The Iceland Greenland Seas Project

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Abstract [250 words; limit 250]

The Iceland Greenland Seas Project (IGP) is a coordinated atmosphere-ocean research program investigating climate processes in the source region of the densest waters of the Atlantic Meridional Overturning Circulation. During February and March 2018, a field campaign was executed over the Iceland and southern Greenland Seas that utilized a range of observing platforms to investigate critical processes in the region – including a research vessel, a research aircraft, moorings, sea gliders, floats and a meteorological buoy. A remarkable feature of the field campaign was the highly-coordinated deployment of the observing platforms, whereby the research vessel and aircraft tracks were planned in concert to allow simultaneous sampling of the atmosphere, the ocean and their interactions. This joint planning was supported by tailor-made convection-permitting weather forecasts and novel diagnostics from an ensemble prediction system. The scientific aims of the IGP are to characterize the atmospheric forcing and the ocean response of coupled processes; in particular, cold-air outbreaks in the vicinity of the marginal-ice-zone and their triggering of oceanic heat loss, and the role of freshwater in the generation of dense water masses. The campaign observed the lifecycle of a long-lasting cold-air outbreak over the Iceland Sea and the development of a cold-air outbreak over the Greenland Sea. Repeated profiling revealed the immediate impact on the ocean, while a comprehensive hydrographic survey provided a rare picture of these subpolar seas in winter. A joint atmosphere-ocean approach is also being used in the analysis phase, with coupled observational analysis and coordinated numerical modelling activities underway.

Capsule

A coordinated atmosphere-ocean research project, centered on a rare wintertime field campaign to the Iceland and Greenland Seas, seeks to determine the location and causes of dense water formation by cold-air outbreaks.

Background and motivation

The subpolar region of the North Atlantic is crucial for the global climate system. It is where densification and sinking of ocean waters takes place, driven by strong air-sea buoyancy fluxes, constituting the headwaters of the Atlantic Meridional Overturning Circulation (AMOC; e.g. Buckley and Marshall 2015). As such, coupled atmosphere-ocean processes, on a variety of spatial scales, require an integrated approach for their improved understanding and prediction. This region has ‘enhanced communication’ between the atmosphere and ocean; wintertime atmospheric forcing strongly dictates ocean properties, thermal structure and circulation. While during warm, moist mid-latitude air mass intrusions the air-sea fluxes are moderate and can even lead to ocean warming (e.g. Moore et al. 2012; Pithan et al. 2018); intermittent cold-air outbreaks (CAOs) result in large surface fluxes of heat and moisture that make the surface waters colder, saltier and denser. This drives convective overturning that contributes to the lower limb of the AMOC. These subpolar seas are therefore a ‘mixing pot’ for the water-masses of the North Atlantic. Previous studies suggest that the dominant contribution to the AMOC and its variability comes from the subpolar seas to the east of Greenland (Spall and Pickart, 2007; Holte and Straneo, 2017; Lozier et al. 2019). *However, exactly where, when and how the water-mass transformations occur remain unclear.*

The dense water formed in the Nordic Seas (collectively the Norwegian, Greenland, and Iceland Seas) enters the North Atlantic through gaps in the submarine ridge between Greenland and Scotland (Østerhus et al. 2019). The largest amount of water flows through Denmark Strait. Debate about where the Denmark Strait Overflow Water (DSOW) originates from has been ongoing for decades. Originally the Iceland Sea and/or the Greenland Sea was thought to be the source of the dense water via open-ocean convection to intermediate depths (e.g. Swift and Aagaard 1981; Strass et al. 1993). However, subsequently it was argued that the light-to-dense transformation takes place in the boundary current system encircling the Nordic Seas. In particular, the warm, salty water in the northward-flowing Norwegian Atlantic Current is made colder and fresher, and this dense water then returns southward in the East Greenland Current ultimately exiting through Denmark Strait (Mauritzen, 1996; see **Figure 1**). While this 'rim current' overturning loop is now well established, a current carrying dense overflow water towards Denmark Strait was subsequently discovered along the northern Iceland slope (Jónsson and Valdimarsson 2004). This has been dubbed the North Icelandic Jet (NIJ), and it provides the densest third of the DSOW (Harden et al., 2016). However, the process by which the NIJ is formed, and the source of the dense water it advects, remain unknown. It has been argued that the dense water is formed in the Iceland Sea or southern Greenland Sea as part of an interior overturning loop (Våge et al., 2011; Våge et al. 2015), but this remains a hypothesis. In terms of physical oceanography and meteorology, this region is arguably the least well-studied of the North Atlantic's subpolar seas.

The broad-scale climate of the Iceland Sea region is dominated by the climatological Icelandic Low – the northern centre-of-action of the North Atlantic Oscillation (NAO). When this climatological low is deep (NAO+), extratropical cyclones bring relatively warm maritime air from the south and east over the Iceland Sea. When it is shallow (NAO-) other synoptic-scale weather regimes dominate, e.g. a deep Lofoten Low can bring cold polar air from the north over the Greenland and Iceland Seas (e.g. Jahnke-Bornemann and Brümmer 2009), while a northeasterly displaced Icelandic Low can force barrier winds off Eastern Greenland over the Iceland Sea (e.g. Harden et al. 2011). The interplay between the NAO and other climate modes – such as the East Atlantic and Scandinavian patterns – has a profound impact on the atmospheric circulation of the subpolar North Atlantic and the associated forcing of the ocean (e.g. Cassou et al. 2004). Compared to the rest of the subpolar North Atlantic, the wintertime surface turbulent heat fluxes over the Iceland Sea have a local minimum (Moore et al. 2012). This is the result of a balance between low heat-flux events (warm air from the south), and high heat-flux events (CAOs from the north). Harden et al. (2015) illustrate this synoptically-driven episodic nature using rare meteorological buoy observations from the central Iceland Sea. They show that CAOs with surface turbulent heat fluxes of ~200 W m^{-2} typically last 2-4 days and occur every 1-2 weeks. It is these CAOs that are responsible for the majority of the high heat-flux events in the western Nordic Seas, with the amount of oceanic heat loss governed by air-mass pathways, location, surface conditions and the meteorological environment (e.g. Papritz and Spengler 2017; Brümmer 1997).

