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Model resolution influence on simulated sea ice decline

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Abstract

Satellite observations and model predictions of recent and future Arctic sea ice decline have raised concerns over the timing and potential impacts of a seasonally ice-free Arctic Ocean. Model predictions of seasonally ice-free Arctic conditions are, however, highly variable. Here I present results from fourteen climate system models from the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset that indicate modeled Arctic sea ice sensitivity to increased atmospheric CO_2 forcing is strongly correlated with ice/ocean model horizontal resolution. Based on coupled model analyses and ice only simulations with the Los Alamos National Lab sea ice model (CICE), the correlation between declining Arctic sea ice cover and ice/ocean model resolution appears to depend largely on ocean model resolution and its influence on ocean heat transport into the Arctic basin. The correlation between model resolution, northward ocean heat transport, and the degree of Arctic ice loss is independent of ice model physics and complexity. This not only illustrates one difficulty in using numerical models to accurately predict the timing and magnitude of Arctic sea ice decline under increasing atmospheric greenhouse gas forcing, but also highlights one area where improved simulation (of northward ocean heat transport) could greatly decrease the uncertainties associated with predictions of future Arctic sea ice cover.

1 Introduction

In recent years, concern over the observed decline in Arctic sea ice cover (e.g. Comiso, 2002; Hassol, 2004; Stroeve et al., 2005; Holland et al., 2006; Shein et al., 2006; Nghiem et al., 2007; Stroeve et al., 2007) has grown as the ice recedes. At some, as yet unknown, time in the future, the Arctic Ocean is expected to reach a seasonally ice-free state (Hassol, 2004; Arzel et al., 2006; Holland et al., 2006; Teng et al., 2006; Zhang and Walsh, 2006). As the ice cover declines, the ice albedo feedback will begin to play a larger role in warming high northern latitudes and, it is expected, the remainder of the planet as well (see Serreze and Francis (2006) for a review). Projections of the future ice state, and the level of concern associated with the implications of those projections, are based largely on results from coupled general circulation models (GCMs) (e.g. Lindsay and Zhang, 2005; Dethloff et al., 2006; Holland et al., 2006; Singarayer et al., 2006; Zhang and Walsh, 2006). The response of various GCMs to future climate forcing scenarios is, however, variable (e.g. Zhang and Walsh, 2006). Most modeling studies underpredict current levels of Arctic ice loss (Stroeve et al., 2007) and uncertainties abound as to when, or under what conditions, a seasonally ice free Arctic might occur. In an analysis of the Arctic sea ice response in fourteen fully coupled GCMs from the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset (Table 1) under conditions of CO_2 quadrupling, I find that the magnitude of decrease in modeled Arctic sea ice cover is significantly (correlation coefficient=0.65 for Annual Averaged (ANN)differences) correlated to the horizontal resolution of the ice/ocean model utilized in the simulation (Fig. 1). Given the time and effort that has gone into accurately modeling sea ice cover (see Table 1 and e.g. Hunke and Lipscomb, 2006), the apparent control of horizontal ice/ocean model resolution on modeled ice response to CO_2 forcing is of some concern if we are to reduce the uncertainties associated with the future state of the Arctic sea ice cover (e.g. Holland et al., 2006; Stroeve et al., 2007).

2 Methods

2.1 CMIP3 models

All 14 models from the CMIP3 dataset were run under conditions of CO_2 increases of 1%/year until a quadrupling of the atmospheric CO_2 concentration was reached. At that point, the atmospheric CO_2 concentration was fixed, and most simulations were integrated for an additional 150 years. With two exceptions (the NCAR CCSMv3 and

