Identifying Uncertainties in Arctic Climate Predictions

Final Project Report for NERC

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Executive Summary

We have examined the uncertainty (spread) in future projections of Arctic climate change. Our conclusions are:

- There is considerable uncertainty in projections of the changing Arctic climate. The majority of this spread is due to uncertainties related to variations in model structure and sub-gridscale parameterisation schemes rather than intrinsic climate noise.
- Both Sea Ice Volume and Northward Ocean Heat Transport into the Arctic are significant factors in the uncertainty in projections of future Arctic climate change.
    - The uncertainty due to sea ice volume is likely related to uncertainties in sea ice albedo parameterisation.
    - The uncertainty in northward ocean heat transport into the Arctic is likely due to structural variations between models.

There is considerable scope for reducing these uncertainties and improving future projections of Arctic change by:

- Better constraining sea ice volume climatologies in models by
    - Better observational estimates of sea ice volume.
    - Better constraints on ice albedo parameters e.g. with better ice albedo observations.
- Better constraining northward ocean heat transports into the Arctic by better long term observational estimates of heat transports into the region.

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Introduction

The Arctic is a region in which climate change is expected to produce very rapid change; in the form of rising temperatures, and other global pressures. This situation may lead to a step change within the Arctic system associated with rapidly declining summer sea ice and melting permafrost, resulting in major impacts both within the Arctic and more widely within the Earth System, via physical and biogeochemical feedbacks. Improvements in our predictive capability within the Arctic rely on the quantification and understanding of the uncertainties involved and the detailed modelling of these and other important climate processes within the Arctic. This report summarises the work that was carried out for the **Identifying Uncertainties in Arctic Climate Predictions** scoping study for the NERC Arctic Research Programme.

Goal of this project

The goal of this project is to quantify and understand the uncertainties in current projections of Arctic climate change. We use a consistent methodology to assess uncertainty for all the key Arctic climate variables across two independent climate model ensembles. This report aims to quantify the uncertainties for processes that are currently resolved in the IPCC AR4[3] generation of coupled climate models. This report does not attempt to estimate the complete uncertainties (i.e. the known unknowns e.g. permafrost, and the unknown unknowns); rather it acts as a guide to reducing uncertainty where we can, via improved processes in climate models.

[3] See Appendix for details of the IPCC AR4 ensemble.

Processes in Arctic Climate

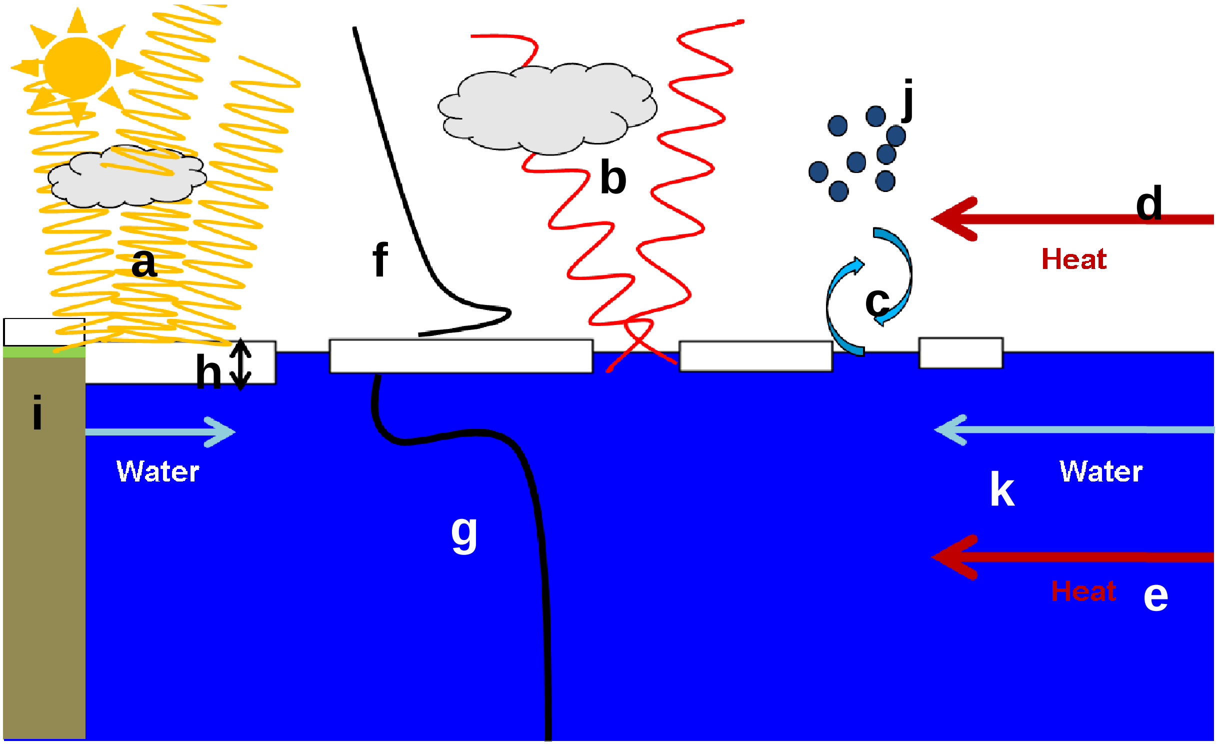

Figure 1: Key processes governing Arctic climate. a) Net shortwave (SW) solar radiation (modulated by scattering of radiation by clouds and surface albedo) b) Net longwave radiation emitted by surface and by clouds c) Turbulent (sensible + latent) fluxes d) Atmosphere heat transport e) Ocean heat transport f) Atmosphere temperature profile g) Ocean temperature/salinity profile h) Sea ice, thickness and extent i) Land surface processes j) Precipitation k) Freshwater flux e.g. from rivers.

Climate within the Arctic is an emergent property from a number of processes (Figure 1). The climate is often defined by the temperature and salinity profiles in the ocean and the temperature and humidity profiles in the atmosphere. The structures of both profiles are highly seasonal, and changes in the annual mean properties likely stem from a change in seasonality arising from a change in the forcings.

The climate system has strong feedbacks with cloud cover controlling the surface heat fluxes, and latent heat release in the atmosphere, which in turn adjust the profile. The ocean profiles are adjusted by sea ice melt, resulting in fresh water and solar (SW) input at the surface, these stratify the ocean layer increasing the surface temperatures and creating more ice melt. The global response to increased CO_2 can alter the heat transport to the Arctic resulting in different forcings in both the ocean and the atmosphere. However, the Arctic changes can feedback on the heat transports by changing the northward global temperature gradient. Processes over land also play a key role. A retreat of the seasonal snow cover reduces the land surface albedo, and melting permafrost increases the availability of soil moisture for evaporation. Changes to the freshwater budget in terms of precipitation and river runoff can alter the ocean salinity.

Known processes missing from models

Some processes that occur within the climate system are simply not included within the generation of climate models used for the IPCC AR4 (see appendix and Randall et al. 2007). For example the processes that occur within the shelf seas of the Arctic are still not resolved in the models and the land surface schemes, due to a lack of vertical depth in the soil, are not able to represent the permafrost.

Other areas of current development of climate models, which are not included in the AR4 set of models[4], are earth system components such as interactive chemistry and biogeochemistry.

All of these missing processes will have an impact on the hydrological and carbon cycles in the climate system and are therefore an uncertainty we are unable to quantify in this report.

Model Uncertainty

There are four sources of uncertainty in climate model projections of Arctic climate:

- **Scenario uncertainty** - Future levels of greenhouse gases.
- **Structural uncertainty** - The different methods different models use to represent the same physical process e.g. Model resolution, coordinate systems (constant density vs. constant height vertical).
- **Parameter uncertainty** - The value of a parameter within a parameterisation (e.g. surface ice albedo) chosen from within the given observational range.
- **Intrinsic internal variability** - The inherent variability, or noise, within the climate system, due to its chaotic nature.

In this report we will not examine scenario uncertainty since this is in the most part defined by future economic factors; such factors lie outside of current coupled climate models (hence can be considered an external forcing). Improvements in climate models are unable to address this source of uncertainty. We therefore eliminate this source of uncertainty by examining the behaviour of the Arctic climate when subjected to a specific level of greenhouse gases rather than at a specific point in future time[5]. Hence we will consider the uncertainty, or the *spread*[6] in projections of

[4] It should also be noted at this point that due to limitations in the data archived from the IPCC AR4 ensemble there are some processes which are present in the models but it has not been possible to analyse in this study. e.g. snow on land.

[5] Here we assume that the climate response is path independent – i.e. that the climate responds to the current levels of CO_2 – rather than the rate at which that level was achieved.

Arctic climate change when the concentration of CO_2 is double that of pre-industrial[7] times. When we are considering how we might improve model predictions it is structural and parameter uncertainty that we wish to reduce. Any reduction in uncertainty is limited by the model internal variability.

Model Parameterisation

Many important climate processes cannot be modelled explicitly; often they occur on a spatial scale (e.g. convection) or timescale (e.g. cloud microphysics) that is below the resolution of the model. Therefore such processes need to modelled in a simplified for so that a climate model can represent the impact on the climate system. This may mean the processes need to be modelled *statistically* or there is a generalisation of a process for an entire model grid box. Such simplified models are termed *parameterisations*. For example, the surface albedo within the Arctic varies dramatically within an area the size of model grid box. Even if an entire grid box was full of sea ice there would be variations in albedo due to pooling of water on the ice, leads etc. Therefore over the tens of km represented in one model grid box a simplified or "parameterised" version of the real physical processes is applied. Such parameterisations may contain parameters that are only weakly constrained by observations. Such parameters are then open to use as a means to tune models to observed climate.

Uncertainties in Key Variables and Model capabilities

In this section we briefly outline the observations for key Arctic quantities and compare them with model means and spread6 for the IPCC AR4 ensemble. A more detailed discussion of the model means and spreads will be presented in a subsequent section.

Surface Air Temperature

Surface Air Temperature (SAT) within the Arctic is the product of a complex balance of Arctic processes. Consequently there is a large spread of mean Arctic

[6] We will commonly refer to the spread in this report. We define this as one standard deviation of a given variable computed for all models in a given ensemble of models. We also use this as our definition of *uncertainty*.

[7] Three of the IPCC AR4 models use present-day concentrations of CO_2 in their controls. This will not affect the value of the radiative forcing between experiment and control, which depends on the ratio of the CO_2 concentrations. It may, however, influence the mean climate state in the control – which, we will show, can be important in defining the change in Arctic climate.

temperatures in the IPCC AR4 ensemble (–10.2 ± 3.8℃ , Liu et al., 2008)[8], however, this is consistent with observational estimates, which range from –9.4 to –7.9℃ (Liu et al., 2008). The seasonal cycle is reasonably well represented in the IPCC AR4 ensemble, but the spread is far larger in winter than in summer – likely due to the different processes that control SAT during these two seasons. The regions of greatest spread in the IPCC AR4 ensemble (Barents Sea, Greenland Sea, North Pole and Baffin Bay) are consistent with the model spread in sea ice cover (Liu et al., 2008). This may in turn be due to variations in the impacts of Atlantic Ocean heat transport into the region (see below).

Temperature change in the Arctic is 2 to 3 times greater than in the global mean, a characteristic referred to as polar amplification.

Precipitation

Precipitation is one of the main components of the freshwater budget in the Arctic. The IPCC AR4 ensemble mean (0.8 ± 0.4 mm day^{-1}) is comparable with the reanalysis data (0.9 mm day^{-1}), and the seasonal cycle is in qualitative agreement with the observations, but with a smaller amplitude (Kattsov et al., 2007). For the 21st century, precipitation in the Arctic region is projected to increase by 16%–57% (SRES A2 scenario) with a polar amplification of the global change, due to a warmer atmosphere being able to hold more moisture. The precipitation increases are larger in winter than summer. River discharge into the Arctic is also projected to increase by around 20%. The IPCC AR4 ensemble mean precipitation minus evaporation over the Arctic is slightly higher (0.45 mm day^{-1}) than the observed estimate (0.38 mm day^{-1}) (Kattsov et al., 2007).

Sea ice

The extent and thickness of sea ice within the Arctic is controlled by: freeze-melt processes; convergence (driven by wind stresses and ocean currents) and ice transport out of the Arctic. The thermodynamic processes are considered to drive the majority of the seasonal variation in sea ice extent throughout the year (Barry et al., 1993, Holland et al., 2010).

Arctic sea ice extent varies seasonally with a maximum occurring in March (~15 x 10^6 km^2) and a minimum in September (~7 x 10^6 km^2). The September ice extent has declined over the latter part of the 20th century at a rate of 2.4–3.3x10^5 km^2 $decade^{-1}$ (Arzel et al., 2006, Parkinson et al., 2002). The AR4 ensemble hindcasts of the late 20th century reproduces many features of the observations, although the model spread is large. The magnitude of the sea ice annual cycle is well reproduced, but the exact timing of the summer ice minimum and the length of the melt season (3-5 months) varies between the models (Parkinson et al., 2006, Holland et al., 2010).

[8] Note, this figure differs from than given in Table 1, but this is likely due to the differences in the definitions of the Arctic region. Mean Surface temperature is highly dependent on this.

The AR4 ensemble produces a decline of 2.1 ± 2.2x10^5 km^2 $decade^{-1}$ (Zhang and Walsh, 2006) over the recent past, and a further decline of 3.6 ± 1.9 x 10^6 km^2 over the 21st century (SRES A1B, Arzel et al., 2006) pointing to an ice-free Arctic by the end of the century. The net transport of ice out of the Arctic, via the Fram strait, also varies widely between models (Holland et al., 2010).

Ice thickness observations are sparse (mainly from submarine sonar sections), but Laxon et al., (2003) report that the winter mean ice thickness across the Arctic is ~2.7 ± 0.3m. The AR4 ensemble has an average annual mean thickness of 2.0 ± 0.8m (Holland et al. 2010), where the range may be attributed to the sophistication of the ice model (both thermodynamic and dynamics) and biases in the atmospheric models (Gerdes and Köberle, 2007). The decline in sea ice volume over the 21st century is projected to be 13.1 ± 5.8 x 10^3 km^3 (Arzel et al., 2006).

A number of studies have previously examined the causes of this model spread within the Arctic (see Arzel et al., 2006, Zhang et al., 2007, Holland et al., 2010, Holland et al., 2003, Zhang, 2010, Boé et al., 2010, Boé et al., 2009 and Ridley et al., 2007).

For a more extensive review of the literature on model and observational comparisons in the Arctic please see the literature review associated with this study (Keeley et al., (2010).

Methodology

Many definitions of the Arctic exist. Throughout this report we define the Arctic as the region north of 70˚N. All area average quantities are therefore calculated between 70˚N and 90˚N.

In order to compare the different sources of model uncertainty, we investigated two ensembles: a multi-model ensemble (IPCC AR4), and a perturbed-parameter ensemble of the Hadley Centre model HadCM3, to be referred to as the THC-QUMP ensemble. The latter includes parameter and internal uncertainty, the former structural uncertainty also. More details for these ensembles can be found in the appendix. The parameter and structural uncertainty in a given variable is calculated as the spread (standard deviation) within the THC- QUMP and AR4 ensembles respectively.

