Advantages of the latest Los Alamos Sea-Ice Model (CICE): evaluation of the simulated spatiotemporal variation of Arctic sea ice

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ABSTRACT
The Los Alamos Sea-Ice Model (CICE) is one of the most popular sea-ice models. All versions of it have been the main sea-ice module coupled to climate system models. Therefore, evaluating their simulation capability is an important step in developing climate system models. Compared with observations and previous versions (CICE4.0 and CICE5.0), the advantages of CICE6.0 (the latest version) are analyzed in this paper. It is found that CICE6.0 has the minimum interannual errors, and the seasonal cycle it simulates is the most consistent with observations. CICE4.0 overestimates winter sea-ice and underestimates summer sea-ice severely. Meanwhile, the errors of CICE5.0 in winter are larger than for the other versions. The main attention is paid to the perennial ice and the seasonal ice. The spatial distribution of root-mean-square errors indicates that the simulated errors are distributed in the Atlantic sector and the outer Arctic. Both CICE4.0 and CICE5.0 underestimate the concentration of the perennial ice and overestimate that of the seasonal ice in these areas. Meanwhile, CICE6.0 solves this problem commendably. Moreover, the decadal trends it simulates are comparatively the best, especially in the central Arctic sea. The other versions underestimate the decadal trend of the perennial ice and overestimate that of the seasonal ice. In addition, an attempt is made to objectively describe the difference in the spatial distribution between the simulation and observation shows that CICE6.0 produces the best simulated spatial distribution.

1. Introduction
The rapidly changing Arctic sea-ice has caused widespread concern (Screen and Francis 2016). Maslanik et al. (2011) found that the reduction of the Arctic perennial ice area is more significant than the total sea-ice area. Moreover, there is a tendency that the perennial ice is turning into the seasonal ice (Comiso and Hall 2014). In this case, the decrease in the perennial ice and the increase in the seasonal ice will change the characteristics of Arctic sea-ice greatly (Hao, Su, and Huang 2015). More importantly, the positive feedback mechanisms involving snow and sea-ice will lead to an accelerated decline in sea-ice cover (Comiso 2012).

Given the difficulty to observe polar regions, numerical modeling is essential to understand sea-ice processes (Rousset et al. 2015). However, the simulated spatiotemporal variations of the sea-ice are still different from observations in some respects. McLaren et al. (2006) evaluated the sea-ice simulated by HadGEM1, and found that the HadGEM1 ice drift speeds tend to be greater than observed. Dorn, Dethloff, and Rinke...
(2012) pointed out that HIRHAM-NAOSIM cannot reasonably simulate the decreasing trend of the Arctic sea-ice cover in summer. Rouset et al. (2015) found that LIM3.6 overestimates the sea-ice in winter but severely underestimates it in summer.

The Los Alamos Sea-Ice Model (CICE), having the most complete physics parameterizations, is the most widely used sea-ice component model in coupled climate models (Wu, Zeng, and Bi 2015). The latest version of CICE was released in December 2018, being the 6th version of CICE. Compared with its predecessors (CICE4.0 and CICE5.0), it has more complex physics parameterizations. However, they are often accompanied by more uncertainties. Meanwhile, different physical parameterizations and the selection of parameters may cause great differences in the simulation (Stroeve et al. 2012; Urrego-Blanco et al. 2016). In this study, the main purpose is to verify the improvement from CICE4.0 and CICE5.0 to CICE 6.0. To this end, the model versions are evaluated in terms of their simulation of Arctic sea-ice, wherein the Arctic perennial ice and seasonal sea-ice are analyzed in particular detail.

2. Model, experiments, and data

CICE is a thermodynamic–dynamic sea-ice model developed by the Los Alamos National Laboratory. The main versions used most frequently are CICE4.0 and CICE5.0. However, recently, CICE6.0 was released. The physical parameterizations of these three versions are quite different (see Table 1 for details). In this study, we ran three experiments using the above three versions of CICE with the default settings (see Table 2 for details). The models were run for the years 1979–2009, and data between 1980 and 2009 were used for the analysis.

