What is causing rapid change in the Arctic at the moment?

www.arp.arctic.ac.uk

Arctic Research Programme

NATURAL ENVIRONMENT RESEARCH COUNCIL

www.arp.arctic.ac.uk

British Antarctic Survey, Twin Otter research aircraft

Reducing the uncertainty in Arctic climate and associated regional biogeochemistry predictions

Modelling the complex interplay between ocean, atmosphere, terrestrial and sea ice processes allows us to make predictions of future changes in the Arctic and its impact on the rest of the world. One of the main objectives of the NERC Arctic Research Programme (ARP) is to further improve existing models based on research undertaken by scientists. Just how changes in the Arctic might affect the UK and other areas of the world, on timescales of months to decades and beyond, requires the Arctic to be tied-in to global-scale models.

The single largest uncertainty in representing Arctic climate is the poor understanding and representation of cloud and aerosol processes in climate models, particularly in the Arctic. The '**Aerosol-Cloud Coupling and Climate Interactions in the Arctic**' **(ACCACIA)** project of the NERC ARP aimed to provide a sound foundation for making improved predictions of future Arctic climate. It focussed on cloud microphysical and boundary layer processes which directly affect the surface energy budget, and the sources of aerosols that control cloud microphysical properties. The '**Environment of the Arctic: Climate, Ocean and Sea Ice' (TEA-COSI)** project aimed to reduce the uncertainties in our understanding of how atmosphere, sea ice and ocean interact to influence Arctic climate and so develop better predictive capabilities.

Aims of the research:

ACCACIA set out to:

Understand the microphysical properties of Arctic clouds and their dependence upon aerosol properties, and to develop new parameterizations of cloud properties specifically tuned to Arctic conditions.

Quantify the surface sources of aerosol and precursor gases as a function of season and sea ice conditions from the open ocean, and marginal ice zone into dense pack ice conditions. This included direct aerosol production (i.e. sea spray) and secondary production via gas particle conversion.

Estimate the entrainment flux of aerosols from the free troposphere into the boundary layer. Then to develop parameterizations of aerosol surface sources that can be scaled up to Arctic Ocean basin scale and included within the large scale models of aerosol processes.

Determine the relationships between the vertical structure and turbulent mixing properties of the boundary layer, surface fluxes, and radiatively driven turbulence in clouds, and to develop and test new parameterizations of turbulent dynamics for shallow/stable Arctic boundary layers.

Quantify the feedbacks between clouds, aerosols, sea ice, and the wider Arctic climate system. Resulting parameterizations will be built into the UK Met Office models to evaluate and assess the impact on the future climate of the processes they represent.

TEA-COSI set out to: answer whether increased melting of sea ice in the Arctic Ocean will affect the so-called Thermohaline Circulation (THC). Since the THC is driven by water sinking when it encounters the cold waters of the Arctic, large quantities of freshwater may disrupt it as the lower density relative to saline water prevents the sinking of water masses.

The **ACCACIA** project was led by Dr Ian Brooks and colleagues at the University of Leeds with Co-investigators from University of Manchester, University of York, University of East Anglia and The British Antarctic Survey. The **TEA-COSI** project was headed by PI Prof. Sheldon Bacon, National Oceanography Centre, with Co-investigators from University of Reading, University College London, University of Southampton, Scottish Association for Marine Science, British Antarctic Survey, University of Oxford, and Bangor University. Full lists of partners can be found on the ARP website.

Polar aerosols and cloud processes

Current climate models predict that the late summer Arctic could be ice-free in less than fifty years. Inevitably such ice loss will result in an increase in emissions of aerosols and precursor gases from the ocean surface. A logical consequence of this is an aerosol-cloud feedback mechanism through which a large increase in sea-salt aerosol from the newly exposed Arctic Ocean increases the cloud albedo, effectively cancelling out the loss of surface albedo due to ice loss. However the response of aerosol to sea ice loss has remained unclear, largely due to a lack of knowledge on the aerosol sources and hence inadequate descriptions of them in models. ACCACIA scientists, using the Global Model of Aerosol Processes (GLOMAP-mode) were able to examine the response of Arctic cloud condensation nuclei (CCN) to sea ice retreat against aerosol observations from the Arctic Summer Cloud Ocean Study (ASCOS). They found that while emission fluxes of sea-salt, marine primary organic aerosol and dimethyl sulphide (DMS) increased, the CCN concentration was weak. This result is counter-intuitive and contrary to existing theories, but it may be due to an increase in DMS derived sulphuric acid vapour in an efficient 'scavenging' environment, encouraged by extensively drizzling stratocumulus clouds. In this environment particles grow to sizes where they are more readily scavenged so reducing the accumulation mode particles.

Microphysical cloud properties important

Arctic climate is complex and the interactions between the part of the atmosphere directly influenced by the Earth's surface, clouds, overlying sea ice and water can lead to a number of feedback mechanisms. These interactions are not well understood due to variability and inaccurate parameterisation, brought about by a paucity of data, when used in global climate models but clouds are important in some of the proposed feedbacks. In the Arctic where they are the dominant factor controlling the surface energy budget, they usually produce a mostly positive forcing when there is more incoming than outgoing energy so warming the system. Turbulent sea surface, which transfers heat between ocean and atmosphere, is also influenced by clouds. The internal structure of clouds is a key factor, especially the microphysical characteristics, such as the amount of condensed water and the nature of cloud particles. In an effort to reduce some of the uncertainty in the effects of aerosols and clouds on the Arctic energy balance and climate, airborne ACCACIA campaigns took place in March-April and July 2013 with flights measuring the vertical structure of cloud microphysics and aerosol properties. Measurements taken during two cases studies from the spring and two from the summer flights were used for analysis. Results showed that cloud layers during summer spanned a warmer temperature range than in spring. Spring clouds were more uniform than the multi-layered summer clouds. Interestingly, ice number concentrations in summer clouds were higher by a factor of five than in spring clouds. This is thought to be a result of secondary ice production when cloud droplets collide with existing ice, creating splinters of ice which then grow through water deposition over a few minutes to sizes when they can produce yet more splinters, leading to even higher ice particle concentrations. These measurements showed differences of an order of magnitude lower in primary ice concentrations in the Antarctic summer clouds compared to spring Arctic clouds. The work has provided valuable detail about the structure of clouds in the Arctic and highlighted differences from those in the Antarctic, so allowing for better parameterisation in future models.

Diatoms, ice and clouds

Just how much ice there is in a cloud determines how long it lasts, how much precipitation it produces and its radiative properties, which are of interest due to the part they play in climate. The presence of ice-nucleating particles (INPs) facilitates the formation of ice in clouds, but while sea-spray is largely recognised as one of the major global sources of atmospheric particles it has remained unclear to what extent they are capable of nucleating ice. Modelling studies show that the ocean is a potentially important source of biogenic atmospheric particles, especially in remote high-latitude areas, but the link to organic material found in sea water or spray has never been directly shown. ACCACIA scientists working with colleagues demonstrated through a series of experiments, measurements and modelling studies that marine organic material may indeed be an important source of nucleating particles in remote areas far from the influence of terrestrially originated particles such as desert dust, for example.

Sea-spray aerosol contains large amounts of organic material that is ejected into the atmosphere as bubbles burst in the organic-rich sea surface microlayer at the sea-atmosphere interface. The ACCACIA-led study, built upon previous studies by directly sampling the microlayer during a research cruise on the RRS *James Clark Ross*. It shows that this organic material can act as nucleating particles under conditions relevant to mixed-phase cloud formation (where water vapour, liquid droplets and ice occur together) and higher latitude ice-cloud (a cloud composed of ice crystals, as its name implies) formation. Further experimental work showed that exudates separated from the marine diatom *Thalassiosira pseudonana* nucleate ice and suggest that organic material and exudates from phytoplankton is a likely ice-nucleating candidate. Data shows that in areas where the largest concentrations of INPs occur (Southern Ocean, N. Atlantic and N. Pacific) marine organic sea-spray is at least as important if not more so than desert sources of particles.

Sea ice break up, iodine and clouds

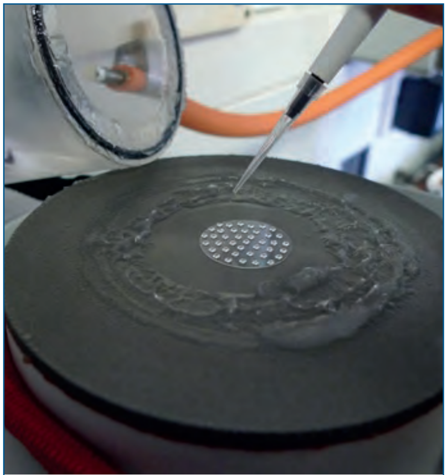
Clouds may be the most important factor in controlling the incoming and outgoing energy balance at the Earth's surface, in the Arctic and elsewhere, but are the single greatest source of uncertainty in climate prediction. Key to improving predictions of clouds and thus weather and climate is a better understanding of atmospheric aerosols, especially accounting of new particle formation (NPF). Particles in the atmosphere act as condensation nuclei and so the thickness and lifetime of clouds is dependent upon the population of particles that can act as cloud condensation nuclei (CCN). In Arctic summer CNN concentration is typically very low, and the formation and survival of clouds is very sensitive to the formation and growth of particles to a size where they act as CCN. Clouds play a huge role in relative warming and cooling in the Arctic so understanding these processes is critical for predicting Arctic climate. NPF numbers can dramatically increase aerosols in the atmosphere, contributing with directly emitted particles from, combustion, sea spray and suspended dust, around half the global CCN burden. Previous ship-based measurements in the Arctic have shown that NPF events are occurring, but their origins have been unclear. During an ACCACIA summer cruise aboard the RRS *James Clark Ross* in the Greenland Sea frequent NPF events, associated with gaseous iodine at low tide, were detected, suggesting the gas as a dominant source of particles 'feeding' CCN and radiation scattering. At lower latitudes iodine is produced in abundance by brown seaweeds (macroalgae) leading to NPF when exposed at low tide, and it may be that the observed iodine was generated from as yet unobserved macroalgae or as microalgae aggregations were released with the break-up of sea ice during the Arctic summer. This is significant as it represents a source of particles associated with sea ice loss and thus might provide an important climate feedback mechanism. The work highlights the requirement for knowledge of how iodine contributes to new particle formation and nucleation.

Variability of aerosol particles

Aerosol particles, acting as Cloud Condensation Nuclei (CCNs) or Ice Nucleating Particles (INPs), are essential to cloud formation. How they influence the optical properties of clouds and the numbers of droplets and ice crystals in clouds is dependent on properties including their size, ability to attract and absorb water, and their composition. Previous studies have shown that particles originated mostly from organic material, continental pollutants and local sources such as sea salt. Year-round studies have shown seasonality, especially demonstrating the influence of the Arctic Haze, a trapped layer generated from anthropogenic sources, which further complicates the picture of how particles interact and affect clouds in the Arctic. As part of the spring ACCACIA campaign individual particles in samples collected during flights were analysed and measured to determine size, composition and potential sources. Composition of all particles was strongly dependent on size with crustal minerals and sea salts dominating particles above one micron and carbon and sulphur-based particles prevalent in particles below 0.5 micron. There were also large fractions of complex internal mixtures of silicates and chlorides. Differences in size, and hence composition, between samples appears to be a reflection of the sources and air mass histories (trajectories from source, for example). One flight (B768) underpinned this assertion, the samples' distinctness being explained by hypothesised sources along the trajectory. Back-projected trajectories also suggest that the crustal mineral particles had undergone long-range, high-altitude transport and, whilst unproven in this study, the elemental characteristics of the particles suggest an Asian, rather than a European/North American origin.

Shipping regulation on its own insufficient to control Arctic black carbon

As the Arctic opens up to shipping, shortened trips may reduce global emissions from the shipping industry but there are concerns that additional black carbon (BC), emitted and hence deposited on snow and ice, could decrease albedo and speed up melting. A study led by researchers at the University of Leeds brought together Arctic shipping inventories for 2004, projected inventories for 2050 and a global aerosol model and found that 2050 emissions will contribute less than 1% of the total BC deposition north of 60 degrees North. A much larger relative contribution is from non-shipping, lower latitude sources. In order to achieve Arctic black carbon deposition reduction controls over more distant stationary sources such as wildfires, changes in transport efficiency, or reductions in low latitude anthropogenic emissions, should be considered alongside any international agreements to control shipping emissions.



Droplet freezing experiment, looking for Ice Nucleating Particles
Credit: Theo Wilson, Leeds University.

Asian black carbon is the most important source in the Arctic

Black carbon deposited to Arctic sea ice or retained as an aerosol in the troposphere is known to affect the Earth's radiation budget by absorbing short wave radiation, decreasing albedo and accelerating melting. However, the sources of the plumes that transport it to the region are poorly understood. Aircraft measurements taken during an ACCACIA campaign detected pollutant plumes across a range of levels in the troposphere, including black carbon, and traced it back to ground sources. A key finding was that in contrast to previous observations, over 90% of the black carbon was shown to have originated from anthropogenic sources. Also it was clear that within the plumes that were observed, Asian sources were found to have the most significant influence at all levels in the Arctic troposphere, peaking in the middle troposphere. The Asian contribution is delivered via a persistent and consistent pathway in less than 12 days from source. As this pollution is likely to continue to rise in future, it is likely that radiative forcing in the Arctic will continue to increase.

Steeper dome, more freshwater, less winter ice

It is estimated that more than 70,000 km3 of freshwater is stored in the upper layer of the Arctic Ocean, separated from warmer, more saline, water below by the halocline. The majority of the Arctic freshwater is in the Beaufort Gyre within the Canada Basin and is supplied by river runoff, precipitation, evaporation, sea ice and from the North Pacific and Atlantic. Spatially and temporally limited observations over recent decades indicate that the Arctic Ocean's freshwater content has increased, especially so in the west. Models point to wind-driven convergence as the driver for the freshwater accumulation, resulting in a rise in sea surface height and a lowering of the halocline – creating a doming effect. By using a continuous data set of satellite observation over 15 years up to 2010 TEA-COSI researchers can demonstrate that the dome in the Beaufort Gyre has been steepening; the gyre has been 'spun-up'. At the same time the trend in wind field curl, which is a measure of spatial gradients in winds that lead to convergence and hence control freshwater variability, follows a similar pattern. Over the satellite observation period the scientists estimate an increase in freshwater storage of around 8,000km3, which is in line with other hydrographic observations. Pertinently they conclude that if this wind field reverses, the Beaufort Gyre might spin down so releasing large amounts of freshwater to the Arctic Ocean. The spin up of the gyre might increase stratification of the Arctic Ocean, but the scientists also suggest that it could also, through increased turbulence, enhance vertical transport of heat from the warmer waters usually below the halocline. Providing additional warmth to the cold upper waters, in turn, could lead to a decrease in winter ice growth, so adding another positive feedback to the ice-albedo effect as ice continues to retreat.

