Temperature and salinity time series in Svalbard fjords – 'Integrated Marine Observatory Partnership (iMOP II)'

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1. Introduction

The Svalbard Archipelago is located at one of the key oceanic gateways to the Arctic. Its environment is heavily dominated by its maritime location and many of the processes occurring in the region are strongly influenced by the state of the ocean and ice (Ellis-Evans and Holmen 2013). There are extensive networks of marine observations around the Arctic to observe processes and change in this data-sparse region (Smith et al. 2019) and autonomous technologies are becoming increasingly prevalent as a mean of capturing data on appropriate spatial and temporal scales (Sørensen et al. 2020). Svalbard Integrated Arctic Earth Observing System (SIOS) makes an important contribution to this international effort for monitoring the Arctic through the placement of observatories in selected fjord locations. These observations have relevance to both marine processes and the broader connections to atmospheric and glaciological systems.

Many of the marine observations that are made in Svalbard are biased towards summer and autumn, though in recent years there has been an increased effort on marine observations during the polar night (Berge et al. 2015, Berge et al. 2020, Lønne et al. 2015). Due to intense seasonality in Arctic regions, this bias in observations can skew our understanding or, at worst, present a misleading picture of rates and processes that are active in the marine environment. Moored observatories have the capacity to make year-round measurements of key physical, geochemical and biological properties (Hauri et al. 2018, Henley et al. 2020, Hop et al. 2019a). In this report, we define an observatory or mooring to mean an arrangement of sub-surface instrumentation, fixed to a vertical wire or rope, that take regular measurements throughout in the water column to examine physical, geochemical or biological parameters over timescales that span at least one season.

In the first SESS report in 2018 (Cottier et al. 2019) – hereafter referred to as SESS-18 – we reported on four marine observatories in Svalbard and the scope of the report was limited to temperature only (Cottier et al. 2019). In this updated report we also introduce one of the longest seasonally resolved salinity records. Salinity is a key parameter in marine systems particularly in Arctic waters where it is the primary factor determining water density. Coastal and fjord oceanography is dominated by the existence of strong vertical and horizonal density gradients (Sundfjord et al. 2017) such that salinity is one of the primary determinants of the fjord circulation (Cottier et al. 2010, Davison et al. 2020). Further, the gradual warming of Arctic waters through the process of 'Atlantification' has been extensively reported for the Barents Sea region of the Arctic (Årthun et al. 2012, Barton et al. 2018) and for the West Spitsbergen fjords (Promińska et al. 2017, Skogseth et al. 2020, Tverberg et al. 2019) where the warm, high salinity water masses are a signature of enhanced Atlantic influence. In this update we:

1. Extend the temperature series for 4 observatories previously reported in SESS-18
2. Include an additional time series of temperature from a mooring located in the inner part of Kongsfjorden, giving a more glacial-proximate environment
3. Report on the salinity characteristics in the bottom water of the outer part of Kongsfjorden

2. The state of Marine Observatories

There have been many mooring deployments in the waters around Svalbard over the last decades and there exists a rich network of observatories around the Svalbard Archipelago and adjacent shelf seas (Bensi et al. 2019, Hop et al. 2019a, Renner et al. 2018, Skogseth et al. 2020). Historically, many of the observatories were located within the fjord systems and were operated for just a few years to support short-term projects. More recently, both coastal and offshore moorings have been established as part of more extensive observational networks and many have been maintained for multiple years, providing key insights into interannual variability.

The iMOP project has focused exclusively on inshore observatories (within fjords). The work does not include all inshore observatories and does not consider any of the existing offshore time series observations. The criteria for inclusion in this report and in SESS-18 were as follows:

- Observatories that are currently deployed in fjords around Svalbard
- Observatories that have a minimum of three years of continuous operation
- Observatories which are likely to be maintained for another three years

With these criteria, we are then able to focus on time series that are likely to contribute to future SESS reports rather than short-term, process oriented observations. The observatories that were considered are listed in Table 1. Two of the moorings presented herein (outer Kongsfjorden and Isfjorden) are implemented in the Norwegian infrastructure project SIOS-InfraNor[1], which in effect will ensure that these two moorings will both be coordinated and in operation until 2027.

