

Spitsbergen Oceanic and Atmospheric interactions – SOA



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Introduction

The SOA (Spitsbergen Oceanic and Atmospheric interactions) project aims at contributing to the first SESS report released by SIOS in 2019. The main scope of the project was providing results from an integrated analysis of meteorological and oceanographic data collected in the south-western offshore Svalbard area within the period 2014-2016. The scientific objective of the project is to deepen the knowledge of the role of atmospheric forcing that can drive and influence the variability of the deep current flow and thermohaline properties below 1000 m depth along the continental slope west of Spitsbergen.

Circulation and long-term changes in the Fram Strait

The Fram Strait is the only deep passage linking the Nordic Seas and the Arctic Ocean. The northward transport of relatively warm and salty Atlantic water (AW) has a significant impact on conversion and circulation of water masses (Rudels et al. 2015) as well as on sea ice and atmospheric fluxes in the Arctic. AW is carried poleward by two branches of the Norwegian Atlantic Current (NAC), a baroclinic branch linked to the Arctic Front and a barotropic jet, following the Norwegian and Barents Sea shelf break (Mork and Skagseth 2010). Of the latter flow, one part turns eastward into the Barents Sea Opening, while the larger portion enters Fram Strait and continues northward as the West Spitsbergen Current (WSC, Gascard et al. 1995; Walczowski 2013). The eastern Fram Strait is characterised by a steep slope between the shelf and deep basin. The warm and salty AW is transported northward within the WSC core, a fast and confined current located above the shelf break and the upper slope west of Svalbard (Beszczynska-Möller et al. 2012). The West Spitsbergen Shelf (WSS) is a region where waters of Atlantic and Arctic origin converge, mix and exchange (Saloranta & Svendsen 2001). In the surface layer on the shelf, the Sørkapp Current transports cold and fresh Arctic-type water, advected from Storfjorden around the southern tip of Spitsbergen, to the north. It consists mostly of the Storfjorden surface water, a mixture of local meltwater, heated by solar radiation, and the Arctic Water, warmed already in the shallow Barents Sea and advected into Storfjorden by the East Spitsbergen Current (Haarpaintner et al. 2001; Skogseth et al. 2005). The Arctic-type water carried by the Sørkapp Current along the shelf and Atlantic water transported by the WSC above the shelf break are typically separated by a frontal zone, a part of the large Polar Front system in the Barents Sea and farther north (Loeng 1991; Walczowski 2013). The Polar Front west of Spitsbergen is characterised by a density gradient only in the 50 m thick surface layer, while beneath this layer the front is density compensated and manifested through strong temperature and salinity gradients (Saloranta and Svendsen 2001; Walczowski 2013).

Warm anomalies observed in the WSC are mostly advected to the region from the North Atlantic, where increased AW temperature and salinity has been observed since the 1990s (Holliday et al. 2008). They are modified along the way by ocean-atmosphere heat fluxes and variable strength of ocean currents (Årthun and Eldevik 2016; Wåhlin and Johnson 2009). Two warm AW anomalies passing through the Fram Strait were observed in 1999–2000 and 2005–2007 and statistically significant positive trends were found in AW temperature ($0.06^{\circ}\text{C y}^{-1}$, Beszczynska-Möller et al. 2012) and salinity (0.003 y^{-1} , Walczowski et al. 2017) in the upper layer of the southern Fram Strait. At the same time, no significant trends in AW volume transport in the WSC have been observed (Beszczynska-Möller et al. 2012).

Dense water formation within fjords and on the WSS depends on the rate of cooling (heat loss to the atmosphere), homogenisation of the AW and upper waters, sea ice growth, and brine rejection. Strong and cold winds trigger the dense water formation and the shelf dynamics (Boyd and D'Asaro 1994; Skeie and Grønås 2000; Nilsen et al. 2016), by elevated heat loss to the atmosphere as well as sea-ice formation. The densest water is the brine-enriched shelf water (BSW) formed during intensive ice formation in winter in the coastal latent heat polynya in Storfjorden and wind forcing is crucial for preconditioning such events. BSW gradually fill the fjord to the sill crest and initiates a density-driven overflow (Schauer, 1995; Geyer et al. 2009). Density-driven currents move along the shelf and the continental slope reaching velocities as high as 0.6 m s^{-1} at the shelf break and sinking to deep layers according to their density anomaly and following bathymetric constraints (Wobus et al. 2013; Jungclauss et al. 1995; Fer and Ådlandsvik 2008). *Downslope cascading and evolution of dense water plumes as they propagate along the slope are however difficult to observe due to their intermittent and localized occurrence and to model due to challenges with parameterization of turbulent mixing and bottom friction in the bottom boundary layer.* A key question is *how recent climate changes have been influencing the dense water production and spreading along the WSS and what effects this had on the deep circulation in the Arctic Ocean and in the Fram Strait.*

State of the art of the measurements in the Fram Strait

In the Fram Strait, temperature and salinity profiles have been collected fairly regularly since 60' as part of the Norwegian monitoring around Svalbard (<http://www.mosj.no>) and international observing campaigns. Year-round observations with single or few oceanographic moorings have been collected since the early 70s to study the properties and dynamics of the Atlantic water inflow to the Arctic Ocean (e.g., Greisman 1976; Hanzlick 1983). Until the mid-80s, moorings were confined to the WSC and later years they were occasionally distributed in the entire strait. Since 1997, a sustained moored array has been established in collaboration between the Norwegian NPI (Arctic Ocean Outflow Observatory, <http://www.npolar.no/framstrait>) and German AWI (<https://www.awi.de/en/expedition/observatories/>

