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Recent Ice Conditions in North-Norwegian Porsangerfjorden

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ABSTRACT

Ice is a common occurrence in mainland Norwegian fjords in the vicinity of river mouths in winter. Fjord ice provides a wide array of services to society, including (1) acting as a coastal buffer (e.g. from pollution) and marine hazard; (2) providing a platform for recreational activities (e.g., travel and fishing); (3) serving as a full-scale model for Arctic sea ice (e.g., response training); and (4) participating in the fjord and coastal ecosystems. In spite of the local importance of ice in mainland Norwegian fjords, systematic investigations of its seasonal development and geophysical properties appear to be scarce. This study presents a summary of ice conditions in Porsangerfjorden from satellite observations of the past two decades (2000-2016) and discusses these in the context of local air temperature data and regional measurements of flow rates in rivers. Maximum ice extent was observed in March and a useful first approximation of ice extent in March could be derived from freezing degree days of February. However, local distribution of ice appears to be governed by factors beyond air temperature.

KEY WORDS: Ice extent; Fjord; Freezing degree day; River discharge; Wind

INTRODUCTION

While the development of ice in Norwegian fjords has enjoyed considerable scientific attention in fjords of Svalbard (e.g., Gerland et al., 1999; Haarpaintner et al., 2001; Høyland 2009), there seems to be a lack of published studies on ice in mainland Norwegian fjords. Norway's climate is influenced by the North Atlantic (Seager et al., 2002), and ice conditions in fjords of Svalbard have been linked to water temperatures (Pavlov et al. 2013). Fjords are mostly ice-free along the coast of mainland Norway. However, according to local common lore, ice may be found in bays, coves, or at the end of fjords if there is a flow of freshwater from a river or creek leading into the fjord and if the winter is sufficiently cold. In various parts of the world local ice formation in larger water bodies has been attributed to a freshwater layer overlying saltwater that acts to suppress mixing and reduced heat exchange throughout the water column (e.g., Nof et al., 2006). In Norway, this form of ice is probably most often exploited as a platform for fishing, but it has also found entry into cultural entertainment (e.g., Markussen, 2001). Similar to sea ice, ice in fjords is of wide relevance to society (cf. Eicken et al., 2009). Fjord ice provides a wide array of services to society, including (1) acting as a coastal buffer (e.g. from pollution) and marine hazard; (2) providing a platform for recreational activities (e.g., travel and fishing); (3) serving as a full-scale model for Arctic sea ice (e.g., response training); and (4) participating in the fjord and coastal ecosystems.

In an attempt to provide a systematic assessment of system services of fjord ice, a preliminary analysis of ice conditions in one particular north Norwegian ford has been performed in this work. At this point, the analysis is based on remote sensing data and data archives with only limited input on specific local conditions. If successful, such an approach could be easily transferred to a larger number of fjords.

While ice formation and break-up of coastal sea ice has been linked to both generally warm weather and solar irradiance (e.g., Petrich et al., 2012 and references therein), predictive power is often found in simple freezing degree day assessments that only consider air temperature, or in statistical correlation with a wide range of potential parameters (e.g., Petrich et al. 2014 and references therein).

In this study, ice conditions in Porsangerfjorden were assessed from MODIS satellite images and correlations were attempted with a number of basic weather parameters.

METHODS

Ice conditions were investigated at the southern end of Porsangerfjorden, approx. 70.12° N, 25.0° E. Porsangerfjorden is split into two arms by Oldereidneset peninsula in the south, Vesterbotn in the West and Østerbotn in the East (Figure 1). Either or both arms may contain ice. The maximum northern ice extent is a few km north of Austmo. Two significant rivers end in Vesterbotn, one at its southern end at Banak airport and another on in Austmo. No information about significant river influx into Østerbotn is available.

Daily river flow data of the Norwegian Water Resources and Energy Directorate were available for Skoganvarre (through 2009 and in 2012) and Lombola measurement stations, representing the discharge at Banak and Austmo, respectively. Both measurement stations are located at fast-flowing points and do not usually freeze in winter. In addition, flow data were manually quality controlled by NVE to account for potential problems due to ice formation in winter. The rivers are fed by separate catchments. Since flow rates were measured upstream of the respective river mouths, absolute discharge rates into the fjord may be underestimated but are expected to be proportional.

