POAC'23
Glasgow, United Kingdom

Proceedings of the 27th International Conference on
Port and Ocean Engineering under Arctic Conditions
12-16 June 2023, Glasgow, United Kingdom

Examination of ice reports from vessel traffic along the Norwegian coastline, 2014- 2022

Megan O'Sadnick[1], Chris Petrich[1]
[1] SINTEF Narvik, Narvik, Norway

ABSTRACT

The Norwegian Coastal Administration provides information on ice conditions for vessels traveling in Norwegian waters primarily from the Swedish border to Kristiansand as well as Kirkenes, a port located in the far north of Norway. Reports are submitted from vessels following the Baltic Sea Ice Code and provide a description of the amount of ice, ice thickness, the topography of the ice, and the navigation conditions. We analyzed all reports in six areas South of Oslo made by vessel traffic since 2014 to obtain an overview of specifically ice thickness recorded in these areas. Reports are analyzed in line with SAR imagery to provide context of the season including freeze up and break up dates. Given the lack of systematically compiled data on ice conditions in fjords along the coast of Norway, vessel reports are valuable in providing more information than is provided by remote sensing data, in particularly an estimate of ice thickness. Seasonal maximum freezing degree days were typically between 100 and 300 °C days, and the thickest ice was reported to fall into the category of 15 to 30 cm. Ice of this thickness had been reported in all areas in at least one winter. The three areas at the Skagerrak South-West of Oslo tended to have reports of thick ice most consistently. The other three areas saw no ice in the winter of 2019/20, which was the winter with the fewest freezing degree days (<100 °C days). While winters with low freezing degree days tended to be associated with thinner maximum ice thickness in each area, it was found that FDD are not a good predictor of ice thickness when aggregating observation across all areas in this dataset.

KEY WORDS: Sea ice; Fjords; Ice thickness; Observations; Icebreaker

INTRODUCTION

The Norwegian Coastal Administration (Kystverket) provides ice reports made by ships for specific fairways and ports from 1 December through 31 March each winter into spring (Kystverket, 2023). These observations follow the Baltic Sea Ice Code and include a description of the amount and arrangement of ice, ice thickness, ice topography specifically the size of ice floes, and navigation conditions including if an ice breaker is needed.

Due to warm Atlantic water and wind mixing, larger fjords along the Norwegian coastline stay ice free throughout winter (Aure et al., 1996; Eilertsen and Skarðhamar, 2006). In smaller fjords and inlets, however, ice has potential to form, the result of freshwater flowing into these areas creating a stratified water column (O'Sadnick,2022; Kvambekk, 2010, Asvall 2010).

When mixing is limited and air temperatures below freezing, cooling of this upper fresh or brackish layer can occur quickly resulting in the formation of ice. The initial layer may continue to grow downwards under the quiescent conditions now provided by the ice cover or from the surface upwards through the creation of snow ice (O'Sadnick et al, 2022). Once present, ice can create an obstacle for ships and boats transiting an area. While thin layers of ice are easily broken, ice breakers may be needed as the ice thickens, creating channels allowing safe passage for boats without ice sheathing.

Six specific areas are examined here (Fig. 1), chosen primarily for the length of the ice observation record in addition to the relatively consistent appearance of ice each winter. These are Svinesund – Halden (Halden), Mossesundet (Moss), Drammensfjorden (Drammen), Tønsberg indre havn (Tønsberg), Hellefjorden (Kragerø), and Kilsfjorden (Kragerø).

While it is common knowledge that ice forms in these regions, little if any description of ice thickness and further characterization exists in the scientific literature. Thus, observations made by ships provide perhaps the only record publicly available. When examined in combination with satellite imagery, a valuable perspective on ice conditions in these regions including general trends and potential impact on coastal traffic can be gained.