[ocean-fram.html](#)) across the entire northern Fram Strait at approx. 79°N. The array consists of between 14 and 17 oceanographic moorings with up to 5 levels of sensors measuring temperature, salinity and ocean currents covered the continental slopes west of Svalbard and east of Greenland, and the deep interior (Beszczynska-Möller et al. 2012). In addition, the deep-sea, long-term multidisciplinary observatory Hausgarten was established in the northern Fram Strait in 1999 to monitor environmental changes and deep-sea biodiversity near the Molloy Hole (Soltwedel et al. 2016). In 2014, the AWI oceanographic moored array and Hausgarten observatory were combined and extended into the FRAM (Frontiers in Arctic Marine Monitoring) observatory. Since 2012 the moored array north of Svalbard (at approx. 31°E) has been operated by Norwegian NPI, IMR, and Polish IOPAN under the A-TWAIN project (<http://www.npolar.no/en/projects/a-twain.html>) to monitor Atlantic water in the Arctic Ocean Boundary Current and its interactions with atmosphere and sea ice (Renner et al. 2018). While most of these observational activities were concentrated in the northern Fram Strait, a limited number of moorings were also deployed in the early 90s in the southern Fram Strait, in the Storfjorden region to investigate dense water formation and spreading (Schauer, 1995). Observations of brine production and Storfjorden outflow have been continued afterwards with single bottom moorings (Geyer et al. 2009; Skogseth et al. 2013) or ice-moored platforms (Jardon et al. 2014) complemented by ship-borne CTD sections. Single moorings were also deployed for one or more years in the vicinities of the West Spitsbergen fjords' outlets (e.g., Isfjorden or Hornsund) to monitor fjord-shelf exchanges. Four moorings were deployed for a period of one year (2010-2011) along the SW margin of Spitsbergen within the FP7-HERMIONE (Hotspot Ecosystem Research and Man's Impact on European Seas) project to investigate particle sources and downward fluxes under the influence of the WSC (Sanchez-Vidal et al. 2015). Two moorings have been deployed more recently (since 2014) in the southern Fram Strait by the Italian OGS and CNR in collaboration with UGOT and the Italian Navy (Hydrographic Institute), to study the deep flow variability (Lucchi et al., 2014; Bensi et al., 2017).

In addition to moored measurements, until the 90s hydrographic data were collected during regular Norwegian cruises and several international campaigns (e.g., MIZEX'84), usually along a few irregular sections and mostly during the summer period. A summary of early observations is given e.g. in Gascard et al. (1995). Since the 60s, the joint ecosystem surveys for fish stock assessments, including also oceanographic measurements, have been carried on in the Barents Sea and southern Svalbard region (Eriksen et al. 2017) by the Norwegian IMR and Russian PINRO. IOPAN has carried out regular summer cruises into the Nordic Seas and Fram Strait under the long-term monitoring program AREX since 1987 (Walczowski et al. 2017), measuring oceanographic and ecosystem parameters along several (10-15) repeated sections (the regular station grid established since the mid-90s). Since the mid-90s, the coast-to-coast hydrographic section in the northern Fram Strait, covering the entire width of the strait, has been repeated yearly by AWI and/or NPI to complement the moored array. Occasional oceanographic sections have been covered every year during

international research cruises in the Svalbard area. In order to optimise a large number of observational activities, a large effort has been paid in the last decade by the scientific community to extend and integrate the observing systems in the Arctic and around Svalbard through several projects, programmes, and consortiums/networks. Among currently on-going activities, we can mention e.g., the H2020 project INTAROS (coordinated by Norwegian NERSC, <https://www.nersec.no/project/intaros>), the Norwegian programme Nansen Legacy (<https://arvenetternansen.com/>), the EuroGOOS regional system ArcticROOS (Arctic Regional Ocean Observing System, <https://arctic-roos.org/>), and SIOS (Svalbard Integrated Arctic Earth Observing System, www.sios-svalbard.org).

SOA - Summary of used data

In this section, we present briefly the data used and the results obtained from their analysis within the SOA project.

Atmospheric data

The atmosphere plays a fundamental role in the process concerning the dense water formation along the coast of Spitsbergen. Large-scale pressure fields are responsible for the general atmospheric circulation, whose patterns above the ground modify due to the strong influence of the complex local geographical features. As local observations cannot always be assumed as representative for large areas, they need to be analysed with reference to the general atmospheric circulation. Along the west coast of Spitsbergen meteorological stations are located in e.g., Kongsfjorden, Isfjorden, and Hornsund fjords (Fig. 1 and 2). They coherently revealed a positive trend of the air temperature. Wind measurements show different regimes due to different geographic position and elevation, as well as to the distance from the open continental margin. The climatological wind direction over the Svalbard archipelago during the fall-winter season is easterly. It is characterised by high nonlinearity (Skeie and Grønås 2000) and by strong topographic steering of the atmospheric flows across the Svalbard Archipelago. Cisek et al. (2017) highlighted significant differences between meteorological parameters at Ny-Ålesund and Hornsund. For an integrated data analysis that includes both atmosphere and ocean to study the dense water formation, time and spatial scale of the processes, type of measurements, representativeness and homogeneity of the data have to be carefully taken in consideration. The comparison between wind data collected on land stations (e.g., the Arctic station Dirigibile Italia in Ny-Ålesund, <http://www.isac.cnr.it/~radiclim/CCTower/>) and those obtained from ECMWF (European Centre for Medium-range Weather Forecasts) show a large similarity (correlation > 0.84). Hence, to study significant atmospheric events we employed ERA-Interim wind dataset from the ECMWF, which covers both land and open sea areas on a

