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Rajmund Przybylak

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To wife Dorota
and our daughters Anna Maria and
Julia Dorota

Preface

At the end of the nineteenth century, researchers put forward the hypothesis that the Polar regions may play the key role in shaping the global climate. This supposition then found full confirmation in empirical and model research conducted in recent decades. The intensification of global warming after about 1975 brought into focus the physical causes of this phenomenon. The first climate models, created at that time, and analyses of long observation series consistently showed that the Polar regions are the most sensitive to climate changes. This aroused the interest of numerous researchers, who thought that the examination of the processes taking place in these regions might help determine the mechanisms responsible for the 'workings' of the global climate system. The urgent need to better recognize these processes in the Polar regions was probably the main impulse behind the organization of the fourth International Polar Year (IPY) in 2007–2008. The success of this international scientific effort also influenced the decision to continue the greater than usual activity in the coming years, after the official end of the fourth IPY (International Polar Initiative, http://internationalpolarinitiative.org/IPIabout.html).

The first edition of this book was published in 2003, just before the birth of the idea for that fourth IPY. Since that time, interest in the study of the Arctic climate has significantly increased, due – among other reasons – to the dramatic changes in the environment observed in the Arctic following the large-scale warming of the area (more that 1°C above the long-term mean) that began in the mid-1990s. The most spectacular change was observed in sea ice characteristics (extent and thickness). Suffice to say, that in 2007 and 2012, a record minimum sea ice was noted during September in the Arctic Ocean. The previously mentioned unprecedented level of interest in the Arctic climate resulted in the publishing of many new important papers, books, reports, etc., of which the majority have been taken into account in this new edition of the *Climate of the Arctic*.

The primary aim of the 11 chapters of this publication is to present the current state of knowledge of: (1) the Arctic climate in the second half of the twentieth century and its main drivers (Chaps. 1, 2, 3, 4, 5, 6, 7, 8, and 9), and (2) changes in the Arctic climate over the last 10–11,000 years (Chaps. 10 and 11). In view of the importance of climate change, this issue has been given more attention than is customary in similar studies. In the first chapter, a review of the criteria proposed at the beginning of the twentieth century to delimit the southern boundary of the Arctic is presented, along with the main geographical factors (geographical latitude, relief, type of surface, etc.) significantly influencing changes in the Arctic climate. In Chap. 2, a history of the development of views on atmospheric circulation in the Arctic is presented. Large-scale atmospheric circulation, as a climatic process, is described in detail for all seasons. The yearly cycle of sea-level atmospheric pressure is also analysed. The chapter ends with the characterization of synoptic- and local-scale circulation. Chapter 3 starts with a description of the history of actinometric measurements in the Arctic and a review of the literature describing radiation and energy conditions. Then, sunshine duration conditions are described for some months of the year. Very detailed information is also given on the spatial distribution of radiation balance and all of its components in the Arctic for key months of the year, as well as for the entire year. The chapter ends with an analysis of the heat balance and its components (sensible and latent heat) in the study area. In Chap. 4, a complex description of air temperature parameters (mean, maximum, minimum and diurnal temperature range) is presented. Analysis is made of, amongst others, spatial distributions of mean seasonal and annual values of these parameters in the Arctic, annual and daily cycles, and year-to-year variability. In addition, the effects of the influence of cloudiness on air temperature are presented. The chapter concludes with a description of the results of recent studies of the frequency of occurrence of air temperature inversions, as well as other of their characteristics such as height, thickness and intensity. In Chap. 5, a comparison of surface-, satellite-, model- and reanalyses-based cloudiness climatologies is presented. Annual cycle and spatial distribution features of cloudiness and fog in the Arctic are described and discussed. The different aspects of air humidity in the Arctic are presented in Chap. 6. The annual cycles of air humidity characteristics as well as their mean spatial distributions in the two main seasons of the year (winter and summer) are described and discussed. The chapter ends with an analysis of vertical humidity changes in the troposphere, including the occurrence of humidity inversions. In Chap. 7, a review of the available literature on the different aspects of the occurrence of precipitation and snow cover in the Arctic is made. The moisture content of the atmosphere in January and July is described first, followed by a very detailed analysis including spatial distribution of precipitation and its changes in the annual course. The precipitation issue concludes with a description of the characteristics of the main features of the occurrence of the number of days with precipitation in the Arctic. At the end of the chapter, the main features of snow cover are summarized and discussed. Chapter 8 includes an analysis of 'Arctic haze' and the influence of this phenomenon on the climate through changes in the radiation balance of the atmosphere. Much time and attention is also given to the main sources and pathways of transport of pollutants between the mid-latitudes and the Arctic, as well as within the Arctic. The major chemical components of the Arctic haze in winter and summer are also described. In Chap. 9, factors influencing climate diversity in the area of the Arctic and available climate regions are presented. A substantial part of the chapter is devoted to a description of the most important features of the climate in the seven distinguished climate regions. In Chap. 10, the state of knowledge of climate change and variability in the Arctic for three time periods (the Holocene, the last millennium and the instrumental period) is presented. A synthesis is separately conducted for three regions of the Arctic: Greenland, the Canadian High Arctic and the Eurasian Arctic. Besides standard climate change characteristics, the influence of atmospheric circulation on air temperature is also described at the end of the chapter. In Chap. 11, the results of model simulations of the present-day Arctic climate are described and discussed. Scenarios for the future Arctic climate for four meteorological variables (air temperature, precipitation, atmospheric pressure and cloudiness) are then presented, based mainly on results obtained from the General Circulation Models.

