The Cryosphere Discuss., 5, 2437–2463, 2011 www.the-cryosphere-discuss.net/5/2437/2011/ doi:10.5194/tcd-5-2437-2011 © Author(s) 2011. CC Attribution 3.0 License.



This discussion paper is/has been under review for the journal The Cryosphere (TC). Please refer to the corresponding final paper in TC if available.

An Antarctic monitoring initiative for fast ice and comparison with the Arctic

P. Heil¹, S. Gerland², and M. A. Granskog²

¹Australian Antarctic Division & ACE CRC, University of Tasmania, Private Bag 80, Hobart, TAS 7001, Australia ²Norwegian Polar Institute, Fram Centre, 9296 Tromsø, Norway

Received: 27 December 2010 – Accepted: 6 September 2011 – Published: 21 September 2011

Correspondence to: P. Heil (petra.heil@utas.edu.au)

Published by Copernicus Publications on behalf of the European Geosciences Union.



Abstract

5

While Arctic and Antarctic fast-ice observations are required by a number of interest groups for planning and logistical activities, or to support scientific research, obtaining those data is not trivial. Sea-ice extent is reasonably well observed using camerabased or satellite-borne instruments, however, in situ and satellite-based ice-thicknesss measurements remain a challenge. As the seasonal fast-ice thickness is directly linked

- to regional atmospheric and oceanographic conditions, monitoring of fast-ice thickness across a station network around Antarctica and in the Arctic is crucial to assess how climate change affects the polar system. The Antarctic Fast-Ice Network (AFIN) was
- recently established to provide the scientific community with fast-ice observations from sites operated by international contributors. Based on AFIN data a recent increase in interannual variability in annual maximum ice and snow thicknesses has been identified. Maximum Arctic fast-ice thickness generally exhibits a similar interannual variability, however, both positive and negative trends in ice thickness have been observed
- ¹⁵ in the Arctic. Comparing the two hemispheres, we find that in the Arctic the fast ice establishes itself at a faster rate than in the Antarctic, where repeated cyclone action tends to intermittently remove the fast ice during autumn. Also, Arctic sites investigated here exhibit less snow cover than those from East Antarctic coastal sites.

1 Introduction

- ²⁰ In recent decades the Arctic sea ice has seen substantial reduction in thickness and summer extent (Comiso, 2002; Haas et al., 2008; Rothrock and Zhang, 2005; Stroeve et al., 2008). Conversely, there has been a small but positive trend for the mean Antarctic sea-ice extent (Comiso, 2010). On regional scales variability in Antarctic sea-ice extent and concentration have been linked to changes in atmospheric forcing as driven
- ²⁵ by the Southern Oscillation (e.g. Kwok and Comiso, 2002), with strong correlations identified for the Ross, Bellingshausen and Amundsen seas. This is in agreement with Turner and Overland (2009), who associated the autumn increase in sea-ice extent



in the Ross Sea sector with strengthened northward flow off the Ross Ice Shelf due to intensified cyclonicity over West Antarctica. Due to a paucity of large-scale measurements little is known about any changes in Antarctic sea-ice thickness (Worby et al., 2008). However, (intermittent) records of Antarctic fast-ice thickness and extent are available (e.g. Heil, 2006). While much of the fast ice is annual, it is a ubiquitous feature of the Antarctic coastal zone. With Antarctic fast ice contributing about 14 to 20% (by volume) of the total Antarctic sea ice at its annual maximum (Fedotov et al., 1998), understanding the changes observed in fast ice will provide valuable insight into the climate response of the polar system.

- In recent years, the interannual variability in thickness, extent, morphology and persistence of the polar fast ice increased markedly, indicating that fast ice may be a harbinger of climate change. Fast-ice data collected in both hemispheres proves also to be an invaluable source of information for the logistical support of shipping or station-based activities. Furthermore, in the Northern Hemisphere fast ice is crucial
- to indigenous subsistence hunting, transportation and cultural heritage. To attribute the changes in fast-ice characteristics, a better understanding of the atmosphere-iceocean interactions is required. Field measurements are crucial to improve our knowledge of this system. Despite the importance of such observations, there is a lack of sustained measurements in both hemispheres. In response to these challenges AFIN
- has been set up for data collection at multiple coastal sites; and a proto-type integrated observing system has been developed and tested in situ off the East Antarctic coast. In the Arctic, the demise of many long-term fast-ice measurement sites in the Chukchi and Beaufort seas and in the Canadian Archipelago during the 1970s and 1980s (Bilello, 1980; Brown and Coté, 1992; Polyakov et al., 2003) severly reduced the number of active long-term records. However, early this century increased interest
- 25 the number of active long-term records. However, early this century increased interest in long-term records, for example in support of climate-change studies, saw renewed data collection in the Arctic, where fast-ice observations are forthcoming, e.g. from several re-opened Canadian stations (Environment Canada, 2010) and from Svalbard (Gerland and Renner, 2007; Gerland et al., 2008).



Here we present the standard configuration of AFIN fast-ice observatories, discuss challenges encountered, provide an overview of auxiliary data collected, and show recent results from selected AFIN monitoring sites, before discussing future plans, including scope for increased automisation and expansion of the fast-ice observatories.

- For example, we collect coincident satellite-derived imagery to assess the regional evolution of the fast ice, especially with view to track changes in the surrounding pack ice. Rolling out a number of AFIN sites to stretch around large swaths of the Antarctic coastline is crucial to detect regional- and large-scale variability in the fast-ice response to current climate change, as communicated into the system by atmospheric and oceanic
- forcing. Furthermore, to study physical-biological interactions within the fast-ice system our current observatories will be expanded to integrate optical measurements of ice algal biomass and suspended chlorophyll. We do conclude with a brief comparison of fast-ice properties in the Antarctic and the Arctic, highlighting some crucial differences in the coastal ice cover of the two poles.

15 2 Data and methods

drastically different ice conditions.

