Weighing the importance of surface forcing on sea ice—A September 2007 CICE modeling study

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ABSTRACT

The sea ice minimum of September 2007 is well represented in a 50-year simulation using the Los Alamos Sea Ice Model, CICE, in spite of the fact that only 4 atmospheric forcing fields vary interannually in the model simulation—all other atmospheric and oceanic forcing data are monthly-mean climatologies. Simulation results confirm prior conclusions that an anomalous pressure pattern, ice-ocean albedo feedback effects on sea surface temperature, and the long-term sea ice thinning trend are primarily responsible for the sea ice minimum of 2007. In addition, the simulation indicates that cloudiness, precipitation, and other forcing quantities were of secondary importance.

Here we explore the importance of applied atmospheric and oceanic surface forcing for the 2007 sea ice minimum event, along with a group of model parameterizations that control the surface radiation budget in sea ice (melt ponds). Of the oceanic forcing fields applied, only the sea surface temperature requires interannual variability for simulating the 2007 event. Interannual variations of temperature and humidity play a role in the radiation balance applied at the snow and ice surface, and they both have the potential to significantly affect the ice edge. However, humidity (exclusive of clouds) is far less influential on ice volume than is air temperature. The inclusion of albedo changes due to melt ponding is also crucial for determining the radiation forcing experienced by the ice. We compare the effects of four different pond parameterizations now available in CICE for the September 2007 case, and find that while details may differ, they all are able to represent the 2007 event. Feedback strength associated with the radiation balance differs among the pond simulations, presenting a key topic for future study.

1 Introduction

In September 2007, the Arctic sea ice cover shrank to an extent that made headlines in the popular media (e.g., [16]), generated a slew of scientific studies of its cause and effects (see below), and provided ready motivation for many funding proposals. While the basic mechanisms influencing the event were well understood soon afterward by sea ice modelers, mechanisms continue to be proposed (e.g., melt ponds [3]) with some potential to affect modeling outcomes. In this paper, I present a simpler simulation than those used previously, which captures the important mechanisms already understood but that, in addition, clearly indicates those that are unnecessary or of lesser influence.

A number of researchers have investigated various aspects of this event. Two early studies [14, 18] asked whether clear skies that summer contributed. There was a large sea level pressure anomaly over the Arctic, in some places more than 2 standard deviations above normal, that produced largely clear skies; the cloud fraction in 2007 was more than 2 standard deviations below normal [18]. Using a coupled ice-ocean model, [18]'s simulation of the September ice area matched observations well, and they performed some sensitivity runs testing various radiation fields. In general they found that radiation anomalies were not responsible for the 2007 minimum ice event. [14] concluded that with thinner ice, radiation can have a larger effect than it would otherwise.

[22] discuss the same simulation as [18], analyzing various other fields to form a more complete picture of the event. They find that 30% of the ice loss was due to export through Fram Strait, especially in in August and September; the remaining 70% melted, with a decrease in upwelling shortwave flux—reduced surface albedo—as a significant driver.

[15] further analyze the same simulation and determine that the observed long-term sea ice thinning trend preconditioned the Arctic ice pack for the 2007 event. A diagnostic called "open water formation efficiency," the fraction of open water created for each meter of ice thinning [7], increases as ice thins. [15] show that as the ice thinned through the years, the open water formation efficiency in their simulation increased. Thus, the sea ice had been preconditioned by thinning to be more susceptible to forcing that would increase the amount of open water in the Arctic. Moreover, they conclude that this preconditioning was necessary for the event.

[13] used an ice-ocean adjoint model to identify the critical parameters in their model. They find that the initial ice thickness was critical—the preconditioning—along with the wind stress in May and June. They also noted the 2m air temperature in September, which warmed partly due the ice-ocean albedo feedback; [14] found that the air temperature increased also due to advection from lower latitudes. In [13], wind was not important later in the summer, contrary to the results of [22].

There have been many more studies of other possible forcing mechanisms for the September 2007 event (e.g. the Dipole Anomaly [21], ocean warming [19] and melt ponds [12]). [20] provide a comprehensive overview of observed processes and feedbacks contributing to sea ice extent minima in recent years.