Stronger currents encourage more 'hotspots' in future Arctic Ocean

The Arctic Ocean receives heat from external sources, the largest being inflowing Atlantic water entering at depths between 40-200 metres and at a temperature around 4°C warmer than the overlying fresher water above the halocline. It is effectively separated from mixing by this stratification, although there is some heat exchange due to the double diffusion gradients of salinity and temperature. However the fate of most of the incoming heat is unknown. Whilst mixing and hence heat flux is limited in the Arctic Ocean basins, observations show that where rough topography dominates turbulence is enhanced, this is particularly noticeable in the slope regions. Information gathered by TEA-COSI researchers from 84 profiles during observational campaigns between 2008 and 2013 further demonstrated this. Their measurements showed that the average heat flux across a slope profile south of Svalbard and Severnaya Zemlya were two orders of magnitude higher than in the central Arctic Ocean. They conclude that the existing paradigm of slow double diffusion over the Arctic Ocean as a whole is correct, but they point out that modest tidal currents can increase turbulence and heat fluxes. Models predict that continued retreat of ice cover will result in increased momentum to the Arctic Ocean and enhanced currents (note Beaufort Gyre above). The potential of stronger currents may grow the spatial extent of turbulent mixing to other areas of rough topography, so driving expansion of the existing small 'hot spots' and hence more heat flux to surface waters. They suggest that this will feedback onto the already declining sea ice, further increasing momentum transfer between the atmosphere and an increasingly inhomogeneous Arctic Ocean-sea ice system.

TEA-COSI equipment on ice.
Credit: TEA-COSI ARP project

Key findings:

- For the first time iodine was identified as playing a key role in new particle formation (NPF) over the Greenland Sea in summer. Accurately accounting for NPF is crucial to understanding cloud properties and in turn climate feedback mechanisms. The source of the iodine is yet to be identified, but it is clear that atmospheric models must consider it in future.
- Organic material from sea spray, at the sea surface-atmosphere interface (microlayer), plays a key role as ice nucleating particles (INPs) and hence cloud formation. The organic material is thought to come from a biogenic source, probably phytoplankton cell exudates. This organic material is likely to be an important source of INPs in the absence of other more usual sources, especially in remote marine environments.
- Field work resulted in the largest dataset of its kind, doubling the current total number of observations on surface roughness over the marginal ice zone, which show detailed differences in ice roughness between locations. This knowledge can tune and validate models, that include the wind drag on ice which removes energy from the Arctic system, leading to more accurate ice-position and storm forecasts which are of particular interest to shipping.
- The response of aerosols to sea ice retreat has proven to be counter-intuitive. Increased aerosol emissions will not cause a climate feedback through increased cloud cover and resulting increased albedo. There is a need to better understand aerosol and cloud processes in the Arctic.
- Over 90% of black carbon in the Arctic troposphere is anthropogenic in origin; the largest ground source for this black carbon is mid-latitude Asia; and the potential contribution from increased ship traffic in the Arctic is minimal.
- Stronger currents may increase the spatial extent of turbulent mixing to other areas of rough topography, so driving expansion of the existing small ‘hot spots’ and more heat flux to surface waters. This will feedback onto the already declining sea ice.

Outputs

A selection of papers is included here. For a full list of publications arising to date from this component of the NERC Arctic Research Programme, see separate hard-copy document or visit; *www.arp.arctic.ac.uk*

Allan, J. D., Williams, P. I., Najera, J., Whitehead, J. D., Flynn, M. J., Taylor, J. W., Liu, D., Darbyshire, E., Carpenter, L. J., Chance, R., and McFiggans, G. (2015): **Iodine observed in new particle formation events in the Arctic atmosphere during ACCACIA**, *Atmos. Chem. Phys.*, 15, 5599-5609, 2015, doi: 10.5194/acp-15-5599-2015

Browse, J., Carslaw, K. S., Mann, G. W., Birch, C. E., Arnold, S. R., and Leck, C. (2014): **The complex response of Arctic aerosol to sea-ice retreat**. *Atmos. Chem. Phys.*, 14, 7543-7557, doi:10.5194/acp-14-7543-2014.

Elvidge, A. D., Renfrew, I. A., Weiss, A. I., Brooks, I. M., Lachlan-Cope, T. A., King, J. C.(2016): **Observations of surface momentum exchange over the marginal-ice-zone and recommendations for its parameterization**. *Atmos. Chem. Phys.* (in press)

Lloyd, G., et al., (2015): **Observations and comparisons of cloud microphysical properties in spring and summertime Arctic stratocumulus clouds during the ACCACIA campaign**, *Atmos. Chem. Phys.*, 15, 3719-3737, doi:10.5194/acp-15-3719-2015, 2015.

Rippeth, T. P., Lincoln, B. J., Lenn, Y-D, Green, J. A., Sundfjord, A., Bacon, S. (2015): **Tide-mediated warming of Arctic halocline by Atlantic heat fluxes over rough topography**. N*ature Geoscience 8*, doi: 10.1038/ngeo2350

Wilson, T. W., et al. (2015): **A marine biogenic source of atmospheric ice nucleating particles**, *Nature*, 525, 234-238, doi:10.1038/nature14986

Images courtesy of ARP projects ACCACIA and TEA-COSI

Climate Change and the Arctic Region

The Arctic is a region of higher than average climate change and is predicted by the Intergovernmental Panel on Climate Change assessment Report 4 (IPCC AR4) to remain so. The most iconic evidence of this rapid climate change is the loss of summer sea ice, with recent loss rates exceeding most model projections for reasons that remain unclear. The sea ice loss and degradation of permafrost represent potential tipping points in the Earth System, leading to major physical and biogeochemical feedbacks with global impacts. These changes might also lead to destabilization of gas hydrates, causing major methane release and potentially marine landslides and tsunamis which could impact the Arctic, N.E. Atlantic and the UK. There is an urgent need to advance understanding of the processes that are controlling Arctic climate change, particularly over months to decades and how they reflect both natural variability and the response to anthropogenic radiative forcing. Anthropogenic radiative forcing is the difference between sunlight energy absorbed at the Earth's surface and the energy radiated back to space; it arises from increased levels of greenhouse gases in the atmosphere and from changes in other radiatively active constituents, such as anthropogenic aerosols and ozone. The relative importance of these different contributions, particularly for forcing regional scale climate change, is poorly understood. The response of the Arctic to changing radiative forcing involves changes in the atmosphere, ocean, cryosphere, land surface and biosphere. There is a need to understand the role of specific processes within each of these components and, very importantly, the interactions between them.

What is the NERC Arctic Research Programme?

Because of the importance of understanding the Arctic region and its interactions with the global Earth System, the UK Natural Environment Research Council has invested £15m (2010-2016) in the Arctic Research Programme; its four key objectives were formulated into questions, which formed the drivers for a series of research projects:

1. **What is causing rapid change in the Arctic at the moment?**
2. What are the processes influencing the release of greenhouse gases, such as methane and carbon dioxide, and how much of these gases could enter the atmosphere in future?
3. How can we improve our predictions of what will happen to the climate of the Arctic and the amounts of greenhouse gases released into the future?
4. Are the risks of natural hazards in the Arctic region increasing as a result of regional warming and what are the threats to the UK?

The NERC ARP was funded by the Natural Environment Research Council and managed by the British Antarctic Survey and is linked to the NERC Arctic Office.

Compiled by Kelvin Boot from materials supplied by and interviews with NERC ARP scientists.

www.arp.arctic.ac.uk

Arctic Research Programme
NATURAL ENVIRONMENT RESEARCH COUNCIL

NERC
SCIENCE OF THE ENVIRONMENT

The processes influencing the release of greenhouse gases

www.arp.arctic.ac.uk

Arctic Research Programme

NATURAL ENVIRONMENT
RESEARCH COUNCIL

The processes influencing the release of greenhouse gases:

Methane (CH_4) is now universally recognised within the scientific community as being a powerful greenhouse gas (GHG), which is 28 times more potent than carbon dioxide and is the second most important in terms of radiative forcing. However, the Intergovernmental Panel on Climate Change (IPCC) points out that more work needs to be done to reduce the uncertainties that surround terrestrial carbon fluxes and especially the role of CH_4 in the atmosphere. In the light of increasing temperatures and destabilization of CH_4 sources, a better understanding of Arctic CH_4 is a priority.

Methane is a short-lived gas which remains in the atmosphere for just nine years, meaning that a reduction in emissions could produce a measurable reduction in atmospheric greenhouse gases very quickly. Quantifying the anthropogenic and natural sources of greenhouse gases – particularly methane – in the Arctic, using data from satellites as well as observations made on the ground and from ships and aircraft, is essential for future predictions.

Lakes play a particularly important role in the interaction between climate, vegetation and soils. Not only do their sediment deposits contain accurate records of past changes in regional carbon cycles, but they also produce methane, making them important parts of the terrestrial carbon cycle.

Vegetation generally absorbs carbon emissions from the atmosphere, and a warming Arctic is predicted to support more plant life which could offset rising emissions. However, in recent years improving knowledge and models of permafrost thawing suggest that its impacts might completely offset the benefits of more vegetation, leaving the role and net greenhouse gas contribution of the Arctic uncertain.

The melting of permafrost has the potential to release large quantities of carbon dioxide and methane, two of the most common greenhouse gases, into the atmosphere and into water flowing through these areas. The hydrological and carbon cycles of the Arctic are therefore both affected by thawing permafrost, with water routing changing as previously frozen soils become permeable.

Projects and research objectives:

Methane and other greenhouse gases in the Arctic: Measurements Process Studies and Modelling (MAMM). Methane is a potent greenhouse gas present throughout the Arctic and this project is investigating and modelling its sources, its transport and its role in Arctic atmospheric chemistry. PI—Prof John Pyle, University of Cambridge, with Co-investigators from Royal Holloway, London, University of Manchester, Centre for Ecology and Hydrology and University of East Anglia.

Carbon Cycle Linkages to Permafrost Systems (CYCLOPS). Arctic warming will release greenhouse gases but will also lead to more the growth of vegetation which generally absorbs carbon emissions. We need to understand how those processes interact. PI—Prof. Mathew Williams, University of Edinburgh with Co-investigators from University of Exeter, University of Sheffield and University of Sussex.

Hydrological Controls on Carbon Cycling and Greenhouse Gas Budgets (HYDRA). Studying sites in Arctic Canada to investigate the biological, chemical and physical controls on the release of greenhouse gases from permafrost into melt water and to the atmosphere and how these emissions will influence global warming. PI—Prof Philip Wookey, Heriot-Watt University with Co-investigators from University of Aberdeen, University of Stirling, Centre for Ecology and Hydrology and Durham University.

Lakes and the Arctic Carbon Cycle (LAC). The study of sediment records from Arctic lakes to determine vegetation changes associated with past climate warming events, and how these have impacted on the lakes' role as carbon sinks or carbon emitters. PI—Prof John Anderson, Loughborough University with Co-investigators from University of Southampton, University of Nottingham and University College London.

Where does the methane come from?

During the Methane and other greenhouse gases in the Arctic: Measurements, process studies and Modelling (MAMM) project an approach that combined interpretation of multiple tracers and transport modelling was designed to obtain a better understanding of methane sources, locations and magnitude. Airborne sensors on the NERC's FAAM Atmospheric Research Aircraft were deployed to sample an air mass enriched in methane between the North coast of Norway and Svalbard. The air mass was backtracked through the Numerical Atmospheric-dispersion Modelling Environment (NAME), and indicated that the air mass had travelled, at near-surface height, across central Europe and over northwest Russia before moving higher over the Barents Sea. Analysis of the carbon-13 isotopes in the CH_4 showed a signature characteristic of wetlands. While the researchers acknowledge that there are large uncertainties in the inventory of CH_4 sources, the likelihood is that this source was from wetlands or coastal shelf permafrost in north western Russia. The sampled air mass had enhanced methane, which shows quite clearly that large scale regional sources of methane are being transported over long distances to the Arctic, so influencing the Arctic methane budget. It is important, say the researchers, to include these extraneous sources when interpreting Arctic methane measurements. Further to this, the researchers have demonstrated that combining techniques to sample air masses from otherwise inaccessible sources is a powerful method to determine the influence of regional scale inputs on both methane mixing ratios and isotopic signatures.

New technique for airborne measurements

Existing ground-based greenhouse gas (GHG) monitoring stations have performed well in identifying changes at global and hemisphere scales, but have not been able to attribute changes to individual sources at regional scales. Such information is required for confirmation of future feedbacks and mitigation of further growth. Airborne measurements, on the other hand, have been recognised as a powerful tool in assessing GHG budgets because they can sample large spatial areas at high resolution; sample otherwise inaccessible locations; provide vertical concentration profiles and can be used to validate column-integrated measurements from remote sensing techniques. Thus far the challenge has been to replicate the sensitivity and reliability of ground-based instruments onto airborne platforms where immediate environmental impacts on instruments compromised readings. ARP scientists have now developed an airborne system for measuring carbon dioxide (CO_2) and methane (CH_4), the first and second most significant long-lived GHGs. CH_4 has steadily increased with some variation more recently, but appears to be increasing once again. The emissions of CO_2 have been dramatic although full understanding of sources and sinks away from ground stations is far from clear. Airborne sensors thus have the capability to fill at least some of these gaps in knowledge, which can then better inform models used for future prediction and mitigation. The system developed for operation on board the FAAM BAe-146 research aircraft can take continuous airborne measurements of both CO_2 and CH_4. The performance of the system, which was based on an infrared spectrometer using the cavity-enhanced absorption spectroscopy technique, was monitored against World Meteorological Office (WHO) calibration gases and was shown to be accurate to 1.28 parts per billion for CH_4 and 0.17ppm for CO_2. Importantly the system is robust with no major motion or altitude dependency being detected.

Airborne GHG measurements reconcile local and regional fluxes

Palaeo-records show that as temperatures rose there was an increase in greenhouse gas emissions from boreal wetlands, permafrost and methane hydrates. In turn this caused more warming—a strong positive feedback. Recent studies show new sources as well as increases in some existing emissions from such carbon reservoirs. Wetland regions are the single largest source of atmospheric methane (CH_4) emissions, accounting for around one third of global emissions and the boreal and Arctic regions are responsible for about 25% of that total (tropical wetlands account for most of the remainder). Soil moisture, temperature and the availability of organic matter influence CH_4 emission rates, while in some areas methane consuming bacteria prevent it from reaching the atmosphere, so emissions show a large degree of spatial and temporal variability. Likewise the exchange of CO_2 between the surface and the atmosphere is equally complex with plant growth increasing as temperatures rise making the impacts of a warmer climate on the net carbon budget of these regions difficult to unravel. Previous estimates of the carbon flux have relied upon up-scaling surface measurements at point locations however due to the heterogeneous nature of the Boreal and Arctic regions models have not been confident in simulating the regional picture. Airborne measurements have been shown to be a powerful tool in reducing the uncertainties. As part of the MAMM campaign ARP scientists collected *in situ* measurements on board the FAAM research aircraft to quantify greenhouse gas fluxes over the Fennoscandian wetlands. They were also able to compare them with ground-based measurements from the same sampling area over the same time periods in July 2012, August 2013, September 2013 and July 2014. One of the flights was chosen as a case study because of particularly favourable weather and showed that when regionally scaled, aircraft-derived fluxes were comparable to simultaneous seasonally averaged ground measurements. This demonstrates that such seasonal ground-based measurements are, in fact, potentially scalable to be regionally representative. They also indicate that existing predictive models underestimate the net CH_4 flux from the regions studied. However, the researchers caution that a regionally representative flux from a single day should not be extrapolated, but point out that the results highlight the need for more case studies to validate such models to ensure closer agreement with *in situ* observations.

