COMNAP

Council of Managers of
National Antarctic Programs

COMNAP Sea Ice Challenges Workshop

Hobart, Tasmania, Australia
12–13 May 2015

WORKSHOP REPORT

Photo: Volker Siegel
Front and back cover photo: Jan L Lieser

COMNAP Sea Ice Challenges Workshop

Hobart, Tasmania, Australia 12–13 May 2015

Workshop Report

The Council of Managers of National Antarctic Programs

The Council of Managers of National Antarctic Programs (COMNAP)

COMNAP Secretariat
Private Bag 4800
Christchurch, New Zealand
www.comnap.aq

ISBN 978-0-473-34368-2

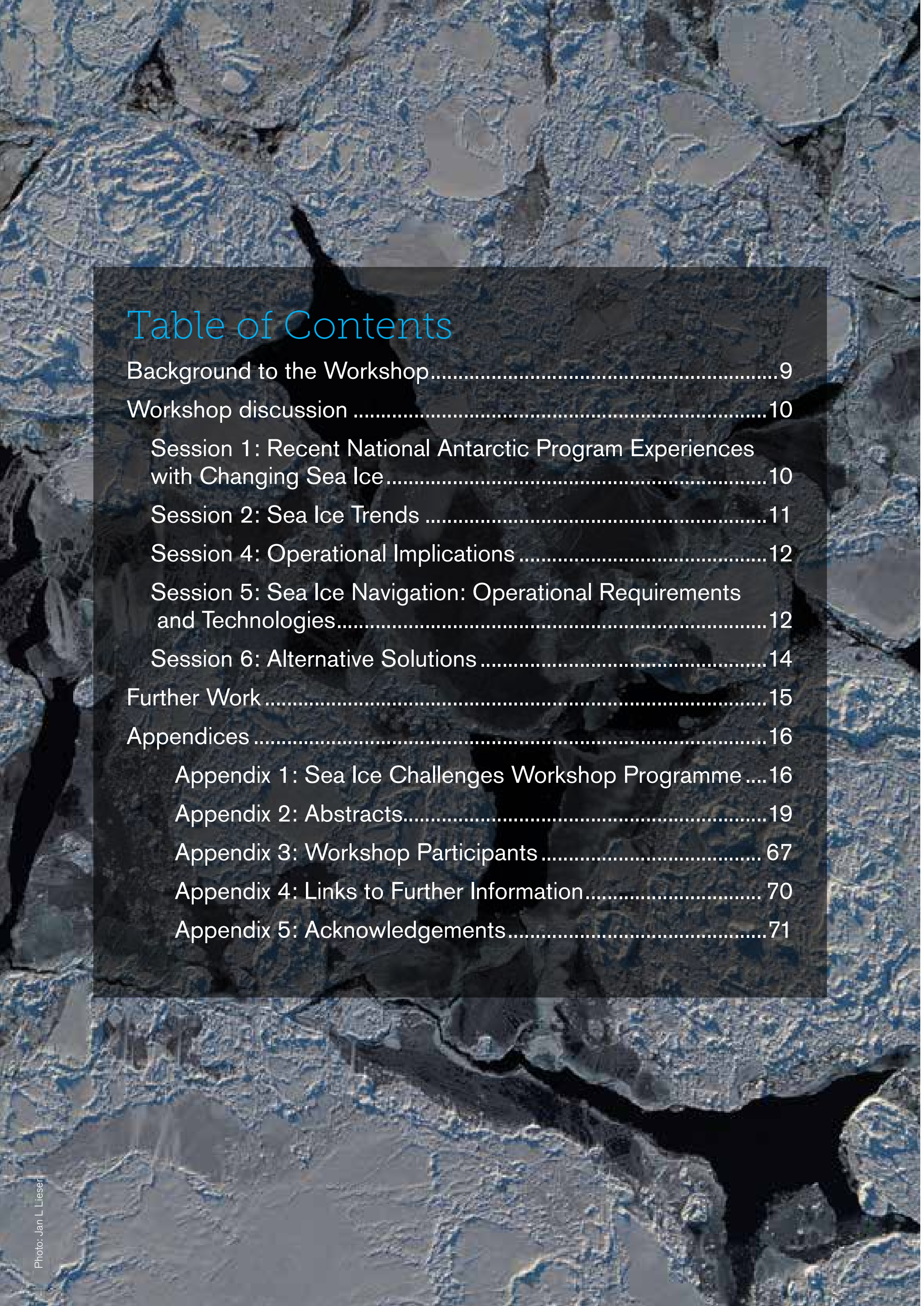


Photo: Jan L. Lieser

Table of Contents

Background to the Workshop

Sea ice conditions are one of the many challenges for vessels operating in the Antarctic marine area. In recent years, in some parts of the Antarctic, sea ice conditions have been such that those conditions have affected science, science support and logistics operations in the regions. Some parts of the Antarctic are experiencing expanding sea ice extent while other areas are seeing multi-year sea ice remain in areas where, previously, that was not the norm. The nature of changing sea ice conditions creates problems with resupply of both coastal and inland Antarctic research stations and also poses threats to human safety and has the potential to create emergency situations quickly.

Given the challenging nature of recent sea ice conditions in many parts of the Antarctic region, COMNAP agreed at its Annual General Meeting (AGM) 2014 to convene the Sea Ice Challenges Workshop in Hobart, Tasmania, Australia, on 12 and 13 May 2015.

On behalf of COMNAP, the workshop convenor was Dr. Rob Wooding, Australian Antarctic Division (AAD) General Manager Support & Operations and COMNAP Vice Chair. The workshop was co-hosted by the AAD with thanks to its Director, Dr. Tony Fleming, and by the Antarctic Climate and Ecosystems Cooperative Research Centre (ACE CRC) with thanks to its Chief Executive, Professor Tony Worby. Dr. Yves Frenot, Director of Institute Paul Emile Victor (IPEV) and COMNAP Vice Chair, provided oversight of the workshop. The Chair of COMNAP, Professor Kazuyuki Shiraishi, Director-General of the National Institute for Polar Research (NIPR), presented the welcome and opening address at the workshop.

The workshop brought together scientists, Antarctic program managers, sea ice forecasters, ice navigators and shipping experts from around the world to work together in addressing a multi-faceted issue of critical importance to everyone who operates in the area. Workshop presenters were invited from the science community and there was an open call for presentations from COMNAP Members organisations.

The overall aim of the Sea Ice Challenges Workshop was to discuss the latest scientific advice on the causes and likely future trends in sea ice expansion, to scope the challenges sea ice will pose for national Antarctic programs and other operators, and to identify and discuss potential solutions.

The specific aims of the workshop were to:

- Understand the causes of the expansion in sea ice in the waters around Antarctica;
- Scope the challenges sea ice expansion pose for sustaining Antarctic stations that depend on over water refuelling and resupply; and
- Identify and explore potential solutions.

Twenty-five speakers from nine different countries presented. In addition, there was one poster presentation and two presentations that were sent by way of information papers to the workshop.

The following sessions were part of the workshop programme (Appendix 1):
Session 1: Recent National Antarctic Program Experiences with Changing Sea Ice
Session 2: Sea Ice Trends
Session 3: Sea Ice Technology (poster session)
Session 4: Operational Implications
Session 5: Sea Ice Navigation: Operational Requirements and Technologies
Session 6: Alternative Solutions (Including Icebreakers)

This report presents the key outcomes of the workshop.

Workshop discussion

SESSION 1: RECENT NATIONAL ANTARCTIC PROGRAM EXPERIENCES WITH CHANGING SEA ICE

Session Chair: Rob Wooding
Session Presenters: Yves Frenot, Takeshi Tamura, Robb Clifton, Lei Ruibo

National Antarctic programs have operated vessels in the Antarctic marine area for more than 50 years. Vessel operators are first-hand witnesses to changing sea ice conditions, patterns and trends. Changes are regional, and there is no one overarching statement in regards to sea ice that would fit a "whole of Antarctic" situation. But, certainly for most areas beyond the Peninsula and West Antarctic regions, sea ice conditions have proved challenging for the past several years.

Such challenging conditions have meant that national Antarctic programs have had to: implement alternative solutions for resupply of their Antarctic stations, accept increases in their operational costs, work with an impacted ability to deliver Antarctic science and science support, and consider assistance to a range of other vessels which have encountered problems due to sea ice conditions.

All this increases risk to personnel safety, introduces delays in service - including delays to planned construction, and inhibits ability to transport into the Antarctic necessary supplies, scientific equipment and personnel, and to transport out of the Antarctic wastes and cargo to be retrograded.

The impact is felt not only at coastal Antarctic stations, but in regards to inland station resupply, where regular resupply is critical to maintaining and operating such stations year-round. Inland stations cannot be closed and reopened easily since winter temperatures plunge to temperatures close to or below -80 degrees Celsius.

When we envision sea ice, many of us picture solid, flat, continuous platforms which form and extend for kilometres out from the Antarctic coast. But while sea ice extent is certainly a challenge, there are four major factors making operating conditions difficult: the extent of ice cover, icebergs (that may have sea ice built up around them), rafted and ridged ice, and multi-year fast ice-especially in areas where such ice has not usually accumulated in the past. These obstacles impact shipping schedules which creates its own set of challenges given the relatively short Antarctic summer season.

All this means that national Antarctic programs can no longer rely on what they thought they knew. They now have to develop contingency plans, especially for delivery of fuel supplies. Such contingencies often cost more money and fuel to implement than is usual, an example being the need to burn aviation fuel in order to deliver the diesel fuel which would normally be delivered by ship. This adds to the challenges also, as ship off-load of fuel from greater distances away from the station leads to greater risk of fuel spill or accident. Even the most experienced national Antarctic programs and the most capable ice-breaking vessels are being faced with challenging conditions, so lesser vessels will certainly be challenged. This diverts resources from resupply and science to emergency situation.

While national Antarctic programs have always built flexibility into planning schedules, new methods are being sought. Sea ice challenges may not appear to have impacts beyond ship movements, but they do. Contingency planning often means thinking about cargo container sizes and increasing fuel and food storage capacity on stations. Such contingency planning must also include increased renewable option considerations, power usage strategies to decrease power requirements on stations (of a behavioural and technical nature) and the introduction of increased station self-sufficiencies (such as introduction of hydroponics) can have other benefits in the long-term.

SESSION 2: SEA ICE TRENDS

Session Chair: Tony Worby
Session Presenters: Rob Masson, Marilyn Raphael, Sharon Stammerjohn, Will Hobbs, Xavier Crosta, Mark Curran, Petra Heil, Phil Reid

National Antarctic programs are interested in knowing if the changes they have been observing in sea ice condition will continue for a period of time, or whether sea ice challenges are on the decline, thus they are interested in understanding trends. Keeping an eye on Antarctic sea ice year-by-year, one might be correct in thinking sea ice extent appears to be very similar each year. However, duration and thickness are increasing in many regions, and taken together it is this trend that is worrying in terms of national Antarctic program operations and science support.

Understanding trends is important but complicated and requires consideration of many factors, including waves, grounded iceberg numbers and extent, information on extreme events, and melt and accumulation of snow rates. Collecting such data requires high resolution remote sensing capabilities over extensive areas at regular (daily to sub-daily) intervals.

There is strong spatial, temporal and regional variability in Antarctic sea ice, driven by many drivers. For example, when the Southern Annular Mode (SAM) is positive (something that appears to be happening more and more), it strengthens westerly winds and as they strengthen, the surface currents strengthen and push cooler water and sea ice further north. This results in growth of sea ice extent. Localised changes in wind patterns also affect the distribution of sea ice and partially explain the increase in sea ice extent off the Ross Sea and decrease west of the Antarctic Peninsula. Another factor affecting surface winds is the depletion of ozone in the stratosphere, which cools the stratosphere and leads to stronger gradients in temperature to the surface – propagating a signal of strengthening westerly winds at the surface during summer. Sea ice models are not currently capturing many of these processes very well and are therefore not particularly good tools for predicting future trends.

While first-hand experience confirms sea ice challenges are increasing in parts of Antarctica, the climate models are showing no detectable trends, or a reduction in mean sea ice extent. There are strong feedback actions occurring with differing coastal icescapes and differing continental shelf bathymetry also having a profound influence on sea ice trends. Model resolution is not as good as it needs to be and there is a need for increased resolution of global-coupled models.

Scientific understanding of conditions can be assisted through first-hand knowledge from vessel operators who log positions where ships stop on each voyage due to thick, fast ice. Software to assist with standardised recording of observations has been used for many years, and is currently undergoing an update as part of the "Antarctic Sea Ice Processes and Climate" (ASPeCt) program. There is a critical need for more, standardised observations including bridge-based observations to be collected on all voyages into the southern pack-ice zone. Along with information on pack-ice conditions and total sea ice extent, there is also a need to understand landfast ice extent and the processes controlling the presence or absence of landfast ice. Landfast ice can present the final, impenetrable barrier to Antarctic operations if it persists along the coast where Antarctic stations are located.

Even with uncertainty in models, what we know is that historic records related to sea ice extent going as far back as 30 years are being regularly broken. We also know large-scale or extreme events influence sea ice conditions. Such events may become more common as our climate changes, so there is an urgent need to improve our ability to understand the likelihood of such events and how they influence sea ice growth. Proxy records from marine and ice cores allow reconstruction of Antarctic sea ice extent from before the instrumental period. Measurements from ice cores reveal decadal cycles in sea ice extent and show that sea ice extent may have declined by up to 20% between the mid and late 20th Century, at least in the East Antarctic sector near Casey Station where the study was conducted. It is therefore possible that coastal stations along the East Antarctic coast were established during a period of reduced ice cover, and that the extent is now increasing on multi-decadal scales.

SESSION 4: OPERATIONAL IMPLICATIONS

Session Chair: Rob Wooding
Open discussion

The uncertainty of the models, the highly regional variation and the need for higher resolution and temporal data mean that the current science cannot give national Antarctic programs the certainty they require for annual implementation and planning of their programmes. Even knowing the trends with certainty would not be the end in itself. Of greatest importance to national Antarctic programs is reliable information at a regional level at a "now-cast" timescale.

No matter what the sea ice situation is, national Antarctic programs are required to provide support to their research programme. Understanding sea ice extent and duration will therefore allow national Antarctic programs to make smart decisions about when and where to operate and to have confidence in investments related to infrastructure and to any necessary contingencies.

Having a definitive information paper produced periodically (perhaps annually) which outlines what the current scientific consensus on the "state of play" in regard to sea ice could therefore be very helpful in planning. Also, national Antarctic programs need to explain clearly to the science and forecasting community what their needs are, the timings of their requirements and the areas where operations are planned. Open lines of communications across communities are therefore very important.

SESSION 5: SEA ICE NAVIGATION: OPERATIONAL REQUIREMENTS AND TECHNOLOGIES

Session Chair: Yves Frenot
Session Presenters: Lei Ruibo, Caryn Panowicz, Lin Zhang, Andrew Fleming, Xiao Cheng, Penelope Wagner, Thomas Krumpen, Neal Young, Jan Lieser, Scott Carpentier

Understanding trends and long-term forecasting is important, but so is information in real-time. During an Antarctic season, vessel operators and national Antarctic programs require the ability to select the best route through sea ice in terms of safety and timely delivery of supplies, people and science support.

Some national Antarctic programs provide training to ice pilots/ship navigators. These specialists have vast practical experience in performing ship-based and airborne ice observations and in receiving, processing and interpreting satellite sea ice images in the Arctic and the Antarctic. Such specialists work on board the expedition vessels in the Antarctic and at Antarctic stations. In addition to receiving and processing satellite images of sea ice, personnel from Antarctic stations also carry out coastal observations of the state of landfast ice, assessing all its age stages (beginning of seawater freeze up, establishment of landfast ice, onset of its decay and complete or partial destruction).

Examples of post-processing technologies include new work which focusses on albedo measurements of sea ice from aerial photography to identify "types" of sea ice. While such methods are proving useful to operations, there is often limited time available to conduct such science on-board the ship, since most national Antarctic program ships serve the dual purpose of resupply and conducting science support. New ships, dedicated to science programs are in planning stages and will be on-line as early as 2018.

There are a range of products that are available for "now-time" forecasting. These include an iceberg database, the Global Ocean Forecasting System (GOFs) 3.1 (7-day forecast with up to a 3km resolution), seasonal statistics model predictions of sea ice and Polar View which uses SAR imagery to deliver near real-time data for ship operations. Other "now-casting" services are being developed. These include such products as "Tie-Points", but such services are currently only available to the national Antarctic program of the organisation which provides the service, in this case the USA, but there are other examples provided by China and India. Joining together in collaborative organisations and groups, such as the International Ice Charting Working Group (IICWG) can mean that resources and products can be shared amongst members of such groups. In the Arctic, the Sea Ice Prediction Network (SIPN) connects scientists and stakeholders to improve sea ice predictions in a changing Arctic sea ice environment.

New technologies, like CubeSat, mean better resolution imagery is becoming available to deliver near real-time data and information. Examples include sea ice deformation data and new SAR imagery, GF-2 satellite imagery which has an 0.8m resolution, UAV use and OSSI software which uses Sentinel-1 data that is high resolution and less than two hours old. The IICWG is developing a collaborative ice chart for safer navigation in Antarctic waters. During the period October 2015 through April 2016, Weddell Sea ice charts will be made available. First-hand observations from vessel operators would be welcome to inform those charts during that period.

As critically important as understanding sea ice is, understanding weather and provision of weather-forecasts is equally important. National Antarctic programs rely on accurate weather forecasts, but there may be an inconsistency across service levels, and therefore, there may be a need for Antarctic forecaster competency training programs coupled with a commercial service provided to national Antarctic programs which could be based on their ship use days and areas.

The International Programme for Antarctic Buoys (IPAB) has recognised a crucial need for more co-ordinated launches of sophisticated sea ice buoys to provide real-time information on the evolution of ice and snow thickness and temperature in space and time, ice drift and key meteorological information. Costs, ship communications limitations, lack of buoys in place or lack of ship-time for placement of buoys, and placement of buoys which is science-driven and not operations-driven, all impact the ability of service providers to deliver timely and robust sea ice products for real-time use by national Antarctic program vessel operators. Parallel information is required from increased investment in sophisticated measurement stations and Automatic Weather Stations deployed in fast ice.

Particular attention should be paid to stepping up such activities during the Year of Polar Prediction (YOPP) 2017/19.

SESSION 6: ALTERNATIVE SOLUTIONS

Session Chair: Michelle Finnemore
Session Presenters: Patrice Godon, Doug Thost, Guy Williams, Ted Maksym

In situations where icebreakers are unable to advance through sea ice to approach land-based targets, national Antarctic programs are resorting to traverse operations from the ship to stations, associated facilities and field camps. In recent years, in some parts of the Antarctic, the number of traverses required has increased, as has the length of the required traverse. That is, in some circumstances the minimum distance that a ship is able to approach is now farther away due to the presence of impassable sea ice.

Traverse operations require a range of vehicles to support various terrain encountered and to cope with lift requirements. Traverse operations also require trained personnel to adequately support long distance and long duration operations and technology employed for safety, such as Ground Penetrating Radar (GPR), Electro-Magnetics (EM) and Remotely Piloted Aircraft (RPA).

More and more vessels and traverses are being supported by remotely piloted aerial technologies, since they can be easily deployed with an on-board camera that can relay, in real-time, images of the forward sea ice conditions and sea ice traverse routes. Such technologies can be tethered and can therefore be powered for long duration and can be wind-aware and ship-aware.

Technologies such as this, deployed for an operational situation, can also be important data collectors for scientists, that is, they can provide data to the scientific community. For example, GPR data from Global Position System (GPS)-referenced sea ice traverses are valuable for the sea ice community who can use such data to understand sea ice thickness which can ground truth satellite data and models. All ice edge data and fast ice edge data can also be GPS-referenced by ship's captain and can also be a useful source of information to the scientific community.

