Ice2sea Final Report

Section 4.1

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Executive Summary

The future security and prosperity of European coastal cities and the survival of many unique 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 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 established a substantial European capability in sea-level projection, and has identified where uncertainties still exist and which processes are still not adequately understood.

Ice2sea was a scientific programme 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. Ice2sea focussed the efforts of researchers in 24 institutes in a coordinated programme of fieldwork, satellite observations, and computer simulations. The cooperation achieved between key institutes and scientific disciplines 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 around the globe, 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 enabled ice2sea to develop projections of continental ice-loss using computer models based on representations of the physics at work in glaciers and ice sheets, including for the first time, several important glacial processes.

Many advances achieved by ice2sea directly addressed issues that were central to the concerns expressed in IPCC AR4, and ice2sea publications contributed to the consensus sea-level projections developed by IPCC Working Group I in their Fifth Assessment Report (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 - 36.8 cm to global mean sea-level rise by the year 2100 for a mid-range emissions scenario (A1B). Ice2sea results also indicate sea levels will continue to rise, initially at an accelerating rate, for several centuries after 2100.

Ice2sea also investigated several factors that cause regional sea level to differ from the global mean, showing that European coastlines open to the oceans will experience a sea-level rise of 10 to 20% less than the global mean. However, to understand sea-level rise at a local scale, other factors such as patterns of vertical land movement, and projected changes in ocean circulation and storminess, also need to be taken into account.

Increased understanding and more rigorous projections provides policy-makers with a more complete and more certain basis for the design of coastal defences, in planning of adaptation projects, and in flood-risk management strategies. Ice2sea has thus helped to protect the future of investment in coastal regions, and allow management of risk for coastal populations.

Project Context and Objectives

The text of the call (ENV.2008.1.1.1.1. Sea-Level Rise: Trends in contributions from continental ice, processes and links to climate change) set out the areas to be addressed and the impacts that are expected. In the following sections, we describe how the concepts expressed in the call, and our reasoning regarding this text, led to the specific features in the ice2sea programme, its key objectives, and direct relationship to the text of the call.

Background - The threat of sea-level rise in Europe

Within the 27 nations of the EU there is a huge coastal concentration of populations, economic investment and ecological value.

- Economic assets located within 500 metres of the EU's coastline, including beaches, agricultural land and industrial facilities, have an estimated value of €500 to €1,000 billion.
- There are 47,500 km2 of sites identified as having high ecological value within 500 m of the coastline.
- In the last 50 years, the population living in coastal municipalities in the EU has more than doubled to 70 million people (14% of the population entire EU population).

Fifteen of the EU countries[1] have substantial coasts that are open to the world's oceans and are directly affected by global sea-level rise. For these countries, sea-level rise will exacerbate the risks of coastal flooding, increase rates of coastal erosion, and accelerate the destruction of natural sea defences. These impacts imply substantial threats to human lives and livelihoods.

The worst European storm surge in living memory occurred in 1953. It killed more than 2,000 people in England and the Netherlands. Since then, many cities have become more reliant on sea-defences, and the risk associated with inundation has grown substantially. The annual expense in protecting coastal assets is an estimated €3.2 billion, and this will increase, in some areas non-linearly, as sea-level rises. Within decades several major sea-defence projects will have to be specified, planned, and built - some of which have projected costs in excess of €20 billion. Elsewhere, coastal assets that until now have been protected by natural coastal environments are, for the first time, becoming vulnerable as these are eroded. For example, in 2001, dunes that have protected part of the Gulf of Riga (Latvia) for many years collapsed during a storm and led to flooding.

Outside the most highly populated areas the cost of sea defences may be too high to meet and "managed-retreat" may be the only option. Here the delicate balance that supports many of the most valuable and protected ecological habitats (listed in the EU's NATURA 2000 network of protected areas) may be disrupted. For example, rates of erosion are projected to increase on the areas covered by the Machair environments in Western Isles of Scotland, a unique and beautiful habitat, home to numerous endangered species of flowering plants and birds.

[1] France, Spain, Portugal, Belgium, Netherlands, Denmark, Sweden, Finland, Estonia, Republic of Ireland, Latvia, Lithuania, Poland, Germany, and the United Kingdom.

Understanding the likely risks and potential costs of protecting our coasts is a necessity for maintaining European quality-of-life and international competitiveness. Accurate and reliable projections of sea-level rise, will allow for timely planning of investment of enhanced sea-defences, and avoid unnecessary spending to raise sea-defences beyond that required. Reliable and sound projections of sea-level rise are the basic requirement for effective coastal defence planning.

Concept - Nature and longevity of impact

With climate science developing, and improving, at such a fast rate, it would be unrealistic to imagine that any one set of sea-level rise projections, or indeed, any climate change projections, will remain the state-of-the-art for more than a limited period. This fact is recognized in the cycles of the IPCC report series, which suggests that lifetime of much longer than 5-years cannot be expected for any climate projections.

For this reason, the ice2sea programme was designed to deliver projections of sea-level rise that represent the state-of-the-art and inform IPCC assessments, and provide a basis for debate within Europe; but also to deliver a legacy that will provide a substantial benefit to European citizens for long after the shelf-life of the ice2sea sea-level rise projections. This legacy comprises:

- improved understanding of the key processes that drive and amplify glacier-response;
- an improved framework for glacier-response modelling, and a suite of models that can be used to represent and investigate these processes;
- Finally, ice2sea has trained a new generation of ice-modellers who can be called upon in future to take this area of science forward towards increasingly secure sea-level projections.

These specific outcomes can be tied to specific deliverables in the ice2sea plan. These outcomes have fed to the IPCC's Fifth Assessment Report (AR5), most notably in Working Group II, but also in Working Group III. Due to the nature of the IPCC AR cycles, ice2sea understanding, results, and researchers trained by the project will also feed into the next report, AR6, although mostly in an indirect manner – the project has however created a platform for the next phase of understanding.

Concept – Delivering a European perspective

Projections of sea-level rise, such as those provided by the IPCC, represent global average sea-level given for a range of emission scenarios. However, in reality, specific geographical regions will experience substantially different regional sea-level rise, modified by a series of local issues. The most significant of these are:

- Regional rates of Post-glacial Isostatic Adjustment (PIA)
- Geoid modifications mean sea-level changes induced by gravity field modifications arising from repositioning of large masses on the Earth surface (e.g. ice sheet change).
- Geographic variations in the thermal and salinity structure of oceans and continental seas (so-called thermosteric effects)
- Effects due to changes in ocean circulation patterns driven by thermosteric changes in the oceans.

To provide a specific European focus and increase relevance of the ice2sea programme, and to optimize the value of the ice2sea deliverables within the European context, we also projected how the cryosphere will impact European sea level. Thus the effects of Post-glacial isostatic adjustment and geoid modification were included in our final assessments, and the potential scale of thermosteric effects were assessed. Projections of the effects of changing ocean circulation patterns are considered beyond the scope of ice2sea, as producing these would require a substantial ensemble of global ocean models to be run.

Concept - Uncertainty

At present the projections of sea-level rise presented to policy-makers and their advisers (for example in the Summary for Policymakers of IPCC-AR4) tend to include only a summary level of uncertainty information. While the IPCC identified different sources of uncertainty (“unpredictability”, “structural uncertainty” and “value uncertainty”), the projections supplied in the SPM conflated these sources. There is undoubtedly a value in providing such unified uncertainty ranges, but with appropriate communications, there is also a clear value in dissociating the sources of uncertainty in such projections. In particular, such understanding will guide where future research effort would best employed geographically, and by techniques. It would, for example, highlight whether an improvement in the projections of contribution to sea-level rise from Arctic ice caps would be better served by improvements in glacier-modelling techniques or by simple field-survey of the ice-caps to determine how much ice they currently contain.

Ice2sea tracked the sources of uncertainty in the final projections. These include assessments of how uncertainty arises, and thus demonstrate where further improvements in scientific understanding are most needed to reduce uncertainty still further. Similarly, from the point of view of sea-defence planning, a thorough understanding of how uncertainty in sea-level rise projections grows in time is vital and in some areas is missing. It is increasingly clear that major capital investments in sea-defences cannot be simply triggered by certain amounts of sea-level rise. Since many such projects require decades of planning and have projected a lifespan of decades to centuries, proper account must be taken of rates of sea-level rise, and the potential that rates will accelerate substantially.

Concept - Delivery and impact

To an extent the debates surrounding “climate change” and “sea-level rise” have appeared to be conflated and confused. A lay-person whose opinion were derived largely from broadcast and print media might be justified in believing that climate change and sea-level rise are simply two sides of the same coin, and need to be addressed in the same way, through a single strategy (mitigation and adaptation). However, this disregards many significant unique aspects of the sea-level rise issue, that must be considered in building a EU-wide / global response strategy (for example: the long-term commitment to sea-level rise that is now unavoidable and dictates an adaptation response, and/or, the natural instabilities in ice-sheets that could mean we eventually come to understand that sea-level rise is only in part caused by climate change).