Although the broad-scale atmosphere-ocean coupling is dictated by synoptic-scale variability, there are a myriad of mesoscale weather features – including orographic jets, ice-edge jets, Arctic fronts and polar mesoscale cyclones – that are much more challenging to characterize, simulate and predict (e.g. Vihma et al. 2014). These mesoscale features can have a significant impact on the ocean; for example, increasing the mixed-layer depth in the subpolar North Atlantic and the amount of DSOW transported south when accounted for in ocean models (Condron and Renfrew 2013; Jung et al. 2014). This highlights the requirement of resolving the atmospheric forcing on both synoptic- and meso-scales. Current numerical weather prediction (NWP) models, and some high-resolution climate simulations, can potentially provide accurate atmospheric forcing, but there are a variety of concerns about their quality. For example, air-sea-ice interactions over sea-ice – particularly over the marginal-ice-zone (MIZ) – are difficult to observe and are often crudely represented in models. Biases in surface fluxes over the MIZ can be substantial and extend hundreds of kilometres downstream (e.g. Bourassa et al. 2013). Such biases are caused by poor representation of surface exchange (for example, unrepresentative drag coefficients – see Elvidge et al. 2016) or inadequate atmospheric boundary-layer parameterizations (e.g. Renfrew et al. 2009; Boutle et al. 2014; de Roode et al. 2019).

Consequently, even though the broad-scale meteorology can be reasonably well simulated, the associated air-sea interaction can be difficult to capture accurately, particularly during CAOs over the MIZ.

The Iceland and Greenland Seas are also experiencing profound changes related to anthropogenic climate change. The dramatic retreat of summer sea ice over the high Arctic is well known and its causes and impacts are active areas of research. By contrast, relatively little attention has been paid to the equally dramatic retreat of winter sea ice: a 10% per decade decline in extent for a region encompassing the Greenland, Iceland and Irminger Seas (Parkinson and Cavalieri 2008). Moore et al. (2015) show that this wintertime retreat is influencing the climatological pattern of surface heat fluxes over these seas, leading to a significant negative trend in heat fluxes over both the central Iceland and Greenland Seas. This in turn implies a change in the properties and volume of dense water created in these locations. The retreat can also lead to water mass transformation in areas along the Greenland continental slope that were previously insulated from the atmosphere underneath sea ice, perhaps even directly into the East Greenland Current (Våge et al., 2018). It is argued that changes in water-mass modification appear to be one of the contributing factors to an exceptional slowdown in the overturning of the AMOC in recent years (Ramstorf et al. 2015; Caesar et al. 2018), although there is no evidence that the dense water overflowing from the Nordic Seas has weakened (Østerhus et al. 2019). This is broadly consistent with Sévellec et al. (2017) who argue that changes in surface fluxes in the subpolar North Atlantic have the greatest impact on the AMOC over decadal timescales, while changes in the Nordic Seas and Arctic Ocean have the greatest impact over multi-decadal timescales, driven by a reduced sea-ice pack. Additional processes, such as increased run-off from the glacial melt of Greenland (Böning et al. 2016) or changes in the characteristics of the Atlantic-water entering the Nordic Seas region (Glessmer et al. 2014), are also likely to be critical. In short, profound changes in the way the atmosphere and ocean interact in this region are underway, yet we do not understand their consequences largely because we don't know how the present system works.

The Iceland Greenland Seas Project (IGP) has been developed in response to some of these uncertainties in the North Atlantic climate system. It focuses on the atmosphere-ocean coupling, air-sea-ice interaction, and the resulting impacts on the atmospheric and oceanic characteristics and circulation. The overarching hypothesis for the IGP is:

Wintertime convection in the northwest Iceland Sea and southwest Greenland Sea, forced by intermittent cold-air outbreaks, forms the densest component of the AMOC.

The IGP is endorsed by the World Meteorological Organisation's decade-long *Polar Prediction Project* with a focus on the *Year of Polar Prediction (YOPP)* from 2017-2019 (Jung et al. 2016; see https://www.polarprediction.net). Our project contributes towards the over-arching YOPP aims by providing observations and insights on processes that are necessary to improve environmental forecasts from days to seasons, which are presently far less skilful for the polar regions compared to mid-latitudes.

A novelty of the IGP has been to develop and execute our research *entirely within a coupled atmosphere-ocean framework*. This coupled framework has guided: the development of our scientific hypothesis and objectives; our securing of funding from different international agencies; our field campaign planning and execution; and our observational analysis and numerical modelling experiments. At times this has been testing! Wintertime field work in the subpolar seas brings a host of challenges; and coordinating a research vessel and research aircraft added another. But our approach has brought many benefits too, including a deeper understanding of the coupled system. Indeed, it is envisioned that our joint observational data sets will lead to a number of important steps forward – as we preview in the remainder of this article.

The wintertime cruise

In February-March 2018, we carried out a 43-day cruise on the NATO research vessel *Alliance* consisting of two legs in the northwest Iceland Sea and southwest Greenland Sea. Our main objectives were to: (1) document the ventilation of dense water in the region; (2) characterize the ocean's and atmosphere's response to CAOs downwind of the ice edge; (3) determine the exchange of newly-ventilated dense water between the Greenland and Iceland Seas; (4) elucidate the dynamics and timescales that link the ventilation process, the circulation and mixing of the newly-formed water, and the manner in which the dense water feeds the NIJ; and (5) continuously characterize the structure of the atmospheric boundary layer (ABL).

Our shipboard oceanographic instrumentation included: a conductivity-temperature-depth (CTD) system attached to a rosette with 12 5-L Niskin bottles for sampling salinity, dissolved oxygen, nutrients, the transient tracers CFC-12 and SF_6, and the stable water isotopologues $H_2{}^{18}O$ and HDO. We used expendable CTDs (XCTDs) and bathythermographs (XBTs) in inclement weather and to increase the spatial resolution. We made velocity measurements using two hull-mounted acoustic Doppler current profilers (a 150 KHz unit and a 75 KHz unit), and sampled sea surface conditions continuously via an underway CTD. A summary is given in **Table 1**. The *Alliance's* "Inside CTD" was deployed - hands free - from a small, heated hanger on the starboard side of the ship; this was essential due to the sub-freezing air temperatures and high sea state experienced. It allowed us to carry out CTD casts in sustained 30-35 knot winds.

The *Alliance* departed Reykjavik, Iceland on 6 February for Leg I of the cruise, which focused on the northwest Iceland Sea (**Fig. 2**). This Leg can be characterized as the "section phase" of the cruise: we carried out six transects with the CTD package, or with XCTDs if the sea state or timing demanded. Most of the CTD casts reached the bottom, the exception being in the Iceland

Sea gyre. Three of the sections extended into the East Greenland Current. Leg I operations ended on 21 February in Ísafjörður, Iceland.