IPSL CM4), I compare Arctic sea ice concentrations from 50-year averages at the time of CO_2 quadrupling (the 25 years prior and subsequent to actual quadrupling) to averages of the last 50 years of each model's 20th century control simulation (1950–1999). In the case of the NCAR CCSMv3 and IPSL CM4, 20-year averages at the time of CO_2 quadrupling are compared to the final 50 years of the 20th century. In addition, while the NCAR CCSMv3 ran a 1%/year to 4x CO_2 run and contributed some results to the CMIP3 dataset, the ice concentration and thickness and ocean heat flux results used in this analysis are derived from the NCAR simulation b30.026.ES01 years 530–549 which can be obtained from the Earth System Grid (http://www.earthsystemgrid.org). For all models, I analyzed, where available, sea ice concentration and thickness in the minimum season (August, September, October averaged; ASO), maximum season (February, March, and April averaged; FMA), and annual average (ANN) and FMA northward ocean heat flux. In all CMIP3 analyses, standard linear regressions were fitted to both post processed output and, to reduce the influence of outliers, log transformed data. Plotted data for post processed output and correlation coefficients for both post processed output and log transformed data are presented here.

2.2 Sea ice modeling

To cleanly investigate the influence of ice model resolution on changes in modeled Arctic ice extent in response to elevated CO_2 forcing, I conducted a pair of sensitivity studies with the Los Alamos National Lab (LANL) sea ice model (CICE; Hunke and Lipscomb, 2006). CICE can be run at two different operational resolutions. One is a nominally 3° grid (gx3) and the other is a nominally 1° grid (gx1). I completed two simulations, one at the gx3 resolution and the other at the gx1 resolution. Both simulations were forced by 20 years of daily data from CMIP3 participating model MIROC3.2(medres) under conditions of quadrupled CO_2 (years 271–290 of the 1%/year CO_2 increase to quadrupling run. Quadrupling was reached at ~year 140.).

3 Results and discussion

Modeled changes in Arctic sea ice cover vary widely between the 14 models from the CMIP3 database (Fig. 1; Table 1). Differences in the Arctic sea ice response to CO_2 quadrupling do not appear to be correlated to the complexity or details (e.g. number of layers, presence of ice dynamics, ice rheology, treatment of snow) of the various sea ice models but only related to the differences in horizontal model resolution (Fig. 1; Table 1). Although the correlation is not as strong (correlation coefficient=0.32 in ANN), the highest resolution models also exhibit the greatest decline in sea ice thickness (Fig. 2a, b, c) under elevated CO_2 forcing, removing the possibility that high resolution models are simply losing ice concentration while lower resolution models experience greater thickness losses for a volumetrically equivalent response. This conclusion is further supported by the strong correlation (correlation coefficient=0.76 in ANN) between sea ice thickness loss and sea ice concentration loss (Fig. 2d, e, f).

Stand alone sea ice modeling to cleanly investigate the influence of ice model resolution on ice response to elevated CO_2 forcing conditions shows no influence of ice model resolution on modeled ice response. At both the gx3 and gx1 resolutions, LANL CICE exhibits the same initial drop in Arctic ice concentration and thickness in the first year and then stabilization of the Arctic ice cover at nearly identical levels for the 19 years thereafter (Fig. 3). In fact, the Arctic averaged FMA ice concentrations and thicknesses are slightly higher (49.68% vs. 45.09% and 0.37 m vs. 0.33 m) for the gx1 simulation (Fig. 3).

Resolution dependent differences in ice-albedo feedback and summer solar heating of the surface ocean in the Arctic might account for differing degrees of ice loss at CO_2 quadrupling in the CMIP3 models. However, ice only simulations, where resolution dependent differences would also influence model response, show no relationship between modeled ice decline and ice model resolution; this points towards the potential for ocean resolution to, somehow, be exerting control on the degree of Arctic sea ice loss at CO_2 quadrupling.

