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Arctic tide gauges: a status report

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Arctic tide gauges: a status report

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Abstract

Tide gauges in the Arctic are of high potential value for global change studies. They have the potential to provide a valuable contribution to global observing systems of the ocean and the climate system. Moreover, they are crucial if tide gauges are to be used to study present-day changes in the Arctic ice sheets. Nevertheless, in a large part of the Arctic, the present situation is characterised by a rapid reduction in the number of operational Arctic tide gauges and, consequently, a serious degradation of the observing system. Partly, this degradation is due to a lack of international requests for sea-level observations or a general lack of interest for sea-level data. In this report, the present status of the Arctic tide gauges is described and recommendations for the improvement of the operational observing are given. Metadata is not always readily available and in some cases, considerable uncertainties remain concerning the history and the present operational status of the gauges. Trends determined for the available Arctic tide gauge data indicate a spatial pattern in sea-level consistent with significant changes in the ice cover on Greenland and the larger ones of the Arctic islands. However, due to lack of data on crustal motion, ambiguities remain in the separation of geocentric crustal motion and geocentric sea-levels as well as the attribution of the observed trends to past or present changes in the ice loads.

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1. Introduction

The Arctic is a region highly susceptible to climate changes. The Arctic is expected to be sensitive to global and regional changes, and the Arctic may turn out to be the region where significant changes can be detected first. It can be expected that environmental parameters monitored in the Arctic have indicative value particularly for the early detection of climate change as well as the study of climate variability. Due to the much slower response of the ocean compared to the atmosphere, sea-level low-pass filters climate variability and thus emphasises long-term changes. Therefore, Arctic tide gauges providing long records of relative sea-level variations may turn out to be of key indicative value in global Earth observation. Moreover, the Arctic is poorly covered by satellite altimetry with TOPEX/POSEIDON being limited to 66ºN and ERS1 and ERS2 reaching not higher than 80ºN. Consequently, in most parts of the Arctic, tide gauges are the only source of observations of sea-level variations.

As discussed in the second assessment of the Intergovernmental Panel on Climate Change (IPCC, see Houghton et al., 1996), the contribution of the two large ice sheets on Greenland and Antarctica remains one of the largest uncertainties in explaining the global change in sea-level (Warrick et al., 1996). Estimates for the contribution to sea-level change from the Greenland and Antarctic ice sheets are $\pm$0.4mm/yr and $\pm$1.4mm/yr, respectively (Table 1). These uncertainties are due to several circumstances. (1) Direct measurements of volume changes of the ice sheets by satellite altimetry are still not accurate enough to reduce the uncertainties. The accuracy is particularly low over areas with steep topography, where the largest changes are likely to occur. Moreover, the time interval covered by satellite altimetry is limited to the last decade. (2) The response of glaciers and ice sheets to climate change involves long time scales of up to several centuries. Climate variability (i.e. the input forcing function) is not well enough determined both in space and time to successfully force ice mass balance models. Additionally, the available *in situ* measurements are insufficient to constrain these ice models. (3) Observations of global ocean mass (GOM) changes could help to constrain the overall mass balance of the cryosphere. However, the determination of GOM changes from relative sea-level (RSL) observations at tide gauges is uncertain in itself due to the temporal and spatial structure of the global tide gauge data set as well as the complex physical relation between GOM and RSL. Moreover, RSL is strongly affected by other factors than GOM changes. In particular, steric (volume) effects due to temperature changes of the sea water influence RSL and are difficult to separate from mass changes. (4) The determination of GOM changes from satellite altimetry is still not possible with sufficient accuracy due to the short interval of observation and problems in the separation of steric and mass effects in sea-level.

In many recent sea-level studies based on the global tide gauge data set available at the Permanent Service for Mean Sea-Level (PSMSL), the aim has been to determine a global sea-level rise. This approach suffers from inherent problems as summarized, for example, by Warrick et al. (1996) and discussed in detail in Zerbini et al. (1996) However, local RSL trends at tide gauges close to ice loads may be used to infer information about changes in these loads, particularly, if interpreted together with other geophysical signals induced by ice load changes. Thus, the sea-level equation derived by Farrell & Clark (1976) can be used to compute the RSL foot-print for a given ice history, which then can be compared to tide gauge observations (Plag, 1998; Plag & Jüttner, 2000). In this approach, tide gauges in the near-field of the changing iceload are of particular importance.

Table 1: Major contributions to global sea-level changes
Contributions are converted into equivalent rates of a globally uniform sea-level change in mm/yr. Rates taken from (Warrick et al., 1996)

Source	**Estimated rate of sea level change (mm/yr)**
Steric effects	0.2 to 0.7
Antarctica	-1.4 to 1.4
Greenland	-0.4 to 0.4
Glaciers	0.2 to 0.5
Continental ground waters	0.5 to 0.7

The need for a comprehensive observing of the Earth system is thoroughly documented in the Report of the Global Climate Observing System (GCOS) to the Fourth Conference of the Parties (COP) of the United Nations Framework Convention on Climate Change (UNFCCC) (GCOS-48, 1998). This report provides a firm scientific basis for why global observing is needed and how it needs to be carried out to provide the observational basis to detect climate change and to design measures to mitigate the impact. Moreover, the report clearly documents a severe degradation in the global observing capabilities, and this fact led to several resolutions being accepted by the Subsidiary Body for Scientific and Technological Advice (COP, 1998). These resolutions request an increased effort of the signatories of the UNFCCC to establish and maintain a comprehensive observing system for the ocean, atmosphere and terrestrial sphere. The resolution explicitly mentions sea-level as a crucial parameter to be observed.

There are many scientific applications for sea-level observations (for inventories, see, for example, IOC, 1997; Baker et al., 1997; Plag et al., 2000), which are also of particular interest for studies of changes in the Arctic region. For example, variability of ocean currents can be detected in the variability of sea surface topography, which, in turn, can be observed with pairs of tide gauges. Particularly across straits like the Fram Strait, such pairs of tide gauges would allow to monitor the flow through the strait. Since much of the variability of ocean currents happens at low frequencies, emphasis has to be on long time operation. Long-term tide gauges are also required to detect reliable local trends in sea-level.

The importance of a sea-level observing system as integral component of an Earth observing system has been emphasised in several research and observing programmes. For example, in its second scientific assessment of climate change, the IPCC stresses the need for a global sea-level monitoring system including global networks of tide gauges (Warrick et al., 1996). Already in the first implementation plan for the World Climate Research Programme (WCRP), sea-level is mentioned in several WCRP projects (WCRP, 1985). The European component of the Global Ocean Observing System (EuroGOOS) emphasises sea-level as an important parameter in its science plan (Prandle & Flemming, 1998). Finally, the recent position paper of the COST Action 40 "European Sea Level Observing System (EOSS)" summarises the many scientific and non-scientific applications of sea-level information (Plag et al., 2000).

In view of the general importance of sea-level information and the particular importance of the Arctic tide gauges for a global observing system it is worthwhile to review the operational status of these gauges and to discuss the availability and quality of the data. The report attempts to give such an overview. However, it should be mentioned that access to information on the operational status of tide gauges differs very much between the six countries involved and the information collected here cannot be considered complete or up-to-date in all cases.

As pointed out by the Arctic Monitoring and Assessment Programme (AMAP) many different definitions of the Arctic are given, which may be based on physical-geographical characteristics or on political and administrative considerations (see http://www.grida.no/amap/). For the purpose of this report, we adopt the AMAP definition of the Arctic region (Fig. 1) with the exception that we exclude the Norwegian Coast south of the Arctic circle and the Faeroes. Thus, the region considered here essentially includes the coasts north of the Arctic Circle (66º32'N), and north of 62ºN in Asia and 60ºN in North America, modified to include the northern coasts of the Aleutian chain, Hudson Bay, and parts of the North Atlantic Ocean including the Labrador Sea.

In the next section, we first describe the operational status of the tide gauges in the region described above. In Section 3, we discuss scientific demands for sea-level data from Arctic tide gauge and give a few climate-related examples of scientific applications of tide gauge data from the Arctic. In Section 4, we discuss the trends in relative sea-level as determined from Arctic tide gauges with records longer than 5 years. In both these sections, emphasis is on the demonstration of the high potential of the Arctic tide gauge network for climate variability and change studies. In Section 6, steps for the improvement of the Arctic tide gauge network are discussed, including the co-location of these gauges with space-geodetic techniques. In the final section, we summarise relevant resolutions accepted at the 1999 meeting of the GLOSS Group of Experts.