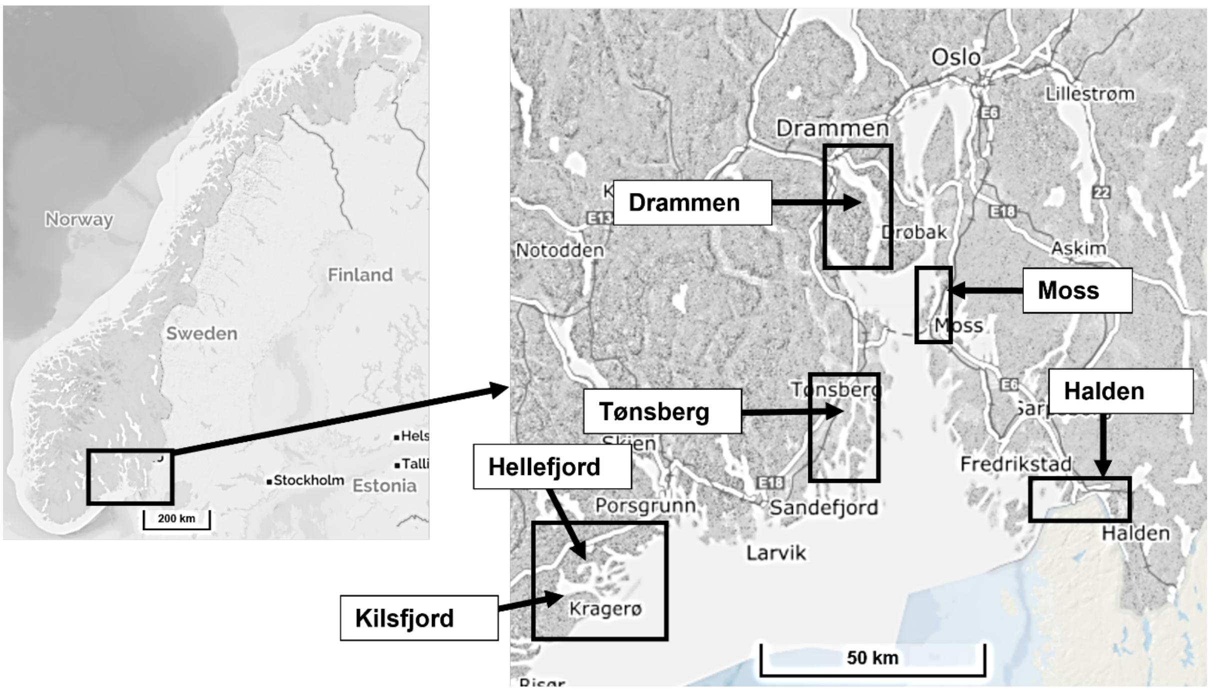

Figure 1: Map of fjords examined

METHODS

Boat observations

Boat logs from the eight winter seasons spanning 2014 – 2015 up to 2021 – 2022 were obtained from the ice service. The ice reports were next organized and filtered to pull out reports of ice thickness. The classification system for ice thickness is shown in Fig. 2 and based on a scale of 0 – 9. An additional category, '/', represents 'no information'. During the analysis of observations, it became apparent that category '/' is commonly used to denote ice-free conditions. This is based on comparison with SAR imagery.

SB	Stage of development (ice thickness)
0	New ice. Less than 5cm.
1	Light nilas. 5-10cm.
2	Grey ice. 10-15cm.
3	Grey-white ice. 15-30cm.
4	White ice, first stage. 30-50cm.
5	White ice, second stage. 50-70cm.
6	Medium first year ice. 70-120cm.
7	Ice predominately thinner than 15cm.
8	Ice predominately 15-30cm.
9	Ice predominately thicker than 30cm.
/	No info. or unable to report.

Figure 2: The Baltic Sea Ice Code for ice thickness

SAR Imagery

For comparison to boat logs and to obtain an approximation of the freeze up and break up dates of ice in the selected regions, synthetic aperture radar (SAR) scenes from the Sentinel 1 C-band instruments, were examined. Backscatter images were produced with Google Earth Engine (Gorelick et al., 2017). Each image was reviewed manually to determine if and where ice was present. Examples of images with ice are provided in Fig. 3. Ice was often difficult to identify with certainty in individual images. It was therefore the appearance of an apparent ice edge consistent in two or more images that was used as an indicator for ice.

Observations made by ships were compared to SAR imagery to find the first day ice was present, which defines the start date of an ‘ice season’. The end of the ice season is the date of the first SAR image with no ice, with no further ice being present in any subsequent images that winter. During an ice season, ice may have broken up and reformed or been consistently present. A note was taken when such behavior occurred however given the limited frequency of satellite imagery and boat logs such break-ups are difficult to record with certainty so the number provided can be interpreted as lower estimate.