Measurements above Svalbard methane seeps suggest no influence on the atmosphere

Methane (CH_4) has been called 'the other greenhouse gas' and has been estimated to contribute around 20% of the 'enhanced greenhouse effect'; it is also a gas that has large natural reservoirs vulnerable to climate change. Global growth of atmospheric CH_4 has increased in the last decade with a marked Arctic growth event in 2007, however the causes remain unclear. Decomposing methane hydrates in marine sediments have been highlighted as a potential source but just how much Arctic subsea CH_4 escapes to the atmosphere remains an open question. One estimate suggests there are 1200Gt of CH_4 stored in gas hydrates and some of these deposits are thought to be close to instability. A large escape of CH_4 could trigger positive feedback and accelerate climate change so it is important to understand how it reaches the sea surface, if it enters the atmosphere and how that might change in future. MAMM scientists working with colleagues from Norway combined efforts to gain measurements from the seabed, the ocean and the atmosphere using land-based, ship and aircraft platforms during a summer campaign at Svalbard, where CH_4 bubbles from natural seeps on the seabed. They found, as might be expected, that there were high concentrations of dissolved CH_4 above the sea floor but there was a sharp decrease above the pycnocline (a natural density boundary separating surface from deeper water, acting as a 'lid' so preventing upward movement of water). Thus in the Svalbard area very little CH_4 reached the atmosphere either as bubbles or as dissolved gas during the campaign period. The scientists point out, however, that when physical processes remove the barrier, shorter periods with large fluxes might indeed occur, but any large CH_4 releases with strong impacts on the atmosphere are likely to be transient. Further investigation of the pycnocline and the complex seasonal variations in Arctic CH_4 cycles are planned as part of long-term ocean observations.

Diffuse light enhances photosynthetic ability

Radiation from the Sun provides the energy for photosynthesis, underpinning plant productivity and providing the 'engine' for the biological part of the global carbon cycle. At a leaf level, the biochemistry and its associated processes which leads to a linear response to increasing light followed by a saturation response, is well known. Simulations of these responses are built into predictive models concerned with crops to ecosystems, yet uncertainties remain, largely due to the different responses at the canopy level, which are more complex and need to be correctly modelled for predicting climate sensitivity of the global carbon cycle. The ARP Carbon Cycle Linkages to Permafrost Systems (CYCLOPS) research group led from the University of Edinburgh, investigated how radiation conditions within a tundra canopy were linked to canopy photosynthesis and its sensitivity to sky conditions from diffuse to total radiation. The research was undertaken in Arctic shrub tundra which is of interest as it is a significant part of the Arctic biome that is currently expanding and is likely to have feedbacks to global processes. Coincident measurements, in time and space, of light, climate and photosynthesis were made, collating light and flux measurements. The uniquely detailed measurements of light conditions within shrub canopies and their net ecosystem exchange of CO_2 were made under various conditions. In and around shrub canopies the radiation can be direct or diffuse, scattered by molecules in the air or other obstructions. Perhaps surprisingly, the researchers found that diffuse radiation was more consistent than direct radiation, which has a propensity to shade lower leaves, in fact there can be a three-fold increase in shading under direct illumination. The leaves use of the light also varies; in high light levels leaves become saturated and cannot make use of all of the light available, while in shade they make the best use of little light and so are 'more efficient' albeit with lesser quantities. In diffuse lighting a balance is struck which results in a higher light use efficiency which in turn increases photosynthesis by up to 17%. Whilst the researchers caution that this technique is limited to a single community, high latitude shrub tundra, the unique information gathered should inform testing of radiative transfer, photosynthetic efficiency and ultimately provide more accuracy for climate models and the carbon cycle.

Can Arctic tundra be considered a single ecosystem for carbon balance?

Modelling the regional carbon (C) balance and how it may change in response to weather and climate change is made questionable by the high level of spatial variability in ecosystem types. Current models of pan-Arctic C-cycling typically see the Arctic as consisting of one or a very few ecosystem types, usually grouped as 'tundra', which respond to weather and climate changes in the same way. The reality is that the Arctic landscape is composed of much greater diversity, a patchwork of ecosystem types often sharply defined and each differing from others in key processes including C-cycling and net ecosystem exchange (NEE) of CO_2. These vegetation patches may be herbaceous or woody and deciduous, evergreen, wintergreen, graminoid, moss or lichen. Their size, composition and frequency vary across the Arctic, which raises questions about whether the existing approach is accurate or whether a more detailed approach is needed. If the latter how many kinds of tundra should be considered for developing new models?

ARP scientists, working with colleagues from the USA and the Netherlands, continued the development of a model of NEE that can predict the CO_2 fluxes across a wide range of subarctic and low Arctic ecosystems. Rather than requiring detailed knowledge of species composition, it is based upon the light response of whole canopies of tundra vegetation and the soils beneath them. The aim was to find a single model, and ideally a single parameterization of the model that could make accurate predictions of NEE through the Arctic. It would appear that the diversity of Arctic ecosystems, dominated by different functional vegetation types, have been shaped by the Arctic environment so that an overall measure of NEE can be described in a single parameterization of a single model. The research established that indeed it is reasonable to model short-term changes in the C-balance of the entire Arctic as if it were a single ecosystem.

During sunny conditions, a diffuser screen (translucent panel, left) was used to manipulate the light climate, removing direct irradiance from the shrub canopy within the Perspex chamber (centre) to generate a diffuse light environment. During cloudy conditions, opaque white panels were used similarly to enhance illumination of the chamber by concentrating reflected diffuse light.

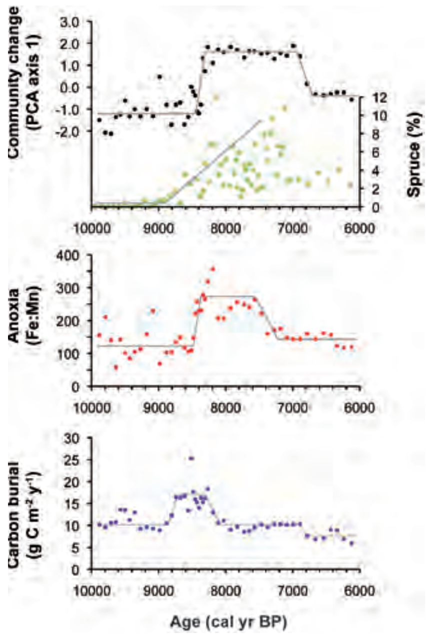
Vegetation may not store more carbon in future Arctic

An estimated 1.68 trillion tonnes of carbon is stored in the soils and sediments of permafrost regions and most of this is currently frozen into the permafrost itself, thought to be protected, in 'deep freeze', from breakdown by soil microorganisms. If the permanently frozen ground begins to thaw however, then soil microorganisms can convert this carbon into the greenhouse gases carbon dioxide and methane. When released to the atmosphere they can speed up global warming, leading to further thawing and vegetation change and hence further carbon releases - a positive feedback. Much of the permafrost is in the Arctic, which is undergoing warming of substantially greater magnitude than the rest of the planet so understanding carbon cycling and hydrology in permafrost environments is crucial. The ARP HYDRA project was about specifically linking carbon cycling and hydrology in permafrost environments undergoing change and focused on the exchanges between land and atmosphere, land and freshwater, and freshwater and atmosphere, of biogenic greenhouse gases (carbon dioxide and methane), as well as downstream transport and fate of organic and inorganic carbon in stream waters. HYDRA scientists carried out extensive fieldwork at Trail Valley Creek, Canada which included measuring vegetation and soil characteristics, fluxes of carbon dioxide and methane between the land and the atmosphere, and between freshwaters and the atmosphere, and stream flow transfers of dissolved and particulate carbon. Thaw depth and temperature variations in different parts of the landscape and vegetation were also measured. The growing evidence shows that the most productive plant communities – dwarf birch and alder - are associated with the rapid exchange and release of carbon in the soil, and then to the atmosphere. The results further suggest that continued 'shrubification' (due to warming) in the Arctic may not result in the region storing more carbon; in fact the reverse may be true. The researchers conclude that we cannot rely on the landscape to be a carbon sink in future. We need to understand both the land-atmosphere and the land-freshwater exchanges of carbon and their fate down-stream, as well as how vulnerable the massive existing stores of soil carbon are to microbial metabolism (now and in the future), in order to predict how global changes will influence how these systems function.

Shifting vegetation can impact carbon budgets

The biological processes in Arctic lakes, controlled by their flora and fauna, determine whether a lake will be a net carbon (C)-sink or C-emitter. Since the species composition and C-fixing productivity of a lake depend on the vegetation surrounding it, determining how Arctic lakes will change in response to vegetation shifts is an important undertaking. The Lakes and the Arctic Carbon Cycle (LAC) project studied sediment records from Arctic lakes to determine vegetation changes associated with past climate warming events, and how these impacted on the lakes' role in the C-cycle. The team investigated groups of lakes around the Arctic – near Walker Lake in Alaska's Brooks Range, Sisimiut in southwest Greenland and in northern Norway – so that a range of vegetation transitions could be studied. The results arising from the project indicate that terrestrial vegetation shifts have a clear effect on the structure and functioning of lake ecosystems and biogeochemistry, indicating that Arctic "greening" has the potential to substantially modify net carbon fluxes between the lake and catchment, with implications for terrestrial carbon budgets on the landscape scale.

Studies of an Holocene sediment record from Ruppert Lake in Alaska provided an extensive suite of proxies; the sediment core included pollen and plant macrofossils to detect shifts in terrestrial vegetation and remains of aquatic biota (diatoms, zooplankton, macrophytes) as well as a range of geochemical analyses, including stable isotopes analysed on the organic fraction of sediment, chlorophyll and carotenoid pigments; the results indicate that the catchment vegetation changes (e.g. the expansion of Spruce) resulted in a period of anoxia with associated methanogenesis.



Key findings:

- The diversity of Arctic ecosystems, dominated by different functional vegetation types, have been shaped by the Arctic environment so that an overall measure of net ecosystem exchange of CO_2 can be described in a single parameterization of a single model.
- NERC ARP world-first experimental approach shows that at canopy level there is variation in light use efficiency and hence photosynthesis and CO_2 exchange. Diffuse lighting results in a 17% increase in photosynthesis over direct lighting. Better simulations using this technique will lead to more accurate predictions of effects of climate on the carbon cycle.
- Large scale regional sources of methane are being transported over long distances to the Arctic, so influencing the Arctic methane budget from many thousands of kilometres distance.
- NERC ARP scientists have developed a unique airborne system for operation on board the FAAM BAe-146 UK research aircraft that can take continuous airborne measurements of both carbon dioxide (CO_2) and methane (CH_4), the first and second most significant long-lived GHGs.
- Research at Svalbard shows that when physical processes remove the pycnocline barrier, short periods with large CH_4 fluxes might occur, but any large CH_4 releases with strong impacts on the atmosphere are likely to be transient.
- Continued 'shrubification' (due to warming) in the Arctic may not result in the region storing more carbon; in fact the reverse may be true and we cannot rely on the landscape to be a carbon sink in future.
- Arctic "greening" has the potential to substantially modify net carbon fluxes between lakes and catchments, with implications for terrestrial carbon budgets on the landscape scale.

Outputs

Only a few key papers are listed here, more publications can be found in the NERC ARP publications brochure. Other papers are in process of publication or being prepared—a current comprehensive listing can be found on the NERC ARP website.

France, J. L., et. al (submitted 2016): **Identifying Sources of Long-Distance Transported Methane to the Arctic using δ13C in CH_4 and Particle Dispersion Modelling**. In: American Geophysical Union - Fall meeting; 08 Dec 2013-13 Dec 2013; San Francisco. 2014.

Myhre, C. L., et al. (2016): **Extensive release of methane from Arctic seabed west of Svalbard during summer 2014 does not influence the atmosphere**, *Geophys. Res. Lett.*, 43, 4624–4631, doi:10.1002/2016GL068999

O'Shea, S. J., et, al (2014). **Methane and carbon dioxide fluxes and their regional scalability for the European Arctic wetlands during the MAMM project in summer 2012.** *Atmos. Chem. Phys.*, 14, 13159-13174, doi:10.5194/acp-14-13159-2014, 2014.

Shaver, G.R., Rastetter, E.B., Salmon, V., Street, L.E., van de Weg, M.J., Rocha, A., van Wijk, M.T., Williams, M. (2013) **Pan-Arctic modelling of net ecosystem exchange of CO_2.** *Phil Trans R Soc B* 368: 20120485.

Williams, M.R., Rastetter, E.B., Van der Pol, L., Shaver, G.R, (2014) **Arctic canopy photosynthetic efficiency enhanced under diffuse light, linked to a reduction in the fraction of the canopy in deep shade**. *New Phytologist* 202:1266-1276. doi:10.1111/nph.12750

Images courtesy of ARP Projects CYCLOPS, HYDRA, LAC and MAMM.

Climate Change and the Arctic Region

The Arctic is a region of higher than average climate change and is predicted by the Intergovernmental Panel on Climate Change Assessment Report 4 (IPCC AR4) to remain so. The most iconic evidence of this rapid climate change is the loss of summer sea ice, with recent loss rates exceeding most model projections for reasons that remain unclear. The sea ice loss and degradation of permafrost represent potential tipping points in the Earth System, leading to major physical and biogeochemical feedbacks with global impacts. These changes might also lead to destabilization of gas hydrates, causing major methane release and potentially marine landslides and tsunamis which could impact the Arctic, N.E. Atlantic and the UK. There is an urgent need to advance understanding of the processes that are controlling Arctic climate change, particularly over months to decades and how they reflect both natural variability and the response to anthropogenic radiative forcing. Anthropogenic radiative forcing is the difference between sunlight energy absorbed at the Earth's surface and the energy radiated back to space; it arises from increased levels of greenhouse gases in the atmosphere and from changes in other radiatively active constituents, such as anthropogenic aerosols and ozone.
The relative importance of these different contributions, particularly for forcing regional scale climate change, is poorly understood. The response of the Arctic to changing radiative forcing involves changes in the atmosphere, ocean, cryosphere, land surface and biosphere. There is a need to understand the role of specific processes within each of these components and, very importantly, the interactions between them.

What is the NERC Arctic Research Programme?

Because of the importance of understanding the Arctic region and its interactions with the global Earth System, the UK Natural Environment Research Council has invested £15m (2010-2016) in the Arctic Research Programme; its four key objectives were formulated into questions, which formed the drivers for a series of research projects:

1. What is causing the rapid changes in the Arctic at the moment?
2. **What are the processes influencing the release of greenhouse gases, such as methane and carbon dioxide, and how much of these gases could enter the atmosphere in future?**
3. How can we improve our predictions of what will happen to the climate of the Arctic and the amounts of greenhouse gases released into the future?
4. Are the risks of natural hazards in the Arctic region increasing as a result of regional warming and what are the threats to the UK?

The NERC ARP was funded by the Natural Environment Research Council and managed by the British Antarctic Survey and is linked to the NERC Arctic Office.

