Temperature time-series in Svalbard fjords. A contribution from the "Integrated Marine Observatory Partnership (iMOP)"

F Cottier[1, 2], R Skogseth[3], D David[4], J Berge[2, 3, 5]

1 Scottish Association for Marine Science, United Kingdom
2 UiT, The Arctic University of Norway, Norway
3 University Centre in Svalbard, Norway
4 ESSO-National Centre for Polar and Ocean Research, India
5 Centre for Autonomous Marine Operations and Systems (AMOS), NTNU, Norway

Corresponding author: Finlo Cottier, Finlo.cottier@sams.ac.uk,
ORCID number: 0000-0002-3068-1754

Keywords: Svalbard, fjords, mooring, temperature, observatory

Introduction

The environment of Svalbard 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. It is located close to the major marine inflows and outflows for the Arctic Ocean in an area where important boundary fluxes (between atmosphere, ocean, and sea-ice) are occurring [*Ellis-Evans and Holmen*, 2013]. Long-term monitoring of key arctic ocean gateways have revealed important changes in the system [*Carmack et al.*, 2016; *Onarheim et al.*, 2014; *Polyakov et al.*, 2017] and it is important that the Svalbard Integrated Observing System (SIOS) contributes to those international efforts to monitor and report on decadal change in the ocean. This has relevance not only to marine processes but also the broader connections to the atmosphere and glaciological systems.

Many of the marine observations that are made on Svalbard are biased towards summer and the fall. Due to the 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. In this report we define an observatory to mean an arrangement of sub-surface instrumentation mounted in the water column to examine physical, geochemical or biological parameters over timescales that span at least one season. Sometimes we abbreviate this to just the word "mooring".

Datasets from such moored observatories capture processes occurring on sub-hourly to decadal time-scales [*Nilssen et al.*, 2015] and when combined with complementary data are very powerful in determining the drivers and impacts of environmental change. Moored observations also enhance our predictive capabilities by acquiring data that can be used to support modelling work of the Arctic system – either to provide the essential boundary conditions to drive the model, or to provide robust in situ data for model calibration and validation [*Cottier et al.*, 2007; *Drysdale*, 2017; *Sundfjord et al.*, 2017; *Wallace et al.*, 2013].

Although often regarded as routine monitoring tools, moored observatories have opened up new frontiers of research. As little as a decade ago, it was not widely appreciated how active the winter marine ecosystem is. However, important winter observations of zooplankton migration revealed by acoustic instruments demonstrated that an important component of the marine ecosystem was active [*Berge et al.*, 2009a] which paved the way for new winter observations [*Berge et al.*, 2015; *Wallace et al.*, 2010]. The use of moorings in understanding polar night ecology has gone beyond single site observations on Svalbard and has been used in a fully pan-Arctic context to understand the response of zooplankton to moonlight [*Last et al.*, 2016].

Integration with complementary Earth System parameters is also well supported by moored observations. For example, glaciological time series, collected throughout the year with 11-day repeat satellite passes require a similarly resolved marine time series with which to interpret change. Such a combination of data has demonstrated highly significant geophysical correlations that allow us to understand glacier ablation [*Luckman et al.*, 2015]. Marine observations in Svalbard have also been used to derive decadal records of change. These are principally linked to the physical system [*Pavlov et al.*, 2013], but also aligned with records of the benthic ecology [*Berge et al.*, 2009b] and geochemical proxies of environmental change [*Ambrose et al.*, 2006; *Vihtakari et al.*, 2017].

Current Status of marine observatories

There have been many mooring deployments in Svalbard waters over the last decades and there exists a rich network of observatories around the Svalbard archipelago and adjacent shelf seas [*Hop et al.*, in press]. Historically, many were located within the fjord systems and were operated for just a few years. More recently, both coastal and offshore moorings have been established as part of more extensive observations networks and many have been maintained for multiple years providing key insights into interannual variability.

There have been a number of efforts to collate our understanding of long-term data series [Renaud and Bekkby, 2013] and collating information on marine observing activities through the Svalbard Science Forum Ocean Flagship [*Beszczynska-Moller and Sagen*, 2015; *Falk et al.*, 2016] and community workshops. Importantly, however, two of the moorings presented herein (outer Kongsfjorden and Isfjorden) are implemented in the Norwegian SIOS Infrastructure programme SION InfraNOR, which in effect will ensure that these two moorings will both be coordinated and in operation until 2026.

