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Impacts of climate change on Arctic sea-ice

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EXECUTIVE SUMMARY

Arctic sea-ice extent has declined at a rate of over 4% per decade since satellite records began in 1979. This rate is faster in the summer season (13% per decade in September) with a record low occuring in 2012. There is also evidence that the ice has thinned at a rate of approximately 60 cm per decade.

The September 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. Model studies suggest that some (5 to 44%) of the decline can be attributed to natural variability.

Models predict that the Arctic ocean will become ice free in the summer between 2030-2080.

Potential impacts of the reduction in sea-ice extent are both climatic (e.g. changes to the weather in the UK and Europe and the global climate) and socio-economic (e.g. new shipping routes, offshore mineral exploration).

Both improvements to models and a sustained observation system are required to reduce uncertainty in predicting changes to the sea-ice cover and its impacts and to better understand the physics of the atmosphere-ice-ocean system.

1. WHAT IS ALREADY HAPPENING?

Observations of sea-ice area and extent changes

The Arctic sea-ice cover has been declining during the satellite observational record (1979-present) (Figure 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 monthly ice extent has declined at a rate of 0.53 x 10^6 km^2 per decade (Figure 1), or 4.4% 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 0.88 x 10^6 km^2 per decade, or 12.8% 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 1979 to 1995 was 0.50 x 10^6 km^2 per decade, compared to 1.89 x 10^6 km^2 per decade between 1996 and 2012.

The 2013 seasonal minimum (September) ice extent was 5.35 x 10^6 km^2 (NSIDC, 2013), 1.72 x 10^6 km^2 above the record low value observed in September 2012. The last seven years have seen the seven lowest September ice extents recorded during the satellite era.

The decline in September ice concentration from 1979-2012 has been strongly focused on the Pacific side of the Arctic (Figure 2, West *et al.*, 2012), with the area of fastest loss (over 3%/year) between about 170-200°E, in the East Siberian Sea and Chukchi Plateau (Figure 3). Slower, but still substantial, rates of decline are observed north of Siberia in the Laptev and Kara seas. By contrast, September concentration north of 84°N 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.

Observations of sea-ice thickness changes

Unlike ice extent, where near continuous observations have been available since the 1970s, 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 1960s and 1990s revealed a 40% decrease in ice draft[1], although the data covered only

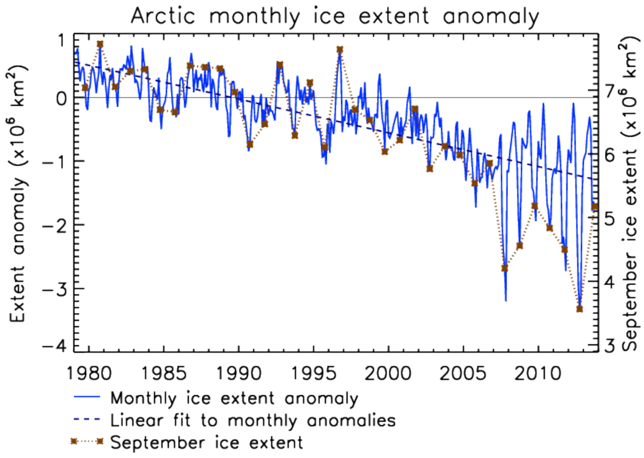


Figure 1: Monthly Arctic sea-ice extent anomalies (HadISST, Rayner et al.*, 2003), 1979-2013, with September actual ice extent. The anomaly for each particular month is calculated by subtracting from that monthly value the mean ice extent for that month between 1979-2010.*

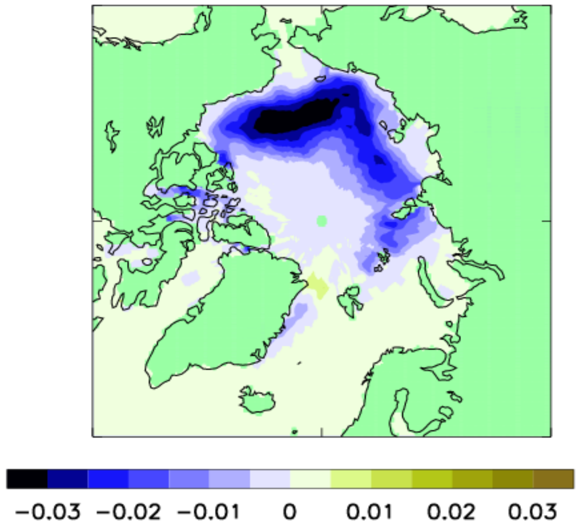


Figure 2: Linear trend (1979-2012) in September ice concentration (yr-1) from HadISST (Rayner et al.*, 2003). West* et al.*, 2012.*