Atmospheric and oceanic forcing fields are used to drive the standalone CICE. The modified Common Ocean-Ice

Table 1. The main physical parameterizations in the three versions of the Los Alamos Sea-Ice Model.

| Physical parameterizations | CICE4.0 | CICE5.0 | CICE6.0 |
|---------------------------|---------|---------|---------|
| Thermodynamic             | Zero-layer (BL99) | Zero-layer (BL99) | Zero-layer (BL99) |
| Rheology                  | EVP | (Revised) EVP | EAP | EVP | (Revised) EVP |
| Melt pond                 | CESM | CESM | CESM | CESM | CESM |
| Biogeochemistry           | – | Skeletal Layer | Skeletal Layer | Skeletal Layer | Vertical BGC |
| Drag coefficients         | Constant | Constant | Constant | Constant | Constant |
| Seabed stress             | – | Parameterization | Revised Parameterization | Revised Parameterization |

Table 2. The main default settings in the three versions of the Los Alamos Sea-Ice Model.

| Physical parameterizations | CICE4.0 | CICE5.0 | CICE6.0 |
|---------------------------|---------|---------|---------|
| Number of zbgc layers     | –       | 1       | 5       |
| Number of EVP subcycles   | 120     | 120     | 240     |
| Snow porosity for brine height | 0     | 0.15   | 0.15   |
| Tuning parameter for snow  | –       | 0.5     | Parameterization |
| Thermodynamic              | BL99 | Mushy | Mushy |
| Melt pond                  | CESM | Level-ice | Level-ice |
| Biogeochemistry            | – | Skeletal Layer | Vertical BGC |
| Snow ice formation         | simple | Revised | Revised |
| Rheology                   | EVP | EVP | EVP |
| Drag coefficients          | Constant | Constant | Constant |

Reference Experiments, version 2, is applied for 10-m air temperature, specific humidity, wind components (all 6-hourly), daily downward radiation (longwave and shortwave) and monthly precipitation and snowfall. The monthly sea surface temperature comes from the ERA-Interim datasets. The monthly climatology of sea surface salinity is obtained from the World Ocean Atlas 2009 datasets. Also, the monthly sea near-surface velocity is taken from the Simple Ocean Data Assimilation datasets, version 2.2.4. All the variables are interpolated into a global 320 × 384 (1°) displaced polar grid. Meanwhile, the monthly sea-ice concentration data provided by National Snow and Ice Data Center, and the monthly sea-ice thickness from Pan-Arctic Ice Ocean Modeling and Assimilation System, are used as the observation data.

3. Evaluation of the model results

3.1 Temporal variation of sea ice

Figure 1(a,b) compare the temporal variation of the simulated Arctic sea-ice area with the observation. The annual averaged area of CICE6.0 is the closest to the observation (Figure 1(a)). Although that of CICE4.0 is also similar to the observation, it overestimates the sea ice in winter and severely underestimates it in summer (Figure 1(b)). In addition, through analyzing the seasonal cycle of the sea-ice area, we find that the simulated minimum sea-ice area is in August, not in September (Figure 1(b)). Meanwhile, their errors are different in each season. As mentioned above, the amplitude in CICE4.0 is larger than that in the other versions and the observation. Also, the errors of CICE5.0 in winter are comparatively the largest. Although CICE6.0 overestimates the sea-ice area in all seasons, the errors it simulates are smaller than in the other versions, especially in winter.

The sea-ice volume, determined by area and thickness, is one of the most important indicators to measure the ability of a sea-ice model. Figure 1(c,d) compare the temporal variation of the simulated Arctic sea-ice
volume with the observation. Generally, the three versions of CICE can all reasonably simulate the decreasing trend and the seasonal cycle of the sea-ice volume. Meanwhile, the sea-ice volumes of CICE5.0 and CICE6.0 are very similar. They both overestimate the ice volume, and CICE4.0 underestimates it.