Implementation of an observing system depends strongly on how the monitored variables and the sampling locations and rates are specified. From the perspective of geophysical research, the measurement approach is dictated by the relevant spatiotemporal scales of the phenomenon under study, technical feasibility, and the types of questions asked. For example: will Arctic summer sea ice vanish entirely in coming decades, and if so, when? Answering this question requires a combination of numerical simulations and observations of the mass budget of the Arctic ice cover as a whole (Hutchings and Bitz, 2005). A study by Lindsay and Zhang (2006) suggests that for this specific purpose measurements of ice thickness over time at only two to three
strategically placed points may be sufficient. However, such ice-thickness data likely would contribute little if anything to help Arctic stakeholders in planning for a future with



Near-coastal fast ice offers a reliable means to access the sea ice over many years and repeatedly during each growth season enabling a high temporal sampling frequency. It also lends itself as a natural laboratory for regional scale studies. Where dynamic contributions and platelet accumulations can be excluded, fast-ice growth can

- ⁵ be modelled as a thermodynamic process, allowing us to verify numerical models. So far, fast-ice observations have been carried out via a number of methods, including bore-hole measurements, electro-magnetic induction methods, or profiling of the vertical temperature distribution. Antarctic fast ice has been measured by the New Zealand (Trodahl et al., 2000) and the Australian Antarctic programmes, for example via a mass ¹⁰ balance station on the fast ice off Davis Station (East Antarctica).

3 AFIN observatories

Initiated as a legacy project during the 2007/09 International Polar Year, by 2010 the following international partners have joined into AFIN: Australia[#], China[#], France, Germany[#], Japan[#], Malaysia, New Zealand[#], Norway[#], and Russia. (Active partners are indicated by [#].) It is antipated that these countries will provide one or more nodes within the network of observatories around much of the Antarctic coast line (Fig. 1). Further countries have signed up to AFIN or indicated strong interest to become involved in AFIN, contingent on securing national funding.

A wide spread of AFIN nodes is crucial to fill acknowledged gaps in the observational data base of the Antarctic climate system. AFIN-derived data will contribute to improve our understanding of the role of sea ice in the global climate system, on how the system is changing and on potential impacts of such change. Data from this network will be highly relevant to a wide range of scientific disciplines, including physical oceanography, climate and ecosystem modelling, ecosystems research in ice covered regions. In detail, AFIN data will be used for numerical modelling initiatives and will

regions. In detail, AFIN data will be used for numerical modelling initiatives and will also play a pivotal role for the further development of ecosystem models (e.g. an algal primary productivity model (such as that being developed at the Antarctic Climate and Ecosystems CRC).



The primary focus of AFIN nodes is to provide observations on the physical quality and its spatio-temporal persistence. As mentioned above, a number of AFIN nodes have been established with further ones to be established under various investigators. Due to site-specific conditions at each AFIN node, the realisation of the various nodes ⁵ are expected to differ from each other. However, here we wish to describe a typical AFIN observing node detailing targeted parameters and the associated measurement specifications (Table 1), as well as the various components a node may include.

3.1 Manual ice-thickness sites/transects

Manual ice-thickness measurements at one or more sites have traditionally been carried out in the close vicinity of coastal Antarctic stations, often in support of safe access to the sea ice or to support ship- and airplane-based logistics. Within AFIN drillhole measurements of fast-ice thickness are ideally carried out along transects that cut across features of regional interest (e.g. gradient in bathymetry), however point measurements will also contribute to the data base. Sampling frequency, especially during formation (up to about 0.6 m thickness) and during melt should not be less than weekly, if possible. Peopular observations provide information on processes contributing to ice

if possible. Regular observations provide information on processes contributing to ice growth (i.e. tidal cracking) as well as on the local-scale variability of the fast ice.

Once the sea ice is safely accessible, individual measurement sites or transect lines are marked using GPS receivers to ensure that measurement sites are located at ex-

- actly the same location from year to year. Where an iceshelf, icebergs or any other intermittent obstacle prevent repeat sampling at exactly the same location, an alternative site with similar characteristics (i.e. water depth, distance to coastline) will be occupied for that season. Repeat measurements take place in close proximity of the site stake in a previously undisturbed area. Each visit is initiated by measurement of snow
- thickness and any surface ablation. Ice thickness and freeboard are obtained from the drill-hole measurements. Additional observations may include the degree of erosion (honeycombing) of the ice and the length of any dendrites that may have been brought



2443

up with the auger. Visual observations of breakout, freeze-up, swell-penetration, tidal buckling and the fast-ice extent are also recorded.

3.2 Automated mass-balance stations

As some manned Antarctic bases are a considerable distance from accessible fast-ice sites, and as automated observatories provide higher data sampling rates, autonomous observatories have been developed, mainly in form of mass-balance stations. For example, in 2006 the Chinese National Antarctic Research Expedition deployed magnetostrictive displacement sensors on the fast ice off Zhongshan Station, East Antarctica to measure the vertical fast-ice extent every 3 h (Lei et al., 2010). The magnetostrictivedelay-line technique detects the position of moving permanent magnets relative to the

- delay-line technique detects the position of moving permanent magnets relative to the sensing element (Karagiannis et al., 2003), making it an ideal candidate for position measurements, such as sea-ice thickness (Lei et al., 2009). Off Davis Station, East Antarctica a mass-balance station has been deployed since 2007, providing data at 1 min or coarser intervals. This station consists of a thermistor string, air-pressure and
- ¹⁵ air-temperature sensors, and acoustic pingers above and below the fast ice. The thermistor string is 2.00 m long with thermistors mounted every 0.02 m. During deployment the top 0.10 m of the rod was above the upper ice surface to obtain snow temperatures. Data collected near Davis Station during 2007 (Fig. 2) show that the temperature of the snow and the upper layers of fast ice respond quickly to changes in the surface air tem-
- ²⁰ perature. Below about 0.28 m the internal ice temperatures the response to short-term changes in air temperature is damped. This depth also corresponds to the ceiling for vertical temperature inversions with the fast ice. Crystal stratigraphy of an ice core obtained in October 2007 from this AFIN site shows that this depth coincides with the lower end of the uppermost layer of columnar ice crystals.
- A proto-type mass-balance station has been deployed during austral winters 2007, 2008 and 2009 on the fast ice off Davis Station, East Antarctica. Data from all sensors except the underwater acoustic pinger were retrieved successfully. The performance of the underwater pinger has been affected by floating ice crystals, so-called platelet



ice. In the absence of consistent location data of the base of the fast ice, we have estimated the thickness of the fast ice using thermistor data. The derived ice thickness agrees well with that from coincident manual observations (Fig. 3).