The constraint surrounding the delivery of the IPCC-AR4 results have meant that the issues remain very confused. The single IPCC assessment hits the headlines in one single event, and so encourages the media to cover both climate change and sea-level rise as a single issue. Ice2sea has the opportunity to focus on sea-level rise, and bring some of these unique aspects of this issue closer to the front of the consciousness of policy-makers and the general public alike. Along with key scientific publications, the publication of the ice2sea briefing document (From Ice to High Seas) at the end of the programme was an opportunity for a substantial media campaign. In addition to our mass communications, we also targeted particular EU and national instruments and governments with a particular responsibility for sea-defence planning though policy-focused briefings (see Impacts section for more details).

Concept – Timescales of projections

The call requests sea-level rise projections on timescales of decades to centuries. This is a sensible timeframe since the planning of major infrastructure projects required for coastal flood protection is undertaken on this timescale. For example, London's Thames Barrier was first considered after the 1953 North Sea flood, it was opened exactly 30 years later in 1983. This barrier reaches its design life in 2030, and is due for replacement at that time. This demonstrates a clear requirement for sea-level rise projections on century timescales that will underpin policymaking and planning in Europe and elsewhere. Similarly, the recent activities of the Delta Commission of the Netherlands Government have requested and argued the importance of sea-level projections up to 2200.

The core of the ice2sea effort was to deliver sea-level rise projections for the next 100–200 years, although given the IPCC's emphasis on the period up to 2100, we also focused on this period. Projections beyond this period would have substantially greater uncertainty and thus much lower significance, and we will limit our efforts beyond this timescale to identifying thresholds and tipping points that could imply a long-term and/or irreversible commitment to sea-level rise. Such factors may be beyond most planning horizons, but have importance since they could influence the debate on long-term emissions control.

Key objectives

The key objectives of the ice2sea programme can be succinctly summarised by the following objectives / mission statements:

- Reduce the uncertainties in projections of cryospheric contributions to sea-level rise on decadal to centennial timescales, especially those highlighted by the IPCC AR4;
- Improve understanding of the key processes that control the cryospheric contribution to sea-level rise, and improve our ability to represent these processes in glacier-response models;
- Understand the recent rapid changes in the Greenland and Antarctic ice sheets and their significance for future sea-level predictions;
- To provide specific and well-validated projections of the cryospheric contribution to sea-level rise with defensible estimates of the uncertainties, and to present this in a context that has particular relevance to coastal planning in Europe;
- To provide a clear quantification of the magnitude and nature of the sources of uncertainty in predictions of cryospheric contributions to sea-level rise. Specifically, to understand the effects of uncertainties in emission scenarios, projections of climate forcing, glacier mapping, understanding of key processes, and approximations inherent in glacier-response modelling;
- Understand the recent "higher-than-expected" sensitivity of mountain glaciers to climate change;
- Evaluate the extent to which increased snow accumulation over the polar ice sheets may slow sea-level rise in coming decades and centuries;
- Produce a legacy of tools, skill, and understanding that will be used to predict the cryospheric contribution to sea-level rise long after the completion of ice2sea;
- Identify and quantify the risk of "surprises" still inherent in predictions of sea-level rise.

Main Results

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 established a substantial European capability in sea-level projection, and has identified where uncertainties still exist and which processes are still not adequately understood.

Ice2sea was a scientific programme 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. Ice2sea 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 between key institutes and scientific disciplines 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 around the globe, 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 enabled ice2sea to develop projections of continental ice-loss using computer models based exclusively on representations of the physics at work in glaciers and ice sheets. For the first time, several important processes were incorporated into these models.

Ice2sea has contributed to more than 160 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.

Many advances achieved by ice2sea directly addressed issues that were central to the concerns expressed in IPCC AR4, and as a consequence many publications from ice2sea, including projections, were cited Working Group I in the Fifth Assessment Report (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 - 36.8 cm to global mean sea-level rise by the year 2100 for a mid-range emissions scenario (A1B). To obtain a projection of total global sea-level rise, other contributions, not explicitly addressed by ice2sea, have to be added (e.g. thermal expansion of the oceans, and changes in terrestrial water storage). Ice2sea results also indicate, sea levels will continue to rise, initially at an accelerating rate, for several centuries after 2100.

Ice2sea also investigated several factors that cause regional sea level to differ by as much as tens of centimetres to the global mean. Ice2sea has investigated the global pattern of this variation showing that European coastlines will experience a sea-level rise of 10 to 20% less than the global mean. However, to understand sea-level rise at a local scale, other factors such as patterns of vertical land movement, and projected changes in ocean circulation and storminess, also need to be taken into account.

Increased understanding and more rigorous projections have provided policy-makers with a more complete and more certain basis for understanding future sea-level change, and this can be used in the design of coastal defences, in adaptation projects more generally, and in flood-risk management strategies. Ice2sea has thus helped to protect the future of investment in coastal regions, and allow management of risk for coastal populations.

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.

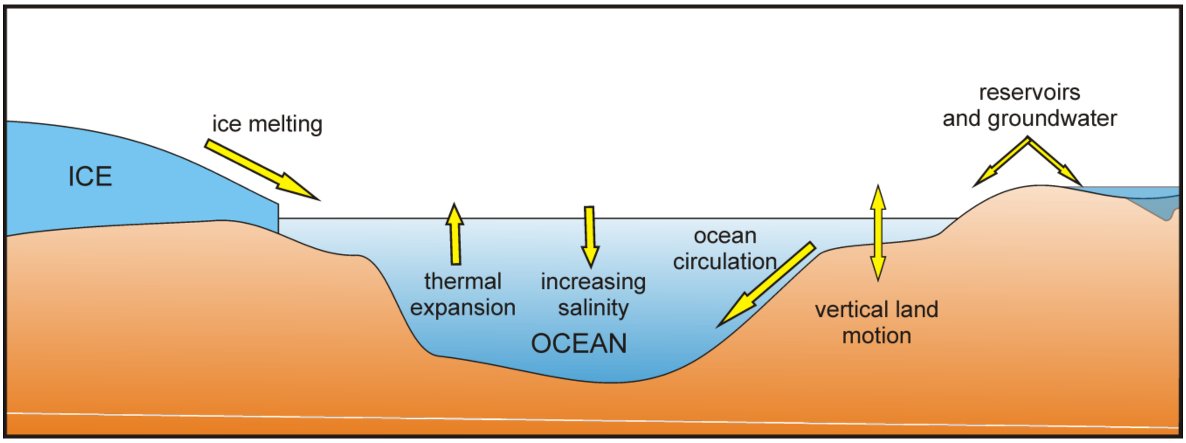
Around the world, a network of gauges, initially established to measure tides, has provided measurements of sea-level for almost 150 years. In recent decades, these records have been supplemented by satellite measurements. The composite records show that global sea-level has been rising throughout this 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.

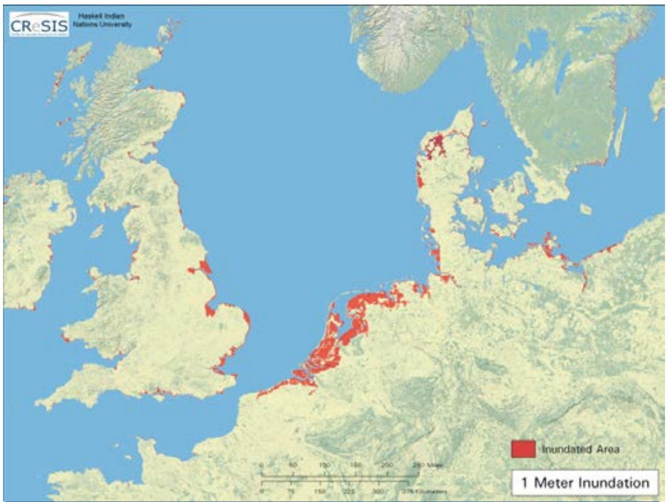
The risk to our coasts

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."



Areas of Northern Europe lying within 1m of sea level.

(Source: CReSIS)

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.

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.

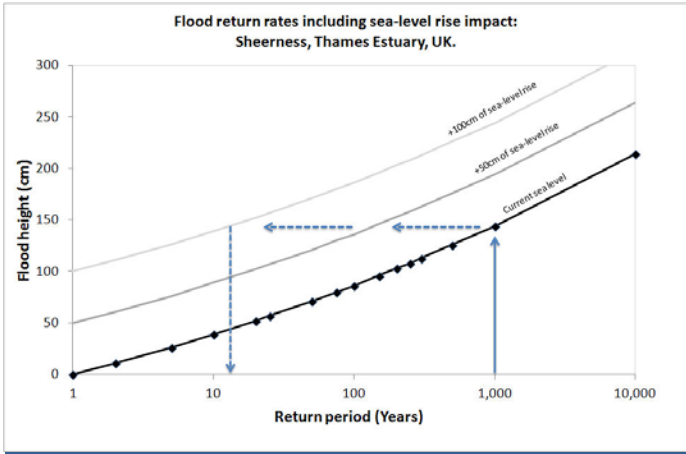
Case Study: London and the Thames Barrier: flood risk in a densely populated area

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.

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

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!



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)

The UK Environment Agency, which is responsible for flood defence across the UK, has developed a plan ('Thames Estuary 2100'[2]) 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.