2.1. Temperature

We follow the same methodology for temperature analysis as described in SESS-18. In summary, temperature data recorded on mooring sensors were interpolated onto a regular grid of 10-m vertical resolution and 6-hour time resolution.

Table 1: Summary of the four observatories that collected temperature data for this report. Precise distribution and the instrumentation on each mooring is documented within the cited literature. Derived from (Hop et al. 2019a).

Location	Start	Latitude*	Longitude*	Water Depth (m)	Institution and point of contact
Isfjorden	2005**	78°03.64’ N	013°31.44’ E	205	UNIS Ragnheid Skogseth
Kongsfjorden (inner)	2010***	78°54.86’ N	12°15.53’ E	105	CNR Italy Stefano Aliani
Kongsfjorden (middle)	2014	78°56.4’ N	12°6.00’ E	193	NCPOR Divya David
Kongsfjorden (outer)	2002	78°57.75’ N	011°48.30’ E	230	SAMS/UiT Finlo Cottier/Daniel Vogedes
Rijpfjorden	2006****	80°18.08’ N	022°17.44’ E	236	UiT/SAMS Daniel Vogedes/Finlo Cottier

* Positions are approximate as over the course of many years of deployment the moorings will have been in slightly different positions. Nevertheless, the positions are sufficiently similar to make realistic assessments of interannual change.

** No deployment between Feb 2008 and Sep 2010.

*** Analysis for this SESS report only started in 2012 when at least three temperature sensors were deployed on the mooring

**** No deployment between Sep 2008 and Sep 2009

1 https://sios-svalbard.org/InfraNor

Temperature values from 50 m and deeper (to avoid seasonal surface warming effects) were then reduced to a single depth-average value for each time step. The following metrics were then derived from each time series:

Monthly mean temperature: A single value representing the depth mean for each calendar month.

Maximum mean temperature: A single annual value representing the mean value for the months which climatologically show the warmest depth-mean temperatures (September/October/November).

Warmest 5-day temperature: An annual value for the warmest depth-mean temperature recorded across a series of 5-day periods.

Minimum mean temperature: A single annual value representing the mean value for the months which climatologically show the coldest depth-mean temperatures (March/April/May).

Coldest 5-day temperature: An annual value for the warmest depth-mean temperature recorded across a series of 5-day periods.

Note that we do not make reference to the terms 'summer' and 'winter' as these are a) generally defined inconsistently and b) the climatological extremes do not coincide with the perception of summer and winter being warmest, and coldest respectively.

2.2. Salinity

The salinity time series under analysis is from the SAMS/UiT mooring in the outer part of Kongsfjorden. This has been in operation since 2002, though it was not deployed September 2002 to September 2003 and there were no salinity sensors in the deployment September 2004 to September 2005. We focus on the bottom sensor at a depth of approximately 180-200 m depending on the deployment location but typically 10-15 m from the seabed. This choice of salinity record was motivated by it yielding the longest record (mid-depth sensors were only used in the later half of the deployment period) and salinity changes recorded in the bottom water are not associated with transient wind-driven displacements of the halocline (Cottier et al. 2005) giving a more consistent record of the water mass evolution with time.

The underlying methodology was similar to that used for temperature with the salinity data interpolated onto a regular 6-hour resolution time coordinate. From this, the mean annual cycle of salinity was derived by calculating the mean salinity value for each month from all years. From this we establish that the highest salinities are centred around October (aligning in time with the highest temperatures) and represent the period of maximum penetration of water masses of Atlantic origin, either Atlantic Water (AW: salinity >34.9 and temperature >3°C) or the modified form of Atlantic Water called Transformed Atlantic Water (TAW: salinity >34.7 and temperature >1°C) – water mass definitions from Tverberg et al (2019). To look at the long term evolution of salinity, the mean salinity for the period August to November each year was calculated as the best estimate of salinity during the period when the presence of Atlantic-origin water in Kongsfjorden was greatest. Finally, the proportion of AW and of the combined Atlantic Water types (AW +TAW) present in the bottom water for each year was calculated as a fraction of the entire year.

