Toward Prediction of Environmental Arctic Change

Models help researchers understand past and present states as well as predict scenarios of environmental change in the Arctic. The authors analyze results on melting sea-ice from a regional coupled ice–ocean model and demonstrate their robustness independent of timescales for surface temperature and salinity relaxation.

Recent studies suggest that the Arctic Ocean is a variable system experiencing major shifts at timescales from several years to decades due to changing atmospheric dynamics and exchanges with lower-latitude oceans. In particular, the Arctic Ocean has experienced intensified warming since the late 1990s, as observed from satellites, submarines, and other in situ measurements.[1] Some of the critical signatures of recent change include an increased heat flux into the Arctic Ocean[2,3] and a dramatic reduction in the thickness and extent of the Arctic's perennial sea-ice cover. If this warming trend continues, it will significantly affect the global climate as well as the Arctic Ocean's strategic and economic importance (both for its commercial shipping routes and natural resources). Climate models predict the Arctic Ocean could experience ice-free summers by the middle-to-end of the century.[4]

Analyses based on observations and models suggest that at least two regimes in the Arctic atmospheric circulation directly influence sea-ice conditions and the distribution and fluxes of freshwater[5] and Atlantic water.[6] Whether these regimes are cyclic, driven by coupling with lower latitudes, or part of a trend related to other global changes remains to be determined. In this article, we analyze sea-ice results from multiple simulations with a regional coupled ice-ocean model covering the Arctic. Our main goal is to demonstrate the robustness of sea-ice thickness reduction in response to realistic atmospheric forcing but independent of timescales for surface temperature and salinity restoring.

Problem and Methodology

Before we can predict future changes in the Arctic Ocean, we need a proper understanding of recent variability in the region. Some ongoing analyses imply that existing global climate predictions might have errors due to insufficient model resolution or "missing" physics.[7] Sea-ice response to variable atmospheric regimes, for example, strongly depends on the model's representation of sea-ice and upper-ocean conditions before and during the time of change. However, the sea-ice and ocean models used in global climate studies are typically configured at fairly coarse resolutions (> 1°) so that they can include the entire globe and run long simulations given computer resource constraints. Climate models also often use crude parameterizations of the thermodynamic and dynamic processes that determine ice thickness and extent and upper-ocean conditions. All these limitations have had an impact on global models' representation of past and present sea-ice variability in the Arctic Ocean and their prediction of future changes.[8]

Regional high-resolution modeling is an alternative and complementary approach to global climate studies. High-resolution regional models can take advantage of recent advances in sea-ice and

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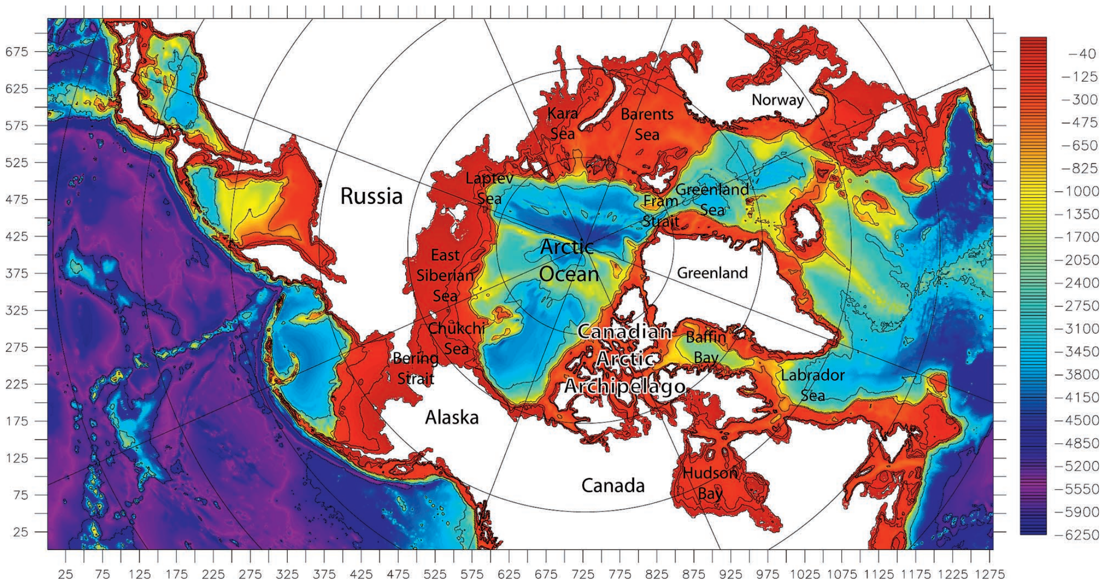

