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The increase in the length of the ice-free season in the Arctic

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ABSTRACT

The length of the ice-free season and a variable designated by inverse sea ice index are used to quantify the rapid decline of the Arctic sea ice of the last decades. It is argued that for this purpose they are at least as suitable as the other variables more often found in the literature, namely the sea ice area and extent at the times of annual minimum. Daily sea ice concentrations obtained from satellite passive microwave imagery are used to calculate the length of the ice-free season and the inverse sea ice index in each point of the Arctic for each year between 1979 and 2008. Time-series for these two quantities are constructed and analysed to investigate how they have been varying in the last 30 years in 85 disjoint regions of the northern hemisphere. It is shown that between 1979 and 2006 the spatially averaged ice-free season in the Arctic increased at a steady rate of 1.1 days/year and that the growth was considerably faster (5.5 days/year), and monotonic, in the 2001–2007 period. In 2007 and 2008 the average ice-free seasons in the Arctic were 168 and 158 days long, respectively, making them the longest and the fourth longest since the beginning of the systematic satellite monitoring of the Arctic.

1. The decline of the Arctic sea ice

The unprecedented depletion of sea ice in large sectors of the Arctic Ocean in the summer of 2007, which followed the rapid, but steady, decline of the Arctic sea ice cover in the past few decades, has generated renewed interest in the possible causes behind such abrupt changes and prompted an effort to improve global climate models that aim to tell us what lies ahead for the Arctic. For instance, assuming that a negative trend is here to stay, we would like to know when the Arctic Ocean will be totally free of ice. However, the diversity of possible scenarios for the evolution of the concentration of greenhouse gases and the insufficient quantitative agreement between the predictions of the plethora of available climate models preclude, for the time being, a unique answer to this question. Of the models considered in the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR4) some point to an ice-free Arctic (at the end of the melt season) some time in the late 21st century while others predict that such situation will not occur before 2100, if at all (Stroeve et al., 2007).

The possibility of a much faster disappearance of the Arctic sea ice was first suggested by Holland et al. (2006) who found, on the basis of simulations from the NCAR CCSM model (Collins et al., 2006), that sharp reductions in the sea ice area might be common in the 21st century and that possibly we will see an almost totally ice-free Arctic in the month of September as early as 2040.

More recently, Maslowski et al. (2007b), who developed the high-resolution NPS coupled ice-ocean model (Maslowski et al., 2007a), showed that there is a high probability of an ice-free Arctic during the summer in the next few years. They also pointed out that the majority of climate models fail to incorporate some key aspects of the processes that drive the melting or advection of sea ice, leading to systematic errors in the estimates of the current and future rates of change of the Arctic sea ice area or extent (Maslowski et al., 2008). In fact, there are strong differences between the trends for the Arctic sea ice extent (which is the area limited by the 0.15 ice concentration contour) derived from the IPCC AR4 models and the ones actually observed. The latter show that the rate of change between 1979 and 2006 is approximately −9.1% per decade in September and −2.9% in March. The magnitude and plausible causes of such discrepancies can be found in Stroeve et al. (2007).

Many published studies tend to highlight the faster and more spectacular disappearance of the sea ice at the time of minimum ice cover, which normally occurs in mid-September, or to emphasise the loss of ice at very high latitudes (while the popular press seems to be more attracted by the prospect of the opening next summer of an ice-free channel extending from the Bering Strait to the North Pole, radically modifying the concept of Arctic travelling).

However, minimum values can be strongly affected by specific circumstances occurring in a comparatively short time interval. It was noticed, for instance, that in the summer of 2007 there were unusually clear skies over the Arctic Ocean which would have favoured a rapid melting and a particular wind pattern which would have led to a strong advection of the ice out of the Arctic Ocean through Fram Strait. These special conditions may partly explain the extraordinary depletion of sea ice in the Arctic Ocean in the summer of 2007. In 2008 the ice recovered just slightly from the losses of the previous melting season. It is perhaps worthwhile to recall that some sort of recovery also took place in the summer of 1996 after a big loss in the summer of 1995. For example, prior to 2005 the absolute minimum ice

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area in the Russian Arctic that occurred in September 1995 was followed by a record high (in the 1979–2008 period) for the month of September in 1996. However, there are no examples in recent history of recoveries immediately after a period of 6 years of sharp decline such as the one we have been experiencing since 2001. It is thus possible (or even likely) that we are entering a new phase characterised by a much higher rate of sea ice decline, in which case the particular weather conditions registered in the summer of 2007 would have had little effect on the small amount of ice in the Arctic.

In this paper, instead of limiting ourselves to the September minimum or the March maximum, we are going to consider the ice conditions throughout the year. This could be done, for instance, with a thorough analysis of the values of the ice extent and area month by month. However, we have opted for a different, less used, and hopefully more convenient approach.

In order to describe quantitatively the evolution of the sea ice situation in the Arctic Ocean and peripheral seas in the 1979–2008 period we have chosen as variables the length of the ice-free season and the inverse sea ice index which will be defined in the next section. The former also appears in the works of Parkinson (1994) and Laxon et al. (2003).

Although the rate of decrease of the total area covered by sea ice in the Arctic Ocean and, more generally, in the Arctic, is a good indicator of the global changes that we are witnessing in the high latitudes, it is also interesting to investigate what is happening at the regional level. For example, the channels across the Canadian Archipelago that form the Northwest Passage and the waters along the north coast of Russia known as the Northern Sea Route are especially relevant when considering the maritime transport between the Atlantic and the Pacific. Changes in the ice cover in oil rich areas such as the north coast of Alaska and the east coast of Sakhalin will attract the attention of the oil industry. Finally, the disappearance of the sea ice in Hudson Bay and other low latitude regions of the Canadian Arctic will strongly affect their wildlife.

For this purpose, we divide the Arctic in the 85 distinct regions shown in Fig. 1 and proceed to examine how the length of the ice-free season and the inverse sea ice index have been changing in each of them since 1979. We consider four sectors in the Arctic Ocean, four regions in the Baltic, seven in the European Arctic, 23 in the Russian Arctic, seven in the far east Russia and 40 in the Canadian Arctic. We do not include in our study points north of 86°N because of lack of complete satellite coverage during the period under study.

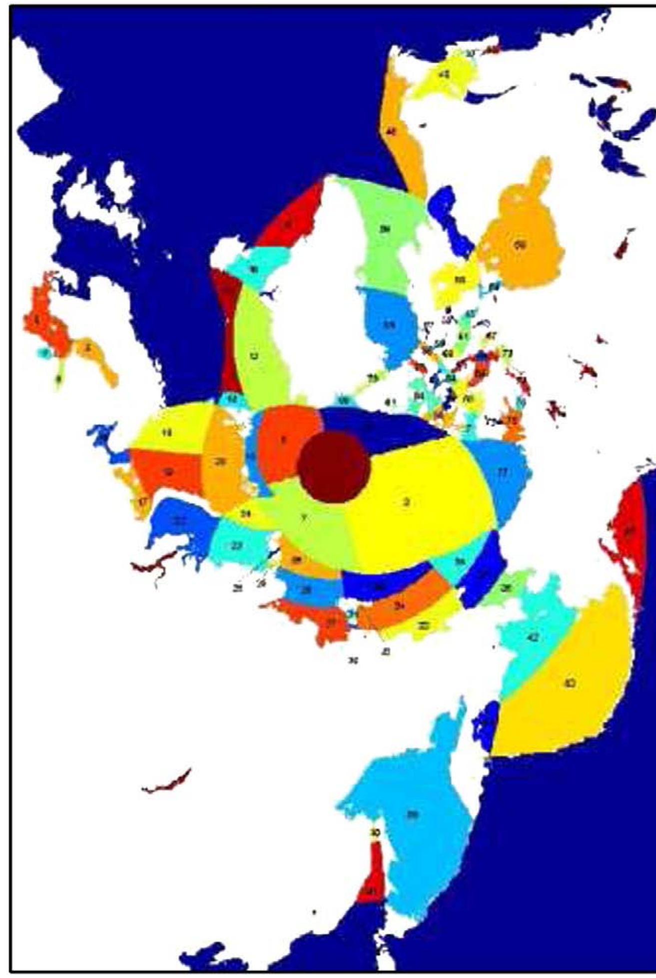

Fig. 1. The 85 regions of the Arctic.

2. The length of the ice-free season and the inverse sea ice index

Our study makes use of sea ice concentration data obtained from passive microwave satellite imagery and processed with the Bootstrap algorithm (Comiso, 1986, 1990, 1995) for the SMMR (02 January 1979 to 10 August 1987) and SSM/I (12 August 1987 to 31 December 2002) periods, and processed with the Enhanced NASA Team algorithm (Markus and Cavalieri, 2000) for the AMSR-E period (01 January 2003 to 31 December 2008). The concentrations thus calculated are projected onto polar stereographic grids whose equal-area cells have dimensions 25×25 km^2 for the SMMR and SSM/I data and 12.5×12.5 km^2 for the AMSR-E data. The final sea ice concentration data sets used here are Comiso (1999) for the SMMR and SSM/I periods and Cavalieri and Comiso (2004) for the AMSR-E period, both archived and distributed by the National Snow and Ice Data Center. For a recent overview on the retrieval of sea ice properties (such as ice area and extent and respective trends) from these satellite sensors see Comiso and Nishio (2008) and references therein.

The uncertainty associated with the sea ice concentrations derived with the Bootstrap algorithm from the raw SMMR and SSM/I data is estimated as 5–10% (Comiso, 1999). The general consensus is that the sea ice concentrations generated from the more modern AMSR-E sensors have a smaller uncertainty. For a summary of the error sources in the AMSR-E datasets see Cavalieri and Comiso (2004). For this reason, we chose to work with the AMSR-E data for 2003 to 2008. A combined analysis of the SSM/I and AMSR-E data for 2003 made by the author Rodrigues (2008) showed that the differences between the ice concentrations obtained from the two sensors are small (in general much smaller than the quoted error associated with the SMMR and SSM/I data). Thus, it is legitimate to expect that the consequences of the change of sensors between 2002 and 2003 will be negligible for the final results that we are about to present. This may not be the case, however, for narrow straits. These occupy only a small number of pixels in the 25×25 km^2 grid, most of them adjacent to land, and about four times that number in the 12.5×12.5 km^2 grid, where a smaller fraction of pixels will be adjacent to land. In these cases the well-known problem of land contamination in coastal regions (Comiso, 1999) may become significant and, consequently, some properties of the ice cover in narrow channels derived from satellite passive microwave imagery have to be taken with caution. Specifically, this effect may partly explain the occasional abrupt jumps observed in the time-series of some channels in the Canadian Archipelago from 2002 to 2003. This will be discussed later in this paper. For a discussion on the compatibility between the three data sets see Comiso and Steffen (2008).

We derive the length of the ice-free season (LIFS) and the inverse sea ice index (ISII) in each point for each year between 1979 and 2007 from the daily sea ice concentrations $\{C(y,d;i)\}$ for cell i on day $(y,d)\equiv(year, day)$. In order to minimise possible isolated errors in the recording of the concentrations by the sensors, we work with *smooth* ice concentration time series instead of the original ones. In each point i the former are obtained from the latter by replacing the value of the ice concentration for day d in the original time series for year y by the average of the concentrations over a five-day period centred on d.

We define the LIFS $L(y;i)$ at a certain point i in year y as the number of days between the clearance of the ice and the formation (more exactly, the appearance) of the ice in that point in that year. If the number of clearances and formations is larger than one the LIFS is defined as the sum of the lengths of all periods between an ice clearance and the following ice formation. If there is only one ice clearance and no ice formations the LIFS is given by the number of days between the date of ice clearance and the end of the year. If there is only one ice formation and no ice clearances the LIFS is given by the number of days from the beginning to the year until the date of ice formation.

The criteria to identify dates of ice clearance and ice formation are as follows. We assume that there is clearance on day d if the ice concentration is 0.15 or higher in days $d-4$, $d-3$, $d-2$ and $d-1$ and below 0.15 in days d, $d+1$, $d+2$, $d+3$ and $d+4$. We consider that there is formation on day d if the ice concentration is below 0.15 in days $d-4$, $d-3$, $d-2$ and $d-1$ and 0.15 or higher in days d, $d+1$, $d+2$, $d+3$ and $d+4$. With these criteria we ignore contributions from periods of less than 5 days without ice which lie between two periods of 5 days or more with ice, and from periods of less than 5 days with ice between two periods of 5 days or more without ice.

In a region $\mathcal{R}$ where ice has occurred in all points at least once in the 1979–2008 period (not necessarily at the same time) the LIFS $L(y,\mathcal{R})$ is, by definition, the spatially averaged LIFS over all points within that region. However, this definition appears inadequate for a small number of regions (such as the west Barents Sea and the south Bering Sea) which have portions of open water all year round. We find that the most convenient way to determine the evolution of the LIFS in such regions is to discard those portions where the LIFS is trivial and define $L(y,\mathcal{R})$ as the average over the points of $\mathcal{R}$ for which the LIFS is non-trivial.

The ISII $S(y;i)$ for point i in year y is given by

$$S(y;i) = 1 - \frac{\sum_{d=1}^{N} C(y,d;i)}{N},$$

where N is the number of days in the year. This quantity, which varies between zero (when there is a perennial ice cover) and one (when there is open water all year round), measures the absence of sea ice throughout the year, hence the name *inverse* sea ice index. The calculation of the ISII for a region $\mathcal{R}$ follows the rules described for the LIFS.

The functions $L(y;i)$ are not, in general, monotonic with y because sea ice distributions tend to exhibit large interannual fluctuations. In most cases, however, it will be possible to recognise long-term trends in the LIFS. This is best done by finding the linear fit to the graph of LIFS versus time with a linear least squares regression. In the process, we construct a set of new functions $L'(y;i)$, one for each pixel i, which vary linearly with y. In this paper the linear fit is calculated using data for the 1979–2006 period only and thus $L'(1979;i)$ and $L'(2006;i)$ which we call, respectively, *early* and *late* LIFS, are expected to give the approximate values of the LIFS around 1979 and 2006, respectively. Data points for 2007 and 2008 will illustrate how the ice situation in those years was in many instances quite diverse from what could be anticipated assuming the continuation of the same linear trend. We find that the most suitable quantity for studying the trends is $\Delta L'(i) \equiv L'(2006;i) - L'(1979;i)$. On the other hand, dL'/dt, measured in days per year (or, for short, d/y), is assumed to give the approximate rate of increase of the LIFS.

Given a finite region $\mathcal{R}$ and the observed values $L(y;\mathcal{R})$, we can also perform a linear regression to obtain $L'(y;\mathcal{R})$ and from this new function the *early*, *late* and the variation of the LIFS in that region as well as its typical rate of change. Thus, in the following sections, the term LIFS *variation* automatically refers to the variation of the LIFS between 1979 and 2006 upon linear regression.

The standard error of the linear approximation should give a first indication of the legitimacy of the linear fit. However, because a small value does not necessarily mean that all data points lie approximately in a straight line, other simple criteria must be met in order to ensure that the approximation is reasonable. For example, L' must be between zero and the number of days in the year. This is not always the case and, when it happens, it simply means that the time evolution of the LIFS is highly non-linear. Cases of strong non-linear increase abound in the Canadian Arctic, namely in regions which until a few years ago were permanently ice-covered but are now enjoying comparatively long ice-free spells. In these situations we refrain from quoting the values of $L'(1979)$, which would be negative, and of $L'(2006)$. Instead, we give the average values of the LIFS in the five-year periods 1979–1983 and 2002–2006.

A similar procedure is used to analyse the evolution of the ISII. Instead of the variation of S' between 1979 and 2006 we prefer to show its *relative change* defined by

$$\Delta' S' \equiv 100 \times \frac{S'(2006) - S'(1979)}{S'(1979)}. \tag{1}$$

It turns out that the ISII has a much more linear growth than the LIFS. This is a consequence of our definition of LIFS, which involves a lower cutoff of 0.15 in the ice concentrations and a required minimum period of 5 days without ice to contribute to the LIFS. As a result of the linearity of the ISII, S', averaged over each of the 85 regions, is always between 0 and 1 (and we will not need the help of the first and last five-year periods to quote reasonable values for the beginning and the end of the time-series), except in the Gulf of Alaska, for which the data imply a quite singular evolution.

3. Global changes

Fig. 2 shows the ISII distribution at the beginning and at the end of the 1979–2006 period, $S'(1979)$ and $S'(2006)$, respectively, as well as the distribution of the actually observed values in 2007, $S(2007)$. Similar figures for the evolution of the LIFS can be found in (Rodrigues, 2008).

Fig. 3, the result of adding all 85 regions together, shows that the LIFS increased almost 30 days between 1979 (early LIFS approximately 118.5 days) and 2006 (late LIFS close to 148.5 days), or 1.1 d/y. 2007 was overall the longest ice-free season on record with almost 168 days while 2008, with 158 days, ranked fourth. The shortest melting season was in 1982 (121 days). The increase has been much faster since 2001. We find that taking into account the seven-year period 2001–2007 the rate of increase was approximately five times that of the 28-year period.