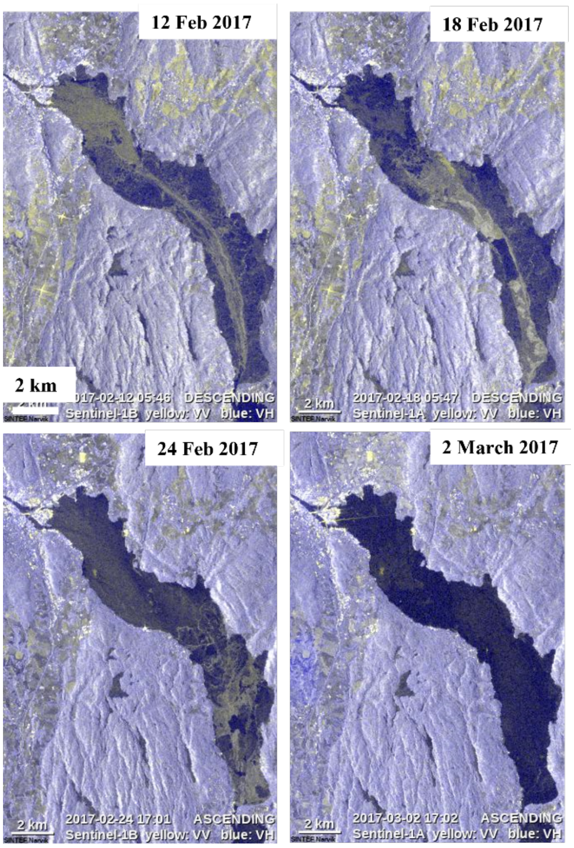

Figure 3: Examples of satellite imagery showing ice in Drammensfjorden from 12 Feb 2017 to 2 March 2017. Image of 2 March 2017 is ice free. Yellow represents VV polarization and blue represents VH polarization

Temperature data

Values for average daily air temperature were obtained from the openly available web portal seNorge.no (Lussana et al., 2018), providing spatially interpolated observational data by the Norwegian Meteorological Institute and the Norwegian Water Resources and Energy Directorate (NVE). A point approximately mid-fjord at the coastline was chosen for each location examined here. Temperature data was analyzed to calculate freezing degree days (FDD) between 1 November to 1 April or the date of approximate ice freeze-up (beginning of the ice season) to the date of observation. FDDs are derived by summing all average daily air temperatures (T_a) below freezing point (T_f= 0 °C) from the start date (i=1, date of freeze-up or 1 Nov) to end date (i=N, date of observation or 1 April):

$$FDD = \sum_{i=1}^{N} \Delta t \begin{cases} T_f - T_{a,i}, & T_{a,i} < T_f \\ 0, & T_{a,i} \geq T_f \end{cases} \qquad (1)$$

where Δt= 1 day.

RESULTS AND DISCUSSION

Length of ice seasons

For the six regions examined, the beginning of the ice season occurred anytime between the end of November and mid-January. The length of ice seasons varied widely from between 0 days (Drammen and Halden, 2019/20 season) to as long as 139 days (Tønsberg, Kilsfjord, and Hellefjord, 2017/2018 season). From the 2014/2015 to the 2018/19 season, Tønsberg consistently had the longest ice season. However, the 2019/20 season brought a short ice season of only 12 days. During the latter, in Moss, Kilsfjord, and Hellefjord, the ice season lasted 77, 55, and 55 days respectively. In the following season, 2020/21, Kilsfjord, Hellefjord, and Drammen all displayed similar ice season lengths. In the final season, 2021/22, Hellefjord was shown to hold ice 6 weeks longer than Kilsfjord despite being located near to each other. In all previous seasons, the two mimicked each other more closely at least from the perspective gained by SAR imagery and boat logs.