3.3 Coastal digital imaging

Near Davis Station an automatic digital camera is trialled to obtain oblique image records of the horizontal ice extent. The digital imagery provides a visual repository of local changes at the surface of the fast ice and its snow cover, as well as information on the local ice-edge position, and the timing of formation, breakout(s), melt ponding and surface melt. High sampling rates (10 min or less) allows us to derive trajectories
 of ice export and to obtain a measure of herding of ice floes into the coastal region, where they may lay the foundation for perennial ice within the coastal fast ice.

During 2009 at Davis the fast-ice camera was deployed to the south of the main AFIN site, to record changes in fast-ice extent associated with a flaw lead extending away from the front of the Sørsdal Glacier. The digital camera was programmed to

take a photographic image every 30 min during daytime or moonlit hours. We used a digital Single Lens Reflex camera with a 18–55 mm EF-S lens. The camera is mounted in a weatherproof enclosure with a special mechanical rotating shutter covering the front lens to protect it from damage due to snow or debris. We intend to deploy similar camera systems at other AFIN nodes too, and currently investigate near real-time data
 transfer.

3.4 Automatic weather stations

Generally the manned coastal (research) stations operate a meteorological observatory. However, it is important to obtain a record of meteorological conditions on the fast ice, as small-scale features, such as fjords, coastal islands, icebergs or floating glacier tounges tend to modify the coastal atmospheric conditions by micro-meteorological ef-

²⁵ tounges tend to modify the coastal atmospheric conditions by micro-meteorological effects. Hence an automatic weather station has been deployed at some AFIN nodes



to record exact atmospheric data for the fast-ice site. During 2009 off Davis Station, a Vaisala HydroMet Automatic Weather Station MAWS201 was used. Typically we seek to include sensors to monitor air temperature and pressure, wind speed and direction and relative humidity.

5 3.5 Satellite remote sensing

Under AFIN we currently obtain data from (Advanced) Synthetic Aperture Radar [(A)SAR], Moderate Resolution Imaging Spectroradiometer [MODIS] (visible and thermal InfraRed), Advanced Very High Resolution Radiometer [AVHRR] and Advanced Microwave Scanning Radiometer [AMSR-E] to complement the analysis of our in situ data records. Pending data availability we intend to collect remotely-sensed products for the circum-Antarctic fast ice. For example, Envisat's ASAR imagery is obtained under a current grant from the European Space Agency, and a proposal for ongoing support to be submitted. ASAR imagery is used to monitor the horizontal fast-ice extent and the concentration of the nearby pack. The fast-ice extent is mapped from sequential images using a software (Giles et al., 2011) derived from the original IM-CORR tool (Bindschadler and Scambos, 1991). Where available, cloudfree MODIS and also AVHRR imagery will be used to fill in temporal gaps in the ASAR data.

3.6 Structural ice cores

Vertical cores of the fast ice, obtained just after reaching annual maximum ice thick ness, provide information on the structural composition of the fast ice and its vertical salinity profile. This analysis is complemented by oxygen isotope analysis, which is used to distinguish inclusions of freshwater ice from the ice formed from salt water. For example, full vertical ice cores of the fast ice have been obtained near Davis and Mawson stations and analysed since the early 2000s. Based on those the inclusion of platelet ice in the fast-ice matrix has been verified, for example, explaining sudden and rapid thickening of the fast ice.



4 Historic data

4.1 Antarctica

Early measurements of Antarctic fast-ice thickness have been made in support of station support (Mellor, 1960). Changing supply technology and infrastructure meant that
the locations of the measurement sites and techniques varied over the years. It might be difficult to derive a clear temporal signal from those data, due to likely spatial dependencies. For example, local bathymetry and topography influence the basal growth rate of the fast ice by regulating the amount of oceanic heat available at the underside of the fast ice and the amount of wind-blown snow, respectively (Heil, 2006). Nevertheless the analysis of historic fast-ice observations is of value. For example data, available from intermittent years, from Mawson station have been used to investigate the long-term change in the oceanic heat flux (Heil et al., 1996); and from Davis have

been analyzed for the effect of atmospheric forcing parameters on the growth, decay and breakout characteristics of the fast ice. Recovery of historic fast-ice data from the ¹⁵ AFIN community and other holdings has been made an immediate task for AFIN.

4.2 Arctic

20

In the absence of platelet accumulations and sea-ice deformation, Arctic fast ice acts as an indicator of climate change in response to oceanic and atmospheric forcing. Similar to Antarctic fast ice, the Arctic fast ice supports unique ecosystems (Tynan et al., 2010). Furthermore it forms integral part of the environment and infrastructure of the indigenous population (Eicken et al., 2009). Arctic fast ice has been measured at many sites in the Siberian and American/Canadian Arctic for most of the 20th century, often as part of long-term monitoring (Zubov, 1945; Bilello, 1980; Brown and Coté,

1992). While several observations sites were abandonded during the 1970s and 1980s,
 a renewed push for long-term monitoring early this decade has seen the revitalisation of some of the Arctic observation sites. For example, around the mid 1940s the first



stations in the Canadian Arctic were established, and ice- and snow-thickness data had been collected on up to 195 Canadian sites (Environment Canada, 2010). While by the end of the 20th century most of these monitoring sites had been closed, increased interest in the historical fast-ice data in support of climate change studies saw a new program established in late 2002 (Environment Canada, 2010). Data from Svalbard are also available, with i.e. fast-ice thickness from Hopen, Barents Sea have been observed intermittently since 1966, while further observations sites have been added in recent years (Gerland and Renner, 2007).

