Chapter 13
Autonomous Marine Observatories in Kongsfjorden, Svalbard

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Abstract Several moored autonomous marine observatories, with a variety of sensors and scientific instruments have been installed in Kongsfjorden, Svalbard, since 2002. These provide seasonal and inter-annual data on a number of physical, chemical and biological variables, as well as biological variables that serve as important baselines for the measurement of seasonal variability and the interpretation of climate-induced changes in this fjord system. Oceanographic and ecological changes observed in Kongsfjorden are, to some extent, related to larger-scale changes in Fram Strait because of the advection of Atlantic Water into the open fjord. We here provide an account of the location of moored observatories in Kongsfjorden, with a list of parameters measured at the different moorings, and review the scientific advances that have been made through data collection from these marine observatories. Several nations collaborate on moorings in Kongsfjorden (Norway, Sweden, UK, Germany, and France), whereas others have separate moorings in the fjord (India and Italy). Some of the moorings in Kongsfjorden have become part of The Svalbard Integrated Arctic Earth Observing System (SIOS). To maximise the scientific benefits of moorings, two priorities need to involve:

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(i) coordination of the infrastructure and (ii) securing their long-term viability in support of Arctic marine science.

Keywords Moorings · Long-term monitoring · Climate change · Svalbard · Arctic

13.1 Introduction

Svalbard is located in the high-Arctic and many of the processes occurring in the region are strongly influenced by the state of the ocean and ice. The west coast of Spitsbergen is affected by inflow of Atlantic Water in the West Spitsbergen Current (WSC) in an area where important boundary fluxes (between atmosphere, ocean and sea-ice) are occurring. Long-term monitoring of key Arctic Ocean gateways has revealed important changes in the Arctic Ocean and its marginal seas, such as increased influence of Atlantic Water (Polyakov et al. 2017; Lind et al. 2018), reduced winter sea ice cover (Onarheim et al. 2014) and modified fluxes of freshwater (Carmack et al. 2016).

Fram Strait is the main gateway with regard to heat and water mass exchange in the Arctic Ocean, and the large quantities of heat carried northwards by the WSC influence climatic processes throughout the Arctic (Beszczyńska-Möller et al. 2011, 2012; Hunt et al. 2016). Regionally, the oceanographic conditions in Fram Strait directly influence the fjords of West Spitsbergen (Pavlov et al. 2013), particularly open fjords such as Kongsfjorden (Hop et al. 2006; Tverberg et al., Chap. 3) and Isfjorden (Nilsen et al. 2008, 2016). Warm Atlantic Water in the WSC crosses the West Spitsbergen Shelf where it mixes with colder Arctic-origin water before being advected into the fjords as Transformed Atlantic Water (Svendsen et al. 2002; Cottier et al. 2005; Nilsen et al. 2008). In recent years, this process has also become more prevalent during winter (Cottier et al. 2007) leading to reductions in sea ice within the fjords (Muckenhuber et al. 2016; Pavlova et al., Chap. 4). The Atlantic Water influences the entire fjord, although the inner basin is largely influenced by run-off from tidal glaciers (Calleja et al. 2017; D'Angelo et al. 2018).

Traditionally, most of the field observations conducted in Svalbard fjords have been biased towards the spring, summer and autumn. This is particularly the case for the collection of biological data (e.g. Hop et al., Chap. 7), whereas oceanographic surveys have also included the winter and polar night periods (e.g. Berge et al. 2015c; Tverberg et al., Chap. 3). Kongsfjorden is arguably the best-studied Arctic system during winter and polar night, partly due to the year-round observatories that have been in operation there over the last two decades, but also to field expeditions that have specifically targeted the polar night in this fjord (Berge et al. 2015a; Lønne et al. 2015; Grenvald et al. 2016). The application of autonomous technologies in marine science to improve seasonal observations have become more prevalent (Nilssen et al. 2015; Ludvigsen et al. 2018), but in restricted coastal locations the use of ocean gliders, autonomous underwater vehicles (AUVs) or drifting buoys each brings their own challenges. The radio silence area in the vicinity of

Ny-Ålesund limits the use of AUV's in Kongsfjorden, especially within the 2–32 GHz frequency range (kingsbay.no/research/radio_silence/).

Instrumentation deployed on moorings have the capacity for making year-round measurements of key physical, geochemical and biological properties. Such moorings that contain some level of complexity in the arrangement of instrumentation (e.g. incorporating physical, optical and biogeochemical sampling) are commonly referred to as marine observatories (e.g. Smyth et al. 2015). They can capture processes occurring on sub-hourly to decadal time-scales (Nilssen et al. 2015), and when the datasets are integrated with complementary earth system parameters they become a powerful resource for determining the drivers and impacts of environmental change. An example of data integration within Kongsfjorden is the co-analysis of satellite imagery of glacier dynamics, collected throughout the year with 11-day repeat satellite passes, with similarly resolved time series of water temperature from a mooring to establish significant geophysical correlations that allow us to better understand glacier ablation (Luckman et al. 2015).