2.3. Results

2.3.1. Temperature

The updated temperature records are shown in Figure 1. Taking each location in turn we report specifically on the updated trends and comment on the additional data. Due to the variable mooring designs, duration of operation and data gaps, the trends reported are indicative in nature rather than a full statistical linear model of temperature change in the fjords.

Kongsfjorden (outer): This mooring failed during the period 2019 to 2020. As reported in SESS-18, the trends for temperature for the full monthly record and for both the warmest and coldest periods exceed a rate of warming of 1°C per decade, though the new additional data show a slightly cooler period towards the end of the record. 2006 was regarded as an anomalously warm period when it was first reported (Cottier et al. 2007) and we see in the temperature record for the coldest part of the year an increase from typically sub-zero pre-2006 to around +1°C in 2006. The trend line for the coldest period exceeded +1°C in 2014 and is currently around +2°C as typical value for the coldest period. Consequently, temperature values in 2006 that were considered anomalously warm are now considered cooler than normal.

Kongsfjorden (middle): The temperature record from this mooring is now 5 years long yet the trend for the monthly data series actually shows a small decrease of around 0.07°C per year – an important contrast to the outer part. The positive summer trend is also relatively small but the winter trend is similar in magnitude and sign to the trend in the outer part of Kongsfjorden at +0.15°C per year.

Kongsfjorden (inner): This is a new record included in this report. This mooring is located to the south-east of Ny-Ålesund at a water depth of around 100 m. Thus this mooring is not only the most glacial-proximate location of all the Kongsfjorden moorings but also located shallower than the outer and middle mooring locations and near a sill separating the main body of the fjord from the inner basin. Water temperatures in this location are rather steady over time, and actually show a slightly decreasing trend in the coldest period in contrast to the other locations in Kongsfjorden.

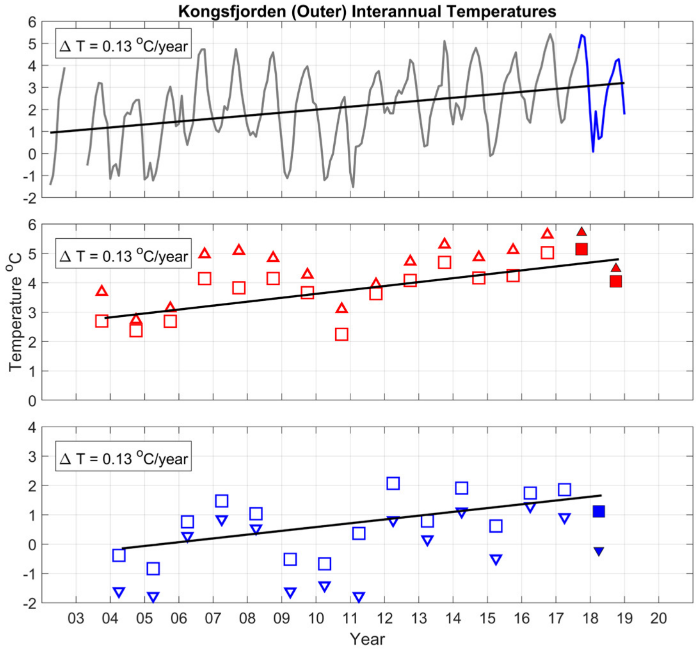
Isfjorden: The new data added to this series include some relatively cold years resulting in a slight decrease in the temperature trend over the duration of the record. Nevertheless, the data continue to show a positive increase with time, most marked in the warmest period where there is an increase of +1.5°C per decade similar to the outer and middle locations of Kongsfjorden.