Of all 85 regions considered, the LIFS increased in 83 of them, the exceptions being the East Coast of Kamchatka and the Gulf of Alaska. It is likely that the long-term trend for the former will soon become positive, in line with the rest of the Arctic. As for the latter, the results may have been strongly influenced by the reduced amount of ice that is normally found in the region and by the change of grid or sensor from 2002 to 2003. A small decline in the length of the melting season was also observed in other (more localised) places, notably on the southeast coast of Greenland near Kap Farvel, on stretches of the east coast of Novaya Zemlya, in the central part of the North Bering Sea and in some points of the Beaufort Sea.

In many areas $\Delta L'$ exceeded 100 days. The list of these depressing places (for the sea ice scientist) includes the sector of the Baltic Sea near the Gulf of Finland (140 days), the southern part of the Gulf of Bothnia (100 days), some areas of the Gulf of Finland (130 days), the Gulf of Riga as a whole (the region of the northern hemisphere with the highest rate of growth) and, specifically, its central part (above

140 days), some stretches of the east coast of Greenland (100 days), the waters of the Greenland Sea where the Odden ice tongue used to form (140 days), the north coast of Spitsbergen (130 days) and, to a smaller extent, that of Nordaustlandet, the White Sea (on average over 100 days, in some places 150 days), Pomarski Proliv, in the south Barents sea (100–120 days), specific areas in the east and north Barents Sea (120 days), the north coast of Alaska near Point Barrow (100–120 days), the Bay of Fundy (110–120 days), some areas of the Labrador Sea (120 days), Frobisher Bay and Cumberland Sound (100 days), north Baffin Bay (100–125 days) and the northwest sector of Foxe Basin (100 days).

In many parts of the Arctic, notably in the channels of the Canadian Archipelago, it is not possible to assign a constant (or approximately constant) rate of change because the recent ice conditions are totally diverse from those of three decades ago. Places like Admiralty Inlet, Committee Bay and Barrow Strait, among many others, which used to be ice-covered all year round, have been free of ice (at least partially) for long periods in recent summers.

The summer of 2007 deserves a special reference not only because it was overall the longest ice-free season in the Arctic but due to the non-zero values that existed at record high latitudes.

Table 1 summarises our results for the evolution of the LIFS in recent times in each of the sectors in which the Arctic can be divided as well as in the Arctic as a whole. The difference in the rate of increase in the periods 1979–2006 and 2001–2007 is evident in all sectors. The Russian Arctic appears as the sector where the changes are currently taking place at the fastest pace.

4. Regional changes

In this section we discuss the regional variations of the LIFS. We show maps with the early and late spatial distributions $L'(1979)$ and $L'(2006)$, and with the actually observed distribution L(2007, preferred to $L(2008)$ because in most regions the melting season in 2007 was longer than in 2008.

In Tables 2–11 we present the average values (in days) of the early, late, 2007 and 2008 LIFS, as well as the difference between 1979 and 2006 (upon linear regression), for each region of the northern hemisphere where sea ice is known to occur. The tables also show the corresponding values for the ISII, except that we prefer to show the relative (Eq. (1)) rather than the absolute change. We offer plots with time-series of the actually observed values of the LIFS for each year since 1979, together with the best linear fit (if the linear approximation is valid). In the text we identify the areas where the variations are greater.

The regions marked with an asterisk (*) in the tables are those for which the linear approximation for the LIFS is not valid. In these cases the values shown in columns one (two) refer to the average over the 1979–1983 (2002–2006) 5 year period. Because the ISII has a much more linear growth than the LIFS, the values quoted for the ISII are indeed those obtained for 1979 and 2006 upon linear regression for all regions with the exception of the Gulf of Alaska, which is signalled by a double asterisk (**).

The 85 regions cover essentially all points where sea ice can be found in the northern hemisphere, with the exception of the central part of the Arctic Ocean, where we assume that there is no ice-free season (at least for the time being).

In most instances the exact boundaries of the regions considered in this paper can be found in the Nautical Pilots published by the United Kingdom Hydrographic Office, in *Limits of Oceans and Seas* published by the International Hydrographic Organisation or, for the case of the Russian Arctic, in nautical charts provided by the Arctic and Antarctic

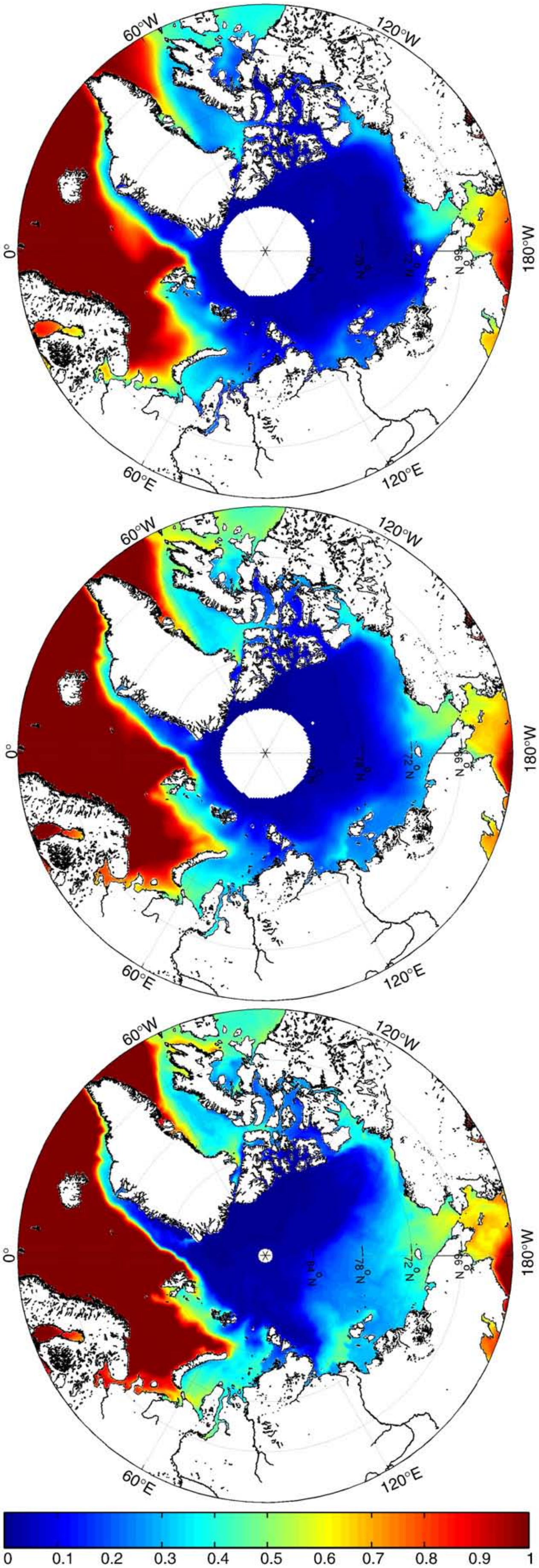

Fig. 2. Distributions of the inverse sea ice index in the Arctic: $S'(1979)$, top, $S'(2006)$, middle, and $S(2007)$, bottom.

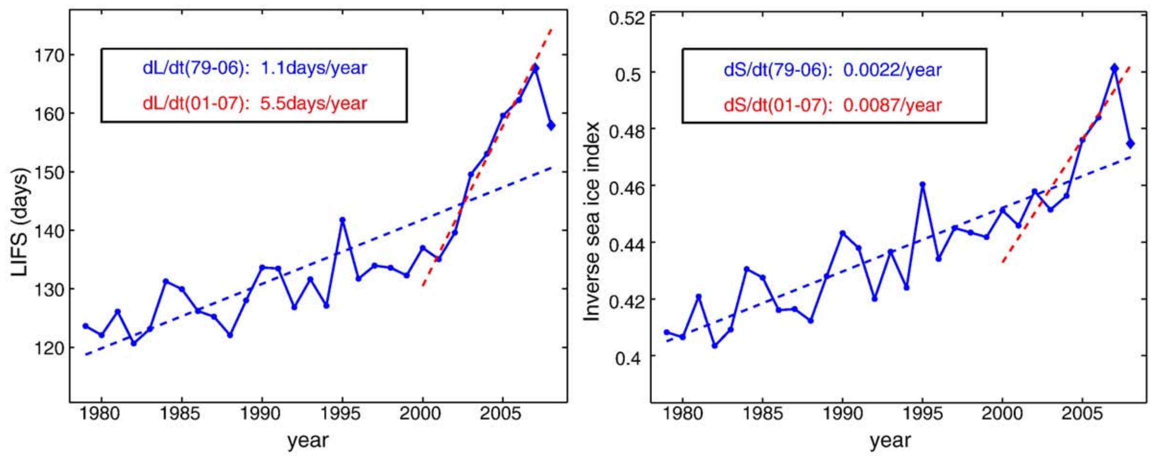

Fig. 3. Time-series of the length of the ice-free season (left) and inverse sea ice index (right) between 1979 and 2008.

Research Institute in St. Petersburg. The regions that were created arbitrarily (such as the separation of the Arctic Ocean in four sectors and the division of the seas of the eastern Russian Arctic in southern, mid-latitude and northern sectors) will be rigorously defined in due time.

4.1. Arctic Ocean

We divide the portion of the Arctic Ocean below 86°N in four sectors. Sector I lies between 30°W and 60°E, sector II between 60°E and 150°E, sector III between 150°E and 120°W, and sector IV between 120°W and 30°W. While all the sectors were entirely monitored by the satellites carrying the SSM/I and AMSR-E sensors, coverage of the very high latitudes was slightly irregular during the SMMR period. As a consequence, we were unable to determine the LIFS and the ISII in a comparatively small number of points (which, depending on the sector, occupy between one and five percent of its area).

Especially interesting are the recent transformations of the ice cover in sectors II and III. Other than in 2005 and 2007, the average ice-free season in sector II in the years between 1979 and 2008 was less than 5 days long. The majority of points in this sector have a permanent ice cover and more often than not no summer break-up occurred at all in this region. In 2005 the LIFS reached 13 days but it was in the summer of 2007 that its highest value was attained. In sector III the LIFS was essentially zero until 2006 (with the exception of 12 days in 1998). In 2007 it went up to 34 days (see Table 2), far and away the highest value of the time-series.

The contour map in Fig. 4 shows the LIFS distribution in sectors II and III of the Arctic Ocean, which gets its main contribution from the band of longitudes 120°E–160°W. We see that some points at latitudes higher than 83°N enjoyed ice-free seasons longer than 40 days and that there were areas beyond 84°N with ice-free spells of more than 20 days. The contours also show that open water was found as far north as 85°N.

4.2. Baltic

Ice formation has occurred during the period covered by this study in all points of the Gulf of Bothnia, Gulf of Finland, Gulf of Riga and Baltic Sea proper except in 1% of the area of the latter. The changes in the sea ice cover in some sectors of the Baltic region are among the most spectacular in the northern hemisphere, as shown by the remarkable increase in both LIFS and ISII, particularly in the Gulfs of Finland and Riga (see Table 3).

The largest variations in the LIFS in the Gulf of Bothnia are observed in its southern half, where, in some points, they exceeded 100 days. In its northernmost portion, where the ice conditions are often as severe as those found at much higher latitudes, the changes have been slower, with the increase of the LIFS typically below 30 days. In 2008 ice formation took place only in the northernmost sectors of the gulf and nowhere was it below 230 days.

The Gulf of Finland ranks third among the 85 regions in the rate of increase of the LIFS, with an average annual growth of 3.8 days. While in the innermost parts of the gulf the increase in the LIFS was between 80 and 90 days, in the other areas it was mostly in the range 100–130 days. 2008 was by far the mildest ice season on record. In this year ice formation occurred only in the innermost parts of the gulf (near St. Petersburg). By contrast, in 2007 (the second mildest season), only the portion near the junction with the Baltic Sea was free of ice all year round (a similar situation occurred in 1993, when the average LIFS in the gulf was 322 days).

The average ISII and LIFS in the Gulf of Riga have been changing faster than anywhere else in the northern hemisphere, with the latter growing at a rate of 4.1 d/y. The increase in the LIFS between 1979 and 2006 was more than 100 days almost everywhere in the gulf, reaching a maximum of 144 days in its central part. In recent years the central part of the Gulf of Riga has been ice-free essentially all year round (late LIFS close to 360 days). In 2007 a good portion of the gulf did not freeze at all and in 2008 ice only occurred in the northeast corner and

Table 1
Length of the ice-free season (in days) and its rate of increase (in d/y) in the different sectors of the Arctic.

Sector	$L'(79)$	$L'(06)$	$\frac{dL'}{dt}\big\|_{[79,06]}$	$L(07)$	$L(08)$	$\frac{dL'}{dt}\big\|_{[01,07]}$
Arctic Ocean	0	4	0.2	23	13	2.3
Baltic	292	342	1.9	350	360	3.4
European Arctic	165	210	1.7	213	220	2.8
Russian Arctic	75	121	1.7	164	141	10.5
Far East Russia	277	288	0.5	296	288	4.9
Canadian Arctic	109	148	1.5	159	154	4.7
Arctic	119	148	1.1	168	158	5.5

Table 2
Length of the ice-free season (in days) and inverse sea ice index in the Arctic Ocean.

	Sector	$L'(79)$	$L'(06)$	$\Delta L'$	$L(07)$	$L(08)$	$S'(79)$	$S'(06)$	$\Delta' S'$	$S(07)$	$S(08)$
1	Sector I	2	5	3	3	1	0.06	0.06	−2.0	0.04	0.02
2	Sector II*	0	3	3	22	4	0.03	0.04	23.4	0.10	0.03
3	Sector III*	0	6	6	34	22	0.03	0.05	80.7	0.14	0.10
4	Sector IV	0	0	0	0	0	0.03	0.01	−54.5	0.01	0.02

Table 3
Length of the ice-free season (in days) and inverse sea ice index in the Baltic.

	Region	$L'(79)$	$L'(06)$	$\Delta L'$	$L(07)$	$L(08)$	$S'(79)$	$S'(06)$	$\Delta' S'$	$S(07)$	$S(08)$
5	Gulf of Bothnia	243	316	73	328	349	0.74	0.91	22.6	0.92	0.97
6	Gulf of Finland	182	283	101	329	361	0.67	0.86	27.9	0.93	0.99
7	Gulf of Riga	204	315	111	344	361	0.72	0.92	28.2	0.97	0.99
8	Baltic Sea	336	364	28	364	365	0.96	1.00	4.3	1.00	1.00

in the straits between Saaremaa and Hiiumaa and the mainland. This is not exceptional: the LIFS was zero in 1992, 1993 and 1995.

The average ice season in the Baltic Sea proper is short, except in its northernmost areas. Yet, the average LIFS has increased approximately 1 day each year since 1979. The most noticeable variations occurred near the junction with the Gulf of Finland (100–150 days) and on the northwest coast of the island of Saaremaa (110–130 days). Less impressive, but still worth a mention, are the changes in and near the Gulf of Gdansk (around 65 days) and in some points of the coast of Lithuania (around 60 days). The Baltic (proper) was also totally free of ice in 1992, 1993 and 1995 (Fig. 5).

4.3. European Arctic

The seven regions in which we partition the European sector of the Arctic are shown in Table 4. In the sector as a whole the longest ice-free season was observed in 2004 (234 days).

The region referred to as *southeast coast of Greenland* (shown in red in Fig. 1) is bounded on the north by the line joining Kap Gustav Holm on the east coast of Greenland and Bjargtangar on the northwest coast of Iceland (which is also the southwest entrance of Denmark Strait), on the east by the line joining the latter point to Kap Farvel, and on the west by the east coast of Greenland between Kap Farvel and Kap Gustav Holm. Only 72% of the points of this region had at least one non-trivial ice season between 1979 and 2008 (and just 43% since 2003).

As a consequence of the existence of periods of short ice-free seasons (such as the early 1980s and the early 1990s) and periods of long ice-free seasons (the mid 1980s and 2003–2005, for instance), the average growth of the LIFS here is modest (less than 1 d/y). The longest and the shortest ice-free seasons occurred in 2003 (333 days) and in 1989 (222 days). This study shows a shortening ice-free season (by 30–60 days) in most points along the east coast of Greenland between Kap Farvel and 62°N but quite the opposite between 62°N and the entrance to Denmark Strait. Within the later range of latitudes the increase in the LIFS between 1979 and 2006 was mostly in the interval 20–40 days in the waters close to the coast but more likely to have been between 60 and 100 days in points 75–100 km away from the coast. The highest variations (100–120 days) were observed in the vicinity of (65°N, 38°W).

