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D2.1.2 Time series of sea ice data to describe changes over 50 years

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SUMMARY

This report describes an inventory of sea ice data sets and model fields to be used in compilation of a climate-data base of the Arctic ocean in support of an Arctic Ocean synthesis. The compilation is targeted at data of primarily ice area, ice concentration and ice drift to describe changes over 50 years based on a combination of data from a variety of sources, including synoptic ice observations from operational ice services and passive microwave time series satellite data from 1979.

Data sources as projects and archives include MyOcean, EUMETSAT OSI SAF, GLOBEICE and national archives, including those available in Canada and the US. Russian expeditions, including the North Pole Drifting stations, provide thickness and drift data over six decades starting in the 1930s

Ice buoys provide drift data at scattered locations across the Arctic, while moorings provide ice drift and thickness data in a few locations such as the Fram Strait. Ice thickness data for the Arctic Basin are obtained primarily from submarine cruises and scientific expeditions.

A list of model simulations is provided from which output can be used to bridge the gaps in the incomplete data coverage to create 30-50 years time series.

MONARCH-A CONSORTIUM

Participant no.	**Participant organisation name**	**Short name**	**Country**
1 (Coordinator)	Nansen Environmental and Remote Sensing Center	NERSC	NO
2	The University of Sheffield	USFD	UK
3	Universität Hamburg	UHAM	NO
4	Centre National de la Recherche Scientifique	CNRS	FR
5	Scientific foundation Nansen International Environmental and Remote Sensing Center	NIERSC	RU
6	Universitetet i Bergen	UiB	NO
7	Danmarks Tekniske Universitet	DTU	DK
8	Institut Francais de Recherche pour l'Exploitation de la Mer	IFREMER	FR

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1 Introduction

In MONARCH-A the ice Essential Climate Variable is *ice drift*. In addition, ice thickness, concentration and extent will be pulled from existing archives without refinement. Recent development in climate prediction has spawned increasing concern about feedback mechanisms between multi-domain Earth System processes contribution crucially to climate warming. This is recognized as one of the greatest sources of uncertainty in climate prediction (IPCC 2007) and points to the need for simultaneous use of multiple ECVs in models.

Lack of long in-situ time series at adequate spatial and temporal coverage are challenging our knowledge on e.g. ongoing or past major sea ice changes, as well as detailed knowledge on the variability of the Arctic Ocean in the past or what causes a drift in the Arctic system observed during the most recent decades. Existing estimates of the circulation in the high latitude and Arctic Ocean show significant discrepancies in their basic description of the flow field. New merged data from remote sensing (ENVISAT, ICESat and CryoSat altimetry combined with geoid models) may resolve some of these discrepancies.

The length of existing sea ice data records increases, in some cases now to around 20-30 years, and they gradually become of better quality and accuracy, adequate validation and adaptation to better initialization are becoming feasible. The objective is, therefore, to assess the quality of all available historical data in the Arctic region during the last 30-50 years.

Since, most of the data will be incomplete in both spatial and temporal coverage and are often not overlapping it will be important to use models for their interpretation. Output from such models has already been analyzed with respect to the ocean circulation, e.g., those from ECCO, GECCO, MICOM and BCM. ECCO and GECCO are here very important ingredients since they are at present the only dynamically self-consistent approaches to data assimilation (Stammer et al. (2003); Köhl and Stammer (2008a,b)). The ECCO/GECCO environment will also comprise the basis for the synthesis work in the project.

2 The data sets

The majority of the ice parameter data sets described in the following are from open sources accessible via the internet, using standard formats, like NetCDF. Remote sensing and in situ data sets are summarized in Table 1, whereas output from model simulations are shown in Table 2. Nearly all data sets are referenced in the peer review literature, so the current overview does not undertake any validation of the data sets. The major pan-Arctic data sets are emphasized, whereas smaller data sets of limited regions are not cover, although the listed sources also may point to such information. In the following an over-all description of the coverage and properties of the datasets is provided, whereas some examples of ice concentration and ice drift are provided in Sections 2.1 and 2.2, respectively. In Section 2.3, for ice thickness, we describe more thoroughly some analysis of the Sever expeditions in the Arctic 1928 – 1993.

