From Ice to High Seas

SEVENTH FRAMEWORK PROGRAMME

Sea-level rise and European coastlines

www.ice2sea.eu

Writing team

Edited by Dr. Elaina A. K. Ford

Scientific contributors: Prof. David G. Vaughan, Dr. Guðfinna Aðalgeirsdóttir, Dr. Cécile Agosta, Prof. Jonathan L. Bamber, Dr. Valentina Barletta, Dr. Gael Durand, Dr. Tamsin L. Edwards, Dr. Xavier Fettweis, Prof. Olivier Gagliardini, Dr. Hartmut H. Hellmer, Mr. Paul B. Holland, Dr. Tom Howard, Prof. Antony J. Payne, Dr. Jeff Ridley, Dr. Paul Smeets, Prof. Giorgio Spada, Dr. Ralph Timmermann, Dr. Alexandre Trouvilliez, and Prof. Michiel van den Broeke.

Design and Layout: Ralph Design Ltd.

Details of the ice2sea grant

Ice2sea is a European Framework-7 Programme (grant no. 226375)

Programme Office contacts

Ice2sea Programme Office

British Antarctic Survey
High Cross
Madingley Road
Cambridge
CB3 0ET
United Kingdom

ice2sea@bas.ac.uk
+44(0)1223 221 453
www.ice2sea.eu

www.ice2sea.eu
ice2sea@bas.ac.uk

ISBN 978-0-85665-206-6

Suggested citation

From Ice to High Seas: Sea-level rise and European coastlines, The ice2sea Consortium, Cambridge, United Kingdom, (2013).

Notes

Superscripts within this document indicate ice2sea publication numbers, for which references are listed from page 43.

Ice2sea project partner acronyms are listed at the end of the document.

Photo: D. Ignatiuk, US

Table of Contents

Foreword

For decades, tourists and visitors to mountain regions have been able to see evidence of glacier retreat. Today on every continent, bare and barren rock once covered by ice is revealed in valleys and on mountain sides. Beyond the tourist's gaze and on a grander scale, it has taken a decade of data collected by sophisticated satellites to show us that similar changes are going on in the great ice sheets that cover Antarctica and Greenland.

Today, as the glaciers and ice sheets lose their ice, the water that they once held has melted and flowed in to rivers and seas, increasing their volume and raising global sea-levels. Current rates of sea-level rise are already having impacts on the most vulnerable communities and ecosystems. If as expected, rates of sea-level rise increase in the coming decades, the global humanitarian and financial costs will multiply enormously. During the lifetimes of those being born today, our coastal environments may change dramatically. It is likely that some future ice-loss and sea-level rise is now unavoidable. But nevertheless, understanding why changes are occurring today and how they could increase in the future is, perhaps, the first step in maintaining the security of our coastal regions for future generations.

The ice2sea programme arose from a call for grant proposals issued by the European Commission in 2008 in the wake of statements made in the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). This identified the contributions of ice from glaciers, and in particular ice sheets, as the major remaining uncertainty in projections of sea level.

Since the beginning of ice2sea, researchers at each of the 24 partner institutions have worked towards three common goals:

- To develop the knowledge and tools to enable a more robust prediction of sea-level rise;
- To produce the first projections of the contribution of continental ice (glaciers and ice sheets) based solely on physically-based models and tied to specific scenarios of greenhouse gas emissions;
- To identify and train a new generation of young scientists with the insight, skills, and collaborative networks to take the science of sea-level projection forward in future decades.

How far ice2sea has achieved these goals is not for us to judge, but several of us who have been involved in scientific research for longer than we care to admit have remarked that the strength of purpose and common commitment we have experienced working in ice2sea has been hugely motivating.

It would be wrong to suggest that all of the science presented in the following text was derived solely through the efforts of ice2sea – that we have not wherever possible stood on the shoulders of the giants who have gone before, or indeed, those with whom we currently collaborate. But the range of ice2sea's science has been wide, from developing instruments for measuring drifting snow in some of the most inhospitable wastes of Antarctic; to recording the pressure of water in the system of channels beneath the Greenland ice sheet; to running intricate and complex numerical simulations of ice sheets, oceans, and atmosphere, which have tied up some of Europe's largest supercomputers for several months. From the start, the multi-disciplinary nature of ice2sea has been its strength, and the interactions between scientists of very different scientific backgrounds and nationalities has already spawned new lines of research.

Finally, for me, as ice2sea's coordinator, I am perhaps most proud of the young researchers who have grown in skill, confidence and ambition within ice2sea. These researchers will take the science forward into new levels of sophistication and insight, and provide future policy makers with the information they need to manage the risk to our coastal regions.

DG Vaughan

Overview of document

In this document, we seek to provide an overview of the main issues surrounding the future of sea-level rise, and how this will affect European coastlines. Our emphasis is to improve understanding of the very real issues facing individuals and governments, and the institutions responsible for protecting and managing our coastal environments.

The document is not simply a report from the ice2sea programme, but draws on established and recent science to provide what we hope will be a valuable primer and sourcebook for policy-makers and general interest readers alike. Numbers in superscript refer to the publications list at the end of the document, which is a list of all ice2sea publications both published or submitted to peer-reviewed journals. The results and figures given here are current as of April 2013, but the nature of scientific research means that these results will continue to develop over time. And because scientific progress depends solely on the creativity and tenacity of the scientists involved, we include a few more personal perspectives, which we hope will provide inspiration for anyone considering a future in science.

Where specific regions or cities are used as examples in the following text, they are chosen only to highlight particular issues that are actually generic to many areas. We do not seek to disadvantage individuals and businesses in these areas. Future adaptations to coastal management and sea-defence planning will improve outcomes for many areas, and can in many cases be expected to maintain risk at acceptable levels.

Some ice2sea participants at the Second ice2sea Open Forum, in Copenhagen, Denmark, March 2011

Summary of outcomes

The future security and prosperity of European coastal cities and the survival of many unique European coastal habitats are threatened by rising sea-levels and increased risk of coastal flooding. Reliable projections of future sea-level change provide a basis for planning associated adaptation and risk-management strategies.

Ice2sea has reduced uncertainty in the contribution of ice sheets and glaciers to sea-level projections by: making key measurements of current changes; improving understanding of their causes; and by developing new methods for projection. Ice2sea has established a substantial European capability in sea-level projection, has identified where the remaining uncertainties exist, and which key processes are still not fully understood.

Ice2sea is a scientific programme that was developed in response to the Fourth Assessment Report (AR4, 2007) of the Intergovernmental Panel on Climate Change (IPCC), which identified a major uncertainty in the understanding of the contributions of glaciers and ice sheets to future sea-level change.

Funded by the European Union, ice2sea has focussed the efforts of researchers in 24 institutes from across Europe and around the world - in a coordinated programme of fieldwork, satellite observations, and computer simulations. The cooperation achieved by ice2sea between key institutes and scientific disciplines has advanced the understanding of present and future sea-level change to a degree that would not otherwise have been possible. Ice2sea has made fundamental progress in measuring ongoing changes in ice sheets and glaciers, and in understanding the processes responsible for rapid ice-loss, and both global and regional sea-level rise.

Combining expertise across a wide range of scientific disciplines has enabled ice2sea to develop projections of continental ice-loss using computer models that are based exclusively on representations of the physics at work in glaciers and ice sheets. Several important processes, that were previously not included due to insufficient understanding, have been incorporated in these models.

These advances achieved by ice2sea directly address issues that were of concern to the IPCC AR4. Ice2sea projections have been presented to the IPCC, to contribute to the development of best estimates of future sea-level rise that will be published by Working Group I in the Fifth Assessment Report in autumn 2013 (AR5, 2013).

The ice2sea projections based on simulations of physical processes suggest lower overall contributions from melting ice to sea-level rise than many studies published since AR4. They suggest a contribution of 3.5 - 36.8cm to global mean sea-level rise to the year 2100 for a "business as usual" mid-range emissions scenario (A1B). To obtain a projection of total global sea-level rise, other contributions, not explicitly addressed by ice2sea, must be added (e.g. thermal expansion of the oceans, and changes in terrestrial water storage). For the period after 2100, sea levels will continue to rise, initially at an accelerating rate, for many centuries.

These numbers represent the state-of-the-art in projections based on a clearer understanding of the physics, but inevitable uncertainties remain both in how the climate is expected to change over the century, and in the ice sheets' response. To explore these remaining uncertainties, ice2sea has used a less-formal approach of an "expert elicitation." This method concluded that there is a less than 1-in-20 risk of the contribution of ice sheets to global sea-level rise exceeding 84cm by 2100.

Several factors cause local and regional sea level to differ by as much as tens of centimetres to the global mean. Ice2sea has investigated the pattern of this variation. Our simulations of ice loss indicate that European coastlines will experience a sea-level rise of 10 to 20% less than the global mean. However, sea-level rise needs to be taken together with known patterns of vertical land movement, and projected changes in ocean circulation and storminess. These indicate that 50-year extreme storm-surge events could approach 1 metre higher than at present on some European coasts.

Increased understanding and more rigorous projections have provided policy-makers with a more complete and more certain basis for addressing future change. This can be used in the design of coastal defences, in adaptation projects more generally, and in flood-risk management strategies. This will therefore help to protect the future of investment in coastal regions, and allow management of risk for coastal populations.

Ice2sea has contributed to more than 150 papers submitted to peer-reviewed scientific journals to date. Many of these have transformed our understanding of glaciers and ice sheets, and their interactions with climate. For example:

- Sea-level rise is not even across the globe and has regional variations. Ice2sea studies have shown that equatorial regions will see the greatest sea-level rise and Europe will experience slightly less than the global mean. Additionally, studies on return periods for storm surges show the importance of different contributions to sea-level rise at different locations around European coastlines.
- Ice2sea has contributed to a new digital inventory that, for the first time, includes descriptions of almost all of the world's glaciers and provides an improved basis for projection of global glacier retreat. Groundbreaking research into the isolated glaciers and ice caps surrounding the Greenland ice sheet showed significant current ice loss. Projections indicate this will increase in coming decades.
- The impact of climate change on the rate of iceberg production by the Greenland ice sheet has been incorporated into projections for the first time.
- A collaboration involving many ice2sea scientists has resolved important questions regarding the comparison of different satellite-based measurements of ice-loss, giving a reliable picture of the current state of the Greenland and Antarctic ice sheets.
- Ice2sea has created new highly detailed digital maps of the bedrock of Greenland and the seabed of the Southern Ocean, which greatly enhance the reliability of ice-sheet and ocean modelling.
- Satellite studies have demonstrated the significant role that changing ocean circulation is having in driving changes in the glaciers that drain ice from the Antarctic and Greenland ice sheets.
- Projections of future climate-driven changes in ocean circulation around Antarctica indicate areas of ice that are potentially vulnerable to melting in the future. Identifying these areas has allowed the planning of studies to acquire measurements against which these future changes will be assessed.
- Ice2sea researchers have developed a new generation of ice sheet models that overcome important inadequacies of their predecessors. These models represent the state-of-the-art in ice-sheet modelling on which future improvements will be built.
- Across the board, measurements and projections are more reliable than ever before, and the systematic and comprehensive vision of ice2sea has identified the important remaining gaps.

SECTION 1

Sea-Level Rise and Society

Throughout geological time global sea level has changed. In the coming decades, the rates of future sea-level rise will likely exceed those seen in recent centuries, and pose a risk to Europe's coastal communities and assets.

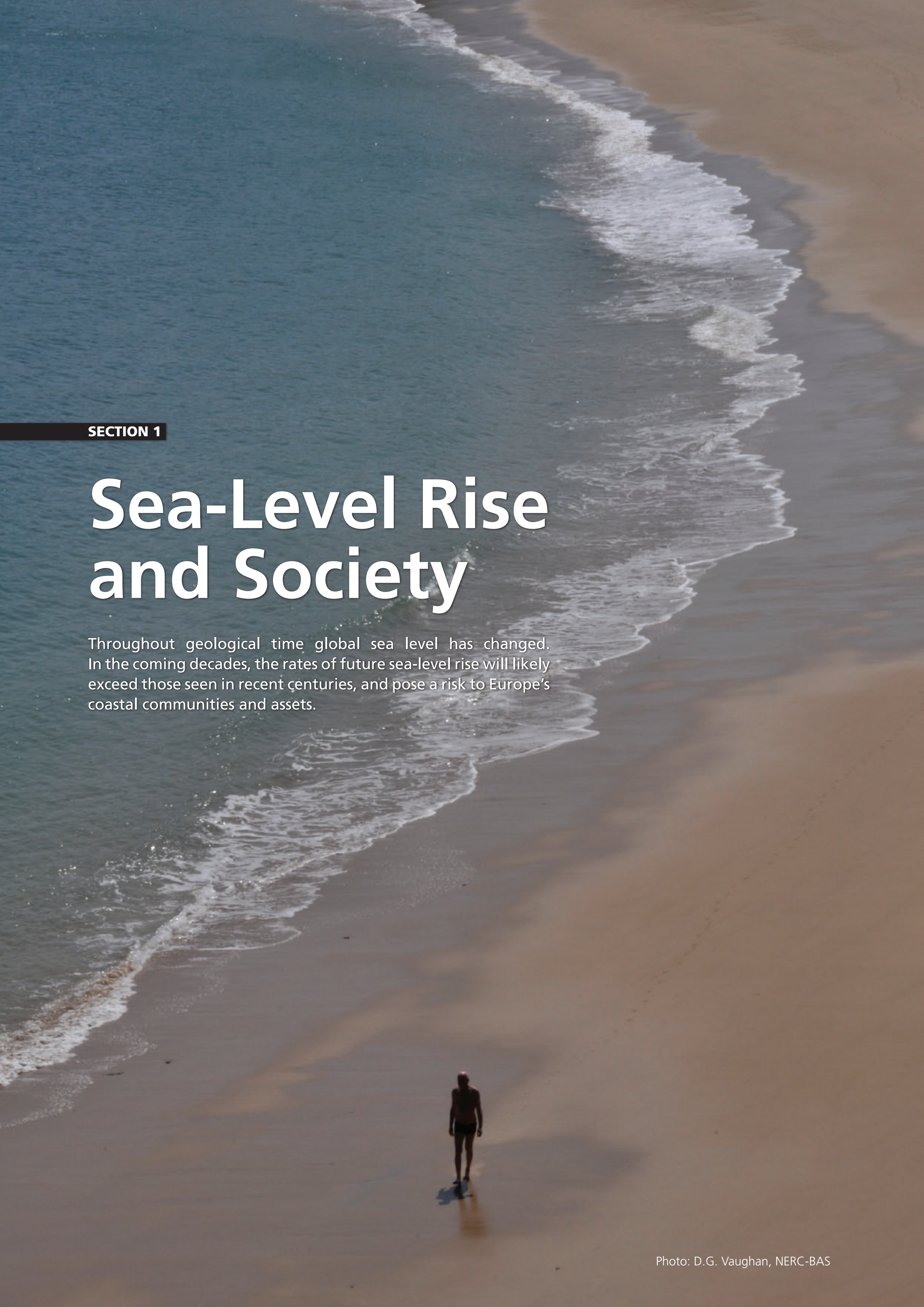


Photo: D.G. Vaughan, NERC-BAS

Sea-level change in the past

At the height of the last glacial period - around 20,000 years before the present - massive ice sheets covered much of North America, Scandinavia, and northern Asia. These ice sheets held a vast quantity of ice, and consequently the planet's oceans contained much less water. Global sea level was more than 120 metres lower than it is today. Most of what we know today as the North Sea was dry land, and early Europeans could walk across the English Channel.

As climate warmed, the ice sheets retreated from most of the Northern Hemisphere, and global sea-levels rose. From around 11,400 years ago, sea-level rise reached rates of 4cm per year and persisted for several centuries, rapidly changing the world's coastlines. Today, there is much less ice on the planet, but Antarctica still holds enough ice to raise global sea level by around 57m, Greenland by 7m, and glaciers in mountain ranges elsewhere by around 40cm.

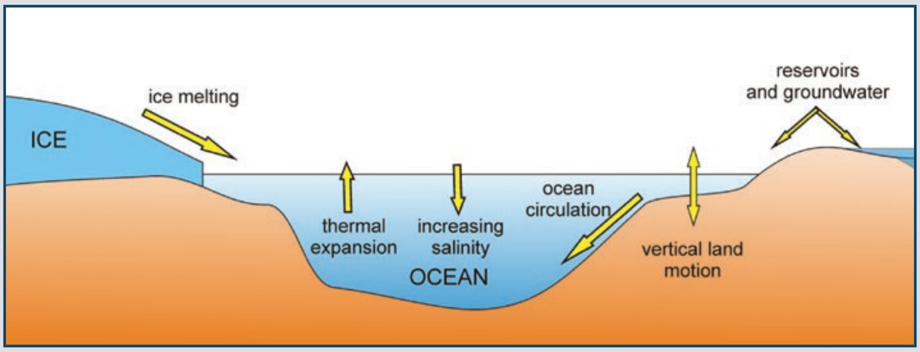
Around the world, a network of gauges, initially established to measure tides, has provided measurements of sea-level for almost 150 years. In recent decades, these records have been supplemented by satellite measurements. The composite records show that global sea-level has been rising throughout this period, but in the late 20th Century this rate has increased. Today, global sea level is rising at more than 3mm each year.

Most of the factors that affect global sea-level rise are consequences of climate change. It is therefore almost inevitable that global warming as a consequence of increased greenhouse gas emissions will drive sea-level rise to even higher rates in coming decades. This may threaten our coastal environments and assets. However, to fully understand the likely impact of sea-level rise, it is essential to understand something of the nature of coastal flooding and its sensitivity to changes in local and global factors.

Contributions to sea-level change

Global contributions: Future changes in sea level will be influenced by a wide range of processes some of which are related to climate change and other which are not. Factors affecting global average sea level are:

- the loss of ice from glaciers and ice sheets;
- thermal expansion of the water in the oceans;
- changes in the volume of water stored on land in: natural lakes and seas, groundwater, and man-made reservoirs.



Local contributions: Seas such as the Mediterranean are also affected by changes in salinity, as the rate of evaporation changes. A further set of regional and locally-specific processes affect the rate of sea-level change experienced along a particular coastline. These include: vertical land movements, changes in ocean circulation, and gravitational effects. Projections of global average and local sea-level change must take into account all the relevant processes for a region.

The risk to our coasts

The sea could inflict damage on our coastal environment in a number of ways. In the long term, invisible damage could occur through brine contamination of ground water, but the most immediate and visible effect occurs through coastal flooding. Whilst this might not be a problem for the planet overall, it can have significant impact on human activities. In the more distant past, populations were less constrained to one location through settlements, so could adapt more easily to changes in sea levels and flooding. Nowadays however, we have significant communities and assets that cannot simply be moved if sea levels are to rise, or if floods become more frequent.

Coastal flooding occurs when one or more factors raise sea-level and drive sea water further inland than is normally expected. Such factors include: high tides, low atmospheric pressure, onshore winds, and even tsunamis. The worst floods often occur when two or more of these factors occur simultaneously. The flooding that results may persist for only a few hours, but the damage caused can take many years to put right.

In Europe, particularly dramatic floods have occurred several times in past centuries when high tides and low atmospheric pressure in the North Sea coincided with the arrival of storm surges that originally formed in the Atlantic Ocean. In 1953, when such conditions occurred, thousands of lives were lost in the Netherlands, southern England, Scotland, and Belgium.

Given the element of chance in how the factors that contribute to particular storm events coincide, the risk of coastal flooding can be understood most clearly through statistics. For many areas around Europe, excellent historical records exist that allow the frequency and magnitude of flood events to be quantified. These statistics are often presented in terms of the flood height that could be expected only once in a particular period – the so-called "flood return period."

The following case studies (see boxes) show the dramatic impacts that even modest sea-level rise would have on the statistics of flood events in some regions. The examples show very well how the risk of a damaging storm increases rapidly with even rather modest sea-level rise. While the case studies are only examples, similar reasoning applies to many other coastlines in Europe.

Areas of Northern Europe lying within 1m of sea level.
(Source:CReSIS)

A rational approach to the quantification, and therefore management, of the risk of coastal flooding begins with a thorough understanding of the statistics of flooding events at the particular location in question, but this is not the only consideration. Where there are concentrations of assets with high capital value or high population density, levels of sea-defence must be built high to provide a high level of protection (e.g. 1-in-1,000 years). Conversely, in sparsely populated areas, a similar level of protection may be unaffordable, or too disruptive to provide, and lower levels of protection (e.g. 1-in-10 years) may be all that is practically achievable. Eventually, as flooding becomes too frequent some areas may find their use changed, or even have to be abandoned altogether.