In Denmark Strait, whose northeast entrance is taken as the line joining Hrannhofnaragni (on the northeast coast of Iceland) to Kap Brewster (at the entrance of Scoresby Sund), the percentage of points with at least one non-trivial ice season is 98%. The evolution of the LIFS is similar to that of the previous region but with a higher rate of increase (1.4 d/y). The shortest melting seasons happened in 1981 (173 days) and 1989 (175 days), whilst the exceptionally mild ice conditions observed in 2003 and 2004 led to LIFS of 282 and 267 days, respectively, much above the linear trend for the 1979–2006 period. 2008 was the third longest ice-free season in the strait.

The changes in the LIFS in the Icelandic half of the strait are very modest (but positive), in accordance with the usually small amount of ice in these waters. The variations in the northwestern half, on the other hand, are much more significant: typically 30–60 days but reaching 100 days near the axis of the strait and even slightly higher values in the central part of the northeast entrance.

The LIFS in Denmark Strait increases almost linearly with the distance to the coast of Greenland. Currently it stands at around 80–90 days at the coast, 200–250 days at the axis of the strait and open water exists all year round well away from the coast of Iceland.

Let us now turn our attention to the Greenland Sea, which is well defined in the nautical charts, but not its division into west and east sectors. For the analysis presented here we considered the west Greenland Sea as the portion limited on the east by a line joining the northwest corner of Spitsbergen to a point approximately mid-way on the northeast entrance of Denmark Strait with coordinates (68°21′N, 18°54′E), on the south by the western half of the northeast entrance of Denmark Strait, on the west by the coast of Greenland between Kap Brewster and the mouth of Frederick Hyde Fjord (83°19′N, 26°00′E), and on the north by a line joining the latter point to the northwest corner of Spitsbergen. Most of the ice of the Greenland Sea is contained in this western half, where points with trivial LIFS in the last 30 years are rare.

The time-series of the LIFS for the west Greenland Sea shows a high interannual variability and an average increase of 2.1 d/y. The shortest melting season lasted just 81 days (in 1988) and the longest one (in 2004) was 187 days long. 2007 was the 9th longest in the 1979–2008 period (and the shortest since 2001), in agreement with observations of an unusually high amount of ice transported southwards from Fram Strait along the east coast of Greenland during the summer of that year.

Along the east coast of Greenland between Scoresby Sund and 75°N the LIFS increased non-linearly, making it impossible to define proper early or late LIFS. Hence, in order to give an idea of the changes in the ice conditions in the area, we quote the values of the average LIFS over the 1979–1983 and 2004–2008 periods. In the former the LIFS decreases northwards from 30–40 days in the vicinity of Scoresby Sund to values close to zero at 75°N. In the latter it also decreases northwards but now from approximately 80 days near Scoresby Sund to 20–40 days at 75°N. In the same band of latitudes but now excluding the points adjacent to the coast and including those whose distance to the coastline does not exceed 150 km, the temporal increase of the LIFS becomes approximately linear, from an early LIFS of around 10 days to a late one of around 65 days.

In the stretch of coast between 75°N and 78°N the increase in the length of the melting season is again non-linear. In the 1979–1983 period the LIFS was here close to zero but in the 2004–2008 period it averaged between 0 and 20 days in the southernmost points and was

Table 4
Length of the ice-free season (in days) and inverse sea ice index in the European Arctic.

	Region	$L'(79)$	$L'(06)$	$\Delta L'$	$L(07)$	$L(08)$	$S'(79)$	$S'(06)$	$\Delta' S'$	$S(07)$	$S(08)$
9	SE Greenland	259	284	25	293	288	0.83	0.86	3.8	0.86	0.84
10	Denmark Strait	197	234	37	235	255	0.68	0.73	6.9	0.71	0.75
11	Scoresby Sund	0	52	52	55	73	0.12	0.24	93.3	0.21	0.28
12	W Greenland Sea	101	157	56	148	167	0.45	0.54	17.8	0.48	0.52
13	E Greenland Sea	324	362	38	365	366	0.94	1.00	6.2	1.00	1.00
14	W Spitsbergen	244	299	55	357	353	0.83	0.91	10.0	0.99	0.98
15	N Svalbard and FJL	19	61	42	96	54	0.20	0.30	50.4	0.36	0.23

Table 5
Length of the ice-free season (in days) and inverse sea ice index in the Western Russian Arctic.

	Region	$L'(79)$	$L'(06)$	$\Delta L'$	$L(07)$	$L(08)$	$S'(79)$	$S'(06)$	$\Delta' S'$	$S(07)$	$S(08)$
16	White Sea	138	243	105	288	291	0.57	0.75	30.3	0.84	0.85
17	S Barents Sea	124	194	70	239	250	0.50	0.63	26.8	0.73	0.75
18	W Barents Sea	311	346	35	358	359	0.91	0.96	5.7	0.99	0.99
19	E Barents Sea	247	316	69	349	359	0.78	0.91	17.4	0.97	0.99
20	N Barents Sea	76	139	63	216	177	0.34	0.49	46.4	0.66	0.57
	Barents Sea	177	239	62	287	275	0.64	0.75	18.4	0.83	0.80
21	P. Karskiye Vorota	84	124	40	149	219	0.40	0.53	30.7	0.54	0.71
22	W Kara Sea	72	106	34	132	134	0.29	0.36	24.7	0.41	0.44
23	E Kara Sea	19	59	40	101	87	0.15	0.24	58.9	0.33	0.30
24	N Kara Sea	8	40	32	79	85	0.10	0.19	98.5	0.29	0.30
25	P. Borisa Vil'kitskogo*	0	19	19	33	47	0.10	0.15	60.7	0.18	0.18
26	P. Shokal'skogo	0	7	7	11	8	0.10	0.12	23.2	0.11	0.10
	Kara Sea	41	77	36	110	108	0.20	0.28	39.6	0.36	0.36

essentially zero near 78°N. On and near the coast of Greenland from 78°N to its northernmost point, including the long fjords of Peary Land, the ice cover normally persists all year round, with the interesting exception of the Northeast Water polynya, a clearly distinctive feature of the sea ice distribution in the north of the Greenland Sea (visible, for instance, in the bottom map in Fig. 6). In the last 5 years the average LIFS in some areas of the polynya exceeded 70 days and in 2008 open water remained there for over 100 days.

The most significant changes in the ice cover of the Greenland Sea took place in the area limited by the 72°N and 76°N parallels and the 0° and 18°W meridians. Here the average LIFS increased from 175 days in the late 1970s to the current 270 days. In some points of this area, namely in the vicinity of (76°30′N, 5°W), the difference between the late and the early LIFS reached 140 days, which puts this area among those of the northern hemisphere with the largest variations.

The eastern sector of the Greenland Sea, where the fraction of points with non-trivial LIFS is 0.84, has been totally or almost totally free of ice since 2002 (a situation that also occurred in other years, namely in 1984). One of the most interesting oceanographic features of the Greenland Sea is that protuberance clearly visible in the top map of Fig. 6, known as the Odden ice tongue. In recent years the Odden either failed to form or had a discrete presence, which explains the observed sharp increase in the LIFS in the points of the east Greenland Sea where the extremity of the Odden used to be.

The region designated by *west coast of Spitsbergen* is limited by the following lines: a line joining the northwest corner of Spitsbergen to position (78°00′N, 6°20′E) on the eastern boundary of the west Greenland Sea, a line drawing from the latter point to position (76°00′N, 10°00′E), and a line from the latter point to position (76°00′N, 17°30′E) at the western boundary of the Barents Sea.

The linear increase in the LIFS of the region over the 1979–2006 period was just over 2 d/y but in 2006, 2007 and 2008 the LIFS was far above the expected linear trend, with most of the region free of ice all year round. In 2007 and 2008 the only portion of this region with ice was the vicinity of the coast of Spitsbergen south of the entrance to Isfjorden.

What is called *north coast of Svalbard and Zemlya Frantsa Iosifa* in this paper is a region north of the Barents Sea (and, partially) of the Greenland Sea, bounded by the following lines: a line joining the northwest corner of Spitsbergen to position (80°30′N, 5°00′E) in the Arctic Ocean, a line joining the latter point to position (83°N, 70°E) near the northeast corner of Zemlya Frantsa Iosifa, and a line joining the latter point to the eastern extremity of Zemlya Frantsa Iosifa, on the coast of Ostrov Graham Bell, approximate position (81°N, 66°E). On the south this region is limited by the northern boundary of the Barents Sea. In spite of being technically part of the Arctic Ocean, it is appropriate to analyse this region separately due to its specific ice conditions. This is a region which is often free of ice in the summer and, recently, has enjoyed long ice-free spells in the winter (Fig. 7).

The LIFS in the last three decades oscillated between values close to zero (in 1980 and 1988) and above 100 days (in 1984, 2004 and 2006). Some of the most spectacular variations in the LIFS in the northern hemisphere are observed on and near the north coast of Spitsbergen and parts of the north coast of Nordaustlandet. In the waters within 120 km of the north coast of Spitsbergen we find an early LIFS of approximately 60 days and a late LIFS of around 190 days (250 days was the average for the 2004–2008 period, 287 days in 2006, 265 days in 2007 and 205 days in 2008). At the same time, the early LIFS on the north coast of Nordaustlandet climbed from about 25 days in the late 1970s to the typical present value of 120 days (160 days was the average of the last 5 years, 242 days in 2006, 175 days in 2007 and 113 days in 2008). In Zemlya Frantsa Iosifa the variations are much smaller, typically in the range 20–50 days in the waters surrounding the archipelago (with the largest differences found on the west side) and below 20 days in the channels between the islands.

Table 6
Length of the ice-free season (in days) and inverse sea ice index in the Eastern Russian Arctic.

	Region	$L'(79)$	$L'(06)$	$\Delta L'$	$L(07)$	$L(08)$	$S'(79)$	$S'(06)$	$\Delta' S'$	$S(07)$	$S(08)$
27	S Laptev	41	70	29	102	66	0.21	0.26	26.8	0.33	0.23
28	Mid-lat Laptev	18	58	40	84	43	0.14	0.22	50.6	0.28	0.17
29	N Laptev*	1	15	14	27	6	0.05	0.10	99.5	0.11	0.05
	Laptev Sea	22	51	29	75	41	0.14	0.20	42.8	0.25	0.16
30	P. D. Lapteva	22	51	29	93	68	0.15	0.23	54.1	0.29	0.23
31	P. Sannikova	20	53	33	87	66	0.15	0.23	56.2	0.28	0.22
32	P. Blagoveshchenskiy	0	47	47	74	58	0.11	0.22	101.2	0.27	0.22
33	S East Siberian	9	69	60	123	72	0.13	0.27	109.4	0.38	0.24
34	Mid-lat East Siberian	9	44	35	101	60	0.09	0.19	116.8	0.32	0.21
35	N East Siberian	2	29	27	91	57	0.06	0.14	139.2	0.29	0.20
	East Siberian Sea	7	46	39	103	63	0.09	0.20	115.6	0.32	0.22
36	S Chukchi	110	153	43	178	145	0.38	0.47	23.8	0.53	0.43
37	Mid-lat Chukchi	54	120	66	157	120	0.26	0.39	52.4	0.47	0.37
38	N Chukchi*	10	66	56	124	70	0.06	0.23	263.3	0.38	0.25
	Chukchi Sea	52	109	57	153	111	0.23	0.36	57.4	0.46	0.35

Table 7
Length of the ice-free season (in days) and inverse sea ice index in the seas of Far East Russia and in the Gulf of Alaska.

	Region	$L'(79)$	$L'(06)$	$\Delta L'$	$L(07)$	$L(08)$	$S'(79)$	$S'(06)$	$\Delta' S'$	$S(07)$	$S(08)$
39	Sea of Okhotsk	267	292	25	298	301	0.79	0.85	6.8	0.85	0.86
40	Strait of Tartary	151	179	28	197	206	0.53	0.58	9.6	0.60	0.62
41	Gulf of Tartary	306	324	18	332	336	0.90	0.92	3.1	0.93	0.94
42	N Bering Sea	224	227	3	245	220	0.70	0.69	−2.4	0.71	0.65
43	S Bering Sea	326	329	3	327	303	0.93	0.93	−0.1	0.92	0.86
44	E Kamchatka	296	281	−15	328	317	0.90	0.85	−5.0	0.93	0.90
45	Gulf of Alaska**	365	322	−43	302	310	1.00	0.92	−8.2	0.89	0.90

4.4. Western Russian Arctic

2007 was the year with the longest melting season in the Russian Arctic as a whole, with an average LIFS of 164 days. It is followed by 2005 (146 days), 2006 (144 days) and 2008 (141 days). 2007 was also the year when the LIFS reached a maximum in each of the five seas of the Russian Arctic. Because the disappearance of the sea ice in this sector seems to be accelerating, it is worth to consider separately the shorter and more recent period 2001–2007. Table 5 summarises the evolution of the LIFS and the ISII in the 11 regions (and two seas) of the Western Russian Arctic.

The average LIFS in the Barents Sea increased at a rate of 2.3 d/y from 1979 to 2006 and at a rate of 12.8 d/y from 2001 to 2007. We note that while 2007 was the longest ice-free season in the Barents Sea as a whole since 1979, this was not the case for any of its five subregions. The maximum LIFS occurred in 2008 in four of them, the exception being the northern Barents Sea, where the melting season in 2008 was substantially shorter than in the two previous years.

The White Sea exhibits the sharpest rise in the LIFS in the whole Russian Arctic, with an annual increase of 3.8 days between 1979 and 2006, only surpassed (among the 85 regions under consideration) by that of the Gulf of Riga (and the Bay of Fundy, though in the latter the amount of ice is almost negligible). In recent years the disappearance of the sea ice in the White Sea accelerated, leading to a stunning increase in the LIFS of 15.2 d/y during the 2001–2007 period. The most remarkable changes took place in the channel that links the White Sea to the rest of the Barents Sea, where the LIFS increased by as much as 150 days, one of the highest values in the northern hemisphere. In the margins of the White Sea the variation was typically 130–140 days while in its central part it tended to be in the interval 80–90 days (Fig. 8).

In the south Barents Sea, defined as the part south of the line that joins Mys Karin Nos (at the entrance of the White Sea) and Mys Kusov Nos (at the entrance of Proliv Karskiye Vorota), significant changes occurred more or less everywhere, leading to an average rate of increase of 2.6 d/y between 1979 and 2006. The variations were especially high in the passage between Malozemel'skaya Tundra and Ostrov Kolguyev (100–120 days) and in Cheshskaya Guba (60–80 days). 2008 and 2007 had the longest ice-free seasons, followed by 1995 (228 days), a year with an exceptional low amount of ice in the Russian Arctic.

The central-west Barents Sea is the portion of the Barents Sea south of 76°N and west of 39°50′E from where we only take into account points where ice existed at least once in the last 30 years (which constitute 65% of the area of this region). This is at the origin of the discrepancy between the values quoted in this paper and those found in (Rodrigues, 2008), where all points were used to calculate the average LIFS. Large fluctuations characterise the time evolution of the LIFS in this part of the Russian Arctic in the last decades. For instance, pronounced minima existed in 1979 (265 days), 1998 (298 days) and 2003 (292 days). The best linear fit to the time-series leads to an average increase of 1.3 d/y. Since 2005 the LIFS has been approximately 360 days, which suggests that the whole sector may soon become free of ice all year round.

The central-east Barents Sea is the subset of points of the Barents Sea that lie south of 76°N and east of 39°50′E (and that are not included in the south Barents). The LIFS time-series exhibits, again, strong fluctuations, from a minimum of 187 days in 1979 to a maximum of 359 days in 2008, passing through values close to 340 days in 1984 and 1995 and by a local minimum of 203 days in 1998. The linear growth is 2.5 d/y. The last four were the longest ice-free seasons. The fast increase in the LIFS took place nearly everywhere but especially in the region east of the line joining the westernmost point of Novaya Zemlya to position (76°N, 39°50′E). In this area the increase has been of the order of 80–100 days (above 100 days in some localised areas). In 2008 the whole sector was free of ice throughout the year with the exception of the points in the vicinity of the west coast of Novaya Zemlya and those near the boundary with the southern sector.

In the north Barents (the portion north of 76°N), the average increase in LIFS was 2.3 d/y. The shortest ice-free season was in 1982 (48 days) and the longest one in 2006 (226 days). In the region between 76°N and 77°N the mean increase in LIFS was higher than 100 days, reaching 120 days (one of the highest values in the whole Russian Arctic) in an area centred at approximately 77°N, 54°E.

We now turn our attention to the Kara Sea, in which we distinguish three sectors: the west Kara (the portion west of the line joining Mys Zhelaniya to Dikson), the east Kara (the portion east of the latter line and south of the line that joins Mys Zhelaniya to Mys Molotova), and the north Kara. To these we add Proliv Karskiye Vorota and the two main Severnaya Zemlya straits because, according to the Russian charts, they are technically part of the Kara Sea.

In the Kara Sea as a whole the LIFS increased at a rate of 1.3 d/y between 1979 and 2006, and at a rate of 8.2 d/y between 2001 and 2007. The longest ice-free season was 2007, closely followed by 2005 and 2008.