From the late 1970s, i.e. for the last 30 years or so, there are **ice concentration** and ice extent data from passive microwave remote sensing available from the Nimbus-7 Scanning Multichannel Microwave Radiometer (SMMR) operating from 1978, followed by the Defense Meteorological Satellite Program Special Sensor Microwave/Imager (SSM/I). These parameters are the best covered ones in time and space.

For **ice thickness** the Soviet *Sever* expeditions go all the way back to 1928, ending with the collapse of the Soviet Union in 1993, although with many gaps and a bias towards spring and the Eurasian part of the Arctic. A comprehensive compilation, also including US/UK submarines includes the one of Lindsay et al., 2010. For recent years freeboard data from ICEsat are available (see delivery report 2.6.1 - Time series of grids of sea ice thickness, and improved SSH measurements).

Ice drift estimates include those based on passive microwave, utilizing the maximum correlation method, such as the data set by Fowler et al. (2003/2008), starting in 1978, and several products from IFREMER starting in 1991. Estimate by drifting buoys exist as well – notably from the Arctic Ice Bouy Program – although naturally containing gaps due to missing buoy coverage.

For recent years there is an increasing number of compilations of all ice parameters, thanks to the new satellites carrying ice observing sensors and the increased effort in field campaigns. In general, MyOcean and the EUMETSAT OSI SAF (Table 1) will be the important sources. Ice buoys also provide drift data at scattered locations across the Arctic, while moorings provide ice drift and thickness data in a few locations such as the Fram Strait. Ice thickness data for the Arctic Basin are obtained primarily from submarine cruises and scientific expeditions. Of particular relevance are the Russian expeditions, including the North Pole Drifting stations, which provide thickness and drift data over six decades starting in the 1930s. Additional data will be obtained from GLOBEICE and national archives, including those available in Canada and the US. Also in this case the challenging compilation of data incomplete data coverage into 30-50 years time series will be carried out using sea ice models to bridge those gaps

Project or institution	Link or pointer to data sets	Parameters and references	Time span
MyOcean	http://www.myocean.eu/web/45-sea-ice.php	Most sea ice parameters. Links	2008 –
Arctic ROOS	http://arctic-roos.org/observations	Concentration, area, extent	1978 –
(EUMETSAT) OSI SAF	http://saf.met.no/p/ice/#mrdrift	drift, concentration, calibrated with buoys	2005 –
Globeice	http://globice.mssl.ucl.ac.uk/product_access.php	Drift (3-daily and monthly), concentration	2004 – 2010 (not 2006)
IFREMER	http://cersat.ifremer.fr/data/discovery/by_parameter/sea_ice/psi_sea_ice_drift http://cersat.ifremer.fr/data/discovery/by_parameter/sea_ice/psi_amsr_drift	Drift etc	1991 – 2002 –
NSIDC	http://nsidc.org/data/docs/daac/nsidc0116_icemotion.gd.html#dataaccess http://nsidc.org/data/docs/daac/nsidc0116_icemotion.gd.html Concentration: http://nsidc.org/data/nsidc-0051.html	Drift etc 25km gridded daily, monthly, Fowler, 2003/2008	**1978 – 2006**
NSIDC	http://nsidc.org/data/docs/noaa/g01358_arctic_ocean_drift_tracks/	Ice drift: ships, buoys, manned stations	1872 – 1973
IABP	http://iabp.apl.washington.edu/data_slp.html	Ice drift from buoys, Optimal interpolation	1979 – 1998
NERSC SAR	kjell.kloster@nersc.no Smedsrud et al., 2011	Ice drift from SAR Fram Strait drift + area flux	2004 –
DTU SAR	http://www.space.dtu.dk/English/Research/Research_divisions/Microwaves_and_Remote_Sensing.aspx	Ice drift, SAR	Recent years
NP drifting stations	http://www.aari.ru/resources/d0014/np38/default.asp?id=archive&lang=0	Meteo, drift, thickness (2007 – not on files)	(1937) 1950 –
AARI	http://www.aari.ru/main.php?lg=1	Ice concentration, drift stations	
PSC, Washington	http://psc.apl.washington.edu/sea_ice_cdr/data_tables.html	Thickness, Moorings, US/UK submarines. Lindsay et al., 2010	1975 –
NASA (/ UHAM)	http://www.aari.ru/resources/d0014/np38/default.asp?id=archive&lang=0 http://icdc.zmaw.de/seaicethickness_satobs_arc.html?&L=1	Thickness / freeboard ICEsat	Winters 2003/04 until 2007/08
NERSC/ NIERSC	http://nsidc.org/data/g02140.html and V. Alexandrov, NIERSC	Thickness, snow density	1928 – 1993 (gaps)

