Responses to the Reviewer

Sea ice cover in Isfjorden and Hornsund, Svalbard (2000-2014) from remote sensing data

Muckenhuber et al.

Dear Referee #2,

Thank you very much for helping us improving our paper.

Answers (in **Bold**) to specific comments:

1. P. 1, Lines 1-18: The authors have added the analysis of atmospheric and ocean data, but have not mentioned this in the abstract. Perhaps the linkages suggested by the analysis with the new data can be briefly mentioned, along with a sentence describing how the dataset could potentially be used in future studies.

Thanks, agree. The following part will be added to the abstract (P1, L18): *'Fast ice coverage generally correlates well with remote-sensing sea surface temperature and in-situ air temperature. An increase of autumn ocean heat content is observed during the last few years when the DFI values decrease. The presented sea ice time series can be utilised for various climate effect studies linked to e.g. glacier dynamics, ocean chemistry and marine biology.'*

2. P. 2, Line 30: Change "also during winter" to "during both winter and summer", or to "during winter" if it is only true during winter.

Thanks, agree. The sentence will be changed to (P2, L28): *'The WSC contributes strongly to Svalbard's relatively warm climate and makes eastern Fram Strait the northernmost permanently ice-free ocean (Onarheim et al., 2014).'*

3. P. 2, Line 44: Add "(Fig. 1)" after "Spitsbergen" to indicate the specific location of the fjords.

Thanks, agree. We will add *'(Figure 1)'* in (P2, L44).

4. P. 2, Line 40 or P. 3, Line 66: As I understand it, the authors don't intend this paper to be a comprehensive study of the causes of sea ice variability in these fjords. Rather, the paper mainly focuses on presenting the dataset, revealing the variability in sea ice cover that it is able to show, and showing that the observed variability is consistent with other observations and previous studies. Future studies may be able to use the dataset to further understand linkages and drivers of the observed variability. If the authors agree, think these points should be briefly mentioned in one or two sentences in either of these locations to make it clear what the authors' objectives are.

Thanks, agree. The following part will be added to (P2, L66): *'The focus of this paper is to present a new sea ice cover time series, revealing the variability in sea ice cover and showing that the observed variability is consistent with other observations. Future studies may be able to use the dataset to further understand linkages and drivers of the observed variability.'*

5. P. 3, Lines 70-72: Also mention the ocean and atmospheric data now included in section 4.

Thanks, agree. The following sentence will be changed to (P3, L72): *'The sea ice cover time series for Isfjorden and Hornsund, the resulting DFI values and the dates for onset of freezing are presented in Sect. 4 and compared to atmosphere and ocean time series.'*

6. P. 3, Line 93: Change “Medium resolution” to “Medium resolution (300-500 m)” for clarity.

Thanks, agree. Will be changed to *'Medium resolution (300-500 m)'*.

7. P. 4, Line 96: Can the authors provide the MODIS product number?

The utilised MODIS datasets are MOD02HKM (MODIS/Terra Calibrated Radiances 5-Min L1B Swath 500m) and MYD02HKM (MODIS/Aqua Calibrated Radiances 5-Min L1B Swath 500m).
Agree, the sentence in (P4, L96) will be changed to: *'MODIS images from the datasets MOD02HKM (Terra) and MYD02HKM (Aqua) can be ordered pre-processed, which allows to download all available images of the considered area and time period.'*

8. P. 4, Line 130: The fact that temperatures were used to calculate degree days, and the calculation for this should be mentioned.

Thanks, agree. The following will be added to (P4, L130): *'The temperatures of days with average temperature below -2C between October and May are added together to derive negative degree days for each winter.'*

9. P. 5, Line 162: The name of this index still seems to be a bit misleading, since it is not really an index of the number of days with fast ice coverage, but rather indicates of the number of days that the fjord would be covered with ice, if it was completely covered every day. Really it is an index of the cumulative percentage ice cover. Perhaps the name could be changed to reflect this, or the authors can briefly clarify in this section why they choose to include the word “days” in the name of the index.

Thanks, agree. The following will be added to (P6, L169): *'The unit days shall give a quick understanding of the range (considered time period) and linear scaling. The index indicates the number of days that the fjord would be covered 100% with fast ice.'*

10. P. 6, Line 171: Figure 2a appears to show some anomalously dark areas in the radar image, yet these areas are classified as fast ice. Is this a potential additional source of error?

You are right, fast ice cannot be recognised without doubt on a single SAR scene. However, having a time series of SAR images allows to follow the motion of the surface cover. Fast ice is attached to the coastline and does not change its position on consecutive SAR images. This makes it possible to detect dark fast ice areas with no (or very little) doubt also during polar night and cloud cover, when no VIS/NIR images are available. See also (P5, L147-149).

11. P. 6, Line 180: Perhaps change “results in different error estimates.” to “is another potential source of error.”

Thanks, agree. Will be changed to (P6, L180): *'The different resolutions of the utilized satellite images is another potential source of error.'*

12. P. 7, Line 206: In the response to reviewers, it is mentioned that because errors on monthly timescales are believed to be very small, they are not considered explicitly in the interpretation of results on monthly timescales. Please mention that here as well.

Thanks, agree. The following will be added to (P7, 206): *'The error of these values are*

therefore not considered in the following, since they do no influence the interpretation of the results.'

13. P. 7, Lines 227-228: Because there is no data before March for the earlier years, it is not really known if the peak is in March or not. But it is known that the peak is either in March or before March. I suggest changing "March" to "March or earlier", and "the peak in March is..." to "the value in March is..."

Thanks, agree. The sentences in (P7, L227-228) will be changed to: *'Considering the mean over the entire observation period 2000–2014 (black line, Fig. 5), the highest value is reached in March (35.7%) or earlier. Before 2005 (blue line, Fig. 5), the value in March is 57.5%.'*

14. P. 8, Line 234: Mention the maximum is assumed to be March for these numbers. I.e. change "(relative to the value for 2000-2005)" to "(relative to the value for 2000-2005, assuming the maximum occurs in March)"

Thanks, agree. Will be changed to (P8, L234) *'(relative to the value for 2000-2005, assuming the maximum occurs in March)'*.

15. P. 8, Line 245: "Higher difference" relative to what? Perhaps say "higher than average difference". Also the value for 2009 is fairly large for Hornsund.

Thanks, agree. Will be changed to (P8, L245) *'higher than average difference'*.

16. P. 9, Lines 275-277: I feel some additional details are necessary: i.e. change "winter sea surface temperature (SST), ocean heat content during autumn and winter atmospheric temperatures,..." to "satellite-derived winter sea surface temperatures (SSTs) near the mouth of the fjord, ocean heat content from in situ profiles taken at the mouth of the fjord for 25-100m depth, as well as winter atmospheric temperatures from a nearby weather station,..."

Thanks, agree. The sentences in (P9, 275-277) will be changed to: *'In Figure 8, the DFI values for Isfjorden are compared with satellite-derived winter sea surface temperatures (SSTs) near the mouth of the fjord, ocean heat content from in situ profiles taken at the mouth of the fjord for 25-100m depth, as well as winter atmospheric temperatures from a nearby weather station, represented by negative degree days.'*

17. P. 9, Lines 288-296: This paragraph seems out of place. I suggest moving it either to the end of the "Data" section, where the different products used are described, or to follow the 3rd paragraph of the "Error estimates" section following the discussion of the impact of different resolutions.

Thanks, agree. The paragraph will be moved to the end of the 'Data' section (P4, L130).

18. P. 10, Lines 322-323: The meaning of this sentence is not clear. Perhaps change to "But care must be taken in attributing changes in sea ice cover to atmospheric variability, as reduced sea ice cover and a warmer ocean can also increase the atmospheric temperature."

Thanks, agree. Will be changed to (P10, L322-323): *'But care must be taken in attributing changes in sea ice cover to atmospheric variability, as reduced sea ice cover and a warmer ocean can also increase the atmospheric temperature.'*

19. P. 10, Line 338 – P. 11, Line 340: I still don't think there is enough data provided to prove definitively that Hornsund is less influenced by AW, as this sentence seems to suggest. Suggest changing to: "A comparison of the DFI time series in Figures 8 and 9 suggests that interannual sea ice cover variability in Hornsund may be less influenced by intrusion of AW residing on the shelf."