As shown in Table 1, CICE6.0 introduces many new physical parameterizations, which can be divided into seven different areas: (1) thermodynamic, (2) rheology, (3) melt pond, (4) biogeochemistry, (5) drag coefficients, (6) seabed stress, and (7) snow-ice formation. Meanwhile, some studies have pointed out that the new physical parameterizations introduced in CICE6.0 can greatly improve the simulation of sea ice (Tsamados et al. 2015; Turner and Hunke 2015; Lemieux et al. 2016).

3.2 Perennial ice and seasonal ice

The simulation of the rapidly changing perennial ice and seasonal ice can demonstrate the ability of a sea-ice model. Ke et al. (2013) selected the sea-ice concentration when the sea-ice extent was smallest to study the perennial ice. Meanwhile, they stated that the seasonal ice is the sea-ice that reaches maximum cover in winter and melts during summer. We refer to their methods and obtain the concentration of the perennial ice and seasonal ice from the observation and the simulations. The perennial ice is mainly located in the central Arctic, and the seasonal ice mainly exists at the edge of the Arctic (Figure 2(a,e)). For the perennial ice, the spatial distribution simulated by CICE6.0 is highly consistent with the observation (Figure 2(d)), while CICE4.0 and CICE5.0 underestimate it, especially in the Atlantic sector (Figure 2(b,c)). For the seasonal ice, CICE4.0 and CICE5.0 overestimate it in the central Arctic and the outer Arctic (Okhotsk, Bering, Baffin Bay, and East Greenland seas) (Figure 2(f,g)). Fortunately, CICE6.0 solves this problem commendably (Figure 2(h)).

The root-mean-square error (RMSE) is introduced to quantify the differences between the observation and the simulations. The spatial distributions of RMSEs are shown in Figure 3. For the perennial ice, the large-value centers of RMSEs are mainly in the central Arctic (especially in the Atlantic sector), East Siberian Sea and Beaufort Sea, indicating the errors of the simulated perennial ice mainly occur in these sea areas (Figure 3(a–c)). Furthermore, the regionally averaged RMSEs for them are calculated to be 0.0945, 0.0867, and 0.0805. Obviously, the errors of CICE6.0 are smaller than in the other versions. For the seasonal ice, the large-value centers of RMSEs are mainly located in the central Arctic sea (especially in the Atlantic sector), and the outer Arctic,
representing the error centers of the simulated seasonal ice (Figure 3(d–f)). Meanwhile, the regionally averaged RMSEs for them are 0.1835, 0.1802 and 0.1266, respectively. Similar to the perennial ice, the errors of CICE6.0 are the smallest. To summarize, the errors of the perennial ice and seasonal ice simulated by CICE6.0 are smaller than in the other versions.

The interannual evolutions of the perennial ice area and seasonal ice area are shown in Figure 4(a,b). According to the observation, the perennial ice is
Figure 3. Spatial distribution of RMSEs for the (a–c) perennial ice and (d–f) seasonal ice: (a, d) CICE4.0; (b, e) CICE5.0; (c, f) CICE6.0.

Figure 4. Interannual evolution of the simulated (a) perennial ice area and (b) seasonal ice area (units: $10^6$ km$^2$) for the observation and the simulations from 1980 to 2009; and the interannual evolution of spatial RMSEs for the (c) perennial ice and (d) seasonal ice from 1980 to 2009 (black line: observations; green line: CICE4.0; blue line: CICE5.0; red line: CICE6.0).
decreasing notably, and the trend is \(-0.74 \times 10^6 \text{ km}^2\) per decade. Meanwhile, the trend of the seasonal ice is \(0.45 \times 10^6 \text{ km}^2\) per decade, showing rapid growth. The simulated trends are significantly different. For the perennial ice, the trend simulated by CICE6.0 (\(-0.71 \times 10^6 \text{ km}^2\) per decade) is the most similar to the observation, while CICE4.0 and CICE5.0 underestimate it (\(-0.58 \times 10^6 \text{ km}^2\) and \(-0.64 \times 10^6 \text{ km}^2\) per decade, respectively). On the other hand, CICE4.0 and CICE5.0 overestimate the trends of the seasonal ice (\(0.55 \times 10^6 \text{ km}^2\) and \(0.58 \times 10^6 \text{ km}^2\) per decade, respectively). Meanwhile, the trend of the seasonal ice simulated by CICE6.0 is \(0.41 \times 10^6 \text{ km}^2\) per decade, which is the nearest to the observation.