Moorings, by design, support data collection with rather limited spatial resolution. More powerful analyses of processes of varying spatial scale can be achieved through coordination and integration of data collected from multiple moorings. Since 2006, a pair of marine observatories in Kongsfjorden (Atlantic dominated fjord) and Rijpfjorden (Arctic dominated fjord) have been operated in a coordinated manner to investigate the role of water masses, sea ice cover and species diversity on the timing and rates of ecologically-relevant processes (e.g. Berge et al. 2009, 2014; Wallace et al. 2010) or to contrast the conditions and responses to aid interpretation of paleo-records of the environment (e.g. Howe et al. 2010; Ambrose et al. 2012). Data from paired moorings in Kongsfjorden have been used to describe complex wave propagations that support the exchange of water in the fjord (Inall et al. 2015), and integration of Svalbard moorings with those from around the Arctic Ocean have been used to establish pan-Arctic responses of zooplankton to winter illumination (Last et al. 2016) and sea ice (Hobbs et al. 2018).

Marine observations around Svalbard have been collated to derive long-term records of change (e.g. Renaud and Bekkby 2013). These are principally linked to the physical system (Pavlov et al. 2013), but also aligned with long-term records of pelagic and benthic ecology (e.g. Soltwedel et al. 2005, 2016; Beuchel et al. 2006; Kedra et al. 2010; Kortsch et al. 2012; Bauerfeind et al. 2014; Nöthig et al. 2015; Hop et al. (Chap. 7)), and proxies of environmental change (Ambrose et al. 2006; Vihtakari et al. 2016, 2017). An array of oceanographic moorings have been maintained in Fram Strait at 78° 50′N since 1998 extending from the shelf west of Svalbard through the deep part (2500 m) to the eastern Greenland shelf (Schauer et al. 2008). Thus, it covers the oceanographic variability in temperature, heat transport, sea ice and salinity both in the WSC and the cold East Greenland Current (Beszczyńska-Möller et al. 2011). The Long Term Ecological Research observatory HAUSGARTEN has been maintained in the eastern Fram Strait since 1999 (Soltwedel et al. 2005, 2016). Ecological variability as well anthropogenically-induced variation have been determined based on annual sampling campaigns coupled with autonomous instruments in anchored devices (i.e. moorings and profiling systems). Observatories can also acquire data in support of modelling – 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; Wallace et al. 2013; Drysdale 2017; Sundfjord et al. 2017).

Marine observatories have been an important element for many years in the community data collection within Kongsfjorden, and the number of moorings increased after the fjord became closed for commercial trawling in February 2007. Whilst there have been some actions to document the existence of marine observatories around Svalbard (e.g. www.sios-svalbard.org), there is no systematic review within the scientific literature. Over recent decades, scientific endeavours with respect to the Kongsfjorden system have drawn on data collected during long deployments of automated recording instruments within the fjord. Either these have been designed primarily for the deployment of moorings, or the availability of mooring data has been opportunistic, providing valuable ancillary data to the sampling program. Despite the prevalence of marine databases, awareness of these mooring deployments and the availability of the data are often retained within a rather limited subset of Arctic researchers, and the locations of moorings and operators are not widely known. The aim of this paper is to present a brief overview of the recent moorings in Kongsfjorden and review the scope of publications from these marine observatories. Note that these are fixed, autonomous instruments, rather than sites of monitoring by sampling. However, moorings may change in composition and position over time, and thus, our presentation represents the current situation in Kongsfjorden.

13.2 Moored Instrumentation and their Scientific Advances

Sensors for physical and chemical parameters have been installed on marine observatories in Kongsfjorden for monitoring: currents, temperature and salinity, fluorescence, turbidity, dissolved oxygen, photosynthetically active radiation (PAR), nitrate (NO_3), pCO_2 and pH (Table 13.1). Biological parameters are also collected by sediment traps, active acoustic instruments (e.g. acoustic zooplankton and fish profilers) and water samplers, and passive acoustics are used for monitoring of vocalizing marine mammals (Table 13.1).

Biofouling is a common problem of moored instrumentation, particularly in fjords where sediments from tidal glaciers are an additional source of fouling. Much of the fouling can be mitigated by wipers or covers that are automatically moved before recording, and flushing of sensors with pumped systems can also be effective. Nevertheless, it is essential for the sensors to undergo cleaning during maintenance periods. All scientific sensors will experience drift in recorded values because of sensor degradation, which may not occur linearly over time. Ideally, sensors should have pre- and post-deployment calibrations, but often this is not done routinely due to limited numbers of instruments and the need to replace them in the field annually. Finally, battery endurance, rather than data storage, is the usual limiting factor for moored instrumentation, particularly for acoustic instruments. This requires that the sampling frequency optimises the balance between endurance, temporal resolution of the data and measurement biases. Some instruments allow variable sample frequencies; an example of this is the multi-bottle sediment trap. Sampling interval can be set for each bottle independently with increased frequency during periods of rapid change or high activity (e.g. during spring bloom) and low frequency during the rest of the year.

