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Assessment of Possibility and Impact of Rapid Climate Change in the Arctic

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Assessment of Possibility and Impact of Rapid Climate Change in the Arctic

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Executive Summary

Sea ice decline is iconic of climate change in the Arctic. Sea ice reductions represent the integrated changes which are taking place in both the ocean and atmosphere. Arctic surface temperature is also warming. The presence of sea ice determines the accessibility of the Arctic Ocean and its presence can also affect European and global climate.

Arctic sea ice extent has declined at an annual rate of over 4% per decade since satellite records began in 1979. This rate is faster in the summer season and there is evidence that the rate of loss has increased over the latter half of the satellite period. There is also evidence that the ice has thinned at a rate of approximately 60cm per decade. However, the heating required to melt the ice at this rate is very small - just 1 W/m^2 representing only 2% of the magnitude of the seasonal cycle, implying that observing and modelling the mechanisms underlying these changes will be challenging.

The record lowest ice extent was observed in September 2007. However, in any particular summer, the sea ice extent can be influenced by the state of the sea ice at the end of the previous winter, the heat content of the Arctic Ocean and the synoptic weather conditions.

Individual climate models are capable of capturing the observed decline in sea ice extent, although as a group they tend to predict a slower decline than observed. Models do not generally show ice loss at the current rate until later in the 21st century and the modelled spatial pattern of the decline in ice extent is not the same as observed. In different models there are a variety of mechanisms that can cause long term change such as winter warming, clouds and summer processes such as meltponds; currently available observations cannot fully determine the contributions of such processes in the real world.

Climate models simulate low ice events (such as occurred in 2007) in simulations with prescribed historical climate forcing factors. However, low ice events of similar magnitude are unusual in the models occurring only once in every 100 years. The modelled mechanisms for these events are plausible but they may not be the same as in specific observed events such as 2007.

Climate models submitted to the CMIP5 intercomparison project show a range of dates for a seasonally ice free Arctic from 2030 to 2080 and a local rate of increase in surface temperature from 0.9 to 1.5ºC per decade. Uncertainty is due to both internal and structural (inter-model) variability while scenario uncertainty is only important later in the century. In particular, in HadGEM2-ES we find that all Representative Concentration Pathways scenarios show a similar rate of commitment to ice loss until 2030 and only the aggressive mitigation scenario RCP2.6 results in a sustainable September sea ice cover. However, this level of commitment to sea ice loss varies across the CMIP5 ensemble.

There are plausible mechanisms which could lead to more rapid changes in the Arctic including mixing of heat from the subsurface ocean. However, further observations are required to establish if any of these mechanisms are occurring. Claims of a seasonally ice-free Arctic by 2013, based on extrapolating model output, have to be viewed with scepticism. Climate models do not predict that rapid changes will occur in the near horizon but they are capable of producing periods of rapid decline in ice extent, as well as slowdowns in ice loss. While it is possible to identify processes that are not well-represented in climate models, such models remain our best tool for predicting the likelihood of rapid change in the Arctic, and some models are able to capture aspects of changes that have been observed. However, an ongoing assessment of the likelihood of rapid change is required, taking account of the constantly developing evidence from observations, and the continuous improvement in models.

Changes in Arctic sea ice are likely to have impacts locally in the Arctic with economic implications related to shipping and mineral exploration as well as driving changes in European and global climate. Changes in European climate may occur due to high pressure over the Arctic driving easterly winds across Europe, particularly in winter. Forcing from the Arctic could affect the magnitude of the thermohaline circulation leading to changes in global climate.

Further work is required to i) better observe the Arctic, ii) further develop our understanding of model processes and iii) to better represent Arctic processes in climate models. As models improve, we can better develop our operational attribution capability for year-to-year changes in the Arctic.

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1. Introduction

The most dramatic indicator of Arctic climate in recent years has been the summer extent of Arctic sea ice, observed from space. The extent of Arctic sea ice has been declining since satellite records began thirty years ago (IPCC, 2007) and has been shown to be attributable to human influence (Gregory et al., 2002). Climate models project that the Arctic will become ice-free during summer at some point this century (IPCC, 2007). However, in September 2007, sea ice extent reached a dramatic all-time record low. This has raised the question of whether the sea ice is likely to melt more quickly than has been projected by climate models (Stroeve et al., 2007).

While sea ice attracts a lot of high profile interest from the media, it is important to recognise that sea ice is in many ways the 'barometer' for changes which are occurring in the atmosphere and the ocean. The atmosphere and the ocean provide fluxes at the top and bottom interfaces of the sea ice. It is therefore important to understand not just the sea ice in the Arctic but rather to take a holistic view of the entire Arctic climate system.

Sea ice is important because it is more than just a sensitive indicator of climate change. As we will discuss in the report, sea ice changes have potential implications for the Arctic region and beyond. With the low summer ice extents during 2007 and subsequent years, there have been several instances of shipping routes opening up through the Arctic in summer (Stephenson et al., 2011) which has economic implications as well as possible political implications due to the presence of mineral resources in the Arctic (Young, 2011).

Low sea ice extents may also be one of the factors leading to wet summers and cold winters over Northern Europe. The global thermohaline circulation is also linked to the Arctic and therefore changes in the ocean circulation in the Arctic may have implications for global climate.

In this paper, we review observations and climate model results to assess the possibility of rapid change in the Arctic. By rapid change we mean whether the Arctic is likely to be seasonally ice free within the next twenty years (i.e., earlier than any physically based climate models currently project). We also assess the likely impact of rapid changes in the Arctic locally, globally and more specifically on European climate. There are undoubtedly many topics that this paper does not cover and these along with priorities for future work will be discussed briefly in the final section.

2. Review of Observations

2.1 Sea ice area and extent changes

The Arctic sea ice cover has been declining for a number of years (Figure 2.1.1), and the downward trend in both summer and winter ice extent is now well established as being statistically significant (Meier et al, 2007). The annual ice extent has declined at a rate of 0.53 x 10^6 km^2 per decade (Figure 2.1.1), or -

4.3% per decade compared to the 1979-2000 annual mean ice extent. The fastest rate of decline occurs in September, the month of seasonal minimum extent, when the ice cover has declined at a rate of 0.81 x 10^6 km^2 per decade, or 11.7% per decade compared to the 1979-2000 mean September ice extent. There is mounting evidence that the rate of decline of September ice extent has increased in the more recent part of the observed period. (Comiso et al, 2008). For example the mean rate of decline from 1980 to 1995 was 0.58 x 10^6 km^2 per decade, compared to 1.75 x 10^6 km^2 per decade between 1996 and 2011.

The **lowest recorded extent occurred in September 2007** when the coverage reduced to 4.28 x 10^6 km^2, some 1.7 x 10^6 km^2 lower than the previous September. The September ice extent was again relatively low in 2008, and despite some recovery in 2009, the last 5 years have seen the 5 lowest ice extents recorded during the satellite era.

The decline in September ice concentration from 1979-2011 has been strongly focussed on the Pacific side of the Arctic (figure 2.1.2), with the area of fastest loss (over 3%/year) between about 170-200ºE, in the East Siberian and Chukchi seas (figure 2.1.3). This area showed large ice loss in 2007 but this pattern of loss is independent even of the last five years. Slower, but still substantial, rates of decline are observed north of Siberia in the Laptev and Kara seas. By contrast, September concentration north of 84ºN and near the Archipelago has not yet decreased substantially. In a very small area on the west of Fram Strait, September concentration has actually increased.

2.2 Sea ice thickness and volume changes

Unlike ice extent, where near continuous observations have been available since the 1970's, mapping ice thickness has proved a more difficult challenge. The first wide area estimates of sea ice thickness change were obtained from measurements of ice draft from US Navy submarines. Analysis of data between the 1960's and 1990's revealed a 40% decrease in ice draft[1], although the data covered only the central part of the Arctic (Rothrock et al., 1999). A later comparison of submarine transects between 2004 and 2007 revealed no change on the mean ice draft but a decrease in the modal thickness (Wadhams et al., 2011).

Arctic wide estimates of ice thickness became available from 1993 from the ERS satellite radar altimeter measurements of freeboard[2] and revealed a high year-year variability of average Arctic winter ice thickness, primarily controlled by the length of the summer melt season (Laxon et al., 2003). Although the eight year time-series revealed a downward trend over the period, the time interval is too short to be considered significant. A later time-series of data from the Envisat radar altimeter revealed a near-constant ice thickness between 2002-7 but a substantial drop in circumpolar thickness following the 2007 ice extent minimum

[1] Ice draft refers to the depth of ice below the sea surface and accounts for approximately 90% of the total ice thickness
[2] Ice freeboard refers to the depth of ice above the sea surface and accounts for approximately 10% of the total ice thickness.

(Giles et al., 2008). This change was later confirmed by data from the IceSat satellite laser altimeter which in addition showed a decrease in ice volume between 2002-8 (Kwok et al., 2009). There is evidence therefore of a decreasing ice thickness from each satellite time-series but there is still a need to build a consistent long term series through cross-calibration of the satellite sensors. Data from the CryoSat-2 satellite is now becoming available and should provide the capability to monitor changes in autumn and winter ice thickness over almost the entire Arctic.

A combination of IceSat and submarine data was also used to estimate a decrease of mean ice thickness in the central Arctic from 3.64m to 1.89m over the period 1980 to 2008 (Kwok and Rothrock, 2009) which gives an approximate average rate of thinning of **60cm per decade**. Serreze et al. (2007) estimate that an additional annual heat flux of **1 W/m^2** would be sufficient to melt 10cm of ice at its melting point which demonstrates that the ice thickness is very sensitive to small changes in the heat flux at either the surface or the base of the ice.

Another way to estimate recent changes in ice thickness is through reanalyses (models constrained by observations). There is currently one published reanalysis of Arctic ice volume based on the Pan-Arctic Ice-Ocean Modeling and Assimilation System (PIOMAS) (Schweiger et al., 2011). PIOMAS has been developed at the Polar Science Center at the University of Washington and is based on a state of the art sea ice model (comparable in complexity to HadGEM1; McLaren et al., 2006) coupled to the POP ocean model with a high resolution Arctic model (~22km) which is nested within a global model. The ocean-ice model is forced by NCEP/NCAR reanalysis and assimilates ice concentration and Sea Surface Temperature. The modelling system is similar in many ways to the Met Office GloSea4 system (Arribas et al., 2011) based on the HadGEM3 model (Hewitt et al., 2011).

It is important to note that the use of prescribed atmospheric forcing to create reanalyses such as PIOMAS has its own issues in terms of physical plausibility. In particular, the effect of clouds on the radiation budget is likely to be a major source of uncertainty. The disadvantage of ice-ocean models that are forced by reanalysis data is that they do not fully capture the interactive nature of the coupling between the ice/ocean and atmosphere and assume that this coupling is appropriately represented in the reanalysis.

PIOMAS has been compared with ICESat observations (Kwok and Rothrock, 2009) from 2003-2007 and shown good agreement in both October/November and February/March (Schweiger et al., 2011) which demonstrates that PIOMAS has considerable skill when simulating the historical timeseries of ice volume. Schweiger et al. (2011) estimate that sea ice is thinning at a rate of 25/39 cm/decade for March/October and ice volume is declining at a rate of $2.8 \pm 1.0 \times 10^3$ km^3/decade.

2.3 Ocean changes

Although sea surface height (SSH) is measured by radar altimeters over the world ocean, different processing techniques must be used over ice. These techniques are relatively recent and the following paragraph summarises the current contributions from remote sensing to our understanding of changes to the Arctic Ocean.

The European Space Agency (ESA) satellite, ERS-2, provided the first map of Arctic SSH variability (Peacock and Laxon, 2004) and the NASA ICESat laser altimeter provided the Arctic dynamic topography (which provides information on surface currents) for February/March, 2004-2008 (Kwok and Morison, 2011). An estimate of the Arctic Ocean mean dynamic topography has also been calculated by combining ICESat and Envisat altimetry data with GRACE and GOCE gravity data (Farrell et al., 2012).

Data from the ICESat satellite has more recently implied that between 2005 and 2008, atmospheric circulation patterns, associated with a positive Arctic Oscillation (AO), have diverted river runoff from the eastern side of the Arctic to the western Arctic, resulting in an accumulation of freshwater in the western Arctic. However the total fresh water storage in the Arctic Ocean has remained constant over this 4 year period (Morison et al., 2012). Over a longer time frame (1995 to 2010), data from the ESA satellites ERS-2 and Envisat, have shown an accumulation of ~8000 km^3 of freshwater in the western Arctic (between 2002 and 2010) associated with a strengthening anti-cyclonic (clockwise) wind (Giles et al., 2012). These data also indicate that other forces aside from the wind are playing a role in the storage and distribution of freshwater in the Arctic and the authors speculate that changes to the sea ice cover are enhancing the effect of the wind on the ocean (Giles et al., 2012).

Inferences of changes in the Arctic Ocean derived from *in situ* measurements are rather different in character due to the sparseness of such measurements. Multi-decadal changes in wide-area temperature and salinity have generally been obtained by aggregating data into long time periods. This approach has been used to provide another view of changes in freshwater storage, whether by comparing International Polar Year (IPY: 2007-8) data with climatology (McPhee et al., 2009) or with the 1990s (Rabe et al., 2011). Aspects of long-term interior Arctic Ocean temperature and salinity variability have also been revealed. Steele and Boyd (1998) first exposed the retreat of the cold halocline layer from the Amundsen Basin back into the Makarov Basin; and Polyakov et al. (2004, 2008) look at changes in Arctic Ocean temperature and salinity over a century. The use of moored installations around the Arctic Ocean boundary has enabled the identification and tracking of substantial property anomalies as they enter the Arctic and progress around the boundary (Polyakov et al., 2011) during a particular decade (the “noughties”) when sufficient measurements were available.

2.4 Synoptic forcing changes

Sea-ice cover reduces the sensible and latent heat fluxes to the cold atmosphere from a relatively warm ocean. Thus, it alters significantly the longwave radiation budget (Walsh and Johnson, 1979). Changes in sea-ice concentration can affect the atmospheric circulation through changes in surface fluxes of heat, momentum and moisture (Deser et al., 2000). The atmospheric circulation can be sensitive to the heat fluxes associated with changes in the sea-ice cover, as for example, in the stormy region east of Greenland. The heat fluxes associated with sea-ice changes can be an order of magnitude higher than mid-latitude sea surface fluxes. Changes in Greenland sea-ice cover induced by the large-scale circulation may feed back upon the atmosphere by changing the cyclone activity locally.

Extratropical storms impact a sea-ice region by bringing heat/moisture and fostering sea-ice melting. The sea-ice changes in turn affect the downstream development of storm tracks (Honda et al., 1999; Mesquita et al., 2010). This two-way interaction process alters local albedo and fluxes of heat and temperature, with large implications for the Northern Hemisphere (Yamamoto et al., 2006). This interaction may also affect the large-scale variability through a Rossby wave response (Alexander et al., 2004).