It is now commonly accepted that the mean physical state of the atmosphere is one of the key elements of the Arctic Climatic System. Consequently, having a variety of climate data is indispensable not only to climatologists but also for other researchers of the Arctic environment (glaciologists, oceanographers, botanists, etc.). Up-to-date and reliable climate data are also requisite for validating climatic models. The author hopes that this book will be of particular interest to all researchers who represent the above scientific disciplines in their research. It should also be helpful to students of geography and related disciplines, both in the didactic process and in research, and may also be of use to all those who are interested in this part of the world. Finally, I would like to express my hope that the reader will find the book gratifying in terms of readability and the usefulness of the information it contains. I would also like to apologize for any mistakes in the text that went unnoticed in the publication process.

It would not have been possible to carry out the research for the present volume without the financial support provided by the Nicolaus Copernicus University in Toruń. For its assistance in securing this support I would like to thank the Dean of the Faculty of Earth Sciences, Professor Wojciech Wysota. I am very grateful to Elżbieta Rudź, M.Sc., and Tomasz Strzyżewski, M.Sc., for contributing their knowledge and computer expertise in reproducing some of the graphics for the book. Special warm thanks are also directed to my editor at Springer, Mariëlle Klijn, for her assistance in the preparation of this book. Last but not least, I would like to thank my wife Dorota for assisting me in many ways and for all her personal support, particularly during the periods which I had to spend away from home.

Toruń, Poland Rajmund Przybylak
May 2015

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Contents

Chapter 1
Introduction

The word "Arctic" is derived from the Greek word *Arktos* ('bear'). In its Latin equivalent, this occurs in the names of two constellations – *Ursa Major* and *Ursa Minor* – which circle endlessly around the one fixed point in the heavens: *Polaris*, the North Polar Star.

1.1 Boundaries of the Arctic

The Arctic is not an easily definable geographic entity similar to, for example, Iceland, Lake Baykal, or even the Antarctic. Therefore, until recently, it has not been possible to arrive at any single definition of the area. Since the 1870s a large number of researchers representing different disciplines such as geography, climatology, and botany have tried to establish a widely accepted criterion to delimit the Arctic boundary (Fig. 1.1). In almost all the geographical monographs and other books dealing with Arctic or Polar regions one can find a variety of attempted definitions (e.g. Bruce 1911; Brown 1927; Nordenskjöld and Mecking 1928; Baird 1964; Sater 1969; Sater et al. 1971; Baskakov 1971; Petrov 1971; Barry and Ives 1974; Weiss 1975; Sugden 1982; Young 1989; Boggs 1990; Stonehouse 1990; Barry 1995; Bernes 1996; Przybylak 1996; Niedźwiedź 1997; Mills and Speak 1998; McBean et al. 2005; Hinzman et al. 2005). However, the most comprehensive reviews have been given by Petrov (1971) and Baskakov (1971). The oldest conception of the Arctic is one which considers it to be a region of the Northern Hemisphere lying north of the Arctic Circle ($\varphi = 66°33'$N). The majority of the above authors agree that this astronomically distinguished line of latitude cannot be considered to be the real Arctic boundary. This fact was noted as early as 1892 by Bruce (Bruce 1911) and later in 1927 by Brown, who wrote, "The Arctic and Antarctic circles merely mark the equatorial limits of the zones in which the sun is never more than 23°30′ above the horizon. […] The circles are astronomical lines without climatic significance." The careful reader will note that here Brown gives the wrong value of