When run uncoupled but with a simple mixed-layer ocean representation, the Los Alamos Sea Ice Model, CICE, performs well in simulations of the minimum ice event of September 2007 (Fig. 1a). This model configuration is simpler than other modeling studies of that event, to date, in that (1) the ocean model is highly simplified, and (2) only 4 surface forcing fields (temperature, specific humidity, and 2 components of wind velocity) include interannually varying information; annual, monthly-mean climatologies are applied for all other forcing. The studies cited above explain the ability of our uncoupled CICE simulation to capture the first-order effects, as discussed in the following sections.

An interesting aspect of this CICE simulation consists of what was not important for that event—for instance, climatologies are used for all of the oceanic forcing fields except sea surface temperature (SST). Here I also confirm that the interannual variation of relative humidity and cloudiness are not important for the 2007 event on interannual time scales, and demonstrate that more complex melt pond parameterizations do not necessarily add fidelity to the solution.

2 Model configuration and experiments

The present investigation of mechanisms important for the September 2007 sea ice event seeks to weigh the influence of melt pond parameterizations and atmospheric forcing fields in the context of a simplified, 1° model configuration. The thermodynamic slab ocean mixed layer model in CICE computes SST based on the surface energy balance of fluxes through the sea-ice and open-water interfaces. The model and forcing are configured as described in [9] and [10], but using an updated model version (CICE version 5.0β, r639).

In particular, modified NCEP forcing is applied for the wind, air temperature and humidity, for 1958–2007 as in [10]. Precipitation, clouds and ocean forcing fields (sea surface currents, slope, salinity, and deep ocean heat flux from CCSM3 output) are provided as monthly mean climatologies. In addition to SST, the turbulent heat fluxes, wind stress, downwelling longwave and shortwave radiation are computed as described in [8] and below; these fields also depend on the state of the ice. Although air temperature is provided as an input data set, it is adjusted in the presence of sea ice to prevent warm temperature

label	pond scheme	Q_a	T_a
a	level-ice	interannual	interannual
b	level-ice	normal year	interannual
c	level-ice	interannual	normal year
d	topo	interannual	interannual
e	cesm	interannual	interannual
f	ccsm3	interannual	interannual

Table 1: Simulations performed, labeled as in the figures. The ccsm3 pond parameterization is implicit within the ccsm3 shortwave parameterization; all other simulations used the delta-Eddington shortwave radiation scheme [1, 11].

preconditioning for ice melt: if there is at least 10% sea ice cover in a grid cell, then the air temperature is not allowed to be greater than 0.5°C [8].

The model was run for 50 years (1958–2007) using the level-ice melt pond parameterization [10]; results are very similar to those of [10]. We test the sensitivity of this model solution for September 2007 using climatological fields for humidity and air temperature, and for 3 other melt pond parameterizations available in CICE, listed in Table 1. Sensitivity runs branched from the 50-year control run on 1 Jan 1980 and ran through 2007.

The model was tuned in [9] using the default ‘ccsm3’ shortwave parameterization, in which melt ponds are implicitly modeled through reduction of albedo as the ice thins and its surface warms. At the time of that study, the interannual atmospheric fields (CORE version 2, [5]) were available only through 2006. That paper [9] demonstrates that the pattern of ice thickness, ridged ice area, and ridging activity is similar to submarine and satellite observations, through 2006. With 2007 CORE data now available, the model simulations are continued with no change to the tuning parameters; thus the 2007 results shown in Fig. 1f represent a clean validation of this model configuration. Notably, the model simulates the 2007 sea ice retreat using a great deal of climatological forcing data, with just wind, humidity, and air temperature varying interannually.

3 Humidity and Temperature

Humidity (Q_a) appears in three thermodynamic forcing terms in the model: evaporation (latent heat flux) and both longwave and shortwave radiation. Downwelling longwave is computed as

$$F_{lw\downarrow} = \varepsilon\sigma T_s^4 - \varepsilon\sigma T_a^4(0.39 - 0.05 e_a^{1/2})(1 - 0.8 f_{cld}) - 4\varepsilon\sigma T_a^3 (T_s - T_a)$$

where the atmospheric vapor pressure (mb) is $e_a = 1000 Q_a/(0.622 + 0.378 Q_a)$, $\varepsilon = 0.97$ is the ocean emissivity, σ is the Stephan-Boltzman constant, f_{cld} is the cloud cover fraction, and T_a is the surface air temperature (K). The first term on the right is upwelling longwave due to the mean (merged) ice and ocean surface temperature, T_s (K), and the other terms on the right represent the net longwave radiation patterned after [17]. $F_{lw\uparrow} = \varepsilon\sigma T_i^4$ where T_i is the ice or snow surface temperature, computed as part of the net thermal energy balance over the sea ice fraction. The value of $F_{lw\uparrow}$ is different for each ice thickness category, while $F_{lw\downarrow}$ depends on the mean value of surface temperature averaged over all of the thickness categories and open water.