Thanks, agree. The sentence in (P10, L338-P11, L340) will be changed to: *'A comparison of the DFI time series in Figures 8 and 9 suggests that interannual sea ice cover variability in Hornsund may be less influenced by intrusion of AW residing on the shelf.'*

20. P. 11, Line 371: Change "March to April" to "March (or earlier) to April"

Thanks, agree. Will be changed to (P11, L371) *'March (or earlier) to April'.*

21. P. 11, Line 374: Change "serve for" to "can be used to obtain".

Thanks, agree. Will be changed to (P11, L374) *'can be used to obtain'.*

22. P. 11, Line 376: I think the authors are referring to future studies here, but it is not entirely clear. Perhaps change "can be used" to "can be used in future studies" for clarity.

Thanks, agree. Will be changed to (P11, L376) *'can be used in future studies'.*

23. Figure 1: It would be nice to see some geographic coordinates (even at the four corners of the figure) and possibly a scale bar on this figure, if possible.

Thanks, agree. We added a scale bar and the locations of the two weather stations as a reference. The coordinates of the weather stations will be mentioned in the caption of Figure 1 (Caption, Figure 1): '*The respective weather stations, marked with green dots, are located at 78.25 N, 15.50 E (Isfjorden) and 77.00 N, 15.54 E (Hornsund).'*

24. Figures 3 and 4: This is not absolutely necessary, but it would be nice to see the DFI values centered at the center of the short season, rather than at the beginning of the year, to match up with the peak in ice concentration.

We agree, that Figure 3 and 4 would look nicer with a slightly shifted DFI time series, but in order to be consistent with Figure 8 and 9, we would prefer to keep the DFI values at the beginning of the year. Also, the center of the short season is different each year. For Figure 8 and 9, we have decided to shift only the autumn data to August and leave all winter data (DFI, SST and degree days) at the beginning of the year in order to visually pronounce the difference between autumn and winter.

25. Figures 8 and 9 captions: A lot of the details here were described in the methods section. I think the captions can be shortened somewhat by removing some details.

Thanks, agree. The caption of Figure 8 will be changed to: *'Isfjorden's (red) "Days of fast ice" (DFI) values of the short season compared to (blue) winter sea surface temperature (SST), (black) autumn heat content above -2C of the 25-100 m depth water column and (green) winter negative degree days below -2C. Winter SST values represent the mean for the period January-April at 78.25◦N, 14.75◦E. Heat content values are calculated using the mean temperature profile during autumn (July-September) at the Isfjorden mouth area. Negative degree days have been derived from temperature measurements at the Svalbard airport station (78.25◦N, 15.50◦E). Note the reversed SST and heat content axis.'*

The caption of Figure 9 will be changed to: *'Hornsund's (red) "Days of fast ice" (DFI) values of the short season, compared to (black) autumn heat content above -2C of the 25-100m depth water column and (green) winter negative degree days below -2C. Heat content values are calculated using the mean temperature profile inside Hornsund during autumn (July - September). Negative degree days have been derived from temperature measurements at the*

Hornsund station at 77.00◦N, 15.54◦E. Note the reversed heat content axis.'

Answers (in **Bold**) to technical corrections:

1. P. 2, Line 29: Change “makes eastern Fram Strait contain” to “causes the eastern Fram Strait to contain”.

Agree, will be changed.

2. P. 3, Line 74: Change “like” to “such as”.

Agree, will be changed.3. P. 4. Lines 96-97: Change “which allows to download all available images of the considered area and time period.” To “which allows all available images of the considered area and time period to be downloaded.”

Agree, will be changed.

4. P. 4, Line 113: Change “get” to “obtain”.

Agree, will be changed.5. P. 5, Line 135: Change “created by using” to “created using”.

Agree, will be changed.6. P. 5, Line 138: Change “needs” to “needed” and “this is” to “this was” for consistency.

Agree, will be changed.

7. P. 5, Line 141: Change “followed” to “follows”.

Agree, will be changed.

8. P. 5, Line 161: Change “data is” to “data are”.

Agree, will be changed.

9. P. 6, Line 178: Change “make up” to “be up”.

Agree, will be changed.

10. P. 6, Line 181: Change “are not varying” to “do not vary”.

Agree, will be changed.

11. P. 6, Line 188: Change “of the satellite” to “for the satellite”.

Agree, will be changed.

12. P. 6, Line 189: Change “few pixel” to “few pixels”.

Agree, will be changed.

13. P. 6, Line 190: Change “in the same” to “of the same”.

Agree, will be changed.

14. P. 6, Line 193: Change “Hornsund in” to “Hornsund on”.

Agree, will be changed.

15. P. 6, Line 198: Change “polygon,” to “polygon”.

Agree, will be changed.

16. P. 7, Line 202: Change “daily value error” to “daily error”.

Agree, will be changed.

17. P. 8, Line 244: Change “capture well” to “effectively capture”.

Agree, will be changed.

18. P. 8, Line 260: Change “the days with first appearance of drift and fast ice...” to “the days on which drift and fast ice first appear...”.

Agree, will be changed.

19. P. 8, Line 265: Change “have been” to “were”.

Agree, will be changed.

20. P. 9, Line 269: Change “and beginning” to “and the beginning”.

Agree, will be changed.

21. P. 9, Line 270: Change “underlays” to “underlies”.

Agree, will be changed.

22. P. 10, Line 319: Change “made the AW” to “caused the AW to”.

Agree, will be changed.

23. P. 10, Line 320: Change “show” to “shows”, change “form” to “from”.
Agree, will be changed.
24. P. 11, Line 340: Change “seem to revert” to “seems to revert”.
Agree, will be changed.
25. P. 11, Line 345: Suggest changing “can serve” to “could serve”.
Agree, will be changed.
26. P. 11, Lines 358-359: Change “merely that some protected side fjord within the larger fjord system have a fresher and colder surface layer that are able to produce sea ice...” to “merely that some protected side fjords within the larger fjord system may have a fresher and colder surface layer, allowing for sea ice production...”.
Agree, will be changed.
27. Table 1 caption: Change “database: list” to “databases used,”.
Agree, will be changed.
28. Table 2 caption: Change “total season refers to” to “ “total season” refers to”, and “short season refers to” to “ “short season” refers to”.
Agree, will be changed.

Thanks again for your comments. We are looking forward to your reply!

Best regards,
Stefan Muckenhuber

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Sea ice cover in Isfjorden and Hornsund, Svalbard (2000-2014) from remote sensing data

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Abstract. A satellite database including 16 555 satellite images and ice charts displaying the area of Isfjorden, Hornsund and the Svalbard region has been established with focus on the time period 2000–2014. 3319 manual interpretations of sea ice conditions have been conducted, resulting in two time series dividing the area of Isfjorden and Hornsund into "Fast ice" (sea ice attached to the coastline), "Drift ice" and "Open water". The maximum fast ice coverage of Isfjorden is $> 40\,\%$ in the periods 2000–2005 and 2009–2011 and stays $< 30\,\%$ in 2006–2008 and 2012–2014. Fast ice cover in Hornsund reaches $> 40\,\%$ in all considered years, except for 2012 and 2014, where the maximum stays $< 20\,\%$. The mean seasonal cycles of fast ice in Isfjorden and Hornsund show monthly averaged values of less than 1 % between July and November and maxima in March (Isfjorden, 35.7 %) and April (Hornsund, 42.1 %) respectively. A significant reduction of the monthly averaged fast ice coverage is found when comparing the time periods 2000–2005 and 2006–2014. The seasonal maximum decreases from 57.5 to 23.2 % in Isfjorden and from 52.6 to 35.2 % in Hornsund. A new index, called "days of fast ice" (DFI), is introduced for quantification of the interannual variation of fast ice cover, allowing for comparison between different fjords and winter seasons. Considering the time period from 1 March until end of the sea ice season, the mean DFI values for 2000–2014 are 33.1 ± 18.2 DFI (Isfjorden) and 42.9 ± 18.2 DFI (Hornsund). A distinct shift to lower DFI values is observed in 2006. Calculating a mean before and after 2006 yields a decrease from 50 to 22 DFI for Isfjorden and from 56 to 34 DFI for Hornsund. Fast ice coverage generally correlates well with remote-sensing sea surface temperature and in-situ air temperature. An increase of autumn ocean heat content is observed during the last few years when the DFI values decrease. The presented sea ice time series can be utilised for various climate effect studies linked to e.g. glacier dynamics, ocean chemistry and marine biology.