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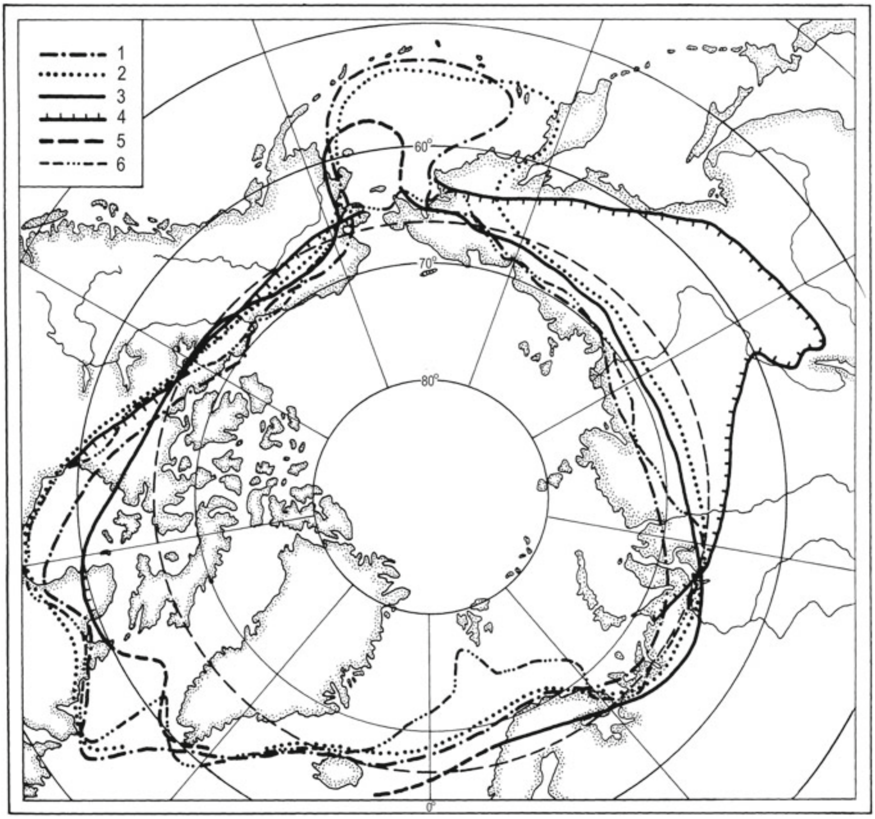

Fig. 1.1 Boundaries of the Arctic. *1* – isotherm of the warmest month 10 °C, *2* – boundary of the Arctic after Nordenskjöld, *3* – line denoting net radiation of 62.7 kJ/cm²/year (15 kcal/cm²/year), *4* – boundary of the permafrost, *5* – Arctic Circle, *6* – boundary of the Arctic (After *Atlas Arktiki* 1985)

the height of the sun. The correct value is 47° and can be ascertained using the formula $h = 90° - \varphi + \delta$, where φ is the geographical latitude and δ is the declination of the sun.

A more meaningful and more frequently used definition of the Arctic is a climatological one. Among the many known climatic criteria, the most popular is still the older proposition given by Supan (1879, 1884), i.e. the 10 °C mean isotherm of the warmest month. This criterion was later modified, first by Vahl (1911) and then by Nordenskjöld (1928). Vahl did not determine the precise borders of the Polar regions, but, as he seems to have let it coincide with the tree line, he regarded the equation $V < 9.5° - 1/30$ K to be the most favourable for the determination of the position of this boundary. In this formula V and K denote the mean temperature of the warmest and coldest months, respectively. Nordenskjöld (1928) found that the role of the coldest month in determining the Arctic boundary should be greater than was assumed Vahl (1911). Therefore, he proposed a new formula: V < 9° − 0.1 K. In addition, he also extended it to the seawater areas (see Fig. 1.1). According to this criterion the Arctic includes regions in which the temperature of the warmest month ranges from 9 °C (when the temperature of the coldest month is 0 °C) to 13 °C (when the temperature of the coldest month is −40 °C).

The boundary of the Arctic can also be drawn using the criterion proposed by Gavrilova (1963) and Vowinckel and Orvig (1970). According to them, all areas where the net radiation balance is lower than 62.7 kJ/cm²/year (15 kcal/cm²/year) may be considered to belong to the Arctic (Fig. 1.1). The authors of the *Atlas Arktiki* (1985) have recently presented a new, very good, proposition. The southern Arctic boundary has been delimited using mean long-term values of almost all meteorological elements. Thus, the concept of climatic regionalisation is employed. The Arctic perimeter on the continents lies mostly between the boundaries of the 10 °C mean isotherm of the warmest month and the so-called Nordenskjöld line (Fig. 1.1). In addition, the authors of the *Atlas* have also distinguished seven climatic regions within the Arctic (Fig. 1.2). These facts have persuaded me to adopt their definition of the Arctic for the purposes of this monograph.