2 http://www.environment-agency.gov.uk/homeandleisure/floods/104695.aspx

Case Study: 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[3] 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.

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

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

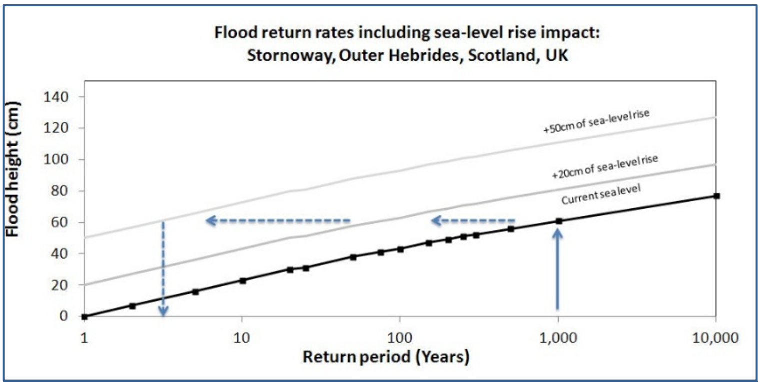
Machair. (Photo: Alison Cook)

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

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.

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.



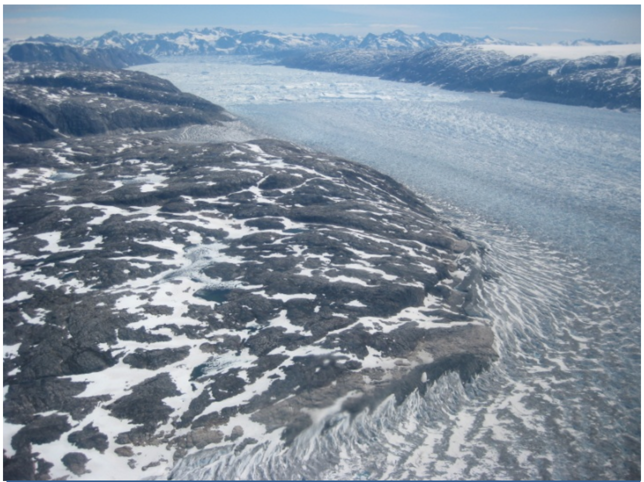
Flood statistics for the Isle of Harris. Heights are above the highest annual expected storm surge. Storm return periods in this area alter considerably as regional sea-level rises.

(Data: Proudman Oceanographic Laboratory.)

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.

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.

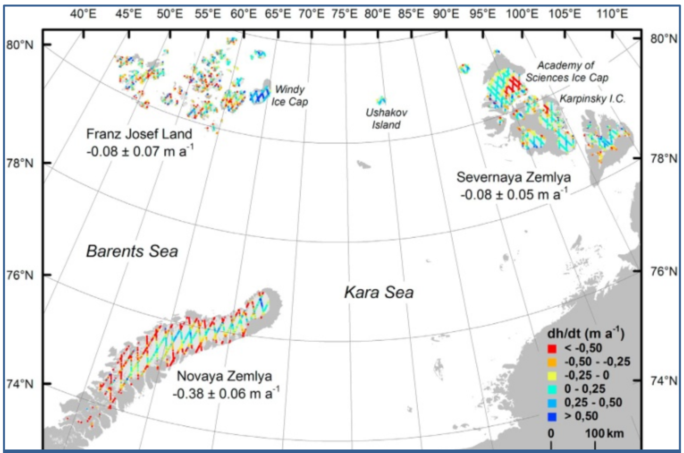


Helheim Glacier, Southeast Greenland, near the town Tasiilaq.

(Photo: Andreas Peter Ahlstrøm, Geological Survey of Denmark and Greenland)

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.

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.



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]

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.

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.

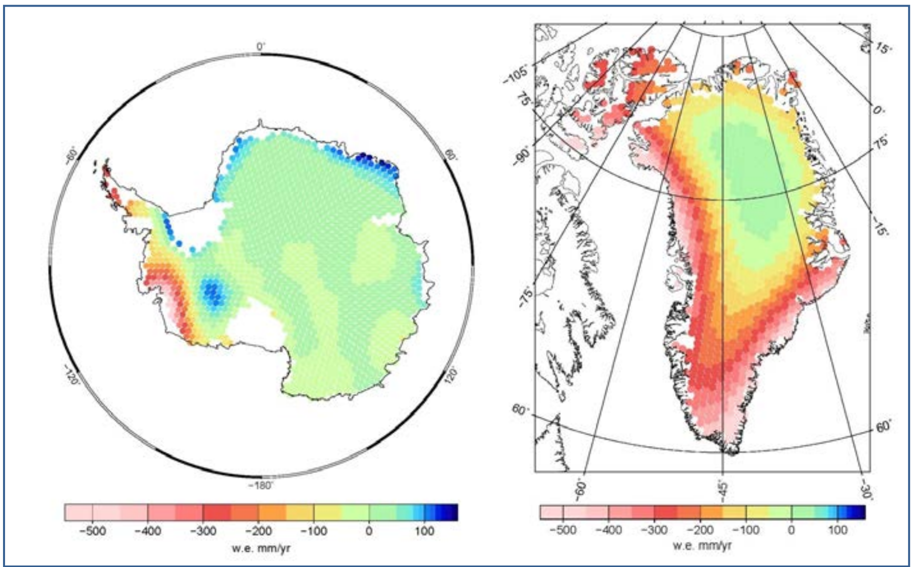
Measuring ice-sheet change from space

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[4] project, Greenland lost ice at a rate of 263±30 Giga-

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

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].

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:

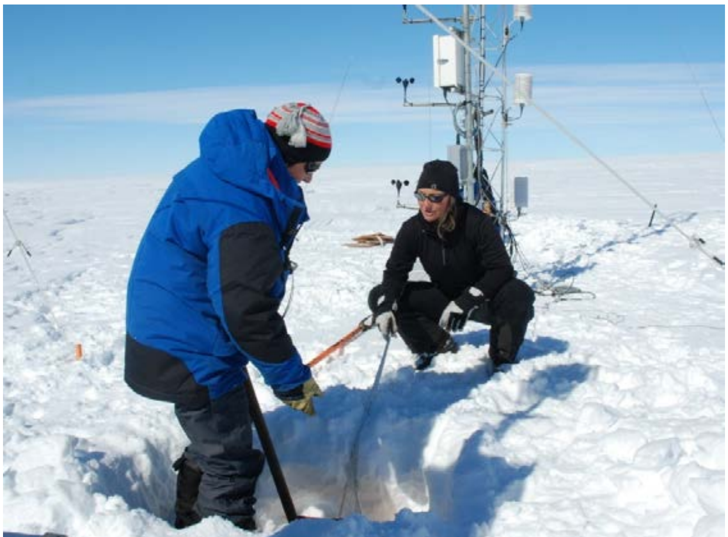
- Ice2sea researchers and our collaborators used data from satellites from the European Space agency, NASA, and the Canadian (CSA), Japanese (JAXA), and German (DLR) space agencies, to measure recent ice loss from Antarctica and Greenland, and several Arctic areas. These measurements allow understanding 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]

Case Study: 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.



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)

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.

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]

Case Study: 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.

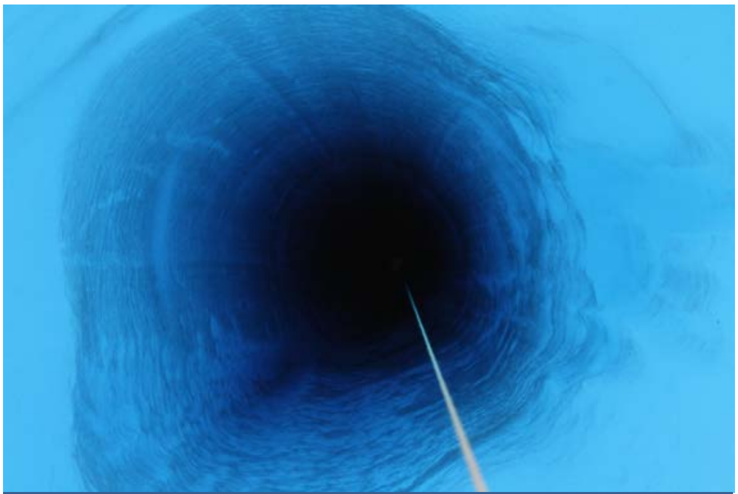
A hot water drill (supplied by AWI, Germany) in operation on Russell Glacier, Greenland, 2010. The black pool in front holds the water supply for the drill. The water is heated and compressed by the six heaters in the orange frames. The yellow winch in the background holds 650m of insulated drill hose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

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.



Hole drilled 600m deep into the ice by hot water, with probe suspended on 3mm thick Kevlar rope. Greenland 2010.
(Photo: Uni Utrecht/AWI)

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]

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…").