Compiled by Kelvin Boot from materials supplied by and interviews with NERC ARP scientists.

www.arp.arctic.ac.uk

Arctic Research Programme
NATURAL ENVIRONMENT RESEARCH COUNCIL

NERC
SCIENCE OF THE ENVIRONMENT

Improving predictions of Arctic climate

www.arp.arctic.ac.uk

Arctic Research Programme

NATURAL ENVIRONMENT RESEARCH COUNCIL

Improving predictions of Arctic climate

Predicting the Arctic environment in the short and medium term would be useful to numerous groups of people, including local policymakers, indigenous populations and decision makers around the world trying to understand the impact of changes in the Arctic on their regions. Changing environmental conditions affect wildlife, food resources and hence local cultures; of particular interest to shipping is the accessibility of routes that pass through Arctic waters. Also given the significant effects of high-latitude climate in mid– and lower latitudes, the ability to make confident predictions of developments in the high North is very desirable. The Arctic is a complex and variable region with many factors influencing its climate and how it develops over short and longer terms. Observations and measurements that help us to understand Arctic climate have been limited because of remoteness of locations and the harshness of the environment. Modern observational techniques have improved the situation but there are still large gaps which need to be addressed. Computer modelling has proven to be a powerful prediction tool and by bringing different models together, comparisons can be made, adjustments included and the overall 'skill' of the models increased. Modelling and observational science are now inextricably linked as models make sense of observations and observations populate and inform models. Thus, it is no surprise that modelling has been used throughout the NERC Arctic Research Programme as an aid to understanding and extrapolating observations and measurements, and particular examples can be seen in other documents in this short series of booklets. Building Arctic forecast systems is recognized as a complex task, involving the construction of a detailed observation system to monitor Arctic climate, and sophisticated forecast models that can use these observations to enhance predictive capabilities. Recognizing that such a programme will require time and financial commitment, a first step is to assess the likely benefits that such a system may bring. In short can Arctic climate be predicted over differing timescales, and what operational developments are required to facilitate such predictions?

Aims of the research:

The Arctic Predictability and Prediction on Seasonal to Interannual Timescales (APPOSITE) was designed with such an assessment in mind: by answering four key questions:

- What aspects of Arctic climate can we predict?
- How far in advance can we predict these aspects, and is this seasonally dependent?
- What physical processes and mechanisms are responsible for this predictability?
- What aspects of Forecast models should be prioritised for development?

A second NERC ARP project: **Submarine Estimates of Arctic Turbulence Spectra (SEATS)** looked at how the presence of sea ice plays an important role in controlling the nature of turbulence in near-surface water. SEATS uses a high-quality dataset spanning the entire Arctic Ocean that has not previously been used in order to investigate the effect of changing ice cover on turbulence and ocean circulation.

Arctic Predictability and Prediction on Seasonal to Inter-annual Timescales (APPOSITE). PI - Dr. Ed Hawkins, NCAS, University of Reading; with Co-investigators from University of Reading and University of Exeter.

Submarine Estimates of Arctic Turbulence Spectra (SEATS). PI - Dr John Allen, University of Portsmouth, with Co-investigators from the National Oceanography Centre.

Prediction by design

As Arctic sea ice declines the possibilities for using the region for shipping, resource extraction and tourism increase. However, usage and concomitant risks will always be predicated by sea ice cover, so being able to predict this on a seasonal and interannual basis becomes an imperative, although detail of what information potential users need remains to be clarified. The use of dynamical global climate models, which have been tested for their skill by hindcasting, or retrospectively predicting, has been encouraging but the models tend to work best over long term declines in sea ice cover and do not have the skill or resolution to predict on a shorter seasonal basis. It is this shorter term predictability that will be important to the new users of the Arctic who require predictions for the coming season. Global climate models are the standard prediction systems but they are limited in skill when it comes to predicting the crucial September (Arctic summer) sea ice cover. There may be three reasons for this: either the limits of predictability have been reached, or because models being used for prediction are inadequate, or there is a lack of observational data to populate the models. If an operational Arctic sea ice prediction system is to be designed there are some fundamental questions that need to be answered, including the size of the ensemble, the methods of generating the different members and the number of hindcasts required to test the skill of the model, and what metrics are best for testing skill. Members of the APPOSITE consortium looked at these practical issues, focusing on shorter-term predictions on a pan-Arctic scale of sea ice thickness and extent to inform the design of future modelling approaches. Sea ice predictability can be best studied with a hierarchy of 'experiments' including control simulations, perfect model predictability and hindcast skill. They concluded from their analyses that using more than one metric is essential and that different choices can significantly alter conclusions about whether skill is present or absent. Both the size of the ensemble (the number of different starting points, or members for the model) and the number of hindcasts is important if the correlation and expected error in forecasts is to be assessed. They also established that the various techniques used to generate the different ensemble members can produce surprisingly different outcomes. The modellers point out that their analysis is for pan-Arctic predictions and that more localised predictions will be of most use to potential users of the summer Arctic, so there is need for further refinement of models. There is also a requirement from users for 'real-time' forecasts which can be tested independently of model samples, and there is great potential in using empirical benchmarks such as melt pond formation that has been shown elsewhere as having significant skill for predicting the crucially important September ice extent. What is clear from this analysis of sea ice prediction design is that the full potential of forecast skill is yet to be reached and that will be improved with more observations, better assimilation techniques, and improved models.

Forecast uncertainty

Model errors and initial state uncertainty are widely discussed as contributing to uncertainties in Arctic seasonal to interannual predictions. Less attention has been paid to forecast uncertainties due to the chaotic nature of the Arctic climate system, but this irreducible forecast uncertainty (IFU) can help to unravel the mechanisms through which predictability is lost and so is of great interest in model development and observation deployment. By using a set of idealized ensemble prediction experiments, scientists from the APPOSITE consortium found that uncertainty in atmospheric and oceanic heat fluxes are often equally important for driving unpredictable Arctic-wide changes in sea ice and surface water temperature, and so contribute equally to IFU. However, there were differences; the atmospheric heat flux dominates Arctic-wide changes for lead times of up to a year, while oceanic heat flux dominates regionally and on interannual time scales. Additionally they found that the unpredictable ocean heat flux is largely due to wind-driven lateral heat transport and so is mainly forced by atmosphere. The results of this modelling exercise help to explain why current forecasting systems perform poorly and inconsistently in the Arctic. It seems that the vertical heat exchange in the upper ocean, which is affected by the entrainment of warm water from below, requires better representation if forecast quality is to be improved, and "getting the right results for the wrong reasons" is avoided.

Intermodel sea ice comparison

Future projections of climatic conditions in a warming world depend heavily on reliable and skilful computer models, but how well do these models perform and what are their limitations? In the first coordinated, multimodel suite of so-called "perfect model" ensemble prediction experiments, an ARP-led group of modellers set out to compare four state-of-the-art global climate models' predictability of present day Arctic climate and to diagnose the potential inherent seasonal to interannual predictability of Arctic sea ice in current global climate models (GCMs). Having confidence in such predictions is essential if the Arctic is to be opened up to shipping and resource exploitation, but two key questions have remained unanswered: how can the skill level of models be increased beyond a few months; and how can we predict sea ice thickness and volume, in addition to the better understood sea ice area and extent?

The four models chosen for comparison showed considerable differences when it came to simulating present-day Arctic sea ice mean state and variability. However there was better agreement on the growth rate and magnitude of potential forecast errors, which showed a fast growth of forecast error and a fast decline in potential predictive skill. Aggregated quantities of sea ice extent and volume are often used in models but sea ice thickness and concentration are far more difficult to predict. Locally ice is less predictable than the average pan-Arctic values often applied. The study highlights that all models consistently simulated an amplification of forecast error close to Arctic coasts in winter, implying that sea ice predictions are especially difficult in the very areas where societal benefits would be highest!

This work, the researchers conclude, is an excellent starting point which provides a lower boundary of forecast errors and an upper boundary of predictive skill showing there is room for improvement. There is a need for more data on sea ice thickness and further work is necessary to compare potential skill with the actual skill demonstrated by the models when forecasting observed climate.

There's a right time and a wrong time for predicting summer sea ice

Arctic summer sea ice is rapidly reducing, potentially increasing accessibility to ships, for example. In parallel the demands for seasonal and inter annual forecasts of sea ice conditions have also increased. Predicting summer sea ice conditions has encouraged the development of seasonal sea ice prediction systems, but there are still challenges in overcoming forecasting errors. Errors can occur because important physical processes are inadequately represented in models or key variables such as sea ice thickness and subsurface ocean properties are not well observed. A further complication is that Arctic climate systems are subject to chaotic atmospheric variability, which brings an inherent limit to predictability. If a forecast system is close to this limit then any improvement in sea ice prediction would prove futile. APPOSITE modellers addressed the question of whether there is potential to improve operational prediction systems through an idealized approach by analysing "perfect model" experiments coupled with global climate models. The "perfect model" uses perfect knowledge of the initial model state, so removing model biases. Previous work indicated that sea ice predictability may be dependent on the start month and this was tested using multicentennial simulations with five fully coupled atmosphere-ice-ocean global climate models, understanding this should lead to a better idea of when to initiate model forecasting. To achieve this the modellers used several sets of idealized perfect model forecasts with a version of the Hadley Centre Global Environmental Model (HadGEM1.2). These were initialised in January, May and July, before, during and after the melt season and using more start months than have been previously used in such studies. This would test the start month dependence of the potential skill in pan-Arctic and regional sea ice extent and volume to be investigated. Although the five models varied in some aspects they all indicated that the skill of predictions for both extent and volume of sea ice summer minima improve sharply when the initialization time is after May for a September verification time. This was borne out by the perfect model predictions which showed forecasts initialized in May rapidly lost more skill in the ensuing four months, than those initialized in July and January. The study also showed that sea ice extent in the seasonal ice zone of the North Atlantic regions can be considered predictable 1.5-2.5 years ahead, and that thickness is predictable for longer than extent. The modellers conclude that the summer extent of sea ice is less predictable from ensembles initialised on or before May 1st than those after, thus being important to forecasters. Currently May is when many operational summer forecasts are initialised.

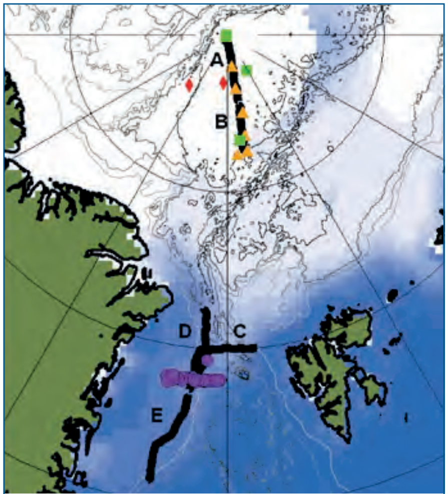
MAVRIC improves sea ice thickness projections

As the climate warms, changes to sea ice thickness (SIT) are expected to lead to significant implications for polar regions and beyond. A reduction in SIT is a prerequisite to opening up the Arctic Ocean to economic exploitation, especially for shipping routes and natural resources; other impacts will affect Arctic ecosystems and there are potential links to mid-latitude weather. SIT is far more informative than sea ice cover (SIC), especially in the central Arctic as thinning can occur without any significant reduction in local cover. The absolute value of SIT is important, especially for ships which cannot be used over a critical SIT threshold, while SIT variability also has an impact on prediction of ice-free dates. Existing global climate models (GCMs) exhibit a wide range of sea ice volume and thickness, spatially and temporally. This uncertainty and differences between the models is a result of three factors: uncertainty in the models; internal variability in the ice; and scenario uncertainty, i.e. variations in temperature and precipitation. ARP modellers set out to redress this situation by using bias correction, which has the potential to reduce the differences between models and hence potentially increase confidence in near-time climate prediction. However SIT is particularly challenging due to its variability, so the modellers developed a new technique which reflects truer values for SIT against observations. The modellers successfully corroborated the idea that uncertainty in future climate projections of SIT was a reflection of the uncertainty in models. By using the Mean and VaRIance Correction (MAVRIC) they reduced this model uncertainty in future predictions of SIT until 2100 – it is the correction of both mean and variance of models that was found to be critical in improving robustness of SIT projections. They also showed that internal variability is the dominant source of uncertainty until 2022, thereafter scenario uncertainty (temperature and precipitation) increases in importance until it equals model uncertainty in importance by 2100. By applying the bias correction, September ice-free conditions in the Arctic (under RCP8.5) could occur ten years earlier than without the correction. Using the MAVRIC also demonstrates that it is more beneficial to spend time running many ensembles to sample internal variability rather than running many future emission scenarios for near-time projections, and can improve the performance of GCMs at least for 50 year projections.

Submarines aid understanding

Atmospheric temperatures across the Arctic have been rising at around twice the rate as elsewhere in the Northern Hemisphere and an ice-free Arctic Ocean is predicted by the end of the century. As the extent of multi-year ice continues to decrease and the ice pack loosens, energy transfer from ocean to the atmosphere is expected to become more efficient and turbulence within the ocean may increase. Once the 'lid' of ice is removed, wind can act directly on the water surface and upper ocean leading to increased turbulence, more mixing and modified stratification of the water column. These may have consequences for the biogeochemical properties and dynamics of the Arctic Ocean. Turbulence also plays a key role in ocean circulation and acts at scales ranging across ocean basins down to just a few millimetres. However, little is known about how velocity, temperature and salinity transfer across the various scales and even less is known concerning what happens under a covering of ice. Understanding the energy exchange pathways, and especially how they differ between ice-covered and ice-free zones is essential for parameterizing predictive models of future climate. There have been some observations and measurements at the surface but under-ice measurements remain elusive.

In a unique collaboration between SEATS scientists, from the National Oceanography Centre, the University of Portsmouth, and The Royal Navy, data collected during routine submarine operations in the summer of 1996 was made available for analysis. Submarines are equipped with sensors collecting various ocean parameters such as temperature and salinity but for operational reasons they have remained confidential until this study, when the Ministry of Defence permitted exclusive access to the data. Once analysed the data revealed that the dynamics did indeed vary between ice-covered and ice-free seas, although turbulence was similar in areas of low and high sea ice cover. This implies that it is the way the ice affects the stability and structure of the water column rather than simply a 'lid' of ice protecting the ocean from wind that influences how energy is transferred between different scales in the Arctic Ocean.



Positions of five sections of data where submarine depth and speed were approximately constant and the locations of depth profiles taken during summers (August–October) between 1991 and 1999. Summer sea-ice concentration (August 1996) and bathymetry contours are also shown.

Key findings:

- Using more than one metric in models for sea ice prediction is essential and different choices can significantly alter conclusions about whether skill is present or absent.
- The full potential of forecast skill in sea ice prediction is yet to be reached and will be improved with more observations, better assimilation techniques, and improved models.
- Atmospheric heat flux dominates Arctic-wide changes for lead times of up to a year, while oceanic heat flux dominates regionally and on interannual time scales. Additionally unpredictable ocean heat flux is largely due to wind-driven lateral heat transport and so is mainly forced by atmosphere.
- It is more beneficial to spend time running many ensembles to sample internal variability rather than running many future emission scenarios for near-time projections.
- The summer extent of sea-ice is less predictable from ensembles initialised on or before May 1st than those after, thus being important to forecasters. Currently May is when many operational summer forecasts are initialised.
- Submarine data shows that it is the way ice affects the stability and structure of the water column rather than simply a 'lid' of ice protecting the ocean from wind that influences how energy is transferred between different scales in the Arctic Ocean.