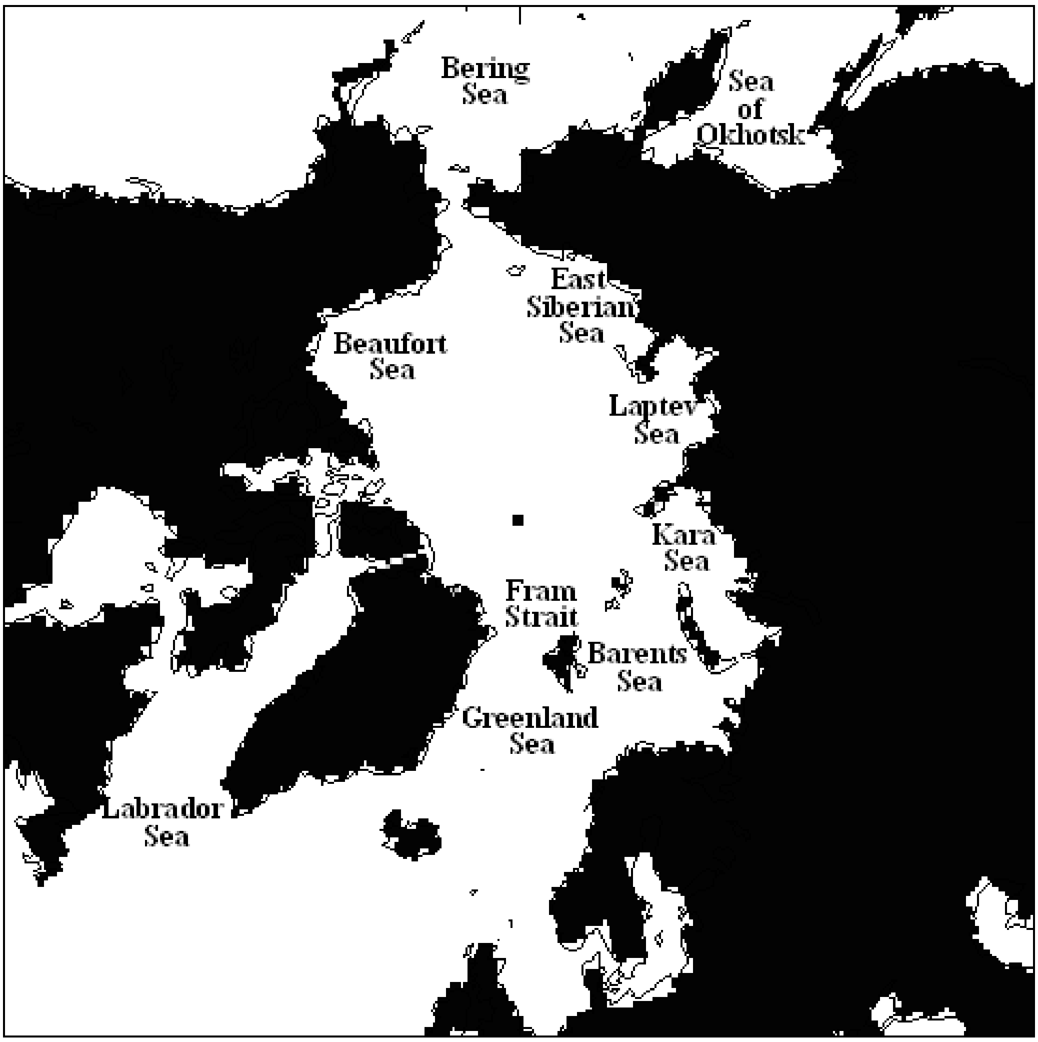


Figure 3: The Arctic Ocean, with its peripheral seas (McLaren et al.*, 2006)*

the central part of the Arctic (Rothrock *et al*., 1999). A later comparison of submarine transects between 2004 and 2007 revealed no change in 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 (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). 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 rate of thinning of 60cm per decade. Recent data from the CryoSat-2 satellite suggests that between 2010 and 2012 the equivalent rate of thinning was 75 cm per decade (Laxon *et al*., 2013) 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 CryoSat-2 should provide the capability to monitor changes in winter ice thickness over almost the entire Arctic.