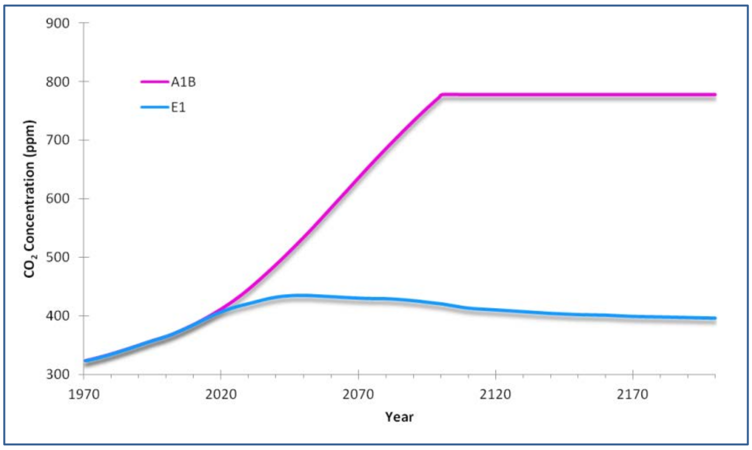
Ice2sea has used this type of process-based model to explore the effect of uncertainties on these projections. This is done at every stage of the chain from the greenhouse gas emissions scenarios through to regional sea-level change. For the Greenland and Antarctic ice sheets, ice2sea has used groups ("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[5], 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

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

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.

The ice2sea model approach

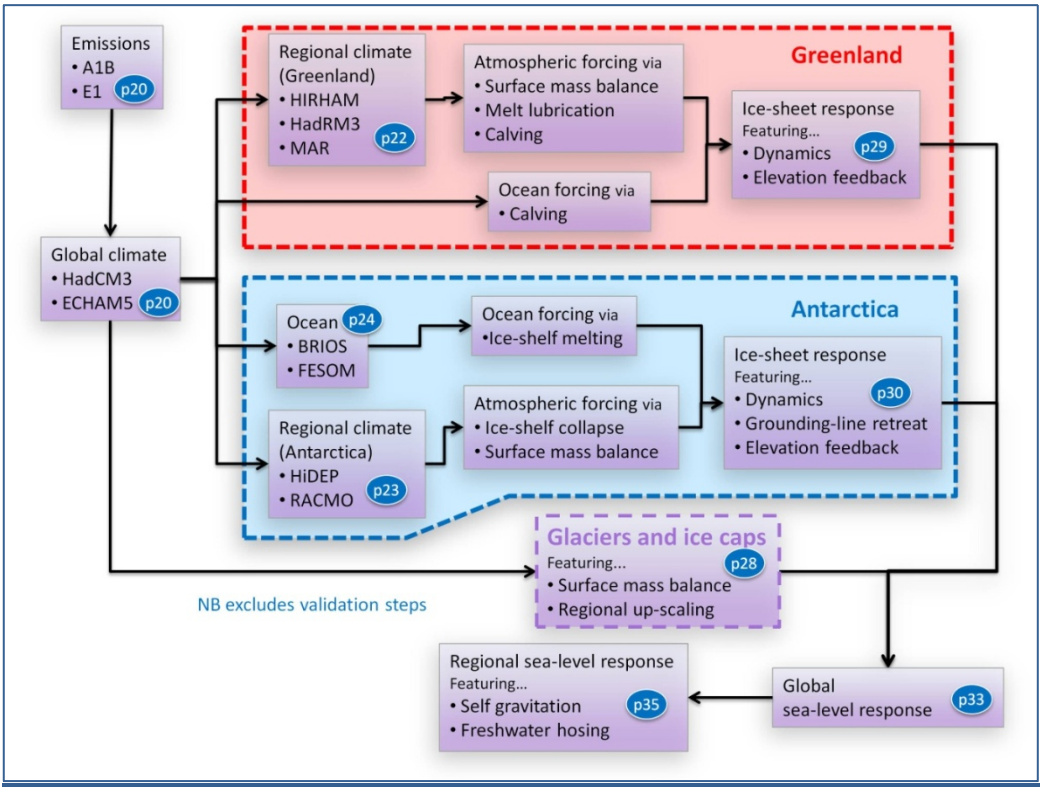
Several statements in the Fourth Assessment Report of the IPCC (AR4, 2007) identified shortcomings in the capability of the scientific community to build robust and complete projections of the contribution of ice sheets to sea-level rise.

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 icesheet 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 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 icesheet 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 (SeaRISE6), 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.



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.

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

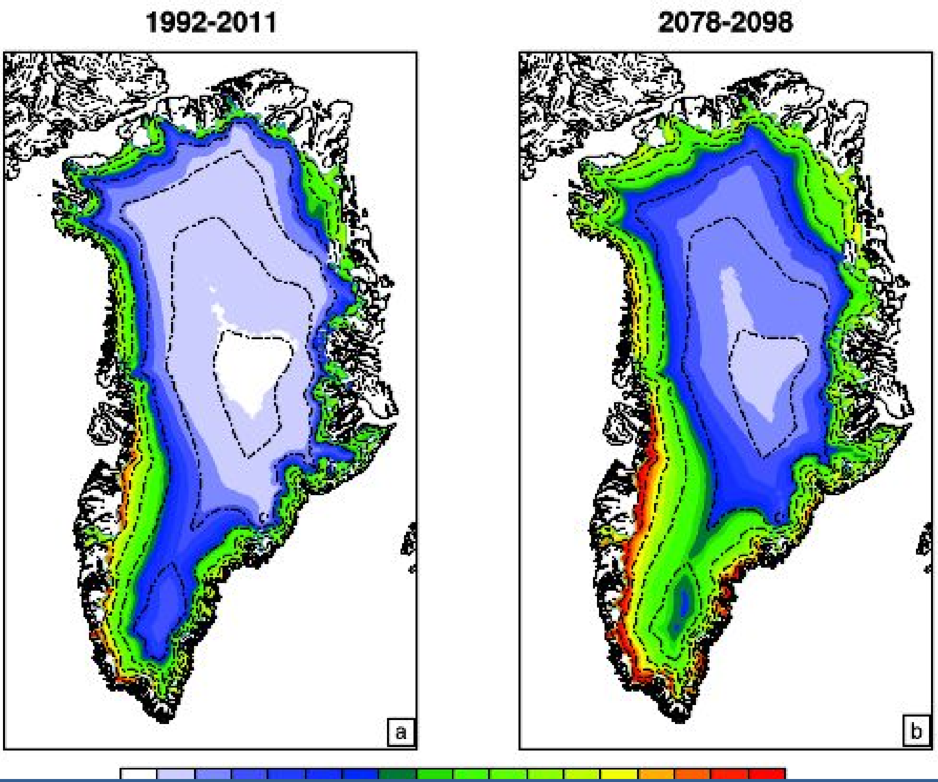
One of ice2sea's strengths has been its use of regional climate models (RCMs) in conjunction with global general circulation models (GCMs). This has allowed our scientists to focus in on particular areas of interest. The RCMs give a more detailed picture of Greenland, which is required by the ice-sheet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

[6] 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.

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]

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.



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]

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.

Melt water pooling on the George VI ice shelf.

(Photo: E. King, BAS)

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 iceshelf retreat and associated glacier acceleration could become widespread around coastal Antarctica.[123]

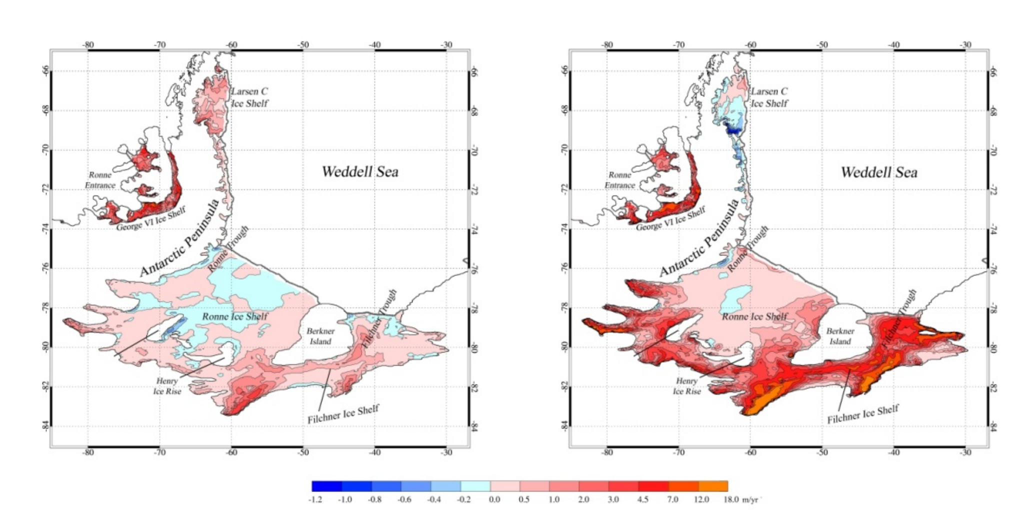
A very different scenario awaits the interior of the ice sheet. It is much colder as it is further south, further away from the open ocean, and higher in elevation. Ice2sea projections show that in 2200, even with a warming of 2-5°C, these areas remain too cold for significant melting to occur. Instead, 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.

Case Study: 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.



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.

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.