Since 1979 neither the ERA-40 nor the NCEP2 data sets show significant trends in any of the cyclone variables (Simmonds et al., 2008). However, over the entire record starting in 1958 the NCEP1 reanalysis exhibits a significant increase in summer cyclone frequency (due mainly to the increase in closed strong systems), as well as in their mean depth and intensity in that season.

A study using the JRA-25 atmospheric reanalysis reveals an autumn increase in cyclone-associated precipitation over the past decade (Stroeve et al., 2011). This is linked to a shift in atmospheric circulation towards more frequent and more intense cyclones in the Atlantic sector of the Arctic. Low sea ice extents result in more autumn cyclones, and associated precipitation and column water vapour. However, difficulties in establishing cause and effect, including the absence of a clear association between spatial patterns of recent precipitation changes and ice extent anomalies, leads to the conclusion that attribution of recent autumn precipitation increases to reduced ice cover is premature.

2.5 Arctic heat budget

Many authors make measurements of components of the Arctic climate system and attempt to draw conclusions about heat fluxes from their component observations, but they are hampered in their efforts to integrate their conclusions in a pan-Arctic sense through three issues: (i) reference values (reference temperature for heat flux, reference salinity for freshwater flux); (ii) synopticity (when attempting to compare with other measurements); and (iii) pan-Arctic mass balance, without which net flux calculations are meaningless. Tsubouchi et al. (2012) is the first study to generate a quasi-synoptic estimate of Arctic Ocean heat (and freshwater) flux, employing an inverse model applied to hydrographic and velocity data from the Arctic Ocean boundary for the summer of 2005.

Before Tsubouchi et al. (2012), the Arctic Ocean and sea ice heat flux was consistently estimated by Serreze et al. (2007), furthering the pioneering efforts of Nakamura and Oort (1988). Serreze et al. (2007) use atmospheric model reanalysis output with top-of-the-atmosphere (TOA) radiation measurements to produce monthly estimates of ocean surface heat flux as residuals. They find values ranging from 105 W m^{-2} (July, heat gained by ocean from atmosphere) to ca. –50 W m^{-2} (winter months, heat lost by ocean to atmosphere), which, for their ocean domain area of 9.56×10^6 km^2, equate to net surface heat fluxes of ca. 1,000 TW and –480 TW. Their annual mean (ocean domain) surface heat flux is 11 W m^{-2} from ocean to atmosphere, or 105 TW. They also describe substantial shortcomings with the method, such as non-conservative energy budgets, deficiencies in TOA radiation, and mass balance errors in atmospheric transports.

Mauritzen (1996a,b), employs a asynoptic collection of hydrographic data from the summers of 1980–1989 to estimate a net heat flux of 96 TW (±20%). This is half the size of Tsubouchi et al. (2012), who tentatively identify the reasons for the difference: in the later study, (i) the mass flux through the Barents Sea Opening (BSO) is higher, and (ii) the ocean temperatures in the BSO and the West Spitzbergen Current are higher (Holliday et al., 2008).

The Tsubouchi et al. (2012) heat flux represents a net heat loss by the ocean (including sea ice) to the atmosphere of 189 ± 37 TW, equivalent to 16.7 ± 3.3 W m^{-2}. It is hard to reconcile this result with the ocean heat flux calculations of Serreze et al. (2007, table 2). It is not close to his peak monthly summer or winter values of ca. 1,000 TW input to the ocean or 500 TW loss from the ocean (respectively). It most nearly resembles his annual mean value of 105 TW loss from the ocean.

In summary, the Arctic Ocean heat flux is not well known, although work presently being conducted within the UK NERC Arctic Research Programme will improve the state of knowledge in the next two years (2012-14).

2.6 Mechanisms determining the minimum sea ice extent

Sea ice extent can be changed not only by melting of ice (reducing the volume of ice) but also by redistribution of ice (where ice volume is conserved). Sea ice extent reaches a minimum in September and there is much to be gained from understanding the mechanisms determining the magnitude of the ice extent in September. As an example of this, we look at the causes of the record low extent in September 2007 (see figure 2.1.1.).

From observations it is hypothesised that the low ice extent in 2007 was due, in part, to unusual weather patterns (Stroeve et al, 2012). A strong pressure dipole persisted over the Arctic, with high pressure over Greenland and the western Arctic, and low pressure over Siberia and Europe. This pressure pattern favours ice retreat by bringing warm air into the Arctic and moving ice away from the Siberian coast (Stroeve et al. 2008), and across the Arctic basin towards the Fram Strait. Both the melting and advection of the ice increased the open water fraction, allowing greater solar heating of the ocean due to the reduced albedo.

It is also claimed that the weather conditions of summer 2007 would have been unlikely to lead to the extremely low ice extent if it were not for the long term thinning of the Arctic ice (Lindsay et al, 2009, Stroeve et al, 2008, Maslanik et al, 2007) . Although the ice was not especially thin at the start of the 2007 melt season in comparison to the years immediately before (Giles et al., 2008), the long term decline in ice volume due to melting and export has left a thin ice cover vulnerable to natural variability in atmospheric and oceanic conditions. Figure 2.1.1 shows that the variability in ice extent has increases since 2007 which is consistent with the theory of Notz (2009).

Another factor with the potential to influence the ice extent is the state of the Arctic ocean, in particular the surface temperature. For example, Shimada et al. (2006) relates changes in summer sea ice extent in the Beaufort sea to increases in the temperature of Pacific Surface water (PSW) in the Arctic. Comiso et al. (2008) show anomalously high surface temperatures before the start of the 2007 melt season, which can inhibit ice growth. Sea surface temperatures (SSTs) over the Arctic were much warmer than average during summer 2007. However it is not clear to what degree the high SSTs in 2007 caused the low ice extent or were a response to it.

Since 2007, while there have been years with near-record low ice cover (Figure 2.1.1), there has not been a new record set, despite an ongoing decline in multi-year ice (Maslanik et al, 2011). For example in 2008 the melt season started with thinner ice than in 2007 (Giles et al, 2008), but the atmospheric conditions were not so conducive to melt and the minimum extent was (at the time) the second lowest on record. Stroeve et al (2012) suggest that a key reason that no further record has been set so far is that the persistent atmospheric pressure dipole pattern observed during 2007 has not been repeated to the same degree.

In summary, there are **a number of mechanisms that influence the seasonal minimum ice extent**, including the synoptic conditions over the summer, the heat content of the Arctic Ocean, and the state of the sea ice at the start of the melt season. Through observational studies we can determine which factors are likely to have played a dominant role in any particular year, although it remains a challenge to quantify the impact of each factor.

3. Modelling the Arctic

3.1 Model descriptions

In this paper, we refer to a range of climate models used in CMIP3 (IPCC AR4) and CMIP5 (IPCC AR5) model intercomparison projects including results obtained by examining an ensemble of climate models to span the range of structural uncertainty (i.e., uncertainty due to model differences, although in practice, initial conditions are also important). Due to the availability of extensive data and detailed diagnostics, here we also focus on results from models developed at the Met Office Hadley Centre. HadCM3 (Gordon et al., 2000), HadGEM1 (Johns et al., 2006; McLaren et al., 2006) and HadGEM2-ES (Martin et al., 2011; Collins et al., 2011). Although not referred to extensively here, HadGEM3 (Hewitt et al., 2011) is the latest coupled atmosphere-ocean-sea ice-land model under development and is currently used in the GloSea4 system (Arribas et al., 2011) which is used for seasonal forecasting.

HadCM3, HadGEM1 and HadGEM2-ES each have control runs with preindustrial greenhouse gas forcing as well as projections of future climate change. These three models represent a progression in resolution as well as physical and Earth System processes. For HadCM3 and HadGEM1, the projections were based on the SRES scenarios (Nakićenović and Swart, 2000) while HadGEM2-ES is run using Representative Concentration Pathway (RCP) scenarios (Moss et al., 2010) which follow from the year 2005 in the historical simulation. The RCP nomenclature is such that the numerical component indicates the global mean radiative forcing at year 2100 (e.g. RCP8.5 has a radiative forcing of 8.5 W m^{-2}).

In results which follow, we will also refer to results from 1) a perturbed physics ensemble from HadCM3 where each ensemble member has a 140 year control run with preindustrial greenhouse gas forcing and a 140 year run with CO_2 concentrations increasing at 1% per year up to four times preindustrial CO_2 concentration by year 140; 2) two ensembles of HadGEM1; one with solar, volcanic and anthropogenic forcings (ALL), and the other with anthropogenic forcing only (ANT).

3.2 Evaluation of mean state and changes

Evaluation of the performance of sea ice-ocean general circulation models in the Arctic by the Arctic Ocean Model Inter-comparison Project (AOMIP) (Proshutinsky et al., 2007) has revealed many issues, such as differences in the predicted intensity and even sense of direction of the flow in the Atlantic water layer, a substantial water mass accounting for much of the heat and salt content of the Arctic Ocean. AOMIP models show variations of a factor 2 in sea ice speed and a factor 4 in sea ice vorticity (a measure of the sea ice circulation), implying a poor representation of atmosphere-to-ocean momentum transfer. They also exhibit ice speeds ~2-5 cm s^{-1} higher than observed (Martin and Gerdes, 2007). Considerable variability is seen in AOMIP simulations of ice concentration, an important moderator of momentum, mass, and energy transfer between the atmosphere, sea ice, and ocean, with differences of up to 40% compared with observations (Johnson et al, 2007).

As might be expected, fully coupled climate (atmosphere, sea ice, ocean) models tend to perform less well than the more constrained sea ice or sea ice-ocean models. Holland et al. (2007) examined the performance of IPCC-class climate models in the Arctic Ocean by analysing Arctic Ocean freshwater budgets from 10 climate models participating in CMIP3. Holland et al. (2007) diagnosed substantial problems with the present representation of the Arctic Ocean and sea ice in climate models and concluded that, in general, models had problems representing both ocean and atmosphere. **The multi model ensemble mean of the participating climate models predic ts a slow er decline in sea ice than has been observed.**

Despite the poor performance of particular climate models, we can have greater confidence in models such as HadGEM1 (e.g., Wang and Overland, 2009; Bitz et al., 2012) which represent both the seasonal cycle of ice extent to within 20% and the general distribution of ice thickness (Gerdes and Köberle, 2007).This is largely due to the inclusion of more sophisticated sea ice physics (McLaren et al., 2006) and a good representation of dynamical atmospheric forcing. **In particular, HadGEM1 captures the observed decline in ice extent.** Weaknesses remain however; for example, the sea ice simulation in HadGEM1/2 shows thick ice in the Canadian Archipelago (McLaren et al., 2006) which is due to an error in shortwave radiation at coastal points. This has been resolved in later versions of the model and the sea ice simulation remains within the range of CMIP5 models.

We also have increased confidence in the model ensemble; IPCC AR4 (IPCC, 2007) states that for the Arctic the annual mean warming was very likely[3] to exceed the global annual warming, that the annual precipitation was very likely to increase and that sea ice was very likely to decrease. However, of the ocean it states simply that it is uncertain how the Arctic Ocean circulation will change.

Schweiger et al. (2011) compare PIOMAS ice volume estimates (see section 2.2 for a description) and ice volume estimates from the CCSM3 coupled climate model. They show that CCSM3 estimates of ice volume agree with PIOMAS over the period 1979-2006. The same conclusion is reached when HadGEM1 and HadGEM2-ES are compared against PIOMAS. However, since 2007 the PIOMAS volume estimates are lower than those from climate models. Since 2007, the Arctic in the real world has been subjected to anomalous atmospheric forcing with years such as 2007 and 2011 where stronger than normal winds have displaced large volumes of ice (eg, Lindsay et al., 2009) and exposed larger areas of open water which can absorb more heat from the atmosphere. These Arctic circulation anomalies may have been driven in part by El Nino/La Nina (L'Heureux et al., 2008). It is therefore possible that the divergence between PIOMAS and the climate models since 2007 represents internal variability of the climate system. Further research and subsequent years' observations will confirm whether recent years have been anomalous, or whether they are part of a trend that is underestimated by climate models.

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[3] 'very likely' is specified as 90% certain (IPCC, 2007)

In section 2.1 it was noted that the rate of decline of Arctic sea ice has been much faster over the last 15 years of the satellite record, than the first 15 years. Although HadGEM1 and HadGEM2-ES capture the observed decline in ice area they do not capture the recent increase in the rate of ice loss over the latter half of the satellite period. Examination of the CMIP3 ensemble suggests that **models do not show an acceleration of the rate of loss of ice at the observed magnitude as earl y as the present day** (Helene Hewitt, unpublished). In terms of the spatial pattern of decline in ice area, HadGEM1 (figure 3.2.1a) does not capture the pattern (figure 2.1.2) except in one ensemble member of an anthropogenic forcing run. However, there is some indication that HadGEM2-ES (figure 3.2.1b) shows a more realistic pattern of decline with greater ice loss in the Pacific sector although this also varies between ensemble members. This issue with the pattern is likely due to systematic errors in Arctic processes and interannual variability in forcing.

Capability is now being developed to evaluate the modelled heat budget of the Arctic against emerging observational estimates (see section 2.5). The model annual mean heat budget in a control simulation of HadGEM1 is shown in figure 3.2.2. By far the largest fluxes are the atmospheric heat convergence and the top-of-atmosphere flux, being 1,066 TW and 1,139 TW respectively. The sum of the ice-to-atmosphere and ocean-to-atmosphere fluxes is 73 TW, which is not far from the reanalysis ice-and-ocean-to-atmosphere flux reported by Serreze et al. (2007, see section 2.5) especially given that the observed estimate includes part of the Nordic Seas in the budget domain, a region of very high sensible heat loss from the ocean. However, our modelled value is a very long way from the 189 TW reported by Tsubouchi et al. (2012). Our modelled ocean heat convergence (41 TW) and ice heat convergence (32 TW) are also quite close to 30 TW, the value reported by Serreze et al. (2007).

3.3 Long term changes in sea ice

In order to understand the drivers of the long term decline in ice volume, it is useful to analyse the components of the heat budget of the snow and ice (as listed in figure 3.3.1). In this way we can determine whether, for example, the ice declines mainly due to atmospheric or to oceanic processes. Figure 3.3.1 shows that most of the long term decline in ice volume in the HadGEM1 model is due to extra ice loss during the summer melting period (Keen et al, in preparation). The year on year loss is mostly due to extra melting at the top surface of the ice during June, and extra melting at the sides and base of the ice due to extra heat from the ocean during August. Both of these mechanisms are related to the ice albedo feedback; the first via the parameterisation of meltponds (where albedo is related to surface temperature) and the second by more heat being absorbed by exposed ocean accelerating melting.