Images courtesy of ARP projects APPOSITE and SEATS and from the British Antarctic Survey

Outputs

A selection of papers is included here. For a full list of publications arising to date from this component of the NERC Arctic Research Programme, see separate hard-copy document or visit *www.arp.arctic.ac.uk*

Day, J. J, Hawkins, E., Tietsche, S. (2014): **Will Arctic sea ice thickness initialization improve seasonal forecast skill**? *Geophysical Research Letters*, Vol 41, Issue 21, Pages 7566-7575. doi: 10.1002/2014GL061694

Day, J. J, Tietsche, S. & Hawkins, E. (2014): **Pan-Arctic and regional sea ice predictability: initialisation month dependence**. *Journal of Climate*, 27, 4371, doi: 10.1175/JCLI-D-13-00614.1.

Hawkins, E., Titesche, S., Day, J., Melia, N., Haines, K., Keeley, S., (2015): **Aspects of designing and evaluating seasonal-to-interannual Arctic sea-ice prediction systems**. *Quarterly Journal of the Royal Meteorology Society*, DOI:10.1002/qj.2643

Guemas, V. et al. (2016): **A review of Arctic sea ice predictability and prediction on seasonal-to-decadal timescales**. *Quarterly Journal of the Royal Meteorology Society*, doi: 10.1002/qj.2401

Marcinko C.L.J., Martin A.P., Allen J.T. (2015): **Characterising Horizontal Variability and Energy Spectra in the Arctic Ocean Halocline**. *Journal of Geophysical Research: Oceans*, Vol 120, Issue 1. doi: 10.1002/2014JC010381

Swart, N. C., Fyfe, J. C., Hawkins, E., Kay, J. E., Jahn, A. (2015): **Influence of internal variability on Arctic sea-ice trends**. *Nature Climate Change 5*, 86-89 (2015) doi: 10.1038/nclimate2483

Tietsche, S. et al. (2014): **Seasonal to interannual Arctic sea ice predictability in current global climate models**. *Geophysical Research Letters*, Vol. 41. Issue 3, pages 1035-1043. doi: 10.1002/2013GL058755

Climate Change and the Arctic Region

The Arctic is a region of higher than average climate change and is predicted by the Intergovernmental Panel on Climate Change assessment Report 4 (IPCC AR4) to remain so. The most iconic evidence of this rapid climate change is the loss of summer sea ice, with recent loss rates exceeding most model projections for reasons that remain unclear. The sea ice loss and degradation of permafrost represent potential tipping points in the Earth System, leading to major physical and biogeochemical feedbacks with global impacts. These changes might also lead to destabilization of gas hydrates, causing major methane release and potentially marine landslides and tsunamis which could impact the Arctic, N.E. Atlantic and the UK. There is an urgent need to advance understanding of the processes that are controlling Arctic climate change, particularly over months to decades and how they reflect both natural variability and the response to anthropogenic radiative forcing. Anthropogenic radiative forcing is the difference between sunlight energy absorbed at the Earth's surface and the energy radiated back to space; it arises from increased levels of greenhouse gases in the atmosphere and from changes in other radiatively active constituents, such as anthropogenic aerosols and ozone. The relative importance of these different contributions, particularly for forcing regional scale climate change, is poorly understood. The response of the Arctic to changing radiative forcing involves changes in the atmosphere, ocean, cryosphere, land surface and biosphere. There is a need to understand the role of specific processes within each of these components and, very importantly, the interactions between them.

What is the NERC Arctic Research Programme?

Because of the importance of understanding the Arctic region and its interactions with the global Earth System, the UK Natural Environment Research Council has invested £15m (2010-2016) in the Arctic Research Programme; its four key objectives were formulated into questions, which formed the drivers for a series of research projects:

1. What is causing the rapid changes in the Arctic at the moment?
2. What are the processes influencing the release of greenhouse gases, such as methane and carbon dioxide, and how much of these gases could enter the atmosphere in future?
3. **How can we improve our predictions of what will happen to the climate of the Arctic and the amounts of greenhouse gases released into the future?**
4. Are the risks of natural hazards in the Arctic region increasing as a result of regional warming and what are the threats to the UK?

The NERC ARP was funded by the Natural Environment Research Council and managed by the British Antarctic Survey and is linked to the NERC Arctic Office.

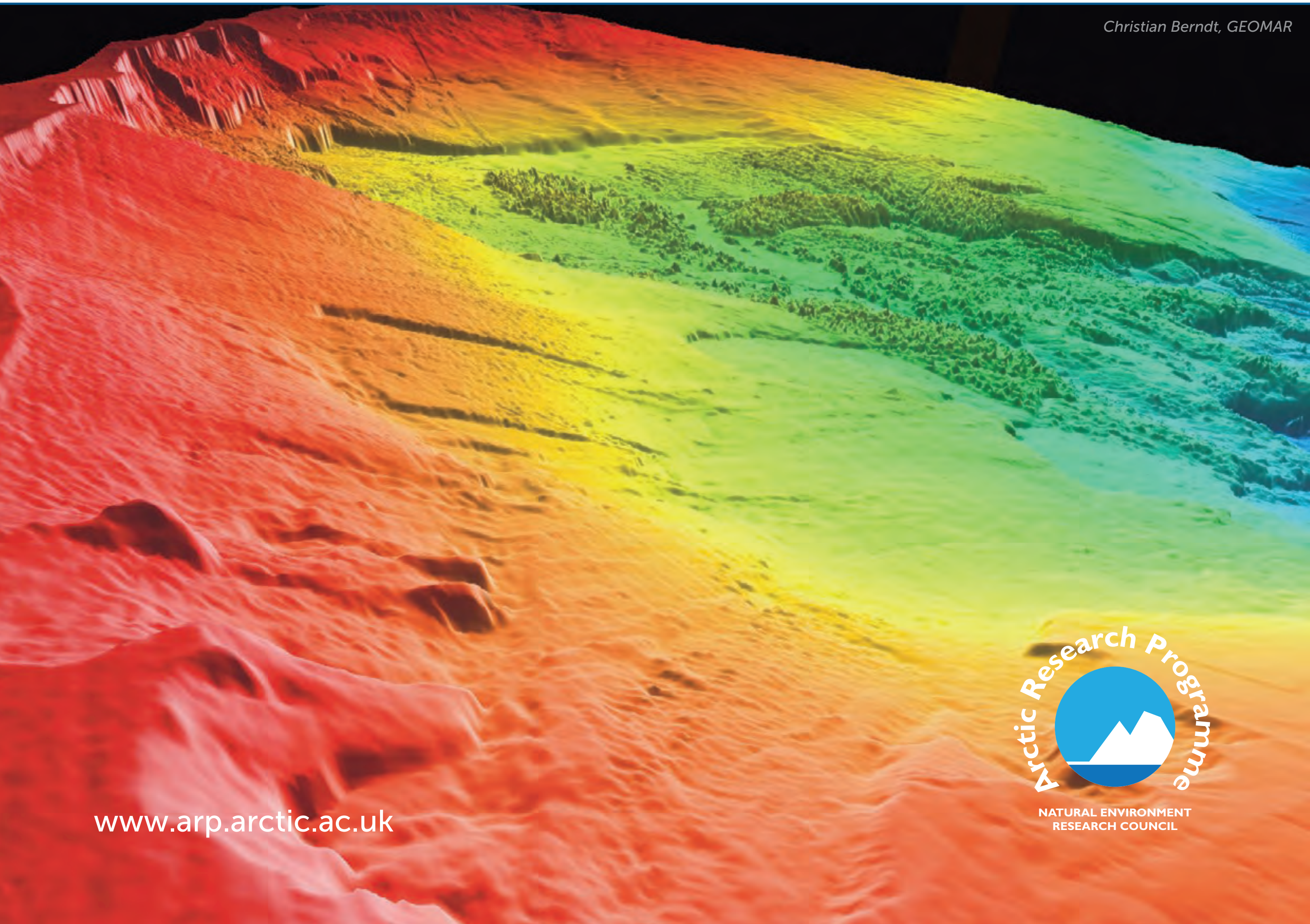
Compiled by Kelvin Boot from materials supplied by and interviews with NERC ARP scientists.

www.arp.arctic.ac.uk

Arctic Research Programme
NATURAL ENVIRONMENT RESEARCH COUNCIL

NERC
SCIENCE OF THE ENVIRONMENT

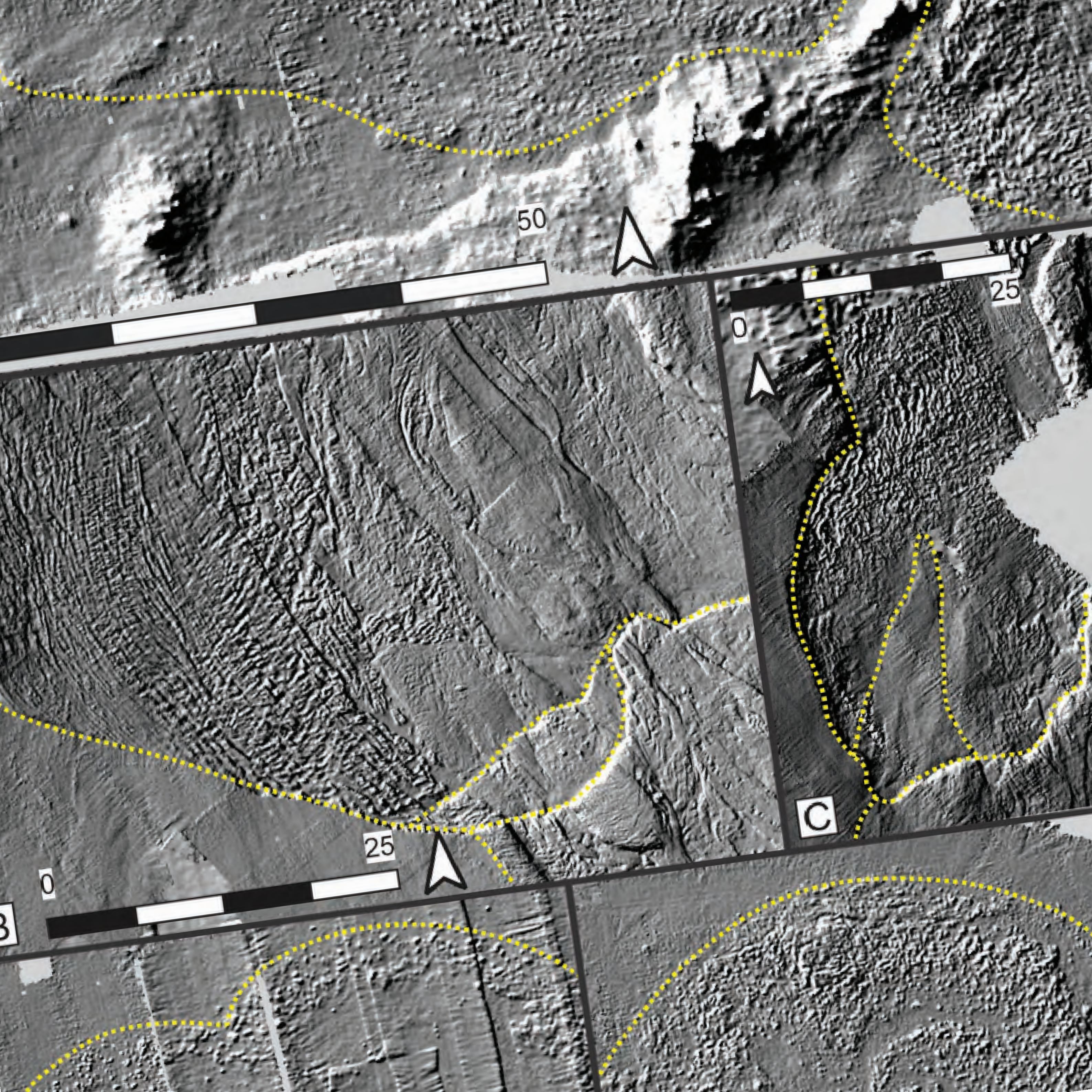
Assessing the likely risks of submarine hazards associated with rapid Arctic climate change


Christian Berndt, GEOMAR

www.arp.arctic.ac.uk

Arctic Research Programme

NATURAL ENVIRONMENT RESEARCH COUNCIL

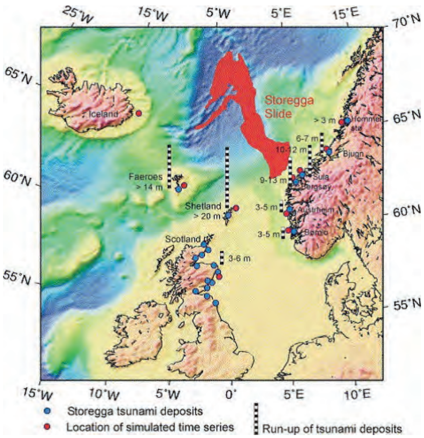


50
0
25
C
25
0
B

Are the risks of natural hazards in the Arctic region increasing as a result of regional warming and what are the threats to the UK?

Submarine landslides can be far larger than terrestrial landslides, and many generate destructive tsunamis. The Storegga Slide offshore Norway covers an area larger than Scotland and contains enough sediment to cover all of Scotland to a depth of 80 metres. It reminds us that such slides are not restricted to distant locations but can occur in close proximity to the UK and have the potential to be highly destructive. The Storegga slide occurred around 8200 years ago and extends for 800km downslope. It produced a tsunami with a run up in excess of 20 metres around the Norwegian coast and 3-8 metres on the Scottish mainland. The UK faces few other natural hazards that could cause damage on the scale of a repeat of a slide and tsunami of this magnitude.

Other slides have occurred since the Storegga event, and sedimentary deposits in Shetland dated at 5500 and 1500 years, as well as the Storegga deposit are thought to indicate tsunamis. Clearly, given the possible impacts of tsunamis generated by Arctic landslides, we need a rigorous assessment of the hazards they pose to the UK over the next 100-200 years, especially in the light of climate change and their potential to increase risk.



The Storegga Slide involved more than 3000 km³ of material, an area larger than the size of Scotland. From Talling et al 2014

The specific aims of the research project are four-fold:

1. to determine the frequency and timing of major Arctic submarine slides;
2. to better understand trigger factors and assess whether the frequency of the slides is likely to increase as climate changes and oceans warm;
3. to assess the magnitude necessary for landslide-tsunamis to flood parts of the UK coast
4. to quantify the likely cost to the UK of different types of inundation triggered by different types of landslide occurring in different locations.

The project uses a range of techniques, including shipboard Arctic seafloor mapping and seabed sediment coring, fieldwork to identify and date coastal tsunami deposits, slope stability modelling, laboratory experiments showing how hydrate dissociation affects sediment strength, and modelling future trends in seismicity. Also included is modelling of landslide motion, tsunami wave generation and propagation, and how tsunami waves would interact with existing UK coastal defence structures. Based on these results, recommendations on measures that can be taken to offset a tsunami's impact on the UK coast can be given. Finally, a sensitivity analysis will aim to capture uncertainties, and determine societal cost.

The natural hazards, Landslide-Tsunami project PI is Prof Peter Talling, Durham University with Co-investigators from National Oceanography Centre, British Geological Survey, University of Aberdeen, University of Manchester, University of Dundee, University of Southampton, University of Cambridge, University of Ulster and Imperial College London.