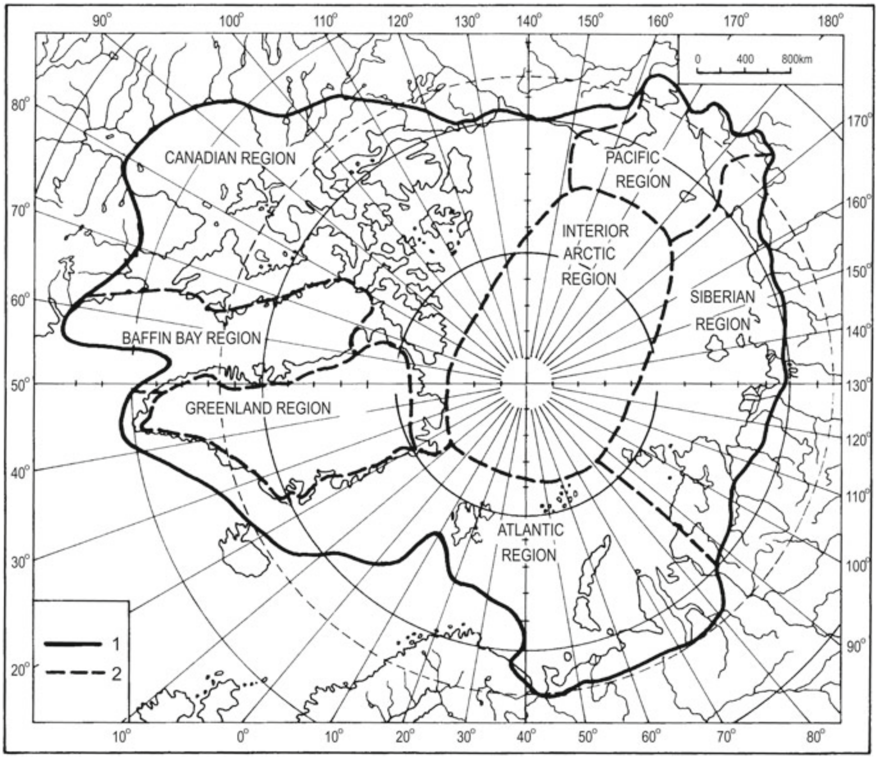

Fig. 1.2 Boundaries of the Arctic (*1*) and climatic regions (*2*) (After *Atlas Arktiki* 1985)

The third criterion quite often used (aside from astronomical and climatological criteria) is a (geo)botanical one. The southern boundary of the tundra or the northern boundary of the tree line is considered to be the natural boundary of the Arctic. Supan (1879, 1884), in his classification of climates, was probably the first to distinguish the Arctic area using both climatological and geobotanical criteria. The areas distinguished show a good correlation and most other later analyses confirm Supan's finding. Sugden (1982) presents several advantages of using the tree line to delimit the southern land boundary of the Arctic. He writes, "Not only does it represent a fundamentally important vegetation boundary, but it is also important in terms of animal distributions. It coincides approximately with a mean July temperature isotherm of 10 °C and thus is also of climatic significance." However, one must be aware that there are also some disadvantages of this criterion. For example, as many as three possibilities to define the boundary of the Arctic can be used: a northern limit of continuous forest, a northern limit of erect trees, or a northern limit of species. For more details, see Hare (1951) and references therein.

Almost all the above-presented criteria should be used exclusively with reference to land Arctic regions. However, in the present analysis we also need to establish boundaries over sea areas. A number of researchers, mainly oceanographers, have suggested replacing the boundary at sea delimited using the above criteria with a boundary delimited using more appropriate criteria for a water environment. For example, Baskakov (1971) suggests that the boundary of the Arctic in the sea areas should be drawn according to oceanological characteristics, i.e. hydrological, ice, and geomorphologic. He has provided us with the most comprehensive definition of the oceanic Arctic region and I cite here only the most important fragment: "Those water areas may be considered part of the oceanic Arctic region which, during the cold period of the year, are generally (average outflow over a several year period) covered by sea ice of various ages including perennial ice, and in which the upper layer of water under the ice (of a depth of not less than 30 m) has negative temperature and low salinity (less than 34.5 ‰)." Simply speaking, as a sea boundary of the Arctic one can accept the southernmost extent normally reached by the Arctic Waters.

At the end of this section, one should also mention the opinion of some researchers (Armstrong et al. 1978; Sugden 1982; Stonehouse 1990) who are convinced that it is practically impossible to achieve a delimiting of the precise boundary of the Arctic which will gain the acceptance of scientists from different disciplines. Sugden (1982) has written, "…the boundaries should remain flexible. Some boundaries seem appropriate for some purposes and other boundaries for others." To a certain extent it is possible to agree with this view. However, I think that an Arctic boundary should be at least agreed on among scientists of the same discipline, e.g. among climatologists. In an era of global warming, this is becoming more and more urgently needed. Otherwise, our estimations of mean Arctic climatic trends may be equivocal (see Przybylak 1996, 2000, 2002).