Currents are measured with either electromagnetic (EM) sensors or acoustic Doppler technology. An acoustic Doppler current profiler (ADCP) is primarily used to measure depth-varying currents in layers of water either for long-term measurement of exchange or for short-term dynamics (Inall et al. 2015; Tverberg et al., Chap. 3). Secondary data streams include vertical velocity and acoustic backscatter from which the vertical movements of organisms in the water column can be quantified (Cottier et al. 2006; Wallace et al. 2010). Presence and absence of sea ice can also be derived from such acoustic profiling instruments (Hyatt et al. 2008) to give additional environmental context to the time series.

Temperature sensors are the most robust and reliable instruments. The accuracy may be better than 0.01 °C, and the drift of such instruments is generally small. There is a range of manufacturers of temperature sensors, but there are no agreed protocols on ensuring data quality. Each operator of an observatory tends to follow their own protocol – either calibrated *in situ* using a ship CTD system or with sensors being brought ashore for calibration at fixed temperatures.

Salinity, derived from measurements of conductivity, is a key parameter for determining water density, but it is more difficult than temperature to attain high quality records in long-term measurements due to issues of fouling and sensor drift. During long deployments in water with high sediment loads, the performance of the conductivity cells can deteriorate. Again, a variety of sensors are used and calibration is not done systematically across all operators of the observatories. In a region of high fouling, it may not be possible to apply calibrations to correct the data to the highest oceanographic standards. However, *in situ* calibration will indicate major drift/offsets and temperature-salinity scatter plots of the data will highlight portions of the data that are significantly affected by fouling. It is important that the salinity sensors receive factory refurbishment and calibration on regular intervals.

Optical instruments are generally placed in the upper water column to monitor phytoplankton biomass (chlorophyll *a*) of the water through their fluorescent properties. Photosynthetically active radiation is often measured in addition to fluorescence (Wallace et al. 2010; Pavlova et al., Chap. 4). Fouling issues associated with the lens can be a problem, but wipers can be used on lenses before recordings. To circumvent the issues of fouling and attaining precise calibrated values, fluorescence and PAR data have been published as normalised values relative to the maximum value (e.g. Wallace et al. 2010; Hegseth and Tverberg 2013; Berge et al. 2014) from which onset, duration and peak can be reliably determined for each parameter. Fluorescence data have also suffered from significant spikes caused by the occupation of the beam path in the sensor by zooplankton (e.g. feeding individuals have green guts). Recent deployments have used simple mesh coverings to maintain a flow of water and limit the impact of zooplankton on the signal.

Chemical sensors have been installed on some recent moorings, including recorders for dissolved oxygen, nitrate, pCO_2 and pH.

Sediment traps are used on some moorings (e.g. in Kongsfjorden and Rijpfjorden) to record the seasonal vertical flux of particulate organic matter (POM) (Howe et al. 2010; Darnis et al. 2017). Both algae and faecal pellets from zooplankton can be recorded, as well as zooplankton (swimmers) that eventually end up in the traps (Willis et al. 2006, 2008). The trap contains a number of bottles with fixative (2% formalin buffered with sodium borate), and its rotational sampling frequency can be set. Typically, the sampling is more frequent in association with the spring plankton bloom, although the main flux of particles generally occur in late autumn.

Water samplers on moorings can sample water periodically. These include pumps that push water through changing filters, and samples can be fixed in preservative. Measurements of nutrients (e.g. nitrate concentration) from these samplers can be used to calibrate continuously recording moored nitrate sensors located at the same depth (E. Leu, Univ. Oslo, pers. comm.).

Biological samples, such as clams or settlement plates, have been suspended from the mooring cable at different depths. Growth or uptake rates (e.g. chemical elements) in shells can then be directly correlated with measurements of the physical parameters from the mooring (Ambrose et al. 2012; Vihtakari et al. 2016, 2017).

Remote controlled stereoscopic camera systems are used to assess species abundance, species compositions and length-frequency distributions in shallow water. In Kongsfjorden, a vertical profiling system is located close to the old pier in Ny-Ålesund at 12 m water depth.

Passive acoustics, or listening devices, are hydrophones moored at different locations to detect vocalizing marine life, such as seals and whales, as well as ship traffic and airgun surveys. These have been used to record vocal complexity of the bearded seal (*Erignathus barbatus*) in Kongsfjorden (Parisi et al. 2017).

13.3 Marine Observatories in Kongsfjorden

Several marine observatories have been installed in Kongsfjorden by different nations responsible for their operation (Table 13.1, Fig. 13.1). Most of these observatories have been of the 'single-point, sub-surface' variety, resolving the vertical structure of the water column for some parameters. Typically, these moorings are deployed with annual schedules for maintenance and data retrieval. The hydrographical setting of the moorings can be related to seasonal and inter-annual variability in hydrography along the Kongsfjorden Transect (Kb1-Kb7; Tverberg et al., Chap. 3), as well as detailed descriptions of the respective moorings (e.g. Aliani et al. 2016; Venkatesan et al. 2016).