The extra melting at the top surface of the ice occurs throughout the melting period, with a peak during June. This is seen not only in the ensemble mean shown here, but also in each individual ensemble member (not shown here). In June there is a large amount of top melting in the control integration, and this can be enhanced under climate change by the ice-albedo feedback: as the ice surface warms, the ice albedo decreases (as a representation of the effect of meltponds) and so more melting can occur. By July, the ice surface temperature in the control integration is already at, or very close to, the melting temperature and little further reduction in albedo over the ice is possible in the model. So although there is some extra top melting during July compared to the control, there is no further enhancement due to changes in the ice surface albedo. It is possible that a more realistic meltpond parameterisation may have a slightly different response to anthropogenic and natural forcing.

There is extra melting of the ice at the base and sides throughout the melting season, due to increased heat from the ocean. The anomaly in the ocean to ice heat flux increases during June and July and reaches a maximum in August. This seasonal signal is seen in each of the individual ensemble members. This is most likely to be due to in-situ heating of the ocean due to the ice-albedo feedback, as the increased melting occurs only during months when the sun is above the horizon, and the largest change is during August, when the ice extent is approaching its seasonal minimum, and there will be areas of open water within the ice pack. If the extra melting due to ocean heating were primarily due to the oceanic advection of heat from lower latitudes, the effect would be more evident year-round.

The complex problem of the Arctic climate processes may be reduced by only examining the large-scale energy budget as is done by Serreze et al. (2007). They conclude that the net surface flux has first-order impacts on the atmospheric large-scale energy budgets of the Arctic, and that a net difference of the order of 1 W m^{-2} is important, because a sustained net surface heat flux of this amount over a year equals about 0.1 m of sea ice melt (at its melting point). The simulated annual cycle of the Arctic surface energy balance (70°–90°N), across a selection of the CMIP3 climate models, is discussed in Sorteberg et al. (2007). They find both the downward and upward longwave radiation to be underestimated in many models. The across-model variability of longwave radiation is largest during winter. This is found to be associated with the different model boundary layer structures (Svensson & Karlsson, 2011) which result in groupings of models to warm/wet and cold/dry winter boundary layers, arising from the different treatment of turbulent heat fluxes. HadGEM1 lies in the cold/dry regime and consequently, although the winter cloud cover is in good agreement with observations it has very low liquid water content and so does not result in a rise in winter temperatures. On the other hand, the climate model developed at NCAR in the US (CCSM3) has a warm/wet winter. This results in a 40% greater ice volume loss by 2050 over HadGEM1 (where both models start from the same thickness). Winter heat loss from the North Atlantic drives the northward turbulent heat flux, and the local climatic warming is greater in CCSM3 than in HadGEM1 (Bitz et al., 2012). With HadGEM1, and the majority of CMIP3 climate models, biased cold in winter, an increased summer melt is required to match the observed sea ice decline.

In summary, in the HadGEM1 model, the **Arctic sea ice volume gradually declines as the climate warms, due to extra melting during the summer**. This melting is mainly due to extra heat from the atmosphere, which melts the ice directly at the surface, and indirectly via in-situ warming of the ocean as the ice cover retreats. In both cases the ice albedo feedback plays an important role in determining which months have the greatest extra melt. This means that a change in the parameterisation of the ice albedo – for example by explicitly including melt ponds – has the potential to change the response of the sea ice to climate change. However, in other models, **processes such as winter warming and clouds may play a greater role**.

3.4 Low ice events

HadGEM1 is capable of producing an especially low September ice extent, similar to that observed in 2007. Such **events are relatively rare in HadGEM1, occurring about once in 100 years in both control and historical ensembles**. One occurs in modelled year 2002 of a climate change integration including a range of natural and anthropogenic forcings (ALL4 in figure 3.4.1), and this event has been studied using a heat budget analysis to understand the factors contributing to the decrease and subsequent recovery of the ice cover (Keen et al., submitted).

During the model integration, the September ice extent reached a minimum value in model year 2002, some 1.15 x 10^6 km^2 lower than the value expected by a linear trend, and 1.73 x 10^6 km^2 lower than the value the previous September. The model produced a low extent again the following year, before recovering to a value above the linear trend by September 2004. A key factor contributing to the low ice extent was the pre-conditioning of the snow and ice at the beginning of the summer melt season.

Between April 2002 and April 2004 the model ice volume was anomalously low, due to extra heat melting the snow and ice during the year April 2001 to April 2002 (figure 3.4.2). This was partly due to extra heat entering the ice from the ocean, and partly due to a reduction in the heat loss through the ice in the late autumn. The ice volume recovers between April 2004 and April 2005, as the ice receives less heating from the ocean, and loses less heat via the diffusive heat flux through the ice and snow (figure 3.4.2).

So at the start of the summer 2002 melt season the ice thickness was relatively thin, especially in the eastern Arctic, making it more vulnerable to melting away completely over the summer. In the region of anomalous ice loss in 2002, nearly 70% of the volume loss was due to advection, and the remaining 30% melted in-situ, mainly via the ocean to ice heat flux. During April, May and June, a protrusion of low pressure from Siberia caused the ice to move away from the Siberian coast and across the Arctic towards the Fram Strait, reducing the ice cover and exposing areas of open ocean. This resulted in extra warming of the ocean which, in turn, contributed to extra melting via the ocean to ice heat flux. Then during August, a region of high pressure over the Arctic causes strong anti-cyclonic circulation and convergence of the ice pack, which helped to keep the ice cover compact towards the end of the melt season.

So, in summary, the low ice cover modelled by HadGEM1 in summer 2002 was caused partly by the ice state at the start of the melt season being particularly conducive to summer melt, and partly due to the synoptic conditions over the summer causing ice to move away from the Siberian coast and reduce the ice cover both directly and via extra melting by the ocean.

These mechanisms of ice melt are broadly similar to those believed to have caused the record low ice extent observed in 2007. However, the synoptic state of the model was not the same as that observed in 2007, and there is no observational evidence that the ice was especially thin at the start of the 2007 melt season. Rather it thinned *following* the summer of 2007 (Giles et al., 2008). So the **HadGEM1 model is capable of producing a very low summer ice extent by plausible mechanisms, although not following the exact conditions observed in summer 2007** (Stroeve et al., 2012). Although we need to appreciate that models will never capture the evolution of the climate in exactly the same way as observed due to internal variability, there is some indication that models may have a tendency to recover from low ice events more easily than the real world (Vavrus et al., in press).

3.5 Synoptic changes

Ensemble simulations of Arctic circulation can develop multiple dynamical regimes (Fisel et al. 2011). Multiple-regime states tend to be preferred slightly more in June, July, and August than October, November, and December. September has the fewest multiple-regime periods. September is also the month of sea ice minimum, suggesting that open ocean may inhibit the occurrence of multiple regimes in ensemble simulations compared to periods when substantial sea ice is present. The occurrence of this behaviour suggests that as future summer ice cover wanes in the Arctic, the predictability of the atmosphere may increase.

Northward-moving cyclones over the western Nordic Seas have been observed to strongly influence the Barents Sea ice extent (Sorteberg & Kvingedal, 2006). This relationship was particularly strong on decadal time scales and when the ice extent lagged the cyclone variability by 1-2 yr. The lag indicates that the mechanism is related to the cyclones' ability to modulate the inflow of Atlantic water into the Nordic Seas and the transport time of oceanic heat anomalies from the Nordic Seas into the Barents Sea.

3.6 Freshwater changes in the Beaufort gyre

The Beaufort Gyre (BG) constitutes the largest store of freshwater in the Arctic and has been identified as a regulator of Arctic climate variability (Proshutinsky et al., 2002). Periods of high sea level pressure (SLP) over the BG promote an anti-cyclonic circulation, which is associated with freshwater accumulation within the gyre and reduced export of freshwater through Fram Strait. During periods of low SLP over the BG, there is enhanced export of freshwater into the North Atlantic through the Fram Strait and Canadian Archipelago.

Analysis of multi-millennial control runs in HadCM3 (Jackson and Vellinga, under review) shows that the BG is a key player in multi-decadal to centennial variability in the Atlantic meridional overturning circulation (AMOC). Naturally occurring variations of high (low) salinity in the Greenland-Iceland-Norwegian Seas enhance (reduce) convection in the model sinking regions, with a corresponding strengthening (weakening) of the AMOC. These salinity variations originate either from the tropical Atlantic, as discussed in Vellinga and Wu (2004), or from the storage and release of freshwater by the BG, and propagate towards the Greenland-Iceland-Norwegian Seas.

In HadCM3 the BG multi-decadal variability is generated by random atmospheric fluctuations of sea level pressure that force an ocean salinity mode of variability (see also Frankcombe and Dijkstra, 2010). The strength and frequency of this variability may be dependent on the underlying model physics and climate state: in Jackson and Vellinga (under review) models with lowest global mean temperature had little variability of salinity in the BG. The paper suggests that climatically important variations in BG freshwater storage occur on multi-decadal time scales.

4. Assessment of the possibility of rapid change

4.1 Projections of seasonally ice free Arctic from climate models

Global temperature change over time in the HadGEM2-ES RCP scenarios reveals that no matter which concentration scenario is followed, the temperature pathways are similar until 2030, after which they start to diverge. This initial commonality in global temperature change represents a commitment to change based on past emissions plus a limited spread in forcing in the RCPs over the next few decades (Stott et al., 2006).

Arctic mean temperature is rising faster than global mean temperature, a characteristic known as *polar amplification*. The degree of extra warming is different in the various CMIP3 climate models, a factor ranging from 2 to 4.5, and is the main uncertainty in climate model projections of sea ice change. For example, in HadGEM2-ES the polar amplification is 3 (i.e., Arctic temperature rise is 3 times the global rise). Much of the mean Arctic temperature rise occurs in winter and arises due to a reduction in extent and thinning of the winter sea ice. In the strongest forcing scenario (RCP8.5) Arctic temperature in HadGEM2-ES rises at a rate of 1.5°C per decade.

Climate models suggest that annual mean sea ice extent and global temperatures are related linearly. The sensitivity of sea ice cover in the Arctic to global temperature rise is expected to be -15% per °C (Gregory et al., 2002). This implies that the *rate* of sea ice loss will only increase if the rate of global temperature rise increases. However, in HadGEM2-ES we see a deviation from the linearity as the winter sea ice starts to disappear at a global temperature rise of ~5°C.

The uncertainty in Arctic sea ice projections may be ascertained from the wide range of simulations of the recent past and future projection, by the CMIP5 models[4] (figure 4.1.1). The simulations bracket the recent observations (Rayner et al., 2003). The CMIP5 models each depict different initial states of the Arctic ice extent (with HadGEM2-ES at the low end). The initial state is related to the local energy balance depicted by the climate model (e.g. clouds, heat transport, aerosols), and since sea ice responds to the local energy balance, and local feedbacks, one should not infer that differences in the initial state are only a reflection of the representation of sea ice physics in a particular model.

The future September sea ice extent, depicted by the CMIP5 models (figure 4.1.1), shows a range of projections for a **seasonally ice-free Arctic from 2030 to 2080**. However, many of the models with later ice-free dates are not in agreement with observations in their historical simulations, and consequently a greater confidence should be given to the projections of an early ice-free Arctic. In HadGEM2-ES, only the **RCP2.6 simulation**, which sees a peak in global temperatures at +2°C in 2040 and stabilisation thereafter, **permits a sustainable amount (~1 million km^2) of September sea ice cover** (figure 4.1.2). While there are other models in the CMIP5 ensemble which also show a similar level of commitment to sea ice loss as HadGEM2-ES there is considerable variability across the multi-model ensemble. The source of this variability is subject to further investigation.

The CMIP5 models also depict an uncertainty in the increase of Arctic annual mean temperature from 1900 to present of 2°C (with the exception of one outlier). The increase in temperature to 2100 of between 5-13°C indicates a considerable uncertainty. With the exception of two of the models, which appear to be outliers, the **rate of increase in temperature ranges from 0.9 to 1.5 °C per decade**. This places HadGEM2-ES as the model with the fastest warming Arctic in CMIP5. Consequently, we should consider the temperature projection of HadGEM2-ES (1.5°C per decade) with caution. Hodson et al. (in preparation) show that from the CMIP3 ensemble, **uncertainty in temperature projections is dominated in the short term by internal variability, while structural (inter-model) differences and scenario differences only become important later in the century** (Figure 4.1.3).

4.2 Possible mechanisms for rapid change and observational evidence

One of the possible mechanisms for rapid change in the Arctic is warming from the ocean; either from upward mixing of warm water in the subsurface ocean, or input of warm water from the shelf sea or the Atlantic ocean. There is a suggestion that increased speed of sea ice motion (Rampal et al., 2009) and consequent increase in the intensity of the Beaufort Gyre (Giles et al., 2012) could act to increase turbulent upward heat transport (Lenn et al., 2009; Rainville and Woodgate, 2009) from the Atlantic layer underneath and melt the sea ice. This is a mechanism that could plausibly operate throughout the Arctic in a more

[4]Note: not all agencies providing CMIP5 models simulations have produced sea ice data for the RCP scenarios.

intense Arctic circulation regime. In addition, the increased spin-up could intensify the boundary currents circulating water around the Arctic, increasing the import of Atlantic water and thereby the heat content of the Arctic Ocean, which could further reduce the ice cover. Since is it speculated that the increase in the intensity of the gyre may also be related to decreasing ice cover, allowing a greater transfer of momentum from atmosphere to ocean, this could constitute a new positive feedback mechanism in terms of reducing the ice cover. In addition, if increased summer ice retreat results in a greatly increased rate of ice growth in the winter this could increase the rate of dense water formation on the Siberian shelves which could have potential impacts on the thermohaline circulation.

Furthermore, it is possible that the recent faster than global average warming of the North Atlantic Ocean (Parker et al, 2007) has accelerated Arctic warming. Chylek et al (2009) provided evidence that this warming, and a previous rapid Arctic warming in the 1930s, is related to periods of warm North Atlantic sea surface temperatures that they relate to the Atlantic Multidecadal Oscillation (AMO). The AMO in turn may be partly influenced by variations in the thermohaline circulation as shown in some long model control runs (Delworth and Mann, 2000; Knight et al, 2005), or to changes in aerosol forcing (Booth et al. 2012). Evidence for natural multidecadal AMO variations stretching back 8000 years has recently been published (Knudsen et al, 2011). So in addition to recent anthropogenic effects, including those on the AMO itself, there may be a natural component to the recent fast Arctic warming which could reverse in future. **Further observations are req uired to understand if these mechanism s are taking place.**

4.3 Rapid decadal changes and tipping points in sea ice

Although some fast decreases in sea ice extent have been observed (see section 2.1), models also strongly suggest that the ice cover can recover (e.g., Tietsche et al., 2011; Armour et al., 2011; Ridley et al., 2012). The lack of a tipping point is illustrated in figure 4.3.1 where Arctic sea ice declines in response to increasing CO_2 and grows again as CO_2 is subsequently reduced. In HadGEM2-ES, we find that even though there is a delay in the recovery of the Arctic ice cover, due to a hysteresis in global temperature, the ice cover exhibits no irreversible characteristics.