Sea ice conditions were derived from data of the Moderate Resolution Imaging Spectroradiometer (MODIS) on board satellite TERRA. MOD09 Surface Reflectance product data were used from collection 6 (Vermote et al., 2015). The product is an estimate of the surface spectral reflectance for each band as it would have been measured at ground level as if there were no atmospheric scattering or absorption. It corrects for the effects of atmospheric gases and aerosols. False-color images were generated of bands 3-6-7 to facilitate the distinction between snow/ice (appearing red) and clouds (appearing white). For the present application, the product gives weekly ground conditions at a nominal pixel resolution of 500 m that are mostly cloud free. Light conditions are sufficient for reflective bands from early February. The ice season in Porsangerfjorden starts typically in February (earlier in some years) and ends in April. Maximum ice extent is observed in March.

Local air temperature data were obtained from three different sources: (1) 6-hourly eKlima weather station data of Banak airport provided by the Norwegian Meteorological Institute (mostly continuous record since 2005), (2) daily average gridded air temperature interpolation of seNorge (extracted at the eastern and western shores of Østerbotn and Vesterbotn, respectively), and (3) 3-hourly 0.75°x0.75° ERA40 Interim reanalysis, interpolated to Oldereidneset (71.12° N, 25.0° E), i.e. in the center of region of interest. Air temperatures were used to calculate monthly freezing degree days.

10 m surface wind data were analysed from ERA40 Interim since the airport weather station is located near a steep topographic rise (600 m). Monthly wind roses were generated from data interpolated at Oldereidneset.

Solar irradiance reanalyses of ERA40 Interim were investigated but will not be discussed due to a lack of local measurements for validation.

1°x1° gridded monthly measured (ship-borne) sea surface temperatures at the northern end of Porsangerfjorden were extracted from the International Comprehensive Ocean-Atmosphere Data Set (ICOADS). Data of two grid cells were averaged, representing 71°-72°N and 25°-27°E. The data are averaged ship-borne observations of unknown and varying accuracy.

RESULTS

Ice Conditions

Ice extent was classified in southern Porsangerfjorden separately for the eastern part (Ø) and western part (V) (Figure. 1). Distinction was made between essentially no ice (0), ice not extending Oldereidneset peninsula (1), ice not extending past Austmo (2), and ice extending past Austmo (3). An area of open water (>1 km^2) was visible offshore of Austmo when ice extended past Austmo – we cannot say whether this is a result of water from Lombola or effluent since area of open water existed each year. Maximum ice extent was observed in March although a few years had similar ice extent already in late February at the beginning of the period of satellite observation. The ice cover generally appeared to be solid (bright red in Figure. 1) although in particular the eastern section showed signs of thin ice or open ice cover (dark red as seen in section Ø3 in Figure. 1). The classification of ice conditions in Tab. 1 shows that maximum ice conditions range from as low as 1/0 (V/Ø) to as high as 3/3. Approximately half of the years saw very little or no ice in the eastern part (Ø), while the western part had ice (V).

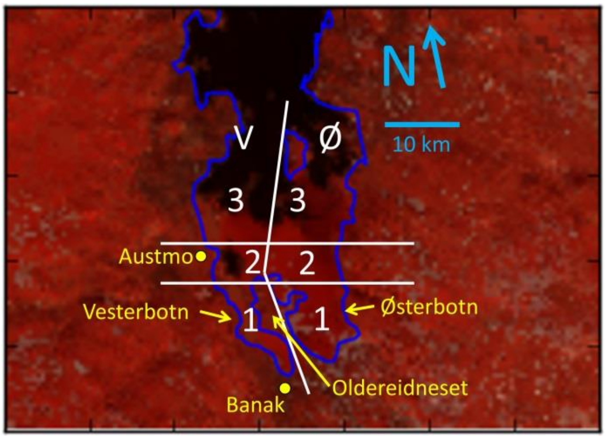

Figure 1. Classification of ice conditions at the southern end of Porsangerfjorden (blue outline) from MODIS false-color images used in Table 1. Red indicates snow or ice. Note the characteristic area of open water offshore Austmo. Image of 6 Mar 2001.