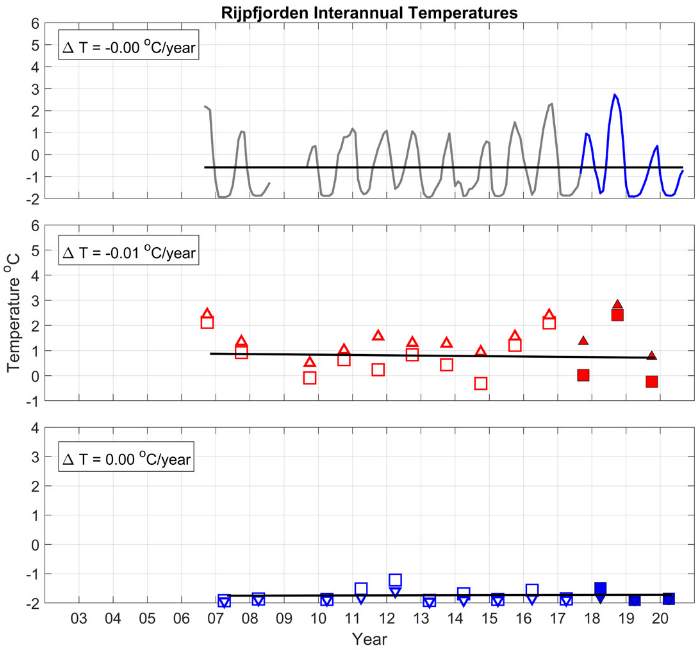
Rijpfjorden: The new data provide a very consistent record of temperatures which show zero trend in temperature for any of the derived parameters. The only perceivable change is an increase in the interannual variation in temperature in the warmest periods during the last four years, but this can't be confirmed statistically due to the short data record. Nevertheless, it could represent an early indication of oceanic change in Rijpfjorden which has previously shown to be relatively stable.

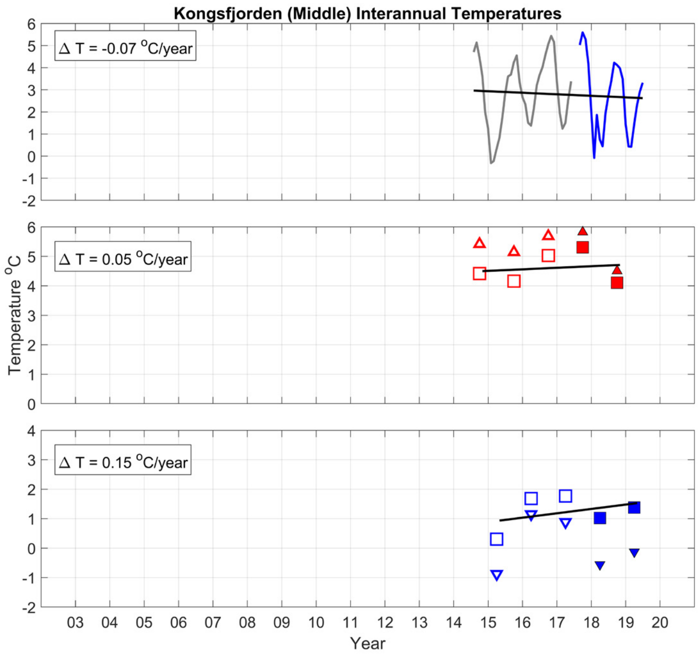
2.3.2. Salinity

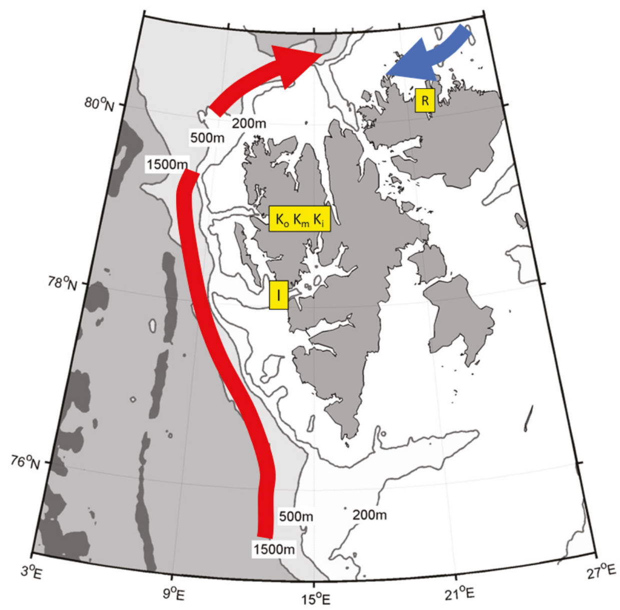
The data for the bottom water salinity from the outer part of Kongsfjorden is shown in Figure 2. The annual cycle shows highest salinity in October (S=34.90) and lowest salinity in January (S=34.75). This corresponds to the occurrence of warm and saline AW at the end of each summer. Looking at the time series of mean salinity during the months August to November we see that there has been a steady increase in salinity at a rate of around 0.1 per decade. This rate of increase is similar to increases in salinity found for Isfjorden of 0.21 per decade (January-May for the period 1999-2017) and 0.07 per decade (July-September for the period 1987-2017) from profiling CTD data (Skogseth et al. 2020). Since 2014 the mean bottom salinity in Kongsfjorden for August-November has regularly exceeded the criteria for AW (S=34.9). Similar observations in the Isfjorden system since 2003 found the greatest salinity in the bottom water in 2014 (Bloshkina et al. 2021). However, in longer records (Skogseth et al. 2020) we note occurrence of high bottom salinities in 1988, 1990 and 1994) though there is still a decadal trend of increasing salinity. The increase in AW occupation in Kongsfjorden is seen in the lower panel of Figure