Model Experiments

We use a collection of models (an ensemble) to examine the impact of model variation on Arctic projections. For each model in the ensemble we perform two experiments[9] a *Control* experiment and a *2xCO₂* experiment. In the *Control* experiment the atmospheric concentration of carbon dioxide (CO_2) is held at a constant level (usually pre-industrial levels of 285 ppmv) throughout the model experiment; any variations in the climate system seen in this experiment are hence solely due to internal variability, random fluctuations due to the chaotic nature of the system. In the *$2xCO_2$* experiment the carbon dioxide concentration is increased at a rate of 1% per annum starting from the *Control* experiment concentration. This means that at around year 70 of the *$2xCO_2$* experiment the model reaches a carbon dioxide concentration that is double that of the control run. The difference[10] in a quantity (e.g. surface temperature) between the two experiments ($2xCO_2$ – Control) then gives the response of the system to the increased levels of CO_2.

A note about ice extents: data availability constraints meant that when calculating mean ice extents across periods of 20 years, the method used was to take the mean ice concentration across the whole 20 years, and then integrate the area with a concentration greater than 0.15. Note that this method produces a different result to that of calculating monthly ice extents directly from monthly concentration fields, and taking the mean of these.

Estimation of Internal Variability, Structural and Parameter Uncertainty

To determine whether the changes ($2xCO_2$ – Control) in Arctic quantities are significant (large enough to be detected) we need to estimate the internal variability within the climate system. The internal variability, on a given timescale, of a particular variable is determined by considering the spread of the values of within the *Control* experiment.

To achieve an estimate of the *ensemble internal variability*:

1. For each model of the ensemble we calculate the variance of the Control run.
2. We calculate the mean variance across the ensemble.
3. We take the square root of the mean variance; thus giving us the mean standard deviation; the *ensemble internal variability*

Uncertainty in the change

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[9] In this document model experiment refers to an *integration* of the climate model.

[10] In terms of assessing the climate change response, unless otherwise stated, results are for the difference of 20 year averages centred on year 70 (years 61-80) of the control and $2xCO_2$ experiments. We take the same years to analyse in the model control and $2xCO_2$ experiments to minimise the impact of any potential model drift (i.e. in some climate models, the climate changes very slowly over time in the absence of external forcing agents (e.g. increased concentrations of CO_2.

As well as the spread in the model control climatologies, the *ensemble internal variability,* we are also interested in the spread in the projected change. To calculate the spread in the projected change within an ensemble:

1. We take time averages within the control experiment and 2xCO_2 experiment (e.g. 20 year means) around the year of CO_2 doubling (year 70).
2. For each model in the ensemble, we calculate the change (2xCO_2 – Control).
3. We calculate the mean of the variance in the change across the ensemble.
4. take the square root of the mean variance; thus giving us the mean standard deviation; the *ensemble spread in the change*

Results

We analyse the AR4 and THC-QUMP ensembles to assess the causes of uncertainty (the spread6) in both the model control climatology[11] and the climate change ($2xCO_2$) response (the spread in the difference between $2xCO_2$ and Control experiments). We analyse the Arctic climate system in terms of forcings and feedbacks within the Arctic and Arctic heat budgets. Finally, to provide some formal assessment of the uncertainties within the Arctic, we analyse the relationships between different processes in the Arctic.

Climatology and ensemble spread in key climate variables

In this study we are principally concerned with the spread in the projected *changes* in the Arctic under a doubling in the concentration of atmospheric CO_2. However, there is also a spread in the *climatologies* of the control experiments of the models, from which the changes are measured. This spread in climatologies would be unimportant if each model responded linearly to a doubling of $CO_{2.}$ However, results presented later will show that this is not the case always the case (see page 24), and for a number of variables the climatology is important in determining the magnitude of the projected changes. Hence we briefly outline the spread in the climatologies. The main differences in the AR4 model climatologies are well documented in the IPCC report (Randall et al., 2007). In Figure 2 we present a 20 year mean sea ice fraction from the control experiment of 11 of the IPCC AR4 models, together with the mean observed sea ice fractions (1960-1979). The figure shows that there are a wide range of sea ice extents within the IPCC AR4 ensemble, with one model (IAP-FGOALS) having annual mean sea ice as far south as the UK. The plot also highlights the resolution differences across the ensemble and the subtleties of regional differences that may be hidden by analysis of the climatology within our chosen definition of the Arctic (e.g. >70ºN).

[11] Climatology is defined as the long term mean of a climate variable.

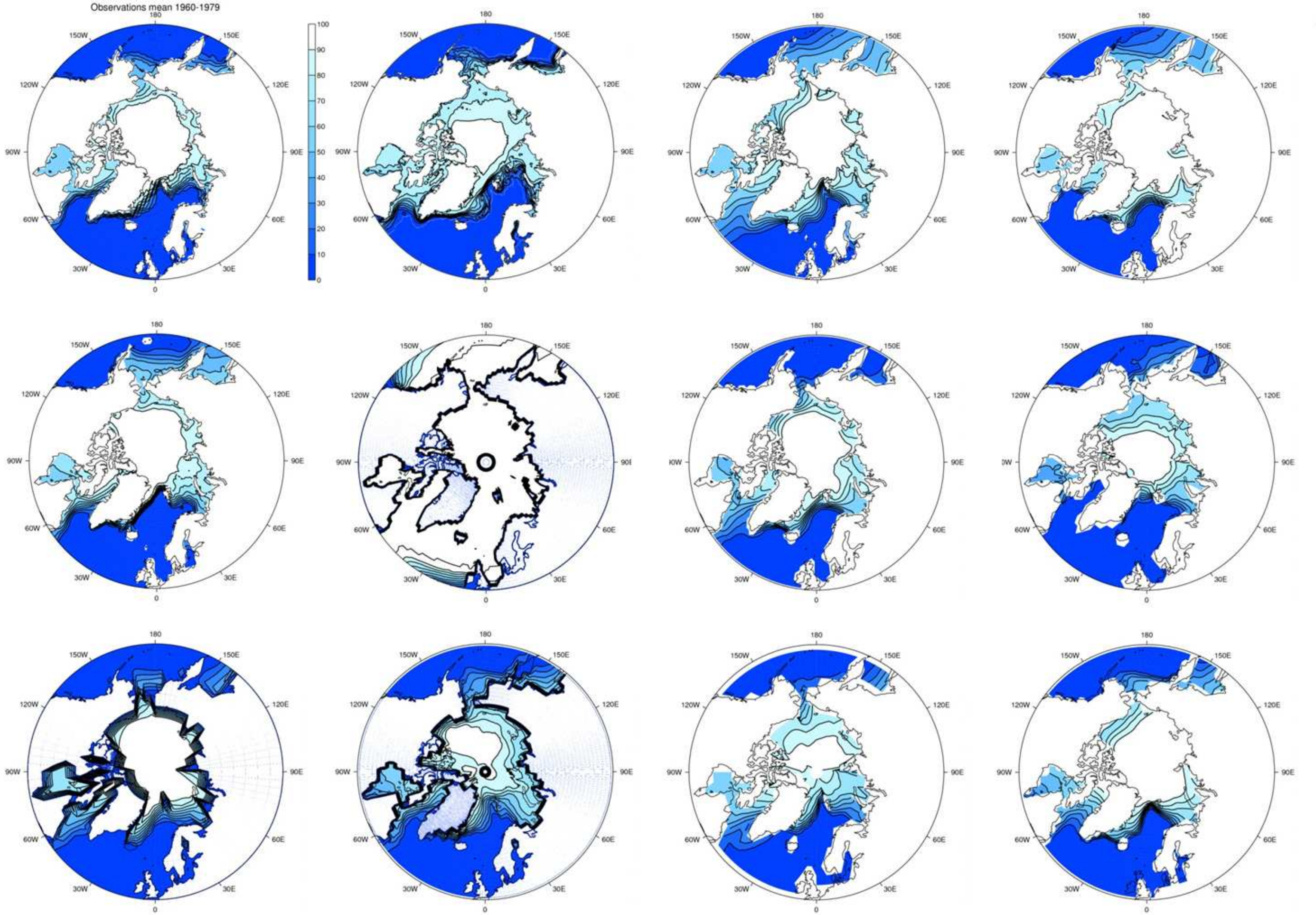

Figure 2: Climatology of sea ice fraction in the Control experiment for 11 of the IPCC AR4 models. Observed Sea ice fraction (1960-1979).

Ensemble Internal Variability

Table 1 shows estimates of the *ensemble mean* and *ensemble spread* for several key Arctic variable in the control experiments of each ensemble (IPCC AR4 and THC-QUMP). The *ensemble mean* of a variable (e.g. ice volume) is defined as follows: for each model in the ensemble, compute the mean of the variable between years 61 and 80 (centred on the doubling year, 70). The ensemble mean is then the mean of all these means. *Ensemble spread* is then the standard deviation of these means. Table 1 also shows the *internal variability* – this is defined as follows: for each model in the ensemble, compute the variance of the variable (e.g. Ice volume) in the control. The *internal variability* is then the square root of the mean of all these.

The ensembles have mean values that are generally consistent with each other – all quantities are within their associated uncertainty (except for mixed layer temperature) and are comparable to the observations[12].

Some quantities have a large ensemble spread (uncertainty, one standard deviation across the ensemble), for example, sea ice volume[13], and mixed layer temperatures. Whilst others, notably surface air temperature and precipitation, have a smaller ensemble spread. Hence some Arctic quantities are modelled more precisely than others. Some of this spread will be due to systematic differences between models but a portion will be due to sampling of the intrinsic *internal variability* within each control. We have estimated this contribution for each model. It is clear that, although this contribution is larger for some quantities than others, it is not the dominant source of spread in the ensemble (except perhaps for sea ice extent in the THC-QUMP ensemble[13]). In other words, the ensemble spread in these variables is mostly due to the parameter and structural uncertainties contained within the ensemble, and is not solely and artefact of the sampling of internal variability. Note also, that the spread in quantities within the THC-QUMP ensemble are always smaller in magnitude than those in the IPCC AR4 ensemble. This implies that the parameter uncertainty is not likely to entirely explain the spread in the IPPC AR4 ensemble, and that structural uncertainty must play a role (but see footnote on page 36).

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[12] Comparison between observations and the ensembles is limited because the values quoted in the literature use varying definitions of the Arctic region, not always consistent with our definition of >70˚N.

[13] It should be noted that the small spread in ice extent is due to our definition of the Arctic; within the control run most models have extents further south than 70˚N. This also explains why the internal variability appears to be the dominant source of uncertainty for this variable.

Ensemble	Climatology and variance of Arctic variables in the control experiments (20 year means)				
	ice extent $/10^6\ km^2$	**ice volume $/10^3\ km^3$**	**surface air temperature (SAT) /°C**	**precipitation (mm/year)**	**mixed layer (70m) temperature /°C**
THC-QUMP (parameter uncertainty)	10.8 ± 0.29 **3%**	14.5 ± 6.41 **44%**	-14.03 ± 2.48 **18%**	315. ± 31. **10%**	-0.07 ± 0.04 **48%**
THC-QUMP Contribution from internal variability, $\boldsymbol{\sigma_v}$	± 0.15 *54%*	± 0.46 *7%*	± 0.26 *9%*	± 4.67 *15%*	± 0.01 *33%*
IPCC AR4 (structural +parameter uncertainty)	10.70 ± 0.61 **6%**	19.65 ± 9.21 **47%**	-16.45 ± 3.24 **20%**	295 ± 72 **24%**	-1.14 ± 0.45 **40%**
IPCC AR4 Contribution from internal variability, $\boldsymbol{\sigma_v}$	± 0.04 *7%*	± 0.37 *4%*	± 0.18 *6%*	± 3.9 *5%*	±0.02 *4%*
Observations	10.1[a]	29.0[b]	-8.62[c]	234[d]	*N/A*

Table 1: Table shows *x*±*y*. Where *x* is the mean (and *y* the standard deviation) of key Arctic parameters across the ensembles for the control experiments. Numbers in **bold** show ***100*y/x***, for that ensemble. Numbers in *italics* show the contribution from internal variability (σ_v) as a percentage of the uncertainty in the mean (e.g. $100*\sigma_v/\sigma$) for that ensemble. This contribution was calculated by computing the variance (σ_k^2) of the control experiment for each model (k) (years 1-80) and then taking the mean of the variances for all models. This mean variance (σ_m^2) was then used to estimate the spread in the differences between the 20 year means. I.e. $\sigma_v=(2/20)^{\wedge}0.5\ \sigma_m$. Observations are derived as follows: a) Computed from Observed sea ice coverage (HadISST) >70ºN (see http://hadobs.metoffice.com/hadisst). b) An estimate created by multiplying the Zhang and Walsh, (2006) figure for extent (10.6 x 10^6 km^2) by Laxon et al., (2003) estimate of *winter time* mean ice thickness in the Arctic (2.73m), hence this should be regarded as an upper bound on the true volume. c) Mean of Station observations and Reanalysis values given in Liu et al., (2008). Note – Liu et al define the Arctic as the region bounded by the mean sea ice extent, whereas we choose latitudes >70ºN d) Kattsov et al., (2007). **Note:** precipitation has been scaled up from mm/day to mm/year, in all cases, by multiplying by 360.0 (the number of model days in HadCM3). See Appendix (page 40) for definitions of Artic variables.

Mean and Spread in projected changes under 2xCO_2

The spread (one standard deviation) in the projected changes in key Arctic variables, for both the IPCC AR4 and THC-QUMP ensembles are documented in Table 2. The table shows that there is a considerable variation in the magnitude of the uncertainties across variables of interest. In both ensembles, the uncertainty in sea ice volume changes is about half the size of the mean change. However, changes in surface air temperature are much better constrained, with uncertainties less than a third of the mean change in both ensembles. For some variables (e.g. sea ice volume) the THC-QUMP uncertainty/spread is comparable to that in the IPCC AR4 ensemble. Hence the sampling of parameter uncertainty (THC-QUMP) results in a similar uncertainty range for projections of ice volume change as does the sampling of structural and parameter uncertainty (IPCC AR4). We cannot however, confidently conclude that parameter uncertainty is the dominant contributor to uncertainty in the IPCC AR4 projections, since the parameter and structural uncertainties in the IPCC AR4 ensemble are very likely to be anti-correlated (see footnote 18 on page 36.). Nevertheless, we can conclude that future constraints on model parameter uncertainty are likely to lead to a reduction in the uncertainty of future projections of sea ice volume.

The situation is somewhat different for surface air temperature – the sampling of parameter uncertainty (THC-QUMP) results in a much smaller uncertainty range than the IPCC AR4 ensemble. This implies that the sampled range of parameter uncertainty is not sufficient to explain the projected spread in surface air temperatures. The caveats are that THC-QUMP may not have sampled the full range of parameter uncertainty present in the IPCC AR4 ensemble and that some of the IPCC AR4 models may use different parameterization schemes. Regardless of these caveats, it is clear from the table that, in both ensembles, the uncertainty in the spread is greater than the contribution from the internal variability (except for sea ice extent in THC-QUMP – but see footnote 13 on page 13), where (sea ice extent aside) it never contributes more than half of the uncertainty. This implies that there is great scope for reducing uncertainties in Arctic projections by improving model structure and parameterizations, since projections are not dominated by fundamental internal climate uncertainties.