There are striking differences between the interannual trends in different Arctic sea areas (Table 3). According to the observation, the perennial ice in all sea areas is decreasing, and the maximum trend is \(-0.1819 \times 10^6 \text{ km}^2\) per decade, which is located in the central Arctic sea. Meanwhile, the seasonal ice in the Barents Sea, East Greenland Sea, Baffin Bay and Okhotsk Sea is decreasing too, and the trend in the Barents Sea is the maximum among all sea areas (\(-0.068 \times 10^6 \text{ km}^2\) per decade). However, it is increasing in other sea areas, and the maximum trend is \(0.1848 \times 10^6 \text{ km}^2\) per decade, which is located in the East Siberian Sea. Generally, the errors of the simulated trends mainly occur in the central Arctic sea, Laptev Sea, Beaufort Sea, Arctic Archipelago, Bering Sea and Okhotsk Sea. Meanwhile, the errors of CICE6.0 are the smallest, especially in the central Arctic Sea, Barents Sea, East Greenland Sea, Arctic Archipelago, and Okhotsk Sea.

Table 3. The interannual trend of the perennial ice and seasonal ice in different sea areas for the observation and the simulations (units: \(10^6 \text{ km}^2\) per decade).

| Sea area               | Sea ice | OBS  | CICE4.0 | CICE5.0 | CICE6.0 |
|------------------------|---------|------|---------|---------|---------|
| Central Arctic Sea     | perennial | -0.1819 | -0.3124 | -0.2812 | -0.1952 |
|                        | seasonal | 0.1534 | 0.3174 | 0.2967 | 0.2249 |
| East Siberian Sea      | perennial | -0.1698 | -0.1071 | -0.1141 | -0.0677 |
|                        | seasonal | 0.1848 | 0.1152 | 0.1226 | 0.0768 |
| Laptev Sea             | perennial | -0.0368 | 0.0125 | 0.0148 | 0.0067 |
|                        | seasonal | 0.0435 | -0.0142 | 0.0132 | 0.0063 |
| Kara Sea               | perennial | -0.0418 | -0.0164 | -0.0491 | -0.0541 |
|                        | seasonal | 0.0363 | 0.0198 | 0.0490 | 0.0555 |
| Barents Sea            | perennial | -0.0046 | -0.0015 | -0.0055 | -0.0049 |
|                        | seasonal | 0.0068 | -0.0193 | -0.0014 | 0.0109 |
| East Greenland Sea     | perennial | -0.0190 | -0.0003 | -0.0074 | -0.0086 |
|                        | seasonal | 0.0031 | 0.0042 | 0.0060 | 0.0058 |
| Baffin Bay             | perennial | -0.0057 | 0.0046 | 0.0070 | 0.0030 |
|                        | seasonal | 0.0036 | -0.0123 | -0.0207 | -0.0154 |
| Arctic Archipelago     | perennial | -0.0195 | 0.0011 | -0.0002 | -0.0022 |
|                        | seasonal | 0.0273 | 0.0010 | -0.0012 | -0.0009 |
| Beaufort Sea           | perennial | -0.1067 | -0.0511 | -0.0375 | -0.0237 |
|                        | seasonal | 0.1265 | 0.0569 | 0.0420 | 0.0236 |
| Chukotka Sea           | perennial | -0.1536 | -0.1173 | -0.1244 | -0.1075 |
|                        | seasonal | 0.1715 | 0.1182 | 0.1315 | 0.1137 |
| Bering Sea             | perennial | -0.0003 | -0.0198 | 0.0406 | 0.0391 |
|                        | seasonal | 0.0018 | 0.0146 | 0.0073 | 0.0213 |