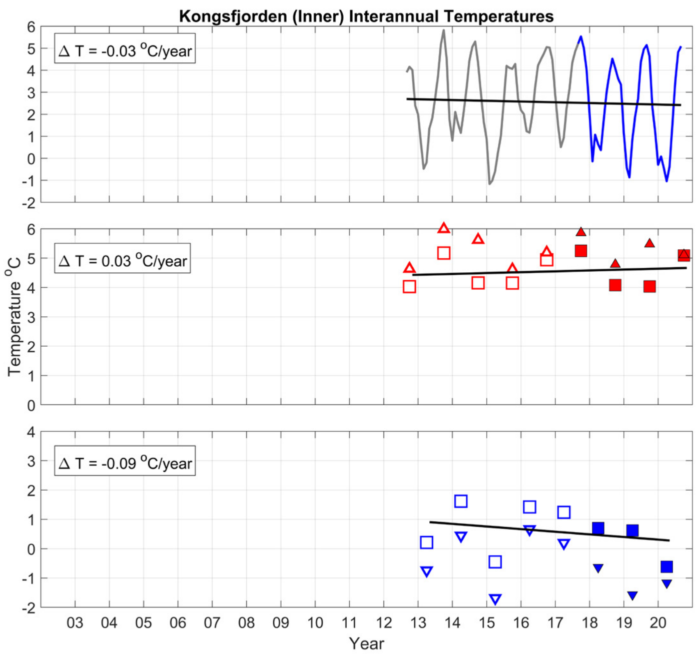
Figure 1: Multipanel figure showing the temperature time series of depth-averaged water column temperature (50 m > bottom) at five locations in Svalbard: Kongsfjorden outer (K_o), middle (K_m) and inner (K_i) basins, Isfjorden (I) and Rijpfjorden (R). Each location data comprises three panels. Upper panel: monthly temperature values (grey reported in SESS-18, blue updated or new data), middle panel (red markers) is warmest months (Sep/Oct/Nov) mean (square) and the peak temperature values in the season (triangle) – open shapes are values reported in SESS-18 and filled shapes are new data, lower panel (blue markers) is coldest months (Mar/Apr/May) mean (square) and the minimum temperature values in the season (triangle).