Ensemble	Change at double pre-industrial CO_2 concentration (20 year means)						
	ice extent $/10^6$ km^2	**ice volume $/10^3$ km^3**	**surface air temperature (SAT) /°C**	**precipitation (mm/year)**	**mixed layer (70m) temperature /°C**	**polar amplification of SAT**	**polar amplification of MLT**
THC-QUMP (parameter uncertainty)	-0.57 ± 0.23 **40%**	-5.77 ± 3.17 **55%**	4.26 ± 0.63 **15%**	54 ± 11 **21%**	0.67 ± 0.26 **39%**	2.25 ± 0.22 **10%**	0.42 ± 0.14 **33%**
THC-QUMP Contribution from internal variability	± 0.15 *67%*	± 0.46 *14%*	± 0.25 *39%*	±4.67 *42%*	± 0.01 *5%*	*N/A*	*N/A*
IPCC AR4 (structural +parameter uncertainty)	-0.40 ± 0.23 **56%**	-8.49 ± 4.18 **49%**	3.96 ± 1.11 **28%**	53 ± 16 **31%**	0.45 ± 0.36 **80%**	2.14 ± 0.38 **18%**	0.35 ± 0.21 **60%**
IPCC AR4 Contribution from internal variability	± 0.04 *17%*	± 0.37 *9%*	± 0.18 *16%*	± 3.9 *25%*	±0.02 *4%*	*N/A*	*N/A*

Table 2: Table shows *x*±*y*. Where *x* is the Ensemble mean differences between 1% and Control experiments for AR4 and THC-QUMP ensembles for key Arctic variables of interest. And *y* is the uncertainty/spread in ensembles differences (one standard deviation (σ) across the ensemble.) Differences are computed as the differences between means of years 61-80 – centred on the CO_2 doubling time (year 70). **Note:** precipitation has been scaled up from mm/day to mm/year, in all cases, by multiplying by 360.0 (the number of model days in HadCM3). See Table 1 for details of definitions.

Forcings and Feedbacks

In the previous sections we quantified some of the spread (uncertainty) in key variables within the Arctic climate system. In this section we aim to analyse the connections between the spread in these variables and attempt to deduce the factors responsible for the spread (uncertainty).

Winton forcing and feedback analysis

A key phenomenon in the Arctic region is Polar amplification – where the surface temperature increase, in response to increased levels of greenhouse gases, is greater than the global mean temperature increase. Winton (2006) sought to examine the importance of external forcings and internal Arctic feedbacks to the process of Polar Amplification. We use his analysis as a starting point for our examination of the uncertainties in Arctic climate change.

We directly follow the approach of Winton (2006) by examining the roles of the forcings and feedbacks involved in Arctic temperature amplification. In this method, Winton separated the *forcing* of the climate system into:

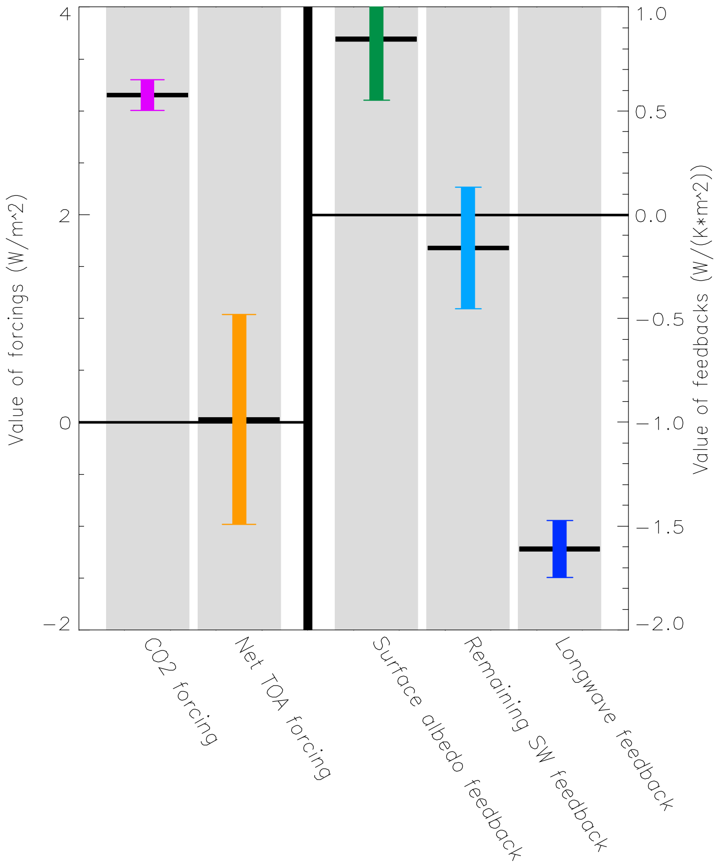
1) direct CO_2 radiative forcing, F_{CO2}.
2) net top of the atmosphere (TOA) radiative forcing, F_N, (approximately the net surface heat flux plus the convergence of the atmospheric heat transport into the Arctic).

The *feedbacks* were divided into:

1) longwave (LW; influenced by clouds, water vapour and temperature)
2) shortwave (SW) radiative feedbacks, which were further separated into:
   a) surface albedo feedback (SAF)
   b) non-SAF shortwave feedback, i.e. contributions from clouds aerosols and water vapour.

More details of the method can be found in our interim report (see the Appendix) or Winton (2006).

This analysis was carried out for both the THC-QUMP ensemble and the AR4 ensemble. Winton showed that the spread between outliers amongst the AR4 models had multiple causes but was particularly associated with the non-SAF shortwave feedback. Figure 3 shows the mean and spread for the forcings and feedbacks over the Arctic as defined above. Both ensembles show a positive surface albedo feedback and a negative longwave feedback, demonstrating that surface albedo processes tend to amplify Arctic warming, whereas longwave radiation processes tend to dampen Arctic warming. The non-surface-albedo shortwave feedback is negative in both ensembles – suggesting that the processes that contribute to this feedback (e.g. clouds) tend to dampen Arctic warming. All feedbacks have a notable spread, but the shortwave feedbacks show greater spread than the longwave feedbacks. This suggests that variations in surface albedo and cloud sensitivity are important contributions to Arctic climate uncertainty.



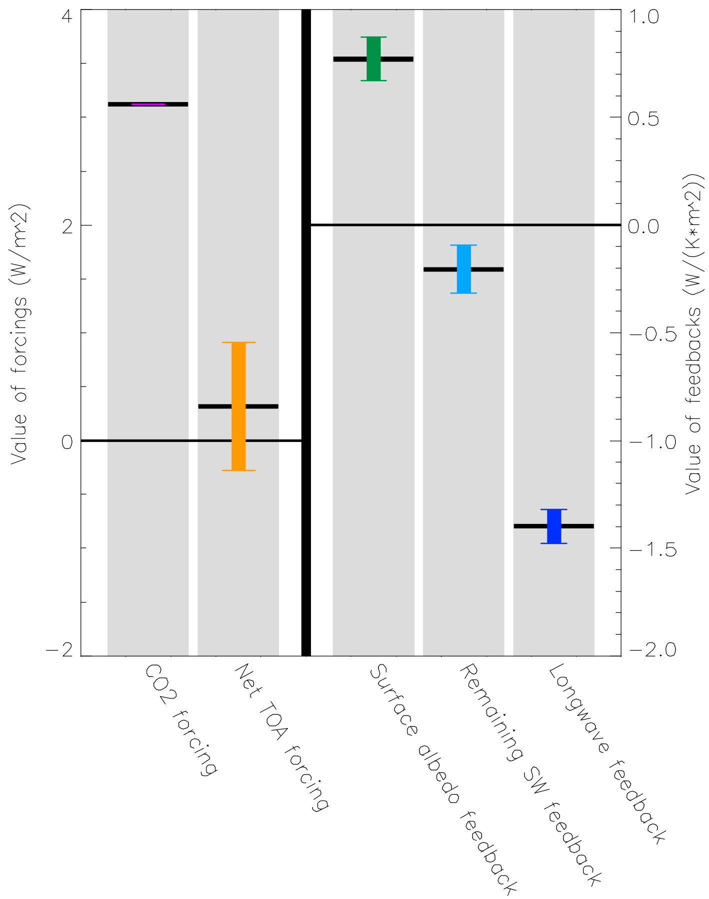


Figure 3: Winton (2006) forcings and feedbacks computed for IPCC AR4 (left) and THC-QUMP (right) ensembles.

The net top-of-atmosphere forcing (F_N) includes components from a number of processes; surface albedo changes, longwave forcing and cloud changes as well as atmospheric and oceanic heat transport.Since F_N represents an external forcing, rather than a feedback, and has a greater spread than F_{CO2}, we might expect that it is playing a significant role in setting the model spread in the Arctic[14]. In order to do this, we need to decompose F_N, or more accurately, the Arctic heat budget.

Hence, in the next section we present analysis of the constituent terms in the Arctic heat budget to determine if there is one principal mechanism within the budget, such as ocean heat transport, that is the cause of the large inter-model differences in F_N.

Heat budgets within the Arctic

The heat that flows into and out of the Arctic ultimately determines the Arctic climate. Therefore, in order to understand Arctic climate change we need to understand the budget of heat within the Arctic. The previous section highlighted the need for a more detailed understanding of the terms in the Arctic heat budget. Here we estimate the Arctic heat budget in both ensembles.

To calculate heat transports into the Arctic requires data that allows us to calculate the complete energy budget for the atmosphere and for the ocean. This requires the budgets to be diagnosed while the model is being run or output at high temporal resolution (6 hourly). In the case of the IPCC AR4 ensemble, the available model diagnostics are not suitable for the explicit evaluation of the atmospheric heat transports. Exact *ocean* heat transports are available, but only for a few models in the ensemble. The exact method requires large amounts of data, which is difficult to process; consequently a method approximating the transports using surface fluxes is widely used by the climate modelling community and is outlined in the Appendix (see Glecker et al., (1994) for more details) and illustrated in Figure 4. This method was used to estimate atmosphere and ocean heat transports into the Arctic for the IPCC AR4 ensemble. Exact ocean heat transports were available for all members of the THC-QUMP ensemble. Hence the approximation was only required for the atmospheric transports in this ensemble.

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14 It should be noted that it is not possible to directly compare the forcing term F_N with the feedbacks, which are measured in different units. It is therefore not possible to identify any single cause of this uncertainty, although changes in outgoing longwave are unlikely to be contributing**.**

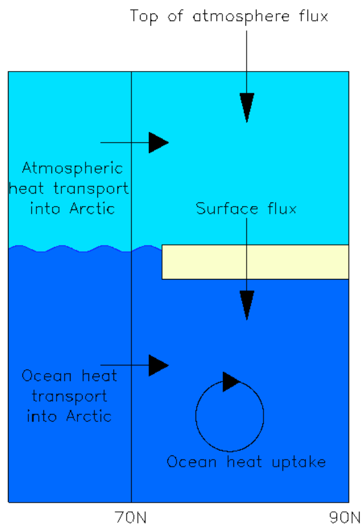

Figure 4: Relationship between surface fluxes and heat transport. Atmospheric heat transport into the Arctic (T_a) is balance by surface (N) and top of the atmosphere (R) fluxes ($N=T_a+R$). Ocean heat transport into the Arctic (T_o) is balanced by surface fluxes and ocean heat uptake (dQ/dt) ($dQ/dt=T_o+N$).

The atmospheric heat transport is the residue of the surface and top of atmosphere energy fluxes (see Figure 4). In the IPCC AR4 ensemble the ocean heat transport is calculated using the surface flux approximation (see appendix). An error arises in this estimation because the ocean has a non-zero heat capacity and hence will store some amount of heat as it warms. We expect that the global integral of the ocean transport (T_A) (from the South Pole to the North Pole) should equal zero (as there is no northward heat transport at the pole. Hence the global integral of surface fluxes (N) is the rate of heat storage in the global oceans (Figure 4). The standard method is to redistribute this non-zero integral across the globe and then to recalculate the transport at each latitude. This assumes the rate of heat storage within the ocean is the same at each latitude, any deviation from the mean at that latitude will introduce a slight under or overestimate of the transport. This can be seen in Figure 5 when we compare the simple method of calculating the ocean transport with exact calculation of ocean heat transport which is produced as the model runs and calculates transport contributions from gyre, overturning and eddy circulations.

Comparing our approximate calculations with those exact ocean heat transports that are available, within the IPCC AR4 ensemble indicates that any differences between the exact and approximate method are within the bounds of natural variability in half the cases (Figure 5). The transport at these latitudes by the ocean is dominated by the Atlantic Ocean. Overestimates of the heat transport by the approximate method are seen in with much more southerly sea ice extent models (e.g. IAP FGOALS), which may alter the surface fluxes and heat storage in the Arctic. The MIROC_HIRES and MIROC_ MIDRES models have exact ocean heat transports (shown in blue in Figure 5) that are approximately 50% greater than flux transport value. The ice extent in the Atlantic in these models is somewhat smaller in the Atlantic and may have an impact on the flux calculations and may reduce the heat stored in the ocean. The results in Figure 5 show that there is some limitation to the flux calculation of heat transport budgets[15].

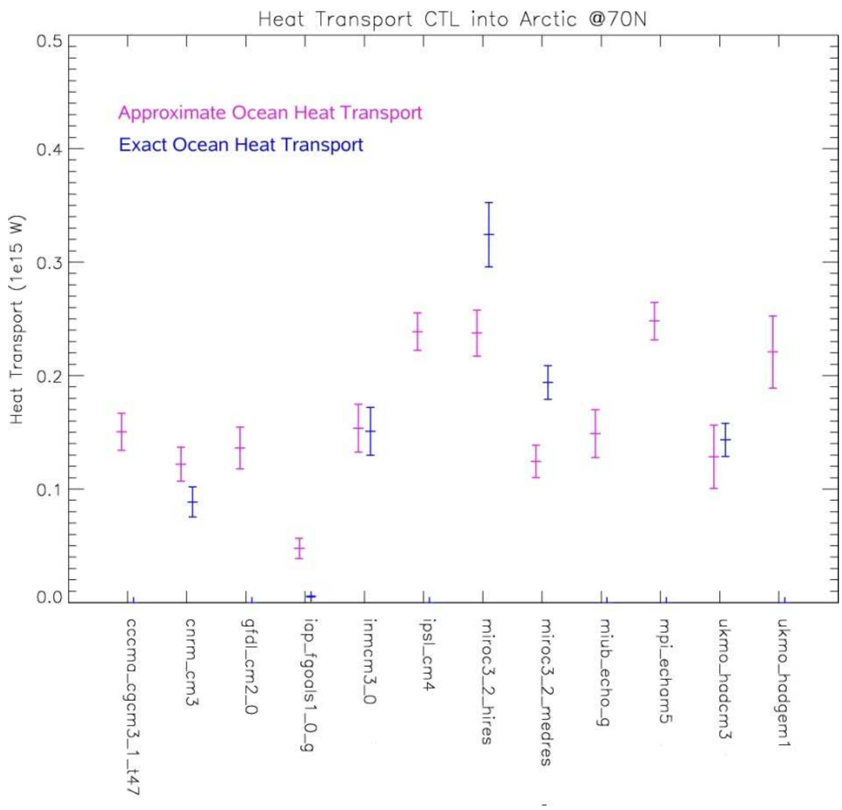

Figure 5: AR4 models average northward ocean transports at 70˚N in the control experiment years for 60-79. Transports are calculated using: model fluxes (approximate) (pink); and taken from the model diagnostics (exact) (blue) - for the models that have data on the AR4 archive). The mean and the internal variability for the 20 years is plotted.

The evolution of the change (2xCO_2 - Control) in components of the heat budget, surface heat fluxes and transports under CO_2 are shown in Figure 6.

A strong signal does not emerge in the ocean and atmosphere transport terms by the end of the 80 year period analysed, and trends across ensemble members can be either positive or negative. This is probably due to Bjerknes compensation, that is any change in the atmospheric transport within a model will be compensated by an equivalent change in the ocean and vice versa[16]. As we don't see a consistent

[15] Hopefully this will not be a problem with the future AR5 ensemble as transport calculations have been requested for the archive.

