

Projected changes in Arctic Ocean freshwater budgets

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Received 25 October 2006; revised 12 February 2007; accepted 16 March 2007; published 26 October 2007.

[1] Arctic Ocean freshwater budgets are examined from 10 models participating in the Intergovernmental Panel on Climate Change Fourth Assessment Report. This includes an analysis of sea ice transport and storage, ocean transport and storage, and net surface flux exchange. Simulated budgets for the late 20th century are compared to available observations, followed by an analysis of simulated changes from 1950 to 2050. The consistent theme over this period is an acceleration of the Arctic hydrological cycle, which is expressed as an increase in the flux of water passing through the hydrologic elements. Increased freshwater inputs to the ocean from net precipitation, river runoff, and net ice melt result. While generally attended by a larger export of liquid freshwater to lower latitudes, primarily through Fram Strait, liquid freshwater storage in the Arctic Ocean increases. In contrast, the export and storage of freshwater in the form of sea ice decreases. The qualitative agreement between models for which the only common forcing is rising greenhouse gas concentrations implicates this greenhouse gas loading as the cause of the change. Although the models perform quite well in their simulations of net precipitation over the Arctic Ocean and terrestrial drainage, they differ significantly regarding the magnitude of the trends and their representation of contemporary mean ocean and sea ice budget terms. To reduce uncertainty in future projections of the Arctic freshwater cycle, the climate models as a group require considerable improvement in these aspects of their simulations.

Citation: Holland, M. M., J. Finnis, A. P. Barrett, and M. C. Serreze (2007), Projected changes in Arctic Ocean freshwater budgets, *J. Geophys. Res.*, 112, G04S55, doi:10.1029/2006JG000354.

1. Introduction

[2] The Arctic system is undergoing substantial and coordinated changes [e.g., Serreze *et al.*, 2000; Overland *et al.*, 2004], a number of which pertain to its freshwater cycle [White *et al.*, 2007]. Changes in the amount and seasonality of river discharge have occurred and a 7% increase in annual Eurasian river runoff from 1936 to 1999 has been documented [Peterson *et al.*, 2002]. Since 1958, net precipitation over the Arctic Ocean has increased [Peterson *et al.*, 2006]. Freshwater storage in high-latitude glaciers has declined [Dyurgerov and Carter, 2004] and recent reductions in the volume of the Greenland ice sheet have been documented [Box *et al.*, 2004; Chen *et al.*, 2006]. Reductions in sea ice volume and extent, representing reduced freshwater storage within the floating ice cover, have occurred since the 1960s [Rothrock *et al.*, 1999; Serreze *et al.*, 2003; Stroeve *et al.*, 2005] some of which are associated with an increased export of ice to lower latitudes [Rigor *et al.*, 2002]. Altered patterns of atmospheric circulation associated with the phase of the Northern Annular Mode (NAM) and rising air temperatures contrib-

ute to these changing conditions [e.g., Dickson *et al.*, 2000; Rigor *et al.*, 2002].

[3] Arctic Ocean hydrography has also undergone considerable change. This includes warming of the Atlantic layer which lies at 200–800 m depth [Quadfasel *et al.*, 1991; Carmack *et al.*, 1995; Polyakov *et al.*, 2004], a general increase of salinity in the upper ocean from 1948 to 1993 [Swift *et al.*, 2005], and considerable freshening in some shelf regions [Steele and Ermold, 2004]. However, an assessment of change in the total Arctic Ocean freshwater storage remains elusive owing to a lack of adequate salinity and ice volume data. Changes in the cold halocline layer that provide a buffer between the warm Atlantic layer and the sea ice have also been observed, with weakening from 1991 to 1998 [Steele and Boyd, 1998] followed by partial recovery from 1998 to 2000 [Boyd *et al.*, 2002].

[4] Alterations in the Arctic hydrological cycle can have important downstream impacts. Observations indicate substantial freshening of the northern North Atlantic from 1965 to 1995 [Curry *et al.*, 2003; Curry and Mauritzen, 2005], linked primarily to increasing Arctic river discharge and net precipitation, and increasing sea ice melt and export [Peterson *et al.*, 2006]. These findings are of interest as freshening can affect North Atlantic deep water formation with potential implications for the global thermohaline circulation (THC). Numerous modeling studies have examined these effects and the far-reaching consequences that a changing THC may exert [e.g., Manabe and Stouffer, 1999].

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Table 1. Models Used in the Analysis^a

Model	Model Center	Ice Data	P-E Data	Ocn Data	Atm Resolution	Ocn Resolution
CGCM3.1 (T63)	Canadian Centre for Climate Modeling and Analysis, Canada	X	X	X	T63	1.4 × 0.94
CNRM-CM3	Météo-France/Centre National de Recherches Météorologiques, France	X	X	X	T42	2 × 2
CSIRO-Mk3.0	CSIRO Atmospheric Research, Australia	X	X	X	T63	1.9 × 0.84
GFDL-CM2.1	NOAA/Geophysical Fluid Dynamics Laboratory, U.S.A	X	X	None	2.5 × 2	1 × 1
GISS-AOM	NASA Goddard Institute for Space Studies, USA	X	X	X	4 × 3	4 × 3
GISS-ER	NASA Goddard Institute for Space Studies, USA	X	X	X	4 × 5	4 × 5
MIROC3.2(med)	Center for Climate System Research (The University of Tokyo), National Institute for Environmental Studies, and Frontier Research Center for Global Change, Japan	X	X	X	T42	1.4 × 1.4
CCSM3	National Center for Atmospheric Research, USA	X	X	X	T85	1 × 1
UKMO-HadCM3	Hadley Centre for Climate Prediction and Research/Met Office, UK	X	X	X	2.75 × 3.75	1.25 × 1.25
UKMO-HadGEM1	Hadley Centre for Climate Prediction and Research/Met Office, UK	X	X	None	1.25 × 1.875	1 × 1

^aInformation on the models is available from http://www-pcmdi.llnl.gov/ipcc/model_documentation/ipcc_model_documentation.php.

[5] Observed changes in the Arctic hydrologic system are broadly consistent with the climate model response to rising greenhouse gases. This includes simulated increases in Arctic river discharge [Arora and Boer, 2001; Wu *et al.*, 2005] and net precipitation [Kattsov and Walsh, 2000]. Studies which examine the entire simulated budget within individual climate models [Miller and Russell, 2000; Holland *et al.*, 2006; Koenigk *et al.*, 2007] point to increases in river runoff and net precipitation as well as decreases in Arctic sea ice export. Other studies suggest that changes in the Arctic freshwater cycle, particularly in the transport of water to the North Atlantic, may substantially influence the THC [e.g., Delworth *et al.*, 1997; Mauritzen and Hakkinen, 1997; Holland *et al.*, 2001]. Regional changes in the flux of Arctic freshwater to the North Atlantic can have important implications for this THC response [Koenigk *et al.*, 2007; Rennermalm *et al.*, 2007].

[6] Here we expand on previous work by comparing and contrasting 20th and 21st century simulated Arctic Ocean freshwater budgets from 10 models participating in the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC-AR4) (section 2). Climatological mean budgets for the late 20th century are discussed and evaluated against observed estimates (section 3). Simulated changes in the budgets from 1950 to 2050 are analyzed and compared among the models (section 4). Discussion and conclusions follow in section 5.