1.2 Main Geographical Factors Shaping the Climate

Undoubtedly, geographical latitude is the main factor determining the weather and climate both in the Arctic and elsewhere. For the purpose of this work, the Arctic has been defined after *Atlas Arktiki* (1985) (Fig. 1.2). From Fig. 1.2, it can be seen that the southern boundary of the Arctic thus defined ranges between about 54 °N (the Labrador Peninsula) to about 75 °N near Spitsbergen. No matter how we define the Arctic, its location in high latitudes limits significantly the magnitude of receiving energy from the sun. In regions lying beyond the Arctic Circle, the most unusual feature is the occurrence of seasonal day and night. As we know, the length of both polar night and polar day varies from 1 day at the Arctic Circle to about 6 months at the North Pole (Fig. 1.3). In addition, because of the atmospheric refraction, the total time when the sun is visible over the horizon during the year is greater at high latitudes than in more temperate latitudes. Also, since the sun crosses the horizon at a shallow angle in the Arctic, dawn and dusk persist for long periods before and after the sun is visible. As a result, winter days are much longer here than summer nights. The elevation of the sun in noon anywhere cannot be higher than about 47°. This fact is mainly responsible for the lower income of the solar energy (on an annual basis) here than in lower latitudes. However, the total solar radiation in June, which the Arctic receives at the top of the atmosphere, is even higher than in equatorial areas. For example, the solar irradiance flux reaching the upper boundary of the earth-atmosphere system is equal to 129 kJ/cm^2 (31 kcal/cm^2) and 98.2 kJ/cm^2 (23.5 kcal/cm^2) at the 80 °N and the equator, respectively (Budyko 1971). From a climatological point of view, however, it is only the solar radiation absorbed by the surface which is important. Due to the high albedo of the earth-atmosphere system in the Arctic, this component of the radiation balance is markedly lower than in the rest of the globe. Looking at the map of the Arctic, one can easily see that the Arctic, in contrast to the Antarctic, consists of an ocean encircled by land. The central main part of the ocean is called the Arctic Ocean and is ice covered year-round, while snow and ice are present on the land for almost all the year. The land encompasses the northern parts of two major land masses – Eurasia and North America – as well

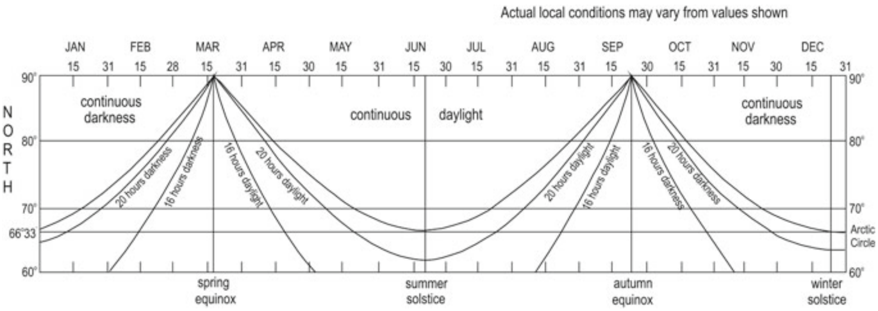

Fig. 1.3 Duration of daylight and darkness in the latitude band 60°–90 °N (After CIA 1978)

as quite a large number of islands, especially on the American side. Of these the largest are Greenland (2,175,600 km^2), Baffin Island (476,070 km^2), Ellesmere Island (212,690 km^2), and Victoria Island (212,200 km^2) (*The Times Atlas of the World* 1992). The area of Greenland, including the islands, is 2,186,000 km^2 (Putnins 1970). A substantial break in the ring of land exists only between Greenland and Norway (Fig. 1.2). Other breaks between Asia and America (the Bering Strait) and between the islands of the Canadian Arctic Archipelago are of marginal significance. The highest mountains are to be found in south-eastern Greenland, where two summits rise over 3000 m a.s.l.: Gunnbjörn Fjeld (3700 m, $\varphi = 68°54'$N, $\lambda = 29°48'$W) and Mt. Forel (3360 m, $\varphi = 67°00'$N, $\lambda = 37°00'$W) (*The Times Atlas of the World* 1992). Much of the Arctic is low lying, except for the Greenland ice sheet, the ice-covered mountains of Ellesmere and Axel Heiberg islands, and the mountains in the northern part of the Beringia region. The differentiated influence of land and sea areas on the climate of the Arctic is significantly lower than in the moderate latitudes. This is true, particularly in winter, when the land and most of the sea areas are covered by snow. The long-term mean depths of snow cover for May, calculated from measurements taken mainly in Russian drifting stations NP3– NP31 over the period 1954–1991, vary from 30 to 40 cm in the central part of the Arctic to more than 80 cm in the mountainous regions. The maximum snow-cover depth is most often observed in April or May except in the Canadian Arctic, where it is observed in March. The decay of the snow cover begins in the south of the Arctic in the first 10 days of June and in the vicinity of the Pole in mid-July. The number of days with snow cover is greatest in the central Arctic (more than 350 days). This number decreases towards the south and is equal to about 280–300 days across those Arctic islands which have a continental climate (for more details see sub-Sect. 7.3).