regular grid. Data are available at 6-hour time intervals and regularly spaced at 0.25° latitude \times 0.25° longitude over the entire Svalbard archipelago. We extracted ECMWF data at two locations close to the moorings S1 and ID2 (Fig. 2). Overall, the most energetic events occur coherently in the bottom current flow and in the wind speed (Bensi et al. in preparation).

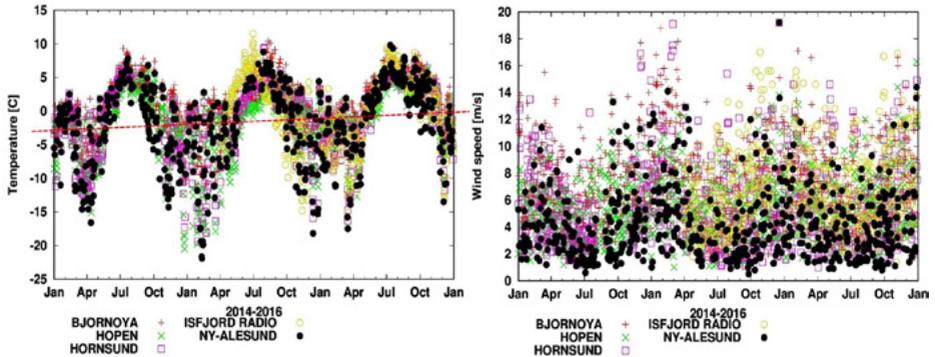


Figure 1: Air temperature ($^\circ\text{C}$) and wind speed (m s^{-1}) at different meteorological stations in Svalbard (see the map in Fig. 2 for their locations).

Oceanographic moorings S1 and ID2 (South-west Spitsbergen margin)

With the aim of collecting multi-annual time-series in an area of potential interaction between the West Spitsbergen Current and dense water cascading along slope, two deep moorings (ID2, S1) were deployed in 2014 offshore southwestern Svalbard, at depths of ~ 1000 m (Lucchi et al. 2014; Bensi et al. 2017; Ivaldi et al. 2017). The moorings were designed to collect data (temperature, salinity, turbidity, dissolved oxygen, currents, sediment trap) in the near-bottom layer (100-150 m thick), in areas where two contourite deposits (Bellsund and Isfjorden sediment drifts, Rebesco et al. 2013) were detected. Mooring ID2 recorded data from June 2014 to June 2016 (and re-deployed in 2018), S1 from June 2014 to July 2018 and it is still active (the last maintenance was accomplished in July 2018 during the “High North 18” cruise, on board the Italian r/v Alliance). The most interesting feature revealed by these data is the high variability observed during the winter period. In particular, occasional intrusions of warmer ($+2^\circ\text{C}$) and saltier (~ 35) water (resulting less dense than ambient water) often in concomitance with intense near-bottom currents, were detected (Bensi et al. in preparation). These intrusions modify the properties of the local bottom layer, occupied by the Norwegian Sea Deep Water (NSDW, $\theta_0 \sim -0.90^\circ\text{C}$, $S \sim 34.90$, $\sigma_\theta \sim 28.07 \text{ kg m}^{-3}$). The comparison among 2-yr long time series collected at S1, ID2, and at the observatories HAUSGARTEN and FRAM show a similar variability (Fig. 2). *These anomalies may be attributed to topographically trapped waves generated by barotropic*

oscillations modulated by atmospheric forcing (Nilsen et al. 2006) confined over the slope area. Enhanced currents at 1000 m depth, with a time delay of about 1 day (at S1) and 2 days (at ID2) with respect to strong wind events, took place mainly between October and April. A linkage between the variability of the deep currents and wind was found, with periodicities from diurnal (24 h) to 10 and 20 days. The diurnal signal of the variability connected to the cross-shore current component may be the result of propagating topographically trapped waves at 1000 m depth, similarly to what observed by Nilsen et al. (2006) at shallower depths (250 m) in the same area. It indicates that meteorological factors (winds) can modulate the current flow. We argue that this phenomenon protrudes into depth, where also occasional cascading of sediment-enriched shelf waters occurs. Indeed, dense waters form over the shelf by the combined effects of cooling, strong evaporation, and brine rejection phenomena induced by cold and dry winds blowing over the whole archipelago. They are then able to descend downslope collecting sediment. However, the intrusion of less dense waters observed at S1 and ID2 is counterintuitive. A hypothesis is that high concentration of suspended sediment (SSC) can substantially contribute to increasing the kinetic energy and the density of the downslope flow (Fohrmann et al. 1998). Turbidity peaks at S1 appeared time delayed with respect to density ones (Fig. 2). We calibrated the turbidity sensor in a laboratory by using particles collected at S1 (sediment trap) to obtain the corresponding values of SSC. However, maximum values of SSC associated with episodes of density minima were about 16 - 18 mg L⁻¹, which are not sufficient to compensate the low density calculated solely from temperature and salinity. We cannot exclude that low values of SSC could depend also on the position of the instruments and further investigations are needed to better understand this phenomenon. Samples from the sediment trap at S1 revealed major peaks (0.65 g m⁻² d⁻¹) in the total mass flux in late March and late May 2016 but also minor peaks in Dec 2015 and Feb 2016, coherently with data recorded by the turbidity sensor. Sanchez-Vidal et al. (2015) measured values of total mass flux 20 times higher (up to 11.6 g m⁻² d⁻¹) in their station A (same location of S1) in Feb-Mar 2011. Total mass flux values at S1 were higher/lower when organic carbon content was lower/higher, respectively. Organic carbon content peaked, in late August 2015, in late April 2016, and at beginning of June 2016.