2. Models and Observations

2.1. Model Integrations and Analysis

[7] The 10 models are summarized in Table 1. The 20th and 21st century simulations have been archived at the

Program for Climate Model Diagnosis and Intercomparison (PCMDI <http://www-pcmdi.llnl.gov>). The 20th century integrations apply variations in external forcing based on observed records and offline chemical transport models. Different centers use different specified forcings in the 20th century. They all include changing greenhouse gases and may also apply variations in solar input, volcanic forcing, and ozone concentrations. The 21st century integrations use the Special Report on Emissions Scenarios (SRES) A1B scenario for projected changes in greenhouse gas emissions [Intergovernmental Panel on Climate Change (IPCC), 2001]. In this scenario, carbon dioxide levels reach approximately 720 ppm by 2100 as compared to approximately 370 ppm in 2000. Holland *et al.* [2006] found that differences in the projected 21st century freshwater budget terms in a series of different scenarios from a single climate model are fairly small. This is in part because the CO₂ concentrations in the A2, A1B, and B1 scenarios are quite similar until year 2040, by which time much of the changes in the simulated freshwater budgets had already occurred.

[8] For the ice and surface flux terms, output is analyzed from all of the 10 models listed in Table 1. These differ in their resolution and physics packages, but all include a dynamic-thermodynamic sea ice model. A number of models do not have ocean data available through the PCMDI archive. Hence assessments of oceanic transports and storage are based on a smaller subset (Table 1).

[9] Simulated freshwater budgets for an Arctic Ocean domain (Figure 1) are computed for the individual models. This is the same ocean domain as used by Serreze *et al.* [2006] in their observationally based assessment of the budget, facilitating a direct comparison. The budget terms computed include precipitation and evaporation over the



Figure 1. Location map of the Arctic Ocean domain and its contributing terrestrial drainage. Thick lines show the straits defining the Arctic Ocean.

Arctic Ocean domain and its contributing terrestrial drainage, the latter also defined as by *Serreze et al.* [2006]. It is assumed that net precipitation over the terrestrial drainage equals river discharge into the Arctic Ocean. This introduces some error since it ignores changes in soil moisture storage and the nuances of the individual model's watershed definition. Additionally, it ignores any changes in glacier mass budgets and permafrost which influence river discharge and are projected to be quite large in some models [e.g., *Lawrence and Slater*, 2005]. While acknowledging these errors, this method ensures consistent comparison between the models.

[10] The sea ice and ocean components of the budget include the storage of freshwater and the transports of freshwater through Fram Strait, the Barents Sea, the Bering Strait, and the Canadian Arctic Archipelago (CAA) (the latter not represented in all models). The ocean liquid freshwater storage (ignoring the sea ice component) is computed as:

$$H(S) = \int \int_{-z}^0 \frac{(S_0 - S)}{S_0} dz dA \quad (1)$$

and the ocean transports from

$$M(u, S) = L \int_{-z}^0 u \frac{(S_0 - S)}{S_0} dz \quad (2)$$

where L is the length of the transect through which the transports are computed, u is the velocity (current speed) perpendicular to the transect, S is the ocean salinity, and S_0 is a reference salinity. The ocean terms are integrated over the entire ocean column and the storage is integrated over the Arctic Ocean domain. A reference salinity of 34.8 on the Practical Salinity Scale is used to allow for comparison with previous studies [e.g., *Serreze et al.*, 2006]. Monthly mean values are used in the computations, which introduces a small error (of less than 1% when compared to select integrations that use instantaneous values in this computation). The ice transport and storage are computed in an analogous way using an assumed ice salinity of 4 and a density of 900 kg m^{-3} . The models resolve the passages through the Canadian Arctic Archipelago (CAA) with different degrees of realism owing to different model resolution. The majority of models have no flow through the CAA into Baffin Bay. The ice and ocean transport terms are computed on the native model data grid to avoid

Table 2. Freshwater Budget Terms for the Individual Models Averaged From 1980 to 1999 in km³ per Year^a

Model	Land P-E	Ocn P-E	Ocean Transport				Ice Transport		
			Fram	Bar	Ber	CAA	Fram	Bar	Ber
Observations	2900 ± 160	2000 ± 170	-2660	-110	2500 ± 270	-3200	-2300 ± 530		
CGCM3.1(T63)	2698	1320	-2617	-379	4159	NA	-1381	-406	-316
CNRM-CM3	3165	1386	-1720	-359	277	NA	-1041	-501	-61
CSIRO-Mk3.0	2458	1579	-9330	-1642	7516	NA	-2146	-2621	58
GFDL-CM2.1	2822	1475	NA	NA	NA	NA	-841	-35	57
GISS-AOM	4187	1796	274	237	1303	NA	-953	-166	-539
GISS-ER	2240	1412	346	-1498	42	NA	-1535	1	0
MIROC3.2(med)	3414	1604	-4323	-778	2770	-1046	-854	-117	-57
CCSM3	4724	1842	-3933	59	2202	-1362	-2927	-81	126
UKMO-HadCM3	2728	1521	-3439	-714	444	NA	-587	-35	19
UKMOHadGEM1	3186	1498	NA	NA	NA	NA	-1479	-130	145
Multimodel mean	3162	1543	-3093	-634	2339	NA	-1375	-409	-57
Stan Deviation	776	169	3082	673	2521	NA	708	794	213

^aThe sign convention is such that a source of freshwater for the Arctic basin is positive. Observed values are obtained from the climatology of *Serreze et al.* [2006] and include the interannual standard deviation where available. For the Fram Strait ocean transport, the observed estimate includes a contribution from Fram Strait Deep Water, Fram Strait Upper Water, and the West Spitsbergen Current. For the Barents Sea transport, the observed value includes a contribution from the Norwegian Coastal Current and the Barents Sea Branch.

interpolation errors. This leads to differences in the transect definitions used for the different models but does not significantly affect the results.

2.2. Observations

[11] Observed annual mean profiles of salinity and estimates of liquid freshwater storage in the Arctic Ocean (based on the 34.8 reference) used for model evaluation rely on data from the Version 3.0 University of Washington Polar Science Center Hydrographic Climatology (PHC) (<http://psc.apl.washington.edu/Climatology.html>). The PHC uses optimal interpolation to combine data from the 1998 version of the World Ocean Atlas [*Antonov et al.*, 1998; *Boyer et al.*, 1998] with records from the regional Arctic Ocean Atlas [*Environmental Working Group (EWG)*, 1997, 1998] and the Bedford Institute of Oceanography. *Steele et al.* [2001] provide an overview of Version 2.0. Many of the measurements were collected in the 1970s and most are from spring and summer.

[12] The annual mean freshwater budget compiled by *Serreze et al.* [2006] is based on assembling the best available estimates of the primary budget terms, partly from values in the published literature and partly from analyses conducted for that study. Liquid freshwater storage in the Arctic Ocean is based on the PHC data set. Estimates of ocean transports draw strongly on results from coordinated national and international efforts such as the Arctic System Science FreshWater Integration (FWI) Study of the National Science Foundation, Variability of Exchanges in the Northern Seas (VEINS, <http://www.ices.dk/ocean/project/veins>) and the Arctic and Subarctic Ocean Fluxes (ASOF, <http://asof.npolar.no>) program. For comparison to the model simulations, transports for some individual ocean current systems (e.g., the Norwegian Coastal Current and the Barents Sea inflow Branch) have been summed to obtain the total transport through certain regions (Table 2). Precipitation and net precipitation over the Arctic Ocean and terrestrial drainage are assessed from available observations and information from the European Centre for Medium Range Forecasts ERA-40 reanalysis [*Uppala et al.*, 2005].