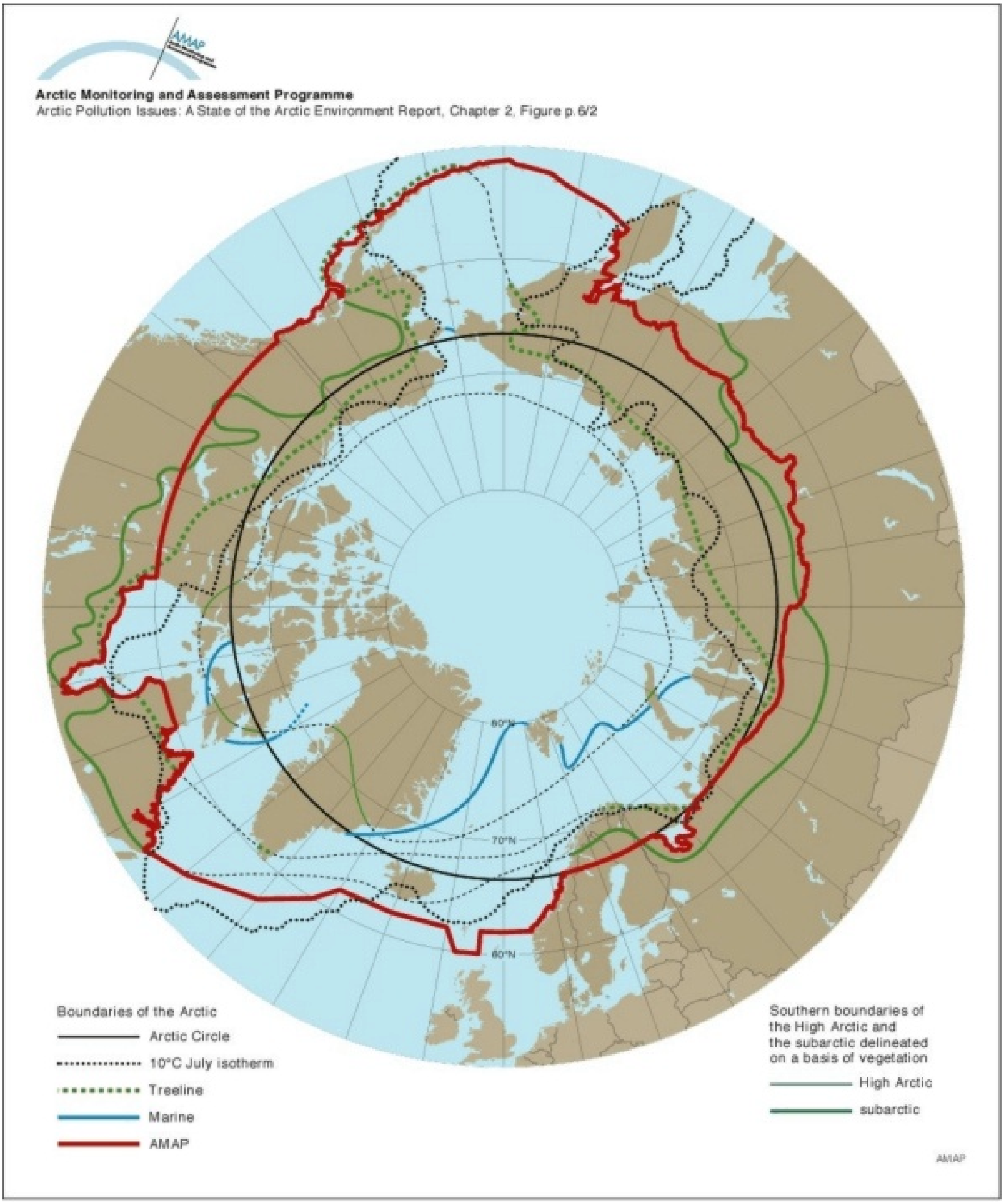

Figure 1: Definition of the Arctic region.

The lines delineate several characteristic regions used to define the Arctic. For the report, the AMAP definition is followed, which is indicated by the heavy line, excluding, however, the Norwegian coast south of the polar circle and the Faeroes. From http://www.amap.no/.

2. Operational status of Arctic tide gauges

As mentioned in the introduction, access to information on the operational status of tide gauges differs considerably between the six countries operating tide gauges in the Arctic. These countries are the USA, Canada, Denmark, Iceland, Norway, and Russia. In Russia, no central information source could be identified and the status report is based on information from individuals. However, information flow is often slow and sometimes information is contradicting and appears to be incomplete. For Canada, the Marine Environmental Data Service (MEDS) provides a comprehensive overview of the tide gauge data available on its web page[1.] Moreover, a number of individuals from different national agencies readily provide information on tide gauges. For the USA, the Center for Operational Oceanographic Products and Services of the National Oceanic and Atmospheric Administration (NOAA) maintains a comprehensive and well organised data inventory on a WWW page[2] which also allows to extract data on-line. For Iceland, no tide gauge related web site could be identified, and information is based on input from individuals, only. In Greenland, both the Danish Meteorological Institute (DMI) and the Royal Danish Administration of Navigation and Hydrography (RDANH) operated tide gauges. Both institutes maintain web pages[3] but no inventory of the tide gauge sites in Greenland or the available data is accessible through these pages. Information flow was slow and often second-handed and not very clear. In some case, different names are used for the same location. Finally, the Hydrographic Department of the Norwegian Mapping Authority has no web page dedicated to tide gauge sites and data inventory. However, together with the Norwegian Meteorological Institute (DNMI), a web page[4] is maintained giving access to a limited amount of sea-level data.

The support for operation of Arctic tide gauges differs greatly between the six countries involved. In the subsequent sub-sections, the status is described for each country separately. The most important point to mention here at the beginning is that over the last few years, a significant degradation has taken place in the tide gauge network of the Arctic. Canada has closed down all Arctic tide gauges except for Churchill at Hudson Bay. Reduced funds have led to a down-prioritising of sea-level observation, mainly because of a lack of voiced international interest in these data. In Russia, support for tide gauges is declining and a severe degradation is taking place. In Alaska, the U.S. is maintaining two high latitude tide gauges at Prudhoe Bay and at Nome, and it is likely, that these gauges will remain operational. In Greenland, several tide gauges were closed down very recently. The main purpose of most of the Danish sea-level observations was for tidal analysis and surveying. There was no other interest voiced towards the responsible agencies and this led to the closure of the gauges. In Iceland, 15 new gauges have been installed since 1992 in addition to the old one in Reykjavik, and all these gauges are likely to remain operational. In Norway, a significant number of tide gauges being operational in the Arctic are not threaten of being closed down within the next few years. However, upgrading of the important gauges on Jan Mayen to a state-of-the art gauge and installing a new gauge on Bear Island depends on external funding.

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1 see http://www.meds-sdmm.dfo-mpo.gc.ca/ and particularly http://www.meds-sdmm.dfo-mpo.gc.ca/meds/Databases/TWL/TWL_e.htm

2 see http://co-ops.nos.noaa.gov/ and particularly http://co-ops.nos.noaa.gov/usmap.html.

3 see http://www.fomfrv.dk/index.html for RDANH and http://www.dmi.dk/vejr/gron/index.html for DMI.

4 http://www.dnmi.no/forskning/index.html

2.1 Russia

The institutional background for the operation of tide gauges in the Russian Arctic has been changing rapidly over the last years creating large uncertainties. In 1998, the Russian Federal Services for Hydrometeorology and Environmental Monitoring (Roshydromet) was wound up for a short period to be restored a little later. However, the future development of the resources of Roshydromet currently is highly uncertain.

At present, Roshydromet maintains a network of 30 tide gauges in the Arctic (not including the White Sea). In the past, there were many more gauges, but a considerable number of gauges were closed because of insufficient funding for remote hydrometeorological station operation. Moreover, during recent years, the quality of hydrometeorological observations has generally decreased due to reduced support to the observational system, low payments of observers as well as staff shortages at observing sites. This development in particular affects the operation of remote stations.

At all Russian sites the sea-level heights are determined relatively to major and auxiliary geodetic bench marks. All benchmarks, except those on islands, are tied to the unified national geodetic reference system with its basic benchmark in Kronstadt, which is the zero datum of the height network.

According to the GLOSS requirements, the optimal distance between global sea-level monitoring stations is in the range from 500 to 1000 km (IOC, 1997). The GLOSS stations selected in the Russian Arctic are listed in Table 2, where the data coverage is given, too. At most of the GLOSS stations in Russia, the accuracy of level measurements meets the GLOSS requirements. Sea-level errors do not exceed 1-2 cm, and errors in time of observation are less than 1 minute. Unfortunately, the accuracy of calibration and levelling connection to the bench mark is less good, and there are considerable delays in the routine observations. Moreover, at some stations, tide gauges are damaged or lacking and observation are made using tide poles.

