THE EVALUATION OF THE EAST GREENLAND SEA ODDEN ICE FEATURE USING THE COMMUNITY CLIMATE SYSTEM MODEL 3.0 (CCSM 3.0)

Dissertation

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ABSTRACT

The Odden event is a dominant mode of the Arctic sea ice variability, which is very important for the Arctic climate. The Odden sea ice feature extends northeastward from the Arctic pack ice of the east Greenland Sea during winter and spring, typically covering an area between 8°W and 5°E, and between 73° and 77°N. The key causes and forcing of Odden sea ice variability in the atmosphere and ocean is examined using the Community Sea Ice Model5.0 (CSIM5) within a Slab Ocean Model (SOM) called the M configuration of Community Climate System Model3.0 (CCSM3) provided by the National Center for Atmospheric Research (NCAR). A 26 year control run is made with the T62 NCEP/NCAR Reanalysis (NNR) atmospheric data from 1979 – 2004, and the simulated northern Atlantic sea ice is compared with that from the Hadley Center Sea ice and Sea Surface Temperature (HadISST) observational dataset in order to evaluate the model’s capabilities. The control run sea ice data were subjected to a rotated principal component analysis (RPCA) that revealed a component (#3) mode of variability that exhibited Odden-like variability similar to that obtained in observational data.

To further investigate the single or multiple effects from the atmospheric and oceanic parameters associating with the Odden sea ice, 18 experiments are conducted with the NNR and a 1°×1° Simple Ocean Data Assimilation (SODA) for the atmospheric and oceanic forcing, respectively. In one set of experiments the atmosphere and ocean
model are run simultaneously in efforts to simulate the Odden while other experiments evaluate Odden forcing of individual atmospheric parameters with other parameter forcing being held in a non-Odden state. Model forcing data for Odden ice conditions are from 1997 (January – December) while those from 1994 are used as the forcing for non-Odden conditions, in keeping with observational studies. Results show that the model sea ice concentration (SIC) and ice thickness exhibit large variability in an area on the eastern end of the Odden region found in observational data. It does so particularly in response to air temperature and surface wind and ocean current forcing when the model output is averaged from February through April and May through July. The annual cycle of model parameter output shows that SIC peaks from March through May in experiments with full atmospheric forcing in the Odden and non-Odden years and where the ocean is held to climatological forcing. Parameters such as air temperature, overlying winds, longwave radiation, specific humidity and surface ocean currents make some of the larger contributions to SIC and ice thickness variations through the model year. At the time of peak model SIC and thickness (e.g., April, May) the wind forcing and that of surface currents appear to be larger than the SIC/thickness contribution by air temperature. In other words, the Odden mode in the model is mainly produced by dynamical effects of atmospheric winds and ocean currents.
DEDICATION

Dedicated to my parents
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CHAPTER 1: INTRODUCTION

The Nordic Seas (Greenland-Iceland-Norwegian Seas) lie in an area between Greenland, Iceland, Svalbard and Norway (Figure 1.1) from approximately 60° to 80°N, and 20°E to 20°W. The Nordic Seas include Fram Strait to the north, the Greenland Sea to the west, the Norwegian Sea, the Barents Sea on the east, and the Denmark Strait between the Greenland and Iceland on their southern boundary. Due to the distributions of continents and island, and the complex topography on the ocean floor that includes mid-ocean ridges, deep basins, continental shelves, and shelf margins (Schäfer et al. 2005), the ocean circulation system is mainly driven by the inflow of Polar Water (PW) from the north, and North Atlantic Water (NAW) from the south along the North Atlantic Current (NAC in Figure 1.1). PW is brought by a northerly current along the continental slope off East Greenland called the East Greenland Current (EGC) through Fram Strait from the Arctic Ocean (Figure 1.1). The EGC brings PW along the coast of East Greenland as far southwestward as Demark Strait. The southerly North Atlantic Current carries NAW northward along the Norwegian continental slope into the Nordic Seas. Due to the interactions of these two currents, the Nordic Seas have a complex oceanographic environment related to atmosphere and sea ice variability. The meteorological environment in the Nordic Seas is dominated by the variability of the atmospheric circulation, and mainly affected by the AO (Arctic Oscillation) and the NAO (North
Atlantic Oscillation) associated with the winter storm activity impacting the sea surface temperature (SST), surface air temperature (SAT), and sea level pressure (SLP) in this area (Rogers 1984; Rogers et al. 1998, 2004, 2005; Dickson et al. 2000; Hilmer and Jung 2000; Jung and Hilmer 2001; Rigor et al. 2002).

The Nordic Seas are a sea ice transition area connecting the Arctic Ocean and the Atlantic Ocean. Typically, the total ice extent of the Northern Hemisphere varies from
the maximum $15.2 \times 10^6$ km$^2$ in midwinter to its minimum $6.7 \times 10^6$ km$^2$ during summer. However, recent study shows that this sea ice cover has an overall negative trend with $-3.7 \pm 0.4\%$/decade in the yearly average (Parkinson and Cavalieri 2008) potentially reducing the ice flux into the Nordic Seas. One of the mechanisms of sea ice production in the Northern Atlantic is its export from the Arctic Ocean. The sea ice is advected by the EGC (Martin and Wadhams 1999; Toudal 1999; Toudal and Coon 2001) through Fram Strait, possibly forced by the atmospheric sea level pressure (SLP) features such as the NAO and AO and associated surface wind-driven forcing through Fram Strait into the Greenland Sea (Hilmer and Jung 2000; Jung and Hilmer 2001; Dickson et al. 2000; Rigor et al. 2002; Watanabe et al. 2006). The increasing sea ice fluxes through the Fram Strait can reach $39,000$ km$^2$, which agrees with model calculations from Harder et al. (1998).

Northern Atlantic sea ice is also produced in situ, in places in and along the EGC. The Odden ice formation is the key example of in situ ice formation, taking place associated with the Jan Mayen Current (JMC), which is an extension of the EGC in winter (Brandon and Wadhams 1999; Schäfer et al. 2001). The East Greenland sea ice also produces deep-water formation through vertical convection events (Roach et al. 1993; Schott et al. 1993; Budéus et al. 1998; Shuchman et al. 1998).

Changes of in northern Atlantic sea ice can have feedbacks to the climate system. One is through ice albedo variations. Sea ice albdeo ($0.7 \sim 0.9$) is much higher than that of seawater (Pegau et al. 2001; Perovich et al. 2007), so that it can reflect most of the incoming solar radiation back to space instead of being absorbed by the ocean. When sea ice cover decreases, the ocean absorbs more solar radiation and the surface warms up.
This causes more sea ice melting yielding more open water and absorption of more heat by the surface. Through this positive feedback process, the sea ice can turn on this self-reinforcing cycle to impact the Arctic and even global climate.

A second feedback of sea ice can change ocean circulation patterns. The southerly ocean current (e.g., NAC) brings warm and light water to the Nordic Seas. This water becomes cold and dense when sea ice forms and salt is rejected. The colder and denser water sinks into the deep ocean and pulls more NAC water into the area. This process drives an ocean conveyor belt called the global thermohaline circulation (THC). If the abnormally heavy sea ice variation occurs, it slows down the THC, slowing the vertical convective ocean mixing, and formation of deepwater (Saenko et al. 2004). The inhibited vertical mixing process also resists carbon dioxide on the surface and boundary layer, and raises its concentration on the surface that can rapidly build up the warming effect. Globally, decreasing the THC transport will weaken the function of ocean currents, which is the energy balance between tropics and arctic in the earth climate system. That delays the rate of heating in some regions, and might cause regional cooling for several decades although warming may still occur in other places on the planet.

The Odden feature in the East Greenland Sea is not only a place of in situ formation but one that also affects Northern Atlantic ice and ice albedo variability, as well as deep water formation through the sinking process driving the THC that balances the energy budget between tropics and Arctic. Therefore, the Odden sea ice feature is potentially an important key indicator of the Arctic and even global climate change. The Odden region is an important key indicator that might help to monitor the regional
climate interactions between high and mid latitude in the Northern Hemisphere
(Singarayer et al. 2005; Parkinson and Cavalieri 2008).

The goal of this dissertation is to investigate the Odden sea ice variability
response to the specific atmospheric and oceanic forcing by using the National Center for
Atmospheric Research (NCAR) Community Climate System Model 3.0 (CCSM3;
Collins et al. 2006; Drake et al. 2005). The research evaluates the critical physical
mechanisms affecting Odden sea ice, and attempts to improve our understanding of
linkages among the Greenland, the Greenland Sea, and the Labrador Sea. The work
applies CCSM3 to examine meteorological and oceanographic parameters to improve
understanding of the Odden and its environment. Chapter 2 is a review of literature
related to the Odden sea ice feature. The climate model, CCSM3, and the experimental
designed are described in chapters 3 and 4, respectively. Chapter 5 describes the results
while chapter 6 is discussion and conclusions.
CHAPTER 2: LITERATURE REVIEW

2.1 Overview and impacts

The Odden is a phenomenon in which sea ice extends northeastward from the Arctic pack ice of the East Greenland Sea during winter and spring. It is located on the eastern edge of the Greenland ice stream derived mostly from wind-driven motions of ice drifted out of the Arctic Ocean under the influence of the North Atlantic Oscillation (NAO), and the Arctic Oscillation (AO) (Hilmer et al. 1998; Hilmer and Jung 2000; Dickson et al. 2000; Rigor et al. 2002; Holland 2003; Watanabe et al. 2006). Figure 2.1 from Toudal et al. (1999) shows a typical Odden ice tongue extending northeastward into the Greenland Sea with its open water Nordbukta embayment to the west, separating the Odden from the East Greenland advected ice. The typical Odden region covers an area between 8°W and 5°E, and between 73 and 77°N (Shuchman et al. 1998). In some heavy years, the Odden ice simply bugles in one large mass from the Greenland ice stream eastward to 5°E. This sea ice feature can rapidly reach a maximum extent of 250,000 to 330,000 km² (Wadhams and Comiso 1999; Comiso et al. 2001; Shuchman et al. 1998), and shrink back to the east coast of Greenland in few days. An Odden sea ice time sequence is shown in Figure 2.2 (Comiso et al. 2001) for the winter of 1996 – 97. In this figure the period from January 25 to February 14 best illustrate the
eastward ice bulge in which Nordbukta is not evident, while Nordbukta is evident in images for March 1997.

The variability of the Odden sea ice is considered to be an important phenomenon affecting the salt and heat flux exchange in ocean convection (Budéus et al. 1998; Shuchman et al. 1998). This ocean vertical circulation plays an important role in transporting biological nutrients and changes in sedimentation distribution, so that the seasonal Odden sea ice variability impacts the long-term particle flux and other parts of the environment (Ramseier and Carrity 1999).

Figure 2.1: The position of the Odden ice edge on February 12, 1993, as observed from BAC 1-11 aircraft, compared with SSM/I concentration contours. Figure source is from Toudal et al. (1999).
The large scale ice cover in this area has been found to be a place where winter vertical convection occurs through the processes of sea water freezing and salt released into the ocean (Aagaard and Carmack 1989; Roach et al. 1993; Rudels 1990; Toudal and Coon 2001) that helps establish the large scale convective cells inducing the renewal of bottom water (Budéus et al. 1998).

Figure 2.2: The development of the sea ice concentration varies with time in the Odden area. Figure source is Comiso et al. (2001).
2.2 Physical processes associated with the Odden

Roach et al. (1993) monitored the seasonal and interannual sea ice distribution, development processes, and circulation of the upper ocean in the Greenland Sea during winter 1988 – 1989. Their results illustrated the processes of sea ice formation and decay in the upper layer of ocean. When the sea ice formed, the SST decreased below freezing point under subfreezing air temperature and strong northerly wind flow. Through this process, the salinity was increased (about 0.016 m d\(^{-1}\)), reducing the vertical stability of the upper water, and increasing the ambient convective overturning in December 1988, and January 1989. In late January, warmer entrainment water was mixed into the mid-depth of the ice-water boundary, heating the upper layer of water, and started the melting process from the bottom of the ice.

Excess fresh water discharge from the Arctic Ocean has been shown to play an important role during several heavy ice years on the East Greenland Sea, being associated with the Great Salinity Anomaly event (GSA; Dickson et al. 1988; Belkin et al. 1998; Belkin 2004) in the late 1960s (Aagaard and Carmack 1989; Deser et al. 2000). The Jan Mayen Current (JMC) flowing eastward out from the East Greenland Current (EGC) is another factor that has been associated with the Odden sea ice extension and retreat (Hurdle 1986; Bourke et al. 1992; Brandon and Wadhams 1999). The relative positions of the JMC, the EGC, and the Greenland are shown on Figure 1.1 (Schäfer 2001). The surface water in the JMC is relatively cold and fresh, making the sea water freeze. So, in the cold season, the position of the JMC is considered a driver of Odden sea ice variability. The investigation of the near surface hydrography beneath the Odden ice
tongue from Brandon and Wadhams (1999) also showed that the severity of a storm and the degree of haline stratification can make Odden ice envelop the Greenland Sea. Shuchman et al. (1998) used the satellite measurements, aircraft, and ship observations to analyze meteorological parameters connected with the Odden sea ice intraannual and interannual variability from 1978 to 1995. Their results suggest that the Odden sea ice will significantly advance when monthly surface air temperature (SAT) is below -8.7°C, while a moderate northwesterly wind, while temperatures above -6°C, with strong wind out of the south, can make the Odden sea ice decay.

Satellites with various instrument packages have been applied to analyze physical and radiative characteristics of Odden ice activity. Toudal et al. (1999) used three satellites with different instruments to trace the processes of Odden formation and decaying during 1978 – 1995. The first instrument is a passive microwave radiometer named the Special Sensor Microwave/Image (SSM/I) carried by U.S. Defense Meteorological Satellite Program satellites (DMSP). The SSM/I has seven channels, which can observe four wavelengths to study the time-series and large scale of the Odden sea ice variability. The Advanced Very High resolution Radiometer (AVHRR) part of a series of weather satellites operated by US National Oceanic and Atmospheric Administration (NOAA) is the second satellite instrument applied to analyze the Odden feature. Since AVHRR is designed for scanning the visible, near-infrared, and the thermal infrared part of the electromagnetic spectrum, this instrument can only evaluate the Odden sea ice under cloud free conditions. The third instrument carried by the ERS-1 satellite is called synthetic aperture radar (SAR). The images provided from the SAR are
independent of the cloud cover. Both of its low-resolution and high-precision images provide information helping understand the Odden spatial and temporal distribution. Their results found the correspondence between Odden ice variability and the monthly SAT anomalies at Jan Mayen Island back to the mid 1960s. This result implies that the SAT may be an indicator of the ice cover earlier in the century and supports results from Shuchman et al. (1998).

The seasonal variability of the Odden sea ice tongue and its environmental effects are also examined by Comiso et al. (2001). The results from their correlation analysis supports conclusions of Shuchman et al. (1998) and Toudal (1999), and pointed out that the Odden ice extent has strong negative correlation to the monthly SAT in Jan Mayen Island (-0.74) and the satellite retrieved temperature (-0.89), but is rarely correlated with the NAO (0.4), concluding that the Odden ice variability is not controlled by the NAO. Their results also showed that the daily and shorter timescale wind effect plays an important role in building the size and shape of the Odden sea ice feature, and sometimes initiating the formation of Nordbukta. Chasmer and LeDrew (2001) used principal component analysis (PCA) to study weekly interactions between the Odden sea ice concentration and the NAO. Their results showed -0.34 correlations with the Odden and the NAO on weekly time scales. Therefore, they concluded that, in some weeks or months, the negative mode of the NAO generally with colder SAT in the Greenland Sea would cause the sea ice to extend to the Greenland Sea (forming a peninsula). The positive mode of the NAO, associated with warmer SAT, limits the sea ice along the coast of the Greenland.
Wadhams and Comiso (1999) reported that there are two modes to the appearance of the Odden ice tongue. The first mode is called a thermodynamic Odden, which forms from November through all winter, retreating in May. This type of Odden ice is generated during cold air outbreaks, and changes the shape to a tongue, island, or bulge, due to surface wind stresses. This type of Odden occurs with high salt release, and triggers open water convection around it. The thermodynamic Odden appeared every year from 1978 through 1997 except in 1984, 1994, and 1995. Compared to the first mode, an advective Odden is mostly composed of older ice, and forced by the EGC. The second mode of the Odden forms in spring or summer such that thermodynamic conditions cannot support the growth of new ice, and has been observed only in 1978 and 1996.