Observed river discharge was combined with estimates for ungauged parts of the terrestrial drainage by assuming that runoff (discharge divided by drainage area) for ungauged regions was the same as that for the gauged area.

[13] The compiled observed annual budget should be viewed with the important caveat that estimates for a number of ocean transport terms rely on sparse hydrographic data that do not adequately sample interannual variability. The difference between freshwater inflows to the Arctic Ocean (8450 km³) and outflows (9160 km³) in the *Serreze et al.* [2006] budget is indistinguishable from zero when errors are considered. Particularly large uncertainties characterize freshwater flows through the CAA and the liquid exports through Fram Strait.

[14] Simulated changes over the late 20th century are compared to estimates from *Peterson et al.* [2006], which synthesize observations of changes in the Arctic freshwater system from 1950 to 2000, including changes in river runoff, net precipitation, and storage of freshwater in the ice pack. A quantitative comparison is complicated by the fact that the observed changes have a strong imprint from natural variability and different model simulations will be in different phases of their own internal variability. So, for example, if the observed excess Arctic-North Atlantic freshwater transport during the late 1960s Great Salinity Anomaly event [*Dickson et al.*, 1988] was driven by natural variability, one would not expect the models to simulate a similar event over the same temporal window. In section 4 only the observed long-term trends from 1950 to 2000 are compared to the multimodel ensemble mean values in an effort to reduce the impacts from interannual or decadal-scale variability.

3. Simulated Contemporary Arctic Ocean Freshwater Budgets

3.1. Arctic Ocean Salinity and Sea Ice

[15] Simulated sea surface salinity (SSS) fields averaged from 1990 to 1999 for the eight models for which this term is archived are shown in Figure 2 along with observations

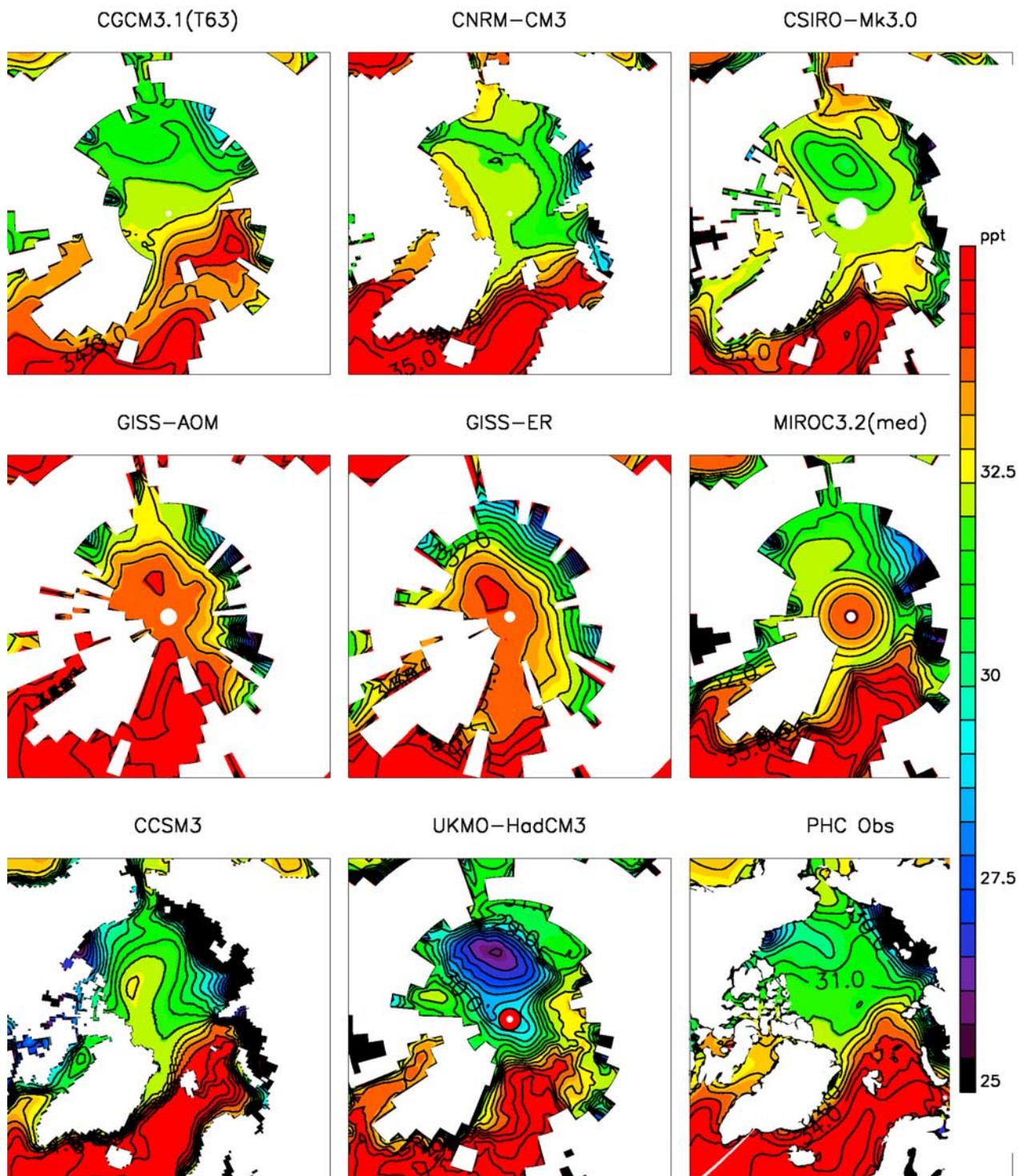


Figure 2. Sea surface salinity (SSS) from the models averaged for 1990–1999 and from the Polar Hydrographic Climatology (PHC) Observations [Steele *et al.*, 2001].

from the PHC. This comparison is generally insensitive to the exact time period used. All models simulate a relatively fresh Arctic Ocean surface compared to a saltier North Atlantic, but there are large differences between the models and few consistent biases when compared to observations. The observed low salinities along the Eurasian shelf,

particularly in the East Siberian Sea, are typically less well expressed in the simulations, except in CCSM3. However, the CCSM3 is perhaps too fresh along the Eurasian shelves, likely associated in part with a larger total river runoff as compared to other models (Table 2). Differences in ocean circulation among the models also influence how the river