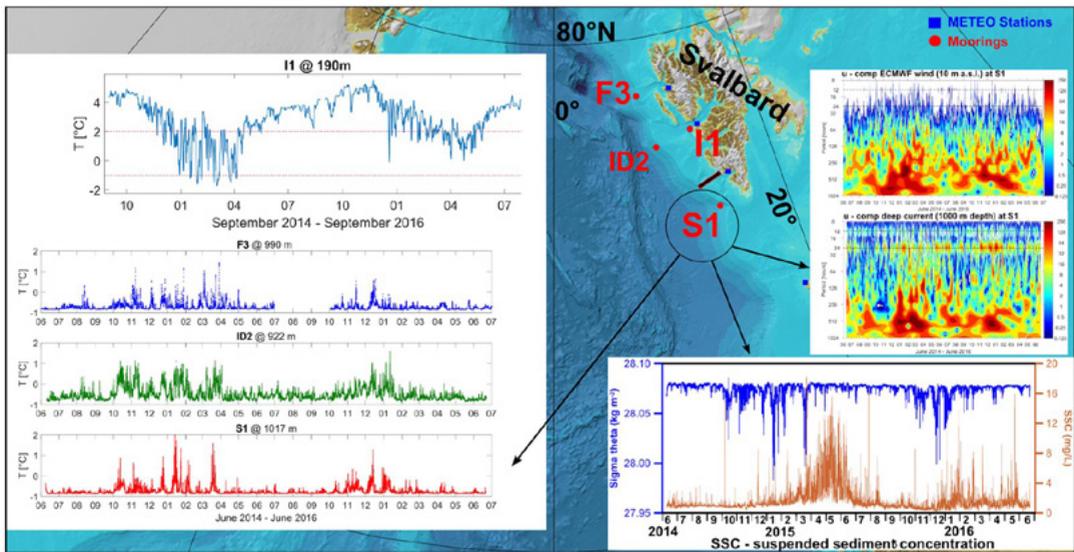


Figure 2: In-situ temperature, density anomaly, calculated SSC, and wavelet power spectrum of u-component from deep currents and wind at S1. Temperature at ID2, I1 (shelf), and F3 (von Appen et al. 2015, 2017) are also shown. The thick line on the WSS, north of Hornsund fjord, indicates the position of CTD profiles shown in Fig. 3. The bathymetry chart is taken from Jakobsson et al. (2012).

Oceanographic mooring I1 (West Spitsbergen Shelf)

To capture the AW intrusions into the Isfjorden, temperature, salinity, and current at several depths have been measured from moored instruments since 2010. The mooring is located at 78.068°N, 13.528°E at 203–214m depth and maintained yearly every September. It is equipped with three Aanderaa current meters with CTD sensors (either RCM9, RDPC or Seaguard) at ~50 m, ~100 m and ~190 m depths, three SeaBird SBE37SM MicroCATs at ~40 m, ~75 m, and ~150 m, and five evenly distributed VEMCO temperature loggers. The along-slope current velocities measured at 50 m and 190 m depths represent the upper and lower layer of the water column. In general, both the upper and lower layers cool during autumn and winter, but the cooling is often interrupted with intrusion or advection of warmer water. *This occurs every year, and in particular, during winter 2012 the temperature hardly dropped below 1 °C (Nilsen et al. 2016).* These warm water intrusions during winter are due to inflow of AW triggered by air–ocean interaction processes as described by the shelf circulation model in Nilsen et al. (2016). *The along-slope velocities (towards Isfjorden) increase during the winter months (December–March). These are also the months when the along-coast wind stress and the wind stress curl on the southern WSS are strongly positive and negative, respectively (Nilsen et al. 2016).* The amount of AW on the WSS varies annually, for instance in winter 2013–2014 the WSS outside Isfjorden was flooded with AW from bottom to the surface, while in winter 2014–2015 the

WSS was occupied with cold and fresh Arctic Water (Fig. 2). During winter 2015-2016 warm waters were observed again at I1 site.