PIOMAS estimates of ice volume have been used to argue that, despite a recovery in extent, ice volume continues to decrease (Schweiger et al., 2011). However, looking at the age of the sea ice, Maslanik et al. (2011) show that multiyear ice up to three years old may be recovering following the low ice extent of 2007. Careful cross-examination of in-situ measurements, satellite retrievals and model results is necessary to assess whether conclusions about total volume changes over such relatively short periods are possible given the substantial errors associated with either source of information.

Claims that the Arctic will be seasonally ice-free by 2013[5] are based on extrapolating the PIOMAS or other model output (for example, Maslowski et al. (2012). Given the demonstrated importance of internal variability and the non-linear nature of the evolution of the sea ice volume trajectory, such extrapolations should be viewed with scepticism as they appear to have no demonstrated skill and little scientific basis[6].

While **events showing rapid loss of Arctic sea ice do occur in models, the y do not appear in the near horizon** . The possibility of abrupt changes in September sea ice extent due to the sea ice albedo feedback has been extensively investigated, particularly since the low ice events following September 2007. Holland et al. (2006) examined timeseries of September sea ice extent in an ensemble of runs forced by the SRES A1B emissions scenario and found many periods of abrupt change, defined as periods of 5 years or more in which the annual rate of decline of the 5-year running mean ice extent was 0.5 x 10^6 km^2 or more. In the most extreme of these, ice extent fell from around 6 x 10^6 km^2 to 2 x 10^6 km^2 between 2024 and 2034.

In models, the surface albedo feedback appears to play only a small part in rapid ice loss events, a forcing from ‘pulses’ of increased ocean heat transport to the Arctic playing a major part in initiating the changes (Kauker et al., 2005) A positive feedback by which decreased sea ice concentration in late autumn leads to increased autumn cloud fraction and higher cloud radiative forcing has also been identified (Vavrus et al., 2009). However, no modelled rapid ice loss event appears to have been initiated by anomalous atmospheric circulation patterns such as the Arctic Dipole anomalies that have characterised recent years. Instead, rapid ice loss events are forced by rapid changes in external forcing, exacerbated by the feedbacks of clouds and surface albedo, and in many cases simply helped by internal variability.

4.4 Slowdown of ice loss can be modelled

Just as HadGEM1 is capable of simulating periods of low Arctic sea ice within the ongoing decline, it is also capable of simulating periods of little or no ice loss. Between about the years 2010-2030, a significant slowdown in loss of September ice volume is projected by five model runs in both the all-forcing (ALL) and anthropogenic forcing (ANT) ensembles. The slowing is most apparent in ALL4, the ensemble member discussed in section 3.4, in which ice volume actually increases from 2010-2020 (figure 4.4.1). Note that these decreases are temporary, and declining ice extents are generally resumed after 2020.

West et al (submitted) calculated the heat budget of the Arctic region in HadGEM1 dividing into the components of atmosphere, ice and ocean (see figure 3.2.2). Vertical energy fluxes between the components, horizontal fluxes entering the region through each component, and heat uptake in the ice and

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[5] http://www.vmine.net/scienceinparliament/specials/12.pdf
[6] http://www.realclimate.org/index.php/archives/2012/04/arctic-sea-ice-volume-piomas-prediction-and-the-perils-of-extrapolation/

ocean were all calculated. In HadGEM1, ice heat uptake is directly proportional to ice volume loss.

The slowdown in ice loss is clearly visible in the heat budgets as a reduction in ice heat uptake from the 2000s to the 2010s. In the ALL experiments the change is caused by a large reduction in ocean-to-ice heat flux, associated with either a reduction in ocean heat transport (OHT) into the Arctic or an increase in ocean-to-atmosphere heat flux. In the ANT experiments ice loss is caused by a large reduction in ice export from the Arctic, with decreases in atmosphere-to-ice heat flux also contributing, associated with decreases in atmospheric heat transport (AHT) into the Arctic.

The indices of the Meridional Overturning Circulation (MOC) and Sub-polar Gyre (SPG) were examined, as two circulation patterns with strong effects on conditions near the Atlantic-Arctic boundary. A decreasing MOC index is a feature of all integrations; however, in the ALL experiments a step change downwards of about 1.8 Sv occurs in about 2008. This is a major cause of the temporary decreases in AHT and OHT in the ALL experiments. In addition, the SPG index displays a strong weakening in ALL4, reaching a minimum of 2-3 Sv below the long-term mean in 2013, explaining why the slowdown in ice loss is strongest in this experiment.

The sharp decreases in ice export in the ANT ensemble were also examined, and found to be due to a sudden reduction in ice thickness in the region north of Greenland in Ellesmere Island, a major feeder region for Fram Strait, the main route of ice export. These were in most cases preceded by ‘flushing’ events, in which large amounts of ice were exported from the region. This mechanism partly reflects natural variability, and suggests years of high ice export tend to be followed by several years of low ice export. In all cases however this was exacerbated by the ongoing decline in ice thickness.

In summary, HadGEM1 is able to produce periods of reduced ice loss due to several mechanisms: a) a negative feedback by which reduced ice thickness is able to reduce ice export; b) an ‘oscillation’ in which periods of high ice loss from the region north of Greenland, where the sea ice is thickest, are followed by periods of low ice loss; c) temporary reductions in oceanic heating of the ice caused by the weakening MOC. It is possible that the weakening of the MOC is itself exacerbated by the fast ice melt of the 1990s, but this has not yet been demonstrated. While this analysis demonstrates that **there are plausible mechanisms in the climate system to slow down temporarily the rate of loss of ice**, there is,as yet, no observational evidence suggesting that this will occur.

4.5 Evidence for upward mixing of heat from the ocean in models

Graham and Vellinga (under revision) carried out a heat budget analysis of the upper Arctic Ocean in the perturbed physics ensemble (PPE; Jackson et al., 2011) of HadCM3 and a single HadGEM1 experiment. It was initially found that the changes in the fluxes were highly correlated with the sea ice extent in the control run of each ensemble member. To remove this effect all of the results presented herein are calculated over the area where the control run annual mean sea ice concentration is greater than 15%.

First we consider the change in surface heat fluxes as CO_2 is increased and the sea ice area is reduced. During summer the reduced sea-ice area means that more solar radiation is absorbed into the ocean surface since the albedo of the ocean surface is lower than that of the sea ice. During autumn and early winter, however, the reduced ice cover means that more heat is lost from the ocean surface to the atmosphere. Overall this second effect is dominant and more heat is lost from the ocean surface than is gained.

Even though more heat is being lost from the ocean surface than is being gained, the SST increases. This implies that there must be another source of heat bringing energy to the Arctic Ocean surface. Figure 4.5.1 shows contributions to the change in the upper 40m heat budget as a mean of the Perturbed Physics Ensemble (PPE) (panel a) and for HadGEM1 (panel b). In both the ensemble and HadGEM1 the mixed layer physics term is one of the largest contributions to the model's heat budget changes. This term describes the warming of upper ocean as a result of the model's mixed layer parametrisation scheme, demonstrating that **heat is being mixed upwards from the subsurface ocean**. It is hypothesised that this increase may be a result of increased surface wind stress on the ocean driving more mixing since the surface is no longer ice covered. In the PPE the heat flux from ice to ocean is also large. This is thought to be because the summers quickly become ice free in most of the PPE runs and the amount of winter sea ice gradually decreases. Therefore the amount of heat energy required to melt the sea ice each year will gradually decrease.

The full depth heat budget (figure 4.5.1 lower panels) shows that heat is transported into the Arctic Ocean via increased advection. Bitz et al. (2006) showed that although the meridional overturning circulation (MOC) in the Atlantic Ocean becomes weaker under climate change the MOC in the Greenland Sea increases as the deep convection sites moved further North. This is consistent with the increased warming by advection in the HadCM3 PPE and HadGEM1.

4.6 Do we have confidence in models?

Sea ice responds sensitively and non-linearly to changes in atmospheric circulation, incoming radiation, atmospheric and oceanic heat fluxes, and the hydrological cycle. It is therefore not surprising that relatively small perturbations in forcing or initial conditions of climate models result in large changes in simulated ice extent and thickness. As we have demonstrated, in any individual model, there are a variety of mechanisms which can cause long term change, low ice events, rapid changes and slowdowns. However, while mechanisms are plausible, they may not be the same as currently observed (e.g., low ice events, Keen et al., submitted).

Due to the fact that there are various processes known to be important (from model sensitivity studies and/or observations) but which are not yet included in climate models, it is not possible to definitively ascribe any deficiency of existing sea ice predictions to one particular process. Sea ice is a complex material and existing sea ice models simplify many aspects of the physics of phase change and deformation. Simulated quantities such as ice volume, extent, and mass fluxes are sensitive to uncertainty in the model physics. In sea ice-only models, where the atmosphere and ocean fluxes come from forcing, the observed range of sea ice states over the last several decades can be obtained by varying sea ice model parameters such as albedo or ice strength within their range of existing uncertainty (Miller et al, 2006), indicating that sea ice model uncertainty alone, i.e. excluding the effect of atmospheric and oceanic uncertainty, may be responsible for the discrepancy between observed summer sea ice extents and climate model predictions.

Creating more reliable climate models of Arctic change requires, among other things, (i) greater use of wide-area data to calibrate and test models, e.g. there is a paucity of oceanographic measurements in the Arctic and many sea ice models are only calibrated against sea ice extent, which is closely tied to the ocean surface temperature, rather than sea ice thickness, which is a more complete measure of the Arctic mass balance; and (ii) implementation into climate models of more realistic representations of physical processes affecting the heat, mass, and momentum balances. A concrete example of where we anticipate that more sophisticated model parameterisations could impact on model evolution is given by Keen et al. (submitted) who show that a simple meltpond parameterisation is playing a significant role in the evolution of the melt season in HadGEM1 (see section 3.3).

While it is possible to identify processes that are not well-represented in climate models, they remain our best tool for predicting the likelihood of rapid change in the Arctic and some models are able to capture aspects of changes that have been observed. However, as models are continuously being improved and evaluated and new observations become available that challenge our understanding of the Arctic, an ongoing assessment of the likelihood of rapid change is required.

5. Potential impacts of rapid change

5.1 Local impacts

Climate change in the Arctic has the potential to change transportation in the Arctic dramatically. Compared to routes via the Panama or Suez canals, trans-Arctic shipping offers potential for cost savings in excess of 30% to shipping companies. Stephenson et al. (2011) have used the output from one climate model driving a transport model to predict that accessibility to offshore exclusive economic zones will increase while accessibility inland will suffer due to melting permafrost. West and Hewitt (2011) and Khon et al. (2010) have estimated **access to shipping routes** directly from climate models. However, this is currently not sufficiently accurate (especially for the Northwest passage) due to the limited resolution of climate models. These two approaches highlight the disconnect between the climate modelling and impact communities in this area – Stephenson et al. (2011) used results from the CMIP3 model which shows the fastest decline of ice and do not address the potential uncertainty in the climate model forcing data (internal, scenario or structural) while a climate model based approach does not build on transportation knowledge. As transportation in the Arctic changes, this opens up the possibility that Arctic states will consider offshore **mineral exploration** with geopolitical implications (Young, 2011). This represents a potential tipping point not necessarily in the climate system but socioeconomically.

5.2 Impacts on European climate

Low Arctic sea ice cover is now being linked with significant changes in the winter jet stream and hence the severity of European winters. It is possible that continued low Arctic sea ice during the coming years to decades might increase the probability of cold winters in northern Europe. These effects would in some cases partly counteract the more direct, thermodynamic effects of climate change on Europe.

A number of studies now indicate that Arctic Ice depletion, in isolation, may increase sea level pressure over the Arctic in winter and thereby drive more easterly winds across Europe in both observations (Strong et al. 2009, Francis et al. 2009, Wu and Zhang 2010, Overland and Wang 2010) and modelling studies (Alexander et al 2004, Magnusdottir et al. 2004, Deser et al. 2004, 2007, Petoukhov and Semenov 2010, Sedlacek et al. 2011). There is also limited modelling evidence that reduced Arctic sea ice might lead to low pressure over Europe during summer (Balmaseda et al. 2010)but this needs much more research using fully coupled climate models.

The mechanisms for this influence are still under debate but the modelling and observational studies are beginning to indicate a consensus. Most studies see a barotropic response throughout the depth of the troposphere with both **surface high pressure anomalies and high geopotential heights over the Arctic**. These are **balanced by easterly wind anomalies from the surface up into the jet stream and above**. Similar signatures are found in observations and bespoke modelling experiments carried out in several different climate models. At least some studies suggest that Eurasian snow cover could act as an intermediary, with decreased sea ice leading to increased Eurasian snow and a subsequent increase in blocked European winters where more easterly flow occurs (Cohen et al. 2012, Allen and Zender 2011).

Some of these results are tentative and have not yet been robustly reproduced across a broad range of climate models. We have therefore begun to investigate possible links between low Arctic sea ice cover and atmospheric circulation in a long (~100 year) control simulation of the latest high resolution Hadley Centre coupled climate model, HadGEM3H. This latest model has an atmosphere resolution of around 60km in mid-latitudes and 85 vertical levels, enabling processes throughout the full depth of the atmosphere to be simulated (HCCP deliverable D3.2.7). Biases in north Atlantic sea surface temperatures and atmospheric winds are greatly reduced in HadGEM3H compared to previous Hadley Centre models, leading to much improved simulations of the blocked flow conditions associated with cold winters (Scaife et al., 2011).

Composite maps averaged over all December to February periods for years when the preceding September to October Arctic sea ice cover is low (at least one standard deviation below average) do show anomalously high pressure over the Arctic and cold temperatures over Europe (Figure 5.2.1). Similarly, June to August composites for periods with low June to August sea ice cover also show low pressure over Europe (Figure 5.2.2).

These preliminary results are consistent with other studies, and provide further evidence that declining Arctic sea ice might increase the probability of cold winters (and perhaps wet summers) in northern Europe. It is therefore important to clarify the physical mechanisms through which sea ice influences the atmospheric circulation and to quantify this atmospheric response relative to other factors such as the direct warming effects of increasing greenhouse gases. Further experiments are planned to address these questions.