[16] It is observed that in these ensembles the atmospheric and ocean heat transport are negatively correlated (QUMP r=-0.6, , AR4(exact) r=-0.42), for the AR4 approximate method r=-0.7, but this result is expected due to the way the transports are calculated, likely as a consequence of compensation mechanisms in the Greenland and Norwegian seas (Vellinga et al., 2007).

change in the transports across his suggests that is the model climatology of the transports that is key to setting any changes in the climate, This hypothesis is also suggested by the significant positive trend both ensembles have a in the regional rate of ocean heat uptake. The calculation of ocean heat uptake contains both of the transport terms and therefore presents a clearer trend. The increase of ocean heat uptake and therefore ocean heat content within these short timescales does not show a clear impact on the surface fluxes within the QUMP models. In the AR4 ensemble we do see a change in net surface heat flux, showing that there is a consistent signal of increase heat from atmosphere into the ocean. The change in ocean heat uptake could have a significant impact on ocean bottom temperatures in the Arctic and in turn impact the stability of methane clathrates (O'Connor et al ,in press). The local TOA fluxes remain balanced, across the ensemble members, throughout the simulations to 2xCO_2. This suggests either, that cloud albedo is compensating for any change in sea ice extent, or that with warming an increase in winter LW emissions are counteracting the decreased summer reflectivity. Consequently we need to break down the heat fluxes into their components and relate these to the key climate variables.

These results do not allow us to clearly determine the dominance of a particular term within the heat budget that leads to the structural or parameter uncertainty within the ensembles. The impact of compensation of atmospheric and oceanic transports within each model means that looking at a particular latitude does not give us insight into how the transports are impacting the Arctic climate. Each model will have a different structure of heat transport partitioning between the atmosphere and ocean at a given latitude depending on the model climatology, that is the climatology of the control run, which is an equilibrium state set by the interplay of all the processes represented in the model. Therefore it may be more informative to understand the spread (uncertainty) in the changes of Arctic climate within the context of the uncertainty of ensemble climatology. With this in mind we go onto assess the spread in Arctic change firstly in terms of the spread in model climatology (control climatology).

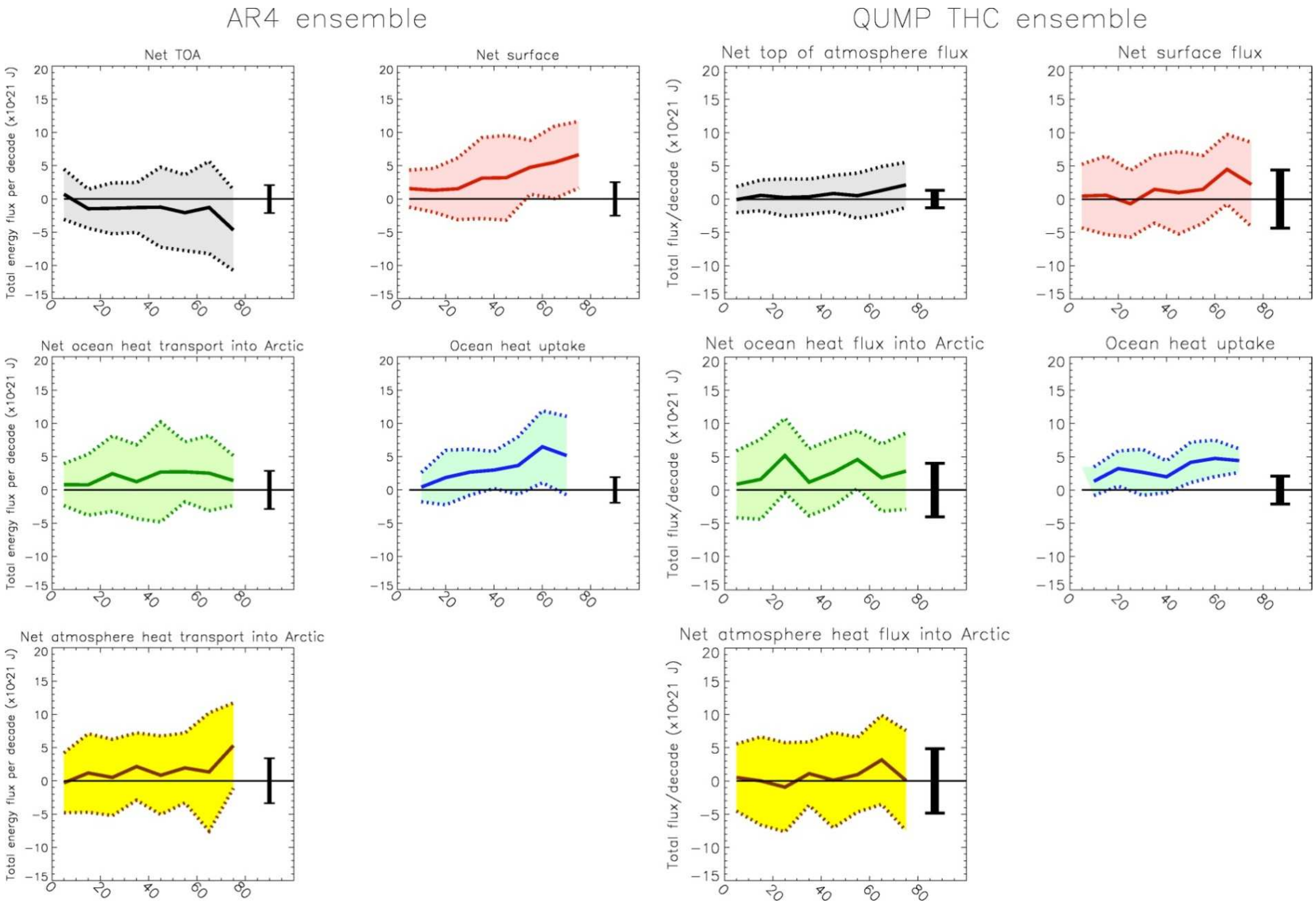

Figure 6: Change in heat budget components for AR4(left) and THC-QUMP(right) ensembles. The coloured shading marks 1 standard deviation of the ensemble. Terms of the heat budget in the two ensembles (decadal means), change from control to 1% experiment. The ensemble mean, ± one standard deviation, is plotted, evolving in time. The black bars on the right show RMS (interdecadal standard deviation) across the ensemble.

Correlations within the Arctic System

The impact of the model control climatology on projected changes

As noted previously, the different models that compose each ensemble all have a different *control climatology* – the long-term time mean of the model climate (see Figure 2). This spread would be unimportant if the model Arctic climate responded linearly to the doubling of CO_2, however previous studies have demonstrated (Holland et al., 2010) that such a spread in the climatologies is partly responsible for the spread (hence uncertainty) in projections of Arctic climate change.

To determine the relationship of the spread in the climatologies with the spread in the projected changes under a doubling of CO_2 we look at the correlations across each ensemble. For example, Figure 7 shows the change in sea ice volume at CO_2 doubling against the sea ice volume climatology (the initial conditions) in the Control run plotted for each model in the IPCC AR4 ensemble. This shows a clear negative relationship between the initial volume of sea ice (climatology) and the magnitude of the change in sea ice volume at CO_2 doubling and is the identical relationship discovered by Holland et al. in 2010. That is, the ice volume at the start of 1% experiment, determines, in a large part, the magnitude of the sea ice volume reduction upon CO_2 doubling. It is perhaps surprising that the correlation is negative, suggesting that a large initial ice volume leads to a greater projected magnitude of the change under $2xCO_2$.

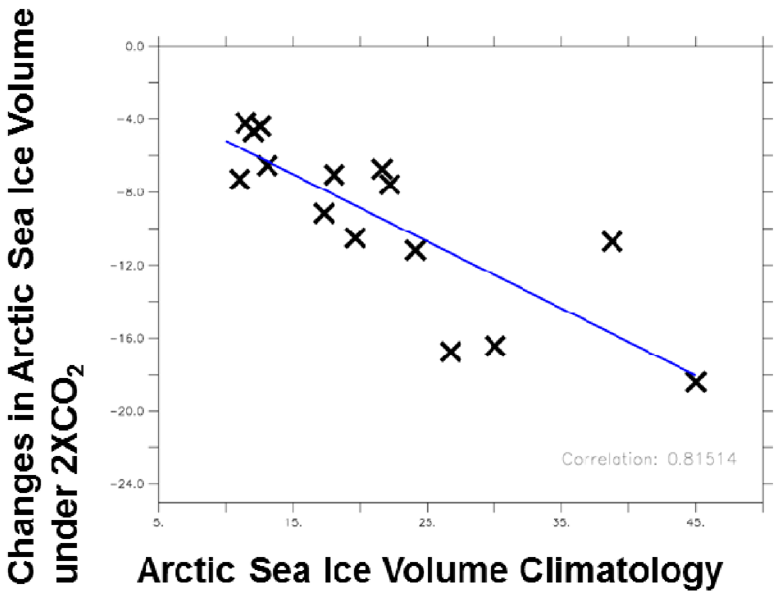

Figure 7: The relationship between the projected changes in sea ice volume under CO_2 doubling and the climatology of the sea ice volume for all models in the IPCC AR4 ensemble. The correlation is -0.82.

To further examine the dependence of Arctic climate change on the spread of model climatologies we repeat this correlation analysis for the change in seven key Arctic variables (as in Table 2) and their relation to a range of quantities in the control climatology (means of years 61-80 in the control experiments). The results are presented for both ensembles in Table 3. There are clear similarities and differences between the two ensembles. The large (negative) correlations between sea ice volume climatology (in the Control experiments) and the sea ice volume change are seen in THC-QUMP as well as the IPCC AR4 ensemble. As noted previously (and discussed in the Appendix), models in the THC-QUMP ensemble differ in the values of certain parameters within key model parameterisations. The similarity of the correlation of the sea ice volume change and climatology between the two ensembles suggest that the relationship if fundamentally due to parameter uncertainty. Figure 8 suggests that this is the case. It shows the dependence of the sea ice volume climatology in the control run on one of the model parameters; Ice albedo at 0˚C. These linked relationships suggest that sea ice volume change under a doubling of CO_2 is directly related to the value of parameters contained within the sea ice albedo parameterisation. Hence uncertainty in sea ice volume projections is explained, in part, by the uncertainty in the sea ice albedo parameterisation schemes. This is physically consistent since the surface albedo controls the climatological radiation balance within the region hence the albedo defines the energy balance of the ice during the control simulation and hence sets the climatological ice volume.

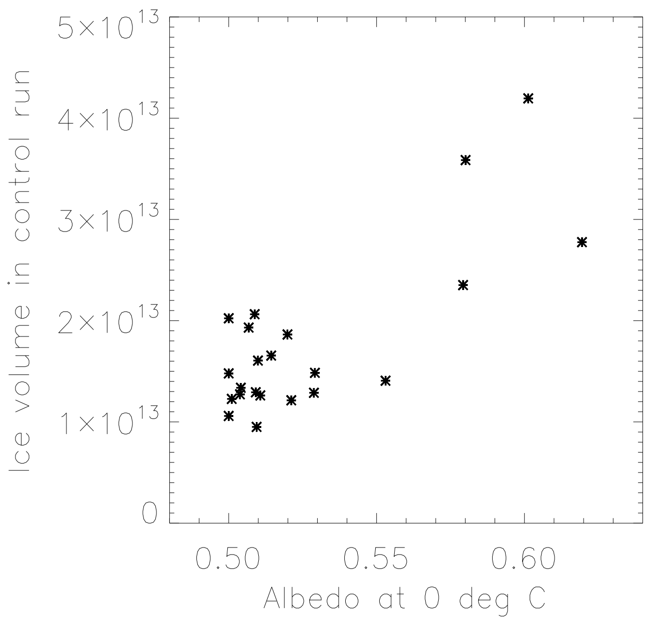

Figure 8: The relationship between sea ice volume climatology and variations in the albedo parameter in the THC-QUMP ensemble. The correlation coefficient is 0.78.

Examination of Table 3 reveals a number of other interesting relationships. In the IPCC AR4 ensemble, the Northward ocean heat transport climatology (in the Control experiment) is significantly correlated with changes in five of the seven Arctic variables. This suggests that the climatology of the model ocean heat transport into the Arctic explains a substantial part of the spread (uncertainty) in some aspects of Arctic climate change (e.g. surface air temperature, precipitation, mixed layer temperatures). A similar relationship is entirely absent from the THC-QUMP ensemble[17]. This suggests that this dependence may be due to *structural* uncertainty, rather than parameter uncertainty.

The THC-QUMP ensemble also shows a strong positive correlation between the control climatological surface air temperature and sea ice volume change. However, this is likely due to the link between control climatological sea ice volume and temperature. Higher control temperatures are linked to lower ice volumes; lower ice volumes have smaller ice volume changes, but such changes are always negative (a reduction) in a warming climate. Hence higher temperatures are related to smaller negative changes and therefore we would we expect a positive correlation between control SAT and sea ice volume. Similarly, we expect that many of the other significant correlations in the THC-QUMP table are related to the spread in sea ice volume climatologies (e.g. TOA Up SW – High sea ice volumes are likely to have high sea ice coverage, increasing the upward top of the atmosphere flux in the shortwave band. High sea ice coverage results in less heat being stored in the mixed layer during summer – hence lower annual mean mixed layer temperatures). The lack of some of these relationships in the IPCC-AR4 table may be due to the interaction of the spread in ocean heat transport and sea ice volume – an interaction that does not occur in the THC-QUMP ensemble.

The implications of the result shown in Figure 7 and Table 3 are that reductions in the spread in Arctic model climatologies an important step in reducing uncertainty in future Arctic climate projections. Figure 8 suggests that for ice volume this uncertainty can be reduced by better constraining the ice albedo parameter in model parameterisations. Furthermore, Table 3 demonstrates the importance of having the correct model ocean heat transport climatology.

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[17] A caveat to this comment is that the model parameters in the THC-QUMP weren't targeted to cause a spread In ocean heat transport –hence they may be under-sampling the parameter uncertainty that exists.