Methods

In this first edition of the SESS report, 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 were as follows

- Observatories that are currently deployed in Svalbard fjords
- Observatories that have a minimum of three years of continuous operation
- Observatories which are likely to be maintained for another 2 years

With these criteria, we were 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.

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.

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)	2014	78.94°N	12.01°E	193	ESSO-NCAOR Divya David T
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

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

Data processing was identical for each time series. Each data provider was responsible for sensor calibration and quality control of the data. Accuracy of the temperature data is typically better than 0.1°C. The data were collected from multiple temperature sensors, fixed to a vertical mooring line that extended from the seabed to within typically 20 m from the surface. The sensors had varying vertical spacing on the mooring line, but generally were more closely spaced in the upper 100 m, for example [*Cottier et al.*, 2005]. These data were interpolated on to a regular grid of 10m vertical resolution and 6-hour time resolution. Temperature data at each point in time were reduced to a single depth-average value. Water within the fjord can be warmed by either local heating through surface heat fluxes or advection into the fjord of warmer waters. It is anticipated that in summer months the local surface heating is limited to the upper 50m due to the formation of surface freshwater layers and a well-developed pycnocline [*Cottier et al.*, 2005]. To quantify the impact on water temperature through local heating the depth-averaged temperature was calculated for a) the full water column and b) the water column deeper than 50 m. The following metrics were then derived from each time series:

<u>Monthly mean temperature:</u> A single value representing the depth mean for each calendar month.

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

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

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

<u>Coldest 5-day temperature:</u> An annual value for the warmest depth-mean temperature recorded across a series of 5-day periods. In many cases, this equates to the mean freezing point of the water and is not a unique value in the time series.

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.

Results

Analysis showed that there was rather little difference between metrics derived from the full water column and derived from waters 50m and deeper. For consistency, we just report the data from 50m and deeper. Key metrics were then represented as time series with simple linear regression analysis and are shown in Figure 1.

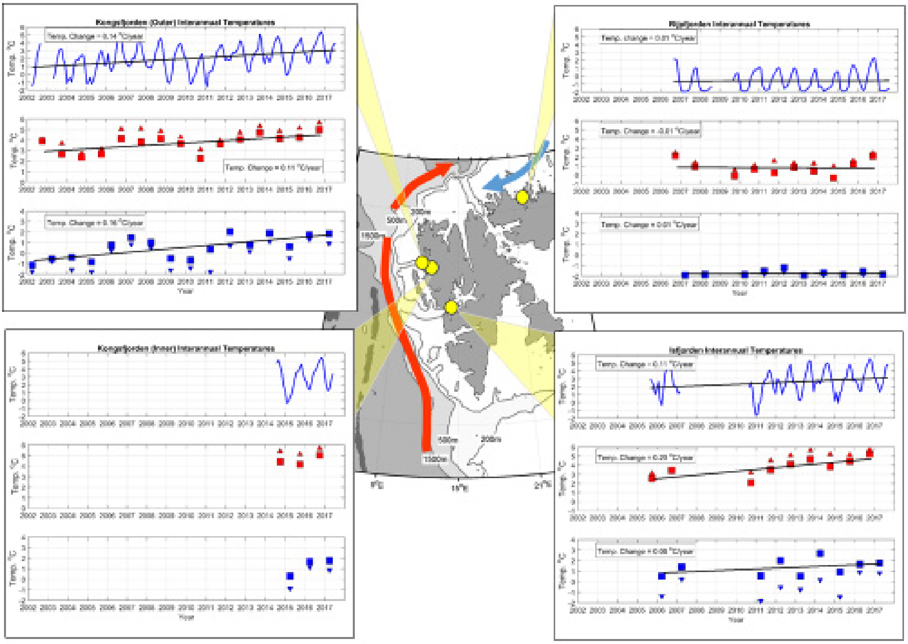

Figure 1: Time series of depth-averaged water column temperature (50m > bottom) at four locations in Svalbard: Kongsfjorden outer and inner basins, Isfjorden and Rijpfjorden. Each location data comprises three panels. Upper panel (blue line) monthly temperature values, middle panel (red markers) is warmest months (Sept/Oct/Nov) mean (square) and the peak temperature values in the season (triangle), lower panel (blue markers) is coldest months (March/April/May) mean (square) and the minimum temperature values in the season (triangle). Data series longer than 9 years are fitted with a simple linear regression model.