5.3 Impact on thermohaline circulation and global climate

The effects of the Atlantic MOC on climate are extensive and well documented, including on air temperature throughout the Northern hemisphere, tropical precipitation, midlatitude Atlantic storm tracks and ocean and land ecosytems and carbon uptake. See HCCP report D2.2.5, Feb 2012 for more detail. Recent results have suggested a role for the Arctic in driving AMOC change over the 21st Century.

Simulations with HadGEM2-ES have highlighted the potential role of anthropogenic aerosols in shaping atmospheric circulation patterns in the northern high latitudes over the 20th Century (Menary et al., in prep). HadGEM2-ES simulations and an independent atmospheric reanalysis (Compo et al., 2011) over the period 1871 to present suggest extended periods of high pressure anomaly over the Beaufort Gyre and low pressure anomaly over the Atlantic sub-polar gyre for much of the 20th Century.

In the model, these pressure patterns are associated with a long-term build-up of freshwater in the BG and decreased ice export through Fram Strait over the 20th Century. In combination with locally enhanced evaporation, the reduced freshwater export acts to salinify the upper water column in the subpolar gyre, promoting convection and leading to a long-term strengthening of the AMOC. The reduction in ice export through Fram Strait is qualitatively supported by the independent observation-based analysis of Schmith and Hansen (2003).

Model simulations that include the effects of anthropogenic aerosols show an increased decline of the AMOC over the first few decades of the 21st century compared to those using only greenhouse gas forcings (-0.8 Sv dec^{-1} vs -0.2 Sv dec^{-1}). It is possible that release of freshwater from the BG accounts for some of the additional decline in the AMOC seen in these model simulations.

6. Further work

6.1 Observations

An Arctic ice and ocean sustained observation system requires three elements: (i) fixed installations around the boundary in key gateways (Fram, Davis and Bering Straits, and the Barents Sea Opening; see Tsubouchi et al., 2012) to continuously measure velocity, temperature and salinity, to enable calculation of net fluxes of heat and freshwater; (ii) remote-sensed measurements to provide continuous coverage of the entire Arctic Ocean surface, measuring sea surface height and sea ice thickness and their variability; and (iii) systems to provide continuous measurements of upper-ocean (the top 1000 m) hydrographic and circulation variability.

For element (i), existing monitoring arrays provide observations of ocean exchanges around the boundary in the key gateways, except for the upper ocean above the shallowest instruments on moored arrays (typically the top 50 m), and the shallow shelf waters, some of which support substantial rectified freshwater fluxes. For element (ii), Cryosat can now provide continuous and complete measurements of winter ice thickness and sea surface height changes but further work is required to fully understand the uncertainties in these new measurements. For element (iii), although Ice Tethered Profilers (ITPs) are more numerous than in previous years, the coverage is still insufficient to resolve the circulation and variability within the Arctic Ocean. Looking to the future, this needs to be improved by increased international investment in ITPs to increase the measurement density, and ultimately by the replacement of ITPs with improved glider technology. This means longer endurance, better navigation and practical under-ice communication for gliders. The advantage of gliders over ITPs is that the former are steerable. What is still an active research topic is the extent to which (or even whether) fixed (moored) arrays are required in the Arctic Ocean interior. New features are still being identified in the Arctic Ocean (e.g. Askenov et al., 2011) and their significance is being assessed. It may be that ITPs need to be supplemented by fixed installations to continuously measure other Arctic Ocean features of importance to climate, such as the narrow circum-Arctic boundary current system, and the dense water formation regions. While other fixed arrays are present in the Arctic and providing highly valuable research data, it is not yet clear whether (from a climate perspective) they need to form part of a sustained observation system.

In addition to new observations, effort is also required on data processing. For example, to enable long timeseries of ice extent to be maintained, cross calibration of records from different satellites is required. A similar process will be required as we develop long timeseries of other quantities.

6.2 Model process understanding

To further our understanding of the key processes in the Arctic, we propose to focus model evaluation efforts around the framework of the Arctic heat and freshwater budgets. Holland et al. (2010) as well as Keen et al., West et al. (in preparation) demonstrate the value of this approach in understanding the factors contributing to both long term and seasonal changes in Arctic sea ice conditions.

By building on existing work using the Hadley Centre models, this approach can be extended to understand not just the sea ice processes but also the atmosphere and ocean processes contributing to sea ice changes. For example, Vavrus et al. (2011) suggest that clouds can amplify low sea ice events (less ice results in more clouds and this is a positive feedback during the September sea ice minimum) although clearly increased clouds in June and July will act to reduce ice melt. Cloud feedback is proposed to explain approximately 40% of the Arctic warming (Vavrus, 2004).

For the Arctic ocean, there are significant uncertainties in model representation. While we can demonstrate that models are able to represent observed processes such as the build-up of freshwater in the Beaufort Gyre and plausible processes such as heat being mixed to the surface to melt sea ice, there is significant uncertainty in the basic representation of the Arctic Ocean (Proshutinsky et al., 2007). This demonstrates the need for better observations to allow assessment of the ocean state and the processes at play.

It is currently very difficult to explain any apparent discrepancy between model and observational trajectories of sea ice (Stroeve et al., 2007). Since observational estimates of the Arctic heat budget are now beginning to emerge (see section 2.5), a thorough evaluation of modelled heat budgets may be the only way to identify the possible sources of discrepancy and quantify model and observational uncertainty in the Arctic.

6.3 Representation of processes in models

Focussing on sea ice, we can say that while existing climate model representations of sea ice are relatively crude, there is general consensus on which aspects of the physics require improvement (Sea Ice Mass Budget of the Arctic; SIMBA, 2005). Physical processes poorly represented in sea ice models that have a significant (around 50-100%) influence on either the sea ice mass or export are melt ponds (Arctic only), ice interior radiation transfer, ice rheology, mechanical redistribution of ice in ridging, sea ice formation in leads and polynyas (frazil ice), uncertainty in snow thickness, ocean-ice drag (especially the role of keels), air-ice drag, ice-ocean heat flux, and tidal interaction. By including this model physics into sea ice climate models, the range of uncertainty of model parameters is reduced, e.g. albedo becomes a predicted quantity rather than a tuning parameter, and sea ice models become physically more realistic allowing greater confidence in their predictions.

As discussed earlier in this paper, while sea ice may be iconic of climate change in the Arctic and reproducing the observed sea ice decline in climate models is a key target, the sea ice is in part an integrator of errors in other parts of the climate system. Therefore, in addition to improving sea ice processes, it is important that we develop the representation of other areas of the Arctic climate system. Improvements in the representation of ocean and atmosphere processes are expected to occur with a particular focus on clouds (for example, Birch et al., 2009) and ocean mixing processes. By improving the representation of snow cover with a multi-layer snowpack model (Best et al., 2011) we can expect this to lead to an improved representation of soil temperatures and water content, particularly in spring while a subsequent development of a permafrost scheme will improve the representation of methane fluxes and soil water hydrology.

6.4 Operational prediction and attribution

The Met Office regularly briefs government on sea ice conditions throughout the summer melt season. While much of the information we have on likely sea ice conditions is observationally based, seasonal prediction of sea ice is an emerging capability. The Study of Environmental Arctic Change (SEARCH) group produces an annual sea ice Outlook (http://www.arcus.org/search/seaiceoutlook). The Outlook is a community-wide summary of the expected September Arctic sea ice minimum, and the submitted values are based on a range of methods including physical modelling, statistics and heuristics. The predictions include one from the Met Office's GloSea4 seasonal forecasting system (Arribas et al., 2011).

The SEARCH sea ice Outlook for 2011 contained 21 projections of the seasonal minimum ice extent, ranging from 3.96 to 5.4 x 10^6 km^2, with a median value of 4.6 x 10^6 km^2 (see for example figure 6.4.1). This value was slightly higher than the observed value of 4.5 x 10^6 km^2 from HadISST (Rayner et al., 2003). However, the results do suggest that the GloSea4 system based on HadGEM3 may have some skill at predicting the summer sea ice minimum several months in advance and further work is planned to investigate this further. The Arctic budgets described in section 6.2 have the potential to improve our capability in this area.

As the Arctic gradually opens up in summer, there is an anticipated need for weather forecasts that include expected ice and ocean conditions. The Met Office move towards a fully coupled global NWP system will provide opportunities to test forecasts on an operational basis as part of our seamless forecasting initiative.

6.5 Synthesis of Arctic activities and Met Office-NERC collaboration

The work presented here has mainly focussed on the roles of the sea ice and the ocean in the Arctic. However, to look at this in a more holistic manner and attempt to fully understand the complex interactions of the whole system, we need to work to integrate the view presented here with the roles of clouds, permafrost and snow over land as well as the Greenland ice sheet. This is an activity that will be undertaken in the near future building on our expertise in these areas.

Met Office-NERC collaboration in this area is also increasing. The Met Office is actively collaborating with NERC partners within the NERC Arctic Research Programme which will improve the state of knowledge in the next two years (2012-2014) on a number of specific issues including monitoring of sea ice volume, determining the Arctic heat and freshwater budget, understanding the role of clouds and seasonal prediction. We have also recently set up a Joint Sea Ice Modelling Programme for the UK (chaired by Helene Hewitt and Danny Feltham) which will aim to deliver the best possible configuration and physics of sea ice models to UK users.

6.6 Exploring impacts on European climate

As discussed previously, in the long term, increasing levels of greenhouse gases are expected to lead to increased westerly winds over the Atlantic, with milder and wetter winters. However, there is mounting evidence that a reducing Arctic sea ice cover might drive anomalous easterly winds over the Atlantic sector, especially in winter. Over the coming decade therefore, global warming might also act through a reducing sea ice cover to increase the probability of cold European winters. If this is the atmospheric response to declining sea ice and it turns out to be large relative to other factors, then this would be an important, and potentially predictable, impact of climate change.

However, the physical mechanisms through which sea ice influences the atmospheric circulation need to be understood to increase our confidence that the impacts are robust. Furthermore, the likely balance between the impacts of declining sea ice, the direct effects of greenhouse gases, and other factors, needs to be quantified in order to predict European climate for the coming decade. Further analysis and experiments are planned to address these questions. Existing model simulations forced by observed sea surface temperatures (SSTs) will be analysed to see whether they capture the recent cold European winters. Given sufficient resources, further simulations driven by idealised sea ice and SST anomalies could be performed to quantify the impact of sea ice relative to other factors.

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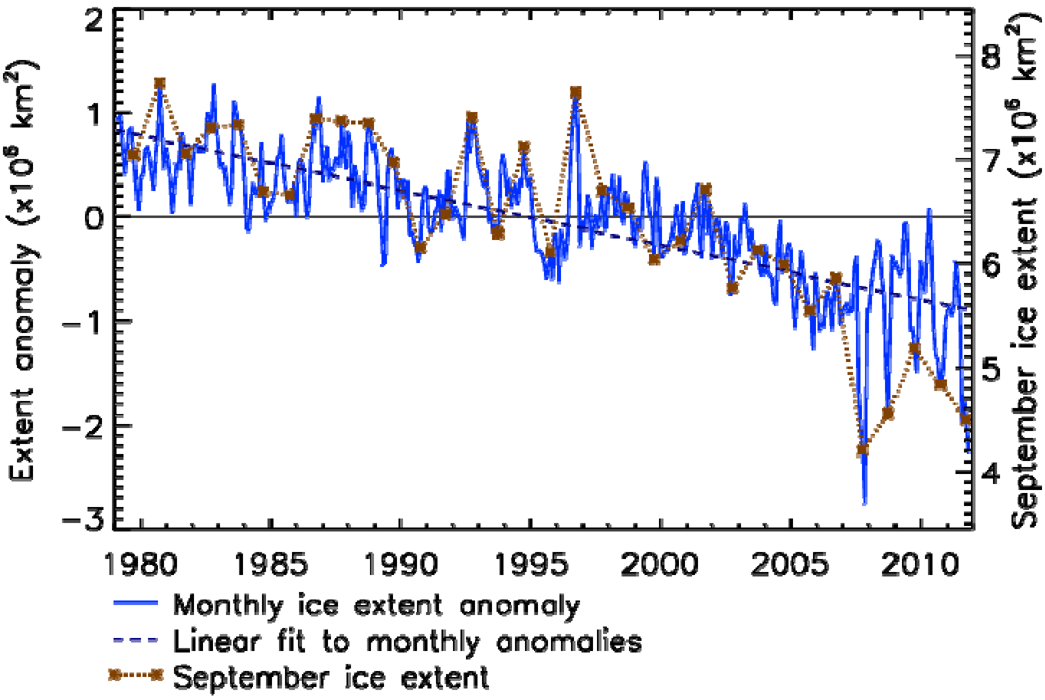

Figure 2.1.1: Monthly Arctic sea ice extent anomalies (HadISST, Rayner et al., 2003), 1979-2011, with September actual ice extent. The anomaly for each particular month is calculated by subtracting the mean ice extent for that month from 1979-2010.

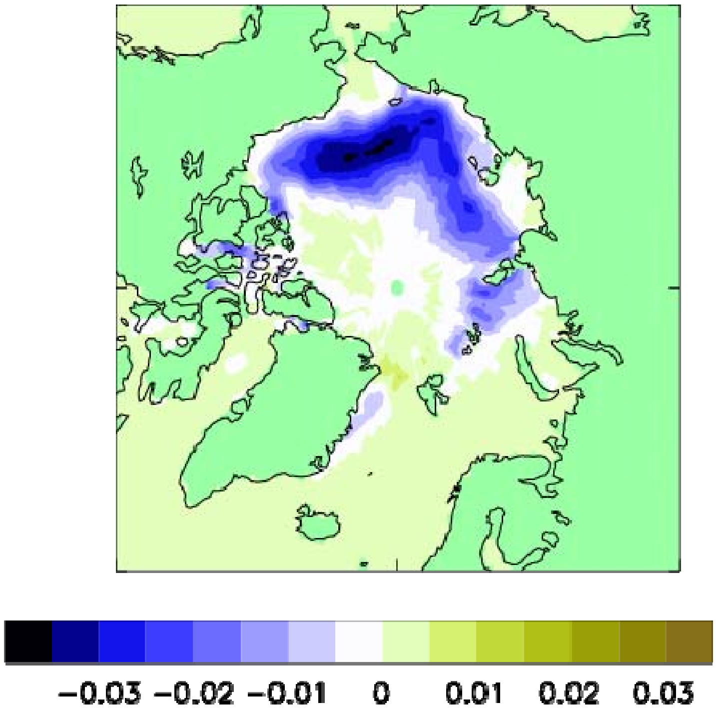

Figure 2.1.2: Linear trend (1979-2011) in September ice concentration (yr^{-1}) from HadISST (Rayner et al., 2003).