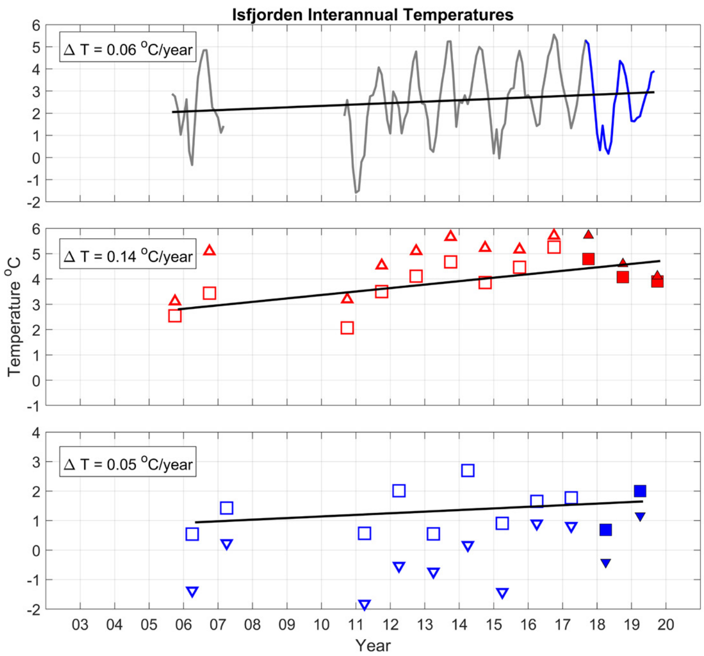

Kongsfjorden (Outer) Interannual Temperatures
Δ T = 0.13 °C/year
Δ T = 0.13 °C/year
Δ T = 0.13 °C/year
Temperature °C
Year


Rijpfjorden Interannual Temperatures
Δ T = -0.00 °C/year
Δ T = -0.01 °C/year
Δ T = 0.00 °C/year
Temperature °C
Year


Kongsfjorden (Middle) Interannual Temperatures
Δ T = -0.07 °C/year
Δ T = 0.05 °C/year
Δ T = 0.15 °C/year
Temperature °C
Year


80°N
78°N
76°N
3°E
9°E
15°E
21°E
27°E
200m
500m
1500m
R
Ko Km Ki
I
500m
200m
1500m


Kongsfjorden (Inner) Interannual Temperatures
Δ T = -0.03 °C/year
Δ T = 0.03 °C/year
Δ T = -0.09 °C/year
Temperature °C
Year


Isfjorden Interannual Temperatures
Δ T = 0.06 °C/year
Δ T = 0.14 °C/year
Δ T = 0.05 °C/year
Temperature °C
Year