	Air Temperature (SAT):	Polar Ampl. of SAT:	Sea Ice Extent:	Sea Ice Volume:	Precip:	Mixed Layer Temp:	Polar Amp of MLT:
Air Temperature (SAT):	0.24	−0.21	−0.47	0.28	0.43	0.58	0.61
Sea Ice Extent:	−0.14	0.09	0.36	0.2	−0.03	−0.34	−0.39
Sea Ice Volume:	0.08	0.09	0.27	−0.79	−0.21	−0.12	−0.04
Sea Ice Thickness:	0.14	0.14	0.15	−0.85	−0.2	−0.04	0.06
Precip:	−0.07	0.35	0.36	−0.16	0.24	−0.06	−0.13
Mixed Layer Temp:	0.77	0.37	−0.68	−0.08	0.77	0.85	0.81
Total N Heat Trans:	0.1	0.46	0.35	0.1	0.15	−0.11	−0.18
Total N Atmos Heat Trans:	−0.12	0.32	0.5	0.27	−0.03	−0.3	−0.38
Total N Ocean Heat Trans:	0.76	0.48	−0.78	−0.12	0.72	0.81	0.86
Atl Ocean Heat Transport:	0.76	−0.03	−0.85	0.54	0.8	0.95	0.94
Latent Heat Flux:	0.53	0.12	−0.7	−0.28	0.62	0.79	0.82
Sensible Heat Flux:	0.27	0.21	−0.34	0.13	0.46	0.38	0.48
Surface Up LW:	0.5	0.32	−0.42	0.25	0.45	0.58	0.67
Surface Down LW:	0.31	0.2	−0.2	0.36	0.34	0.4	0.52
TOA Up LW:	0.29	−0.04	−0.48	0.22	0.5	0.49	0.56
Surface Down SW:	0.02	0.08	0.09	−0.59	0.17	0.21	0.08
Surface Up SW:	−0.06	0.17	0.37	−0.81	−0.03	−0.16	−0.27
TOA Up SW:	−0.11	0.1	0.46	−0.34	−0.29	−0.37	−0.39
Net Down TOA Flux:	−0.49	−0.24	0.42	0.47	−0.58	−0.58	−0.66
Net Down Surf Flux:	−0.72	−0.47	0.7	0.17	−0.58	−0.7	−0.79
Cloud Forcing (SW):	0.04	−0.02	−0.16	0.28	0.2	−0.04	−0.09
Cloud Forcing (LW):	−0.43	−0.44	0.46	0.1	−0.22	−0.13	0
Cloud Forcing (TOTAL):	−0.08	−0.1	−0.1	0.3	0.11	0.01	0.09
Cloud Forcing over Ice:	0.38	−0.33	−0.33	−0.45	0.25	0.52	0.33
Atmos Inversion:	−0.06	0.27	0.36	−0.2	−0.01	−0.38	−0.48
Fresh Water Flux:	−0.43	−0.13	0.04	−0.07	−0.2	0.34	0.24

	Air Temperature (SAT):	Polar Ampl. of SAT:	Sea Ice Extent:	Sea Ice Volume:	Precip:	Mixed Layer Temp:	Polar Amp of MLT:
Air Temperature (SAT):	−0.21	−0.29	−0.38	0.84	0.35	0.66	0.66
Sea Ice Extent:	−0.04	0.24	0.02	−0.41	−0.36	−0.56	−0.49
Sea Ice Volume:	0.37	0.37	0.39	−0.96	−0.22	−0.54	−0.57
Sea Ice Thickness:	0.38	0.36	0.4	−0.97	−0.22	−0.53	−0.57
Precip:	0	−0.12	−0.39	0.66	0.49	0.73	0.72
Mixed Layer Temp:	−0.07	−0.24	−0.29	0.69	0.47	0.73	0.7
Total N Heat Trans:	−0.31	−0.33	−0.17	0.57	−0.05	−0.01	−0.02
Total N Atmos Heat Trans:	−0.25	−0.17	−0.23	0.37	−0.09	−0.12	−0.1
Total N Ocean Heat Trans:	0.02	−0.18	0.23	0.13	0.12	0.25	0.2
Atl Ocean Heat Transport:	0.02	−0.18	0.23	0.13	0.12	0.25	0.2
Latent Heat Flux:	−0.16	−0.26	−0.31	0.75	0.3	0.58	0.56
Sensible Heat Flux:	−0.3	−0.46	−0.12	0.68	0.15	0.35	0.32
Surface Up LW:	−0.2	−0.29	−0.38	0.83	0.37	0.67	0.67
Surface Down LW:	−0.21	−0.3	−0.33	0.77	0.31	0.61	0.61
TOA Up LW:	0	−0.05	−0.45	0.72	0.55	0.8	0.8
Surface Down SW:	0.53	0.49	0.04	−0.59	0.2	−0.12	−0.17
Surface Up SW:	0.46	0.48	0.31	−0.94	−0.12	−0.48	−0.5
TOA Up SW:	0.1	0.15	0.46	−0.82	−0.45	−0.67	−0.67
Net Down TOA Flux:	0.25	0.26	0.07	−0.32	0.17	0.23	0.24
Net Down Surf Flux:	−0.15	0.05	−0.43	0.34	0.08	0.12	0.19
Cloud Forcing (SW):	0.56	0.53	−0.09	−0.4	0.38	0.1	0.06
Cloud Forcing (LW):	−0.34	−0.33	−0.12	0.51	−0.09	0.15	0.17
Cloud Forcing (TOTAL):	0.42	0.38	−0.31	0.07	0.47	0.37	0.34
Cloud Forcing over Ice:	0.39	0.35	−0.32	0.1	0.47	0.39	0.36
Atmos Inversion:	0.36	0.36	0.36	−0.87	−0.16	−0.49	−0.51
Fresh Water Flux:							

Table 3 Correlations between changes in Arctic variables (1% -Control: columns) and a variable in the control experiment climatology (Control). (left:IPCC AR4, right THC-QUMP). Coefficients in a coloured box are significant (p<0.05) for the ensemble size, with blue and red colours showing negative and positive correlations respectively. Variables are defined in the **Appendix.** Some models are missing some variables in the IPPC AR4 archive – hence IPCC AR4 ensemble size is not always the same size. Consequently the sample size varies and hence so does the magnitude correlation required for a significant value. The number of models used ranges from 6-18.

Across-ensemble correlations of change within the Arctic System

We examine how the across-ensemble variations in the projected changes (2xCO2 minus Control) in Arctic climate variables are correlated with each other, in the same manner as Table 3. The goal is to determine if there is a consistent relationship in the changes between variables across the ensemble. However, as discovered above, some of the spread in the change in some Arctic variables is due to the spread in the model climatologies (e.g. sea ice volume). Hence this relationship may mask relationships between the changes. To isolate these relationships we try to remove the climatology dependencies by using linear regression. First, we remove the effects of the dependence on sea ice volume climatology from the change in sea ice volume. Then we remove the dependence on northward ocean heat transport climatology from the remaining six Arctic variable of interest (see Table 3 and Appendix for details). The resulting correlations are shown in Table 4. The # or * in the table denotes which dependence has been removed in each case. In the IPCC AR4 ensemble, many significant correlations between variables are lost after this process, because they were due to common dependences on the spread in the model climatologies rather than direct relationships with each other. More significant relationships are retained in the THC-QUMP ensemble, due to the weaker dependence on the spread in ocean heat transport climatology.

	#Air Temperature (SAT):	#Polar Ampl. of SAT:	#Sea Ice Extent:	*Sea Ice Volume:	#Precip:	#Mixed Layer Temp:	#Polar Amp of MLT:
#Air Temperature (SAT):	1	0.84	0.74	−0.35	0.88	0.58	0.51
#Polar Ampl. of SAT:	0.84	1	0.63	−0.68	0.8	0.39	0.39
#Sea Ice Extent:	0.74	0.63	1	−0.26	0.59	0.53	0.56
*Sea Ice Volume:	−0.35	−0.68	−0.26	1	−0.05	0.22	0.3
Sea Ice Thickness:	−0.08	−0.14	−0.37	0.15	0.43	−0.51	−0.29
#Precip:	0.88	0.8	0.59	−0.05	1	0.62	0.43
#Mixed Layer Temp:	0.58	0.39	0.53	0.22	0.62	1	0.87
#Polar Amp of MLT:	0.51	0.39	0.56	0.3	0.43	0.87	1
Total N Heat Trans:	−0.3	−0.05	−0.25	−0.05	0.05	−0.38	−0.36
Total N Atmos Heat Trans:	0.07	0.14	−0.07	−0.53	0.2	−0.75	−0.56
Total N Ocean Heat Trans:	−0.23	−0.17	−0.06	0.54	−0.18	0.74	0.47
Atl Ocean Heat Transport:	−0.56	−0.41	−0.71	0.72	−0.26	0.95	0.18
Ocean Heat Uptake:	−0.34	0.25	−0.43	−0.36	−0.15	−0.67	−0.5
Latent Heat Flux:	0.5	0.77	0.53	−0.62	0.51	0.41	0.3
Sensible Heat Flux:	0.39	0.54	0.43	−0.45	0.24	0.59	0.55
Surface Up LW:	0.05	0.55	0.09	−0.69	0.05	0.22	0.19
Surface Down LW:	0.07	0.59	0.09	−0.69	0.07	0.15	0.15
TOA Up LW:	0.15	0.54	0.26	−0.52	0.25	0.3	0.34
Surface Down SW:	−0.08	−0.53	−0.11	0.49	−0.15	0.01	0
Surface Up SW:	−0.23	−0.63	−0.37	0.65	−0.15	−0.23	−0.24
TOA Up SW:	−0.35	−0.59	−0.47	0.51	−0.15	−0.37	−0.46
Net Down TOA Flux:	0.38	0.17	0.37	−0.24	−0.09	0.31	0.3
Net Down Surf Flux:	−0.52	−0.4	−0.19	0.55	−0.52	−0.73	−0.51
Cloud Forcing (SW):	−0.1	−0.41	0.07	0.32	−0.12	0.16	0.23
Cloud Forcing (LW):	−0.14	0.24	0.19	−0.67	−0.49	−0.38	−0.09
Cloud Forcing (TOTAL):	0.13	0.54	0.34	−0.42	−0.01	−0.05	0.2
Cloud Forcing over Ice:	0.47	0.74	0.53	−0.28	0.35	0.13	0.48
Surface albedo feedback:	0.27	0.36	0.58	−0.63	−0.1	0.46	0.46
Non−SA SW feedback:	0.31	0.35	0.15	0.01	0.25	0.63	0.67
Longwave feedback:	−0.37	−0.18	−0.19	0.06	−0.32	−0.16	−0.28
Atmos Inversion:	0.08	−0.31	−0.16	0.46	−0.19	0.05	0.19
Fresh Water Flux:	0.13	−0.31	0.6	0.54	0.07	0.32	0.74

	#Air Temperature (SAT):	#Polar Amp of SAT:	#Sea Ice Extent:	*Sea Ice Volume:	#Precip:	#Mixed Layer Temp:	#Polar Amp of MLT:
#Air Temperature (SAT):	1	0.82	−0.42	−0.71	0.71	0.37	0.29
#Polar Amp of SAT:	0.82	1	−0.42	−0.65	0.48	0.22	0.26
#Sea Ice Extent:	−0.42	−0.42	1	0.44	−0.63	−0.64	−0.63
*Sea Ice Volume:	−0.71	−0.65	0.44	1	−0.57	−0.37	−0.35
Sea Ice Thickness:	−0.5	−0.44	−0.38	0.34	0.07	0.41	0.45
#Precip:	0.71	0.48	−0.63	−0.57	1	0.84	0.76
#Mixed Layer Temp:	0.37	0.22	−0.64	−0.37	0.84	1	0.98
#Polar Amp of MLT:	0.29	0.26	−0.63	−0.35	0.76	0.98	1
Total N Heat Transport:	0.4	0.42	−0.11	−0.68	0.32	0.16	0.13
Total N Atmos Heat Transport:	0.05	0.13	0.05	−0.52	0.06	−0.02	−0.01
Total N Ocean Heat Transport:	0.28	0.18	−0.17	0.18	0.2	0.17	0.14
Atl Ocean Heat Transport:	0.28	0.18	−0.17	0.18	0.2	0.17	0.14
Ocean Heat Uptake:	0.21	−0.02	−0.08	−0.41	0.36	0.38	0.33
Latent Heat Flux:	0.86	0.73	−0.63	−0.55	0.73	0.49	0.43
Sensible Heat Flux:	0.63	0.54	−0.09	−0.1	0.3	0.04	−0.01
Surface Up LW:	0.95	0.74	−0.49	−0.83	0.78	0.51	0.44
Surface Down LW:	0.89	0.65	−0.68	−0.53	0.88	0.64	0.56
TOA Up LW:	0.93	0.72	−0.28	−0.56	0.63	0.32	0.25
Surface Down SW:	−0.22	0.07	−0.29	−0.21	0.03	0.2	0.28
Surface Up SW:	−0.84	−0.64	0.01	0.5	−0.39	0	0.08
TOA Up SW:	−0.91	−0.83	0.26	0.75	−0.59	−0.24	−0.18
Net Down TOA Flux:	−0.35	−0.5	0.09	0.57	−0.18	0.02	0.02
Net Down Surf Flux:	−0.17	−0.17	0.12	−0.32	−0.05	−0.01	0
Cloud Forcing (SW):	0.03	0.25	−0.45	−0.35	0.27	0.35	0.41
Cloud Forcing (LW):	0.65	0.47	−0.2	−0.07	0.3	−0.01	−0.11
Cloud Forcing (TOTAL):	0.35	0.49	−0.59	−0.46	0.48	0.44	0.45
Cloud Forcing over ice:	0.29	0.43	−0.59	−0.46	0.42	0.38	0.38
Surface albedo feedback:	0.76	0.65	0.05	−0.54	0.34	−0.01	−0.08
Non−SA SW feedback:	0.63	0.69	−0.42	−0.66	0.56	0.38	0.37
Longwave feedback:	0.28	0.34	−0.45	−0.46	0.3	0.17	0.15
Atmos Inversion:	−0.77	−0.77	0.26	0.62	−0.35	0.03	0.06
Fresh Water flux:	[redacted]						

Table 4: Correlations between changes in Arctic variables (1% -Control: columns). As **Table 3**. Variables defined in the Appendix. # = dependence on Northward Ocean heat transport climatology removed. * = dependence on Sea Ice volume climatology removed.

The correlations in Table 4 pick out some standard physical relationships that we would expect to see, for example both ensembles show that there is a significant correlation between changes in precipitation and surface air temperature (as expected from the Clausius Clapyron relation).

Perhaps the first thing to note when considering the correlation tables presented in Table 4 is that there are far more significant correlations for the 7 Arctic variables in the THC-QUMP ensemble than the AR4 ensemble. This may in some way reflect the uncertainty we are trying to capture within the different ensembles. The THC-QUMP ensemble tends to have strong correlations across the variables for parameters linked with the radiation balance. This is what we might expect from ensemble that is perturbing model parameters associated with clouds, ice and precipitation. In the same way we do not see strong correlations in the THC-QUMP ensemble with the large scale flow of heat within the atmosphere and ocean, which are more likely to be determined by the model structure; we don't see strong correlations with heat transport changes. The one variable in the THC-QUMP ensembles that does have a significant relationship with the total and atmospheric transports is the sea ice volume, but as these transports are approximated from the top of atmosphere fluxes and surface fluxes it may just be a reflection of the impact of the parameters on the radiation balance.

We do see a consistent response from the AR4 ensemble in terms of transport when the impact of the mean state of ocean heat transport has been removed. Table 4 shows us that the ocean mixed layer temperature changes are responding to the heat transport changes. Firstly we observe the Bjerknes compensation mechanism – there are equal and opposite correlations between the atmosphere and ocean heat transports. We also see that when we use the exact ocean heat transport (Atl Ocean heat transport) we see a much stronger correlation suggesting that the relationship is stronger than our approximation method. The resultant negative correlation between ocean heat uptake changes and mixed layer temperatures in the AR4 may be a seasonal relationship. In winter we may be picking up a seasonal signal with less ice there is greater loss of heat from the mixed layer to the atmosphere and therefore reduced ocean uptake. This mechanism is suggested by the significant negative correlation with net surface fluxes and the positive correlation between mixed layer temperature and sea ice extent in theAR4 ensemble but not significant and may be limited by our annual analysis.

In the THC-QUMP ensemble there is a significant correlation between the sea ice thickness change and air temperatures suggesting that the parameter uncertainty is setting the thickness change with temperature and is likely linked to the albedo uncertainty. The sea ice volume changes are also linked to the precipitation changes in the ensembles as the negative correlation shows that greater ice volume loss is related to an increase in the precipitation change, presumably due to increased latent heat flux (positive correlated with precipitation) as a result of greater areas of open water.

The cloud forcing changes in the THC-QUMP ensemble seem to have an impact on all the key Arctic variables in the table with the exception of the ocean and atmospheric surface temperatures. The signal for influence on the surface temperatures again may be lost due to the fact that we are using seasonal data as the polar amplification signal is stronger in the winter where we see a stronger correlation this may be because it allows us to pick out winter phenomena in our analysis. This may also explain why we do not see a clear signal in the AR4 response; it will be harder to pick out a coherent "winter" response from this ensemble as the seasonal cycles of sea ice are very different across the models.