Freezing Degree Days

Calculated freezing degree days agree generally between data sources for all years (Tab. 1). Banak weather station data resemble seNorge Vesterbotn data, and seNorge Østerbotn data resemble ERA Interim data. seNorge Vesterbotn is consistently warmer than seNorge Østerbotn by an equivalent of about 1 °C per day. Notable disagreement exists only between seNorge Østerbotn data and ERA Interim in 2004 where seNorge suggested a notably colder month then ERA.

With few exceptions, ice extent seems to correlate with ERA Interim temperature data. Ice extent never exceeded category 1 in years with February FDD>-150 °C days, and only reached category 3 on either side of the fjord in years with FDD<-300 °C. Exceptions are 2008 which had ice extent lower than expected from February FDD, and 2003 which had an ice extent larger than expected from February FDD. 2004 and 2006 had almost identical ERA FDDs but considerably different ice covers. It appears as though either 2004 had too little ice given the February temperatures or 2006 had too much. A more close-up look at the temporal development of air temperatures and ice cover may explain the differences between 2004 and 2006.

Table 1. March ice extent in Østerbotn (Ø) and Vesterbotn (V), and freezing degree days (FDD) in February (°C days). In 2002, ice extent reached category 3 in Østerbotn but the ice cover appeared to be rather dispersed than continuous, hence the category is put in brackets. FDDs are given for Banak weather station (wx), seNorge (V, Ø), and ERA Interim (ERA). March flow rates at Lombola and Skoganvarre are indicated as low (-), medium (o), and high (+) as defined in the text.

Year	V	Ø	FDD wx	FDD V	FDD Ø	FDD ERA	Lom	Sko
2000	2	2		-205	-229	-245	+	+
2001	3	3		-292	-317	-334	-	-
2002	2	(3)		-216	-240	-243	+	+
2003	**2**	**3**		**-100**	**-120**	**-121**	+	**o**
2004	**2**	**0**		**-310**	**-347**	**-277**	**o**	**o**
2005	2	0	-168	-164	-183	-190	**o**	**o**
2006	**3**	**3**	**-235**	**-238**	**-266**	**-261**	-	**o**
2007	3	1	-396	-376	-408	-415	-	**o**
2008	**1**	**0**		**-164**	**-186**	**-205**	**o**	**o**
2009	3	3	-268	-294	-323	-316	-	-
2010	3	3	-400	-385	-415	-397	-	nd
2011	3	3	-372	-357	-389	-402	+	nd
2012	3	3	-266	-261	-292	-301	**o**	+
2013	2	0	-177	-184	-205	-197	+	nd
2014	1	0	-68	-71	-83	-108	+	nd
2015	2	0	-136	-139	-155	-178	+	nd
2016	2	0	-167	-177	-194	-196	nd	nd

River Discharge

Discharge rates measured in Lombola and Skoganvarre vary widely between years (Figure. 2). While flow rates are positively correlated between the stations in some years (2001), other years show anticorrelation (2003). Changes between positive correlation and anticorrelation can be found throughout the record since the 1920s (not shown) and may be related to wind and precipitation patterns across the respective catchments. Flow rates between months were generally correlated with low January flow rates corresponding to low flow rates in February and March.

Tab. 1 indicates whether March flow rates were ≤2.5 (-) or >3.0 m^3/s (+) at Lombola, and ≤3.0 (-) or >4.5 m^3/s (+) at Skoganvarre gauges. There is a general tendency for low flow rates to be associated with high ice extent in Vesterbotn.