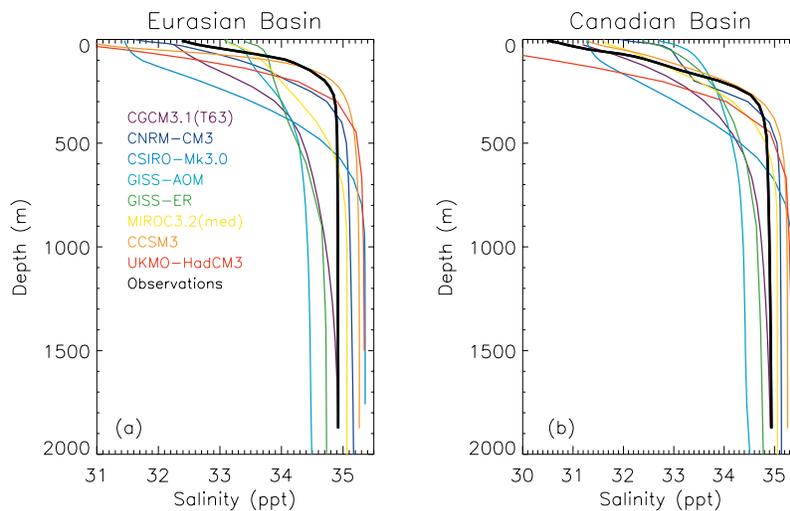


Figure 3. The 1990–1999 mean salinity profiles for the different models averaged over (a) the deep Eurasian and (b) the deep Canada basins. The Eurasian basin is defined as the region from 38°W to 138°E and from 82° to 90°N that is deeper than 2000 m. The Canada basin is defined as the region from 180° to 280°W and from 70° to 85°N that is deeper than 2000 m. The thick black line shows the PHC observations.

runoff is dispersed in the Arctic Ocean. The SSS over the deep Canada basin is generally too high in the simulations except for the UKMO-HadCM3, which has very fresh surface waters there. For the deep Eurasian basin, there is no consistent model bias at the surface. Instead, the GISS models and MIROC3.2(med) are too saline and the other models are typically too fresh.

[16] Vertical profiles of salinity also vary greatly (Figure 3). All models show a halocline (an increase in salinity below the surface layer, meaning vertical stability) but it is too weak in several, particularly the coarse-resolution GISS-ER and GISS-AOM models. Others simulate an anomalously strong halocline (meaning very strong stability), especially the UKMO-HadCM3 which as mentioned has very fresh surface conditions in the Canada Basin. Salinity of the deeper waters also varies considerably between models.

[17] The Arctic Ocean depth integrated salinity referenced to 34.8 gives a measure of the liquid storage of freshwater within this region. As expected from Figure 3, there is little agreement in simulated liquid freshwater storage (Figure 4). Three, the CGCM3.1(T63), GISS-AOM, and GISS-ER, simulate a liquid freshwater storage that is from 1.7 to 3 times larger than the multimodel mean, and much larger than the 24,000 km³ obtained from the PHC data (note this value is different than that given by *Serreze et al.* [2006] which ignores “negative freshwater,” that is, waters with salinity higher than the 34.8 reference). Referring back to Figure 3, this is associated with relatively fresh conditions at depth. In the GISS-AOM and GISS-ER models, these fresh conditions are present despite the relatively salty conditions at the surface. In sharp contrast, the CNRM-CM3, UKMO-HadCM3, and CCSM3 models have a negative liquid freshwater storage (i.e., the column integrated salinity is higher than the 34.8 reference). This is associated with relatively saline conditions at depth.

[18] The stability of the water column as indicated by the salinity profiles can have important effects on the vertical ocean heat transport and ice-ocean heat exchange. These in combination with the atmospheric flux exchange and net ice transport flux determine the sea ice mass budget for the Arctic and ultimately ice thickness and extent. This thickness and extent is shown in Figure 5. Again, the models show little consistent bias when compared to observations [*Bourke and Garrett, 1987; Laxon et al., 2003*]. Instead, there is a large range in mean ice thickness, the spatial distribution of ice thickness, and the average March ice extent (March is the month of maximum extent in observations). Several models obtain a reasonable mean ice thickness and some have a reasonable spatial distribution, with relatively thick ice along the north coast of Greenland and the CAA (e.g., CCSM3 and UKMO-HadGEM1). However, others have a maximum (or secondary maximum) within the East Siberian Sea (e.g., CCSM3 and CNRM-

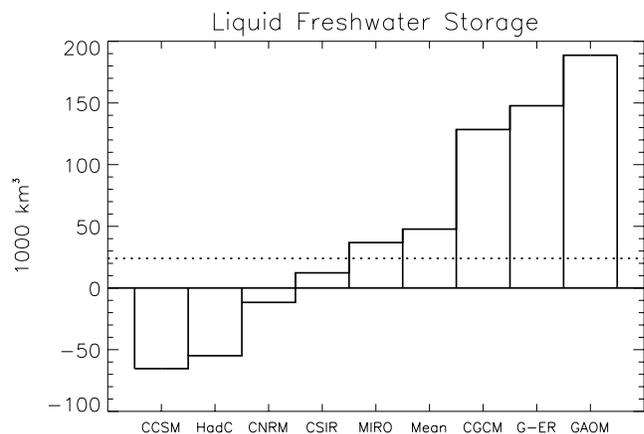


Figure 4. Ocean freshwater storage from the models and for the multimodel ensemble mean averaged for the period 1990–1999. The dotted line shows the observed value.