Q_a also contributes to the shortwave forcing through the atmospheric vapor pressure:

$$F_{sw\downarrow} = \frac{1353 \cos^2 Z}{10^{-3}(\cos Z + 2.7) e_a + 1.085 \cos Z + 0.1} \left(1 - 0.6 f_{cld}^3\right) > 0$$

where $\cos Z$ is the cosine of the solar zenith angle.

Changing Q_a from the CORE interannually varying data to the CORE normal year data increases evaporation by up to 0.07 cm/day. It also reduces downward longwave by up to 3 W/m^2 (generally less than 1 W/m^2 over most of the Arctic) and increases downward shortwave by up to 2 W/m^2. The net effect is a thickening and increase in extent of the ice cover (Fig. 1b), accompanied with a reduction in snow volume (Fig. 2b) and resulting increase in the area of melt ponds visible above the snow (Fig. 3b). Note that these radiatively induced changes are independent of the cloud fraction, which is a climatology.

In addition to downwelling longwave radiation, T_a also appears in the sensible heat flux. Using the normal year data set for T_a causes significant differences in the overall thermal balance of the ice, including the radiative fluxes at the surface, leading to a much different solution (Fig. 1c). In particular, snow remains deep over a large fraction of the Arctic Ocean (Fig. 2c), preventing melt ponds from appearing above the snow and lowering the albedo (Fig. 3c). Rather than attempt to thoroughly explore the myriad temperature effects, this simulation is presented as an example of a critical forcing factor, beside which humidity's effect on the ice pack (and that of melt pond details, described in the next section) is relatively small.

4 Melt Ponds

The melt pond parameterizations available in CICE are fully described elsewhere [10, level-ice], [6, cesm], [4, topo], [9, ccsm3]. They include some or all of the following physical processes: liquid melt water and rain collect into ponds (all schemes) that may drain through permeable sea ice (level-ice, topo) or over floe edges (all). Pond water infiltrates snow, can refreeze and melt at the top, and snow collects on top of refreezing ponds (level-ice, topo). Snow shades both ponds and sea ice (all).

The fundamental difference between the level-ice and topo schemes lies in how the pond volume is tracked. The level-ice ponds scheme carries them only on the level ice and assigns a particular depth-to-area ratio for changes in pond volume [10]. The topo scheme carries them on both level and ridged ice, but covers the thinnest ice categories first, assuming a maximum pond area that depends on ice thickness. In the cesm scheme, pond depth is a fixed fraction of pond area, applying empirical relationships for the physical processes that alter pond volume.

The ice concentration is not very different among the four schemes (not shown), but ice extent varies slightly (Fig. 1). The topo scheme has thicker ice than the others (Fig. 1d), due to a reduced feedback within that scheme: very few ponds affect the radiation budget (Fig. 3d) because of excess pond ice (refrozen ice lids on top of the ponds). In the topo parameterization, radiation is not allowed to penetrate any pond lid more than 1 cm thick [4], and therefore essentially no radiation reaches the ponds or the ice below in this simulation (Fig. 3d). This effectively cuts off the feedback between increasing pond volume and decreasing albedo. By September 2007, the net effect is a much thicker ice pack that does not melt back as much during the minimum ice event, as in the other schemes. Note that this is not a deficiency of the topo scheme; the limiting pond ice parameter could be increased to approximately reproduce the ice volume and extent as simulated in the other configurations, and it likely will need to be calibrated for any forcing data set or coupled model configuration.