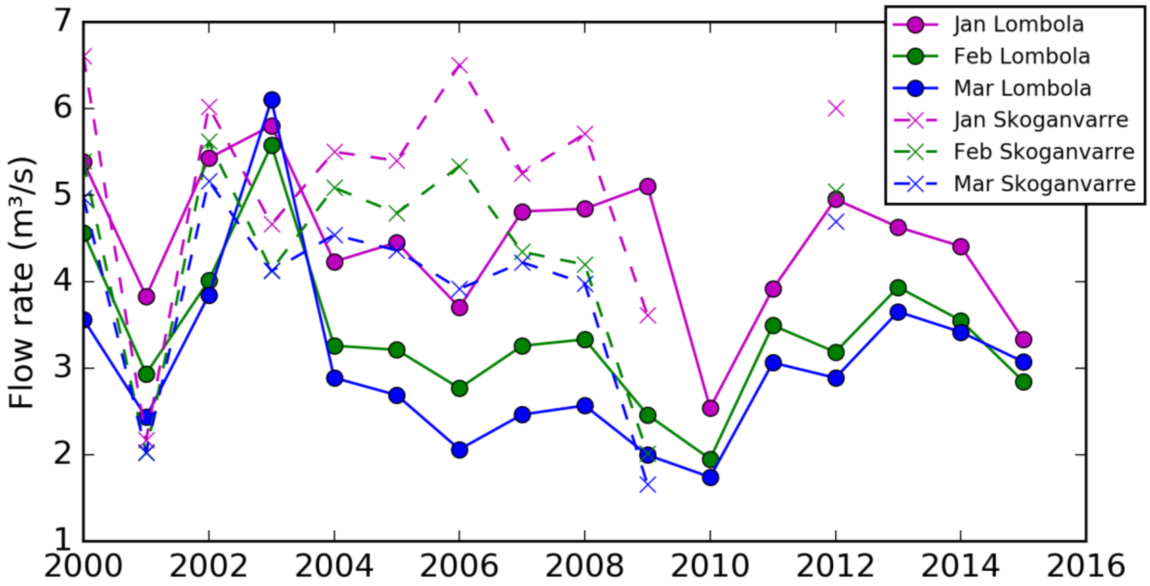

Figure 2. River discharge rates at the measurement stations averaged separately over months January, February, and March. Note that the vertical axis does not start at 0.

Winds

The local wind patterns have been assessed through monthly wind roses. Winds from south tend to dominate in the region through the years. No immediately obvious patterns were found explaining the years of no ice in Østerbotn. However, Figure 3 shows the winds for two years that had great ice extent (level 3), i.e. ice past Oldereidneset, on only one side of the fjord (Tab. 1, 2003 and 2007; Figure 4). In these years, there should have been sufficient ice available for drift. Figure 3 shows that February 2007 experienced winds from South-East while February 2003 experienced winds from West, which is consistent with ice distributed west and east in 2007 and 2003, respectively (Figure 4). Of all years investigated, 2003 had the strongest contribution from West in February in terms of both frequency and wind speed.

While years 2008 and 2014 had the smallest ice extent, 2008 was reasonably cold (Tab.1, Figure 6). Figure 5 shows that 2008 did not seem to have experienced persistently strong southerly winds that could have blown out the newly forming ice.

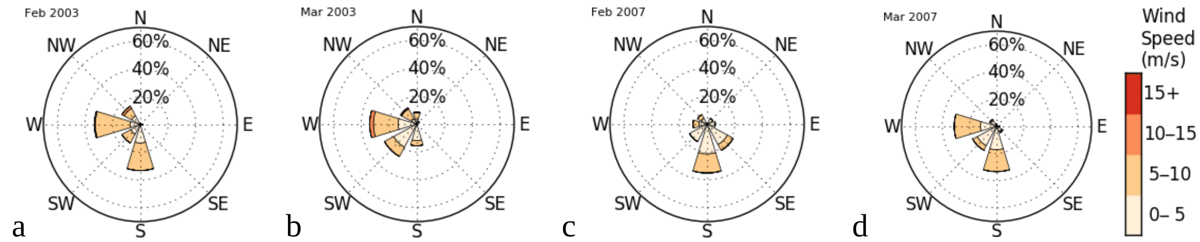

Figure 3. Wind conditions in February and March of two year that have large ice extent on predominantly one side of the fjord. 2003: East, 2007: West. (a) Feb 2003, (b) Mar 2003, (c) Feb 2007, (d) Mar 2007.