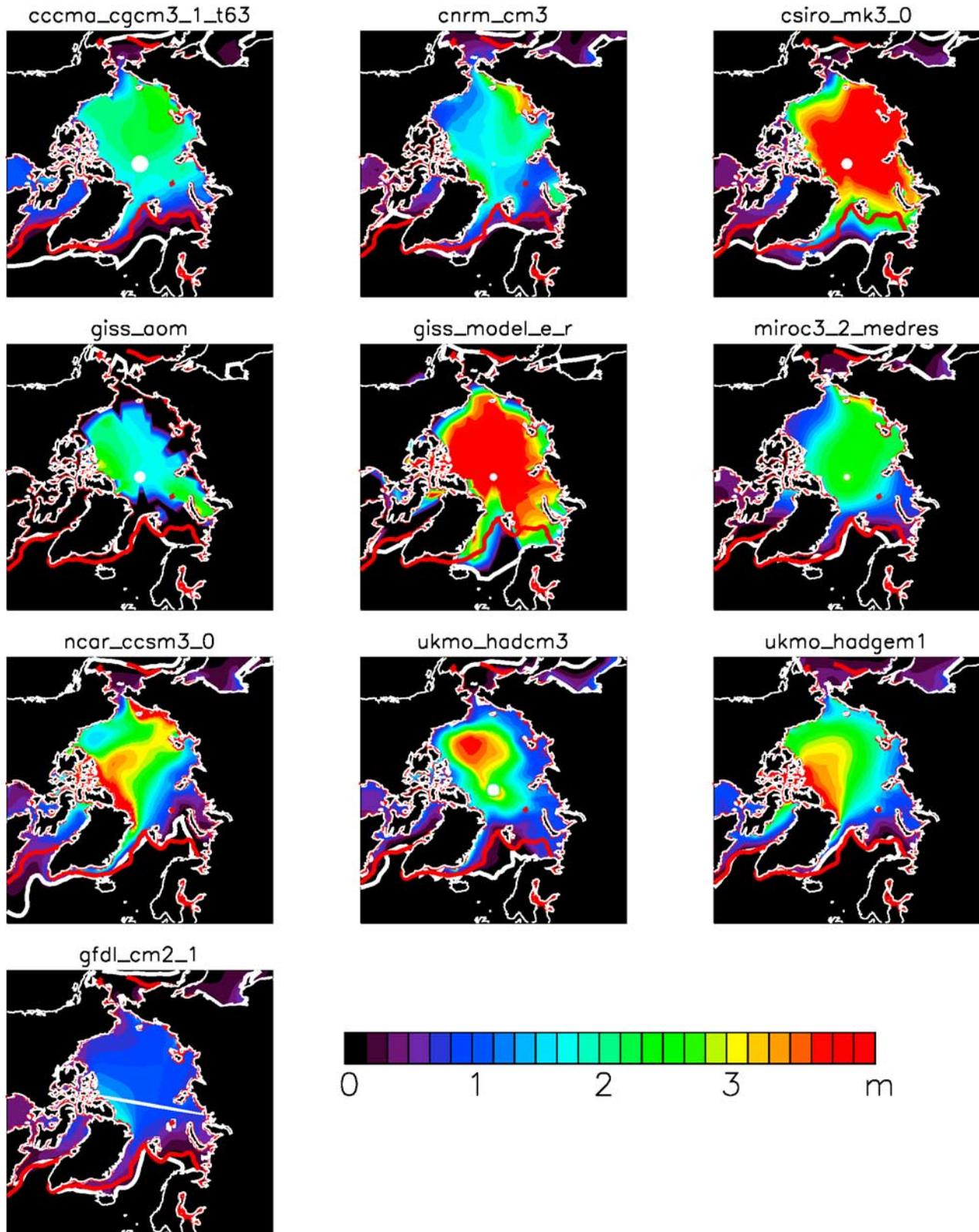


Figure 5. Annual mean ice thickness as simulated in the different models averaged for 1990–1999. The simulated 20% March ice concentration contour is shown in white. March ice extent based on satellite data [Cavalieri et al., 1997] is shown in red.

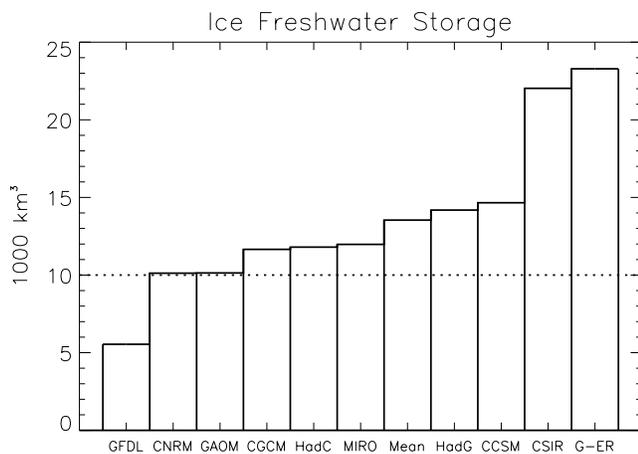


Figure 6. Mean sea ice freshwater storage over the period 1990–1999 from each model and for the multimodel ensemble mean. The observed value from *Serreze et al.* [2006] is shown by the dotted line.

CM3) where observations show thinner ice. A number of models simulate only small gradients in thickness across the Arctic. The large spread in simulated ice thickness directly relates to the freshwater storage within the ice pack, which also shows a large range (Figure 6).

3.2. Freshwater Budget

[19] The multimodel ensemble mean Arctic Ocean freshwater budget averaged from 1980 to 2000 is shown in Figure 7 in schematic form. All terms are referenced to a salinity of 34.8. Overall the multimodel mean budget is qualitatively similar to observations, with river runoff providing the largest source of freshwater ($3162 \text{ km}^3 \text{ a}^{-1}$), followed by Bering Strait inflow ($2339 \text{ km}^3 \text{ a}^{-1}$) and net precipitation over the ocean ($1543 \text{ km}^3 \text{ a}^{-1}$). This is balanced in part by the ice and ocean freshwater export to the North Atlantic. Transport through Fram Strait is the primary sink, with the liquid transport accounting for a freshwater loss of $3093 \text{ km}^3 \text{ a}^{-1}$ and the solid (ice) transport accounting for $1375 \text{ km}^3 \text{ a}^{-1}$. Transports of ice ($409 \text{ km}^3 \text{ a}^{-1}$) and ocean waters ($634 \text{ km}^3 \text{ a}^{-1}$) through the Barents Sea also act as a sink of freshwater from the Arctic Ocean. Some models have additional transports through the CAA. However, as many have no open channels within the CAA, a multimodel ensemble mean was not computed and is not included in Figure 7.

[20] The multimodel ensemble mean precipitation, evaporation, and net precipitation totaled over the Arctic terrestrial drainage are within 10% of the estimates reported by *Serreze et al.* [2006]. For comparison, the observed 1979–2001 standard deviation of net precipitation is about 6% of the mean [*Serreze et al.*, 2006]. There is also a relatively small intermodel standard deviation (model spread) in these terms (less than 25% of the mean) pointing to a good group mean model performance. This net terrestrial precipitation is assumed equal to the river runoff to the Arctic Ocean, and the multimodel ensemble mean of $3162 \text{ km}^3 \text{ a}^{-1}$ is in excellent agreement with the observed runoff of $3200 \text{ km}^3 \text{ a}^{-1}$ and within the observed interannual variability [*Serreze et al.*, 2006].

[21] Over the Arctic Ocean, the atmospheric freshwater exchange compares less favorably to observations (the combination of too little precipitation and evaporation implying a less vigorous hydrologic cycle than observed). The ensemble mean of net precipitation is within 23% of the *Serreze et al.* [2006] estimate, which is considerably larger than the observed interannual variations. The intermodel standard deviation is quite low (11% of the mean) for the Arctic Ocean net precipitation, that is, the models are in reasonable agreement regarding this term. However, all of the models simulate less net precipitation than observed (Table 2).

[22] The multimodel mean ocean transport through Bering Strait of $2339 \text{ km}^3 \text{ a}^{-1}$ is surprisingly close to observations and within the observed interannual variability. However, this is largely a result of competing biases, as the intermodel standard deviation is larger than the multimodel mean. As summarized in Table 2, the freshwater inflow through Bering Strait for different models ranges from an

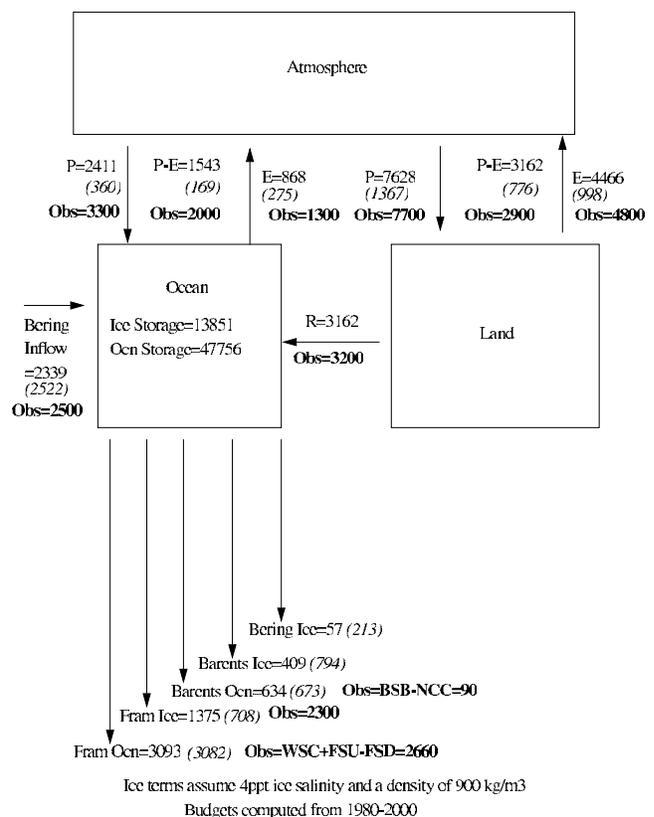


Figure 7. The 1980–1999 mean Arctic Ocean freshwater budget for the multimodel ensemble mean with transports in $\text{km}^3 \text{ per year}$ and stores in km^3 . The intermodel standard deviations are shown in italics. Estimates from *Serreze et al.* [2006] are shown in bold. For the Fram Strait ocean transport, the observed estimate includes a contribution from Fram Strait Deep Water, Fram Strait Upper Water, and the West Spitsbergen Current. For the Barents Sea transport, the observed value includes a contribution from the Norwegian Coastal Current and the Barents Sea Branch. Because most models did not include transports through the Canadian Arctic Archipelago, no transport numbers for this region are included in the figure.