Leg II began on 26 February 2018 and can be characterized as the "survey phase" of the cruise, with the sampling closely coordinated with the research aircraft. Shortly after leaving port a CAO developed in the Iceland Sea, and over the next week we worked in concert with the aircraft to sample the different stages of this event. After a pre-CAO XCTD survey, we began repeat occupations of two triangles in the northwest Iceland Sea (see Fig. 2b) to document the water column response to the enhanced surface heat fluxes. One aim was to calculate both ocean and atmospheric heat budgets in order to better quantify the coupled evolution of this event. We also began occupying a "timeseries station", which we visited seven times over the cruise. During the last phase of Leg II we steamed to the southwest Greenland Sea and occupied sections 7-10, including an excursion into the central part of the Greenland Sea gyre (Fig. 2a). By this point the ship had become more comfortable working in the MIZ, and, consequently, we sampled well into the East Greenland Current on these sections. During our steam back south, a final CTD transect (the so-called Látrabjarg Line; section 12 on Fig. 2a) was occupied to capture the structure of the overflow water passing through Denmark Strait. The cruise ended on 22 March when the *Alliance* docked in Reykjavik.

We designed the atmospheric observing programme on the *Alliance* cruise to focus on the thermodynamic structure of the ABL – see **Table 1** for a summary of instrumentation. During the 43 days at sea we released 100 radiosondes, with all sounding data uploaded to the GTS (Global Telecommunication System) and so available for operational forecasting. Our strategy was to release one sounding a day by default and more frequent soundings (up to 3-hourly) during periods of 'interesting' weather or in coordination with research aircraft flights. The radiosonde observations covered the Iceland and Greenland Seas region, filling a gap in the operational observing network (**Figure 3**). To provide a continuous characterization of the ABL we deployed a HatPro radiometer (e.g. Tjernström et al. 2019) sitting on a motion-correction platform (following Achtert et al. 2016) and a Windcube Doppler lidar which has an inbuilt motion-correction algorithm (e.g. see Kumer et al. 2016). The profiling instruments were configured to focus on the ABL and record profiles approximately every 10 minutes. The radiometer, its motion-correction platform and the wind lidar all generally performed well, yielding near-continuous data sets. We also deployed an MRR2, Metek GmbH vertically-pointing rain radar. All of this instrumentation was located on the boat deck (one level up from the fantail). In addition, we had standard meteorological observations ~15 m above sea level on the bow mast. Unfortunately, a new anemometer that was installed prior to the cruise did not function properly and hence the wind data are of lower quality for Leg I of the cruise; the anemometer was replaced for Leg II.

Figure 4 shows a time series of wind speed from the *Alliance* with measurements from the ship's bow-mast anemometer, the wind lidar and from radiosonde profiles. The period illustrated, from 28 February to 2 March 2018, shows the dramatic increase in wind speed associated with the start of a long-lived CAO. Winds increased from 2 to 20 m s^{-1} in less than 12 hours. The various wind speed measurements generally match and show the expected increase of wind speed with altitude. The exceptions are some 50-m radiosonde measurements, which appear to under-record just after release (the balloons were sometimes caught in turbulence around the ship), and a period when the ship's anemometer was sheltered by the ship's superstructure. This long-lived CAO was comprehensively sampled during the campaign and is illustrated throughout this article.

Water vapor isotopes can provide information about the evaporative conditions at the ocean surface and thus pinpoint the origin of water vapor in air parcels. We sampled the isotope composition of water vapor continuously during Leg II of the cruise using a Picarro L2140i with a heated inlet system. In addition, we performed isotope analysis of precipitation samples, of water column samples from the CTD rosette and on 10 of the research flights. A precipitation sampling program along transects near Akureyri, in northern Iceland, further supplemented the IGP water isotope sampling and will provide unique insight into the water turnover; in particular, the evaporation sources of a CAO's water cycle (Papritz and Sodemann 2018). The water isotope measurements provide key information on mass fluxes in the coupled ocean-atmosphere system, which we will use to validate the water cycle in isotope-enabled weather prediction and climate models (e.g. following Sodemann et al., 2017).

Science operations on the *Alliance* were carried out 24 hours a day. Each afternoon at 1245 we held a science briefing to discuss upcoming plans, address any problems, and review the data being collected to help guide our sampling strategies. In total we occupied 189 CTD stations (152 of them with chemical sampling, 29 with water isotopes), 120 XCTDs, and 144 XBTs. This resulted in 453 profiles of the ocean mixed layer. We released 100 radiosondes and obtained near-continuous temperature and wind profiles of the atmospheric boundary layer. In short, we collected a wealth of data during a harsh wintertime period where there is a dearth of historical measurements.

Figure 5 illustrates the coupled sampling of the atmosphere and ocean that we managed from the *Alliance,* showing cross-sections of the atmosphere and ocean across the East Greenland continental slope (see Figs. 2b, 3b for location), on the first day of the CAO. It shows a moderately cold well-mixed ABL, with a near-constant potential temperature (θ) and a height of ~800 m delineated by the strong vertical θ gradient. Winds increase from west to east from about 8 to 14 m s^{-1} and are from the N to NNW, so approximately perpendicular to the cross-section. The specific humidity is relatively high within the ABL, with a slight increase to the east where the relative humidity reaches 100% at the top of the ABL. This is consistent with the shallow convective clouds seen in satellite images from this day (e.g. Fig. 7). The underlying ocean is significantly warmer than the ABL, and hence is losing heat and moisture via surface sensible and latent heat fluxes. The location of the MIZ is marked in the figure and is evident from the lower potential temperatures of the air and ocean, and the fresher surface layer of the ocean. The isopycnals indicate some mixed-layers of near-constant density, but these are relatively shallow (~100 m) so do not suggest much dense water mass formation at this time.

The wintertime aircraft campaign

The main platform for our atmospheric measurement program was the British Antarctic Survey's instrumented DH6 Twin Otter research aircraft. This is a relatively small aircraft, with an operations team of just a few people, making it cost effective and flexible with regard to operations and airports. It was fitted with an internal fuel tank that gave it an extended range to nearly 800 nm (or 6 hours). The instrumentation is summarized in Table 1 and described in more detail in, e.g., King et al. (2008) and Fiedler et al. (2010). We had 70 flight hours for the aircraft campaign and flew 14 science missions, mostly over the Iceland Sea and the MIZ off southeast Greenland (see **Fig. 6**). We were based out of Akureyri Iceland, but also refuelled three times at Constable Point (Nerlerit Inaat) Greenland, enabling us to fly two missions on those days.

The primary science objective for the meteorological campaign was to characterize the structure and development of CAOs – focusing on surface fluxes and the ABL – especially over and downstream of sea ice. By combining the aircraft and *Alliance*-based observations, we aimed for a unique and comprehensive sampling of the marine ABL during CAOs. Two secondary science objectives were to characterize the ABL structure of orographic flows and to quantify variations in water vapor isotopes in the lower troposphere. **Table 2** provides a summary of the meteorological field campaign, listing all the research flights as well as key periods of radiosonde releases from the *Alliance*; it is color-coded by science objective. The Twin Otter is ideally suited for measuring the turbulent and thermodynamic structure of the ABL. Missions were planned to focus on straight and level legs in the surface layer (typically 20-50 m above the sea surface), or in the ABL (between 50-1500 m), or via 'sawtooth' legs ascending or descending through the depth of the ABL.