The effective melt pond fraction in the cesm pond parameterization (Fig. 3e) is highly sensitive to snow depth (Fig. 2e), as discussed in [10], and yet it is able to produce a reasonable simulation of the September 2007 event using empirical descriptions of physical melt pond processes. This result, in particular, indicates that melt pond processes themselves are not critical for this event. The 'ccsm3' simulation, using a less complex shortwave radiation scheme (the other simulations all employ a multiple-scattering "delta-Eddington" scheme [1, 11]) that parameterizes the effects of ponds through simple albedo reductions, similarly captures the 2007 event. However, the ccsm3 parameterization does not include melt pond volume explicitly, making it less suitable for modeling experiments requiring sea ice permeability and flushing events, or delayed freshening of the ocean surface by runoff, for instance.

Although a representation of the effect of melt ponds on sea ice albedo is critical for modeling the evolution of sea ice, the details of that representation may be less important because other forcing effects such as wind and air temperature have a larger influence. It is clear that the feedback mechanisms at work in these simulations differ in their strength and effectiveness. More detailed study of such feedback processes is needed to ensure that models produce the correct solution for the right reasons.

5 Discussion and Conclusions

Feedback processes are important for strengthening sea ice variability. In the ice albedo feedback, changing ice surface characteristics enhance or reduce melting; this feedback process is weak in the topo pond simulation. Similarly the ice-ocean albedo feedback operates in this model configuration (with all pond schemes) via a thermodynamic slab-ocean mixed layer. As discussed previously, long-term thinning made the ice pack more susceptible to loss; a strong sea level pressure anomaly with unusual winds could be considered the trigger for the event, and then albedo feedbacks accelerated the process.

Despite its climatological forcing, this CICE model configuration includes the essential elements for simulating long-term thinning and retreat of the summer ice pack, including the 2007 wind anomaly and albedo feedback processes, in agreement with prior work [18, 22, 15, 13]. In particular, use of a cloud climatology is sufficient for simulating the 2007 event, in agreement with [18]'s conclusion that the relatively cloud-free conditions that year were not a critical factor. The CICE tests of climatological Q_a and alternative pond parameterizations also support the conclusion that radiative effects were less important for the 2007 event.

Current sea ice models incorporate parameterizations for most "first-order" processes known to be important for simulating the seasonal and interannual evolution of sea ice at climate scales, such as the energy balances at the top and bottom of the ice/snow column, thermodynamic conduction, ice motion and deformation, and mechanical redistribution processes such as ridging that affect the ice thickness distribution. Given realistic atmospheric and oceanic surface forcing fields along with a thermodynamic ocean mixed layer calculation of SST, sea ice models can capture the character and extent of summer sea ice retreat as measured by large-scale metrics such as ice extent and spatial patterns of ice concentration and thickness.

Applying less realistic forcing fields, such as climatological air temperature, to the same sea ice model produces a less realistic sea ice simulation. Thus sea ice, both real and simulated, primarily responds to the applied forcing. However, sea ice tends to amplify whatever change is already underway through feedback processes (especially albedo), and in this manner becomes a critical player in the polar regions. From this we conclude that (1) any atmospheric or oceanic process that alters the ice cover even slightly has the potential to contribute significantly to polar change, and (2) in order to predict the sea ice cover, we must be able to predict the atmosphere and the ocean. Internal ice physics parameterizations do affect the ice state, but sea ice models are much more sensitive to the external (atmosphere, ocean) forcing than they are to internal parameters, provided they include the essential, first order physics [9]. For example, some representation of albedo changes associated with liquid water ponding is necessary to capture the ice-albedo feedback, but the physical details of the parameterization are not crucial in forced sea ice experiments. Such details may play a larger role in fully coupled systems, however.

Therefore, to improve physical simulations of sea ice and polar regions, focus needs to be on the interaction of sea ice with the atmosphere and ocean—particularly the strength of feedbacks. The equilibrium state produced in any sea ice simulation will depend a great deal on the applied forcing, and the strength of feedbacks in turn depends on that equilibrium state. For example, in the topo ponds simulation the positive feedback between ice albedo and pond area is weak, resulting in a thicker ice cover that further weakens the feedback.

In summary, the Los Alamos Sea Ice Model, CICE, captures decadal and interannual variation in Arctic sea ice volume for the period 1958–2007. An anomalous pressure pattern, ice-ocean albedo feedback effects on sea surface temperature, and the long-term sea ice thinning trend were primary contributors to the extreme sea ice minimum of 2007. The simulations indicate mechanisms of secondary importance to the 2007 event, including cloudiness, precipitation, and most oceanic fields (other than SST), that are either not included or are climatological forcings. These variables are critical for the climatological sea ice state and may also be important for the long-term thinning trend or for extreme ice events in other years, hypotheses ripe for future work.