In Proliv Karskiye Vorota 2008 was by far the longest ice-free season on record, followed by 1995 (195 days) and 2006 (186 days). These values are to be contrasted with the lows of 1998 (18 days) and 1999 (26 days).

Table 8
Length of the ice-free season (in days) and inverse sea ice index in the Atlantic sector of the Canadian Arctic.

	Region	$L'(79)$	$L'(06)$	$\Delta L'$	$L(07)$	$L(08)$	$S'(79)$	$S'(06)$	$\Delta' S'$	$S(07)$	$S(08)$
46	Gulf St Lawrence	264	301	37	319	298	0.81	0.88	8.3	0.92	0.87
47	Northumberland St.	231	270	39	272	255	0.69	0.80	15.2	0.81	0.78
48	Bay of Fundy	221	339	118	333	337	0.71	0.97	35.7	0.96	0.97
49	W Labrador Sea	227	278	51	277	264	0.73	0.83	13.5	0.82	0.78
50	Davis Strait	191	243	52	250	223	0.62	0.73	16.9	0.73	0.66
51	Baffin Bay	78	114	36	126	123	0.31	0.38	22.5	0.39	0.38

Table 9
Length of the ice-free season (in days) and inverse sea ice index in the Eastern Canadian Arctic.

	Region	$L'(79)$	$L'(06)$	$\Delta L'$	$L(07)$	$L(08)$	$S'(79)$	$S'(06)$	$\Delta' S'$	$S(07)$	$S(08)$
52	Hudson Strait	103	165	62	171	163	0.41	0.54	34.0	0.53	0.50
53	Hudson Bay	119	155	36	155	158	0.41	0.48	17.5	0.46	0.47
54	Roes Welcome Snd*	26	114	88	116	127	0.20	0.39	93.7	0.38	0.40
55	Fury and Hecla St.*	5	63	58	101	82	0.16	0.26	64.3	0.33	0.28
56	Foxe Basin	40	96	56	104	94	0.23	0.35	50.9	0.34	0.31
57	Eclipse Sound*	0	50	50	72	70	0.07	0.18	164.2	0.24	0.24
58	Lancaster Sound*	9	96	87	119	95	0.22	0.34	54.5	0.38	0.30
59	Admiralty Inlet*	0	56	56	86	79	0.09	0.22	154.3	0.28	0.27
60	Prince Regent Inlet*	3	50	47	92	53	0.13	0.24	80.6	0.28	0.22
61	Gulf of Boothia	0	31	31	67	60	0.08	0.18	129.1	0.24	0.22
62	Committee Bay*	0	8	8	64	76	0.03	0.12	256.3	0.22	0.25
63	Pelly Bay*	0	45	45	82	91	0.04	0.18	373.3	0.27	0.29

In the west Kara the increase in the LIFS has been quite steady, with the exception of a pronounced dip in 1999 (40 days). 2005, 2007 and 2008 were the longest ice-free seasons. In the area south of the line joining Ostrov Shokal'skogo and Dikson the typical increase was 50 days, reaching 80 days in the vicinity of Dikson. Near Mys Zhelaniya and in Baydaratskaya Guba the growth was between 60 and 80 days. The increase was minimal on most points of the east coast of Novaya Zemlya, where we can actually find places in which the LIFS decreased, a rarity in the Russian Arctic.

But it is in the east Kara that the most visible changes took place. In the central part of this sector the increase in LIFS was 50–60 days, along the coast between Dikson and the entrance to the Severnaya Zemlya straits was around 40 days, and in the area southwest of the Severnaya Zemlya archipelago was slightly negative.

The evolution of the LIFS in Proliv Borisa Vil'kitskogo was highly non-linear. Prior to 1995 the strait had a perennial (or almost perennial) ice cover but since 1995 there was an ice-free period almost every year and since 2005 that period has always exceeded 30 days. The highest values of the LIFS were 48 days in 2005 and 47 days in 2008. In Proliv Shokal'skogo ice-free periods longer than 5 days were only observed in 1985, 1995 (35 days, by far the longest ice-free spell in the strait) and in 2005–2008. Among the 23 regions of the Russian Arctic considered in this study, Proliv Shokal'skogo is the one where the ice conditions have been improving at the slowest pace.

4.5. Eastern Russian Arctic

In the Laptev Sea as a whole the LIFS grew at the pace of 1.1 d/y from 1979 to 2006 and 8.75 d/y from 2001 to 2007. The longest melting seasons happened in 1995 (78 days), 2005 and 2007 (both with 75 days), while the shortest ones were registered in 1996 (5 days) and 1979 (6 days).

The LIFS increased particularly fast in the mid-latitude sector, which is defined as the portion between the 75°N and the 78°N parallels. The largest values of $\Delta L'$, as high as 70 days, were observed in the waters north of the Lena Delta and in those near the northwest coast of Ostrov Kotel'nyy. Variations above 60 days occurred on most points of the direct route between these two regions. On the other hand, on the route from Proliv Borisa Vil'kitskogo to the north of Novo Sibirskiye Ostrova they were mostly between 40 and 60 days. Near the northeast coast of Poluostrov Taymyr the rise in the LIFS was generally between 40 and 50 days but higher than 50 days near Proliv Borisa Vil'kitskogo. A clear increase in the LIFS also took place in Khatangskiy Zaliv (50 days in the head of the bay) (Fig. 9).

In the north Laptev Sea there are no records of LIFS higher than 10 days before 1990, whereas after that year such values were often surpassed (51 days in 1995 and 41 days in 2005, for instance). In 2007 the LIFS was around 160 days on the corridor between the Lena Delta and the northwest coast of Novo Sibirskiye Ostrova (which is the part of the Laptev Sea that normally enjoys the longest ice-free periods). In this area the early and late LIFS are of the order of 35 and 90 days, respectively, which is indicative of the exceptional ice conditions of the summer of 2007.

The annual growth of the LIFS in the East Siberian Sea was 1.4 days in the 1979–2006 period and 10.8 days from 2001 to 2007. Its longest melting season since 1979 was (by far) the summer of 2007, followed by those of 1990 (80 days) and 2005 (75 days). By contrast, the average LIFS in 1979 and 1996 were 2 and 3 days, respectively. 2007 was also the longest ice-free season in each of the three sectors of the East Siberian Sea and in each of the straits that connect it to the Laptev Sea.

It is in the southern sector (the portion south of 72°N), particularly in a band 50–150 miles that stretches along the coastline from 162°E to the western entrance of Proliv Longa, that we find the most important variations in the LIFS. Here they were normally between 60 and 80 days but attained values in the interval 80–90 days in the proximity of the north coast of Ostrov Ayon as well as in the vicinity of

Table 10
Length of the ice-free season (in days) and inverse sea ice index in the Western Canadian Arctic.

	Region	$L'(79)$	$L'(06)$	$\Delta L'$	$L(07)$	$L(08)$	$S'(79)$	$S'(06)$	$\Delta' S'$	$S(07)$	$S(08)$
64	Barrow Strait*	0	30	30	78	53	0.10	0.17	63.9	0.26	0.21
65	Peel Sound*	0	19	19	70	64	0.08	0.15	76.6	0.24	0.24
66	Larsen Sound	1	21	20	63	60	0.11	0.16	47.5	0.23	0.23
67	Rasmussen Basin*	0	49	49	74	78	0.10	0.22	117.8	0.25	0.27
68	Viscount Melville Snd*	1	5	4	30	18	0.07	0.10	49.9	0.14	0.12
69	McClintock Channel*	2	8	6	52	21	0.08	0.11	35.4	0.20	0.14
70	Victoria Strait*	3	34	31	67	71	0.12	0.19	63.2	0.24	0.25
71	McClure Strait	0	4	4	40	45	0.08	0.09	15.5	0.17	0.20
72	Prince of Wales St.*	0	54	54	56	90	0.10	0.22	116.9	0.22	0.31
73	Queen Maud Gulf*	3	62	59	86	85	0.15	0.26	78.6	0.28	0.28
74	Coronation Gulf*	0	74	74	94	97	0.15	0.29	86.2	0.30	0.31
75	Dolphin Union St.*	0	73	73	102	113	0.14	0.30	106.6	0.32	0.36
76	Amundsen Gulf	53	95	42	124	144	0.27	0.35	29.9	0.38	0.43
77	Beaufort Sea	23	45	22	69	94	0.16	0.20	27.8	0.26	0.32

Table 11
Length of the ice-free season (in days) and inverse sea ice index in the Northern Canadian Arctic.

	Region	$L'(79)$	$L'(06)$	$\Delta L'$	$L(07)$	$L(08)$	$S'(79)$	$S'(06)$	$\Delta' S'$	$S(07)$	$S(08)$
78	Jones Sound*	0	45	45	62	62	0.16	0.21	26.4	0.24	0.24
79	Nares Strait*	0	12	12	20	27	0.10	0.11	15.3	0.16	0.14
80	Lincoln Sea	0	0	0	0	0	0.03	0.02	−46.9	0.01	0.02
81	Nansen Sound*	0	10	10	9	18	0.04	0.07	66.4	0.08	0.11
82	Wellington Channel*	0	31	31	62	30	0.11	0.17	57.3	0.23	0.16
83	Byam Martin Channel*	1	5	4	17	9	0.07	0.09	19.6	0.09	0.08
84	Queen Elizabeth A. E*	0	3	3	8	9	0.06	0.07	19.0	0.07	0.08
85	Queen Elizabeth A. W*	0	0	0	3	3	0.04	0.05	11.5	0.04	0.04

Proliv Longa. In the strait itself the rise was between 60 days (at the eastern entrance) and 90 days (at the western entrance). Partly because of these extraordinary changes, the rate of increase of the LIFS in the southern sector was about twice that of the whole East Siberian Sea. In 2007 the average LIFS in the points that form this band was around 150 days, whereas in 2008 (which was an ordinary season in the southern sector, well below the average of the last 7 years) it was just 80 days. We remark, however, that in this area the early LIFS was, on average, just a few days.

The other region with significant changes in the LIFS is the northern coast of Novo Sibirskiye Ostrova (part of what we define as the northern sector of the sea, which is the portion north of 75°N), where the average increase was 50–70 days.

We notice that in 2007 the LIFS had non-zero values in all points of the East Siberian Sea, including those at the northern boundary, which is the line drawn from position (79°N, 139°E) to position (76°N, 180°). This is equivalent to say that the ice edge at the time of minimum extent was located north of that boundary. In fact, the ice edge in September 2007 was far beyond this boundary. That was not the case in the summer of 2008, when some ice persisted north of the Novo Sibirskiye Ostrova at latitudes lower than 79°N.

Of the seas of the Russian Arctic, it was in the Chukchi Sea (and in the Barents Sea) that the fastest changes in the LIFS of the last three decades were observed. From 1979 to 2006 its rate of growth was 2.1 d/y while in the 2001–2007 period it was about five times this value. The longest melting season happened in 2007, and was followed by the ones of 2005 (127 days) and 2003 (126 days). In 1983 the melting season lasted only 33 days (Fig. 10).

In the southern sector of the Chukchi Sea (the portion south of 69°N) the changes are comparatively modest. We note that the LIFS has increased by about 33 days in Bering Strait (to the current value of around 180 days) and by 50–70 days along the coast of Russia between the eastern entrance of Proliv Longa and the northern entrance of Bering Strait.

In the mid-latitude sector the growth has been 2.4 d/y, the highest in the eastern Russian Arctic (see Table 6). The maximum of 2007 (157 days), is to be contrasted with the minimum of 28 days in 1983. The most striking changes in this sector (and, in fact, in the whole Chukchi Sea) took place on the north coast of Alaska between Point Lay (69°45′N, 163°00′W) and Point Barrow, a region where the ice-free season grew by an average of 95 days (120 days in some stretches of the coast), from approximately 30 days in the late 1970s to 125 days at present.

In the north Chukchi (the portion north of 72°N) the LIFS was frequently below 10 days between 1980 and 2001. In 2002 it jumped to 48 days and attained a maximum of 124 days in 2007. This is indicative of two different ice regimes, the first one from 1979 to 2001, characterised by very short melting seasons, and the second one between 2002 and 2008, with an extremely fast increase in the length of the melting season.

4.6. Far East Russia and Gulf of Alaska

This part of the world contains the only significantly large regions where sea ice appears to be on the increase. This singular behaviour had already been noticed in e.g. (Rodrigues, 2006), where it was reported that a southwards shift of the winter ice edge led to a net increase in the winter ice area and extent in the Bering Sea between 1979 and 2003. As we show below, a somewhat similar pattern is found when the LIFS is used to estimate the amount of sea ice.

In the Sea of Okhotsk the LIFS has been increasing at a pace of 0.9 d/y. The shortest melting season was observed in 1979 (238 days) and the longest one in 2006 (308 days). In the most severe ice seasons of the 1970s and 1980s the Sea of Okhotsk would be almost entirely

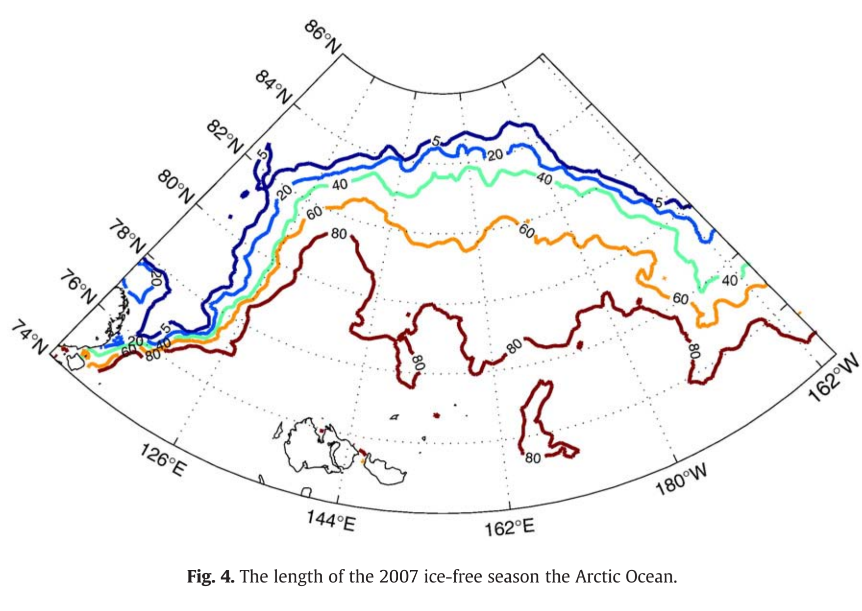

Fig. 4. The length of the 2007 ice-free season the Arctic Ocean.

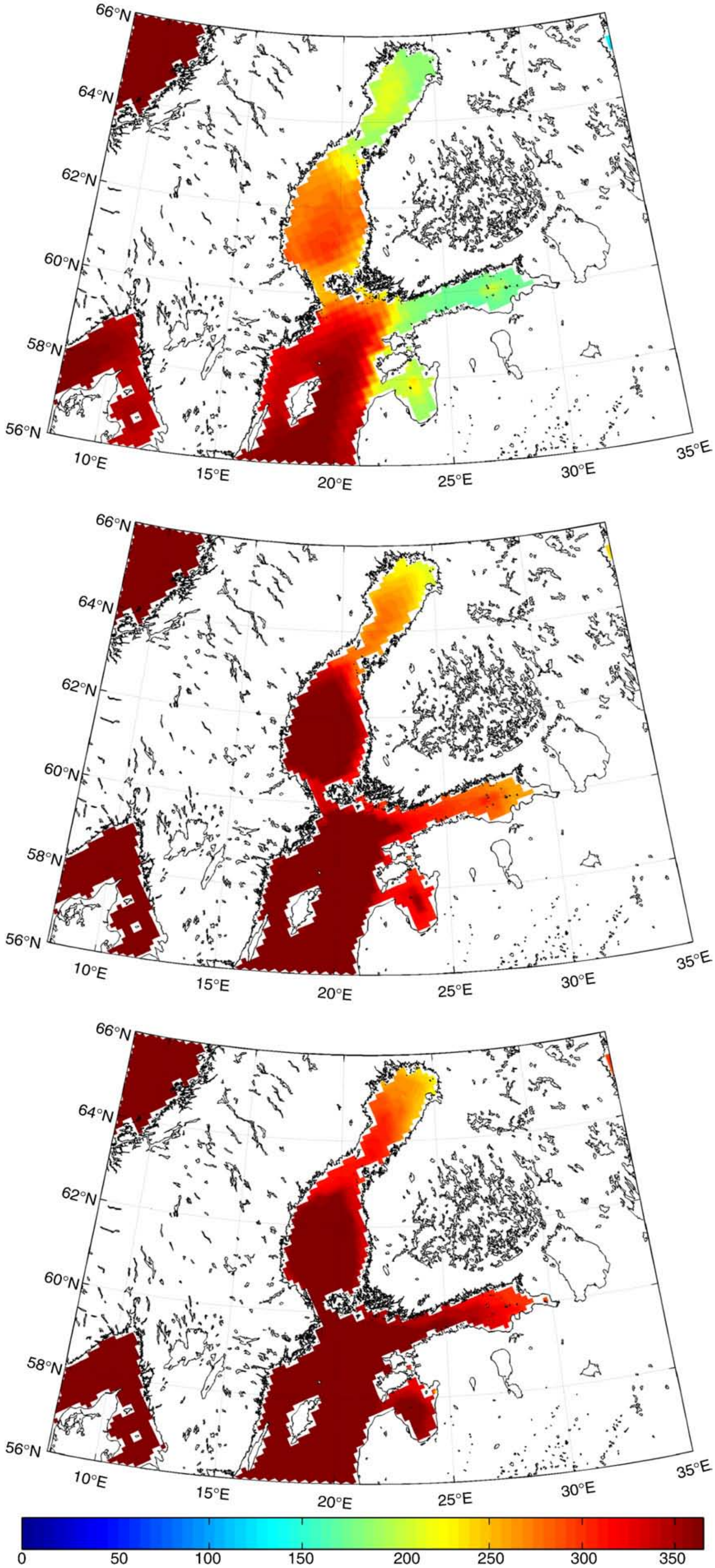

Fig. 5. Distributions of the length of the ice-free season in the Baltic: $L'(1979)$, top, $L'(2006)$, middle, and $L(2007)$, bottom.