Fast ice also occurs in marginal seas such as the Baltic Sea and the Sea of Okhotsk,
where fast-ice observations have been conducted for more than 120 yr. In these seas, the fast ice is often limited to near coastal regions and water depth of less than 15 m. For example, fast-ice growth and melt in the Baltic Sea correlate closely with the surface air temperature, and the brakish water of the Baltic Sea result in a relatively high freezing point just below 0°C (Leppäranta and Myrberg, 2009). Similarly to the Baltic Sea, the fast-ice evolution in the Sea of Okhotsk correlates well with environmental conditions (Shirasawa et al., 2005).

5 Results: interannual variability of Antarctic fast ice

5

Changes in the atmospheric circulation over the Southern Ocean have been documented in various studies. For example, using numerical re-analysis data, Simmonds and Keay (2000) found – based on centre pressures – an intensification of synoptic-scale depressions over the Southern Ocean and an increase in the frequency of those systems. Identification of links between the atmosphere and pack ice has been subject to several studies (e.g. Watkins and Simmonds, 2000; Turner et al., 2009). Less attention has been paid to the interaction between atmosphere and the fast ice. However
 ²⁵ for the East Antarctic a direct link between changes in the atmospheric forcing and

²⁵ for the East Antarctic a direct link between changes in the atmospheric forcing and variability in the fast-ice parameters has been identified (Heil, 2006).



5.1 Davis (East Antarctica)

Davis lies on the eastern rim of Prydz Bay (68°35′ S and 77°58′ E), in a relatively wide but shallow region of the shelf. Davis is separated from the Antarctic plateau by the low-lying Vestfold Hills, protecting it largely from katabatics. Davis also supports an

AFIN node. Heil (2006) provides an analysis of atmospheric and fast-ice condition off Davis up to 2003, with additional data up to 2009 available here.

Based on 26 yr of intermittent data of annual maximum ice thickness we find no clear trend on the long-term mean (1.70 ± 0.14 m). On the other hand, there the interannual variability of the annual maximum ice thickness remains dominated by large year to 10 year changes rather than longer-term trends (Heil, 2006). The most recent decade, again, experienced a range of maximum thicknesses, underlining the high interannual variability within the system. The greatest annual maximum ice thickness during the current decade was attained in 2008 (1.90 m), being the winter following the 2007/08 summer when wind-driven southward convergence compacted much of the summer sea ice off East Antarctica against the continent. We also note that the date at which the annual maximum ice thickness is reached, has moved further into spring, continuing with a trend of +0.43 d yr⁻¹.

5.2 McMurdo (Ross Sea sector)

Fast-ice observations in McMurdo Sound, Ross Sea have been carried out during several seasons. During 1996, 1997, 1999, 2000, 2002, and 2003 thermistor chains had been deployed near 77°43′ S, 166°26′ E and 77°50′ S, 166°37′ E (Pringle et al., 2007). Platelet ice, generated from ice crystals that nucleate in the ocean and grow either at depth or loosely attached to the ice-water interface (Leonard et al., 2006), is a recurring feature in the region, and is typically observed in thick (>1 m) fast ice (Jeffries et al., 2007).

1993; Leonard et al., 2006; Smith et al., 2001). The presence of platelet ice within the fast ice has been correlated to the amount of frazil suspended in the underlying water column (Leonard et al., 2006).



5.3 Fimbul (Dronning Maud Land)

Operated by the Norwegian Polar Institute (NPI) the Troll/Fimbulisen fast-ice site has been established within the long-term monitoring programme. While Fimbul is an AFIN node, it is also linked to NPI's project on shelf ice-ocean interactions underneath the

- ⁵ Fimbulisen (ICE-Fimbul). The fast-ice site is located in a natural bay, caused by an ice rise just to the south, of the Fimbul ice shelf (70°7′ S, 5°20.5′ E). The location is routinely visited in austral summer for supply of the Norwegian wintering base Troll. Since 2005/06 (with an exception for 2009/10) opportunistic measurements using ice augers and thickness gauges and stakes have been carried out during austral sum-
- ¹⁰ mer. Usually, fast-ice measurements are available for November and December, with ice breakout occurring in December or January. Consequently, the observed summer thicknesses can be used to approximate the annual maximum ice thickness. With Troll being more than 200 km from the fast-ice site, the wintering crew is not able to conduct drill-hole measurements beyond these opportunistic summer measurements. To fill this
- ¹⁵ observational gap, we plan to deploy an autonomous mass-balance station, similar to the setup described in Sect. 3.2.

In summary, observations of fast-ice thicknesses at Fimbul from five recent summers shows a distinct mode at a thickness of 1.50 to 1.75 m (Fig. 4a). Snow thicknesses were generally under 0.40 m, but occasionally also thicker snow (of up to 2 m) was encountered (Fig. 4b). Freeboard data (Fig. 4c) show two modes. The negative freeboard coincides with heavy snow load. On 2 December 2010, a larger series of snow thickness measurements shows that distributions can be relatively broad, even though the Fimbul fast ice itself is usually level. In that case, the snow was very hard and the surface exhibited a typical wind related rough surface structure.

²⁵ With data at Fimbul from only five summers it is not yet possible to derive information on interannual variability of the fast-ice parameters. Very thick ice (>3 m), as observed in 2005/06 and 2008/09, was likely to have been second year ice, as generally some fast ice in the area is protected from break up by icebergs. Alternatively, it is plausible



that accumulation of platelet-ice layers contributed to thicken the first-year fast ice. To improve our knowledge of the processes contributing to the fast-ice growth, in future the thickness monitoring will be supplemented with information from the analysis of structural ice cores (see Sect. 3.6), as well as further monitoring using in situ cameras and remotely sensed satellite products.

6 Discussion

5

25

A hemispheric dichotomy in the trends of polar sea-ice extent exists. In the Arctic Ocean and marginal seas the sea-ice extent has severly reduced ((-3.4 ± 0.2) % per decade) since 1978, while it has increased slightly ((0.9 ± 0.2) % per decade) in the Southern Ocean (Comiso and Nishio, 2008). In this context, a link between strato-spheric ozone depletion and an increase of Antarctic sea-ice extent has been suggested (Turner et al., 2009) via trends in the surface temperature due to a poleward shift of the large-scale circulation patterns, including the westerly jet, storm tracks and the poleward Hadley cell expansion (Son et al., 2009). To investigate such a link Sig-mond and Fyfe (2010) forced a climate model with observed stratospheric ozone depletion for 1979 to 2005. Their simulations revealed a consistent reduction in Antarctic sea-ice extent with stratospheric ozone depletion. During summer this ice reduction was due to offshore Ekman sea-ice transport forced by increased Westerlies, while in winter the bulk of the Antarctic sea-ice zone was affected by warming of the surface

²⁰ ocean, consistent with a poleward shift of the large-scale ocean fronts.