***Table 1**: Ice parameters of Arctic data sets, including data providing institution or project, web site, short description and approximate temporal coverage.*

In order to extrapolate ice data back in time, output from ocean – sea ice models will be used. Several model runs exist, but we will primarily consider those analyzed in the Monarch-A project (see delivery report "D2.4.1 Assessment of existing descriptions of the Arctic Ocean circulation and its transport properties"). Models that have been participating in the comparison include the following):

- Regional setup of MITgcm model ATL (Serra et al., 2010) in three different resolutions from the Institute of Oceanography, University of Hamburg
- Regional setup of MICOM model (Hátún et al., 2005) from the Nansen Environmental and Remote Sensing Center.
- Global setup of MPIOM model (project STORM https://verc.enes.org/community/projects/national-projects/german-projects/storm/) from the Max Planck Institute for Meteorology.

All models are forced by 6 hourly NCEP ERA 1 reanalysis (Kalnay et al., 1996), provide monthly averaged data stored as NetCDF. Details of model setups and output are presented in Table 2.

Model run	Region	Mean spatial resolution in the Arctic	Period of integration	Vertical grid	Documentation (data report, paper, wiki/web page, etc.) :
ATL03	Atlantic Ocean north of 33◦S including the Nordic Seas and the Arctic Ocean.	~ 30 km	1948-2009	z-coordinates, 50 levels	Serra et al., 2010
ATL06	Atlantic Ocean north of 33◦S including the Nordic Seas and the Arctic Ocean.	~ 15 km	1948-2007	z-coordinates, 50 levels	Serra et al., 2010
ATL12	Atlantic Ocean north of 33 S including the Nordic Seas and the Arctic Ocean.	~8 km	1948-2009	z-coordinates, 50 levels	Serra et al., 2010
MICOM	North of 30 S with Nordic Seas and Arctic Ocean included	~15 km	1948-2007	σ-coordinates, 35 levels	Hátún et al., 2005
MPIOM	Global	~7 km	1948-2010	z-coordinates, 80 levels	https://verc.enes.org/community/projects/national-projects/german-projects/storm/

Table 2: Available simulated ice parameters from model runs, including model, version, layout, spatial resolution, simulation period, vertical coordinate and reference.