In general, three physical characteristics of snow – high reflectivity, high infrared emissivity, and high insulating property – mean that it plays a very important climatic role. The high albedo of the snow surface significantly reduces the net radiation balance of the surface and low troposphere. The high infrared emissivity of snow is one of the most important factors, which causes near-surface atmospheric temperature inversions, especially in the cold half-year. In addition, it helps in the development and stabilising of the anticyclones. Snow cover, as one of the best insulators of all known natural surfaces, is a very important element in the atmosphere-cryosphere-ocean system, and thus significantly influences heat transport. A snow cover of more than 15 cm in depth may completely stop the heat transport between the atmosphere and land or sea ice.

The Arctic Ocean and its bordering seas occupy an area of 14 million km^2 (Barry 1989). In late winter (February–March) almost all this area is covered by sea ice. During the summer (August–September), and particularly in September, the sea ice is at its minimum extent (approximately 8 million km^2). In recent years, however, a dramatic decline in the area of the sea ice has been observed. Over the period of modern satellite observations (1979–2006), the decline in September sea ice has been equal to −9.1 % per decade (Stroeve et al. 2007). As a result of this continuing tendency, in two years (2007 and 2012), when the lowest extent of sea ice in September was observed, its area had fallen below 5 million km^2 (Fig. 1.4).

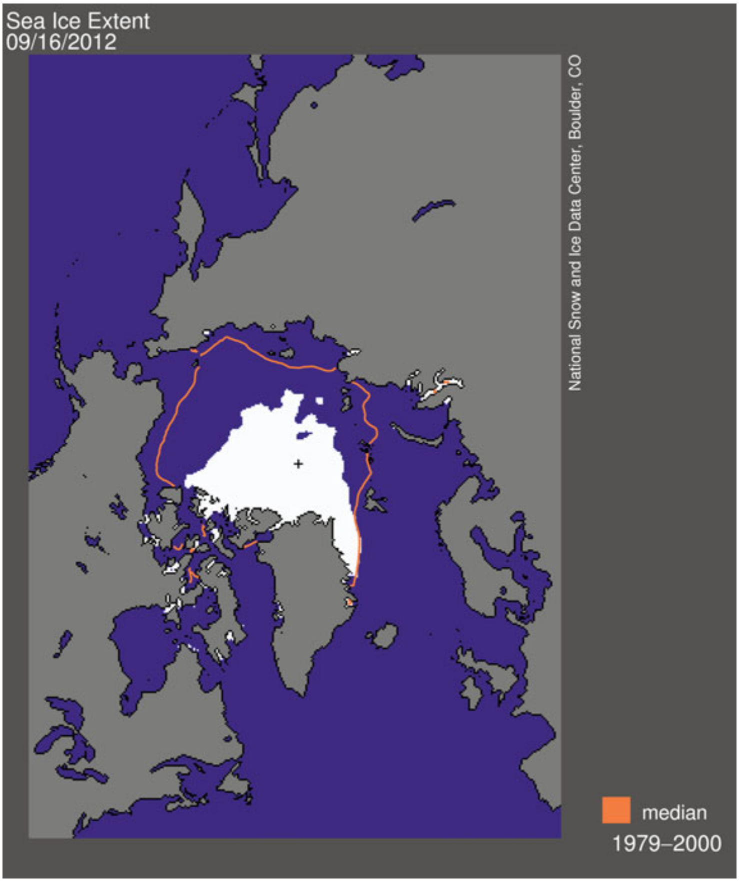

Fig. 1.4 Arctic sea ice extent for September 16, 2012. The orange line shows the 1979–2000 median extent for that day. The black cross indicates the geographic North Pole (After National Snow and Ice Data Center, University of Colorado, Boulder)

The role of the sea ice in shaping the climate of the Arctic, and indeed that of the whole globe, is crucial. Generally, four main properties of the sea ice contribute to this. The first property is the significantly higher albedo of sea ice (0.5–0.7) in comparison to an open ocean (0.1). As a result, water covered by sea ice absorbs much less radiation than do open waters. A second property is the insulating role of the sea ice, restricting the exchange of heat and moisture between ocean and atmosphere. Maykut (1978) reported that the measurements of wintertime sensible heat flux showed that between 10 and 100 times more heat is transferred from a calm open-water ocean to the atmosphere than from an ocean covered by a 2-m layer of sea ice. A third property is the large latent heat of freezing and melting, which makes sea ice act as a thermal reservoir delaying the seasonal temperature cycle. These processes also alter the salinity content of the upper layers of the ocean. During freezing, a sea salt is forced out of the sea ice (resulting in an increase of salinity in the water); on the other hand, during melting, the fresh water transferred to the upper layers reduces its salinity. Wadhams (1995) has drawn our attention to the fact that sea-ice motion (a fourth property), driven mainly by wind stress, is also very important for climate and climate-change studies. Processes connected with this motion, such as divergence and convergence of sea ice, create leads and pressure ridges, respectively. The latter forms contain about half of the total Arctic ice volume (Wadhams 1981). As a result of these processes, atmosphere–ocean heat and moisture fluxes are highly time- and space-dependent.