Case Study 1 - London and the Thames Barrier: flood risk in a densely populated area

The 100th closure of the Thames Barrier. Although there is localised flooding downstream, the city behind is protected.
(Photo: UK Environment Agency)

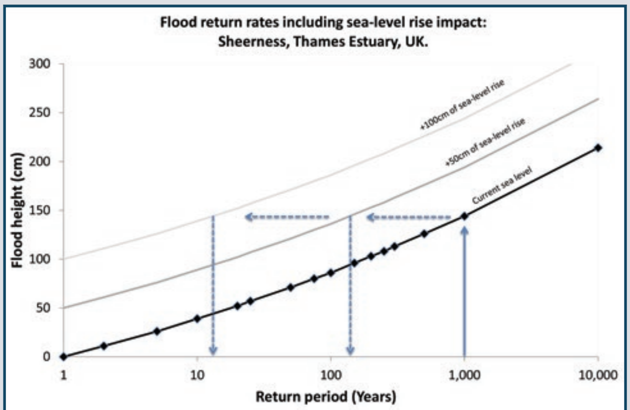
What's at risk? London is a city that sits on the tidal reaches of the River Thames. For centuries, Londoners have sought protection from storm surges behind protective walls. These have been raised several times in response to flooding and near-flooding events. Today a more systematic approach to risk management is required.

What has been done? The Thames Barrier (see photo) was designed following the North Sea floods of 1953. On the basis of historical records, statistics were developed for London such as those shown in the graph below. These allowed engineers to determine the height they needed to build the Thames Barrier to achieve a specific level of protection of better than only once-in-one-thousand years. Since it opened in 1983, the Thames Barrier has successful protected the city of London; it is routinely closed when storms are predicted.

The future? The statistics can also be used in another way. If there was no other change in statistics of storm events or their magnitude, but sea-level in the Thames estuary was to rise by say 50cm, the level of protection provided by the current Thames Barrier would be degraded and we could expect a storm to overtop the barrier once per 150 years. Similarly, a sea-level rise of 100cm would increase the frequency of flooding to an average of once in only 12 years!

The UK Environment Agency, which is responsible for flood defence across the UK, has developed a plan ('Thames Estuary 2100[a]') that will allow them to maintain the risk to London at a level acceptable to its inhabitants. This will be achieved through progressive improvements to defences along the banks, and to the Thames Barrier and associated infrastructure. However, implementing this plan requires foresight and reliable projections of future sea levels.

[a]http://www.environment-agency.gov.uk/homeandleisure/floods/104695.aspx



Flood statistics for the Thames Estuary. Heights are above the highest annual expected storm surge. Current defences are adequate to provide protection to the one-in-one thousand years, but this would be substantially reduced with a change in regional sea level – to approximately once in 12 years with a metre rise.
(Data: Proudman Oceanographic Laboratory)

Case Study 2 - Port of Rotterdam: Economic engine of the Netherlands

What's at risk? The Rhine delta is a densely populated area, where 1.5 million people work and live. It also includes one of the largest economic centres in Europe: the port of Rotterdam. Through this port and its connections inland, mainland Europe is supplied with goods from all over the world. In this region, sea water from the North Sea meets fresh water from the Rhine and Meuse. These both represent an inundation threat for Rotterdam, its port, and the surrounding cities, and require innovative techniques of management. However, the water in this area is also needed to support economic activities: the port needs good access for large vessels to and from the North Sea, and the fresh water is needed for the local industrial cooling and irrigation for large-scale greenhouse food production.

What has been done? After the North Sea flood of 1953, which killed more than 1,800 people in the Netherlands, an ambitious flood defence system was conceived and deployed, called the Delta Works. The Delta Works were designed to protect the estuaries of the rivers Rhine, Meuse, and Scheldt. The works were completed in 1998, when the storm surge Maeslant Barrier, in the Nieuwe Waterweg near Rotterdam, was completed (see photo). The design of the Maeslant Barrier is such that it allows passage of vessels under normal conditions, and can be closed when water levels are predicted to be high.

Maeslant Barrier, Rotterdam, The Netherlands.
(Photo: Beeldbankvenw)

The future? Following the damage caused by Hurricane Katrina to New Orleans September 2007, the Delta Commission[b] published a report to consider the anticipated effects of global warming and associated rise in river and sea levels for the next two centuries. This report advised that the Netherlands would need to expand on the Delta Works to strengthen the country's water defence. The plans include more than €100 billion in new spending by 2100 for water protection measures. This includes broadening coastal dunes and strengthening sea and river dykes. The Commission advised that in the most extreme case the country must plan for a rise in the North Sea of 1.2m by 2100. The ice2sea project will help to refine these estimates and make more accurate extrapolations of sea-level rise, and also beyond 2100.

[b] http://www.deltacommissie.com/

Glaciers

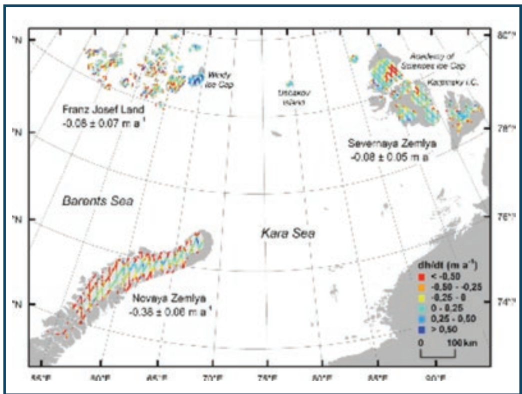
A glacier is defined by glaciologists as a body of snow and ice in which the ice itself is moving from an area of snow accumulation to an area of loss (ablation). This means that the ice within a glacier is constantly on the move, usually at a few tens of metres per year, but occasionally up to several kilometres per year.

Glaciers are naturally self-regulating systems that have internal processes that control their size and the volume of ice that they contain. The processes naturally adjust the size of the glacier until it reaches an equilibrium where the ice lost each year, by melting and in some cases iceberg production, is balanced by new snowfall. When a changing climate alters rates of accumulation or loss, the glacier will tend to adjust its shape and volume to find a new equilibrium. The time taken to reach this new equilibrium depends on many factors, but larger glaciers tend to take longer to fully respond to changes in climate.

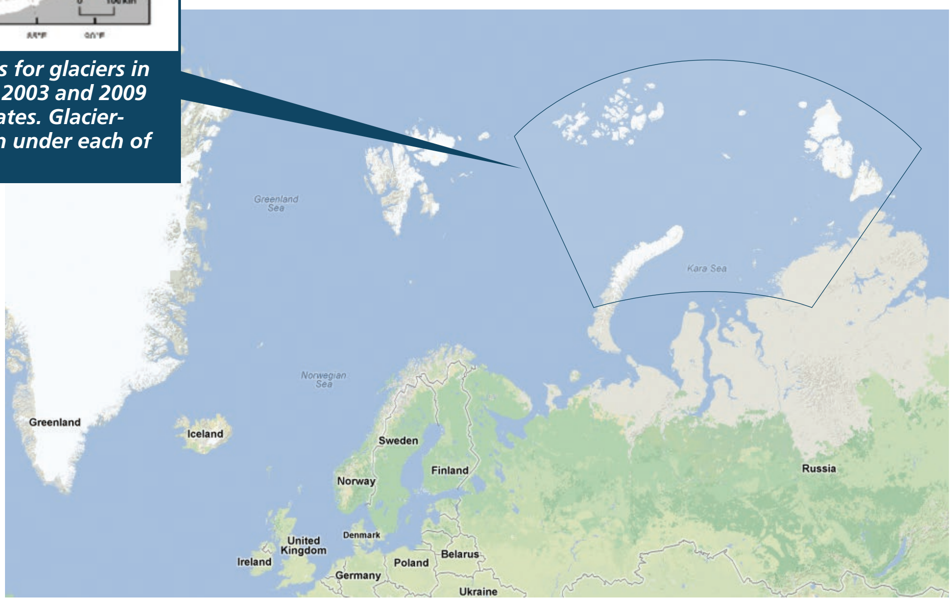
Helheim Glacier, Southeast Greenland, near the town Tasiilaq.
(Photo: Andreas Peter Ahlstrøm, Geological Survey of Denmark and Greenland)

Glaciers experience some of the most visible and dramatic impacts of climate change. Many provide valuable long-term records of the direct effects of climate change. Around the world glaciers are disappearing in response to changing climate. In some areas (e.g. the Alps, Andes, and Rocky Mountains) many small glaciers have disappeared entirely since the 1850's, and many more are losing ice year-by-year.

In some areas, notably remote Arctic regions, there are very few in-situ measurements of glacier change. Ice2sea researchers have used satellite data to produce some of the first comprehensive assessments of glacier change in the Russian Arctic archipelagos[051], and peripheral glaciers of Greenland[150]. Our results add both regions to the list of glaciated areas losing ice at dramatic rates.



ICESat satellite data repeat-tracks for glaciers in the Russian High Arctic between 2003 and 2009 with average elevation change rates. Glacier-wide elevation changes are given under each of the three region names.[051]



Ice Sheets

Ice sheets are particularly large bodies of glacier ice that cover continental-sized areas. As recently as 20,000 years ago, ice sheets covered much of the northern hemisphere land masses, but today there are only two ice sheets in existence, one covering Antarctica and the other covering most of Greenland.

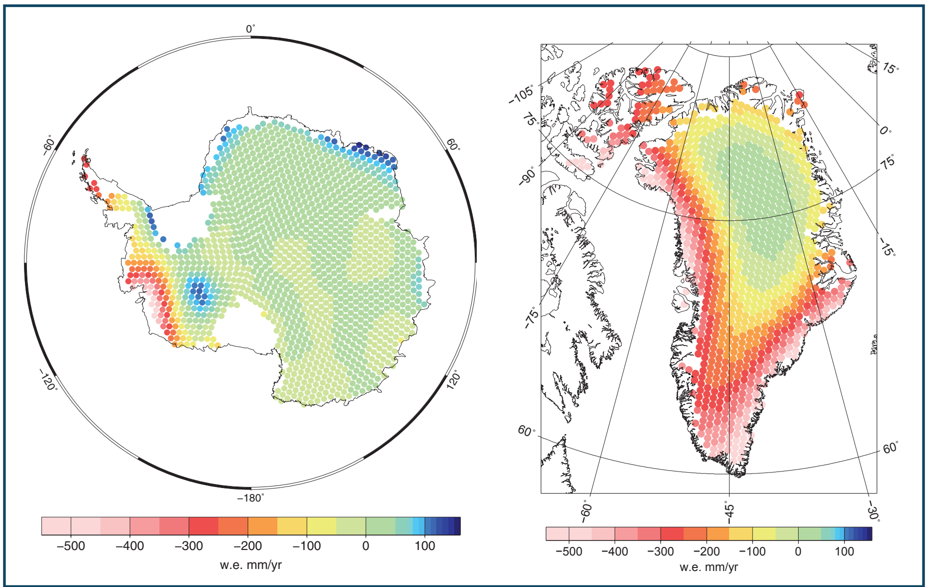
The two ice sheets contain far more ice than all the glaciers in the world combined, and have the potential to alter sea-level dramatically. There is evidence that some parts of the Antarctic ice sheet are still responding to changes that occurred at the end of the last ice age some 10,000+ years ago. Recent studies have shown that ice sheets can be surprisingly sensitive to changes in the climate of the atmosphere and ocean.

It is unlikely that either of the two great ice sheets will melt completely in the foreseeable future, if ever. Nevertheless, they are among the least understood, and potentially biggest, contributors to future sea-level rise, and as such it is of the utmost importance to understand how these great ice masses will develop in the future.

Measuring ice-sheet change from space

The assessment of current rates of ice loss from Antarctica and Greenland is crucial to future projections of change. Even in the late 1990s, scientists had little idea whether the ice sheets were growing or shrinking. With the advent of increasingly sophisticated instruments onboard satellites we can measure both the geographical pattern of ice loss and gain, and the year-by-year changes that occur.

Ice2sea and our collaborators have used laser, radar, and gravity-measuring satellites to measure ice-sheet change.[014,039,116,125] In the period 2005-2010, the IMBIE[c] project, Greenland lost ice at a rate of 263±30 Giga-tonnes per year, Antarctica 81±37Gt per year.[125] This is equivalent to 414 Giza Pyramids each day, and this much water would fill 138 million Olympic sized swimming pools every year, or Lake Geneva four times over. In total, this amounts to 4mm of global sea-level rise over the four years.



Patterns of ice-loss (reds) and gain (blues) in Antarctica and Greenland measured using data from the GRACE satellite mission[116].

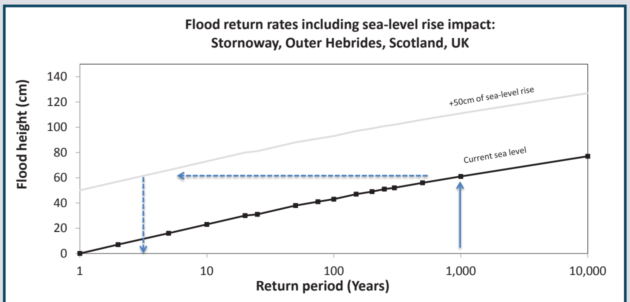
[c] IMBIE: The Ice Sheet Mass Balance Inter-comparison Exercise: www.imbie.org

Case Study 3 - Irish and Scottish Machair: flood risk to sensitive natural environments

Machair. **(Photo: Alison Cook)**

What's at risk? Machair is a unique habitat occupying 25,000 hectares of the low-lying Atlantic coasts of the Republic of Ireland and the Scottish mainland and Western Isles. For a few weeks each summer, the Machair becomes a carpet of beautiful wildflowers of many different shapes, sizes, and colours. It supports rare species, such as Irish Lady's Tresses, orchids and Yellow Rattle, and provides a home for a diverse array of birds, as well as rare insects such as the Northern Colletes bee.

What has been done? Although the Machair is not an entirely natural system, in that much of it has been managed for generations, it survives because of its close proximity to the sea. Indeed, the Machair exists in a delicate balance with the sea, which provides a dressing of lime-rich shell sand, helping to neutralise the acid from the peaty soil to create an alkaline environment on which this system thrives.



Flood statistics for the Isle of Harris. Heights are above the highest annual expected storm surge. Storm return periods in this area alter considerably as regional sea-level rises.
(Data: Proudman Oceanographic Laboratory.)

The future? Storm statistics for the Machair environments tell a different story to that of the coastal cities from previous case studies. Some Machair is already threatened by coastal erosion, but this would be exacerbated by more frequent flooding from rising sea levels. The storm statistics (see figure) show that this area is sensitive to change. Even moderate rises in regional sea-level (e.g. an increase of 50cm) would mean that storms currently expected only every 1,000 years could come more than once each decade. The equivalent scenario for London, for example, would need an increase of a metre to achieve this same effect.

Machair covers large areas, and is of ecological and cultural significance, but rather low commercial value. It may therefore be impractical to defend this habitat against sea-level rise, but understanding the vulnerability of this unique environment may help us safeguard its future.

SECTION 2

Understanding Ice: Observing the Cryosphere

Insight into the future of glaciers and ice sheets will only come about from a thorough understanding of the natural processes that shape the ice on our planet today.

Photo: P. Smeets, UU

Key observations

Reducing the uncertainties in climate projections, and particularly in sea-level rise projections, requires not only the development of more sophisticated computer models, but also improved understanding of the processes that lead to change. Measurements of past and current rates of change are also required, to provide data that allow models to be set up and tested.

Ice2sea has undertaken collaborative field campaigns in many locations to improve understanding of the key processes that lead to change in ice sheets and glaciers, and has processed huge volumes of satellite data to measure current rates of change. The insight gained from these activities has been incorporated into the development of the models we use to predict the contribution of glaciers and ice sheets to sea-level rise.

The complete details of these campaigns are reported in scientific journals (see the Publications list), but include the following highlights:

- Ice2sea researchers and our collaborators used data from satellites from the European Space agency, NASA, and the Canadian (CSA), Japanese (JAXA), and German (DLR) space agencies, to measure recent ice loss from Antarctica and Greenland, and several Arctic areas. These measurements allow understanding of the contribution of ice to sea-level rise, and provide a starting point that is used to guide future projections;[014, 017, 039, 051, 116, 125, 136]
- Since the 1980s, climatic-driven collapse of floating ice shelves around the Antarctic Peninsula has caused the glaciers that fed the ice shelves to accelerate dramatically. Ice2sea has developed an understanding of the specific climate conditions that cause ice shelves to collapse; this will allow scientists to make predictions for all Antarctic ice shelves under various climate change scenarios;[123]
- Monitoring of iceberg production and ice flow on key glaciers on Svalbard and Greenland has been undertaken using GPS receivers designed to operate autonomously for up to two years. Several years of high-quality records[130] allowed ice2sea researchers to discriminate seasonal and long-term changes in glacier flow, and understand the processes causing them;[024, 025, 029]
- Four new ice cores were drilled by ice2sea high on the ice sheet in northern Greenland. These cores were acquired from sites where ice cores were originally collected in the 1970s and 80s. The new cores show that, as expected, atmospheric temperature has increased in this area. However at present there is no evidence of the increased snowfall that is eventually expected in this area;[103]
- Ice2sea contributed to an international effort in the development of the most globally complete inventory of glaciers to date.[097, 138] The *Randolph Glacier Inventory* contains more detailed descriptions of glaciers than has ever previously been compiled;
- Using data from meteorological stations and satellites, ice2sea researchers showed statistically significant increases in the occurrence of summer melt on the Antarctic Peninsula and increased ice-loss through summer melting;[082]
- Finally, ice2sea and our collaborators have delivered several improved datasets that are essential foundations for ice-sheet modelling. These include: new digital descriptions of the seabed and subglacial topography of Antarctica[013, 035] and Greenland,[142] and the first comprehensive map of Antarctic ice-shelf thickness.[027]

Whiteout and the mystery of the disappearing snow

Early explorers of Antarctica were particularly surprised by the strength of the winds they experienced, and the blinding blizzards and whiteouts that would occur quite suddenly as the winds grew. Today, we have a better understanding of the processes that cause whiteouts, as above a critical wind speed snow can be suddenly lifted into the air. We also understand that once in motion, this snow can be transported considerable distances, which redistributes it across the continent. It can even be removed entirely from the ice sheet. This removal will occur, either where snow that fell on the ice sheet is blown into the surrounding ocean, or the "blowing snow" can sublime into the air and be transported away as water vapour. However, neither of these two processes are currently well-represented in climate models, nor are they fully accounted for in assessments of the loss of ice from the ice-sheet.

For decades, scientists have tried to measure blowing snow, but were hampered by the limitations of their instruments and the severity of Antarctic storms, during which wind speeds frequently exceed 150km/hr. This meant that at the beginning of ice2sea, no Antarctic measurement station had survived long enough to record blowing snow for a full year.

Cécile Agosta and Caroline Halle dig a hole to tether the automatic weather stations (which hold the new acoustic gauges) into the snow. This will allow these stations in Terre Adélie, Antarctica to withstand the strong polar winds. This system will measure meteorological data and blowing snow fluxes for several years before it needs replacement.
(Photo: A. Trouvilliez, CNRS)

However, a new technology has recently become available. Instruments have been developed by IAV Technology that detect acoustic impulses that are created as snowflakes collide with a hollow tube. After considerable processing, the signal of these impulses can be converted to a measurement of the flux of blowing snow passing the tube.

In 2010, after testing and calibration in the French Alps, ice2sea researchers deployed the new acoustic gauges at three points in Adélie Land, Antarctica. Over the following three years, they acquired a unique database of half-hourly measurements of blowing snow. These records show that blowing snow episodes are very frequent and can last for more than a month. The mass of snow blown past one site was phenomenal – 3,000 times more than the amount from snowfall. The records of blowing snow acquired by ice2sea are crucial to understanding the processes described above, and they will lead the way to a more effective comparison between observations and climate simulations.[016]

In hot water

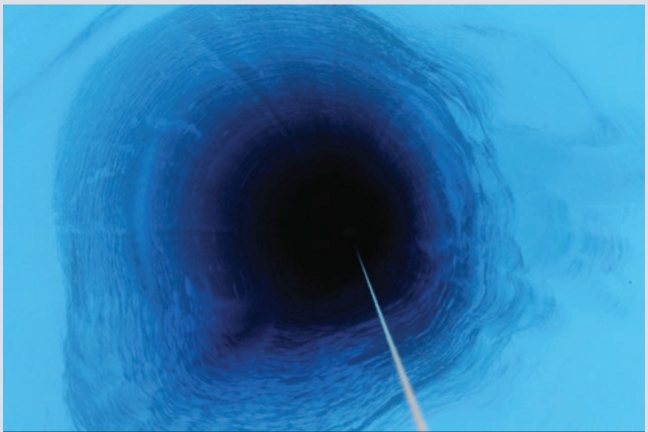
For decades it has been understood that Alpine glaciers show a marked increase of ice velocity during periods of summer melt. Surface melt water penetrates glacier ice via crevasses and moulins (circular vertical shafts). This lubricates the glacier at its base and increases the speed the glacier flows. The speed of the glacier therefore strongly varies with the pressure and speed at which meltwater is routed underneath the ice, through subglacial pathways.