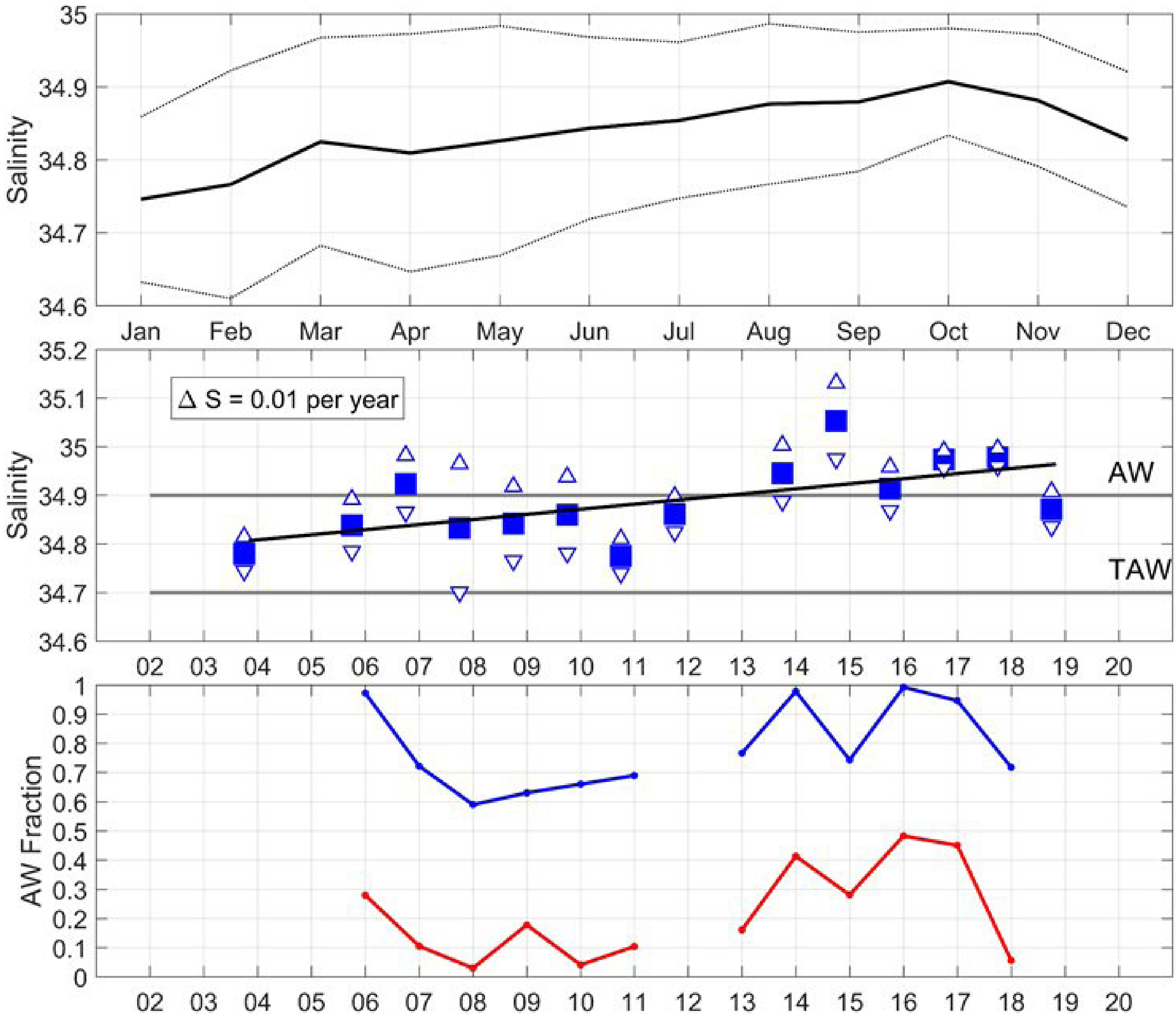


Figure 2: Multipanel figure for salinity parameters measured at the bottom of the outer part of Kongsfjorden. Upper panel shows the annual cycle of salinity by month with standard deviation (dotted line). Middle panel shows the mean salinity (blue squares) with standard deviation (triangles) by year for those months with highest salinity (Aug-Nov) with an indicative linear trend marked in black and the salinity boundaries for Atlantic Water (AW) at 34.9 and Transformed Atlantic Water (TAW) at 34.7 indicated by horizonal grey lines. Lower panel shows the proportion of the year when AW is recorded in the bottom water (red) and when any form of Atlantic Water (AW or TAW) is recorded (blue) for each year of mooring operation.

2, peaking at 50% of the year in 2016. Taking both Atlantic water types into account (AW and TAW), we note that in 2006 as well as 2014 and 2016 Kongsfjorden was fully occupied with either AW or TAW. We note an increase in the fraction of AW with little additional TAW, such that the total contribution of Atlantic-type water does not rise substantially in 2009. Data for 2018 shows a decrease in Atlantic water types for Kongsfjorden. Nevertheless, this pronounced increase in occurrence of Atlantic water types since 2014 has been reported for both Kongsfjorden and Isfjorden (Skogseth et al. 2020, Tverberg et al. 2019).

3. Unanswered questions

1. The extent to which oceanographic changes are driving zooplankton communities around Svalbard has received some attention previously (Daase and Eiane 2007, Dalpadado et al. 2016). There are observations that inter-annual variations in the mesozooplankton community composition and abundance are strongly related to hydrographic fluctuations

in Kongsfjorden (Hop et al. 2019b) leading to changes in the energy flow to higher trophic level (Vihtakari et al. 2018). In the colder, more sea ice-dominated Rijpfjorden, studies have shown a delay in the spring developmental stages of zooplankton compared to the warmer Kongsfjorden (Weydmann-Zwolicka et al. 2021). However, there is an overall lack of monitoring of long-term changes of marine biological communities with high seasonal resolution, coordinated with equivalent ocean timeseries, to enable studies of how the observed changes in oceanic conditions across the archipelago affect the coastal and fjord ecosystems.