The impact of the radiation balance is much stronger in the THC-QUMP ensemble with significant correlations with all the Arctic variables with the LW forcing and the SW forcing affecting the surface temperatures and ice volume. In the AR4 ensemble we see significant negative correlations with the LW forcing and latent heat flux with the ice volume changes with the mean volume influence regressed out this may be a response however of the fluxes to the volume changes rather than them explaining the uncertainty in the volume. This is also suggested by the positive correlation with the surface SW radiation upwards.

In summary the parameter uncertainty seems to dominate the uncertainty in the radiation balance processes and variables, which influence the seven Arctic variables and the structural uncertainty dominates the transports i.e. the large scale circulation, which affects the Arctic key variables.

Discussion

The goal of this project is to assess and quantify the uncertainty in current Arctic climate projections.

The range of models used in current projections of Arctic climate change have climatologies (time mean of the control experiment) that are generally consistent with historical observations of Arctic climate, although the spread of the climatologies can be quite large, particularly for some quantities (e.g. sea ice volume).

Examination of these spreads between the two ensembles (IPCC AR4 and THC-QUMP) revealed that this spread is not just due to (the sampling of) intrinsic climate noise (internal variability) but that structural and parameter uncertainties likely dominate the spread in many quantities. It is unlikely that parameter uncertainty is the source of all uncertainty in all Arctic variables – climatology spread is generally greater for the IPPC AR4 ensemble than the THC-QUMP ensemble, suggesting that structural uncertainty must play a significant role. This implies that there is considerable scope for reducing uncertainty in model projections of Arctic climate.

Our initial analysis of the forcings and feedbacks within the Arctic (Winton analysis) confirmed that similar feedbacks were occurring in both ensembles and highlighted the need for a detailed heat budget of the Arctic. It was not possible to compute an exact heat budget for the two ensembles, due to a lack of the required data having been stored for the two ensembles. However, a simpler method using surface and top of the atmosphere fluxes gives an approximate answer. The heat budgets show that the oceans warm over time, and have warmed significantly by the time atmospheric CO_2 concentrations have doubled. This may have implications for the stability of marine hydrates in the subsurface within the Arctic basin (O'connor et al. ,2010). There remains a considerable spread in the all the heat budget components at the time of CO2 doubling, therefore we further analysed these spreads to see how they and other quantities related to other Arctic processes. Examination of correlations between the model climatologies of the control experiment and the changes the models display under a doubling of CO_2 reveal that a significant portion of the uncertainty (spread) in Arctic climate projections is due to the spread in both the sea ice volume climatology and the northward ocean heat transport into the Arctic across the ensemble in the control experiment. The spread in the sea ice volume climatologies may be largely due to uncertainties in the underlying parameters in the sea ice parameterisation scheme, notably the ice albedo parameters. The spread in the northward heat transport climatologies may be more due to model structural uncertainties.

Once the dependences on the control climatology sea ice volume and northward ocean heat transport are regressed out, the correlations between the spread in the changes of Arctic variables reveals much of the expected physics and feedbacks present in the Arctic system. It is difficult to directly attribute the source of model spread in the changes because we are examining simultaneous correlations. However, the differences in the correlations between the Arctic processes between the two ensembles are revealing. It appears that the parameter uncertainty (spread) seems to dominate the uncertainty (spread) in the radiation balance processes and variables, and the structural uncertainty dominates the transports i.e. the large scale circulation, which affects the Arctic key variables.

One limitation of this study is that we have only considered the variations in annual mean processes. . However, the Arctic climate system is strongly seasonal with no sunlight for 6 months in winter; a high surface pressure and strong atmospheric inversion persist. This results in heat loss to space, sea ice growth and increase in the mixed layer depth. sea ice insulates the ocean from atmosphere with consequent very cold air temperatures. In summer, the permanent sunlight induces surface melting of the sea ice, a well-mixed boundary layer and 90% cloud cover. Solar uptake by the ocean, combined with melt water, induces a shallow mixed layer. Consequently, very different processes determine Arctic climate during summer and winter and Model spread varies with season across the AR4 ensemble. We have partly analysed the seasonal dependence in the analysis of shortwave (SW) and longwave (LW) fluxes, both which dominate at different parts of the year – hence capture some of the seasonality. But a full analysis will require seasonally resolved data. Such an analysis may reveal stronger signals in the relationships between processes.

This study is not a complete assessment of the uncertainties in Arctic climate – it has made no attempt to assess how known unknowns (e.g. permafrost) or unknown unknowns might impact on future projections of future climate. However, the assessment that has been made points to clear directions in which model spread can be reduced, which will hence produce more precise projections of Arctic climate change.

Conclusions

We have examined the uncertainty (spread) in future projections of Arctic climate change. Our conclusions are:

- There is considerable spread in the projections (large spread as a fraction of ensemble mean) of the change in Arctic quantities (e.g. sea ice volume).
- The majority of this spread is due to uncertainties related to sub-gridscale parameterisations and model structure variations rather than intrinsic internal variability.
- The spread in model climatologies (model biases) of both sea ice volume and northward ocean heat transport into the Arctic are significant factors in the uncertainty in projections of future Arctic climate change.
    - The spread in sea ice volume climatologies is likely due to uncertainties in sub-gridscale parameterisations (sea ice albedo parameters).
    - The spread of the climatologies of northward ocean heat transport into the Arctic across the models is more likely due to structural variations between models rather than uncertainties in sub-gridscale parameterisations
- Parameter uncertainty (spread) seems to dominate the spread in the radiation balance processes and variables, and the structural uncertainty (spread) dominates the transports i.e. the large scale circulation, which affects the Arctic key variables.

There is considerable scope for reducing these uncertainties and improving future projections of Arctic change by:

- Better constraining sea ice volume climatologies in models by
    - Better observational estimates of sea ice volume
    - Better constraints on ice albedo parameters e.g. with better ice albedo observations.
- Better constraining northward ocean heat transports into the Arctic by better long term observational estimates of heat transports into the region.
- Detailed analysis of the structural differences between models in the IPCC AR4 model to directly attribute structural differences to Arctic spread (along the lines of Figure 8).

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Appendix.

Description of ensembles

We examine two ensembles of CO2 doubling experiments in this study. The first (IPCC AR4) samples some of the structural and parameter uncertainty present in climate projections.18 The second (THC-QUMP) samples some of the parameter uncertainty present in climate projections.

AR4

The IPCC AR4 multi model ensemble contains 22 coupled climate models (See Table 5 and Randall et al., 2007). The models vary in their structure, parameterization, resolution, and whether or not they employ flux adjustments to ensure a stable climate[19]. The variance in model structure arises from the different approximations and numerical methods used to model the physical the equations that describe physical process (e.g. fluid flow, radiation) and also the interaction with the different co-ordinate systems that may be employed (e.g. vertical levels vs. density levels, location of poles (over land or ocean) etc). Models also differ in the way in which they represent sub-gridscale processes (parameterization). The inter-model variations in these methods contribute to the structural and parameter uncertainty in climate projections.

bccr bcm2.0	cccma cgcm3.1 t47	cnrm cm3
csiro mk3.0	csiro mk3.5	gfdl cm2.0
gfdl cm2.1	giss model e h	giss model e r
iap fgoals1.0 g	ingv echam4	inmcm3.0
ipsl cm4	miroc3.2 hires	miroc3.2 medres
miub echo g	mpi echam5	mri cgcm2.3.2a
ncar ccsm3.0	ncar pcm1	ukmo hadgem1
ukmo hadcm3		

Table 5: Models comprising the IPCC AR4 ensemble used in this study. Not all variables are stored for all models. Hence for many parts of the analysis in this study only a subset of this model set was used. Significance testing, where applied, has been adjusted to reflect this.

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[18] It is clear that these two sources of uncertainty are not independent in the IPCC AR4 ensemble, since climate models are in part constrained by past observations of climate. Hence it is likely that some of the structural uncertainty is compensated for by the parameter uncertainty, i.e. they are negatively correlated. This mean that we cannot simply compare the IPCC AR4 and THC-QUMP ensembles to deduce whether parameter or structural uncertainty play a greater role in a given process.

[19] Only 5 out of the 22 models in the IPCC AR4 ensemble require some flux adjustment. See Table 8.1 [Randall et al., 2007]

THC-QUMP
The HadCM3 (QUMP) experiments use perturbed parameters and the ensemble can be broadly described as atmospheric parameter changes without flux correction. The aim of the ensemble is to span the range of climate sensitivities consistent with a uniform prior on parameters but in the process maximise the chance of getting plausible model versions and span a wide range of parameter settings (Collins et al. 2006).

Each ensemble comprises of the unperturbed member, the base state which has the same parameter settings as HadCM3 in the IPCC AR4, The other members have been perturbed away from the base state through changes to multiple model parameters, according to a “Latin Hypercube” design which maximises the number of potential interactions between perturbations. Perturbations to these parameters causes some minor climate drift in some ensemble member. However, no flux adjustment was applied to nudge these members back to the climatology of the unperturbed model. Some ensemble members exhibit climate drift in the Arctic resulting in low initial states of sea ice extent, such that the summer ice cover was lost early on in the 2xCO_2 experiments. 22 versions of a single coupled climate model (HadCM3) created by varying values for model parameters, e.g.:

- cloud formation and precipitation
- ice structure and albedo

Each member was first run for 100 years as a spin-up, to assess the amount of climate drift and model stability. After the spin-up phase each model was run through a control phase for 140 years. Parallel to this control phase, each model was also run through an idealised greenhouse gas scenario for 150 years, in which concentrations increase at a rate of 1% per year, as discussed above.

Across the ensemble a gradual weakening of the THC occurs as concentrations increase, within the range reported in the Third Assessment Report (Cubasch et al., 2001). No rapid shutdown is seen.

Heat Budget Calculations:

For AR4 the method out lined here is based on the approach from Glecker et al. (1994).

The schematic for the transport calculations is given in Figure 9; the transport in the atmosphere (T_A) and ocean (T_O) at a given latitude (φ) are defined as follows:

$$N_{Ocn} = R_{Ocn} + LH + SH$$

$$T_A(\varphi) = 2\pi a^2 \int_{-\frac{\pi}{2}}^{\psi} (R_{Top} - N_{Ocn}) \cos\varphi \, d\varphi$$

$$T_O(\varphi) = 2\pi a^2 \int_{-\frac{\pi}{2}}^{\psi} N_{Ocn} \cos\varphi \, d\varphi$$

Where all fluxes are defined as positive downwards and R is the radiative flux at a given surface, LH and SH are the latent and sensible heat fluxes at the sea surface respectively and a is the radius of the earth. The top of the atmosphere flux is defined as:

$$R_{Top} = SW_{\downarrow} - SW_{\uparrow} - LW_{\uparrow}$$

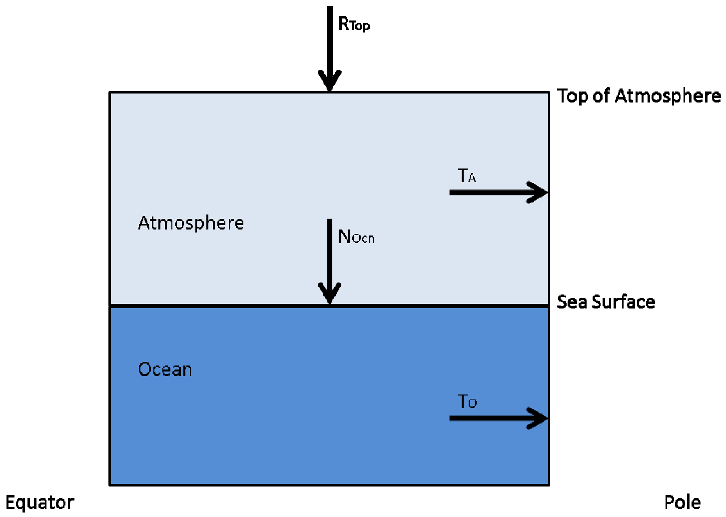

Figure 9: Schematic to show how the atmospheric and oceanic heat transports (T_A and T_O) are calculated. The net top of the atmosphere radiative fluxes (R_{Top}) and the net surface fluxes (N_{Ocn}) are defined as positive downward. Northward heat transports are positive.

An important point to note:

The implied oceanic transports will be in error if long term net energy flux over land is non-zero or if the energy is accumulating in the atmosphere or ocean. To account for this any non-zero annual mean of the globally average fluxes at the boundaries i.e. any non-zero transport at the North Pole is removed uniformly over the globe.

For QUMP the ocean heat transports were diagnosed exactly as the model was run.

The **atmospheric heat transport** was calculated by:

The same definitions of R_{Top} was used as the AR4 model but surface flux into the ocean N_{Ocn} also included the latent heating due to ice melt.

For both ensembles the ocean heat uptake was calculated using the equation:

$$\text{Ocean Heat uptake} = Cv \int_{Arctic} \int_{-z}^{U} T_O \, dV \, dA$$

Where Cv is the volumetric specific heat capacity of sea water (4.09169 J/m^3/K).

Removal of climatology dependence using regression

If we assume a linear dependence between the spread of the change in a variable across the ensemble and the spread of the model climatologies of some variable, e.g.

$$\Delta Precipitation = \beta \, Nortward\ ocean\ heat\ transport + \varepsilon$$

We can determine β by linear regression (least squares fit). The remaining variation we are interested in is contained within the residual term, ε. Hence we can form:

$$\Delta Precipitation^* = \Delta Precipitation - \beta \, Nortward\ ocean\ heat\ transport = \varepsilon$$

We then use $\Delta Precipitation^*$ in subsequent correlations.