A hot water drill (supplied by AWI, Germany) in operation on Russell Glacier, Greenland, 2010. The black pool in front holds the water supply for the drill. The water is heated and compressed by the six heaters in the orange frames. The yellow winch in the background holds 650m of insulated drill hose which is guided down the yellow mast into the hole.

(Photo: P. Smeets, Uni. Utrecht)

Until recently, this mechanism has not been given much consideration in studies of ice dynamics of the vast Greenland ice sheet. However, the last 10 years of satellite imagery and GPS instrumentation at the ice surface has shown[026, 130] that speed-up events occur along the margin of the Greenland ice sheet during summer melt. This can be as far as 100km in from the ice edge.

In order to investigate this behaviour and compare it with that of Alpine glaciers, ice2sea researchers performed an experiment in west Greenland in July 2010. Their aim was to obtain simultaneous measurements of ice velocity, surface melt rates, and subglacial water pressure on Russell Glacier. This is a land terminating glacier at the Western edge of the Greenland ice sheet near Kangerlussuaq. A site was chosen 15km from the edge.



Hole drilled 600m deep into the ice by hot water, with probe suspended on 3mm thick Kevlar rope. Greenland 2010.

(Photo: Uni Utrecht/AWI)

They drilled two holes to the glacier bed, approximately 600m deep, using a hot water drill.[037] Innovative wireless pressure and temperature sensors were installed in the holes (see figure) and lowered down to close to the glacier bed. At the ice surface, an automatic weather station and five accurate GPS systems were placed at and around the drill site. To date, a continuous two-year time series has been collected showing the variations in ice flow, surface melt, and subglacial water pressure.

First results show that the summer speed-up behaviour of land terminating glaciers from the Greenland ice sheet shares many similarities with small Alpine glaciers. It appears that as the supply of water increases over the summer, water flowing beneath the ice switches between large channels and a network of much smaller channels. This is in relation to the amount and variability of the supply of surface melt water.[026] Increases in surface melt water in the future will change the lubrication at the bedrock. Such understanding contributed to development of computer models used in ice2sea to predict the future of the Greenland ice sheet.[121]

SECTION 3

Understanding Ice: Climate, Oceans, and Glaciers

Ice2sea has used existing computer models, and developed many new ones, to simulate future changes in the Earth system and their impact on sea-level rise.

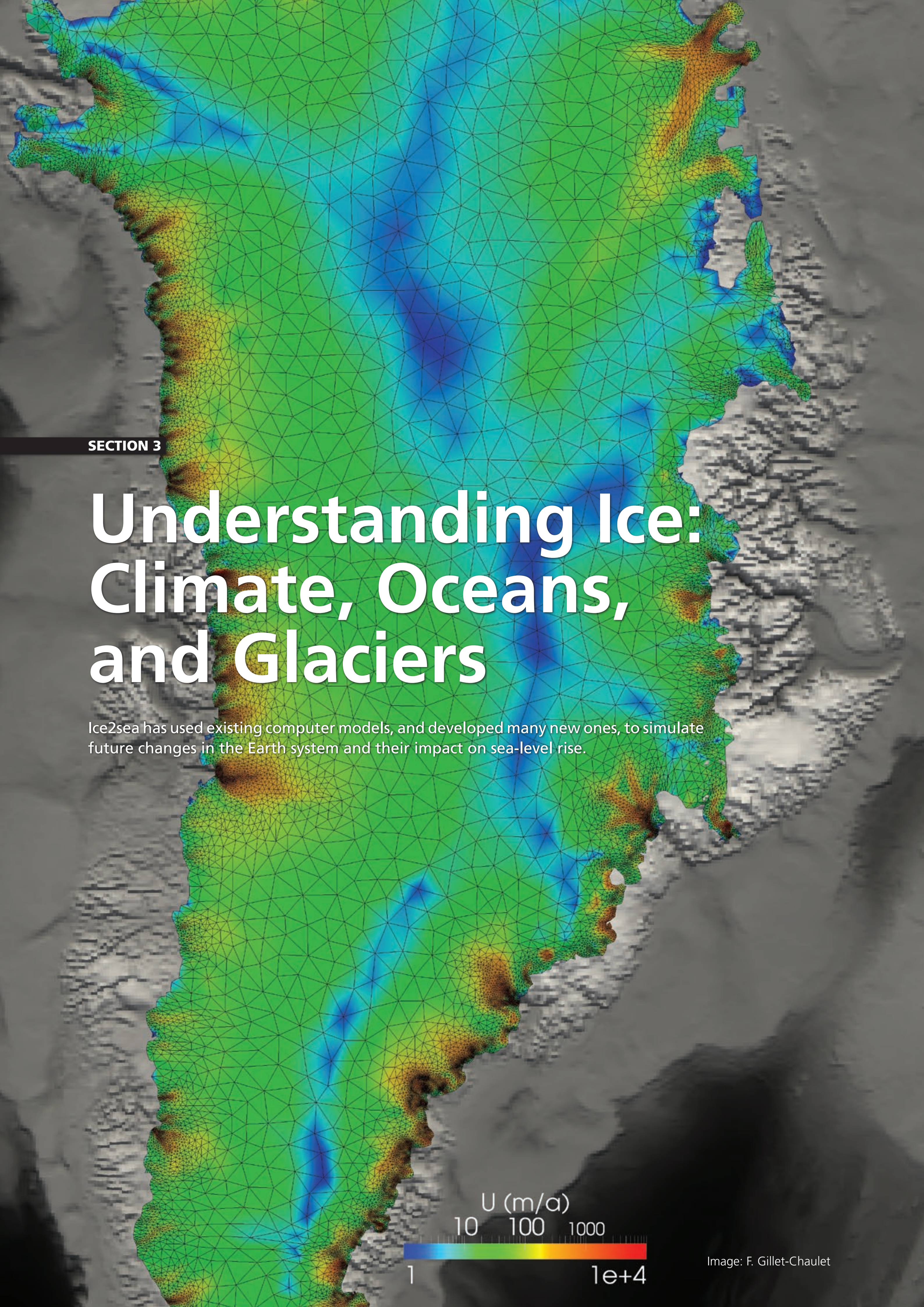


Image: F. Gillet-Chaulet

What are 'models' and what can they do for us?

Scientists use a variety of techniques to make projections of the future of planet Earth and, in particular, the future climate. The most appropriate technique depends on the specific scientific question, the parts of the Earth system and time-scales of interest. Insight into the short-term future (a few years) can be gained simply by examination of records of past events (see the earlier discussion on storm statistics). In the medium-term (a few decades), extrapolation of recent trends may be sufficient, although this requires considerable caution. But for the longer-term (several decades and longer), more powerful techniques are needed.

For these longer-term projections, scientists use computer programmes (models) that incorporate scientific knowledge about physical processes to simulate the Earth system. Each model has a grid ("mesh"), such as that for Greenland on the opposite page, and many complex mathematical calculations are performed at each point on the grid. These calculations are based on physical processes, so an important part of ice2sea has been to improve the understanding of the physics of the ice sheets, to improve the detail, accuracy, and efficiency of the calculations.

These models are powerful because they can be run using different scenarios for the factors driving change (e.g. greenhouse gas emissions) to depict the difference in the physical responses over time. It is not crucial to know exactly how driving factors ("forcings") will change, because a range of plausible scenarios and the responses they produce can be explored.

The results of such models are usually referred to as "projections" of future change, rather than "predictions", since the latter implies a single expected outcome ("what will happen…"), rather than a set of possible outcomes ("what would happen if…").

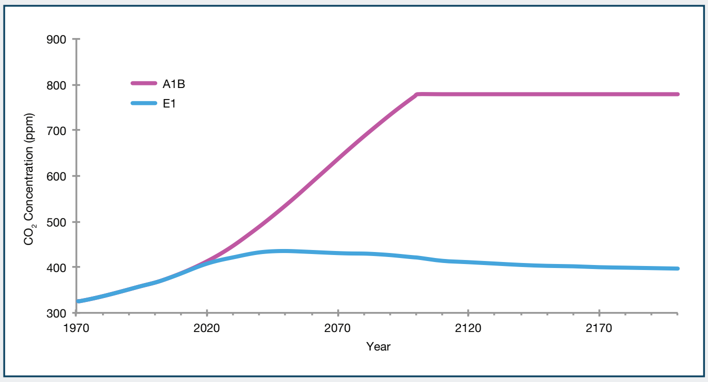
Ice2sea has used this type of process-based model to explore the effect of uncertainties on these projections. This is done at every stage of the chain from the greenhouse gas emissions scenarios through to regional sea-level change. For the Greenland and Antarctic ice sheets, ice2sea has used groups ("ensembles") of process-based models, developed by both ice2sea partners and external collaborators. These have been used to explore the effect of different emissions scenarios on the ice sheets, as well as the effect of uncertainties in climate and ice-sheet modelling. An important step is the comparison of model results with past observations of climate and ice-sheet change, which are used to assess the relative success of the models.

For mountain glaciers, ice2sea has developed new process-based models to make projections for specific benchmark glaciers. The models were compared against past observations of these glaciers, then used to determine future possibilities for various climate change scenarios. Finally, we used statistical techniques to extrapolate the results from the benchmark glaciers to the global set of nearly 200,000 glaciers. In computational terms this was relatively cheap, and could be achieved on a single desktop computer. In comparison, the physics-based modelling for the climate and ice-sheet projections required the use of state-of-the-art supercomputers and computing clusters.

Carbon emissions and climate change modelling

Climate change is driven by a variety of external factors: principally the emission of greenhouse gases, but also volcanic emissions, changes in the sun's output, and stratospheric ozone concentrations. To allow comparison of the output of climate models, various "scenarios" have been defined which represent a range of how anthropogenic (human) factors will change over future decades. The scenarios are not "predictions" of the future, but are merely representative of possible futures.

A range of scenarios was developed for the IPCC "Special Report on Emissions Scenarios" (SRES) in 2000. In ice2sea we have used the "A1B" scenario, which represents continued increases in carbon emissions through the 21st Century. To compare with this, we have also used the "E1" scenario that was created by ENSEMBLES[d], an EU Framework 6 Programme. E1 represents the world under an assumption of rapidly reducing carbon emissions. In the context of ice-sheets, the E1 scenario represents the minimum changes against which the effect of high carbon emissions on sea-level change can be measured.



In essence, A1B represents "business as usual" and E1 represents the situation where efforts on mitigation of climate change are successful (see figure).

These two greenhouse gas emission scenarios have been used by ice2sea to "drive" a variety of global and regional climate projections, which includes changes to both the atmosphere and oceans.

Although there has been convergence between global climate models in recent years, the different models produce a range of climate projections even for the same scenario. This arises largely because the processes, especially feedbacks - such as snow/ice reflectivity (albedo) or clouds - are represented differently in each model. At present, it is not possible to determine which models produce the most reliable projections, and we consider all model projections to be equally likely. The differences between the models give us a partial assessment of the uncertainty in the projections.

In addition to incorporating different emissions scenarios, ice2sea has also incorporated results from several leading global climate models. In particular these are HadCM3, a variant of this HadCM3-Q0 (developed by the UK's Met Office Hadley Centre) that performs better over Greenland, and the ECHAM5-MPIOM atmosphere-ocean coupled climate model developed by the Max Plank Institute in Germany.

There is, however, a further complication. Global climate models produce results at relatively low geographic resolution - this is insufficient to show the response of the ice sheets. For this reason, we need to refine the global climate projections to a higher resolution. Rather than using crude interpolation schemes, ice2sea has used regional climate models (RCMs) to refine the global projections. These RCMs have similar representations of physical processes to global climate models, but are run with a spatial resolution of anywhere between one and fifty kilometres. And again, because all RCMs are different, several different RCMs have been used (see next page) to provide the variety of high-resolution projections of future Greenland and Antarctic climate needed in ice2sea.

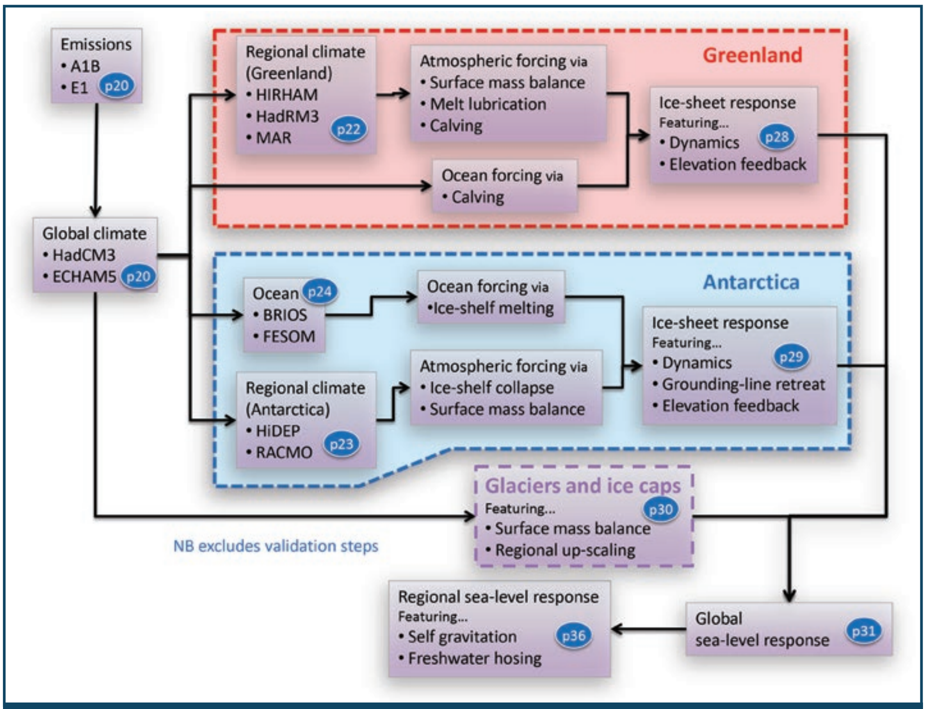
[d]http://ensembles-eu.metoffice.com/

The ice2sea model approach

Several statements in the Fourth Assessment Report of the IPCC (AR4, 2007) identified shortcomings in the capability of the scientific community to build robust and complete projections of the contribution of ice sheets to sea-level rise.

The ice2sea community has focussed on addressing these shortcomings in time to contribute to the Fifth Assessment Report (AR5), which is due for publication in autumn 2013. In particular, ice2sea set out to build process-based models capable of delivering projections of glacier and ice-sheet change to the year 2200. They incorporate new physical descriptions of glacial processes that contribute to ice flow. Regional climate projections were in turn used to drive glacier and ice-sheet models. Wherever possible the models were tested against real-world data.

This strategy for ice2sea of a cascade of modelling can be summarised by a complex flow diagram (see figure). In this approach, specialist models developed by many different research groups working in different fields were enlisted to contribute towards the ice2sea effort. Many transfers of data and model output have been required between researchers across Europe.



This flow diagram shows the strategy for ice2sea projections. It shows the complexity of the approach required to achieve the modelling goals of ice2sea. The blocks indicate particular models and modelling tasks, and black arrows show specific transfers of data, insight, and model results between the models, and between ice2sea partners. Each transfer contributes towards projections of global and regional sea-level rise. Bubbles indicated the pages of this report where components are discussed.

This approach could not capture all of the possible feedbacks between ice, ocean, and atmosphere, but nonetheless it is still a major advance on what was previously available. In particular, the incorporation of regional climate and ocean projections as drivers of ice-sheet models provides valuable improvements in the quality of sea-level projections.

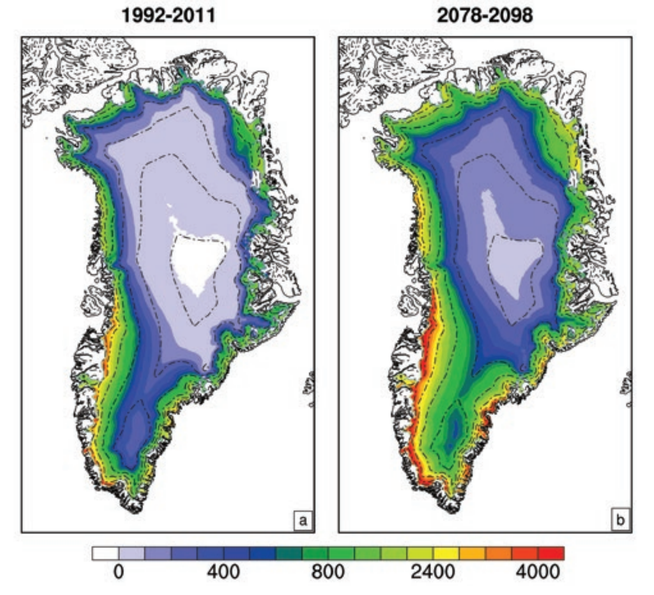
The efforts of ice2sea should not be seen in isolation. Several other individual research groups, and at least one international programme (SeaRISE[e]), have worked in parallel. These have all made significant advances in understanding the future of ice sheets and glaciers. Indeed, there is little doubt that collectively the scientific community has achieved huge steps forward in the sophistication of ice-sheet and glacier models between AR4 and AR5.

[e]Sea-level Response to Ice Sheet Evolution (SeaRISE) is a coordinated research effort to estimate the upper bound of ice-sheet contributions to sea level, and is led by researchers in the USA.

Greenland projections of climate change: More snow, but increases in ice loss

One of ice2sea's strengths has been its use of regional climate models (RCMs) in conjunction with global general circulation models (GCMs). This has allowed our scientists to focus in on particular areas of interest. The RCMs give a more detailed picture of Greenland, which is required by the ice-sheet modellers.

Unlike Antarctica, Greenland experiences sufficiently high summer temperatures that melting of snow and ice is widespread across the ice sheet. This represents a significant challenge for climate modellers, as they need to include processes by which the ice-sheet surface is warmed and melted. Surface melt water can then either refreeze, or run off the ice-sheet into streams and channels. One particular difficulty for projections is that if summers get warmer, snow cover is progressively lost revealing bare ice underneath. Since ice tends to be less reflective than snow (lower albedo), this change will further alter the energy balance at the surface, leading to further increased warming and more melting. Capturing this snow-ice albedo feedback in models has been a particular emphasis of ice2sea.[038, 083, 084, 098]



The presence of water is corrosive to the ice sheet, altering its energy balance. Even the presence of water for a few weeks per year can have a detrimental effect. The figure on the right shows one projection of the increase in the quantity (in mm) of water produced by rainfall and melting, compared to present day (left), across the Greenland ice sheet.[107]

A similar feedback occurs between surface elevation and snow accumulation and melt, because melting lowers the altitude of the surface, thereby placing it in a warmer environment. This has also been investigated by ice2sea and included in models for the first time.[062, 120] To determine the consequences on the relationships resulting from future changes in climate, both of these feedback mechanisms need to be understood for the present day situation.

Results from all the RCMs (HadRM3, HIRHAM5, and MAR) for the A1B emissions scenario show warming trends of 3.4-4.5°C over Greenland for the next century. All these models suggest both increasing snowfall and also increasing snow melt and run-off. However, they show smaller increases in the amounts of snow that will refreeze, giving overall projections of reduced snow/ice accumulation over the ice sheet during this period. Two out of the three models predict negative surface mass balance (net ice loss) from around the middle of the century. Towards the end of the century most of the summer precipitation falls as rain rather than snow. As most of the rain would run off directly to the ocean, the rate of mass loss will be accelerated.

The differences between the RCMs used in ice2sea are largely in the parts of the model that address albedo and refreezing. The comparison between the models indicates that refinement of these processes is extremely important in improving the reliability of future models. However, the largest uncertainty in Greenland's climate still arises from uncertainty concerning future emissions of greenhouse gases.

Antarctic projections of climate change: Ice-shelf retreat

Antarctica is the highest, coldest, driest, and windiest continent on Earth. Annual mean temperatures vary from -60°C in the high interior of East Antarctica, to just below freezing on the northern tip of the Antarctic Peninsula. Rates of snowfall tend to mirror temperature, and are similarly wide-ranging. The interior of the East Antarctic ice sheet receives less than 10cm of snowfall per year and can justifiably be called a "desert," while locally on the western Antarctic Peninsula more than 10 metres of snow falls each year.

Ice2sea used state-of-the-art climate and snow models to generate projections of the future climate of the Antarctic ice sheet. These projections were used to drive ice-sheet models, but they have also led to significant improvements in understanding of future ice-climate interactions.