Figure 1. Our ice-ocean model domain and bathymetry (m). We initialized the model from no motion with 3D climatological temperature and salinity fields, and then integrated it for 48 years in spin-up mode.

ocean modeling as well as the availability of powerful parallel supercomputers for high-resolution environmental modeling. (Note that this approach is just a temporary step until computational resources become available for global model configurations at grid resolutions sufficient to realistically represent state and variability.) The main challenges in modeling the Arctic Ocean and its sea ice include realistically representing the physical processes specific to polar regions and the resolution of small-scale features such as narrow boundary currents on the order of 100 km, the Rossby radius of deformation on the order of 10 km, and the bottom bathymetry and land geometry that control the physics. Fortunately, highly parallel regional models optimized for modern computer architectures can incorporate state-of-the-art physics on high-resolution numerical grids.

Recent Experiments

To account for the influence of buoyancy and heat fluxes between the atmosphere and ocean, ocean general-circulation models (GCMs) commonly use some type of relaxation to measured climatological surface temperature and salinity data. However, in climate-change studies, this surface relaxation could limit the ocean's ability to realistically interact with atmospheric forcing and sea-ice cover at timescales from years to decades and centuries. Here, we present the results of sensitivity studies that can provide insights into the impact of surface relaxation on the representation of sea-ice conditions and their multidecadal variability.

We developed a coupled ice–ocean model of the sea-ice-covered northern hemisphere configured on a rotated spherical coordinate system grid at a resolution of 1/12° (or approximately 9 km) in the horizontal direction and 45 levels in the vertical direction (see Figure 1).[9] Our sea-ice model[10] includes a parallel version of Hibler's dynamic model (with viscous-plastic rheology) and a thermodynamic model based on other research (with a zero-layer approximation for heat conduction through ice[11]). Researchers have often used this type of model in ocean and climate simulations.[12]

We coupled our model to a regional adaptation of the Los Alamos National Laboratory Parallel Ocean Program (POP), which is using a free-surface approach[13] and unsmoothed realistic bathymetry. We initialized the model from no motion (zero velocities at time = 0) with 3D climatological temperature and salinity fields, and then integrated it for 48 years in spin-up mode using climatological and 1979–1981 atmospheric data from the European Centre for Medium-Range Weather Forecasts (ECMWF) to force it toward a self-consistent state of initial conditions at the end of the 1970s. This approach is important for establishing realistic ocean-circulation and water-mass properties representative of the time period at the beginning of real interannual integration experiments.

We completed four 24-year experiments, each

Table 1. Relaxation times for surface salinity and temperature for each experiment.

Experiment	S_{surf} (days)	T_{surf} (days)
Case 1 (strong relaxation)	30	30
Case 2 (intermediate relaxation)	120	365
Case 3 (weak relaxation)	365	∞
Case 4 (no relaxation)	∞	∞

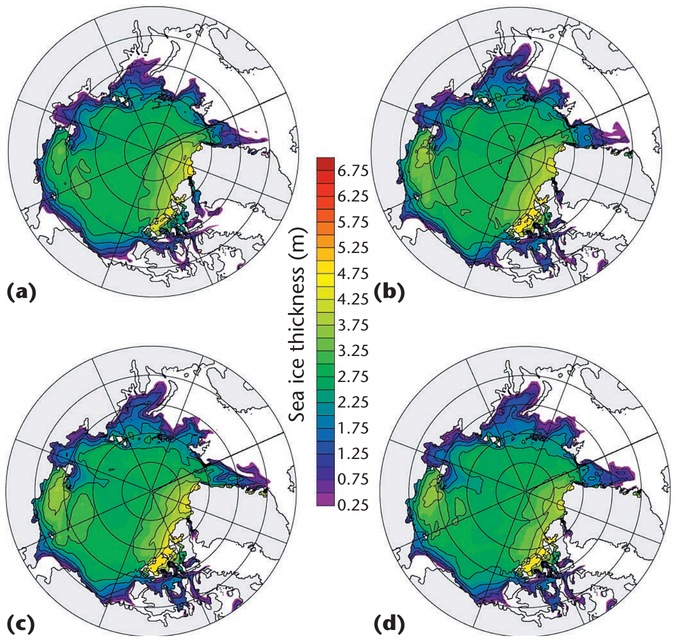

Figure 2. Sea-ice thickness distribution for September 1982. The contour interval is 0.5 meters for (a) Case 1 (strong relaxation), (b) Case 2 (intermediate relaxation), (c) Case 3 (weak relaxation), and (d) Case 4 (no relaxation). The estimated ice extent suggests only minor differences among the four cases.