O. Zilberstein (1999, private communication) has collected the following data of the Russian Arctic GLOSS stations in his database at Roshydromet:

Site name	Available data
Murmansk	1949-1997
Barentsburg	1949-1997
Russkaya Gavan	1952-1991
Dikson	1977-1990
Tiksi	1977-1993
Providenia bay	1977-1993

In this database, information for monthly mean sea-level data at other Russian Arctic tide gauges is available, too. Currently, analyses of the temporal variability of mean sea-level in the Russian Arctic are under way and it is hoped to obtain permission for open publication of results (excluding primary information on the tide gauges). However, there is no open access to the database.

Table 2: Russian Arctic GLOSS stations.

Name	Longitude	Latitude	Observation period (1)		PSMSL-data		comment
			Begin	End	Begin	End	
Murmansk	33º03'E	68º58'N	1917	1997	1952	1997	
Barentsburg	14º15'E	78º04'N	1933	1997	1948	1997	
Russkaya Gavan	62º35'E	76º14'N	1932	1997	1953	1991	(2)
Dikson	80º39'E	73º22'N	1915 1981	1979 1997	-	-	(3)
Tiksi	128º45'E	71º40'N	1932 1981	1979 1997	-	-	(3)
Buktha Providenia	173º11'W	64º30'N	1934	1997	1977	1990	(3)
Nakhodka	77º31'E	67º45'N	?	?			

Comments:
(1): Some part of these data is likely to be forfeited but no firm information seems to exist.
(2): The station Russkaya Gavan is closed.
(3): Roshydromet authorities have still not released monthly mean sea-level data.

V. Pavlov (2000, private communication) has available annual and monthly mean time series of sea-level elevations from 44 tide gauges in the coastal zone of the Kara, Laptev East-Siberian and Chukchi seas. Observation period for these time series is within the time window from the end of the 1940s to the beginning of the 1990s. The data are from the data set of the Arctic and Antarctic Research Institute in St. Petersburg, Russia. V. Pavlov may use the data for hisown research but no permission is given to distribute the data.

Only for a few Russian Arctic tide gauges, all the monthly and yearly mean values are available for international exchange and these records are stored in the PSMSL database (see Table 2). However, at the majority of the tide gauges, no data are released up to now.

The longest series of observations at the Russian GLOSS stations, which are available for international exchange, is at Murmansk (1917-1997). Observations at Barentsburg span the period from 1933 to 1997, when the gauge broke down. In Russkaya Gavan the series starts in 1932 but the tide gauge operation was stopped in 1991.

Among the Russian GLOSS stations, which at present are not involved in data exchange, the longest series are found at Dixon (1915-1979 and 1981-1997) and at Bukhta Providenia (1934-1997). It should be noted, however, that due to changes in gauge locations as well as repairs of tide poles and gauges there can be no guarantee that the gauge datum for those stations remained unchanged and/or accurate reference was ensured during all that period. According to O. Silberstein (1999, private communication), trends determined from the monthly means stored in his archive at Roshydromet do not agree with trends determined from the data for the same stations available in the PSMSL archive. This discrepancy indicates serious data problems for the internationally available Russian GLOSS stations.

2.2 Greenland

In Greenland, two Danish authorities operate tide gauges, namely the Danish Meteorological Institute (DMI) and the Royal Danish Administration of Navigation and Hydrography (RDANH). In Table 3, the information available to the author is compiled. DMI operated tide gauges at least at three sites. However, two of the gauges in Eastern Greenland were closed down in 1998. These gauges were GLOSS sites but since there were no other demands for the tide gauge data, DMI decided to cease operation. At Nuuk, both RDANH and the DMI operate a tide gauge each. Sea-level data from the DMI tide gauge are delivered to PSMSL, where the record is available under the station name Godthab for the interval 1958-1997.

RDANH operates a number of tide gauges in Greenland. The first measurements started in 1990. The times for establishment and - in some cases – withdrawal of the tide gauges are given in Table 3. For locations of some of the tide gauges, see Figure 2. Apart from the new gauges in Aasiaat and Maniitsoq, data exist for at least 5 years (apart from some gaps) at each tide gauge. Air pressure sensors were mounted on the gauges in Qaqortoq and Sisimiut in 1992, i.e. in the year after the establishment of the stations. Thus, the first year of data is not corrected for air pressure changes.

RDANH uses the data basically for tidal analysis and prediction. Tide tables based on these predictions are produced in the official Tide Tables Greenland. The Hydrographic Department surveys in Greenlandic waters every summer. The sea-level data are used for correction of soundings to Chart Datum defined as Lowest Astronomical Tide (LAT). As one or two years of sea-level data are sufficient for a tidal analysis, RDANH cannot guarantee that the tide gauges will continue their operation many years ahead. Thus, in 1997, the gauges in Ilulissat and Uummannaq were withdrawn when the gauges in Aasiaat and Maniitsoq were established, instead.

Table 3: Tide gauges in Greenland

Station	Long.	Lat.	Established	Withdrawn	Comment
Ammassalik	37º00	65º30	09-7-1990		GLOSS
Aasiaat			26-6-1997		Operated by RDANH
Ilulissat	51º06	69º13	29-6-1992	23-6-1997	Operated by RDANH
Maniitsoq			30-6-1997		Operated by RDANH
Nuuk	-51º44	64º10	24-6-1992		Operated by RDANH
			~1958		GLOSS, operated by DMI
Qaqortoq	46º02	60º43	04-9-1991		Operated by RDANH, 18-6-1992: pressure sensor mounted
Sisimiut	53º40	66º56	10-9-1991		operated by RDANH, 04-7-1992: pressure sensor mounted
Uummannaq			13-7-1993	24-6-1997	Operated by RDANH
Danmarkshaven	18º45	76º46	9-1993	1998	GLOSS, operated by DMI
Scoresbysund			1993	1998	GLOSS, operated by DMI, also named Ittoqqortoormiit

Figure 2: Location of tide gauges in Greenland

Tide gauges are at Ammassalik, Nuuk, Qaqortoq, and Sisimiut. Additional gauges are at Aasiaat, and Maniitsoq (both not shown). The gauges at Ilulissat and Uummannaq were withdrawn in 1997 (both not shown). At Danmarkshaven and Scoresbysund, the GLOSS stations were closed in 1998.

In the past, RDANH sent sea-level data from Ammassalik, Ilulissat, Qaqortoq, and Sisimiut to the PSMSL once a year. Currently, the data are available at the PSMSL up to and including 1996. At Uummannaq, the conductivity sensor in the instrument did not work. However, an approximate sea-level can be derived by use of a constant value of conductivity. Nevertheless, RDANH decided not to submit the data to PSMSL.

2.3 Iceland

The Icelandic Hydrographic Service (IHS) has been operating a float and stilling well tide gauge in Reykjavik since 1951. In 1994, IHS installed a new pressure sensor tide gauge beside the old one and has been operating both since. In connection with the new tide gauge, there are also air pressure sensors, sensors for wind speed and direction and air temperature. Since 1957 IHS has sent the sea-level data from Reykjavik to PSMSL.

From 1992, The Icelandic Maritime Administration (IMA) has installed a number of tide gauges around Iceland in cooperation with harbour masters in each of the harbours given in Table 4. Most of these tide gauges have not been levelled to the Hjorsey-Datum even though they have been running for some years and some tide gauges have not been working properly.

Table 4: Position of tide gauges on Iceland.
All gauges are operated by IMA since 1994, except for the GLOSS site at Reykjavik, which operates since 1951.

Harbour	Latitude	Longitude
Hafnafjordur	64º04'N	21º57'W
Grundartangi	64º21'N	21º47'W
Akranes	64º19'N	22º06'W
Ólafsvik	64º54'N	23º42'W
Patreksfjordur	65º35'N	24º00'W
Skagastrond	65º49'N	20º20'W
Dalvik	65º58'N	18º31'W
Husavik	66º02'N	17º21'W
Hvanney	64º14'N	15º11'W
Skinneyjarhofdi	64º13'N	15º29'W
Porl	63º51'N	21º22'W
Vestmanneyjar	63º27'N	20º13'W
Grindavik	63º50'N	22º26'W
Sandgerdi	64º02'N	22º43'W
Keflavik	64º00'N	22º33'W
Reykjavik	64º09'N	21º56'W

The data from these gauges are collected from each of the stations through telephone lines every day to the (IMA) headquarters. IMA is working on the levelling process, the data will then be corrected and are expected to be available sometime in 2000. Each of these tide gauges has also sensors for air pressure, for wind speed and direction, and air temperature.

2.4 Norway

Norwegian Authorities have been operating a number of tide gauges in the Arctic, some for more than four decades. The stations delivering data to the PSMSL are included in Table 8. The GLOSS sites are listed in Table 5. Today, the Norwegian Hydrographic Service of the Norwegian Mapping Authority (NMA) operates 10 tide gauges north of 67º. All these tide gauges record digitally and are connected to the telephone network. No other environmental variables, except barometric pressure, are recorded in addition to sea-level. The hourly data are compiled in a database which currently is being quality-checked.