On the low-lying floating ice shelves, where for a few days per year temperatures are already close to melting, the length of the summer melt season will dramatically increase in a warmer future climate.[082, 085] Most of the water produced during these melt periods will percolate into the snow surface, and refreeze. This process will lead to a loss of permeability in the snow, and lead to the creation of surface melt water ponds. This is reason for concern, because since the 1970s, increased melt water pooling has led to the loss of approximately 20% of all Antarctic Peninsula ice shelves – an area of floating ice equal in size to Belgium.

Because ice shelves are afloat, their melting does not appreciably impact sea level. But their loss has led to acceleration of the inland glaciers that fed them, and that has contributed to sea-level rise. Ice2sea research shows that if warming continues into the 22nd Century, continued ice-shelf retreat and associated glacier acceleration could become widespread around coastal Antarctica.[123]

A very different scenario awaits the interior of the ice sheet. It is much colder as it is further south, further away from the open ocean, and higher in elevation. Ice2sea projections show that in 2200, even with a warming of 2-5°C, these areas remain too cold for significant melting to occur. Instead, the warmer atmosphere will carry more moisture, enhancing snowfall. On a global scale, the effect of increased snowfall is significant, being equivalent to a fall in global sea level of 20-43mm by 2100 and 73-163mm by 2200. However, this process is in competition with all those leading to increased ice-loss and sea-level rise.

Melt water pooling on the George VI ice shelf.
(Photo: E. King, BAS)

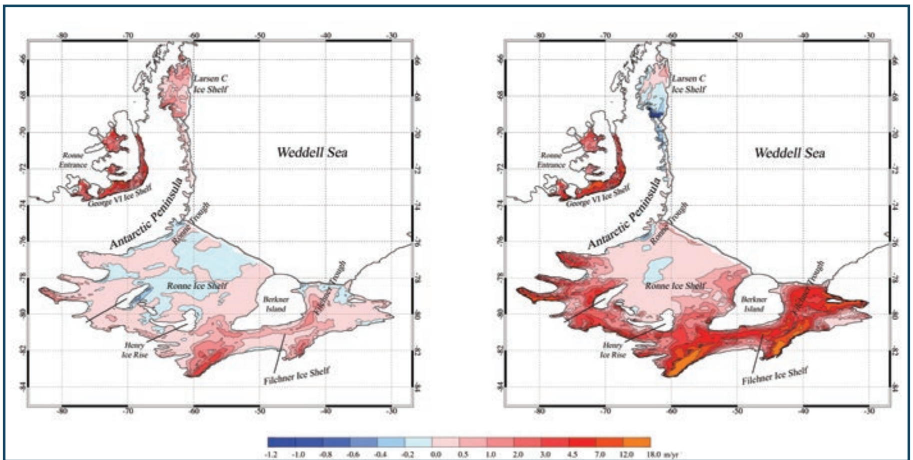
Effects of oceans on ice loss in Antarctica

A key finding of our research has been understanding the effect of warming seas on the Antarctic ice shelves. Increases in water temperature of more than 2°C would boost average melting on the Filchner-Ronne Ice Shelf from 0.2m/yr to almost 4m/yr. This will lead to thinning and perhaps total loss of the ice shelf. Analysis of model output suggests that the changes are caused indirectly by reduced sea ice formation, and a thinning of the formerly consolidated sea-ice cover in the south-eastern Weddell Sea. Loss of this major ice shelf would dramatically re-draw the map of Antarctica and could trigger rapid ice loss from the deep interior of the East Antarctic ice sheet, a region previously thought to be quite stable.

Previously, the difficulty had been that global ocean models were still simply too coarse to resolve the three key processes at work around Antarctica. These are:

- transport of warm waters onto the Antarctic continental shelf;
- interaction of these warm waters with the deep base of the ice shelves around Antarctica that help stabilise the ice sheet;
- modification of continental shelf waters by glacial melt water.

In the framework of ice2sea, researchers at AWI simulated oceanographic conditions on the Antarctic continental shelf, using two ocean models, BRIOS ("Bremerhaven Regional Ice–Ocean Simulations"), an established model with uniform resolution around the Antarctic continent, and FESOM ("Finite-Element Sea-ice Ocean Model"), a global model with high resolution of the Antarctic marginal seas. Both models were driven with atmospheric projections from two global climate models (see page 20), using historical simulations (1860-1999), and future projections (emissions scenarios E1 and A1B). Both models represent the feedbacks between ocean and sea ice, and both could account for the effects of melting ice,[041, 134] although the shape of the ice sheet was fixed throughout the model run.



Basal melt rates for ice shelves in the vicinity of the Antarctic Peninsula averaged over 1990-1999 (left) and the increase until 2150 (right) in the FESOM simulation forced with output from the HadCM3 climate model for the A1B scenario.

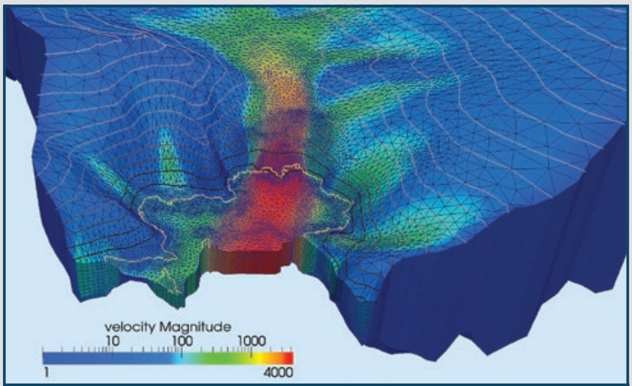
The projections of future ice-loss from the ice shelves around Antarctica were similar for both emissions scenarios, but different between the climate models used. The most significant change in ocean temperature resulted from HadCM3 output for the A1B scenario. The simulations showed that all ice shelves face a likely increase in melting at the base, but the strongest changes occurred on the very large Filchner-Ronne Ice Shelf. Here, changes in coastal currents may bring warmer water into the ocean cavity beneath the ice shelf during the second half of the twenty-first century.

New generation ice sheet models - Elmer/Ice

The last generation of ice sheet models was originally developed to simulate ice ages and sea-level change over millions of years. These time scales meant that, due to computational demands, approximations of ice flow had to be used. In addition, those models had very coarse geographic resolution, barely reproducing even the largest glaciers. These compromises meant that although these models minimised the computation resources needed, this was at the expense of accuracy. They were incapable of reproducing recent changes observed in ice sheets, and that cast doubt on their ability to make robust projections of future change.

In ice2sea, substantial efforts have been made to overcome the limitations of that older generation of ice-sheet models. Four specific features were developed that define a new-generation of ice sheet models.

- The equations governing ice flow can now be solved without approximations. Approximating the conditions provides simpler equations, which require less computer time to complete, but at the expense of accuracy;
- Models now use adaptable meshes (grids) that allow high resolution calculations to be made in the key areas – such as the rapidly-changing coastal regions. This is however more computationally demanding than the lower resolution, which is used for the less changeable regions;
- Advanced procedures are used to define the initial state of the ice sheet. Velocity measurements from satellites are inserted into the models to calculate the slipperiness of the bottom surface of the glacier. This is then used to calculate the speed of the glacier in the future;
- New methods have been designed to track the migration of grounding lines (i.e. where the grounded ice-sheet meets the floating ice shelf). The location of the grounding line is important to the evolution of the ice lost from the ice sheet, and was previously one of the main weak points of ice-sheet models.



Modelled velocities (m/year) of Pine Island Glacier in Antarctica using the finite-element model Elmer/Ice. Contour lines are regularly spaced by 100m and the mesh is vertically exaggerated by a factor of 50.[052]

(Figure: L. Favier, LGGE/CNRS)

All the models used in ice2sea incorporate one or more of these features, and the "finite element" model *Elmer/Ice*, incorporates all four of these developments. This model is the glaciological extension of the model *Elmer*, which was mainly developed by ice2sea partner CSC in Finland. The mesh grids have a high horizontal resolution on coastal regions, which gives the model the ability to capture even small outlet glaciers, and grounding lines can also be calculated with considerable precision.[043] There is also now sufficient confidence in the performance of Elmer/Ice that it is being used to design benchmark tests against which other ice-sheet models are validated.

Most recently, the ice2sea partner LGGE in France used Elmer/Ice to deliver decadal projections of Pine Island Glacier in Antarctica (see figure). This glacier is particularly difficult to simulate because it is changing so rapidly, and has several tributaries that give it a complex structure. Elmer/Ice has also been applied successfully at the continental scale. This allowed us to confirm that the current increase in the rate of Greenland ice loss can be reproduced, and it suggests that this loss will be maintained throughout the next 100 years.[052]

SECTION 4

Projections: Future Global Sea-Level Rise

The most recent report from the Intergovernmental Panel on Climate Change identified the loss of ice from ice sheets and glaciers as the greatest uncertainty in sea-level projections

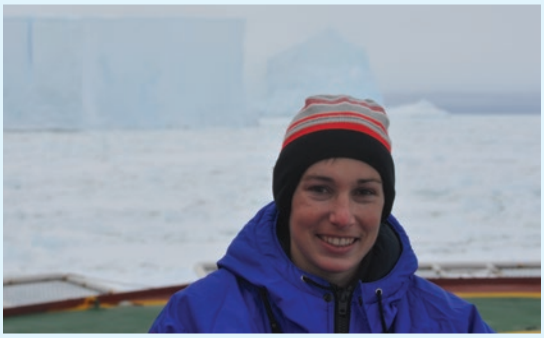
Photo: A. Trouvilliez, CNRS

Ice loss projections

Previous sections have described the improvement in understanding of ice, glaciers, and ice sheets; advances in instrumentation and updated observational data sets; and improvements in models of glaciers and ice sheets as well as global and regional climate. All of these components of the ice2sea programme are necessary for the next key step: making projections of the contribution of glaciers and ice sheets to sea-level rise over the next 100 – 200 years.

Process-based modelling is used within ice2sea to project future changes in global mean sea level (GMSL) by combining a range of studies of the two ice sheets and the global population of glaciers and ice caps. A chain of models is employed beginning with global climate models using a particular greenhouse gas emission scenario, through regional ocean and atmosphere models of Antarctica and Greenland, and finally to ice-flow models of the two ice sheets. For global glaciers and ice caps, global climate model output is used directly to drive the models of glacier responses. The majority of projections made by ice2sea employed the "business as usual" emissions scenario A1B, with the HadCM3 and ECHAM5 global climate models. GMSL can be affected by changes in surface mass balance (SMB, primarily by increased melt water runoff or snowfall changes) or by increases in outflow (ice lost directly to the ocean either by calving or marine melt). The latter effect was a major source of uncertainty in the Fourth Assessment Report of the IPCC and a great deal of effort was therefore focussed on this issue.

Profile: Dr. Cecile Agosta – from the Caribbean to Antarctica.



I grew up on a Caribbean island and when I finished high school I still had no idea of what I wanted to be. I began studying mathematics and physics in Marseille, France, where I was lucky to meet many passionate researchers. Year after year, it became clearer that I fitted this way of working and thinking. Admitted to an engineering school in Lyon, I turned my mandatory internships into research projects in hydrology laboratories.

One of these was in Grenoble, and biking through the campus every day I passed in front of a sign saying "Glaciology," which sounded very exotic to me. So when this glaciology laboratory proposed a PhD project on surface mass balance in Antarctica, I took the opportunity, even if it looked like working in a climate similar to the planet Mars.

Fortunately, I discovered that Antarctica was an exciting area of study, and although I spent most of my time behind a computer, I was lucky enough to be able to walk on the ice sheet. Research is thought to be a lonely job, and that is not a totally wrong impression. But it is firstly collaborative work, which I was able to enjoy thanks to my supervisors, Christophe Genthon and Vincent Favier, and my closest colleagues, Gerhard Krinner and Hubert Gallée.

"I learned that you can be a mum and a researcher, and I really enjoy both."

Taking part in an integrated European project such as ice2sea was a great opportunity to meet researchers from many countries and to be kept aware of their latest advances. It was great for my research to feel like a stone in a well built edifice. I finished my doctorate before the end of the project, but I was pleased to continue to be invited to the annual meetings, and remain part of the research team.

Following my travel from tropics to poles, I now continue studying the Antarctic climate at the University of Liege with Xavier Fettweis, who I met through ice2sea. I learned that you can be a mum and a researcher, and I really enjoy both. I work on fascinating topics. I also travel and meet people from many cultures. So even if getting a permanent position may be difficult, I am deeply convinced that I made the right choice.

Key projections from the northern hemisphere

Greenland's peripheral glaciers
Around the Greenland ice sheet there are about 20,000 many isolated glaciers and ice caps. Better models and observations have improved understanding of their vulnerabilities and potential contributions. Research at GEUS[135] projects these peripheral ice caps and glaciers (separate to the main ice sheet) will contribute 0.6cm to sea level under the A1B emissions scenario by 2100.

Glaciers and ice caps in the Canadian Arctic
The Canadian Arctic Archipelago (CAA) contains one-third of global land ice outside the ice sheets. Work at UU110 projects that snowfall does not balance surface melting, leading to continuing net ice loss, for the CAA throughout the coming century for the vast majority of climate model projections and scenarios, including those that limit global warming to 2°C.

Greenland ice dynamics and iceberg calving
More complete representation of dynamics in ice sheet models by UJF/CNRS, VUB, and UoB finds that some processes previously thought important - glacier speedup at the base by increased meltwater,[052, 121] and fast inland propagation of changes at the ice sheet margin[131] - have relatively small effects on projected SL contributions.

Work by ULB and UU[118] finds the four marine outlet glaciers draining around a fifth of the ice sheet do not sustain recent high rates of loss. This gives projected contributions under A1B of 0.9-1.3cm by 2100 and 1.9-3.0cm by 2200 for a range of plausible glacier model parameters.

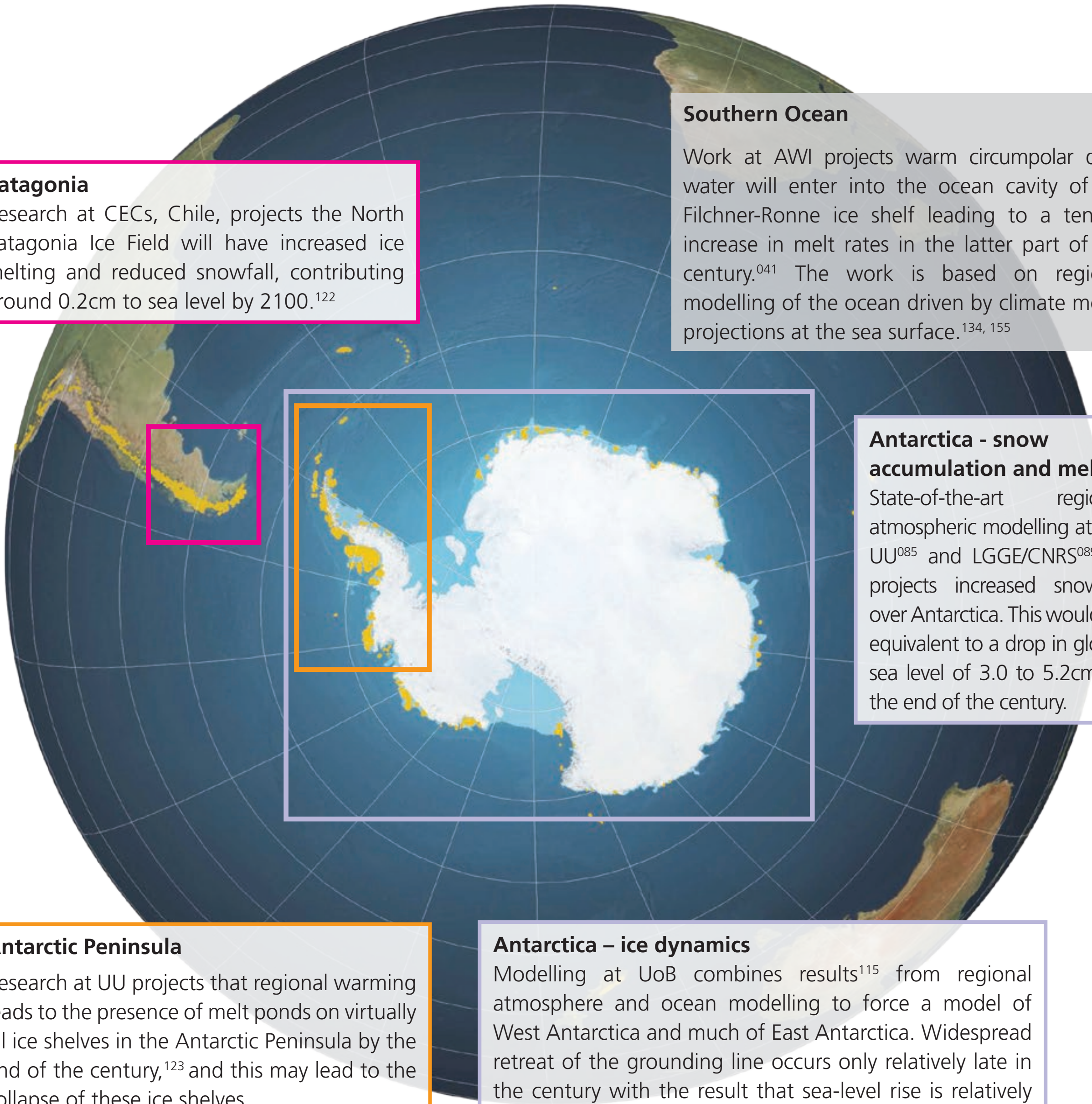
Greenland – snow accumulation and melt
Improved models of surface mass balance[083, 098, 107] project accelerating melting and runoff with warming, which are not compensated by increased snowfall. Work at the ULg[098] projects sea-level contributions under the A1B scenario of 7.4 and 9.8cm at 2100 using two global climate models, and a threshold of around 3°C global warming for irreversible change. Work by the UU[062] and UoB[120] enable use of these projections by ice sheet models while incorporating the feedback between surface mass balance and ice sheet surface elevation.

Greenland – total ice-sheet contribution
Projections of sea-level contribution from 2000 under the A1B scenario range from 5.1 to 7.6cm at 2100 and 14.0 to 21.5cm at 2200 for a range of climate and ice sheet models (UoB[151]) and plausible ice sheet modelling choices (UJF/CNRS;[052] VUB[114]). The VUB study finds outlet glacier dynamics much less important than changes in snow accumulation and melt for future projections (6-18% of sea-level contribution at 2200 under A1B).

Glaciers in the Alps
Ice2sea collaborated in a study led by the University of Fribourg[113] to model 101 glaciers representing 75% of the ice in the Swiss Alps. The results project a greater than 80% loss in volume by 2100 under A1B using seven regional climate models.

Note full institute names are given on the inside back cover.

Key projections from the southern hemisphere



Patagonia
Research at CECs, Chile, projects the North Patagonia Ice Field will have increased ice melting and reduced snowfall, contributing around 0.2cm to sea level by 2100.[122]

Southern Ocean

Work at AWI projects warm circumpolar deep water will enter into the ocean cavity of the Filchner-Ronne ice shelf leading to a tenfold increase in melt rates in the latter part of this century.[041] The work is based on regional modelling of the ocean driven by climate model projections at the sea surface.[134, 155]

Antarctica - snow accumulation and melt
State-of-the-art regional atmospheric modelling at the UU[085] and LGGE/CNRS[089, 090] projects increased snowfall over Antarctica. This would be equivalent to a drop in global sea level of 3.0 to 5.2cm by the end of the century.

Antarctic Peninsula

Research at UU projects that regional warming leads to the presence of melt ponds on virtually all ice shelves in the Antarctic Peninsula by the end of the century,[123] and this may lead to the collapse of these ice shelves.

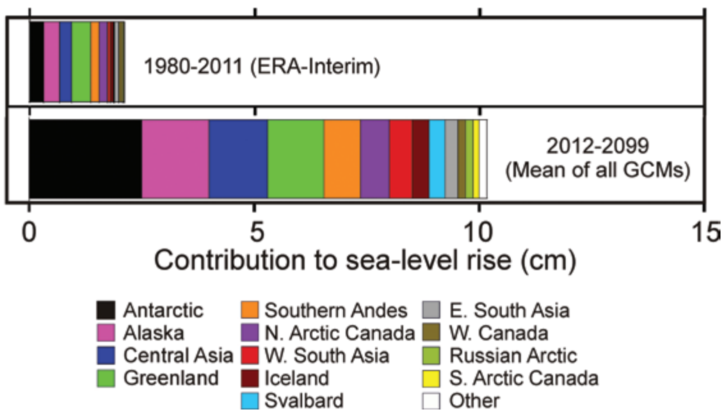
Modelling studies at NERC-BAS of the Antarctic Peninsula that incorporate ice-shelf collapse scenarios and increased snowfall suggest a contribution of 0.7 to 1.6cm by the end of the century.[126]

Antarctica – ice dynamics
Modelling at UoB combines results[115] from regional atmosphere and ocean modelling to force a model of West Antarctica and much of East Antarctica. Widespread retreat of the grounding line occurs only relatively late in the century with the result that sea-level rise is relatively limited at between -0.8 (i.e. fall) and 3.2cm by the end of the century.