Accounting for the changes in the Arctic 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 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[3].

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 (Maslanik *et al.*, 2007; Stroeve *et al*., 2008; Lindsay *et al*., 2009). 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.

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) relate 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.

Modelling studies have attempted to explain the potential significance of natural variability in accounting for the changes in sea-ice extent. Between 5-44% of the change can be attributed to natural variability. For example, Kay *et al*. (2011) show that modelled internal[4] variability explains 44% of the observed 1979-2005 September sea-ice extent loss. Day *et al.*'s, (2012) modelling study investigates the potential sources of this natural variability and suggests that between 1979-2010, 5-30% of the observed decline can be attributed to the natural cycle of the Atlantic multi-decadal oscillation (AMO)[5]. Chylek *et al*. (2009) also provide observational evidence that recent rapid warming of the Arctic is partly related to the AMO, which is also implicated in the last major Arctic warming in the 1930s. However, modelling representations of sea ice in climate models requires improvement (see next section).

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.

2. WHAT COULD HAPPEN?

Projections of seasonally ice free Arctic from climate models

The Coupled Model Intercomparison Project (CMIP5) models generally predict that the summer Arctic will be 'nearly' ice free (an ice extent of less than 1.0 million km^2) by the 2030s (Wang and Overland, 2012). In the UK Met office model, HadGEM2-ES, the September Arctic sea-ice extent

[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.
[3]Albedo is a measure of the amount of solar energy reflected from the Earth back to space.
[4]Defined as variability intrinsic to a climate state
[5]The AMO is a 65-80 year oscillation in the sea surface temperature in the North Atlantic [Schlesinger and Ramankutty, 1994], which is thought to be a response to Atlantic–Arctic salinity exchanges [Knight *et al*., 2005].

halves approximately every 15 years, and by 2030 most of the September ice has been lost. Figure 4 shows that, in only one of the Representative Concentration Pathways[6] (RCP2.6 simulation), which sees a peak in global temperatures at +2°C in 2040 and stabilisation thereafter, results in a sustainable amount (~1 million km²) of September sea-ice cover.

The future September sea-ice extent, depicted by the models that will be included in the IPCC Fifth Assessment report (AR5) (Figure 5), shows a continuous 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. Moreover, there are considerable uncertainties in the physics of these models, with the Arctic Ocean Model Intercomparison

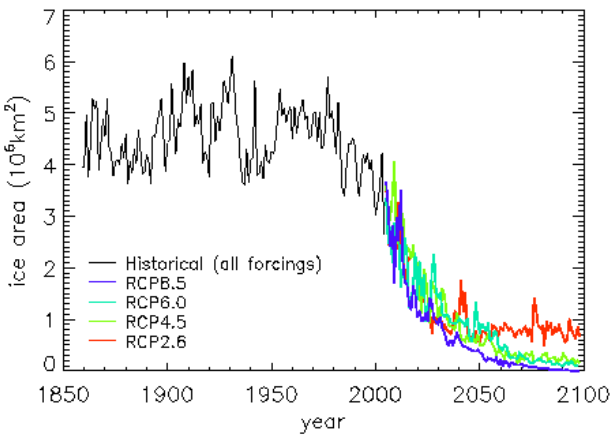


Figure 4: HadGEM2-ES projected September ice area in four future RCP scenarios.

project (Proshutinsky and Kowalik, 2007) demonstrating inconsistency between ice-ocean models in the way both their thermodynamics and dynamics are described. Maslowski *et al.* (2012) advocate the use of global Earth system models (GESMs), combined with regional climate models and an integrated Arctic observing system, to better understand the state of the Arctic sea-ice and its future trajectory.