Further Work

Based on workshop discussions it appears there are three key items of further work required, which, if implemented, would assist national Antarctic programs when Antarctic sea ice conditions prove particularly challenging. They are:

1. All sea ice scientists engaged in research, monitoring or forecasting in relation to the southern hemisphere should work together, with input from COMNAP where appropriate, to build a global network to produce, *inter alia*:
    - An annual report on the scientific consensus on major drivers and trends for patterns of sea ice coverage in the southern hemisphere; and
    - One or two collaborative forecasting and analysis services to cover the entire marine area around the Antarctic continent (noting this would need to be resourced by national operators not from research funding).
2. Antarctic Treaty countries to work together through COMNAP to provide access to greater telecommunications bandwidth across the continent and surrounding marine areas, to facilitate the real time upload of sea ice data to research, monitoring and modelling facilities and researchers, and thereby, improve the accuracy of monitoring, forecasting and analysis.
3. Sea ice research and analysis to be pursued by interested scientists from Antarctic Treaty countries as a priority.

Appendices

APPENDIX 1: SEA ICE CHALLENGES WORKSHOP PROGRAMME

TUESDAY 12 MAY: *WORKSHOP DAY ONE*

8.45 am: Welcome and Opening of Workshop Professor Kazuyuki Shiraishi, COMNAP Chairman

9.00am: Session 1: Recent National Antarctic Program experiences with changing sea ice
(Session Chair: Rob Wooding)

9.00–9.20 Yves Frenot (Institute Paul Emile Victor, France)
The impact on the French Antarctic Program of sea ice conditions around Dumont D'Urville since 2011

9.20–9.40 Takeshi Tamura, Shuki Ushio & Daisuke Simizu (National Institute of Polar Research, Japan)
Recent tough sea ice conditions around Syowa Station

9.40–10.00 Robb Clifton (Australian Antarctic Division)
Adapting to a new normal for sea ice access and operations at Australian Antarctic stations

10.00–10.20 Wang Jianzhong, Yuan Shaohong & Lei Ruibo (Polar Research Institute of China)
China's experiences with impenetrable and changing sea ice in the Antarctic

10.30am: Morning coffee/tea break

11.00am: Session 2: Sea Ice Trends
(Session Chair: Tony Worby)

11.00–11.30 Rob Massom (Australian Antarctic Division)
An overview of sea ice and challenges for navigation

11.30–11:50 Marilyn Raphael (University of California Los Angeles (UCLA), USA)
Antarctic sea ice: variability, trends and 21st century projections

11.50–12.10 Sharon Stammerjohn (University of Colorado, USA)
Comparing and contrasting regional sea ice challenges around Antarctica

12.10–12.30pm Will Hobbs (Institute for Marine and Antarctic Studies, Australia)
Antarctic sea ice changes – natural or anthropogenic?

12.30pm: Lunch and official opening

Session 3: Sea ice technology (display)

1.30 pm: Session 2 (continued): Sea Ice Trends
1.30–1.50pm Xavier Crosta (University of Bordeaux, France)
Sea ice dynamics off George V Land, East Antarctica: beyond the instrumental period

1.50–2.10 Mark Curran (Australian Antarctic Division)
A 100-year reconstruction of Antarctic sea ice extent from ice cores

2.10–2.30 Petra Heil (Australian Antarctic Division)
Fast-ice variability in East Antarctica

2.30–2.50 Phil Reid (Australian Bureau of Meteorology)
Summation of Antarctic sea ice: What we know and where we should go

2.50–3.00 Questions/discussion

3pm: Afternoon coffee/tea break

3.45pm: Session 4: Operational Implications (Session Chair: Rob Wooding)
Responses from national Antarctic programs to the latest scientific findings.

5.00pm: Close of Workshop Day One

WEDNESDAY 13 MAY: *WORKSHOP DAY TWO*

9.00am: Session 5: Sea Ice Navigation: Operational Requirements and Technologies (Session Chair: Yves Frenot)

9.00–9.20 Lei Ruibo (Polar Research Institute of China)
Ship-based measurements on sea ice morphology during the CHINARE Antarctic and Arctic cruises

9.20–9.40 Caryn Panowicz (US National Naval Ice Center)
US National Ice Center – Sea Ice Analysis in Antarctic Waters

9.40–10.00 Lin Zhang (National Marine Environmental Forecasting Center, Polar Environmental Research & Forecasting Division)
Operational sea ice forecasting and navigation service for the Chinese National Antarctic Research Expedition

10.00–10.20 Andrew Fleming (British Antarctic Survey, UK)
Polar View – Developing and delivering operational sea ice information for the polar regions

10.20am: Morning coffee/tea break

11.00–11.20 Xiao Cheng (Beijing Normal University, China)
Navigational sea ice analysis for the RV *Xuelong* in Prydz Bay, East Antarctica 2011/12 to 2013/14

11.20–11.40 Penelope Wagner (Norwegian Meteorological Institute)
International Ice Charting Working Group (IICWG) collaborative Antarctic sea ice product

11.40–12.00 Thomas Krumpen, Lasse Rabenstein, Stefan Hendricks, Paul Cochrane (Drift & Noise Polar Services GmbH, Germany)
On-Site Sea Ice Information (OSSI): a system to support operations in polar regions

12.00–12.20 Scott Carpentier, Neal Young & Jan Lieser (Australian Bureau of Meteorology)
A case for coordinating Antarctic marine weather services

See also information paper which will not be presented but is sent to share information by: D. Ram Rajak, R. K. Kamaljit Singh, Jayaprasad P., Sandip R. Oza, Space Applications Centre, ISRO, Ahmedabad, India) and M. Javed Beg (National Centre for Antarctic and Ocean Research, Goa, India)
Sea Ice Advisories for Indian Research & Supply Vessels Operating in central Dronning Maud Land & East Antarctica

12.00–12.30 Summary of morning session/questions and discussion

12.30pm: Lunch

1.30pm: Session 6: Alternative Technologies (Session Chair: Michelle Finnemore)

1.30–2.00 Patrice Godon (Institute Paul Emile Victor, France)
Dealing with the sea ice around Dumont d'Urville

2.00–2.20 Doug Thost (Australian Antarctic Division) & Guy Williams (Institute for Marine and Antarctic Studies)
Using remotely piloted aircraft (RPA) in ice reconnaissance roles: from crystal ball gazing & some practical results

2.20–2.40 Ted Maksym (Woods Hole Oceanographic Institution, USA)
Autonomous platforms: emerging technologies for sea ice research and operations

See also information paper which will not be presented but is sent to share information by: A. Korotkov, V. Korablev and V. Lukin (Arctic & Antarctic Research Institute of Roshydromet)
Ice navigation support for marine operations of the Russian Antarctic Expedition

2.40–3.30 Questions/answer session

3.30 pm: Afternoon coffee/tea break

4pm: Summing up/future directions
(Session Chair: Rob Wooding)

5.00pm: Close

Appendix 2: Abstracts

SESSION 1: RECENT NATIONAL ANTARCTIC PROGRAM EXPERIENCES WITH CHANGING SEA ICE

Recent Tough Sea Ice Conditions Around Syowa Station

Takeshi Tamura, Shuki Ushio, and Daisuke Simizu

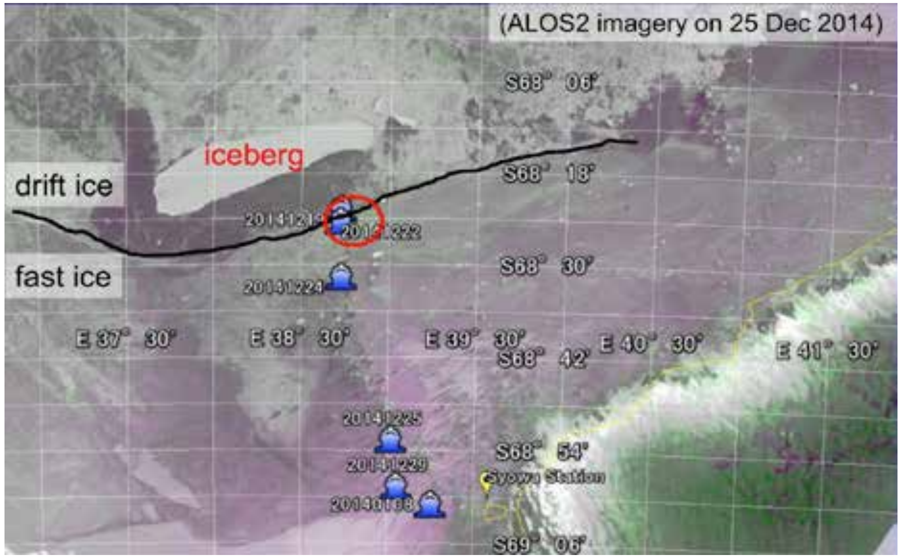
National Institute of Polar Research, Japan
tamura.takeshi@nipr.ac.jp

Recent sea ice condition around Syowa Station is very tough. Rafted (and ridged) drifting sea ice, huge icebergs, ridged (and rafted) fast ice, and multi-year fast ice are four major factors to make this difficult situation for our icebreaker *Shirase*.

1. Rafted (and ridged) drifting sea ice

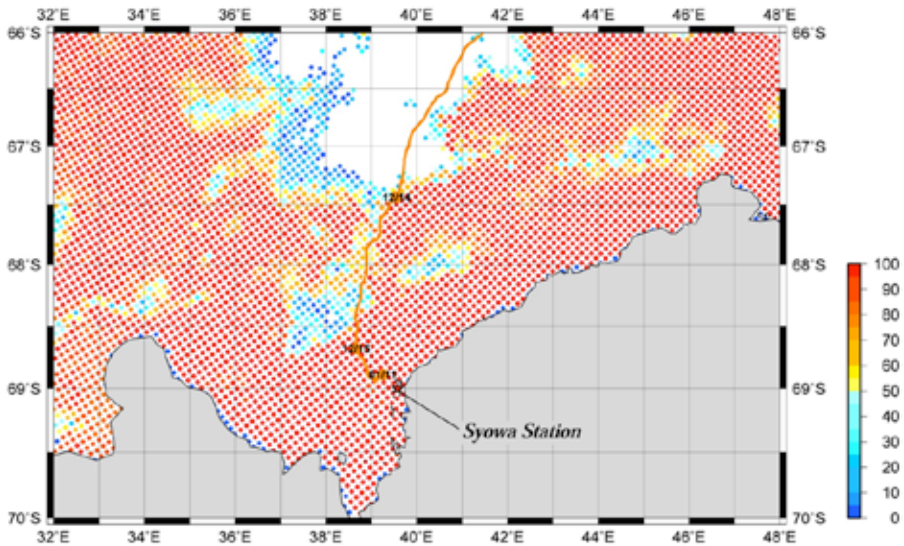
During 2011/12 season cruise, *Shirase* spent more than two weeks to go through the heavy rafted first-year ice zone (black circle in the above figure) which are considered to be formed by the strong prevailing southward wind during December 2011.

2. Huge icebergs and ridged (and rafted) fast ice



During 2014/15 season, *Shirase* spent approximately 5 days to go through the heavy ridged fast ice zone close to the boundary of drifting ice and fast ice (red circle in the above figure), and a huge iceberg has passed around the rote of the vessel within 1 week.

3. Multi-year fast ice



During 2012/13 season, *Shirase* could not go through the heavy multi-year fast ice zone (black circle in the above figure) and gave up reaching the Syowa station.

SESSION 2: SEA ICE TRENDS

Overview of Antarctic Sea Ice and Challenges

Rob Massom

Australian Antarctic Division and Antarctic Climate and Ecosystems Cooperative Research Centre
rob.massom@aad.gov.au

Due to its a vast coverage (ranging seasonally from ~3-4 to ~19-20 million km2) of the seas surrounding Antarctica and highly-dynamic nature, sea ice in the form of both moving pack ice and stationary fast ice abutting the coast (both with an accumulated snow cover, which is an important factor) represents a considerable challenge for logistical operations/shipping activities in the Southern Ocean. By the same token, the ice represents a unique natural laboratory for crucially-important scientific research towards unravelling the key role of the ice and its snow cover in high-latitude ecological and biogeochemical processes and the Earth's climate system. Sea ice is not only a sensitive indicator of climate variability and change (which is amplified at high latitudes), by virtue of its intimate association with the atmosphere and ocean; it also contributes to climate change through complex and poorly-understood interactions involving the coupled ice-ocean-atmosphere system (see other abstracts).

At circumpolar and seasonal scales, patterns of annual sea ice advance, retreat and duration closely mirror climatological temperature, wind and ocean current patterns, and vary considerably between regions and years. Crucially, the current overall trend in Antarctic sea ice coverage (since 1979) is made up of different and contrasting regional changes in seasonality (Stammerjohn et al., 2012). An issue/challenge is the need for seasonal ice forecasting capability tuned to different regions pan-Antarctic, to support voyage operations and science experiments (planning).

Understanding the scale-dependency of the air-sea-ice interaction system is crucial to understanding Antarctic sea ice (Massom and Stammerjohn, 2010). At hourly to daily scales, the notorious dynamism of the Antarctic sea ice zone is strongly associated with the frequent passage of storms around the high-latitude S Ocean. These drive rapid changes in air temperature and wind direction and strength (while dumping large amounts of snow on the ice – typically under blizzard conditions), and result in a complex interplay of thermodynamic (freeze/melt) and dynamic (ice motion and deformation) processes. Alternating synoptic-scale periods of ice divergence and convergence thicken the pack ice beyond ~1-2 m (Worby et al., 1998), with constant reworking of the ice leading to a high degree of heterogeneity in ice concentration and ice and snow thickness and properties on horizontal scales of metres to kilometres.

Snow is a key factor that both limits and contributes to thermodynamic ice growth – the former due to its strong insulating properties, and the latter by "snow-ice" formation (freezing of slush created by the flooding of the ice surface following depression below sea level by a snow overburden). Snow also exhibits complex internal structure with layers of variable density and properties, and can have a first-order effect on the efficiency of icebreakers (depending on snow type and wetness). Enhanced precipitation predicted in future (Bracegirdle et al., 2008) may lead to both greater snow-ice formation and shielding of the ice surface to delay summer melt.

There is, however, considerable uncertainty, given our poor knowledge of the current contribution of snow-ice to overall Antarctic sea ice mass balance. Major challenges revolve around the need to better measure, monitor and model precipitation and accumulation/loss over sea ice (Leonard and Maksym, 2011). Please see Sturm and Massom (2010) for a review of snow on sea ice.

While Antarctic sea ice is characterised by strong small-local scale variability, it exhibits recurrent patterns on the larger scale of hundreds of kilometres in the form of zones with distinctive characteristics but variable width depending on geographic location and season (Massom and Stammerjohn, 2010). These are: i) the highly-dynamic marginal ice zone (MIZ); ii) the inner pack; and iii) coastal zone. In the MIZ, the ice is strongly affected by ocean swell and waves. The ice edge itself seldom forms a clear-cut boundary, unless persistent northerly winds persist; more typically, it constitutes a diffuse zone up to tens of kilometres wide and comprising series of ice bands.

Ocean waves play a key role in both ice formation and destruction (including fast ice breakup), and can penetrate and affect the entire sea ice zone at times e.g., in East Antarctica (Kohout et al., 2014). They can also make fieldwork and operations hazardous. Given these factors, there is a strong need for improved information on sea-state and wave-ice interaction (both in real-time and for research purposes) i.e., from models, satellite SAR, ship's radar and wave buoys. A current issue is that wave-ice interaction processes are typically not included in coupled climate models. These challenges/issues are underpinned by the predicted future scenario of increased storminess (and "waviness"), particularly in summer and autumn (Turner et al., 2013).

To the south, the inner or central pack ice zone is generally characterised by higher ice concentrations, larger floe sizes (due to the damping effect of sea ice to the north on encroaching wave energy) and thicker sea ice and snow cover. It is typically traversed by networks of leads that are largely ephemeral. During freezing periods, leads are areas of rapid new ice formation, and become areas of enhanced ice melt in the melt season. Lead opening and closing is a challenge to observe and model, requiring regular high-resolution information over an extensive area. Key to successful operations is improved timely information on the local-regional ice convergence and divergence fields; this will require enhanced space borne Synthetic Aperture Radar (SAR) coverage over all key areas around Antarctica.

In the coastal zone, complex interactions occur between pack and fast ice, polynyas, ice sheet coastal promontories and icebergs (including assemblages of small icebergs grounded on offshore banks <~350-400 m deep) (Massom et al., 2001). Recurrent regional patterns once again occur, but these can be rapidly disrupted by persistent changes in atmospheric forcing, the influx of large icebergs and/or change in coastal configuration. For example, persistent northerly winds can create hazardous compaction of sea ice against the coast/offshore obstructions accompanied by extreme ice thickening – with the same northerly winds also bringing in enhanced amount of snowfall e.g., Massom et al. (2006). Also, "wildcard" events involving abrupt change in coastal cryosphere "elements" can have a dramatic effect on the coastal "icescape" - as highlighted by the 2010 calving of the Mertz Glacier Tongue and repositioning of iceberg B9B off Commonwealth Bay (Tamura et al., 2012).

Given the complex nature of the interactions and their scale i.e., kilometres to tens of kilometres, observing, modelling/forecasting and understanding sea ice conditions in the near-coastal icescape represents a considerable challenge. Overcoming this challenge requires: i) region-specific, high-resolution modelling that couples the different interactive cryosphere elements in a realistic fashion; ii) improved bathymetric data and information on (small grounded) iceberg distribution; iii) frequent high-resolution and near real-time satellite coverage involving SAR-derived ice motion/deformation and fast ice mapping over more extensive areas than is currently the case; and iv) an understanding of the regional setting in the longer term – the Mertz/B9B event was, for example, a decadal-scale event that was difficult/impossible to predict.

A critical knowledge gap remains our inability to accurately & routinely measure/monitor Antarctic sea ice (and snow cover) thickness on the large scale from space. Satellite altimetry holds the key, but thickness derivation requires independent knowledge of sea ice density and snow thickness and density, and is undermined by the typically small freeboard of Antarctic sea ice.

Given the challenges and complexities outlined above, combined with the vast coverage of Antarctic sea ice and the difficulties involved in carrying out research there, there is a pressing need for collaborative international and cross-disciplinary sea ice research in support of enhancing our:

- Observational, modelling and forecasting capability; and
- Understanding of key processes e.g., wave-ice interaction (notably in the MIZ), regional air-sea-ice interaction, and seasonal evolution of the coupled ice and snow system etc.

This will involve (amongst other things) dedicated field campaigns involving careful coordination to upscale in situ observations with remote sensing (also involving cross-calibration/validation of satellite products), and extensive use of state-of-the-art autonomous surface, airborne and under-ice technology (Maksym et al., 2012). Within this is a crucial need for more launches of sophisticated sea ice buoys coordinated within the International Programme for Antarctic Buoys (IPAB, http://www.ipab.aq) to provide crucial real-time information on the evolution of ice and snow thickness and temperature in space and time, ice drift and key meteorological information for transmission via the GTS. Parallel information is required from increased investment in sophisticated measurement stations and AWSs deployed in fast ice within the international Antarctic Fast Ice Network. Particular attention should be paid to stepping up such activities during the Year of Polar Prediction (2017-19, http://www.polarprediction.net/yopp.html), with a view to improving sea ice modelling and forecasting capabilities.

References

Bracegirdle, T.J., W.M. Connolley, and J. Turner (2008). Antarctic climate change over the twenty first century. Journal of Geophysical Research, 113(D3), D03103, doi:10.1029/2007JD008933.

Kohout, A.L., M.J.M. Williams, S.M. Dean and M.H. Meylan (2014). Storm-induced sea-ice breakup and the implications for ice extent. Nature, 509, 604-607.

Leonard, K.C., and T. Maksym (2011). The importance of wind-blown snow redistribution to snow accumulation on Bellingshausen Sea ice. Annals of Glaciology, 52(57), 271-278.

Maksym, T., S.E. Stammerjohn, S. Ackley and R. Massom (2012). Antarctic sea ice – A polar opposite? Oceanography, 25(3), 140-151, http://dx.doi.org/10.5670/oceanog.2012.88.

Massom, R.A. and S.E. Stammerjohn (2010). Antarctic sea ice change and variability – Physical and ecological implications. Polar Science, 4, 149-186.

Massom, R.A., Stammerjohn, S.E., Smith, R.C., Pook, M.J., Iannuzzi, R.A., Adams, N., Martinson, D.G., Vernet, M., Fraser, W.R., Quetin, L.B., Ross, R.M., Massom, Y. and Krouse, H.R. (2006). Extreme anomalous atmospheric circulation in the West Antarctic Peninsula region in austral spring and summer 2001/2, and its profound impact on sea ice and biota. Journal of Climate, 19, 3544-3571.