At Jan Mayen, the tide gauge is operated by the Geodetic Institute of NMA and this gauge is still analog. It is planned to replace this tide gauge within the next two or three years when all other tide gauges will also be upgraded. It will be necessary to find a new location for the tide gauge on Jan Mayen to avoid local effects of the present site. At Bjørnøya, a preliminary reconnaissance has revealed considerable problems in finding a suitable location for a tide gauge.

At Longyearbyen, Svalbard, a tide gauge is operated by the Norwegian Polar Institute.

Table 5: Norwegian Arctic GLOSS gauges.

Station	Latitude	Longitude	Status
Bjørnøya	74º26’N	19º10’E	No gauges
Honningsvåg	70º59’N	25º59’E	to be replaced by Hammerfest
Hammerfest	70º40’N	23º40’E	To be submitted
Jan Mayen	70º55’N	8º43’W	Old analog gauge
Ny-Ålesund	78º56’N	11º56’E	To be submitted
Andenes	69º19’N	16º09’E	To be submitted

2.5 Canada

Over many years, Canada has carried out tidal recordings at many locations over short time intervals (typically 30 to 80 days). In a very worthwhile effort, the Institute of Ocean Sciences recently has compiled most of the tide gauge data into a digital archive with an impressive list of sites. This archive is available at the Marine Environmental Data Service (MEDS) (an inventory of the data is available at http://www.meds-sdmm.dfo-mpo.gc.ca/Meds/e_home.html). In addition to short campaign-type observations, a number of tide gauges were operated for longer periods. Sites with more than 365 days of observations are listed in Table 6. For most of the sites given there, monthly mean values have been submitted to PSMSL for approximately the interval given in the Table 6 (compare to Table 8).

At the present time, Canada has no functioning Arctic tide gauges (except for Churchill in the Hudson Bay), although in at least one location (Tuktoyaktuk) the infrastructure remains in place to re-establish a tide gauge easily. The station at Alert was closed several years ago, and during the last few years of operation may only have been gauged with a submersible Aanderaa pressure gauge. The station at Little Cornwallis Island stopped operation in 1994. The gauge structure was left in place but it is not clear what it would take to reactivate the site. The station at Sachs Harbour was shut down in 1996 or 1997 and for the last few years of operation, it was most likely only a submersible Aanderaa pressure recorder. With the closure of Tuktoyaktuk and Cambridge Bay in 1997, Canada lost the last tide gauges in the Arctic. Some water level data is being collecting by the Atmospheric and Hydrologic Sciences Division of Environment Canada at the mouth of the Mackenzie River as part of their development of a Mackenzie River discharge model.

The primary functions of the Canadian Hydrographic Service (CHS) are to service navigation requirements and international treaty obligations. Budget limitations required decisions on the basis of these primary functions. The led to the recent constriction of the sea-level measurements, since science applications of the sea-level network are not a significant aspect of the current interpretation of the CHS mandate. However, the science community in Canada recognises the need for Arctic water level gauging as part of the global climate observing system and as a necessary input to regional coastal development plans, and there are concerns about the demise of tide gauges throughout Canada and particularly in the Arctic. At present, attempts are being made to re-establish abandoned Arctic tide gauge stations in Canada under the auspices of GCOS and of GOOS. Of first priority is a gauge at Alert at the northern end of Ellesmere Island, which could provide a zero-order sea-level signal from the Arctic Ocean of relevance to the forcing of flow from the Arctic Ocean into the Labrador Sea. For the same purpose, but at lower priority, a second site is proposed at Cape Parry on the mainland coast, 2000 km to the southwest. In the sub-Arctic on the east coast of Canada, a gauge is proposed for installation at Nain, on the central Labrador coast.

Table 6: Tide gauges in the Canadian Arctic with at least 365 days of observations.
All stations with at least one year of observations are given as listed on http://www.meds-sdmm.dfo-mpo.gc.ca/ALPHAPRO/TWL/products/B_PT_INV.HTML.Latitudes are in º N and longitudes in º W. Start and end are given for hourly values. Highs and lows, daily means and monthly extremes may cover different intervals. Note that the actual operational interval might be longer than those given for the hourly values available in the digital archive. For more information, the home page of the Marine Environmental Data Service (MEDS) at http://www.meds-sdmm.dfo-mpo.gc.ca/Meds/Home_e.htm may be consulted.

Station	Lat.	Long.	From	To	Days	%
NAIN AST	56.55	61.68	10/09/1983	05/08/1986	681	64.2
NAIN	56.54	61.69	17/10/1963	01/12/1988	4337	47.3
ALERT	82.50	62.32	01/11/1961	15/08/1979	4493	69.2
FROBISHER BAY	63.74	68.53	20/08/1963	29/08/1977	1212	23.7
LAKE HARBOUR	62.85	69.88	18/08/1970	24/07/1975	1334	74.0
KOARTAC	61.03	69.63	02/09/1970	30/04/1974	539	40.3
NORTH KOPAK ISLAND	60.00	77.75	26/07/1975	16/09/1976	102	24.3
INUKJUAK	58.45	78.10	20/08/1957	31/10/1980	2529	29.8
CORAL HARBOUR	64.13	83.26	05/09/1970	30/06/1979	1139	35.4
HALL BEACH	68.75	81.25	02/08/1970	16/08/1982	370	8.4
RESOLUTE	74.68	94.89	01/11/1961	12/06/1977	5398	94.7
SPENCE BAY	69.53	93.52	01/01/1971	29/04/1982	1948	47.1
FORT CHURCHILL	58.77	94.07	01/01/1972	30/09/1974	998	99.4
CHURCHILL	58.77	94.19	01/11/1961	31/03/2000	12682	90.4
CAMBRIDGE BAY	69.12	105.07	01/11/1961	23/03/1982	4911	65.9
COPPERMINE	67.88	115.20	11/11/1972	27/04/1982	1382	40.0
CAPE PARRY	70.15	124.67	24/07/1966	19/05/1982	3472	60.1
SACHS HARBOUR	71.97	125.15	03/09/1971	31/07/1982	2128	53.4
TUKTOYAKTUK	69.43	133.00	01/11/1961	02/10/1991	5187	47.5
LITTLE CORNWALLIS IS.	75.38	96.95	06/11/1986	28/09/1994	2883	100.0
REA POINT	75.37	105.60	10/08/1975	11/08/1976	368	100.0

In low-lying areas where there is human habitation, notably the Mackenzie River delta in the Beaufort Sea, and on the western shore of Hudson Bay, focus is on erosion and flooding. Tentatively, gauges at Tuktoyaktuk and at Churchill are proposed to address these concerns.

Observations to detect change in Arctic Ocean sea-level associated with change in freshwater storage (contributing a steric anomaly analogous to that associated with the warming of temperate oceans) have yet to be addressed. Since altimeter technology is not suited to determining the topography of the sea surface in the presence of sea ice, tide gauges would provide valuable observational constraints.

Recent meetings to define a Canadian GOOS indicated that there was little support for Arctic observations, in part because the international GOOS did not yet define an Arctic component. Here, a request for Arctic sea-level observations from the global observing systems would be helpful.

2.6 U.S.A.

The U.S. National Oceanic and Atmospheric Administration (NOAA) has succeeded in the collection of high quality continuous year-round data for the last few years at Prudhoe Bay, Nome, and Nikiski, AK. There are many other historical station locations with shorter observational time periods north of 60ºN, with most of these historical locations located in northern Cook Inlet and Prince William Sound.

Prior to the early 90s, the tide gauge stations used various configurations of float driven gauges or bubbler pressure gauges. A list of the presently operational U.S. tide gauges in Alaska north of 60ºN including additionally those on the Aleutian chain is given in Table 7. These stations are operated by NOAA. The tide gauges at Cordova, Valdez, and Seward are configured with downward-looking acoustic sensors using a sound path tube inside a protective well as the primary gauge and a digital-bubbler pressure gauge as the backup. Due to the ice problem, the tide gauges at Nikiski, Anchorage, and Nome are configured with a dual orifice digital-bubblers using Paroscientfic pressure transducers. The two bubbler-orifices are a fixed distance part in the water column so that an estimate of a water density correction can be made to each measurement. The transducers are fully vented to the atmosphere. The tide gauge at Prudhoe Bay uses an acoustic sensor during the ice-free summer months and is switched to a single-orifice digital bubbler using a Paroscientific transducer in the winter months. All stations report at 6-minute intervals derived from a 3-minute average of higher rate samples centered every 6-minutes in time. The data are collected every hour by GOES satellite transmitters using telephone backup. Preliminary raw data are run through automated quality control checks and loaded into NOAA's data base for Web access and further quality control and derivation of standard products after monthly verification. Annual maintenance is performed, including level checks between the sensor zeros and the local bench mark networks.