Beside SAT, surface radiation flux, and cloud properties are among other important thermodynamic mechanisms that have been found to correspond with sea ice variability in the Greenland Sea and the subarctic areas (Deser et al. 2000; Francis et al. 2002, 2005; Wang and Jeffrey 2003, 2005; Gorodetskaya et al. 2008). Rogers and Hung (2008) expanded upon previous studies with Rotated Principle Component Analysis (RPCA; Horel 1981; Van den Dool 2007) of Arctic sea ice concentration (SIC) and evaluation of the meteorological, and radiative, forcing of the Odden using the Hadley Centre Sea Ice and Sea Surface Temperature data (HadISST; Rayner 2003), and as well as NCEP/NCAR Reanalysis data (NNR; Kalnay et al. 1996). The RPCA was used to determine the spatial distribution modes of SIC and associated time series variability. They found that sea ice variability in the Odden region is the second most important rotated SIC spatial variability pattern in the Atlantic Arctic (19.8% of the rotated variance). In their Odden
Figure 2.3: (a) The magnitude of the HadISST RPC4 winter spatial loadings of Atlantic Arctic 1951-2005 sea ice concentration (SIC) and (d) their time series. The January mid-January SIC in (b) 1969, and (c) 1997 (Rogers and Hung 2008).
pattern, the largest SIC variability occurs at 15°W and 5°E, and between 70° and 76°N, the center of the Odden sea ice region (Figure 2.3a). The Odden pattern exhibits out-of-phase sea ice variability with an area southwest of Svalbard and to the north of 75°N through Fram Strait, as well as in the Davis Strait/Labrador Sea area southwest of Greenland (Figure 2.3a; Rogers and Hung 2008). The characteristics of this mode are best represented by the heavy Odden events of 1969 and 1997 (Figure 2.3b and 2.3c). In the time series variability (Figure 2.3d; Rogers and Hung 2008), the positive scores of Odden RPC4 correspond to known extreme Odden years in 1979, 1982, 1986, 1989, 1997 and 1998 (based on Comiso et al. 2001, Plate 7; Shuchman et al. 1998, their Figure 3a, 3b). Rogers and Hung (2008) confirmed the roles of both westerly wind and low SAT in creating Odden sea ice. They showed the NAO correlation to Odden sea ice extent is -0.38, opposite in sign to that found by Comiso et al. (2001). Their wind field analysis agreed with the conclusions of Shuchman et al. (1998) and Comiso et al. (2001), that the negative/weak NAO mode is associated with a strong northerly (most maximum ~ 15 m s⁻¹) and westerly (most maximum ~ 10 m s⁻¹) anomalous flow over the Odden region that enhances ice formation. In contrast a strong NAO (deep Icelandic low) produces more easterly flow over the Odden region, reducing ice formation.
Table 2.1: Correlations between the winter Odden time series scores and NNR temperature, cloud, and flux parameters for the concurrent winter, and the preceding autumn and winter\(^a\) (Rogers and Hung 2008).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>DJF(_0)</th>
<th>SON(_{-1})</th>
<th>DJF(_{-1})</th>
<th>NAO1</th>
<th>DJF (_{1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Temperature</td>
<td>-0.79</td>
<td>-0.60</td>
<td>-0.47</td>
<td>+0.49</td>
<td>+0.46</td>
</tr>
<tr>
<td>Total Cloud</td>
<td>-0.69</td>
<td>-0.28</td>
<td>-0.32</td>
<td>+0.57</td>
<td>+0.24</td>
</tr>
<tr>
<td>Latent Heat Flux</td>
<td>-0.69</td>
<td>+0.24</td>
<td>-0.36</td>
<td>+0.30</td>
<td>+0.41</td>
</tr>
<tr>
<td>Sensible Heat Flux</td>
<td>-0.63</td>
<td>+0.38</td>
<td>-0.33</td>
<td>+0.20</td>
<td>+0.35</td>
</tr>
<tr>
<td>Downward LWF</td>
<td>-0.82</td>
<td>-0.56</td>
<td>-0.45</td>
<td>+0.54</td>
<td>+0.36</td>
</tr>
</tbody>
</table>

\(LWF = \text{longwave flux}, \text{SON}_{-1} = \text{autumn and DJF}_{-1} = \text{winter}\). NAO index coefficients are correlations with the concurrent parameter values during DJF\(_0\). Coefficients that are statistically significant with 95\% (99\%) confidence, after determining \(N_{\text{eff}}\) based on time series lag 1 autocorrelations (\(r_1\)) among winters (shown in the far right column), are indicated in bold (bold italics).

The correlations between Odden and the seasonally averaged radiative parameters from NNR include regional air temperature, total cloud latent/sensible heat fluxes, and downward longwave fluxes, along with the NAO index, were also evaluated by Rogers and Hung (2008). As shown in Table 2.1, all parameters have highly negative correlations with DJF Odden ice \((r < -0.63)\) indicating that in the concurrent winter (DJF\(_0\); column 1) temperatures, cloud, and fluxes are the low when Odden ice is high. Conversely, the anomalously strong Icelandic low increases the total cloud raising downward longwave flux, sensible/latent heat flux and air temperature near the surface and reduces the ice. In the preceding autumn (SON\(_{-1}\); column 2), the air temperature and downward longwave flux are also significantly correlated to DJF Odden ice extent while low positive correlations occur between latent heat and sensible heat fluxes and DJF Odden ice yield. This implies greater loss of heat from the ocean surface to the atmosphere in autumn leads to more ice in winter. According to their stepwise regression model evaluation, the highest \(r^2\) with the Odden time series occurs with a combination of
either downward longwave flux and latent heat flux or with longwave flux and sensible heat (both have $r^2 = 0.75$). The correlations of the NNR parameters with the NAO index are shown in column 4 of Table 2.1. The relatively high positive correlations shown in column 4 mean that positive NAO conditions bring warm and cloudy air into the Odden region reducing the ice while the negative mode would decrease clouds and temperature and increase the ice. It increases the total cloud cover (with $r = +0.57$), is associated with more downward longwave flux back to the surface (with $r = +0.54$), and tends to raise the air temperature near the surface (+0.49). Column 5 shows the lag 1 autocorrelation ($r_1$) representing significant winter-to-winter persistence in each parameter except cloud cover. This is consistent with results in column 3 (DJF$_1$) showing that flux, cloud, and air temperature from the preceding winter are also linked to current Odden ice conditions. Although Brandon and Wadhams (1999), and Rogers and Hung (2008) described the relationships between the Odden ice feature and the radiative fluxes variability, the detailed interactions between the Odden sea ice and radiative fluxes are still largely unknown. This dissertation conducts experiments using the CCSM3 to clarify the main factors affecting on sea ice variability in the Nordic Seas, especially in the Odden region, and their linkages with the global climate change.
3.1 Overview of CCSM3

The Community Climate System Model (CCSM; Blackmon et al. 2001) is a coupled global climate model that is primarily funded by the National Science Foundation (NSF) and the United States Department of Energy (DOE). This climate model was created, developed, and is maintained by the National Center for Atmospheric Research (NCAR). The CCSM is a fully coupled model composed of four separate component models simulating the earth’s atmosphere, ocean, land surface, and sea ice all integrated by the central coupler component (Figure 3.1). As one member of the Intergovernmental Panel on Climate Change (IPCC) models, CCSM is designed to study the continental-scale interannual and interdecadal variability of paleoclimate, and contribute the understanding of the relation between climate change and human activities. The newest official version is CCSM3 released on 23 June 2004 (Collins et al. 2006; Drake et al. 2005).
The first generation Climate System Model version 1 (CSM1) was released in 1996 (Boville and Gent 1998). This was followed by the second generation Community Climate System Model version 2 (CCSM2; Kiehal et al. 2004), released in 2002. CCSM2 largely improved the sea ice thickness distribution and thermodynamics in the sea ice model, and displaced the Northern Hemisphere pole onto the Greenland land mass so that the grid covers all the Arctic Ocean and sea ice areas, efficiently eliminating errors during the integration processes (see Figure 3.2). Although the products of CCSM2 have better simulations than those of CSM1, it still has systematic biases including a double ITCZ problem, overestimation of winter land temperature, problems with surface energy...
and cloud response with SST changes, and errors in tropical tropopause temperature and tropical variability. These problems have been improved in CCSM3. The energy, mass, total water, and freshwater in each component are conserved for the other components in the new CCSM3 system in enhancing the model physics and reducing and eliminating the biases produced in previous versions. The upgraded physical schemes include the new cloud process, aerosol radiative forcing, land-atmosphere fluxes, ocean mixed layer processes, and sea ice dynamics. These significant advancements improve simulations in sea ice thickness, polar radiation budgets, tropical SSTs, and cloud radiative effects, and provide more realistic simulations for evaluating past, present and future global climate. Based on the previous versions, the CCSM3 system has a “hub-and-spoke” structure, which is characterized by four individual component models connected with a coupler.

The CCSM3 atmosphere model is named the Community Atmosphere Model version 3 (CAM3; Collins et al. 2004, 2006) which is the fifth generation of the NCAR atmospheric GCM. CAM3 basically solves the six basic meteorological variables (i.e., surface pressure, zonal wind, meridional wind, temperature, moisture, and geopotential height) for six three-dimensional, time-dependent equations (the hydrostatics equation, two equations for horizontal motions, the thermodynamic, water vapor, and mass continuity equations). The physics schemes involved in CAM3 are radiation transport, convection, moist cloud processes, precipitation, and treatments of aerosols computed with physical parameterization schemes. In order to capably simulate the atmosphere, proficiently compute gradients, and reduce the computation times on a horizontal surface, CAM3 is designed to convert atmospheric fields to a wave form by running the Eulerian
spectral dynamical core with triangular spectral truncation at T31 ($3.75^\circ \times 3.75^\circ$), T41 ($2.8^\circ \times 2.8^\circ$), and T85 ($1.4^\circ \times 1.4^\circ$) configurations. It is also possible to run in Lagrangian coordinates with a finite-volume dynamical core (FV; Lin and Rood 1996; Lin 2004; Mirin and Sawyer 2005) with $2^\circ \times 2.5^\circ$ resolution, which is particularly advantageous for conservative transport of chemical

Figure 3.2: Low-resolution ocean/sea ice horizontal grid ($3^\circ \times 3^\circ$) from CCSM3 (Yeager et al. 2006).
tracers. The atmosphere model has 26 vertical levels (L26) with a hybrid terrain-following coordinate system, which has the pure sigma structure in the lowest layer up
through a hybrid sigma-pressure region and with a pure pressure region on the top above around 83mb (Figure 3.3). By using this system, the top of the vertical levels can reach a really pressure level less than approximately 2.2 hpa. For the time integration, CAM uses a three-level leapfrog scheme and the semi-implicit system to solve fast gravity waves in the transform domain.

The ocean component model is based on the Parallel Ocean Program version 1.4.3 (POP; Smith and Gent 2002) developed by the Los Alamos National Laboratory. POP is a level-coordinate ocean general circulation model, which considers depth as the vertical coordinate. This ocean model solves the three-dimensional primitive equations (i.e., momentum equations for two components, continuity equation, hydrostatic equation, equation of state, and tracer transport equation) for ocean dynamics. Compared to CCSM2, the solar radiation absorption in the upper ocean is more realistic and designed to be varied monthly and spatially depending upon in situ chlorophyll and satellite observations. Different from the atmosphere model, POP is operated under an orthogonal curvilinear coordinate system (Hunke and Dokuwicz 2002; Smith and Gent 2004; Drake et al. 2005; Collins et al. 2006), which relocates the northern pole onto Greenland and leaves a smooth, singularity-free grid in the Arctic Ocean (Figure 3.2; Yeager et al. 2006). Under this system, the model south pole still remains in the same location as the true South Pole in South Hemisphere. In the vertical dimensions, as an isopycnal ocean model (density as vertical coordinate; Drake et al. 2005), the POP has 40 levels associated with gx1v3, and 25 levels with gx3v5 horizontal coordinate system, respectively (Table 3.1). By using a higher order (quadratic) interpolation scheme in the
\( K \)-profile parameterization (KPP) of vertical mixing, it not only efficiently solves a problem in the boundary layer, but also expands the range from 10 m near the surface to 250 m in the deep ocean. A leapfrog time-step scheme is also adopted by the POP using a three-dimension solution for time integration.

The land surface component model in CCSM3 is called the Community Land Surface Model version 3 (CLM3; Oleson et al. 2004; Dickson et al. 2006). For coupling purposes, the integrations from CLM3 are able to offer surface albedos from visible and infrared wavebands, heat fluxes over the vegetated surfaces, and two component wind stresses for the requirements of the atmosphere component model. CLM3 applies a nested subgrid hierarchy of scales representing land units, soil or snow columns, and the land cover classification scheme with plant functional types (PFTs; Bonan et al. 2001; Oleson et al 2004). To approach more realistic simulation, PFTs in CLM3 are capable of sharing a single soil column with the effects of competition for water. This progress strengthens the ability of CLM3 to simulate leaf phenology, stomatal physiology and the hydrologic cycle in different environment conditions such as ecological differences among vegetation types, hydraulic and thermal differences among soil types. CLM3 is run on the same horizontal grid resolution as the atmosphere, but with 10 subsurface soil layers in the vertical dimension (listed in Table 3.1).

The sea ice simulations are integrated by running the Community Sea Ice Model version 5 (CSIM5; Briegleb et al. 2004), which is a dynamic-thermodynamic model released in 2004. CSIM5 can be operated coupled or uncoupled depending upon the user’s objectives. Besides running with the coupler and other active component models
(i.e., a fully coupled run), CSIM5 can be run and coupled with other components prescribed in a framework called Active Ice Only (AIO). Under the AIO framework, the sea ice component model is operated with a very simple mixed layer ocean model called the slab ocean model (SOM), which is simplified in such a way that the sea ice variability only responds to the heat flux transported from the ocean but without ocean currents or circulation effects. Since the sea ice model is a central part of this study, the detailed physics will be presented within the descriptions of the AIO framework and the M configuration of CCSM3 in section 3.3 below.

The coupler component model is designed for connecting and interacting with the four component models (atmosphere, land, sea ice, and ocean) of the CCSM system (Figure 3.1). Communications between each component are operated by the flux coupler version 6 (CPL6), which provides flux boundary conditions and exchanges physical state information to each model in a completely asynchronous manner. The coupler requires two libraries, the Model Coupling Toolkit (MCT; Craig et al. 2005; Darke et al. 2005; Jacob et al. 2005; Larson et al. 2005) and the Multi-Program Handshaking (MPH; Darke et al. 2005; He and Ding 2005, 2006), which works on the flux exchange and the data mapping in the different gridding systems. This framework yields the CCSM system structured by four separated components, and forces them to communicate with each other through the coupler. The coupler can modulate, decompose, and isolate each component model in the CCSM system. This modularity gives CCSM users a choice of many model configurations to customize the model for the different applications in the different computer architectures.
For the flux intercalculations between components, the coupler provides an appropriate boundary condition and a surface interface for all component models to exchange fluxes, which are then conserved and quantized. To avoid the double-computing of the flux, the coupler monitors that a flux field be computed only once, in one component, and confirms that the flux be computed in the most desirable place. Due to the different physical properties between atmosphere and ocean, the time to reach equilibrium is much longer for the ocean than for the atmosphere. The coupler has to arbitrarily choose different internal time steps for each component model, and controls the execution and time evolution of the system by synchronizing and controlling the data flow interacted between the different components. For the spatial grids,

<table>
<thead>
<tr>
<th>Component</th>
<th>Resolution</th>
<th>Lon.×Lat.</th>
<th>Transform Grids</th>
<th>Vertical Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>atmosphere, land</td>
<td>T85</td>
<td>256 × 128</td>
<td>1.4° × 1.4°</td>
<td>26 for atmosphere</td>
</tr>
<tr>
<td></td>
<td>T42</td>
<td>128 × 64</td>
<td>2.8° × 2.8°</td>
<td>10 for land</td>
</tr>
<tr>
<td></td>
<td>T31</td>
<td>96 × 48</td>
<td>3.75° × 3.75°</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2 × 2.5</td>
<td>144 × 91</td>
<td>2.5° × 1.978°</td>
<td></td>
</tr>
<tr>
<td></td>
<td>T62</td>
<td>192 × 94</td>
<td>1.875° × 1.91°</td>
<td></td>
</tr>
<tr>
<td>ocean, ice</td>
<td>gx1v3</td>
<td>320 × 384</td>
<td>1° × 1°</td>
<td>40 for ocean</td>
</tr>
<tr>
<td></td>
<td>gx3v5</td>
<td>100 × 116</td>
<td>3° × 3°</td>
<td>25 for ocean</td>
</tr>
</tbody>
</table>

Table 3.1: The resolutions for each component of CCSM3.
Model Component Descriptions

<table>
<thead>
<tr>
<th>Model</th>
<th>Component</th>
<th>Descriptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atmosphere</td>
<td>cam3</td>
<td>Fully active atmospheric model</td>
</tr>
<tr>
<td></td>
<td>datm6</td>
<td>Standard data atmospheric model</td>
</tr>
<tr>
<td></td>
<td>latm6</td>
<td>Climatological-data atm model</td>
</tr>
<tr>
<td></td>
<td>xatm</td>
<td>Dead atmospheric mode</td>
</tr>
<tr>
<td>Land</td>
<td>clm3</td>
<td>Fully active land model</td>
</tr>
<tr>
<td></td>
<td>dlnd6</td>
<td>Standard data land model</td>
</tr>
<tr>
<td></td>
<td>xlnd</td>
<td>Dead land model</td>
</tr>
<tr>
<td>Ocean</td>
<td>pop</td>
<td>Fully active ocean model</td>
</tr>
<tr>
<td></td>
<td>docn6</td>
<td>Standard data ocean model</td>
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<tr>
<td></td>
<td>xocn</td>
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<tr>
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<td>xice</td>
<td>Dead ice model</td>
</tr>
<tr>
<td>Coupler</td>
<td>cpl6</td>
<td>Coupler</td>
</tr>
</tbody>
</table>

Table 3.2: The components of each geophysical model and their descriptions in CCSM3.

CCMS3 requires that atmosphere and land components be on the same spatial grid (T85, T42, T62, T31, and 2 × 2.5), and ocean and sea ice components be on the same spatial gird (gx1v3, and gx3v5) shown in Table 3.1. The coupler can handle the different component models to integrate on different spatial grids for any purpose.

In order to apply CCSM3 to specific applications in different fields of study, the four dynamical CCSM3 models are designed to use “active”, “data”, or “dead” components when running “plug and play” combinations. The descriptions and abbreviations of the model components with the versions are shown in Table 3.2. The CCSM3 can be alternatively used with many different combinations for different scientific purposes. Although CCSM3 has officially supported several component
combinations (Table 3.3), the users can also manually define their own component set (or called configuration) for the “out of the box” applications.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>atmosphere</th>
<th>land</th>
<th>ocean</th>
<th>ice</th>
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<td>pop</td>
<td>dice</td>
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</tr>
<tr>
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<td>docn</td>
<td>csim</td>
<td>cpl</td>
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<td>pop</td>
<td>csim</td>
<td>cpl</td>
</tr>
<tr>
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<td>docn</td>
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<td>dice</td>
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</tr>
<tr>
<td>X</td>
<td>xatm</td>
<td>xlnrd</td>
<td>xcon</td>
<td>xice</td>
<td>xpl</td>
</tr>
</tbody>
</table>

Table 3.3: The officially supported component set (configuration) from CCSM3. *csim: Sea ice model is with mixed layer ocean model.

3.2 The M Configuration – Active Ice Only (AIO) framework

To examine the key forcing of Odden sea ice variability in the atmosphere and ocean, the experiments conducted will use the M configuration. The main purpose of running CCSM3 under the M configuration is to see the responses of the active sea ice model to the prescribed input data periodically contributed from the data models containing atmosphere, land surface, and ocean components. In the M configuration, CSIM5 is operated with data-cycling models of the atmosphere, land, and ocean components, which function to provide the prescribed variables for sea ice simulations. All components are interacted with the coupler component. Additionally, this sea ice
model within a mixed layer ocean model is an active model, which is different from the other components under this configuration. The mixed layer ocean model called Slab Ocean Model (SOM) only limits sea ice variability by affecting the ocean mixed layer temperature. The detail of each component model in the M configuration is specified in the following sections.