Key projections from global glaciers

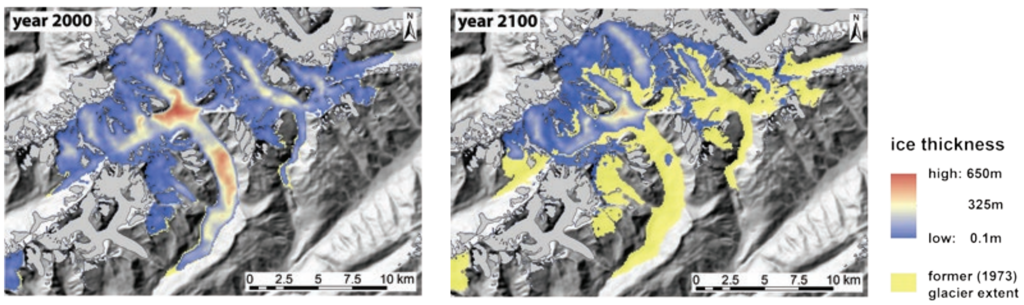
Global Glaciers

Work at UU[133] used the new global glacier inventory and a more physically realistic model of the glacier response to climate than previous studies. Using a range of eight global climate models, the study indicates a global loss of glacier ice of 13 – 23% from 2012 to 2099 under the A1B emission scenario. This is equivalent to a sea-level contribution of 7.4 – 13cm. Additional uncertainties in the modelling procedure and input data increase this range to 3.9 – 16.5cm.



Together, ice loss from the glaciers in Alaska and Central Asia, and the peripheral glaciers of Antarctica and Greenland, accounts for 65±4% of the total. Ice-loss from glaciers in the Southern Andes, Northern Arctic Canada, South Asia, and Svalbard, make up most of the rest.

The projected sea-level contribution was 35±17% larger when only changes in air temperature were taken into account, demonstrating the important compensating effect of increased precipitation and possibly increased water content in the atmosphere, an issue that is particularly important in Arctic regions. The study identified that the largest contribution to the remaining uncertainty resides in the projections of summer air temperature.[133, 079]



The projected decrease in ice thickness, and total loss of glaciers in some areas, is apparent in these figures of projected thickness change in the Swiss Alps in the Aletch (A) and Lang (L) glaciers. The left panel shows the ice thickness in 2000, and right shows projected ice thickness in 2098 under the A1B scenario. The colours show ice thickness from blue (>0m) to red (650m). Grey areas show glacier extent in 1973. This result used projections from four regional climate models.[113]

Sea-level projections: the full story

In Antarctica, likely triggers for changes in ice outflow will be the collapse of ice shelves (a consequence of increasing formation of melt ponds), and ice-shelf thinning due to warming ocean temperatures. Ice2sea projections show that by 2100, the melt-water ponds will probably not extend beyond the Antarctic Peninsula[123] and are very unlikely to affect the major ice shelves of the continent (the Ross and Filchner-Ronne ice shelves). Regional ice-flow modelling of the Antarctic Peninsula that combines this effect with projected changes in snowfall suggest GMSL rise of between 0.7 and 1.6cm. Ocean modelling projects strong regional warming around Antarctica for HadCM3 forcing, in particular in the Weddell and Amundsen Seas,[041, 134, 155] but not ECHAM5 forcing. Two different regional atmospheric models[085, 089, 090] agree that a strong increase in snowfall is likely by the end of the century. These contrasting signals were used to drive an ice-flow model[115] of West Antarctica and the sectors of East Antarctica that drain into the Ross and Filchner-Ronne ice shelves (approximately 40% of the ice sheet). While strong grounding-line retreat was found in many sectors, the effect on GMSL was relatively small because retreat occurred late in the century, much of the lost ice was already displacing ocean water and retreat tended to be confined to bedrock troughs of limited spatial extent. The resulting projection of the contribution to GMSL ranged between -0.7cm (fall) and 4.4cm (rise), which taken together with the Antarctic Peninsula, suggest a total Antarctic contribution of 0.0 to 6.0cm. It should be stressed that these results do not include much of East Antarctica, where both oceanographic warming (although to a lesser extent than around West Antarctica) and increased snowfall are expected to occur.

+

In Greenland, both increased melt-water runoff (a contrast to Antarctica) and increases in glacier outflow will contribute to GMSL rise. Two likely triggers to changes in outflow were explored by ice2sea: increases in the lubrication of ice flow that could arise with increasing amounts of surface melt water reaching the bed, and increases in iceberg calving. An inter-comparison of ice-sheet models indicates that the former, while being effective at redistributing mass within the ice sheet, does not lead to a significant contribution to GMSL[121] by 2100. Simulation of the evolution of four major calving outlet glaciers (accounting for 22% of the ice sheet) suggests that changes in outflow are responsible for a mass loss four times greater than that due to increased runoff.[118] When generalised to the whole ice sheet and combined with SMB projections,[098] projected GMSL rise ranges between 6.5 and 18.3cm by 2100. Two alternative studies[114, 132] employed ice-sheet models forced by changes in calving, lubrication, and SMB, and produced projections ranging from 5.1 to 7.6cm and from 0.5 to 15.4cm, respectively. A total range of 0.5 to 18.3cm therefore encompasses the majority of these various projections.

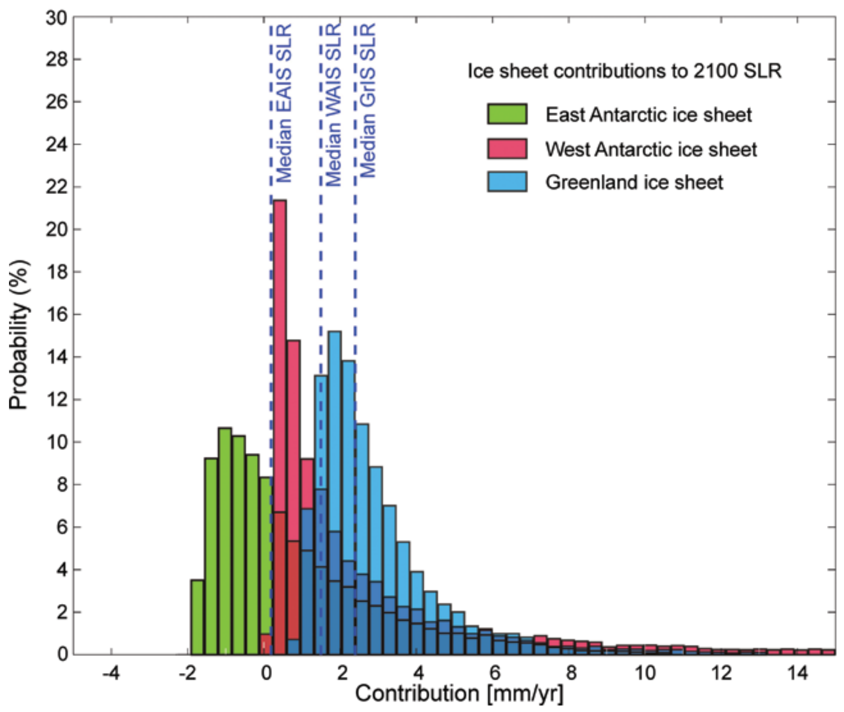
+

Finally, a projection of the global population of mountain glaciers and ice caps was undertaken using a model[079, 133] calibrated using the observed mass change of 89 sample glaciers from varying climatic regions, and employing the new, comprehensive Randolph Glacier Inventory.[100] The mass of these small ice bodies is projected[133] to decline by 13 to 23% up to 2100, which contributes a total of 3.0 to 12.5cm to GMSL rise (where the Antarctic Peninsula has been removed from valley glaciers and ice caps to avoid double accounting). In addition, more detailed modelling of the Greenland peripheral glaciers,[135] the Patagonian ice fields,[122] and the Alps[113] was performed focussing on the unique aspects in each area. There projections were generally in line with the global analysis, albeit with a bias towards lower mass loss.

Summing the GMSL ranges for the two ice sheets and for global glaciers and ice caps, results in an overall range for the contribution of continental ice of 3.5 to 36.8cm rise by 2100. This range is derived using the best available process-based ice flow models, many of which were developed specifically for ice2sea. Nonetheless, it is appropriate to stress three caveats to this range. First, it has been derived specifically assuming the A1B scenario, which is a mid-range emission scenario, and may not be appropriate for more severe scenarios. Second, the geographical coverage of the ice-sheet models (most notably East Antarctica) is incomplete, although it is unlikely that the omitted sectors will increase projected GMSL rise greatly. Finally, the methodology employed by ice2sea assumes that global climate affects regional climate, which then affects the ice masses. This methodology provides only limited opportunities to include coupling and feedbacks between the ice masses and the atmospheric and ocean systems, which may well become significant. It should also be noted that a feature common to the majority of ice2sea projections is that sea level rise will continue rising after 2100, with sea-level rise in the period 2100 to 2200 greatly exceeding that from present to 2100.

An alternative approach to estimating uncertainty

Sea-level rise is one area of climate science where progress in observation (e.g. from satellites) has been so rapid in recent years that scientists readily admit that we do not yet fully understand all the underlying processes behind the observations. Rapid progress has been made within programmes like ice2sea in the development of process-based models, but even the state-of-the-art models do not simulate all the processes and feedbacks that might be significant. It is therefore important that we use all methods to quantify uncertainties associated with all processes – those that are represented in the models and those that are not.



Results from ice2sea's 2012 expert elicitation[129] showing the collective opinion regarding the probability of the contribution of the Greenland ice sheet (GrIS), and the East and West Antarctic ice sheets (EAIS and WAIS) to the sea-level rise (SLR) in 2100.

The figure shows that experts are in good agreement that Greenland and West Antarctica will be contributing significantly to sea-level rise in 2100. However they believe that East Antarctica is as likely to be adding to sea-level rise as it is to be slowing the rate of sea-level rise. The collective opinion is that whilst high rates are unlikely, at present no absolute upper-bound can be put on the rate of sea-level rise by 2100.

Ice2sea conducted a study,[129] the first of its kind in glaciology, to shed light on the largest remaining uncertainty in sea-level rise projections, the contribution of the ice sheets in Greenland and Antarctica. Researchers, led by University of Bristol, employed a technique called "structured expert elicitation." This method is already used in other scientific fields such as forecasting volcanic eruptions. It uses a pool of experts to provide opinions, which are combined in a mathematically rigorous way to produce an assessment of probability.

Expert judgment is not a substitute for process-based modelling, but it provides important insights into remaining areas of uncertainty and their magnitude. This study used 13 international experts and was first conducted in 2010, and repeated in 2012 to assess the robustness of the findings (see figure).

An important finding of the study was that experts collectively give a low, but not insignificant, likelihood to rates of sea-level rise higher than those produced by most process-based models. This reflects the opinion that instabilities[019, 050] may exist in the dynamic response of East and West Antarctica that are not fully captured by those models.

In summary, the modelling described on the previous page gives our estimate of the most likely contribution of continental ice to sea-level rise by 2100 of 3.5 – 36.8cm. The opinion of the pool of experts is that there is only a low (1-in-20) likelihood that the ice sheets will contribute more than 84cm to sea-level rise by 2100.

Profile: Dr. Xavier Fettweis – pursuing a passion for meteorology

As a child, I was already a budding meteorologist, thanks to a small weather station installed at my parents' house. But in 1996, I entrusted my weather station to my father and went to study for a degree in maths at University of Liège (ULg, Belgium), with the intention of becoming a mathematics teacher in secondary school. During my maths degree, however, I developed a taste for research and teaching at university level, and I realised that my passion for meteorology had not waned.

> *"I found studying Greenland's climate fascinating"*

In 2000, I decided to continue my training with a post-graduate diploma in climatology and meteorology at the Catholic University of Louvain, Belgium. There, I was enthused by the professors who taught climatology and climate modelling. So I began a PhD studying the Greenland climate using a regional climate model called MAR. Initially, understanding the model and getting it to run was not an easy task, but after several months I really got into it. I found studying Greenland's climate fascinating because it is an area of the world where climate has been changing rapidly. I presented my thesis in 2006.

Since my return to ULg in 2007, I have continued my work on Greenland as a postdoctoral researcher. During 2010, I had the opportunity to join Prof. M. van den Broeke in Utrecht. Working with his team was very stimulating and a great experience for me. Currently, when I am not at Liège, I work with colleagues in New York and Grenoble.

The ice2sea project has been a good opportunity for me to meet the ice-sheet community and use MAR to help understand the future of the Greenland ice sheet. Thanks to the opportunities I've had within ice2sea, I'm proud to say that this year my research is being recognised by the award of a prize by the European Geophysical Union.

Xavier Fettweis receiving the Arne Richter Award for Outstanding Young Scientist by the European Geophysical Union at the 2013 General Assembly in Vienna, Austria. Left to right: Donald Bruce Dingwell (President of EGU), Arne Richter, Xavier Fettweis, Jonathan L. Bamber .
(Photo: Johannes Bouchal - Copernicus)

The Greenland research community is small but it is very friendly and, after several years, many have become friends with whom I collaborate on a daily basis. With a model, we can do anything that we want (except when the supercomputers are full!) and improving this model is a challenge every day. My only regret is that because computer modellers do not need to do fieldwork, although I have been to the Glacier de Cheilon in Switzerland (see photo); I have not yet the chance to walk on the Greenland ice sheet. But I have not given up hope - perhaps that opportunity will come!

SECTION 5

Projections: Future Regional Sea-Level Rise

Robust projections of global mean sea-level are only one step towards providing regionally specific projections that will allow societies to begin effective adaptation to sea-level rise.

Photo: D.G. Vaughan, NERC-BAS

In recent years, scientists have measured global sea-level change with some confidence, but have been unable to evaluate all the contributions equally. It has recently become possible to show definitively that the sum of the measured contributions corresponds to the overall rate of global sea-level rise, as measured using satellites.[f] This breakthrough is an essential requirement for projecting global sea-level rise, through the individual contributions using physically-based models tied to specific climate scenarios. Ice2sea has addressed the specific contribution from ice sheets and glaciers, while elsewhere in the scientific community progress has been made in understanding other contributions to global sea-level change.

Although the issue of rising sea-level is often discussed in terms of the "global sea-level rise," it is an understanding of the sea-level rise at regional and even local scales that will truly support communities and policy-makers in identifying specific vulnerabilities, and planning their management and adaptation strategies.

Regional sea-level change will reflect the global sea-level rise, but is heavily modified by several factors.

High seas caused by Hurricane Sandy.
(Photo: Indiana Dunes National Lakeshore)

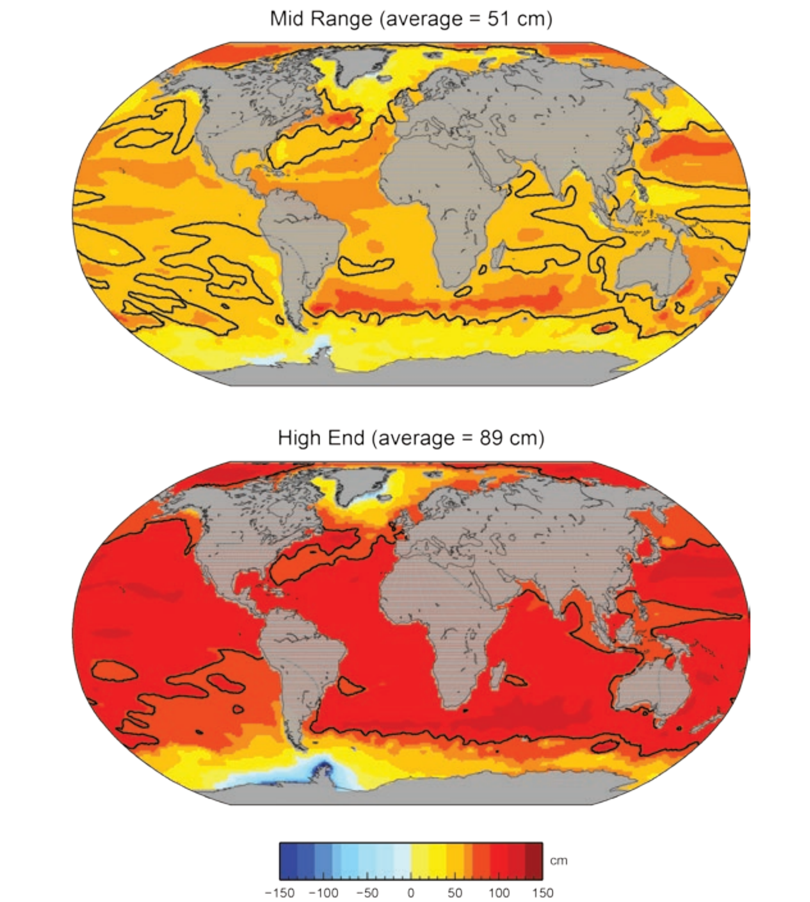
- Movement of ice and water around the planet subtly alters the planet's gravitational field. If the ice-sheets shrink, sea-level falls near the north and south poles, but in the tropics increases by more than the global average.[104]
- Ocean circulation patterns, which affects local sea level, are influenced by changes in freshwater input (e.g. from melting ice) and changes in wind patterns.[146]
- In land-locked seas that are largely isolated from the global ocean (e.g. the Mediterranean), changes in water salinity, caused by increased evaporation, can have a strong control on local sea level.[010]
- In many regions the land itself is subsiding or rising compared to sea-level. In some areas this is due to a continuing response to the loss of ice since the end of the last glacial period,[036] and in others is due to ground-water extraction or geotechnical activities.
- Changes in the intensity of tropical cyclones and mid-latitude storms will alter the frequency and intensity of the storm surges that give rise to the most damaging coastal flood events.[146]
- Additionally, thermal expansion of the oceans will not be uniform around the world, and this is reflected in regional sea-level rise.

[f]See the ground breaking paper: Church et al., (2011), Revisiting the Earth's sea-level and energy budgets from 1961 to 2008, *Geophys. Res. Let*., 38, 8

How regional sea-level will differ from the global mean

When adaptation measures are planned for specific coastlines, it is not the global sea-level rise that is important, but rather the local effect. One important process, which has a strong influence on the distribution of sea-level rise, involves changes in the Earth's gravitation field that occur as ice is lost from ice sheets and glaciers.

The strength of the Earth's gravitational field varies around the planet, although it is much too subtle to detect with our senses. When measured against a reference frame fixed on the centre of the Earth, sea level is modified by these differences in gravity by tens of metres. For example, the huge mass of the Greenland ice sheet exerts an attraction on the water in the coastal seas surrounding it. This currently draws up the sea-level close to Greenland by several metres. If ice was lost from the ice sheet, that attraction would also be lost, and the sea-level close to Greenland would fall. This would result in a consequential rise in the level of the more distant oceans. This is also true for the Antarctic ice sheet. So in the future, if ice is lost from both ice sheets, this effect would tend to drive the maximum rates of sea-level changes from the Polar Regions towards the equator.



Ice2sea projections of regional variations in sea-level rise to 2100, undertaken[104] for two scenarios of ice loss. Top shows the "mid-range" scenario of ice loss (MR), and bottom the high-end scenario (HE). These scenarios were developed[146] from ice2sea projections and expert elicitation exercises (see section 4). They take account of uncertainty in emissions, global climate, and glacial projections. The black lines show the contour of mean global sea-level rise due to continental ice-loss, thermal expansion of the oceans. In both cases, sea-level rise is higher than the global mean in the low and mid latitudes and lower in the Polar Regions.[104]

But that's not the whole story. Due to similar physics, when ice is lost (from ice sheets and glaciers) there is a small compensation in the position of the Earth's rotational axis. This effect, the so-called "true polar wander," tends to modify the pattern of sea-level rise in an east-west direction. Finally, there is a third and smaller effect in which the Earth's crust moves vertically in response to the mass (e.g., of ice) resting on it. Here, both instantaneous and long-term responses occur.