We illustrate a typical mission (flight 294) in **Figure 7** showing a map of aircraft altitude overlaid on a visible satellite image. During this flight we sampled the structure of the ABL via a sawtooth cross-section of four profiles and two stacks of straight and level legs at three heights that were immediately upstream and downstream of the *Alliance*. **Figure 8** shows a cross-section of potential temperature (θ), relative humidity w.r.t. ice (RH_i) and turbulent sensible heat flux based on the eddy covariance technique (e.g. Petersen and Renfrew 2009). It shows a more detailed snapshot of the cross-section illustrated in Fig. 5. There is a cold surface layer (< 100 m deep) overlying the MIZ, embedded within a near-neutral ABL of about 800 m depth. RH_i shows an increase in moisture content to the east, consistent with the development of a shallow cumulus cloud deck, as apparent from satellite images at the time of the flight (e.g. Fig. 7). Turbulent heat flux observations are surprisingly close to zero throughout most of the ABL and over the MIZ, only reaching 10-20 W m^{-2} in places in the surface-layer leg over the MIZ. They are higher, up to 80 W m^{-2}, in the surface layer and around cloud level off the ice-edge where there is also a systematic increase in the wind stress and TKE (not shown). These sorts of observations of the turbulent structure of CAOs will be of great value in the evaluation of models and bulk flux algorithms.

Overall the aircraft campaign was highly successful. We coordinated research flights in the vicinity of the ship on three separate days (shaded in Table 2) during the development and evolution of the long-lived CAO over the Iceland Sea. This enabled the first simultaneous and coordinated water vapor isotope measurements from aircraft and ship. We have over 500 minutes of observations from the atmospheric surface layer – over 400 minutes during CAO conditions and over 200 minutes over sea ice – providing nearly 200 estimates of turbulent surface exchange. In addition, the ABL was thoroughly sampled with over 300 minutes of straight and level flying and 10 long (and 13 short) ABL sawtooth cross-sections.

Climate conditions during winter 2017-2018

In order to properly interpret our observations, it is important that we place our winter field campaign period into climatological context. Our region of interest is characterized by wintertime sea ice that has been retreating since the turn of the 20^{th} century, if not longer (Parkinson and Cavalieri 2008; Moore et al., 2015). **Figure 9** shows the mean sea ice concentration in the region during January-March 2018, as well as the climatological mean concentration for 1979-2018 (data from Peng et al. 2013). The loss of sea ice in the region reflects a reduction in the width of the MIZ, from ~230 km during the 1980s to ~110 km during the 2010s. Also notable is the loss of a tongue of sea ice known as the Odden Ice Tongue (Germe et al., 2011) that used to extend eastwards over the Greenland Sea. Included in Figure 9 is a time series of winter-mean open water area for the region. There is a 40-year trend of increasing open water area (38,000 km^2/decade) as well as pronounced inter-annual variability that reduced dramatically around 2000, associated with the loss of the Odden Ice Tongue (Rogers & Hung, 2008). As discussed by Moore et al (2015) and Våge et al (2018), this sea-ice retreat has profound implications for the intensity of ocean convection in the Iceland and Greenland Seas.

Atmospheric conditions during the field phase of the experiment were influenced by the occurrence of a Sudden Stratospheric Warming (SSW) as well as a transition from NAO positive to NAO negative conditions. A SSW Index (Charlton & Polvani, 2007) indicates the SSW occurred on 8 February 2018 (the transition to negative values); while an NAO Index (Barnston & Livezey, 1987) indicates a transition on 26 February 2018 (**Figure 10).** These two events are related (Moore et al. 2018), in that NAO negative conditions typically occur as part of a delayed tropospheric response to a SSW (Baldwin and Dunkerton, 2001; Kolstad et al., 2010). A sea-level pressure (SLP) time series – from ECMWF Interim Reanalysis data (ERA-I; Dee et al. 2011) averaged over the oceanic area of interest shown in Fig. 9 – illustrates these two drivers (Fig. 10c). In particular, there was anomalously high SLP (in excess of 2 standard deviations (σ) above the mean) throughout the region in late February and early March. This was likely the transient response to the SSW that led to high pressures and cold temperatures over northern Europe (Moore et al., 2018). It was also coincident with a sharp transition to NAO negative conditions.

The 10m wind speeds over the study region were on average close to the climatological mean, although there was significant variability (Fig. 10d). In contrast, the ERA-I near-surface air temperatures were anomalously warm throughout the period of interest, with mean values 1σ above the climatological mean (exceeding 2σ above the mean during the SSW, Fig. 10e). This period of extreme warmth was associated with a strong meridional pressure gradient that resulted in above freezing conditions in north Greenland (Moore et al., 2018). The end of the SSW and the transition to NAO negative conditions resulted in a dramatic drop in air temperatures around 1 March 2018; this was the start of the long-lived CAO over the Iceland Sea sampled in detail during the IGP (see Table 2 and Figs. 4, 5, 7, 8). Forecast charts showing the early stages of this CAO and its likelihood of occurrence are discussed below. The CAO lasted more than 10 days, but did not bring a particularly cold air mass over the region – temperatures stayed typically around -5^{o}C, just above the long-term mean. Associated with the CAO were elevated surface turbulent heat fluxes, peaking at 200 W m^{-2} (Fig. 10f). This is in contrast with the below-average heat fluxes of the first half of the IGP period, which were especially low during the SSW. We note that a second, stronger CAO occurred over the Greenland Sea towards the end of the IGP period, starting on 16 March (Table 2). This event, however, is not very clear in Fig. 10 because of the large averaging area.

Longer term observations

Gliders

We had planned on carrying out a comprehensive survey of the Iceland and Greenland Seas using autonomous ocean gliders for the duration of winter 2017-18. The gliders were upgraded with ice avoidance software to operate more safely in the MIZ (e.g. Curry et al., 2013). However, a series of sensor failures, pump failures and communication problems limited the glider measurement program to a few weeks in early January in the Greenland Sea, and to mid-February to mid-April in the Iceland Sea. The latter glider operated primarily between the ice edge and the location of the subsurface mooring and meteorological buoy in the Eggvin Offset (Fig. 2), a deep passage between the West Jan Mayen Ridge and the Kolbeinsey Ridge (see the mooring discussion below). The transect was the same as that previously occupied by a glider in winter 2015-16 (Våge et al, 2018).