The key observation from these time series is the increase in water temperature (both the maximum and minimum temperatures) observed consistently for the west-facing fjords of Isfjorden and Kongsfjorden. The current rate of increase is of the order 1°C per decade. Perhaps most significantly we see consistent warming trend during the coldest months (March/April/May) In contrast, the temperatures (annually, warmest and coldest period) in Rijpfjorden show no increase and very little variation over a decade of observations.

Data accessibility

The data that forms the basis of the figures in this report is available at the Norwegian Infrastructure for Research Data (NIRD).

Discussion

The monthly temperature values (upper panel) for each location show a classic annual temperature cycle. The metrics for the coldest and warmest months provide a robust measure of the maximum and minimum temperature values for each year. It is apparent that data from the west-facing fjords (Kongsfjorden and Isfjorden) show a different response during the record period than the north-facing fjord (Rijpfjorden). The warmer water temperatures in the west-facing fjords can be attributed to both warming of the offshore West Spitsbergen Current and the regional wind stress [*Pavlov et al.*, 2013]. In the longer records of Kongsfjorden and Isfjorden we see some evidence for sub-decadal cycling within the time series, but the clear trend is one of increasing water temperature at a rate of the order 1-2 °C per decade. We note a similar sub-decadal variation (particularly in Kongsfjorden) for the coldest temperatures, suggesting a degree of correlation between successive warm and cold periods. Similarly, a clear warming trend is noted in the coldest periods at a rate of order 1-1.5 °C per decade. The clear implication of this warming is that there are now fewer years experiencing temperatures close to freezing point for the full water column – limiting the formation of sea ice. This change has been noted in satellite observations of sea ice cover over approximately the same period [*Muckenhuber et al.*, 2016].

The major difference between the mooring sites are the data from Rijpfjorden. Whilst the annual temperature cycle is clear, there is no significant increase in either the warmest or coldest temperatures. In particular, the coldest depth-averaged temperatures are always at or close to the freezing point such that the ice cover in Rijpfjorden is still able to form annually [*Wallace et al.*, 2010]. In the last three years in Rijpfjorden there has been a small increase in the warmest temperatures which may be linked to the increased presence of

Atlantic Water offshore [*Polyakov et al.*, 2017] which may become more prevalent on the northern Barents Sea shelf [*Lind et al.*, 2018]. Nevertheless, whilst the offshore changes in water temperature are increasingly well-documented, it will take more years of observation to show any robust trend in Rijpfjorden.

Future perspectives

In this report, we have only considered a subset of the inshore observatories and not considered the offshore time series at all. Future iterations of this report will look to provide a more consistent treatment of the data in terms of archiving, calibration and analysis. Further, many of these time series have records of ocean salinity – an important parameter in determining the timing and extent of ocean inflows to the coastal regions. Salinity will be another parameter to consider in future reports of interannual change.

A number of observatories have been used for investigating multiple, coupled parameters [*D'Angelo et al.*, 2018; *Venkatesan et al.*, 2016; *Wallace et al.*, 2010], and data from observatories have been linked to non-marine systems, e.g. glacial dynamics [*Luckman et al.*, 2015]. Future research opportunities exist by linking the existing time series of the fjord properties recorded by observatories with other marine time series around the archipelago [*Renaud and Bekkby*, 2013]. It is likely that we will see either immediate or lagged responses of the marine ecosystem to the observed trends in oceanic temperatures. Awareness of, and accessibility to, the marine time series data is critical for stimulating the research interactions between other Earth System Science groups operating in Svalbard. There are clear links to be made between marine, terrestrial, glacial and atmospheric processes. Cross-disciplinary investigations of the data series need to be supported.