In face of these opposing results on the link between stratospheric ozone depletion and any trend in Antarctic sea-ice extent, and the difficulties associated with investigating any trend in the Antarctic sea-ice volume, AFIN will provide crucial information on the fate of the coastal Antarctic ice. At some AFIN sites, fast-ice data have previously been collected, and are gathered into a long-term data set. To assess any regional

differences, AFIN seeks to extend its data collection around most of the Antarctic continent. To enable such wide coverage by AFIN, it is crucial to develop and harden



2451

automomous observation systems, and also to expand into observing any embedded systems, such as the ecosystem parameters.

6.1 Integrated observing system: the challenge

The complexity and connectedness of the polar fast ice requires an integrated observing ing system to assess its fate within a changing climate system. This requires not only observing the fast ice itself, but also of the equatorward pack ice as well as of surrounding ocean and atmosphere. While we presented details on the AFIN components in the previous section, we need to review the impact of loss of any data stream onto the overall assessment of the status of Antarctic fast ice. The challenge of instrument deployment in Antarctic waters is the icing-up of underwater instrumentation. This is detrimental for sensors that rely on a field of view or a contact surface to obtain their data, such as visual cameras, radiometers, or acoustic pingers. In Sect. 3.2 we have refered to sampling problems of the underwater acoustic pinger, which has been integrated into the mass-balance station to provide information of growth and melt on the base of the fast ice.

lcing-up of underwater sensors is a prevalent concern at many sites in Antarctic waters, while not extensively discussed in the context of Arctic deployments. In Antarctic waters, the insertion of any ice-mounted sensor or item into the surface ocean presents a nucleation surface for platelet crystals, which are an unconsolidated mass of freely

- drifting ice crystals, either near the surface or suspended at depths to 250 m (Leonard et al., 2006). The cold bridge associated with any sensor or item immersed into the surface ocean attracts platelet ice to settle out nearby, hence obstructing the sensing surface of the underwater instrument. To overcome this problem the AFIN mass-balance station has been redesigned. During austral winter 2011 we will deploy a tilt-pan-zoom
- camera, which is mounted within a heatable dome. The camera will provide footage of the under-ice environment to derive information on the amount of platelet ice within the water column, and the conditions under which it settles out. In a follow-up from laboratory tests, we will furthermore study a number of materials with different surface



properties, by deploying those through the ice into the surface ocean. It is anticipated that we may overcome substantial ice accretion on the mass-balance station, using a combination of favourable materials, i.e. for the thermistor rod, and pulsed heating, i.e. for the underwater radiometer.

5 6.2 Expanded system: biological sampling

As the breeding and birthing ground for species such as Emperor penguins (Massom et al., 2009) and Weddell seals (Lake et al., 1997), fast ice is also a habitat. For example, the breeding cycle of Emperor penguins lasts 9 months, and this species would be vulnerable to a reduction in the seasonal fast-ice duration or its thickness. On the other hand, compact or excessive ice cover are similarly detrimental to the Emperor's breeding success, as they bring on longer and more demanding passage to dive holes (Massom et al., 2009). Data on the physical character will provide relevant information on the habitat itself. However, additional data will be required for detailed studies of systems of micro-organisms embedded with the fast ice. Hence we have redesigned

- the fast-ice mass-balance station to also include instrumentation for the measurement of biological parameters, both at the underside of the ice and within the water column. This is important as, for example, sea-ice micro-organisms, such as ice algae, form an intergral part of marine food web. It has been estimated that ice algae contribute between 5–25 % of the overall primary production in ice-covered waters of the Southern
- Ocean (Arrigo and Thomas, 2004). However, these are crude estimates as the seaice algal biomass and production cannot be monitored on large scales (Mundy et al., 2007), giving rise to the need for middle – to longer – term observational records.

6.3 Intercomparison of Antarctic and Arctic fast ice

In both hemispheres, fast ice is a ubiquitous feature of the coastal polar zone. Weekly data on fast-ice thickness from several locations in the Canadian Arctic are available from the 1950s to 1990s, with further data for the American and Siberian Arctic (Bilello,



1980; Brown and Coté, 1992; Polyakov et al., 2003), and information on the fast-ice cover from the European Arctic (Gerland and Renner, 2007). Annual maximum ice thickness observed at Arctic sites tend to exceed those of Antarctic fast ice, which can be explained by the higher freezing potential of the Arctic fast ice associated with

- ⁵ higher latitudes where the Arctic fast ice is encountered. The exception to this is found in the old (in excess of decades) fast ice found in the lee of Antarctic iceberg tongues or similar features: While no in situ measurements are available to verify, using ICESat laser altimetry Massom et al. (2010) estimated the thickness of multi-year fast ice to be 10 to 55 m.
- Maximum Arctic fast-ice thickness generally exhibits a similar interannual variability, however, both positive and negative trends in ice thickness have been observed in the Arctic. Comparing the two hemispheres, we find that in Arctic the fast ice establishes itself at a faster rate than in the Antarctic, where repeated cyclone action tends to intermittently remove the fast ice during autumn. Also, Arctic sites investigated here exhibit less snow cover than those from East Antarctic coastal sites.