A comparison between the February 2016 transect, which did not extend very close to the ice edge, and the IGP glider transects from March and April 2018, which nearly reached the East Greenland Current, demonstrate that the ocean mixed layer during the 2017-18 winter was substantially shallower, warmer, and less dense than in winter 2015-16 **(Fig. 11).** Despite this, the Atlantic-origin water (density>27.8 kg m^{-3} and T >0^{o}C) that was being transported toward Denmark Strait by the East Greenland Current was ventilated by the end of the weaker 2017-18 (IGP) winter – as evident in the bottom panel of Fig. 11. This implies that transformation of this water mass in the Iceland Sea is not dependent on severe winter conditions and may occur regularly when the East Greenland Current is ice free (Våge et al., 2018).

Unfortunately, our attempts during the *Alliance* cruise to directly quantify the turbulent mixing rates associated with water mass transformation via glider-based microstructure measurements were unsuccessful due to glider malfunctions. As such, we will attempt to infer transformation rates using indirect mixing rate estimates from the glider data collected; specifically by using our fine-scale vertical velocity and density measurements to infer dissipation via the large-eddy method (Beaird et al, 2012), and using our fine-scale density measurements to infer dissipation from a strain-based parameterization (e.g. Shaun Johnston and Rudnick 2015).

Moorings

We deployed subsurface ocean moorings at two locations during the IGP from summer 2016 to summer 2018. These deployments relied on a number of additional research cruises or additional time on monitoring cruises. Firstly, an array of four moorings was deployed across the NIJ north of Iceland (see Fig. 2a for location). The moorings were placed on the Slétta repeat hydrographic transect near 16°W that is occupied four times a year by the Icelandic Marine and Freshwater Research Institute. This represents the first mooring array deployed across the current to the east of the Kolbeinsey Ridge, where previously there have been only snapshots from shipboard hydrographic/velocity surveys (Våge et al., 2011; Semper et al. 2019). These continuous, long-term measurements will shed light on the magnitude and properties of the NIJ only a short distance downstream of where it is thought to originate. They will also provide a contrast to the previous moored measurements of the NIJ from the Kögur line to the west of the Kolbeinsey Ridge (Harden et al. 2016).

Secondly, a single subsurface mooring was deployed in the Eggvin Offset on the northern end of the Kolbeinsey Ridge (near 70°N, 16°W; see Fig. 2b) – in the northwest part of the Iceland Sea where the deepest mixed layers were expected to be found (Våge et al., 2015). We chose this location to be in ice-free waters through winter, but sufficiently close to the ice edge so that it would be subject to high ocean-atmosphere heat fluxes during intense CAOs. The mooring was equipped with a combination of point hydrographic instruments and temperature loggers sampling at high frequency (see Table 1). The vertical resolution was 25 m in the upper 300 m of the water column, then every 50 m down to 800 m in order to monitor the wintertime evolution of the mixed layer. Profiling current meters covered most of the water column above 700 m. Preliminary analysis indicates that the ocean mixed layer was deeper, colder, and denser in winter 2016-17 relative to the 2017-18 winter (**Fig. 12**). But even during the weaker IGP winter there were mixed-layers up to 200 m deep and colder than 0.3°C by the end of the convective season.

Meteorological buoy

During the first part of the *Alliance* cruise a Seawatch Wavescan meteorological buoy was deployed adjacent to the subsurface mooring in the Eggvin Offset in the northwest Iceland Sea. The buoy was configured to record standard meteorological variables, sea surface temperature (SST) and surface ocean currents every hour (see Table 1). The buoy worked well for 2.5 months, until it broke loose from its anchor and stopped recording on 6 May 2018. It was recovered soon after.

Forecasting and Coordinating Activities

To inform day-to-day operations and plan research flights, we made use of several bespoke weather forecasts during the campaign period. The UK Met Office ran a limited area 48 h forecast using their operational MetUM model for the Iceland Sea region in support of the IGP; while the Icelandic Met Office (IMO) and their partners at the Danish Meteorological Institute (DMI) gave us access to a trial HARMONIE-AROME 48-66 h forecast that encompassed the same region. Both models were convection-permitting – with horizontal grid sizes of 2.2 and 2.5 km, respectively. The Met Office forecasts were initialized twice daily from their global operational system, while the DMI-IMO forecasts were run with 3-hourly 3DVAR data assimilation. We had access to a comprehensive set of charts from both these forecasts and the respective global operational forecasts. The Met Office forecasts included specialized diagnostics which were important for flight planning, such as maps of cloud base height and surface sensible heat flux as well as cross-sections of potential temperature and cloud liquid water. We also converted all the charts into geo-referenced files (tiff and kmz formats) to allow import into flight-planning tools. **Figure 13** shows 36-h forecast charts for 12 UTC 1 March 2018, the same day highlighted in Figs. 4, 5, 7 & 8. Indeed, a comparison against Fig. 7 illustrates the overall high quality of the forecast cloud field: the two forecasts are very similar, showing the meridional orientation of the isobars and northerly winds associated with the early stages of the CAO. In the Iceland Sea, the 10-m winds increase from around 4 to 12 m s^{-1} in the MetUM forecast and from around 6 to 14 m s^{-1} in the HARMONIE-AROME forecast – broadly consistent with the observed winds (Figs. 4, 5). To the south of Iceland there is a coherent band of precipitation at the leading edge of the CAO that is similar in location and magnitude in both forecasts. Notably, there are convective snow showers behind this rain band, to the SE of Iceland, that are not forecast in the global models (not shown).

To inform medium-term field operations and coordination between the *Alliance* team and the aircraft team, we developed a probability-based forecast for our primary meteorological science target: cold air outbreaks. We used the 50 members of the ECMWF ensemble prediction system to estimate the likelihood of a CAO up to 10 days ahead, based on a well-established CAO index ($\Delta\theta = \theta_{surface} - \theta_{850hPa}$); see Papritz and Spengler (2017). A positive CAO index indicates an atmosphere that is colder than the ocean and so is characterized by upward surface sensible heat fluxes. **Figure 14** shows the probability of a CAO 4.5 and 5.5 days ahead, as well as the ensemble-mean CAO strength and the associated surface sensible heat flux (we could also examine individual ensemble members). Figure 14 indicates a >90% probability of a CAO over the northern Greenland Sea and ~30% probability of a CAO over the eastern Iceland Sea on 1 March 2018, with the likelihood of a CAO clearly increasing and extending over the entire Iceland Sea for the next day. This sort of lead time enabled us to coordinate our observing program; e.g. guiding both the ship and aircraft planning to capture the onset and development of this CAO (see Table 2). As the forecast lead time reduced, the probability of this CAO occurring over the Iceland Sea steadily increased, giving us further confidence in our planned operations. The forecast was for relatively mild conditions, with typical surface sensible heat fluxes of around 100 W m^{-2} (Fig. 14), broadly consistent with the short-range forecasts available closer to the event.