Hydrographic cruises (West Spitsbergen margin)

IOPAN has been conducting repeated summer surveys (June-July) in the Nordic Seas and Fram Strait from RV Oceania since 1987 under the long-term monitoring program AREX (Walczowski et al. 2017). Hydrographic measurements cover the grid of regular CTD/LADCP stations (conductivity, temperature, depth, and current velocities measured from ocean surface to the bottom). In addition, the upper-ocean currents were recorded underway by the vessel mounted ADCP. The hydrographic sections (10 zonal and several meridional) are located in the eastern Greenland Sea, along the Barents Sea Opening, in the eastern Fram Strait and north of Svalbard and cover shelf, continental slope and deep basins. To complement the standard stations (~200 per year), high-resolution sections with a towed CTD system (operating down to approx. 300 m depth) are measured in a few locations across the shelf break, in Spitsbergen fjords and near the marginal ice zone north of Svalbard. The collected data enable analysing AW properties and long-term changes of the AW inflow in the Nordic Seas and Fram Strait towards the Arctic Ocean (Walczowski et al. 2017). *In 2013-2017 in the north-eastern Greenland Sea, the AW temperature slightly exceeded the long-term mean, while salinity was close to the long-term average. In the south-eastern part of the Fram Strait, near the South Cape, the AW temperature dropped below its long-term mean in 2013, becoming higher than the mean in the following years, while the salinity has remained constantly high since 2004, with no clear trend (González-Pola et al. 2018). The deep waters in the annually measured part of the Nordic Seas reveal a positive trend in temperature (as in other northern regions), and high interannual variability in salinity.*

UNIS student cruises carried out in April 2014 with R/V Lance and May 2015 with R/V Helmer Hanssen collected CTD profiles across the WSS north of Hornsund (Fig. 2). *Data revealed different conditions on the shelf between winters 2014 and 2015 (Fig. 3). In winter 2013-2014, the WSS was occupied with warm and saline Atlantic Water whereas in winter 2014-2015 the conditions were more "normal" with colder and less saline Arctic Water on the shelf and with a clear temperature-salinity front between Arctic and Atlantic waters at the shelf break. I1 mooring data confirm the presence of colder water in January - April 2015.*

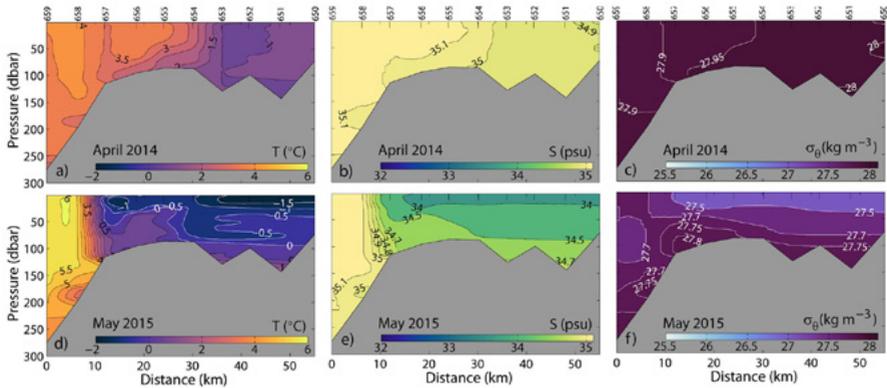


Figure 3 - Distribution of a)-d) in-situ temperature ($^{\circ}\text{C}$), b)-e) salinity (psu), and c)-f) potential density anomaly (kg m^{-3}) across the WSS north of Hornsund fjord in a)-c) April 2014 and d)-f) May 2015. West side is on the left.

Geophysical and geological datasets (bathymetric constraints and insight into the past)

Seafloor topography controls the oceanic circulation and sedimentary processes, which in turn, reshape the seafloor morphology. The pathway of bottom currents is controlled by the topographic steering of the continental slope and affected by deviations of its direction causing perturbations of the flow. Moreover, dense water produced on the shelf fills the topographic depressions and spills over bathymetric sills to find its way towards the continental slope along troughs, gullies, and canyons. High-resolution bathymetry and morphological information are hence needed to identify the bottom-current related features (sediment drifts and corresponding bedforms) and to detect the path of episodic dense water cascading along the continental slope. In this way, it is possible to identify flow paths and direction and possibly infer a speed range. Moreover, this kind of data is needed to plan targeted measurements (mooring sites) and sampling (coring sites). Extensive multibeam bathymetry and sub-bottom profiles on the Storfjorden-Kveithola Trough-Mouth Fan system and partial coverage of Bellsund and Isfjorden sediment drifts have been collected during a series of scientific expeditions in the last 10 years (e.g., *Svais*, *Eglacom*, *Coribar*, *HighNorth*). These data already contributed to the International Bathymetric Chart of the Arctic Ocean (IBCAO, Jakobsson et al. 2012). *Sedimentary samples* and in particular two Calypso cores (19-17 m long) and three box cores were collected during the PREPARED cruise (June 2014) on the Bellsund and Isfjorden sediment drifts. They help to reconstruct the paleoclimate at centennial/millennial scales. In fact, surface geological data provide information on the characteristics of present and modern sediments deposited and shaped by bottom currents and/or cascading phenomena. Conversely, long piston/gravity cores enable extrapolating

this kind of information to the past, when the climate conditions were different. Analysis of sediments deposited in geologic periods, when the atmospheric Carbon Dioxide concentration (and hence temperatures) were higher than today, allows predicting future scenarios connected to the present climatic change and global warming.