Stammerjohn, S., R. Massom, D. Rind and D. Martinson (2012). Regions of rapid sea ice change: An inter-hemispheric seasonal comparison. Geophysical Research Letters, 39, L06501, doi:10.1029/2012GL050874.

Sturm, M. and R.A. Massom (2010). Snow & Sea Ice. In D. Thomas & G. Dieckmann (editors): Sea Ice. 2nd Edition, Wiley-Blackwell, New York (USA) & Oxford (UK), pp. 153-204. NB A new edition is currently in press.

Tamura, T., G. D. Williams, A. D. Fraser, and K. I. Ohshima (2012). Potential regime shift in decreased sea ice production after the Mertz Glacier calving. Nature Communications 3: 826. doi:10.1038/ncomms1820.

Turner, J. et al. (2013). Antarctic climate change and the environment: an update. Polar Record, 50(03), 237-259.

Worby, A. P., R. A. Massom, I. Allison, V. I. Lytle, and P. Heil (1998). East Antarctic Sea Ice: A Review of Its Structure, Properties and Drift. In Antarctic Sea Ice: Physical Processes, Interactions and Variability, ed. O Jeffries, 41–67. Washington, D.C.: AGU. doi:10.1029/AR074p0041.

Antarctic Sea Ice: Variability, Trends, Drivers and 21st Century Projections

Marilyn Raphael

UCLA Department of Geography, Los Angeles, California, USA
Raphael@geog.ucla.edu

Unbounded by land, Antarctic sea ice extent grows from an average minimum of near 5x106 km2 in March to an average maximum near 20x106 km2 by September. While the whole sea ice system experiences this pronounced regular annual cycle, as might be expected within such a vast system, there is variability in space and time in the size and timing of the maximum and minimum extents. Antarctic sea ice can be divided into regions of internal coherent variability – each region displays distinct differences in timing of advance and retreat and the length of time that they remain at maximum extent that may underlie the differences in variability that the regions exhibit (Raphael and Hobbs, 2014). In recent years temporal Antarctic sea ice variability has been marked by a positive trend in annual total sea ice extent. This positive trend in the total sea ice extent is led chiefly by the positive trend in the Ross Sea in autumn (Turner et al, 2009). Other regions around Antarctica are experiencing negative trends in sea ice (for example the Bellingshausen Sea) and in the other seasons the negative trend is more dominant than the positive trend (Simpkins et al, 2012).

There are several proposed contributors to the trend in Antarctic sea ice and perhaps that fact is a measure of the complexity of the system. These contributors include the high latitude, largescale atmospheric circulation system (SAM, ZW3, ASL), Tropical influences, freshwater influx from basal melting of ice shelves, winds on ice motion and drift, ice-ocean feedback, and atmosphere-ocean feedback. The index measuring the strength of the Southern Annular Mode (SAM) has a positive trend in the later decades of the 20th century and in the early 21st century. A positive SAM is associated with stronger westerlies. The resulting enhanced Ekman transport causes surface cooling by moving cold surface waters northward from Antarctica, creating conditions for enhanced sea ice growth. ZW3 induces preferred regions of equatorward and poleward flow thereby influencing the meridional transport of heat into and out of the Antarctic with resulting impact on temperature and sea ice extent. Research suggests that ZW3 has the potential to influence the regionality of Antarctic sea ice trends (Raphael, 2007).

Like ZW3, the ASL variability influences the climate of West Antarctica by controlling the meridional component of the large-scale atmospheric circulation, with consequences for meridional wind velocity, surface air temperature, precipitation, and sea ice concentration. A persistent and deep ASL over the Amundsen–Bellingshausen Seas (ABS) sector leads to enhanced northerly airflow across the western Antarctic Peninsula sector, resulting in higher surface air temperature, and reduced sea ice extent in the Bellingshausen and eastern Amundsen Seas. Conversely, the enhanced southerly flow of cold continental air along the western flank of the ASL results in increased sea ice extent in the western Amundsen and Ross Seas. While the ASL has deepened, analysis suggests that it is the location of the ASL that is most important because the location determines where the associated winds would prevail (Hoskings et al, 2013). Turner et al, (2009) indicate that the annual increase in sea ice is led by autumn increases in the Ross Sea associated with stronger ASL. Ongoing analysis suggests that the ASL location has a significant negative trend suggesting that it lies west of its average location. The influence of winds on ice motion and subsequently on the trends in sea ice is discussed in Holland and Kwok (2012) who show that large and statistically significant changes in ice motion are driven by changes in the winds.

Tropical influences on Antarctic sea ice include ENSO and the AMO (Atlantic Multidecadal Oscillation). While the effect of ENSO is on the atmospheric circulation and is concentrated largely in the Bellingshausen Sea and on the Peninsula, it is suggested that sea surface warming related to the AMO reduces the surface pressure in the Amundsen Sea thereby contributing to the observed sea ice dipole between the Ross and Amundsen, Bellingshausen and Weddell seas (Li et al, 2014).

Bintanja et al (2013) proposed that freshwater influx from basal melting of Antarctic ice shelves leads to freshening seawater, which then allows ice to form more easily. However Swart and Fyfe (2013) find that this input is not significant enough to produce sea ice to match the observed increase in extent.

The two major feedbacks proposed are an atmosphere-ocean feedback where a warmer climate leads to more precipitation (snow) and more snow-ice formation (Powell et al 2005; Zhang, 2007) and an ice-ocean feedback where an increase in SIE is associated with decreased mixed layer depth and stabilization of the water column due to the net inflow of water and brine rejection. The stratified water column becomes very stratified, limiting the vertical transfer of the oceanic heat flux that would melt the ice from below, thereby maintaining a larger sea ice extent (Goosse and Zunz, 2014). While it is not clear which of the proposed mechanisms is chiefly responsible for the observed trends, it seems clear that they are due to a multiplicity of contributing agents.

There are few published studies on recent CMIP5 model results that focus on Antarctic sea ice but those that do show that climate models simulate a weak decrease of sea ice extent (e.g. Mahlstein et al., 2013; Turner et al, 2013; Zunz et al., 2013). These studies conclude that the observed SIE trend is within the range of the models' internal variability and that the simulated decrease in Antarctic SIE since 1979 is also within the range of internal variability (e.g. Swart and Fyfe, 2013). However Hobbs et al (2015) suggest that the differences between the model simulations and observations cannot be explained by internal variability alone. That all the models fail to reproduce the observed increase in SIE may indicate that there are common failings in the representation of sea ice in the models. The disagreement with the observed increase might be due, among other things, to the misrepresentation in climate models of some important feedbacks, or because model resolution is too largescale to allow accurate representation of sub-gridscale processes in the ice and ocean. Projected sea ice trends for the 21st century suggest continued decrease of sea ice extent.

References

Bintanja, R., G. J. van Oldenborgh, S. S. Drijfhout, B. Wouters, and C. A. Katsman, 2013: Important role for ocean warming and increased ice-shelf melt in Antarctic sea-ice expansion. Nat. Geosci., 6, 376–379, doi:10.1038/ngeo1767.

Ferreira, D., J. Marshall, C. M. Bitz, S. Solomon, and A. Plumb, 2015: Antarctic Ocean and Sea Ice Response to Ozone Depletion: A Two-Time-Scale Problem. J. Climate, 28, 1206–1226. doi: http://dx.doi.org/10.1175/JCLI-D-14-00313.1

Goosse, H. and V. Zunz, 2014: Decadal trends in the Antarctic sea ice extent ultimately controlled by ice–ocean feedback. The Cryosphere, 8, 453–470, 2014, doi:10.5194/tc-8-453-2014

Hobbs, W.R, N. L. Bindoff, and M. N. Raphael, 2015: New Perspectives on Observed and Simulated Antarctic Sea Ice Extent Trends Using Optimal Fingerprinting Techniques (doi: 10.1175/JCLI-D-14-00367.1)

Holland, P.R. and R. Kwok, 2012: Wind-driven trends in Antarctic sea-ice drift. Nat. Geosci., 5, 872–875, doi:10.1038/ngeo1627.

Hosking, J. S., A. Orr, G. J. Marshall, J. Turner, and T. Phillips, 2013: The influence of the Amundsen–Bellingshausen Seas low on the climate of West Antarctica and its representation in coupled climate model simulations. J. Climate, 26, 6633–6648, doi:10.1175/JCLI-D-12-00813.1.

Li, X., D. M. Holland, E. P. Gerber, and C. Yoo, 2014: Impacts of the north and tropical Atlantic Ocean on the Antarctic Peninsula and sea ice. Nature, 505, 538–542, doi:10.1038/nature12945.

Mahlstein, I., P. R. Gent, and S. Solomon, 2013: Historical Antarctic mean sea ice area, sea ice trends, and winds invCMIP5 simulations. J. Geophys. Res. Atmos., 118, 5105–5110,vdoi:10.1002/jgrd.50443.

Powell, D.C., Markus, T., Stössel, A., 2005: Effects of snow depth forcing on Southern Ocean sea ice simulations. J. Geophys. Res.: Oceans 110, C06001.

Raphael, M. N., 2007: The influence of atmospheric zonal wave three on Antarctic sea ice variability. J. Geophys. Res., 112, D12112, doi:10.1029/2006JD007852.

Raphael, M.N. and W. Hobbs, 2014: The influence of the large-scale atmospheric circulation on Antarctic sea ice during ice advance and retreat seasons. Geophys. Res. Lett., 41, 5037–5045, doi:10.1002/2014GL060365.

Swart and Fyfe, 2013 Swart, N. C., and J. C. Fyfe, 2013: The influence of recent Antarctic ice sheet retreat on simulated sea ice area trends. Geophys. Res. Lett., 40, 4328–4332, doi:10.1002/grl.50820.

Simpkins, G. R., L. M. Ciasto, D. W. J. Thompson, and M. H. England, 2012: Seasonal relationships between large-scale climate variability and Antarctic sea ice concentration, J. Clim., 25, 5451–5469, doi:10.1175/JCLI-D-11-00367.1.

Turner, J., and Coauthors, 2009: 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.

Turner, J., T. J. Bracegirdle, T. Phillips, G. J. Marshall, and J. S. Hosking, 2013: An initial assessment of Antarctic sea ice extent in the CMIP5 models. J. Climate, 26, 1473–1484, doi:10.1175/JCLI-D-12-00068.1.

Zhang, J. L., 2007: Increasing Antarctic sea ice under warming atmospheric and oceanic conditions. J. Climate, 20, 2515–2529, doi:10.1175/JCLI4136.1.

Zunz, V., H. Goosse, and F. Massonnet, 2013: How does internal variability influence the ability of CMIP5 models to reproduce the recent trend in Southern Ocean sea ice extent? Cryosphere, 7, 451–468, doi:10.5194/tc-7-451-2013.

Comparing and Contrasting Regional Sea Ice Changes

Sharon Stammerjohn

Institute of Arctic and Alpine Research, University of Colorado Boulder
Sharon.stammerjohn@colorado.edu

Acknowledgements: The presenter thanks the many esteemed colleagues referenced throughout the presentation and NSF, with special thanks to Dr. Scott Borg and to the Palmer LTER (ANT-1440435)

This presentation gives a quick overview of the regional and seasonal differences in Antarctic sea ice concentration and annual ice season duration, and how those differences relate to winds, waves, sea ice motion and sea ice thickness.

The seasonal growth and decay of Antarctic sea ice is a function of both thermodynamical and dynamical processes. For example, in addition to seasonal cooling in autumn and warming in spring, winds, waves and ocean currents also affect ice growth and melt processes, as well as ice edge location and ice motion, and thus ice concentration (here meaning percent ice cover) and ice thickness. There can also be seasonal ocean feedbacks between spring and autumn. Finally, regional differences in geography (e.g., low latitude coastlines versus high latitude embayments; narrow versus wide continental shelf areas) lead to regional differences in local atmosphere and ocean forcing that also contribute to regional differences in Antarctic sea ice. In the following, we first focus on regional differences in mean seasonal conditions and then we explore how regional and seasonal conditions have changed over time.

Antarctica consists of a vast glaciated polar continent (about 14 million square kilometres), which is surrounded by the Southern Ocean, a large portion of which becomes covered by seasonal sea ice (about 16 million square kilometres), with a much smaller portion covered by year-round sea ice (about 3 million square kilometres). In winter, maximum sea ice extent (the area inside the ice edge containing both sea ice and open water areas) is about 19 million square kilometres. This seasonal wax and wane of sea ice is more than a six-fold change in ice-covered area and is one of the largest seasonal signals on earth (Lieser et al., 2013).

Temporal variability in sea ice concentration (Slide 3) is highest at and inside the ice edge where concentrations range from 0% to ~75% (Simpkins et al., 2012). Here is where the influence from storms (thus winds and waves) is highest in terms of variability. The width of this high-variability zone depends both on the season and on the direction and magnitude of the storm tracks. Seasonal means show high variability throughout most of the pack ice in summer and autumn. The high variability zone then follows the ice edge northward in winter and spring, such that the interior pack ice during these seasons show low variability. In spring, the high-variability zone becomes slightly more compact and zonally symmetric.

To determine the annual ice season duration (Stammerjohn et al., 2008; Massom and Stammerjohn, 2010; Stammerjohn et al., 2012; Massom et al., 2013), the ice year begins and ends during the mean summer minimum, defined here to begin on 15 February and end on 14 February of the following year. Within that period, the annual ice season duration is the total number of days between the day of ice edge advance in autumn and the ice edge retreat in spring (both reported in year day; see Stammerjohn et al., 2008 for more details). Once computed, the mean ice season duration map (Slide 4) for the period 1979-80 to 2012-13 shows, as expected, the longest ice season along most coastal regions, with exceptions being in the polynya areas (e.g., in the southwestern Ross Sea) and along the north-western side of the Antarctic Peninsula. Although there is only one region showing, in the mean, year-round (or perennial) sea ice cover (located in the western Weddell Sea), there is indeed summer sea ice in many of the other coastal regions and embayments. However, summer sea ice varies considerably in its extent and location from year to year; thus, coastal areas with summer sea ice fall within the 330-360 day range when averaged over all years.

As mentioned, ice season duration is the time elapsed between the autumn ice edge advance and subsequent spring ice edge retreat at a given location. Variability in those two metrics (ice advance and retreat) shows high variability along the outer ice edge most everywhere except in the Weddell Sea and Indian Ocean sectors (~30W to 90E) and in the coastal regions in the western Weddell Sea, Amundsen Sea and eastern Ross Sea.

Antarctic sea ice variability is largely wind-driven (Assmann et al., 2005; Massom et al., 2008; Holland and Kwok, 2012), particularly in spring, with possible ocean feedbacks contributing to autumn sea ice changes (Nihashi and Ohshima, 2001; Stammerjohn et al., 2012; Holland, 2014). An analysis of winds and ice motion (Slide 5) show them to be highly correlated through most of the winter pack ice area, with exceptions being in the western Ross Sea and East Antarctic sector (~120E to 180E), where respectively convergent zones (in strong outflow areas) or strong coastal currents play a greater role in determining ice motion variability (Holland and Kwok, 2012).

Winds not only contribute to the spatial and temporal variability of sea ice extent but also sea ice thickness, as divergence and convergence of the sea ice cover drive sea ice production and deformation (mechanical thickening by rafting and ridging). Overall, the Antarctic pack is thin (relative to Arctic pack ice), showing a mean thickness < 1 m (Slide 6), with thinner sea ice (< 0.5 m) along the outer pack ice during autumn and winter (Worby et al., 2008; Kurtz and Markus, 2012; Holland et al., 2014). The thin sea ice in the outer pack ice is maintained by wind-driven divergence, which creates areas of new sea ice (Worby et al.,2008), and a high ocean heat flux, which limits basal ice growth (Martinson and Iannuzzi, 1998). Sea ice is thickest in summer, when the thinner, outer pack has melted, leaving behind thicker, mostly heavily deformed sea ice (i.e., thick enough to survive the summer melt).

We next explore regional trends in sea ice, winds, ice motion, waves, and ice thickness. Trends in ice season duration (Slide 9) show large contrasting regional trends, with decreases ranging from 2 to 3 months in the western Antarctic Peninsula, southern Bellingshausen (Stammerjohn et al., 2008) and eastern Amundsen Seas (Stammerjohn et al., 2015), as well as in isolated areas along East Antarctica (Massom et al., 2013). Increasing trends ranging from 1 to 2 months are most pronounced in the western Ross Sea (Stammerjohn et al., 2008; Turner et al., 2009; Stammerjohn et al., 2012), with weaker increasing trends in the Weddell Sea and Indian Ocean sectors.

Regional trends in sea ice concentration largely reflect trends in winds and wind-driven ice motion (Holland and Kwok, 2012) (Slide 10), and these trends in turn project onto the trends in ice season duration (discussed above). The largest trends in northward ice motion and increases in sea ice concentration during the ice growth period (here defined from April to June) are in the outer pack ice zones of the western Amundsen and Ross Sea sector (~120W to 160E) and eastern Weddell Sea and Indian Ocean sector (~0E to 60E). Southward trends in ice motion and decreases in sea ice concentration are centred in the eastern Bellingshausen Sea. The decreases in sea ice concentration in the East Antarctic sector (~90E to 120E) are related to the increase in southward winds, but ice motion shows a mix of trends due to this area being a convergent zone with strong coastal currents.

Although the influence of winds and waves on sea ice will be most pronounced near the ice edge, large storms can generate long period waves, and those waves can travel hundreds of kilometres into the pack ice, affecting ice concentration and thus ice growth or melt processes well into the pack ice interior (Kohout et al., 2014) (Slide 11). For example, the relationship between changes in ice edge latitude and modelled significant wave height by longitude was examined over the ice growth period (here defined from March to August) and ice decay period (September to February), which showed high regional correspondence between trends in waves and ice edge location (for details see Kohout et al., 2014).

In addition to winds, trends in air and ocean temperature and in precipitation (and hence snow depth) and ocean freshwater content also exert considerable control on trends in sea ice growth and melt processes (e.g., Meredith and King, 2005; Sturm and Massom, 2009; Maksym et al., 2012). Due to weak ocean stratification and the presence of warm deep waters, seasonal sea ice thickness is also limited by high ocean heat flux (Martinson and Iannuzzi, 1998). Given these factors, thick Antarctic sea ice evolves either through wind driven rafting and ridging or from the top-down through surface flooding (caused by a thick snow cover), freezing and thickening (rather than the more usual way of thickening from the bottom-up) (Maksym et al., 2012). Thus, trends in winds and precipitation can affect trends in ice thickness. Since we do not have long enough observations of sea ice thickness, we must rely on models to explore potential trends in sea ice thickness (Slide 12). Most models show increases in sea ice thickness in the western Weddell Sea and in some coastal regions (in the southern Bellingshausen and Amundsen Seas) and decreases in the western Antarctic Peninsula and Bellingshausen Sea regions (Massonnet et al., 2013; Holland et al., 2014). Otherwise, model results are mixed, some showing increases in ice thickness in the Ross Sea or in Amundsen Sea or in the outer eastern Indian Ocean.

Regional trends in ocean surface properties (temperature and salinity) (e.g., Meredith and King, 2005) and in seasonal feedbacks also correspond to regional sea ice changes. For example, regional changes in sea ice can lead to increases (or decreases) in surface ocean warming that were caused by an earlier (or later) ice edge retreat spring, which then caused a later (or earlier) ice edge advance in autumn (Nihashi and Ohshima, 2001; Stammerjohn et al., 2012; Holland, 2014). Evidence for this feedback is indicated by the high correlations between yearly anomalies in the spring ice edge retreat and the subsequent autumn ice edge advance (i.e., over summer) (Slide 13) as observed throughout most of the pack ice, in particular the interior pack ice areas in the West Antarctic sector (Stammerjohn et al., 2012). Conversely, very low correlations are detected between yearly anomalies in the autumn ice edge advance and the subsequent spring ice edge retreat (i.e., over winter), consistent with this type of ice-albedo-ocean feedback being operative during the sunlight periods. There are indications of other ocean feedbacks affecting the outer ice edge due to changes in net freshening or the inner pack ice area due to changes in net sea ice production as well (Goosse and Zunz, 2013).