Acknowledgements

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Figure 1: September 2007 ice thickness (m) for the six simulations described in Table 1. The white line is the 15% ice concentration contour from the model, and the red line is the 15% concentration contour from passive microwave satellite data [2].

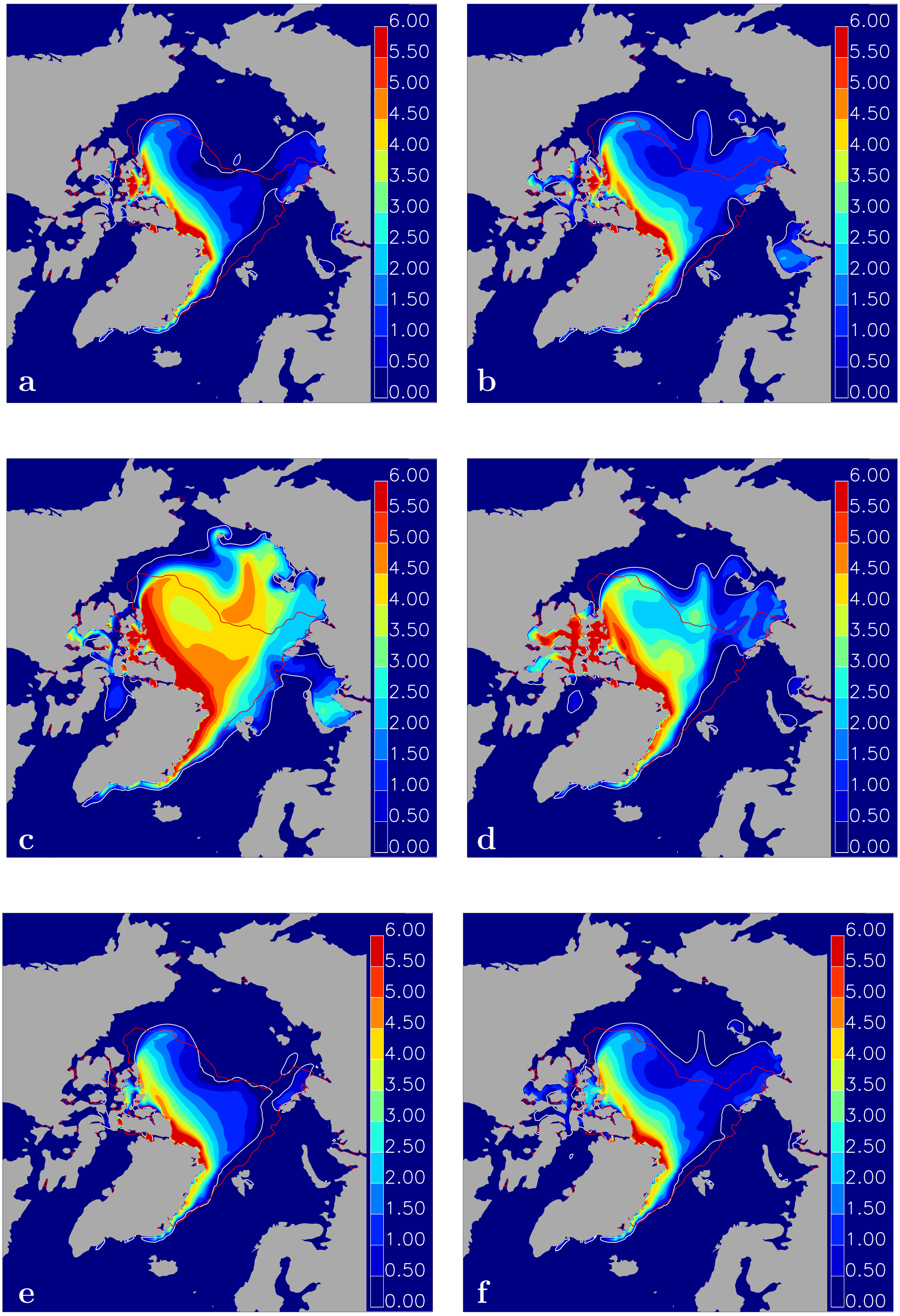

Figure 2: September 2007 snow depth (m) for the six simulations described in Table 1. The white line is the 15% ice concentration contour from the model, and the red line is the 15% concentration contour from passive microwave satellite data [2].