Preliminary and verified 6-minute data for the most recent several months and verified hourly heights, high and low tides and monthly means for much of the entire series are available over the Web at http://www.co-ops.nos.noaa.gov. From dates given in Table 7 are for availability of verified digital hourly and monthly mean data.

There is an ongoing effort to stage and verify historical hourly heights, high and low waters, and monthly means for the entire series at each station onto NOAA's new data base management system which serves as the source of data available over the Web. For Alaska, the web data base includes the sites shown in Figure 3.

Table 7: Operational USA Tide Gauges in the Arctic.

Note that tide gauges may have been installed much earlier than the start of the data interval. Data intervals may include gaps and/or changes of the tide gauge. For full information, see http://co-ops.nos.noaa.gov/usmap.html.

Name	Latitude	Longitude	Hourly from	Monthly from
Cordova	60 33.5N	145 45.2W	1/96	4/64
Valdez	61 07.5N	146 21.7W	1/96	5/73
Seward	60 07.2N	149 25.6W	1/96	4/29
Nikiski	60 40.0N	151 23.8W	10/96	6/71
Anchorage	61 14.3N	149 53.3W	1/96	5/64
Nome	64 30.0N	165 25.8W	4/93	10/92
Prudhoe Bay	70 24.0N	148 31.6W	10/94	9/88
Seldovia	59 26.4N	151 43.2W	07/75	06/64
Kodiak Island	57 43.9N	152 30.7W	07/84	01/49
Sand Point	55 20.2N	160 30.1W	09/72	11/72
Unalaska	n.a	n.a.	01/82	05/55
Adak Island	51 51.8N	176 37.9W	03/50	05/43

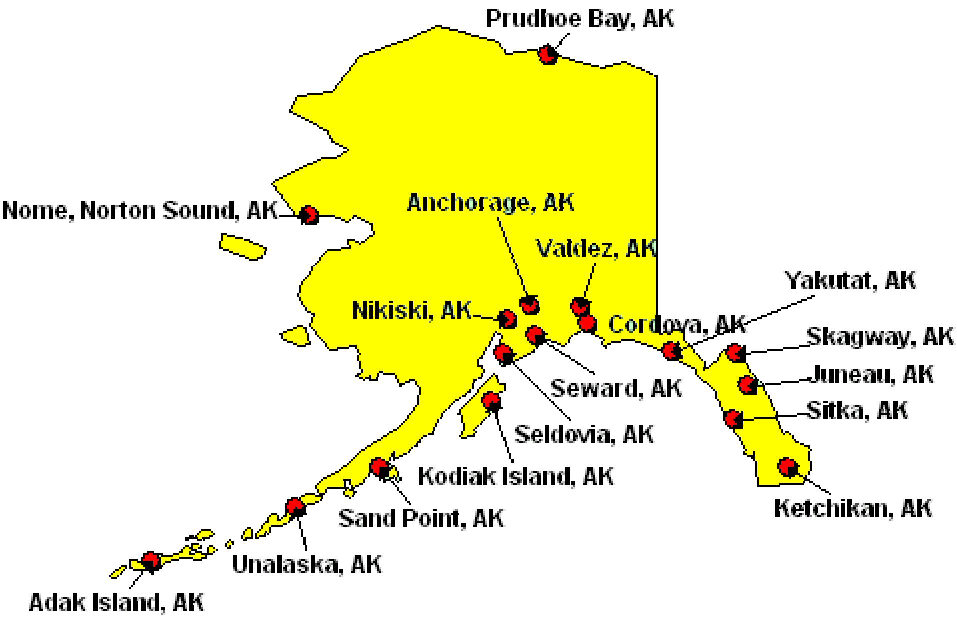

Figure 3: Location of USA Tide gauges in Alaska.

Note that the tide gauges Yakutat, Skagway, Juneau, Sitka, and Ketchikan are not included in Table 7, as they are outside the Arctic as defined in Figure 1. Figure is from http://co-ops.nos.noaa.gov/usmap.html.

3. Scientific demands for Arctic Tide gauges

Here we give a few examples of scientific applications of sea-level information in the Arctic. Interest in coastal sea-level monitoring in the Arctic arises in a number of areas including:

- post-glacial isostatic rebound due to past changes in the ice sheets;
- sea-level changes due to present-day changes in ice sheets;
- Pacific-Arctic-Atlantic sea-level gradient;
- navigation in shallow coastal seas;
- erosion of ice-bonded coastal cliffs;
- storm surge and flooding of low-lying coastal areas;
- climate related changes in ocean circulation.

Present-day trends derived from tide gauges have been used in a number of studies to validate post-glacial rebound models (e.g. Davis & Mitrovica, 1996; Peltier, 1998; Milne et al.,1999). In turn, model predictions of the present-day trends in relative sea-level due to post-glacial rebound have been used to de-contaminate tide gauge trends for the post-glacial rebound signal in studies of global sea-level changes (e.g. Peltier & Tushingham, 1989, Douglas, 1997).

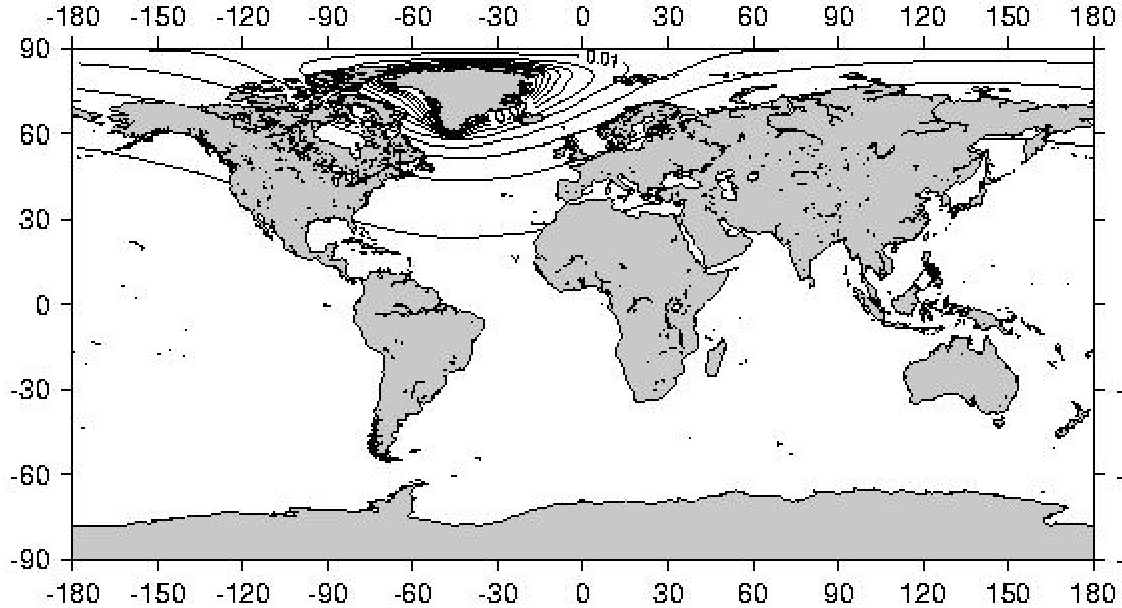

Figure 4: Sea-level finger-print of ice mass changes on Greenland.
The isolines indicate the spatial pattern of a unit ice-load change over Greenland in sea-level. Note the strong spatial gradients in the Arctic. From Plag & Jüttner, 2000.

In Section 4, it is pointed out that at many Arctic tide gauges, there are significant discrepancies between the local relative sea-level trends and the trends predicted by post-glacial rebound models. As discussed in Plag & Jüttner (2000) and Mitrovica et al. (2000), in the near-field to the large ice sheets, large sea-level signals can be expected as a consequence of present-day changes in the ice sheets. Figure 4 shows the finger-print in sea-level resulting from a unit change in the ice mass of the Greenland ice sheet. Around Greenland and throughout the Arctic, sea-level changes display a significant space-dependency. Therefore, Arctic (and also Antarctic) tide gauges are of particular value in constraining changes in the Greenland (and Antarctic) ice sheets.

The analysis of sea-level observations at coastal and island stations in the Siberian shelf seas of the Arctic Ocean reveals large interannual to decadal variability in sea-level with a general tendency of a positive sea-level trend during the last 5 decades (Pavlov, 1998; Pavlov & Pavlov, 1999; Pavlov et al.,1999). Figure 5 shows four typical examples from stations in the Kara, Laptev, East-Siberian and Chukchi Seas (from Pavlov et al., 1999).