3.2.1 The CCSM Observational Data Atmosphere Model (latm)

The atmosphere component model in the M configuration is the Observation Data Atmosphere Model (latm) version 6.0. As in an active model, the latm is connected and interacts with the coupler. However, it only provides the input climatological or time averaged observational data cycled through continuously, and ignores any data sent back from the coupler. The input data sets must have the same spatial resolution, but it is not necessary to have the same temporal resolution. The latm uses NCEP/NCAR Reanalysis data as input forcing files. The three forcing streams provided from the latm are atmospheric states, precipitation, and radiation. The variables of atmospheric state are zonal and meridional 10m winds, surface 2m (extrapolated to 10m) air temperature, specific humidity, and density. The radiation data include longwave down, shortwave down and shortwave up. Since the latm is a data forcing model, it must be run with land, sea ice, and ocean components with the coupler (Figure 3.1).
3.2.2 The CCSM Climatological Data Ocean Model (docn)

The data ocean model is called the Climatological Data Ocean Model (docn) version 6.0, like the other data models, functions as an ocean component within a CCSM configuration and interacts with the coupler. This data ocean model can only contribute either climatological SST or a time series of multi-year data through the coupler to the other components, but ignores data coming back from the coupler. The SST data include an annual SST (12 months of climatological dataset) and a multiyear SST (monthly data spanning more than one year). The dcon only plays a role in providing the prescribed SST in the initial time step. Following the integration forward in time, SST will be fed to it from the calculations made in the SOM from sea ice model.

3.2.3 The CCSM Climatological Data Land Model (dlnd)

The land surface component run in the M configuration is the Climatological Data Land Model (dlnd) version 6.0 that is connected to the coupler and operated as the land component in a CCSM configuration. The dlnd gives the mean monthly data contributed from an active CCSM land model. Being a data model, the dlnd must be incorporated with the atmosphere, ocean, sea ice, and the coupler component in the full CCSM system (Figure 3.1).
3.3 The Community Sea Ice Model (CSIM) with Slab Ocean Model (SOM)

3.3.1 Overview of the Community Sea Ice Model (CSIM)

The sea ice component is the only active model in the M configuration of CCSM3. Based on the Los Alamos CICE model, CSIM5 employs an elastic-viscous-plastic (EVP; Hunke and Lipscomb 1997 2002) rheology to capture the sea ice response to the dynamic mechanism (e.g., wind forcing), and uses an energy conserving thermodynamic scheme designed by Bitz and Lipscomb (1999) to describe the thermodynamic processes of sea ice growth and decay. For the sea ice distribution, CSIM5 uses a linear incremental remapping scheme (Lipscomb and Hunke 2004) to evaluate horizontal sea ice advection. In using a Lagrangian ice thickness distribution algorithm (Thorndike et al. 1975; Bitz and Lipscomb 1999), CSIM5 can group sea ice for five ice and one open water category within each grid cell. These enhance the ice thickness simulation in flux exchange under different surface conditions over each category. The model includes linear remapping for thickness spatial distribution (Lipscomb 2001), mechanical redistribution for rafting and ridging (Hibler 1980), ice strength computed from energetics (Rothrock 1975), lateral and bottom melt processes (McPhee 1992), second order horizontal advection using an incremental remapping scheme developed from Lipscomb and Hunke (2004) and an albedo parameterization with implicit melt ponds. CSIM5 uses two-dimensional domain decomposition and time split thermodynamics and dynamics for efficient parallel performance. Compared to previous version, CSIM5 is well vectorized for efficient performance. The code is written
by standard parallel and Fortran 90 running in different architectures (Briegleb et al. 2004; Drake et al. 2005; Collins et al. 2006).

### 3.3.2 State variables

CSIM5 uses seven state variables to present sea ice activity. The variables are sea ice area, volume, velocity and internal energy, snow volume, surface temperature of snow/ice, and stress tensor components listed in Table 3.4. Subscript \( n \), \( \{ n = 0, 1, 2, \ldots N \} \) refers to the \( n^{th} \) ice thickness (\( n = 0 \) is open water), where \( N \) is the total number of categories. For CSIM5, the default \( N = 5 \). Subscript \( l \), \( \{ l = 1, \ldots L \} \) refers to vertical level, with \( L = 4 \). For each category, ice thickness \( (h_n = \sum_{l=1}^{L} V_{nl}/A_n) \) lies within constant category thickness limits. Ice velocity \( \mathbf{u} \) and the associated stress tensor \( \sigma \) (components \( i=1, 2; j=1, 2 \)) are not resolved across the ice thickness distribution.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>( A_n )</td>
<td>Sea ice area (fraction)</td>
<td>0 ~ 1</td>
</tr>
<tr>
<td>( V_{nl} )</td>
<td>Sea ice volume</td>
<td>m(^3) m(^{-2})</td>
</tr>
<tr>
<td>( E_{nl} )</td>
<td>Sea ice internal energy</td>
<td>J m(^{-2})</td>
</tr>
<tr>
<td>( V_{sn} )</td>
<td>Snow volume</td>
<td>m(^3) m(^{-2})</td>
</tr>
<tr>
<td>( T_{sn} )</td>
<td>Surface temperature of snow/ice</td>
<td>°C</td>
</tr>
<tr>
<td>( \mathbf{u} )</td>
<td>Sea ice velocity</td>
<td>m s(^{-1})</td>
</tr>
<tr>
<td>( \sigma_{ij} )</td>
<td>Stress tensor components</td>
<td>N m(^{-1})</td>
</tr>
</tbody>
</table>

Table 3.4: The state variables are used in CSIM5.
3.3.3 Fundamental equations

The goal of the fundamental equations is to determine the spatial and temporal evolution of the state variables in CSIM5. Many properties of sea ice depend on ice thickness (Thorndike et al. 1975); for example, ice compressive strength, growth rate, surface temperature, turbulent and radiative flux exchange with the atmosphere. The thickness can be described by accretion and ablation against lead opening and ridging of ice (Thorndike et al. 1975). Formally, the thickness distribution is described by the distribution function \( g(h,x,t) \), where \( h \) is ice thickness (hereafter we suppress the explicit space and time dependence). The evolution of \( g \) is governed by the distribution equation:

\[
\frac{\partial g}{\partial t} = -\frac{\partial}{\partial h}(\dot{h}g) + L(h,g) - \nabla \cdot (ug) + R(h,g,u) \tag{3.3.3.1}
\]

where \( \dot{h} \) is the rate of change in ice thickness due to vertical thermodynamic process, \(-\frac{\partial}{\partial h}(\dot{h}g)\) is the change in distribution due to thickness space transport, \( L(h,g) \) is the change in distribution due to lateral melt/formation processes, \(-\nabla \cdot (ug)\) is the change in distribution due to horizontal advection (\( \nabla \) is the horizontal gradient operator and \( u \) is the velocity field over the thickness distribution), and \( R(h,g,u) \) is a redistribution function due to rafting and ridging processes.

To solve Equation: 3.3.3.1, a discrete set of \( N \) ice categories is assumed, delimited by the thickness \( h^*_n \), \( \{n = 0, 1, 2, \ldots N\} \) for which \( h^*_0 = 0 \). Thus, Equation 3.3.3.1 is
integrated over the thickness limits for each category, resulting in a discrete set of N equations to be solved for ice fraction in each category n:

\[ A_n = \int_{h_{n-1}}^{h_n} g(h) dh \]  

(3.3.3.2)

where the total (aggregate) ice fraction \( A = \sum_{n=1}^{N} A_n \).

Hibler (1980), and Flato and Hibler (1995) developed a method to solve Equation 3.3.3.1. The thickness is assumed to be distributed uniformly within each category resulting in Eulerian advection in thickness space due to sea ice growth and melt processes. Such advection is very diffusive unless a large number of categories are employed. Another Lagrangian method was developed by Thorndik et al. 1975. In this method, ice is free from the diffusion of the Eulerian thickness advection, allowing for a smaller number of categories, as well as the resolution of the vertical temperature profile in snow and ice (Bitz et al. 2001). It is used here for the present sea ice model, except for the linear remapping which uses a combination of both Eulerian and Lagrangian methods. Thus, fundamental equations for the present sea ice model start with the discrete form of Equation 3.3.3.1 are as follows.

Sea ice fraction \( (A_n) \) is

\[
\frac{\partial A_n}{\partial t} = S_{Tn} - \nabla \cdot (u A_n) + S_{Mn} \quad (n = 1, 2, \ldots 5). 
\]  

(3.3.3.3)
Sea ice volume \((V_n)\) is

\[
\frac{\partial V_n}{\partial t} = \nabla \cdot (u V_n) + S_{MVn} \quad (n = 1, 2, \ldots 5). \tag{3.3.3.4}
\]

where terms \(S_T\) denote sources/sinks due to thermodynamic processes and thickness space transport, while terms \(S_M\) denote sources/sinks due to mechanical redistribution. The sea ice thickness \(h_n\) is derived from the fraction and volume as \(h_n = V_n/A_n\).

The ice internal energy \(E_n\) (vertically varying) is

\[
\frac{\partial E_n}{\partial t} = \nabla \cdot (u E_n) + S_{ME_n} \quad (n = 1, 2, \ldots 5). \tag{3.3.3.5}
\]

Snow volume \((V_{sn})\) is

\[
\frac{\partial V_{sn}}{\partial t} = \nabla \cdot (u V_{sn}) + S_{MVsn} \quad (n = 1, 2, \ldots 5). \tag{3.3.3.6}
\]

Surface temperature \((T_{sn})\) is

\[
\frac{\partial T_{sn}}{\partial t} = \nabla \cdot (u A_{sn} T_{sn}) + S_{MTsn} \quad (n = 1, 2, \ldots 5). \tag{3.3.3.7}
\]

Sea ice velocity \((u)\) is
\[
\frac{\hat{m}}{\hat{t}} \frac{\partial u}{\partial t} = -\hat{m} f k \times u + \tau_a + \tau_o + \hat{m} g_e \nabla H_o + \nabla \cdot \sigma
\]  

(3.3.3.8)

where \( \hat{m} = \rho_s \sum_{n=1}^{N} V_{sn} + \rho_i \sum_{n=1}^{N} V_{in} \), the non-linear \( u \) advection terms are ignored as they are negligibly small when the equations are scaled, \( f \) is the Coriolis parameter, \( k \) is the local vertical unit vector, \( \tau_a + \tau_o \) are air and water stress respectively, \( g_e \) is the gravitational acceleration, \( H_o \) is the sea surface height and \( \nabla \cdot \sigma \) is the force per unit area due to internal ice stress, where \( \sigma \) is the stress tensor.

The stress tensor \( (\sigma_{ij}) \) is

\[
\frac{\partial \sigma_{ij}}{\partial t} + \frac{e^2}{2T_{ew}} \sigma_{ij} + \frac{1-e^2}{4T_{ew}} \sigma_{kk} \delta_{ij} = \frac{P}{2T_{ew}} \Delta' \hat{\varepsilon}_{ij} - \frac{P}{4T_{ew}} \delta_{ij}
\]  

(3.3.3.9)

where \((i,j = 1,2)\) refer to the four components of the stress tensor, \( e \) is a constant ratio of the major to minor axes or the elliptical yield curve, \( T_{ew} \) is a damping time scale for elastic waves, \( \delta_{ij} \) is the Kronecker delta. \( P \) is the ice compressive strength (or mechanical pressure, a function of the thickness distribution), \( \hat{\varepsilon}_{ij} \) is the rate of strain tensor, in turn a function of velocity gradient, and \( \Delta' \) is a function of the rate of strain tensor.

3.3.4 Parameterizations

The model calculations in CSIM5 can be generally separated into ice thermodynamic and dynamic parameterizations. The thermodynamic calculations focus
on the ice thickness and ice temperature structure based on energy conservation. For the
ice thermodynamic calculations, the ice thickness distribution (ITD) is the first physics
parameterization in CSIM5. Based on the category limit formula of Lipscomb (2001), the
number of ice thickness categories N is set to 5. The detail of each category is shown in
Table 3.5 (Briegleb et al. 2004). Beside ITD, the ice thermal properties, snow and ice
albedo feedbacks (Curry et al. 1995; Ebert and Curry 1993) are also included in CSIM5.
CSIM5 parameterizes flux exchange between ice and atmosphere, and comprehensively
describes the forcing and flux interactions between CSIM5 and the coupler. In order to
represent vertical heat transfer through ice in different surface boundary conditions,
CSIM5 follows the method developed by Maykut and Untersteiner (1971) and Bitz and
Lipscomb (1999) that solves the vertical heat conduction through four ice layers under
four different surface cases based on presence or absence of snow, and whether melting
or no-melting conditions pertain (Table 3.6; Briegleb et al. 2004). The CSIM5
parameterizations also contain thickness changes dealing with top, bottom and snow-to-ice
cconversion, lateral formation with side and bottom melt fluxes, and linear remapping
for thickness space transport depending upon the different thermodynamic conditions.

The goal of the dynamic calculations is to determine the motion of ice basically
under momentum conservation considerations. For ice dynamic calculations, the elastic-
viscous-plastic (EVP) rheology (Hunke and Dukowica 1997) combines the viscous-plastic

<table>
<thead>
<tr>
<th>n</th>
<th>Range (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Snow Accumulated</td>
</tr>
<tr>
<td>---</td>
<td>-----------------</td>
</tr>
<tr>
<td>Case I</td>
<td>Yes</td>
</tr>
<tr>
<td>Case II</td>
<td>No</td>
</tr>
<tr>
<td>Case III</td>
<td>Yes</td>
</tr>
<tr>
<td>Case IV</td>
<td>No</td>
</tr>
</tbody>
</table>

Table 3.6: Top surface boundary cases (Briegleb et al. 2004)

rheology (VP; Hibler 1979; Kreyscher et al. 2000) with the elastic wave mechanism to calculate the ice velocity in CSIM5. The EVP rheology derived from the simple stress-strain relation can improve the sea ice response to the forcing on both short and long timescales, and makes the computing process more efficient. For the horizontal advection evaluation, CSIM5 applies an incremental remapping algorithm from Lipscomb and Hunke (2004) to quantify the advection equation:

\[
\frac{dh}{dt} = \frac{\partial h}{\partial t} + u \cdot \nabla h = 0 , \text{ where } h \text{ is a tracer.}
\]

To reconstruct area and tracer fields, values of ice area and tracer fields are given in each grid cell in the first step. The algorithm generates linear approximations and limits the field gradients to preserve monotonicity. Through the second step, locating departure triangles, ice velocities are produced at grid cell corners. The algorithm identifies
departure regions for the transports across each cell edge, and then divides these departure regions into triangles and computes the coordinates of the triangle. In the third step, the remapping processes begin the integration of ice transports by integrating these fields over the departure triangles to obtain the area, volume, and energy transports across each cell edge. By updating state variables in the last step, the algorithm will transfer the above quantities across cell edges, update the state variables and complete the remapping calculation processes.

The mechanical redistribution of sea ice thickness due to rafting and ridging processes also belongs to the ice dynamic calculations. Based on Thorndike et al. (1975), the mechanical redistribution considers two aspects, (i) the relation between the distribution function and the deformation/compressive strength used in the ice dynamics, and (ii) the redistribution source terms in the conservation equations. After development by Hopkins and Hibler (1991), Flato and Hibler (1995) and Bitz et al. (2001), this method has been optimized for the modeling of sea ice thickness variability.

3.3.5 Boundary conditions and solution

The boundary conditions in CSIM5, described in this subsection, are taken form the CSIM5 scientific description from NCAR Technical Report NCAR/TN-463+STR (Briegleb et al. 2004). The boundary conditions in CSIM5 are represented vertically by atmospheric/oceanic forcing from the coupler, consisting of states and interfacial fluxes summarized in Table 3.7, and horizontally by no-slip $u \rightarrow 0$ along coastlines and $u \rightarrow u_o$ (ocean surface current) on the open ocean edge. The fundamental equations are solved
subject to these boundary conditions, and selected states along with atmosphere and ocean fluxes are returned to the coupler as listed in Table 3.8.
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$z_a$</td>
<td>reference height</td>
<td>m</td>
</tr>
<tr>
<td>$u_a$</td>
<td>x direction wind speed at $z_a$</td>
<td>m s$^{-1}$</td>
</tr>
<tr>
<td>$v_a$</td>
<td>y direction wind speed at $z_a$</td>
<td>m s$^{-1}$</td>
</tr>
<tr>
<td>$\theta_a$</td>
<td>potential temperature at at $z_a$</td>
<td>K</td>
</tr>
<tr>
<td>$T_a$</td>
<td>air temperature at $z_a$</td>
<td>K</td>
</tr>
<tr>
<td>$q_a$</td>
<td>Specific humidity at $z_a$</td>
<td>kg kg$^{-1}$</td>
</tr>
<tr>
<td>$\rho_a$</td>
<td>air density at $z_a$</td>
<td>kg m$^{-3}$</td>
</tr>
</tbody>
</table>

**Atmospheric States**

**Atmosphere ==> Sea Ice Fluxes (+ downwards)**

- $F_{SW_{vd}}$ direct, visible downwelling shortwave $\text{W m}^{-2}$
- $F_{SW_{vsf}}$ diffuse, visible downwelling shortwave $\text{W m}^{-2}$
- $F_{SW_{nidr}}$ direct, near infrared downwelling shortwave $\text{W m}^{-2}$
- $F_{SW_{nidf}}$ diffuse, near infrared downwelling shortwave $\text{W m}^{-2}$
- $F_{LW_{DN}}$ downwelling longwave $\text{W m}^{-2}$
- $F_{RN}$ water flux due to rain $\text{kg m}^{-2} \text{s}^{-1}$
- $F_{SNW}$ water flux due to snow (liquid equivalent) $\text{kg m}^{-2} \text{s}^{-1}$

**Ocean States**

- $T_{ocn}$ sea surface temperature $\text{K}$
- $S_{ocn}$ sea surface salinity ppt
- $u_o$ x direction ocean surface current $\text{m s}^{-1}$
- $v_o$ y direction ocean surface current $\text{m s}^{-1}$
- $(\nabla H_o)_x$ x direction sea surface slope $\text{m m}^{-1}$
- $(\nabla H_o)_y$ y direction sea surface slope $\text{m m}^{-1}$

**Ocean ==> Sea Ice Fluxes (+ downwards)**

- $F_{Qoi}$ Freezing/melting potential $\text{W m}^{-2}$

Table 3.7: State variables and forcing received by sea ice model from the coupler (Briegleb et al. 2004; Schramm et al. 2004).