starting at the end of the 48-year spin up and forced with 1979–2002 ECMWF data (but with different temperature and salinity-relaxation times at the surface). Daily averaged annual cycles of salinity and temperature at river mouths are a function of river discharge, but other surface buoyancy fluxes, such as precipitation and ungauged runoff from land, aren't well known in the Arctic region, especially over decadal timescales.

We applied ocean-surface (5-meter thick) layer relaxation to monthly Polar Science Center Hydrographic Climatology (PHC)[14] temperature and salinity (T/S) values as a correction term to the explicitly calculated (but not readily available) heat and buoyancy fluxes between the ocean and the overlying atmosphere or sea ice. In addition, we restored a 4°-wide, or 48-gridpoint-thick, curtain along the model domain's lateral boundary on a 10-day timescale to annually average PHC temperature and salinity climatology. This curtain restoration partially compensates for the effects of the closed boundaries near mid-latitude currents, but it's far enough away from the primary region of interest to minimize the impact of the curtain's restoration. The relaxation term in the model is $(S_{clim} - S_{pred})/\tau_{surf}$, where the S_{clim} monthly climatological value at point S_{pred} is the model-predicted value at this point, and τ_{surf} is the relaxation timescale. This term acts to limit $S_{clim} - S_{pred}$ over a timescale τ_{surf}. Table 1 lists the surface-relaxation timescales for temperature (T_{surf}) and salinity (S_{surf}) for each 24-year experiment. Longer relaxation timescales weaken the surface relaxation term's effect on surface salinity and temperature.

We designed our four experiments to study the sensitivity of sea-ice model behavior to the strength of ocean-surface T/S relaxation, ranging from a relatively strong relaxation case (Case 1) to intermediate relaxation (Case 2) to weak relaxation (Case 3) to no relaxation at all (Case 4). During the 48-year spin up, we applied Case 1's strong relaxation. Each experiment required roughly 760,000 processor-hours of a Cray T3E supercomputer at the Arctic Region Supercomputer Center (ARSC) and the US Army Engineering and Research Development Center (ERDC).

Results

To address concerns about the validity of using surface relaxation to parameterize surface buoyancy flux effects on Arctic sea-ice simulations, we compared the results from these integrations both to each other and to the sea-ice extent and thickness data available over this period. The results also point to the growing need for understanding recent ocean-warming trends and the subsequent decrease of the Arctic ice pack in the late 1990s and 2000s.

Figure 2 shows the sea-ice thickness distribution in September 1982 for each case; the results are quite similar for all values of τ, except along the ice edge in marginal seas (such as the Kara, Greenland, and Siberian seas). A comparison of the three-year (1979–1981) mean ice thickness distribution from Case 1 (strong relaxation) shows good agreement[16] with limited ice-thickness observations from previous research.[15] The averaged ice thickness in the central Arctic Ocean ranges between 2.5 and 3.5 meters, with the thickest ice found along the Canadian Archipelago and Greenland's northern coast.

The estimation of ice extent in Figure 2 suggests only small differences among the four cases and that they're relatively insignificant for climate-change studies. However, the distribution of differences in Figure 3 suggests a decreasing trend for the central Arctic's ice thickness as the relaxation is weakened by increasing the relaxation times. Positive thickness differences indicate thicker ice during stronger relaxation. It's worth noting that differences between Cases 1 and 2 are predominantly negative, which doesn't support our earlier conclusion that weaker relaxation produces less (or thinner) ice in the central Arctic.