1 Introduction

Svalbard is an Arctic archipelago located between 76–81° N and 10–34° E. It is surrounded by the Arctic Ocean in the north, with the Greenland Sea and Fram Strait to the west and the Barents Sea to the east. Spitsbergen is the largest island in the archipelago and the study area of this work includes two fjords along the west coast of Spitsbergen (Figure 1).

Water masses along the west side of Spitsbergen are strongly influenced by the West Spitsbergen Current (WSC), that is steered along the slope between the West Spitsbergen Shelf and the deep ocean, the coastal current (CC) on the shelf, and freshwater input from glacier and river runoff along the coastline (Figure 1). The WSC transports warm and salty Atlantic Water (AW) northward, representing the major oceanic heat and salt source for the Arctic Ocean. The WSC contributes strongly to Svalbard's relatively warm climate and ~~makes~~ causes eastern Fram Strait ~~contain the northernmost~~ the northernmost permanently ice-free ocean ~~, also during winter~~ (Onarheim et al., 2014). The fjords along western Spitsbergen are usually separated from the WSC by the colder and fresher water masses of the northward flowing CC. This, in combination with low temperatures and fresh water input from glacier and river runoff, makes seasonal sea ice growth inside the fjords possible. But AW from the WSC can reach the upper shelf and eventually flood into the fjords (Nilsen et al., 2008, 2012). These warm water intrusions have a strong effect on the seasonal sea ice cover inside the fjords. The fjord-shelf exchange is controlled by the density difference between the fjord water masses and the AW, which is determined by the sea ice and brine production during winter (Nilsen et al., 2008). This means that the sea ice cover inside the fjords is not only a result of advected or advecting water masses, but can alter the fjord water significantly and influence the exchange with the shelf.

The aim of this study is to investigate sea ice conditions between 2000–2014 in two representative fjords along the west coast of Spitsbergen (Figure 1), where ocean and atmosphere data are available for further analysis. The two considered fjords are Isfjorden, the largest fjord of Spitsbergen with its 2490 km^2 (as defined from 2013 Landsat 8 images), and Hornsund, a smaller fjord (320 km^2) located in southern Spitsbergen. Both fjords reveal a seasonal sea ice coverage with strong variations between different years. Information about sea ice coverage in Isfjorden has been collected between 1974 until 2008 in Grønfjorden (Zhuravskiy et al., 2012), which is a small sub fjord at the southern entrance of Isfjorden, but no data for the entire fjord area has been published so far. Previous studies have investigated sea ice conditions in Hornsund during the winter seasons of 2005 through 2011 and the results have been published in Styszyńska and Kowalczyk (2007), Styszyńska and Rozwadowska (2008), Styszyńska (2009) and Kruszewski (2010, 2011, 2012). These studies compare in-situ observations from the Polish Polar Station in Isbjørnhamna, a bay at the northern entrance of Hornsund, with atmospheric and oceanic measurements and mean monthly sea ice concentration at the approach to Hornsund. The survey concentrates on regional ice conditions near Isbjørnhamna and no time series for the entire fjord is given.

The data for this article was collected and interpreted within the framework of the Polish-Norwegian AWAKE-2 project. The aim of AWAKE-2 is to understand the interactions between the main components of the climate system in the Svalbard area: ocean, atmosphere and ice, to identify mechanisms of interannual climate variability and long-term trends. The main hypothesis of AWAKE-2 is that the AW inflows over the Svalbard shelf and into the fjords have become more frequent during the last decades and this results in new regimes and changes in atmosphere, ocean, sea ice and glaciers in Svalbard. Being a link between land and ocean, Arctic fjords are highly vulnerable to warming and are expected to exhibit the earliest environmental changes resulting from anthropogenic impacts on climate. Sea ice cover is a key parameter for monitoring climate variability and trends, since it captures the variability of both ocean and atmosphere conditions. Due to the major role sea ice cover plays in air–sea interactions, knowledge about the ice cover is crucial for a better understanding of the Arctic fjord system. The focus of this paper is to present a new sea ice cover time series, revealing the variability in sea ice cover and showing that the observed variability is consistent with other observations. Future studies may be able to use the dataset to further understand linkages and drivers of the observed variability.

The paper is organised as follows: Sect. 2 explains the collected satellite images and gives an error estimate for the established sea ice cover time series. A method for manual interpretation of satellite data to describe sea ice conditions in a fjord is introduced in Sect. 3 as well as a new index, the days of fast ice (DFI) index, for quantifying fast ice coverage in a fjord. The sea ice cover time series for Isfjorden and Hornsund, the resulting DFI values and the dates for onset of freezing are presented in Sect. 4 and compared to atmosphere and ocean time series. The discussion can be found in Sect. 5.

2 Data

Investigating sea ice conditions, ~~like~~ such as spatial extent and ice type, via satellite remote sensing in comparable small areas like Isfjorden and Hornsund requires a spatial resolution of a few 100 m or lower. Daily images throughout the year with this resolution are only produced by Synthetic Aperture Radar (SAR), which is an active microwave sensor capable of penetrating cloud cover and taking images during polar night. Since the interpretation of sea ice conditions from SAR images can be ambiguous, high and medium resolution visual/near infrared (VIS/NIR) images provide valuable additional information during polar day. They can also be utilised, if SAR images are not available. However, good temporal coverage with VIS/NIR sensors is only achieved with a resolution above 250 m. Hence, lower accuracy is expected if only VIS/NIR images are utilized.

A satellite database including 6571 SAR images, 9123 VIS/NIR images and 861 ice charts displaying the area of Isfjorden and Hornsund has been established (see Table 1). Focus was placed on the time period 2000 until 2014 and the part of the season when sea ice was present in the fjords.

NERSC maintains a large satellite database including several thousand Level 1 SAR images from ASAR (Advanced Synthetic Aperture Radar on ENVISAT) and Radarsat-2. To select the images which are recorded at the considered region and time period, the NERSC MAIRES online service (http://web.nersc.no/project/maires/sadweb.py) has been used. 4326 ASAR and 2245 Radarsat-2 sub images covering Isfjorden and Hornsund respectively have then been created and stored in GeoTIFF format. The collected SAR data represent a time series from 2005 until 2014 with a temporal resolution of around 1–2 images per day and a spatial resolution between 50-150 m.

Medium resolution (300–500 m) VIS/NIR images from MERIS (Medium Resolution Imaging Spectrometer on ENVISAT) and MODIS (Moderate Resolution Imaging Spectroradiometer on Terra and Aqua) covering the Svalbard region have been downloaded from websites hosted by NASA (National Aeronautics and Space Administration). MODIS images from the datasets MOD02HKM (Terra) and MYD02HKM (Aqua) can be ordered pre-processed, which allows ~~to download~~ all available images of the considered area and time period to be downloaded. A total of 8501 MODIS images represents a temporal resolution of up to several images per day for the period 2000 until 2014. The relevant MERIS images had to be chosen prior to downloading via online quicklooks to select images with cloud free conditions. About 10 MERIS images per year have been chosen and added to the database.

High resolution VIS/NIR images have a distinct lower spatial and temporal coverage, but when available, view the ice conditions with an unmistakable clarity. 335 images from Landsat 1–8 and 161 from ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer on Terra) have been chosen for downloading via quicklooks provided by USGS (United States Geological Survey) and the Japan Space System.

In addition to the satellite images, 861 ice charts from the Norwegian Meteorological Institute (met.no) have been added to the database. These ice charts are based on the same satellite images that are used for this paper. The resolution of the met.no ice charts is too low to give sufficient accurate estimates about daily ice conditions in fjords like Isfjorden and Hornsund. Nevertheless, the met.no charts can serve as additional information about the overall sea ice concentration outside the boundary of the high resolution SAR image. Most of the stored ice charts depict ice conditions during polar night when no visual images are available to ~~get~~ obtain a quick overview of the large scale sea ice concentration.