Figure 4(c, d) and show the interannual evolution of spatial RMSEs for the three versions of CICE. Generally, the increases in spatial RMSEs indicate increasing model errors for CICE. For the perennial ice, the mean spatial RMSEs for CICE4.0 and CICE5.0 are 0.330 and 0.306, respectively. They are larger than that for CICE6.0 (0.284). For the seasonal ice, the mean spatial RMSEs for them are 0.331, 0.329, and 0.270. Obviously, the seasonal ice simulated by CICE6.0 is the most similar to the observation.

In order to objectively measure the differences in the spatial distribution between the simulation and the observation, we introduce an index, \(P\), including \(P_o\) and \(P_u\), which are, respectively, the ratios of the simulated ice areas that are overestimated and underestimated (Wu, Simmonds, and Budd 1997). The formulas are as follows:

\[
P_o = \frac{A_o}{A_{obs}} \times 100, \quad (1)
\]

\[
P_u = -\frac{A_u}{A_{obs}} \times 100, \quad (2)
\]

where \(A_{obs}\) is the total ice area from the observation (units: \(10^6 \text{ km}^2\)), \(A_o\) is the area that is covered by sea ice in the model but not in the observation (units: \(10^6 \text{ km}^2\)), and \(A_u\) is the area that is covered by ice in the observation but not in the simulation (units: \(10^6 \text{ km}^2\)). For the perennial ice, CICE6.0 overestimates it in the Pacific sector, which leads to the \(P_o\) of CICE6.0 being the largest, and CICE4.0 and CICE5.0 underestimate it in the Atlantic sector, leading to the absolute values of their \(P_o\) being more than for CICE6.0 (Figure 5(a,c)). Meanwhile, CICE4.0 and CICE5.0 overestimate the seasonal ice in the central Arctic and the outer Arctic, which leads to the \(P_o\) for them being more than for CICE6.0, and the absolute value of \(P_u\) of CICE6.0 is larger than in the other versions, which is mainly due to the low simulation of seasonal ice in the Pacific sector by CICE6.0 (Figure 5(b,d)). These conclusions are consistent with Figure 2.

### 4. Conclusions and discussion

In this study, three experiments were conducted to compare three versions of CICE. The results indicate the overall performance of CICE6.0 is better than for the other versions.

Generally, CICE6.0 has the smallest interannual errors, and the seasonal cycle it simulates is the most consistent with the observation. Meanwhile, CICE4.0 overestimates the sea ice in winter and severely underestimates it in summer, and the errors of CICE5.0 in winter are larger than in the other versions.
We focused on the simulated perennial ice and seasonal ice. Their errors are mainly located in the central Arctic sea (especially in the Atlantic sector), and the outer Arctic. Moreover, CICE4.0 and CICE5.0 underestimate the perennial ice and overestimate the seasonal ice in these areas. Meanwhile, CICE6.0 solves this problem commendably. The trends of the perennial ice and seasonal ice simulated by CICE6.0 are $-0.71 \times 10^6$ and $0.41 \times 10^6$ km$^2$ per decade, respectively, and are closest to the observation, especially in the central Arctic sea and the peripheral seas. CICE4.0 and CICE5.0 underestimate the trends of the perennial ice and overestimate the trends of the seasonal ice.

In this paper, we analyze the advantages of CICE6.0 in detail. This work plays a guiding role in using CICE6.0 in the future. Furthermore, we intend to further analyze the performance of CICE6.0 in climate system models and tune the main parameters in CICE6.0 through sensitivity analysis to improve it.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This research is supported jointly by the National Key R&D Program of China [grant numbers 2016YFA0602100 and 2018YFC1407104], the China Special Fund for Meteorological Research in the Public Interest [grant number GYHY201506011], and the National Natural Science Foundation of China [grant number 41975134].

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