As mentioned, weak ocean stratification and high ocean heat flux (caused by the presence of warm deep waters) can limit sea ice thickness (Martinson and Iannuzzi, 1998). There is regional variability in the geography of where these warm deep waters have access to the continental shelf regions of Antarctica (Martinson, 2012), e.g., along the Bellingshausen and Amundsen continental shelf break areas and along some continental shelf break areas of East Antarctica (e.g., ~90-100E) (Slide 14). Since we do not have sufficient in situ observations of contemporaneous ice-ocean changes, we cannot assess the space/time variability in ocean heat flux to the surface mixed layer. But the geographic similarity between ice season duration trends and the proximity of deep ocean heat to the continental shelf areas is striking. Where these warm deep waters have access to the continental shelf regions along West Antarctica is also where the strongest trends in ice shelf thinning have been observed (Rignot et al., 2013; Paolo et al., 2015).

In summary:

- Regional differences in sea ice changes largely reflect regional differences in atmospheric circulation patterns, which in turn can lead to differences in wind- and wave-forcing on ice motion, ice concentration and ice thickness.
- Seasonal sea ice changes exhibit strong feedbacks between spring and the subsequent autumn, consistent with ice-albedo/ocean feedbacks, accentuating regions of strong sea ice changes.
- Continental shelf regions differ in their bathymetry and proximity to the Antarctic Circumpolar Current, thus differ with respect to shelf currents and proximity to warm Circumpolar Deep Water.
- Although not directly discussed in this presentation, continental shelf regions also differ in their coastal icescapes (e.g., polynyas, ice tongues, fast ice), which in turn contribute to regional differences in sea ice.

References

Assmann KM, Hellmer HH, Jacobs SS. 2005. Amundsen Sea ice production and transport. *J Geophys Res* **110**: doi:10.1029/2004jc002797.

Goosse H, Zunz V. 2013. Decadal trends in the Antarctic sea ice extent ultimately controlled by ice-ocean feedback. *The Cryosphere Discuss* **7**: 4585-4632. doi:10.5194/tcd-7- 4585-2013.

Holland PR. 2014. The seasonality of Antarctic sea ice trends. *Geophysical Research Letters* **41**: 4230-4237. doi:10.1002/2014gl060172.

Holland PR, Bruneau N, Enright C, Losch M, Kurtz NT, et al. 2014. Modeled Trends in Antarctic Sea Ice Thickness. *Journal of Climate* **27**: 3784-3801. doi:10.1175/jcli-d-13-00301.1.

Holland PR, Kwok R. 2012. Wind-driven trends in Antarctic sea-ice drift. *Nature Geoscience* 5: 872-875. doi:10.1038/ngeo1627.

Kohout AL, Williams MJ, Dean SM, Meylan MH. 2014. Storm-induced sea-ice breakup and the implications for ice extent. *Nature* **509**: 604-607. doi:10.1038/nature13262.

Kurtz NT, Markus T. 2012. Satellite observations of Antarctic sea ice thickness and volume. *Journal of Geophysical Research* **117**: doi:10.1029/2012jc008141.

Lieser JL, Massom RA, Fraser AD, Haward MG, Heil P, et al. 2013. Position analysis: Antarctic sea ice and climate change 2014. Hobart, Tasmania, Australia: Antarctic Climate & Ecosystems Cooperative Research Centre. Report no. PA07-131115.

Maksym T, Stammerjohn S, Ackley S, Massom R. 2012. Antarctic Sea Ice—A Polar Opposite? *Oceanography* **25**: 140-151. doi:10.5670/oceanog.2012.88.

Martinson DG. 2012. Antarctic circumpolar current's role in the Antarctic ice system: An overview. *Paleogeog, Paleoclim, Paleoecol*: doi:10.1016/j.palaeo.2011.04.007.

Martinson DG, Iannuzzi RA. 1998. Antarctic ocean-ice interaction: implications from ocean bulk property distributions in the Weddell gyre. Pages 243-271 in Jeffries MO, ed.

Antarctic Sea Ice: Physical Processes, Interactions and Variability, vol. Antarctic Research Series 74. Washington, D.C.: American Geophysical Union.

Massom R, Reid P, Stammerjohn S, Raymond B, Fraser A, et al. 2013. Change and variability in East Antarctic sea ice seasonality, 1979/80-2009/10. *PloS one* **8**: e64756. doi:10.1371/journal.pone.0064756.

Massom RA, Stammerjohn SE. 2010. Antarctic sea ice change and variability – Physical and ecological implications. *Polar Science* **4**: doi:10.1016/j.polar.2010.05.001.

Massom RA, Stammerjohn SE, Lefebvre W, Harangozo SA, Adams N, et al. 2008. West Antarctic Peninsula sea ice in 2005: Extreme compaction and ice edge retreat due to strong anomaly with respect to climate. *J Geophys Res* **113**: doi:10.1029/2007JC004239.

Massonnet F, Mathiot P, Fichefet T, Goosse H, König Beatty C, et al. 2013. A model reconstruction of the Antarctic sea ice thickness and volume changes over 1980–2008 using data assimilation. *Ocean Modelling* **64**: 67-75. doi:10.1016/j.ocemod.2013.01.003.

Meredith MP, King JC. 2005. Rapid climate change in the ocean west of the Antarctic Peninsula during the second half of the 20th century. *Geophys Res Lett* **32**:doi:10.1029/2005GL024042.

Nihashi S, Ohshima KI. 2001. Relationship between the sea ice cover in the retreat and advance seasons in the Antarctic Ocean. *Geophysical Research Letters* **28**: 3677-3680. doi:10.1029/2001gl012842.

Paolo FS, Fricker HA, Padman L. 2015. Volume loss from Antarctic ice shelves is accelerating. *Science*: doi:10.1126/science.aaa0940.

Rignot E, Jacobs S, Mouginot J, Scheuchl B. 2013. Ice-shelf melting around Antarctica. *Science* **341**: 266-270. doi:10.1126/science.1235798.

Simpkins GR, Ciasto LM, Thompson DWJ, England MH. 2012. Seasonal Relationships between Large-Scale Climate Variability and Antarctic Sea Ice Concentration. *Journal of Climate* **25**: 5451-5469. doi:10.1175/jcli-d-11-00367.1.

Stammerjohn S, Massom R, Rind D, Martinson D. 2012. Regions of rapid sea ice change: An inter-hemispheric seasonal comparison. *Geophysical Research Letters* **39**: L06501. doi:10.1029/2012gl050874.

Stammerjohn SE, Maksym T, Massom RA, Lowry KE, Arrigo KR, et al. 2015. Seasonal sea ice changes in the Amundsen Sea, Antarctica. *Elem Sci Anth*: accepted.

Stammerjohn SE, Martinson DG, Smith RC, Yuan X, Rind D. 2008. Trends in Antarctic annual sea ice retreat and advance and their relation to ENSO and Southern Annular Mode Variability. *J Geophys Res* **113**: doi:10.1029/2007JC004269.

Sturm M, Massom RA. 2009. Snow and sea ice. Pages 153-204 in Thomas D, Dieckmann G, eds. *Sea Ice, 2nd Edition*. Wiley-Blackwell: Oxford.

Turner J, Comiso JC, Marshall G, Lachlan-Cope TA, Bracegirdle T, et al. 2009. 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**: doi:10.1029/2009GL037524.

Worby AP, Geiger CA, Paget MJ, Van Woert ML, Ackley SF, et al. 2008. Thickness distribution of Antarctic sea ice. *Journal Geophysical Research* **113**: doi:10.1029/2007JC004254.

Antarctic Sea Ice Changes – Natural or Anthropogenic?

Will Hobbs

Antarctic Climate and Ecosystems Cooperative Research Centre
whobbs@utas.edu.au

Confidence in short and long term projections of the future Southern Ocean sea ice state is only possible with a complete understanding of the processes involved, and an evaluation of whether climate models adequately represent those processes. For the Southern Ocean, the situation is particularly complicated since sea ice variability in different regions is affected by quite different modes of atmospheric variability (Raphael and Hobbs, 2014). For long term logistics planning that is influence by ice cover changes, there is a clear need to understand whether observed changes in sea ice cover are anthropogenic and likely to continue in the future, or simply the result of natural multidecadal variability.

Detection and Attribution is the branch of climate science that seeks to determine whether an observed change:

1. Is outside the range of internal variability (i.e. Detection).
2. Is directly attributable to some external forcing or combination of forcings (i.e. Attribution).

The methods used rely heavily on model simulations. Given the short length of most observational records (especially in the polar oceans) models are usually necessary to characterise the system's internal variability on multidecadal to century timescales. An expected theoretical response of the system to an external forcing is also required, which is usually only obtainable from climate model simulations. Therefore, the Detection and Attribution method is also a comprehensive means of model evaluation. Applying these methods to the question of Southern Ocean sea ice change is invaluable for validating model projections, since the level of external forced response is quantified, and the models are simultaneously tested against the observed climate.

The work presented here is an overview of the current state-of-the-science of Antarctic sea ice cover Detection and Attribution work, along with suggested directions for future progress.

Almost all coupled climate models, when driven by realistic estimates of natural and anthropogenic 20th century climate forcings, show a decrease in Antarctic sea ice cover since 1979, which is the exact inverse of what is observed. Are the models then incorrect? Several studies say no, because the internal variability of Antarctic sea ice is so high that neither the observed nor modelled trends can be distinguished from 'noise' (Mahlstein et al, 2013; Polvani and Smith, 2013; Zunz et al, 2013). However, those studies used total sea ice extent, whereas it is well established that the observed changes have a strong spatial pattern. In particular a strong increase in Ross Sea cover is counterbalanced by the strong decrease in Amundsen/Bellingshausen Sea ice cover. By using the spatial pattern of sea ice trends and applying formal Detection and Attribution methods, (Hobbs et al, 2014) show that:

- Observed winter sea ice changes are small compared to model internal variability.
- Very few coupled climate models are able to replicate the observed changes, even accounting for internal variability.
- The discrepancy between models and observations occurs largely in the Ross Sea.

The short record of passive microwave observations of sea ice cover is a source of significant uncertainty in these conclusions. However, new work presented here that compares century-scale proxy reconstructions of sea ice cover is consistent with these findings. Where proxies are available they show a long-term pattern that agrees with the models in the E. Antarctic, Weddell Sea and Amundsen/Bellingshausen Sea. Both the models and reconstructions show a decrease in ice cover from the early to mid-1960s. However, the magnitude of this change is small compared with the internal variability indicated by both the models and simulations. Projections using only models that are consistent with the observed sea ice climate indicate that the small response is unlikely to be significant for the next two to three decades.

A confounding factor is the Ross Sea, where there are clear and significant discrepancies between the models and observations. A number of hypotheses have been suggested to explain the Ross Sea changes, none of which are adequately represented in global coupled climate models. It is suggested that Antarctic Detection and Attribution efforts should focus on using long-term model experiments using high-resolution regional models, to overcome these uncertainties.

References

Hobbs, W. R., N. L. Bindoff, and M. N. Raphael, 2014: New Perspectives on Observed and Simulated Antarctic Sea Ice Extent Trends Using Optimal Fingerprinting Techniques. *Journal of Climate*, 28, 1543-1560, 10.1175/jcli-d-14-00367.1.

Mahlstein, I., P. R. Gent, and S. Solomon, 2013: Historical Antarctic mean sea ice area, sea ice trends, and winds in CMIP5 simulations. *Journal of Geophysical Research: Atmospheres*, 118, 5105-5110, 10.1002/jgrd.50443.

Polvani, L. M., and K. L. Smith, 2013: Can natural variability explain observed Antarctic sea ice trends? New modeling evidence from CMIP5. *Geophys Res Lett*, 40, 3195-3199, 10.1002/grl.50578.

Raphael, M. N., and W. Hobbs, 2014: The influence of the large-scale atmospheric circulation on Antarctic sea ice during ice advance and retreat seasons. *Geophys Res Lett*, 41, 5037-5045, 10.1002/2014gl060365.

Zunz, V., H. Goosse, and F. Massonnet, 2013: How does internal variability influence the ability of CMIP5 models to reproduce the recent trend in Southern Ocean sea ice extent? *The Cryosphere*, 7, 451-468, 10.5194/tc-7-451-2013.

Sea Ice Dynamics off George V Land, East Antarctica, Beyond the Instrumental Period

Crosta X[1], Campagne P[1-2], Dunbar R[3], Escutia C[4], Etourneau J[1], Houssais M-N[5], Massé G[2], Schmidt S[1]

[1] UMR 5805 EPOC, Université de Bordeaux, 33615 Pessac Cedex, France
[2] UMI 3376 TAKUVIK, Université Laval, Québec City, Canada
[3] UMR 7159 LOCEAN, Université Pierre et Marie Curie, 75252 Paris Cedex, France
[4] IACT, CSiC-Universidad de Granada, 18100 Armilla, Spain
[5] Department of Environmental Earth Systems Science, Stanford University, USA
x.crosta@epoc.u-bordeaux1.fr

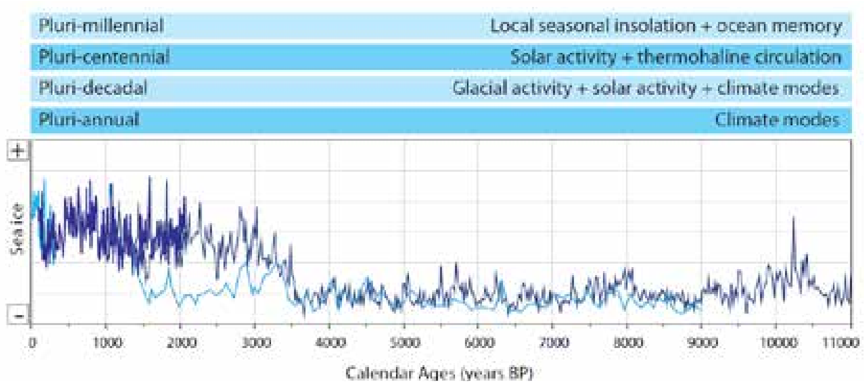
Antarctic sea ice is the most seasonal physical parameter on Earth, which waxing and waning is of major importance for global climate through modulation of the Southern Hemisphere radiative balance, transfer of energy and gas at the ocean-atmosphere interface, atmospheric and oceanic circulation and regional and remote oceanic productivity. Antarctic sea ice cover slightly increased over the last decades, opposite to numerical models' output that infer a global decrease. Reasons of such an increase, in the context of global warming, is still under debate but may rely on Southern Ocean atmospheric reorganization forced by the anthropogenic-induced recent trend to positive Southern Annular Mode (SAM) or on natural variability. The instrumental and historical observations are unfortunately too short to robustly document the relationships between Antarctic sea ice and climate. Proxy records from marine and ice cores allow to reconstructing Antarctic sea ice cover beyond the instrumental period and to documenting the forcings of sea ice dynamics and their predominance and interactions from geological to annual timescales. It is worth noting that these forcings dictated sea ice dynamics mainly through changes in ocean and atmosphere temperatures and circulations.

Winter sea ice cover was twice the modern one during the last glacial period (30.000 to 18.000 years before present, kyrs BP) and started to melt back to its modern position at ~18 kyrs BP in phase with the last deglaciation. Off George V Land, deglaciation was initiated at ~12 kyrs BP and lasted until ~9 kyrs BP when a modern-type seasonal sea ice cycle set up. Sea ice duration was shorter during the 9-4 kyrs BP period (mid-Holocene hypsithermal) and subsequently increased during the 4-0 kyrs BP period (Late Holocene Neoglacial). This pluri-millennial trend resulted from long-term changes in local seasonal insolation modulated by the memory effect of the ocean. Centennial and pluri-decadal variations were superimposed onto the Holocene trend in sea ice duration, including the last 2 kyrs. Off George V Land, the strong variations in sea ice duration over the last 2 kyrs were out-of-phase compared to the Northern Hemisphere climatic periods. The Dark Ages and Little Ice Age were generally warm while the Medieval Warm Period and Current Warm Period were mainly cold and icy as a result of changes in the timing of spring sea ice melting and autumn sea ice freezing. Changes in the timing of spring sea ice melting probably responded to the pluri-centennial expression of the Southern Oscillation Index (SOI) while changes in the timing of autumn sea ice freezing responded to the pluri-centennial expression of the SAM. Variations in both sea ice proxies, SOI and SAM present periodicities similar to solar activity cycles (Gleissberg and Suess cycles) showing an influence of solar activity on atmospheric and oceanic circulation through the modulation of the SOI and SAM. Last decades monitoring and geological proxy data have demonstrated that these two climate modes interact to shape inter-annual variations of Antarctic sea ice cover.

At the pluri-centennial to pluri-millennial timescales, proxy records therefore indicate that the main forcings of sea ice cover and duration off George V Land are precessional insolation, solar activity and thermohaline circulation. Other processes such as volcanic activity and, more locally, glacial discharge may have had a secondary influence.

At a shorter timescale, glacial processes are conversely of prime importance for sea ice history off George V Land. Spectral analysis of a 250-year long record of local sea ice conditions reveals a ~70-year periodicity, associated with the Mertz Glacier Tongue (MGT) calving and regrowth dynamics. When long enough (~110-160 km long) the MGT acts as a barrier to westward drifting ice and funnels katabatic winds, both processes creating a polynya downstream of the MGT. Concurrently, icier conditions are observed off Dumont d'Urville (DDU). After a calving, the MGT cannot act as a dam anymore and fast ice covers the formal polynya region. In the same time, more open conditions prevail off DDU. This "natural" opposite response between the Mertz Polynya and DDU regions is not observed today, whereby the 2010 calving conducted to heavy sea ice conditions in both regions.

Investigation of several sediment cores off George V Land and Adélie Land suggests that regional sea ice evolution results from the non-linear interaction of different forcing factors taking action at different timescales (Figure above). Of special interest, the heavy sea ice conditions observed today ensue from the combination of the 2010 calving and the highly positive SAM. However, more paleo-data are needed to understand whether these modern conditions represent a unique situation or already occurred in the past and, if so, at which periodicity.



Composite sea ice record off George V Land and Adélie Land (dark blue = diatoms, light blue = diatom biomarkers) over the last 11,000 years along with the main forcing factors acting at the millennial to annual timescales.

Fast-Ice Variability off East Antarctica & Challenges for Sea Ice Science

Petra Heil

Australian Antarctic Division and ACE CRC, University of Tasmania, Hobart, Tasmania, Australia
petra.heil@utas.edu.au

East Antarctic fast-ice variability
Maritime accessibility of the Southern Ocean all the way to the Antarctic coastline is a basic requirement to all engaged in exploration of the Southern Ocean and the Antarctic coastline, in moving expeditioners and supplies to/from their Antarctic stations, and conducting marine-based science. Operations off East Antarctica benefit from the largely seasonal sea ice in that region. At annual maximum extent, a belt of moving pack ice may extend in excess of 300 km north from the coast off East Antarctica [Worby et al., 1998], while during late summer the sea ice retreats close to the East Antarctic coast. Nevertheless, in the so-called Antarctic Paradox, contrary to accelerated loss of Arctic sea ice, the annual maximum Antarctic sea ice extent has been increasing slightly during recent years [Comiso and Nishio, 2008]. On 17.09.2014 the Arctic sea ice reached its annual minimum extent, down to 5.02 million km^2, making it the sixth lowest on record, while on 19.09.2014 the Antarctic sea ice reached 20.07million km^2, a new maximum since routine observations commenced in the 1970s [NSIDC, 2014]. A number of hypotheses have been suggested to explain the increase in Antarctic sea ice extent. Wind-driven changes, inducing both, direct ice advection (Bellingshausen and Amundsen seas) and changed thermodynamic ice advance (remaining Antarctic pack-ice area) have been proposed to drive expanding Antarctic sea ice [Holland and Kwok, 2012]. On the other hand, increased glacial and ice-sheet melt forms expansive pools of newly melted cold freshwater, which insulates sea ice from the underlying warmer salty deep water, aiding the expansion of Antarctic sea ice [Bintanja et al., 2013].