To validate and discuss the remote sensing sea ice observations, in-situ air, ocean and remote sensing sea surface temperature (SST) data are considered. Monthly SST values are provided by ESA for the time period 1993–2010 with a grid spacing of 25 km x 25 km (http://catalogue.ceda.ac.uk/uuid/1dc189bbf94209b48ed446c0e9a078af, doi:10.1002/gdj3.20). This dataset is used to calculate winter SST for Isfjorden, representing the mean January-April at 78.25°N, 14.75°E. Moreover, 285 CTD (conductivity, temperature and depth) profiles taken between 2000–2014 at the Isfjorden mouth area (78.08–78.16°N, 13.5–14.3°E) and 107 CTD profiles taken between 2009–2014 inside Hornsund have been used to calculate the mean heat content of the 25–100m depth water column for each year during autumn (July–September). The 25–100 m depth range was chosen in order to avoid the shallow atmospheric heated surface layer and rather concentrate on the layers that represent fjord circulation of either Atlantic Water (AW) or Arctic Water (ArW). The CTD data was extracted from the UNIS Hydrographic Database (UNIS HD) where the CTD profiles used in this study are mainly collected by UNIS with additional profiles from the Norwegian Marine Data Centre (NMDC). ~~UNIS~~ Air temperature measurements from weather stations in Isfjorden (Svalbard airport, 78.25°N, 15.50°E) and Hornsund (77.00°N, 15.54°E) are provided by the Norwegian meteorological institute (eklima.met.no) for the entire observation period. The temperatures of days with average temperature below -2°C between October and May are added together to derive negative degree days for each winter.

Continuity of the presented sea ice time series is expected, since VIS/NIR images from the same sensor are considered for the entire observation period. Including SAR as additional data source for the time period 2005–2014 provides useful data during cloud cover and leads to an increased temporal resolution compared to the period prior 2005, which is solely based on visible data. Visible images are not able to capture sudden sea ice condition changes, if the fjord is covered by clouds. However, complete cloud cover usually did not exceed a few days. The formation and melting of sea ice takes place over time scales of days, but sea ice advection from or into the fjord and break up of fast ice can happen within a few hours. These sudden changes are captured in the time series prior 2005 on the first succeeding day with little or no cloud cover.

3 Methods

The downloaded Level 1 satellite data from ASAR, Radarsat-2, MODIS and MERIS were processed with the open-source python toolbox “Nansat” (developed by NERSC) into geoTIFF and PNG Level 2 images, which can be displayed by ArcGIS and several other programs. Within ArcGIS, two polygons covering Isfjorden and Hornsund were created ~~by~~ using a high resolution VIS/NIR image from Landsat 8 as reference. This polygon describes the fjord area very accurately and can be subdivided in order to evaluate the sea ice coverage by area. Due to the large amount of considered days and images, the processing chain ~~needs~~ needed to be fast and efficient. This ~~is~~ was achieved by implementing most steps into a python code working inside ArcGIS.

For the time period 2005–2014, both SAR and VIS/NIR images are available and the processing chain for a specific date (leading to one data point in the time series) is as ~~followed~~follows: The SAR images of the considered day are loaded into ArcGIS and their symbology is adjusted to increase the visual difference between water and ice. Then the mentioned polygon is superimposed on the images and divided by a sea ice expert into the regions “Fast ice”, “Drift ice” and “Open water” (Fig. 2 a,b). Both “Fast ice” and “Drift ice” appear white on the visible image and are characterized by high backscatter values on the SAR image. “Open water” appears dark blue on the visible image and has low/high SAR backscatter values during low/high wind speeds. “Fast ice” is attached to the coastline and does not change its position on consecutive SAR images. This makes it easy to identify “Fast ice”, but the difference between “Drift ice” and “Open water” can be ambiguous during high wind speeds, if only SAR data ~~is~~ are available. The origin of the sea ice, which can result from both freezing inside the fjord or advection from the shelf, is not considered during the manual interpretation. The area of each region is calculated in m^2 using a built in function of ArcGIS and the results are saved in a text file. In case VIS/NIR images are available for the same date, they are used for validation and interpretation support of the SAR images (Fig. 2 c).

Prior to 2005, no high quality SAR images could be accessed and the time series is solely based on VIS/NIR images. During polar night it is therefore not possible to describe the ice conditions. During polar day high accuracy is only achieved for days with high resolution VIS/NIR images and lower accuracy is expected for the other days, due to the lower resolution of MODIS and MERIS compared to SAR. The method yields still high reliability for the analysed years before 2005, since water and ice can be separated unmistakably on visual images. Continuity of the time series is expected, since MODIS, Aster and Landsat data is available and considered for the entire time series.

Days of fast ice (DFI)

To quantify sea ice coverage in a defined region (in our case Isfjorden and Hornsund), a new index called “Days of fast ice” (DFI) is introduced. The index describes fast ice conditions over a considered time period in a single value with unit days. Both temporal and spatial extent of the fast ice is included. The DFI are calculated by building the sum over the fast ice area of all considered days relative to the total area, i.e. in our case the entire fjord area (Eq. 1).

$$\mathrm{DFI} = \sum_{\mathrm{days}} \frac{\text{fast ice area}}{\text{total area}} \tag{1}$$

The unit days shall give a quick understanding of the range (considered time period) and linear scaling. The index indicates the number of days that the fjord would be covered 100 % with fast ice. The DFI values allow a simple comparison between different regions and time periods and with external parameters like atmospheric or oceanic data.

Error estimates

Since the time series is based on manual interpretation, defining an exact error value for spatial sea ice extent is not possible. Nevertheless, possible error sources can be evaluated and an error estimate from the analysing sea ice expert can be given.

The biggest error source is wrong interpretation of ambiguous SAR images during polar night, when no visible images are available for validation. As mentioned above, “Fast ice” is easy to identify, whereas the separation of “Drift ice” and “Open water” is sometimes inconclusive. This error for "Drift ice" and "Open water" is hard to quantify, but can ~~make~~ be up to 10 % and in some cases even more.

The different resolutions of the utilized satellite images ~~results in different errorestimates~~is another potential source of error. In our study, the areas covered by "Fast ice", "Drift ice" and "Open water" ~~are not varying~~ do not vary randomly from pixel to pixel, but are usually divided by defined edges. Using different resolutions should not affect the classification of a certain region but only the accuracy of the edge position in the order of one pixel. Hence, a relative error estimate can be given by multiplying the edge length with the pixel size and dividing the result by the fjord area. Assuming an edge of 20 km and 7 km, which is about the fjord width of Isfjorden and Hornsund, and a resolution range of 15 m (Landsat, ASTER) to 500 m (MODIS), the resulting error range is 0.01-0.4 % for Isfjorden and 0.03-1 % for Hornsund.

Insufficient geographic information ~~of~~ for the satellite image can lead to a slightly stretched satellite image compared to the fjord polygon in the order of a few ~~pixel~~pixels. This can lead to an additional error ~~in~~ of the same order of magnitude as the discussed resolution error, but only a small number of the satellite images are affected by that.

The observed glacier retreat has a negligible effect on larger fjords like Isfjorden, but can change the total area of smaller fjords like Hornsund ~~in~~ on the order of 0.5 % per year. Blaszczyk et al. (2013) quantified the total glacier retreat area at the marine margin in Hornsund to be 18.8 km^2 between 2001 and 2010 (equal to 5.8 % of the fjord area measured in 2013). The utilized Hornsund coastline was created using a Landsat image from 2013, meaning that the coastline represents the fjord area very well during the later years, but overestimates the total fjord area during the first few years in the order of up to 5 %. The glacier covered area along the coastline polygon ~~,~~ was not classified separately but added to the surface coverage at the glacier front. This might lead to a slight overestimation of the surface type next to the glacier front, which is most likely "Fast ice" during winter. The resulting error is negligible for the second half of the time series and in the order of 0-1 % for the first half.

The daily ~~value~~ error estimate based on consideration of the mentioned sources and personal appraisal of the analysing sea ice expert is in the order of 1 % for "Fast ice" and between 1 % up to 10 % for "Drift ice" and "Open water" depending on the availability of VIS/NIR images for validation. The error propagation from a single day to a time period of several months leads to a very high accuracy for all given monthly averaged fast ice cover and days of fast ice (DFI) values. The error of these values are therefore not considered in the following, since they do no influence the interpretation of the results.