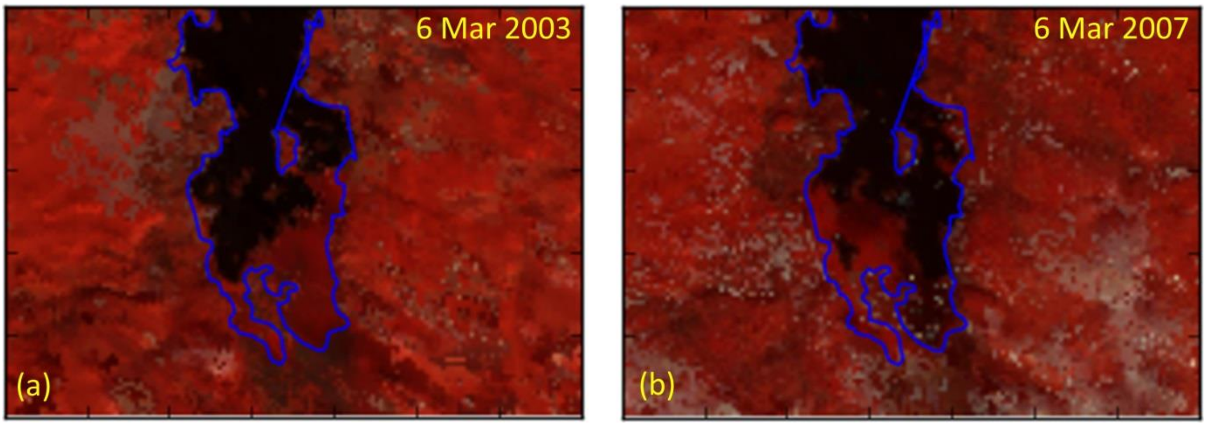

Figure 4. March ice extent in (a) 2003, and (b) 2007.

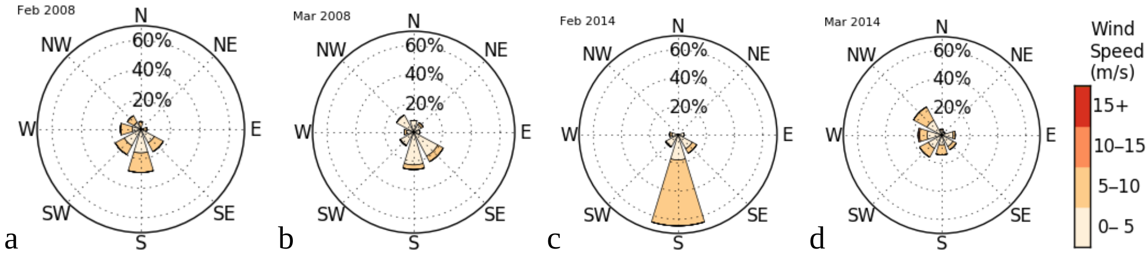

Figure 5. Wind conditions in February and March of the two years with the smallest ice extent. (a) Feb 2008, (b) Mar 2008, (c) Feb 2014, (d) Mar 2014.

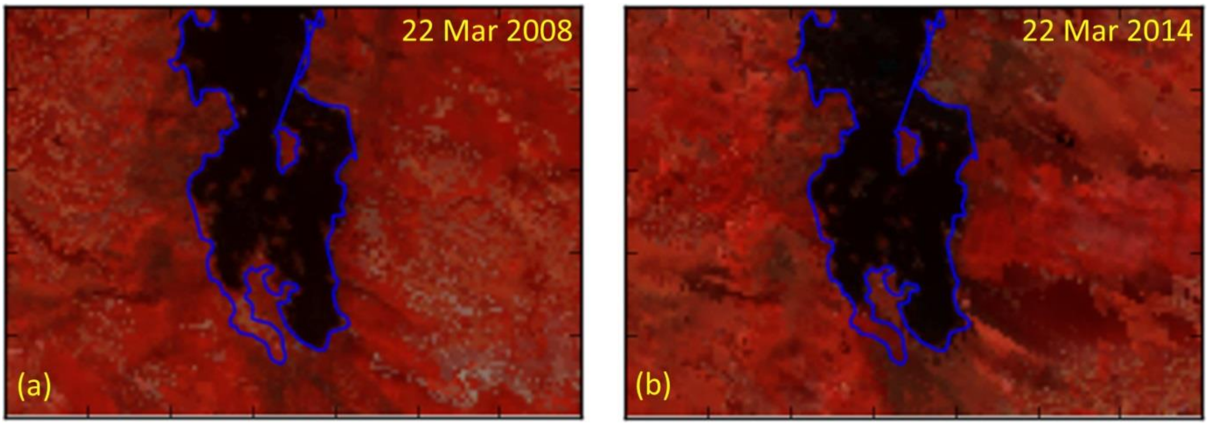

Figure 6. The two years of smallest March ice extent. (a) moderately cold year 2008, and (b) warm year 2014.