Also provided in Table 1 is the number of periods during the ice season where the area was clearly ice free. This is an approximate given the temporal frequency of images and the difficulty in identifying ice but provides insight into where ice coverage may vary to a greater degree over a winter season. For example, the two fjords with the most consistently thick ice, Hellefjord and Kilsfjord, show the fewest number of periods where these regions were ice free once the ice season began. In comparison, Halden, where ice seasons were comparatively short, experienced most often at least one period where the area became ice free. This finding aligns well with the estimated ice thickness, with fjords having generally thicker ice also showing fewer periods when ice was no longer present. In comparison, areas where thinner ice was present were more prone to break up and reformation.

Table 1. Observations of ice. (a) Start of ice season (b) End of ice season, (c) Length of ice season, (d) Number of observations made by ship during ice season, (e) Total number of observations from ships between 1 Dec and 31 March, (f) Maximum ice thickness rating (see Fig. 2), (g) Number of periods of no ice, (h) Freezing degree days between 1 Nov. to 1 April. Filled dark gray fields are the earliest observation of ice and latest observation of no ice for each fjord. A '*' denotes ice in SAR images while ship log notes no ice.

Moss	**(a)**	**(b)**	**(c)**	**(d)**	**(e)**	**(f)**	**(g)**	**(h)**	**Kilsfjord**	**(a)**	**(b)**	**(c)**	**(d)**	**(e)**	**(f)**	**(g)**	**(h)**
14/15	5-Feb	12-Feb	7	2	6	1	0	101	**14/15**	8-Jan	24-Feb	47	1	5	0	0	64
15/16	7-Jan	12-Feb	36	6	9	1	0	274	**15/16**	13-Jan	31-Mar	78	9	11	3	0	177
16/17	13-Feb	2-Mar	17	0	1	n/a	0	142	**16/17**	19-Jan-17	20-Mar	60	4	5	3	0	111
17/18	8-Jan	3-Apr	85	9	11	3	1	304	**17/18**	2-Dec	20-Apr	139	11	12	3	1	232
18/19	24-Dec	15-Jan	82	3*	4	/	0	198	**18/19**	28-Dec	27-Mar	89	3*	4	1	1	121
19/20	no ice	no ice	n/a	n/a	1	n/a	n/a	52	**19/20**	28-Dec	21-Feb	55	0	2	n/a	0	26
20/21	16-Jan	19-Mar	62	8*	14	2	1	224	**20/21**	30-Dec	5-Apr	96	14*	19	3	0	262
21/22	7-Dec	13-Jan	44	2*	7	/	0	127	**21/22**	7-Dec	23-Feb	78	8	10	3	0	182
Hellefjord	**(a)**	**(b)**	**(c)**	**(d)**	**(e)**	**(f)**	**(g)**	**(h)**	**Tønsberg**	**(a)**	**(b)**	**(c)**	**(d)**	**(e)**	**(f)**	**(g)**	**(h)**
14/15	8-Jan	24-Feb	47	1	5	0	0	60	**14/15**	26-Dec	24-Feb	60	3*	6	2	1	77
15/16	13-Jan	31-Mar	78	9	11	3	0	177	**15/16**	15-Dec	26-Mar	101	7	7	3	1	233
16/17	19-Jan	20-Mar	60	4	5	3	0	107	**16/17**	2-Dec	20-Mar	108	7*	7	3	1	119
17/18	2-Dec	20-Apr	139	11	12	3	1	221	**17/18**	3-Dec	20-Apr	139	4	5	3	2	269
18/19	28-Dec	27-Mar	89	3	4	3	1	124	**18/19**	11-Dec	17-Mar	96	3	3	2	0	166
19/20	28-Dec	21-Feb	55	0	2	n/a	0	25	**19/20**	30-Nov	11-Dec	12	2	4	0	0	44
20/21	30-Dec	5-Apr	96	14*	19	3	0	230	**20/21**	10-Jan	23-Mar	72	0	2	n/a	0	245
21/22	7-Dec	10-Apr	124	11	11	3	0	145	**21/22**	18-Dec	24-Mar	96	6	6	3	0	138
Drammen	**(a)**	**(b)**	**(c)**	**(d)**	**(e)**	**(f)**	**(g)**	**(h)**	**Halden**	**(a)**	**(b)**	**(c)**	**(d)**	**(e)**	**(f)**	**(g)**	**(h)**
14/15	26-Dec	17-Feb	53	5	7	1	1	151	**14/15**	29-Dec	17-Feb	50	1	3	1	0	66
15/16	6-Jan	7-Mar	61	13	13	3	0	304	**15/16**	7-Jan	7-Feb	31	8	12	3	0	233
16/17	2-Jan	3-Mar	60	4	5	1	1	202	**16/17**	16-Jan	2-Mar	45	3*	4	n/a	1	104
17/18	21-Dec	8-Apr	108	6	8	2	1	416	**17/18**	8-Jan	23-Ma	74	2	4	0	2	206
18/19	16-Jan	26-Feb	41	4	5	2	0	262	**18/19**	28-Nov	14-Feb	106	2	2	2	1	125
19/20	no ice	no ice	n/a	n/a	6	n/a	n/a	74	**19/20**	no ice	no ice	n/a	n/a	9	n/a	n/a	33
20/21	11-Dec	18-Mar	97	14	16	3	0	337	**20/21**	12-Jan	7-Mar	54	3	9	2	0	238
21/22	6-Dec	9-Feb	65	6	6	2	1	173	**21/22**	6-Dec	16-Feb	72	3	3	1	1	148