4 Results

By utilising the created satellite database (Sect. 2) and applying the described method (Sect. 3), two time series dividing the area of Isfjorden and Hornsund into “Fast ice”, “Drift ice” and “Open water” have been created (Figs. 3 and 4). In total, 3319 manual interpretations of sea ice conditions were conducted by a sea ice expert, leading to an almost daily resolution between 2000 and 2014. Unclassified gaps occur in both time series when SAR images were unavailable during the dark season (white gaps in Figs. 3 and 4).

The daily surface coverage in Isfjorden between 2000 and 2014 is shown in Fig. 3. A maximum fast ice coverage of 40 % and higher is reached in the time periods 2000–2005 and 2009–2011. During the periods 2006–2008 and 2012–2014, the fast ice area stays always below 30 %. Figure 4 displays the daily surface coverage in Hornsund for 2000 until 2014. Maximum fast ice cover values above 40 % are reached in all years, except for 2012 and 2014, where the fast ice season is significantly shorter and the maximum stays below 20 %. Late growth of fast ice is also observed in 2006, 2008 and 2013.

Monthly averaged fast ice cover, based on the time series shown in Figs. 3 and 4, are shown in Figs. 5 and 6, respectively. The monthly averaged values display the seasonal cycle of fast ice growth and melt/break up in Isfjorden and Hornsund. Values for the dark season (November–February) before 2006 are missing, since no high quality SAR images were available for this period.

Less than 1 % monthly averaged fast ice cover were observed in Isfjorden between July and November (Fig. 5). Considering the mean over the entire observation period 2000–2014 (black line, Fig. 5), the highest value ~~with 35.7~~is reached in March (35.7 %) or earlier. Before 2005 (blue line, Fig. 5), the ~~peak~~ value in March is 57.5 %. The mean for 2006–2014 (red line, Fig. 5) shows the highest value with 23.2 % in April. Monthly averaged fast ice coverage in Hornsund is shown in Fig. 6. Less than 2 % fast ice is observed between July and November. April is the month with the highest fast ice coverage values: 42.1 % for the mean over all considered years (black line, Fig. 6), 52.6 % for the period 2000–2005 (blue line, Fig. 6) and 35.2 % for 2006–2014 (red line, Fig. 6). Comparing the time periods 2000–2005 and 2006–2014 yields a significant reduction of the monthly averaged fast ice coverage. The seasonal maximum decreases by 60.2 and 33.1 % (relative to the value for 2000–2005, assuming the maximum occurs in March) in Isfjorden and Hornsund respectively.

4.1 Days of fast ice (DFI)

Utilising Eq. (1) and the time series shown in Figs. 3 and 4, DFI values have been calculated for Isfjorden and Hornsund and the results are shown in Table 2. For each sea ice season, two different time periods were considered. The “total season” refers to the entire sea ice season, which lasts usually from November of the previous year until June, and the “short season” lasts from 1 March until the end of the sea ice season. The “short season” can also be calculated for years where only VIS/NIR images are available, whereas SAR images are necessary for the “total season”.

High correlation coefficients (R) between the total and short season DFI time series for both Isfjorden ($R = 0.89$) and Hornsund ($R = 0.94$) suggest that the short season values ~~capture well~~ effectively capture the interannual variability of the entire season. Only the ice season 2011 shows a higher than average difference in the short and total season DFI values (Table 2), due to very early fast ice growth (Fig. 7) and a high fast ice peak before March.

The DFI mean values (total and short season, Table 2) for Isfjorden are around 10 DFI lower than the mean values for Hornsund, which means around 25 % less fast ice coverage in Isfjorden relative to the total area of each fjord. Similar high standard deviations for both fjords indicate strong variations from year to year.

Both “short season” time series show a strong decrease in 2006. Isfjorden’s DFI values between 2000 and 2005 are all above the mean, whereas after 2006 only 2009 has more than the average “days of fast ice”. Calculating a mean before and after 2006 shows a drop from 50 to 22 DFI. The situation of Hornsund is similar, yet not so pronounced. The mean value decreases from 56 to 34 DFI before and after 2006. Low values are reached in 2006 and particularly in 2012 and 2014, where the fast ice coverage goes down to almost 0 DFI.

4.2 Onset of freezing

The sea ice season in Isfjorden and Hornsund starts usually between late autumn and beginning of winter. Figure 7 shows the days ~~with first appearance of~~ on which drift and fast ice first appear, i.e. the start of the sea ice season in Isfjorden and Hornsund. The year refers to the winter season, which starts during the previous year. This means, that January in Fig. 7 refers to the beginning of the respective year. The first sea ice of the season appears during polar night and SAR images are necessary to define the date of the freezing onset. Since no SAR images were available prior 2005, the time series in Fig. 7 starts with the sea ice season 2006. Too few satellite images ~~have been~~ were available to give an reliable estimate of the freezing onset in Isfjorden 2007.

Drift ice starts to grow in Isfjorden in all examined years around the beginning of November. The appearance of fast ice in Isfjorden varies between mid November (2011), December (2009, 2010 and 2012) and the beginning of January (2008, 2013 and 2014). The start of the sea ice season in Hornsund ~~underlays~~ underlies stronger variations. The first drift ice of the season was found in November or December in all years except for the last two years, during which an early start in October was observed. Fast ice starts to appear in Hornsund between the end of November and mid March. Late fast ice formation was observed during 2006, 2008 and 2013.

4.3 Ocean and atmospheric data

In Figure 8, the DFI values for Isfjorden are compared with satellite-derived winter sea surface ~~temperature (SST)~~ temperatures (SSTs) near the mouth of the fjord, ocean heat content ~~during autumn and~~ from in situ profiles taken at the mouth of the fjord for 25–100 m depth, as well as winter atmospheric temperatures from a nearby weather station, represented by negative degree days. Fast ice coverage generally correlates well with winter SST and air temperature. The SST time series deviate somewhat in 2003, 2004 and 2006 compared to the observed DFI values, and fast ice coverage in 2011 is relatively low considering the relatively low air temperatures. Low DFI values between 2006 and 2008 are reflected in the ocean heat content time series and a general increase of autumn ocean heat content is observed between 2010 and 2014 when the DFI values decrease.

The DFI values for Hornsund are shown together with autumn ocean heat content and winter atmospheric temperatures in Figure 9. Except for 2001 and 2010, relatively low/high fast ice cover occurs during winters with relatively high/low air temperatures. The water masses found inside the fjord during autumn show a distinct higher heat content in 2013 and 2014 compared to 2009–2011.

5 Discussion and outlook

~~Continuity of the presented sea ice time series is expected, since VIS/NIR images from the same sensor are considered for the entire observation period. Including SAR as additional data source for the time period 2005–2014 provides useful data during cloud cover and leads to an increased temporal resolution compared to the period prior 2005, which is solely based on visible data. Visible images are not able to capture sudden sea ice condition changes, if the fjord is covered by clouds. However, complete cloud cover usually did not exceed a few days. The formation and melting of sea ice takes place over time scales of days, but sea ice advection from or into the fjord and break up of fast ice can happen within a few hours. These sudden changes are captured in the time series prior 2005 on the first succeeding day with little or no cloud cover.~~

Isfjorden has two periods with relatively high sea ice cover (2000–2005 and 2009–2011, Fig. 3) and two periods with relatively low sea ice cover (2006–2008 and 2012–2014, Fig. 3). All periods last 3 years or more, which suggests the involvement of an oceanic mechanism since the atmospheric conditions underlay variations with shorter time scales. However, wind forcing of the West Spitsbergen Shelf (WSS) on timescales from days to months is shown to be one of the mechanisms of starting a shelf circulation of warm AW towards the fjords (Cottier et al., 2007; Nilsen et al., 2012). Cottier et al. (2007) reported that during the Arctic winter of 2005/2006, periods of sustained along-shelf winds generated upwelling and cross-shelf exchange that caused extensive flooding of the coastal waters with warm Atlantic Water from the West Spitsbergen Current (WSC) (Cottier et al., 2007). The winter temperature of the WSS reverted to that typical of fall, interrupting the normal cycle of sea ice formation in the region, including both the shelf and the fjords along the west coast of Spitsbergen.