Arctic sites can vary strongly in duration of ice cover and amount of precipitation. Perennial fast ice in the Arctic is only known from some sites in the Canadian Archipelago. In most regions, Arctic fast ice disappears completely in summer. Regional hydrography and large scale ocean dynamics influence Arctic fast ice, with for
²⁰ example higher ocean heat fluxes where Atlantic water is influencing ice growth off west Spitsbergen (Svalbard). Secondary ice growth (snow ice and superimposed ice) on the surface of fast ice, as it is known from Antarctic fast ice (Kawamura et al., 1997), has been also observed at one Arctic site (Svalbard, Nicolaus et al., 2003), but it is

not clear if those effects play also a major role in large parts of the Arctic, including the pack ice. The main difference between Arctic and Antarctic fast ice appears to be the amount of platelet ice: there have been very few confirmed reports of platelet ice in the Arctic (e.g. by Jeffries et al., 1995), while the presence of ice platelets in the Antarctic has been well documented (e.g. Jeffries et al., 1993; Leonard et al., 2006).



7 Conclusions

Under AFIN a fast-ice observing system is being developed using an integrated but staged approach, which has been found to best suit the coastal Antarctic environment. While components of the system have been deployed and have collected data

- for several seasons, the (site specific) integrated AFIN observing system remains under development. At the same time, we strive to expand the observational network in order to obtain further sites that will provide long-term records for our analysis of how climate change affects the Antarctic system.
- In light of increased atmospheric variability we anticipate increased interannual variability in the Antarctic sea-ice concentration, extent and thickness and linked with these we may expect increased variability of the Antarctic fast-ice properties (Heil, 2006), with impact on coastal shipping and air operations, or penguin breeding success (Massom et al., 2009). Information from the AFIN site at Davis has already proven invaluable in assessing polar change, and also in support of logistical undertakings. We anticipate that Davis and other AFIN stations will deliver a wealth of information on the climate
- and ecosystem response, hence we work towards a sustained and expanded AFIN community.

Acknowledgements. P. H. is grateful to D. Correll, M. Milne and R. Stehle for their field support and maintenance of the equipment, and to P. Jansen, S. Whiteside, K. Newberry, M. Richard son and G. Mayhew for engineering and building the various instruments. S. G. and M. G. thank base personnel from Sverdrup Station (Kongsfjorden, Svalbard), Hopen (Svalbard, measurements by the Meteorological Institute of Norway) and Troll (Dronning Maud Land, Antarctica) as well as H. Goodwin, T. Hattermann, and E. Brossier for doing ice thickness measurements, and K. Pedersen for logistical support. K. Meiners, R. A. Massom and J. L. Innis are thanked for
 their comments. Australian AFIN stations have been supported through the Australian Antarctic Science scheme's grants #2500 and #3032. This research was supported by the Australian government's Cooperative Research Centre (ACE CRC), NPI's long-term monitoring of Antarctic fast ice, and NPI's ICE centre's project ICE-Fimbul.



References

10

- Arrigo, K. R. and Thomas, D.: Large scale importance of sea ice biology in the Southern Ocean, Antarct. Sci., 16, 471–486, 2004. 2452
- Bilello, M. A.: Decay patterns of fast sea ice in Canada and Alaska, in: Sea Ice Processes and
- Models, Proceedings of the Arctic Ice Dynamics Joint Experiment, Seattle, WA, 1977, edited by: Pritchard, R. S., University of Washington Press, 313–326, 1980. 2439, 2446, 2452
 - Bindschadler, R. A., and Scambos, T. A.: Satellite-image-derived velocity field of an Antarctic ice stream, Science, 252, 242–246, 1991. 2445
 - Brown, R. D. and Coté, P.: Inter-annual variability of land-fast ice thickness in the Canadian High Arctic 1950–89, Arctic, 45, 273–284, 1992. 2439, 2446, 2453
- Comiso, J. C.: A rapidly declining perennial sea ice cover in the Arctic, Geophys. Res. Lett., 29, 1956, doi:10.1029/2002GL015650, 2002. 2438
- Comiso, J. C.: Variability and trends of the global sea ice cover, in: Sea Ice, edited by: Thomas, D. N. and Dieckmann, G., ISBN 978-1-4051-8580-6, 205–246, 2010. 2438
- ¹⁵ Comiso, J. C. and Nishio, F.: Trends in the sea ice cover using enhanced and compatible AM-SRE, SSM/I, and SMMR data, J. Geophys. Res., 113, C02S07, doi:10.1029/2007JC004257, 2008. 2450
 - Eicken, H., Lovecraft, A. L., and Druckenmiller, M. L.: Sea-ice system services: A framework to help identify and meet information needs relevant for Arctic observing networks, Arctic, 62, 110, 120, 2000,
- ²⁰ **119–136, 2009. 2446**
 - Environment Canada, http://www.ice-glaces.ec.gc.ca/App/WsvPageDsp.cfm?ID=217, last access: 23 July 2011, 2010. 2439, 2447
 - Fedotov, V. I., Cherepanov, N. V., and Tyshko, K. P.: Some features of the growth, structure and metamorphism of East Antarctic landfast ice, in: Antarctic sea ice physical processes, inter-
- actions and variability, Antarct. Res. Ser., edited by: Jeffries, M. O., 74, AGU, Washington, D.C., 141–160, 1998. 2439
 - Gerland, S. and Renner, A. H. H.: Sea ice mass balance in an Arctic fjord, Ann. Glaciol., 46, 435–442, 2007. 2439, 2447, 2453

Gerland, S., Renner, A. H. H., Godtliebsen, F., Divine, D., and Løyning, T. B.: Decrease of sea

³⁰ ice thickness at Hopen, Barents Sea, during 1966–2007, Geophys. Res. Lett., 35, L06501, doi:10.1029/2007GL032716, 2008. 2439

Giles, A. B., Massom, R. A., Heil, P., and Hyland, G.: Semi-automated feature-tracking of East



Antarctic sea ice from Envisat ASAR imagery, IEEE Remote Sens. Environ., 115, 2267–2276, doi:10.1016/j.rse.2011.04.027 2011. 2445