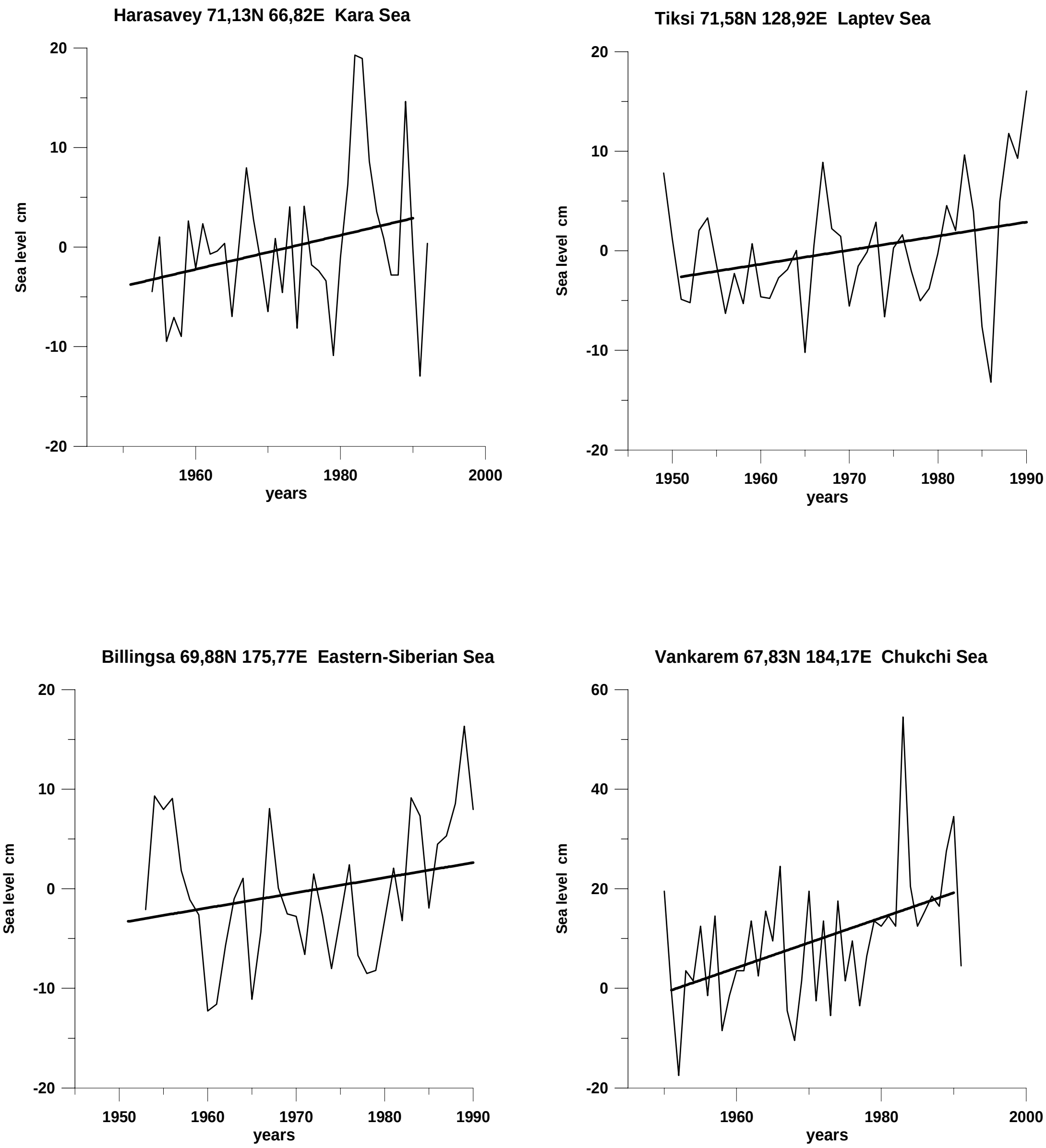

Figure 5: Interannual sea-level variability at coastal sites in the marginal Arctic Seas. *The figure shows typical examples of the interannual variability of the sea-level at stations in the Kara, Laptev, East-Siberian and Chukchi Seas. From Pavlov et al. (1999).*

According to Pavlov & Pavlov (1999), the cause for decadal variations and the positive sea-level trend is related to a decrease in salinity and an increase in water temperature as well as a reorganisation of the large scale water circulation, which is attributed to a warming in the Arctic. Observations of the temperature and salinity in the surface layer in the coastal zone of the Siberian shelf seas covering the last 3 decades indicate a positive (0.01° C/year) trend for temperature and negative (-0.0427 Psu/year) trend for salinity (Pavlov et al., 1999). In the deep regions of the Arctic Ocean, the water temperature has increased during the 1990s (Pavlov & Stanovoy, 1998).

These few examples demonstrate the value of sea-level observations from Arctic tide gauges for different scientific applications, particular those related to studies of climate variability and change in the Arctic. In the light of these examples, the continuation and even an improvement of the Arctic tide gauge network appears to be a necessary component of the Earth observing system.

4. Relative sea-level trends at the Arctic tide gauge data

The PSMSL global tide gauge data set contains a large number of quality-controlled records (Spencer & Woodworth, 1993). Currently, the data set comprises approximately 1800 records. Table 8 gives an overview of the monthly mean tide gauge data available at the PSMSL for Arctic tide gauges.

In Figure 6 the monthly mean values for the Arctic tide gauge records found in the global database of the PSMSL are shown after an annual and semi-annual harmonic constituent and a linear trend has been removed (see figure caption for more explanation). In the Figure, we have compiled all Arctic records available in the PSMSL database with more than 5 years of data. In some cases, the national authorities responsible for maintaining the tide gauges have far more data available than stored in the PSMSL data base (see Section 2). The model fitted to the time series also includes a linear trend. In the rest of this section, we will mainly focus on the discussion of this trend.

A change in sea-level measured relative to a benchmark on land is the difference between geocentric sea surface changes and geocentric vertical motion of the tide gauge benchmark (ideally this is identical to the vertical motion of the crust). For linear trends, we therefore can write

(1) $r = t + v$

where r is the geocentric sea-level trend, t the relative sea-level (RSL) trend (positive for rise), and v the geocentric vertical crustal motion (positive for uplift). The determination of the geocentric sea-level changes thus requires knowledge of the vertical crustal motion v. At most tide gauges, this is currently not available.

A major contribution to RSL is the post-glacial rebound signal (pgs). To decontaminate RSL trends from the pgs, Peltier & Tushingham, (1989) used a model to compute the pgs in RSL p and computed a decontaminated geocentric sea-level

(2) $s = t - p.$

In another approach, Zerbini et al. (1996) used

(3) $w = -(t-p-e);$

with e = 1.8 mm/yr to determine crustal vertical motion in the Mediterranean and found small (of the order of $\pm$1 mm/yr) and spatially consistent values for the crustal motion. In Table 9, s and w are given for the Arctic stations of Figure 6 using two different postglacial rebound models provided by Mitrovica (1996, personal communication). Model 1 has an elastic lithosphere of 120 km, and upper and lower mantle viscosities of 1×10^{21} Pas and 2×10^{21} Pas, respectively. Model 2 is identical to Model 1 except for a lower mantle viscosity of 4.75×10^{21} Pas. The ice model used is ICE-3G (Tushingham & Peltier, 1991).

Table 8: Arctic tide gauges available at PSMSL.

Name	Longitude (º)	Latitude (º)	Start year	End year
REYKJAVIK	-21.93332	64.15003	1951	1997
GRINDAVIK	-22.43332	63.83333	1957	1965
JAN MAYEN	-8.71675	70.91666	1974	1983
TORSHAVN	-6.76667	62.01667	1957	1996
BARENTSBURG	14.25000	78.06667	1948	1996
NY-ALESUND	11.93333	78.93333	1976	1997
RUSSKAYA GAVAN	62.58333	76.20000	1953	1991
MURMANSK	33.05000	68.96667	1952	1996
CAPE ZHELANIJA	68.58337	76.95000	1957	1959
LINAKHAMARI	31.36667	69.65003	1931	1939
CAPE CHELYUSKIN	104.28333	77.71667	1957	1959
CAPE SCHMIDT	179.46666	68.91666	1957	1959
VARDO	31.10000	70.33337	1947	1997
VARDO II	31.10000	70.36670	1880	1885
VADSO	29.75000	70.06667	1969	1987
BERLEVAG	29.10000	70.85000	1939	1944
HONNINGSVAG	25.98333	70.98333	1970	1997
HAMMERFEST	23.66667	70.66666	1995	1997
TROMSO	18.96667	69.65003	1952	1997
ANDENES	16.15000	69.31667	1938	1997
RISOYHAMN	15.65000	68.96667	1955	1956
HARSTAD	16.55000	68.80003	1952	1997
EVENSKJAER	16.55000	68.58337	1947	1970
NARVIK	17.41667	68.43333	1928	1997
KABELVAG	14.48333	68.21667	1880	1997
BODO	14.38333	67.28333	1949	1997
LERWICK	-1.13333	60.15003	1957	1997
SULLOM VOE	-1.29999	60.45000	1985	1986
UGOLNAJA BAY	179.41673	63.03333	1957	1959
PROVIDENIYA	-173.18333	64.50000	1977	1989
POINT BARROW	-156.76666	71.33337	1957	1958
ANCHORAGE	-149.89999	61.23333	1964	1997
NIKISKI	-151.39999	60.68333	1973	1997
SEWARD	-149.43333	60.11666	1925	1997
VALDEZ	-146.36670	61.13336	1973	1997
CORDOVA	-145.76666	60.55000	1964	1997
FROBISHER BAY	-68.53333	63.75000	1965	1973
CORAL HARBOUR	-83.16666	64.13333	1971	1979
IGLOOLIK	-81.79999	69.38333	1975	1976
RESOLUTE	-94.88333	74.68333	1957	1977
LITTLE CORNWALLIS IS	-96.95011	75.38333	1992	1994
ALERT	-62.31665	82.50000	1965	1977
SPENCE BAY	-93.60005	69.50000	1975	1982
CAMBRIDGE BAY	-105.06667	69.11670	1965	1982
COPPERMINE	-115.25000	67.88333	1972	1982