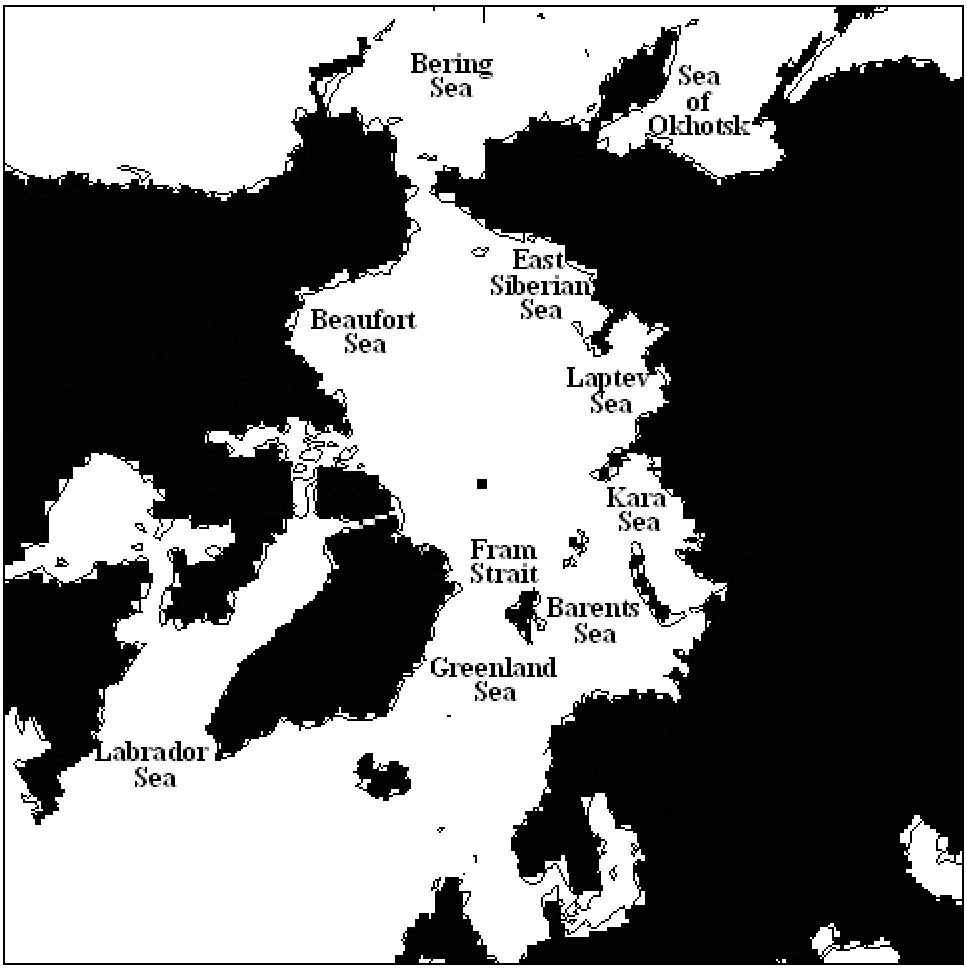

Figure 2.1.3: The Arctic Ocean, with its peripheral seas (McLaren et al., 2006)

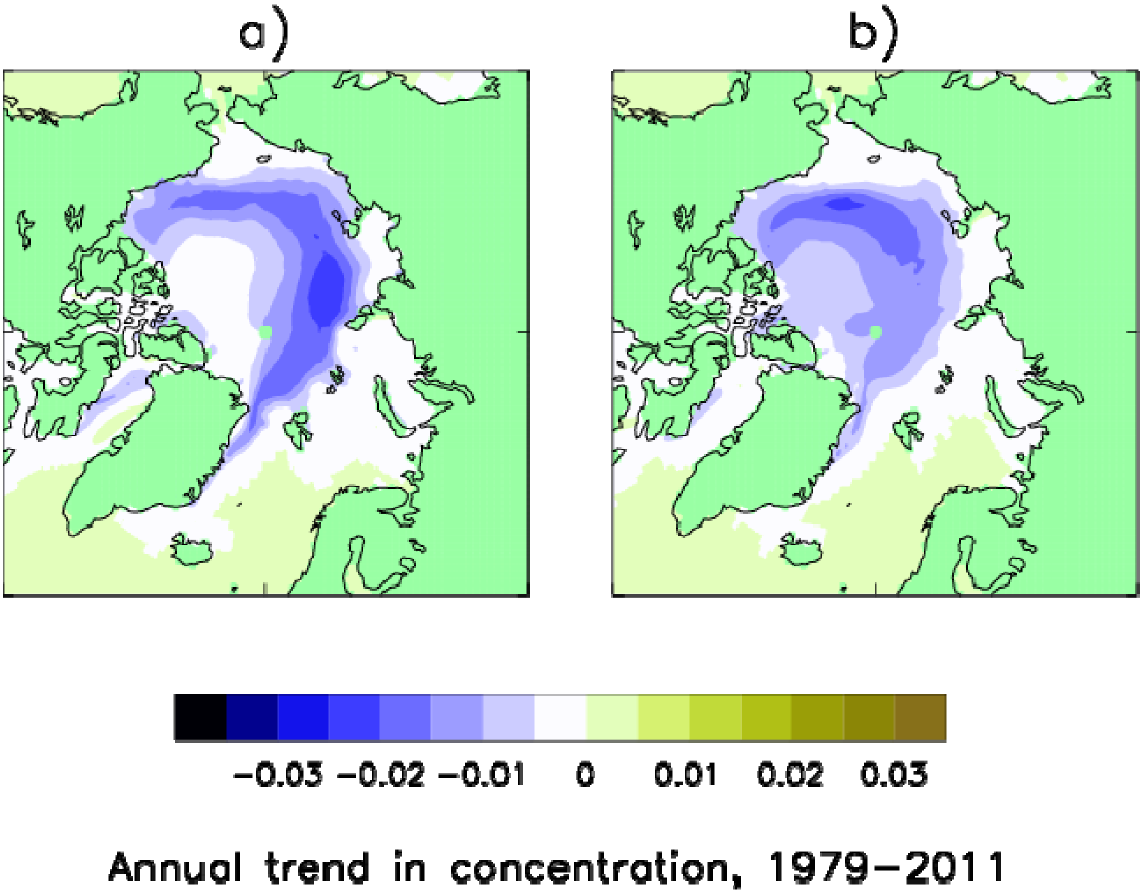

Figure 3.2.1 Linear trend (1979-2011) in September ice concentration (yr^{-1}) from a) HadGEM1 and b) HadGEM2-ES, both an ensemble of historically forced runs.

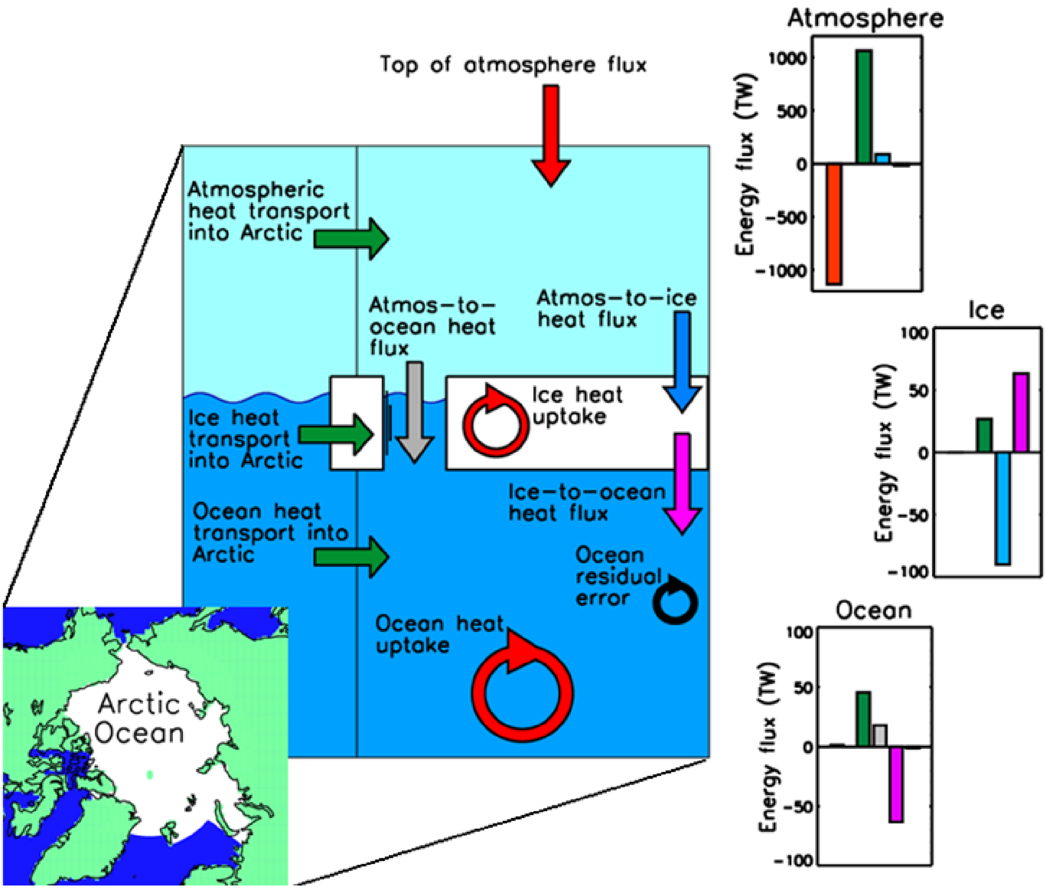

Figure 3.2.2: Schematic demonstrating the Arctic Ocean energy budget as modelled by HadGEM1. Bars on the right correspond to arrows on the left of the same colour. Note the smaller scale for the atmosphere budget.

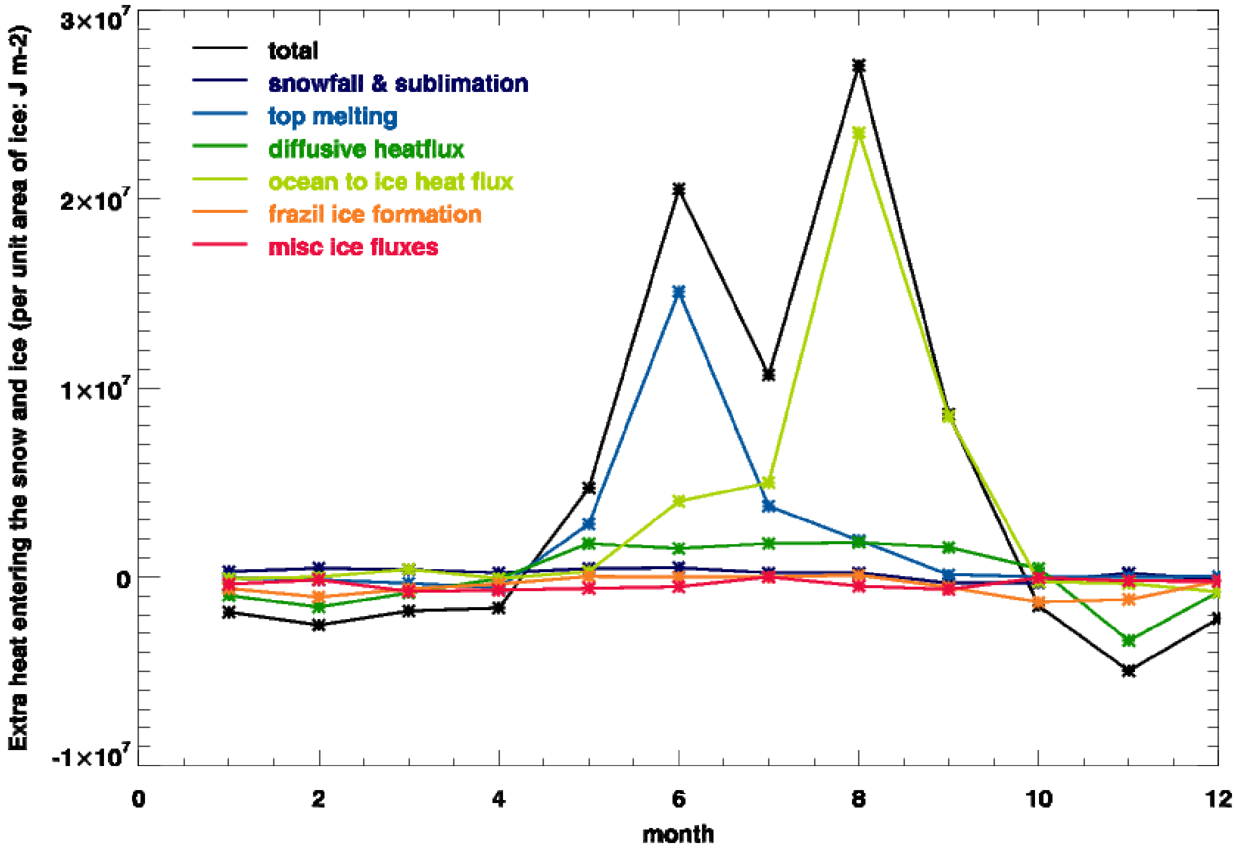

Figure 3.3.1: Mean extra heat (per unit area of ice) entering the Arctic sea ice and overlying snow for the years 1980-2010 of four HadGEM1 integrations including a full range of natural and anthropogenic forcings, compared to the matching 30 year period of the control integration in each case.

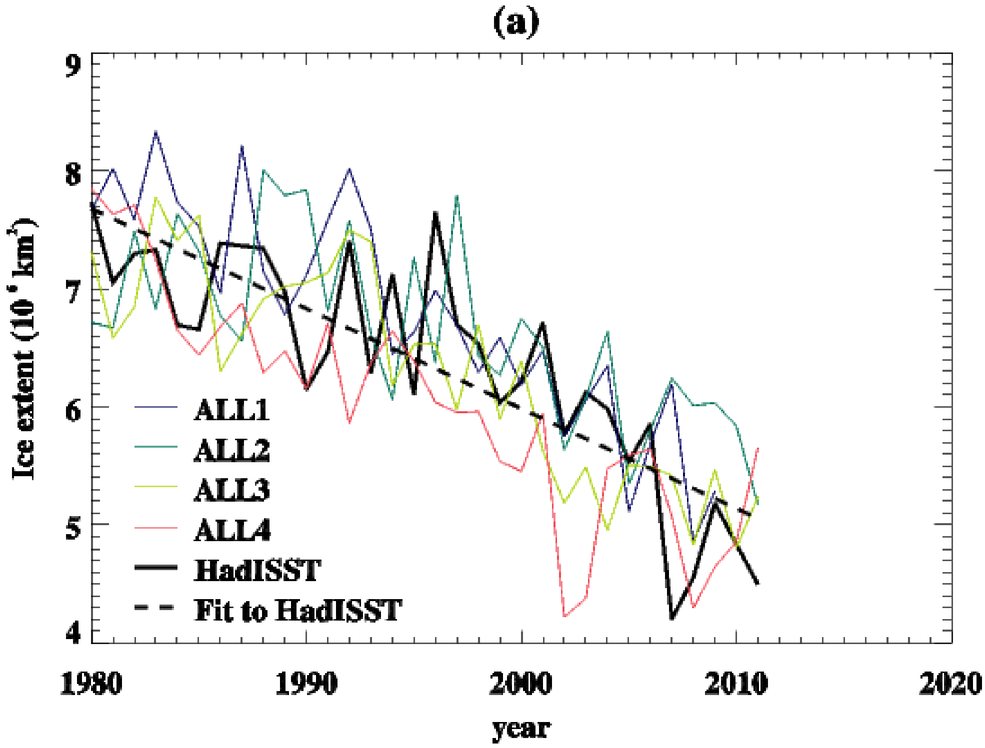

Figure.3.4.1: Time series of Arctic September sea ice extent from the HadISST observational dataset, together with a linear least squares fit to this data. Also shown is the ice extent from an ensemble of four HadGEM1 simulations, each including observed changes in anthropogenic greenhouse gases and solar and volcanic forcing.