UK and Norway have established *The Kongsfjorden Marine Observatory*, which is operated in collaboration by Scottish Association for Marine Sciences (SAMS), UiT The Arctic University of Norway, and The University Centre in Svalbard (UNIS). This mooring contains an array of sensors and a rotating sediment trap

Table 13.1 Recent moorings in Kongsfjorden, Svalbard, with responsible institutions, locations, depth (distance to the surface) and parameters being monitored (i.e. in operation 2017–2018), including currents by current meter (not acoustic) (CM), Acoustic Doppler Current Profiler (AP), temperature (T) and salinity (S), fluorescence (FL), turbidity (TU), dissolved oxygen (DO), photosynthetically active radiation (PAR), nitrate (NO_3), pCO_2, total alkalinity (TA), pH, sediment trap (ST), water samplers (WS), passive acoustics (PA) for wildlife monitoring, stereooptic time-lapse camera (SCA). Reference, or contact e-mail, and number for registered projects in Research in Svalbard (RiS) are listed together with start/end time for mooring deployment

Mooring name	Institution	Country	Latitude (N)	Longitude (E)	Depth (surface) (m)	Parameters	Reference (or contact)	RiS #	Start time	End time
CNR-ISMAR	CNR-Dirigible Italia	IT	78°54.863’	12°15.530’	105 (15)	CM, TS, STR	Aliani et al. (2016)	4375	2010	Ongoing
KB-FRAM-AMUST	AWI	GE	78°56.501’	11°57.053’	303 (21)	TS, FL, DO, PAR, NO_3, $p\ CO_2$, pH, WS	Daniel.Scholz@awi.de	6790	2017	2018
IndARC-3	NCAOR	IN	78°56.789’	12°00.889’	198	CM, AP, TS, FL, TU, DO, PAR, NO_3, $p\ CO_2$	Venkatesan et al. (2016)	10,309	2016	Ongoing
IndARC-3	NCAOR/NPI/IMR	IN/NO	78°56.789’	12°00.889’	30	pCO_2	Agneta.Fransson@npolar.no	10,139	2016	Ongoing
LoTUS-Bottom Lander #8	Uni. Stockholm/UNIS	SE/NO	78°53.046’	12°32.141’	82 (67)	T	nina.kirchner@natgeo.su.se	10,783	2016	2017
Hydrophone-SM2-Open	CNR-Dirigible Italia	IT	79°03.219’	11°32.814’	75	PA	Giuseppa.buscaino@cnr.it	6616	2015	Ongoing
Hydrophone-SM2-Glacier	CNR-Dirigible Italia	IT	78°54.732’	21°24.250’	75	PA	Giuseppa.buscaino@cnr.it	6616	2015	2016
Hydrophone-SM2-Harbour	CNR-Dirigible Italia	IT	78°56.199’	11°54.628’	30	PA	Giuseppa.buscaino@cnr.it	6616	2015	2016
Hydrophone-Cabled-Harbour	CNR-Dirigible Italia	IT	78°55.902’	11°56.403’	30	PA	Giuseppa.buscaino@cnr.it	6616	2015	2017
Kongsfjorden Marine Obs.	SAMS, UIT, UNIS	UK/NO	78°57.4’	11°49.6’	225 (18)	TS, AP, FL, DO, PAR, NO_3, pH, $p\ CO_2$, ST, PA	www.mare-incognitum.no	11,107	2002	2027
AWIPEV-COSYNA	AWIPEV	GE/FR	78°55.747’	11°54.99’	11 (0)	TS, AP, FL, TU, DO, PAR, pH, $p\ CO_2$, TA, SCA	Fischer et al. (2016)	5742	2012	Ongoing

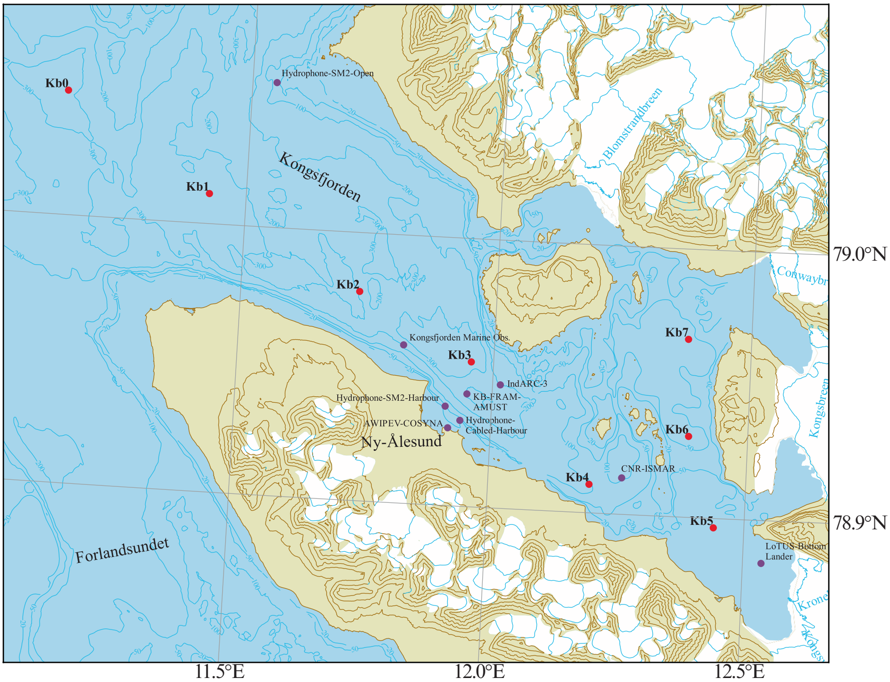

Fig. 13.1 Kongsfjorden, Svalbard, with locations of moorings and standard sampling stations (Kb1-Kb7) for the annual research survey in Kongsfjorden during July-early August (www.mosj.npolar.no; see Hop et al., Chap. 7). These stations, as well as others are also sampled annually in Kongsfjorden by the Institute of Oceanology, Sopot, Poland. Mooring information is in Table 13.1