Definition of quantities used in correlation Table 3 and Table 4

Air Temperature (SAT)	mean surface air temperature (SAT) 70-90ºN
Polar Ampl. of SAT	(mean SAT 70-90ºN)/(mean SAT global)
Sea Ice Extent	integral of area where sea ice concentration (sic) >0.15 for 70-90ºN
Sea Ice Volume	integral of ice volume 0-90ºN
Precip	mean Precipitation (pr) 70-90ºN
Mixed Layer Temp	mean Ocean Potential Temperature 0-70m 70-90ºN
Polar Amp of MLT	(mean Ocean Potential Temperature 0-70m 70-90ºN)/(mean Ocean Potential Temperature 0-70m)
Sea Ice Thickness	mean thickness (over ice) 70-90ºN
Total N Heat Trans	mean total northward heat transport – sum of Total N Atmos Heat Trans and Total N Ocean Heat Trans.
Total N Atmos Heat Trans	mean atmosphere northward heat transport diagnosed via surface and top of atmosphere fluxes at 70ºN
Total N Ocean Heat Trans	mean ocean northward heat transport diagnosed via either surface and top of atmosphere fluxes at 70ºN (IPCC AR4) or ocean velocities and temperatures (THC-QUMP).
Atl Ocean Heat Transport	mean Atlantic ocean northward heat transport at 70ºN computed from ocean velocities and temperatures.
Ocean Heat Uptake	difference of ocean heat content >70ºN between mean of years 71:80 and mean of years 61:70.
Latent heat Flux	mean latent heat flux from surface (hfls) 70-9º0N
Sensible heat Flux	mean sensible heat flux from surface (hfss) 70-90ºN
Surface albedo feedback	As defined by Winton(2006) 70-90ºN detrended
Non_SA SW feedback	As defined by Winton(2006) 70-90ºN detrended
Longwave feedback	As defined by Winton(2006) 70-90ºN detrended
Surface Up LW	mean surface upward longwave radiation flux (rlus) 70-90ºN
Surface Down LW	mean surface downward longwave radiation flux (rlds) 70-90ºN
TOA Up LW	mean top of atmosphere upward longwave radiation flux (rlut) 70-90ºN
Surface Down SW	mean surface downward longwave radiation flux (rsds) 70-90ºN

Surface Up SW	mean surface upward longwave radiation flux (rsus) 70-90ºN
TOA UP SW	mean top of atmosphere upward longwave radiation flux (rsut) 70-90ºN
Net Down TOA Flux	mean (rsdt-rsut-rlut) 70-90ºN
Net Down Surface Flux	mean (rsds-rsus+rlds-rlus-hfss-hfls) 70-90ºN
Cloud Forcing (SW)	mean (rsds-rsdscs) 70-90ºN (rsdscs is downward shortwave radiation at surface assuming clear sky conditions)
Cloud Forcing (LW)	mean (rlds-rldscs) 70-90ºN (rldscs is downward longwave radiation at surface assuming clear sky conditions)
Cloud Forcing (TOTAL)	mean (rsds-rsdscs + rlds-rldscs) 70-90ºN
Total cloud over Ice	mean (rsds-rsdscs + rlds-rldscs) 70-90N where sea ice concentration (sic) in the CONTROL experiment is >0.15
Atmos Inversion	mean over 70:90ºN: (Ta(900hpa)-Ta(1000hpa)) (IPCC AR4) (Ta(925hpa)-Ta(1000hpa)) (THC-QUMP) (Ta is atmospheric temperature on pressure levels) Definitions differ because the two ensembles reported temperature on different levels.
Fresh Water Flux	Water flux into ocean: mean (wfo) 70-90ºN (wfo is total water flux)

INTERIM REPORT

What is Forcing Amplified Arctic Climate Change in Perturbed Parameter and Structural Change Ensembles?

Met Office-NCAS joint project for NERC Arctic programme

Executive summary

Analysis of perturbed parameter experiments with the HadCM3 climate model and the AR4 models have been used to interpret the main sources of model parameter and structural uncertainty respectively; with the aim of indicating where better understanding and/or more accurate observational values will help to reduce the uncertainty in Arctic climate predictions.

We find the following key results:

- The spread in Arctic temperature is largest in the AR4 ensemble (a standard deviation of 1.06˚C) and the ensemble with perturbed atmospheric parameters (1.10˚C). Sea ice change, in both extent and volume, is largest across the AR4 model ensemble[20].(extent: 1.32x1012m2, volume: 7.16 x1012m3) ; the perturbed parameter ensembles have similar spread in absolute ice volume (0.52x1012m2 and 0.74 x1012m2) and extent (3.97 x1012m3 and 4.03 x1012m3) changes. The spread in regional amplification of global warming in the Arctic is greatest in the AR4 ensemble (0.37).

- Changes in sea ice area are significantly correlated with annual mean Arctic temperature change, and more strongly with ice volume. Arctic temperature change is also significantly correlated with the Arctic amplification, but this correlation is stronger when no atmospheric parameters are perturbed. However, the correlations are considerably weaker across the multti-model (AR4) ensemble.

- The mean values of forcings and feedbacks are similar to those seen by Winton (2006a) which suggests that, in addition to the CO2 forcing, surface albedo feedback, longwave feedback and net top-of-atmosphere forcing all play a role in Arctic temperature change.

- The largest uncertainty in the Arctic temperature change is seen in the net top-of-atmosphere forcing which includes components from a number of factors; surface albedo changes, longwave forcing and cloud changes as well as atmospheric and oceanic heat transport. It is therefore not possible to identify any single cause of this uncertainty, although changes in outgoing longwave are unlikely to be contributing. We intend to analyse terms in the

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[20] It should be noted that the model FGOALS has a very different sea ice climatology which may have an affect on the model spread

Arctic heat budget to discover the principal reasons for the large inter-model differences.

1.Introduction

The Arctic is a region which is both inhabited and accessed for transport and resources. For that reason, there are two key quantities for the Arctic; the projected temperature change and the sea ice cover. The rise in Arctic near-surface air temperatures has been almost twice as large as the global average in recent decades (Solomon et al., 2007), a feature known as „Arctic amplification‟. Increased concentrations of atmospheric greenhouse gases have driven Arctic and global average warming (Gillett et al., 2008); however, the underlying causes of Arctic amplification remain uncertain. The roles of reductions in snow and sea ice cover (Screen & Simmonds, 2010) and changes in atmospheric (Simmonds & Keay, 2009) and oceanic circulation (Graversen et al, 2008), cloud cover and water vapour (Schweiger et al, 2008), are still matters of debate.

Current climate models show a large spread in projections for a wide range of Arctic variables, most of which are linked, directly or indirectly, to changes in temperature. For this report, we made extensive use of a method devised by Michael Winton (2006a) to examine the roles of various forcings and feedbacks in Arctic temperature amplification, including the vital surface albedo feedback term.

In this method, Winton separated the forcing term into: i) direct CO2 radiative forcing, and ii) net top of the atmosphere (TOA) radiative forcing, FN, which is approximately equal to the perturbation net surface heat flux plus the convergence of the atmospheric heat transport into the polar region. The feedbacks were divided into longwave (LW; influenced by clouds, water vapour and temperature) and shortwave (SW) radiative feedbacks. The SW feedback was further separated into surface albedo feedback (SAF) and non-SAF shortwave feedback, the latter being associated with contributions from clouds aerosols and water vapour.

In his 2006 analysis, Winton concluded that, in the multi-model ensemble mean, FN and the SAF and LW feedbacks contribute to Arctic amplification, whereas the direct CO2 radiative forcing and the non-SAF feedback oppose amplification. He also showed that the spread between outliers amongst the AR4 models had multiple causes but was particularly associated with the non-SAF shortwave feedback. Interestingly, the Met office model, HadGEM1, is one of the two models which showed largest amplification and has also been found to capture the magnitude of the recent September sea ice decline (pers. comm. Winton, 2010).

He also computed AR4 models‟ Arctic temperature amplification, compared to the global mean, and found an ensemble mean amplification of 1.9 with a standard deviation of 0.4.[21]

Here we analyse three sets of ensemble experiments using the coupled climate model HadCM3 (Gordon et al., 2000), and the AR4 ensemble of models, to enable us to explore the parameter and structural uncertainties in Arctic climate change.

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[21] These values differ slightly from those quoted in section 3. See section 3 for details.

We follow the approach of Winton (2006a) and look at the balance of forcing and feedback terms across the ensembles which will enable us to identify the main causes of uncertainty in Arctic temperature change in the HadCM3 model. We then examine various top-of-atmosphere fluxes for one of the HadCM3 ensembles to try and understand the source of this uncertainty.

2. Analysis

2.1 Ensemble experiments

We compare two sets of coupled model experiments in this study. The first set (QUMP – Quantifying Uncertainty in Model Predictions) consists of three ensembles designed to sample *parameter* uncertainty in a single model (HadCM3). The second set (IPCC AR4) is a multiple model ensemble which enables an assessment of *structural* uncertainty.

The HadCM3 (QUMP) experiments use perturbed parameters and the three ensembles can be broadly described as atmospheric parameter changes 1) with flux correction and 2) without flux correction, and 3) ocean parameter changes with flux correction. The aim of the ensembles is to span the range of climate sensitivities consistent with a uniform prior on parameters but in the process maximise the chance of getting plausible model versions and span a wide range of parameter settings (Collins et al., 2006).

Each ensemble comprises of the unperturbed member, the base state which has the same parameter settings as HadCM3 in the IPCC AR4, The other members have been perturbed away from the base state through changes to multiple model parameters, according to a "Latin Hypercube" design which maximises the number of potential interactions between perturbations. In light of parameter settings that could cause substantial model drift, the ensemble members has a surface flux adjustment applied, sufficient to relax the control simulation sea surface temperatures to observations (Collins et al, 2004). The flux adjustment is fixed throughout the simulations of future scenarios.

Experiments were performed with CO2 levels rising from pre-industrial to quadruple pre-industrial levels at a rate of 1% per year.

1.Atmos-QUMP

This is a 17 member ensemble with 31 parameters perturbed from the base state. Parameters were perturbed in the atmosphere (radiation, large scale cloud, convection, boundary layer, dynamics), surface scheme and sea-ice components in order to generate the ensemble and sample the uncertainties in climate feedback processes.

The rate of time-dependent global-mean temperature change depends jointly on atmospheric feedbacks associated with climate change and the efficiency of processes which remove heat from the surface to the deep ocean (e.g. Raper et al.

2002). The use of identical ocean components, coupled to atmospheric components with perturbed parameters, means we can isolate the component associated with atmospheric feedbacks. However, it also means that this study cannot attempt to capture the full range of uncertainty in transient climate change possible with HadCM3.

2. THC-QUMP

An ensemble of 22 members based on the coupled climate model HadCM3. Like the Atmos-QUMP it uses „perturbed physics" in the atmosphere component, however, it does not use flux adjustments and so some members of the ensemble showed minor climate drift. In the Arctic the „drift" exhibited itself as such low initial states of sea ice extent, that the summer ice cover was lost early on in the climate change simulation.

Each member was first run for 100 years as a spin-up, to assess the amount of climate drift and model stability. After the spin-up phase each model was run through a control phase for 140 years. Parallel to this control phase, each model was also run through an idealised greenhouse gas scenario for 150 years, in which concentrations increase at a rate of 1% per year.

Across the ensemble a gradual weakening of the THC occurs as concentrations increase, within the range reported in the Third Assessment Report. No rapid shutdown is seen. There is some relation between the rate of weakening and the effective climate sensitivity in the members. Preliminary analysis suggests that compensating changes in the hydrological cycle over the Atlantic limit the range of responses.

3. Ocean-QUMP

This is a 17 member perturbed ocean parameter ensemble. Three logical parameters were perturbed, which allow us to switch between or activate different parts of the ocean model code and 14 continuous parameters. The processes perturbed include the horizontal mixing of heat and momentum, the vertical diffusivity of heat, isopycnal mixing, mixed layer processes and water type. Parameters and ranges were determined in consultation with experts (Brierley et al., 2006).

Flux adjustments are applied to all 16 members to limit climate drift and bias. Experiments are initialised from an equilibrated flux-adjusted standard HadCM3 experiment. Perturbations are then introduced, and each member is run for 100 years with a Haney relaxation to seasonally-varying SST and surface salinities. The last 30 years of the Haney phase is then used to compute a flux-adjustment term and this was applied for a further 50 years of spin-up.

4. IPCC AR4

The IPCC AR4 multi model ensemble contains 23 coupled climate models (Randall et al., 2007) with different resolutions, structures and may or may not have flux adjustments.

Model structures differ in the ways of modelling the physical the equations that describe fluid flow (e.g. different grid types and different numerical methods for solving the equations) and/or different methods to represent sub-grid scale processes. Within the AR4 ensemble 14 models have archived the relevant data to carry out the Winton analysis.

Flux adjustments of freshwater and/or heat are applied to 6 of the 23 models in the archive. Each model has its own methodology for applying the flux adjustments if they are made.

2.2 Methods

In all cases we analyse the changes around the point of CO2 doubling in experiments where CO2 is increased at a rate of 1% per year (years 61-80 of these experiments) relative to the same period in the corresponding control.

Throughout, we define the Arctic as the region north of 70˚N when calculating energy fluxes, as this is the region which defines the Arctic Ocean. This region differs from that of Winton (2006a), who extended the Arctic region down to 60˚N.

When calculating mean ice extents across periods of 20 years, the method we used was to take the mean ice concentration across the whole 20 years, and then integrate the area with greater than 0.15 concentration. Note that this method produces a different result to that of calculating monthly ice extents directly from monthly concentration fields, and taking the mean of these. It should be noted that when we define ice extents and volume, and changes in these, the whole Northern Hemisphere is used and not just the region north of 70˚N.

A full description of the method used for calculating surface albedo feedback from various standard surface fluxes is given in Winton (2006b) (“Surface Albedo Feedback Estimates for the AR4 Climate Models”). In addition, a description of his method for then calculating all other forcings and feedbacks, is given in Winton (2006a) (“Amplified Arctic climate change: What does surface albedo feedback have to do with it?”)

3. Results

In this section, results shown in the form a ± b refer, respectively, to ensemble mean (a) and ensemble standard deviation (b).

3.1 Surface temperature, Arctic amplification and sea ice decline

While ice-albedo feedback is likely to account for much of the polar amplification, the strength of the feedback depends on numerous physical processes and parametrisations which differ considerably among models. An intercomparison of model results also shows that increases in poleward ocean heat transport at high latitudes and increases in polar cloud cover are significantly correlated to amplified Arctic warming (Holland & Bitz, 2003).

Table 1 shows the changes in Arctic temperature, Arctic amplification and ice extent in all four ensembles between pre-industrial and doubling (years 61-80 of a transient simulation with compound increase of CO_2, from 285ppm, at 1% per annum) of CO_2.

The change in Arctic temperature, and polar amplification, in the QUMP ensembles is least in the THC-QUMP (not flux adjusted) ensemble. This suggests that flux adjustment alters the behaviour of the model, increasing the climate sensitivity of the Arctic region. This conclusion is consistent with the smaller values seen in the AR4 ensemble. (Although some of the AR4 models are flux adjusted, only 2 out of 16 models used to create the AR4 ensemble for this study use such adjustments. Consequently the impact of these adjustments is likely to be small compared to the flux adjusted QUMP ensemble.)

However, the *spread* across each ensemble is least in Ocean-QUMP, suggesting that uncertainty in Arctic change is dominated by the parameterisations in the atmosphere. This conclusion is consistent with the change in Arctic temperature seen in the AR4 ensemble. However, the spread in the polar amplification is greater in the AR4 ensemble. This suggests that the parameter uncertainty sampled by the QUMP ensemble does not capture the full spread in structural uncertainty present within the AR4 ensemble for the polar amplification.

The strong relationship between ice characteristics and temperature (Ridley et al., 2007) is consistent with Table 1. It is clear that the sea ice volume is the more sensitive indicator of regional climate change. However, this may be a function of the sea ice thermodynamics used in HadCM3 (the change is smaller in the AR4 ensemble) . There are negative feedbacks arising from a thinning of the ice (Bitz & Roe, 2004) in which winter ice growth rate increases for thin ice.

Ensemble	ΔT_A (ºC)	$\Delta T_A / \Delta T_G$	ΔIce Extent (10^{12} m^2)	ΔIce Extent (% change)	ΔIce volume (10^{12} m^3)	ΔIce volume (% change)
QUMP-Atmos	5.70 ±1.10	2.60 ±0.22	-3.13 ±0.52	-19.52 ±3.33	-15.9 ±3.97	-56.7 ±11.0
THC-QUMP	4.26 ±0.63	2.25 ±0.22	-2.56 ±0.74	-15.6 ±3.03	-7.49 ±4.03	-41.4 ±5.38
QUMP-Ocean	5.24 ±0.57	2.41 ±0.18	*Ice data is not available for the Ocean ensemble*			
IPCC AR4	3.99 ±1.06	2.13 ±0.37	-2.30 ±1.32	-10.6 ±5.40	-11.5 ±7.16	-38.7 ±12.0

Table 1: *Spread of Arctic temperature change (ΔT_A) , amplification ($\Delta T_A/\Delta T_G$) and Arctic sea ice area and volume changes (absolute and percentage). ΔT_A was calculated for the region north of 70N. Ice quantities were formed by integrating over the entire northern hemisphere. Ice extent is defined as where sea ice concentration >0.15. Errors are one standard deviation of the ensemble spread.*

An examination of the correlation of Arctic temperature change with the change in ice extent, the change in ice volume and the Arctic amplification itself across each of the ensembles is shown in Table 2.