Correlation of ice thickness with FDD

In Table 1, the maximum ice thickness rating for each fjord as well as the total freezing degree days for the season are provided. Hellefjord and Kilsfjord had the greatest number of seasons with ice 15 – 30 cm in thickness (a rating of 3), six and five respectively followed by Tønsberg having four seasons with ice in the same thickness range. The remaining three fjords had two, Drammensfjorden, or one season, Moss and Halden with 15 – 30 cm ice with thickness, and less all other years. Moss had the fewest number of years with observed ice with two seasons having no ice in both ship logs and SAR imagery, and two seasons showing small amounts of ice in SAR imagery but with no record of ice thickness from the ship logs available while ice was present. This may be due to ice only being present outside of ship routes or freeze and break up occurring between ship transits. Within each area there is a tendency for thinner maximum ice reported in winters of fewer freezing degree days.

No ice was reported to be thicker than 15 – 30 cm. This range was reported for freezing degree days from 107 °C days in Hellefjord during the 2016/17 season, to upwards of 304 °C days in Moss during 2017/18 season. Similarly, the rating of '2' for ice being from 10 – 15 cm appeared in seasons when FDD ranged from 77 °C days in Tønsberg during the 2014/15 season all the way up to 416 °C days in Drammen during the 2017/18 season. The latter, Drammen, had consistently the coldest winter conditions in comparison to all other fjords although most often thinner ice. This particular fjord, however, is both much wider and longer than all other regions. As a result, the freshwater that is often linked to ice formation in may be more exposed to wind, current, and relatedly, mixing, as it flows down fjord, unhindered by necks or bends in the coastline. Hellefjord, in comparison, often had the warmest winter with fewest freezing degree days yet often held the thickest ice. Additionally, it is smaller than all other fjords examined here and has a very narrow neck of approximately 250 m. Freshwater that enters into Hellefjord therefore has potential to be trapped with limited mixing thus enabling ice formation. In addition, a mild winter with variations in temperature above and below freezing can result in greater snowmelt and rain entering the fjord in comparison to other regions where temperatures stay consistently below freezing limiting runoff into the fjord.

In Fig. 4a, the number of total freezing degree days from 1 November to 1 April is compared to maximum ice thickness. Freezing degree days calculated from the start of the ice season to the day of observation is also compared to the estimated thickness provided by ship logs. Both plots show large variation in the freezing degree days for a given ice thickness. A trendline set to Fig.4b shows a positive relationship with ice thickness increasing with increasing freezing degree days. While the trend is significant ($p < 0.05$), variance is large with an r^2 value of 0.08. Thus, this data further supports other factors, e.g. atmospheric and oceanic conditions, contributing greatly to the formation and growth of ice.