Table 8: Arctic tide gauges available at PSMSL (continued).

Name	Longitude (º)	Latitude (º)	Start year	End year
CAPE PARRY	-124.66666	70.15003	1970	1982
SACHS HARBOUR	-125.25000	71.96667	1971	1982
TUKTOYAKTUK	-132.96666	69.41666	1962	1982
ILULISSAT	-51.10006	69.21667	1992	1996
SISIMIUT	-53.66666	66.93333	1991	1996
GODTHAB	-51.73336	64.16666	1958	1997
QAQORTOQ	-46.03333	60.71667	1991	1996
AMMASSALIK	-37.00000	65.50000	1990	1996

Under the assumption that the pgs predicted by the two models is close to the actual pgs, then *s* can be interpreted as the difference between geocentric sea-level changes and any vertical crustal motion other than postglacial rebound. A value of *s* close to zero indicates that these two contributions nearly compensate each other while a positive/negative value indicates a geocentric sea-level change larger/smaller than vertical crustal motion. For the Norwegian stations south of 68.6ºN, there is a tendency for uplift larger than the geocentric sea-level trend while further north and east, the geocentric sea-level appears to be larger than uplift. Only for those sites with short records, this pattern is disturbed. At all other stations except for Tuktoyaktuk (with a short record), *s* is close to zero.

Assuming a global sea-level rise of 1.8 mm/yr (Douglas, 1997), *w* tends to be positive except for Murmansk, Russkaya Gavan, Tuktoyaktuk (short record), and Honnigsvåg (with possible problems in the geodetic control). This pattern is consistent with an overall deloading due to a decrease of the Arctic land-based cryosphere, particularly the Greenland ice sheet (Plag & Jüttner, 2000). However, problems in the predictions of the pgs may bias the *w*. Moreover, the values for *w* may also partly be due to tectonics.

A more reliable interpretation of the sea-level trends and a separation of sea-level changes from crustal motion require additional measurements at the tide gauges.

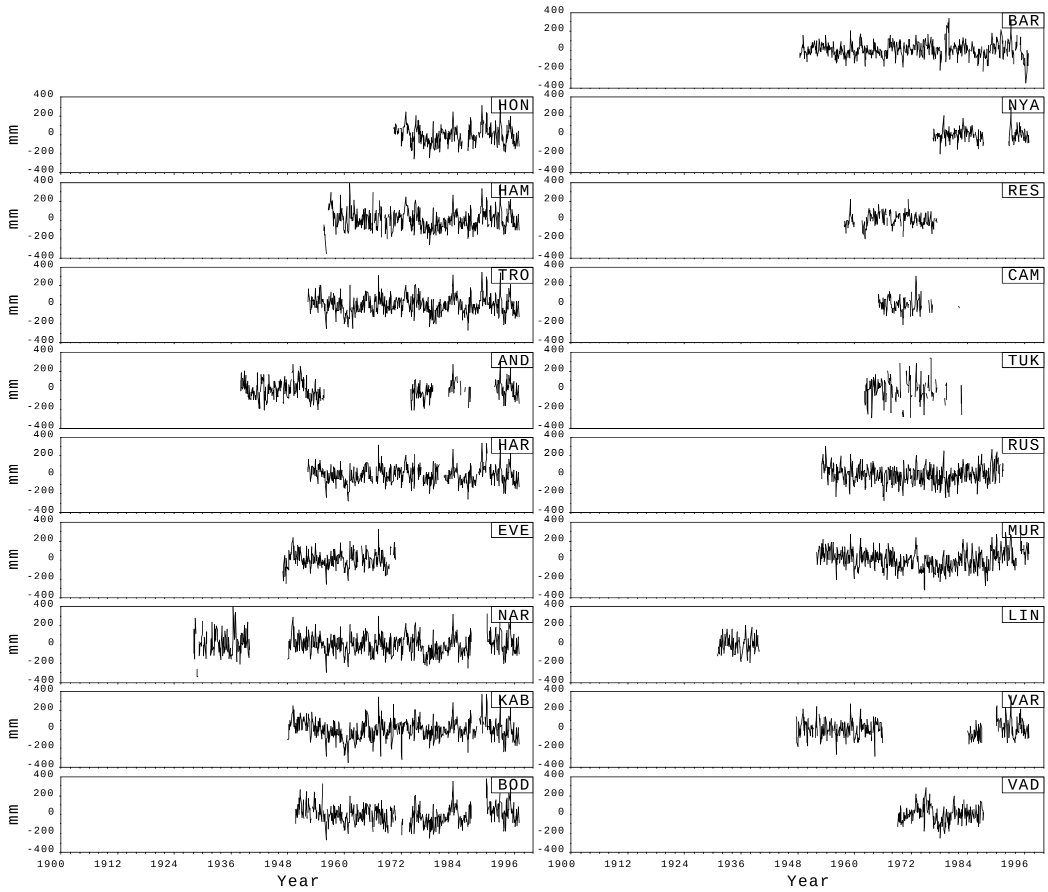

Figure 6: PSMSL's Arctic tide gauge records.

For the full names of the sites, see Table 9. Displayed are the residual monthly means after a model consisting of a seasonal cycle and a linear trend has been removed. The model is fitted to the time series in a least squares fit. The seasonal cycle is represented by an annual and a semiannual harmonic constituent. Thus, the full model $m(t) = A\{Sa\} \sin(\omega\{Sa\}\, t + \varphi\{Sa\}) + A\{Ssa\} \sin(\omega\{Ssa\}\, t + \varphi\{Ssa\}) + a + bt$ *with t being the time, A the amplitude,* ω *the angular frequency,* φ *the phase of the constituent, and Sa and Ssa denoting the annual and semi-annual constituents, respectively. The trends resulting from the fits are compiled in Table 9 together with other relevant parameters of the two time series. Note the non-linear behaviour at both Russkaya Gavan and Murmansk. Unfortunately, the tide gauge at Russkaya Gavan was closed in 1991.*

Some neighbouring tide gauges display some large differences indicating problems in the maintenance or the data. For example, compare Barentsburg and Ny-Ålesund around 1980 and 1994. These features become more elaborated by considering monthly differences between neighbouring tide gauges (see Plag, 1998a).

At all sites, the original monthly means are dominated by the annual and semiannual harmonic constituents with amplitudes of the order of 100 mm and 20 mm, respectively. Only at Cambridge Bay is the semiannual constituent with almost 70 mm much larger than the average. Along the Norwegian Coast and up to Svalbard and along the Siberian Coast maximum sea-levels occur late in autumn while at the North American sites the maximum occurs in summer, a pattern that may be attributed to the presence and absence of the gulf stream, respectively. Non-seasonal variations are generally of the order of $\pm$*150 mm with a few exceptional sea-levels exceeding* $\pm$*200 mm.*

Table 9: Trends at Arctic tide gauges.
N is the number of monthly values in the record, t is the linear term and δt the standard error resulting from the fit of the model equation given in Figure 4 to the time series. s is computed from eq. 2, while w results from eq. 3 assuming e=1.8 mm/yr (Douglas, 1997). The indices 1 and 2 refer to the two models for the pgs (see text). All rates in mm/yr.