Figure 4 shows that 10 years later there's generally more and thicker sea ice throughout the Arctic Ocean, except in Case 4. Still, the general pattern of modeled sea-ice thickness and extent distribution is rather similar for all four cases considered. The mean sea-ice thickness in the deep basin of the central Arctic in Cases 1 through 3 increased by roughly 0.5 meters in 1992 compared to 1982. Significantly thicker ice cover (more than 5 meters) is present along the northern Canadian Archipelago and northern Greenland, which is generally 1 meter more than in 1982 in those areas. The significant warming in the Atlantic layer in the early 1990s[6] doesn't appear to have an effect on the sea-ice cover yet. Case 4 shows the least change from 1982, suggesting unrealistic alteration of oceanic circulation (not shown) and ice–ocean interactions, especially when compared to Case 3, which also doesn't have surface temperature relaxation but includes weak surface salinity relaxation.

As Figure 5 shows, the distribution of ice thickness differences in 1992 has larger amplitudes, both positive and negative. Comparing Cases 1 and 2 indicates that ice was thinner in Case 1 almost everywhere in the Arctic Ocean except north of Fram Strait. Also, we see indications of more than 2 meters of sea-ice deficit in the northern Baffin Bay, where the North Water Polynya (an area of open water surrounded by ice) commonly occurs. The general trend in the four cases is thinner ice in the center of the Arctic Ocean and thicker ice along its perimeter as relaxation time increases and relaxation effects weaken. The effect is such that cases with weak or no surface temperature relaxation overestimate ice extent, especially in the eastern Arctic, compared to Case 1 and satellite observations.[17] We attribute this result to unrealistic changes in simulated ocean dynamics associated with decreasing northward oceanic heat fluxes, which develop in areas without surface salinity and temperature relaxation after 14 years of model integration.

As Figure 6 shows, the mean ice thickness in the central Arctic Ocean decreased dramatically by 2002 to less than 2.0 meters in all four cases, with many marginal seas ice-free in September, in agree-

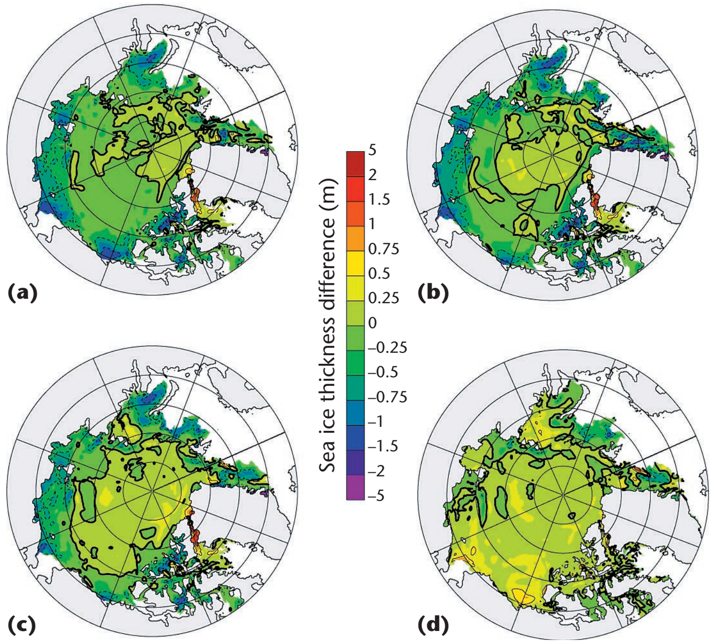

Figure 3. Differences in sea-ice thickness distribution for September 1982. The thick solid line separates positive anomalies from negative ones for (a) Case 1 (strong relaxation) – Case 2 (intermediate relaxation), (b) Case 1 – Case 3 (weak relaxation), (c) Case 1 – Case 4 (no relaxation), and (d) Case 2 – Case 4.