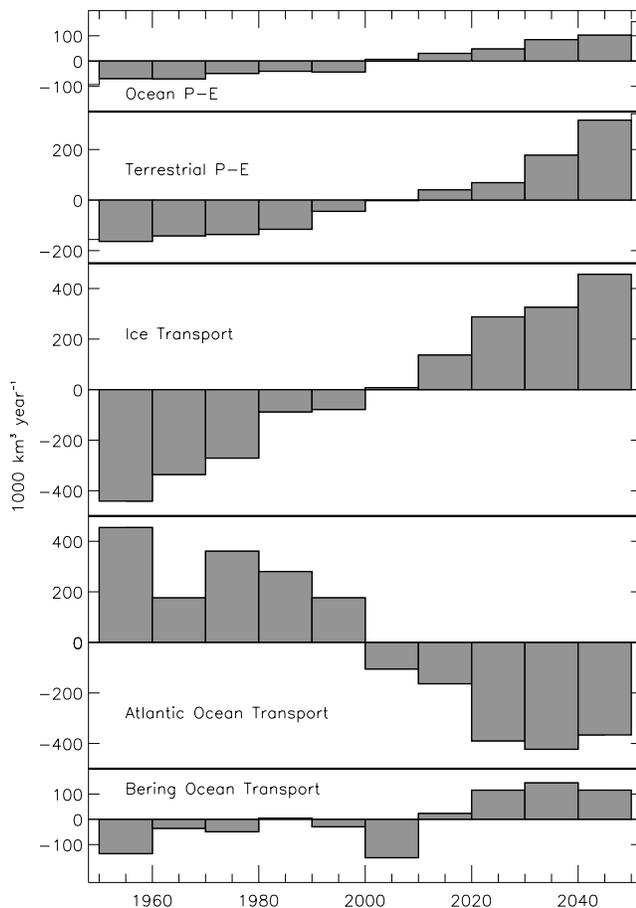


Figure 8. Decadal changes in the multimodel ensemble mean Arctic Ocean freshwater budget terms from 1950 to 2050, expressed as anomalies with respect to the 1950–2050 mean. The terms are the net precipitation over the Arctic Ocean, net precipitation over the terrestrial drainage assumed as equivalent to river runoff, the total ice transport through Fram Strait and the Barents Sea, the total ocean freshwater exchange with the North Atlantic (Fram Strait plus Barents Sea contributions), and the Bering Strait transport. The sign convention is such that a positive anomaly is an increasing source (or decreasing sink) of freshwater for the Arctic Ocean. Transports through the Canadian Arctic Archipelago are not included since most models do not have an open strait there.

almost negligible value ($42 \text{ km}^3 \text{ a}^{-1}$) to a very sizable transport ($7517 \text{ km}^3 \text{ a}^{-1}$), three times larger than observed. Only two of the eight available models have transports that are within 20% of the observed. Because of the different model resolutions, the transect defining Bering Strait is considerably larger in some models than in others. However, the transect length has little relationship with the transport for the different models. The more important factor is the representation of salinity and velocity in the Strait.

[23] The models simulate a net flux of freshwater from the Arctic to the North Atlantic. However, as with the Bering Strait inflow, the intermodel standard deviation in these terms is sizable and is often larger than the multimodel mean. Again, this scatter largely results from differences in both the velocity (or mass transport) and the salinity of the

waters that are transported. In all but one model, the GISS-AOM, the total liquid transport through Fram Strait and the Barents Sea removes fresh water from the Arctic Ocean as observed.

[24] Also in accord with observations, the models consistently export sea ice from the Arctic to the North Atlantic. Some simulate that a sizable amount of this export occurs through the Barents Sea, where observations indicate little transport. This is associated with an anomalously large wintertime ice extent in the afflicted models. The multimodel mean combined transport of sea ice through Fram Strait and the Barents Sea is approximately 22% lower than the observed Fram Strait outflow shown by *Serreze et al.* [2006] which is based on the analysis of *Vinje* [2001]. However, other observationally based estimates [*Kwok et al.*, 2004] suggest a smaller Fram Strait flux of approximately $1800 \text{ km}^3 \text{ a}^{-1}$ in good agreement with the multimodel ensemble mean and four of the individual models. This considerable uncertainty in the observed estimates makes it difficult to assess the realism of individual models. Additionally, there is large interannual variability in the observed Fram Strait ice flux. The models exhibit a large intermodel scatter in the total climatological ice transport to the North Atlantic, indicating that as a group they do not consistently simulate a realistic Arctic–North Atlantic ice flux.

[25] Only two of the models with available ocean data have an opening through the CAA from the Arctic into Baffin Bay. Observations indicate a sizable flux through the CAA. The lack of a CAA opening in most of the models is problematic and will influence the simulated freshwater transports in other regions. This complicates the comparison of modeled transports to observations. As shown in Table 2, both of the models that resolve a CAA yield a lower freshwater transport out of the Arctic than observed. However, there is large uncertainty in the observed value [*Serreze et al.*, 2006; *Prinsenberg and Hamilton*, 2005].

4. Temporal Changes in Arctic Ocean Freshwater Budgets

[26] Decadal-scale changes in the freshwater budget terms from 1950 to 2050 for the multimodel ensemble mean are summarized in Figure 8. These are expressed as anomalies with respect to the 1950–2050 average. Positive anomalies mean a contribution to increased freshwater storage in the Arctic Ocean. Because the multimodel mean averages out the intrinsic (natural) variability present in the model integrations, one can assume that the changes shown in Figure 8 largely represent the response to the common external forcing of greenhouse gas loading that is applied in the model integrations.