Regional variability exists across scales and is largely driven by boundary conditions, such as shape of coastline (including islands) and bathymetry as well as nearby topographic features (including slope of nearby ice sheet, which affects local wind systems). Within the pack, the ice drift is highly mobile and largely driven by synoptic atmospheric systems. Surface ocean currents and tidal forcing are important drivers of sea ice motion in some regions, such as over the Antarctic Slope Current or near shore [Heil et al., 2011]. Close to the coast land-fast ice is encountered. It forms *in situ* and remains immobile to its melt or until it breaks out and resumes life within the pack. The extent of fast ice from the shore is highly variable and depends on the local bathymetry, coastal protrusions or islands and any beset icebergs. Offshore from Davis, the fast ice may extend up to 15 km from the coast, off Mawson the fast ice has been observed more than 80 km offshore [Fedotov et al., 1998], while the fast ice off Casey is generally considered as not reliable. Taken together, factors like these shape the logistical approach best suited for any coastal Antarctic station.

Weekly or monthly fast-ice and snow thickness (plus auxiliary measurements) have been taken intermittently off Mawson and Davis stations since the mid-1950s [Mellor, 1960]. Analysis of these data together with oceanic and atmospheric observations suggest that fast-ice thickness off Mawson Station is determined by both, the oceanic heat transported onto the nearby shelf by intrusion of relatively warm Circumpolar Deep Water and the strength and timing of local katabatics [Heil et al., 1996]. Off

Davis Station, however, the increased cyclonic activity, due to changes in the large-scale circulation in the troposphere and lower stratosphere give rise to large interannual variability in fast-ice thickness, peaking during the 1990s, while the annual maximum ice thickness has changed little over our record [Heil, 2006]. However, dates of annual maximum ice thickness and final fast-ice breakout are delayed (each by +0.43 d yr-1), the latter consequently contribute to a prolonged persistence of the fast ice (+0.67 d yr-1) [Heil, 2006]. Overall the fast-ice characteristics co-varied largely with atmospheric changes. This is also supported by MODIS-derived fast-ice extent [Fraser et al., 2012], which exhibits high year to year as well as regional variability. For 2000 to 2008 their MODIS record shows a small but statistically-significant increase (1.43±0.30% yr-1) increase, which arose from increasing fast-ice extent in the sector from 20E to 90E (4.07±0.42% yr-1), which was counteracted by a (statistically not significant) decrease in the sector from 90o to 160oE (-0.40 ±0.37% yr-1). These changes in East Antarctic fast ice are likely contributors to the recent changes in (East) Antarctic maximum pack-ice extent.

For the wider Mawson region our record from the mid-1950s to current suggests that severe fast-ice conditions (i.e., no breakout) occurred only during the recent decade. However, there is anecdotal evidence that the fast ice survived summer twice before, once in the early 1960s and again in the 1990s. Recent progress in the analysis of high-resolution satellite imagery [Giles et al., 2011] might aid to identify causalities and assist in providing short-term outlooks of fast-ice conditions.

Challenges in sea ice science

The summary above draws on a number of *in situ* measurements and remotely-sensed observations. Here we expand on observational and related challenges in sea ice science.

- Collaborations between the scientific community and the (logistics) operators are crucial to advance our understanding of current sea ice changes and providing a future outlook.
- A common language, shared understanding and common approaches are required.
- Standardised data collection format need to be applied.
- Critical scientific issue to be addressed are:
  - Consideration of scales: most sea ice processes are scale-dependent!
  - Need to understand measurement and model uncertainties.
- Opportunities for operations to assist sea ice research:
  - Antarctica and the Southern Ocean are data sparse (including a lack of high-resolution satellite data). There is a critical need for more, standardised observations (e.g., ASPeCt [Worby and Allison, 1999] bridge-based ice-pack observations to be collected on ALL voyages into the southern pack-ice zone.) http://aspect.antarctica.gov.au/home/conducting-sea-ice-observations/ice-observation-software
  - Event logging system to be integrated within standardised underway (nautical and meteorological) database. If no underway system, then adopt with event logging system.
  - Hosting sites of observation networks, such as AWSes, Antarctic Fast-Ice Network [AFIN; http://seaice.acecrc.org.au/afin/] observatories.
  - Making available shipping plans, and deploying own or scientific drifting (sea ice) buoys.

In light of the shared need to understand the changing Antarctic sea ice conditions, developing active collaborations between science and the national Antarctic programs presents itself as key to address challenges faced by both parties.

Acknowledgements

Fast-ice observations off Mawson and Davis stations have been carried out under a number of projects, most recently under AAS2500 and AAS3328. All contributors are thanked for their assistance.

MODIS data were obtained from the NASA Level 1 Atmosphere Archive and Distribution System (http://ladsweb.nascom.nasa.gov/).

New data acquisition software for ASPeCt sea-ice observations is currently under development. Prototype data have been collected during Australian Antarctic voyages V1, V2 V3 2014/15 (under AAS5032: Dr. J. Lieser, Mr L. Symons, Mr S. Langdon), during the Alfred-Wegener Institute's PS89/ANT XXX-2 (Dr S. Schwegmann) and during CHINARE -31 (S. Kong). All contributors are gratefully acknowledged.

References

Bintanja, R., G.J. van Oldenborgh, S.S. Drijfhout, B. Wouters, and C.A. Katsman, Important role for ocean warming and increased ice-shelf melt in Antarctic sea-ice expansion, *Nat Geosci.,* **6**, 376-379, doi:10.1018/NGEO1767, 2013.

Comiso, J. C. & Nishio, F. Trends in the sea ice cover using enhanced and compatible AMSR-E, SSM/I, and SMMR data, *J. Geophys. Res.* **113**, C02s07, 2008.

Fedotov, V. I., N. V. Cherepanov, and K. P. Tyshko, Some features of the growth, structure and metamorphism of East Antarctic landfast ice, in: Antarctic Sea Ice Physical Processes, Interactions and Variability (Ed. M.O. Jeffries), *Antarct. Res. Ser.*, **74**, AGU, Washington, 141— 160, 1998.

Fraser, A.D., R.A. Massom, K.J. Michael, B.K. Galton-Fenzi, and J.L. Lieser, East Antarctic landfast sea-ice distribution and variability, 2000–2008, . *J. Clim.*, 25, 1137 — 1156, 2012.

Giles, A.B., R.A. Massom, P. Heil and G. Hyland, Semi-automated feature-tracking of East Antarctic fast ice and pack ice from Envisat ASAR imagery, *Rem. Sens. Envirnm.*, 115, 2267 — 2276, 2011.

Heil, P., R.A. Massom, I. Allison, and A.P. Worby, Physical attributes of sea-ice kinematics during spring 2007 off East Antarctica, *Deep-Sea Research II*, **58**, 1158 — 1171, 10.1016/j.dsr2.2010.12.004, 2011.

Holland, P. R. and R. Kwok, Wind-driven trends in Antarctic sea ice drift, *Nat Geosci.*, **5**, 827-875,10.1038/NGEO1627, 2012.

Mellor, M., Sea ice measurements at Mawson and Davis, 1954-58, *ANARE Interim Report*, **19**, 34pp., 1960. NSIDC, Arctic sea ice reaches minimum extent for 2014, 22.09.2014, ***http://nsidc.org/arcticseaicenews***, 2014.

Worby, A.P., and I. Allison, A Technique for Making Ship-Based Observations of Antarctic Sea Ice Thickness and Characteristics PART I Observational Technique and Results, Antarctic CRC Research Report No. 14, ISBN: 1 875796 09 6, 1999.

Worby, A.P., R.A. Massom, I. Allison, V.I. Lytle, and P. Heil, East Antarctic sea ice: A review of its structure, properties and drift, In: Antarctic Sea Ice Physical Processes, Interactions and Variability (Ed. M.O. Jeffries), *Antarct. Res. Ser.*, **74**, AGU, Washington, 41— 68, 1998.

Summation of Antarctic Sea Ice: What We Know and Where We Should Go

Phil Reid

Australian Bureau of Meteorology
p.reid@bom.gov.au

Here we will give a very brief outline of the current state of our knowledge of the variability and trends in Antarctic sea ice extent (SIE), reiterating in general some of what has been presented so far in this workshop. We conclude with providing some suggestions and highlighting some initiatives of where we might go in the future in order to reduce risk to operations within a changing sea ice environment.

There has been an increase in net Antarctic SIE over the last 30+ years (Comiso, 2010; Parkinson and Cavalieri, 2012). This net increase, however, masks the strong contrasting regional differences in extent trends. Predominantly there is a trend towards greater SIE in the Ross and Weddell seas and decrease in extent in the Western Antarctic Peninsula-Bellingshausen Sea region (WAP-BS) (Figure 1). Trends in SIE are evident throughout the year and are very distinctly regional. These regional differences are similarly reflected in sea ice seasonality, particularly in the total duration of sea ice (Stammerjohn et al., 2012). The positive trend in net SIE in the Antarctic is in contrast to the rapid decline in the Arctic (Stroeve et al., 2011).

To put the recent Antarctic SIE trends into a longer-term perspective, there is some evidence, based on ice-core proxies, that regionally sea ice extent in the decades immediately prior to the satellite era was more extensive than it has been in the last 3 decades (Curran et al, 2003; de la Mare, 1997, 2008).

We know that large-scale variability in sea ice distribution, seasonality and concentration on a year-to-year basis is largely modulated by various phases of ENSO (El Niño-Southern Oscillation), the strength of the SAM (Southern Annular Mode) and ozone depletion that determine atmospheric synoptic patterns and ocean circulation (Harangozo, 2006; Holland and Kwok, 2012; Liu et al., 2004; Massom and Stammerjohn, 2010; Simpkins et al., 2012; Stammerjohn et al., 2008, 2012). Wind, ocean currents, wave action, iceberg distribution, precipitation, basal melt of ice shelves, SSTs and a number of other variables all play their role in distribution. But many of these variables are hard to quantify and even harder to model in relation to sea ice since their individual impacts on the ice are often non-linear. When combined, as in real life, these variables impact on the sea ice in possibly counter intuitive ways. Kimura and Wakatsuchi (2011) examine the large-scale processes that influence the seasonal variability of Antarctic sea ice and find that there are regional and seasonal differences in these processes. Stammerjohn et al. (2008, 2012) suggest that there is a relationship between the variability of sea ice retreat and sea ice advance in the subsequent year.

Various mechanisms are suggested for the recent observed trends and their regional distribution. Results from Holland and Kwok (2012) suggest that changes in atmospheric dynamics are impacting on regional sea ice extent: wind-driven ice advection around much of West Antarctica and wind-driven thermodynamic changes elsewhere. Turner et al. (2009) find that a link between ozone depletion and atmospheric circulation in autumn might play a role in the recent increase in SIE. Other research suggests that various changes in SSTs and upper-ocean freshening may also be playing an important role in sea ice trends. During the season of sea ice advance SSTs south of 50°S have decreased over the last few decades (Bintanja et al., 2013), although the Bellingshausen Sea region is a distinct exception to this. Freshening of the upper-ocean in the high southern latitudes, which acts to enhance sea ice growth by stabilising the upper ocean and insulating it from ocean heat, has been attributed to an increase in precipitation entering the Southern Ocean (Liu and Curry, 2010) and increased basal melting of ice shelves (Hellmer, 2012; Pritchard et al., 2012; Rignot et al., 2013). Recent research (Li et al., 2014) suggests a link between trends in the SSTs in the Tropical Atlantic and SIE in West Antarctica via atmospheric Rossby waves. Record-breaking net sea ice extents (post-satellite era) over the last couple of years have been attributed to combined impacts of atmospheric anomalies, SSTs and ocean currents (Massom et al, 2014; Reid et al, 2015; Turner et al, 2013).

It is obvious that complex interactions between a range of drivers are responsible for the observed trends in Antarctic SIE. There is not one simple hypothesis that fully explains the trends that we have observed. The authors of the SCAR Antarctic and Southern Ocean Science Horizon Scan report state: Our understanding of the drivers and impacts of Southern Ocean and sea ice change remains incomplete, limiting our ability to predict the course of future change (Kennicutt et al., 2014). This incomplete understanding is to some degree reflected in climate model results. Simulation of net Arctic SIE from the latest CMIP5 climate models, as analysed by Shu et al. (2014), are consistent with the decreasing trend in observed SIE and, broadly, the spatial distribution of this change. However this is not the case for Antarctic simulations, where the sign of the trend of net SIE is incorrect. It has been suggested that not including ice-shelf basal melt in climate models is one of the reasons global coupled models currently fail to simulate the observed regional increase in Antarctic SIE (Bintanja and others, 2013). It is quite probable that other important mechanisms are similarly missing from climate models. Table 1 contains an extended list of questions raised within the SCAR Horizon Scan process. Answers to these and other questions might help us gain a better understanding of the complex interactions and subsequently help us close the gap between model simulations and observations.

While our understanding of Antarctic SIE drivers might currently be incomplete there are a number of national and international initiatives that, if supported, might help to reduce the risk for Antarctic operators. These initiatives include developing and employing a range of sea ice outlooks or forecasts; from short term nowcasts to longer seasonal outlooks. Much of this is beyond the scope of one individual national Antarctic operator. A solution to this is cooperative and coordinated efforts across nations on global initiatives. Several initiatives include:

- Polar Prediction Project (PPP), whose mission is to: “Promote cooperative international research enabling development of improved weather and environmental prediction services for the Polar Regions, on time scales from hours to seasonal.”
- Polar Climate Predictability Initiative (PCPI) which contributes to the development of GIPPS (the Global Integrated Polar Prediction System) on time scales of a season or beyond.
- International Ice Charting Working Group (IICWG) which was formed in order to promote cooperation between the world’s ice centres on all matters concerning sea ice and icebergs.
- The Sea Ice Prediction Network which has as a mission to “Network scientists and stakeholders to improve sea ice prediction in a changing Arctic”. It is proposed that a similar network be established for the Antarctic (SIPN South).

Trends in Antarctic sea ice extent: 1979-2014

(x103 km2 per decade)

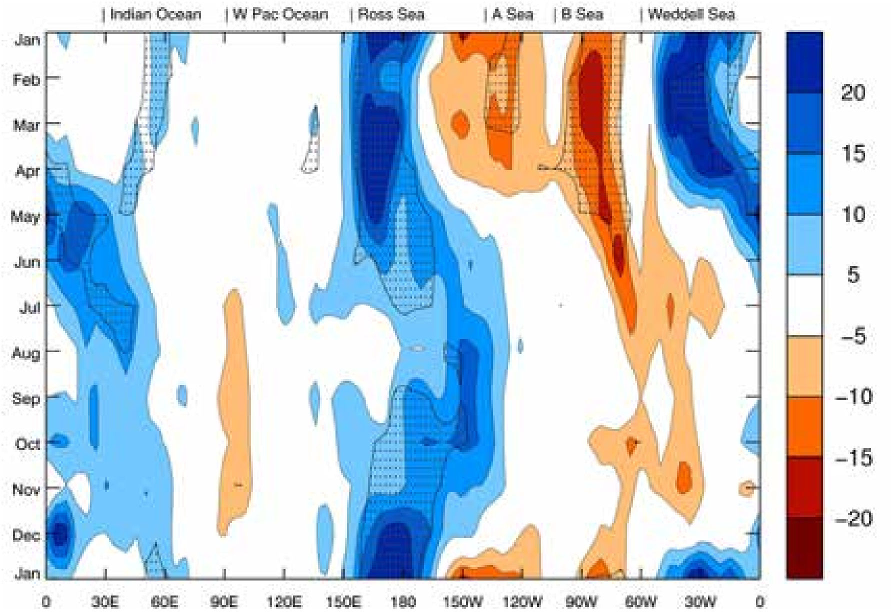


Figure 1: Trends in Antarctic sea ice extent for the period 1979-2014 (x10^3 km^2 per decade). Stippling shows regions of statistical significance ($p < 0.01$). Distinct regional differences in the signs of trends exist, with predominantly the Ross and Weddell seas showing positive trends while the Amundsen and Bellingshousen seas experiencing negative trends. Some interesting things to note are the general propagation over time of trends (positive and negative) to the east during the sea ice mid-advance season (March/April through to August). This eastward propagation is particularly evident in the: Ross Sea; Amundsen into the Bellingshausen seas; and Weddell Sea into the western Indian Ocean sector. A similar westward propagation is present in the sea ice retreat season. Data are NASA Team, based on Cavalieri et al (1996) and Maslanik and Stroeve, (1999)

6. What controls regional patterns of atmospheric and oceanic warming and cooling in the Antarctic and Southern Ocean?
7. How can coupling and feedbacks between the atmosphere and the surface (land ice, sea ice and ocean) be better represented in weather and climate models?
15. What processes and feedbacks drive changes in the mass, properties and distribution of Antarctic sea ice?
16. How do changes in iceberg numbers and size distribution affect Antarctica and the Southern Ocean?
17. How has Antarctic sea ice extent and volume varied over decadal to millennial time scales?
18. How will changes in ocean surface waves influence Antarctic sea ice and floating glacial ice?
19. How do changes in sea ice extent, seasonality and properties affect Antarctic atmospheric and oceanic circulation?
20. How do extreme events affect the Antarctic cryosphere and Southern Ocean?
23. How will changes in freshwater inputs affect ocean circulation and ecosystem processes?

Figure 2

Figure 2: Questions from SCAR Antarctic and Southern Ocean Science Horizon Scan (Kennicutt et al., 2014) that relate to sea ice. Our current understanding of the processes controlling the mass, properties and distribution of Antarctic sea ice (Q.15 and Q.18) and its interaction with the atmosphere and ocean is inadequate to predict future conditions with confidence (Q.6, Q.7, Q.19 and Q.20).

References

Bintanja R, van Oldenborgh GJ, Drijfhout SS, Wouters B, and Katsman CA, 2013 Important role for ocean warming and increased ice-shelf melt in Antarctic sea-ice expansion. Nature Geosc., **6**, 376-379

Cavalieri DJ, Parkinson CL, Gloersen P, and Zwally H, 1996 updated yearly: Sea ice concentrations from Nimbus-7 SMMR and DMSP SSM/I-SSMIS passive microwave data (1981-2011). National Snow and Ice Data Center, Boulder, CO, digital media. [Available online at http://nsidc.org/data/nsidc-0051.html]

Comiso JC, 2010 Variability and trends of the global sea ice cover. In: Thomas, DN, Dieckmann, GS (Eds.), Sea Ice, 2nd Edition. Wiley-Blackwell, Oxford, 205-246

Curran MAJ, van Ommen TD, Morgan VI, Phillips KL and Palmer AS 2003 Ice core evidence for Antarctic sea ice decline since the 1950s, Science. Vol. 302(5648), pp. 1203-1206. doi:10.1126/science.1087888

de la Mare WK, 1997 Abrupt mid-twentieth-century decline in Antarctic sea-ice extent from 41 whaling records, Nature, 389(September), 57–60

de la Mare WK, 2008 Changes in Antarctic sea-ice extent from direct historical observations and whaling records, Climatic Change, 92(3-4), 461–493, doi:10.1007/s10584-008-9473-2

Harangozo SA, 2006 Atmospheric circulation impacts on winter maximum sea ice extent in the west Antarctic Peninsula region (1979-2001). Geophys. Res. Lett., 33(2), L02502. 4, pp. 10.1029/2005GL024978

Holland PR and Kwok R, 2012 Wind-driven trends in Antarctic sea-ice drift. Nature Geosci., 5(12), 872–875 (doi: 10.1038/ngeo1627)

Kennicutt C and 69 others, 2014 A roadmap for Antarctic and Southern Ocean science for the next two decades and beyond. Antarctic Science, 1 - 16. doi:10.1017/S0954102014000674

Li X, Gerber EP, Holland DM, and Yoo C, 2015 A Rossby Wave Bridge from the Tropical Atlantic to West Antarctica. J. Climate, 28, 2256–2273 doi: http://dx.doi.org/10.1175/JCLI-D-14-00450.1

Liu J, Curry JA and Martinson DG, 2004 Interpretation of recent Antarctic sea ice variability. Geophys. Res. Lett., 31, L02205, (doi:10.1029/2003GL018732)

Liu J and Curry JA, 2010 Accelerated warming of the Southern Ocean and its impacts on the hydrological cycle and sea ice. Proc. Nat. Acad. Sci. (PNAS), 107(34), 14 987–14 992 (doi:10.1073/pnas.1003336107)

Maslanik J, and Stroeve J, 1999 updated daily: Near-Real-Time DMSP SSM/I-SSMIS Daily Polar Gridded Sea Ice Concentrations. National Snow and Ice Data Center, Boulder, CO, digital media. [Available online at http://nsidc.org/data/docs/daac/nsidc0081_ssmi_nrt_seaice.gd.html]

Massom RA and Stammerjohn SE, 2010 Antarctic sea ice change and variability – Physical and ecological implications. Polar Sc., **4**, 149-186

Massom RA, Reid P, Stammerjohn S, Barreira S, Scambos T & Lieser J, 2014 [Antarctic] Sea ice extent and concentration, in "State of the Climate in 2013". Bull. Amer. Met. Soc., 95(7), S150-S152

Parkinson CL and Cavalieri DJ, 2012 Antarctic sea ice variability and trends, 1979–2010. Cryosphere, 6(4), 871–880 (doi:10.5194/tc-6-871-2012)

Reid P, Stammerjohn S, Massom RA, Scambos T and Lieser J, 2015: The record 2013 Southern Hemisphere sea-ice extent maximum. Annals of Glaciology, 56(69), 99-106 (doi: 10.3189/2015AoG69A892)

Shu Q, Song Z, and Qiao F, 2015 Assessment of sea ice simulations in the CMIP5 models, The Cryosphere, 9, 399-409, doi:10.5194/tc-9-399-2015

Stammerjohn SE, Martinson DG, Smith RC, Yuan X, and Rind D, 2008 Trends in Antarctic annual sea ice retreat and advance and their relation to El Niño–Southern Oscillation and Southern Annular Mode variability. J. Geophys. Res., 113, doi:10.1029/2007JC004269

Stammerjohn S, Massom R, Rind D, and Martinson D, 2012 Regions of rapid sea ice change: an inter-hemispheric seasonal comparison. Geophys. Res. Lett., 39(6), L06501, doi: 10.1029/2012GL050874

Stroeve J, Serreze M, Holland M, Kay J, Maslanik J and Barrett A, 2011 The Arctic's rapidly shrinking sea-ice cover: A research synthesis. Clim. Change, 110, 1005–1027

Turner J, Hosking JS, Phillips T and Marshal GJ, 2013 Temporal and spatial evolution of the Antarctic sea ice prior to the September 2012 record maximum extent. Geophys. Res. Lett., 40(22), 5894–5898 (doi: 10.1002/2013GL058371)

Turner J, Phillips T, Hosking JS, Marshall GJ and Orr A, 2013 The Amundsen Sea low. Int. J. Climatol., 33, 1818–1829. doi: 10.1002/joc.3558

SESSION 5: SEA ICE NAVIGATION: OPERATIONAL REQUIREMENTS AND TECHNOLOGIES

On-Site Sea Ice Information (OSSI): A System to Support Operations in Polar Regions

Thomas Krumpen, Lasse Rabenstein, Stefan Hendricks and Paul Cochrane

Drift & Noise Polar Services GmbH, Germany
krumpen@driftnoise.com

Decision making for activities in ice-covered oceans can be improved by an increased level of information. The current potential of available remote sensing products is far from being exploited due to limited usability for non-experts. Main usability aspects are data unification, automated processing and ordering, early availability, smaller data packages and improved visualization functions. The OSSI (On Site Sea-ice Information) data-stream was developed to address these issues.