Based on the ice state, snow/ice directional and spectral albedos $\alpha_{vd}$, $\alpha_{vsf}$, $\alpha_{nid}$, $\alpha_{nidf}$ are evaluated, and used to compute the total absorbed shortwave in the ice $F_{SW}$. Of this total a portion $I_{SW}$ penetrates below the surface and is either internally absorbed in the ice $Q_{SW}$ or penetrates or the ocean below as $F_{SWo}$. The new longwave flux at the surface $F_{LW}$ is the difference the upwelling longwave $F_{LW_{UP}}$ and the absorbed downwelling longwave. The upwelling longwave is given by the surface emission $\varepsilon \sigma_{sb} T_s^4$ (where $\varepsilon$ is
the snow/ice longwave emissivity and $\sigma_{sb}$ is the Stefan-Boltzmann constant) and the reflection of downwelling longwave $(1 - \varepsilon)F_{LWDN}$, while the absorbed downwelling longwave is $\varepsilon F_{LWDN}$.

Rain $F_{RN}$ is assumed to run off directly into the ocean, and thus contributes to the ocean-ice water flux $F_{WO}$. Snow $F_{SNW}$ is used to compute snow accumulation $dh/dt = F_{SNW}/\rho_s$. The latent heat flux $F_{LH}$ is associated with an evaporative water flux to the atmosphere $E_{VAP}$, and an associated salt flux $S_\rho dh/dt$ with the ocean, where $h$ is ice thickness and $S_\rho$ is a constant sea ice reference salinity, which contributes to the ocean-ice salt flux $F_{SO}$. This salt exchange with the ocean for sublimation/condensation is required to maintain constant sea ice reference salinity.

The top boundary condition at surface temperature $T_s$ is $F_{TOP}(T_s) = F_{SW} - I_{SW} + F_{LH} + F_{SH} + F_{LH} + kdT/dz$, while the lowest ice interface in contact with the ocean is at ocean freezing temperature. With these boundary conditions and internal shortwave heating, the heat equation can be solved. If $F_{TOP}(T_{melt}) > 0$, where $T_{melt}$ is the snow/ice melting temperature, then snow/ice melt is compute by $F_{TOP}(T_s = T_{melt}) = qdh/dt$ as appropriate for either snow (if present) or ice ($h$ is the thickness of snow or ice). Snow and ice melt is assumed to run off directly into the ocean, contributing to the ocean-ice water flux $F_{WO}$ by the amount $qdh/dt$, where $q$ and $h$ are the density, thickness of snow or ice, respectively. If sea ice melts, then an additional salt flux of $S_\rho dh/dt$ is exchanged with the ocean.
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$</td>
<td>ice area</td>
<td>fraction (0 ~ 1)</td>
</tr>
<tr>
<td>$T_s$</td>
<td>surface temperature</td>
<td>K</td>
</tr>
<tr>
<td>$\alpha_{vsdr}$</td>
<td>albedo (visible, direct)</td>
<td>fraction (0 ~ 1)</td>
</tr>
<tr>
<td>$\alpha_{vdiff}$</td>
<td>albedo (vivibe, diffuse)</td>
<td>fraction (0 ~ 1)</td>
</tr>
<tr>
<td>$\alpha_{nidr}$</td>
<td>albedo (near infrared, direct)</td>
<td>fraction (0 ~ 1)</td>
</tr>
<tr>
<td>$\alpha_{nifdef}$</td>
<td>albedo (near infrared, diffuse)</td>
<td>fraction (0 ~ 1)</td>
</tr>
</tbody>
</table>

**Sea Ice => Atmosphere Fluxes (+ downwards)**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_{LH}$</td>
<td>latent heat flux</td>
<td>W m$^{-2}$</td>
</tr>
<tr>
<td>$F_{SH}$</td>
<td>sensible heat flux</td>
<td>W m$^{-2}$</td>
</tr>
<tr>
<td>$F_{LWUP}$</td>
<td>upwelling longwave</td>
<td>W m$^{-2}$</td>
</tr>
<tr>
<td>$F_{EVAP}$</td>
<td>evaporated water</td>
<td>kg m$^{-2}$ s$^{-1}$</td>
</tr>
<tr>
<td>$\tau_{ax}$</td>
<td>x direction atmosphere-ice stress</td>
<td>N m$^{-2}$</td>
</tr>
<tr>
<td>$\tau_{ay}$</td>
<td>y direction atmosphere-ice stress</td>
<td>N m$^{-2}$</td>
</tr>
</tbody>
</table>

**Sea Ice => Ocean Fluxes (+ downwards)**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_{SWo}$</td>
<td>shortwave transmitted to ocean</td>
<td>W m$^{-2}$</td>
</tr>
<tr>
<td>$F_{Qio}$</td>
<td>heat flux to ocean</td>
<td>W m$^{-2}$</td>
</tr>
<tr>
<td>$F_{Wo}$</td>
<td>water flux</td>
<td>W m$^{-2}$</td>
</tr>
<tr>
<td>$F_{So}$</td>
<td>salt flux</td>
<td>kg m$^{-2}$ s$^{-1}$</td>
</tr>
<tr>
<td>$\tau_{ax}$</td>
<td>x direction ice-ocean stress</td>
<td>N m$^{-2}$</td>
</tr>
<tr>
<td>$\tau_{ay}$</td>
<td>y direction ice-ocean stress</td>
<td>N m$^{-2}$</td>
</tr>
</tbody>
</table>

**Diagnostic Fields**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{ref}$</td>
<td>reference temperature (2m)</td>
<td>K</td>
</tr>
<tr>
<td>$Q_{ref}$</td>
<td>reference specific humidity (2m)</td>
<td>kg/kg</td>
</tr>
<tr>
<td>$F_{SW}$</td>
<td>Ice/ocean absorbed shortwave flux</td>
<td>W m$^{-2}$</td>
</tr>
</tbody>
</table>

Table 3.8: State variables and fluxes sent from sea ice model to the coupler (Briegleb et al. 2004; Schramm et al. 2004).

Ice formation occurs by three processes. Although these processes are distinguished in formation, no distinction is made between ice types. If the freezing/melting potential ($F_{Qio}$ in Table 3.8) is such that heat is required by the ocean to maintain the freezing temperature ($F_{Qio} > 0$), then frazil ice formation occurs, at a rate $dV_f/dt = F_{Qio}/\rho_f q_f$, where $q_f$ is a heat of melting assuming the ice forms at $T = 0^\circ C$ and $S = 0$. 

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Frazil ice formation has an implied salt flux to the ice, sufficient to establish \( S_i \), as the mean salinity of the newly formed sea ice. If the freezing/melting potential indicates ocean heat is available to melt ice \( F_{Q_{oi}} < 0 \), this heat is partitioned between lateral \( F_{SID} \) and bottom \( F_{BOT} \) heat fluxes according to the fraction of absorbed solar energy near the surface and in deeper water. The sea surface temperature \( T_{ocn} \) is used to compute heat fluxes \( F_{SID} \) and \( F_{BOT} \) (sea surface salinity \( S_{ocn} \) is not used). The heat flux for lateral and bottom melting is \( F_{Q_{io}} \), which associated with water and salt fluxes \( \rho_i dh/dt \) and \( S\rho dh/\text{dt} \) to the ocean, respectively.

The bottom boundary condition is \( F_{BOT} - kdT/dz = qdh/\text{dt} \). If bottom ice formation occurs (i.e., \( dh/\text{dt} > 0 \)), this ice is termed congelation ice. If sufficient snow \( h_s \) overlies ice, the snow-ice interface can be depressed below sea level. Snow below sea level is converted into ice conserving mass and energy, and is termed snow-ice. For both of these processes, a salt flux of \( S\rho dh/\text{dt} \) is changed with the ocean.

The ocean surface currents \((u_o, v_o)\) and ice velocity \((u, v)\) are used to compute ocean/ice stress \((\tau_{ox}, \tau_{oy})\). The tilt is computed from the gradient of the sea surface height \(((\nabla H_o)_x, (\nabla H_o)_y)\). With these stresses, sea ice velocity and ridging are computed.

### 3.3.6 Mixed Layer Ocean Model – Slab Ocean Model (SOM)

The mixed layer ocean model or slab ocean model (SOM) is a simplified ocean model representing each grid point as a slab of water with a given depth, so that the model allows for variable ocean temperatures and ice/ocean heat flux exchange without the dynamic influences of horizontal or vertical motions in the ocean circulations.
The prognostic variable in the SOM is ocean temperature $T_o$ determined by the thermodynamic equation:

$$\frac{\partial T}{\partial t} = \frac{\partial T}{\partial t} + \rho_o c_o h_o T + F_{SW} + F_{LW} + F_{SH} + F_{LH} + F_{Q_o} - F_{Q_o}$$  

(3.3.6.1)

In equation (3.3.6.1), $\rho_o$, and $c_o$ are the ocean mass density and the ocean capacity, respectively. Both of them are constants (i.e., $\rho_o = 1.026 \times 10^3$ kg m$^{-3}$, and $c_o = 3.93 \times 10^3$ J kg$^{-1}$ K$^{-1}$). $h_o$ is the ocean mixed layer depth specified from Levitus (1982). $F_{SW}$ is the absorbed shortwave flux, and $F_{LW}$ is the absorbed longwave flux: $F_{LW} = F_{LWDN} = F_{LWUP}$. $F_{SH}$ and $F_{LH}$ are the sensible and latent heat flux fluxes between ocean and atmosphere, respectively. $F_{Q_o}$ is the heat exchanged between ice and ocean including side and bottom melt fluxes. $F_{Q_o}$ is the ocean heat flux which represents seasonal mixed layer heat storage/release and lateral oceanic heat transport. The fluxes include contributions from both open water and sea ice. $F_{Q_o}$ is also called the “Q flux”, which represents an internal heat flux stored in the assigned depth of ocean mixed layer. The “Q flux” computed from the prescribed SSTs and advection can calculate deep water heat exchange and ocean transport for deriving the SSTs, mixed layer temperature, sea ice thickness, and sea ice fractions. Under the SOM integrations, the sea ice will be simulated without any allowance of horizontal or vertical ocean circulation effects. It makes the model quickly reach the equilibrium status, and limited the ocean feedbacks in the thermodynamic consideration. The required input (presently monthly mean) data are the mixed layer
depth, salinity (presently not used), ocean currents, sea surface slopes and ocean heat flux (Table 3.9). The ocean currents and tilt are used in the sea ice dynamic calculation.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h_o$</td>
<td>mixed layer depth</td>
<td>m</td>
</tr>
<tr>
<td>$S_o$</td>
<td>salinity</td>
<td>ppt</td>
</tr>
<tr>
<td>$u_o$</td>
<td>x direction surface velocity</td>
<td>m s⁻¹</td>
</tr>
<tr>
<td>$v_o$</td>
<td>y direction surface velocity</td>
<td>m s⁻¹</td>
</tr>
<tr>
<td>$(\nabla h_o)_x$</td>
<td>x direction surface slope</td>
<td>m m⁻¹</td>
</tr>
<tr>
<td>$(\nabla h_o)_y$</td>
<td>y direction surface slope</td>
<td>m m⁻¹</td>
</tr>
<tr>
<td>$F_{Qo}$</td>
<td>ocean heat flux</td>
<td>W m⁻²</td>
</tr>
</tbody>
</table>

Table 3.9: Ocean fields required for mixed layer (Briegleb et al. 2004).

### 3.3.7 Time-stepping loop

The time-stepping loop of the sea ice model representing the model flow running steps are shown in the Figure 3.4. After initialization of the input variables, the ice model first receives the forcing information from the coupler (Table 3.7) at the beginning of the time loop. The vertical ice thermodynamics are calculated, and the ice state and fluxes are returned to the coupler (Table 3.8) at mid-time step immediately after they are computed. The atmosphere component begins calculations right after receiving the flux information from ice model through the coupler. This process doesn’t need to wait after the ice model finishes the time-steeping loop. The atmosphere component sends the results back to the coupler after calculations are finished. The thermodynamics calculated after returning data to the coupler are mostly related to the ice thickness distribution and include transport in thickness space, lateral growth and melting, and freeboard adjustment. The
dynamics calculations continually run after all thermodynamics calculations are done. The results will be output to the history files, after all calculations are finished, according to choices on the output variable list. The model flow will repeat, and go through to the next time stepping loop till the end of the integration time.

Figure 3.4: The time-stepping loop of sea ice model flow (Schramm et al. 2004).
CHAPTER 4: EXPERIMENTAL DESIGN AND MODEL INPUT DATA

4.1 Experiment design

To examine and quantify the effects of the atmospheric and the oceanic forcing, as described before, the model used in this study has an Active Ice Only (AIO) framework coupled with a simple slab ocean model (SOM) within the M configuration of CCSM3 (see Chapter 3). All simulations are run in T62 resolution for atmosphere and land components, and 1° resolution for ocean and sea ice components. As a control run, the sea ice model is run for 78 years, forced by repeating three cycles of observed 6 hourly surface atmospheric fields during 1979–2004 (Figure 4.1a). During the control integrations, nothing is changed in either atmospheric forcing (shown in Table 4.1) or mixed layer oceanic forcing (shown in Table 3.9). Since the SOM needs at least 20 to 25 years to reach its equilibrium status, all sea ice results are computed by averaging the data from the last 26 years of the 78 year integrations. The analyzed sea ice output includes SIC, zonal and meridional ice velocity, sea surface temperature, sea surface salinity, and other variables shown in Table 3.8. The goal of the control run is to evaluate whether the sea ice model has the ability to represent the variability of sea ice in the Odden region.

Based on the results of Shuchman et al. (1998), and Rogers and Hung (2008), the Odden boundary conditions are derived from the 1997 Odden event. The non-Odden
boundary conditions are derived from 1994, which has the weakest yearly characteristics of the Odden. To clarify the effects of critical atmospheric forcing to the Odden sea ice variability, a number of experiments will be conducted as shown in Table 4.2. All forcing used in experiment #1 (row one) is derived from the Odden boundary conditions. In experiment #2, the non-Odden forcing of 1994 is used instead of the Odden forcing from 1997 in experiment #1. Figure 4.1a shows the integration processes of control run. The simulations in experiment #1 and #2 are branched off a control run of 52 years and for continually run 20 year simulations. The experimental results are averaged over the last 5 year of these integrations for the analysis and compared with that from the control runs and the reanalysis data.

<table>
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<tr>
<th>Atmospheric Forcing Variables</th>
<th>Unit</th>
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<tr>
<td>zonal 10 m winds</td>
<td>m s^{-1}</td>
</tr>
<tr>
<td>meridional 10m winds</td>
<td>m s^{-1}</td>
</tr>
<tr>
<td>surface 2m air temperature</td>
<td>K</td>
</tr>
<tr>
<td>specific humidity</td>
<td>kg kg^{-1}</td>
</tr>
<tr>
<td>Density</td>
<td>kg m^{-3}</td>
</tr>
<tr>
<td>downward longwave</td>
<td>W m^{-2}</td>
</tr>
<tr>
<td>downward shortwave</td>
<td>W m^{-2}</td>
</tr>
<tr>
<td>upward shortwave</td>
<td>W m^{-2}</td>
</tr>
<tr>
<td>Precipitation</td>
<td>kg m^{-2} s^{-1}</td>
</tr>
</tbody>
</table>

Table 4.1: Atmosphere forcing input from the atmosphere model component (latm6)
Figure 4.1: The diagram of experimental integrations. (a.) The processes of control (CTRL), and experiment #1, and #2 (EPX). (b.) The processes of experiments from #3 to #18 under different oceanic forcing (Ocean) and atmospheric forcing (Atmos).

Experiment #10, and #11 are simulations under Odden atmospheric and Odden oceanic boundary conditions, and non-Odden atmospheric with non-Odden oceanic
conditions, respectively (Table 4.2). Both experiments integrate 40 model years, and the last 5 year average is analyzed model product (Figure 4.1b).

To evaluate the factors affecting atmospheric forcing related to the Odden ice variability, experiments #3 to #9 sequentially use one atmospheric parameter with 1997 Odden conditions and hold all other boundary conditions coupled with 1994 non-Odden ocean environment as in experiment #11. These integrations are branched off experiment #11, which has already run for 40 years so that the ocean reaches equilibrium and then starts a 20-years simulation in which the atmosphere varies in experiment #3 through #9 (Figure 4.1b). The only Odden forcing is air temperature in experiment #3, wind field in experiment #4, longwave radiation in experiment #5, and shortwave radiation in experiment #6 (see Table 4.2). In experiment #7, the Odden forcing of 2m air density will be examined. The specific humidity and precipitation will be also examined in experiments #8 and #9, respectively (Table 4.2). The experimental results are averaged over the last 5 year of these integrations and compared with that from experiment #11.

The goal of experiments #12 to #16 is to examine how the Odden sea ice responds to the different ocean environments. In experiment #12 and #13, the sea ice simulations use 26 year climatological atmospheric forcing coupled with a single year of Odden and non-Odden oceanic conditions, individually (Table 4.2). The running processes are the same as experiment #3 to #9 shown on Figure 4.1b meaning that the Odden or non-Odden ocean conditions run an additional 20 years. The results are based on averages over the final 5 years of the integrations. For experiment #14 to #16, the sea ice simulations are consecutively run with one Odden oceanic parameter while keeping the other two oceanic parameters non-Odden forcing, all coupled with 26 year climatological
atmospheric fields (Table 4.2). In experiment #14, the only Odden forcing is ocean surface salinity. The Odden sea surface currents are in experiment #15, and the Odden sea surface slopes are examined in experiment #16. All three of the integration steps are the same as that in experiment #3 and #9 represented by Figure 4.1b.

The last two experiment simulations (#17 and #18) are run with 26 year climatological oceanic boundary conditions that a run for 40 years to achieve model equilibrium. The atmosphere is forced by single year Odden, and non-Odden atmospheric forcing, respectively (Table 4.2) for the 40 year period. The running processes are the same as experiment #10 and #11 shown in Figure 4.1b in which a 40 year model run occurs with an average taken over the final 5 years.
<table>
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<th>Shortwave</th>
<th>Density</th>
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</tbody>
</table>

Table 4.2: The combinations of atmospheric and oceanic forcing examined in model simulations. The “O” is labeled for the Odden forcing. The “X” is labeled for the non-Odden forcing. The “ccsm3” indicates the forcing created by original POP output. The climatological conditions are labeled as “Clim”.
4.2 Model input data

4.2.1 Atmospheric forcing data

The M configuration of CCSM3 provides a framework that contains a single active sea ice model coupled with the data models. The data models periodically sent the forcing data through the coupler to the sea ice model. The main input data used in CSIM5 are from atmosphere component (latm6), ocean component (docn6), and the SOM. As part of the atmosphere component, as represented in Table 4.1, atmosphere state, precipitation, and radiative fluxes in the nine variables of Table 4.1 are based on the data from the NCEP/NCAR Reanalysis Project (Kalnay et al. 1996). The data are used with the horizontal spectral truncations of T62 (1.875° × 1.91°) at 6 hourly temporal resolutions. Additionally, the data of surface 2 meter air temperature are extrapolated to 10 meter for use in the model input.