(Table 13.1, Fig. 13.2), and has produced the longest time series from Kongsfjorden for a fixed mooring. Its record of temperature profiles from 2002–2018 shows the annual cycles in temperature, which can be averaged for the oceanographically warmest (Sept-Nov) and coldest (March–May) months (Fig. 13.2). Temperature variations during the warmest months indicate periods of enhanced warming in 2002, 2007–2009, and years after 2013, on the backdrop of an increasing temperature trend of 0.11 °C y^{-1}. These cycles can also be seen during the coldest months, although with a seasonal shift indicating warming of the coldest months prior to warming of the warmest months and the coldest months having a more pronounced long-term temperature increase of 0.16 °C y^{-1}. Similar long-term increase in fjord temperature has also been found in winter months (Nov-Feb) (Geoffroy et al. 2018).

A more detailed temperature record for the winter 2005–2006 showed the influx of warm water in February 2006 (Fig. 13.3), which has been linked to warming on the shelf in response to large-scale atmospheric circulation (Cottier et al. 2007) and a long-term reduction in fast ice in western fjords (Muckenhuber et al. 2016). These shifts in temperatures became only apparent based on such mooring records and have been used as background information for interpretations of shifts in the marine ecosystem, particularly after the warming events in winter 2006 and 2007, which

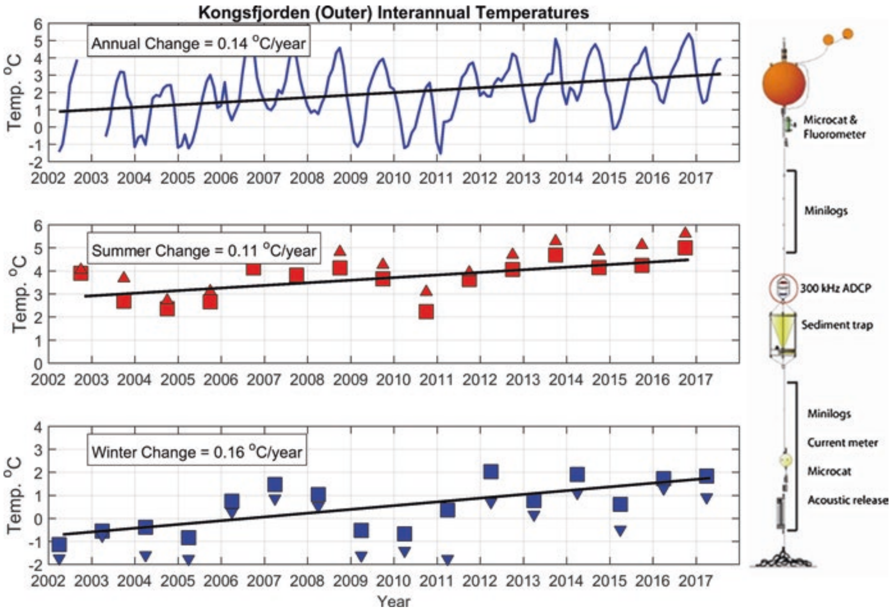

Fig. 13.2 Seasonal cycle of temperature in Kongsfjorden for 2002–2017 (top). Mean temperatures, averaged over depth for September–November – which are climatologically the warmest months (middle). Mean temperature, averaged over depth for March–May – which are climatologically the coldest months (bottom). Triangles show the maximum (warmest) and minimum (coldest) depth-averaged temperatures within the entire record. Simple regression lines indicate the annual change in temperature during the period. Data from Kongsfjorden Marine Observatory (N79°3.250′, E011°18.00′) (SAMS/UiT) are reported to www.sios-svalbard.org. The arrangement of instrumentation for this mooring is included as example. For other mooring arrangements we refer to cited papers