2.1 Ice concentration

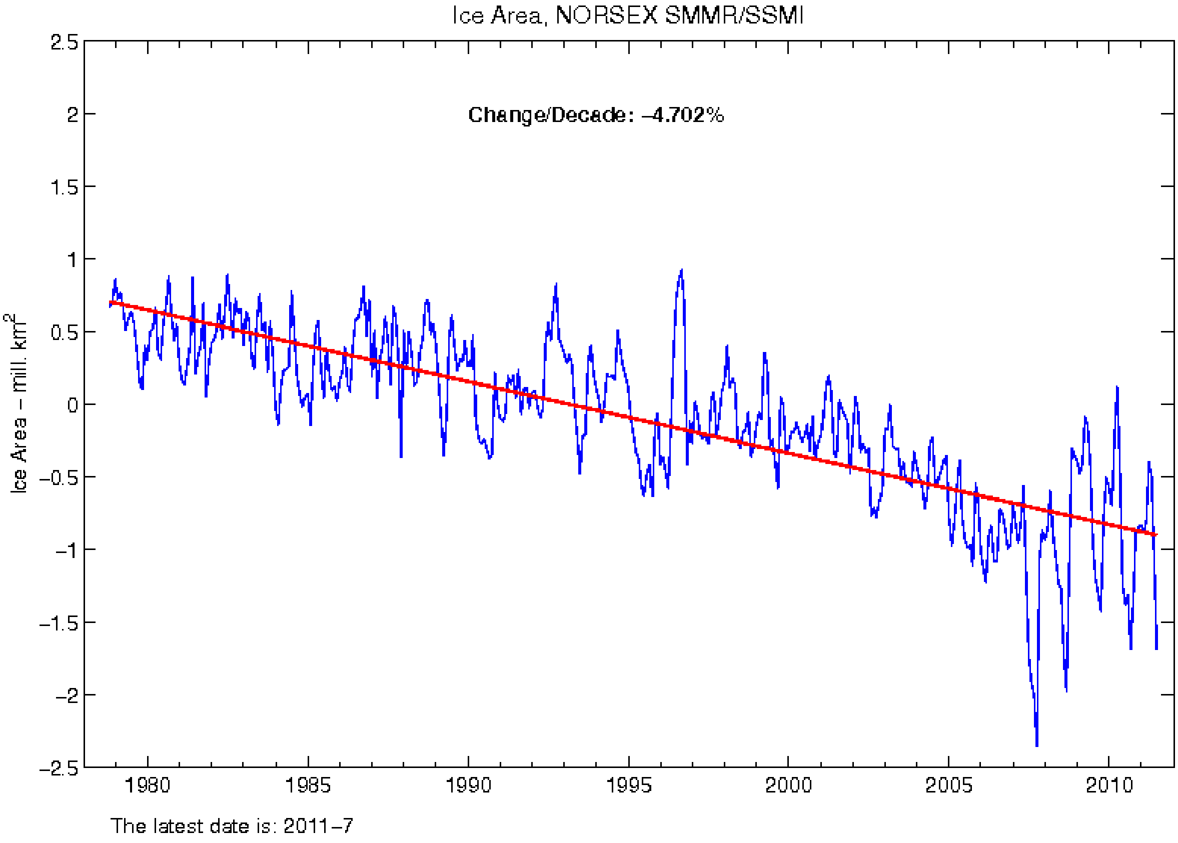


Figure 1: Time series of ice area, i.e. integrated ice concentration, for the Arctic, using combined SMMR/SSMI data. The mean and seasonal cycle have been subtracted. From Arctic ROOS, http://arctic-roos.org/observations

Ice concentration is relatively well captured during the satellite period. Its integral is as frequently used quantity, capturing well the declining trend over the last dacades and the marked interannual variability (Fig. 1).

2.2 Ice drift

Ice drift has been derived from passive microwave observations or from buoy drift by dynamical interpolaton. An example of the latter is shown in Fig. 3, in which the Beaufort Gyre and the Trans Polar Drift Stream are clearly seen.

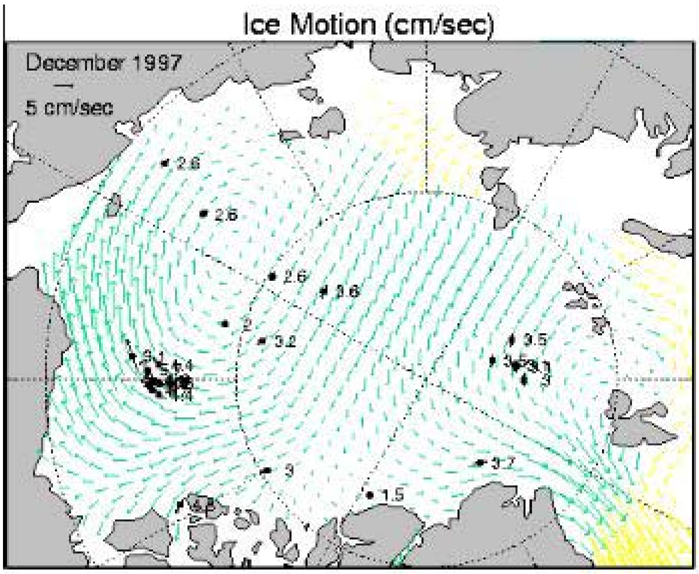


Figure 2: Ice drift vectors for December 1997, based on observed ice buoy drift. Buoy positions marked in black. Source: Polar Science Center, Washington, http://iabp.apl.washington.edu/data_slp.html