4.2.2 Oceanic forcing data

The prescribed SST data (in degrees Celsius) are provided by the data ocean model (docn6) in the initial time step. As soon as the integration process starts up, the SST will be derived from the “Qflux”, which is calculated by the SOM based on seven ocean environmental variables shown in Table 3.9. The original oceanic variables generated by the POP ocean model simulations are the climatological data containing a one-year seasonal cycle. These ocean boundary data are also optional for running with the gx3v5 or the gx1v3 grid for the different purposes. Although these original POP data are not the real observational data, they can provide the preliminary experiments (e.g., control run, experiment #1, and #2) to evaluate the model capability for Odden ice
simulations. To complete the Odden ice evaluations, and examine the Odden ice response to the different ocean environments, the single year and climatological oceanic forcing are also derived from a Simple Ocean Data Assimilation (SODA) to instead of the original POP model output. The data period is the same as atmospheric forcing (i.e., 1979 – 2004). The SODA is developed by the University of Maryland and Texas A&M University (Carton et al. 2000a; 2000b, Carton and Giese 2008). The SODA datasets are global ocean reanalysis datasets based on the POP model forced with wind data from the European Center for Medium Range Weather Forecasts (ERA-40) and the QuikSCAT scatterometer. These oceanic data are in monthly average having 0.5° × 0.5° horizontal resolution at 40 vertical levels. The oceanic parameters are used to evaluate in Odden ice simulations are surface salinity, horizontal ocean velocity (for x-y direction surface velocity), and sea level (for x-y direction surface slope). After being converted to 1° × 1° resolution, these three parameters replace that in the original POP data, and used to the model integrations.

4.3 Reanalysis data

The reanalysis sea ice data used to compare with the sea ice model results are from the Hadley Center Sea ice and Sea Surface Temperature (HadISST; Rayner et al. 2003), which are developed at the Met Office Hadley Centre for Climate Prediction and Research. The global monthly SST and SIC data are combined and derived from many data sources including the in situ data sets, the SSMR and SSM/I satellite observations, and the results from the AGCM and the numeric algorithms (e.g., Walsh and Chapman 2001, Smith 1996, Comiso 1986, and etc.). The period of data used is 1979 – 2004. The
HadISST data are monthly data on 1° by 1° global resolution, which is the same as that of CSIM5 output. The data domain and format are shown on Figure 4.2. Starting from 1978, the HadISST SIC data are based primarily on SSMR and SSM/I satellite data, which can provide a great reference for the examining modeled and actual variability.

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Figure 4.2: The domain of the HadISST sea ice data (from http://hadobs.metoffice.com/index.html)
CHAPTER 5: MODEL RESULTS

5.1 Control run results

Principal Component Analysis (PCA), and Rotated Principal Component Analysis (RPCA) are simple statistical methods widely applied to analyze long term climate variability. Rogers and Hung (2008) applied these methods in analyzing the winter (D-J-F) HadISST sea ice concentration (SIC) during 1951 – 2005. They identified the $4^{th}$ rotated component as that best representing Odden area SIC variability. The pattern explained 19.1% of the overall regional SIC rotated variance, and all components collectively retain 66.1% of total SIC dataset variance. RPC4 (Rogers and Hung, 2008) is shown on Figure 5.1 and indicates that the largest SIC variability extends from an area around $5^\circ$E, $76^\circ$N southwesterly to the location at $15^\circ$W, $70^\circ$N. The center of this variability area is the same as the Odden sea ice feature.

PCA and RPCA can also be used to evaluate the capability of the M configuration of the CCSM3 to reproduce the Odden feature in the model prior to evaluating other Odden sea ice experiments. Table 5.1 shows the total variance explained by the initial four components in PCA and RPCA for the last 26 winters (J-F-M) in model control run integrations. In PCA, PC1 contains 30.6% of variance and the initial four components explain cumulative variance of 67.4% in the SIC dataset. The spatial patterns associated with the first four PC loading components based on the 26 year SICs extracted from 78
year control run are shown in Figure 5.2. PC1 pattern (Figure 5.2a) demonstrates the significant high SIC variability (> +0.8) dominating the Greenland Sea and most the Barents Sea regions. The maximum values lay southwest to northeast area between south of Svalbard and north of Iceland that is the same as where the Odden ice event occurs.

Figure 5.1: The winter (D-J-F) spatial distributions of HadISST SICs during 1951 – 2005 (Rogers and Hung, 2008). (a) RPC1, (b) RPC2, (c) RPC3, and (d) RPC4
<table>
<thead>
<tr>
<th>Component</th>
<th>Total</th>
<th>% of Variance</th>
<th>Cumulative %</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC 1</td>
<td>39513.323</td>
<td>30.635</td>
<td>30.635</td>
</tr>
<tr>
<td>PC 2</td>
<td>20960.214</td>
<td>16.250</td>
<td>46.885</td>
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<tr>
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<td>15503.665</td>
<td>12.020</td>
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<tr>
<td>PC 4</td>
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</tr>
<tr>
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<td>10.680</td>
</tr>
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<tr>
<td>RPC 4</td>
<td>17057.921</td>
<td>13.225</td>
<td>62.256</td>
</tr>
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</table>

Table 5.1: The percentages of explained variance and cumulative explained variance by the control CCSM3 SIC PCAs and RPCAs obtained for winters (J-F-M) of 1979 – 2004.
Variability in PC1 of the opposite sign occurs near Davis Strait and in the western Arctic basin. In the other PC components, a “seesaw” correlation occurs between the Kara Sea and Labrador Sea in PC2 (Figure 5.2b). PC3 exhibits variability between the North
American and Eurasian areas (Figure 5.2c). PC4 exhibits small pockets of regional SIC variability (Figure 5.2d).

Figure 5.3: The winter (J-F-M) spatial distributions of initial four rotated principle components of CCSM3 control run. (a) RPC1, (b) RPC2, (c) RPC3, and (d) RPC4.
In the RPCA, the first four components retain 62.3% of the variance in the 26 year control run results (Table 5.1). Nearly 1/3 of the retained cumulative variance (24.4% of 62.3%) is explained by RPC3 while the rest of three components only individually explain about 10 – 14% of the total variance. It implies that the RPC3 is able to explain the primary SIC variability in the model output. RPC1 in Figure 5.3a shows the large positive values (> +0.5) in the eastern Arctic Ocean, especially in an area between 30° and 60°E around the East Arctic basin including the Kara Sea and a part of the Laptev Sea. The largest negative values (< -0.5) are on the North Pacific Ocean through Chukchi Sea area. The values in Odden area are between ± 0.2 showing poor variability in RPC1. Figure 5.3b (RPC2) has extreme high variability (> +0.8) the west of Greenland, especially on the Labrador Sea. Figure 5.3c indicates the RPC3 pattern. In this pattern, the extreme positive SIC variability (> +0.8) covers a southwest/northeast oriented area between 10°W and 0°E, and between 65° and 75°N. Although slightly southeastward of normal, the center maximum area overlaps the typical Odden region shown, such as is shown in Figure 5.1. The most negative values occur around the Beaufort Sea. In RPC4 (Figure 5.1d), the largest positive variability is on the Barents Sea and it is negatively correlated with the sea ice variability on the northwestern Pacific Ocean. According to the spatial distribution shown above, the winter RPC3 in CCSM3 control run demonstrates more characteristics of the Odden sea ice variability than other patterns.

The loading time series of HadISST RPC4 (blue line) from 1951 to 2005 (Rogers and Hung, 2008), and of the CCSM3 RPC3 (red line) from 1979 to 2004 are presented in Figure 5.4. Generally, both time series have downward trends implying that the sea ice volumes are comprehensively decreasing with time in the Greenland Sea area. This sea
ice retreat has been confirmed by a recent study (Wadhams and Comiso 1999). Several positive values characterize the significant Odden events in 1979, 1982, 1986, 1989, 1997, and 1998 from HadISST and these are also apparent in the CCSM3 time series (Figure 5.4). In contrast, the relatively low/negative scores in 1985, 1991 – 1994 indicate the weak and the low volume ice appearances in the Odden area pointed by both the HadISST dataset and the CCSM3 integrations. This time series score plot is evidence of the agreement between the CCSM3 and the HadISST. Although the M configuration of CCSM3 is only a sea ice active model coupled with SOM and other data model components, under this framework, it still has the reasonable capability to simulate the sea ice activity, and evaluate the mechanisms introducing the sea ice variability in this complex area (e.g., the North Atlantic Ocean, and Greenland Sea).

Figure 5.4: The loading time series of HadISST RPC4 (1951-2005, blue line), and CCSM3 RPC3 (1979-2004, red line).
5.2 Experiment results for FMA

Figures 5.5a–h shows the winter average (F-M-A) differences of atmospheric parameters (Table 4.1) between Odden (1997) and non-Odden (1994) years from the NCEP/NCAR Reanalysis dataset. The results shown in Figure 5.5a (air temperature), 5.2d (downward longwave) and 5.2g (specific humidity) have very similar patterns having the large lowest negative values from 45°E to 80°W, and between 65 and 80°N, while positive differences take place north of Greenland, to the south of 65N including the northern Atlantic Ocean and the European continent. The two main lowest centers around the Barents Sea and the Greenland Sea have differences lower than -4C (Figure 5.5a), -20 W m⁻² (Figure 5.5d), and -0.4 g kg⁻¹ (Figure 5.5g) indicating that these areas are under outbreaks of colder and drier air associated with the Odden events in this season. The colder and drier air is denser and the pattern of air density differences is directly opposite that of air temperature due to its physical characteristics (Figure 5.5f).

The zonal (u component) and meridional (v component) wind average differences are shown in Figures 5.2b and c. In the u component wind (Figure 5.5b), the positive differences (> +2 m s⁻¹) south of 65°N (northern Atlantic Ocean) extend into the northern European continent. The lowest negative differences are located north of Norway and northern Greenland with the values lower than -2 m s⁻¹. A minor positive zonal wind difference covers most of the Greenland Sea. This positive anomaly wind and the negative wind difference toward the Barents Sea create a convergent area between 0° – 5°E, and between 70° – 75°N. The lowest negative v-component difference (< -2 m s⁻¹) in meridional wind takes place on the Barents Sea and the Norwegian Sea, while the
minor positive difference with $+1 \text{ m s}^{-1}$ maximum values in the Fram Strait along the eastern coast of Greenland southward to the northern Atlantic Ocean. Since the $v$ component wind plays an important role in exchange of heat flux in the meridional direction, the large convergence of $v$ component difference between the positive (southerly) and negative (northerly) areas indicates complicated heat flux interactions involved and associated with the sea ice variability in the Odden area during this season (Figure 5.5c). The u- and v-component alternations are consistent with a ridge over the Odden area (during the Odden event), with southwest flow over the east Greenland ice and northwest flow over the Odden area.

Combining with downward and upward shortwave effects, the surface shortwave radiation differences between Odden and non-Odden years are shown in Figure 5.5e. The very low negative ($<-20 \text{ W m}^{-2}$) and very high ($>+20 \text{ W m}^{-2}$) shortwave differences occur over Russia and the Labrador Sea, respectively. Minor positive differences ($+5$ to $+10 \text{ W m}^{-2}$) occur north of Norway, south of Svalbard and a part of the central Greenland Sea. Secondary low negative differences ($-10$ to $-15 \text{ W m}^{-2}$) occur over thin areas west of $0^\circ\text{E}$ (Fram Strait), east of Greenland (between 70 and $75^\circ\text{N}$), and cross the Denmark Strait covering the northern Atlantic Ocean. Figure 5.5h demonstrates the precipitation differences between Odden and non-Odden events in F-M-A. As shown in the figure, precipitation differences are low between Odden and non-Odden seasons. The main negative precipitation differences occur at Fram Strait, through the Greenland Sea and the Denmark Strait, and end southeast of Greenland, while the relatively positive area covers central Greenland, the Norwegian Sea and the European continent.
5.2.1 Sea ice concentration (SIC)

The winter differences (F-M-A) in SIC between Odden and non-Odden events are shown in Figure 5.6a–m. Figure 5.6a represents the SIC differences between experiment #1 and #2, which have different atmospheric forcing but the same original oceanic forcing input from the CCSM3 (indicated in Table 4.2). The differences obtained are based on Odden minus non-Odden atmospheric forcing. The highest SIC variability (> +20%) occurs on the northern coasts of Russia and Norway extending northwestward through the Barents Sea into the Greenland Sea (i.e., an area between 44° and 10°E, and between 68° and 74°N). The other high SIC anomaly extends northeast to southwest over the Greenland Sea ending around 10°W, 68°N. As shown in Figure 5.1d, the second part of this SIC variability overlaps part of the Odden area. Although lacking an Odden/non-Odden ocean environment, Figure 5.6a indicates only the Odden atmospheric forcing can generally affect the Odden SIC variability during this season.

Figures 5.6b–h show the responses of the SIC variability in FMA under the forcing of different individual atmospheric parameters simultaneously with non-Odden oceanic forcing (shown in Table 4.2). In experiments #3 – #9, the greatest SIC anomaly occurs in experiment #4 (Odden zonal and meridional 10 m wind fields; Figure 5.6c). The positive SIC difference (> +20%) covers a region from the Barents Sea (northern coasts of Russia and Norway) westward to Bear Island near 75°N, and then west to the Greenwich Meridian ending between latitudes 72° and 75°N. The northeastern portion of this has a positive percentage SIC difference in part of the model-response Odden region. Low
negative SIC differences (< -20%) appear however, from a northeast/southwest area between 2° and 15°W, and between 60° and 72°N.

The SIC results of experiments #3 (10m air temperature; Figure 5.6b), #5 (10m longwave fluxes; Figure 5.6d), and #8 (10m specific humidity; Figure 5.6g) are similar. The regions of positive maximum SIC differences are located on the Barents Sea (north of the Norway), and the thin southwest/northeast area generally lying between 0° and 10°W, and between 66° and 72°N. However, the air temperature results show at least +20% variability in a larger area while the longwave flux experiment has the variability in 10% – 15%, and specific humidity responds 5% – 10% in a smaller area. The results of experiment #6 (10m shortwave flux; Figure 5.6e), #7 (10m air density; Figure 5.6f), and #9 (precipitation; Figure 5.6h) show that there are low sea ice differences (-5% – +5%) associated with differences between Odden and non-Odden forcing.

Figure 5.6i represents the SIC differences between all Odden (experiments #10) and non-Odden (experiment #11) parameters including ocean variability between 2 cases. The spatial patterns of extreme SIC variability are very similar to the results from experiments #1 and #2 (Figure 5.6a). Comparing with Figure 5.6a, the positive SIC differences extend to higher latitudes in Figure 5.6i and the positive differences lie farther to the northwest although they also reach Iceland. These high SIC differences are generally southwest/northeast between 10°W and 5°E, and between 67° and 75°N, and is compatible in sign to those of experiments #1 and #2. The only difference between these two groups is the oceanic input (i.e., original CCSM3 oceanic input in experiments #1 and #2, and realistic oceanic forcing in experiments #10 and #11). After adding the
realistic oceanic forcing, the SIC anomaly on the Greenland Sea is generally closer to the Odden area, having moved somewhat northwestward in 1°–3° after including oceanic input. Moreover, Figure 5.6i presents more detail features on the sea ice edge area. It indicates that the oceanic forcing might play a role in the ice formation and maintaining the sea ice edge.

To understand the Odden sea ice activities associated with the different Odden/non-Odden oceanic parameters experiments #12 – #16, model integrations are run with general atmospheric forcing derived from 26 year climatological atmospheric data during 1979 – 2004 (Table 4.2). The SIC differences between experiments #12 (Odden oceanic parameters) and #13 (non-Odden oceanic parameters) are shown in Figure 5.6j. The positive and negative SIC fluctuations characterize an irregular area of sea ice variations, which is from the Svalbard southwestwardly through the Greenland Sea and to the southeastern coast of the Greenland. On this area, the greatest differences are of small positive and negative SIC anomalies. On the other side of Greenland (the southern Labrador Sea), small SIC variability covers an area between the southwest coast of Greenland to the east of 60W between 60° – 65°N. In this area, the largest SIC differences are negative (< -20%) to the north, while the positive SIC differences take place to the south of this area.

Since the ocean surface salinity is a constant value (34.7 ppt) in the M configuration of CCSM3 (Briegleb et al. 2004), there is no differences between the results from experiments #14 and #13 (not shown). Figure 5.6k demonstrates the SIC variability response to the ocean surface currents, which is experiment #15. The distribution of the
SIC differences and their spatial patterns are almost the same as that derived from the differences between experiments #12 and #13 in Figure 5.6j. The responses of the SIC to the ocean surface slopes (experiment #16) are presented in Figure 5.6l. The low SIC differences (-5% to +5%) are randomly distributed over the Arctic Ocean, Barents Sea, Greenland Sea, and Labrador Sea, which shows the low SIC feedback associated with the ocean surface slopes. According to experiments #12 – #16, in the oceanic forcing analysis, the great similarity of SIC patterns corresponding to the ocean surface current and to the all Odden oceanic parameters shows that the ocean surface current plays a very important role in sea ice formation and decay processes.

Figure 5.6m represents the SIC variability driven by the Odden/non-Odden atmospheric forcing with 26 year climatological oceanic data (1979 – 2004). The spatial distributions of the largest sea ice differences (> +20%) are generally similar to that in Figures 5.2.1a and 5.2.1i. However, the largest SIC variability area on the Greenland Sea is much thinner, and farther from where the Odden events occur.

5.2.2 Mean ice thickness

The differences of FMA mean ice thicknesses between experiments #1 and #2 are shown in Figure 5.7a. The largest positive ice thickness differences distributes on Barents Sea in the Arctic Ocean (+0.2 to +0.3m), on the northern coast of Norway (+0.3 to +0.4m), and along a southwest/northeast oriented area with a maximum center greater than 0.4m on the central Greenland Sea. Except along the north coast of Greenland, the results show that the negative mean ice thicknesses occur everywhere else between
Odden and non-Odden atmospheric boundary conditions, especially on the western Greenland Sea and over the north coast of Iceland.