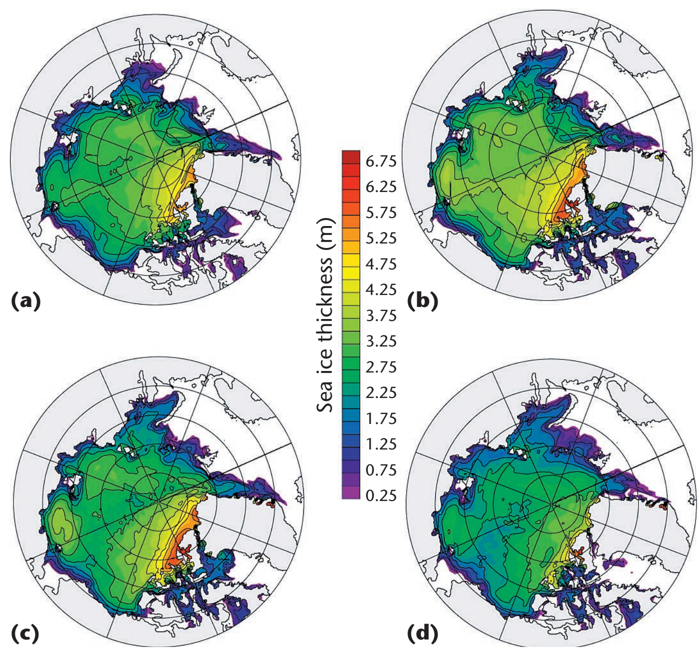

Figure 4. Sea-ice thickness distribution for September 1992. For (a) Case 1 (strong relaxation), (b) Case 2 (intermediate relaxation), and (c) Case3 (weak relaxation), we see generally more and thicker sea ice than 10 years earlier, but for (d) Case 4 (no relaxation), we see relatively fewer changes since 1982.

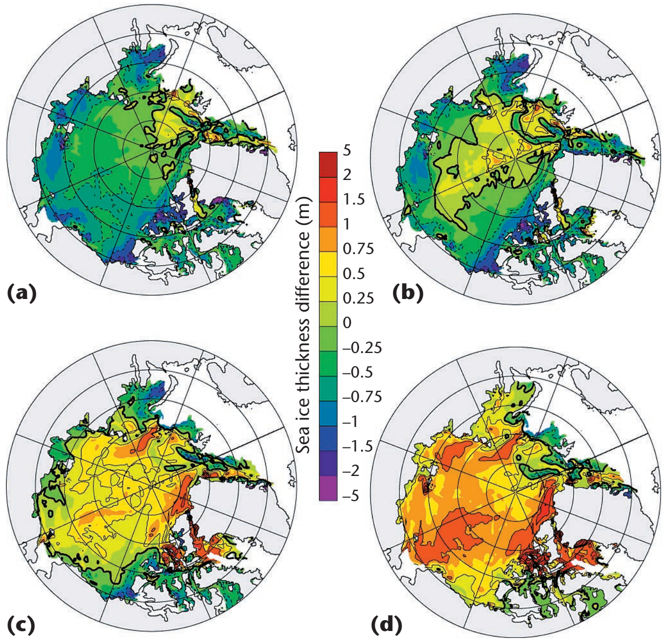

Figure 5. Differences in sea-ice thickness distribution for September 1992. Compared to 1982, (a) Case 1 (strong relaxation) – Case 2 (intermediate relaxation), (b) Case 1 – Case 3 (weak relaxation), (c) Case 1 – Case 4 (no relaxation), and (d) Case 2 – Case 4 have larger thickness amplitudes, both positive and negative. In other words, greater discrepancies exist among cases after 14 years compared to after four years of simulation.

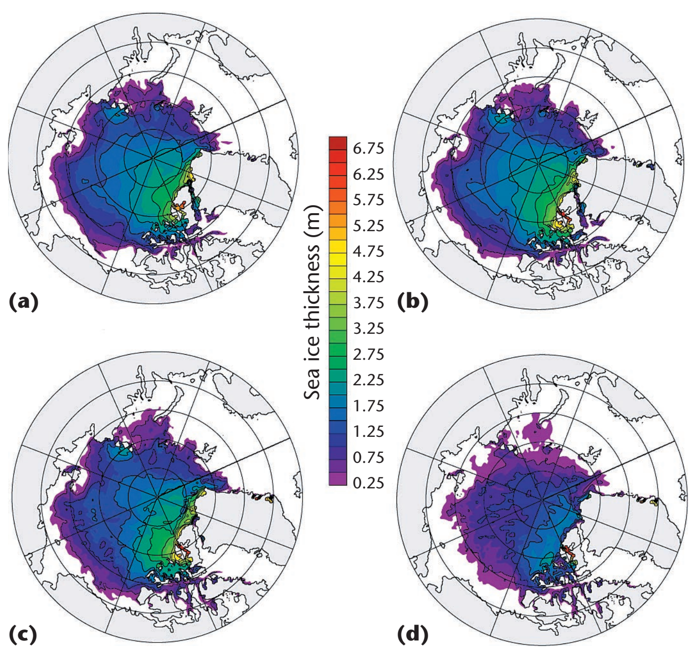

Figure 6. Sea-ice thickness distribution for September 2002. The mean has decreased dramatically for (a) Case 1 (strong relaxation), (b) Case 2 (intermediate relaxation), (c) Case 3 (weak relaxation), and (d) Case 4 (no relaxation).