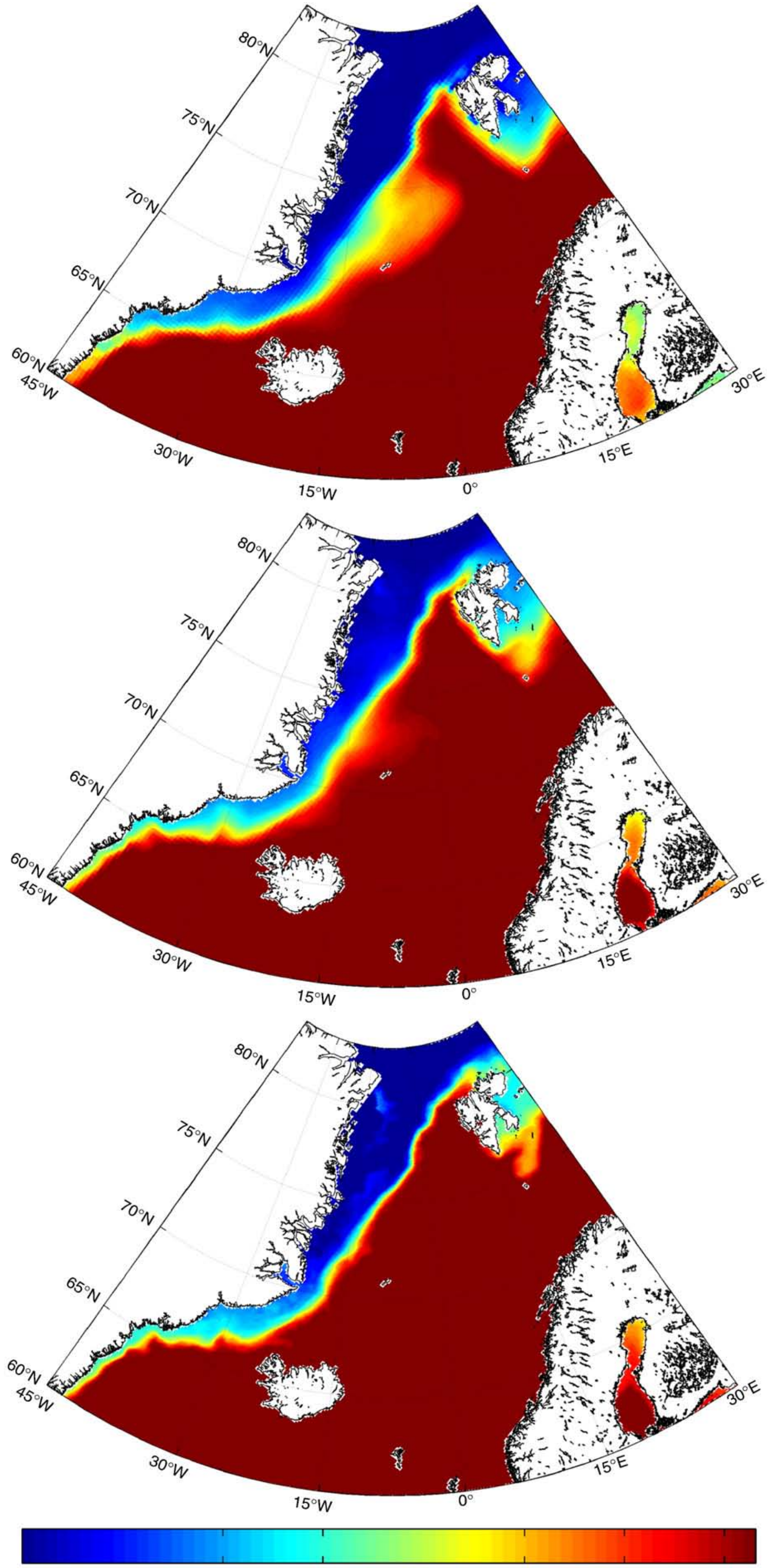

Fig. 6. Distributions of the length of the ice-free season in the European sector of the Arctic: $L'(1979)$, top, $L'(2006)$, middle, and $L(2007)$, bottom.

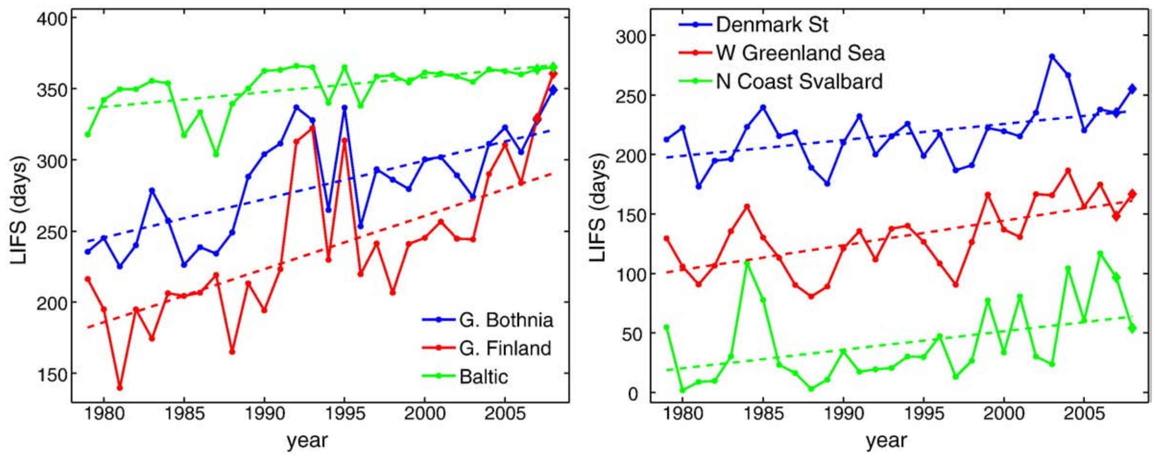

Fig. 7. Time series of the length of the ice-free season in selected sectors of the Baltic (left) and the European Arctic (right).

covered with ice for some weeks, with open water found only in the vicinity of the Kuril Islands (corresponding to non-trivial LIFS in 99% of the points). In the past 6 years, however, the maximum monthly averaged ice-covered area, which occurred in March 2003, was less than two thirds of the total area of the sea.

The largest variations in the LIFS, 60–80 days, took place in the central part of the northern half of the Sea of Okhotsk. In the southern half they were typically 30–50 days and considerably smaller along the shores (Fig. 11).

On the north coast of Hokkaido the current LIFS stands at around 300 days, an increase of 20–25 with respect to the early values. On the east coast of Sakhalin the variations are negative in Zaliv Terpeniya (around 20 days) and negligible south of this bay. They are also negative (but just minus 5 days, on average) in points along and near the coastline between the latter bay and the town of Okha at the northern tip of the island. Along the east coast of the island the current LIFS decreases slightly northwards, from around 220 days just north of Zaliv Terpeniya to around 200 days on the stretch north of Okha.

The most significant variations of the LIFS on the long stretch of the coast of Russia between the northern entrance of the Strait of Tartary and the entrance to Zaliv Shelikova were on the westernmost points of the Sea of Okhotsk, namely in the passage between Shantarskiye Ostrova and mainland Russia. Here the LIFS is now 180–190 days, 30–35 days higher than three decades ago. On the rest of the coast the variations were more modest, typically under 20 days. In Zaliv Shelikova the ice-free season grew by 20–30 days (50–70 days in the central part of Penzinskaya Guba) in the past three decades, and its current average is around 230 days.

In this paper we consider that the north and south sectors of the Bering Sea are divided by the line joining Mys Ol'utorskiy (59°55′N, 170°17′E) on the coast of Russia to the western extremity of Nunivak Island (60°13′N, 167°26′W), thence the north coast of this island, thence the northern entrance of Etalin Strait which meets the coast of Alaska at (60°34′N, 165°25′W). The northern sector is almost totally covered with ice at the time of maximum extent and has no points with trivial LIFS. In the south sector the ice conditions are much milder and the points with non-trivial LIFS cover just 36% of its area.

The LIFS in the northern sector had large fluctuations in the last 30 years, its time-series exhibiting sharp local maxima in 1979 (252 days), 1996 (251 days) and 2003 (254 days) and local minima in 1994 (202 days) and 1999 (192 days). The attempt to fit a linear evolution results in an almost horizontal line, the positive variations being essentially cancelled by the negative ones.

The largest positive variations were 40 days in the innermost points of Norton Sound, 20–30 days in some points of Anadirskiy Zaliv and 20–25 days in the area north of St. Lawrence Island. In the latter region the current LIFS stands at 190–200 days. A small decrease in the LIFS occurred in large areas of the central part of the north Bering, more pronounced in those just above the 60°N parallel.

The ice conditions in the portion of the south Bering Sea where ice formation has occurred in the past 30 years have been irregular. Consequently, no significant trends could be derived from the data. The shortest ice-free season occurred in 1999 (302 days) and 2008, while the longest were 2003 and 1979, both with 349 days. It is interesting to note that the last three melting seasons were shorter than the 30 year average. The most significant growth happened in Bristol Bay (40 days in some points), but was accompanied by a decrease in the neighbouring Kuskokwim Bay and in some points near the boundary with the northern sector (Fig. 12).

The region designated here by East Coast of Kamchatka is formed by the waters west of the line joining Mys Ol'ntorrkig to Mys Kamchatskiy. Though technically part of the Bering Sea, its specific ice conditions suggest that it should be considered separately. The southern half of the east coast of the peninsula will not be included in our study because the quantity of ice that can be found here is negligible.

With the exception of the Gulf of Alaska (whose singular evolution of the LIFS makes it a class of its own), this is the only region of the 85 considered in this study where there was a decrease in the average LIFS (cf. Table 7). However, we note that due to the large oscillations in the time-series the linear fit may be inappropriate. In fact, the negative linear trend of just −0.6 d/y is most likely to be a consequence of the big dip in the time-series between 1998 and 2001, with the minimum of 236 days reached in 2000. Since then the ice cover appears to have been decreasing quickly, and 2007 and 2008 were the longest and third longest melting seasons, respectively. We also observe a small increase of 10 days between the average LIFS in the first and in the last 5 years of the 1979–2008 period.

The results obtained for the Gulf of Alaska presented a challenge to the author, who defers to a future paper a more satisfactory analysis, which will include other sources of sea ice concentrations. They suggest that there was no ice in the gulf during the entire SMMR and SSM/I periods and some ice (in 8% of the points) in the 6 years of the AMSR-E period. It is not possible to assign a linear trend to either the LIFS or the ISII. Instead, in Table 7 we offer the values of the average LIFS and ISII over the 1979–1983 and 2002–2006 periods (which is signalled by the double asterisk). Of the six non-trivial ice-free seasons, 2007 was the shortest and 2003 was the longest (317 days).

4.7. Atlantic Canadian Arctic

The set of six regions found in Table 8 forms what we shall call the Atlantic sector of the Canadian Arctic. In truth, the top four can hardly

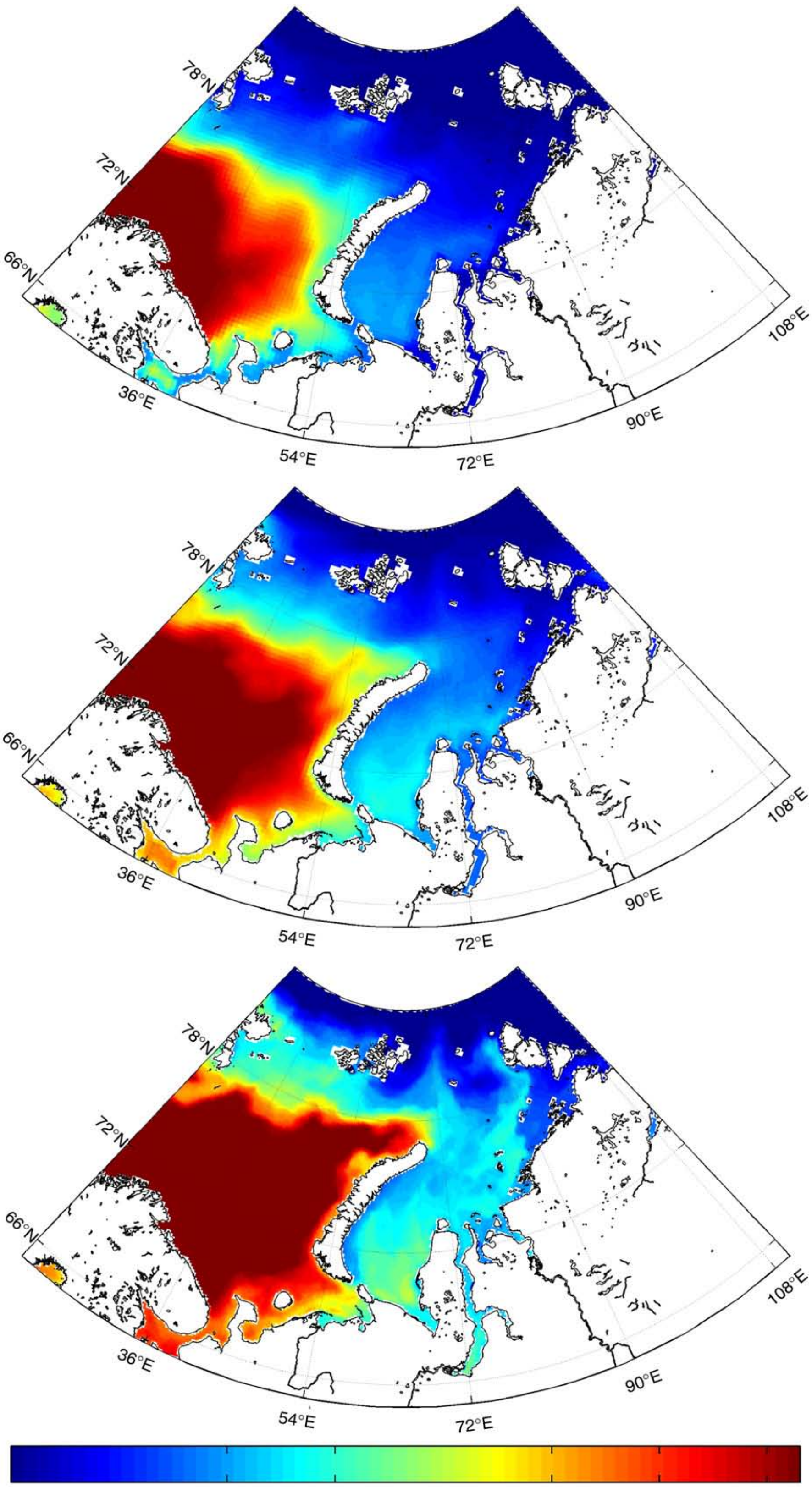

Fig. 8. Distributions of the length of the ice-free season in the Western Russian Arctic: $L'(1979)$, top, $L'(2006)$, middle, and $L(2007)$, bottom.

be considered part of the Arctic but because they normally exhibit a significant ice cover in the winter months they give a non-negligible contribution to quantities such as the global winter ice area and the average LIFS in the northern hemisphere.