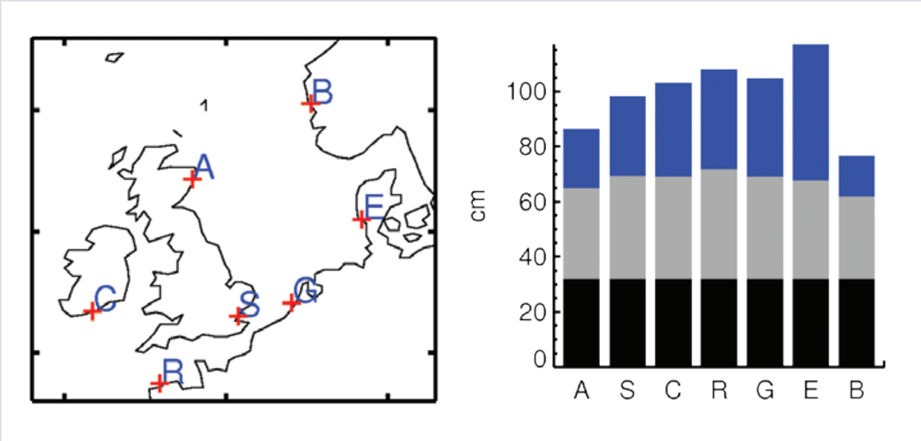
When combined, these three effects produce a complex pattern of sea-level rise that depends crucially on both how much ice is lost from land, and from where it is lost.[104]

Understanding gravitational processes allows us to take account of the effect of ice melt on sea-level. However, it does not account for impacts on ocean circulation, changes in storm intensity, or the thermal expansion of ocean water which play important roles on the regional variation in sea-level.

The figure shows the combined effects of continental ice-loss and changing ocean circulation patterns for two ice-loss scenarios, combined with thermal expansion from the greenhouse gas emissions scenario A1B. The pattern of sea-level rise is complex, with highest rates occurring in the tropics and lower, or negative, rates close to the ice sheets.

Consequences for Europe: increased heights of storm surges in 2100

The most complete study of flood risk undertaken by ice2sea includes not only global sea-level rise and the regional factors discussed above, but also the projected 21st century change in the 50-year return level of storm surges.[146] In the bar chart, projections of this change are shown for several European cities. The cities considered are Aberdeen, Sheerness, Cork, Roscoff, Gravenhage, Esbjerg and Bergen and the projections shown are for the "high end" ice-loss scenarios (HE).



The bars are split into three components:

- The black sections of the bars show the effect of thermal expansion of the oceans in north-west Europe.
- Grey bars show the contribution to local sea-level rise from the high end (HE) ice-loss scenario (see previous page).
- Blue bars show the contributions of the other components considered (e.g. changes in ocean dynamics and density, storm surges, and vertical land movement changes from previous ice cover).

This bar chart helps to put into perspective the components of sea level change aroundthe north-west European coastline. In particular, we can see that the three divisions shown(black, grey, and blue) are all of comparable size and so they all need to be considered in any assessment of sea-level change impacts. It is clear that the components shown in blue can vary in importance significantly from location to location.

Young scientists at the heart of ice2sea

Louise Sandberg Sorensen

Since it began, ice2sea has provided unique opportunities to early-career scientists to participate in the management of the programme. We hope that these experiences will be shared widely, and benefit other early-career scientists as they move towards managing projects of their own. ***David Docquier*** *(Ph.D. student at Université Libre de Bruxelles) and* ***Louise Sorensen*** *(formerly Ph.D. student at University of Copenhagen, now at the Danish Technological University) have participated as early-career members of the ice2sea Steering Committee.*

"As early career members of the ice2sea Steering Committee, our main role in the project has been to attend the meetings every 6 months. It has been an excellent opportunity to participate in top-level discussions linked to our field of research, and to learn how a large multinational science program is run. In particular, it was interesting to see how ice2sea has approached the difficult task of ensuring that the different work packages interact with each other, and the negotiations that occur when deadlines have to be met.

"We encourage well-established scientists to invite an early career scientist to join their project management"

In addition to our participation in the Steering Committee meetings, we have been involved in a series of other activities. For example, this includes the presentation of a poster concerning the involvement of early career scientists in science projects at the European Geosciences Union (EGU) General Assembly 2012; and the provision of comments and suggestions during the update and improvement of the ice2sea website. We have also provided information to teenagers from secondary schools who were working on projects about Antarctica. Another part of our involvement consisted in disseminating the goals and key topics of ice2sea during international conferences (e.g. EGU, AGU, IGS, etc.) and summer schools.

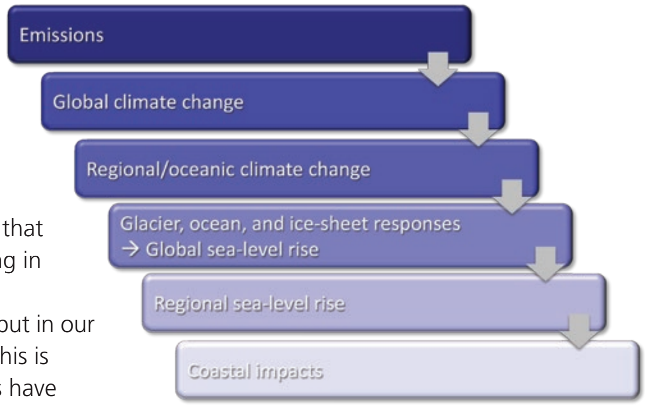
David enjoying being on the ice during a training course in Alaska.
(Photo: D. Docquier, ULB)

This role has really provided us with an unusual and significant training opportunity, and we encourage young scientists to engage themselves in similar projects if they get the opportunity. Likewise, we strongly encourage the well-established scientists who are planning and carrying out such projects to invite an early career scientist to join their project e.g. in a steering committee. After all, when you are gone we will have to take over, and scientists also have to be managers!"

Why is there still uncertainty about future sea-level rise?

Significant uncertainties remain about the future of Earth's climate, and these translate directly into uncertainty in the future of sea-level. Uncertainties about future climate arise both from incomplete scientific knowledge and an intractable uncertainty about the future emissions of greenhouse gases. Our uncertainties about future sea-level are further magnified by our level of understanding of how ice sheets and glaciers respond to all aspects of climate change. This state of affairs was described by the late Stephen Schneider[g] as a "cascade of uncertainty," and is common to all so-called 'climate impacts'.

From the outset, ice2sea recognised this cascade-of-uncertainty and the potential value in identifying where uncertainty arises along the road towards sea-level projections. A proper understanding of this would certainly assist in targeting of resources, and could contribute to a reduction in uncertainty.



There has been considerable progress in recent years, both by ice2sea and the wider scientific community. However, it seems that on a 100-200 year timescale, the greatest uncertainty remaining in sea-level projections lies not in the inherent and unavoidable uncertainties concerning the rate of greenhouse gas emissions, but in our understanding of the various elements of the climate system. This is despite the fact that the rate of emissions of greenhouse gases have apparently grown more rapidly than was anticipated in any of the scenarios developed in the IPCC AR4 (2007).

What's next?

It is clear that significant reductions in uncertainty should be achieved by the effective targeting of scientific effort in coming years. Ice2sea's research and specifically its modelling approach have highlighted specific areas where improved understanding and increased modelling skill would yield significant improvements.

- Ice2sea has demonstrated the potential importance to both Greenland and Antarctica of rather subtle changes in the way the oceans deliver heat to the ice sheet.[041, 056] Our limited understanding of the role of the oceans in driving ice-sheet change is, however, a continuing constraint on the precision of projections.
- Ice2sea and our collaborators have demonstrated that the glaciers in the high latitudes have made a particularly important contribution to sea-level rise in recent years.[008, 009, 017] In general, there have been only limited surveys of these glaciers, and their potential contribution to sea-level rise is only poorly known. Furthermore, these glaciers may be subject to changes in atmospheric and marine climate, and so warrant the development of more sophisticated modelling approaches.
- Ice2sea's effort towards projection of regional sea-level changes in Europe appear to be limited by our incomplete understanding of the effect of changing ocean circulation, and to a lesser but important extent understanding of likely changes in future storm surges.[146]

[g] http://stephenschneider.stanford.edu/

SECTION 6

Supplementary Information

Photo: D.G. Vaughan, NERC-BAS

High seas: Raising awareness of ice2sea

Whilst ice2sea scientists have been answering the big questions about ice melt and sea-level rise, they have also put their minds to another key question – how to bring their findings to a wider audience.

Over 150 papers have been published in scientific journals as you can see when you glance at the pages of names and titles at the end of this document. But those journals have a limited, highly scientific readership, who are often already familiar with the jargon and sometimes inaccessible and dry language.

Therefore, we identified a key task for ice2sea early on – to promote a dialogue between science and society. That meant talking to policy makers to make sure the science discussed was relevant and necessary to inform public policy. It also meant ensuring the wider society was given the opportunity to understand how ice2sea research will benefit citizens of the EU and the economies of its member states.

Crucially, six key audiences were identified – the science community, EU and EC policy makers, member states' policy makers, educators, the public (including young people) and the media.

To reach this wider audience, ice2sea scientists have met with policy makers, given talks, and helped craft easy-to-read press releases to promote parts of our research identified as being of importance to the general public and of interest to the media.

A brief overview of some of that activity shows the breadth of ice2sea's work at explaining the relevance of our science.

- Briefing pamphlet and other documentation and promotional materials produced and circulated to a wide network;
- Presentations to international audiences in conferences all over the globe, including Seoul, Vienna, Melbourne, Oslo, Poland, and Denmark;
- Presentations at universities and institutions in Brussels, the UK, Denmark, Germany, Australia, the USA, the Netherlands and many more. This has included a presentation by ice2sea scientists in New York for an event involving NASA and the European Space Agency;
- Hundreds of articles in the media including television, newspapers, magazines, and online coverage;
- Thousands of social media interactions via the website, blogs, Facebook page, and Twitter account (@ice2seaEU).

Success could be measured in the hundreds of papers published, or the myriad TV and newspaper coverage, but ultimately it will be the legacy of the programme upon which ice2sea is judged.

We wanted people to know that, with the help of the European Union, ice2sea is providing high-quality research at the cutting edge; that ice2sea scientists across Europe are working together to understand the future of sea-level rise; that the research is exciting and relevant to everyone; and finally, ice2sea has invested in the next generation of European scientists. That was our plan. We are proud to have achieved those goals.

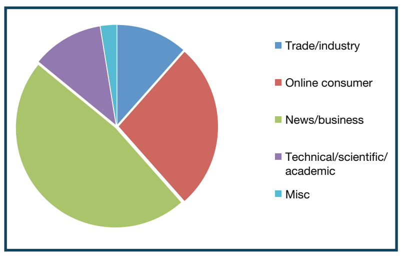
A case in point: Research with a global message to a worldwide audience

In February 2013, the ice2sea communications team at the British Antarctic Survey issued a press release in conjunction with colleagues in the University of Urbino, Italy. It was on Giorgio Spada's paper "The gravitationally consistent sea-level fingerprint of future terrestrial ice loss" which was published in the journal Geophysical Review Letters.

The research centres on predictions of sea-level rise and its uneven spread across the globe compared with the mean, which would most strongly affect the equatorial Pacific countries.

The team worked hard to reduce the long paper down to two sides of A4, whilst explaining the research without compromising the science. We were able to produce something that allowed journalists to easily understand the key message from the paper, and pass it on to hundreds of thousands of readers.

The story was reported in more than 70 media sites across the globe including several in Europe, with a majority in the USA and India, whilst also being reported in Azerbaijan, Malaysia, and the United Arab Emirates. The storied also reached a variety of sectors (see chart).



Sources of further information

Visit our website: **www.ice2sea.eu**

Subscribe to our RSS news feed on **www.ice2sea.eu/news**

Social media

Twitter: Follow us at **@ice2seaEU**

Facebook: like our page **www.facebook.com/ice2seaFP7**

Blog by ice2sea climate modeller Dr. Tamsin Edwards with PLOS (Public Library of Science) blogs: **http://blogs.plos.org/models/**

Publications

For further details of our peer-reviewed publications, as listed below, please see:

The ice2sea website: **http://www.ice2sea.eu/programme/published-papers/**

Google scholar: **http://scholar.google.co.uk/citations?user=zRXJHnMAAAAJ**

OpenAIRE (Open Access Infrastructure for Research in Europe): **http://www.openaire.eu/en/component/openaire/project_info/default/619?id=226375**

Acknowledgements

The ice2sea partners received direct funding from the European Union's Framework-7 Programme (grant no. 226375), and each of the partner institutions (listed on the inside back cover) have contributed additional financial and facilitating support to the programme and our scientists. The programme has benefited throughout from advice and support from the staff at the European Commission.

SEVENTH FRAMEWORK PROGRAMME

Ice2sea has also received support from scientific collaborators for numerous co-authored papers (see list below), and in particular: Anne Le Brocq (Universities of Durham and Exeter), Robert Thomas (SIGMA Space), Peter Nienow (University of Edinburgh), Sophie Nowicki and Robert Bindschadler (NASA) of the US SeaRISE project, Anders Levermann (Potsdam Institute), Killian Scharrer (University of Swansea), Doug Benn (University Centre in Svalbard), Angelika Humbert (University of Hamburg), and Ingo Sasgen (German Research Centre for Geosciences).

Professor Chris Rapley, University College London, has acted as Special Advisor to the programme.

Publications

The list of publications below are all those written through funding from ice2sea, in whole or in collaboration. The order is by date on submission to a journal, and the numbers reflect the citations throughout this document. Most papers have a full citation, those without are still going through the peer-review process.

001: Spada, G., *Love Numbers of a Generalized Maxwell Sphere,* Studia Geophysica et Geodaetica, 1-16, 57, 10.1007/s11200-011-0480-9, (2012)

002: Paul, F., and Linsbauer, A., *Modeling of glacier bed topography using glacier outlines, flowlines and a DEM,* International Journal of Geographical Information Science, 1173-1190, 26, 10.1080/13658816.2011.627859, (2009)

003: Spada, G., Colleoni, F., and Ruggieri, G., *Shallow upper mantle rheology and secular ice-sheets fluctuations,* Tectonophysics, 89-98, 511, 10.1016/j.tecto.2009.12.020, (2011)

004: Gagliardini, O., Durand, G., Zwinger, T., Hindmarsh, R., and Le Meur, E., *Coupling of ice-shelf melting and buttressing is a key process in ice-sheets dynamics,* Geophysical Research Letters, 14501-14506, 37, 10.1029/2010GL043334, (2010)

005: Ma Ying, Gagliardini, O., Ritz, C., Gillet-Chaulet, F., Durand, G., and Montagnat, M., *Enhancement factors for grounded ice and ice-shelf both inferred from an anisotropic ice flow model,* Journal of Glaciology, 805-812, 56, (2010)

006: number not in use.

007: Nick, F.M., van der Veen, C.J., Vieli, A., and Benn, D., *A physically based calving model applied to marine outlet glaciers and implications for their dynamics,* Journal of Glaciology, 781-794, 56, (2010)

008: Moholdt, G., Hagen, J.O., Eiken, T., and Schuler, T.V., *Geometric changes and mass balance of the Austfonna ice cap, Svalbard,* The Cryosphere, 21-34, 4, (2010)

009: Moholdt, G., Nuth, C., Hagen, J.O., and Kohler, J., *Recent elevation changes of Svalbard glaciers derived from ICESat altimetry,* Remote Sensing of the Environment, 2756-2767 114, 10.1016/j.rse.2010.06.008, (2010)

010: Tsimplis, M., Spada, G., and Marcos, M., *Multi-decadal sea level trends and land movements in the Mediterranean Sea with estimates of factors perturbing tide gauge data and cumulative uncertainties.,* Global and Planetary Change, 63-76, 76, (2011)

011: Aðalgeirsdóttir, G., Stendel, M., Christensen, J.H., Cappelen, J., Vejen, F., Kjær, H.A., Mottram, R., Lucas-Picher, P., and Drews, M., *Assessment of the temperature, precipitation and snow in the RCM HIRHAM4 at 25 km resolution, Copenhagen,* Danish Meteorological Institute Report, 09-08. (2010). NPR.

012: Spada, G., Barletta, V.R., Klemann, V., Riva, R.E.M., Martinec, Z., Gasperini, P., Lund, B., Wolf, D., Vermeersen, L.L.A., and King, M., *A benchmark study for glacial-isostatic adjustment codes,* Geophysical Journal International, 106-132, 185, 10.1111/j.1365-246X.2011.04952.x, (2010)

013: Timmermann, R., Le Brocq, A., Deen, T., Domack, E., Dutrieux, P., Galton-Fenzi, B., Hellmer, H., Humbert, A., Jansen, D., Jenkins, A., Lambrecht, A., Makinson, K., Niederjasper, F., Nitsche, F., Nost, O.A., Smedsrud, L.H., and Smith, W.H.F., *A consistent dataset of Antarctic ice sheet topography, cavity geometry, and global bathymetry,* Earth System Science Data, 261-273, 2, 10.5194/essd-2-261-2010, (2010)

014: Sandberg Sørensen, L., Simonsen, S.B., Nielsen, K., Lucas-Picher, P., Spada, G., Adalgeirsdottir, G., Forsberg, R., and Hvidberg, C., *Mass balance of the Greenland ice sheet (2003–2008) from ICESat data – the impact of interpolation, sampling and firn density,* The Cryosphere, 173 - 186, 5, 10.5194/tc-5-173-2011, (2011)

015: Scarchilli, C., Frezzotti, M., and Ruti, P.M., *Snow Precipitation at four ice core sites in East Antarctica: provenance, seasonality and blocking factors, Climate Dynamics, 2107-2125, 37, 10.1007/s00382-010-0946-4, (2011)*

016: Bellot, H., Trouvilliez, A., Naaim-Bouvet, F., Genthon, C., and Gallée , H., *Present weather sensors tests for measuring drifting snow,* Annals of Glaciology, 179-184, 52, (2011)

017: Gardner, A.S., Moholdt, G., Wouters, B., Wolken, G.J., Burgess, D.O., Sharp, M.J., Cogley, J.G., Braun, C., and Labine, C., *Sharply increased mass loss from glaciers and ice caps in the Canadian Arctic Archipelago, Nature, 357-360, 473, 10.1038/nature10089, (2011)*

018: Moholdt, G., and Kääb, A., *A new DEM of the Austfonna ice cap by combining differential SAR interferometry with ICESat laser altimetry, Polar Research, 31, 10.3402/polar.v31i0.18460, (2012)*

019: Moholdt, G., Heid, T., Benham, T., and Dowdeswell, J.A., *Dynamic instability of marine glacier basins of the Academy of Sciences Ice Cap, Russian High Arctic,* Annals of Glaciology, 193-201, 53(60), 10.3189/2012AoG60A117, (2012)

020: Docquier, D., Perichon, L., and Pattyn, F., *Representing Grounding Line Dynamics in Numerical Ice Sheet Models: Recent Advances and Outlook,* Surveys in Geophysics, 417–435, 32, 10.1007/s10712-011-9133-3, (2011)

021: Vaughan, D.G., Barnes, D.B.A., Fretwell, P.T., and Bingham, R.G., Potential seaways across West Antarctica, *Geochem. Geophys. Geosyst., 1-11, 12, 10.1029/2011GC003688, (2011)*

022: Mainardi, F., and Spada, G., *Creep, relaxation and viscosity properties for basic fractional models in rheology,* European Physical Journal, 133-160, 193, 10.1140/epjst/e2011-01387-1, (2011)

023: Agosta, C., Favier, V., Genthon, C., Gallée, H., Krinner, G., Lenaerts, J.T.M., and van de Broeke, M.R., *A 40-year accumulation dataset for Adelie Land, Antarctica and its application for model validation,* Climate Dynamics, 75-86, 38, 10.1007/s00382-011-1103-4, (2011)

024: Dunse, T., Greve, R., Schuler, T.V., and Hagen, J.O., *Permanent fast flow versus cyclic surge behaviour: numerical simulations of the Austfonna ice cap, Svalbard,* Journal of Glaciology, 247-259, 57, (2011)

025: Nuth, C., Schuler, T.V., Kohler, J., Altena, B., and Hagen, J.O., *Estimating the long-term calving flux of Kronebreen, Svalbard from geodetic elevation changes and mass-balance modelling,* Journal of Glaciology, 119-133, 58, 10.3189/2012JoG11J036, (2012)

026: Sundal, A.V., Shepherd, A., Nienow, P., Hanna, E., Palmer, S., and Huybrechts, P., *Melt-induced speed-up of Greenland ice sheet offset by efficient subglacial drainage,* Nature, 521-524, 469, 10.1038/nature09740, (2011)

027: Griggs, J., and Bamber, J.L., *Antarctic ice-shelf thickness from satellite radar altimetry,* Journal of Glaciology, 485-498, 57, (2011)

028: Hurkmans, R.T.W.L., Bamber, J.L., Sorensen, L.S., Joughin, I.R., Davis, C.H., and Krabill, W.B., *Spatio-temporal interpolation of elevation changes derived from satellite altimetry for Jakobshavn Isbræ, Greenland, Journal of Geophysical Research, 1-16, 117, 10.1029/2011JF002072, (2012)*

029: Dunse, T., Schuler, T.V., Hagen, J.O., and Reijmer, C.H., *Seasonal speed-up of two outlet glaciers of Austfonna, Svalbard, inferred from continuous GPS measurements,* The Cryosphere, 453-466, 6, 10.5194/tc-6-453-2012, (2011)