2.3 Ice thickness

One of the most extensive data sets of sea ice and snow measurements was collected in the Soviet Union's high-latitude airborne annual “Sever” (“Sever” means North) expeditions, which took place in 1928, 1937, 1941, 1948-1952, and 1954-1993 [*Romanov*, 1995]. These data sets are especially valuable, since their coverage in space and time is superior to most other data sets before the radar altimetric methods were launched recently. The expeditions took place mainly from mid March to early May, and ice thickness, ice freeboard, snow depth, as well as several other ice parameters were measured. After airplane landing ice thickness was measured at 3-5 locations 150-200 m apart on the runway, and, when second-year and multiyear ice prevailed in the landing area, at 10-20 points on the neighboring ice floes and at fresh fractures. The obtained values were averaged and used for analysis [*Romanov*, 1995]. The data set of these measurements is available on NSIDC server and consists of raw data files from 3771 aircraft landings, beginning in 1928 and ending in 1989. Table 2 specifies the number of landing sites by decade and month.

	January	February	March	April	May	June	July
1920s						4	
1930s				2	5		
1940s				21	24		
1950s		2	21	286	147	4	1
1960s	3	13	107	282	290	46	
1970s			438	679	148		
1980s		3	380	526	339		

Table 3 The number of landing sites by decade and month

The maps below show the position of each landing site by decade. One data record exists for each location. The measurements were taken daily, sometimes at multiple locations, as early as January and as late as July for the years 1928, 1937, 1941, 1948-1952, and 1954-1989. The number of ice thickness measurements, conducted in different years is presented in Table 4