In the series of Figures 5.7b–h represent the difference in ice thicknesses in response to each individual atmospheric forcing. Generally, the ice thicknesses have the greatest response to the surface wind field (Figure 5.7c). As shown in Figure 5.7c, besides the largest thickness increasing (> +0.4m) on the north coast of Canada and Greenland, the relatively positive thickness differences (> +0.3m) occur on parts of the Barents Sea around 75°N to 0°E. Low negative thicknesses take place on the Greenland Sea with the central minimum value < -0.4m between 0°E and 15°W, and between 65° and 73°N in the area where the Odden occurs.

The air temperature experiment has somewhat opposite patterns of ice thickness variations as the wind field. Beside the smaller positive areas on the north coast of Canada, Figure 5.7b shows the slight thickness decreasing on most of the Arctic Ocean, Barents Sea, east of Greenland Sea, Davis Strait and the Labrador Sea. The ice increases the thickness in 0.1 – 0.2m on the southeastern Greenland Sea near the Denmark Strait. The longwave experiment results (Figure 5.7d also show positive thickness differences on the north coast of Canada, but most of the analysis domain represents very small thickness changes (+0.1m), and small decreases (- 0.1m) to the southeast of Greenland. From Figures 5.7e–h, all of the thickness spatial patterns are characterized by the small thickness decreases (-0.1 to -0.2m) covering the Arctic Ocean, Barents Sea, Greenland Sea, and Labrador Sea.
Figure 5.7i shows the mean ice thickness differences between experiments #10 and 
#11. The large thickness differences are positive mainly on the Arctic Ocean, The 
Barents Sea, and eastern Greenland Sea. On the eastern Greenland Sea ice thicknesses are 
increased by greater than 0.4m along the Greenwich Meridian, and between 69° and 
77°N, which is farther east than normal of the spatial domain of the Odden feature. The 
negative thickness differences extend from the Arctic Ocean through Fram Strait and the 
Greenland Sea to the coast of Iceland. The largest negative differences (< -0.4m) occur 
between 2° –10°W, and between 72° and 80°N.

When using climatological forcing rather than Odden atmospheric forcing, Figure 
5.7j shows less thickness response on the analysis domain. The largest increasing and 
decreasing areas are located at northern Greenland. The main positive thickness change 
appears around the southwest of Svalbard in 73° – 77°N, and the largest negative area 
occurs between 75° – 80°N on the Fram Strait. The extreme positive/negative areas are 
smaller than that in Figure 5.7i meaning that the response of sea ice thickness change to 
Odden atmospheric environments is larger than that to the general climatological 
atmospheric data in FMA. The pattern in Figure 5.7k, the response to sea surface 
currents, is very similar to Figure 5.7j, while Figure 5.30l shows minor responses to the 
sea surface slopes. It indicates that the ocean current is the most important factor related 
to the ice thickness.

Figure 5.7m shows that the thickness differences respond to the Odden/non-Odden 
atmospheric with climatological oceanic environments. Relatively high thickness 
increases (+ 0.3m) take place over areas north of Svalbard and in the Barents Sea. Large
areas have decreases in thicknesses (-0.2 – -0.4m); north of Greenland, Fram Strait, central Greenland Sea, Davis Strait and the Labrador Sea. Especially for the Fram Strait and Greenland Sea, the sea ice thickness can decrease more than 0.3m by driving the different atmospheric forcing between Odden and non-Odden conditions.

5.2.3 Sensible heat flux

The responses of surface sensible heat fluxes are examined by the CCSM3. The sensible heat in the CCSM3 is derived by the bulk formulae based on Monin-Obukhov similarity theory (Briegleb et al. 2004):

\[
F_{SHn} = \rho_a c_a \gamma_{hn} u_n^* (\theta_a - T_{sn})
\]  
(5.2.3)

where:

- \( n \) is the \( n^{th} \) category stress components
- \( \rho_a \) is the air density
- \( C_a \) is specific heat for the air
- \( \gamma_{hn} \) is the exchange coefficients of sensible heat
- \( u_n^* \) is the u component wind
- \( \theta_a \) is potential temperature of the air
- \( T_{sn} \) is the surface temperature in Kelvins (ice/ocean/land)
The surface sensible heat differences between experiments #1 and #2 are shown in Figure 5.8a. Four relatively highly positive sensible heat differences are located north of Norway (+20 W m\(^{-2}\)), in Fram Strait (+10 W m\(^{-2}\)), in Davis Strait and the western Labrador Sea (+15 W m\(^{-2}\)), and in the Greenland Sea (> +20 W m\(^{-2}\)). The negative sensible heat differences generally occur on the southwest of Svalbard through the western Greenland Sea, the Denmark Strait, southeast of Greenland and reach the northwestern Atlantic Ocean. The lowest negative sensible heat variability is ~ 10 W m\(^{-2}\), and concentrates to the western Greenland Sea and the Denmark Strait.

Figure 5.8b demonstrates the Odden air temperature experiment result on the sensible heat differences (< -20 W m\(^{-2}\)) with large negative areas over the Barents Sea, east of Greenland, and over the Davis Strait. Only a couple of places have the positive feedbacks in northeastern coast of Greenland and the Labrador Sea with the sensible heat differences > +15 W m\(^{-2}\). According to Equation 5.2.3, the fluxes directed toward the surface are positive. Since all the coefficients in Equation 5.2.3 are positive, the sign of the difference between Odden and non-Odden only depends upon the temperature difference between air and surface (i.e., the vertical temperature gradient). Air temperature are generally lower in the Odden water than in non-Odden (Figure 5.2a) and the lowest negative area in Figure 5.8b in areas where lower Odden air temperature occurs. Based on the same surface temperature in this experiment, when the colder air (Odden air) passes through the same surface, the surface will release more sensible heat into the atmosphere than the warmer air (non-Odden) in order to balance the surface energy budget.
For the feedbacks from the different wind fields, Figure 5.8c presents an area with +5 to +15 W m\(^{-2}\) sensible heat changed is located on the Barents Sea over the south of Svalbard due to the Odden wind stress, which implies the strong wind dragging effects to the sensible heat feedback. Another main negative area (-5 W m\(^{-2}\)) starts from 0\(^\circ\)E, 71\(^\circ\)N through Iceland to south of Greenland. The positive and negative areas have an agreement with the zonal wind difference forcing pattern (Figure 5.2b) indicating an apparent zonal wind influence. The patterns of feedback to the surface longwave flux (Figure 5.8d), and the surface specific humidity (Figure 5.8g) are similar. The positive sensible heat variability has magnitudes of +10 to +15 W m\(^{-2}\) around the Greenland Sea and part of the Barents Sea. In this longwave experiment, the air temperature remains the same; the surface temperature will be proportional to the downward longwave flux. Under the Odden situation, the surface has less downward longwave radiation associated with the lower surface temperature than that under the non-Odden condition. When the air temperature remains the same, the Odden surface needs to gain more energy from the air than non-Odden surface. Therefore, the surface with Odden condition, the sensible heat difference shows positive, while the area with the lower downward longwave radiation. Compared with the forcing in Figure 5.2d, the centers of negative areas are almost the same as the positive centers in Figure 5.8d.

According to the specific humidity difference shown in Figure 5.2g, the Odden has drier air associated with the lower surface specific humidity around the Barents Sea, and Greenland Sea. The lower specific humidity refers the lower humidity around the surface and lower heat storage which also reflects the lower surface temperatures as well. Thus,
with Odden specific humidity, the surface will need more sensible heat from the
atmosphere in order to satisfy the energy balance. In experiments #6 (Figure 5.8e), #7
(Figure 5.8f), and #9 (Figure 5.8h), the barely negative (0 to +5 W m⁻²) areas cover the
Barents Sea, Greenland Sea, and the Baffin Bay, Davis Strait and Labrador Sea (Figure
5.8h). These results indicate the poor negative linkages between sensible heat, and
shortwave, density, and precipitation.

Figure 5.8i displays the sensible heat response between Odden and non-Odden
scenarios. The positive differences of sensible heat occur north of Norway, over the Fram
Strait, and along the Canadian coast on Davis Strait as well as along a
southwest/northeast oriented area from 10° – 5°W, an between 70° – 75°N. The western
Greenland Sea (eastern coast of Greenland) through the Denmark Strait to the southeast
of Greenland is the location that negative sensible heat difference appears. Figure 5.8i
shows results from the effects combined from all Odden/non-Odden parameters. From
Figures 5.8b–h, a similar pattern of positive area in Greenland Sea to that shown in
Figure 5.8.c, while that area shows negative in b, and d–h. That implies the important
relationship between wind parameter and Odden feature.

The sensible heat responses to the oceanic forcing are shown in Figures 5.8j–l. The
results indicate the low negative sensible heat feedbacks around the Greenland Sea, and
the Davis Strait/Labrador Sea areas. In Figure 5.8m, the pattern is similar to that in Figure
5.8a; even through the positive area on the Greenland Sea has a smaller difference that in
Figure 5.8a.
5.2.4 Latent heat flux

The latent heat is calculated by Equation 5.2.4 in CCSM3, which is also based on Monin-Obukhov similarity theory (Briegleb et al. 2004):

\[ F_{LHn} = \rho_a L_s r_{en} u_{n}^* (q_n - q_s(T_{sn})) \]  

(5.2.4.1)

where:

- \( n \) is the \( n^{th} \) category stress components
- \( \rho_a \) is the air density
- \( L_s \) is the latent heat of sublimation from ice to vapor
- \( \gamma_{en} \) is the exchange coefficient of latent heat
- \( u_{n}^* \) is the \( u \) component wind
- \( q_n \) is the air specific humidity
- \( q_s \) is the surface specific humidity depending on the surface temperature
- \( T_{sn} \) is the surface temperature in Kelvins (ice/ocean/land)

The latent heat results of experiments #1 and #2 are shown in Figure 5.9a. The positive latent heat variability areas are located over the Barents Sea, northeast of Greenland through Fram Strait southwestwardly through Denmark Strait. The maximum differences is > +4 W m\(^{-2}\) lying on the center Greenland Sea. The small negative areas appear in the Norwegian Sea, southwestwardly to Iceland and along the coast of Greenland.
Figure 5.9b displays the latent heat changes due to Odden air temperature. According to Equation 5.2.4.1, normally, the latent heat does not directly vary with the air temperature. However, the surface energy budget is in a conserved system, which can be described by the following equation (Briegleb et al. 2004, Kauffman et al. 2004 and Schramm et al. 2004):

\[
\text{net heat flux} = \text{shortwave flux} + \text{longwave flux} + \text{sensible heat flux} + \text{latent heat flux}
\]

(5.2.4.2)

In this conserved system, only sensible heat flux is directly affected by the air temperature \( \theta_a \), while the shortwave flux, longwave flux and the net heat flux remain the same. To maintain the balance in the whole system, the latent heat flux has to be adjusted to the other sign against the sensible heat changed due to the air temperature variation. The spatial pattern of the negative/positive latent heat flux difference (Figure 5.9b) is very similar to that of the positive/negative sensible flux difference (Figure 5.8b), in which the Odden air temperature is colder/warmer than the non-Odden air temperature (Figure 5.2a). In the wind experiment, the moderate negative variability covers the most part of domain. The only positive area (+2 to +3 W m\(^{-2}\)) is located at an area 0° – 15°E and between 72° – 75°N, which is associated with the convergence of the zonal wind difference shown in Figure 5.2b.

The latent heat response to the longwave effects are shown in Figure 5.9d. The significant positive latent heat anomaly takes over the Barents Sea, Greenland Sea, and
the western Davis Strait. This pattern, with opposite sign is compatible with that of the
downward longwave difference shown in Figure 5.2d. In this experiment, the surface
temperature change only is relied on downward longwave change. The surface specific
humidity is dependent on the surface temperature and involved in the magnitude and
directions of the latent heat flux (Equation 5.2.4.1). In this area, the Odden environment
has less downward longwave, lower air temperature, and lower specific humidity. In
order to be satisfied with the energy balance by Equation 5.2.4.1, the surface has to gain
more latent heat flux from the atmosphere. Conversely, most of negative latent heat
differences covering the larger part of the analysis domain with values lower than -3 W
m$^{-2}$ is located at the southern Greenland Sea and the Barents Sea in shortwave experiment
(Figure 5.9e). Comparing with Figure 5.2e, the lower negative latent heat difference areas
have the same locations as that with the positive shortwave flux differences (Figure 5.9e),
which indicates that the shortwave plays the minor role to increase the surface
temperature. The air density $(\rho_a)$ is not only a variable needed to calculate the latent heat
flux, but also proportional to its magnitude (Equation 5.2.4.1). As shown in Figure 5.2f,
positive air density difference has a similar pattern to that of the positive difference of
latent heat in the Odden density experiment shown in Figure 5.9f. The main positive
feedbacks are all in an area east of Svalbard (+1 to +2 W m$^{-2}$) and Greenland (+2 to +3
W m$^{-2}$). Figure 5.9g shows the latent heat flux variability in the Odden air specific
humidity ($q_a$) experiment. The lowest negative difference starts from the Barents Sea
westward 0$^\circ$E and southwestward over the Greenland Sea though the Denmark Strait, and
ends off the southeastern coast of Greenland. This area also shows negative differences in
air specific humidity in Figure 5.2g, meaning the lower air specific humidity with the
drier air in Odden scenario. This result is in agreement with the definition of latent heat
flux described in Equations 5.2.4.1. There is a small negative area located over the
Greenland Sea from the precipitation (Figure 5.9h) experiment showing the negative
latent heat feedbacks and the weak linkage with the Odden/non-Odden feature.

Extreme negative latent heat differences (< -4 W m\(^{-2}\)) are displayed on Davis Strait,
and the southern Barents Sea and parts of the Greenland and Norwegian Seas. The
positive differences are north of Russia coast, northeast of Greenland (Fram Strait), and
east of Greenland. The barely negative (-1 to +0 W m\(^{-2}\)) latent heat feedback on
Greenland and Barents Sea demonstrated in Figures 5.2.4j–l indicate that ocean
environment is not the key factor related to the latent heat flux released. Figures 5.9i, and
5.9m represent very similar patterns to that in Figure 5.9a. Since these experiments have
the same Odden atmospheric parameters but the different oceanic environments, the
similar patterns also imply a small linkage between ocean and latent heat flux.

5.2.5 Sea ice velocity

The Odden/non-Odden sea ice velocity, referred to as the sea ice motion (SIM), is
also evaluated by CCSM3. SIM is an important variable representing the advection of sea
ice associated with a source and sink, which can help to understand the Odden and non-
Odden sea ice movements. Since the simple slab ocean model is without active ocean
circulation effects, the SIM is mainly calculated by the near surface wind and sea surface
currents near the top of the ocean.
The winter (F-M-A) differences of SIM are shown in Figures 5.10a–m. Figure 5.10a shows the largest northerly SIM anomaly (10 cm s\(^{-1}\)) concentrates on the Barents Sea, and near the Greenwich Meridian between 66° and 75°N, while the lowest SIM variability is on the western Greenland Sea. Large northerly differences on these maps would, for example, mean that SIM is more northerly in Odden cases relative to non-Odden. The differences of SIC (Figure 5.6a) and thickness (Figure 5.7a) accumulate in this area due to this anticyclone SIM.

From Figures 5.10b – h, only the Odden wind experiment (Figure 5.10c) shows a large correlation with the SIM anomaly in this season (Figure 5.7a). The results show that the convergence of SIM on northern coast of Russia and Norway yields sea ice concentration and thickness increases in this area (Figures 5.6c and 5.7c). In an area between 5° and 10°E, and between 70° and 75°N, the strong anticyclonic SIM (> 10 cm \(^{-1}\)) helps create high sea ice concentrations and thickness shown in Figures 5.6c and 5.7c). Except for the strong relationship between SIM and wind parameter, there is no large correlations between SIM and the other Odden atmospheric parameters. The minor responses shown in Figures 5.10b and d indicates that there is no significant SIM response to either air temperature or longwave radiative flux. The low SIM activity displayed in Figures 5.10e to 5.10h implies minor linkages between SIM and these parameters.

In Figure 5.10i, the largest SIM convergences occur on the Barents Sea (north of Norway), and Fram Strait (west of Svalbard) along 5°E southward to around 65°N, while the strong SIM to the north occurs immediately to its east side (i.e., the south of
Svalbard), which reduces the SIC differences in this area (Figures 5.6i and 5.7i). By using the climatological atmospheric and Odden oceanic forcing in Figure 5.10j, the main divergence and convergence areas in Fram Strait and Greenland Sea are reduced somewhat, and impact the SIC and mean ice differences in these areas (Figures 5.6j and 5.7j). The SIM pattern in the sea surface current experiment (Figure 5.10k) is very similar to that in Figure 5.10j, while there are very small SIM responses to the surface slope (Figure 5.10l). It suggests that the sea surface current plays the most important role in steering the SIM. Figure 5.10m shows the SIM advection in the Odden atmospheric environment with climatological oceanic input. The pattern is similar to that in Figure 5.10a, which has the same atmospheric forcing from the CCSM3 output. Comparing with Figure 5.10a, the SIM convergence and divergence in Figure 5.10m have weaker magnitudes and smaller areal coverage, which agrees with SIC and ice thickness patterns shown in Figures 5.6m and 5.7m.
Figure 5.2: The FMA average differences of the atmospheric input parameters (Table 4.1) between Odden (1997) and non-Odden (1994) years from the NCEP/NCAR Reanalysis dataset. (a) 10m air temperature, (b) 10m u component wind, (c) 10m v component wind, (d) surface downward longwave flux, (e) total surface shortwave flux, (f) 10m air density, (g) 10m air specific humidity, and (h) precipitation.
Figure 5.6: The FMA average of the sea ice concentration (SIC) difference between Odden and non-Odden conditions. (a) the difference between experiments #1 and #2, (b) – (h) the differences between experiments #3 – #9 and #11, (i) the difference between experiments #10 and #11, (j) the difference between experiments #12 and #13, (k) – (l) the differences between experiment #15 – #16 and #13, and (m) the difference between experiments #17 and #18.
Figure 5.6 continued
Figure 5.7: The FMA average of the mean sea ice thickness difference between Odden and non-Odden conditions. (a) the difference between experiments #1 and #2, (b) – (h) the differences between experiments #3 – #9 and #11, (i) the difference between experiments #10 and #11, (j) the difference between experiments #12 and #13, (k) – (l) the differences between experiment #15 – #16 and #13, and (m) the difference between experiments #17 and #18.
Figure 5.7 continued
Figure 5.8: The FMA average of the surface sensible heat difference between Odden and non-Odden conditions. (a) the difference between experiments #1 and #2, (b) – (h) the differences between experiments #3 – #9 and #11, (i) the difference between experiments #10 and #11, (j) the difference between experiments #12 and #13, (k) – (l) the differences between experiment #15 – #16 and #13, and (m) the difference between experiments #17 and #18.