- Haas, C., Pfaffling, A., Hendricks, S., Rabenstein, L., Etienne, J.-L., and Rigor, I.: Reduced ice thickness in Arctic Transpolar Drift favors rapid ice retreat, Geophys. Res. Lett., 35, L17501, doi:10.1020/2009.01.024457.2009.2429
- ⁵ doi:10.1029/2008GL034457, 2008. 2438
 - Heil, P.: Atmospheric conditions and fast ice at Davis, East Antarctica: A case study, J. Geophys. Res., 111, C05010, doi:10.1029/2005JC002904, 2006. 2439, 2446, 2447, 2448, 2454
 Heil, P., Allison, I., and Lytle, V. I.: Seasonal and interannual variations of the oceanic heat flux
 - under a landfast Antarctic sea ice cover, J. Geophys. Res., 101, 25741–25752, 1996. 2446
- Hutchings, J. K. and Bitz, C.: Sea Ice Mass Budget of the Arctic (SIMBA) Workshop: Bridging Regional to Global Scales, University of Alaska Fairbanks, 80 pp., 2005. 2440
 - Jeffries, M. O., Weeks, W. F., Shaw, R., and Morris, K.: Structural characteristics of congelation and platelet ice and their role in the development of Antarctic land-fast sea ice, J. Glaciol., 39, 223–238, 1993. 2448, 2453
- Jeffries, M. O., Schwartz, K., Morris, K., Veazey, A. D., Krouse, H. R., and Cushing, S.: Evidence for platele ice accretion in Arctic sea ice development, J. Geophys. Res., 100, 10905– 10914, 1995. 2453
 - Karagiannis, V., Manassis, C., and Bargiotas, D.: Position sensors based on the delay line principle, Sens. Actuators A, 106, 183–186, 2003. 2443
- Kawamura, T., Oshima, K. I., Takizawa, T., and Ushio, S.: Physical, structural and isotopic characteristics and growth processes of fast sea ice in Lützow-Holm Bay, Antarctica, J. Geophys. Res., 102, 3345–3355, 1997. 2453
 - Kwok, R. and Comiso, J. C.: Southern Ocean climate and sea ice anomalies associated with the Southern Oscillation, J. Climate, 15, 487–501, 2002. 2438
- Lake, S. E., Burton, H. R., and Hindell, M. A.: Influence of time of day and month on Weddell seal haul-out patterns at the Vestfold Hills, Antarctica, Polar Biol., 18, 319–324, 1997. 2452 Lei, R., Li, Z., Cheng, Y., Wang, X., and Chen, Y.: A new apparatus for monitoring sea ice thickness based on the magnetostrictive-delay-line principle, J. Atmos. Ocean. Tech., 26, 818–827. doi:10.1175/2008JTECHO613.1. 2009. 2443
- Lei, R., Li, Z., Cheng, B., Zhang, Z., and Heil, P.: Annual cycle of landfast sea ice in Prydz Bay, East Antarctica, J. Geophys. Res., 115, C002006, doi:10.1029/2008JC005223, 2010. 2443
 Leonard, G. H., Purdie, C. R., Langhorne, P. J., Haskell, T. G., Williams, M. J. M., and Frew, R. D.: Observations of platelet ice growth and oceanographic conditions during



the winter of 2003 in McMurdo Sound, Antarctica, J. Geophys. Res., 111, C04012, doi:10.1029/2005JC002952, 2006. 2448, 2451, 2453

- Leppäranta, M. and Myrberg, K.: Physical oceanography of the Baltic Sea, ISBN 978-3-540-79702-9, Springer, Germany, 2009. 2447
- Lindsay, R. W. and Zhang, J.: Assimilation of ice concentration in an ice-ocean model, J. Atmos. Ocean. Tech., 23, 742–749, 2006. 2440
 - Massom, R. A., Hill, K., Barbraud, C., Adams, N., Ancel, A., Emmerson, L., and Pook, M. J.: Fast ice distribution in Adelie Land, East Antarctica: interannual variability and implications for emperor penguins Aptenodytes forsteri, Mar. Ecol.-Prog. Ser., 374, 243–257, doi:10.3354/meps07734, 2009. 2452, 2454
- Massom, R. A., Giles, A. B., Fricker, H. A., Warner, R. C., Legresy, B., Hyland, G., Young, N., and Fraser, A. D.: Examining the interaction between multiyear landfast sea ice and the Mertz Glacier Tongue, East Antarctica: Another factor in ice sheet stability?, J. Geophys. Res., 115, C12027, doi:10.1029/2009JC006083, 2010. 2453

10

25

30

- ¹⁵ Mellor, M.: Sea ice measurements at Mawson and Davis, 1954–58, ANARE Report, 19, 1960. 2446
 - Mundy, C. J., Ehn, J. K., Barber, D. G., and Michel, C.: Influence of snow cover and algae on the spectral dependence of transmitted irradiance through Arctic I andfast first-year sea ice, J. Geophys. Res., 112, C03007, doi:10.1029/2006JC003683, 2007. 2452
- Nicolaus, M., Haas, C., and Bareiss, J.: Observations of superimposed ice formation at meltonset on fast ice on Kongsfjorden, Svalbard, Phys. Chem. Earth, 28, 1241–1248, 2003. 2453
 - Polyakov, I. V., Alekseev, G. V., Bekryaev, R. V., Bhatt, U. S., Colony, R., Johnson, M. A., Karklin, V. P., Walsh, D., and Yulin, A. V.: Long-term ice variability in the Arctic marginal seas, J. Climate, 16, 2078–2085, 2003. 2439, 2453
 - Pringle, D. J., Eicken, H., Trodahl, H. J., and Backstrom, L. G. E.: Thermal conductivity of landfast Antarctic and Arctic sea ice, J. Geophys. Res., 112, C04017, doi:10.1029/2006JC003641, 2007. 2448

Rothrock, D. A. and Zhang, J.: Arctic Ocean sea ice volume: what explains its recent depletion?, J. Geophys. Res., 110, C01002, doi:10.1029/2004JC002282, 2005. 2438

Shirasawa, K., Leppäranta, M., Saloranta, T., Kawamura, T., Polomoshnov, A., and Surkov, G.: The thickness of coastal fast ice in the Sea of Okhotsk, Cold Reg. Sci. Technol., 42, 25–40, 2005. 2447