OSSI is characterized by 100% automation, a modular structure designed for implementation of any data product, data compression and a "with one order many data" principle. Improvement of the availability of information needed for navigation or other activities in ice covered areas can be achieved for some remote sensing data by the usage of single swath data in comparison to daily composites. For instance, swath sea ice concentration data is capable of visualizing sub-daily variations in the sea ice cover, such as tidal effects or changes in ice concentration in highly variable ice-edge zones. Furthermore, swath data is made available within two hours of acquisition; whereas daily composites are sent on board with a more than a 24-hour delay.

Developing and Delivering Operational Sea Ice Information for the Polar Regions

Andrew Fleming

British Antarctic Survey
ahf@bas.ac.uk

Developed by an international consortium of ice charting experts led by the British Antarctic Survey, Polar View in the Antarctic provides a near-real-time sea ice information service for ship operators. The service helps them minimise delays, improve efficiency, and take action to avoid life-threatening safety hazards, damage to vessels and potentially severe consequences for the environment.

It is widely used by commercial, fishing and tourist shipping, and by national polar research programmes. The European Space Agency, European Commission, UK Foreign & Commonwealth Office and commercial income fund development and ongoing operations.

SAR (Synthetic Aperture Radar) satellite imagery provides excellent information about sea ice due the high spatial resolution and ability to provide images despite cloud cover and during the polar winter. Since the loss of the ENVISAT satellite, a reduced coverage of SAR data has been available thanks to the EC Copernicus Marine Monitoring Service.

European Sentinel-1a satellite

To support the Copernicus programme, the Sentinel-1 satellite was launched on 3 April 2014. Early in 2015, Sentinel-1 will complete its commissioning phase and begin to deliver SAR imagery to support a range of activities including sea ice monitoring in the polar regions. These new images are freely available through the Polar View service.

The updated Polar View Antarctic website (www.polarview.aq) provides easy access and better visualisation of information. While a number of established features remain, new functionality and a redesigned layout, including an expanded map view, provide a greatly improved interface for all users.

In the near future a number of new data products and imagery from the Sentinel-1 SAR satellite will be integrated into the website. Other options for accessing Polar View information by email or the low-bandwidth interface are still available.

The new and improved Polar View website available at www.polarview.aq.

Ship operators in the Antarctic will also benefit from the EC Polar Ice project, which aims to develop next generation sea ice information service by integrating and building on a wide range of existing European and national-funded activities. This project will develop a number of new sea ice monitoring services, specifically for the Arctic and Antarctic regions, including sea ice pressure, thickness and forecast products.

The project will also improve the delivery and integration of information into user's on-board systems by providing an integrated service (including new information products and imagery from the new Sentinel-1 satellite) for delivery to Arctic and Antarctic marine operators. More information is available at www.polarice.eu.

Collaborative Antarctic Sea Ice Chart

Penelope Wagner

Norwegian Ice Service
penelopew@met.no

Over the years, the ice services of the International Ice Charting Working Group (IICWG) have recognized the value of cooperative activities in ice services supporting maritime navigation and polar environmental awareness. With the implementation of the World Meteorological Organization (WMO) SIGRID3 code used in geodatabases, the possibility of collaborative ice charting has made attaining this goal more realistic. Previously, the Arctic and Antarctic Research Institute (AARI) and the U.S. National Ice Center (US NIC) produced a comprehensive Southern Ocean analysis biweekly, and the Norwegian Ice Service (NIS) analysed sea ice for the Antarctic Peninsula and Weddell Sea on a weekly basis during the austral summer (October-April). Because of this overlapping area of responsibility, these three ice services implemented a regular collaborative method to analyse and disseminate a weekly Antarctic sea ice analysis hence contributing to development of safer ice navigation in the Antarctic waters as well as regional sea ice charts for improved resolution. Per agency specific requirements, all three agencies agreed to use the SIGRID3 to code sea ice concentration, sea ice type, sea ice form, and icebergs. This new product requires AARI and the US NIC to alternate the weeks when they provide comprehensive sea ice charts, in addition to ingesting the NIS sea ice charts.

This allows weekly Antarctic sea ice charts to be available for navigational planning and potential short-term sea ice forecasting methods. The revised Antarctic sea ice product also includes information on sea ice Stage of Development (SoD) and up-to-date iceberg information generated by the US NIC. During the beta testing phase, the new Antarctic sea ice chart product has shown to be an excellent upgrade to what was already available because the continuity allows for a better understanding for ice analysts when assessing sea ice behaviour, timely updates on the ice shelves, improved iceberg tracking, and more satellite-derived sea ice information included in the ice charts. This is especially useful in the Antarctic Peninsula and Weddell Sea areas where there is a lot of ship traffic because the weekly Antarctic sea ice charts will produce analysis to this region twice a week.

Additionally, the US NIC is also making efforts towards improving iceberg analysis. The US NIC is responsible for the naming of the individual icebergs used by anyone tracking icebergs including British Antarctic Survey and British Navy. They track all icebergs over 18 km but are preparing to implement iceberg tracking limits > 5km using the Brigham Young University (BYU) Scatterometer Image Reconstruction data product. Feedback from the community is important during this testing phase because ice charting services need information on how they can improve their products for operational purposes. However, the consistent sea ice archive has also shown potential to be used in the scientific community as another sea ice data source for ingesting real-time data (i.e. ship-based observations or buoy data) and short-term sea ice forecasting.

From the operational community operational community we know sea ice charts are not useful for real-time navigation but can provide useful information for navigational planning. The problem remains that there's not a lot of information available on how to use the data. From user surveys the community would like sea ice charts to be updated more frequently and with timely delivery, however sea ice charting organizations are limited by infrequent high resolution satellite cover needed for real-time data requests. The science community recognizes the importance of sea ice charts, especially because ice charts for the Southern Ocean have had a consistent archive since 1972 from the US NIC. It is used by some researchers as a ground-truth proxy for sea ice edge, extent, and climatology, however, other opinions of researchers are that the bias in the charts from subjective nature from ice analysts are not yet quantified. The current charts can be found at: http://ice.aari.aq/antice/

Antarctic Weather Service Delivery – A Focus on Best Practice and Sustainability

Scott Carpentier and Elizabeth Donovan

Antarctic Meteorological Section, Australian Bureau of Meteorology
s.carpentier@bom.gov.au

Making the most from the weather forecast

It is well recognised that timely, accurate and fit for purpose weather services underpin the safe and efficient running of Antarctic operations. However, weather and sea ice information is not consistently made available to all Antarctic operators. For example, some National Antarctic programs are supported with tailor made products on an expedition specific basis by affiliated national meteorological or research agencies, whilst Antarctic tourist, cargo and fishing vessels are mainly left to their own devices to acquire weather and sea ice information.

Moreover, a key challenge to gaining the most from the information at hand is having an underlying understanding of the limitations of the forecasts. In other words, is the model well-grounded with accurate observations at the time of analysis? Is there sufficient horizontal and vertical resolution in the model to capture moisture exchange through cracks in the sea ice; ocean waves through the marginal ice zone; the extent of katabatic winds slumping onto the coast; barrier winds; tip and gap jets; blocked flow; standing waves and lee vortices? How well do the model physics and parameterisations handle cloud phase, such as super cooled droplets, which is an important consideration for cloud and precipitation forecasts? What about the effects of turbulence? Placed in the context of continuous changes and ameliorations in observing, computing and modelling techniques, the challenge of really understanding the information at hand is considerable for the professional meteorologist, let alone the Antarctic operator who is less familiar with the ever evolving science and who has many other considerations at the forefront of their mind.

Where are Antarctic operators sourcing their weather information from?

A 2015 World Meteorological Organisation (WMO) survey to the Council of Managers of National Antarctic Programs (COMNAP) revealed that those COMNAP members who responded obtain their weather information from a near equal mix of products sourced from National weather services and free internet sites (Figure 1). COMNAP has 29 member countries and 18 responses to the survey were received. Personal communications and a 2014 survey from the International Ice Charting Working Group (IICWG) to the International Association of Antarctic Tour Operators (IAATO) indicated that IAATO members rely less on National weather services, preferring instead to use free internet sites and ship based visualisations of raw model weather data which can be freely emailed from websites such as zygrib (http://www.zygrib.org/) or sailmail (http://www.sailmail.com/).

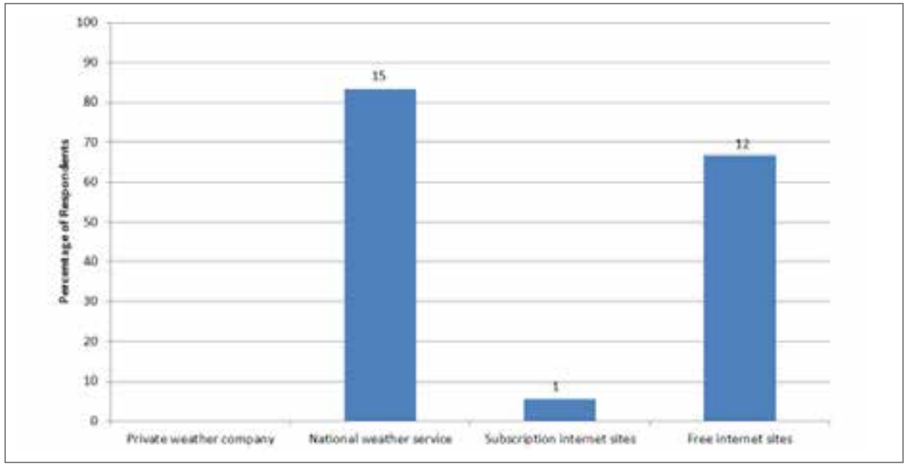


Figure 1: WMO survey to COMNAP (18 responses). Where do you gather your weather information from?

The 18 respondents from COMNAP reported wind, horizontal visibility, precipitation, temperature, sea state and sea ice as the main forecast elements that are imperative for reducing cost and risk to their activities (Figure 2). Around 80% of the respondents reported that these forecasts are imperative for tactical decision making (i.e. < 5 days).

Daily to sub-daily updates and high resolution weather products are reported as most desired. Included in the mix of routinely accessed weather products are cutting edge but often non-validated products such as sea ice motion and thickness analyses and forecasts.

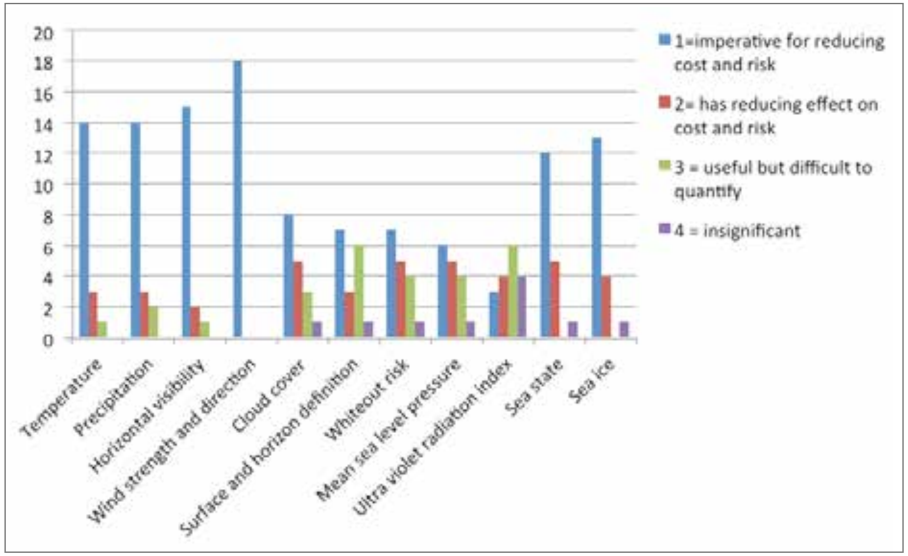


Figure 2: WMO survey to COMNAP (18 responses). How useful are the following forecast elements?

Satellite images, manual and automatic weather station observations are highly regarded by COMNAP (Figure 3) and IAATO members alike. Also of note is that around 70% of respondents indicated that their organisation would benefit from a weather service provided from Antarctica whilst only ~30% of respondents currently benefit from such a service (not shown).

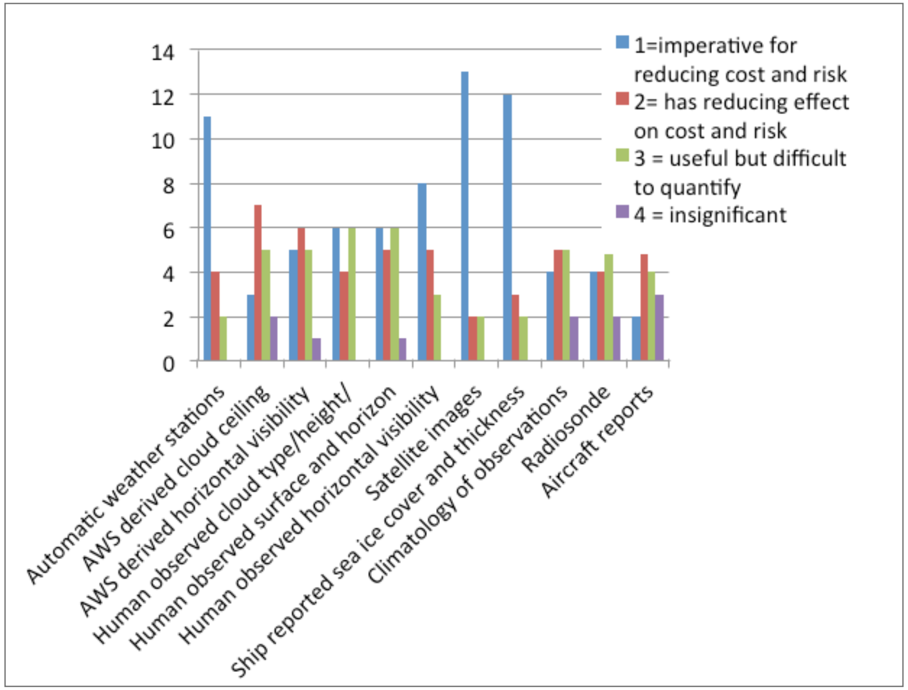


Figure 3: WMO survey to COMNAP (18 responses). How useful are the following observations?

Weather information becomes less critical for operational and strategic planning as opposed to shorter time-scale tactical decision making (Figure 4), though a requirement for seasonal to decadal atmospheric and oceanographic outlooks is still noted as useful by >50% of respondents, with a particular emphasis on sea ice outlooks (not shown). Only one respondent answered that their service requirement for seasonal to decadal atmospheric and oceanographic outlooks is currently being met.

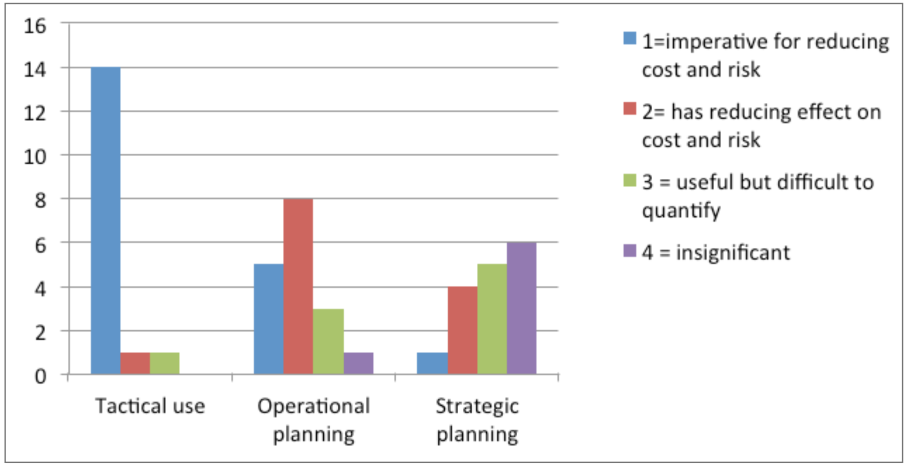


Figure 4: WMO survey to COMNAP (18 responses). Please grade the impact of atmospheric weather information on your marine operations?

Due to the harsher winter environment, most commercial, private or governmental Antarctic operations occur over the summer season. Tourism is concentrated over the Antarctic Peninsula region whilst National programs sporadically cover the breadth of the continent.

Around 70% of COMNAP respondents to the WMO survey noted that their access to weather data is limited by communication bandwidth. This figure is likely on-par if not larger for the smaller tourism and commercial operators represented by IAATO. Graphical products viewed or delivered via the world-wide-web and email is preferred, though plain language text forecasts and on-site briefings are also important weather service delivery methods for COMNAP members (Figure 5).

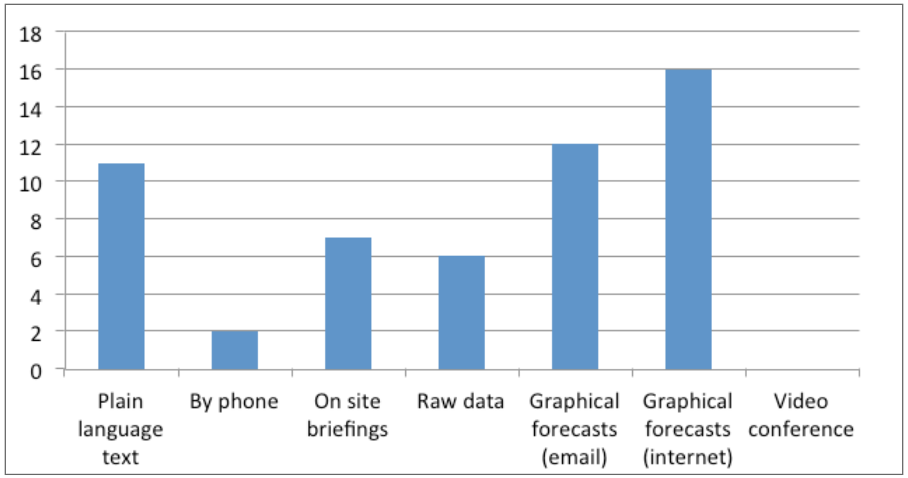


Figure 5: WMO survey to COMNAP (18 responses). How is your weather service currently provided?