Continued
Figure 5.8 continued
Figure 5.9: The FMA average of the latent heat difference between Odden and non-Odden conditions. (a) the difference between experiments #1 and #2, (b) – (h) the differences between experiments #3 – #9 and #11, (i) the difference between experiments #10 and #11, (j) the difference between experiments #12 and #13, (k) – (l) the differences between experiment #15 – #16 and #13, and (m) the difference between experiments #17 and #18.
Figure 5.9 continued
Figure 5.10: The FMA average of the sea ice velocity difference between Odden and non-Odden conditions. (a) the difference between experiments #1 and #2, (b) – (h) the differences between experiments #3 – #9 and #11, (i) the difference between experiments #10 and #11, (j) the difference between experiments #12 and #13, (k) – (l) the differences between experiment #15 – #16 and #13, and (m) the difference between experiments #17 and #18.
Figure 5.10 continued
5.3 Experiments results for MJJ

Figures 5.11a–h show the May – July (M-J-J) mean of the atmospheric forcing differences between Odden and non-Odden scenarios. Comparing with Figure 5.2a, the air temperature differences continue to be negative but decrease in magnitude to -2 to -1°C in the Greenland Sea and become positive in the Barents Sea, east of Svalbard. In the u component wind difference pattern (Figure 5.11b), the lowest negative areas (< -0.5 m s⁻¹) are located on the Norwegian sea with the minimum surface zonal wind anomaly center (< -2 m s⁻¹) on the western coast of Norway, northeastern Atlantic Ocean, and Labrador Sea. A minor positive difference area (+0.5 m s⁻¹) is limited to the east of Greenland around 70°N, which generates convergence on the northeast of Iceland with the easterly flow. The main lowest negative meridional wind component differences (< -2 m s⁻¹) are in the Barents Sea and the Norwegian Sea, while positive differences cover Fram Strait along the coast of Greenland and the Denmark Strait (+1 m s⁻¹). The downward longwave differences are shown in Figure 5.11d and largely correspond in sign to those of Figure 5.11a. The most of negative differences cover the north of Greenland, the Fram Strait, the Greenland Sea, and northern Greenland extending to the Baffin Bay and Davis Strait. The lowest centers are located on Svalbard (<-15 W m⁻²), Fram Strait (<-15 W m⁻²), and northeast of Iceland (< -10 W m⁻²), while the positive difference areas are over northern Canada, the Atlantic Ocean, and the northwestern European continent. The shortwave flux differences between Odden and non-Odden are displayed in Figure 5.11e. Due to the solar angle declination, the Arctic and subarctic areas receive more shortwave radiation than in the previous season (Figure 5.11e). The
highly positive difference areas generally cover the Barents Sea southward to 60°N. The maximum centers (> + 20 W m⁻²) are also located around Svalbard, the middle of Sweden, and the northeast of Iceland. Except the middle of Europe, the lowest negative areas (<-20 W m⁻²) are located over the eastern coast of Greenland from 80°N southwardly though Denmark Strait, along the coast of Greenland into northern Labrador. The differences of surface air density pattern do not show much change between FMA (Figure 5.2f) and MJJ (Figure 5.11f) and is generally apposite in sign to the temperature differences in Figure 5.11a. The main positive difference region (+15 g m⁻³) still occurs the Greenland Sea suggesting the Odden air density is still greater than that in non-Odden condition in this season. In air specific humidity pattern (Figure 5.11g), the primary negative specific humidity differences still mainly cover the Greenland Sea but concentrate in two centers with minimum values less than -0.4 g kg⁻¹ between Svalbard and Iceland, while positive areas widely covers the European continent, and the northern Atlantic Ocean. Although the negative precipitation differences cover most of the Fram Strait, the Greenland Sea, and the Barents Sea, the values are very small (0 to -0.5 g s⁻¹ m⁻²) showing not much difference between Odden and non-Odden events (Figure 5.11h).

5.3.1 Sea ice concentration (SIC)

The MJJ seasonal spatial variability patterns in SIC between Odden and non-Odden scenarios are shown in Figures 5.12a–m. Figure 5.12a presents the SIC difference from experiments #1 and #2. The significantly high SIC difference belts (> 15%) are located at the west of Novaya Zemlya and north of Norway in the Barents Sea. These two areas
generally westwardly merge at Bear Island and extend southwestward into the Greenland Sea, reaching north of Iceland. The another large positive spot (> +20 %) takes place southwest of Svalbard in the Fram Strait around 0°E, 75°N, while the lowest negative SIC anomalies (< -20%) are located at south of Svalbard around 75°N, and from the Fram Strait through the Greenland Sea to Denmark Strait.

The responses of SIC to the different atmospheric forcing in MJJ are examined by experiments #3 – #9, which are demonstrated in Figure 5.12b–h. In these experiments, surface air temperature (Figure 5.12b), downward longwave (Figure 5.12d), and air specific humidity (Figure 5.12g) have similar patterns of SIC differences between Odden and non-Odden environments suggesting high correlations among these parameters. The relatively positive SIC anomalies (> +20% in Figure 5.12b, >15% in Figure 5.12d, and > +10% in Figure 5.12g) concentrate north of Iceland, while the minor positive areas are located between 0° and 5°E, and between 73° and 76°N, and over part of southern Barents Sea.

The pattern of wind driven SIC differences shows a more complicated pattern in Figure 5.12c. The lowest negative SIC differences (< -15%) are located at the southern Greenland Sea (north of Iceland), and south of Svalbard southwestward to 0°E between 71° and 75°N. The positive area (> +15%) starts from Novaya Zemlya across the Barents Sea to south of Svalbard, while the other positive SIC activity (> +20%) takes place in the Fram Strait generally between 75° – 80°N. Figure 5.12e presents the feedbacks of the SIC difference to shortwave radiation. The negative responses cover the most of analysis domains, while the lowest negative SIC differences (< -20%) occur at an area between 0
and 5E, and between 73° and 76°N. The SIC differences have the small negative responses to the surface air density and precipitation in most of analysis region (Figures 5.12f and h, respectively).

Overall, the mixed SIC response (Figure 5.12a) in the region north of Iceland is due partly to air temperature and to wind forcing. The southerly wind forcing east of Greenland (Figure 5.3c) produces a negative SIC difference northwest of Greenland and up the Greenland coast. The low air temperatures (Figure 5.11a) produce greater ice northeast of Greenland (Figure 5.12a).

The MJJ mean of the SIC differences to the all Odden/non-Odden atmospheric and oceanic parameters is shown in Figure 5.12i. After adding the Odden/non-Odden oceanic forcing into the experiments, the positive and negative SIC anomaly spatial patterns are relatively similar to that in Figure 5.12a, but Figure 5.12i shows more detailed SIC variability especially on the ice margins. This implies some important effects from the oceanic forcing in this region. By using 26 year climatological atmospheric forcing with Odden/non-Odden oceanic parameters, Figure 5.12j presents large positive SIC difference limited on the Fram Strait between 0° and 5°E, and between 73° and 80°N. The lowest negative differences concentrate in the area east of Greenland (i.e., between 0° and 5°W, and between 72° and 81°N). Using climatological atmospheric forcing in Figure 5.12j, a positive SIC differences northeast of Iceland has disappeared compared to Figure 5.12i, suggesting the high correlation between the SIC in this area and Odden atmospheric forcing. Similarly, some of the negative differences northwest of Iceland are weaker.
The ocean surface current experiment (Figure 5.12k) shows nearly the same patterns as that in Figure 5.12j, while the results of sea surface slope experiment (Figure 5.12l) shows little linkage to differences occurring between Odden or non-Odden events. Figure 5.12m shows the experiment results from Odden/non-Odden atmospheric environment simulation with 26 year climatological oceanic data. The SIC difference pattern is similar to that shown in Figure 5.12a and 5.12i, but the SIC variability with stronger positive differences intensified south of Svalbard southwestward to the northeast of Iceland, and a weaker negative response in the Greenland Sea.

5.3.2 Mean ice thickness

Figure 5.13a shows the mean ice thickness difference between Odden and non-Odden atmospheric environments integrated with original CCSM3 oceanic data. The positive/negative field patterns are similar to the SIC difference pattern shown in Figure 5.12a. Comparing to the previous season (FMA), the original thickness increase area in the Barents Sea is reduced. The other original positive area in the Greenland Sea not only decreases the magnitude to 0.1m, but also moves to the northeast of Iceland with +0.3m thickness maximum increases.

The ice thickness response to experiments #3 (Figure 5.13b; the Odden temperature) and #5 (Figure 5.13d; the Odden downward longwave radiation) have the similar patterns characterized by relatively high thickness increases north of Iceland and west of Greenland, additionally with extreme high thickness increase in +0.4m response to air temperature (Figure 5.13b), and +0.3m to longwave radiation flux(Figure 5.13d).
The interactions between ice thickness and the wind parameter (Figure 5.13c) present increasing thickness (> +0.3m) north of 73°N including east and west of Svalbard in the Barents Sea and Fram Strait. The largest decrease area (< -0.4m) is mainly located over the Greenland Sea, southward to the north coast of Iceland. Figure 5.13e presents the feedback of thickness to the shorwave radiation flux. The main decreased in thickness (< -0.3m) occurs between 5°E – 5°W, and between 73° – 76°N, while the broadly decreases of sea ice thickness covers the whole domain, suggesting the minor influence of shortwave forcing on ice thickness. Figures 5.13f–h show large areas with low negative thickness difference (< -0.1m) responses to the surface air density (Figure 5.13f), air specific humidity (Figure 5.13g), and precipitation (Figure 5.13h). Although Figure 5.13g shows small thickness increase northeast of Iceland, the main responses from these experiments indicate low correlations between Odden ice thickness and these parameters.

The variability of ice thickness related to full Odden/non-Odden atmospheric and oceanic forcing are shown in Figure 5.13i. The high thickness difference increases (> +0.4) occur at the Barents Sea, the north coast of Greenland and the extreme eastern Greenland Sea. Ice thickness difference patterns are characterized by the positive and negative areas located on east and west side, respectively, suggesting a weak southward ice flow from the Arctic but an eastward expression of the Odden. Figures 5.13j and k display this ease/west increase/decrease thickness pattern as well, even though their increase/decrease regions only generally cover 73° – 80°N. As with results in previous experiments, Figure 5.13l contains poor responses indicating the low relation between sea surface slope and Odden ice thickness variability. Since the results in Figure 5.13j and k
are forced by climatological atmospheric parameters instead of the Odden atmospheric forcing in Figure 5.13i, the thickness reductions northeast of Iceland possibly indicate the effects of Odden atmospheric forcing to this area.

In the simulations of Odden/non-Odden atmospheric conditions with climatological oceanic parameters, the thickness difference pattern shown in Figure 5.13m is similar to that in Figure 5.13i. However, in the Figure 5.13m, the field pattern has higher (> 0.4m)/lower (< -0.4m) thickness increase/decrease in the Greenland Sea, which imply the effects of general oceanic parameters on thickness variability.

5.3.3 Sensible heat flux

The MJJ sensible heat differences associated with Odden and non-Odden year forcing are shown in Figures 5.14a–m. The small negative/positive sensible heat differences in the figures indicate the minor effect of this parameter related to the Odden/non-Odden atmospheric and oceanic forcing to the apparent decrease of the air temperature difference between these two scenarios in MJJ. General speaking, the Greenland Sea is characterized by the minor negative areas (0 to -5 W m⁻²) shown in Figures 5.14a, b, e, and h, while the minor positive feedback takes the same place shown in Figures 5.14c, d, and g. Similar results are represented in experiments #10 – #18. The small negative signal (0 to -5 W m⁻²) located over the most of the Greenland Sea, while several minor positive spots (0 to +5 W m⁻²) distribute in a southwest/northeast oriented area between 10°W and 10°E, and between 67° and 75°N. These results are consistent
and agree with those from the experiments of air temperature, the wind field and air density as related to sensible heat from Equation 5.2.3.

5.3.4 Latent heat flux

Figure 5.15a shows the pattern of the latent heat flux difference between Odden and non-Odden environments. Comparison with previous season (FMA), the original positive difference (> +4 W m⁻²) east of Greenland reduces in magnitude (> +2 W m⁻²) and retreats back to the north of 70°N. A negative latent heat difference from south of Svalbard takes place over the Greenland Sea and Denmark Strait with additional low negative values (< -4 W m⁻²) connect to the north coast of Iceland. In Figure 5.15b, positive latent heat differences between Odden and non-Odden response to the MJJ Odden air temperature occur in northern Canada, north and west of Greenland and the Greenland Sea, especially on the northeastern coast of Iceland with values > +4 W m⁻². At the same time, negative areas cover the eastern Fram Strait and the Barents Sea. Similar pattern occurs in the longwave experiment with smaller positive (+ 3W m⁻²)/negative (-3 W m⁻²) differences shown in Figure 5.15d. These results indicate that although reducing the differences of air temperature and longwave between Odden and non-Odden environments (Figures 5.2a and d, and 5.3a and d), the latent heat still has the sensitive feedback to these parameters in MJJ. An inverse pattern appears in the response of latent heat difference to the Odden air specific humidity experiment in Figure 5.15g, apparent in the negative differences (< -4 W m⁻²) appearing northeast of Iceland, and northwest of Greenland. Positive differences take place over in the Barents Sea and the
northeast coast of Canada at the same time. The difference of latent heat response to the
Odden wind, shortwave and precipitation parameters are shown in Figures 5.15c, e, and h. One similarity in the latent heat patterns is the negative (< -4 W m⁻²) area between
10°W and 5°E, and from 71° to 75°N (Figures 5.15c and e), while most north of
Greenland and the Greenland Sea are also covered with minor negative difference
responses (Figures 5.15c, e and h).

The effects of the full Odden/non-Odden parameters to the latent heat flux
differences are shown in Figure 5.15i. A negative area with the lowest difference less
than -4 W m⁻² appears in the area starting around 10°E, 76°N southwestward to the coast
of Iceland. The minor positive area is located at southeast side of the large negative area.
A similar set of differences (+5 to +10 W m⁻²) occurs in response to Odden atmospheric
and climatological oceanic forcing (Figure 5.15m). The Odden oceanic experiments (i.e.,
experiments #12 – #16) have low negative feedbacks of latent heat differences (0 to -5 W
m⁻²) indicating their low relevance to the Odden ice feature. According to these results,
the patterns in Figure 5.15i seem to point out the important roles of the Odden wind field,
shortwave, and air specific humidity forcing associated with the latent heat responding to
the Odden environment.

5.3.5 Sea ice velocity

Figure 5.16a shows the MJJ sea ice velocity differences between Odden and non-
Odden atmospheric environment with CCSM3 oceanic output. The large northerly SIM
differences (> 10 cm s⁻¹) occur in the Barents Sea, and the east and the northeast of
Iceland, while the SIM difference southwest of Svalbard appears the southerly velocity toward the Arctic Ocean. The relatively high velocity differences northeast of Iceland indicate the potential ice advection in the Odden year (Figure 5.12a and 13a).

As like the previous season (FMA), beside the large responses to the Odden wind parameter, the SIM has no response to the air temperature (Figure 5.16b) and longwave forcing (Figure 5.16d) suggesting no correlation between SIM and these two parameters. Relatively random variations in SIM differences also occur in response to the shortwave radiation (Figure 5.16e), air density (Figure 5.16f), air specific humidity (Figure 5.16g) and precipitation (Figure 5.16h) experiments. As like the low SIC and thickness difference responses to these experiments, the similar SIM patterns suggest that the above parameters have the minor effect to move the sea ice in this period. The SIM difference feedback to the Odden wind parameter is shown in Figure 5.16c. Generally speaking, the SIM pattern in Figure 5.16c is similar to that in Figure 5.16a. However, there is more random variability appearing in the Fram Strait, but overall there is evidence of a good correlation of the SIC and thickness variability with Odden wind driven effects.

The SIM difference response to the full (i.e., atmospheric and oceanic) Odden/non-Odden environment is represented in Figure 5.16i. Two relatively large SIM difference (>15 cm s\(^{-1}\)) convergences appear on northeast of Iceland, and an area between 15\(^\circ\)W and 15\(^\circ\)E, and between 70\(^\circ\) and 80\(^\circ\)N. In the latter, the maximum difference of sea ice velocities can be over 15 cm s\(^{-1}\). The active SIM in this area also indicates the convergence and divergence activities associating with the formation and decay of the SIC (Figure 5.12a) and thickness (Figure 5.13a) in this season. By using climatology
instead of Odden atmospheric forcing (Figure 5.16j), the most important SIM differences only appear in an area between 15°W and 15°E, and between 70° and 80°N. The area of larger differences northeast of Iceland has disappeared in this experiment suggesting that the possible linkage between the Odden atmospheric forcing and the SIM activity in this area. As in FMA, very similar SIM difference patterns occur in Figures 5.3.5j and k with tiny SIM responses shown in Figure 5.16l indicating the great effect of surface currents in the oceanic experiments. Figure 5.16m shows the SIM difference response to the Odden/non-Odden atmospheric forcing with climatological oceanic data. The SIM pattern is similar but the magnitude is most likely lower than that shown in Figure 5.12a suggesting that the Odden oceanic forcing (surface currents) might be a factor to strength or weaken sea ice activity. These results are constant with that in FMA. The different SIM patterns between Figure 5.16a and i are caused by the different oceanic forcing (i.e., CCSM3 output in Figure 5.16a, and Odden/non-Odden oceanic forcing in Figure 5.16i). The different SIM pattern implies that the ocean environment can really affect the sea ice movement in Odden and non-Odden scenarios.
Figure 5.11: The MJJ average differences of the atmospheric input parameters (Table 4.1) between Odden (1997) and non-Odden (1994) years from the NCEP/NCAR Reanalysis dataset. (a) 10m air temperature, (b) 10m u component wind, (c) 10m v component wind, (d) surface downward longwave flux, (e) total surface shortwave flux, (f) 10m air density, (g) 10m air specific humidity, and (h) precipitation.
Figure 5.12: The MJJ average of the sea ice concentration (SIC) difference between Odden and non-Odden conditions. (a) the difference between experiments #1 and #2, (b) – (h) the differences between experiments #3 – #9 and #11, (i) the difference between experiments #10 and #11, (j) the difference between experiments #12 and #13, (k) – (l) the differences between experiment #15 – #16 and #13, and (m) the difference between experiments #17 and #18.
Figure 5.12 continued
Figure 5.13: The MJJ average of the mean sea ice thickness difference between Odden and non-Odden conditions. (a) the difference between experiments #1 and #2, (b) – (h) the differences between experiments #3 – #9 and #11, (i) the difference between experiments #10 and #11, (j) the difference between experiments #12 and #13, (k) – (l) the differences between experiment #15 – #16 and #13, and (m) the difference between experiments #17 and #18.
Figure 5.13 continued
Figure 5.14: The MJJ average of the surface sensible heat difference between Odden and non-Odden conditions. (a) the difference between experiments #1 and #2, (b) – (h) the differences between experiments #3 – #9 and #11, (i) the difference between experiments #10 and #11, (j) the difference between experiments #12 and #13, (k) – (l) the differences between experiment #15 – #16 and #13, and (m) the difference between experiments #17 and #18.
Figure 5.14 continued
Figure 5.15: The MJJ average of the latent heat difference between Odden and non-Odden conditions. (a) the difference between experiments #1 and #2, (b) – (h) the differences between experiments #3 – #9 and #11, (i) the difference between experiments #10 and #11, (j) the difference between experiments #12 and #13, (k) – (l) the differences between experiment #15 – #16 and #13, and (m) the difference between experiments #17 and #18.
Figure 5.15 continued
Figure 5.16: The MJJ average of the sea ice velocity difference between Odden and non-Odden conditions. (a) the difference between experiments #1 and #2, (b) – (h) the differences between experiments #3 – #9 and #11, (i) the difference between experiments #10 and #11, (j) the difference between experiments #12 and #13, (k) – (l) the differences between experiment #15 – #16 and #13, and (m) the difference between experiments #17 and #18.
Figure 5.16 continued
5.4 Experiment results for ASO and ND

The initial atmospheric environment difference between Odden and non-Odden in August – October (ASO) and November – December (ND) are shown in Figures 5.17a–h, and Figures 5.18a–h, respectively. Typically, ASO is a season having the smallest sea ice coverage in the Arctic and subarctic area. The Odden ice area typically has disappeared by these months. The slight decrease of air temperature difference (0 to -1°C) in the Greenland Sea seems to reveals the difference reduced between Odden and non-Odden environments (Figure 5.17a) indicating that there is relatively small differences between these two seasons. The pattern of longwave radiation (Figure 5.17d), specific humidity (Figure 5.17g) and even the v-component wind magnitude has pattern of differences similar to the air temperature difference pattern. The other parameters have bare characteristics, which are not really shown the associations with each other in this moderate season.