For all but one exception (CCCMA CGCM 3.1), the fourteen analyzed models have identical ice and ocean resolutions (Table 1). Consequently, the correlation between increasing ocean model resolution and increased Arctic ice cover decline is as robust as that between increasing ice model resolution and increased Arctic ice cover decline. Taken together, the need for greater availability of ocean heat to both melt more ice and inhibit refreezing in FMA, the identical ice and ocean model resolutions in the majority of the CMIP3 models, and the lack of response to resolution increase in stand alone ice simulations all point towards the ocean component, and, in particular, available ocean heat flux, as the primary source of resolution control on modeled Arctic ice decline. Indeed, it has previously been shown that horizontal model resolution can strongly influence poleward oceanic heat transport. For example, Oka and Hasumi (2006) find that increasing horizontal resolution at northern high latitudes in Ocean General Circulation Model (OGCM) experiments results in more realistic representation of deep water formation in the Greenland, Iceland, and Norwegian (GIN) seas and, thus, the Atlantic meridional overturning circulation (AMOC). As the AMOC is responsible for poleward oceanic heat transport in the Atlantic basin (from whence most ocean heat enters the Arctic basin; Walczowski and Piechura, 2006), it is logical that models that more effectively represent the AMOC will have a more effective transport of heat into the Arctic and, thus, more efficiently melt or, at the least, inhibit winter refreezing of, sea ice.

Although the sample size is small, analyses of the six CMIP3 models for which northward ocean heat flux at the time of CO_2 quadrupling is available support this conclusion; higher ocean model resolution is positively correlated (correlation coefficient=0.72) with higher northward ocean heat transport (Fig. 4a) and higher northward ocean heat transport is, not surprisingly, correlated (correlation coefficient=0.76) with differences in Arctic FMA ice cover (Fig. 4b). These results, and the lack of response to increased resolution in ice-only experiments (Fig. 3), suggest that the influence of ocean model resolution on northward ocean heat flux is, indeed, one of the main, if not the main, factors responsible for the correlation between increased ice/ocean model resolution and increased decline in Arctic sea ice cover in response to elevated CO_2 forcing (Fig. 1).

Prior multi-model analyses have indicated that no single model is without bias in simulating modern sea ice cover (e.g. Arzel et al., 2006; Parkinson et al., 2006; Zhang and Walsh, 2006) and Zhang and Walsh (2006) note that different resolutions in the same coupled model produce different ice responses to climate warming. However, the apparent strong influence of ocean model resolution/northward heat transport – independent of ice model complexity – on predicted Arctic sea ice decline suggests that, in the absence of more accurate and uniform predictions of future poleward ocean heat transport (either through increased resolution or targeted parameterizations given the great computational cost of running ocean models at the 1°–0.25° resolutions suggested by Oka and Hasumi (2006) as necessary for accurate representation of the AMOC), predictions of future Arctic sea ice cover, even from the most sophisticated sea ice models, may continue to be associated with high levels of uncertainty.

4 Conclusions

In analyses of 14 coupled earth system models from the CMIP3 dataset, I have found a strong correlation between ice/ocean model horizontal resolution and the degree of Arctic ice cover loss under quadrupled CO_2 forcing. Given the concern, expectation, and uncertainty associated with the future of the Arctic sea ice cover, accurate modeling of future Arctic conditions is an important aspect of quantifying, planning for, and mitigating future environmental changes in the northern high latitudes. While much effort has gone into refining the simulation of sea ice within the coupled model framework (Table 1), it appears that some of that sophisticated ability is trumped by the ability of the ocean model to transport heat into the Arctic basin. Although high resolution ocean simulations are expensive, it appears that simulation of future Arctic ice states, and, in particular, the uncertainties associated with those predictions, would benefit greatly from improved and more uniform simulation of poleward ocean heat transport.

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References

Arzel, O., Fichefet, T., and Goosse, H.: Sea ice evolution over the 20th and 21st centuries as simulated by current AOGCMs, Ocean Model., 12, 401–415, 2006. 760, 765

Comiso, J. C.: A rapidly declining perennial sea ice cover in the Arctic, Geophys. Res. Lett., 29, 1956, doi:10.1029/2002GL015650, 2002. 760

Dethloff, K., Rinke, A., Benkel, A., Koltzow, M., Sokolova, E., Saha, S. K., Handorf, D., Dorn, W., Rockel, B., von Storch, H., Haugen, J. E., Roed, L. P., Roeckner, E., Christensen, J. H., and Stendel, M.: A dynamical link between the Arctic and the global climate system, Geophys. Res. Lett., 33, L03703, doi:10.1029/2005GL025245, 2006. 761

Hassol, S. J.: Impacts of a Warming Arctic – Arctic Climate Impact Assessment, Cambridge University Press, Cambridge, 2004. 760