Potential impacts of rapid change on the UK and European climate

The winters of 2009-10 and 2010-11 saw low temperatures and heavy snowfalls over much of the UK, and in summer, 2012, the UK experienced record rainfall. At the same time, Arctic sea-ice has been declining dramatically in extent. The diagnosis in the popular press and broadcast media of the proximate cause of these UK weather events has entailed the jet stream. Recent publications (Francis and Vavrus, 2012; Liu *et al.*, 2012), based on hypotheses developed from statistical correlations and evaluated using dedicated atmosphere-only model runs and analyses of reanalysis data respectively, described how a warming Arctic and the decline in sea ice might be linked to weather extremes through changes in the evolution of regional atmospheric circulation patterns, including impacts on the jet stream. However, Sutton and Dong's (2012) statistical correlation links the recent wet UK summers to the high relative warmth in the Atlantic Ocean.

It is possible that continued low Arctic sea-ice during the coming years to decades might increase the probability of cold winters and wet summers in the UK and northern Europe. These effects would in some cases partly counteract the more direct, warming 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 (Francis *et al.*, 2009; Strong *et al.* 2009; Overland and Wang, 2010; Wu and Zhang, 2010) and modelling studies (Alexander *et al.,* 2004; Deser *et al.*, 2004, 2007; Magnusdottir *et al.*, 2004; 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 some of these features are not well reproduced in all current climate models.

Some of these results are tentative and have not yet been robustly reproduced across a broad range of climate models. 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.

The majority of the text in this report has been taken from the Hadley Centre technical note "Report on the Assessment of Possibility and Impact of Rapid Climate Change in the Arctic" (Hewitt *et al.*, 2012).

3. KNOWLEDGE GAPS

a. To better predict future change we need an improved understanding of the physics (and biogeochemical processes, including their feedbacks with physics) of the Arctic system and its teleconnections, which can be achieved through process studies combining modelling and observations.

b. A sustained Arctic atmosphere-ice-ocean observations network is required to better understand the physics of the system and to provide the initial conditions for model simulations.

c. We need an improved understanding and quantification of internal variability and uncertainty in climate models.

[6]The Representative Concentration Pathways are four trajectories of atmospheric greenhouse gas concentration used to drive climate model simulations for IPCC AR5. They are labelled based on how much heating they would produce at the end of the century — 8.5, 6, 4.5 and 2.6 watts per square metre (W m^{-2}). Four trajectories were chosen to avoid the common misconception that the middle scenario is the most likely.

