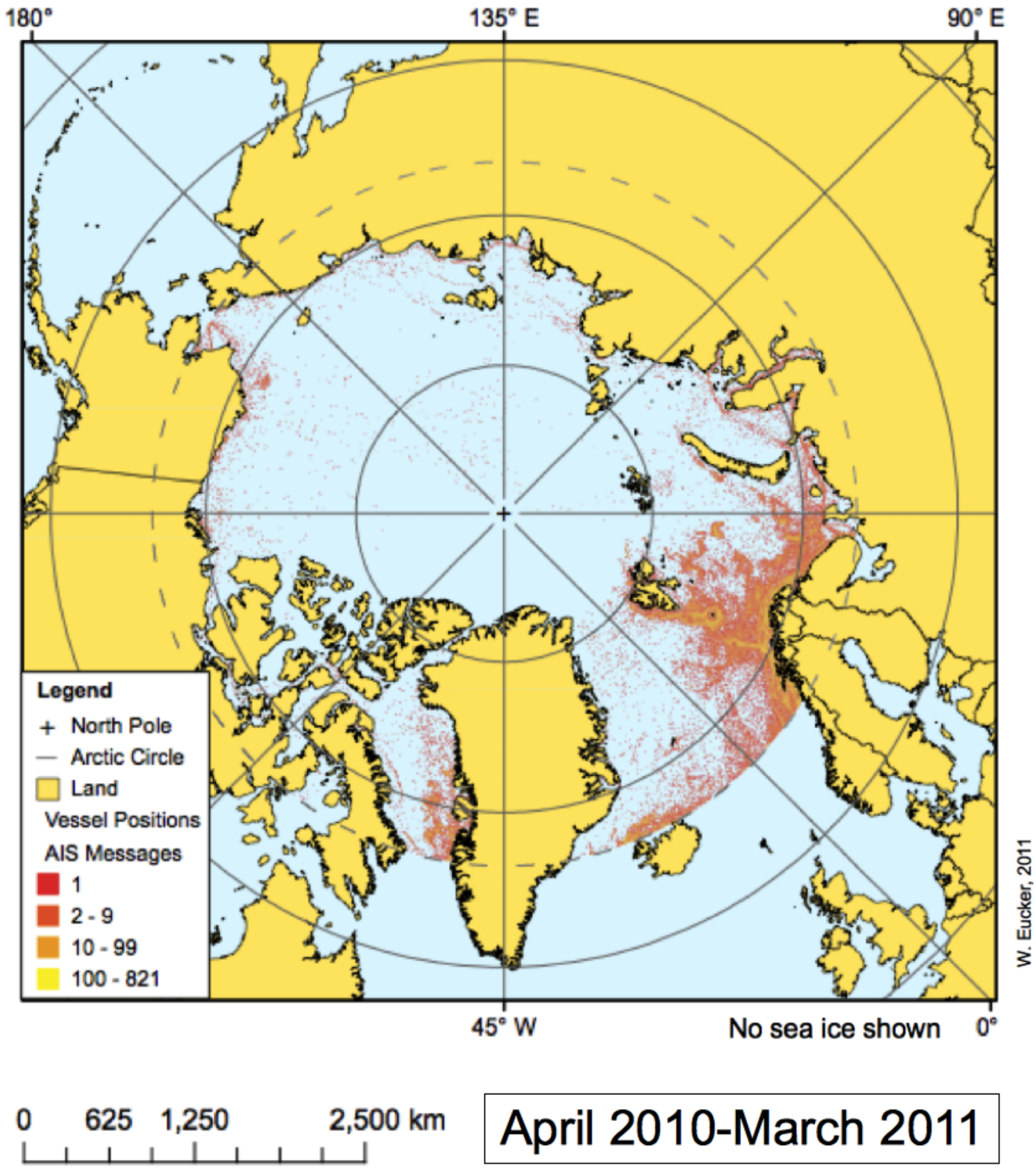
Locations of 1220 distinct surface vessels north of the Arctic Circle during the month of January 2011 based on AIS position report messages received by the SpaceQuest satellite constellation.



Locations of 1208 distinct surface vessels north of the Arctic Circle during the month of February 2011 based on AIS position report messages received by the SpaceQuest satellite constellation.



Locations of 1383 distinct surface vessels north of the Arctic Circle during the month of March 2011 based on AIS position report messages received by the SpaceQuest satellite constellation.



Number of AIS position report messages received by the SpaceQuest satellite constellation north of the Arctic Circle per 6·25 km reference grid cell, aggregated for the year from 1 April 2010 to 31 March 2011.