Images of the morphology of the Traenadjupet Slide based on the complied swath bathymetry dataset. Credits: Landslide-Tsunami ARP project

Frequencies and triggers

Submarine landslides, which can be far larger than those on land, may move so fast that they disintegrate and form hazardous tsunamis at the surface and long run-out turbidity currents that break strategically important cable networks and other sea bed infrastructure. Turbidity currents which carry mud, sand and larger particles rush downwards like an avalanche of debris, picking up sediment and increasing in speed as they flow. Knowing how often such flows are likely to occur and what causes them are key to hazard prediction. By looking at evidence of recurrence of landslide-triggered turbidity currents from three basin plains a NOC led ARP study (Clare et al, 2014) concluded that the time to the next slide is independent of the time since the last. They further conclude from this that, contrary to previous workers' conclusions, non-random events such as glacio-eustatic sea level change, are not dominant single controls on slide timing. Further, it seems that statistical evidence indicates that fluctuating processes (e.g. shelf edge sedimentation rate or hydrate dissociation resulting from ocean warming) associated with such things as eustatic sea level change and climate change also do not dominate slide timing. Earthquakes, they acknowledge, might constitute a single slide trigger, but not all major earthquakes result in disintegrating slides, and not all slides are triggered by earthquakes. When it comes to predicting future large flows resulting from disintegrative slides, their frequency is unlikely to change due to rapid sea level rise in forthcoming decades.

Submarine canyons are one important pathway for sediment transport into ocean basins via turbidity currents; knowing what triggers the turbidity currents filling and flushing submarine canyons is important in geohazard predictions. Led by the National Oceanography Centre (Southampton), ARP scientists have investigated the Nazaré Canyon, offshore Portugal, to gain insights into the frequencies and triggering of such events, to help in predicting where and when they might occur in future (Allin et. al, 2016). Canyon filling appears to be predominantly triggered by sediment instability during periods when sea levels are at their lowest (lowstand). During the current high sea levels storms and nepheloid transport (sediment suspended just above the seabed), are the main suppliers of material. Canyon flushing, on the other hand does not appear to be affected by long-term changes in sea level. Radio carbon dating shows the timings are also different with canyon-flushing turbidity current events recurring on a several thousand year average, an order of magnitude higher than filling events during sea level lowstand and two orders of magnitude higher than present day high sea level conditions. Although determining a trigger for canyon-flushing remains problematic as earthquakes are a candidate, the implication is that potentially hazardous flushing events may not be influenced by future sea level predictions.

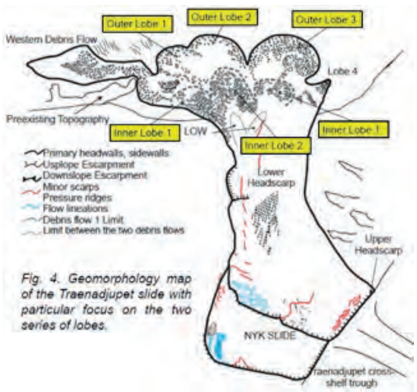
What causes a slope to fail?

Submarine landslides are notable for their large size and because they usually occur on very shallow slopes of less than 2°, about the same slope as a football pitch, which would normally be stable on land. So what is it that causes them to slip and go on to produce huge and potentially damaging tsunamis? The mechanism is not clear and discovering what the weak layers in a slope are and what causes them to fail is a focus for scientific research. High pore pressure in sediments, which carries the load of the overburden, and brings them to the brink of failure appears to be a strong contender, rapid deposition of sediment could tip the slope over the limit and cause it to move. However, some slides had not been subjected to rapid deposition, and can be in depth locations where sedimentation is not highest. Indeed part of this study (Urlaub 2014) showed that it may be the impermeability of the sediment rather than the rate, which is part of the trigger as loss of structure and compaction in the sediments brings pore pressure high enough to fail.

What can the past tell us about submarine landslides in the future?

Knowing how submarine slides are triggered, how they move and spread and whether there are any timing patterns is important when regionally assessing geohazards. So, can analysis of 'fossil' slides provide evidence that helps us understand the mechanisms controlling present day slides and inform future assessments of risk? ARP scientists led from the University of Southampton (Allin et al, 2015) investigated two slides off the coast of Norway: the 4000 year old Trænadjupet Slide and the older Nyk slide which originated from the same section of the Central Norwegian Margin at around 16,000 years ago.

Although of a similar scale to the more famous Storegga Slide which induced a devastating tsunami that affected swathes of north European coasts, these slides do not appear to have triggered tsunamis. The sedimentary deposits of the Trænadjupet and Nyk Slides consist of several 'blocky' lobes extending into the Lofoten Basin, implying that they occurred as a number of smaller, different and possibly temporally disparate slides. Such multi-staged failures result in more, smaller sediment volumes being displaced and so have a much lower tsunamigenic potential than a single large-scale failure. This helps to explain that while overall volumes of shifted material might be similar, there is no contemporaneous tsunami evidence found on nearby shores from the Trænadjupet and Nyk submarine slides. Further evidence to support the multi-stage slide hypothesis is expected from radiocarbon dates for each lobe of the slides.



From Talling. EGU Nordic Seas presentation

Do we know enough to come to any conclusions about timings?

Accurate dating of past submarine landslides is essential if they are to provide any guidance on what may trigger them and how frequent they may be in future. ARP scientists (Urlaub et al, 2013) interrogated a global database with ages of 68 submarine slides with volumes >1km^3. This database is not only the most comprehensive but it is also the only one that includes uncertainty intervals to the age estimates, and changes in local sedimentation rates. It ought to provide the best possible chance of linking climate control to large landslide timing, however no such control was found and the landslide events appear to be random. The sedimentation data also showed that there can be a gap of thousands of years between rapid deposition and slope failure, again implying that climate related deposition does not always lead to landslides. What did become apparent was that despite being the best available database the uncertainties are too large to attribute them to a particular sea level stand.

Some previous studies proposed that there is a strong link between submarine landslides and climate driven changes, while others (including in the ARP) show that the slides are temporally random, suggesting they are not linked to a single non-random global factor such as eustatic sea level change. Another ARP study (Pope et al, 2015) concluded that at present there are too few sufficiently well-dated large slides to know for sure whether they are temporally random or not. So for the future, the recommendation is that well-dated landslides from one setting with similar triggers, local studies with more recurrence, for example, are better able to inform future hazard strategies.

Will a warming world create more landslides?

Previous studies have proposed that on the one hand submarine landslides and ensuing turbidity currents might become more likely due to future global warming releasing marine hydrates and causing slope instability. Other studies have concluded that the large landslides themselves were the trigger for past rapid climate change due to sudden releases of gas hydrates, following a slip. Looking for proxies of similar events in the geological past can help untangle the causes and effects of major landslide events and inform assessment of potential climate related landslides in the future, one such proxy is the Initial Eocene Thermal Maximum (IETM) which occurred around 55 mya. However statistical analysis by a NOC group of researchers (Clare 2015) of 'fossil' large and fast disintegrative submarine landslides recorded in deep sea turbidite deposits, show that turbidity current frequency actually decreased during and immediately following the IETM, indicating that climate change does not necessarily result in increased turbidity current activity - evidence for large landslides.

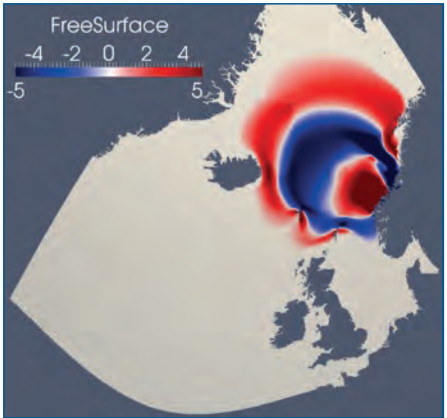
The study also showed that there was no increase in landslide activity prior to the IETM, implying that landslides were not the major trigger for dissociation of hydrates leading to global warming. The conclusions that global warming did not trigger more tsunami-causing and turbidity current-generating landslides, nor was warming a result of hydrates being released by large landslips, helps to clarify risk assessment of future geohazards. The researchers caution however, that further analysis of turbidites deposited during periods of rapid climate change, from other deep sea basins would enhance confidence in future assessments.

What are the risks?

The Storegga slides of 8200 years ago provide a dramatic example of the devastation that can result from the ensuing tsunami which follows a submarine slope collapse. With run up heights of 10 metres in the Shetlands and 3.6 metres on the Scottish mainland, and the total destruction of a civilisation which once inhabited Doggerland, the land bridge that linked Britain to mainland Europe, its impacts were both widespread and destructive. It was thought that a combination of rapid sedimentation from glacial streams and an earthquake caused the slide, with the implication that another glacial cycle would be necessary for a similar slide to occur, and if there was one per glacial cycle the recurrence interval would be around 100,000 years. ARP-collected field data (Talling et. al, 2014) now shows that in fact multiple large slides can occur during one glacial cycle, the recurrence interval is therefore, more like several tens of thousands of years rather than the 100,000 years previously suspected. Smaller slides, but still tsunamigenic, may even occur every few thousand years, indeed the ARP scientists confirmed evidence for local tsunamis at ~1,500 and ~5,300 years ago in the Shetlands. Recurrence intervals shorter than 100,000 years highlight the need to include landslide-tsunamis within the UK National Risk Register. But are the risks amplified by warming oceans and rising sea levels? This perceived link has gained much support in some academic circles and the popular media but the ARP consortium found no evidence to suggest that landslide-tsunami frequency will change significantly as global warming progresses.

What might happen if another large landslide-tsunami occurred?

While several studies have modelled the Storegga slide, and obtained good matches with the observed run up heights, no numerical studies have explored the vulnerability of northern UK coasts from tsunamis generated by submarine-slides in the Arctic Basin. An Imperial College led modelling exercise simulated slide-generated tsunamis, emanating from several potential landslide locations, including known slide scarps and areas of high deposition and several different slide volumes, in the Greenland-Norwegian oceanic basin (Mouradian 2016). By varying slide volume, speed, direction and distance from the UK within the computer models, they investigated the potential wave heights and degree of inundation along the coasts of the UK.



Simulation of the spread and the 'free surface' (wave height from mean sea level) 2 hrs after the Storegga slide tsunami initiation. The outer red arc represents the initial wave, the inner red core is a follow up wave. The off white area is within, dark grey area is outside of the simulation domain. (Image: Simon Mouradian after Jon Hill. (2014).

One highly significant conclusion is that even submarine slides a fraction of the size of Storegga could produce waves that would inundate the UK coast. The models showed that any displacement of sediment over 100 cubic kilometres could generate a large devastating wave. Key factors are the speed of a slide, faster slides generally lead to larger waves, while direction and coastal features play a part too. Slide-generated tsunamis are far more directional than earthquake tsunamis and so two close locations might be affected differently; gradually shelving embayments and estuaries are more likely to amplify the height up to a factor of three, and thus affect the impact of a tsunami. Thus while the predictability of a devastating tsunami at a point location along the coast is far from a simple exercise, it is clear that the most destructive submarine slides are not always the largest. As far as which locations might be most at risk from slides in the Arctic, the north to north eastern coasts of Scotland, the Shetlands, Orkneys and Faroes are particularly exposed to this hazard.

Key conclusions from the project research:

- Large landslides and ensuing tsunamis are not linked to glacial periods and can reoccur at intervals of less than 100,000 years, perhaps as little as a few tens of thousands of years, smaller events can occur at intervals of just a few thousand years. This level of frequency requires that landslide-tsunamis should be included on the UK National Risk Register.
- The north and north-eastern coasts, including the Shetlands and the Orkneys are most at risk from submarine-slide generated tsunamis from the Arctic.
- The mechanism of slope failure is still poorly understood but is likely to be at least in part due to high pore pressure bringing slopes to the brink of collapse.
- There is insufficient evidence to support the notion that landslide-tsunami frequency will increase alongside ocean warming and sea level rise brought about by global warming, and the timing of large slides appears to be random.
- Not all large slides cause major tsunamis but slides as small as 100 cubic kilometres must be seen as potentially devastating. Impacts will depend on volume speeds, direction of slide and resulting tsunami as well as coastal orientation and features at destination.

Outputs

A selection of papers is included here. For a full list of publications arising to date from this component of the NERC Arctic Research Programme, see separate hard-copy document or visit *www.arp.arctic.ac.uk*

Allin, J.R., Mozzato, A., Tappin, D., Talling, P.J., Hunt, J.E.. 2015. Were the Trænadjupet and Nyk Slides multi-staged?

Allin, J.R., Hunt, J.E., Talling, P.J., Clare, M.A., Pope, E., Masson, D.G. 2016. Different frequencies and triggers of canyon filling and flushing events in Nazaré Canyon, offshore Portugal. *Marine Geology* 371(1), 89-105

Pope E.L., Talling, P.J., Urlaub, M., Hunt,J. E., Clare, M.A., Challenor, P. 2015. Are large submarine landslides temporally random or do uncertainties in available age constraints make it impossible to tell? *Marine Geology* 369, 19-33

Clare, M.A., Talling, P.J., Hunt, J.E. 2015. Implications of reduced turbidity current and landslide activity for the Initial Eocene Thermal Maximum – evidence from two distal, deep-water sites. *Earth and Planetary Science Letters* 420, 102–115

Mouradian, S., Collins, G.S., Piggott, M.D., Avjdis, A., Smith, R.C., Hill, J., Talling, P.J., Hunt, J.E. 2016. Investigating the risk of landslide generated tsunami to the UK: A modelling approach. *Geophysical Research Abstracts* Vol. 18, EGU2016-PREVIEW

Talling, P.J., .Clare, M.A., Urlaub, M., Pope, E., Hunt, J.E., and Hunt, S.F.L.. 2014. Large submarine landslides on continental slopes: Geohazards, methane release, and climate change. *Oceanography* 27(2):32-45, http://dx.doi.org/10.5670/oceanog.2014.38.

Urlaub, M., Talling, P.J., Zervos, A., Masson, D. (2015), What causes large submarine landslides on low gradient (<2°) continental slopes with slow (~0.15 m/kyr) sediment accumulation?, *J. Geophys. Res. Solid Earth*, 120, 6722–6739, doi:10.1002/2015JB012347.

Climate Change and the Arctic Region

The Arctic is a region of higher than average climate change and is predicted by the Intergovernmental Panel on Climate Change assessment Report 4 (IPCC AR4) to remain so. The most iconic evidence of this rapid climate change is the loss of summer sea ice, with recent loss rates exceeding most model projections for reasons that remain unclear. The sea ice loss and degradation of permafrost represent potential tipping points in the Earth System, leading to major physical and biogeochemical feedbacks with global impacts. These changes might also lead to destabilization of gas hydrates, causing major methane release and potentially marine landslides and tsunamis which could impact the Arctic, N.E. Atlantic and the UK. There is an urgent need to advance understanding of the processes that are controlling Arctic climate change, particularly over months to decades and how they reflect both natural variability and the response to anthropogenic radiative forcing. Anthropogenic radiative forcing is the difference between sunlight energy absorbed at the Earth's surface and the energy radiated back to space; it arises from increased levels of greenhouse gases in the atmosphere and from changes in other radiatively active constituents, such as anthropogenic aerosols and ozone. The relative importance of these different contributions, particularly for forcing regional scale climate change, is poorly understood. The response of the Arctic to changing radiative forcing involves changes in the atmosphere, ocean, cryosphere, land surface and biosphere. There is a need to understand the role of specific processes within each of these components and, very importantly, the interactions between them.