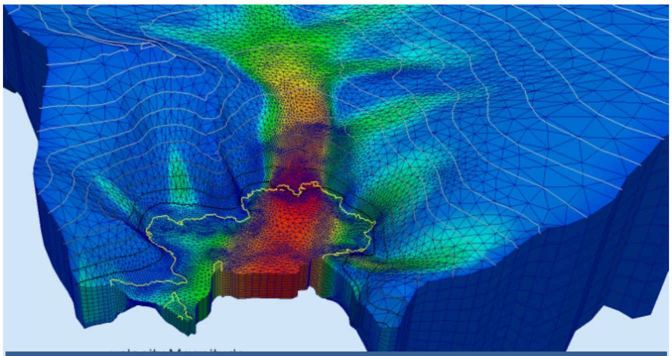
The projections of future ice-loss from the ice shelves around Antarctica were similar for both emissions scenarios, but different between the climate models used. The most significant change in ocean temperature resulted from HadCM3 output for the A1B scenario. The simulations showed that all ice shelves 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.

Case Study: 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 verticallyexaggerated 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]

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.

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.

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 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 UU[110] 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.

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.

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]

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]

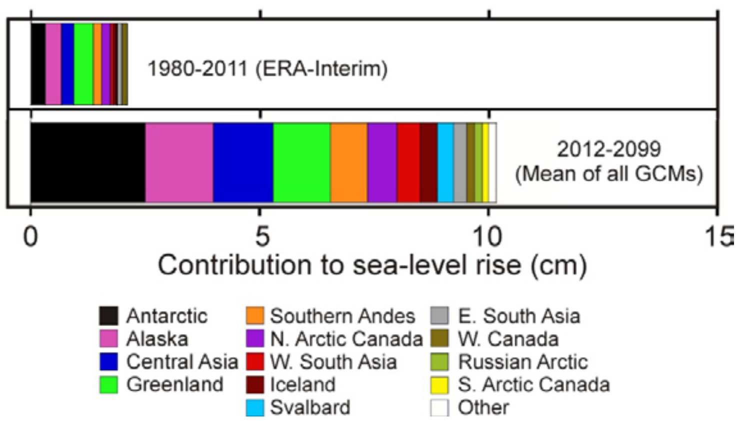
Antarctica - snow accumulation and melt: State-of-the-art regional atmospheric modelling at the UU[085] and LGGE/CNRS[089, 090] projects increased snowfall over Antarctica. This would be equivalent to a drop in global sea level of 3.0 to 5.2cm by the end of the century.

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.

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]

Key projections from 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]

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.

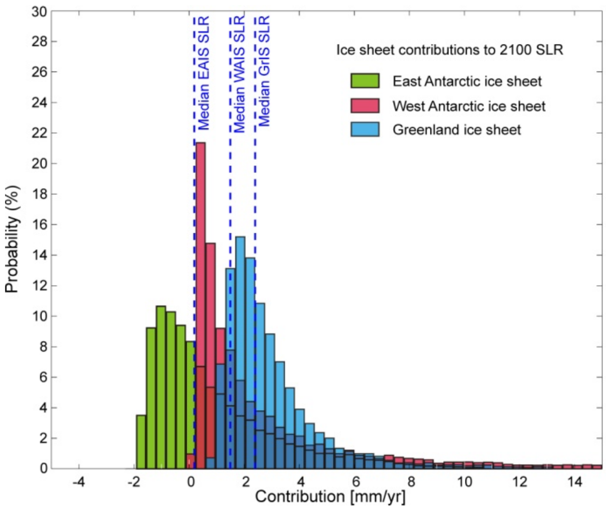
In **Greenland**, both increased melt-water runoff (a contrast to Antarctica) and increases in glacier outflow will contribute to GMSL rise. Two likely triggers to changes in outflow were explored by ice2sea: increases in the lubrication of ice flow that could arise with increasing amounts of surface 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 GMSL121 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 studies114, 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 projected133 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 Alps113 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 icesheet 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.



The EJE study 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 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.

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.

Future Regional Sea-Level Rise

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. 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 as discussed earlier.

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.

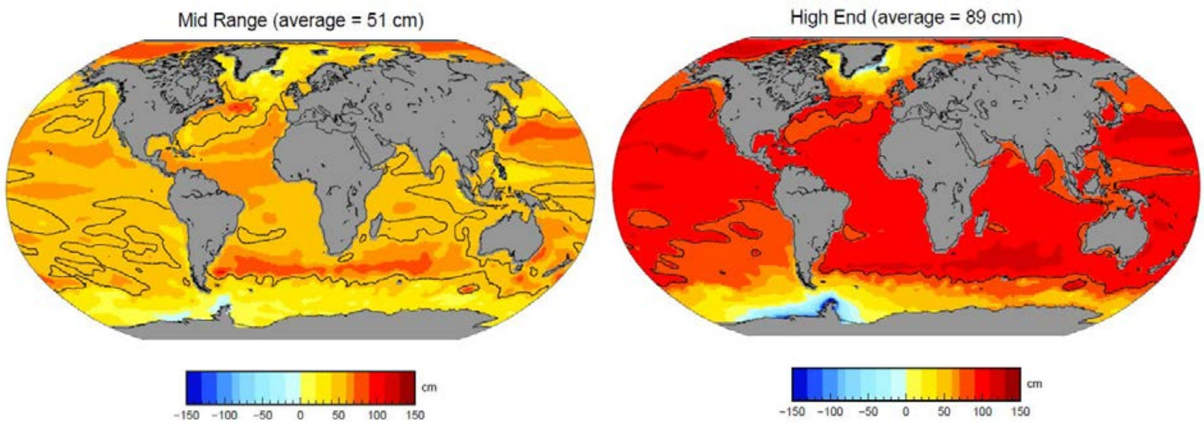
The strength of the Earth’s gravitational field varies around the planet, although it is much too subtle to detect with our senses. When measured against a reference frame fixed on the centre of the Earth, sea level is modified by these differences in gravity by tens of metres. For example, the huge 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.

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.

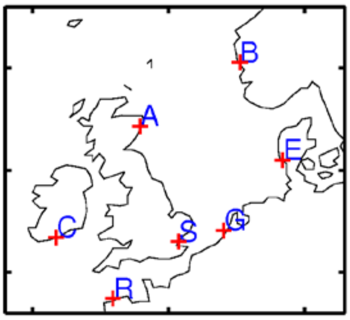
The figure shows the combined effects of continental ice-loss and changing ocean circulation patterns for two ice-loss scenarios, combined with thermal expansion from the greenhouse gas emissions scenario A1B. The pattern of sea-level rise is complex, with highest rates occurring in the tropics and lower,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

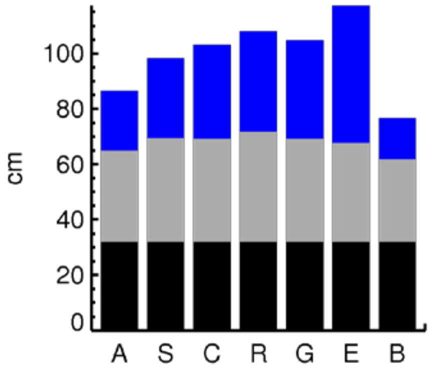


Ice2sea projections of regional variations in sea-level rise to 2100, undertaken104 for two scenarios of ice loss. Top shows the "mid-range" scenario of ice loss (MR), and bottom the high-end scenario (HE). These scenarios were developed[146] from ice2sea projections and expert elicitation exercises (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]

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 helps to put into perspective the components of sea level change around the north-west European coastline. In particular, we can see that the three divisions shown 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.

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.

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 has 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 subtle changes in the way the oceans deliver heat to the ice sheet.[041, 056] Our limited understanding of the role of oceans in driving ice-sheet change is 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]

Impact

The sea can inflict damage on our coastal environment in a number of ways. In the long term, invisible damage can occur through brine contamination of ground water, but the most immediate and visible effect occurs through coastal flooding. In the 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."

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.

Several case studies explored by ice2sea (see From Ice to High Seas, pages 9, 10, 13) show that the change in flood return period decreases dramatically for even modest rises in regional sea level. This highly non-linear response means that uncertainty in the projection of sea-level rise implies significant uncertainty in the measures that must be taken to manage risk and protect coastal communities.

The role of ice2sea has been to reduce the uncertainty in projections of sea-level rise, and increase confidence that policy-makers can have in those projections, thus providing a stronger basis for risk management. Throughout its life, ice2sea has worked to promote understanding of the scientific issues surrounding sea-level rise, and has undertaken a number of specific activities to achieve impact with a variety of stakeholders, as below. The full list of dissemination activities can be found via the EC Sesam system.

Website

Ice2sea's website (www.ice2sea.eu) changed significantly over the Second Reporting Period. Initially, the website was based on a template from another EC project, and edited to suit ice2sea's needs and populated with ice2sea content. Although this wasn't an ideal website in terms of look and ease of maintaining, it was easy to create, which allowed ice2sea to have a running website early in the project, and enabled completion of the associated deliverable (at that time split into Formal and Internal Deliverables)

The website originally had two sections, one for general audiences, and a password protected "members' area." However, part way through the First Reporting Period, the Programme Manager set up a SharePoint site (VOCAL) via NERC (the Natural Environment Research Council, the parent company of BAS), hosted at the University of Liverpool. This made the members area redundant, as this VOCAL site provides a mechanism for all partners and members to share files more easily, and has capabilities for discussion boards, notifications, a calendar, etc.