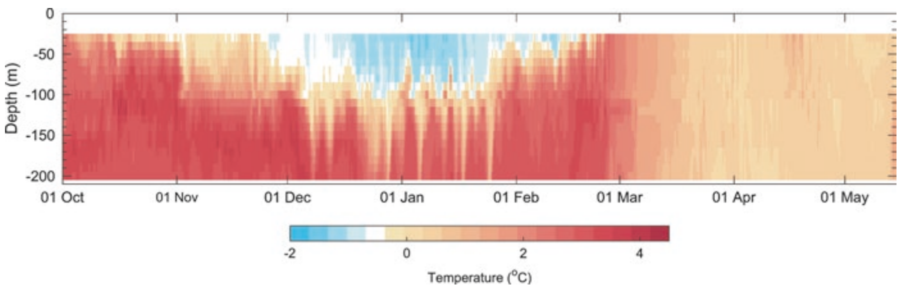

Fig. 13.3 Temperature observations from the Kongsfjorden Marine Observatory between 30 m and 200 m from October 2005 to May 2006. (Modified from Cottier et al. 2007)

resulted in warmer conditions in Kongsfjorden (Tverberg et al., Chap. 3) and less sea ice (Pavlova et al., Chap. 4). These changes in oceanographic conditions caused changes in the pelagic ecosystem, with larger influx of Atlantic species (Willis et al. 2008; Dalpadado et al. 2016; Vihtakari et al. 2018; Hop et al., Chap. 7). Warmer waters in the winter and spring period have also been implicated in the greater prevalence of Atlantic fish species (Berge et al. 2015b) and jellyfish (Geoffroy et al. 2018).

Timing and duration of key primary production events have been interpreted from the complementary data series (Hegseth and Tverberg 2013; Hegseth et al., Chap. 6). Time series of fluorescence (normalised) were recorded in the period 2006–2010 and interpreted against the temperature record from the same mooring. The spring blooms occurred April in 2006, and mainly in May–June during 2007, 2008 and 2010 (Hegseth and Tverberg 2013; Vihtakari et al. 2017), with high biomass of diatoms and *Phaeocystis pouchetii* in the early bloom and low biomass consisting of mainly *Phaeocystis* in the late blooms. The different bloom developments in 2006–2008 were related to the Atlantic Water inflow, which seemed to be the main controlling factor of the spring blooms.

Diurnal vertical migration (DVM), performed by many zooplankton species is a light-mediated behaviour in response to the trade-off between predation risk and the need to feed (Hays 2003). The zooplankton typically form aggregations in the water that can scatter sound and thus the phenomenon can be investigated from the backscatter signal recorded by upward-looking ADCP (300 kHz) mounted on a mooring. Acoustic data have shown the DVM signal is strong in Kongsfjorden during spring and autumn, but absent or unsynchronized during the summer (Fig. 13.4; Cottier et al.

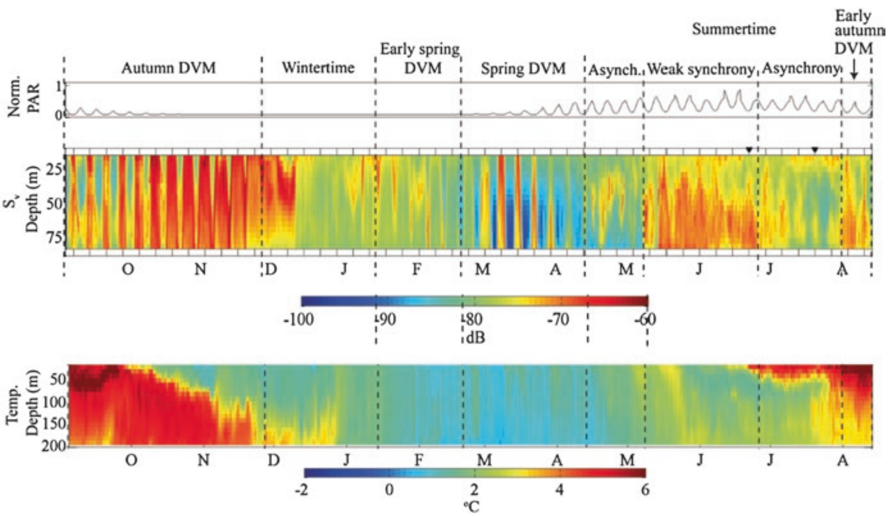

Fig. 13.4 Normalized (relative to maximum) photosynthetically active radiation (PAR), Acoustic Doppler Current Profiler (ADCP) and temperature data from Kongsfjorden, 2006–2007. The patterns in diel vertical migration (DVM) for zooplankton through the annual cycle is indicated above. (Modified from Wallace et al. 2010)

2006; Wallace et al. 2010). However, the DVM signal in autumn continues to some extent through the winter, indicating activity in the pelagic ecosystem even during winter with 24 h of darkness (Berge et al. 2009, 2015a). Further analyses of the ADCP data have shown that the zooplankton can adjust their DVM timing from solar cycle (24 h) to lunar cycle (24.8 h) within days around the full moon (Berge et al. 2009).

A study in Kongsfjorden and Rijpfjorden used marine observatories to understand how changes in the water column properties become imprinted on the growth lines of clams (Ambrose et al. 2012). Greenland cockles (*Serripes groenlandicus*) and hairy cockle (*Clinocardium ciliatum*) were placed in baskets at 25 m depth on the moorings. They had been marked with calcein dye, which becomes imbedded in the shells, and were then retrieved from the moorings a year later. Growth over the year could be studied and related to seasonal temperature and salinity pattern from the thermal loggers and algal biomass determined by Chl *a* fluorescence (Fig. 13.5). The study concluded that growth lines in Greenland and hairy cockle shells are formed inter-annually. Further studies on these clam species determined oxygen isotope signals to model seasonal growth patterns and correlate variation in element ratios (Li/Ca, Mg/Ca, Li/Mg, Li/Sr, Mn/Ca, Sr/Ca, Mo/Ca, and Ba/Ca) with temperature and fluorescence recordings from mooring instruments to determine the clams' potential as environmental proxies (Vihtakari et al. 2016, 2017). These studies found that element ratios in Greenland and hairy cockle shells reflect conditions in the internal body fluids (metabolism) rather than the environment where the bivalves are living.