What is the NERC Arctic Research Programme?

Because of the importance of understanding the Arctic region and its interactions with the global Earth System, the UK Natural Environment Research Council has invested £15m (2010-2016) in the Arctic Research Programme; its four key objectives were formulated into questions, which formed the drivers for a series of research projects:

1. What is causing the rapid changes in the Arctic at the moment?
2. What are the processes influencing the release of greenhouse gases, such as methane and carbon dioxide, and how much of these gases could enter the atmosphere in future?
3. How can we improve our predictions of what will happen to the climate of the Arctic and the amounts of greenhouse gases released into the future?
4. **Are the risks of natural hazards in the Arctic region increasing as a result of regional warming and what are the threats to the UK?**

The NERC ARP was funded by the Natural Environment Research Council and managed by the British Antarctic Survey and is linked to the NERC Arctic Office.

Compiled by Kelvin Boot from materials supplied by and interviews with NERC ARP scientists.

www.arp.arctic.ac.uk

Arctic Research Programme
NATURAL ENVIRONMENT RESEARCH COUNCIL

NERC
SCIENCE OF THE ENVIRONMENT

Peer reviewed publications from the NERC Arctic Research Programme consortia (August 2016)

www.arp.arctic.ac.uk

Arctic Research Programme

NATURAL ENVIRONMENT RESEARCH COUNCIL

Scientific publication by project:

Aerosol-Cloud Coupling and Climate Interactions in the Arctic (ACCACIA). PI – Prof. Ian Brooks University of Leeds with Co-investigators from University of Leeds, University of Manchester, University of York, University of East Anglia, and British Antarctic Survey:

Allan, J. D., Williams, P. I., Najera, J., Whitehead, J. D., Flynn, M. J., Taylor, J. W., Liu, D., Darbyshire, E., Carpenter, L. J., Chance, R., and McFiggans, G. (2015): Iodine observed in new particle formation events in the Arctic atmosphere during ACCACIA. *Atmos. Chem. Phys., 15, 5599-5609, 2015* doi: 10.5194/acp-15-5599-2015

Browse, J., Carslaw, K.S., Schmidt, A., Corbett, J.J. (2013): The complex response of Arctic aerosol to sea-ice retreat. *Atmos. Chem. Phys., 14, 7543-7557,* doi:10.5194/acp-14-7543-2014

Browse, J., Carslaw, K.S., Schmidt, A., Corbett, J.J. (2013): Impact of future Arctic shipping on high-latitude black carbon deposition. *Geophys. Res. Lett.*, 40(16), doi: 10.1002/grl.50876

Chance, R., Carpenter, L., Brooks, I., Wilson, T., Allan, J., and Kirchgaessner, A. (2014) Aerosol, clouds and climate. *Ocean Challenge*, Vol.20, Summer 2014

Elvidge, A. D., Renfrew, I. A., Weiss, A. I., Brooks, I. M., Lachlan-Cope, T. A., King, J. C.(2016): Observations of surface momentum exchange over the marginal-ice-zone and recommendations for its parameterization. *Atmos. Chem. Phys.*, 16, 1545-1563, 2016. doi:10.5194/acp-16-1545-201

Liu, D., Quennehen, B., Darbyshire, E., Allan, J. D., Williams, P. I., Taylor, J. W., Bauguitte, S. J-B., Flynn, M. J., Lowe, D., Gallagher, M. W., Bower, K. N., Choularton, T. W., Coe, H. (2015): The importance of Asia as a source of black carbon to the European Arctic during springtime 2013, *Atmos. Chem. Phys*, 15, 11537-11555, doi:10.5194/acp-15-11537-2015.

Lloyd, G., Choularton, T. W., Bower, K. N., Crosier, J., Jones, H., Dorsey, J. R., Gallagher, M. W., Connolly, P., Kirchgaessner, A. C. R., and Lachlan-Cope, T., (2015): Observations and comparisons of cloud microphysical properties in spring and summertime Arctic stratocumulus clouds during the ACCACIA campaign, *Atmos. Chem. Phys*., 15, 3719-3737, doi:10.5194/acp-15-3719-2015, 2015.

Vihma, T., Pirazzini, R., Fer, I., Renfrew, I. A., Sedlar, J., Tjernström, M., Lüpkes, C., Nygård, T., Notz, D., Weiss, J., Marsan, D., Cheng, B., Birnbaum, G., Gerland, S., Chechin, D.,Gascard, J. C. (2014): Advances in understanding and parameterization of small-scale physical processes in the marine Arctic climate system: a review, *Atmos. Chem. Phys*., 14, 9403-9450, doi:10.5194/acp-14-9403-2014

Wilson, T. W., Ladino, L. A., Alpert, P. A., Breckels, M. N., Brooks, I. M., Browse, J., Burrows, S. M., Carslaw, K. S., Huffman, J. A., Judd, C., Kilthau, W. P., Mason, R. H., McFiggans, G., Miller, L. A., Najera, J., Polishchuk, E., Rae, S., Schiller, C.L., SI, M., Vergara Temprado, J., Whale, T. F., Wong, J. P. S., Wurl, O., Yakobi-Hancock, J. D., Abbatt, J. P. D., Aller, J. Y., Bertram, A. K., Knopf, D. A., Murray, B. J. (2015): A marine biogenic source of atmospheric ice nucleating particles, *Nature*, 525, 234-238, doi:10.1038/nature14986

Young, G., Jones, H. M., Darbyshire, E., Baustian, K. J., McQuaid, J. B., Bower, K. N., Connolly, P. J., Gallagher, M. W., Choularton, T. W. (2015): Exploring the variability of aerosol particle composition in the Arctic: a study from the springtime ACCACIA campaign, *Atmos. Chem. Phys. Discuss*., 15, 29403-29453, 2015, doi: 10.5194/acpd-15-29403-2015

Arctic Predictability and Prediction on Seasonal to Inter-annual Timescales (APPOSITE). PI - Dr Ed Hawkins, NCAS, University of Reading, with Co-investigators from University of Reading and University of Exeter:

Day, J. J, Hawkins, E., Tietsche, S. (2014): Will Arctic sea ice thickness initialization improve seasonal forecast skill? *Geophysical Research Letters,* Vol 41, Issue 21, Pages 7566-7575. doi: 10.1002/2014GL061694

Day, J. J, Tietsche, S., & Hawkins, E. (2014): Pan-Arctic and regional sea ice predictability: initialisation month dependence *Journal of Climate*, 27, 4371, doi: 10.1175/JCLI-D-13-00614.1.

Hawkins, E., Titesche, S., Day, J., Melia, N., Haines, K., Keeley, S., (2015): Aspects of designing and evaluating seasonal-to-interannual Arctic sea-ice prediction systems. *Quarterly Journal of the Royal Meteorology Society*, DOI:10.1002/qj.2643

Guemas, V., Blanchard-Wrigglesworth, E., Chevallier, M., Day, J. J., Deque, M., Doblas-Reyes, F. J., et al., Fučkar N. S., Germe, A., Hawkins, E., Keeley, S., Koenigk, T., Salas y Melia, D., Tietsche, S. (2016): A review of Arctic sea ice predictability and prediction on seasonal-to-decadal timescales. *Quarterly Journal of the Royal Meteorology Society*, doi: 10.1002/qj.2401

Swart, N. C., Fyfe, J. C., Hawkins, E., Kay, J. E., Jahn, A. (2015): Influence of internal variability on Arctic sea-ice trends *Nature Climate Change* 5, 86-89 (2015) doi: 10.1038/nclimate2483

Tietsche, S., Day, J. J., Guemas, V., Hurlin, W. J., Keeley, S. P. E., Matel, D., Msadek, R., Collins, M., Hawkins, E. (2014): Seasonal to interannual Arctic sea ice predictability in current global climate models. *Geophysical Research Letters*, Vol. 41. Issue 3, pages 1035-1043. doi: 10.1002/2013GL058755

Landslide-Tsunami. PI – Prof. Peter Talling, Durham University, with Co-investigators from National Oceanography Centre, British Geological Survey, University of Aberdeen, University of Manchester, University of Dundee, University of Southampton, University of Cambridge, University of Ulster and Imperial College London:

Allin, J.R., Mozzato, A., Tappin, D., Talling, P.J., Hunt, J.E.. (2015). Were the Trænadjupet and Nyk Slides multi-staged? EGU General Assembly Conference Abstracts 18, 2144

Allin, J.R., Hunt, J. E., Talling, P. J., Clare, M. A., Pope, E., Masson, D. G. (2016). Different frequencies and triggers of canyon filling and flushing events in Nazaré Canyon, offshore Portugal. *Marine Geology* 371(1), 89-105

Clare, M.J., Talling, P.J., Hunt, J.E. (2015). Implications of reduced turbidity current and landslide activity for the Initial Eocene Thermal Maximum – evidence from two distal, deep-water sites. *Earth and Planetary Science Letters* 420 (2015) 102–115

Mouradian, S., Collins, G.S., Piggott, M.D., Avjdis, A., Smith, R.C., Hill, J., Talling, P.J., Hunt, J.E. (2016). Investigating the risk of landslide generated tsunami to the UK: A modelling approach. *Geophysical Research Abstracts* Vol. 18, EGU2016-PREVIEW, 2016

Pope E.L., Talling, P. J., Urlaub, M., Hunt, J. E., Clare, M. A., Challenor, P. (2015). Are large submarine landslides temporally random or do uncertainties in available age constraints make it impossible to tell? *Marine Geology* 369, 19-33

Talling, P.J. (2013) Waves on the Horizon – interview with Peter Talling. *Nature Climate Change* 3, 179 (2013) doi:10.1038/nclimate1815

Talling, P.J., .Clare, M.A., Urlaub, M., Pope, E., Hunt, J.E., and Hunt, S.F.L.. (2014): Large submarine landslides on continental slopes: Geohazards, methane release, and climate change. *Oceanography* 27(2):32-45, http://dx.doi.org/10.5670/oceanog.2014.38.

Urlaub, M., Talling, P.J., Zervos, A., Masson, D. (2015): What causes large submarine landslides on low gradient (<2°) continental slopes with slow (~0.15 m/kyr) sediment accumulation?, *J. Geophys. Res. Solid Earth*, 120, 6722–6739, doi:10.1002/2015JB012347.

Methane and other greenhouse gases in the Arctic: Measurements Process Studies and Modelling (MAMM). PI - Prof. John Pyle, University of Cambridge with Co-investigators from Royal Holloway University of London, University of Manchester, Centre for Ecology and Hydrology and University of East Anglia:

Allen, G., Illingworth, S. M., O'Shea, S. J., Newman, S., Vance, A., Bauguitte, S. J.-B., Marenco, F., Kent, J., Bower, K., Gallagher, M. W., Muller, J., Percival, C. J., Harlow, C., Lee, J., and Taylor, J. P. (2014): Atmospheric composition and thermodynamic retrievals from the ARIES airborne TIR-FTS system ¬ Part 2: validation and results from aircraft campaigns. *Atmospheric Measurement Techniques*. 2014 December; 7:4401-4416. eScholarID:222346. <http://www.manchester.ac.uk/escholar/uk-ac-man-scw:222346> | DOI:10.5194/amt-7-4401-2014

France, J. L., Cain, M., Fisher, R. E., Lowry, D., Allen, G., O'Shea, S. J., Illingworth, S., Pyle, J., Warwick, N., Jones, B. T., Gallagher, M. W., Bower, K., Le Breton, M., Percival, C., Welpott, A., Muller, J., Bauguitte, S. J.-B., George, C., Hayman, G. D., Manning, A. J., Myhre, C. L., Lanoisellé, M., andNisbet, E. G. (submitted 2016): Identifying Sources of Long-Distance Transported Methane to the Arctic using δ13C in CH_4 and Particle Dispersion Modelling.

Myhre, C. L., et al. (2016): Extensive release of methane from Arctic seabed west of Svalbard during summer 2014 does not influence the atmosphere, *Geophys. Res. Lett.*, 43, 4624–4631, doi:10.1002/2016GL068999

O'Shea, S. J., Bauguitte, S. J-B., Gallagher, M. W., Lowry D., Percival, C. J. (2013). Development of a cavity-enhanced absorption spectrometer for airborne measurements of CH_4 and CO_2. *Atmospheric Measurement Techniques* 6(5):1095¬1109, 2013. DOI <http://dx.doi.org/10.5194/amt-6-1095-2013>

O'Shea, S. J., Allen, G., Gallagher, M. W., Bower, K., Illingworth, S. M., Muller, J. B. A., Jones, B. T., Percival, C. J., Bauguitte, S. J-B., Cain, M., Warwick, N., Quiquet, A., Skiba, U., Drewer, J., Dinsmore, K., Nisbet, E. G., Lowry, D., Fisher, R. E., France, J. L., Aurela, M., Lohila, A., Hayman, G., George, C., Clark, D. B., Manning, A. J., Friend, A. D., and Pyle, J. (2014) Methane and carbon dioxide fluxes and their regional scalability for the European Arctic wetlands during the MAMM project in summer 2012. *Atmos. Chem. Phys*., 14, 13159-13174, doi:10.5194/acp-14-13159-2014, 2014.

Warwick, N.J., Cain, M., Fisher, R., France, J.L., Lowry, D., Michel, S.E., Nisbet, E.G., Vaughn, B.H., White, J.W.C., Pyle, J.A. (2016): Using δ13C-CH_4 and δD-CH_4 to constrain Arctic methane emissions. *Atmos. Chem. Phys. Discuss*., doi:10.5194/acp-2016-408, 2016

Submarine Estimates of Arctic Turbulence Spectra (SEATS). PI - Dr John Allen, University of Portsmouth, with Co-investigators from the National Oceanography Centre:

Marcinko C.L.J., Martin A.P. and Allen J.T. (2015): Characterising Horizontal Variability and Energy Spectra in the Arctic Ocean Halocline. *Journal of Geophysical Research: Oceans*, Vol 120, Issue 1. doi: 10.1002/2014JC010381

The Environment of the Arctic: Climate, Ocean and Sea Ice (TEA-COSI). PI – Prof. Sheldon Bacon, National Oceanography Centre, with Co-investigators from University of Reading, University College London, University of Southampton, Scottish Association For Marine Science, British Antarctic Survey, University of Oxford and Bangor University:

Rippeth, T. P., Lincoln, B. J., Lenn, Y-D, Green, J. A., Sundfjord, A., Bacon, S. (2015): Tide-mediated warming of Arctic halocline by Atlantic heat fluxes over rough topography. *Nature Geoscience 8*, doi: 10.1038/ngeo2350

Carbon Cycle Linkages to Permafrost Systems (CYCLOPS). PI – Prof. Mathew Williams, University of Edinburgh with Co-investigators from University of Exeter, University of Sheffield and University of Sussex:

Williams, M., Rastetter, E. B., van der Pol, L., Shaver G. R. (2014). Arctic canopy photosynthetic efficiency enhanced under diffuse light, linked to a reduction in the fraction of the canopy in deep shade. *New Phytologist*: 202, 1267-1276.