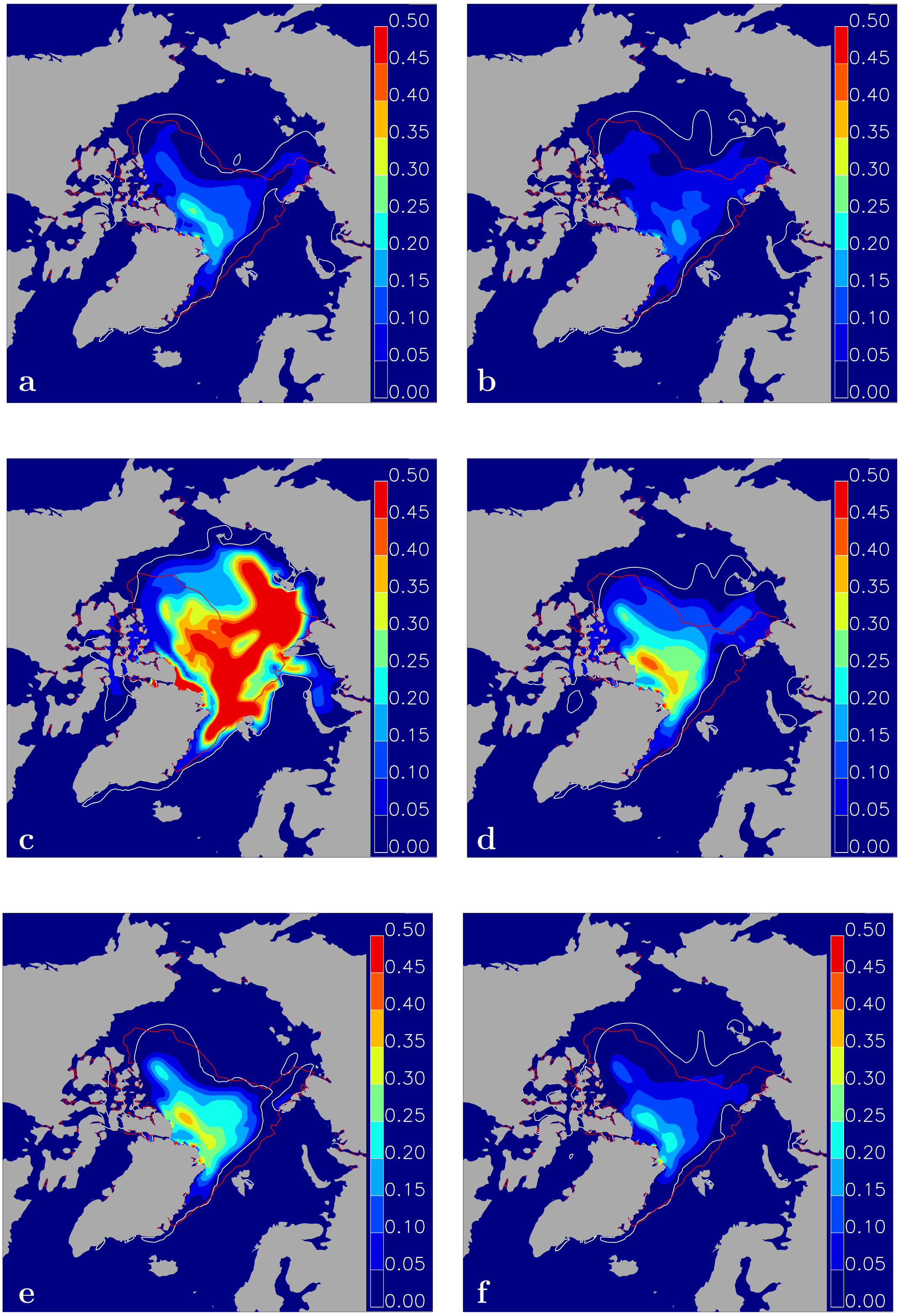

Figure 3: Radiatively-effective pond fraction for July 2007, from five simulations described in Table 1; the 'ccsm3' scheme does not include an explicit melt pond variable. By September 2007, ponds have drained in all simulations.