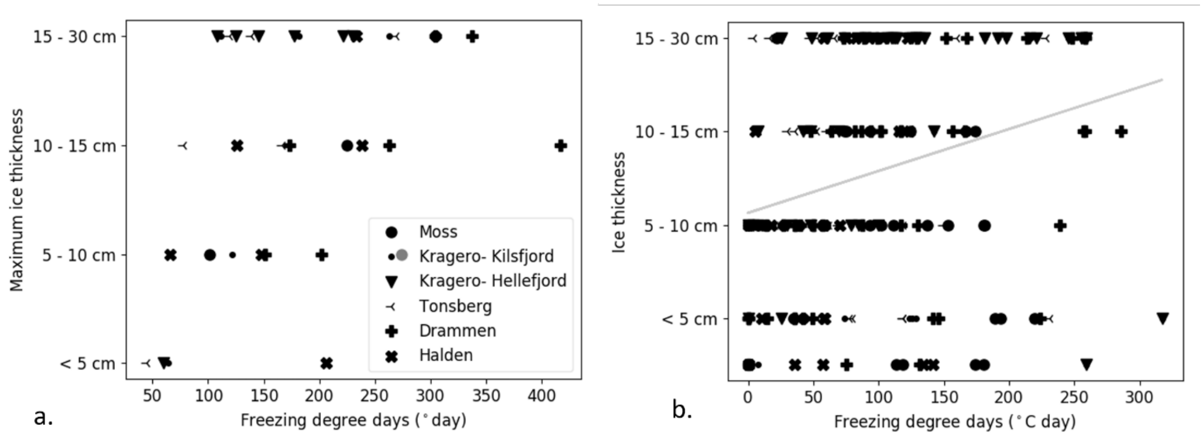

Figure 4: (a) Maximum ice thickness in comparison to freezing degree days between 1 Nov. to 1 April and (b) ice thickness compared to freezing degree days from freeze-up (start of ice season) to the date of observation with trendline in gray (see text for details; legend see (a))

Challenges with Observations

The observations of ice thickness presented here add to the limited archive of ice conditions along the Norwegian coastline. Such data is helpful in assessing if and in what ways conditions may change through time and the impact on transit and shipping industries. The number of observations provided by ships, however, remains limited. As presented in Table 1, there were usually fewer than 10 observations during the winter with even fewer observations made during the ice season. The data are therefore not detailed enough to create thickness versus time record.

The wide range of ice thicknesses within each class also presents challenges if one is investigating methods to model ice formation in these regions. Ice class '3' spans the range from 15 cm to 30 cm, corresponding to freezing degree days different by a factor of four (Anderson, 1961). In application to fjord ice, basic models relating freezing degree days to ice thickness were found to not be a dependable predictor of ice thickness with factors including tides, ocean heat flux, wind, runoff, and snowfall also contributing to the formation and thickening of ice (O'Sadnick et al., 2020; O'Sadnick et al., 2022). Analysis would therefore benefit from consideration of other oceanic and atmospheric conditions during the winter season to better assess the main variables driving ice conditions in individual fjords. To do so, however, more complete observations of ice type (snow ice versus congelation ice) and development through time would be of great use.

SAR imagery does help to fill in gaps in ship logbooks, providing a better overview of where ice was present and variations from day to day. The identification of ice can be challenging however with a main indicator being a consistent edge or object being present when several images are compared. If the frequency of the available images is limited, ice may go unnoticed. With further processing, the identification of thin, coastal ice, often fresh in its composition and thus lacking the brine pores present in sea ice, may be improved.

CONCLUSIONS

In this study, it is shown that for three months out the year, ice is present in the six fjords selected in southern Norway significant enough in thickness to require icebreaker services. While not of focus here, the transit of boats through ice channels was often clear in SAR imagery. Initially narrow channels either widened through time, the result possibly of many ships and/or conditions enabling melt, or showed evidence of needing to be maintained and ice re-broken.

Ice creates an obstacle, slowing ships and potentially stopping small boats from entering a region. In the case of an emergency including the spillage of pollutants, ice will complicate response and clean-up efforts (Oggier et al., 2020). Given the location of these transit routes near to well populated areas, understanding the frequency and length of ice coverage, the expected ice thickness and other properties including ice bulk salinity and ice type allows for better preparation and planning. With sea ice extent decreasing in the Arctic, shipping traffic is increasing particularly in Norwegian waters (Berkmann et al., 2022). While the majority of this increase is centered in the high north and Barents Sea, its influence may extend down the Norwegian coastline through time further supporting the observation and study of ice conditions in this region.