Shaver, G.R, Rastetter E. B., Salmon, V., Street, L. E., van de Weg, M. J., van Wijk, M. T., Williams M.

(2013): Pan Arctic Modeling of Net Ecosystem Exchange of CO_2. *Phil. Tran. Royal Soc. B*. 368: 1624

Arctic Research Programme Publications (as at August 2016) Alphabetical

Allan, J. D., Williams, P. I., Najera, J., Whitehead, J. D., Flynn, M. J., Taylor, J. W., Liu, D., Darbyshire, E., Carpenter, L. J., Chance, R., and McFiggans, G. (2015) Iodine observed in new particle formation events in the Arctic atmosphere during ACCACIA *Atmos. Chem. Phys.*, 15, 5599-5609, 2015 doi: 10.5194/acp-15-5599-2015.

Allen, G., Illingworth, S. M., O'Shea, S. J., Newman, S., Vance, A., Bauguitte, S. J.-B., Marenco, F., Kent, J., Bower, K., Gallagher, M. W., Muller, J., Percival, C. J., Harlow, C., Lee, J., and Taylor, J. P. (2014). Atmospheric composition and thermodynamic retrievals from the ARIES airborne TIR-FTS system ¬ Part 2: validation and results from aircraft campaigns. *Atmospheric Measurement Techniques*. 2014 December; 7:4401-4416. DOI:10.5194/amt-7-4401-2014

Allin, J.R., Mozzato, A., Tappin, D., Talling, P.J., Hunt, J.E.. (2015). Were the Trænadjupet and Nyk Slides multi-staged? *EGU General Assembly Conference Abstracts* 18, 2144

Allin, J.R., Hunt, J. E., Talling, P. J., Clare, M. A., Pope, E., Masson, D. G. (2016). Different frequencies and triggers of canyon filling and flushing events in Nazaré Canyon, offshore Portugal. *Marine Geology* 371(1), 89-105

Browse, J., Carslaw, K. S., Mann, G. W., Birch, C. E., Arnold, S. R., and Leck, C. (2014) The complex response of Arctic aerosol to sea-ice retreat *Atmos. Chem. Phys*., 14, 7543-7557, doi:10.5194/acp-14-7543-2014

Browse, J., Carslaw, K.S., Schmidt, A., Corbett, J.J. (2013) Impact of future Arctic shipping on high-latitude black carbon deposition *Geophys. Res. Lett*., 40(16), doi: 10.1002/grl.50876 http://onlinelibrary.wiley.com/doi/10.1002/grl.50876/

Chance, R., Carpenter, L., Brooks, I., Wilson, T., Allan, J., and Kirchgaessner, A. (2014) Aerosol, clouds and climate. *Ocean Challenge*, Vol.20, Summer 2014

Clare, M.J., Talling, P.J., Hunt, J.E. (2015). Implications of reduced turbidity current and landslide activity for the Initial Eocene Thermal Maximum – evidence from two distal, deep-water sites. *Earth and Planetary Science Letters* 420 (2015) 102–115

Day, J. J, Hawkins, E., Tietsche, S. (2014) Will Arctic sea ice thickness initialization improve seasonal forecast skill? *Geophysical Research Letters*, Vol 41, Issue 21, Pages 7566-7575. doi: 10.1002/2014GL061694

Day, J. J, Tietsche, S., & Hawkins, E. (2014) Pan-Arctic and regional sea ice predictability: initialisation month dependence *Journal of Climate*, 27, 4371, doi: 10.1175/JCLI-D-13-00614.1

Elvidge, A. D., Renfrew, I. A., Weiss, A. I., Brooks, I. M., Lachlan-Cope, T. A., King, J. C.((2015): Observations of surface momentum exchange over the marginal-ice-zone and recommendations for its parameterization. *Atmos. Chem. Phys.*, 16, 1545-1563, 2016. doi:10.5194/acp-16-1545-201

France, J. L., Cain, M., Fisher, R. E., Lowry, D., Allen, G., O'Shea, S. J., Illingworth, S., Pyle, J., Warwick, N., Jones, B. T., Gallagher, M. W., Bower, K., Le Breton, M., Percival, C., Welpott, A., Muller, J., Bauguitte, S. J.-B., George, C., Hayman, G. D., Manning, A. J., Myhre, C. L., Lanoisellé, M., andNisbet, E. G.. (submitted 2016). Identifying Sources of Long-Distance Transported Methane to the Arctic using δ13C in CH_4 and Particle Dispersion Modelling.

Guemas, V., Blanchard-Wrigglesworth, E., Chevallier, M., Day, J. J., Deque, M., Doblas-Reyes, F. J., et al., Fučkar N. S., Germe, A., Hawkins, E.,Keeley, S., Koenigk, T., Salas y Melia, D., Tietsche, S. A review of Arctic sea ice predictability and prediction on seasonal-to-decadal timescales *Quarterly Journal of the Royal Meteorology Society*, doi: 10.1002/qj.2401

Hawkins, E, Titesche, S., Day, J., Melia, N., Haines, K., Keeley, S. (2015) Aspects of designing and evaluating seasonal-to-interannual Arctic sea-ice prediction systems. *Quarterly Journal of the Royal Meteorology Society*, DOI:10.1002/qj.2643

Liu, D., Quennehen, B., Darbyshire, E., Allan, J. D., Williams, P. I., Taylor, J. W., Bauguitte, S. J-B., Flynn, M. J., Lowe, D., Gallagher, M. W., Bower, K. N., Choularton, T. W., Coe, H. (2015): The importance of Asia as a source of black carbon to the European Arctic during springtime 2013, *Atmos. Chem. Phys*, 15, 11537-11555, doi:10.5194/acp-15-11537-2015.

Lloyd, G., Choularton, T. W., Bower, K. N., Crosier, J., Jones, H., Dorsey, J. R., Gallagher, M. W., Connolly, P., Kirchgaessner, A. C. R., and Lachlan-Cope, T. (2015) Observations and comparisons of cloud microphysical properties in spring and summertime Arctic stratocumulus clouds during the ACCACIA campaign, *Atmos. Chem. Phys.*, 15, 3719-3737, doi:10.5194/acp-15-3719-2015.

Marcinko C.L.J., Martin A.P. and Allen J.T. (2015) Characterising Horizontal Variability and Energy Spectra in the Arctic Ocean Halocline. *Journal of Geophysical Research: Oceans*, Vol 120, Issue 1. Doi: 10.1002/2014JC010381

Mouradian, S., Collins, G.S., Piggott, M.D., Avjdis, A., Smith, R.C., Hill, J., Talling, P.J., Hunt, J.E. (2016). Investigating the risk of landslide generated tsunami to the UK: A modelling approach. *Geophysical Research Abstracts* Vol. 18, EGU2016-PREVIEW, 2016

Myhre, C. L., et al. (2016): Extensive release of methane from Arctic seabed west of Svalbard during summer 2014 does not influence the atmosphere, *Geophys. Res. Lett.*, 43, 4624–4631, doi:10.1002/2016GL068999

O'Shea, S. J., Bauguitte, S. J-B., Gallagher, M. W., Lowry D., Percival, C. J., (2013). Development of a cavity-enhanced absorption spectrometer for airborne measurements of CH_4 and CO_2. *Atmospheric Measurement Techniques* 6(5):1095¬1109, 2013. doi <http://dx.doi.org/10.5194/amt-6-1095-2013>

O'Shea, S. J., Allen, G., Gallagher, M. W., Bower, K., Illingworth, S. M., Muller, J. B. A., Jones, B. T., Percival, C. J., Bauguitte, S. J-B., Cain, M., Warwick, N., Quiquet, A., Skiba, U., Drewer, J., Dinsmore, K., Nisbet, E. G., Lowry, D., Fisher, R. E., France, J. L., Aurela, M., Lohila, A., Hayman, G., George, C., Clark, D. B., Manning, A. J., Friend, A. D., and Pyle, J. (2014). Methane and carbon dioxide fluxes and their regional scalability for the European Arctic wetlands during the MAMM project in summer 2012. *Atmos. Chem. Phys.*, 14, 13159-13174, doi:10.5194/acp-14-13159-2014, 2014.

Pope E.L., Talling, P. J., Urlaub, M., Hunt, J. E., Clare, M. A., Challenor, P. (2015). Are large submarine landslides temporally random or do uncertainties in available age constraints make it impossible to tell? *Marine Geology* 369, 19-33

Rippeth, T. P., Lincoln, B. J., Lenn, Y-D, Green, J. A., Sundfjord, A., Bacon, S. (2015): Tide-mediated warming of Arctic halocline by Atlantic heat fluxes over rough topography. *Nature Geoscience 8*, doi: 10.1038/ngeo2350

Shaver, G.R, Rastetter E. B., Salmon, V., Street, L. E., van de Weg, M. J., van Wijk, M. T., Williams M. (2013). Pan-Arctic Modeling of Net Ecosystem Exchange of CO_2. *Phil. Tran. Royal Soc. B*. 368: 1624

Swart, N. C., Fyfe, J. C., Hawkins, E., Kay, J. E., Jahn, A. (2015) Influence of internal variability on Arctic sea-ice trends *Nature Climate Change* 5, 86-89 (2015) doi: 10.1038/nclimate2483

Talling, P.J. 2013 Waves on the Horizon – interview with Peter Talling. *Nature Climate Change* 3, 179 (2013) doi:10.1038/nclimate1815

Talling, P.J., .Clare, M.A., Urlaub, M., Pope, E., Hunt, J.E., and Hunt, S.F.L.(2014) Large submarine landslides on continental slopes: Geohazards, methane release, and climate change. *Oceanography* 27(2):32-45, http://dx.doi.org/10.5670/oceanog.2014.38.

Tietsche, S., Day, J. J., Guemas, V., Hurlin, W. J., Keeley, S. P. E., Matel, D., Msadek, R., Collins, M., Hawkins, E. (2014) Seasonal to interannual Arctic sea ice predictability in current global climate modules. *Geophysical Research Letters*, Vol. 41. Issue 3, pages 1035-1043. doi: 10.1002/2013GL058755

Urlaub, M., Talling, P.J., Zervos, A., Masson, D. (2015), What causes large submarine landslides on low gradient (<2°) continental slopes with slow (~0.15 m/kyr) sediment accumulation?, *J. Geophys. Res. Solid Earth*, 120, 6722–6739, doi:10.1002/2015JB012347.

Vihma, T., Pirazzini, R., Fer, I., Renfrew, I. A., Sedlar, J., Tjernström, M., Lüpkes, C., Nygård, T., Notz, D., Weiss, J., Marsan, D., Cheng, B., Birnbaum, G., Gerland, S., Chechin, D., Gascard, J. C. (2014): Advances in understanding and parameterization of small-scale physical processes in the marine Arctic climate system: a review, *Atmos. Chem. Phys.*, 14, 9403-9450, doi:10.5194/acp-14-9403-2014

Warwick, N.J., Cain, M.L., Fisher, R., France, J.L., Lowry, D., Michel, S.E., Nisbet, E.G., Vaughn, B.H., White, J.W.C., Pyle, J.A. (2016): Using δ13C-CH_4 and δD-CH_4 to constrain Arctic methane emissions. *Atmos. Chem. Phys. Discuss.,* doi:10.5194/acp-2016-408, 2016

Williams, M., Rastetter, E. B., van der Pol, L., Shaver G. R. (2014). Arctic canopy photosynthetic efficiency enhanced under diffuse light, linked to a reduction in the fraction of the canopy in deep shade. *New Phytologist:* 202, 1267-1276.

Wilson, T. W., Ladino, L. A., Alpert, P. A., Breckels, M. N., Brooks, I. M., Browse, J., Burrows, S. M., Carslaw, K. S., Huffman, J. A., Judd, C., Kilthau, W. P., Mason, R. H., McFiggans, G., Miller, L. A., Najera, J., Polishchuk, E., Rae, S., Schiller, C.L., SI, M., Vergara Temprado, J., Whale, T. F., Wong, J. P. S., Wurl, O., Yakobi-Hancock, J. D., Abbatt, J. P. D., Aller, J. Y., Bertram, A. K., Knopf, D. A., Murray, B. J. (2015): A marine biogenic source of atmospheric ice nucleating particles, *Nature*, 525, 234-238, doi:10.1038/nature14986

Young, G., Jones, H. M., Darbyshire, E., Baustian, K. J., McQuaid, J. B., Bower, K. N., Connolly, P. J., Gallagher, M. W., Choularton, T. W. (2015): Exploring the variability of aerosol particle composition in the Arctic: a study from the springtime ACCACIA campaign, *Atmos. Chem. Phys. Discuss.*, 15, 29403-29453, 2015, doi: 10.5194/acpd-15-29403-2015

Climate Change and the Arctic Region

The Arctic is a region of higher than average climate change and is predicted by the Intergovernmental Panel on Climate Change assessment Report 4 (IPCC AR4) to remain so. The most iconic evidence of this rapid climate change is the loss of summer sea ice, with recent loss rates exceeding most model projections for reasons that remain unclear. The sea ice loss and degradation of permafrost represent potential tipping points in the Earth System, leading to major physical and biogeochemical feedbacks with global impacts. These changes might also lead to destabilization of gas hydrates, causing major methane release and potentially marine landslides and tsunamis which could impact the Arctic, N.E. Atlantic and the UK. There is an urgent need to advance understanding of the processes that are controlling Arctic climate change, particularly over months to decades and how they reflect both natural variability and the response to anthropogenic radiative forcing. Anthropogenic radiative forcing is the difference between sunlight energy absorbed at the Earth's surface and the energy radiated back to space; it arises from increased levels of greenhouse gases in the atmosphere and from changes in other radiatively active constituents, such as anthropogenic aerosols and ozone. The relative importance of these different contributions, particularly for forcing regional scale climate change, is poorly understood. The response of the Arctic to changing radiative forcing involves changes in the atmosphere, ocean, cryosphere, land surface and biosphere. There is a need to understand the role of specific processes within each of these components and, very importantly, the interactions between them.

What is the NERC Arctic Research Programme?

Because of the importance of understanding the Arctic region and its interactions with the global Earth System, the UK Natural Environment Research Council has invested £15m (2010-2016) in the Arctic Research Programme; its four key objectives were formulated into questions, which formed the drivers for a series of research projects:

1. What is causing the rapid changes in the Arctic at the moment?
2. What are the processes influencing the release of greenhouse gases, such as methane and carbon dioxide, and how much of these gases could enter the atmosphere in future?
3. How can we improve our predictions of what will happen to the climate of the Arctic and the amounts of greenhouse gases released into the future?
4. Are the risks of natural hazards in the Arctic region increasing as a result of regional warming and what are the threats to the UK?

Publication of research results in the peer reviewed scientific literature is a key output for the NERC Arctic Research Programme. This listing is complete to the beginning of August 2016. Inevitably other publications will appear as observations and measurements are collated and analysed, and results are written up and submitted to scientific journals, as is the nature of science. The aim is to maintain an evolving listing on the NERC ARP website, where other materials including blogs, popular articles and press reports are also to be found. The ARP participants encourage you to visit the website periodically.

The NERC ARP was funded by the Natural Environment Research Council and managed by the British Antarctic Survey and is linked to the NERC Arctic Office.

Compiled by Kelvin Boot from materials supplied by and interviews with NERC ARP scientists.

www.arp.arctic.ac.uk