In terms of developing the observation system, communication and coordination between the many groups operating marine observatories around Svalbard is of primary concern. Recent workshops have recognised that there is still a requirement to establish a cooperative group of mooring operators by which data can be identified and secured and planning can be coordinated to ensure that the Svalbard research community benefits from the best possible arrangement and access to infrastructure. It is often the case that a level of coordination and integration of data collection yields a more valuable insight into the system than single, stand-alone efforts. As a first step, a full audit of the mooring activity around Svalbard is required. One of the objectives of the iMOP project was to initiate a coordinating role for collating existing temperature data from marine observatories to produce consistent data series focused on ocean temperatures for inclusion in the first SESS report.

Looking ahead, it is clear that maintaining time series beyond the lifetime of research project funding is a challenge. Where resource exists to do this (for example through infrastructure funding) it must be applied with due consideration for the existing longevity of a time series, utility of data and logistical constraints to ensure continued monitoring.

Acknowledgements

The moorings have been supported financially by many funding agencies and projects and these are acknowledged individually within the publications cited by this report. In addition the authors thank the various organisations linked to mooring activities for providing in-kind support over the years, particularly UiT The Arctic University of Norway, UNIS and NPI. This work was supported by the Research Council of Norway, project number 251658, Svalbard Integrated Arctic Earth Observing System – Knowledge Centre (SIOS-KC).

References

Ambrose, W. G., M. L. Carrol, M. Greenacre, S. R. Thorrold, and K. W. McMahon (2006), Variation in Serripes groenlandicus (Bivalvia) growth in a Norwegian high-Arctic fjord: evidence for local- and large-scale climatic forcing, Global Change Biology, 12, 1595–1607, doi: 1510.1111/j.1365-2486.2006.01181.x.

Berge, J., et al. (2009a), Diel vertical migration of Arctic zooplankton during the polar night, Biology Letters, 5(1), 69-72.

Berge, J., et al. (2015), Unexpected Levels of Biological Activity during the Polar Night Offer New Perspectives on a Warming Arctic, Current Biology, 25(19), 2555-2561, doi:10.1016/j.cub.2015.08.024.

Berge, J., P. E. Renaud, K. Eiane, B. Gulliksen, F. R. Cottier, Ø. Varpe, and T. Brattegard (2009b), Changes in the decapod fauna of an Arctic fjord during the last 100 years (1908–2007), Polar Biology, 32(7), 953-961.

Beszczynska-Moller, A., and H. Sagen (2015), SSF Ocean Flagship Programme - recognizing the current status of oceanic research in the Svalbard region and neighboring European ArcticRep., 49 pp.

Carmack, E. C., M. Yamamoto-Kawai, T. W. Haine, S. Bacon, B. A. Bluhm, C. Lique, H. Melling, I. V. Polyakov, F. Straneo, and M. L. Timmermans (2016), Freshwater and its role in the Arctic Marine System: Sources, disposition, storage, export, and physical and biogeochemical consequences in the Arctic and global oceans, Journal of Geophysical Research: Biogeosciences, 121(3), 675-717.

Cottier, F. R., F. Nilsen, M. E. Inall, S. Gerland, V. Tverberg, and H. Svendsen (2007), Wintertime warming of an Arctic shelf in response to large-scale atmospheric circulation, Geophys. Res. Lett., 34, L10607.

Cottier, F. R., V. Tverberg, M. E. Inall, H. Svendsen, F. Nilsen, and C. Griffiths (2005), Water mass modification in an Arctic fjord through cross-shelf exchange: The seasonal hydrography of Kongsfjorden, Svalbard, J. Geophys. Res.-Oceans, 110(C12005).

D'Angelo, A., F. Giglio, S. Miserocchi, A. Sanchez-Vidal, S. Aliani, T. Tesi, A. Viola, M. Mazzola, and L. Langone (2018), Multi-year particle fluxes in Kongsfjorden, Svalbard, Biogeosciences, 15(17), 5343-5363.

Drysdale, L. (2017), Arctic Fjords: simplified modelling and the role of freshwater PhD thesis, 250 pp, University of Aberdeen, SAMS.

Ellis-Evans, C., and K. Holmen (2013), SIOS Infrastructure Optimisation ReportRep., 66 pp, https://www.sios-svalbard.org/Documents.

Falk, E., R. Skogseth, H. Sagen, A. Beszczynska-Moller, and T. Hamre (2016), SSF Ocean Flagship Programme – recognizing the current status of oceanic research in the Svalbard region and neighbouring European ArcticRep., 25 pp.