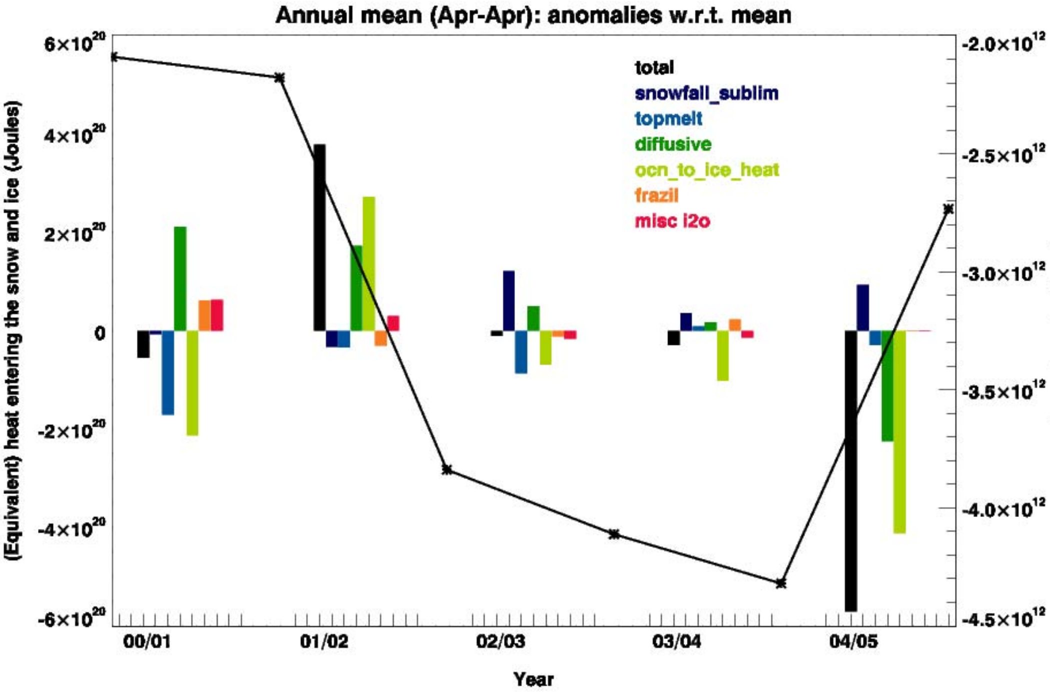

Figure 3.4.2. Anomalies in components of the heat budget of the Arctic sea ice and overlying snow for selected years of the HadGEM1 integration ALL4, expressed as the amount of heat entering the snow and ice each year, and calculated from 15th April. Also shown are anomalies in the mean volume of ice and snow during April (expressed as an effective volume of ice). In each case the anomalies are w.r.t. the 30 year mean.

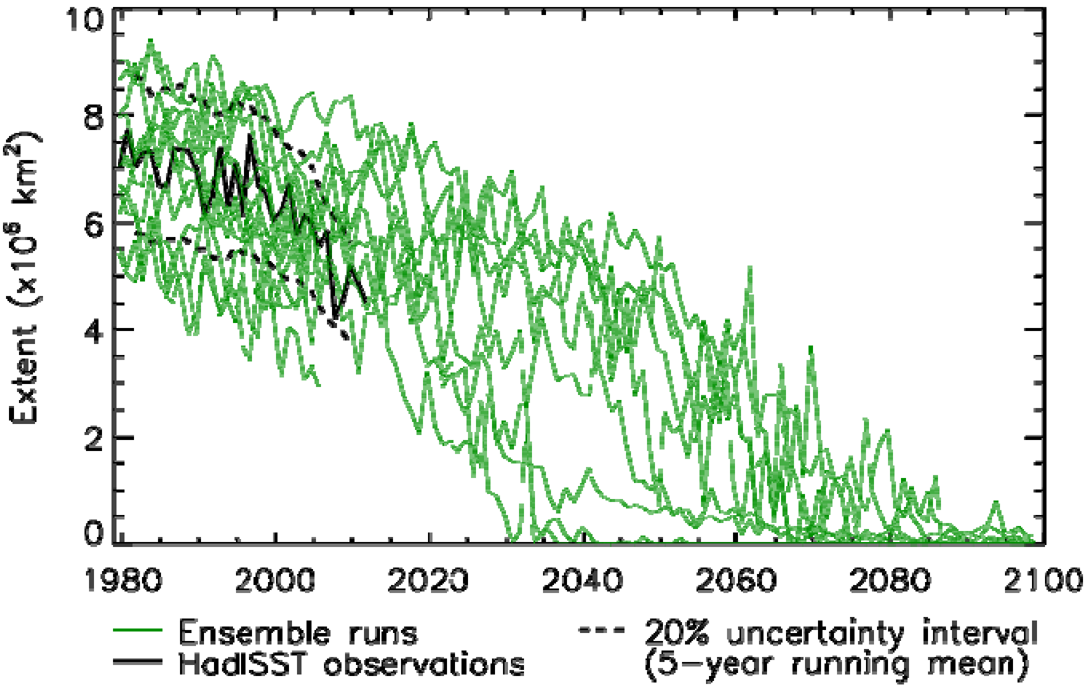

Figure 4.1.1: September Arctic sea ice extent in the CMIP5 multi-model ensemble of experiments, historical forcings (anthropogenic, solar and volcanic) to 2005, followed by RCP8.5 forcing to 2100. The observed sea ice extent (HadISST; Rayner et al., 2003) is shown in black.

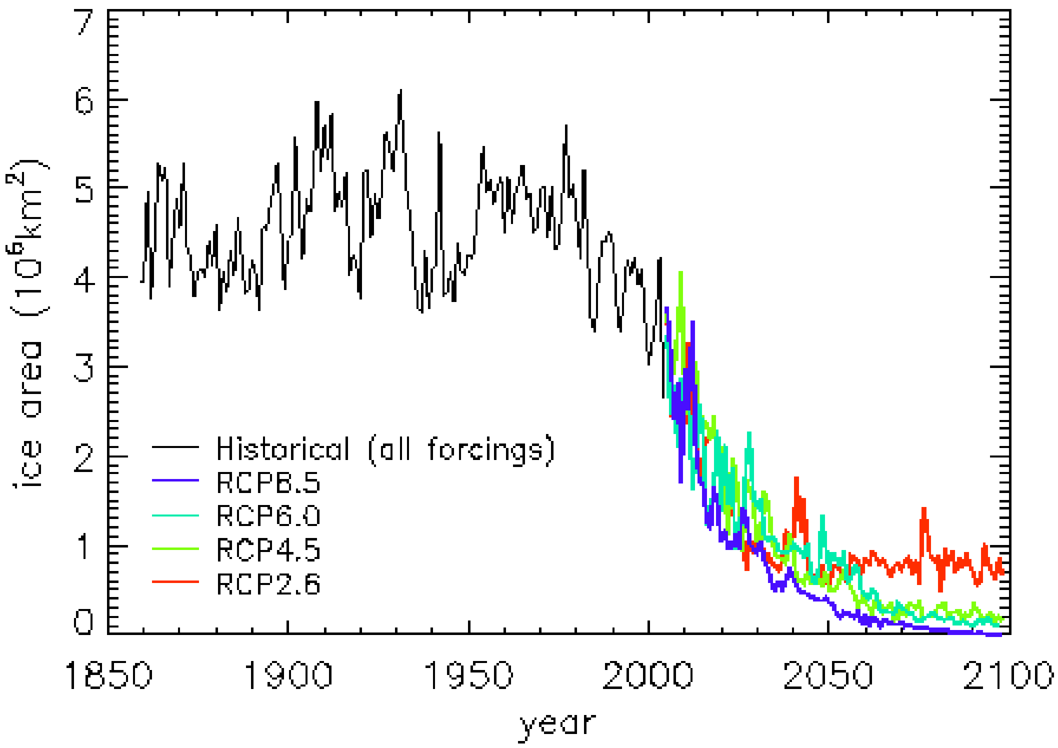

Figure 4.1.2: HadGEM2-ES projected September ice area in four future RCP scenarios.

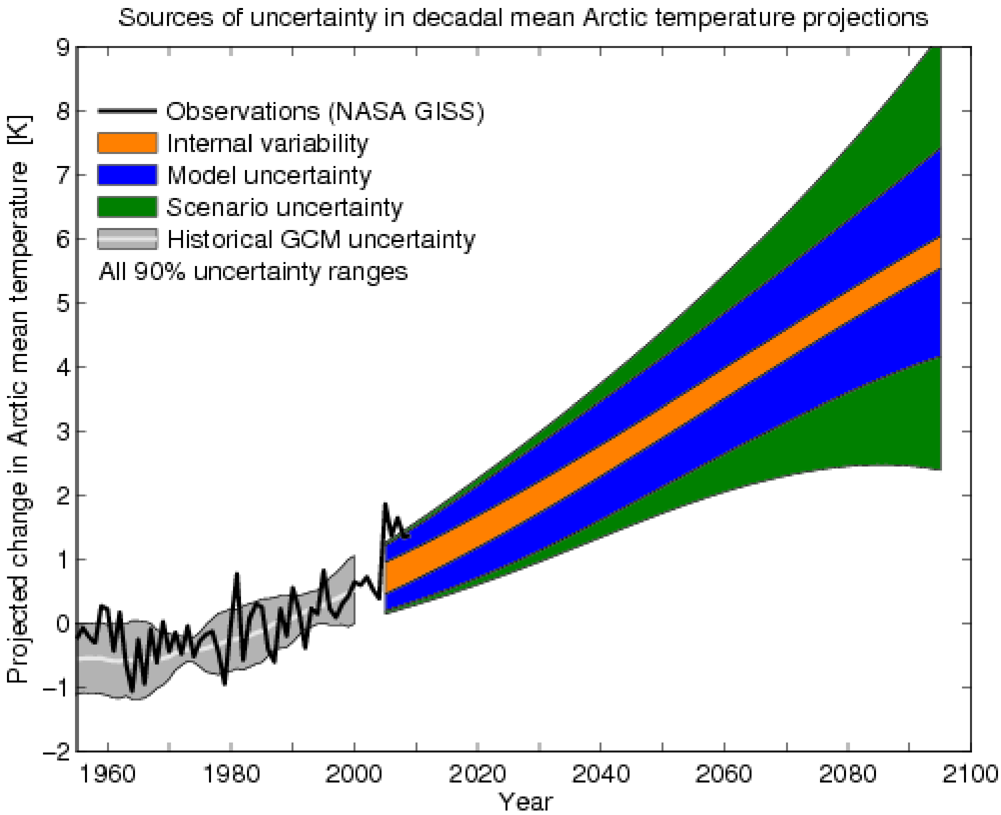

Figure 4.1.3: Estimate of sources of uncertainty in Arctic temperature projections from IPCC AR4 models

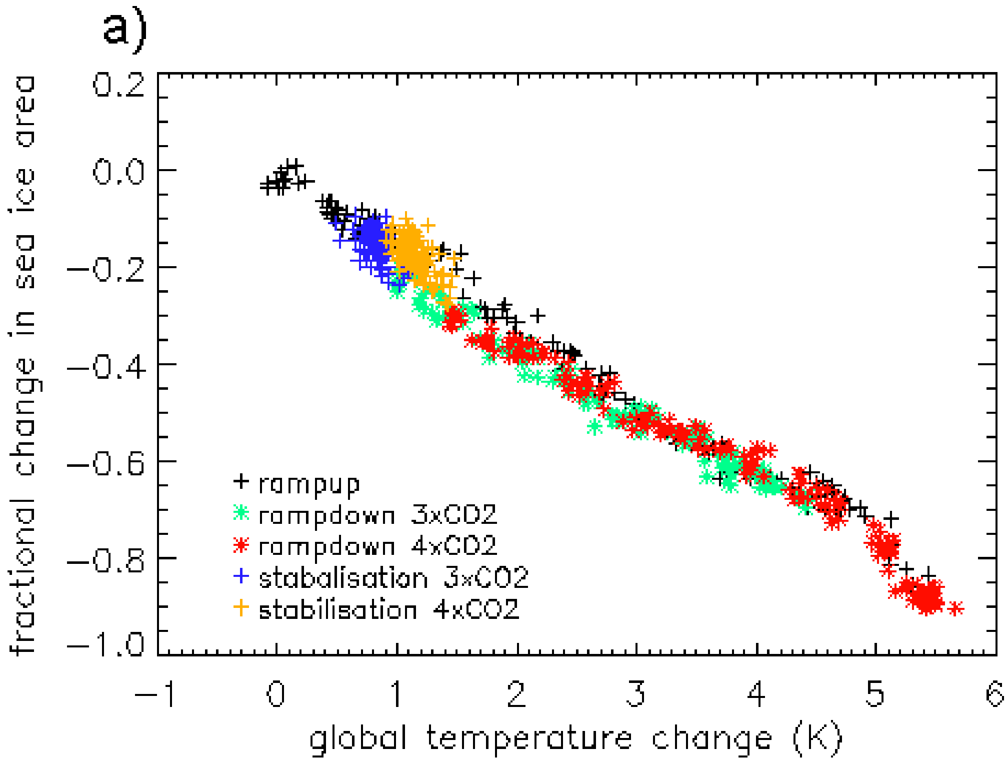

Figure 4.3.1: The sensitivity of Arctic annual mean sea ice area to annual mean global temperature change. When temperature increases the ice area declines linearly. With a reduction of global temperatures the ice area returns along the same trajectory, indicating no irreversible behaviour.