Sea Surface Temperature

The monthly variation in measured sea surface temperatures at the northern end of Porsangerfjorden is shown in Figure 7. While the data may enable the derivation of long term trends, they seem to be too noisy for comparisons between individual years. No further analysis of these data has been attempted.

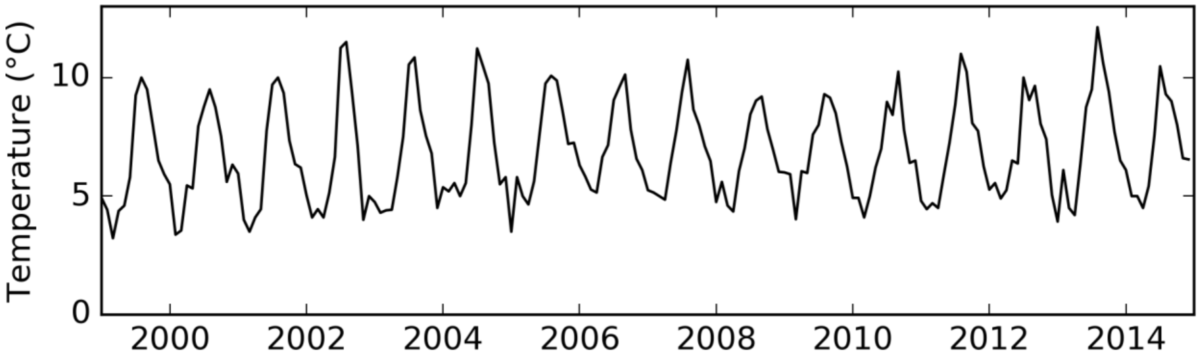

Figure 7. Sea surface temperature north of Porsangerfjorden.

DISCUSSION

Freezing degree days (FDD) can be directly related to ice thickness (Petrich and Eicken, 2017). However, the relationship to ice extent is more indirect. Extended periods of cold with a reasonable amount of wind increase heat removal from the water body, lowering its temperature closer to freezing and allowing ice to cover a larger area. Important parameters in such considerations are water depth and tides, two parameters that have not been addressed in this study. Earlier studies in a lagoon revealed a correlation between ice edge and bathymetry (Petrich et al., 2014), illustrating its relevance when quantitative relationships are being sought and when models developed for one area are to be applied to a different area.

Ice conditions were classified as 1/0 and 2/0 in 2008 and 2013, respectively, yet FDD were similar to each other in those years (Tab. 1). However, the difference between ice conditions of categories 1 and 2 can be quite small in Vesterbotn. It is conceivable that a short period of winds from the right direction leads to different assessments in MOD09 satellite products since floe size and separation may be smaller than image resolution. In that sense, ice conditions in 2008 and 2013 indicate that the monthly FDD approach has limitations in what can be resolved.

Ice extent in 2003 was considerable while February was similarly warm as 2008 (Tab. 1). Tab. 2 shows a more detailed FDD history going back to January. A significant difference between 2003 and 2008 was the very cold January in 2003, which was the coldest in the period studied. However, this alone cannot explain the large ice extent in 2003 since 2016 also had a very cold January but saw only a limited amount of ice in the fjord (Tab. 1, 2). The large ice extent in 2003 is of yet unexplained.

Years 2004 and 2006 had similar February FDDs yet different ice extent at the beginning of March. Tab. 2 shows that this difference may be due to extremely different temperatures during the first week of March. This indicates that monthly FDD are limited in their predictive power of ice extent since ice grows and decays over shorter characteristic time scales. This also indicates that ice has probably not reached particularly high thickness by 6 March 2006.