Coordination between the *Alliance* and the aircraft teams – and ship operations in general – were greatly aided by access to a subset of these forecast charts on the winter cruise. Due to the limited bandwidth at these latitudes, we transferred a selection of key charts, including m.s.l. pressure, near-surface winds and ocean wave heights. We supplemented the charts with a short daily text forecast specifically for the *Alliance's* location, as well as a separate text forecast from DMI. Sea-ice imagery was also vital for operational planning. Three products were emailed daily to the ship: an ice image from the Sentinel satellite from DMI; a digital ice concentration file from AMSR2; and a high-resolution Sentinel SAR (Synthetic Aperture Radar) generated by the University of Toronto (e.g. **Figure 15**). The latter product included the planned sampling locations of the ship for the next 24 hours. These three ice products allowed us to visualize conditions in the MIZ, providing valuable context for maneuvering the ship. As a general rule we would aim to begin each approach into the MIZ at first light, maximizing the number of daylight hours for station work in and near the ice. Of particular concern was the impact on ship operations of small-scale ice features within the MIZ, including eddies and filaments (e.g. Manucharyan and Thompson, 2017); a striking example is shown in Fig. 15.

We incorporated the forecast charts and sea-ice products into *Alliance's* daily operational briefings on the ship, which was invaluable for planning our science activities. We also exchanged our planned operations between the *Alliance* and the aircraft team on a daily basis. When possible, we shared detailed information for the next day and broader guidance for the following few days. This allowed more time to prepare flight missions and schedule ship activities; it also acted as insurance for when the ship lost communication (a regular occurrence when north of 70°N). The daily update from the *Alliance* always included a map of the locations of recent CTD casts as well as predictions of forthcoming ones; while the daily update from the aircraft team included plans for flying over the next few days. This information exchange was time-consuming but essential for achieving the high-levels of coordination we desired; for example, coordinating a repeat ship survey or an intensive period of radiosonde launches (c.f. Table 2).

Future plans

The Iceland Greenland Seas Project has obtained an unprecedented set of coordinated, detailed observations of the ocean and atmosphere during winter in the subpolar seas. Analysis of this wealth of data is well underway. Our coordinated approach will continue throughout the analysis and numerical modelling activities (see Sidebar). It is also embedded within broader YOPP activities; for example, making use of additional forecast products and diagnostics. Over the next few years we anticipate a number of studies addressing our project hypothesis and objectives, by examining among other things: the anatomy of a cold-air outbreak; air-sea fluxes over the MIZ; ABL development over the MIZ; the relationship between CAOs and polar lows; the origin and characteristics of precipitation over the Nordic Seas; ABL turbulent fluxes downstream of orography; the heat budget of a coupled ocean-atmosphere column; water mass modification in the northwest Iceland Sea and southwest Greenland Sea; the impact of small-scale ocean variability and atmospheric wind and buoyancy forcing on convective overturning; the circulation of dense water; and the ventilation/formation of the NIJ. We anticipate such a body of work will lead to a transformation in our understanding of how the coupled ocean-atmosphere-ice system in the Nordic Seas impacts the lower limb of the AMOC.

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SIDEBAR - Numerical modelling plans

Numerical modelling of the atmosphere, ocean and climate system is being carried out in parallel to the observational component of the IGP. Here we describe a few activities as illustrations.

A set of regional climate modelling experiments have been run to investigate the impact of anomalous distributions of sea ice on the frequency and magnitude of high heat flux events in the Iceland and Greenland Seas. We have used the MetUM in atmosphere-only mode with a regional domain (40°E - 5°W, 62°N - 79°N) run at 8 km grid size and nested within a global model. The global model was initialized daily from ERA-I reanalyses and used to force the regional model at the lateral boundaries. We have run simulations for 20 years with four different sets of daily-updated sea-ice and SST surface conditions:

i. A baseline simulation with time varying sea ice and SSTs concomitant with the date of the simulation.
ii. A maximum ice simulation with annually-repeating sea ice and SSTs from 1987/88 – the winter with the greatest sea ice extent in the Iceland-Greenland Seas region.
iii. A median ice simulation with annually-repeating sea ice and SSTs from 2003/4 – the winter with sea ice extent closest to the median value in the region.
iv. A minimum ice simulation with annually-repeating sea ice and SSTs from 2015/16 – the winter with the smallest sea ice extent in the region.

Through this experimental design we are now examining how changes in sea ice concentration and extent influence the distribution, frequency and magnitude of high heat flux events. Interestingly the role of the extreme sea-ice distributions acts differently in the two seas; a result we are now exploring in more detail.

We are running two classes of ocean models in support of the IGP. The first is a realistic, regional primitive equation model with a coupled dynamic/thermodynamic sea ice model that extends from south of Denmark Strait to 79^{o}N, and from Greenland to Norway. This model is forced with fluxes of heat, freshwater, and momentum derived from atmospheric reanalysis using bulk formulae and has open northern and southern boundaries – as in Almansi et al. (2017). We will run it for different time periods, to cover the different regimes of the North Atlantic Oscillation, and also for the winter of 2017/2018 to compare with the in-situ IGP observations. We seek to understand where, when and how the densest waters are formed under different atmospheric conditions, and how they are subsequently advected from these source regions across the sills to the south.

Our second class of ocean models is focused on the influence of wind and surface heat loss on convection in the transition region between the relatively buoyant East Greenland Current and the denser waters offshore. Observations indicate that the low salinity water from the shelf is transported offshore in small, thin patches and eddies, where it can then inhibit deep convection and water mass transformation. The model will be used to understand what controls the offshore flux of fresh water, the amount of water mass transformation, and the depth of deep convection.

Figure Captions

Figure 1 Schematic of the major boundary currents of the Nordic Seas. The sub-tropical origin water entering the Norwegian Sea gradually cools and becomes denser as it circulates around the perimeter of the basins, exiting as overflow water through the west side of Denmark Strait. The warm water entering Denmark Strait is believed to be converted into the overflow water flowing southward through the east side of the strait. The IGP study area is delimited by the black lines. Abbreviations are: NAC = Norwegian Atlantic Current; EGC = East Greenland Current; NIIC = North Icelandic Irminger Current; NIJ = North Icelandic Jet.