Holland, M. M., Bitz, C. M., and Tremblay, B.: Future abrupt reductions in the summer Arctic sea ice, Geophys. Res. Lett., 33, L23503, doi:10.1029/2006GL028024, 2006. 760, 761

Hunke, E. C. and Lipscomb, W. H.: CICE: the Los Alamos sea ice model documentation and software user's manual, T-3 Fluid Dynamics Group, Los Alamos National Laboratory, Los Alamos, NM, 2006. 761, 762

Lindsay, R. W. and Zhang, J.: The thinning of Arctic sea ice, 1988-2003: Have we passed a tipping point?, J. Climate, 18, 4879–4894, 2005. 761

Nghiem, S. V., Rigor, I. G., Perovich, D. K., Clemente-Colon, P., Weatherly, J. W., and Neumann, G.: Rapid reduction of Arctic perennial sea ice, Geophys. Res. Lett., 34, L19504, doi:10.1029/2007GL031138, 2007. 760

Oka, A. and Hasumi, H.: Effects of model resolution on salt transport through northern high-latitude passages and Atlantic meridional overturning circulation, Ocean Model., 13, 126–147, 2006. 764, 765

Parkinson, C. L., Vinnikov, K. Y., and Cavalieri, D. J.: Evaluation of the simulation of the annual cycle of Arctic and Antarctic sea ice coverages by 11 major global climate models, J. Geophys. Res.-Ocean., 111, C07012, doi:10.1029/2005JC003408, 2006. 765

Serreze, M. C. and Francis, J. A.: The arctic amplification debate, Climatic Change, 76, 241–264, 2006. 761

Shein, K. A., Waple, A. M., Menne, M. J., Christy, J. C., Levinson, D. H., Lawrimore, J. H., Wuertz, D. B., Xie, P., Janowiak, J. E., Robinson, D. A., Schnell, R. C., Elkins, J. W., Dutton, G. S., Levy, J. M., Reynolds, R. W., Johnson, G. C., Lyman, J. M., Willis, J. K., Yu, L., Weller, R. A., Lumpkin, R., Goni, G., Baringer, M. O., Meinen, C. S., Merrifield, M. A., Gill, S., Mitchum, G. T., Sabine, C. L., Feely, R. A., Wanninkhof, R., Diamond, H. J., Bell, G. D., Halpert, M. S., McPhaden, M. J., Blake, E., Mo, K. C., Landsea, C. W., Pasch, R., Chelliah, M., Goldenberg, S. B., Bourassa, M. A., Smith, S. R., Hughes, P., Rolph, J., Camargo, S. J., Gleason, K. L., Salinger, M. J., Watkins, A. B., Burgess, S. M., Richter-Menge, J., Overland, J., Proshutinsky, A., Romanovsky, V., Gascard, J. C., Karcher, M., Maslanik, J., Perovich, D., Shiklomanov, A., Walker, D., Box, J. E., Oludhe, C., Ambenje, P., Ogallo, L., Kabidi, K., Thiaw, W. M., Gill, T., Landman, W. A., Kocot, C., Phillips, D., Whitewood, R., Vazquez, M. O., Grover-Kopec, E. K., Rusticuci, M., Camacho, J. L., Pabon, J. D., Marengo, J. A., Martinez, R., Bidegain, M., Bulygina, O. N., Korshunova, N. N., Razuvaev, V. N., Ren, F., Gao, G., Rajeevan, M., Kumar, K. R., Rahimzadeh, F., Khoshkam, M., Kennedy, J. J., Achberger, C., Chen, D., Trigo, R., Garcia-Herrera, R., Paredes, D., Rachold, V., Cappelen, J., Heino, R., Saku, S., Parker, D., Jonsson, T., and Walsh, J.: State of the climate in 2005, B. Am. Meteorol. Soc., 87, S6–S102, 2006. 760

Singarayer, J. S., Bamber, J. L., and Valdes, P. J.: Twenty-first-century climate impacts from a declining Arctic sea ice cover, J. Clim., 19, 1109–1125, 2006. 761