Station	Beg.	End	N	t	δt	p_1	p_2	s_1	s_2	w_1	w_2
Bodø	1949	1996	482	-3.049	0.5	-2.5	-3.6	-0.5	0.6	2.3	1.2
Kabelvåg	1880	1996	572	-0.962	0.3	-0.5	-1.6	-0.5	0.6	2.3	1.2
Narvik	1928	1996	685	-3.245	0.2	-2.2	-3.5	-1.0	0.3	2.8	1.5
Evenskjær	1947	1970	267	-4.000	0.7	-1.3	-2.5	-2.7	-1.5	4.5	3.3
Harstad	1952	1996	497	-0.053	0.4	-0.9	-2.1	0.8	2.0	1.0	-0.2
Andenes	1938	1996	362	1.538	0.5	0.2	-0.9	1.3	2.4	0.5	-0.6
Tromsø	1952	1996	533	0.034	0.3	-0.8	-2.1	0.8	2.1	1.0	-0.3
Hammerfest	1955	1996	471	-0.137	0.4	-1.2	-2.7	1.1	2.6	0.7	-0.8
Honningsvåg	1970	1996	292	2.705	0.5	-1.3	-2.9	4.0	5.6	-2.2	-3.8
Vadsø	1969	1987	206	-2.318	0.6	-2.1	-3.9	-0.2	1.6	2.0	0.2
Vardø	1947	1996	322	-0.755	0.5	-1.6	-3.4	0.8	2.6	1.0	-0.8
Linakhamari	1931	1939	107	-4.377	1.2	-2.2	-4.0	-2.2	-0.4	4.0	2.2
Murmansk	1952	1996	530	1.581	0.3	-2.4	-4.1	4.0	5.7	-2.2	-3.9
Russkaya Gavan	1953	1991	457	-0.851	0.4	-2.8	-4.5	1.9	3.6	-0.1	-1.8
Tuktoyaktuk	1962	1982	156	7.134	1.1	3.0	2.7	4.1	4.4	-2.3	-2.6
Cambridge Bay	1965	1982	121	-3.991	1.0	--3.5	-5.8	-0.5	1.8	2.3	0.0
Resolute	1957	1977	206	-2.338	0.9	-3.2	-4.3	-0.3	1.4	2.1	0.4
Ny-Ålesund	1976	1996	175	-1.373	0.8	-0.9	-1.3	-0.5	-0.1	2.3	1.9
Barentsburg	1948	1996	560	--2.253	0.3	-2.0	-2.6	-0.3	0.3	2.1	1.5

5. Proposed activities

It is proposed to organise the Arctic tide gauges into a more homogeneous regional network, which would constitute a sub-network of GLOSS. The co-location of these tide gauges with space-geodetic receivers and, eventually, absolute gravity measurements is highly recommended.

The objective of the network would be to enhance our knowledge concerning vertical crustal movement and sea-level changes along the Arctic coast on intra-seasonal to decadal time scales in order to contribute to a better understanding of the effects of climate changes on the Arctic and in order to detect such effects at the earliest possible stage.

To achieve the objective, it would be necessary

- to co-locate at least five existing, equally distributed operational tide gauges in the Arctic with continuously recording GPS receivers (CGPS);
- to perform zero-epoch absolute gravity measurements at these tide gauge;
- to connect all operational Arctic tide gauges in a zero-epoch GPS campaign.

The tide gauges selected for potential co-location with CGPS and absolute gravity could be Hammerfest in Norway, Tiksi in Russia, Alert in Canada, Danmarkshavn in Greenland, and Prudhoe Bay in Alaska.

It is considered here, however, that Canada has closed down all Arctic tide gauges. This is a loss for the proposed project and it would be an important step towards a sea-level monitoring in the Arctic, if at least some of the Canadian GLOSS gauges could be reinstalled. Denmark has closed down the gauges in Eastern Greenland, and the tide gauge in Danmarkshaven would have to be re-established.

The tide gauge at Ny-Ålesund, Svalbard is already connected to a CGPS site. Absolute gravity measurements were carried out at the site in July 1998 and 2000, and will be repeated frequently. A co-location of the tide gauge at Barentsburg with one of the longest Arctic record available in the database of the PSMSL should have a high priority, if Barentsburg can be re-established.

The network would involve the responsible agencies from Norway (Norwegian Mapping Authority), Russia (Roshydromet and Institute of Astronomy, Russian Academy of Science (INASAN), Moscow), USA (NOAA), Canada (Canadian Hydrographic Service and Institute of Ocean Sciences) and Denmark (KMS, RDANH, and DMI). The operational part of the network would have to be financed out from the available resources of the participating institutes. Additional funding could be requested from different funding sources both on national and international level to support the improvement of the sites and episodic measurements.

Absolute gravity measurements should also be carried out at the selected tide gauges. For the Norwegian and Danish sites, these measurements would have to be carried out by agencies having absolute gravimeters available.

6. Recommendations of the GLOSS Group of Experts

At the Sixth Session of the IOC Group of Experts on the Global Sea Level Observing System (GLOSS), held at Toulouse, France, 12-14 May 1999, the following recommendations were made (see IOC, 1999):

Realizing the importance of the Arctic Ocean for studies of climate variability and the early detection of climate change, and taking into account that the presently available satellite altimetry observations do not cover the Arctic ocean sufficiently, the GLOSS group of experts:

- recommends that in each country bordering the Arctic Ocean, efforts are made to maintain a network of tide gauges conforming to the GLOSS standards;
- in particular, strongly recommends that the Canadian GLOSS tide gauges are re-established;
- urges the international funding agencies to support projects that will help to reverse the current downward trend in the maintenance of Russian Arctic tide gauges;
- urges Denmark to secure the long-term operation of the GLOSS tide gauges in Greenland;
- urges Norway to establish and operate tide gauges corresponding to GLOSS standards on Jan Mayen and Bjørnøya;
- recommends that international support is given for the continued operation and maintenance of the tide gauge in Barentsburg;
- recommends that efforts are made to co-located an approximately equidistant subset of the Arctic tide gauges with space-geodetic techniques (GPS) and to carry out absolute gravity measurements at these gauges.

ANNEXES

Note on the history of this report

The Arctic report was started on the initiative of the GLOSS Experts group back in 1995 at the Bordeaux meeting. At that meeting Oleg Zilberstein (Roshydromet, Moscow, Russia) and Albert Tolkatchev (IOC, now retired) were asked to take the lead along with Andre Bolduc (MEDS). At the 1997 GLOSS meeting, the topic was reaffirmed to be an important one and Oleg Zilberstein was again asked to try to progress matters. Following these initial stimulation, a first draft report was prepared for the meeting of the GLOSS Expert group held in Toulouse, May 12-14, 1999. After that, the report was finalised taking into account some new information and recent scientific findings.

The report identifies the current gaps in tide gauge monitoring of Arctic sea-level. Severe gaps are found in the Canadian Arctic due to a down-prioritising of environmental monitoring, and in the Russian Arctic, where a lack of resources is causing a degradation of the observation sites. On the other hand, Norwegian stations are found to be in a well maintained state and delivering valuable observations. In Iceland, the situation has very much improved over the last few years and prospects are promising. The situation in Greenland has deteriorated rapidly in 1999 with all but one tide gauges closed down. Hopefully, the report turns out to be helpful in closing some of the observational gaps and reverting or preventing the downward trends in operational stations.

It was also asked for a literature search on users of Arctic tide gauge data. The scientific need for sea-level observations from the seas between Greenland, Norway and eastern Russia is found to be well justified due to the mounting interest in the NAO and the decadal atmosphere-ocean interaction. For the Canadian Arctic, scientific interest in sea-level observations originates from post-glacial rebound, the sea-level gradient between Pacific, Arctic Ocean and Atlantic, as well as effects of variable freshwater input to the Arctic.

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List of Acronyms

AMAP	Arctic Monitoring and Assessment Programme
CGPS	Continuously recording GPS receivers
CHS	Hydrographic Service (of Canada)
COP	Conference of the Parties
DMI	Danish Meteorological Institute
DNMI	Norwegian Meteorological Institute
EOSS	European Sea Level Observing System
EuroGOOS	European component of GOOS
GCOS	Global Climate Observing System
GOM	Global ocean mass
GOOS	Global Ocean Observing System
GPS	Global Positioning System
HIS	Icelandic Hydrographic Service
IMA	Icelandic Maritime Administration
IPCC	Intergovernmental Panel on Climate Change
LAT	Lowest Astronomical Tide
MEDS	Marine Environmental Data Service (Canada)
NMA	Norwegian Mapping Authority
NOAA	National Oceanic and Atmospheric Administration (USA)
PGS	Post-glacial rebound signal
PSMSL	Permanent Service for Mean Sea-Level
RDANH	Royal Danish Administration of Navigation and Hydrography
Roshydromet	Russian Federal Services for Hydrometeorology and Environmental Monitoring
RSL	Relative sea-level
UNFCCC	United Nations Framework Convention on Climate Change
WCRP	World Climate Research Programme