Data policy

To fulfil the SIOS Open data principles allowing free and open access to data gained through research around Svalbard to any person or organisation who requests them, the SOA project will make their datasets available in a timely manner. Participants of the SOA project will provide the metadata for their results either directly to the SIOS Data Management System (SDMS) or via the individual data centres of the participants involved in this study. In the latter case, the SDMS will connect these individual systems to a unified virtual data management system to make all the data visible in the SIOS catalogue. All metadata will then be available through a search interface integrated with the SIOS web portal. Some data may have access restrictions due to the policy of projects funding their collection (e.g., Italian S1 and ID2 moorings and hydrographic stations collected by IOPAN) and they will be handled accordingly by the responsible data centres. Generally, the metadata will be searchable and contain information on how to request access to the dataset.

Unanswered questions and gaps in the knowledge

- a. *What are the effects of the progressive warming and reduction of ice cover, induced by both natural and anthropogenic influences (e.g., CO₂ increase, black carbon on the snow), in the Arctic and around Svalbard archipelago on dense water production and their links to the global thermohaline circulation?*
- b. *What triggers the thermohaline variability observed at depths exceeding 1000 m along the West Svalbard continental margin? Could that variability be linked to vertical fluctuations of the intermediate layer of Atlantic Water modulated by atmospheric events or to oscillations generated by internal waves/eddies?*
- c. *Cascading events along the west Svalbard margin: Which measurements are needed to have a better comprehension of the phenomena involved (i.e., mixing and entrainment, sediment transport and deposition, temporal variation of event frequency)? Turbidity measurements performed in the deep layer at mooring S1 revealed qualitative differences between the two deployment periods as well as between timings of thermohaline and turbidity peaks. This fact highlights the need for more extensive and reliable measurements to assess the role of sediment erosion and resuspension in cascading events and in the variability of the deep flow.*
- d. *Coupling between atmospheric and oceanic measurements: there is a lack of meteorological data collected offshore.*
- e. *Katabatic wind: is it composed only by a local or large scale (or both) component? The measurements gathered at Ny-Ålesund can try to answer at a local scale, as a case study to explore the possible link between the shallow sea and the atmospheric boundary layer above the sea.*
- f. *How can we optimise the future activities along the west margin of Svalbard?*

Requirements for addressing unanswered questions and fill the gaps in the knowledge

Overall, in order to address the *question related to the effects of progressive warming and reduction of ice cover on the sensitive Arctic marine environment we need to sustain integrated long-term time series (>10 years), both at sea and on land.* The collaboration among Nations and Organizations is the only way to provide long-term datasets. A limiting factor to sustain long-term ocean monitoring programmes is the access to icebreakers and research vessels capable of travelling around Svalbard, especially during the winter season. At the moment, the following nations are planning activities in the region: Norway, Germany, Poland, Italy, Sweden, GB, Korea. We need a collaborative framework within which the oceanographic mooring maintenance and the regular collection of hydrographic data could be guaranteed on the long term.

To address unanswered questions, we need the following actions and requirements:

- a. *To implement the number of moorings and their payloads along the West Spitsbergen margin, shelf and deep sea (> 1000 m depth). Only by improving temporal and spatial data coverage we can have a better comprehension of the phenomena involving fjords, shelves, and deep sea areas.*
- b. *To capture seasonal variability of the Atlantic Water properties and of atmospheric and oceanographic forcing influencing shelf dense water formation and cascading.*
- c. *To promote and sustain an adequate observational strategy for monitoring source areas of dense water formation (e.g., Storfjorden and SW Svalbard margin) under the current conditions when the ice-cover is retreating;*
- d. *To fulfil a need for meteorological measurements at sea (e.g., Prins Karls Forland island) a solution could be to establish a connection with jcomm.info for the meteorological data availability from ships of opportunity and research vessels.*
- e. *To Perform oceanographic cruises during winter-spring along established transects; search for ship infrastructures available for the cruises (e.g., Norway, Germany, UK, Korea, etc.).*
- f. *To acquire additional high-resolution Multibeam data to better investigate the role of bathymetric constraints that influence shelf-slope dynamics. The Continental shelf area is well covered by Olex data (<http://www.olex.no/>). Conversely, continental slope and deep areas west of Svalbard Archipelago are only partially surveyed. Beside of Italian bathymetric data contributing to IBCAO, we are aware of extensive Russian and German datasets.*
- g. *To obtain additional multi-corer samples in key areas (e.g., around S1 and ID2 where sediment drift was found) to deepen the knowledge on the sedimentary record of the cascading.*
- h. *To collect biogeochemical data through autonomous platforms for studying specific*

processes (e.g., shelf-deep sea carbon export, acidification, etc.).

- i. To make available harmonized meteorological data from opportunity ships.
- j. To promote collaborations and data sharing among research groups and international Institutions.

To move towards an optimisation of future activities along the west margin of Svalbard:

- a. A constant effort has to be paid to bring scientific research to operational systems with particular attention to the accessibility of data and products.
- b. The maintenance of moored observatories and the duration of time-series should be guaranteed to reach decadal scales in order to study inter-annual variability and possible climate change evolution.
- c. Time series data with high temporal resolution have to be extended to more depths (upper, intermediate, and deep layers) also in the south-west offshore Svalbard area following the approach of the FRAM Observatory (<http://www.fxo3.eu/observatory/fram/>).

Long-term measurements of the physical parameters and particle fluxes along the Svalbard margin can be useful to investigate the temporal variability of the processes driving lateral and vertical particle advection. Such variability hints at possible environmental changes associated with both sea-bottom processes and sea-surface environmental conditions reflecting climate change (e.g., sea ice extension, phytoplankton shift). Long-term measurements can also provide information regarding the exchange of water and biochemical properties between fjords and offshore areas. This approach has been already applied to HAUSGARTEN (Soltwedel et al. 2016). Moreover, specific analysis focused on the microplastic pollution from sediment trap samples could provide useful information particularly on the environmental conditions affected by an anthropogenic factor.