030: Gallée, H., Agosta, C., Gential, L., Favier, V., and Krinner, G., *A downscaling approach towards high-resolution surface mass balance over Antarctica,* Surveys in Geophysics, 507-518, 32, DOI: 10.1007/s10712-011-9125-3, (2011)

031: Durand, G., Gagliardini, O., Favier, L., Zwinger, T., and Le Meur, E., Impact of bedrock description on modeling ice sheet dynamics, Geophysical Research Letters, L20501-20507, 38, doi:10.1029/2011GL048892, (2011)

032: Jay-Allemand, M., Gillet-Chaulet, F., Gagliardini, O., and Nodet, M., Investigating changes in basal conditions of Variegated Glacier prior to and during its 1982–1983 surge, *The Cryosphere, 659-672, 5, 10.5194/tc-5-659-2011, (2011)*

033: Rae, J., Culverwell, I., Gladstone, R., Gregory, J., Lowe, J., and Ridley, J., *Intercomparison of driving global models and observations and on detectability of large-scale drivers of ice sheet change and spread in future projections of these drivers.,* Met Office internal report, Exeter, UK, Report. (2010). NPR

034: Lucas-Picher, P., Wulff-Nielsen, M., Christensen, J.H., Adalgeirsdottir, G., Mottram, R., and Simonsen, S.B., *Very high resolution in regional climate model simulations for Greenland - Identifying added value,* Journal of Geophysical Research, 1-16, 117, 10.1029/2011JD016267, (2012)

035: Le Brocq, A., Payne, A.J., and Vieli, A., *An improved Antarctic dataset for high resolution numerical ice sheet models (ALBMAPv1),* Earth System Science Data, 247-260, 2, 10.5194/essd-2-247-2010, (2010)

036: Spada, G., Ruggieri, G., Sorensen, L.S., Nielsen, K., D., M., and Colleoni, F., *Greenland uplift and regional sea level changes from ICESat observations and GIA modelling,* Geophysical Journal International, 1457-1474, 189, 10.1111/j.1365-246X.2012.05443.x, (2012)

037: Smeets, C.J.P.P., Boot, W., Hubbard, A., Pettersson, R., Wilhelms, F., van de Broeke, M.R., and van de Wal, R.S.W., *A wireless subglacial probe for deep ice applications,* Journal of Glaciology, 841-848, 58, 10.3189/2012JoG11J130, (2012)

038: Fettweis, X., Tedesco, M., van de Broeke, M.R., and Ettema, J., *Melting trends over the Greenland ice sheet (1958–2009) from spaceborne microwave data and regional climate models,* The Cryosphere, 359-375, 5, 10.5194/tc-5-359-2011, (2011)

039: Sasgen, I., van de Broeke, M.R., Bamber, J.L., Rignot, E., Sorensen, L.S., Wouters, B., Martinec, Z., and Simonsen, S.B., *Timing and origin of recent regional ice-mass loss in Greenland,* Earth and Planetary Science Letters, 293-303, 333, http://dx.doi.org/10.1016/j.epsl.2012.03.033, (2012)

040: Thoma, M., Grosfeld, K., Mayer, C., and Pattyn, F., *Ice flow sensitivity to boundary processes: A coupled model study in the Subglacial Lake Vostok area,* Annals of Glaciology, 173-180, 53, 10.3189/2012AoG60A009, (2012)

041: Hellmer, H.H., Kauker, F., Timmermann, R., Determann, J., and Rae, J., *Twenty-first-century warming of a large Antarctic ice-shelf cavity by a redirected coastal current,* Nature, 225-228, 485, 10.1038/nature11064, (2012)

042: Timmermann, R., Wang, Q., and Hellmer, H.H., *Ice shelf basal melting in a global finite-element sea ice--ice shelf--ocean model,* Annals of Glaciology, 303-314, 53, 10.3189/2012AoG60A156, (2012)

043: Favier, L., Gagliardini, O., Durand, G., and Zwinger, T., *A three-dimensional full Stokes model of the grounding line dynamics: effect of a pinning point beneath the ice shelf,* The Cryosphere, 1995-2033, 5, 10.5194/tcd-5-1995-2011, (2011)

044: Determann, J., Thoma, M., Grosfeld, K., and Massmann, S., *Impact of Basal Melting on a Coupled Dynamic 3d-SIA-SSA-Ocean Model,* Annals of Glaciology, 129-135, 53, 10.3189/2012AoG60A170, (2012)

045: Favier, V., Agosta, C., Genthon, C., Arnaud, L., Trouvilliez, A., and Gallée, H., *Modeling the mass and surface heat budgets in a coastal blue ice area of Adelie Land, Antarctica,* Journal of Geophysical Research, 1-14, 116, 10.1029/2010JF001939, (2011)

046: Fettweis, X., Belleflamme, A., Erpicum, M., Franco, B., and Nicolay, S. (2011), *Estimate of the Sea Level Rise by 2100 Resulting from Changes in the Surface Mass Balance of the Greenland Ice Sheet,* in Climate Change - Geophysical Foundations and Ecological Effects, edited by J. B. H. Kheradmand, pp. 503-520, InTech

047: Otero, J., Navarro, F.J., Lapazaran, J.J., Grabiec, M., Puczko, D., Molina, C., and Vieli, A., *Modelling the seasonal and long-term variations of the calving front position of Hansbreen,* Journal of Glaciology, (submitted 2012)

048: Drouet, A.S., Durand, G., Gillet-Chaulet, F., Le Meur, E., Braun, J., Sacchettini, M., Young, D., Blankenship, D., Greenbaum, J., Wright, A., and Rignot, E., *A New Design for Digital Elevation Models of Bedrock Underlying Ice Sheets,* The Cryosphere, (2013)

049: Genthon, C., Krinner, G., and Castebrunet, H., *Antarctic precipitation and climate change predictions: Horizontal resolution and margin vs plateau issues,* Annals of Glaciology, 55-60, 50, 10.3189/172756409787769681, (2009)

050: Hindmarsh, R.C.A., *An observationally validated theory of viscous flow dynamics at the ice-shelf calving front,* Journal of Glaciology, 375-387, 58, 10.3189/2012JoG11J206, (2012)

051: Moholdt, G., Wouters, B., and Gardner, A.S., *Recent mass changes of glaciers and ice caps in the Russian High Arctic,* Geophysical Research Letters, 1-5, 39, 10.1029/2012GL051466, (2012)

052: Gillet-Chaulet, F., Gagliardini, O., Seddik, H., Nodet, M., Durand, G., Ritz, C., Zwinger, T., Greve, R., and Vaughan, D.G., *Greenland ice sheet contribution to sea-level rise from a new-generation ice-sheet model,* The Cryosphere, 1561-1576, 6, 10.5194/tc-6-1561-2012, (2012)

053: Fürst, J.J., Rybak, O., Goelzer, H., De Smedt, B., De Groen, P., and Huybrechts, P., *Improved convergence and stability properties in a three-dimensional higher-order ice sheet model,* Geoscientific Model Development, 1133-1149, 4, 10.5194/gmd-4-1133-2011, (2011)

054: Sundal, A.V., Shepherd, A., van den Broeke, M.R., van Angelen, J., Gourmelen, N., and Park, J., *Controls on short-term variations in Greenland glacier dynamics,* Journal of Glaciology, (2012)

055: Ligtenberg, S.R.M., Helsen, M.M., and van de Broeke, M.R., *An improved semi-empirical model for the densification of Antarctic firn,* The Cryosphere, 809-819, 5, doi:10.5194/tc-5-809-2011, (2011)

056: Pritchard, H.D., Ligtenberg, S.R.M., Fricker, H.A., Vaughan, D.G., van den Broeke, M.R., and Padman, L., *Antarctic ice loss driven by ice-shelf melt,* Nature, 502-505, 484, 10.1038/nature10968, (2012)

057: Kuipers Munneke, P., van de Broeke, M.R., King, J.C., Gray, T., and Reijmer, C.H., *Near-surface climate and surface energy budget of the Larsen C Ice Shelf, Antarctica,* The Cryosphere, 353-363, 6, doi:10.5194/tc-6-353-2012, (2011)

058: Kuipers Munneke, P., Picard, G., van de Broeke, M.R., Lenaerts, J.T.M., and van Meijgaard, E., *Insignificant change in Antarctic snowmelt volume since 1979,* Geophysical Research Letters, 1-5, 39, 10.1029/2011GL050207, (2011)

059: Lenaerts, J.T.M., van de Broeke, M.R., Dery, S.J., van Meijgaard, E., van de Berg, W.J., Palm, S.P., and Sanz Rodrigo, J., *Modeling drifting snow in Antarctica with a regional climate model, Part I: Methods and model evaluation,* Journal of Geophysical Research, 1-17, 117, doi:10.1029/2011JD016145, (2012)

060: Lenaerts, J.T.M., and van de Broeke, M.R., *Modeling drifting snow in Antarctica with a regional climate model: 2. Results,* Journal of Geophysical Research, 1-11, 117, doi:10.1029/2010JD015419, (2012)

061: Lenaerts, J.T.M., van den Broeke, M.R., van de Berg, W.J., van Meijgaard, E., and Kuipers Munneke, P., *A new, high resolution surface mass balance map of Antarctica (1979-2010) based on regional climate modeling Geophysical Research Letters, 1-5, 39, doi:10.1029/2011GL050713, (2012)*

062: Helsen, M.M., van de Wal, R.S.W., van den Broeke, M.R., van de Berg, W.J., and Oerlemans, J., *Coupling of climate models and ice sheet models by surface mass balance gradients: application to the Greenland Ice Sheet,* The Cryosphere, 255-272, 6, doi:10.5194/tc-6-255-2012, (2012)

063: Grabiec, M., Jania, J., Budzik, T., Puczko, D., Gajek, G., and Kolondra, L., Development of subglacial drainage system in relation to geometry changes of Spitsbergen Glaciers, *Hydrological Sciences Journal,* (submitted 2013)

064: Błaszczyk, M., Jania, J., and Kolondra, L., *Fluctuations of tidewater glaciers in Hornsund Fiord (Southern Svalbard) since the beginning of the 20th century,* Polish Polar Research, (submitted 2013)

065: Machguth, H., Haeberli, W., and Paul, F., *Mass Balance Parameters Derived from a Synthetic Network of Mass Balance Glaciers,* Journal of Glaciology, 965-979, 58, (2011)

066: Quiquet, A., Punge, H.J., Ritz, C., Fettweis, X., Kageyama, M., Krinner, G., and Salas-Melia, D., *Sensitivity of a Greenland ice sheet model to atmospheric forcing fields,* The Cryosphere, 999-1018, 6, doi:10.5194/tc-6-999-2012, (2012)

067: Nick, F.M., Luckman, A., Vieli, A., van der Veen, C.J., van As, D., van de Wal, R.S.W., Floricioiu, D., Hubbard, A.L., and Pattyn, F., *The response of Petermann Glacier to shelf retreat and its future stability in context of atmospheric and oceanic warming,* Journal of Glaciology, 229-239, 58, 10.3189/2012JoG11J242, (2012)

068: Barletta, V.R., Bordoni, A., Aoudia, A., and Sabadini, R., *Squeezing more information out of time variable gravity data with a temporal decomposition approach,* Global and Planetary Change, 51-64, 83, doi:10.1016/j.gloplacha.2011.11.010, (2012)

069: Hurkmans, R.T.W.L., Bamber, J.L., and Griggs, J., *Importance of slope-induced error correction in elevation change estimates from radar altimetry,* The Cryosphere, 447-451, 6, doi:10.5194/tc-6-447-2012, (2012)

070: Frezzotti, M., Scarchilli, C., Becagli, S., Proposito, M., and Urbini, S., *A synthesis of the Antarctic Surface Mass Balance during the last last eight centuries,* The Cryosphere, 303-319, 7, 10.5194/tc-7-303-2013, (2013)

071: Gallée, H., Trouvilliez, A., Agosta, C., Genthon , C., Favier, V., and Naaim, F., Transport of Snow by the Wind: *A Comparison Between Observations in Adélie Land, Antarctica, and Simulations Made with the Regional Climate Model MAR,* Boundary Layer Meteorology, 133-147, 146, 10.1007/s10546-012-9764-z, (2013)

072: Scambos, T.A., Frezzotti, M., Haran, T., Bohlander, J., Lenaerts, J.T.M., van den Broeke, M.R., Jezek, K., Long, D., Urbini, S., Farness, K., Neumann, T., Albert, M., and Winther, J.-G., *Extent of low-accumulation 'wind glaze' areas on the East Antarctic Plateau: implications for continental ice mass balance,* Journal of Glaciology, 633-647, 58, 10.3189/2012JoG11J232, (2012)

073: number not in use.

074: Spada, G., and Galassi, G., *New estimates of secular sea–level rise from tide gauge data and GIA modeling, Geophysical* Journal International, 1067-1094, 191, 10.1111/j.1365-246X.2012.05663, (2012)

075: Pattyn, F., School, C., Perichon, L., Hindmarsh, R.C.A., Bueler, E., De Fleurian, B., Durand, G., Gagliardini, O., Gladstone, R., Goldberg, D., Gudmundsson, G.H., Lee, V., Nick, F.M., Payne, A.J., Pollard, D., Rybak, O., Saito, F., and Vieli, A., *Results of the Marine Ice Sheet Model Intercomparison Project, MISMIP,* The Cryosphere, 573-588, 6, doi:10.5194/tc-6-573-2012, (2012)

076: Vaughan, D.G., Corr, H.F.J., Bindschadler, R.A., Dutrieux, P., Gudmundsson, G.H., Jenkins, A., Newman, T., Vornberger, P., and Wingham, D.J., *Subglacial melt channels and fracture in the floating portion of Pine Island Glacier, Antarctica,* Journal of Geophysical Research, 1-10, 117, 10.1029/2012JF002360, (2012)

077: Aschwanden, A., Adalgeirsdottir, G., and Khroulev, C., *Hindcasting to measure ice sheet model sensitivity to initial states,* The Cryosphere Discussions, 5069-5094, 6, doi:10.5194/tcd-6-5069-2012, (2012)

078: Cook, A., Murray, T., Luckman, A., Vaughan, D.G., and Barrand, N.E., *A new 100-m Digital Elevation Model of the Antarctic Peninsula derived from ASTER Global DEM: methods and accuracy assessment, Earth System Science Data, 129-142, 4, doi:10.5194/essd-4-129-2012, (2012)*

079: Giesen, R.H., and Oerlemans, J., *Calibration of a surface mass balance model for global-scale applications,* The Cryosphere, 1463-1481, 6, 10.5194/tc-6-1463-2012, (2012)

080: Niesen, K., Sorensen, L.S., Khan, S.A., Spada, S., Simonsen, S.B., and Forsberg, R., *Towards constraining glacial isostatic adjustment in Greenland by GPS observations,* International Association of Geodesy Symposia, in press, 139, (2013)

081: Williams, C.R., Hindmarsh, R.C.A., and Arthern, R.J., *Frequency response of ice streams,* Proceedings of the Royal Society A, 3285-3310, 468, 10.1098/rspa.2012.0180, (2012)

082: Barrand, N., Vaughan, D.G., Steiner, N., Tedesco, M., Kuipers Munneke, P., van den Broeke, M.R., and Hosking, J.S., *Trends in Antarctic Peninsula surface melting conditions from observations and regional climate modelling,* Journal of Geophysical Research, 1-16, 118, 10.1029/2012JF002559, (2013)

083: Rae, J.G.L., Adalgeirsdottir, G., Edwards, T.L., Fettweis, X., Gregory, J.M., Hewitt, H.T., Lowe, J.A., Lucas-Picher, P., Mottram, R.H., Payne, A.J., Ridley, J.K., Shannon, S.R., van de Berg, W.J., van de Wal, R.S.W., and van den Broeke, M.R., *Greenland ice sheet surface mass balance: evaluating simulations and making projections with regional climate models,* The Cryosphere, 1275-1294, 10.5194/tc-6-1275-2012, (2012)

084: van Angelen, J., Lenaerts, J.T.M., Lhermitte, S., Fettweis, X., Kuipers Munneke, P., van den Broeke, M.R., van Meijgaard, E., and Smeets, C.J.P.P., *Sensitivity of Greenland Ice Sheet surface mass balance to surface albedo parameterization: a study with a regional climate model,* The Cryosphere, 1175-1186, 6, 10.5194/tc-6-1175-2012, (2012)

085: Ligtenberg, S.R.M., van de Berg, W.J., van den Broeke, M.R., Rae, J.G.L., and van Meijgaard, E., *Future surface mass balance of the Antarctic ice sheet and its influence on sea level change, simulated by a regional atmospheric climate model,* Climate Dynamics, in press, 10.1007/s00382-013-1749-1, (2013)

086: Gallée, H., Trouvilliez, A., Agosta, C., Genthon, C., Favier, V., and Naaim, F., *Observation et modélisation avec le Modèle Atmosphérique Régional,* Volumes d'actes du XXVe congres de l'Association Internationale en Climatologie, 315-320, (2012), NPR.

087: Hiess, G., Hindmarsh, R.C.A., Clark, and Larter, R., *Topographic controls on ice-stream formation,* Journal of Geophysical Research, (submitted 2012)

088: Hiess, G., and Hindmarsh, R.C.A., *Effect of geothermal flux on ice-stream plan geometry,* Journal of Geophysical Research, (submitted 2012)

089: Agosta, C., Favier, V., Krinner, G., Gallée , H., and Genthon , C., *High-resolution modeling of the Antarctic mass balance, model description and validation,* Climate Dynamics, (submitted 2012)

090: Agosta, C., Favier, V., Krinner, G., Gallée, H., Fettweis, X., and Genthon, C., *High-resolution modeling of the Antarctic mass balance, application for the 20th, 21st and 22nd centuries,* Climate Dynamics, in press, 40, CLIDY-D-12-00404, (2013)

091: Lenaerts, J.T.M., van den Broeke, M.R., Agosta, C., and Scarchilli, C., *Impact of model resolution on simulated wind, drifting snow and surface mass balance in Adelie Land, East Antarctica,* Journal of Glaciology, 821-829, 58, 10.3189/2012JoG12J020, (2012)

092: Lenaerts, J.T.M., van den Broeke, M.R., van Angelen, J., van Meijgaard, E., and Dery, S.J., *Drifting snow climate of the Greenland ice sheet: a study with a regional climate model,* The Cryosphere, 891-899, 6, 10.5194/tc-6-891-2012, (2012)

093: Paul, F., Barrand, N.E., Berthier, E., Bolch, T., Casey, K., Frey, H., Joshi, S., Konovalov, V., Le Bris, R., Molg, N., Nosenko, G., Nuth, C., Pope, A., Racoviteanu, A., Rastner, P., Raup, B., Scharrer, K., Steffen, S., and Winsvold, S., *On the accuracy of glacier outlines derived from remote sensing data,* Annals of Glaciology, 171-182, 54, 10.3189/2013AoG63A296, (2012)

094: Picard, G., Domine, F., Krinner, G., Arnaud, L., and Lefebvre, E., *Inhibition of the positive snow-albedo feedback by precipitation in interior Antarctica,* Nature Climate Change, 795-798, 2, 10.1038/NCLIMATE1590, (2012)

095: Torbjorn, I., Østby, T.I., Schuler, T.V., Hagen, J.O., Reijmer, C.H., and Hock, R., *Parameter uncertainty, refreezing and surface energy balance modelling at Austfonna ice cap, Svalbard, over 2004-2008.,* Annals of Glaciology, in press, 54, (2013)

096: Le Bris, R., and Paul, F., *Glacier-specific elevation changes in western Alaska,* Geophysical Research Letters, (submitted 2012)

097: Rastner, P., Bolch, T., Molg, N., Machguth, H., Le Bris, R., and Paul, F., *The first complete glacier inventory for entire Greenland,* The Cryosphere, 1483-1495, 6, 10.5194/tc-6-1483-2012, (2012)

098: Fettweis, X., Franco, B., Tedesco, M., van Angelen, J.H., Lenaerts, J.T.M., van den Broeke, M.R., and Gallée, H., *Estimating Greenland ice sheet surface mass balance contribution to future sea level rise using the regional atmospheric climate model MAR,* The Cryosphere, 31469-31489, 7, 10.5194/tc-7-469-2013, (2013)

099: Genthon , C., Trouvilliez, A., Gallée , H., Bellot, H., Naaim, F., Favier, V., and Piard, e.L., *Blizzard, très blizzard,* La Météorologie, No.75, (2011)

100: Pfeffer, T., Arendt, A.A., Bliss, A., Bolch, T., Cogley, G., Gardner, A., Hagen, J.O., Hock, R., Kaser, G., Moholdt, G., Paul, F., Radić, V., Raup, B.H., and GLIMS Contributors, *The Randolph Glacier Inventory: a globally complete digital glacier inventory*, Journal of Geophysical Research, in prep., (2013)