Ongoing hydrographic measurement programs and construction of longer time series (Pavlov et al., 2013) show that fjord systems along west Spitsbergen went from an Arctic state to a more Atlantic water state after winter 2006 (Cottier et al., 2007). In Figure 8, times series for the winter SST in Isfjorden and the autumn heat content (25–100 m depth) at the mouth of Isfjorden show that both the SST and heat content increased in the period 2006-2008. Atlantic water circulated the WSS and Isfjorden during this period (Cottier et al., 2007; Nilsen et al., 2015) and the surface water seldom reached the freezing point temperature (Figure 8). Hence, the effect of forcing event on the time scale of weeks (Cottier et al., 2007), and a corresponding advection of AW, can have an influence on the fjord thermodynamics and local sea ice condition on a yearly time-scale. The fjord-shelf system went towards a more Arctic state during the following years, but in 2012, similar forcing events as for 2006 (Nilsen et al., 2015) ~~made the AW~~ caused the AW to dominate the fjords again and the heat content in Figure 8 ~~show~~ shows an increasing trend after 2011. Calculated negative degree-days ~~form~~ from atmospheric temperature data closely follows the variation in DFI (Figure 8) and can also explain the low DFI values in some years. But care must be taken ~~since a~~ in attributing changes in sea ice cover to atmospheric variability, as reduced sea ice cover and ~~warmer ocean will~~ a warmer ocean can also increase the atmospheric temperature.

Another possible explanation for the perennial duration of both small and large fast ice cover years in Isfjorden can be given by looking at the density difference between the fjord water masses and the AW. In contrast to the external forcing mechanism suggested above, this represents a local forcing mechanism through air–ice–ocean interaction. Nilsen et al. showed that a high ice production during winter, results in a higher formation of dense brine-enriched fjordwater and the local water masses in the fjord proper can end up being denser than the water masses residing on the shelf (Nilsen et al., 2012). This is a key mechanism that enables AW to penetrate into Isfjorden in spring and the following summer and autumn, and determines in which depth the warm AW will circulate in the water column. Considering Isfjorden as a coastal polynya with the opening area restricted by fast ice cover, more sea ice is produced in winters with less fast ice coverage. Hence, low fast ice coverage can cause AW intrusion in the following summer, which then can lead to low fast ice coverage in the following winter if the intruding AW is circulating high in the water column.

The mechanisms described for Isfjorden could apply for Hornsund, but being a smaller fjord, the resident time for different water masses will be smaller and variations on shorter time scales can be expected. ~~Comparing the~~ A comparison of the DFI time series in ~~Figure~~ Figures 8 and 9~~, we see that the interannual variability in~~ suggests that interannual sea ice cover ~~in Hornsund, compared to the sea ice cover in Isfjorden, is~~ variability in Hornsund may be less influenced by intrusion of AW residing on the shelf. The sea ice cover in Hornsund ~~seem~~ seems to revert to a “normal” state after a year with known AW intrusion, while Isfjorden is influenced by the AW for several years after such events (Nilsen et al., 2008, 2015). However, Hornsund responds similarly to Isfjorden during the most extreme years of AW dominance on the WSS and strong external forcing mechanisms (Nilsen et al., 2015), i.e. the winters of 2006, 2012 and 2014. Thus, Hornsund, being the most southern fjord along the west coast of Spitsbergen, ~~can~~ could serve as an indicator of AW dominance for all fjords north of Hornsund along the west coast. Ocean and atmosphere measurements from the Polish research station in Hornsund carried out by the ongoing Polish-Norwegian project AWAKE-2 (Arctic climate system study of ocean, sea ice and glaciers interactions in Svalbard area) will be utilized within AWAKE-2 to explain the difference between average seasons and years with distinct less sea ice coverage, i.e. 2006, 2012 and 2014.

Considering the start of the freezing season, i.e. the first appearance of drift or fast ice in the two fjords, Isfjorden shows in general less variability and earlier ice growth (Fig. 7). A low correlation between the start of the freezing season for the two fjords is observed, suggesting a stronger dependence on local conditions rather than a large-scale ocean and/or atmosphere influence. Occurrence of drift ice always precedes fast ice, often with a time lead of 1–2 months. However, care must be taken when defining the start of the freezing in Arctic fjords using satellite images since the first appearance of drift ice will not necessarily reflect that the surface layer of the fjord proper has reached the freezing point temperature, but merely that some protected side ~~fjord~~ fjords within the larger fjord system ~~have a~~ may have a fresher and colder surface layer~~that are able to produce sea ice~~ , allowing for sea ice production for a limited period. Hence, the true freezing season will start somewhere between the first detection of drift ice and the establishment of fast ice in an Arctic fjord.

Recent observations of the ice cover to the north of Svalbard further demonstrate the intimate link between the heat of the Atlantic water and the distribution of sea ice. Onarheim et al. (2014) have shown that the sea ice area north of Svalbard has been decreasing for all months since 1979 with the largest ice reduction occurring during the winter months at a rate of 10 % per decade (Onarheim et al., 2014). This is in contrast to the observed changes in more central parts of the Arctic Ocean, where largest ice decline is happening during summer. However, the observed reduction is concurrent with a gradual warming of 0.3 °C per decade warming of the AW along West Spitsbergen, and thus, the extra oceanic heat has been the major driver of the sea ice loss, which is concurrent with our results from both Isfjorden and Hornsund. Another indication of warm water as a major driver is the delayed maximum fast ice area in Isfjorden (Fig. 5) from March (or earlier) to April for the 2000–2005 period to the 2006–2014 period, respectively. A warmer water column in late autumn can cause delayed ice formation and consequently lower ice concentrations in early winter.

In conclusion, the presented sea ice time series ~~serve for~~ can be used to obtain a better understanding of interannual variability in Arctic fjord system. Since a sea ice cover reflects the physical state of the ocean and atmosphere, the present sea ice time series can be used in future studies to better understand air–ice–ocean interaction processes within each fjord system, but also in various climate effect studies linked to e.g. glacier dynamics, ocean chemistry and marine biology.

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Table 1. Satellite ~~database: list~~ databases used, including sensor, image type, spatial resolution (i.e. pixel size), amount of collected images, covered time span (i.e. date of first and last image) and source.

sensor	image type	resolution	# of images	time span	source
ASAR	SAR	150 m	4326	21 Jul 2005–7 Apr 2012	NERSC database
ASTER	VIS/NIR	15 m	161	19 Aug 2000–12 Aug 2013	http://gds.ersdac.jspacesystems.or.jp
Landsat 1–8	VIS/NIR	15 m	335	25 Mar 1973–29 Jul 2014	http://earthexplorer.usgs.gov
MERIS	VIS/NIR	300 m	126	25 Jun 2003–7 Apr 2012	http://oceancolor.gsfc.nasa.gov
MODIS	VIS/NIR	500 m	8501	25 Feb 2000–4 Aug 2014	http://ladsweb.nascom.nasa.gov
Radarsat 2	SAR	50 m	2245	5 Apr 2011–30 Jul 2014	NERSC database
met.no	ice chart	–	861	24 Oct 2005–27 Jun 2014	http://polarview.met.no

Table 2. Calculated "days of fast ice" (DFI) for Isfjorden and Hornsund between 2000 and 2014 for two different time periods. "Total season" refers to the entire sea ice season starting during autumn of the previous year and "short season" refers to 1 March until the end of the ice season, i.e. the time period when VIS/NIR images are available. Δ describes the difference between entire and short season.