We had allocated a budget for the development of the website held at BAS so, in June 2011, we employed the services of an external professional web development company (Pedalo) to redesign the ice2sea website. There were several key reasons and goals for this, including:

- To improve the look, feel, and navigation of the website;
- To remove any bugs/issues between different platforms and browsers;
- Increase the attractiveness and usefulness of the website to different user groups – specifically, policy makers, the media, youth (provide a learning tool), and the general interested audience;
- Enable more visually interesting media to be included, such as a photo gallery of field work, an interactive map of field work sites and partner locations, and a front-page slide show;
- Employ a more user friendly content management system (CMS) to enable easier, more regular updating of the website.

All of these goals were achieved with the redesign of the site, which was made live in September 2011. Following the review of the project in October 2011, and the engagement of a communications coordinator, the website underwent a further redesign of page layout, to further improve the targeting of the pages to specific user groups. Previously, the website was considered too internal facing, and needed to better engage with audiences that are not familiar or interested in the internal structure of the project, just the outcomes and what the consequences are to them.

In addition, to aid this, the new layout included pages with descriptions of the background to the project, including the science areas and key questions being addressed. These were written in part by the coordinator and by a science writer that was employed on a temporary short term basis. A further task of the science writer was to write 'layman's abstracts' of published papers – plain English explanations of what the aims and outcomes of key ice2sea papers are, for a general audience. There are now therefore sections of the website with specific goals, which can all be found from the front page and the top menu system.

- Home page – highlights key areas and recent news/headlines. Interesting multi-media – a video introducing the project by the Coordinator, an interactive map, and a photo gallery of field work.

All information for members of the project is through a link at the bottom of the page – the website is not designed for them, as the VOCAL site is used for members.

- Ice2sea science – for general audiences and young people – to explain the background of the science, of sea-level rise, and the three key areas that ice2sea is addressing.
- On the ice – field work summary reports and photographs – describing what it's like out on the glaciers and ice sheets, and what work is done.
- For policymakers – explaining why ice2sea could be of interest to a policy maker, or their advisors, including how we are going to deliver our results in a form that is accessible to them. Includes case study examples of why they should be caring about sea-level rise, for those still to be convinced of its importance.
- The project – this area is mostly aimed at the wider science community, and young people who might be thinking of getting involved either in science, or into a large scale project. Explains how we are planning on, and how we have, addressed the questions and provide the projections. Also includes who is doing the work and who is involved.
- Resources – for all audiences that want more information: a gallery of various activities; and a glossary – this is one area to be developed further, as we hope to turn this into a more useful resource explaining the reasons why the items and areas listed are of importance, or hard to measure, or what they contribute, etc. We also intend to add people profiles – giving a feeling (aimed at young people) of what it is like to work in the various areas of the project, including what skills they need, what the working environment is like, etc.
- News – a news bulletin list, with links to more details, and an RSS feed capability for receiving direct regular updates.

Links are also provided to the EU and FP7 websites on all pages. In addition, we have encouraged partners' and members' websites to link to the ice2sea site, and we have added links to external bodies such as LWEC (Living With Environmental Change), the Tyndall Centre for Climate Change, and Beta Europe. Ice2sea has a page on Wikipedia.

Stakeholder Review

The ice2sea Stakeholder Review was the report or a study undertaken in support of the final delivery of ice2sea. The Stakeholder Review took the form of a series of interviews and encounters between the authors and individuals identified as key or representative stakeholders, and a specific Stakeholder Questionnaire. The Together these activities allowed the identification of 17 lessons that were be used to establish best-practice in the delivery of the ice2sea science outcomes.

http://www.ice2sea.eu/wp-content/uploads/2011/08/ice2sea_D1.2-1_report_stakeholders.pdf

The ice2sea Stakeholder Review was used to inform the development of the *ice2sea Communication & Dissemination Strategy and Delivery Plan*, and to inform the practice of all our engagement and outreach activities, as listed below.

Media interactions

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 160 papers have been published in scientific journals, but those journals have a limited, highly scientific readership, who are often already familiar with the jargon and sometimes inaccessible and dry language.

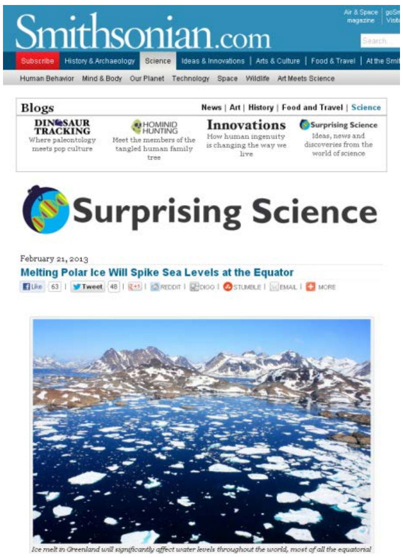
Therefore, we identified a key task for ice2sea early on – to promote a dialogue between science and society. That meant talking to policy makers to make sure the science discussed was relevant and necessary to inform public policy. It also meant ensuring the wider society was given the opportunity to 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 list of our press releases are in the table below, and a link is given to the press release on the website.

No.	Press Release Title	Paper	Reference
PR2012/01	Ice2sea researchers discover warm ocean currents are causing the majority of ice loss from Antarctica	#056	Pritchard, H. D., S. R. M. Ligtenberg, H. A. Fricker, D. G. Vaughan, M. R. van den Broeke, and L. Padman (2012), Antarctic ice loss driven by ice-shelf melt, Nature, 484, 502-505.
PR2012/02	Climate scientists discover new weak point of the Antarctic ice sheet	#041	Hellmer, H. H., F. Kauker, R. Timmermann, J. Determann, and J. Rae (2012), Twenty-first-century warming of a large Antarctic ice-shelf cavity by a redirected coastal current, Nature, 485, 225-228.
PR2012/03	Ice2sea researchers part of landmark study to improve projections for future sea level	#125	Shepherd, A., E. Ivins, A. Geruo, V. R. Barletta, M. Bentley, S. Bettadpur, K. H. Briggs, D. H. Bromwich, R. Forsberg, N. Galin, M. Horwath, S. Jacobs, I. R. Joughin, M. A. King, J. T. M. Lenaerts, J. Li, S. R. M. Ligtenberg, A. Luckman, S. B. Luthcke, M. McMillan, R. Meister, G. Milne, J. Mouginot, A. Muir, J. P. Nicolas, J. Paden, A. J. Payne, H. D. Pritchard, E. Rignot, H. Rott, L. S. Sorensen, T. A. Scambos, B. Scheuchl, E. J. O. Schrama, B. Smith, A. V. Sundal, J. van Angelen, W. J. van de Berg, M. R. van den Broeke, D. G. Vaughan, I. Velicogna, J. Wahr, P. Whitehouse, D. J. Wingham, D. Yi, D. Young, and H. J. Zwally (2012), A Reconciled Estimate of Ice-Sheet Mass Balance, Science, 338, 1183-1189.
PR2012/04	Ice2sea researchers use new approach to assess future sea-level rise from ice sheets	#129	Bamber, J. L., and W. P. Aspinall (2013), An expert judgement assessment of future sea-level rise from the ice sheets, Nature Climate Change, 3, 424-427.
PR2013/01	New projections of “uneven” global sea-level rise	#104	Spada, G., J. L. Bamber, and R. T. W. L. Hurkmans (2013), The gravitationally consistent sea-level fingerprint of future terrestrial ice loss, *Geophysical Research Letters*, *40* (3), 482–486.
PR2013/02	Glaciers will melt faster than ever and loss could be irreversible – warn scientists	#110	Lenaerts, J. T. M., J. H. Van Angelen, M. R. Van der Broeke, A. S. Gardner, B. Wouters, and E. Van Meijgaard (2013), Irreversible mass loss of Canadian Arctic Archipelago glaciers, *Geophysical Research Letters*, *40*, 1-5.
PR2013/03	Significant contribution of Greenland’s peripheral glaciers to sea-level rise	#136	Bolch, T., L. S. Sorensen, S. B. Simonsen, N. Molg, H. Machguth, P. Rastner, and F. Paul (2013), Mass loss of Greenland’s glaciers and ice caps 2003-2008 revealed from ICESat laser altimetry data, *Geophysical Research Letters*, *40*, 875-881.
PR2013/04	Summer melt season is getting longer on the Antarctic Peninsula, new data show	#082	Barrand, N., D. G. Vaughan, N. Steiner, M. Tedesco, P. Kuipers Munneke, M. R. van den Broeke, and J. S. Hosking (2013), Trends in Antarctic Peninsula surface melting conditions from observations and regional climate modelling, *Journal of Geophysical Research*, *118*, 1-16.
PR2013/05	Ice2sea scientist winds award for Greenland ice sheet work	EGU	Dr Xavier Fettweis received the 2013 Arne Richter Award for Outstanding Young Scientists during a ceremony at the European Geosciences Union (EGU) General Assembly.
PR2013/06	Modelling the effect of climate change on iceberg production by Greenland glaciers, and its impact on sea-level rise	#118	Nick, F. M., A. Vieli, M. L. Andersen, I. R. Joughin, A. J. Payne, T. Edwards, F. Pattyn, and R. van der Wal (2013), Future sea level rise from Greenland’s major outlet glaciers in a warming climate, *Nature*, *497*, 235-238.
PR2013/07	Final meeting of ice2sea highlights sophisticated new modelling techniques to measure ice-melt contribution to future sea-level rise	SR/OF	From Ice to High Seas: Sea-level rise and European Coastlines, (2013), The ice2sea Consortium, *ISBN 978-0-85665-206-6*, Cambridge, U.K.
PR2013/08	Sensitivity of the Greenland Ice Sheet	#114	Goelzer, H., P. Huybrechts, J. J. Fürst, F. M. Nick, M. L. Andersen, T. L. Edwards, X. Fettweis, A. J. Payne, and S. Shannon (2013), Sensitivity of Greenland ice sheet projections to model formulations, *Journal of Glaciology*, *59* (216), 733-749.