There was no correlation between river flow rates and ice extent apparent. This was somewhat surprising given the general importance of a freshwater layer to ice formation.

However, river flow rates are dependent on air temperature through snow melt and thus not independent of air temperature. Hence, to identify the impact of river flow rate, the flow rate data may have to be reduced by the effect of air temperature before a correlation with observations is attempted. To address the episodic absence of ice in Østerbotn, influx of water at the east side of the fjord should receive more scrutiny.

It was possible to find two examples where winds may have contributed significantly to the redistribution of ice in the fjord (2003/2007).

Geophysical factors that may be relevant for an understanding of ice extent but were not investigated include: solar radiation, snow cover, fjord bathymetry, tidal flow, ocean heat flux, river water temperature, and wind mixing of the water column. Also, short-term variation of parameters (weeks), in particular strong winds but also cold spells or hot spells, should be investigated in greater detail.

Table 2. Comparison of ERA Interim FDDs for selected years. Note the different lengths of the intervals.

Year	1-31 Jan	1-14 Feb	15-end Feb	1-7 Mar
2003	-455	-125	4.5	-39
2004	-270	-150	-127	-43
2006	-205	-144	-117	-144
2008	-196	-67	-138	-88
2014	-362	-58	-50	-16
2016	-418	-93	-103	-40

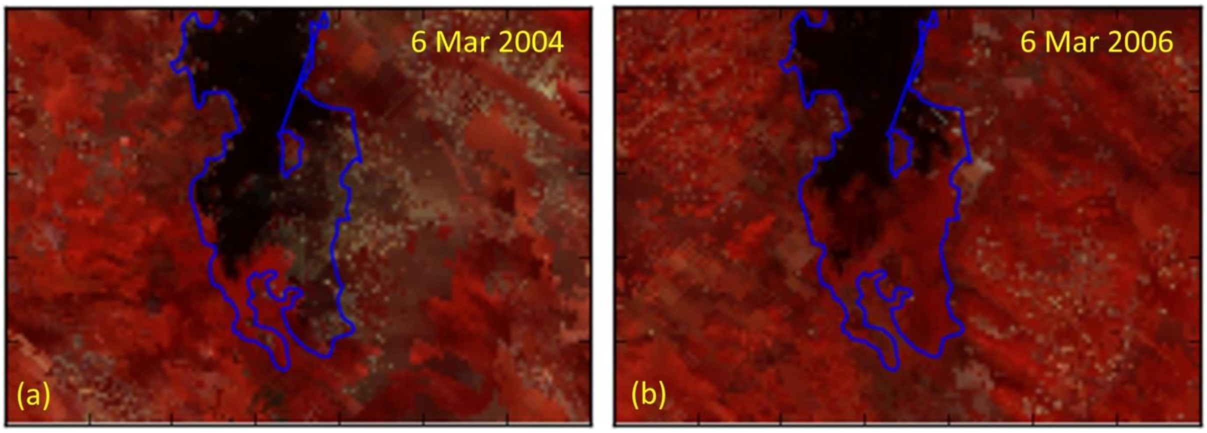

Figure 7. Ice extent in years of similar February FDD, (a) 6 Mar 2004 and (b) 6 Mar 2006. Same dates are shown for comparison but note that in 2006 ice extent was higher at the west side of the fjord and ice appeared more consolidated by 22 March. In 2004, (a) represented the greatest ice extent.

CONCLUSION

Reconstruction of local ice conditions becomes possible once the mechanisms governing ice conditions are understood and suitable environmental data are available. It has been shown that this is possible in principle for saltwater lagoons, and the present work suggests that ice conditions in fjords may also be amendable to prediction based on environmental conditions. Most of the variance of fjord ice extent in Porsangerfjorden in March seems to be explained by freezing degree days in February. Based on the investigated years 2000 through 2016, a relationship has been found that held in good approximation all winters except 2003. While the geophysical investigation into those years could easily be expanded, input from local residents should also be considered as a source of information.

To extend this work, the events that led to the comparatively high and low ice extent in 2003 and 2008, respectively, should be identified. Valuable insights may be gained by trying to address outliers. Also, ice conditions in other fjords should be investigated to assess to what degree results of this study can be generalized and applied on an operational level.

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