The work presented here reveals ice varying from non-existent to being 15 – 30 cm in thickness in the fjords examined. The freezing degree days, a measurement of how cold a given winter may be, correlated with reported ice thickness within specific areas. However, across the areas there was no statistical correlation since the consistently thickest ice was not reported in the areas with greatest freezing degree days. This is an indicator that factors outside of air temperature (e.g. date of onset of ice formation, freshwater flux and timing to sub-freezing temperatures) play an important role. Future work should focus on both improving ice property observations and enhancing understanding of the fjord and weather characteristics that combine to enable ice formation including, for example, fjord width, depth, exposure to mixing forces like wind and current, oceanic heat, and freshwater flux.

ACKNOWLEDGEMENTS

The authors would like to thank Øyvind Rinaldo and the Norwegian Ice Service for inspiration and assistance in the development of this paper. This work was partially funded by the Centre for Integrated Remote Sensing and Forecasting for Arctic Operations (CIRFA), a Centre for Research- based Innovation (Research Council of Norway project number 237906).

REFERENCES

Anderson, D. L. (1961). Growth rate of sea ice. *Journal of Glaciology*, *3*(30), 1170-1172.

Asvall, R. P. (2010). Hvordan is i vassdrag dannes – og hvordan vassdragsreguleringer påvirker isen i norske vassdrag. *Norges Vassdrags- og Energidirektorat Rapport*, *2010*(20).

Aure, J., Molvær, J., & Stigebrandt, A. (1996). Observations of inshore water exchange forced by a fluctuating offshore density field. *Marine Pollution Bulletin*, *33*(1-6), 112-119.

Berkman, P.A., Fiske, G.J., Lorenzini, D., Young, O.R., Pletnikoff, K., Grebmeier, J.M., Fernandez, L.M., Divine, L.M., Causey, D., Kapsar, K.E. & Jørgensen, L.L. (2022). Satellite Record of Pan-Arctic Maritime Ship Traffic. *NOAA technical report OAR ARC, 22-10,* 72 – 80. https://doi.org/10.25923/mhrv-gr76.

Eilertsen, H. C., & Skarðhamar, J. (2006). Temperatures of north Norwegian fjords and coastal waters: variability, significance of local processes and air–sea heat exchange. *Estuarine, Coastal and Shelf Science*, *67*(3), 530-538.

Gorelick, N., Hancher, M., Dixon, M., Ilyushchenko, S., Thau, D., & Moore, R. (2017). Google Earth Engine: Planetary-scale geospatial analysis for everyone. *Remote Sensing of Environment*. https://doi.org/10.1016/j.rse.2017.06.031

Kvambekk, Å. S. (2010). Isforhold, temperatur- og saltmålinger i Holandsfjorden: Fra start på bobleanlegget i oktober 2002 til april 2008. *Norges Vassdrags- og Energidirektorat Oppdragsrapport*, *Serie A*(3).

Kystverket (2023). *Norwegian Ice Service*. Navigation Services. https://www.kystverket.no/en/navigation-and-monitoring/ice-service/

Oggier, M., Eicken, H., Wilkinson, J., Petrich, C., & O'Sadnick, M. (2020). Crude oil migration in sea-ice: laboratory studies of constraints on oil mobilization and seasonal evolution. *Cold Regions Science and Technology*, *174*, 102924.

O'Sadnick, M., Petrich, C., Brekke, C., & Skarðhamar, J. (2020). Ice extent in sub-arctic fjords and coastal areas from 2001 to 2019 analyzed from MODIS imagery. *Annals of Glaciology*, *61*(82), 210-226.

O'Sadnick, M. (2022). *Ice in Norwegian subarctic fjords and coastal regions: An examination of ice formation, properties, and trends based on remote sensing and in situ data* [Doctoral Dissertation, UiT- The Arctic University of Norway]. UiT Munin. https://hdl.handle.net/10037/26462

O'Sadnick, M., Petrich, C., Brekke, C., Skarðhamar, J., & Kleven, Ø. (2022). Ice conditions in northern Norwegian fjords: Observations and measurements from three winter seasons, 2017–2020. *Cold Regions Science and Technology*, *204*, 103663.