ment with satellite observations. Also, the thickest ice cover north of the Canadian Archipelago and Greenland now isn't much thicker than 3.0 meters. The dramatic thinning of sea ice in the 2000s is robust and independent of surface relaxation. Taking into account that 24 years have elapsed since the beginning of each case's integration, it's remarkable how similar the four cases we considered actually are. We could argue that the differences in sea-ice thickness distribution shown in Figure 7 are relatively insignificant compared to typical errors in sea-ice thickness distribution in GCMs, both in terms of ice extent and thickness distribution.

Our calculations show that observed sea-ice variability can be reproduced, if atmospheric and oceanic forcing is realistically represented. Hindcasts of ice thickness distribution obtained with variable surface temperature and salinity relaxation are reasonably insensitive to the strength ($1/\tau_{surf}$) of relaxation. Our results also imply that differences and errors in many existing predictions of Arctic changes are likely due to problems with atmospheric and oceanic forcing as well as insufficient model resolution to account for details of bathymetry, circulation, and exchanges with adjacent oceans. Simply put, surface ocean relaxation doesn't significantly limit the variability of sea-ice extent and thickness distribution. Rather, it allows more realistic representation of surface dynamics and its forcing of sea-ice distributions in the absence of realistic interannual data. But regardless of the cause, the reduction or absence of sea-ice cover in the Arctic Ocean requires significant tactical and logistical modifications on the US Navy's part, so that it can successfully conduct its missions in a partly or seasonally sea-ice-covered environment.

Regional ice–ocean models can provide quite accurate predictions of sea-ice conditions, including ice edge, marginal ice zone, and deformation in the Arctic ice pack, subject to the availability of realistic atmospheric forcing data and sufficient computer resources. One way to alleviate the limitation of realistic atmospheric data for the Arctic region is to use regional climate models at sufficiently high resolution with physics appropriate for polar regions. Such regional models with fully coupled ice, ocean, atmosphere, and land components eliminate the need to prescribe forcing among those components of the Earth system.

Acknowledgments

We completed three experiments (Case 1, Case 2, *and Case 4) on the Cray T3E at the Arctic Region Supercomputer Center and one experiment (Case 3) on the Cray T3E at the US Army Engineering and Research Development Center. All computer resources were provided by the US Department of Defense's High Performance Computer Modernization Program via a Grand Challenge Project entitled "Towards Predicting Scenarios of Environmental Arctic Change." Funding support comes from the US Department of Energy's Climate Change Prediction Program and the US National Science Foundation's Shelf Basin Interaction Program.*

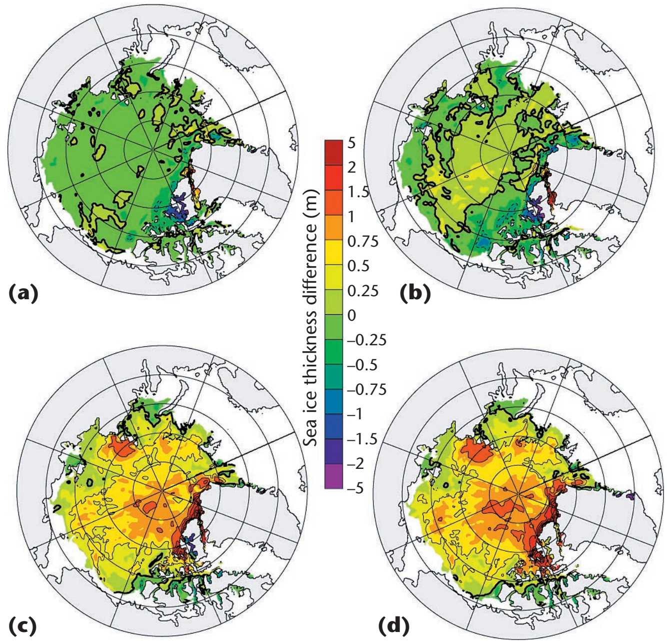

Figure 7. Differences in sea-ice thickness distribution for September 2002. The four cases are remarkably similar: (a) Case 1 (strong relaxation) – Case 2 (intermediate relaxation), (b) Case 1 – Case 3 (weak relaxation), (c) Case 1 – Case 4 (no relaxation), and (d) Case 2 – Case 4.

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