- Discussion Paper TCD 5, 2437-2463, 2011 Antarctic fast ice P. Heil et al. **Discussion** Paper **Title Page** Introduction Abstract Conclusions References Tables Figures Discussion Paper [◀ Back Full Screen / Esc Discussion Printer-friendly Version Interactive Discussion Paper
- Sigmond, M. and Fyfe, J. C.: Has the ozone hole contributed to increased Antarctic sea ice extent?, Geophys. Res. Lett., 37, L18502, doi:10.1029/2010GL044301, 2010. 2450
- Simmonds, I. and Keay, K.: Variability in Southern Hemisphere extratropical cyclone beahviour, 1958–97, J. Climate, 13, 550–561, 2000. 2447
- Smith, I. J., Langhorne, P. J., Haskell, T. G., Trodahl, H. J., Frew, R., and Vennell, M. R.: Platelet ice and the land-fast sea ice of McMurdo Sound, Antarctica, Ann. Glaciol., 33, 21–27, 2001. 2448
 - Son, S.-W., Tanson, N. F., Polvani, L. M., and Waugh, D. W.: Ozone hole and Southern Hemisphere climate change, Geophys. Res. Lett., 36, L15705, doi:10.1029/2009GL038671, 2009. 2450
- Stroeve, J., Serreze, M., Drobot, S., Gearheard, S., Holland, M., Maslanik, J., Meier, W., and Scambos, T.: Arctic Sea Ice Extent Plummets in 2007, Eos Transactions, American Geophysical Union, 89, 13–14, doi:10.1029/2008EO020001, 2008. 2438

10

- Trodahl, H. J., McGuinness, M. J., Langhorne, P. J., Collins, K., Pantoja, A. E., Smith, I. J., and
- Haskell, T. G.: Heat transport in McMurdo Sound first-year fast ice, J. Geophys. Res., 105, 11347–11358, 2000. 2441
 - Turner, J. and Overland, J.: Contrasting climate change in the two polar regions, Polar Res., doi:10.1111/j.1751-8369.2009.00128.x, in press, 2009. 2438

Turner, J., Comiso, J. C., Marshall, G. J., Lachlan-Cope, T. A., Bracegirdle, T., Maksym, T.,

- ²⁰ Meredith, M. P., Wang, Z., and Orr, A.: Non-annular atmospheric circulation change induced by stratospheric ozone depletion and its role in the recent increase of Antarctic sea ice extent, Geophys. Res. Lett., 36, L08502, doi:10.1029/2009GL037524, 2009. 2447, 2450
 - Tynan, C. T., Ainley, D. G., and Stirling, I.: Sea ice: a critical habitat for polar marine mammals and birds, in: Sea Ice An Introduction to its Physics, Chemistry, Biology and Geology,
- edited by: Thomas, D. N. and Dieckmann, G. S., Wiley-Blackwell, Chichester, UK, 395–424, 2010. 2446
 - Watkins, A. B. and Simmonds, I.: Current trends in Antarctic sea ice: The 1990s impact on a short climatology, J. Climate, 13, 4441–4451, 2000. 2447

Worby, A. P., Geiger, C. A., Paget, M. J., Van Woert, M. L., Ackley, S. F., and DeLib-

³⁰ erty, T. L.: Thickness distribution of Antarctic sea ice, J. Geophys. Res., 113, C05292, doi:10.1029/2007JC004254, 2008. 2439

Zubov, N. N.: Arctic Ice, U.S. Navy Electronics Laboratory, San Diego, California, 1963. 2446

Discussion Pa	TCD 5, 2437–2463, 2011 Antarctic fast ice			
per				
_	P. He	P. Heil et al.		
Discu				
Jssio	Title Page			
n Pa	Abstract	Introduction		
per	Conclusions	References		
	Tables	Figures		
Discuss	14	۶I		
ion I	•	•		
Dape	Back	Close		
<u> </u>	Full Screen / Esc			
Dis	Printer-friendly Version			
CUSS	Interactive Discussion			
ion Paper	CC D			

Table 1. Overview of AFIN observations. Abbreviations used here are: Z_{ice} : ice thickness, Z_{snow} : snow thickness, FB: freeboard, T_{ice} : ice temperature, T_{snow} : snow temperature, T_{air} : surface air temperature.

AFIN activity	Parameter	Observation frequency
Thickness transect	$Z_{\rm ice}, Z_{\rm snow}$, FB, growth rate	days-weeks
Mass-balance station	$Z_{\rm ice}, Z_{\rm snow}, T_{\rm ice}, T_{\rm snow}, T_{\rm air}, P_{\rm air}$	10 min
Digital imaging	Ice presence, ice extent and point, breakout	10 min
Weather station	T _{air} , P _{air} , Wind velocity, Relative humidity	10 min
Remote sensing	Ice extent, lead pattern, outer pack and point	hours to days
Structural ice cores	Ice structure, T_{ice} , vertical salinity profile	annual



Fig. 1. Locations of AFIN nodes (blue: existing; green: proposed; red: proposed extension of existing nodes to include ecological observations).





Fig. 2. Davis fast-ice temperatures during 2007 measured every 0.02 m intervals from 0.10 m above the ice-atmosphere interface to 1.88 m below. The top five sensors (in air or snow) are shown in green at bottom of graph. Traces of thermistors in ice/ocean are shown in blocks of ten (by colour). The 2 m air temperature is shown as black dashed line.



Discussion Paper

TCD

5, 2437-2463, 2011

Antarctic fast ice



Fig. 3. Fast-ice thickness near Davis for 2007 from drill-hole measurements (blue stars) and derived from in situ ice-temperature data (black dots). The black dotted line marks rapid thick-ening of the fast ice associated with platelet ice.





Discussion Paper 5, 2437-2463, 2011 Antarctic fast ice P. Heil et al. **Discussion** Paper **Title Page** Abstract Introduction Conclusions References Figures Tables **Discussion** Paper **|**◀ Back Full Screen / Esc **Discussion** Paper Printer-friendly Version Interactive Discussion (cc

TCD

Fig. 4. Histograms of fast-ice (a, top left) and snow (b, bottom left) thickness, and freeboard height (c, top right) near the Fimbul for the five summers 2005/06, 2006/07, 2007/08, 2008/09 and 2010/11. Also shown is the spread of snow thicknesses for a single day near the Fimbul site (**d**, bottom right).