Hop, H., F. Cottier, and J. Berge (in press), Autonomous marine observatories in Kongsfjorden, Svalbard, in The Ecosystem of Kongsfjorden, Svalbard, edited by H. Hop and C. Wiencke, Springer.

Last, K. S., L. Hobbs, J. Berge, A. S. Brieley, and F. Cottier (2016), Moonlight drives ocean-scale mass vertical migration of zooplankton during the Arctic winter, Current Biology, 26(2), 244-251.

Lind, S., R. Ingvaldsen, and T. Furevik (2018), Arctic warming hotspot in the northern Barents Sea linked to declining sea-ice import, Nature Climate Change, 8, 634-639.

Luckman, A., D. I. Benn, F. Cottier, S. Bevan, F. Nilsen, and M. Inall (2015), Calving rates at tidewater glaciers vary strongly with ocean temperature, Nature communications, 6.

Muckenhuber, S., F. Nilsen, A. Korosov, and S. Sandven (2016), Sea ice cover in Isfjorden and Hornsund, Svalbard (2000–2014) from remote sensing data, Cryosphere, 10, 149-158.

Nilssen, I., Ø. Ødegård, A. J. Sørensen, G. Johnsen, M. A. Moline, and J. Berge (2015), Integrated environmental mapping and monitoring, a methodological approach to optimise knowledge gathering and sampling strategy, Mar. Pollut. Bull., 96(1), 374-383.

Onarheim, I. H., L. H. Smedsrud, R. B. Ingvaldsen, and F. Nilsen (2014), Loss of sea ice during winter north of Svalbard, Tellus A, 66, 23933.

Pavlov, A. K., V. Tverberg, B. V. Ivanov, F. Nilsen, S. Falk-Petersen, and M. A. Granskog (2013), Warming of Atlantic Water in two west Spitsbergen fjords over the last century (1912-2009), Polar Research, 32.

Polyakov, I. V., A. V. Pnyushkov, M. B. Alkire, I. M. Ashik, T. M. Baumann, E. C. Carmack, I. Goszczko, J. Guthrie, V. V. Ivanov, and T. Kanzow (2017), Greater role for Atlantic inflows on sea-ice loss in the Eurasian Basin of the Arctic Ocean, Science, 356(6335), 285-291.

Renaud, P. E., and T. Bekkby (2013), Existing time-series of marine biodiversity and the need for nature-type mapping in Svalbard waters: Status, financing, and value for developing management strategies in a changing ArcticRep., 41 pp, Akvaplan-niva, Tromso, Norway.

Sundfjord, A., J. Albretsen, Y. Kasajima, R. Skogseth, J. Kohler, C. Nuth, J. Skarðhamar, F. Cottier, F. Nilsen, and L. Asplin (2017), Effects of glacier runoff and wind on surface layer dynamics and Atlantic Water exchange in Kongsfjorden, Svalbard; a model study, Estuarine, Coastal and Shelf Science, 187, 260-272.

Venkatesan, R., K. Krishnan, M. Arul Muthiah, B. Kesavakumar, D. T. Divya, M. Atmanand, S. Rajan, and M. Ravichandran (2016), Indian moored observatory in the Arctic for long-term in situ data collection, The International Journal of Ocean and Climate Systems, 7(2), 55-61.

Vihtakari, M., W. G. Ambrose, P. E. Renaud, W. L. Locke, M. L. Carroll, J. Berge, L. J. Clarke, F. Cottier, and H. Hop (2017), A key to the past? Element ratios as environmental proxies in two Arctic bivalves, Palaeogeography, Palaeoclimatology, Palaeoecology, 465, 316-332.

Wallace, M. I., F. R. Cottier, J. Berge, G. A. Tarling, C. Griffiths, and A. S. Brierley (2010), Comparison of zooplankton vertical migration in an ice-free and a seasonally ice-covered Arctic fjord: An insight into the influence of sea ice cover on zooplankton behavior, Limnol. Oceanogr., 55(2), 831-845.

Wallace, M. I., F. R. Cottier, A. S. Brierley, and G. A. Tarling (2013), Modelling the influence of copepod behaviour on faecal pellet export at high latitudes, Polar Biology, 36(4), 579-592, doi:10.1007/s00300-013-1287-7.