Italy (CNR) has maintained the oceanographic array named *Mooring Dirigibile Italia* (MDI) since 2010 at 103 m depth in Kongsfjorden, outside the sill severing the inner bay (Fig. 13.1). The array includes current meters and temperature-conductivity recorders and regularly monitors the input of water through the inner morainic sill across Lovénøyane southern passage toward tidewater glaciers. Aliani et al. (2016) used a combination of time series from this mooring and CTD casts in the inner bay to estimate the volume of Atlantic Water in the inner bay and the ocean heat content. The heat content in Atlantic Water advected into the inner bay likely contributes to accelerated melting at the base of tidewater glaciers, which may cause instability of the glacial fronts (Jenkins 2011; Schild et al. 2018). A recent study by D'Angelo et al. (2018) used a data set (2010–2016) from this mooring to determine variability and composition of particle flux in Kongfjorden. The mass fluxes, predominantly from sub-glacial run off, varied by two orders of magnitude over the duration of study and indicate that land-derived input will increase over time in a warming scenario.

India (NCAOR) has run a multi-sensor moored observatory *IndARC* in middle of Kongsfjorden since 2014, with a suite of sensors for physical and chemical data collection (Fig. 13.1). Data include annual records of temperature, salinity, dissolved oxygen, currents based on recordings from current meters and ADCP as well as other parameters (Venkatesan et al. 2016; Table 13.1). Their observations confirm stratification of the water column during summer and mixing during winter. Their mooring data will be used in development of a bio-physical regional model for Kongsfjorden. Norway collaborates with India on this mooring with regard to

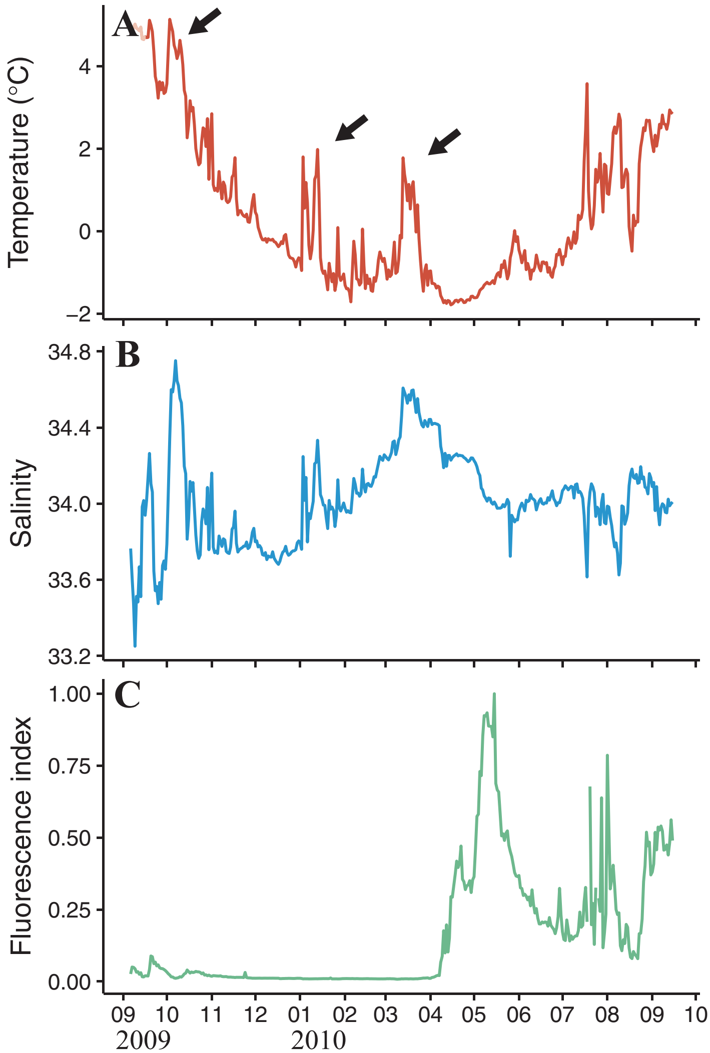

Fig. 13.5 Seasonal data (2009–2010) from the Kongsfjorden Marine Observatory at 36 m depth. A) Seawater temperature, B) salinity, and C) fluorescence index over the deployment period as measured by mooring instruments. Black arrows point to Atlantic inflow events. (Modified from Vihtakari et al. 2016)

annual maintenance (ship-based), and the Norwegian Polar Institute/Institute of Marine Research added a $p\mathrm{CO}_2$ sensor to this mooring in 2016.