The current state of Antarctic weather service delivery

Historically and to this day most National Antarctic weather services were/are built from small dedicated groups operating at the periphery of their homeland national weather service. Some National meteorological services have forecasters with limited or no Antarctic specific experience or knowledge issuing the Antarctic forecasts. Given some of the unique attributes of Antarctic weather, it is no surprise that Antarctic operators look to augment their weather knowledge beyond their National weather services by seeking out research centre and other free website weather products that they may then interpret with their own site specific knowledge and experience.

However, by dealing with multiple service providers, Antarctic operators carry more risk of misinterpreting the information at hand and are more susceptible to breaks in service quality and continuity. For example, National weather services are typically staffed 24/7 with quality assurance systems in place that mitigate risk of breaks in service. Research products usually do not come with a guarantee for service timeliness as they are not designed for service to operators making tactical decisions. Research products are also experimental by nature, so operators should not expect continuity in product quality from such sites.

There is an important and often overlooked step between weather information and weather knowledge. No matter how good the supplied weather information might be, its usefulness will always be limited by the user's ability to interpret that information (i.e. turning information into knowledge) and placing it in the context of the operation under consideration. Weather modelling is a fast evolving and highly complex field based on multiple high-tech observing platforms (satellites, drifting buoys, Automatic Weather stations, aircraft, radar…), complex analysis schemes such as 4-dVar and non-linear modelling techniques carried out by super-computers. Each step of this process is characterised by errors and assumptions. Given the complexity of the field, weather knowledge is arguably best gained through being informed and guided by competent Antarctic forecasters who are cognisant of the weather impacts and critical weather thresholds that concern the Antarctic operator. Such skilled forecasters should employ various briefing techniques to ensure that the user fully comprehends the information being provided. User education and training materials and good communication techniques underpin the transformation of weather information into weather knowledge.

A model to build and expand Antarctic weather service capacity and user knowledge

In early 2015, the WMO released their strategy for service delivery and implementation, which cites key qualities to service delivery as shown in Figure 6.

To meet the WMO criteria of authenticity, credibility, availability, timeliness, dependability and reliability in particular, it is suggested that current service-providing organisations collaborate to define best practice in the science and implement quality management principles in both their training and product delivery systems. This can ensure that the highest-quality service is offered across Antarctica.

Some Antarctic weather services are only staffed during the peak summer months by forecasters on one-off temporary assignments. An operational model that offers continuity in employment and that engages forecasters in competency training, assessment and service building over the quieter winter months would help build more experience and knowledge into the pool of Antarctic forecasters.

Figure 6: The WMO model for service delivery and implementation.

(Source: www.wmo.int/pages/prog/amp/pwsp/documents/WMO-SSD-1129_en.pdf)

It is suggested that service capacity be built up at the National and International level through co-investment, commercial development and improved coordination to minimise duplication of effort and maximise on skill and resource sharing. Consider that in the Prydz Bay region in East Antarctica, Indian, Chinese, Russian and Australian forecasters are all supplying their unique interpretation of weather conditions for stations within a 100km distance. Such multiplication of effort exists across several Antarctic regions.

Though inefficient, the current service delivery model that has National Antarctic programs relying on their respective and often remote homeland National weather services does have historical momentum, addresses language barriers and satisfies national pride. Successful international co-investment into (a) consolidated Antarctic weather service provider(s) will be conditional to not only improving service delivery as per the WMO model but also ensuring that stakeholder nations are engaged throughout the service design process.

It is suggested that the nascent fields of Antarctic sea ice charting, sea ice forecasting and climate services would benefit in particular from considered development via International collaboration and co-investment. The service model is then expandable to other fields if found suitable, like aviation forecasting for example. The World Meteorological Organisation, associated agencies and the Antarctic Treaty system provide an unparalleled framework for coordinating such international collaboration in Antarctic weather service delivery.

Sea Ice Advisories for Indian Research and Supply Vessels Operating in Central Dronning Maud Land and East Antarctica

D. Ram Rajak,[1] R. K. Kamaljit Singh,[1] Jayaprasad P.,[1] Sandip R. Oza,[1] M. Javed Beg[2]

[1]Space Applications Centre, ISRO, Ahmedabad, India
[2]National Centre for Antarctic and Ocean Research, Goa, India
Javed.beg@gmail.com

Approaching Antarctica through formidable sea ice has always been challenge. With modern ice breakers and ice class vessels things were eased out a little but effects of global climate change are affecting Polar Regions differently and thus making navigation easy in the Arctic and difficult in Antarctica especially in the eastern part. Satellite as well as navigational observations over past couple of years suggests increase in lateral extent and thickness of sea ice and thus posing serious hurdle in the logistic operations and supply vessels not being able to navigate to designated landing sites in Antarctica. For the Indian Station, Maitri season 2010-11 being the worst as the supply vessel could not reach the Indian Barrier and Station was starved of jet fuel but managed to survive on the reserve stocks accumulated over years.

Confronted with the sea ice challenges, a programme on providing Sea ice advisory was initiated in 2012. Satellite derived information related to the current status of sea ice, fast ice, and icebergs en-route are acquired, processed and verified with limited ground controls wherever possible. Space Applications Centre (SAC) at Ahmedabad and National Centre for Antarctic and Ocean Research (NCAOR) at Goa keep a constant vigil on changing sea ice scenario near Antarctic coasts adjacent to Indian Antarctic research stations Bharati and Maitri periodic Sea Ice Advisories (SIA) are relayed to supply vessel and the research bases.

The advisories are based on the information derived from multi-satellite data and products. Indian satellites capture Antarctic features in optical as well as microwave regions of electromagnetic spectrum at different spatial resolutions. While Resourcesat-2 LISS-IV (5m), Resourcesat-2 LISS-III (24m), and Resourcesat-2 AWiFS (56m) provide data in optical region; RISAT-1 Synthetic Aperture Radar (SAR) at multiple polarizations and spatial resolutions, and SARAL AltiKa provide data in microwave region. MODIS mosaic at 250m, sea ice concentration at 3.125km, and models predicted atmospheric parameters are the other major inputs which are used in preparing near real time SIA. The SIAs are prepared by integrating information related to sea ice concentration, thickness, drift, deformation, melting/refreezing trend, status of fast ice, predicted weather conditions etc. India has successfully made use of earth observation data for sea ice monitoring required for SIA and plans to include more satellite for refinement of advisories.

SESSION 6: ALTERNATIVE TECHNOLOGIES

Ice Navigation Support for Marine Operations of the Russian Antarctic Expedition

Korotkov A., Korablev V. and Lukin V.

Arctic and Antarctic Research Institute of Roshydromet , St. Petersburg, Russian Federation
lukin@aari.ru

Marine fleet remains the most cost-effective type of transport for intercontinental cargo and passenger shipping at the beginning of the 21st century. Transport operations for supporting activity of the National Antarctic Programs are not exclusion. Sea ice of the Southern Ocean remains however a serious obstacle for ship navigation in this Earth's region, like in the early 19th century when the sixth continent was discovered. Technical characteristics of modern ships and their radio-navigation equipment ensure to a great extent safety of shipping. Nevertheless, serious incidents also occur in our days with ships beset in ice and damages of ship hull and propeller-rudder system. In the second part of the 20th century when planned large-scale investigation of the Antarctic began involving international cooperation, the National Antarctic Programs of different countries used two types of ship support for their activity on the ice continent. The first type applied by USAP was in using a powerful USCG icebreaker for escorting transport and research vessels and tankers to the coast of Antarctica. The second type was in employing ice-strengthened ships-suppliers that were widespread in the Arctic shipping. Later, such countries as the USSR, Germany, Australia, France, RSA, Norway and Great Britain began construction of special multipurpose ships. Technical characteristics of such ships combined capabilities of cargo, research, passenger and tanker vessels equipped with helicopter deck complexes to meet objectives of their national Antarctic expeditions. In the USSR and Russia, these were specially built research-expedition vessels "Mikhail Somov" (1975), "Akademik Fedorov" (1987) and "Akademik Tryoshnikov" (2012), which were widely used in operations of the Soviet and from 1992 – Russian Antarctic Expedition (RAE).

The ice information-prognostic support of shipping in the Antarctic is performed at the present time through delivery of consultation services of specialized ice centers or satellite receiving stations and ice experts onboard the expedition ships and at the Antarctic stations. The RAE applies in its operations the second approach for addressing this practical task. The Arctic and Antarctic Research Institute (AARI) of Roshydromet (St. Petersburg) has a multiyear school for training ice pilots providing practical assistance to ship navigators for ice shipping. These specialists have vast practical experience in performing ship- and airborne ice observations and in receiving, processing and interpretation of satellite sea ice images in the Arctic and the Antarctic. Such specialists work onboard the RAE expedition vessels in the Antarctic and at the coastal Mirny, Progress, Novolazarevskaya and Bellingshausen Antarctic stations. In addition to receiving and processing satellite ice images, personnel of Antarctic stations also carry out coastal observations of the state of landfast ice, assessing all its age stages (beginning of seawater freeze up, establishment of landfast ice, onset of its decay and complete or partial destruction).

Modern satellite information is presented in different ranges of TV, IR, microwave and radar sounding of the underlying surface. In the summer navigation season, continuous ice observations from the pilot bridge at the transit routes of research-expedition vessels are added to satellite information. Primary processing of the aforementioned mutually complementary types of observations results in issuing summary composite ice charts at the AARI twice a month and in weekly quantitative assessments of sea ice extent in the Southern Ocean. Shipborne data serve as a unique material for verification of satellite information, which is especially important for the Antarctic ice belt, which presents an agglomeration of different age types of ice.

All data obtained are analyzed by forecaster, who assesses the character of development of ice processes compared to multiyear averages of sea ice characteristics (Figure 1) and records the individual peculiarities of the year. The results of the analysis are published in the RAE Quarterly Bulletin "State of Antarctic Environment".

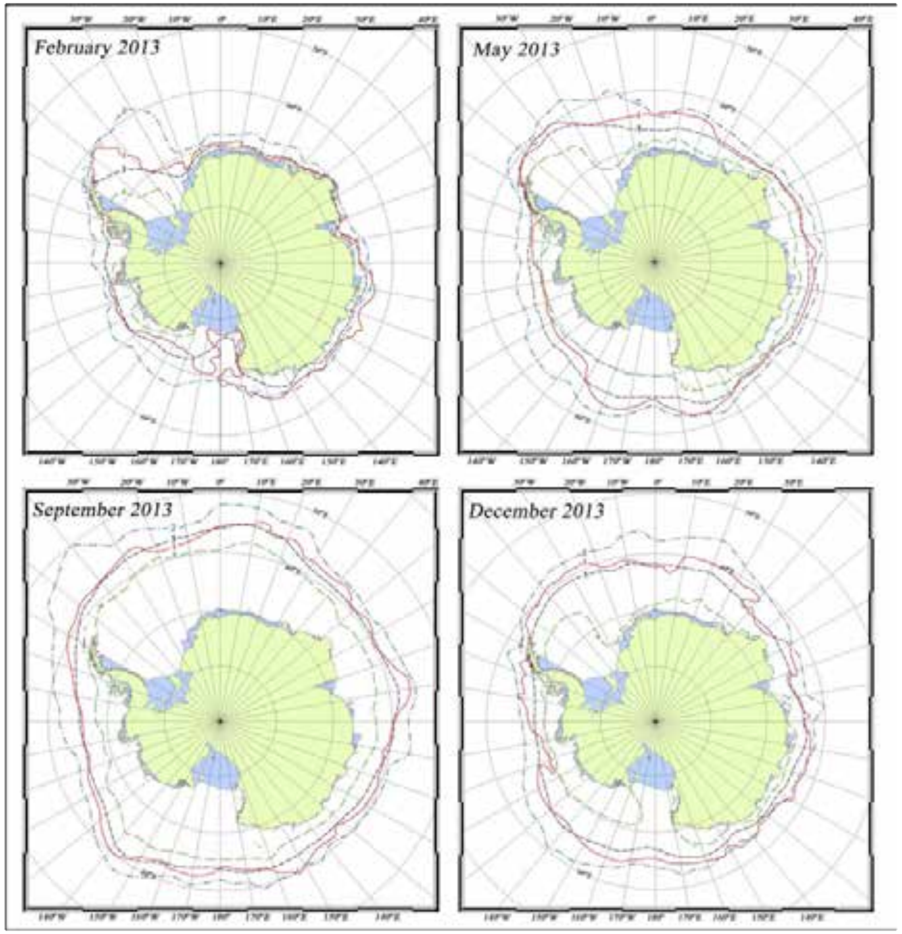


Figure 1: Mean monthly (1) location of external, northern sea ice edge in February, May, September and December 2013 relative to its maximum (2), average (3) and minimum (4) spreading in the Southern Ocean for a multiyear period.

In September-November each year, the AARI develops a long-range forecast for the entire forthcoming navigation season from December to April. The forecast is based on large-scale features of variability of the Antarctic ice cover – seasonal change of the sign of ice anomalies, prevailing quasi-biennial periodicity of sea ice extent fluctuations and opposition of the Atlantic and Pacific Ocean ice massifs. A tendency for the increased sea ice extent of the Southern Ocean, finally manifested in the new millennium, and related worsening of navigation conditions is also taken into account. The main cause is the increased amount of residual ice that has not melt in summer and much later dates of landfast ice decay up to its remaining unbroken.

Remaining landfast ice in the area of Mirny Observatory in 2002 for the first time in its half a century history had extremely negative logistical implications for RAE (Figure 2). Resupply of Novolazarevskaya station was very difficult due to unbroken landfast ice in Belaya Bay in 2000, 2011, 2012 and 2014 (Figure 3), which was used for unloading from 1986 and was practically annually cleared from landfast ice.

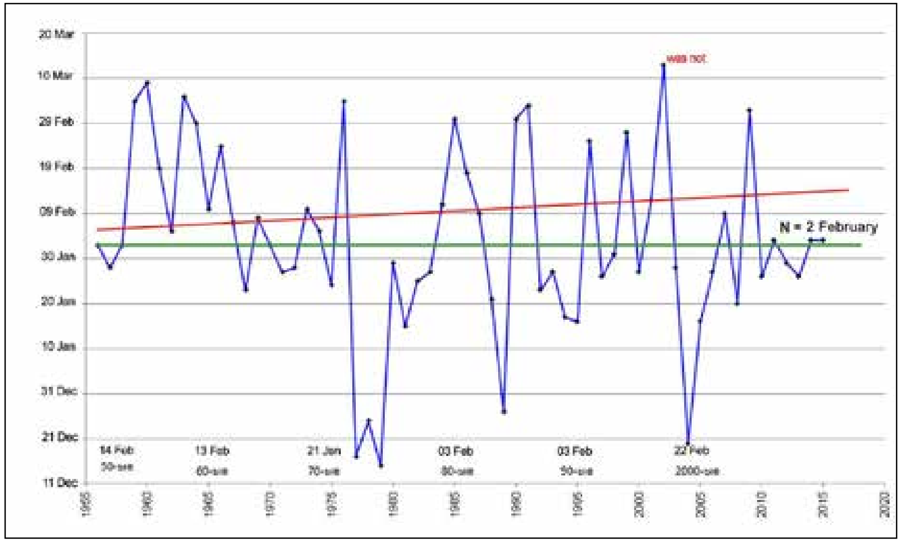


Figure 2: Variability of the dates of breakup of landfast ice at the roadstead of Mirny for a multiyear period (1956–2015).

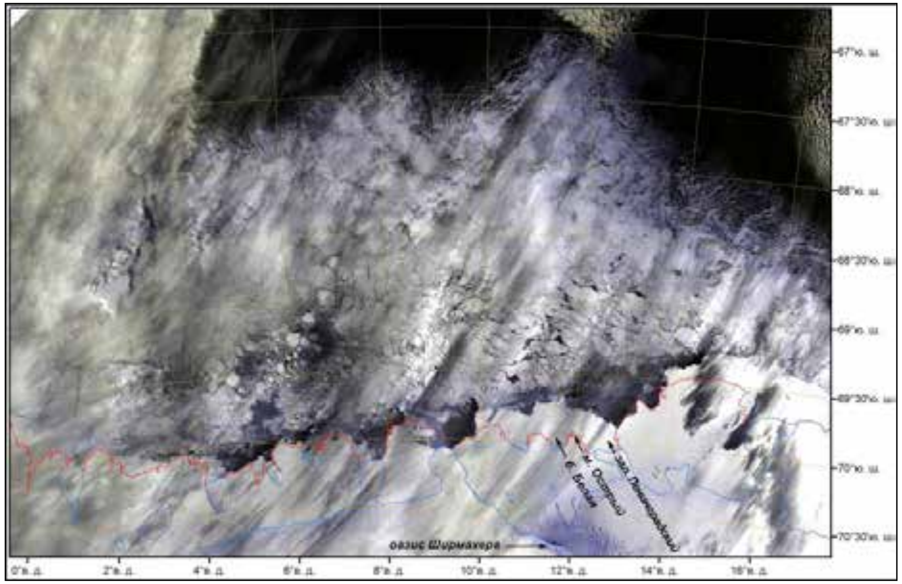


Figure 3: Ice conditions in the area of Novolazarevskaya station on 14 March 2014 from TERRA satellite data.

A methodological principle of forecasting is to determine future ice conditions by the character of development of ice processes in the preceding period. The main problem is a reliable choice of the analogue-years. The priority criteria here are the dates of the main ice phases (ice formation, landfast ice formation and breakup) and the landfast ice thickness measured at the coastal stations (Figures 4 and 5).

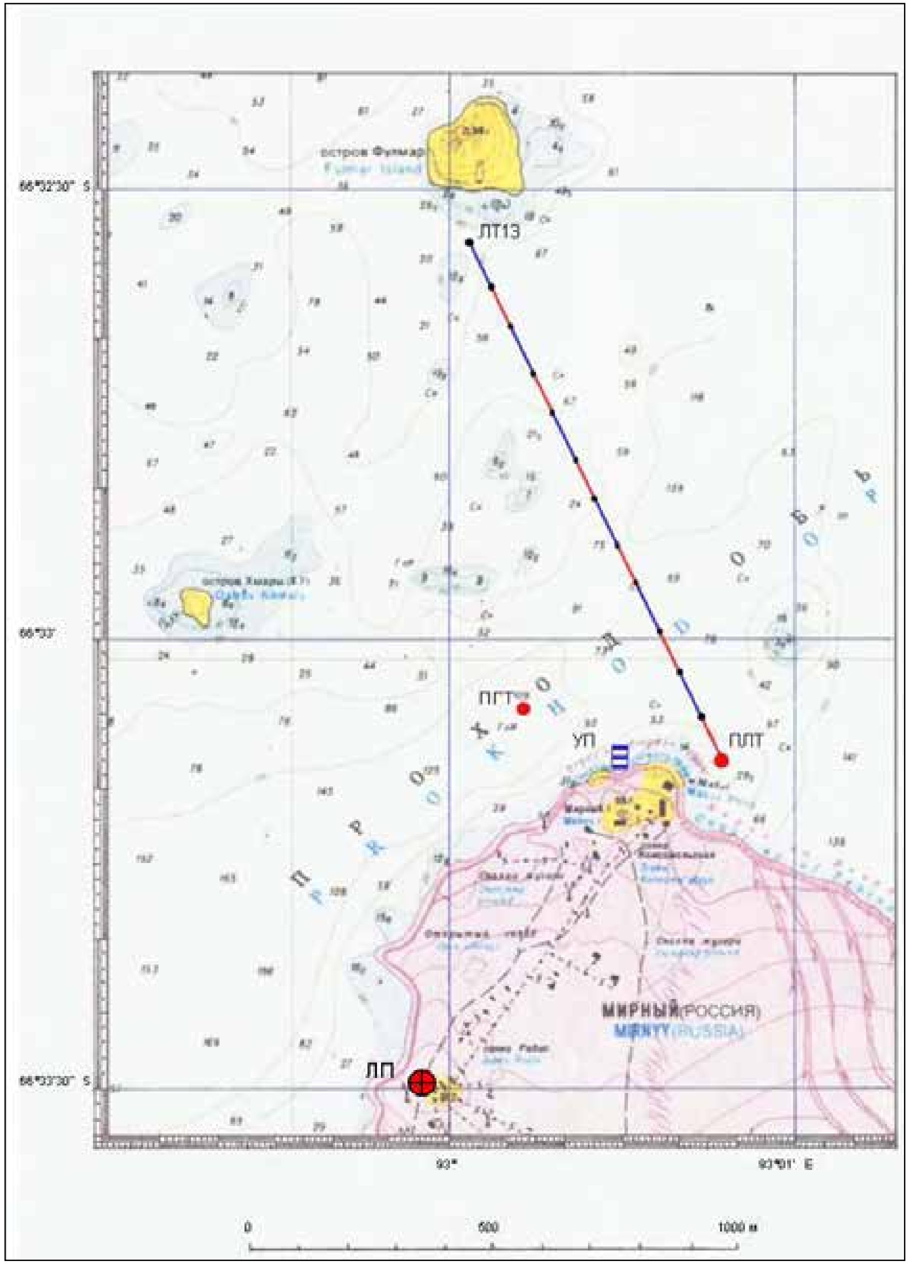


Figure 4: "Secular" profile at the roadstead of Mirny with monthly measurements of landfast ice parameters every 100 m at 13 points, which is made in the unchanged form from 1964 and partly from 1956.