At the present time (2018), two oceanographic moorings (S1 and ID2) are active on the continental slope (> 1000 m depth) in the southwest part of Svalbard. Other moorings arrays are active in the northern part of the Fram Strait and north of Svalbard, on the shelf (e.g., I1) and within Storfjorden, Hornsund, and Kongsfjorden. *A big effort to maintain and harmonize (in terms of measured parameters and protocols) the existing observatories is needed.* Ongoing collaborations strengthened, thanks to the SIOS initiatives, which would aim at planning future joint research activities focused on the scientific questions raised in this scientific report. For example, within the SOA project, we discussed the possibility to share instruments and mooring logistics, and provide complementary measurements in the next future.

Final recommendations

(I) It would be beneficial for the scientific community if SIOS could diffuse annual cruise plans and ship-based operations around Svalbard to make people aware of the possibility to collaborate and optimise the logistics at sea; (II) To address the question regarding the influence of anthropogenic forcing on the “*natural variability, particularly the interannual to multi-decadal modes of variability*”, there is a need for effective implementation and harmonization of in-situ measurements (more observatories, more sensors) and for multidisciplinary numerical modelling.

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References

- Årthun M and T Eldevik (2016) On Anomalous Ocean Heat Transport toward the Arctic and Associated Climate Predictability. *J Climate*, 29, 689–704, <https://doi.org/10.1175/JCLI-D-15-04481>.
- Bensi M et al (in preparation), Deep flow variability off southwest Svalbard (Arctic).
- Bensi M et al (2017) DEFROST (DEep Flow Regime Off SpITSbergen) Cruise Report. OGS Report n° 2017/10 Sez. OCE 5 EXO (Available from mbensi@inogs.it).
- Beszczynska-Möller A, F Eberhard, U Schauer, and E Hansen (2012) Variability in Atlantic water temperature and transport at the entrance to the Arctic Ocean, 1997–2010. *ICES J. of Mar Sc.* (2012), 69(5), 852–863 doi:10.1093/icesjms/fss056.
- Boyd, TJ, and D'Asaro EA (1994) Cooling of the West Spitsbergen Current: Wintertime Observations West of Svalbard. *J Geophys Res*, 99(C11), 22597–22618, doi:10.1029/94JC01824.
- Cisek M, Makuch P, Petelski T (2017) Comparison of meteorological conditions in Svalbard fjords: Hornsund and Kongsfjorden. *Oceanologia* (2017) 59, 413–421, <http://dxdoiorg/101016/jocean201706004>.
- Fer I, and Ådlandsvik, B (2008) Descent and mixing of the overflow plume from Storfjord in Svalbard: an idealized numerical model study. *Ocean Sci.*, 4, 115–132, doi:10.5194/os-4-115-2008, 2008.
- Fohrmann H, Backhaus JO, Blaume F, and Rumohr J (1998) Sediments in Bottom-Arrested Gravity Plumes: Numerical Case Studies. *Journal of Phys. Oceanog.* 28, 2250–2274.
- Gascard JC, Richez C, Rouault C (1995) New insights on large-scale oceanography in Fram strait: The West Svalbard Current. *Coast Estuar Stud*, 49, 131–182.
- Geyer F et al (2009) Dense overflow from an arctic fjord: mean seasonal cycle, variability and wind influence. *Cont Shelf Res*, 29 (2009), pp 2110–2121.
- González-Pola C et al (2018) ICES Report on Ocean Climate 2016 ICES, Cooperative Research Report No 339 110 pp., <https://doi.org/10.17895/ices.pub.4069>.
- Greisman PE (1976) Current Measurements in the East Greenland Sea. PhD Thesis, University of Washington, Seattle.
- Eriksen E et al (2017) Spatial and temporal changes in the Barents Sea pelagic compartment during the recent warming. *Prog in Oceanog* 151, pp 206–226.
- Haarpaintner J, Gascard, J-C and Haugan, P (2001) Ice production and brine formation in Storfjorden, Svalbard *J Geophys Res*, vol 104, no C7, pp 14,001–14,013.
- Hanzlick DJ (1983) The West Spitsbergen Current: transport, forcing and variability. PhD thesis, University of Washington, Seattle.
- Holliday NP et al (2008) Reversal of the 1960s to 1990s freshening trend in the northeast North Atlantic and Nordic Seas. *G Res Lett* 35, L03614, doi:10.1029/2007GL032675.
- Ivaldi R et al (2017) High North 17 Cruise Report, Arctic Mar Geophys Campaign Ist Idrografico della Marina, vol II 3180.
- Jakobsson M et al, (2012) The International Bathymetric Chart of the Arctic Ocean (IBCAO) Version 30 *Geophysical Research Letters* 39, L12609.
- Jardon FP et al (2014) Ice production in Storfjorden (Svalbard) estimated from a model based on AMSR-E observations: Impact on water mass properties. *J Geophys Res Oceans*, 119, doi:10.1002/2013JC009322.
- Jungclauss JH, Backaus JO, Fohrmann H (1995) Outflow of dense water from the Storfjord in Svalbard: A numerical model study. *Journal of Geophysical Research: Oceans*, Volume 100, Issue C12, pp. 24,719–24,728.
- Loeng H (1991) Features of the physical oceanographic conditions of the Barents Sea Polar Research, 10: 5–18 doi:10.1111/j1751-8369/1991tb00630x.
- Mork KA, and O Skagseth (2010) A quantitative description of the Norwegian Atlantic Current by combining altimetry and hydrography. *Ocean Sci*, 6(4), 901–911, doi:10.5194/os-6-901-2010.
- Nilsen FB Gjevik, and U Schauer (2006). Cooling of the West Spitsbergen Current: Isopycnal diffusion by topographic vorticity waves. *J Geophys Res*, 111, C08012, doi:10.1029/2005JC002991.
- Nilsen F et al (2016) A Simple Shelf Circulation Model: Intrusion of Atlantic Water on the West Spitsbergen Shelf *J Phys Oceanogr*, 46, 1209–1230, <https://doi.org/10.1175/JPO-D-15-00581>.
- Notz D & Marotzke J (2012) Observations reveal external driver for Arctic sea-ice retreat *Geophys Res Lett* 39, L08502.
- Overland J et al (2016) <https://www.arctic.noaa.gov/Report-Card/Report-Card-2016/ArtMID/5022/ArticleID/271/Surface-Air-Temperature> .
- Polyakov IV et al (2017) Greater role for Atlantic inflows on sea-ice loss in the Eurasian Basin of the Arctic Ocean. *Science*, 356, 6335: 285–291, DOI: 10.1126/science.1258204.