Germany in collaboration with France (AWIPEV) have established an underwater observatory for long-term monitoring of the shallow water ecosystem in Kongsfjorden in 2012 (Fischer et al. 2016). The installation was done in the framework of COSYNA (Coastal Observation System for the Northern and Arctic Seas).

The Observatory is located in front of the Old Pier in Ny-Ålesund and is the northernmost-cabled online underwater observatory in the world. The system can be controlled from the home institution via high-speed internet connection for remote controlled sensors and *in situ* experiments. The system includes a fully equipped ferry box, with a water intake at 11 m water depth, for year-round measurements of physical and chemical parameters (temperature, salinity, turbidity, dissolved oxygen, pH, pCO_2, Total Alkalinity [TA] and PAR). In addition, recordings are made of water-mass properties and currents (ADCP, 1200 kHz), tides, and ice coverage. Periodical sampling from the ferry box can complement samples from other locations in the fjord, and one recent study used this to elucidate effects of Atlantic advection on spatial phytoplankton chlorophyll *a* and taxonomic composition (van De Poll et al. 2016). They suggested that glacial melt water governs spring bloom spatial timing and composition in the absence of sea ice driven stratification.

Daily profiles of temperature, salinity, turbidity, dissolved oxygen, pH and PAR, are performed vertically from the bottom (12 m depth) to surface along a fixed system at the Old Pier, and concomitant assessments of the mobile fauna in the water column are made by stereo-optic still camera system (Remos1). From these images, the daily and seasonal abundance of large zooplankton (e.g. pteropods, ctenophores, medusas, chaetognaths and decapods) can be determined as well as presence and development of pelagic fish larvae and juveniles based on length measurements. This system has great potential for providing new information about the shallow-water marine ecosystem on a seasonal basis, particularly during seasons of low sampling activity by field campaigns.

Germany (AWI) established a mooring, *KB-FRAM-AMUST*, 1.4 km south of the monitoring sampling station Kb3 in 2017. The purpose of this mooring was to test the long-term performance of different *in-situ* sensors, and it has served to monitor the bio-chemical processes going on close to Kb3 during a full year.

13.4 Further Considerations with regard to Marine Observatories in Kongsfjorden

Long-term observations have been central to documenting fundamental shifts in the Arctic marine environment (Grebmeier et al. 2006; Polyakov et al. 2017). Marine observatories are elements of the core infrastructure for such long-term monitoring, but also play an important role in supporting shorter-term process studies linked to specific research projects. Through this review we have shown that marine observatories offer the capabilities needed to address critical research areas such as the coupling between physical, biological and chemical processes and systems, and ecosystem change or resilience to climate variability. In Kongsfjorden, the utility of marine observatories has resulted in numerous systems being deployed (Table 13.1), all of them funded through different routes. To maximise the scientific benefits, two priorities need to be addressed: (i) coordination of the infrastructure and (ii) securing their long-term viability through financial support.

In terms of coordination, there exists no mechanism to achieve formal coordination of the observatories. They are often driven by national priorities and projects and there is relatively little exchange of information between the operators. However, there have been a number of efforts to summarize long-term data series around Svalbard (e.g. Renaud and Bekkby 2013) and collating information on marine observing activities through the Svalbard Science Forum Ocean Flagship (e.g. Beszczyńska-Möller and Sagen 2015; Falk et al. 2016) and Kongsfjord Flagship Workshops (Gabrielsen et al. 2009).

Despite these efforts to document activity, there exists a desire from both the science community and national agencies to establish a group of mooring operators to provide a more informed and coordinated approach to marine time series in Kongsfjorden. The Svalbard Integrated Arctic Earth Observing System (SIOS) has started to integrate long-term measurements in and around Svalbard (www.sios-svalbard.org) through a cooperative project. This exercise in collating data, joint analyses and reporting necessitates increased collaboration among the partners and may evolve into a coordinating body for marine observatories. Further coordination activity may include agreements on placement of observatories to maximise coverage, standardisation of instrumentation and calibration protocols, joint preparation of data products for the science community, and increased visibility of the marine observatories in Kongsfjorden and around Svalbard. Ultimately, marine observations should become better coordinated with observations currently performed on land, on glaciers and in the atmosphere.

With respect to long-term support of marine observatories in Kongsfjorden, the ocean module of SIOS-InfraNor encompasses several observatories along the west coast of Svalbard and Fram Strait, including the Kongsfjorden Marine Observatory (www.sios-svalbard.org/InfraNor). This provides financial security for observations until 2027. Additional observatories are likely to be supported by national programs and discrete research projects. Further resilience to the observing effort in Kongsfjorden will come when there is a clear network of marine observatories around Svalbard. SIOS may well have a coordinating role to play here, as might the Arctic Regional Ocean Observing System (Arctic-ROOS) and/or the Sustained Arctic Observing Network (SAON; www.arcticobserving.org). Ultimately, to maximise the scientific return and longevity of the observatories in Kongsfjorden, they need to have relevance beyond the fjord and this is best achieved through pan-Arctic data integration initiatives, e.g. Last et al. (2016) and Hobbs et al. (2018).

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