Sea ice in the Arctic never exists as an unbroken cover or as a floating ice cap. Three categories of sea ice can be distinguished here: Polar Cap Ice, Pack Ice, and Fast Ice (Pickard and Emery 1982). Polar Cap Ice covers about 70 % of the Arctic Ocean. It occurs in the vicinity of the Pole near the 1000-m isobath and consists of ice which is several years old. In winter, the average thickness of undisturbed ice is about 3–4 m, but hummocks can increase the height locally up to 10 m a.s.l. In summer, the average thickness decreases to about 2.5 m. The Pack Ice lies outside the polar cap and covers about 25 % of the Arctic area. Its areal extent is greatest in May and lowest in September. The Fast Ice grows seawards from the coast to the pack. It is most often anchored to the shore and extends out to about the 20–30-m isobath. The Fast Ice occurs only in wintertime and its thickness reaches 1–2 m. Sea ice in the Arctic is continually in motion as a result of the effects of wind, tide, and ocean currents. The same factors create open-water areas known as leads and polynyas. Leads are cracks in the ice which are a few kilometres in width and tens of kilometres long, though which are often short lived. On the other hand, polynyas are large open-water areas in the frozen sea and range in size from a few hundred square meters to thousands of square kilometres. Polynyas appear in winter when the air temperature is well below the freezing point of seawater. The role of open-water areas in the Arctic climate system is sufficiently important to be studied more seriously by climatologists. Through these areas the Arctic surface loses huge amounts of heat because sea-surface temperature in winter can be up to 20 °C higher (as in the case of the so-called North Water polynya in the northern part of Baffin Bay) than that of the surrounding areas and because there is no sea-ice cover, which significantly reduces the heat exchange between the ocean and the atmosphere, as was mentioned above.

Another type of ice which occurs in the Arctic takes the form of icebergs and originates as a result of the "calving" of tidewater glaciers. Each year a highly variable number of these navigational hazards (about 1000 across the 55 °N latitude) move southward into the Atlantic together with the cold water of East Greenland and Labrador Currents.

Coachman and Aagaard (1974) distinguished three main water masses in the Arctic Ocean: the surface or Arctic Water from the sea surface to a depth of 200 m, the Atlantic Water from 200 to 900 m, and the Bottom Water below 900 m. For the study of the Arctic, climate knowledge of the Arctic Water is most important and this can be divided into three layers: the Surface Arctic, the Sub-surface Arctic, and the Lower Arctic Waters. The physical characteristics of these types of water masses are provided in Table 1.1 and Fig. 1.5. Surface waters extend from the surface to

Table 1.1 Arctic Sea water masses

Water mass	Properties				
Name (circulation direction)	Boundary depth	Temperature (T) and Salinity (S)			Seasonal variation
	Surface				
Arctic surface	25–50 m	T: Close to F.P., i.e. –1.5 to −1.9 °C S: 28–33.5‰			DT: 0.1 °C DS: 2‰
Arctic sub-surface	100–150 m	T: Canadian Basin −1 to −1.5 °C			Small
		Eurasian Basin −1.6 °C to 100 m, then increase			
		S: Both basins 31.5–34‰			
Arctic lower (all above masses circulate clockwise)	200 m	Intermediate between Sub-surface and Atlantic			
Atlantic (anticlockwise)	900 m	T: Above 0 °C (to 3 °C) S: 34.85–35‰			Negligible
Bottom (uncertain, small)	Bottom		2000 m	Bottom	(rise adiabatic)
		T: Canadian Basin	–0.4 °C	–0.2 °C	
		Eurasian Basin	–0.8 °C	–0.6 °C	
		S: Both Basins	34.90–34.99‰		

After Pickard and Emery (1982)

depths of about 25 and 50 m. Both the salinity and temperature of the water is strongly controlled by melting and freezing. As a result, the temperature oscillates near the freezing point of seawater, which varies only from −1.5 °C at a salinity of 28‰ to −1.8 °C at a salinity of 33.5‰. Throughout the year both salinity and temperature show rather small changes, which range up to 2‰ and 0.1–0.2 °C, respectively.