101: Aðalgeirsdóttir, G., Aschwanden, A., Khroulev, C., Boberg, F., Mottram, R., Lucas-Picher, P., and Christensen, J.H., *Projections of the contribution of the Greenland Ice Sheet to sea level rise for the 21st Century,* Journal of Glaciology, (submitted 2013)

102: Gulley, J.D., Grabiec, M., Martin, J.B., Jania, J., Catania, G., and Glowacki, P., *The effect of discrete recharge by moulins and heterogeneity in flow path efficiency at glacier beds on subglacial hydrology,* Journal of Glaciology, 926-940, 58, 10.3189/2012JoG11J189, (2012)

103: Buchardt, S.L., Clausen, H.B., Vinther, B.M., and Dahl-Jensen, D., *Investigating the past and recent delta18O-accumulation relationship seen in Greenland ice cores,* Climate of the Past, 2053-2059, 8, 10.5194/cp-8-2053-2012, (2012)

104: Spada, G., Bamber, J.L., and Hurkmans, R.T.W.L., *The gravitationally consistent sea-level fingerprint of future terrestrial ice loss,* Geophysical Research Letters, 1-5, 40, 10.1029/2012GL053000, (2012)

105: Jania, J.A., Ignatiuk, D., Puczko, D., Sikora, S., Kostka, S., Welty, E.Z., and Pfeffer, W.T., *Short term changes in dynamics of the Hansbreen Glacier (Southern Spitsbergen),* Polish Polar Research, (submitted 2013)

106: Depoorter, M., and Bamber, J.L., *Grounding lines and ice plains in Antarctica using driving stress,* Geophysical Research Letters, (submitted 2012)

107: van Angelen, J.H., Lenaerts, J.T.M., van den Broeke, M.R., Fettweis, X., and van Meijgaard, E., *Loss of refreezing capacity accelerates 21st century Greenland mass loss,* Geophysical Research Letters, (submitted 2013)

108: Grabiec, M., Jania, J., Puczko, D., Kolondra, L., and Budzik, T., *The surface and bed morphology of Hansbreen, a tidewater glacier in Spitsbergen,* Polish Polar Research, 111-138, 33, 10.2478/v10183-012-0010-7, (2012)

109: Oerlemans, J., Adhikari, S., Anderson, B., Dunse, T., Giesen, R.H., Huybrechts, P., Leclercq, P.W., and van Pelt, W.J.J., *Modelling shrinkage of glaciers in the 21st century, (submitted 2012)*

110: Lenaerts, J.T.M., van Angelen, J.H., van der Broeke, M.R., Gardner, A.S., Wouters, B., and van Meijgaard, E., *Irreversible mass loss of Canadian Arctic Archipelago glaciers,* Geophysical Research Letters, 1-5, 40, 10.1002/grl.50214, (2013)

111: Ligtenberg, S.R.M., Horwath, M., van den Broeke, M.R., and Legresy, B., *Quantifying the seasonal 'breathing' of the Antarctic ice sheet,* Geophysical Research Letters, 1-6, 39, 10.1029/2012GL053628, (2012)

112: Pattyn, F., Perichon, L., Durand, G., Favier, L., Gagliardini, O., Hindmarsh, R.C.A., Zwinger, T., Cornford, S., Docquier, D., Fuerst, J.J., Goldberg, D., Gudmundsson, G.H., Humbert, A., Hutten, M., Huybrechts, P., Jouvet, G., Kleiner, T., Larour, E., Levermann, A., Martin, D., Morlighem, M., Payne, A.J., Pollard, D., Ruckamp, M., Rybak, O., Seroussi, H., Thoma, M., and Wilkens, N., *Grounding-line migration in plan-view marine ice-sheet models: results of the ice2sea MISMIP3d intercomparison,* Journal of Glaciology, in press, (2013)

113: Salzmann, N., Machguth, H., and Linsbauer, A., *The Swiss Alpine glaciers' response to the global 2°C air temperature target,* Environmental Research Letters, 1-12, 7, 10.1088/1748-9326/7/4/044001, (2012)

114: Goelzer, H., Huybrechts, P., Fürst, J.J., Nick, F.M., Andersen, M.L., Edwards, T.L., Fettweis, X., Payne, A.J., and Shannon, S., *Sensitivity of Greenland ice sheet projections to model formulations,* Journal of Glaciology, in press, (2013)

115: Payne, A.J., Cornford, S., Martin, D., Agosta, C., van den Broeke, M.R., Edwards, T., Gladstone, R., Hellmer, H.H., Krinner, G., Le Brocq, A.M., Ligtenberg, S.R.M., Lipscomb, W.H., Ng, E.G., Shannon, S.R., Timmermann, R., and Vaughan, D.G., *Impact of uncertain climate forcing on projections of the West Antarctic ice sheet over the 21st and 22nd centuries,* Earth and Planetary Science Letters, (submitted 2012)

116: Barletta, V.R., Sorensen, L.S., and Forsberg, R., *Variability of mass changes at basin scale for Greenland and Antarctica,* The Cryosphere Discussions, 3397-3446, 6, 10.5194/tcd-6-3397-2012, (2012)

117: Barletta, V.R., and Bordoni, A., *Linear versus Stepwise Ice histories in GIA modeling,* Journal of Geodynamics, (submitted 2013)

118: Nick, F.M., Vieli, A., Andersen, M.L., Joughin, I.R., Payne, A.J., Edwards, T., Pattyn, F., and van der Wal, R., *Future sea level rise from Greenland's major outlet glaciers in a warming climate,* Nature, in press, (2013)

119: Ritz, C., Durand, G., Edwards, T., Payne, A.J., Peyaud, T., and Hindmarsh, R., *Bimodal probability of the dynamic contribution of Antarctica to future sea level,* Nature Geosciences, (submitted 2012)

120: Edwards, T.L., Fettweis, X., Gagliardini, O., Gillet-Chaulet, F., Goelzer, H., Gregory, J.M., Hoffman, M.J., Huybrechts, P., Payne, A.J., Perego, M., Price, S., Quiquet, A., and Ritz, C., *Effect of uncertainty in surface mass balance elevation feedback on projections of the future sea level contribution of the Greenland ice sheet, Part I: Parameterisation,* The Cryosphere Discussions, 635-674, 7, 10.5194/tcd-7-635-2013, (2013)

121: Shannon, S., Payne, A.J., Bartholomew, I.D., van den Broeke, M.R., Edwards, T.L., Fettweis, X., Gagliardini, O., Gillet-Chaulet, F., Goelzer, H., Hoffman, M.J., Huybrechts, P., Mair, D., Nienow, P., Perego, M., S.F., P., Smeets, C.J.P.P., Sole, A.J., van de Wal, R.S.W., and Zwinger, T., *Enhanced basal lubrication and the contribution of the Greenland ice sheet to future sea level rise,* Proceedings of the National Academy of Sciences, (submitted 2012)

122: Schaefer, M., Machguth, H., Falvey, M., and Casassa, G., *Modeling the surface mass balance of the Northern Patagonia Icefield,* Journal of Geophysical Research, in press, 10.1002/jgrf.20038, (2013)

123: Kuipers Munneke, P., Ligtenberg, S.R.M., van den Broeke, M.R., and Vaughan, D.G., *Firn air depletion as a trigger for Antarctic ice-shelf collapse,* (submitted 2013)

124: Loriaux, T., and Casassa, G., *Evolution of glacial lakes from the Northern Patagonia Icefield and terrestrial water storage in a sea-level rise context,* Global and Planetary Change, in press, 10.1016/j.gloplacha.2012.12.012, (2013)

125: Shepherd, A., Ivins, E., Geruo, A., Barletta, V.R., Bentley, M., Bettadpur, S., Briggs, K.H., Bromwich, D.H., Forsberg, R., Galin, N., Horwath, M., Jacobs, S., Joughin, I.R., King, M.A., Lenaerts, J.T.M., Li, J., Ligtenberg, S.R.M., Luckman, A., Luthcke, S.B., McMillan, M., Meister, R., Milne, G., Mouginot, J., Muir, A., Nicolas, J.P., Paden, J., Payne, A.J., Pritchard, H.D., Rignot, E., Rott, H., Sorensen, L.S., Scambos, T.A., Scheuchl, B., Schrama, E.J.O., Smith, B., Sundal, A.V., van Angelen, J., van de Berg, W.J., van den Broeke, M.R., Vaughan, D.G., Velicogna, I., Wahr, J., Whitehouse, P., Wingham, D.J., Yi, D., Young, D., and Zwally, H.J., *A Reconciled Estimate of Ice-Sheet Mass Balance,* Science, 1183-1189, 338, 10.1126/science.1228102, (2012)

126: Barrand, N.E., Hindmarsh, R.C.A., Arthern, R.J., Williams, C.R., Mouginot, J., Scheuchl, B., Rignot, E., Ligtenberg, S.R.M., van den Broeke, M.R., Edwards, T., Cook, A., and Simonsen, S.B., *Computing the volume response of the Antarctic Peninsula ice sheet to warming scenarios to 2200,* Journal of Glaciology, in press, 59, (2013)

127: Drouet, A.S., Docquier, D., Durand, G., Hindmarsh, R.C.A., Pattyn, F., Gagliardini, O., and Zwinger, T., *Grounding line transient response in marine ice sheet models,* The Cryosphere, 395-406, 7, 10.5194/tc-7-395-2013, (2013)

128: Favier, V., Agosta, C., Parouty, S., Durand, G., Delaygue, G., Gallée , H., Drouet, A.S., Trouvilliez, A., and Krinner, G., *An updated and quality controlled surface mass balance dataset for Antarctica,* The Cryosphere, 583-597, 7, 10.5194/tc-7-583-2013, (2013)

129: Bamber, J.L., and Aspinall, W.P., *An assessment of expert opinion on future sea-level rise from melting of ice sheets,* Nature Climate Change, 1-5, 10.1038/NCLIMATE1778, (2013)

130: Ahlstrøm, A.P., Andersen, S.B., Andersen, M.L., Machguth, H., Nick, F.M., Joughin, I.R., Reijmer, C.H., van de Wal, R.S.W., Merryman Boncori, J.P., Citterio, M., van As, D., and Fausto, R.S., *Seasonal velocities of eight major marine-terminating outlet glaciers of the Greenland ice sheet from continuous in situ GPS instruments,* Earth System Science Data Discussions, 27-57, 6, 10.5194/essdd-6-27-2013, (2013)

131: Fürst, J.J., Goelzer, H., and Huybrechts, P., *Effect of higher-order stress gradients on the centennial mass evolution of the Greenland ice sheet* The Cryosphere, 183-199, 7, 10.5194/tc-7-183-2013 (2013)

132: Fürst, J.J., Goelzer, H., and Huybrechts, P., *Ice-dynamic projections of the Greenland ice sheet to future atmosphere and ocean warming,* (submitted 2012)

133: Giesen, R.H., and Oerlemans, J., *Climate-model induced differences in the 21st century global and regional glacier contributions to sea-level rise,* Climate Dynamics, 1-18, 41, 10.1007/s00382-013-1743-7, (2013)

134: Timmermann, R., and Hellmer, H.H., *Southern Ocean warming and increased ice shelf basal melting in the 21st and 22nd centuries based on coupled ice-ocean finite-element modelling,* Ocean Dynamics, (submitted 2013)

135: Machguth, H., Rastner, P., Bolch, T., Molg, N., Sorensen, L.S., Adalgeirsdottir, G., van Angelen, J., van den Broeke, M.R., and Fettweis, X., *Future sea-level rise contribution of Greenland's glaciers and ice caps,* Environmental Research Letters, 025005, 8, 10.1088/1748-9326/8/2/025005, (2013)

136: Bolch, T., Sorensen, L.S., Simonsen, S.B., Molg, N., Machguth, H., Rastner, P., and Paul, F., *Mass loss of Greenland's glaciers and ice caps 2003-2008 revealed from ICESat laser altimetry data,* Geophysical Research Letters, 1-7, 40, 10.1029/2012GL054710, (2013)

137: Sasgen, I., Konrad, H., Ivins, E.R., van den Broeke, M.R., Bamber, J.L., Martinec, Z., and Klemann, V., *Antarctic ice-mass balance 2002 to 2011: regional re-analysis of GRACE satellite gravimetry measurements with improved estimate of glacial-isostatic adjustment,* The Cryosphere Discussions, 3703-3732, 6, 10.5194/tcd-6-3703-2012, (2012)

138: Casassa, G., Rodriguez, J.L., Loriaux, T., Rivera, A., and Bown, F., A new glacier inventory for the Southern Patagonia Icefield and areal changes 1986-2000, Global Land Ice Monitoring from Space (GLIMS), in press, (2013)

139: Depoorter, M.A., Griggs, J.A., Lenaerts, J.T.M., van den Broeke, M.R., and Bamber, J.L., *Calving fluxes and melt rates of Antarctic ice shelves,* Nature, (submitted 2013)

140: Barletta, V.R., Spada, G., Riva, R.E.M., James, T.S., Simon, K.M., van der Wal, W., Martinec, Z., Klemann, V., Olsson, P.-A., Stocchi, P., and Vermeersen, L.L.A., *Fingerprinting sea level variations in response to continental ice loss: a benchmark exercise,* EOS, (submitted 2012)

141: Kjær, H.A., Khan, S.A., Korsgaard, N.J., Wahr, J., Bamber, J.L., Hurkmans, R., van den Broeke, M.R., Timm, L.H., Kjeldsen, K.K., Bjørk, A.A., Larsen, N.K., Jørgensen, L.T., Faerch-Jensen, A., and Willerslev, E., *Aerial Photographs Reveal Late–20th-Century Dynamic Ice Loss in Northwestern Greenland,* Science, 569-573, 337, 10.1126/science.1220614, (2012)

142: Bamber, J.L., Griggs, J.L., Hurkmans, R.T.W.L., Dowdeswell, J.A., Gogineni, S.P., Howat, I., Mouginot, J., Paden, J., Palmer, S., Rignot, E., and Steinhage, D., *A new bed elevation dataset for Greenland,* The Cryosphere, 499-210, 7, 10.5194/tc-7-499-2013, (2013)

143: Rastner, P., Bolch, T., Notarnicola, C., and Paul, F., *A comparison of pixel- and object-based glacier classification with optical satellite images,* IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, (submitted 2013)

144: Mottram, R., Adalgeirsdottir, G., Boberg, F., Lucas-Picher, P., Stendel, M., Bøssing Christensen, O., and Christensen, J.H., *Reconstructing the Surface Mass Budget of the Greenland Ice Sheet with the Regional Climate Model HIRHAM5,* 1989-2011 (2013)

145: Park, J.W., Gourmelen, N., Shepherd, A., Kim, S.W., Vaughan, D.G., and Wingham, D.J., *Sustained retreat of the Pine Island Glacier,* Geophysical Research Letters, in press, (2013)

146: Howard, T., Pardaens, A.K., Lowe, J.A., Hurkmans, R.T.W.L., Bamber, J.L., Edwards, T.L., Giesen, R.H., Payne, A.J., Ridley, J., and Spada, G., *Projections of Combined Ice-Melt and Thermosteric Sea-Level change,* Climate Dynamics, submitted, CLIDY-D-13-00124, (2013)

147: Gladstone, R., Lee, V., Rougier, J.C., Payne, A.J., Hellmer, H., Le Brocq, A., Shepherd, A., Edwards, T.L., Gregory, J., and Cornford, S., *Calibrated prediction of Pine Island Glacier retreat during the 21st and 22nd centuries with a coupled flowline model,* Earth and Planetary Science Letters, 191-199, 333-334, 10.1016/j.epsl.2012.04.022, (2012)

148: Leclercq, P.W., Weidick, A., Paul, F., Bolch, T., Citterio, M., and Oerlemans, J., *Historical glacier length changes in West Greenland,* The Cryosphere, 1339-1343, 6, 10.5194/tc-6-1339-2012, (2012)

149: Williams, C.R., Hindmarsh, R., and Arthern, R.J., *Incorporating membrane stresses into calculations of balance velocities,* Journal of Glaciology, (submitted 2012)

150: Helsen, M.M., van de Wal, R.S.W., van den Broeke, M.R., van de Berg, W.J., and Oerlemans, J., *Coupled regional climate-ice sheet simulation shows limited Greenland ice loss during the Eemian*, Climate of the Past Discussions, 1735-1770, 9, 10.5194/cpd-9-1735-2013, (2013)

151: Edwards, T.L., Fettweis, X., Gagliardini, O., Gillet-Chaulet, F., Goelzer, H., Gregory, J.M., Hoffman, M.J., Huybrechts, P., Payne, A.J., Perego, M., Price, S., Quiquet, A., and Ritz, C., *Effect of uncertainty in surface mass balance elevation feedback on projections of the future sea level contribution of the Greenland ice sheet, Part 2: Projections,* The Cryosphere Discussions, 675-708, 7, 10.5194/tcd-7-675-2013, (2013)

152: Hurkmans, R.T.W.L., Bamber, J.L., and Davis, C., *Time-evolving mass loss of the Greenland ice sheet from satellite altimetry* Journal of Glaciology, (submitted 2012)

153: Gagliardini, O., Zwinger, T., Gillet-Chaulet, F., Durand, G., Favier, L., De Fleurian, B., Greve, R., Malinen, M., Martin, C., Raback, P., Ruokolainen, J., Schaefer, M., Seddik, H., and Thies, J., *Capabilities and performance of the new generation ice-sheet model Elmer/Ice,* Geoscientific Model Development Discussions, 1689-1741, 6, 10.5194/gmdd-6-1689-2013, (2013)

154: McNeall, D.J., Challenor, P.G., Gattiker, J.R., and Stone, E.J., *The potential of an observational data set for calibration of a computationally expensive computer model,* Geoscientific Model Development Discussions, 2369-2401, 6, 10.5194/gmdd-6-2369-2013, (2013)

155: Hellmer, H.H., Timmerman, R., Lee, V., Olbers, D., and Payne, A.J., *Assessment of cavity complexity required for the representation of sub-ice shelf processes in climate models,* Journal of Climate, (submitted 2013)

156: Thorsteinsson, T., Magnusson, E., Palsson, F., Gudmundsson, S., Adalgeirsdottir, G., and Bjørnsson, H., *Glacier sliding velocity related to surface energy balance,* Journal of Glaciology, (submitted 2013)

157: Favier, L., Durand, G., Cornford, S., Gudmundsson, G.H., Gagliardini, O., Gillet-Chaulet, F., Zwinger, T., and Payne, A.J., *irreversible retreat of Pine Island Glacier owing to topographic-induced instability,* Nature Geosciences, (submitted 2013)

Partner list

Belgium

Université Libre de Bruxelles (ULB)
Vrije Universiteit Brussel (VUB)
University of Liege (ULg)

Chile

Centro de Estudios Científicos (CECs)

Denmark

Danish Meteorological Institute (DMI)
Danmarks Tekniske Universitet (DTU)
Geological Survey of Denmark and Greenland (GEUS)
University of Copenhagen, Niels Bohr Institute (NBI)

Finland

CSC - IT Center for Science Ltd (CSC)

France

Centre National de la Recherche Scientifique (CNRS/LGGE)

Germany

Alfred Wegener Institut Helmholtz Zentrum für Polar und Meeresforschung (AWI)

Iceland

University of Iceland (HI)

Italy

Università degli Studi di Urbino (UniUrb)
Agenzia Nazionale per le Nuove Tecnologie, l'Energia e lo Sviluppo Economico Sostenibile (ENEA)

The Netherlands

Universiteit Utrecht (UU)

Norway

University of Oslo (UiO)
Norwegian Polar Institute (NPI)

Poland

University of Silesia (US)
Instytut Geofizyki Polskiej Akademii Nauk (IGF-PAS)

Switzerland

University of Zurich (UZh)

United Kingdom

British Antarctic Survey (NERC-BAS)
Met Office Hadley Centre (MOHC)
University of Bristol (UoB)
University of Leeds (UoL)

"The contribution of ice-loss from glaciers and ice sheets has been identified by an intergovernmental panel as the major uncertainty in predictions of future sea-level rise. It is vital that this uncertainty is reduced so that policy-makers will receive the best possible projections.

The European scientific community has great expertise in climate change research. I'm pleased to see that ice2sea, a programme funded by the EU, through its ambitious research in Antarctica and the Arctic, and through sophisticated computer modelling has contributed towards a real improvement in the understanding of these issues.

But a lot is still ahead of us. The challenges, as we know, are global and so the solutions must be as well. One successful example of science driven policy was the international response to the formation of the ozone hole in the 1980s. Almost thirty years later we can see the benefits of policy actions in response to the scientific evidence."

Anne Glover – Chief Scientific Advisor to the European Commission

ISBN 978-0-85665-206-6

SEVENTH FRAMEWORK PROGRAMME

www.ice2sea.eu