The comparatively low rate of increase of the LIFS in the Gulf of St Lawrence (1.4 d/y) is partly explained by an unusual feature in its LIFS time-series: a big trough in the late 1980s and early 1990s. It was observed that the LIFS decreased nearly monotonically from 316 days in 1981 to a

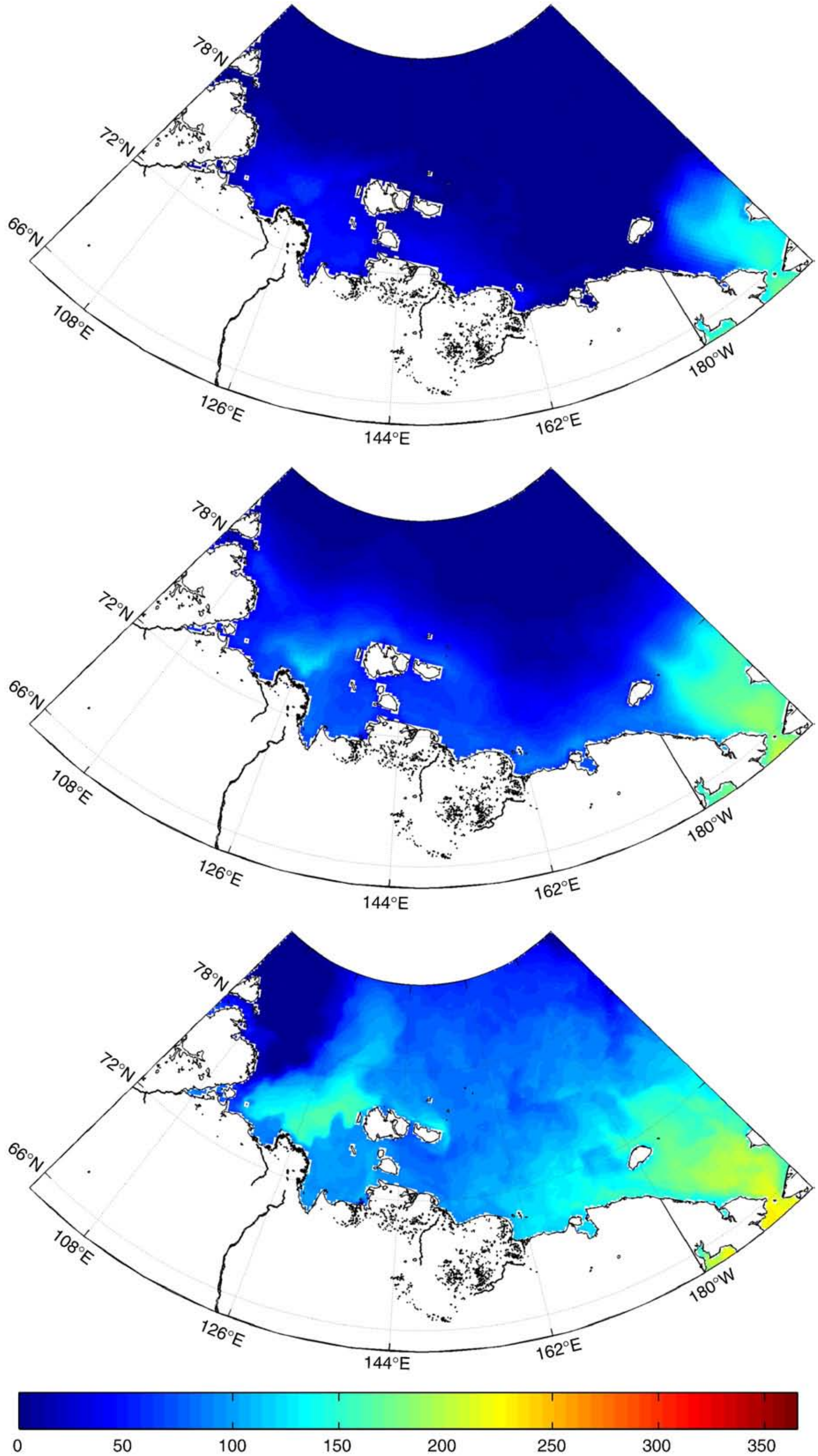

Fig. 9. Distributions of the length of the ice-free season in the Eastern Russian Arctic: $L'(1979)$, top, $L'(2006)$, middle, and $L(2007)$, bottom.

minimum of 234 days in 1991. Since then it has been recovering and reached a maximum of 342 days in 2006. 2007 was the second longest ice-free season since 1979 and 2008 was just average for the last 10 years. The largest variations in the LIFS were observed in the channels that separate Ile d'Anticosti from the mainland: over 90 days in the Jacques Cartier Passage and 80–90 days in the Gaspe Passage. In the rest of the Gulf the variations were around 40 days.

There has been little ice in the Bay of Fundy, especially in the last few years. In fact, ice has only been found in 70% of the area of the bay in the past 30 years and since 2003 the maximum monthly averaged

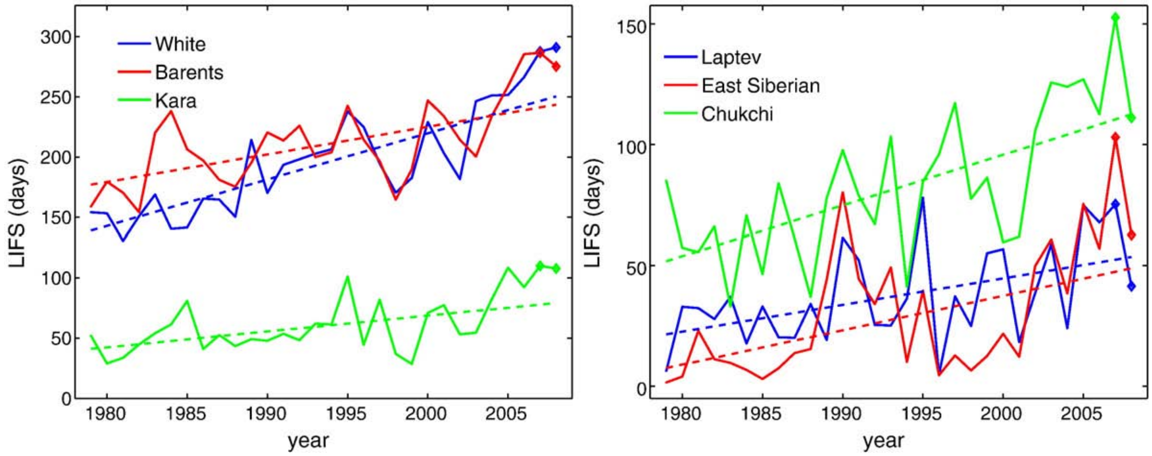

Fig. 10. Time series of the length of the ice-free season in the seas of the Western (left) and Eastern (right) Russian Arctic.

ice covered area was only 15% of the total area of the bay (in February 2003). The Bay of Fundy is actually the only one of the 40 regions of the Canadian Arctic with points where the LIFS was trivial since 1979. The LIFS increased at a pace of 4.3 d/y, the highest of all 85 regions. The growth was particularly high between 1991, when the LIFS recorded was 172 days, and 2000, when the whole bay was free of ice all year round.

Most of the Labrador Sea is ice-free all year round. Ice is only found on and near the coast of Labrador and, to a much smaller extent, on and near the coast of Newfoundland. Thus, instead of considering the whole sea as defined in the charts, we define the west Labrador Sea as the region enclosed by the following three points: position (47°47′N, 52°46′W) on the east coast of the island of Newfoundland, position (55°00′N, 52°40′W) and position (60°00′N, 60°00′W) at the southern entrance of Davis Strait. Ice occurred in all points of this area some time in the last 30 years. We shall ignore the occasional small quantities of ice that may be present outside (but near) this region, namely in the vicinity of the shores of Newfoundland. The most significant variations in the LIFS (between 100 and 120 days) took place in a band about 50 km wide located approximately 150 km away from the coast of Labrador. This is a region that used to be ice-covered in the winter at the beginning of the period under study but is now more likely to be free of ice all year round. In points closer to the coast of Labrador the variation was typically between 40 and 50 days, while along the coast of Newfoundland it was mostly in the range 30–40 days. 2004 was the longest ice-free season (310 days).

The average rate of increase of the LIFS in Davis Strait between 1979 and 2006 was 1.9 d/y. 2005, with 264 days, and 2006, with 263, were the longest ice-free seasons since 1979. 2008 was the shortest one since 1999. Because this is a comparatively large region, we shall describe the spatial distribution of the LIFS variations, starting with the east shore of Canada, proceeding to the west shore of Greenland and ending with a reference to the central part of the strait.

In Frobisher Bay and Cumberland Sound the LIFS in the late 1970s was of the order of 30–40 days while currently it stands at approximately 140 days. Such huge increases are among the largest in the eastern Canadian Arctic, only matched by those observed in Lancaster Sound and in parts of Foxe Basin. On the rest of the east coast of Baffin Island the variations were around 60 days for the stretch between the entrance to Hudson Strait and Cape Dyer, and around 40 days for the stretch between the latter point and Cape Christian (at the entrance of Baffin Bay).

On the southern tip of Greenland (in the vicinity of Kap Farvel) the data show that there was a small decrease in the LIFS in the points adjacent or very close to the coast while in those a few kilometres away the increase was around 20 days. On the rest of the west coast of Greenland up to the entrance to Disko Bay the increase in LIFS was modest (20–40 days) but we note that this is a region where one does not expect large amounts of ice. In Disko Bay itself and in the channels between Disko Island and mainland Greenland the situation is diverse: the early LIFS was about 85 days while the late LIFS is around 120 days.

In the central part of the strait we must distinguish two halves, with very different ice conditions. They are roughly divided by a line joining the northern point of the eastern entrance of Hudson Strait to a point on the west coast of Greenland at approximately 67°N, south of which lies the portion of Davis Strait that is normally free of ice all year round. It is near this line that the largest variations of the LIFS occurred, in the range 80–100 days, what can also be regarded as the northwards retreat of the winter ice edge (Fig. 13).

Baffin Bay enjoyed a relatively steady increase in the LIFS of 1.3 d/y between 1979 and 2006. The shortest ice-free season was recorded in 1996 (42 days) and the longest in 2006 (143 days). 2007 and 2008 ranked 4th and 5th, respectively, among the 30 seasons studied. In the central part of the bay (in points away from the shores), as well as along the coasts of Baffin Island and Devon Island, the increase in LIFS was typically between 20 and 40 days (Fig. 14).

In Ummannaq Fjord, on the west coast of Greenland, the length of the melting season increased from 90 days in the late 1970s to 145 days at present. Variations of 50–80 days were found on the stretch of coast between Ummannaq Fjord and Melville Bay. In Melville Bay itself the average early and late LIFS were 50 and 95 days, respectively, with higher variations (80–90 days) in its innermost parts. But it is in the northernmost sectors of Baffin Bay that we find the most striking changes, especially on the coast of Greenland near the entrance to Nares Strait, where the differences between the LIFS now and 30 years ago are 100–125 days.

4.8. Eastern Canadian Arctic

The melting season of 2006, with an average duration of 159 days, was the longest since 1979 in this sector of the Canadian Arctic, while 2007 (143 days) and 2008 (141 days) ranked 4th and 5th, respectively. Table 9 gives more detailed information.

In Hudson Strait the ice-free season has been growing steadily at a pace of 2.3 d/y, reaching a maximum of 195 days in 2006. 2007 and 2008 were the 4th and 7th longest, respectively, and the shortest one was 1990 (95 days). The points of the strait that enjoyed the largest increase in the LIFS (around 100 days) are those located near the south coast of Foxe Peninsula but the variations were also large (80–100 days) in all other parts of the south coast of Baffin Island (Fig. 15).

The data for Hudson Bay suggest the existence of two periods, 1979–1997 and 1998–2008, with quite distinct ice conditions (see Fig. 17). During the first period the LIFS did not exceed 140 days while in the

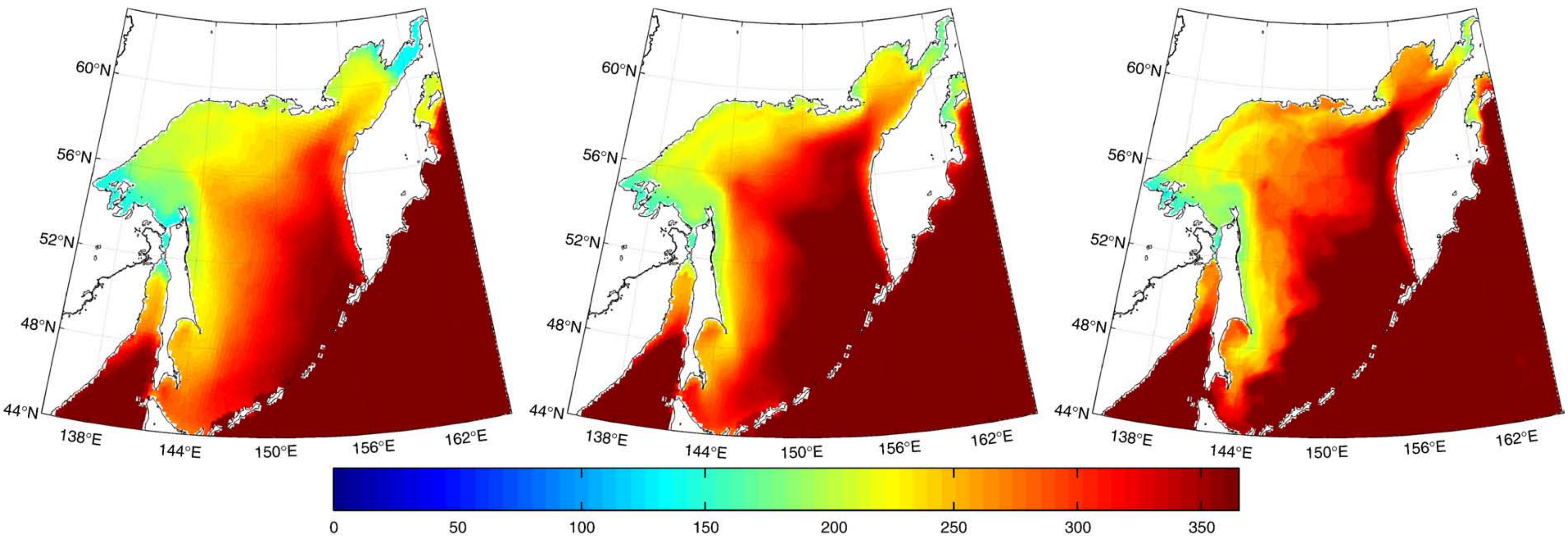

Fig. 11. Distributions of the length of the ice-free season in the Sea of Okhotsk: $L'(1979)$, left, $L'(2006)$, middle, and $L(2007)$, right.

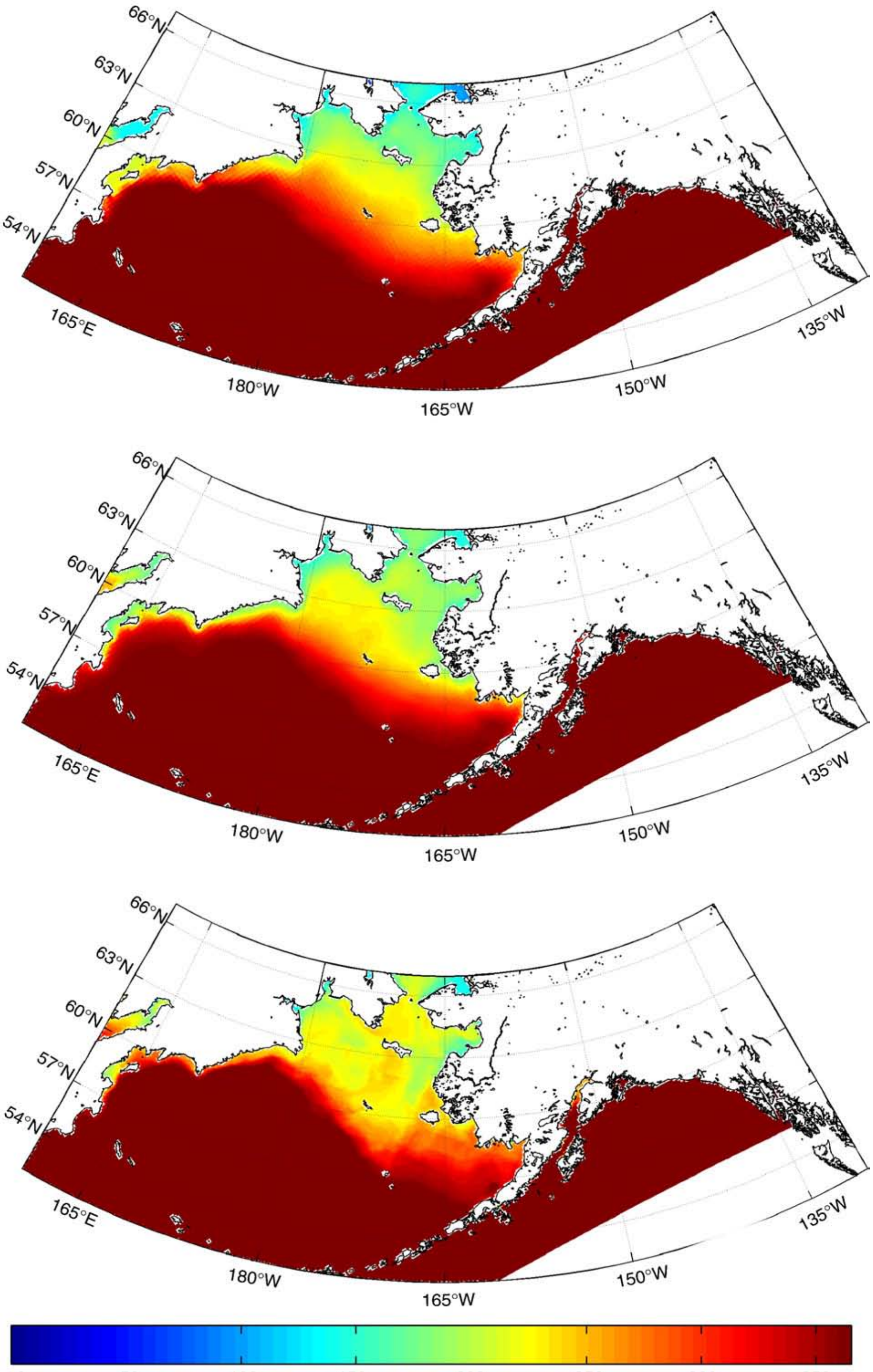

Fig. 12. Distributions of the length of the ice-free season in the Bering Sea: $L'(1979)$, top, $L'(2006)$, middle, and $L(2007)$, bottom.

second one it oscillated between a minimum of 132 days in 2002 and a maximum of 172 days in 1998. The second longest ice-free season in the last 30 years was 2006 (168 days) but there was nothing exceptional about the 2007 and 2008 seasons. The best linear fit to the time evolution of the LIFS leads to an average increase of 1.3 d/y between 1979 and 2006. By far the most remarkable changes took place in Fisher Strait (which separates Southampton and Coates Islands), where we found an early LIFS of 45 days and a late one of 145 days. The second highest variations (60–80 days) occurred in the southernmost points of James Bay. In the vast central part of Hudson Bay the variations were typically between 20 and 40 days, roughly increasing from the centre to the shores. On the west shore the increase in the LIFS was about 60 days, significantly higher than the average increase on the east shore.