- Quadfasel D, Rudels B, Kurz K (1988) Outflow of dense water from a Svalbard fjord into the Fram Strait. *Deep-Sea Research* 35 1143–1150.
- Rebesco M et al (2013) Quaternary contourite drifts of the Western Spitsbergen margin *Deep-Sea Research I*, 79, 156–168, 10.1016/j.jdsr.2013.05.013.
- Renner AHH et al (2018) Variability and redistribution of heat in the Atlantic Water boundary current north of Svalbard, *Journal of Geophysical Research: Oceans*, 123. <https://doi.org/10.1029/2018JC013814>.
- Rudels B et al (2005) The interaction between waters from the Arctic Ocean and the Nordic Seas north of Fram Strait and along the East Greenland Current: results from the Arctic Ocean-02 Oden expedition *Journal of Marine Systems* 55, 1–2 (2005), 1–30.
- Sanchez-Vidal A et al (2015) Particle sources and downward fluxes in the eastern Fram strait under the influence of the west Spitsbergen current. *DSR-I*, 103, 0967-0637.s 49 - 63.s, doi: 10.1016/j.dsr.2015.06.002.
- Saloranta TM & Svendsen H (2001) Across the Arctic front west of Spitsbergen: high-resolution CTD sections from 1998-2000. *Polar Research* 20(2), 177–184.
- Schauer U (1995) The release of brine-enriched shelf water from Storfjord into the Norwegian Sea. *Journal of Geophysical Research* 100, 116028–160515.
- Skeie P and Grønås S (2000) Strongly stratified easterly flows across Spitsbergen. *Tellus* 52, 473–486.
- Skogseth R, Haugan PM, Jakobsson M (2005) Water mass transformations in Storfjorden. *Continental Shelf Research*, 25, 667–695, doi:10.1016/j.jcsr.2004.10.005.
- von Appen W-J, Beszczynska-Möller A, Fahrbach E (2015) Physical oceanography and current meter data from mooring F3-15 Alfred Wegener Institute, Helmholtz Center for Polar and Marine Research, Bremerhaven, PANGAEA, <https://doi.org/10.1594/PANGAEA853902>.
- von Appen W-J, Latarius K, Kanzow T (2017) Physical oceanography and current meter data from mooring F3-16 Alfred Wegener Institute, Helmholtz Center for Polar and Marine Research, Bremerhaven, PANGAEA, <https://doi.org/10.1594/PANGAEA870842>.
- Skogseth R et al (2013) Creation and tidal advection of a cold salinity front in Storfjorden: 1 Polynya dynamics. *J Geophys Res Oceans*, 118, 3278–3291, doi:10.1002/jgrc.20231.
- Wählin A. and Johnson H (2009) The Salinity, Heat, and Buoyancy Budgets of a Coastal Current in a Marginal Sea. *Journal of Physical Oceanography*, 39, 2562 – 2580.
- Soltwedel T et al (2016) Natural variability or anthropogenically-induced variation? Insights from 15 years of multidisciplinary observations at the arctic marine LTER site HAUSGARTEN. *Ecological Indicators*, 65: 89-102.
- Walczowski W (2013) Frontal structures in the West Spitsbergen Current margins. *Ocean Sci*, 9, 957-975, <https://doi.org/10.5194/os-9-957-2013>.
- Walczowski W et al (2017) Oceanographic observations in the Nordic Sea and Fram Strait in 2016 under the IO PAN long-term monitoring program AREX. *Oceanologia*, 59 (2), pp 187-194. DOI: 10.1016/j.jocean.2016.12.003.
- Wobus F et al. (2013) The piercing of the Atlantic Layer by an Arctic shelf water cascade in an idealised study inspired by the Storfjorden overflow in Svalbard, *Ocean Modelling* 71, 54–65, doi:10.1016/j.ocemod.2013.03.003.