[27] Net precipitation over both the Arctic Ocean and terrestrial drainage increase over the 1950–2050 time period, by 11% and 16%, respectively, with most of this change occurring after 2000. From 1950–2000, the simulated multimodel mean change is 2% (ocean) and 4% (terrestrial) which compares to an observed 8% (ocean) and 5% (terrestrial) increase in the 1936–1955 baseline [*Peterson et al.*, 2006]. A considerable portion of this observed change may be driven by natural variability. The simulated increase is consistent with previ-

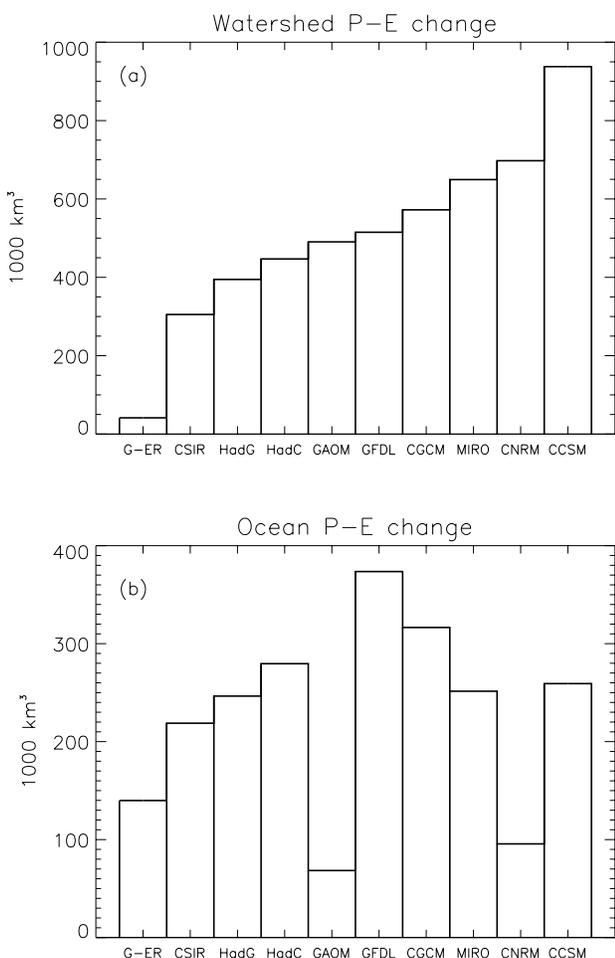


Figure 9. Change in net precipitation (P-E) for (a) the terrestrial drainage and (b) the Arctic Ocean, expressed as means for the period 2040–2049 minus 1950–1959 for each model.

ous modeling studies [e.g., Miller and Russell, 2000; Holland et al., 2006]. As in these previous studies, both high-latitude precipitation and evapotranspiration increase with a warming climate, but the precipitation changes dominate. The extent to which the changes in terrestrial precipitation are associated with changing cyclone activity for the CCSM3 model are discussed by Finnis et al. [2007].

[28] An increase in precipitation, evaporation, and net precipitation is a consistent feature of the models evaluated here. However, the magnitude of change ranges widely (Figure 9) pointing to large uncertainty in future conditions. The change in terrestrial net precipitation among the models is significantly correlated with initial values in 1950 (at $R = 0.7$), and models with higher initial net precipitation generally have larger changes. However, there is no similar relationship for the net precipitation changes over the ocean.

[29] From 1950 to 2050, a net melting of sea ice occurs in all of the models leading to a 40% reduction in the multimodel ensemble mean storage of freshwater within the ice pack. For the 1950–2000 time period, the 10% reduction in multimodel mean ice thickness is much smaller than some observed estimates [Rothrock et al., 1999], although there is considerable uncertainty and a strong imprint from natural

variability in these observed values. The thinning Arctic ice pack results in thinner ice being exported from the Arctic in all of the models, leading to a decrease in the multimodel mean net ice transport from the Arctic to the North Atlantic (Figure 8). This contributes to an increasing liquid freshwater storage in the Arctic Ocean, in that more water in the form of ice melt remains within the Arctic basin. While all models show a decreased ice export, there is again a large range in the magnitude of this change (Figure 10). The reduction in ice export is highly correlated (at $R = 0.8$) to the 1950 conditions meaning that models with high initial ice export typically have larger reductions in export as the climate warms. Additionally, the ice export decrease is correlated to the decrease in Arctic ice volume among the different models at $R = 0.6$. Ice velocity changes also contribute to the changing ice export and are important in some models. However, there is little consistent change in the ice velocity within Fram Strait among the models, with about half showing an increase and the others showing a decrease.

[30] Increasing net precipitation, increasing river runoff, and decreasing ice export lead to an increase in liquid Arctic Ocean freshwater storage in all models except for the CSIRO-Mk3.0 (Figure 11). This is partially offset but typically larger than the decrease in freshwater storage within the ice cover, leading to an increase in total (liquid plus ice) Arctic freshwater storage in all but the CSIRO-Mk3.0 and CCSM3 models. Decreasing ice export and net sea ice attrition is the dominant driver of this change (Figure 8). While the Arctic Ocean freshens, there is a partly compensating increase in the freshwater flow through Fram Strait into the North Atlantic in the multimodel ensemble mean (Figure 8). All models except for the UKMO-HadCM3 have an increased liquid freshwater export through Fram Strait (Figure 12a). In the UKMO-HadCM3, there is an increase in the freshwater transport in the upper 100 m of the water column but decreased freshwater export in the deeper water column. This points out the complexities involved in accurately simulating these transports which rely on accurate salinity and velocity fields across the full ocean column.

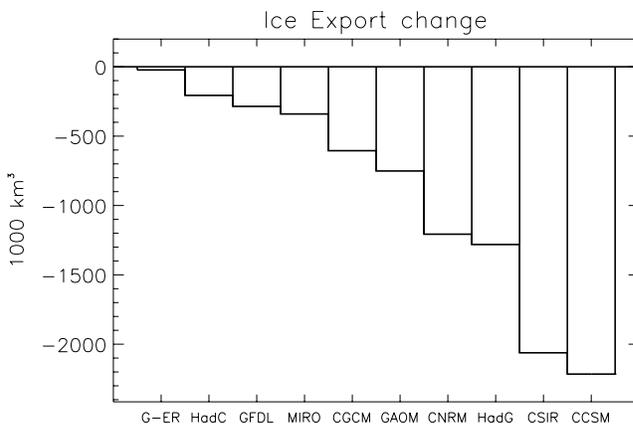


Figure 10. Changes in ice transport to the North Atlantic (through Fram Strait and the Barents Sea) expressed as means for the period 2040–2049 minus 1950–1959 for each model.

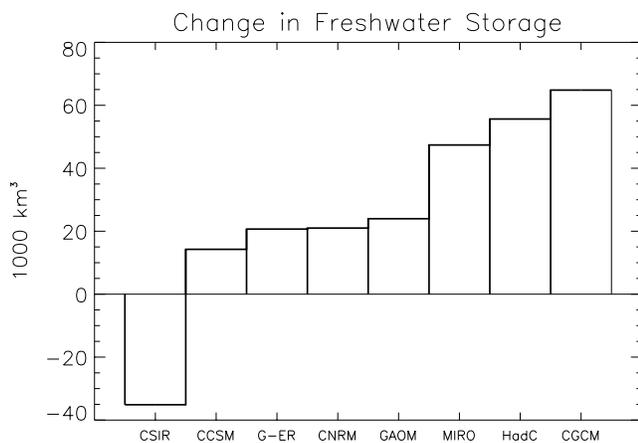


Figure 11. Change in Arctic Ocean freshwater storage expressed as means for the period 2040–2049 minus 1950–1959 for each model.

[31] Changes in the Barents Sea transport are less consistent, with five models showing an increase in the Barents Sea flux of freshwater to the Arctic and the others showing a decrease (Figure 12b). Both salinity and velocity changes contribute. In some, the velocity changes dominate whereas in others the salinity changes dominate. There is also little agreement regarding whether fresher or more saline waters are present across the depth-averaged Barents Sea transect by 2050. Disagreement on not only the magnitude but the sign of changes indicates a high level of uncertainty in the Barents Sea projections and the contribution of this region to changing Arctic Ocean freshwater budgets.