Roes Welcome Sound (by which we designate the set formed by this sound, Frozen Strait and Repulse Bay) is a too small region to have any significant impact on the general trends that we observe in the Canadian Arctic. Nevertheless, it is perhaps instructive to look at some characteristics of its time-series which turn out to be shared by other narrow channels of the Canadian Archipelago. It shows that this is a region where, prior to 2003, the maximum LIFS was 72 days, and where it was not

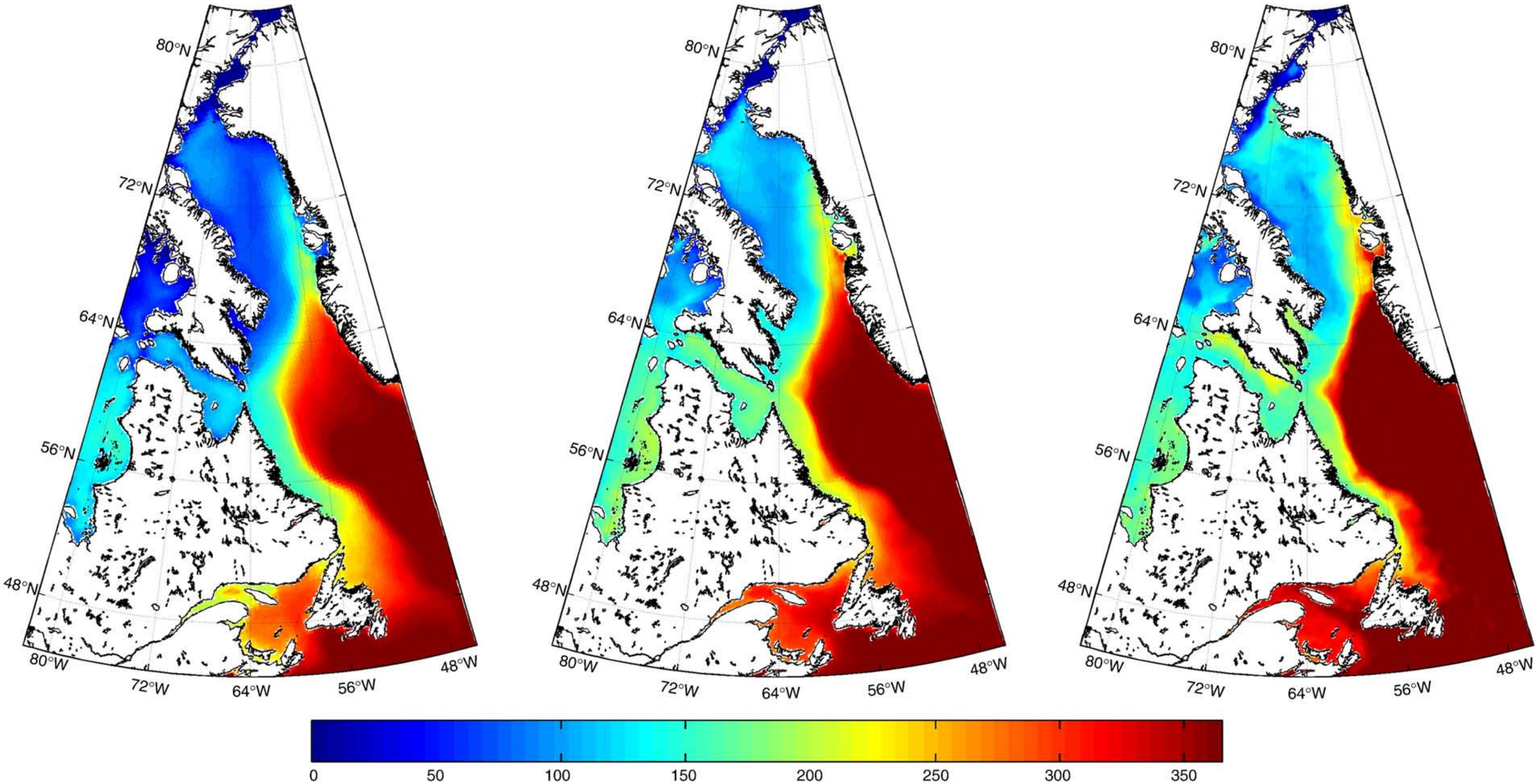

Fig. 13. Distributions of the length of the ice-free season in the Atlantic sector of the Canadian Arctic: $L'(1979)$, left, $L'(2006)$, middle, and $L(2007)$, right.

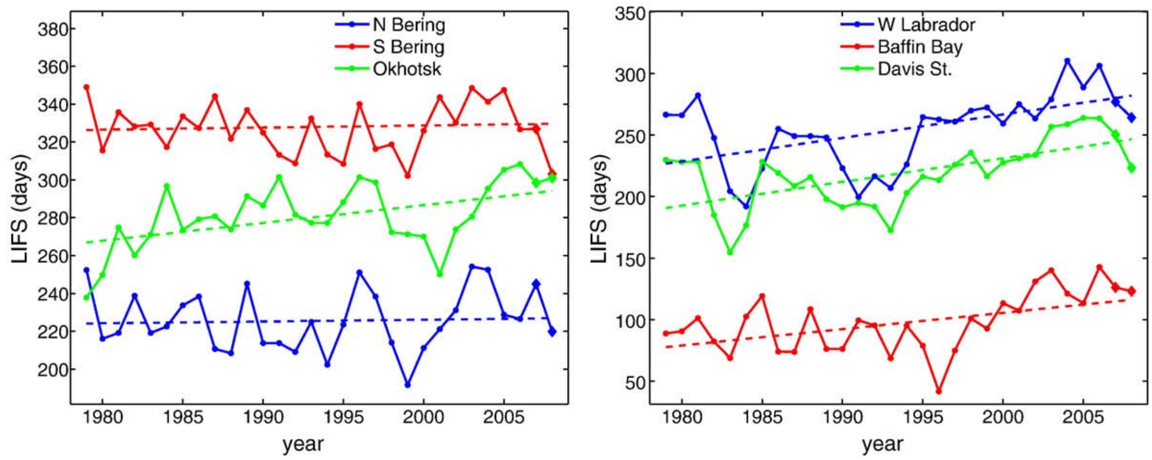

Fig. 14. Time series of the length of the ice-free season in selected regions of Far East Russia (left) and in the Atlantic sector of the Canadian Arctic (right).

uncommon to find a total ice cover all year round. Even in 2002 its average LIFS was below 2 days. However, since 2003 the LIFS has always been higher than 115 days, making this one of the regions of the Canadian Arctic where the ice cover has changed more dramatically in the past few years. Other examples of regions where remarkable discontinuities appear to have occurred between 2002 and 2003 are Fury and Hecla Strait, Eclipse Sound (and the other two channels that separate Baffin Island and Bylot Island), Admiralty Inlet, Jones Sound, Nares Strait and Nansen Strait. While the observed considerable increase of the average LIFS in the northern hemisphere from 2002 to 2003 cannot be an artifact of the changes of sensor or grid, we shall not rule out the possibility that the latter may have influenced the results for some channels of the Canadian Arctic (as discussed in section 2). Interestingly, there is no evidence that the same holds for the straits of the Russian Arctic.

The length of the melting season in Foxe Basin has been growing at a steady rate of 2.1 d/y. In 1983 the average LIFS was as low as 20 days (the minimum of the 30 years time-series), in 1990 it was only 26 days, and reached a maximum of 136 days in 2006. The most noticeable variations, above 100 days, are found on the northwest corner of the basin, near the entrance to Fury and Hecla Strait. This is a place where just a few years ago the ice cover was perennial (or nearly perennial) and that now possesses a decent share of days without ice every year. We also note large variations (60–80 days) in Foxe Channel. In the central part of the basin the growth was of the order of 60 days, decreasing to 50 days near the coastline.

Lancaster Sound has seen big changes in its ice conditions in the last three decades. Until 1997 the LIFS rarely exceeded 10 days and its maximum value was 34 days. After 2002 it was always above 95 days, reaching a maximum of 142 days in 2006. This non-linear growth has been quite uniform throughout the strait.

In Prince Regent Inlet the increase in the LIFS between 1979 and 2006 was also non-linear. The LIFS was below 20 days almost every year until 2002 (when it was 5 days), with the exceptions of 1998 (63 days) and 1999 (24 days). It grew steadily, but fast, between 2003 and 2006, when it reached a maximum of 106 days, to decline in 2007 and again in 2008 (to a value lower than the one attained in 1998).

The ice situation in the Gulf of Boothia has been changing less abruptly than in many other parts of the Canadian Arctic. Here it is possible to assign to the LIFS an approximate linear growth of 1.2 d/y. The melting season of 2006 was the longest on record (72 days), followed by 2007 and 2008 (which had a duration similar to that of 1998).

4.9. Western Canadian Arctic

The mean LIFS in the western Canadian Arctic increased monotonically between 2003, when it was 42 days, and 2008, when it reached 82 days (see Table 10 for other relevant information concerning the evolution of the LIFS and ISII in this sector of Canadian Arctic).

In every point of Barrow Strait the ice cover was more or less perennial between 1979 and 1997. In 1998 the average LIFS jumped abruptly to 33 days, only to become again close to zero between 1999 and 2002. Then, a fast, monotonic, steady increase took place between 2003 and 2007. The changes are much more evident in the eastern part of the strait, where the ice conditions are likely to be more favourable. In 2007, for example, the LIFS reached 140 days at the eastern entrance while it did not go above 70 days at the opposite side (Fig. 16).

A similar pattern can be detected in Viscount Melville Sound. The melting season was essentially non-existent until 1998, a year when it averaged 8 days. From 1999 to 2005 it oscillated between zero and 8 days; it then climbed to 13 days in 2006 and to 30 days in the next year. Some areas on the south shore of the sound were among the rare places on or south of the Parry Channel with an all year round ice cover in 2007. It is well-known that the direct Northwest Passage (composed by Lancaster Sound, Barrow Strait, Viscount Melville Sound and McClure Strait) was open for some weeks for the first time in that summer (a situation that would occur again in the summer of 2008).

McClintock Channel provides a good example of a region where the ice conditions changed rapidly in the last few years. Until (and including) 2005, an ice-free season as such did not exist in the channel (with the exception of 10 days in 1982). Starting from $L \simeq 0$ in 2005, the LIFS reached 33 days in 2006 and a record high of 52 days in 2007, only to decline in 2008 to a value below that of 2006.

McClure Strait illustrates the exceptional character of the last two summers in some parts of the Canadian Arctic. With the exceptions of 1998 and 1999, when the LIFS was 23 and 19 days, respectively, the strait was almost permanently ice-covered from 1979 to 2006. Even in 2006, which was the mildest ice season in about half of the regions of the Canadian Arctic, the average LIFS in McClure Strait was only one day. In 2007 and 2008, by contrast, it was above 40 days.

The LIFS in Queen Maud Gulf had a fast, non-linear increase, from values close to zero until 1986 to a maximum of 93 days in 2006. The changes in the ice cover were particularly significant in the central part of the gulf. At present the spatial distribution of the LIFS in the gulf is quite uniform.

The time-series of the LIFS for Coronation Gulf (which, in this paper, is defined as the region formed by the gulf itself together with Dease Strait, Wellington Bay, Bathurst Inlet, Melville Sound and Elu Inlet) includes an initial period (until 1990) when there was one single ice-free season (10 days in 1987), followed by a period of very large fluctuations in the LIFS, from zero days (in several years) to 108 days in 2006. The most important changes occurred in the southwest sector, near the settlement of Coppermine.

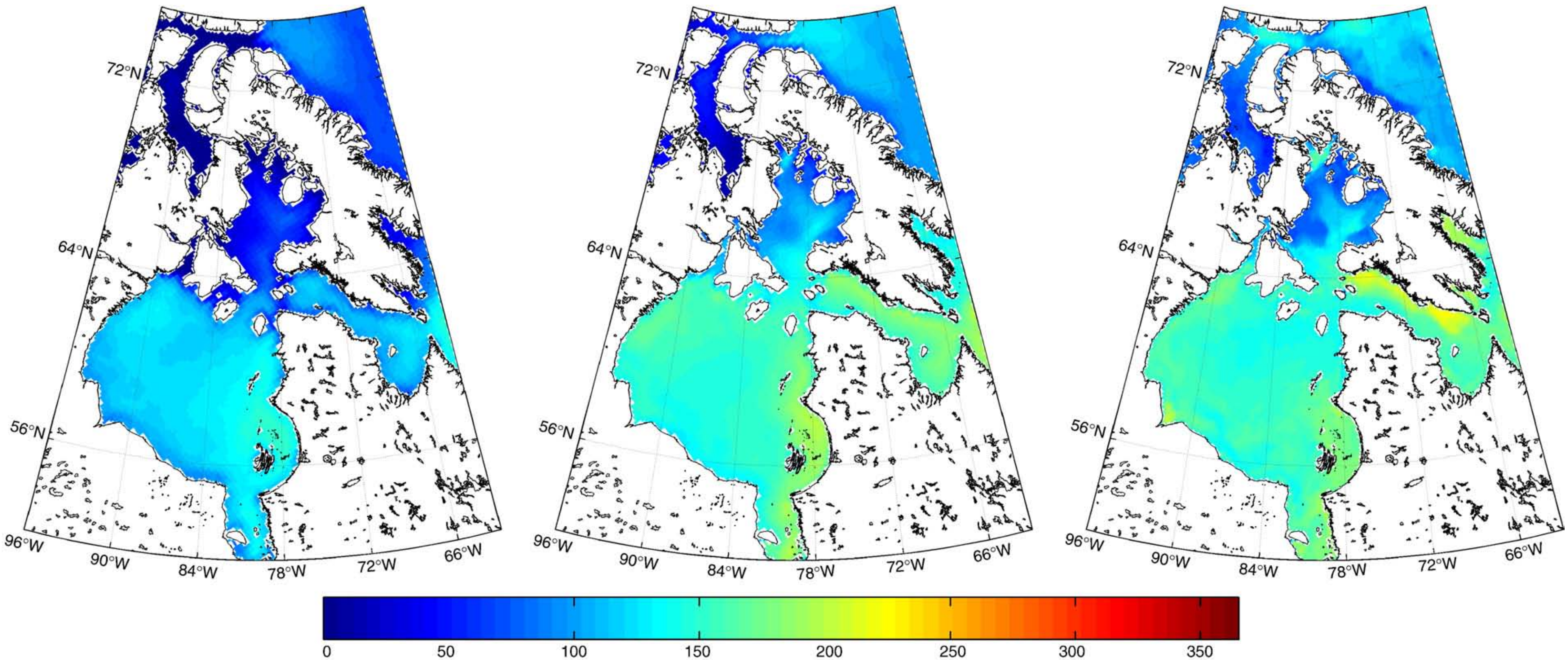

Fig. 15. Distributions of the length of the ice-free season in the eastern sector of the Canadian Arctic: $L'(1979)$, left, $L'(2006)$, middle, and $L(2007)$, right.