Stroeve, J. C., Serreze, M. C., Fetterer, F., Arbetter, T., Meier, W., Maslanik, J., and Knowles, K.: Tracking the Arctic's shrinking ice cover: Another extreme September minimum in 2004, Geophys. Res. Lett., 32, L04501, doi:10.1029/2004GL021810, 2005. 760

Stroeve, J., Holland, M. M., Meier, W., Scambos, T., and Serreze, M.: Arctic sea ice decline: Faster than forecast, Geophys. Res. Lett., 34, L09501, doi:10.1029/2007GL029703, 2007. 760, 761

Teng, H. Y., Washington, W. M., Meehl, G. A., Buja, L. E., and Strand G. W.: Twenty-first century Arctic climate change in the CCSM3 IPCC scenario simulations, Clim. Dynam., 26, 601–616, 2006. 760

Walczowski, W. and Piechura, J.: New evidence of warming propagating toward the Arctic Ocean, Geophys. Res. Lett., 33, L12601, doi:10.1029/2006GL025872, 2006. 764
Zhang, X. D. and Walsh, J. E.: Toward a seasonally ice-covered Arctic Ocean: Scenarios from the IPCC AR4 model simulations, J. Climate, 19, 1730–1747, 2006. 760, 761, 765

Table 1. Model institutions, identifiers, component resolutions, ice model characteristics, and modeled Arctic annual averaged (ANN) sea ice decline in response to CO_2 quadrupling. Table 1 is broken across 4 pages with a different subset of models presented on each page.

Model	MPI ECHAM5	NCAR CCSMv.3	UKMO HADGEM1	INGV ECHAM4
Atmosphere Resolution (latitude×longitude)	~1.9°×1.9° (T63)	~1.4°×1.4° (T81)	1.25°×1.875°	~1.125°×1.125° (T106)
Ocean Resolution (grid points)	180×360	384×320	216×360	180×360
Ice Resolution (grid points)	180×360	384×320	216×360	180×360
Ice Dynamics (y/n)	Y	Y	Y	Y
Ice Rheology	Viscous Plastic	Elastic Viscous Plastic	Elastic Viscous Plastic	Viscous Plastic
Ice layers (number)	1	4	1	2
Ice thickness categories (number)	1	5	5	2
Flux Corrections	None	None	Iceberg flux	None
Arctic ANN sea ice decrease (% average 60—90° N)	73	71	48	48

TCD

2, 759–776, 2008

Table 1. Continued.

Model	MIROC3.2(medres)	MIUB ECHO–G	MRI CGCM2.3.2a	IPSL CM4
Atmosphere Resolution (latitude×longitude)	~2.8°×2.8° (T42)	~3.75°×3.75° (T30)	~2.8°×2.8° (T42)	2.5°×3.75°
Ocean Resolution (grid points)	192×256	117×128	111×144	170×180
Ice Resolution (grid points)	192×256	117×128	111×144	170×180
Ice Dynamics (y/n)	Y	Y	Y	Y
Ice Rheology	Elastic Viscous Plastic	Viscous Plastic	None	Viscous Plastic
Ice layers (number)	0	0	0	2
Ice thickness categories (number)	2	2	0	2
Flux Corrections	None	Heat, water annually outside ice extent	Heat, water, momentum monthly 12°N/S	None
Arctic ANN sea ice decrease (% average 60—90° N)	43	38	35	23

TCD

2, 759–776, 2008

Model resolution influence

J. O. Sewall

Table 1. Continued.

Model	INM CM3.0	GFDL CM2.1	GFDLCM2.0	UKMO HADCM3
Atmosphere Resolution (latitude×longitude)	4°×5°	2.5°×2.0°	2.5°×2.0°	2.75°×3.75°
Ocean Resolution (grid points)	84×144	200×360	200×360	144×288
Ice Resolution (grid points)	84×144	200×360	200×360	144×288
Ice Dynamics (y/n)	N	Y	Y	N
Ice Rheology	None	Elastic Viscous Plastic	Elastic Viscous Plastic	Convergence prevention > 4 m depth
Ice layers (number)	0	2	2	1
Ice thickness categories (number)	1	5	5	1
Flux Corrections	Water, annually GIN, Barents, Kara Seas	None	None	iceberg flux
Arctic ANN sea ice decrease (% average 60—90° N)	22	22	17	8.9

TCD

2, 759–776, 2008

Model resolution influence

J. O. Sewall

Table 1. Continued.