In general, a great deal of attention is paid to Antarctic landfast ice as it serves as a generalizing indicator of the character of development of ice processes. The forecast includes by all means the expected dates of landfast ice decay in the operation areas. Breakup of landfast ice contributes to development of recurring polynyas, usually used for choosing transit routes of ships. It also regulates the dates of ice clearance in most regions being the only source in summer for supplementing a rapidly decreasing external belt of drifting ice.

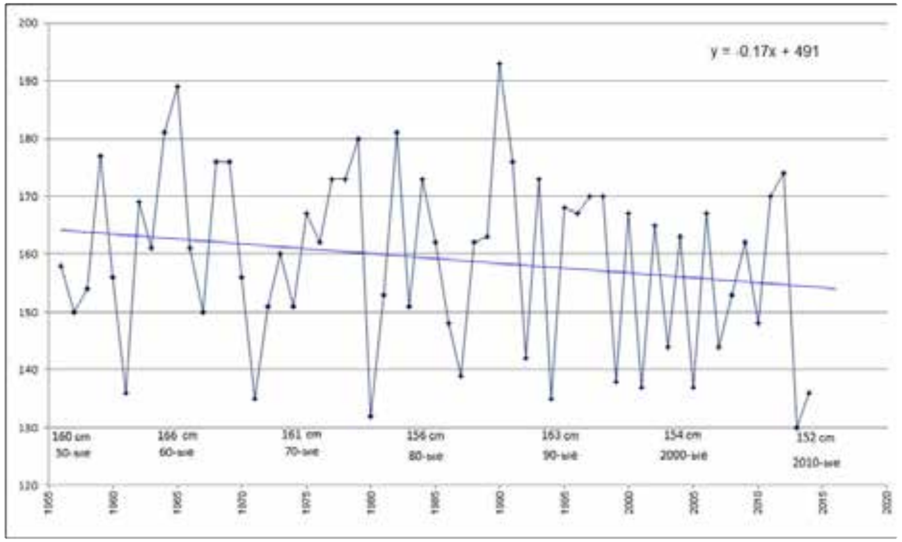


Figure 5: Multiyear variability of landfast ice thickness at the roadstead of Mirny (1956–2015).

Presence of landfast ice is a synonym of elevated sea ice extent and complicated conditions of sea operations. On the one hand, this is decisively an obstacle to ship motion to the coast, and on the other, it is the only possibility of full value resupply of polar stations where there is no natural glacial or artificially created pier. Runways for aircraft and helipads for helicopters are equipped and pipelines for discharge of fuel and ice roads for loading-unloading of heavy transport vehicles and other bulky cargoes are built.

A forecast is transmitted to ships before their departure from Capetown to the Antarctic at the beginning of December. From that time the RAE Logistical Center only monitors transit of ships mainly checking consistency of the actual development of ice events with prognostic expectations and whether the ship follows the worked our recommendations which are updated if necessary. Ship specialists begin to play here the main role.

In complicated or uncertain situations, ice reconnaissance is performed by means of helicopters.

The work of ice pilots is as follows:

- Timely submission to the Master and the Expedition Leader of comprehensive information on the actual ice situation for the operation areas obtained by means of combining data of all ice observations both carried out onboard ship and at the stations and prognostic and analytical information received from the AARI.

- Operational preparation of navigation recommendations including a variant of approach to each station and route coordinates.
- Expert decision on the ways of unloading.
- Direct provision of unloading from ship to the shore – surveying of glacial barriers and ramps, choice of the place of stay, ice anchoring, marking out on landfast ice of cargo sites and runways for aircraft and laying of ice routes on landfast ice, their equipment and safe operation.
- A significant part of preparation work for unloading to sea ice is performed by oceanographers, who work at the coastal stations. They choose in advance the place of ship approach for fuel discharge, considering iceberg situation (Figure 6).
- In general, the programme of ice and oceanographic observations at the stations is oriented to addressing as a priority the RAE logistical tasks by means of determining the state of the ice cover.
- The issued ice forecasts for the area of RAE ship operations are annually updated on the basis of actual data.

Figure 6: Cardinal change of iceberg situation near Progress Station for a quarter of a century. At the top, left, a view from the stations to the northeast on 15 February 1988. At the top, right, on 10 April 2013. At the bottom, on 21 December 2012.

The use of Remotely Piloted Aircraft (RPA) in a Sea Ice Reconnaissance Role: Pre-commitment Contemplation and Some Practical Results

D.E. Thost[1] & G. D. Williams[2]

[1] Australian Antarctic Division
[2] Institute for marine and Antarctic Studies
dougthost@yahoo.com.au

With approximate charter costs of $100,000 per day ($4,200 per hour) for a ship the size of the RSV *Aurora Australis*, cumulative navigation decisions that result in delays to the shipping programme can prove costly. Small, inexpensive, easily deployable aerial observation solutions have the potential to revolutionise the way ice navigation is traditionally done. The ability to "go up and have a look" may becoming the norm, taking minutes to accomplish, rather than being an expensive, labour intensive proposition taking hours.

The RPA can be seen as a useful, re-deployable, "eye in the sky" providing timely answers during, or prior to, ice transit, not necessarily replacing traditional helicopters when they are on-board (with the ability to travel much further to investigate conditions ahead), but complementing them. On voyages that do not have helicopters, they may prove to be the best means of assessing areas of heavy ice prior to committing to them with the vessel. This may be particularly timely with an ageing vessel, and reduced enthusiasm from the operator for engaging with heavy ice.

There is a huge variety of rotary wing RPA options available for the task of ice reconnaissance. Their primary advantage is their Vertical Take-off and Landing (VTOL) ability, and small cargo footprint. Traditional single rotor designs range from toy model helicopters to expensive long-range, long endurance machines (Figure 1a). Multicopters (with 4, 6, or 8 engines/props; Figure 1b) are mechanically simple, but aerodynamically unstable aircraft whose motion is controlled by speeding or slowing the multiple downward thrusting motor/propeller units. They rely on an on-board computer (running complex mathematical algorithms) for stable flight: no computer, no flying.

Their advantages include:

- Ease of deployment/recovery, small cargo footprint.
- Off-the shelf (Ready to Fly) options, with high resolution cameras integrated in the airframe.
- RTF options affordable
- Vertical Take-off and Landing (VTOL)
- Hexa- and Octacopters have motor redundancy as a safety factor
- Unlike an Aerostat, does not require hard-point attachment (winch system)
- With experience, may be flown away from the vessel to investigate areas of interest (endurance and broadcast range dependent).

With some disadvantages too, including:

- Endurance generally <15 minutes
- Operations limited to wind speeds <20 knots, temperatures >-15 °C
- Learning curve to operate successfully and fly in manual mode (flying in full GPS + compass dependent mode may not be possible at high polar latitudes)
- Quadcopter (cheapest option) becomes uncontrollable if one motor/prop fails.

Many Antarctic programs are already using/trialling multicopter technology in various applications, from operational support to science: the British Antarctic Survey took two small RPA (as well as a tethered balloon) on the RV *Ernest Shackleton* in the 2013-14 season, with the intention to help the vessel with sea ice reconnaissance very close to the ship; CHINARE has been using RPA to aid in surveying their runway site in the Larsemann Hills (pers. comm. Cheng Xiao); in the Australian Antarctic Program, Arko Lucieer from UTAS has used model helicopters and octacopters at Casey for moss bed surveys (2009-10, 2011-12).

Already, tourist and private operators are using RPA to capture stunning footage of the Antarctic landscape on their holiday/adventure (e.g. https://vimeo.com/124858722, and https://www.youtube.com/watch?v=yA16wGvwFk4). Some other recent RPA deployments in Antarctica have been less successful, resulting in uncontrolled fly-aways or immediate crashes on deployment. An Australian commercial fishing company used two quadcopters in the 2014-15 season in the Ross Sea, and both ended up "lost": the first crashed shortly after it took off and the other landed on sea ice and then fell into the sea. These incidents may be attributed to poor, incorrect, or no compass calibration while attempting to fly the RPA in flight modes that rely heavily on compass input to the flight controller, coupled with pilot error and minimal training.

Researchers from NOAA successfully deployed a small hexacopter in the South Shetland Islands in 2011 and 2013 for penguin and seal census work. One of their most important recommendations (http://link.springer.com/article/10.1007%2Fs00300-014-1625-4) based on their field experience was that "Pilot training is essential and should include virtual simulations, indoor missions, and supervised outdoor missions. All pilots in [their study] completed multiple hours of training that included simulators, miniature toy drones, indoor, and outdoor flying with full-scale UAS both with and without camera payloads, and under a range of weather conditions prior to actual flight testing in the field. In short, adequate training ensures successful and safe field deployments."

> In March and April 2015, Australian researchers aboard the U.S. Antarctic Program (USAP) research vessel *Nathaniel B. Palmer* carried out trials of two RPA, with special permission - following a separate review from the National Science Foundation, as part of a research cruise in the Southern Ocean.
>
> The flights tested the aerial mapping of Antarctic sea ice to determine floe-size distribution, important for future integrated observation programmes investigating the interaction of waves and ice at the margins of the ice. Preliminary results, and experiences in using RPA from the vessel, will be presented.

On the legal front, most countries' civil aviation authorities (e.g. FAA, CASA) are playing "catch-up" as the technology, and uptake of it by consumers, outstrips their ability to anticipate the required rules and regulations. In September last year, the US Antarctic Program prohibited the use of any RPA without specific authorization from the NSF, while at the same time developing an entire chapter on RPA use for their Air Operations Manual. Both COMNAP and IAATO are keenly aware of the pressure to use this technology that both researchers and tourists are bringing to bear (with IAATO announcing in May a ban on the recreational use of RPA).

Figure 1: Two extremes (a) A $US400,000 Schiebel CAMCOPTER S-100, used by the French, Brazilian, and Italian Navies, capable of autonomous missions of 10 hours endurance with 30 kg payloads, 200 km from its point of origin (b) An octocopter (DJI S1000) of the type used on the RV Nathaniel B. Palmer voyage in 2015. Approximate cost is $AU10,000 with an estimated endurance of 20 minutes, payload dependent.

Appendix 3: Workshop Participants

Surname:	First Name:	Organisation:	Email Address:
Beg	Javed	National Centre for Antarctic & Ocean Research	javed.beg@gmail.com
Bryson	Rob	Australian Antarctic Division	rob.bryson@aad.gov.au
Budd	Kerridwen	Bureau of Meteorology	k.budd@bom.gov.au
Carpentier	Scott	Australian Bureau of Meteorology	s.carpentier@bom.gov.au
Cheng	Xiao	Beijing Normal University	xcheng@bnu.edu.cn
Cincotti	Vincenzo	ENEA	vincenzo.cincotti@enea.it
Clifton	Robb	AAD	robb.clifton@aad.gov.au
Crosta	Xavier	Bordeaux University	x.crosta@epoc.u-bordeaux1.fr
Curran	Mark	AAD and ACE CRC	mark.curran@aad.gov.au
De Rossi	Giuseppe	ENEA	giuseppe.derossi@enea.it
Donovan	Elizabeth	Bureau of Meteorology	edonovan@bom.gov.au
Doyle	Murray	P & O	murraydoyle@hotmail.com
Fenton	Gwen	Australian Antarctic Division	gwen.fenton@aad.gov.au
Finnemore	Michelle	COMNAP	michelle.finnemore@comnap.aq
Fleming	Andrew	British Antarctic Survey	ahf@bas.ac.uk
Fleming	Tony	Australian Antarctic Division	tony.fleming@aad.gov.au
Frenot	Yves	IPEV	dirpol@ipev.fr
Frost	Cameron	Australian Antarctic Division	cameron.frost@aad.gov.au
Fukamachi	Yasushi	Hokkaido University	yasuf@lowtem.hokudai.ac.jp
Gales	Nick	Australian Antarctic Division	nick.gales.aad.gov.au
Godon	Patrice	IPEV / France	pgodon@ipev.fr
Heil	Petra	AAD	petra.heil@utas.edu.au
Hobbs	Will	ACE CRC	whobbs@utas.edu.au
Hughes	Nick	MET Norway	
Johnston	Greg	Rescue Coordination Centre New Zealand	Greg.Johnston@maritimenz.govt.nz
Knuth	Margaret	NSF/USAP	mknuth@nsf.gov
Krumpen	Thomas	DriftNoise.com Polar Services	krumpen@driftnoise.com
Labudda	Sharon	Australian Antarctic Division	sharon.labudda@aad.gov.au
Lei	Ruibo	Polar Research Institute of China	leiruibo@pric.org.cn

Surname:	First Name:	Organisation:	Email Address:
Lenel	Sarah	CCAMLR	sarah.lenel@ccamlr.org
Lieser	Jan	ACE CRC	jan.lieser@utas.edu.au
Maksym	Ted	Woods Hole Oceanographic Institution	tmaksym@whoi.edu
Massom	Rob	AAD and ACE CRC	r.massom@utas.edu.au
Mauderer	Reg	Australian Antarctic Division	reg.mauderer@aad.gov.au
McCarthy	Peter	Antarctica NZ	p.mccarthy@antarcticanz.govt.nz
Millhouse	Leanne	AAD	leanne.millhouse@aad.gov.au
Mundy	Jason	Australian Antarctic Division	jason.mundy@aad.gov.au
O'Farrell	Siobhan	CSIRO Ocean and Atmosphere Flagship	siobhan.ofarrell@csiro.au
Panowicz	Caryn	US National Ice Center	caryn.panowicz@noaa.gov
Payne	Bridget	AAD	bridget.payne@aad.gov.au
Ramm	David	CCAMLR	david.ramm@ccamlr.org
Raphael	Marilyn	University of California	raphael@geog.ucla.edu
Reeve	Jono	Australian Antarctic Division	jono.reeve@aad.gov.au
Reid	Phillip	Bureau of Meteorology	p.reid@bom.gov.au
Reid	Keith	CCAMLR	keith.reid@ccamlr.org
Shiraishi	Kazuyuki	National Institute of Polar Research	kshiraishi@nipr.ac.jp
Slocum	Gill	Australian Antarctic Division	gill.slocum@aad.gov.au
Stammerjohn	Sharon	Institute of Arctic and Alpine Research, University of Colorado Boulder	sharon.stammerjohn@colorado.edu
Sutton	Matthew	Australian Antarctic Division	matthew.sutton@aad.gov.au
Symons	Lloyd	Australian Antarctic Division	lloyd.symons@aad.gov.au
Tamura	Takeshi	National Institute of Polar Research	tamura.takeshi@nipr.ac.jp
Thost	Doug		dougthost@yahoo.com.au
Trousselot	Chrissie	Antarctic Tasmania	Chrissie.Trousselot@stategrowth.tas.gov.au
van Ommen	Tas	Australian Antarctic Division	tas.van.ommen@aad.gov.au
Wagner	Penelope	Norwegian Meteorological Institute	penelopew@met.no
Wallis	Ben	Ocean Expeditions & IAATO	ben@ocean-expeditions.com

Surname:	First Name:	Organisation:	Email Address:
Wang	Jianzhong	Polar Research Institute of China	wangjianzhong@pric.org.cn
Waterhouse	David	Australian Antarctic Division	david.waterhouse@aad.gov.au
Wicks	Nicole	AAD	nicki.wicks@aad.gov.au
Williams	Guy	IMAS	guy.darvall.williams@gmail.com
Wilson	David	Rescue Coordination Centre New Zealand	David.Wilson@maritimenz.govt.nz
Wooding	Robert	Australian Antarctic Division	rob.wooding@aad.gov.au
Worby	Tony	ACE CRC	tony.worby@acecrc.org.au
WU	Yilin	Chinese Consulate-General in Sydney	wuyilin@caa.gov.cn
Yuan	Shaohong	Polar Research Institute of China	yuanshaohong@pric.org.cn
Zhang	Lin	National Marine Environmental Forecasting Center	179863633@qq.com

Appendix 4: Links to Further Information

The NOAA/BAMS Annual State of the (global) Climate Assessment Reports http://www.ncdc.noaa.gov/bams-state-of-the-climate/
The Sea Ice Prediction Network (SIPN), launched in fall 2013, builds and expands on the Sea Ice Outlook project. The goal is to develop a collaborative network of scientists and stakeholders to advance research on sea ice prediction and communicate sea ice knowledge and tools. http://www.arcus.org/sipn/sea-ice-outlook/2014/post-season-highlights

The International Ice Charting Working Group (IICWG) was formed in October 1999 to promote cooperation between the world's ice centres on all matters concerning sea ice and icebergs. https://nsidc.org/noaa/iicwg/

Antarctic Sea Ice Process and Climate (ASPeCt) is an expert group on multi-disciplinary Antarctic sea ice zone research within the SCAR Physical Sciences programme. Established in 1996, ASPeCt has the key objective of improving our understanding of the Antarctic sea ice zone through focussed and ongoing field programmes, remote sensing and numerical modelling. The programme is designed to complement, and contribute to, other international science programmes in Antarctica as well as existing and proposed research programmes within national Antarctic programs. ASPeCt also includes a component of data rescue of valuable historical sea ice zone information.
http://aspect.antarctica.gov.au/

The Year of Polar Prediction (YOPP), scheduled to take place from mid-2017 to mid-2019, is one of the key elements of the Polar Prediction Project. YOPP will cover an extended period of coordinated intensive observational and modelling activities in order to improve polar prediction capabilities on a wide range of time scales in both polar regions and strongly engage in forecast-stakeholder interaction, verification and a strong educational component.
http://www.polarprediction.net/yopp.html

The participants of the WCRP/SCAR International Programme for Antarctic Buoys (IPAB) work together to maintain a network of drifting buoys in the Southern Ocean, in particular over sea ice, to provide meteorological and oceanographic data for real-time operational requirements and research purposes.
http://www.ipab.aq/

Appendix 5: Acknowledgements

COMNAP wishes to thank the following and acknowledge their contributions to the COMNAP Sea Ice Challenges Workshop, which would not have been possible without their support.

The following organisations provided funding or in-kind support for the event:

The Australian Antarctic Division (AAD)

The Antarctic Climate and Ecosystems Cooperative Research Centre (ACE CRC)

The Tasmanian Polar Network

The British Antarctic Survey (BAS)

Institute Paul Emile Victor (IPEV)

The National Institute for Polar Research (NIPR)

Polar Research Institute of China (PRIC)

Australian Bureau of Meteorology

Institute for Marine and Antarctic Studies (IMAS)

National Marine Environmental Forecasting Center, Polar Environmental Research & Forecasting Division

US National Naval Ice Center

Woods Hole Oceanographic Institution