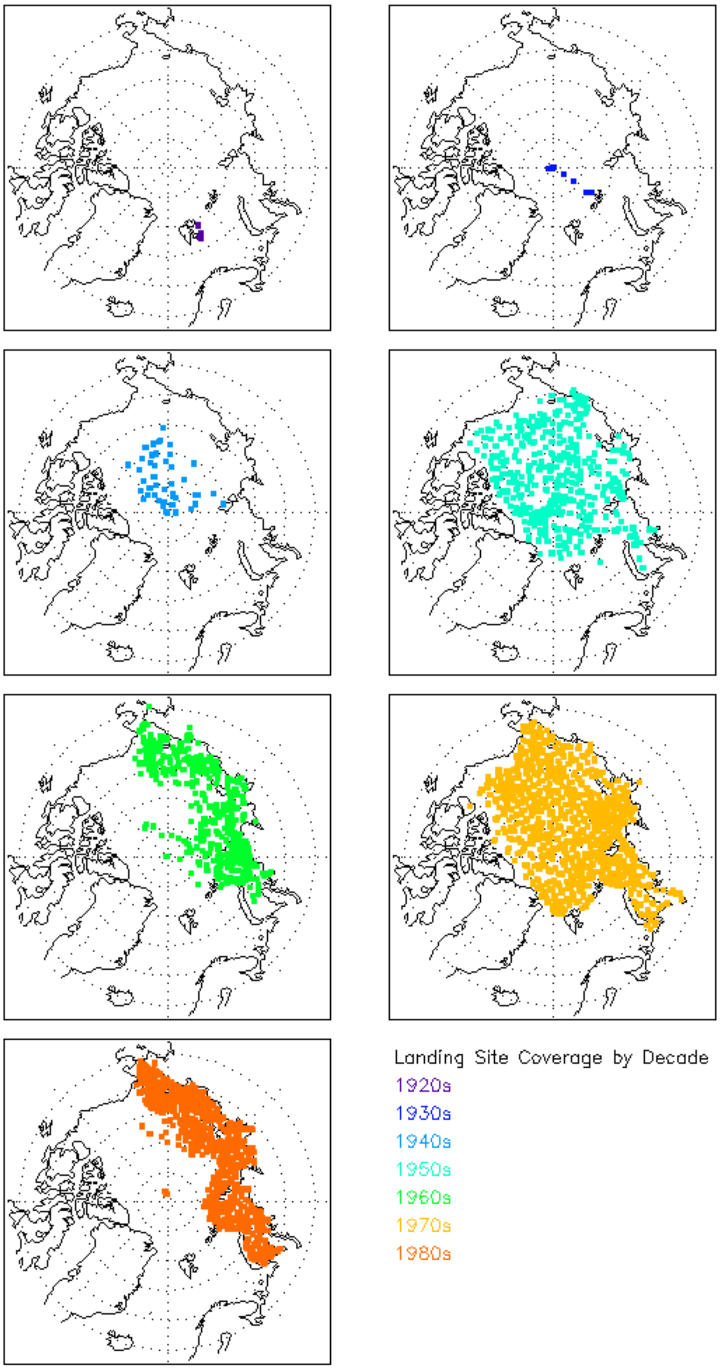


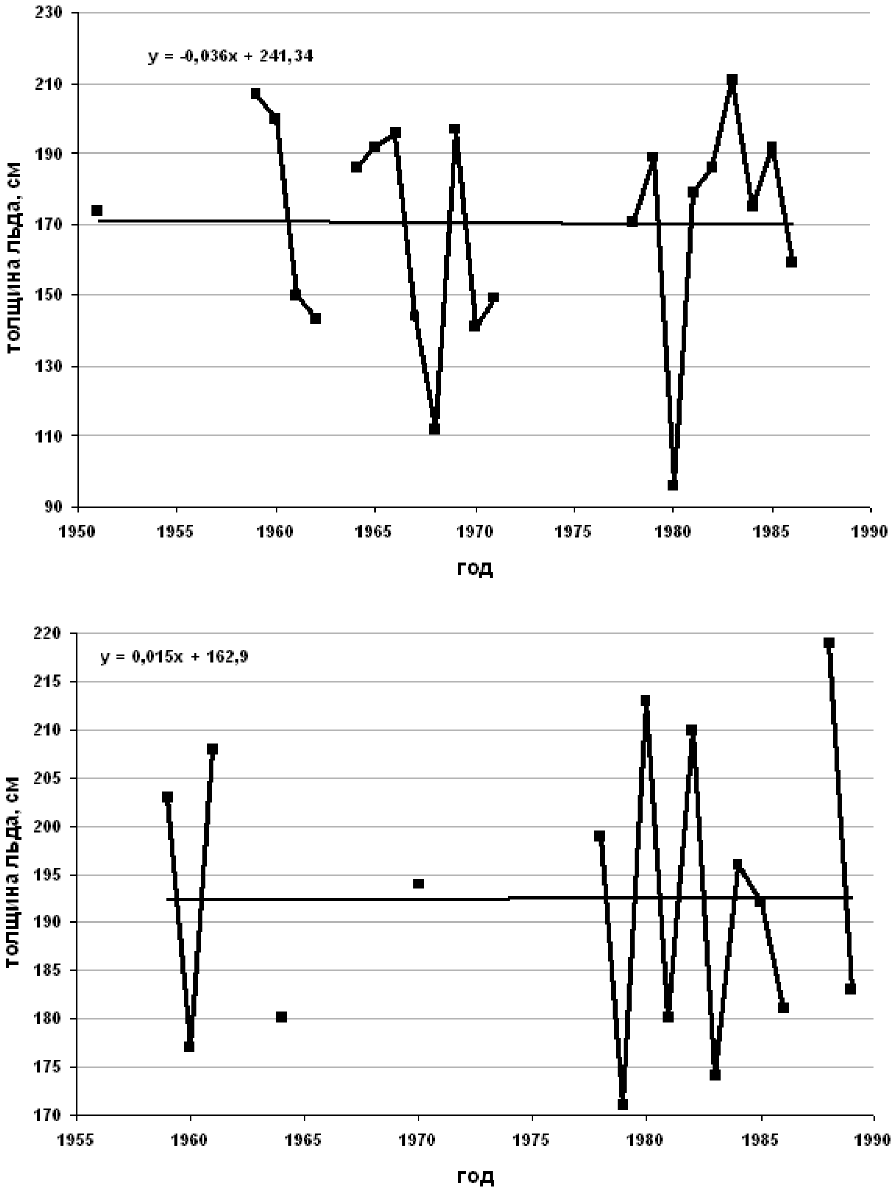
Figure 3: Landing site coverage by decade.