Model	CCCMA CGCM3.1	GISS E R
Atmosphere Resolution (latitude×longitude)	~3.75°×3.75° (T47)	4°×5°
Ocean Resolution (grid points)	100×200	46×72
Ice Resolution (grid points)	48×96	46×72
Ice Dynamics (y/n)	Y	Y
Ice Rheology	Cavitating Fluid	Viscous Plastic
Ice layers (number)	0	4
Ice thickness categories (number)	1	2
Flux Corrections	Heat, water	None
Arctic ANN sea ice decrease (% average 60—90° N)	8.1	3.8

TCD
2, 759–776, 2008

Title Page
Abstract Introduction
Conclusions References
Tables Figures
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

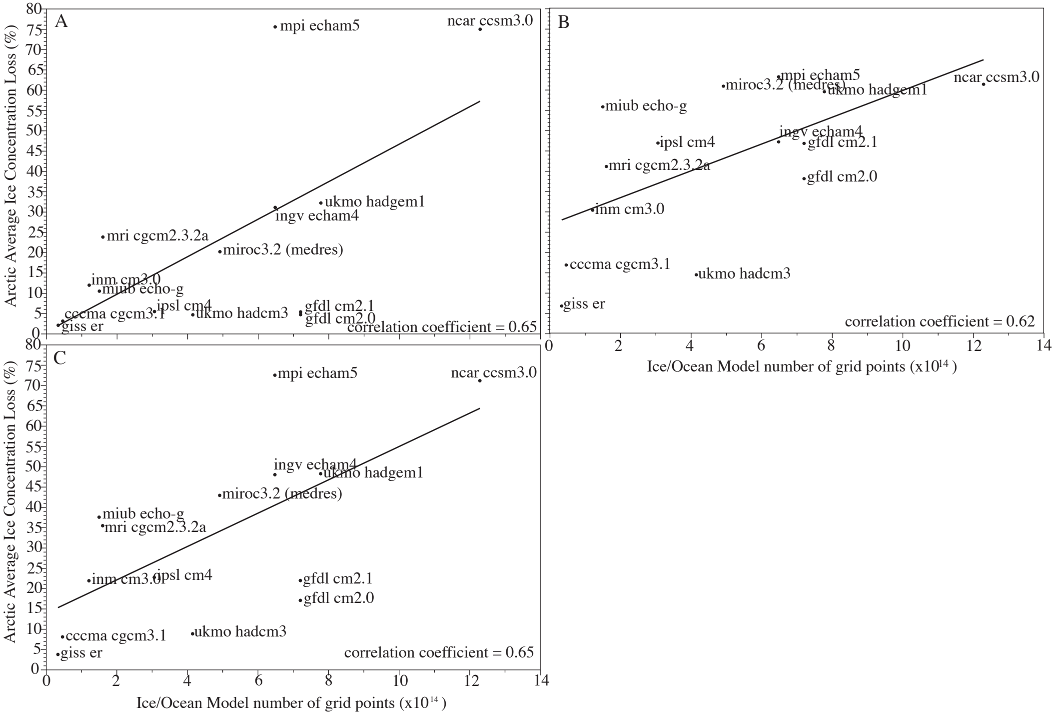

Fig. 1. Arctic averaged (average over 60°–90° N) ice concentration loss (%) at a quadrupling of CO_2 (as compared to the last 50 years of the 20th century) plotted against the number of grid points in the ice/ocean model component of each of 14 CMIP3 models for **(A)** February, March, and April average (FMA), **(B)** August, September, and October average (ASO), and **(C)** annual average (ANN). The correlation coefficients for log transformed data are: 0.61 (FMA), 0.73 (ASO), and 0.70 (ANN).