	Correlation between		
Ensemble	**ΔT_A , $\Delta T_A / \Delta T_G$**	**ΔT_A, ΔIce Extent %**	**ΔT_A, ΔIce Volume %**
QUMP-Atmos	0.77	-0.81	-0.93
THC-QUMP	0.80	-0.85	-0.88
QUMP-Ocean	0.96	Ice data is not available for the Ocean ensemble	
IPCC AR4	0.73	-0.54	-0.68

Table 2: *Correlation of Arctic temperature change with Arctic amplification, ice extent change (as a %) and ice volume change (as a %)*

The correlation of Arctic temperatures with polar amplification is strongest in the Ocean-QUMP, suggesting that ocean parameters are not contributing significantly to the regional uncertainty. There is not much difference between correlations for the flux adjusted Atmos-QUMP and non-adjusted THC-QUMP. This would suggest that the mechanism of flux adjusting is not creating a significant distortion of this correlation (although, as noted above, it does appear to affect the Arctic climate sensitivity). The correlations are all greater for QUMP than the AR4 ensemble suggesting that these relationships may be weaker in other climate models.

All the ensembles show a clear negative correlation between Arctic temperatures change and sea ice extent and volume changes. These correlations are stronger in the QUMP ensembles than the AR4 ensemble, and it is known that the climate sensitivity of sea ice in HadCM3 is at the high end of the AR4 models (Ridley et al., 2007), again suggesting that similar correlations would not be found in all climate models.

Observations of polar amplification indicate that the winter warming dominates (Lu & Chi 2009). In winter the ice cover is almost 100% and consequently the air temperature rise will be a function of ice thinning. However, this does not imply a causal connection. Increased atmospheric winter heat transport to the Arctic would reduce ice growth, resulting in thinner ice prior to the melt season. Conversely, increasing summer melt will lead to a later freeze-up and less time for thermodynamic growth in winter. The sensitivity of ice volume to regional temperature, as shown here, is in agreement with simple model simulations (Dumas et al., 2003).

3.2 Analysis of forcing and feedbacks in the ensembles

Winton (2006a) describes the temperature change in the Arctic as a ratio of forcings (F_i) and feedbacks (f_i):

$$\Delta T=-\Sigma_i(F_i)/\ \Sigma_i(f_i) \qquad (1)$$

Hence the Arctic amplification, ***A,*** is expressible as

$$A=-(\Sigma_i(F_i^A)).(\Sigma_i(f_i^G)))/((\Sigma_i(f_i^A)).(\Sigma_i(F_i^G))) \qquad (2)$$

The forcings are F_{CO2}, the CO_2 forcing, and F_N, the net top-of-atmosphere flux. The feedbacks are f_{SAF}, the surface albedo feedback, $f_{NON\text{-}SAF\text{-}SW}$, the shortwave feedback not associated with surface albedo (mostly clouds), and the long-wave feedback (increased winter heat loss from a warmer surface).

Values of F_{CO2} are not available for each individual member of the three QUMP ensembles due to the calculations required. However, Winton (2006a) notes that F_{CO2} does not vary significantly in the IPCC AR4 models. Therefore we have taken the approach of using the standard HadCM3 value for F_{CO2} available from the CMIP3 database and as quoted in Winton (2006a).

We have repeated the Winton analysis for the IPCC AR4 models. This calculation was performed this using 14 of the models in the CMIP3 archive and for an Arctic defined as north of 70N. By contrast Winton used 12 models and 60N. The values used for F_{CO2} were those given in Winton (2006a), or the model mean for those models not specified in the paper.

This may explain why the means quoted in Table 1 are slightly different to those quoted by Winton, however Winton’s values still lie within the ranges of uncertainty quoted in the table.

Ensemble	F_{CO2}	F_N	f_{SAF}	$f_{NON\text{-}SAF\text{-}SW}$	f_{LW}
QUMP-Atmos	3.12	-0.51±1.05	0.98±0.15	-0.16±0.11	-1.32±0.07
THC-QUMP	3.12	0.32±0.61	0.77±0.10	-0.21±0.11	-1.40±0.08
QUMP-Ocean	3.12	0.38±0.34	0.78±0.06 **(total SW feedback)**		-1.45±0.03
IPCC AR4	3.15±0.15	0.03±1.05	0.85±0.31	-0.16±0.31	-1.61±0.14

Table 3*: mean and standard deviation of forcings and feedbacks from all ensembles based on Winton (2006a).*

Lack of data prevented the decomposition of SW forcings for the QUMP-Ocean ensemble.

Table 3 shows that values for the QUMP ensembles and the AR4 ensemble are not markedly different except in F_N. It also shows that in all cases, F_N displays by far the greatest parameter and structural model uncertainty. The surface albedo feedback provides a relatively small contribution to the uncertainty in the Arctic amplification in the QUMP ensemble, although the contribution is somewhat greater in the AR4 ensemble. For a discussion of the F_N term, see **Section 3.3**. One might expect, given the strong correlation of Arctic temperature to ice thickness (Table 2), that the long-wave feedback would be display considerable uncertainty. However, $\mathbf{f}_{LW}$ is the sensitivity of the loss of heat to space as a function of surface temperature, and is well constrained.

In addition Winton examined the Arctic amplification resulting from the setting of each individual Arctic forcing and feedback term in equation (2) to its corresponding global value, referring to this as 'neutralising' each term. We carried out the same analysis:

Ensemble	No neutralisation	F_{CO2}	F_N	f_{SAF}	$f_{NON\text{-}SAF\text{-}SW}$	f_{LW}
QUMP-Atmos	2.60±0.22	3.79±.024	2.11±1.31	1.09±0.42	7.67±23.14	1.04± 0.28
THC-QUMP	2.25±0.22	2.87±0.36	1.31±0.31	1.42±0.14	0. 70±19.3	1.14±0.19
QUMP-Ocean	2.41±0.18	3.05±0.21	1.22±0.13	2.80±0.36 (from neutralisating total SW)		1.22±0.09
IPCC AR4	2.16±0.39	2.82±0.61	1.80±1.11	1.23±0.41	-2 .68±23.10	1.08±0.38

Table 4: impact of neutralization on Arctic amplification

Terms which, when neutralised, give a higher mean Arctic amplification can be regarded as opposing the amplification, and vice versa. The enormous error margin for the $f_{NON-SAF-SW}$ term indicate that this column should not be taken seriously; the numbers are such that neutralising this term brings the denominator in equation (2) close to 0, thus making the amplification highly sensitive to small changes, and several experiments exhibit an amplification of greater than 10. The manner in which each term is calculated suggest that in the physical world, an alteration to $f_{NON-SAF-SW}$ would entail a change in F_N also, hence the unphysical results obtained in this case.

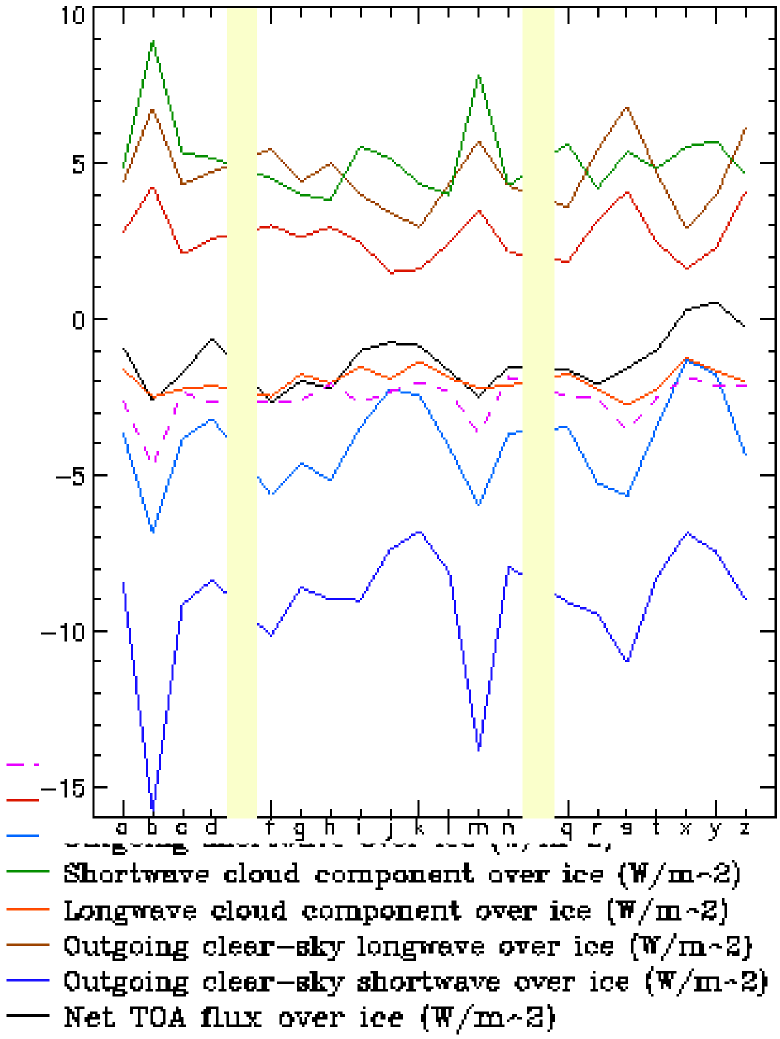
The results in Table 4 are consistent with Winton's conclusions that F_N, f_{SAF} and f_{LW} feedbacks all contribute to Arctic amplification, whereas the direct F_{CO2} radiative forcing opposes amplification. It is unclear, given the concerns raise above, that anything can be concluded about the impact of $f_{NON-SAF-SW}$ on the amplification.

3.3 Causes of uncertainty in F_N

$F_{N,}$ the net top-of-atmosphere energy flux has the largest model uncertainty in all four ensembles. The year-on-year variability in F_N in each model is examined to determine if the uncertainty is a function of time-series sampling. It is found that the standard deviation of detrended F_N across all possible 20-year sampling periods (henceforth called timewise standard deviation) was, in all model runs, considerably lower than the standard deviations across their relevant ensembles. For example, amongst the model runs in the THCQUMP ensemble, in all but two of the models F_N had timewise standard deviation less than 0.3, while across the ensemble itself F_N has standard deviation 0.61. Moreover, models with a high timewise standard deviation do not correspond to outliers in the inter-model analysis.

In figure 1, we show various components of the top-of-atmosphere energy fluxes for 20 experiments of the THCQUMP ensemble (two experiments did not have complete data and appear erased on the graph). The values shown are the difference between preindustrial and doubling of CO_2. Fluxes are derived only over model grid cells with greater than 0.15 mean ice concentration in years 61-80 of the preindustrial simulation. This provides an insight to changes which occur solely as a consequence of a reduction in sea ice extent. The positive direction indicates an increase in upwards fluxes.

The cloud components are defined as the total fluxes minus the clear-sky fluxes for both the longwave and the shortwave cases. Thus they represent the SW and LW TOA forcing. The table on the right of figure 1 shows the correlations observed between all quantities below the diagonal, and the square of the correlations (significance) above the diagonal, with colour coding. Deep blue indicates perfect negative correlation, bright red perfect positive, and white no correlation. Similarly, dark green indicates a significance of 1, and white no significance.



Significance / Correlation	Ext. change	All−sky LW	All−sky SW	Cloud LW	Cloud SW	Clr−sky LW	Clr−sky SW	Net TOA
Ext. change	1	0.46	0.52	0.33	0.61	0.5	0.86	0.28
All−sky LW	−0.69	1	0.68	0.44	0.14	0.93	0.57	0.17
All−sky SW	0.72	−0.82	1	0.57	0.1	0.75	0.71	0.74
Cloud LW	0.57	−0.68	0.76	1	0.05	0.7	0.4	0.37
Cloud SW	−0.78	0.37	−0.31	−0.28	1	0.12	0.6	0.03
Clr−sky LW	−0.71	0.97	−0.87	−0.84	0.35	1	0.6	0.27
Clr−sky SW	0.93	−0.76	0.84	0.63	−0.78	−0.78	1	0.44
Net TOA	0.53	−0.42	0.86	0.61	−0.16	−0.52	0.66	1

Figure 1. Energy fluxes at TOA, (mean of control experiment yrs 61-80) – (mean of 1% CO2/yr experiment yrs 61-80). The change in ice extent is shown also on the same scale: here the mean ice concentration across the 20 years was taken and the area of grid cells of >0.15 concentration taken. LH graph shows the values across the individual ensemble members (a to t) of THCQUMP; the RH table shows the correlations between the quantities.

<u>Short wave</u>: The clear-sky SW represents the change in surface albedo as as would be expected correlates extremely well with ice extent, with a significance value of 0.86. The outgoing SW is the flux including the clouds. The change in clouds halves the impact of surface albedo changes. In addition, the SW cloud forcing (summer) is anti-correlated with changes in sea ice cover. Thus the faster the decrease in ice extent the more the increase in summer cloud cover, that is clouds are replacing ice in the SW budget.

Long wave: The clear-sky LW is an indicator of annual mean surface temperature. Since the summer temperature is constrained by the melting point, the dominant change in LW will be from changes in winter ice thickness. Ensemble members which show a large change in ice extent also show increases in LW, but the correlation is not as good as for SW, suggesting that the combination of winter and summer changes may resulting in partially compensating LW impacts. The LW cloud forcing shows that by CO2 doubling the winter Arctic clouds are trapping an extra 3W/m2 of heat. This is not well correlated with ice extent, and this is not only a consequence of more open ocean in the region.

Net TOA flux (F_N): In the annual mean TOA flux, a combination of SW (summer) and LW (winter) changes in radiative fluxes results in a weak correlation with sea ice extent. The uncertainty in F_N is a consequence of differences in winter and summer changes in the Arctic. These are very likely related to the amplitude of the seasonal cycle of the sea ice (Holland & Bitz, 2003). To better understand the uncertainty in net top of atmosphere fluxes, depicted by the structural and parameter model ensembles, an assessment of seasonality is required.

In order to better understand the source of the uncertainty in F_N, we intend to carry out a complete analysis of the Arctic heat budget for the ensembles (except for the Ocean ensemble for which we have insufficient data). Preliminary results appear to indicate that atmospheric heat transport into the Arctic is a large source of uncertainty but this result needs to be properly verified and investigated.

4. Conclusions

- The uncertainty in Arctic change is dominated by the uncertainty in the parameterisations in the atmosphere, rather than the ocean.
- In all the ensembles, changes in sea ice extent and ice volume are significantly correlated with annual mean Arctic temperature change.
- Arctic temperature change is also significantly correlated with the Arctic amplification, but this correlation greater when no atmospheric parameters are perturbed
- Arctic climate sensitivity is greater in the ensembles that use flux adjustment. Although flux adjustments do not appear to greatly affecting the correlation between Arctic temperature changes and polar amplification (Table 2).
- Results for the Winton analysis are consistent with Winton (2006a), conclusions that F_N, f_{SAF} and f_{LW} feedbacks all contribute to Arctic amplification, whereas the direct F_{CO2} radiative forcing opposes amplification.
- The net top of the atmosphere (TOA) radiative forcing, F_N, is a major source of uncertainty within the Arctic. A full understanding of this uncertainty will required a detailed analysis of the seasonal variation of heat budgets within the Arctic. This will form the basis of future work.

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