2. We lack a full integration of the many data series to assess systematically how oceanic conditions are changing in Svalbard fjords. There are well-resolved time series of change for Isfjorden (Bloshkina et al. 2021, Pavlov et al. 2013, Skogseth et al. 2020), a series of annual sections of temperature and salinity for Hornsund (Promińska et al. 2017), extensively documented hydrography of Kongsfjorden (Promińska et al. 2017, Tverberg et al. 2019) and time series of sea ice conditions in selected fjords (Gerland et al. 2020, Johansson et al. 2020, Muckenhuber et al. 2016, Pavlova et al. 2019) . But there are other fjord locations, notably Storfjorden which is an important region of local water mass modification, where we don't have a clear picture of long term variability. Such a coordinated assessment of the coastal and fjordic conditions should consider the wider system of Atlantic inflow, meteorological forcing, run-off etc. for both inshore and offshore conditions through the many excellent projects addressing aspects of this.

3. To what extent the fjord conditions are coupled with meteorological factors and/or offshore oceanographic conditions is not well understood. Neither do we have a full understanding of the role that ocean forcing is playing on glacial dynamics in the regions. A much greater level of integration could be achieved between disciplines.

4. Recommendations for the future

In SESS-18 we recommended to further develop the network of operators to encourage collaboration, communication and planning of future marine observatories. Initiatives are developing through SIOS Marine Infrastructure workshops and Kongsfjorden Flagship meetings and these efforts should be continued. In practice, we are seeing operational collaboration between nations, e.g. Italian group assisting mooring operations for IndARC. The SIOS-funded mooring operations in Kongsfjorden and Isfjorden provide a long-term platform for mooring operations and provide a basis for many science campaigns and should be continued.

We recommend conducting a community analysis of temperature records of all long-term inshore moorings and to include, where possible, an analysis of water salinity to capture the rates and locations of change around Svalbard. This should be ongoing with an agreed protocol for how data should be analysed for each mooring. There are moorings elsewhere in Svalbard which we have not been able to include in this report. However, the inclusion of the CNR-Italy mooring has demonstrated a quite different character to the temperature trend even within one fjord. We present an analysis of seasonally resolved salinity for Kongsfjorden and demonstrate the increasing prevalence of Atlantic Water; a similar pattern is reported for Isfjorden (Skogseth et al. 2020). A more widespread analysis could be undertaken to find evidence for Atlantification of Svalbard fjord systems. Related to this, we recommend an extensive analysis of offshore moorings; this should be the focus of a distinct SESS report.

In addition, an effort should be made to identify similar long-term marine records (e.g. zooplankton or fish populations) and for other Earth System processes (e.g. records of meteorology or glaciers) and undertake coupled analyses.

5. Data availability

Dataset	Parameters	Period	Location	Metadata access (URL)	Dataset provider
Oceanographic mooring	Temperature Salinity Chlorophyll fluorescence Currents	2002 – present (not present Sep 2002-Sep 2003 and mooring failure 2019-20)	Kongsfjorden outer basin	https://archive.sigma2.no/welcome.xhtml and https://arctic-observatories.webs.sigma2.no/	Jørgen Berge (UiT) Jorgen.berge@uit.no Daniel Vogedes Daniel.vogedes@uit.no
Oceanographic mooring	Temperature Salinity Currents	2014 – present	Kongsfjorden middle basin	http://data.ncaor.gov.in/newhtml	Divya David divya@ncpor.res.in
Oceanographic mooring	Temperature Salinity	2010 – present	Kongsfjorden inner basin	http://iadc.cnr.it/cnr/index.php	Leonardo Langone leonardo.langone@cnr.it
Oceanographic mooring	Temperature Salinity	2005 – present (not 2008-09 and 2009-10)	Isfjorden mouth	https://data.npolar.no/dataset/?filter-links.rel=data&q=Mooring%20Isfjorden%20South%20(I-S)	Ragnheid Skogseth ragnheids@unis.no
Oceanographic mooring	Temperature Salinity Chlorophyll fluorescence Currents	2006 – present (not present 2008-09)	Rijpfjorden	https://archive.sigma2.no/welcome.xhtml and https://arctic-observatories.webs.sigma2.no/	Jørgen Berge (UiT) Jorgen.berge@uit.no Daniel Vogedes Daniel.vogedes@uit.no

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