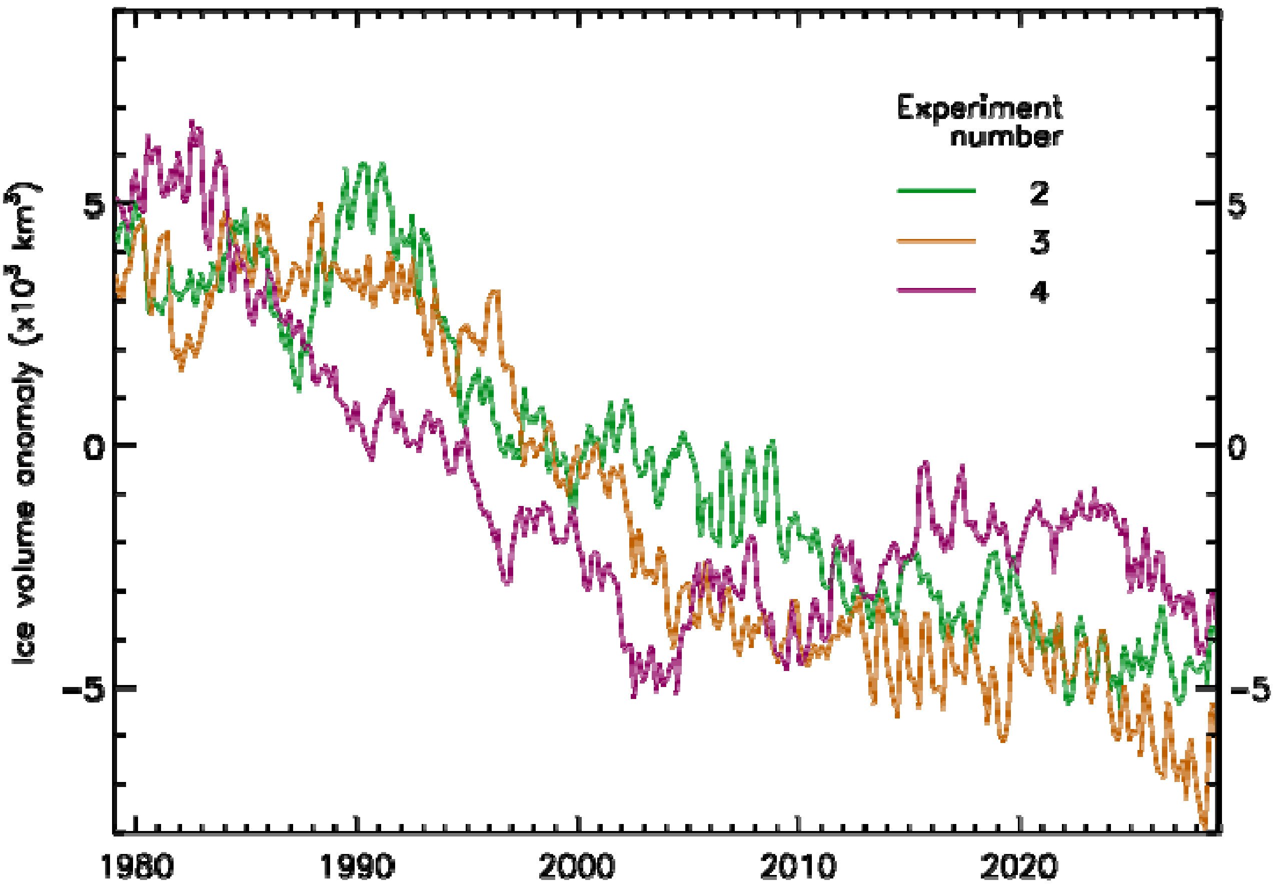

Figure 4.4.1: Monthly ice volume anomalies in the three members of the all-forcing (ALL) ensemble of HadGEM1 continued to 2030, relative to the 1979-2010 monthly means.

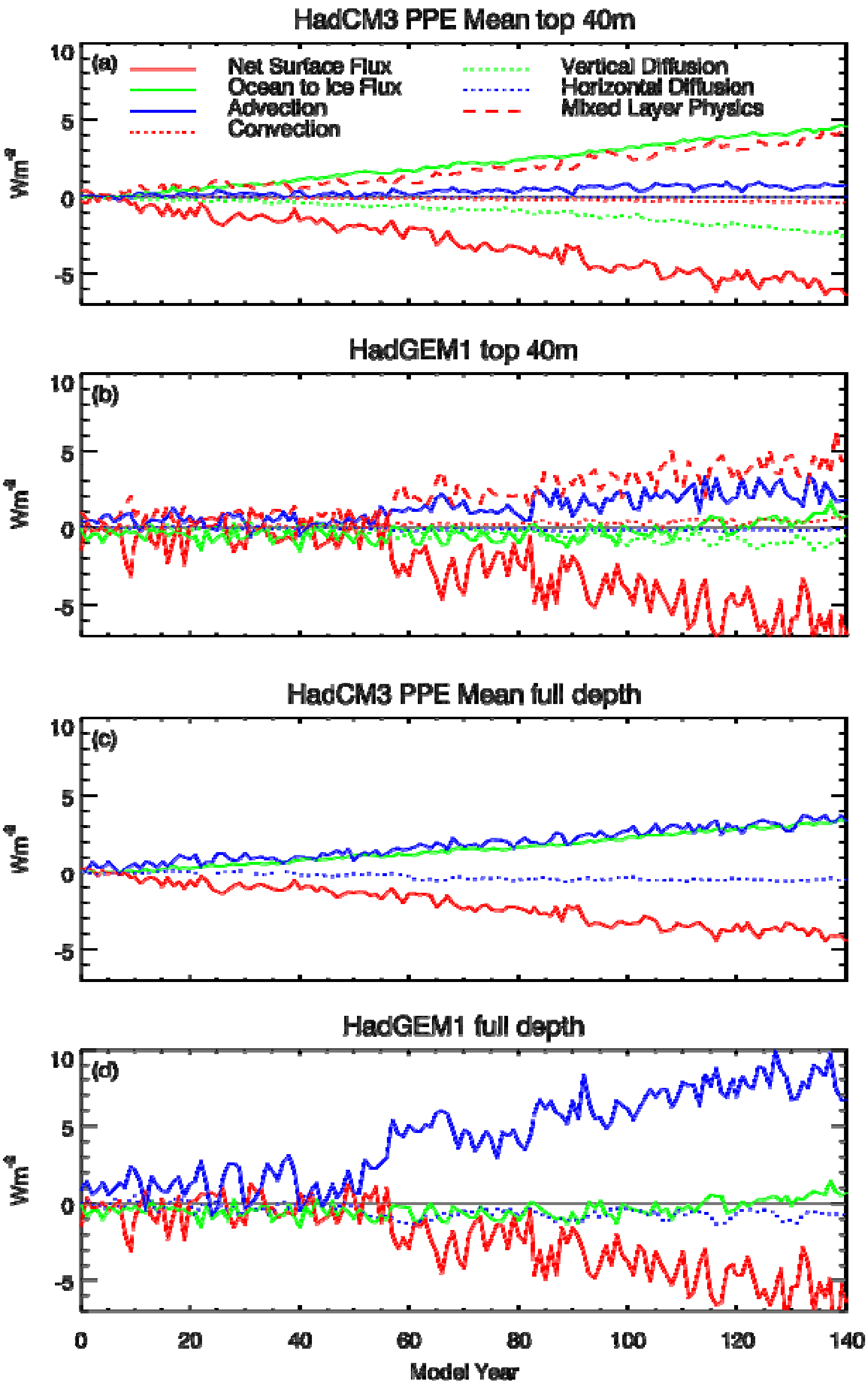

Figure 4.5.1: Time series of heat budget contributions (1% CO_2 – control) for the upper 40m of the HadCM3 PPE (a) and HadGEM1 (b) and for the full depth of the HadCM3 PPE (c) and HadGEM1 (d).

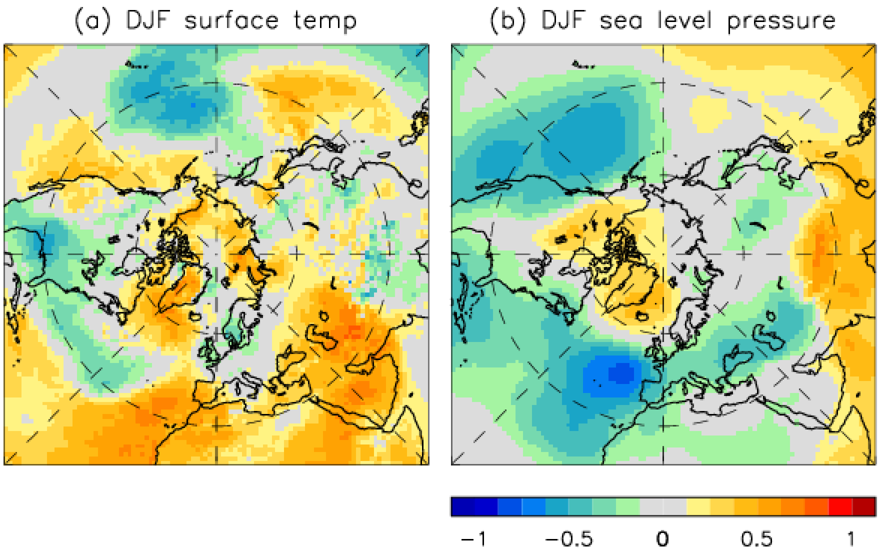

Figure 5.2.1: Potential impact of low sea ice cover analysed from HadGEM3 N216 control simulation. Composite maps showing anomalous (a) surface temperature and (b) sea level pressure averaged over December, January and February (DJF) for years when the preceding September to October Arctic sea ice cover is at least one standard deviation below average. Units are standard deviations.

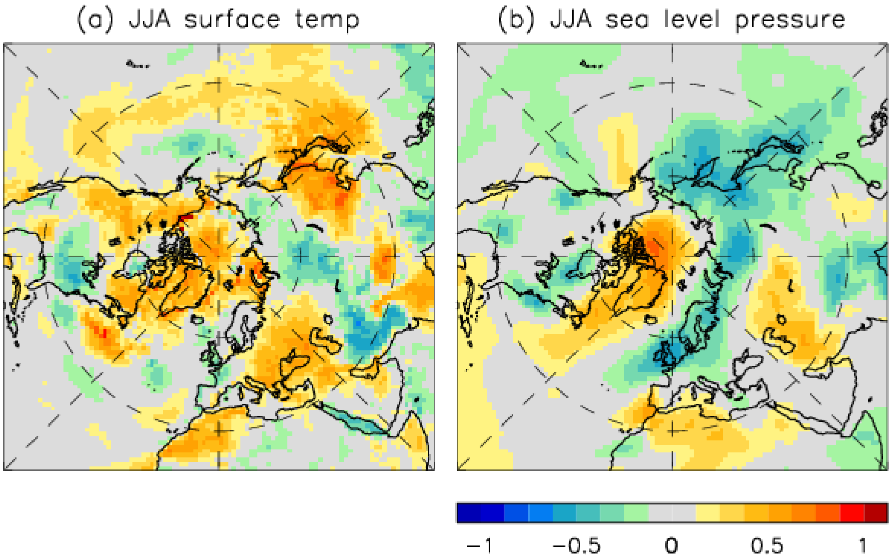

Figure 5.2.2: As Figure 5.2.1 but for summer (June, July and August, JJA) surface temperature and sea level pressure for periods when JJA sea ice is less than one standard deviation below average.

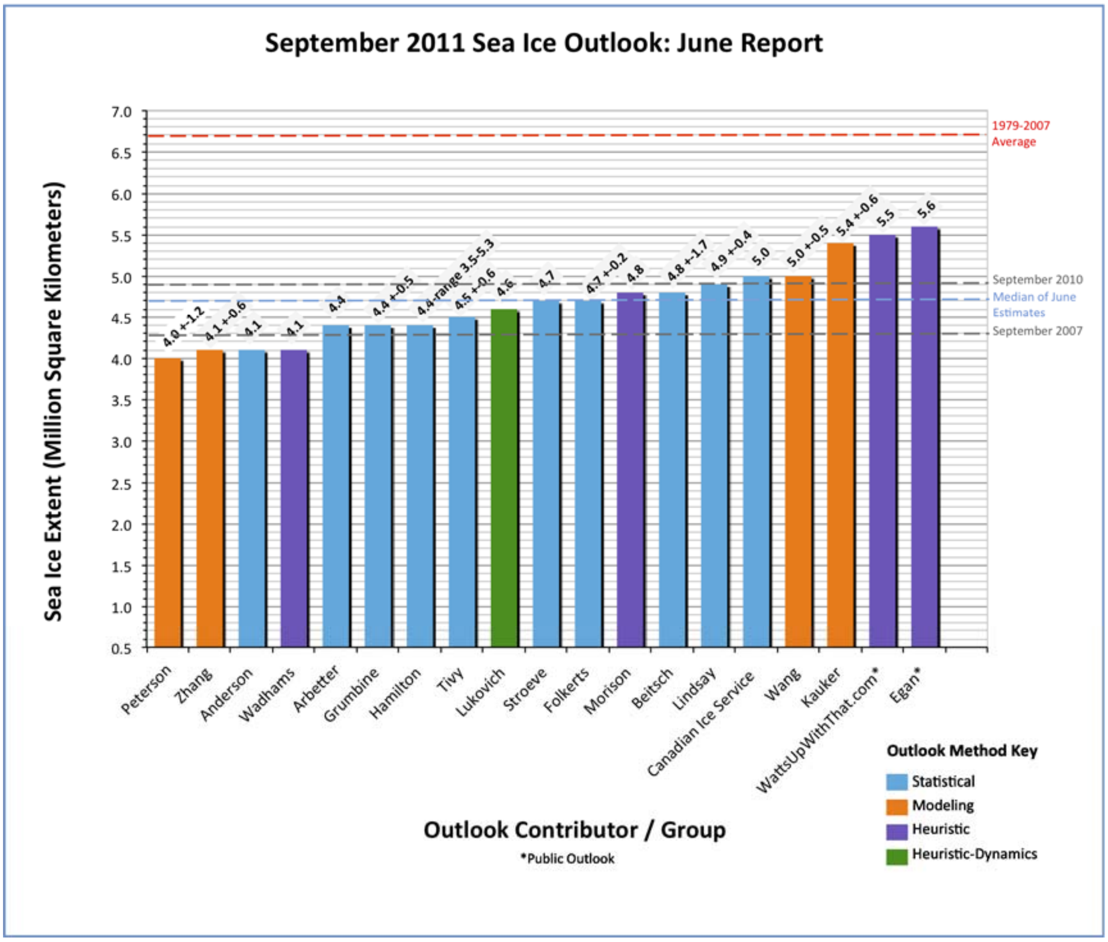

Figure 6.4.1: Estimates of September sea ice extent submitted to the SEARCH Sea ice Outlook, June 2011