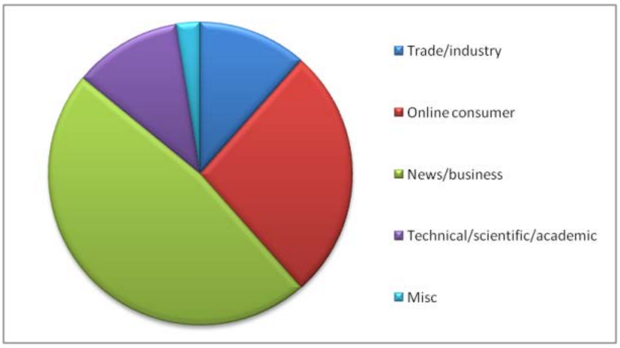
No.	Press Release Title	Paper	Reference
PR2013 /09	Melting water's lubricating effect on glaciers has only "minor" role in future sea-level rise.	#121	Shannon, S. R., A. J. Payne, I. D. Bartholomew, M. R. van den Broeke, T. L. Edwards, X. Fettweis, O. Gagliardini, F. Gillet-Chaulet, H. Goelzer, M. J. Hoffman, P. Huybrechts, D. W. F. Mair, P. Nienow, M. Perego, S. F. Price, C. J. P. P. Smeets, A. J. Sole, R. S. W. van de Wal, and T. Zwinger (2013), Enhanced basal lubrication and the contribution of the Greenland ice sheet to future sea-level rise, *Proceedings of the National Academy of Sciences*, 1-4.
PR2013 /10	Mega-canyon discovered beneath Greenland ice sheet	#158	Bamber, J. L., M. Siegert, J. Griggs, S. Marshall, and G. Spada (2013), Paleofluvial Mega-Canyon Beneath the Central Greenland Ice Sheet, *Science*, *341* (6149), 997-999.
PR2013 /11	Scientists from ice2sea contribute to the IPCC Fifth Assessment Report	N/A	N/A
PR2014 /01	Antarctic's Pine Island Glacier in 'irreversible retreat'	#157	Favier, L., Durand, G., Cornford, S.L., Gudmundsson, G.H., Gagliardini, O., Gillet-Chaulet, F., Zwinger, T., Payne, A.J. & Le Brocq, A.M. (2014). Retreat of Pine Island Glacier controlled by marine ice-sheet instability. Nature Climate Change 5: 1-5.
PR2014 /02	Disappearing snow increases risk of collapsing ice shelves in Antarctica	#123	Kuipers Munneke, P., Ligtenberg, S.R.M., van den Broeke, M.R. and Vaughan, D.G. (2014). Firn air depletion as a precursor for Antarctic ice-shelf collapse. Journal of Glaciology, 60 (220).

An uptake example: 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).

Face-to-face briefings

A major stakeholder of the ice2sea project was policy makers and their advisor, particularly from government department. We deemed, both from previous experience, advice, and the stakeholder review, that as these are busy people with many demands on their time, and much information passed to them, that the best way to inform them of the outputs of the project would be for us to go to them and speak directly to them in small groups. Although this is a more costly approach than the wider-reach methods described further below (such as press-releases and social media), we felt this provided good value for money as it targets key stakeholders in a effectual manner.

To this end, we organised a series of briefings at various locations around Europe that are both represented by the project and that have regions that will be affected by sea-level rise. We started these activities in Brussels, with a primary audience of Members of the European Parliament, but also other organisations such as the European Polar Board, and the EC. We initially held the first briefing in May 2012 – although this was before many of the results of the project were available, we were advised the best way to get recognition from MEPs was to build up a relationship through early contact, then to return to them with further details over a period. We therefore sent them updates after the meeting, and then returned to Brussels around the time of the IPCC report publication. We also used this opportunity to determine how best to present our results and what the information they wanted to know about was. This in turn influenced the production of the final synthesis report “From Ice to High Seas”.

Several other briefings were held, and full reports including answers to the questions asked by participants are available on the ice2sea website.

Ice2sea organised briefings:

Location	Venue	Host	Date	Speakers
Brussels, Belgium	European Parliament	Chris Davies, MEP	27/5/12	David Vaughan, NERC-BAS Hartmut Hellmer, AWI, Frank Pattyn, ULB
The Hague, The Netherlands	The Ministry of Foreign Affairs	Patrick Brandt, Head of Polar Affairs	6/11/12	David Vaughan, NERC-BAS Michiel van den Broeke, UU
Copenhagen, Demark	Ministry of Energy and Climate	Carsten Eskebjerg, Ministerial Advisor	19/2/13	David Vaughan, NERC-BAS Andreas Ahlstrøm, GEUS (DTU & NBI in attendance)
London, United Kingdom	Royal Institution of Great Britain	David Vaughan, Coordinator	14/5/13	David Vaughan, NERC-BAS, Franz Immler, EC
Brussels, Belgium	European Parliament	Chris Davies, MEP	1/10/13	David Vaughan, NERC-BAS Hartmut Hellmer, AWI, Frank Pattyn, ULB
Reykjavik, Iceland	University of Iceland & Arctic Circle	Helgi Björnsson, Háskóla Íslands	11/11/13	David Vaughan, NERC-BAS Guðfinna Aðalgeirsdóttir, HI

Policy-relevant presentations

As well as organising our own briefings for policy makers, we took advantage of events and discussion sessions organised by others. Some key examples of events with an audience influential in policy are given in the table below:

Meeting	Location	Date	Speakers
UNFCCC CoP18	Doha, Qatar	28/11/12	David Vaughan, NERC
Future research priorities for the polar regions	Brussels, Belgium	20/3/13	David Vaughan, NERC
Antarctic Treaty meeting	Brussels, Belgium	21/5/13	David Vaughan, NERC
Cheltenham Science Festival	Cheltenham, United Kingdom	1/7/13	Tamsin Edwards, UoB
Royal Society Discussion Meeting: What's new in climate science?	London, United Kingdom	2/10/13	David Vaughan, NERC
Arctic Circle first annual meeting	Reykjavik, Iceland	11/10/13	David Vaughan, NERC Guðfinna Aðalgeirsdóttir, HI
UNFCCC COP19	Warsaw, Poland	17/11/13	Hartmut Hellmer, AWI

Synthesis document

The ice2sea synthesis report is a 50-page glossy brochure that explains the motivation for ice2sea along with the key findings of the project – aimed at a general audience, specifically policy makers and their advisors. The report is therefore written in a non-scientific manner, whilst keeping remaining scientifically accurate. It has been professionally produced by an external design company and printed professionally on high-quality paper. A total of 1000 copies have been printed and distributed to various stakeholders including policy makers from across Europe, government advisors, and partner institutes.

From Ice to High Seas: Sea-level rise and European coastlines, The ice2sea Consortium, Cambridge, United Kingdom, (2013).ISBN 978-0-85665-206-6

The writing of the report was led and managed by the Programme Coordinator and Programme Office, and had contributions from various partners across all the work packages. We have also included some personal perspectives from selected early-career scientists, with the aim of making the report more relevant and accessible particularly to young people, helping to inspire the next generation of young scientists.

The report was launched at the Final Open Forum in May 2013 at the Royal Institution in London. Following a press conference on the first morning of the Open Forum, the report was launched at a VIP reception for policy makers, their advisors, business, and the media. Each VIP received a copy of the brochure. The report is also available to download from the ice2sea website and printed copies are available on request.

Social media

Social media has been an invaluable part of ice2sea for disseminating information to a wide variety of audiences, with no cost associated, and providing the ability to start discussions on the climate debate.

Twitter

The Twitter account was set up in early 2013. In the early stages of ice2sea it was not seen as important to have an account but, as the importance of that social network grew and as the programme moved into a phase where papers were being produced which required press releases, it was felt an account could support in publicising our work and engaging with a wider audience.

@ice2seaEU

Since then it has been used to advertise every press release (including links to the website) and to highlight major achievements and events (like the Open Forum in London).