Year	Number of measurements	Year	Number of measurements	Year	Number of measurements
1928	3	1961	86	1975	138
1937	5	1962	60	1976	155
1948	10	1963	58	1977	154
1949	32	1964	53	1978	179
1950	45	1965	113	1979	205
1951	20	1966	81	1980	154
1952	2	1967	77	1981	114
1954	54	1968	96	1982	117
1955	79	1969	44	1983	202
1956	135	1970	57	1984	184
1957	17	1971	43	1985	200
1958	26	1972	53	1986	150
1959	80	1973	122	1988	57
1960	64	1974	158	1989	48

Table 4 Number of ice thickness measurements in different years.

2.4 Land fast ice

Fast ice occupies large areas in the Eurasian Arctic Seas, particularly in the eastern part of the Kara and Laptev Seas, and the western part of the East-Siberian Sea. By the end of winter the thickness of first-year land-fast ice over much of the area of the Arctic Seas comprises 180-200 cm, which is 15-20 cm more than the thickness of drifting ice. The only factors affecting thickness are then radiation fluxes, air temperature and snow cover. The oceanic heat flux is negligible. Under these circumstances the thickness of the ice is determined almost entirely by air temperature history, modified by the thickness of the snow cover, which alters the growth rate. Due to the influence of snow cover it is not clear that warming would necessarily lead to a thinning of the fast ice. In this



study we calculated changes in fast ice thickness from measurements, conducted during Sever expeditions.

Using this dataset changes of fast ice thickness were estimated from 1960-s to 1980-s in two regions: 1) Vilkitsky Strait and the western part of the Laptev Sea, and 2) the eastern part of the Laptev Sea and western part of the East-Siberian Sea. Ice thicknesses were recalculated to Julian day 120 (April 30) using prescribed monthly average increments in ice thickness separately for Vilkitsky Strait/western part of the Laptev Sea and eastern Laptev Sea/ western East-Siberian Sea (Alexandrov et al., 2011).

Figure 4 Year-to-year variations of the fast ice thickness in the areas of Vilkitsky Strait-western part of the Laptev Sea (a) and eastern part of the Laptev Sea – western part of the East-Siberian Sea (b). Strait lines present linear regression equations, shown in the upper parts of the plots. Reproduced from Alexandrov et al., 2011)

The year-to-year variability of fast ice thickness in these two regions is shown in Figure 4. The mode of the 20-cm interval of ice thickness distribution was used to assess ice thickness.

Analysis of the presented ice thickness estimates shows significant interannual variability in both areas, but statistically significant trend was not found. Due to a lack of measurements year-to-year variability of fast ice thicknesses cannot be calculated in other regions of the Eurasian Arctic Seas. The average thickness of fast ice in Dikson area in May of 1964 and in the Ob' region in March of 1979 amount to (174.3±12.7) and (188.4±10.7) cm, respectively. The average thicknesses of fast ice near Pevek amount to (148.7±28.8) and (170.6±26.1) cm in April and May of 1959, respectively, and to (138.2±11.75) and (159.3±3.8) cm in February and March of 1960, respectively.

In spite of absence of Sever measurements in the end of 20th and in beginning of 21st centuries we can assume that the fast ice thickness did not change significantly during this period. Calculations show that the increase in air temperature of 0.8C during the 20th century will not cause considerable changes in ice thickness. Year-to-year variations in snow thickness influence ice thickness much more than air temperature changes.

Analysis of five 65-year-long time series (1936-2000) of fast ice thickness measurements from the Kara, Laptev, East-Siberian and Chukchi Seas, presented in (*Polyakov, et al*., 2002), do not show any steady tendency: their trends are relatively small, positive or negative in sign at different locations, and not statistically significant at the 95% level. However, calculations of linear trends for the 30-year periods revealed a positive trend of 0.35 cm/year in the period 1940-1973 and a negative trend of –0.52 cm/year in the period 1973-2000, which agree with the half-century cycle of ice cover oscillations in the Arctic seas, revealed earlier (*Frolov et al.,* 2005).

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