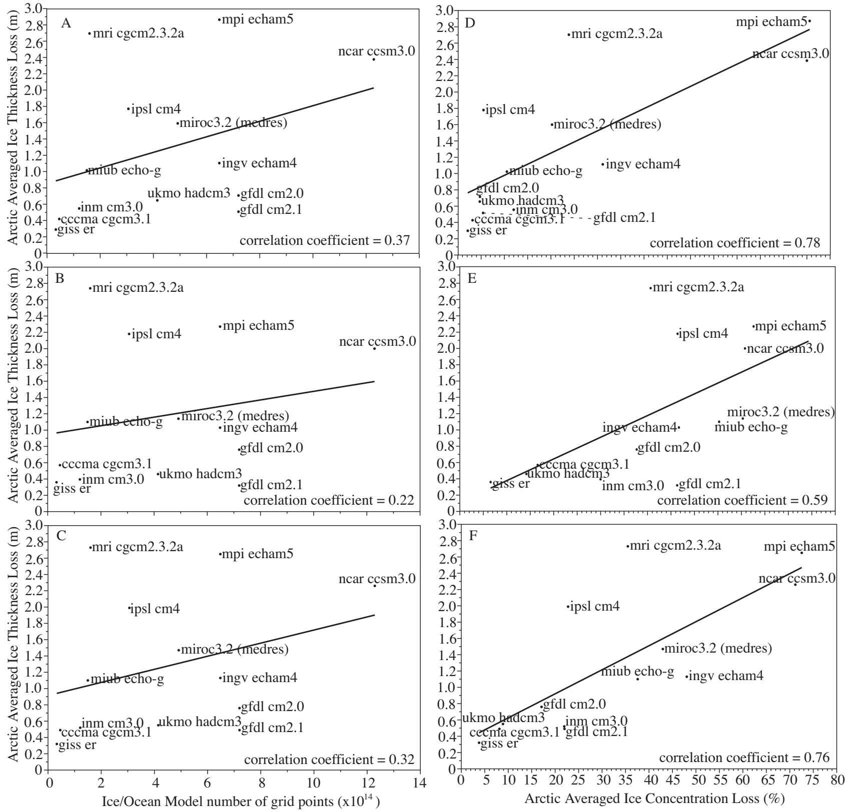

Fig. 2. Arctic averaged (average over 60°–90° N) ice thickness loss (m) at a quadrupling of CO_2 (as compared to the last 50 years of the 20th century) plotted against the number of grid points in the ice/ocean model component of each of 14 CMIP3 models for **(A)** February, March, and April average (FMA), **(B)** August, September, and October average (ASO), and **(C)** annual average (ANN). Correlations between ice/ocean model resolution and Arctic averaged ice thickness loss are weaker than those for ice concentration but are positive. Arctic averaged (average over 60°–90° N) ice thickness loss (m) at a quadrupling of CO_2 (as compared to the last 50 years of the 20th century) correlates strongly with Arctic averaged (average over 60°–90° N) ice concentration loss (%) at a quadrupling of CO_2 (as compared to the last 50 years of the 20th century) in **(D)** FMA, **(E)** ASO, and **(F)** ANN, indicating that the CMIP3 models losing the greatest ice concentrations (those with the highest ice/ocean model resolutions) are also losing the most ice thickness and are, therefore, losing the most ice overall. The correlation coefficients for log transformed data are: 0.55 (Panel A), 0.35 (Panel B), 0.50 (Panel C), 0.83 (Panel D), 0.64 (Panel E), 0.82 (Panel F).