One nice example of Twitter's relevance in this area the following tweets (all re-tweeted by @ice2seaEU):

Huffington Post @HuffingtonPost9 May

Good and bad news about Greenland's glaciers http://huff.to/18Zz7xK

EurekAlert! @EurekAlertAAAS8 May

The effect of climate change on iceberg production by Greenland glaciers : http://ow.ly/kPmKx

Phys.org @physorg_com8 May

The effect of #climatechange on iceberg production by Greenland #glaciers http://phy.so/287236694 @BAS_News

The Huffington post tweeted to its 3,700,000 followers and Phys.Org has almost 240,000 followers – showing how our stories were reaching a large audience through Twitter activity, and how we were able to re-tweet their coverage to keep our constituents informed.

An added benefit of the Twitter account was to create a central place on Twitter for members of ice2sea who were active on social media to interact. Several members of ice2sea have interacted with the account and used it to highlight their work.

Another benefit has been to enable us to interact with more sceptical audiences, particularly at the time of the Open Forum event when the huge surge in coverage for ice2sea created by our Press Conference in London led to several sceptical voices targeting the Twitter account. Active blogger Dr Tamsin Edwards used her account, @flimsin, to support our interactions with those voices.

We only started the Twitter account in January yet we have 244 followers and a Klout score of 34 (out of 100) which is strong for a relatively small amount of followers. Those followers include schools (@geo_sevenoaks), scientists (@St_Matthiesen), institutions (@rigb_venue), journalists (@m_c_marshall) and major organizations like the EGU (@EuroGeosciences).

Blogs

One of ice2sea's early career researchers, Dr. Tamsin Edwards, from the Thanks, of Bristol, started and runs a blog on climate science, particularly on modelling aspects and the difficulty of communicating uncertainty. Between January and December 2012 she ran her own blog, "All Models Are Wrong", allmodelsarewrong.com. This had eight posts, and had an average of 2,400 unique visitors per post, of which 60% were from outside the UK, and 160 comments per post. Although this is not specifically an ice2sea activity, the project and the EC have been mentioned, and the work of the project and the field of climate change in general are discussed by a varied interested audience.

From January 2013, Tamsin was invited to move her post to the US publishers PLOS: "All Models Are Wrong", http://blogs.plos.org/models. She is the first (and currently only) climate blogger for this internationally recognised journal. She has written 11 posts, three of which were under the category of ice2sea, and her most recent post 185 comments. This blog was recommended by Sense About Science in their report "Making sense of uncertainty" and also as teaching material (University of Toronto, Steve Easterbrook)

Additionally, Tamsin was invited to write a blog post for The Guardian in July 2013, which was viewed 23,505 times, had the link tweeted over 400 times and generated at least 2000 tweets, around 300 comment responses, over 30 blog post responses, and this led to an international Google+ Hangout interviewing three senior climate scientists.

IPCC

The requirement and intention for ice2sea to support the development of the IPCC Fifth Assessment Report (AR5) has been at the forefront of ice2sea's partners from the outset. The timescales to achieve this were however challenging due to publication requirements not being publicised until after the signing of the ECGA, and contract completion delays, resulting in delays to hiring staff.

To be cited in the WGI report, papers needed to be "in press" by 13th March, 2013; however, there was also an expectation that they would be submitted to journals by July, 31st 2012 – and this was a couple of months earlier than anticipated.

Despite these difficulties, we did manage to submit publications in time for the IPCC's deadline for all areas of work, and in many cases several more publications than originally intended. After all the papers had then been through the peer-review process, and met the second deadline of the 13th March 2013 to be 'in press', this then resulted in 42 papers being cited in the IPCC report.

As we were eager for the project papers to be included in the report, we took a proactive approach. We identified the coordinating lead authors (CLAs) and interested lead authors for the relevant chapters of the IPCC report, and sent them copies of the submitted manuscripts in July-August 2012, and then updated them on the progress of the manuscript through to publication across 2012 and early 2013. The list below shows the ice2sea papers that were cited in each of the Chapters of Working Group I of the IPCC AR5.

- Chapter 3: 074.
- Chapter 4: 007, 009, 014, 017, 26, 038, 051, 056, 058, 061, 082, 097, 103, 121, 125, 142, 148.
- Chapter 5: 021.
- Chapter 9: 034.
- Chapter 10: 098.
- Chapter 13: 039, 041, 043, 046, 052, 056, 061, 067, 083, 084, 085, 098, 104, 112, 114, 118, 125, 126, 129, 133, 135, 142, 147, 148.

This total of 42 papers cited over the 6 chapters (5 in two chapters), represents 37% of papers submitted!

The Working Group II report is yet to be published at the end of the Reporting Period, and it is possible that further ice2sea publications will be cited in this report.

Website and contact

The ice2sea website address is www.ice2sea.eu

In addition the project has a Twitter feed at #ice2seaEU. (https://twitter.com/ice2seaEU)

The ice2sea Facebook page can be found at https://www.facebook.com/ice2seaFP7.

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Further Information

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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

Universita 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)

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

Publication List

A full list of ice2sea publications, published and still in the peer-review process, are listed below. We will continue to supply publication numbers for work that is produced due to ice2sea-funded work, even if the authors are not directly funded by the project any more, the work is still a consequence of the project. The project, EU, FP7, and grant agreement number will continue to be included in the acknowledgements of these papers.

ice2sea001 - Spada, G. (2012). Love Numbers of a Generalized Maxwell Sphere. *Studia Geophysica et Geodaetica*, 57, 1-16.

ice2sea002 - Paul, F. and Linsbauer, A. (2009). Modeling of glacier bed topography using glacier outlines, flowlines and a DEM. *International Journal of Geographical Information Science*, 26 (7), 1173-1190.

ice2sea003 - Spada, G., Colleoni, F. and Ruggieri, G. (2011). Shallow upper mantle rheology and secular ice-sheets fluctuations. *Tectonophysics*, 511 (3-4), 89-98.

ice2sea004 - Gagliardini, O., Durand, G., Zwinger, T., Hindmarsh, R. and Le Meur, E. (2010). Coupling of ice-shelf melting and buttressing is a key process in ice-sheets dynamics. *Geophysical Research Letters*, 37, 14501-14506.

ice2sea005 - Ma Ying, Gagliardini, O., Ritz, C., Gillet-Chaulet, F., Durand, G. and Montagnat, M. (2010). Enhancement factors for grounded ice and ice-shelf both inferred from an anisotropic ice flow model. *Journal of Glaciology*, 56 (199), 805-812.

ice2sea006 - de Fleurian, B., Gagliardini, O., Zwinger, T., Le Meur, E. and Durand, G. (2009). A coupled hydro-glaciological model to explain post-jökulhlaups dynamics. *Journal of Geophysical Research*.

ice2sea007 - Nick, F.M., van der Veen, C.J., Vieli, A. and Benn, D. (2010). A physically based calving model applied to marine outlet glaciers and implications for their dynamics. *Journal of Glaciology*, 56, 781-794.

ice2sea008 - Moholdt, G., Hagen, J.O., Eiken, T. and Schuler, T.V. (2010). Geometric changes and mass balance of the Austfonna ice cap, Svalbard. *The Cryosphere*, 4, 21-34.

ice2sea009 - Moholdt, G., Nuth, C., Hagen, J.O. and Kohler, J. (2010). Recent elevation changes of Svalbard glaciers derived from ICESat altimetry. *Remote Sensing of the Environment*, 114 (11), 2756-2767

ice2sea010 - Tsimplis, M., Spada, G. and Marcos, M. (2011). 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*, 76 (1-2), 63-76.

ice2sea011 - Aðalgeirsdóttir, G., Stendel, M., Christensen, J.H., Cappelen, J., Vejen, F., Kjær, H.A., Mottram, R., Lucas-Picher, P. and Drews, M. (2010). Assessment of the temperature, precipitation and snow in the RCM HIRHAM4 at 25 km resolution. *Danish Meteorological Institute Report* Copenhagen.

ice2sea012 - 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. (2010). A benchmark study for glacial-isostatic adjustment codes. *Geophysical Journal International*, 185 (1), 106-132.

ice2sea013 - 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. (2010). A consistent dataset of Antarctic ice sheet topography, cavity geometry, and global bathymetry. *Earth System Science Data*, 2, 261-273.

ice2sea014 - Sørensen, L.S., Simonsen, S.B., Nielsen, K., Lucas-Picher, P., Spada, G., Adalgeirsdottir, G., Forsberg, R. and Hvidberg, C. (2011). Mass balance of the Greenland ice sheet (2003–2008) from ICESat data – the impact of interpolation, sampling and firn density. *The Cryosphere*, 5, 173 - 186.

ice2sea015 - Scarchilli, C., Frezzotti, M. and Ruti, P.M. (2011). Snow Precipitation at four ice core sites in East Antarctica: provenance, seasonality and blocking factors. *Climate Dynamics*, 37, 2107-2125.

ice2sea016 - Bellot, H., Trouvilliez, A., Naaim-Bouvet, F., Genthon, C. and Gallée , H. (2011). Present weather sensors tests for measuring drifting snow. *Annals of Glaciology*, 52, 179-184.

ice2sea017 - Gardner, A.S., Moholdt, G., Wouters, B., Wolken, G.J., Burgess, D.O., Sharp, M.J., Cogley, J.G., Braun, C. and Labine, C. (2011). Sharply increased mass loss from glaciers and ice caps in the Canadian Arctic Archipelago. *Nature*, 473, 357-360.
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