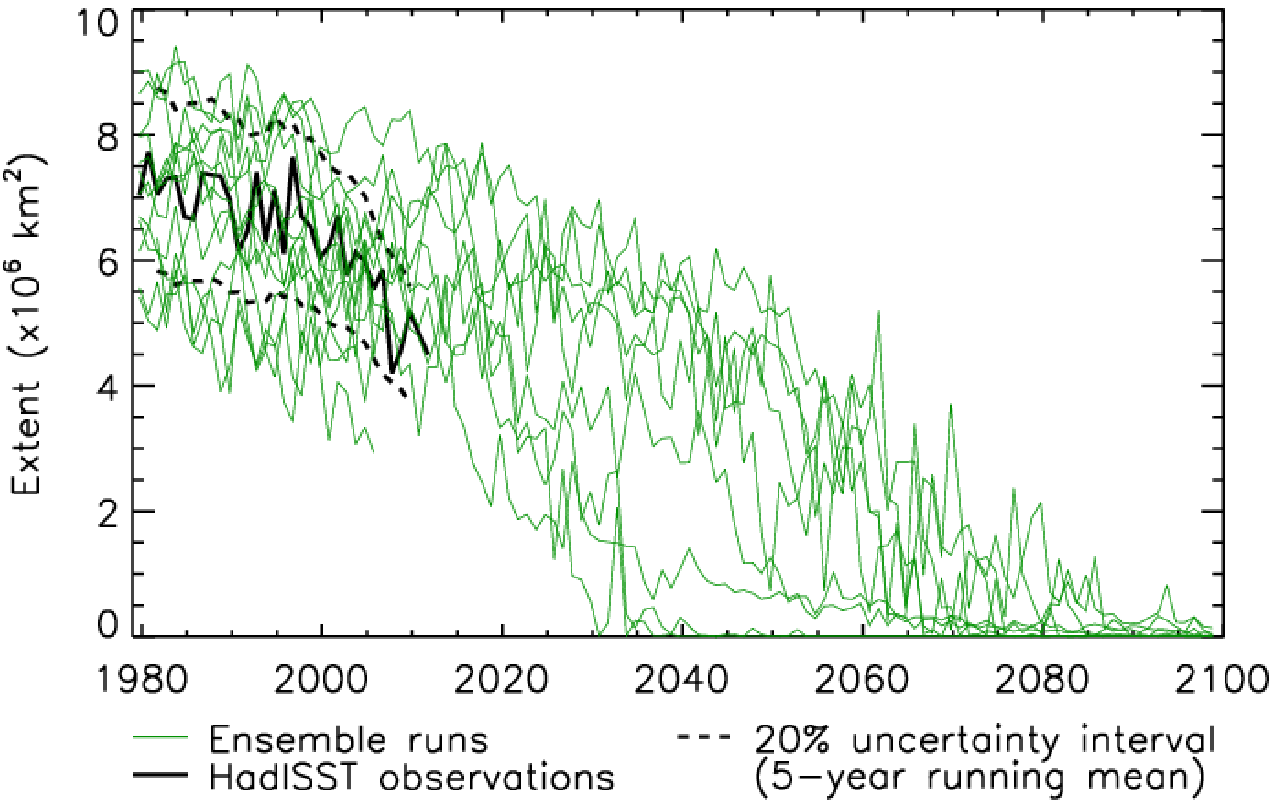


Figure 5: September Arctic sea-ice extent in the AR5 multi-model ensemble of experiments, historical forcings (anthropogenic, solar and volcanic) to 2005, followed by RCP8.5 forcing to 2100. The observed sea-ice extent (HadISST; Rayner et al.*, 2003) is shown in black.*

4. SOCIO-ECONOMIC IMPACTS

a. Climate change in the Arctic is predicted to increase accessibility to offshore exclusive economic zones while accessibility inland will suffer due to melting permafrost (Stephenson *et al.*, 2011). This could affect both tourism and commercial shipping.

b. The sea-ice retreats opens up the possibility that Arctic states will consider offshore mineral exploration with geopolitical implications (Young, 2011).

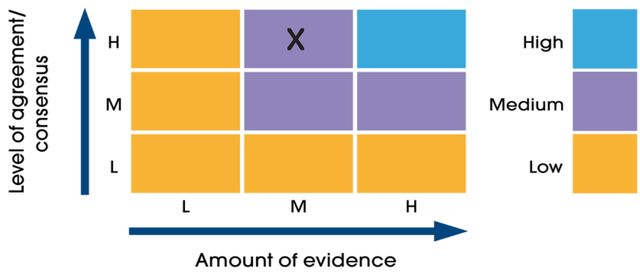
c. Sea-ice retreat will change ecosystems and fisheries (Hassol, 2004).

d. The Arctic is likely to attract substantial investment over the coming decade, potentially reaching $100bn or more (Emmerson and Lahn, 2012). With concomitant increase the insurance industry.

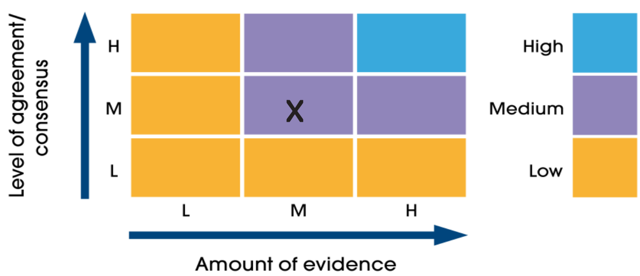
5. CONFIDENCE ASSESSMENT

What is already happening?

The observational evidence is starting to mount, but longer times series are needed for both extent and in particular thickness. In addition we need to observe related variables so we can understand the causes and consequences of change to the sea-ice cover. An Arctic atmosphere-ice-ocean sustained observation system is required.



What could happen?



Prediction of the fate of the Arctic sea-ice cover relies upon models which have an inherent uncertainty due to limitations in both the model representation of the physics of the atmosphere-ice-ocean system and our understanding of the physics of the system, and insufficient knowledge of the initial state of the system. Model intercomparison projects, sensitivity and process studies are required to improve the model representation of the physics of the system and our understanding of the physics of the system. A sustained observation system, as outlined above, is also required for understanding the initial state and physics of the system.

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Dedicated to Katharine Giles and Seymour Laxon.

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