[32] In the Bering Strait, all models except for CGCM3.1(T63), show an increase in the freshwater transport into the Arctic (Figure 12c). Compared to the Fram Strait liquid freshwater transport, these changes are quite small, except in the CSIRO-Mk3.0 simulation. Again, both salinity and velocity changes contribute. In the CSIRO-Mk3.0 run, fresher waters are transported into the Arctic and there are only small changes in current velocity. This results in a fairly sizable change. Other models have comparable salinity changes, but this is countered by generally lower current speeds. This is consistent with freshwater transport changes assessed from multiple ensemble members from CCSM3 [Holland *et al.*, 2006]. In the case of the CGCM3.1(T63), a decrease in Bering Strait velocity overwhelms freshening of these waters and leads to a net decrease in the Bering Strait freshwater transport. The relatively small changes in the Bering Strait transport are also evident in the decadal changes exhibited by the multimodel mean, where an increasing transport is not evident until after 2000 (Figure 8).

5. Results and Conclusions

[33] This paper has analyzed the Arctic Ocean freshwater budgets from 10 climate models participating in the IPCC-AR4. This includes an analysis of the freshwater storage in the Arctic Ocean as liquid and sea ice and the fluxes of freshwater to the Arctic in the form of: (1) net precipitation over the Arctic Ocean; (2) net precipitation over the terrestrial drainage assumed to approximately equal river

runoff; (3) the transport of ice out of the Arctic Ocean; and (4) the ocean freshwater transport through Fram Strait, the Barents Sea, the Bering Strait, and the Canadian Arctic Archipelago (the latter for the models that have an open channel).

[34] The contemporary multimodel ensemble mean budget qualitatively agrees with observations, with a freshening owing to river runoff, the Bering Strait inflow, and net precipitation over the ocean balanced in part by the ice and ocean freshwater transports to the North Atlantic. The multimodel mean net precipitation for the Arctic Ocean and terrestrial drainage compares reasonably well to observations. The intermodel standard deviation in these terms is quite low indicating that as a group the models perform well in this regard.

[35] By sharp contrast, there is a very large range in simulated ice and ocean freshwater transports. This is not

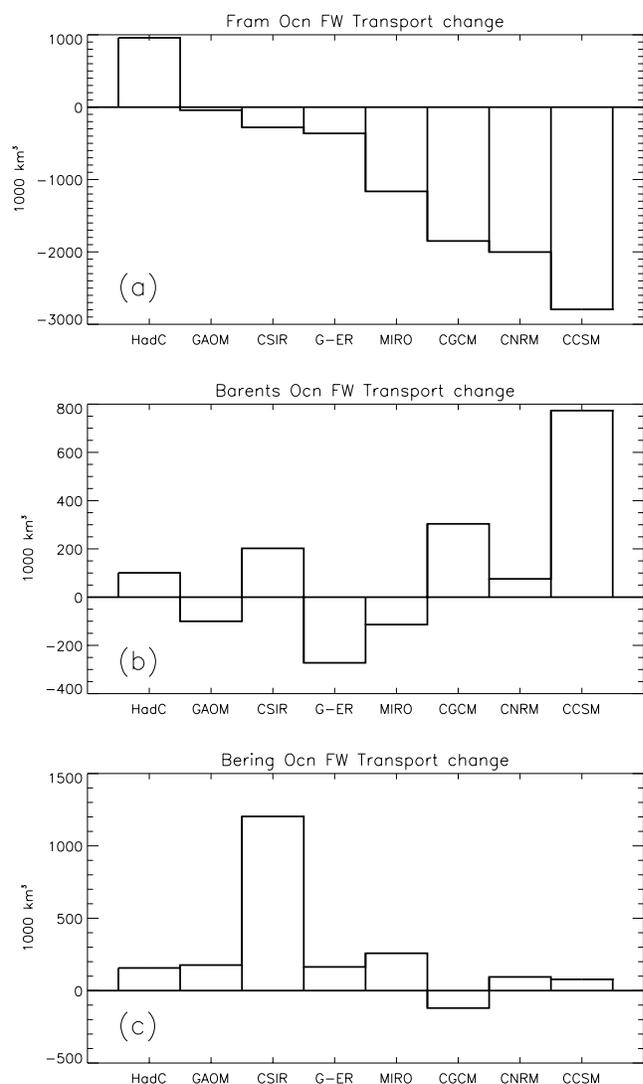


Figure 12. Change in liquid freshwater transport through (a) Fram Strait, (b) the Barents Sea, and (c) the Bering Strait, expressed as means for the period 2040–2049 minus 1950–1959 for each model. A positive change represents an increased source (or decreased sink) of freshwater for the Arctic Ocean.

entirely surprising since the atmospheric terms are averaged over large regions and the ocean transports are obtained at individual transects. However, there is also wide scatter among the models in ice and liquid storage, which represent averages for the entire Arctic Ocean. From this analysis, it appears that the models as a group do not generally simulate the ocean or sea ice conditions with much fidelity, either at the regional or basin scale. This is not to say that all models fare poorly; some perform reasonably well.

[36] Temporal changes in the freshwater budgets over the period 1950–2050 from both the multimodel ensemble mean and the individual models generally suggest an acceleration of the Arctic freshwater cycle with an increase in the flux of water passing through the hydrologic elements. More specifically, the models consistently simulate an increased flux of water entering the Arctic from net precipitation, river runoff, and ice melt. This yields an increase in liquid Arctic Ocean freshwater storage. The rate of increase varies between models, in part owing to differences in compensating outflow of liquid freshwater to lower latitudes, particularly through Fram Strait. As the common external forcing in the integrations is the rising concentration of greenhouse gases, this qualitative agreement among the models in these freshwater budget trends implicates anthropogenic forcing as the underlying cause.

[37] Some of the scatter between models regarding future changes can be related to the simulated mid-20th century conditions. In particular, changes in terrestrial net precipitation and ice export from 1950 to 2050 are highly correlated to the initial (1950) values. Also at issue are competing roles of velocity and salinity for ocean transport terms. While the models generally simulate an increase in the loss of Arctic freshwater through Fram Strait, there is a large range of changes in both the salinity and velocity there, resulting in a large scatter in the simulated transport. The models typically show a small increase in the freshwater inflow through Bering Strait. All indicate freshening of the waters in the region. However, this is compensated to different degrees by a decrease in the velocity (or mass transport) across the transect, again contributing to scatter in the transports. The Barents Strait freshwater transport shows no consistent change across the models. This indicates a high level of uncertainty in how changing conditions within the Barents Sea will affect future Arctic Ocean freshwater change.

[38] In short, the common theme from these and other simulations is that as the Arctic warms through the 21st century in response to greenhouse gas loading, the hydrologic system intensifies. While the Arctic Ocean becomes fresher, there are also larger freshwater transports to the North Atlantic. At issue is the magnitude of these changes, which in turn bears on climate impacts to the larger global system.

[39] **Acknowledgments.** This study was supported by NSF grants ARC-0229651 and OPP-0242125 and NASA contracts NNG04GH04G and NNG04G39G. We acknowledge the modeling groups for providing their data for analysis, the Program for Climate Model Diagnosis and Intercomparison (PCMDI) for collecting and archiving the model output, and the JSC/CLIVAR Working Group on Coupled Modelling (WGCM) for organizing the model data analysis activity. The multimodel data archive is supported by the Office of Science, U.S. Department of Energy.

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