Figure 2 Locations of the oceanographic observations from the winter 2018 cruise and the mooring deployments. The left panel shows the hydrographic sections occupied in the Iceland and Greenland Seas; see the legend for the type of instrument used for each of the lines. The locations of the four moorings deployed across the North Icelandic Jet north of Iceland are also shown. The grey contours are the isobaths. See text for acronyms. The right panel focuses on the northwest Iceland Sea and shows the location of intensive surveys where triangular patterns or lines were repeated several times in coordination with the research aircraft; see the legend for details. The southern triangle was sampled three times using a combination of CTDs and XCTDs, while the northern triangle was sampled once. The timeseries CTD station was occupied seven times during the cruise. The location of the mooring and met buoy deployed in the northern Iceland Sea are also marked.

Figure 3 Locations of radiosonde profiles from the Alliance cruise and relevant land stations. The Alliance radiosonde locations are shaded by low-level potential temperature and the cruise track is shown in grey. Panel (a) shows the locations of soundings 1-22 (4-27 February) and 42-94 (2-18 March); panel (b) provides a close up of the locations of soundings 23-41 (28 February to 2 March). The average sea-ice fractions are contoured, based on the Met Office's Operational Sea Surface Temperature and Sea Ice Analysis (OSTIA) data set.

Figure 4 Wind speed, from 28 February to 2 March 2018, from on board the Alliance. Measurements are from the ship's bow-mast anemometer located approximately 15 m above the sea surface; and from the Wind Cube lidar and radiosonde profiles at 50, 150 and 300 m altitude (see legend). The bow-mast anemometer was sheltered by the ship's superstructure when sailing directly downwind, hence it underestimated wind speeds from about 14 UTC 28 February to 02 UTC 1 March.

Figure 5 A simultaneous cross-section of the atmosphere and ocean on 1 March 2018. The upper panels show atmospheric observations from radiosonde releases (soundings 32-36); the lower panels show oceanographic observations from CTD profiles (casts 81-88). The left panels show potential temperature on a common scale (shading), overlain by contours of wind speed (top) and potential density (bottom). The right panels show specific humidity (shading) overlain by relative humidity contours for the atmosphere, and salinity (shading) overlain by potential density contours for the ocean. The contour intervals are 2 m s^{-1}, 0.02 kg m^{-3} and 10% for wind speed, potential density and relative humidity respectively. The section is approximately west to east; its location is marked on Fig. 7.

Figure 6 Location of all science flights during the aircraft campaign. The average sea-ice fraction from the period is contoured (based on OSTIA data). Flights 293, 294, 295 and 297 were in the vicinity of the Alliance, while flight 305 passed the meteorological buoy.

Figure 7 (a) Aircraft track from flight 294 with aircraft altitude shaded over a VIIRS visible satellite image from 13:24 UTC 1 March 2018. The location of the Alliance cross-sections (Fig. 5) is shown in red. Sea-ice concentration contours at 90% and 10% (dark and light green) from AMSR2 data are also shown. A von Karman vortex street can be seen traced in the low-level clouds south of Jan Mayen. (b) Sketch of the flight track for 294 showing stacks of 3 boundary-layer legs (green), a sawtooth leg (red) and transit legs (blue). The letters indicate way-points between Constable Point (CP) and Akureyri (A). The inset sketch shows the altitude of the legs flown at each stack.

Figure 8 Cross-sections of (a) potential temperature (K); (b) relative humidity w.r.t. ice (%); and (c) turbulent sensible heat flux (W m^{-2}) from 1 March 2018 (flight 294). The cross-section shows observations from sawtooth B to C and the three straight and level legs between D and E sketched in Fig. 7. Also shown is sea ice fraction, based on OSTIA data (grey lines; right-hand axis of each figure panel).

Figure 9 Sea ice concentration for January-March: (a) for 2018 and (b) the mean for 1979-2018; contours at 15% and 80% are overlaid. Panel (c) is a time series of open water area for January-March 1979-2018, for the polygon shown in panels (a) & (b), plus the linear trend (38,000 km^2/decade) and the 5-year moving standard deviation about the linear trend. All data are from the NSIDC Climate Data Record.

Figure 10 Time series from the IGP field campaign period in January-March 2018. (a) a Sudden Stratospheric Warming Index (m s^{-1}); (b) an NAO Index; (c) sea-level pressure (mb); (d) 10 m wind speed (m s^{-1}); (e) 2-m air temperature; and (f) the total surface turbulent heat flux (W m^{-2}). The time series in (c)-(f) are all averaged over the oceanic region bounded by 66°N, 40°W and 78°N, 5°E. Also shown in (c)-(f) are the campaign-period mean (red line) and the climatological mean, as well as the 1/2σ above/below that mean (blue solid, dashed and dotted lines) for the period 1979-2018.

Figure 11 Ocean cross-sections of potential temperature across the East Greenland continental slope to Eggvin Offset near 71°N, derived from glider observations. The top panel is from February 2016 (from Våge et al., 2018); the 2nd and 3rd panels are from March-April 2018. Selected isopycnals (grey contours) and mixed-layer depths (stars) are overlaid.

Figure 12 Ocean temperature time series from a mooring at the Eggvin Offset (70.6°N, 15.6°W). The temperature cross-section consists of observations from 22 depths (black triangles) every 2 hours.

Figure 13 Forecast charts for 12 UTC 1 March 2018 (T+36 hours) showing (a) sea-level pressure (black lines), 500-hPa thickness (blue dashed lines), cloud cover (grey shading) and precipitation (shading); (b) 10-m wind speed and streamlines; (c) sea-level pressure (black lines), 850-hPa temperature (blue dashed lines), 10-m wind vectors (barbs) and precipitation (shading); (d) 10-m wind speed and wind vectors. The top panels are from the UK Met Office, the bottom panels are plotted by the Icelandic Met Office, from forecasts by the Danish Meteorological Institute.

Figure 14 Cold-air outbreak diagnostics based on 50 ECMWF ensemble prediction system members. Panels (a) & (d) show the probability of a cold-air outbreak of strength $\Delta\theta > 2$ K (where $\Delta\theta = \theta_{SST} - \theta_{850hPa}$); panels (b) & (e) show the ensemble-mean CAO magnitude, i.e. $\Delta\theta$; panels (c) & (f) show the ensemble-mean surface sensible heat flux. All panels have the ensemble-mean sea-level pressure field contoured (gray lines every 2 hPa) and the 50% sea ice concentration contour (thick black line). Forecasts are for 4.5 days (T+108 h; left) and 5.5 days (T+132 h; right) from 00 UTC 25 February 2018, which are valid at 12 UTC 1 March and 2 March 2018 as indicated.

Figure 15 Sentinel SAR image of the MIZ off east Greenland at 08 UTC 3 March 2018 showing the complex small-scale variability associated with ocean eddies and fronts that impact the sea ice distribution. Lighter shading is from a higher reflectivity surface. Annotated in blue and red are the two survey triangles that the Alliance carried out during 1-6 March 2018.