TCD

2, 759–776, 2008

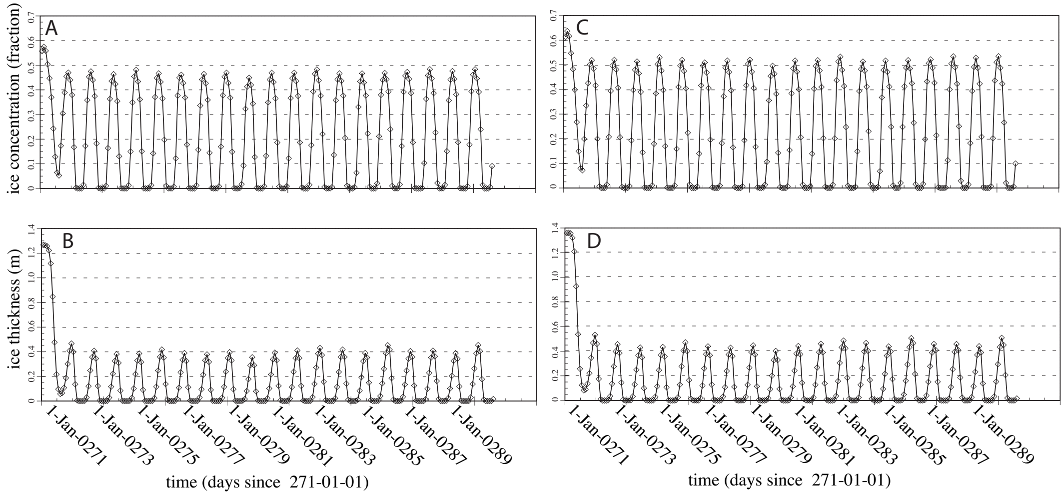

Fig. 3. Modeled ice concentration (fraction; A, C) and ice thickness (m; B, D) from the Los Alamos National Laboratory sea ice model, CICE, at horizontal resolutions of ∼3° latitude×longitude (A, B) and ∼1° latitude×longitude (C, D). The twenty-year-long simulations were forced by 20 years of daily data from CMIP3 participating model MIROC3.2(medres) under conditions of quadrupled CO_2 (years 271–290 of the 1%/year CO_2 increase to quadrupling run. Quadrupling was reached at ∼year 140). In ice-only simulation, increased horizontal model resolution appears to have no influence on the modeled ice response to elevated atmospheric CO_2 forcing.

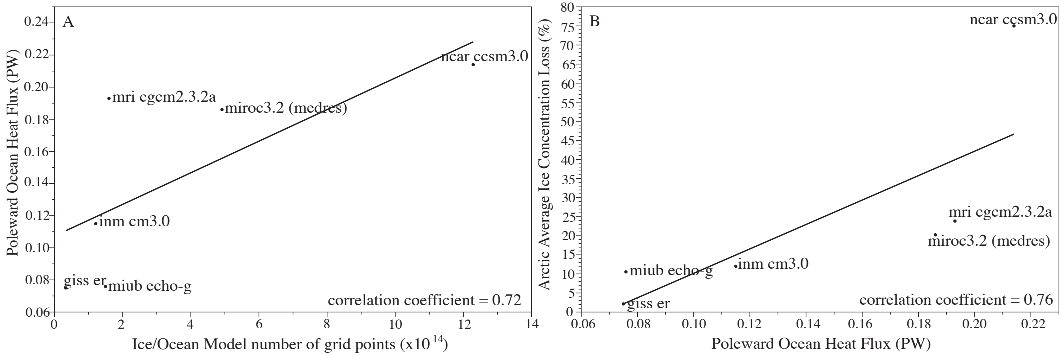

Fig. 4. (A) High latitude northern hemisphere (average over 60°–90° N) poleward ocean heat transport (PW) at CO_2 quadrupling in six CMIP3 models plotted against ice/ocean model horizontal resolution. Increased poleward ocean heat transport is associated with increased horizontal resolution in the ocean model component. **(B)** Arctic averaged (average over 60°–90° N) February, March, and April averaged ice concentration loss (%) at a quadrupling of CO_2 (as compared to the last 50 years of the 20th century) plotted against high latitude northern hemisphere (average over 60°–90° N) poleward ocean heat transport (PW) at CO_2 quadrupling in six CMIP3 models. Higher poleward ocean heat transport is positively correlated with higher ice concentration losses at CO_2 quadrupling. Horizontal ocean model resolution, through poleward oceanic heat transport, is, therefore, positively correlated with higher ice concentration losses at CO_2 quadrupling (see also Fig. 1). The correlation coefficients for log transformed data are: 0.79 (Panel A) and 0.85 (Panel B).