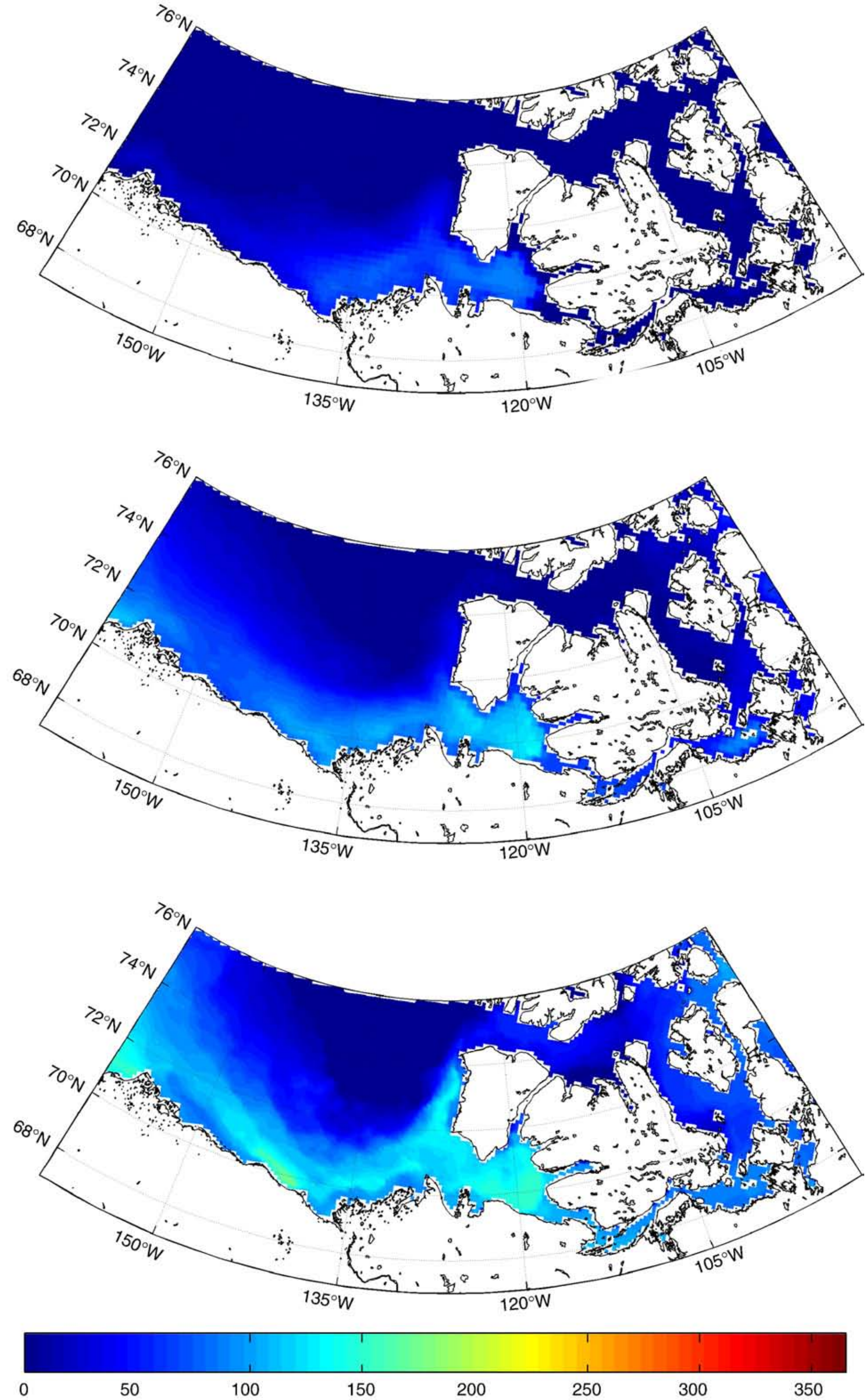

Fig. 16. Distributions of the length of the ice-free season in the western sector of the Canadian Arctic: $L'(1979)$, top, $L'(2006)$, middle, and $L(2007)$, bottom.

The ice conditions in Amundsen Gulf had a large interannual variability, with the LIFS ranging from a minimum of 34 days in 2002 to a maximum of 150 days in 1998. The melting seasons of 2007 and 2008 were the second and third longest, respectively. The best linear fit to the irregular time-series suggests a rate of increase of 1.6 d/y. The most impressive variations (80–100 days) occurred in the easternmost part of the gulf, near the boundary with Dolphin and Union Strait, and at the entrance of Prince Albert Sound. Inside the latter and near the southern entrance of Prince of Wales Strait they were around 60 days. In the rest of the gulf the increase was about 40 days. In the central part the LIFS tends to be uniform, with values similar to those observed on the south shore. On the north shore it is considerably lower, especially in Prince Albert Sound and Minto Inlet (Fig. 17).

In the Beaufort Sea the increase of the LIFS has been steady, at an average rate of 0.8 d/y. The longest melting season happened in 1998 (109 days), whereas 2008 and 2007 were second and third, respectively. The shortest seasons occurred in 1985 (5 days), 1991 (6 days) and 1996 (7 days). One of the most interesting features of the

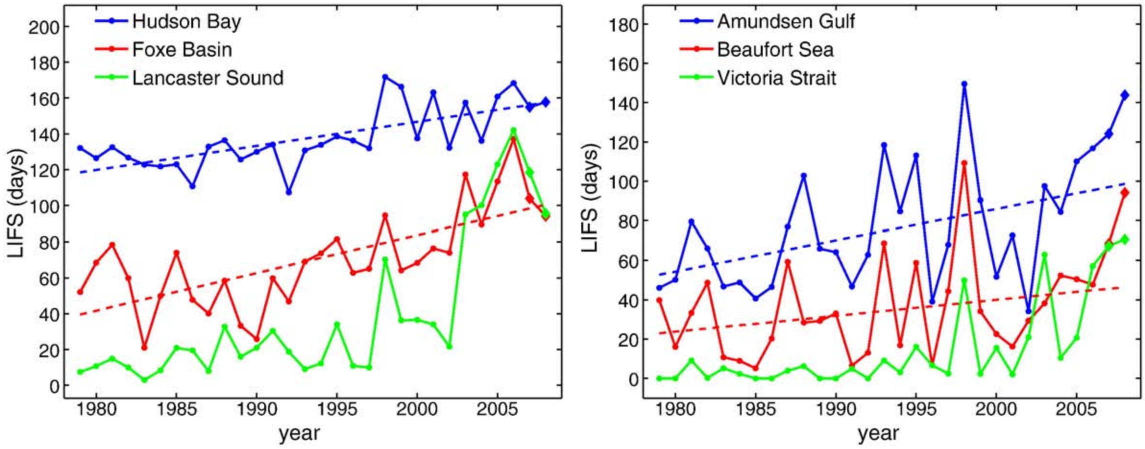

Fig. 17. Time series of the length of the ice-free season in selected regions of the eastern (left) and western (right) sectors of the Canadian Arctic.

sea ice distribution in the Beaufort Sea is the existence of a significantly large area, approximately centred at (73°N, 130°W), where there was a decline in the LIFS. This is likely to be the only place in the Canadian Arctic where such a change took place. The largest (positive) variations of the LIFS are found in the westernmost sectors of the Beaufort Sea, notably near Point Barrow, where they were of the order of 70 days. Variations between 50 and 70 days are common along the coast the mainland, increasing westwards. In 2008 the longest ice-free periods (of the order of 200 days) occurred between the west coast of Banks Island and 130°W, as well as in the vicinity of the coast of mainland Canada between Cape Bathurst and Mackenzie Bay. By contrast, in the late 1970s there were no points of the Beaufort Sea free of ice for more than 80 days per year.

4.10. Northern Canadian Arctic

The waters of this remote sector of the Canadian Archipelago, formed by the set of channels north of the Parry Channel (listed in Table 11), are almost permanently ice-covered. In the last 6 years the average LIFS oscillated between a minimum of 6 days in 2004 and a maximum of 15 days in 2007.

Like in many other parts of the high-latitude Canadian Arctic, no proper melting season existed in Jones Sound between 1979 and 2003 (with the exception of a spell of 41 days in 1998). Since 2003, however, the conditions have changed enormously, especially in the central part of the sound, leading to average ice-free periods longer than 40 days in each year. The longest was recorded in 2006 (67 days).

In Nares Strait the average LIFS was always close to zero until 2002. Since then it has been growing and reached a maximum of 27 days in 2008. The changes in the ice cover occurred mainly at the southern entrance of the strait (with values for the variation of the LIFS similar to those reported for northern Baffin Bay) and, to a smaller extent, in Kane Basin. In 2008 the mean LIFS in the latter was just under 40 days.

Wellington Channel, McDougall Sound, Queens Channel and Penny Strait (which, together, form the region referred to as Wellington Channel in Table 11) had a perennial (or nearly perennial) ice cover between 1979 and 2002 (with the exception of an ice-free spell of 20 days in 1998). Since 2003, however, the average LIFS has been above 25 days, with the maximum attained in 2007. The improvement of the ice conditions in the last few years has been uniform in this set of channels.

The region designated here by Byam Martin Channel (which also includes Austin Channel and Byam Channel) represents another example of the big changes that are taking place in the far north. Here the average LIFS was below 5 days until (and including) 2004. Since that year, however, it has been growing approximately linearly and attained a maximum of 17 days in 2007. The differences in the ice distribution between now and three decades ago are particularly evident in Austin Channel, where, for instance, an ice-free period of 56 days existed in the summer of 2007. At the same time, the ice-free spell did not last longer than 25 days the southern half of Byam Martin Channel and no break-up of the ice took place in the northern half of the latter or in Byam Channel.

In the eastern part of Queen Elizabeth Archipelago nonzero LIFS were observed in 1998 and in the last 4 years, with maxima of 9 days in 2005 and 2008. The biggest contribution to the value of the LIFS in 2008 came from the ice-free spell of approximately 50 days enjoyed by the eastern half of Norwegian Bay. In the western part of the archipelago the ice conditions are even more severe. The time-series of the LIFS for the period under consideration has non-zero values in 2007 and 2008 only. In 2007 this was largely due to a small ice-free period in Crozier Channel and Kellet Strait (which separate Ellington Island from Prince Patrick Island and Melville Island, respectively, at the western end of the archipelago).

5. Concluding remarks

An alternative quantitative description of the evolution of the sea ice conditions in the Arctic in the 1979–2008 period based on the length of the ice-free season (LIFS) and the inverse sea ice index (ISII) has been formulated. The latter is a quantity that measures the degree of absence of sea ice in a year and varies between zero (when there is a perennial ice cover) and one (when there is open water all year round). Sea ice concentration data were obtained from passive microwave satellite imagery and processed with the Bootstrap algorithm for the SMMR and SSM/I periods, and with the Enhanced NASA Team algorithm for the AMSR-E period.

By constructing a linear fit to the observed data, it was found that the (spatially averaged) LIFS in the Arctic went from approximately 119 days in the late 1970s to around 148 days in 2006, which represents an average rate of increase of 1.1 d/y. However, in the more recent period 2001–2007, the LIFS has increased monotonically at an average rate of 5.5 d/y, a result which is in good agreement with the general consensus that the Arctic sea ice is currently in an accelerated decline. It was also found that 2007 was the longest ice-free season on record (168 days) while the shortest (121 days) was observed in 1982. The ISII also reached a maximum of 0.50 in 2007 while the minimum (0.40) was registered in 1982. In 2008 both global LIFS and ISII were lower than in 2007. This appears to be a mere fluctuation in the long-term time-series, all models predicting a decay of the Arctic sea ice in the near future. Regional changes in the ice cover using the same variables were investigated. The Arctic was divided into 85 regions and the way the LIFS and the ISII changed in each of them since 1979 was examined.

Finally, let us not forget that the work of the scientist does not have an end, the completion of a paper being often a step in the preparation of the next. At the time of writing NSIDC (National Snow and Ice Data Center) and EUMETSAT (European Organisation for the Exploitation of Meteorological Satellites) are collaborating to carry out a re-analysis of all available sea ice concentration data obtained from passive microwave imagery (Meyer et al., 2008). This amounts, namely, to identifying the sources and to improving estimate of the magnitude of the errors inherent to each of the algorithms used to extract sea ice concentrations from brightness temperatures. It is hoped that this team effort will eventually lead to an algorithm that can generate sea ice concentrations that are more reliable than those currently available. It may then be necessary to recalculate the trends in the length of the ice-free season in the Arctic and to extend the analysis to the Antarctic.

References

Cavalieri, D., Comiso, J., 2004. AMSR-E/Aqua Daily L3 12.5 km Tb, Sea Ice Concentrations and Snow Depth Polar Grids. National Snow and Ice Data Center, Boulder, CO. Digital Media (updated daily).

Collins, W.D., Bitz, C.M., Blackmon, M.L., Bonan, G.B., Bretherton, C.S., Carton, J.A., Chang, P., Doney, S.C., Hack, J.J., Henderson, T.B., Kiehl, J.T., Large, W.G., McKenna, D.S., Santer, B.D., Smith, R.D., 2006. The Community Climate System Model version 3 (CCSM3). J. Clim. 19, 2122–2143.

Comiso, J., 1986. Characteristics of Arctic winter sea ice from satellite multispectral microwave observations. J. Geophys. Res. 91, 975–994.

Comiso, J., 1990. In: Maslanik, J., Stroeve, J. (Eds.), DMSP SSM/I Daily Polar Gridded Sea Ice Concentrations. In National Snow and Ice Data Center, Boulder, CO. Digital Media (1990, updated current year).

Comiso, J., 1995. SSM/I Sea Ice Concentrations Using Bootstrap Algorithm. NASA Ref. Publ. 1380.

Comiso, J., 1999. Bootstrap Sea Ice Concentrations from Nimbus-7 SMMR and DMSP SSM/I. National Snow and Ice Data Center, Boulder, CO. Digital Media (updated 2005).

Comiso, J.C., Nishio, F., 2008. Trends in the sea ice cover using enhanced and compatible AMSR-E, SSM/I, and SMMR data. J. Geophys. Res. 113, C02S07. doi:10.1029/2007JC004257.

Comiso, J.C., Steffen, K., 2008. Introduction to special section on large-scale characteristics of the sea ice cover from AMSR-E and other satellite sensors. J. Geophys. Res. 113, C02S01. doi:10.1029/2007JC004442.

Holland, M.M., Bitz, C.M., Tremblay, B., 2006. Future abrupt reductions in the summer Arctic sea ice. Geophys. Res. Lett. 33, L23503. doi:10.1029/2006GL028024.

Laxon, S., Peacock, N., Smith, D., 2003. High interannual variability of sea ice thickness in the Arctic region. Nature 425, 947.

Markus, T., Cavalieri, D., 2000. An enhancement of the NASA team sea ice algorithm. IEEE Trans. Geosci. Remote Sens. 38, 1387–1398.

Maslowski, Wieslaw, Clement Kinney, Jaclyn, Jakacki, Jaromir, 2007a. Toward prediction of environmental arctic change. Computing in Science and Engineering 9 (6), 29–34.

Maslowski, W., Whelan, J., Clement Kinney, J.L., Jakacki, J., 2007b. Understanding Recent Variability in the Arctic Sea Ice Thickness and Volume — Synthesis of Model Results and Observations. AGU Invited Talk.

Maslowski, W., Clemente Kinney, J., Jakacki, J., Zwally, J., 2008. State of the Arctic sea ice. Geophysical Research Abstracts, vol. 10. EGU2008-A-06425.

Meyer, W.N., et al., 2008. Progress and ongoing issues in the development of a passive microwave sea ice extent/concentration climate data record. Invited Talk at AGU Fall Meeting, San Francisco.

Parkinson, C.L., 1994. Spatial patterns in the length of the sea ice season in the Southern Ocean, 1979–1986. J. Geophys. Res. 99 (C8), 16,327–16,340.

Rodrigues, J., 2006. Recent changes in the sea ice distribution in the Russian Arctic: ice extent, area and length of the ice-free season. European Commission Arctic Sea Ice Thickness: Past, Present and Future. In: Wadhams, P., Amanatidis, G. (Eds.), Climate Change and Natural Hazard Series, Brussels.

Rodrigues, J., 2008. The rapid decline of the sea ice in the Russian Arctic. Cold Re. Sci. Technol. 54, 124–142.

Stroeve, J., Holland, M.M., Meier, W., Scambos, T., Serreze, M., 2007. Arctic sea ice decline: faster than forecast. Geophys. Res. Lett. 34, L09501. doi:10.1029/2007/GL029703.