Ocean Observations			
Platform	**Instruments**	**Variables**	**PI**
R/V ***Alliance***	CTD, XCTD, XBT, Vessel-mounted ADCP systems Water intake Water sampling - geochemical tracers and isotopes Microstructure glider Argo floats	T, S, p (O_2 CTD only) u, v, SST Nutrients, O_2, CFCs and SF_6 $H_2{}^{18}O$, HDO Turbulence T, S, p, u & v (from drift)	R. Pickart, WHOI R. Pickart, WHOI R. Pickart, WHOI E. Jeansson, NORCE H. Sodemann, UiB S. Waterman, UBC K. Våge, UiB
Mooring	CTD, T recorder, ADCP, RCM	T, S, p, u, v	K. Våge, UiB
Seagliders	CTD, oxygen	T, S, p, O_2, u & v (from drift)	K. Våge, UiB
Atmospheric Observations			
Platform	**Instruments**	**Variables**	**PI**
R/V ***Alliance***	Wavepak Vessel-mounted meteorology Väisälä MW41 Radiosonde system* HatPro radiometer + Motion correction platform Leosphere Windcube lidar Metek Micro Rain Radar Picarro L2130-i Isotope Spectrometer Precipitation sampling	T, u, v, RH, T, p, RH, u, v T, RH, LWP + motion u, v, w, turbulence PPN rate, LWC $H_2{}^{18}O$, HDO of water vapour $H_2{}^{18}O$, HDO	I. Renfrew, UEA I. Renfrew, UEA I. Renfrew, UEA I. Brooks, ULeeds J. Reuder, UiB H. Sodemann, UiB H. Sodemann, UiB H. Sodemann, UiB
DH6 **Twin** **Otter**	Aircraft-mounted meteorology BAT turbulence probe & LICOR DMT Cloud, Aerosol & PPN Spectrometer Grimm spectrometer Picarro L2130-i Isotope Spectrometer	T, p, T_{dew}, T_{sfc}, SW, LW u, v, w, T, q, turbulent fluxes Aerosol & PPN spectra, LWC Aerosol spectra $H_2{}^{18}O$, HDO of water vapour	T. Lachlan-Cope, BAS and I. Renfrew, UEA T. Lachlan-Cope, BAS and I. Renfrew, UEA H. Sodemann, UiB
Met. Buoy	Seawatch Wavescan Buoy*	T, RH, u, v, SST, SW, ocean currents	J. Reuder and E. Kolstad, UiB

Table 1 A summary of the IGP observing system. Variables measured are: T = temperature; S = salinity; p = pressure; O_2 = oxygen; u, v, w = velocities; SST = sea surface temperature; CFC = chlorofluorocarbons; SF_6 = sulfur hexafluoride; RH = relative humidity; LWP = liquid water path; PPN = precipitation; LWC = liquid water content; T_{dew} = dewpoint temperature; SW = shortwave radiation; LW = longwave radiation; q = specific humidity; SST = sea surface temperature. Instruments marked* had data broadcast via satellite and hence were available for operational forecasting.

Time (UTC) and Date	**Flight No.**	**Flight Comments**	***Alliance* radio-sonde times (UTC)**	**Science aims**
28 Feb 2018 07:48 – 11:51	292	6 short ABL cross-sections; *low-level flying hampered by cloud*	00, 03, 06, 09, 12, 15, 18, 21	Cold air outbreak onset over the Iceland Sea
1 Mar 2018 08:13 – 11:45 13:06 – 18:02	293 294	2 long ABL cross-sections; 60 mins (SL) and 60 mins (ABL)	00, 03, 06, 09, 12, 15, 18, 21	Cold air outbreak development and structure
2 Mar 2018			00, 06, 09, 12, 15,	Cold air outbreak structure
3 Mar 2018			00, 12	
4 Mar 2018 10:16 – 15:09	295	2 short ABL cross-sections; 20 mins (SL) and 40 mins (ABL)	00, 06, 09, 12, 15, 18	Cold air outbreak structure
5 Mar 2018 *10:30 – 11:20*	*296*	*Transit from Reykjavik to Akureyri*	06, 09, 12, 18	
6 Mar 2018 08:47 – 14:14	297	1 long/1 short ABL cross-sections; 20 mins (SL) and 40 mins (ABL)	00, 06, 09, 12, 15, 18	Cold air outbreak structure
8 Mar 2018 08:21 – 11:56 13:27 – 19:01	298 299	3 long ABL cross-sections; 135 mins (SL)		Surface fluxes over sea ice and katabatic flow structure
9 Mar 2018 09:58 – 14:47	300	1 long/2 short ABL cross-sections; *low-level flying hampered by cloud*		Boundary-layer structure over sea ice
12 Mar 2018 12:13- 18:13	301	50 mins (SL) and 85 mins (ABL) flying downstream and over a mountainous ridge	00, 12	Orographic flow structures: lee-side fluxes, waves & wakes
14 Mar 2018 *data lost* 12:55 – 18:28	*302* 303	*Most data lost due to file error* 1 long ABL cross-section; 100 mins (SL)	00, 12	Surface fluxes over sea ice
16 Mar 2018 09:55 – 11:45	304	Racetrack patterns at various heights in the ABL	00, 12, 15, 18, 21	Isotope composition survey & instrument calibration Cold air outbreak onset over the Greenland Sea
17 Mar 2018			00, 03, 06, 09, 12, 15, 18	Cold air outbreak development
18 Mar 2018 09:09 – 14:59	305	2 short ABL cross-sections; 80 mins (SL) including past the meteorological buoy	00, 06, 09, 12, 15, 18	Cold air outbreak structure
19 Mar 2018 13:01 – 17:29	306	2 long ABL cross-sections; 20 mins (SL) and 100 mins (ABL)	00, 12	Orographic flow structures: lee-side fluxes, waves & wakes

Table 2 Campaign summary focusing on the meteorological deployments of the research aircraft and key periods of radiosonde launches from the *Alliance*. Flight comments note the number of cross-sections in the atmospheric boundary layer (ABL) – determined from 'sawtooths' between the surface and typically 1500 m; and the amount of time flying in the surface layer (SL) – typically 15-50 m; or in the ABL – typically 50-2000 m. Text is color-coded by science aim: cold air outbreak development and structure (dark blue); surface fluxes over sea ice (cyan); turbulent structures in orographic flows (purple); and isotope composition (red). Days when the aircraft and ship tracks coincided are shaded light orange. Flight patterns are shown in Fig. 6 and radiosonde locations in Fig. 3.