[DFI]	Isfjorden			Hornsund		
year	total season	short season	Δ	total season	short season	Δ
2000	–	46.0		–	56.7	
2001	–	33.8		–	54.3	
2002	–	52.2		–	53.6	
2003	–	43.1		–	53.5	
2004	–	70.7		–	59.9	
2005	–	55.4		–	56.0	
2006	19.4	9.5	9.9	25.8	25.8	0
2007	19.3	14.1	5.2	51.1	40.1	11
2008	28.5	20.5	8	54.2	49.8	4.4
2009	61.6	49.8	11.8	71.4	51.4	20
2010	34.9	24.8	10.1	53.6	47.4	6.2
2011	68.7	32.2	36.5	76.1	44.9	31.2
2012	16.9	12.8	4.1	2.5	2.0	0.5
2013	22.7	19.0	3.7	49.9	47.0	2.9
2014	18.0	13.2	4.8	2.5	0.4	2.1
mean $\pm$ SD	**32.2 $\pm$ 18.5**	**33.1 $\pm$ 18.2**	10.5 $\pm$ 9.6	**43.0 $\pm$ 25.5**	**42.9 $\pm$ 18.2**	8.7 $\pm$ 9.9

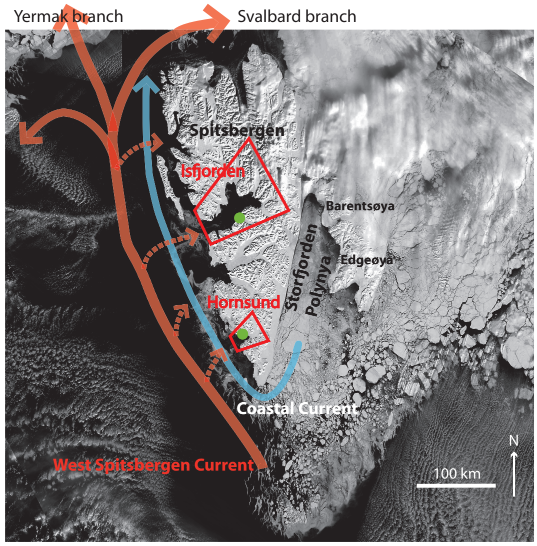

Figure 1. MODIS image of Svalbard taken on 8 April 2009 including a schematic illustration of the ocean currents along western Spitzbergen. The two considered fjords Isfjorden and Hornsund are marked with red polygons. The respective weather stations, marked with green dots, are located at 78.25°N, 15.50°E (Isfjorden) and 77.00°N, 15.54°E (Hornsund).

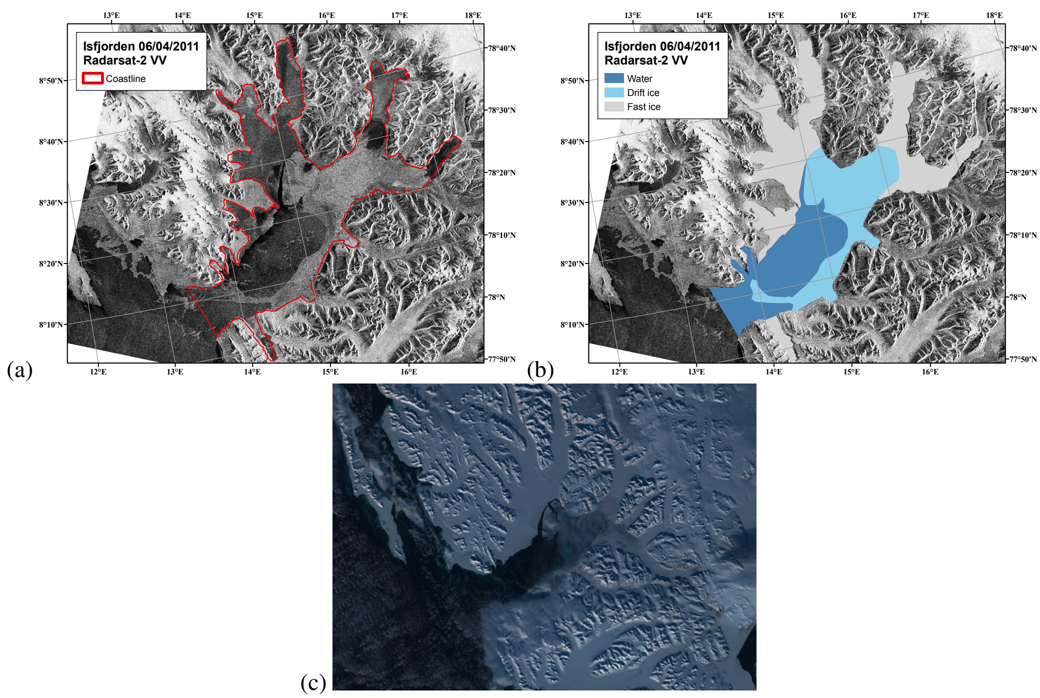

Figure 2. Radarsat-2 **(a,b)** and MERIS **(c)** images of Isfjorden taken on 6 April 2011. Radarsat-2 images are shown in ArcGIS with adjusted Symbology **(a)** before and **(b)** after analysis by a sea ice expert.

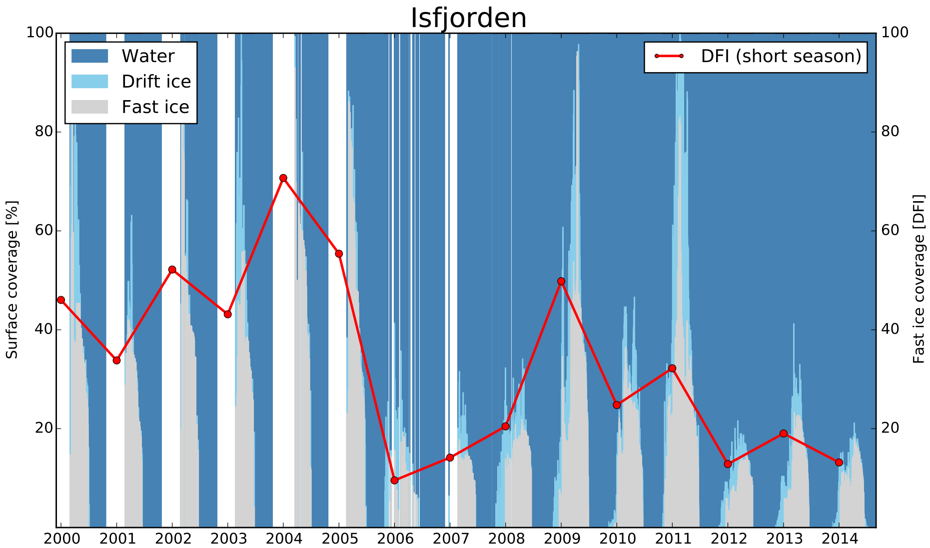

Figure 3. Surface coverage of Isfjorden between 2000 and 2014 divided into "Fast ice", "Drift ice" and "Open water" by a sea ice expert. Total area = 2487.6 km^2 (defined with Landsat image from 19 September 2013). White gaps occur when no satellite data was available. The red dots display the "days of fast ice" (DFI) values of the short season as shown in Table 2.

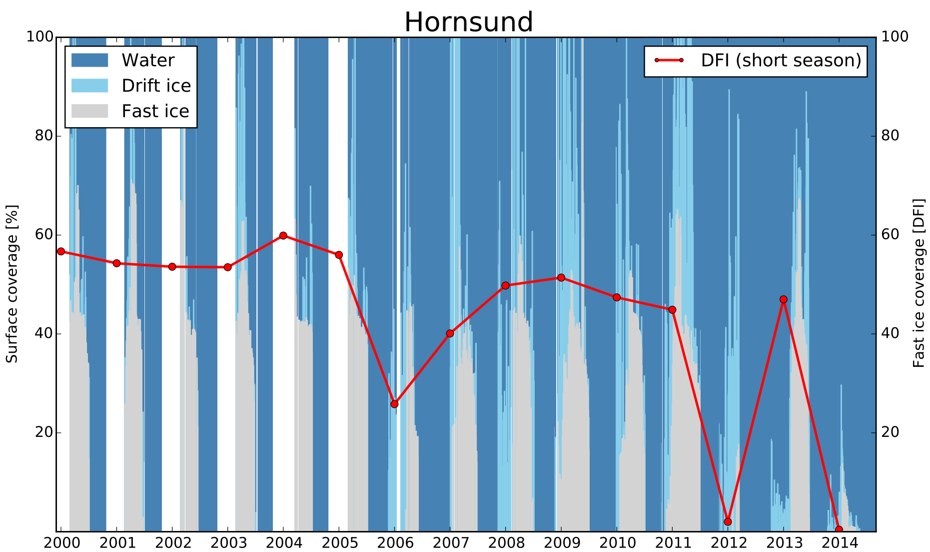

Figure 4. Surface coverage of Hornsund between 2000 and 2014 divided into "Fast ice", "Drift ice" and "Open water" by a sea ice expert. Total area = 324.0 km^2 (defined with Landsat image from 24 August 2013). White gaps occur when no satellite data was available. The red dots display the "days of fast ice" (DFI) values of the short season as shown in Table 2.