The surface water and sea-ice circulation in the Arctic has been largely known from the observed drift of camps on the ice, floe stations, and ships. The earliest information comes from the famous “Fram” drift (1893–1896) and from the icebreaker “Sedov” drift (1937–1940). Observational evidence together with theoretical calculations of upper-layer circulation based on water density distribution give a consistent picture of circulation in the Arctic (Fig. 1.6). In the Beaufort Sea, the surface waters have a clockwise movement in agreement with the anticyclonic pattern of blowing winds and lead out to the East Greenland Current. From the Eurasian side of the Arctic Ocean, the surface waters move towards North Pole and exit the Eurasian Basin as the East Greenland Current. This current is known as the Transpolar Drift Stream. The speeds of these waters are of the order of 1–4 cm/s (300–1200 km/year). It is worth to add here that a sea-ice circulation in the Arctic Ocean is similar to the described above circulation of the surface water currents.

The circulation of the Atlantic Water is basically counter-clockwise around the Arctic Ocean, i.e. in a direction opposite to that of the Arctic Water above it (Pickard

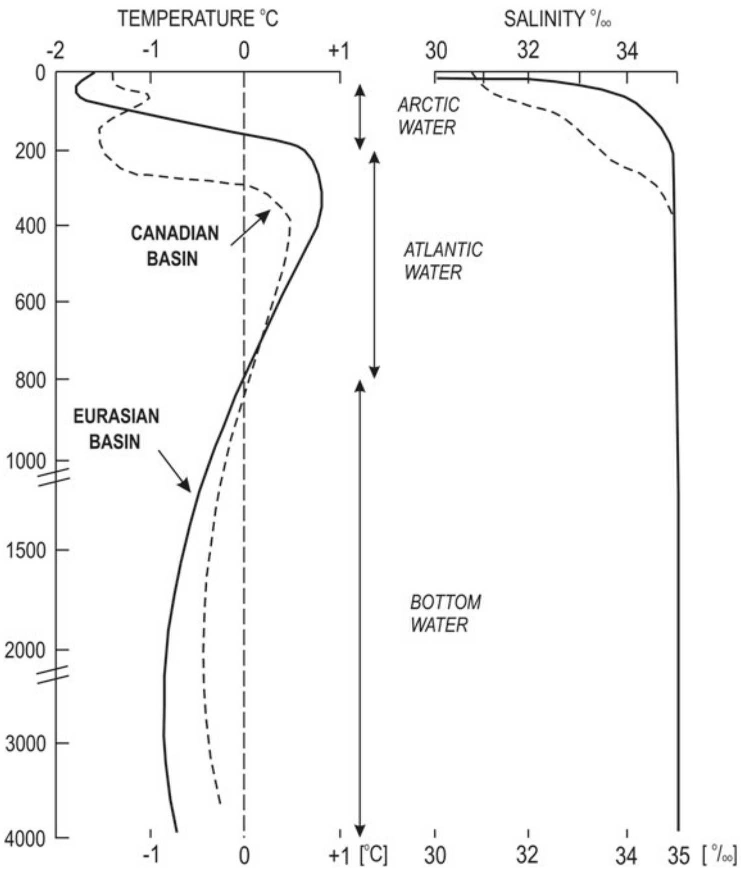

Fig. 1.5 Typical temperature and salinity profiles for the Arctic Sea (the Eurasian and Canadian basins) (After Pickard and Emery 1982)

and Emery 1982). The Atlantic Water (West Spitsbergen Current) enters the Eurasian Basin from the Greenland Sea and flows further east along the edge of the Eurasian continental slope. Some waters branch off to the north and leave the Arctic as part of the East Greenland Current. The remainder flow across the Lomonosov Ridge into the Canadian Basin. The mixed Arctic (East Greenland Current) and Atlantic (Irminger Current, south-west of Iceland) Waters mass round the southern tip of Greenland and reach the Labrador Sea. Further, they flow as the West Greenland Current to Baffin Bay. This inflow of water is balanced by the southward flow of the Baffin Island Current and Labrador Current. There is also evidence that significant quantities of water of Atlantic origin enter the Arctic Ocean via the Barents and Kara shelves, where they may be considerably modified. Some warm water comes to the Arctic from the Pacific through the Bering Strait (see Fig. 1.6). The principal outflows from the Arctic Ocean are through the Fram Strait and the Canadian Arctic Archipelago.

Fig. 1.6 Arctic Sea and North Atlantic adjacent seas: bathymetry and surface currents (After Pickard and Emery 1982)

According to research conducted by Alekseev et al. (1991), the advection of warmth from the lower latitudes supplies more than 50 % of the annual heat supply to the Arctic climate system. Most of this warmth (95 %) is, however, transported by atmospheric circulation, with the remainder (5 %) being transported by oceanic circulation (Khrol 1992, for details see Table 2.16 in Alekseev et al. 2003). However, as Alekseev et al. (2003) argue "…oceanic processes have a significant influence on

Arctic climate formation, which is not restricted to its direct contribution". In winter, during the polar night, only these two fluxes of warmth reach the Arctic and protect it from significant radiation cooling.

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