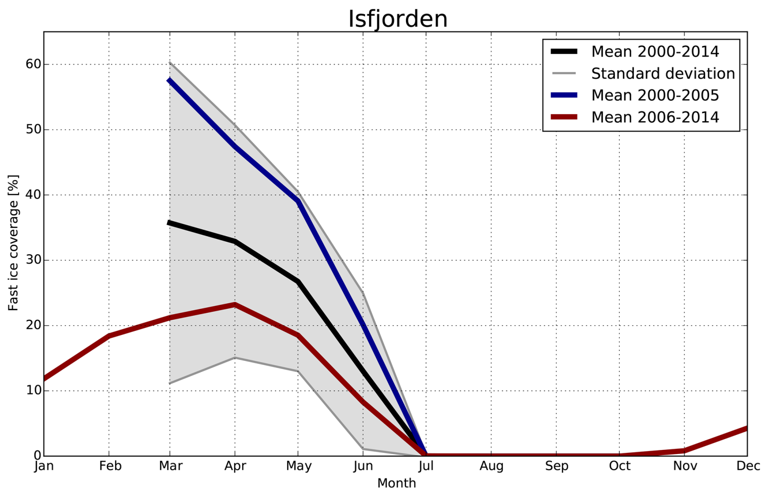

Figure 5. Monthly averaged fast ice coverage in Isfjorden shown for three time periods: 2000–2014 (mean in black and standard deviation in grey) 2000–2005 (blue) and 2006–2014 (red).

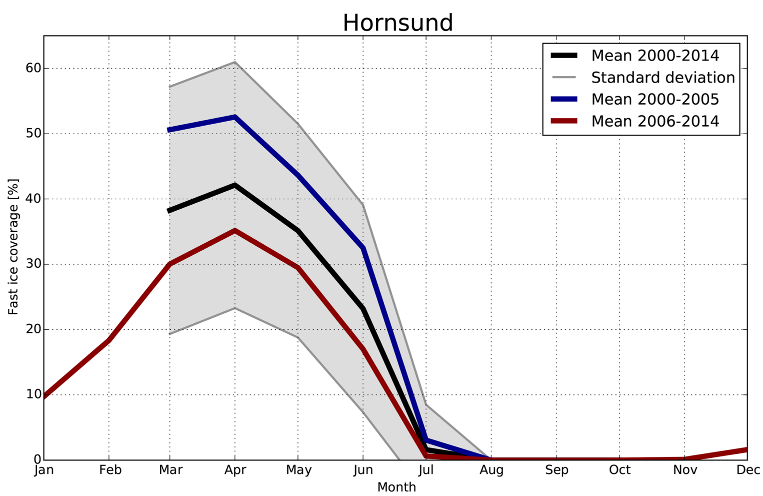

Figure 6. Monthly averaged fast ice coverage in Hornsund shown for three time periods: 2000–2014 (mean in black and standard deviation in grey) 2000–2005 (blue) and 2006–2014 (red).

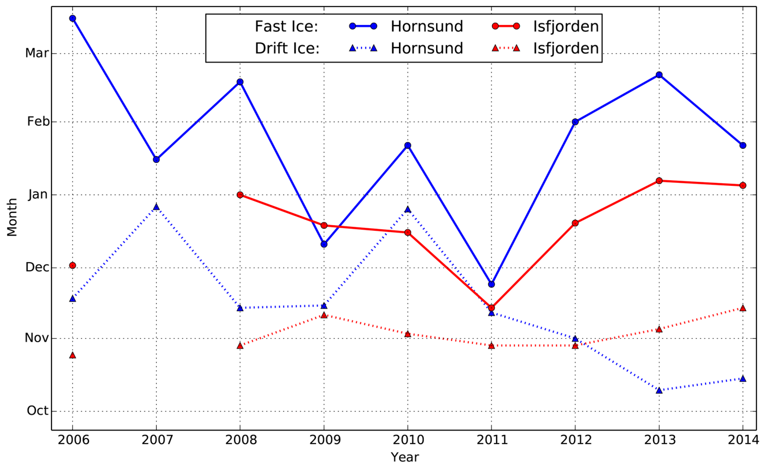

Figure 7. Onset of sea ice cover in Isfjorden and Hornsund. The years refer to the sea ice season, which starts during the previous year, meaning that January marks the beginning of the respective year. The triangles and dots mark the days with first appearance of drift and fast ice, i.e. the start of the sea ice season. Too few satellite images were available for Isfjorden in 2007 to give a reliable estimate.

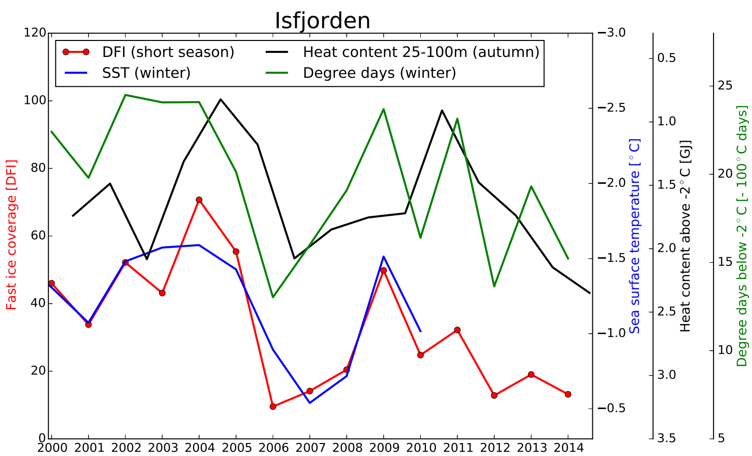

Figure 8. Isfjorden's (red) "Days of fast ice" (DFI) values of the short season ~~, as shown in Table 2,~~ compared to (blue) winter sea surface temperature (SST), (black) autumn heat content above -2°C of the ~~25-100~~25–100 m depth water column and (green) winter negative degree days below -2°C. ~~Mean~~ Winter SST values represent the mean for the period ~~January - April have been calculated for a 25x 25resolution cell~~ January–April at 78.25°N, 14.75°E~~using a satellite remote sensing product provided by ESA (doi:10.1002/gdj3.20)~~. Heat content values are calculated using the mean temperature ~~profiles of each~~ profile during autumn (~~July - September~~July–September) ~~derived from 285 CTD profiles taken between 2000-2014~~ at the Isfjorden mouth area~~(78.08-78.16°N, 13.5-14.3°E)~~. Negative degree days ~~for each winter~~ have been derived from temperature measurements at the Svalbard airport station (78.25°N, 15.50°E)~~provided by eklima~~. ~~met.no.~~ Note the reversed SST and heat content axis.

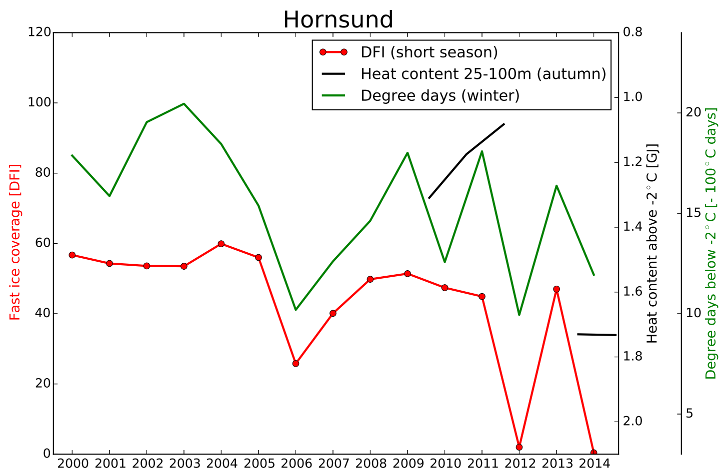

Figure 9. Hornsund's (red) "Days of fast ice" (DFI) values of the short season, ~~as shown in Table 2,~~ compared to (black) autumn heat content above -2°C of the ~~25-100~~25–100 m depth water column and (green) winter negative degree days below -2°C. Heat content values are calculated using the mean temperature ~~profiles of each~~ profile inside Hornsund during autumn (~~July - September~~July–September)~~derived from 107 CTD profiles taken between 1999-2014 in Hornsund~~. Negative degree days ~~for each winter~~ have been derived from temperature measurements at the Hornsund station ~~(~~at 77.00°N, 15.54°E~~) provided by eklima.met.no~~. Note the reversed heat content axis.