In the ND average, the air temperature difference (Figure 5.18a) between two scenarios is built up with the strong zonal (Figure 5.18b) and meridional (Figure 5.18c) winds in the Greenland Sea. The patterns of the longwave radiation (Figure 5.18d), air density inverted (Figure 5.18f) and specific humidity (Figure 5.18g) also have relative similar patterns of differences associated with the temperature difference change, which indicate the closed linkages among these parameters. According to previous studies (Shuchman et al. 1998; Comiso et al. 2001; Rogers and Hung 2008), the large Odden ice feature actually starts from 1996 to 1998. Although 1997 is only Odden year used in the
model simulation, the ND patterns of the initial Odden/non-Odden can still tell us the next Odden onset environment in the following year.

### 5.4.1 Sea ice concentration (SIC)

Figures 5.19a–m show the SIC differences for the different experiments. The negative SIC area covers the Fram Strait in Figures 5.19a, b, i and m, while the secondary negative SIC differences are represented in the other figures indicating that the low SIC feedback in this season. The negative response appears to mostly be limited to the positive temperature differences in the forcing data (Figure 5.17a). Almost comprehensive negative SIC difference response in ASO indicate that the Odden ice is less than the non-Odden in this season.

The ND SIC differences between Odden and non-Odden environments are displayed in Figures 5.20a–m. The main lowest negative areas take place over the Barents Sea westward to south of Svalbard and southwestward to the Denmark Strait and the southeast of Greenland in most of Odden atmospheric experiments shown in Figures 5.20a, b, d, g, and m. Minor negative or positive SIC differences are shown in the remaining figures include a weak positive difference in the shortwave radiation experiment (Figure 5.20e). The SIC response in ND seems again to occur in relation to positive air temperature differences and southerly winds, especially in the Greenland.
5.4.2 Mean ice thickness

The differences of ASO mean ice thicknesses are shown in Figures 5.21a–m. Although Figures 5.21a, b, d, i, j, and k have the some small areas marked by positive values (> 0.4 m) north of Greenland, the patterns of mean ice thickness differences have the same spatial distributions as that of SIC differences shown in Figure 5.19a–m, which also have the minor negative responses appearing in the Greenland Sea in this season. The positive ASO differences north of Greenland appear to be a response a negative temperature and negative v-component forcing (Figure 5.21a and c).

Figures 5.22a–m demonstrate the patterns of the ice thickness differences in ND. There are several lowest thickness decrease areas (< -0.3 m) between Odden and non-Odden in the Fram Strait and the Greenland Sea shown in Figures 5.22a, b, i, and m. A relative high positively (+0.3m) difference occurs in the Fram Strait along the Greenwich Meridian between 75° and 85°N shown in oceanic experiments (Figures 5.22j and k) with a climatological atmosphere and salinity, respectively. The results suggest that ocean currents may play a role in transport and accumulating of ice from the Arctic Ocean to the Fram Strait in this season, which agrees with results from Aagaard and Carmack (1989), Dickson et al. (2000), Rigor et al. (2002), and Alexander et al. (2004).

5.4.3 Sensible heat flux

The sensible heat flux difference responses to Odden/non-Odden environments are shown in Figures 5.23a–m. Relatively high positive sensible heat differences occur off the northeast coast of Greenland (the Fram Strait) in the air temperature (Figure 5.23b),
full Odden/non-Odden forcing (Figure 5.23i), and Odden/non-Odden atmosphere with climatological oceanic forcing experiments (Figure 5.23m). As described before in Equation 5.2.1, the sensible heat is related to the u component wind and the temperature difference between the air and the surface. The easterly u component differences and the positive air-surface temperature differences are likely associated with this local positive sensible heat difference in these experiments (Figures 5.17a and b), while the sensible heat has no primary feedback to the other experiments in ASO.

The ND sensible heat differences have more varied responses than those in ASO. The main differences of sensible heat occur generally between 15°W and 5°E, and between 65° and 80°N in the Greenland Sea with the lowest negative values < -10 W m⁻² (Figures 5.24a, b, c, i, and m) and positive values > +10 W m⁻² (Figures 5.24d and g) associated with the effects of the differences of the initial air temperature (Figure 5.18a), zonal wind (Figure 5.18b), downward longwave radiations (Figure 5.18d) and specific humidity (Figure 5.18g) indicating high associations between sensible heat and these atmospheric parameters. Comparing with SIC and ice thickness, these results also infer that the sensible heat can sensitively reflect the atmospheric environment before the sea ice response to it.

5.4.4 Latent heat flux

The ASO latent heat flux differences are presented in Figures 5.25a–h. The major negative/positive differences occur in the Odden air temperature and the specific humidity experiments. In air temperature experiment shown in Figure 5.25b, the major
negative response with lowest value < -4 W m\(^{-2}\) is located between Greenland and Svalbard (Fram Strait) and along the eastern coast of Greenland area, while a positive area (> +4 W m\(^{2}\)) is around the northern coast of Greenland. The same areas in Odden specific humidity experiment (Figure 5.25g) show very large positive latent heat differences along Greenland’s east coast indicating the high correlations between latent heat and specific humidity. In experiment #8, the specific humidity is only one variable change from Odden to non-Odden condition. According to Equation 5.2.4.1, the latent heat is dependent upon on specific humidity when the rest variables remain the same.

Figure 5.17g shows in the positive specific humidity differences in the Greenland’s coast, which is believed to be associated with appearance of the latent heat in this area. The positive downward latent heat indicates the large area absorbs the latent heat to melt the ice during ASO.

During ND, the major positive differences (> +3 W m\(^{2}\)) of latent heat flux occur in the Barents Sea and Greenland Sea with the lowest negative difference (-1 to > -4 W m\(^{-2}\)) on south of Svalbard, the eastern boundary of the major positive area in the Greenland Sea and through the Denmark Strait based on the Odden air temperature (Figures 5.4.4.2b), downward longwave (Figure 5.26d) and air density experiments (Figure 5.26f). The specific humidity results in Figure 5.26g show a converse pattern from the experiments described above. The strong negative difference area in the Greenland Sea in Figure 5.26g is associated with an area of low \(q\) (specific humidity) in the ND atmospheric background conditions (Figure 5.18g) and an area of negative temperature differences in Figure 5.18a. The background forcing suggests that clod and dry conditions
occur in the Odden year. The latent heat experiment (Figure 5.26g) appears to capture the
cold/dry conditions in the forcing, while the air temperature experiment produces positive
differences (Figure 5.26b) in the Greenland Sea which is suggestive of latent heat
production associated with condensation and higher model temperatures in Odden.

5.4.5 Sea ice velocity

The ASO sea ice velocity differences between Odden and non-Odden conditions are
shown in Figures 5.27a–h. The southerly SIM differences imply the sea ice retreating
between Odden and non-Odden scenarios in this season (retreating in the Odden year). In
the atmospheric forcing experiments (Figures 5.27a–h), the largest SIM difference
reflects in full atmospheric forcing (Figure 5.27a) and wind forcing (Figure 5.27c), while
the very small SIM differences are generated in the other individual atmospheric
parameter (Figures 5.27b, d, e, f, g and h), which indicate that the wind parameter is the
main atmospheric forcing to effect the sea ice activity in this period. Adding with the
Odden/non-Odden atmospheric and oceanic forcing together, the SIMs show even more
southerly forcing north of 80°N. The oceanic forcing experiments (Figures 5.27j, k and l)
show the ocean’s contribution although the SIM differences are smaller than that in
Figure 5.27i indicating that the SIM activity are strongly associated with the dynamic
effects (i.e., wind, and ocean surface currents) in ASO.

The ND mean SIM differences are shown in Figures 5.28a–m. The same
conclusions can be drawn in ND as have been discuss for ASO. The Odden/non-Odden
wind differences appearing in the atmospheric forcing experiments (Figures 5.28a–h) are
largely those found in the in experiment 5.28c. Differing from the ASO, however, there
are slight northerly SIMs difference with maximum 10 cm s\(^{-1}\) appear in the south of
Svalbard, while the southerly SIMs (15 cm s\(^{-1}\)) dominate the Greenland Sea into western
Fram Strait. Under the Odden atmospheric forcing, although two SIMs with different
directions meet in the Fram Strait, while the SIC and ice thickness differences are still
negative in this area. After adding oceanic forcing into the model, the results show
stronger SIMs in both northerly and southerly directions. The maximum speed of both
SIM flows is larger than 15 cm s\(^{-1}\) are shown in Figure 5.28i and m. Meanwhile, the
merge area shows a major positive response from the ice thickness in the same area in
Figure 5.22i and m indicating a majority effect from the oceanic forcing, especially from
the surface currents.
Figure 5.17: The ASO average differences of the atmospheric input parameters (Table 4.1) between Odden (1997) and non-Odden (1994) years from the NCEP/NCAR Reanalysis dataset. (a) 10m air temperature, (b) 10m u component wind, (c) 10m v component wind, (d) surface downward longwave flux, (e) total surface shortwave flux, (f) 10m air density, (g) 10m air specific humidity, and (h) precipitation.
Figure 5.18: The ND average differences of the atmospheric input parameters (Table 4.1) between Odden (1997) and non-Odden (1994) years from the NCEP/NCAR Reanalysis dataset. (a) 10m air temperature, (b) 10m u component wind, (c) 10m v component wind, (d) surface downward longwave flux, (e) total surface shortwave flux, (f) 10m air density, (g) 10m air specific humidity, and (h) precipitation.
Figure 5.19: The ASO average of the sea ice concentration (SIC) difference between Odden and non-Odden conditions. (a) the difference between experiments #1 and #2, (b) – (h) the differences between experiments #3 – #9 and #11, (i) the difference between experiments #10 and #11, (j) the difference between experiments #12 and #13, (k) – (l) the differences between experiment #15 – #16 and #13, and (m) the difference between experiments #17 and #18.
Figure 5.19 continued
Figure 5.20: The ND average of the sea ice concentration (SIC) difference between Odden and non-Odden conditions. (a) the difference between experiments #1 and #2, (b) – (h) the differences between experiments #3 – #9 and #11, (i) the difference between experiments #10 and #11, (j) the difference between experiments #12 and #13, (k) – (l) the differences between experiment #15 – #16 and #13, and (m) the difference between experiments #17 and #18.
Figure 5.20 continued
Figure 5.21: The ASO average of the mean sea ice thickness difference between Odden and non-Odden conditions. (a) the difference between experiments #1 and #2, (b) – (h) the differences between experiments #3 – #9 and #11, (i) the difference between experiments #10 and #11, (j) the difference between experiments #12 and #13, (k) – (l) the differences between experiment #15 – #16 and #13, and (m) the difference between experiments #17 and #18.
Figure 5.21 continued
Figure 5.22: The ND average of the mean sea ice thickness difference between Odden and non-Odden conditions. (a) the difference between experiments #1 and #2, (b) – (h) the differences between experiments #3 – #9 and #11, (i) the difference between experiments #10 and #11, (j) the difference between experiments #12 and #13, (k) – (l) the differences between experiment #15 – #16 and #13, and (m) the difference between experiments #17 and #18.
Figure 5.22 continued
Figure 5.23: The ASO average of the surface sensible heat difference between Odden and non-Odden conditions. (a) the difference between experiments #1 and #2, (b) – (h) the differences between experiments #3 – #9 and #11, (i) the difference between experiments #10 and #11, (j) the difference between experiments #12 and #13, (k) – (l) the differences between experiment #15 – #16 and #13, and (m) the difference between experiments #17 and #18.
Figure 5.23 continued
Figure 5.24: The ND average of the surface sensible heat difference between Odden and non-Odden conditions. (a) the difference between experiments #1 and #2, (b) – (h) the differences between experiments #3 – #9 and #11, (i) the difference between experiments #10 and #11, (j) the difference between experiments #12 and #13, (k) – (l) the differences between experiment #15 – #16 and #13, and (m) the difference between experiments #17 and #18.
Figure 5.24 continued
Figure 5.25: The ASO average of the latent heat difference between Odden and non-Odden conditions. (a) the difference between experiments #1 and #2, (b) – (h) the differences between experiments #3 – #9 and #11, (i) the difference between experiments #10 and #11, (j) the difference between experiments #12 and #13, (k) – (l) the differences between experiment #15 – #16 and #13, and (m) the difference between experiments #17 and #18.
Figure 5.25 continued
Figure 5.26: The ND average of the latent heat difference between Odden and non-Odden conditions. (a) the difference between experiments #1 and #2, (b) – (h) the differences between experiments #3 – #9 and #11, (i) the difference between experiments #10 and #11, (j) the difference between experiments #12 and #13, (k) – (l) the differences between experiment #15 – #16 and #13, and (m) the difference between experiments #17 and #18.
Figure 5.26 continued
Figure 5.27: The ASO average of the sea ice velocity difference between Odden and non-Odden conditions. (a) the difference between experiments #1 and #2, (b) – (h) the differences between experiments #3 – #9 and #11, (i) the difference between experiments #10 and #11, (j) the difference between experiments #12 and #13, (k) – (l) the differences between experiment #15 – #16 and #13, and (m) the difference between experiments #17 and #18.
Figure 5.27 continued
Figure 5.28: The ND average of the sea ice velocity difference between Odden and non-Odden conditions. (a) the difference between experiments #1 and #2, (b) – (h) the differences between experiments #3 – #9 and #11, (i) the difference between experiments #10 and #11, (j) the difference between experiments #12 and #13, (k) – (l) the differences between experiment #15 – #16 and #13, and (m) the difference between experiments #17 and #18.
Figure 5.28 continued
5.5  Time evolution of the model Odden

5.5.1  Analysis of an easternmost model Odden area

Model results indicate the largest sea ice variability in the Odden region occurs a little southeastward of that based on observations. Analysis of the time evolution of meteorological parameters associated with the Odden area is needed to understand their contributions through time to temporal distributions of sea ice variability. In this section, the temporal model evolution of sea ice and meteorological parameters is evaluated for two regions. An easternmost model Odden region is analyzed first and is selected based on the largest FMA SIC difference occurred in the Greenland Sea between experiments #10 and #11, the full Odden/non-Odden atmospheric and oceanic parameter forcing (Table 4.2). The domain is a southwest/northeast oriented area approximately between 4°W and 10°E, and between 69.5° and 74.6°N shown in Figure 5.29. Section 5.5.2 subsequently analyzes a larger Odden region that includes the easternmost area (Figure 5.29) but which extends farther west into the area where Odden is found in observational studies but where the model largely produced a larger more persistent, unchanging, area of ice extending from East Greenland.

5.5.1.1  Sea ice concentration (SIC)

Figure 5.30a shows the time series of the easternmost model Odden SIC variations for the 18 experiments. In previous sections the results presented showed the net mean differences between experiments #1 and #2, #10 and #11, #17 and #18. In Figure 5.30,
the time series of the results are separated out into the 6 individual experiments. In addition, results for the salinity experiment is shown although it was earlier excluded.

Generally, SIC has large variability from January to July, and a minor increase in November and December. The peak Odden ice over occurs in April and May while observational studies indicate the greatest ice is from February into April. In the full Odden atmospheric forcing experiments (i.e., #1, #10, #12 and #17 with blue color), experiments #10 and #17 have the largest SICs (> 80%) in April and May, respectively, which is much larger than that in the other experiments. The SIC in experiment #1 (Odden atmospheric forcing with CCSM3 background oceanic forcing) has a maximum SIC of ~55% in April, while experiment #18 has a higher maximum SIC of ~60% in March, which then rapidly declines. In the series of climatological atmospheric forcing with individual oceanic forcing experiments (i.e., experiments #12 to #16), the sea surface current results are very similar to that in the Odden oceanic environment, while the sea surface slope results have very low impact on SIC between the Odden and non-Odden experiments. These results are reflected by the fact that temporal SIC variability in experiments #15 and #16 are always almost the same as in experiments #12 and #13, respectively. The maximum SIC in experiment #12 with climatological atmospheric forcing is less than 40% in April, less than a half of the SIC (80%) in experiment #10. The highest SIC responses to the Odden atmospheric environment with the Odden ocean (experiment #10) and climatological ocean (experiment #17) indicate that the easternmost model Odden sea ice is the highly correlated with atmospheric forcing.
In the general full non-Odden atmospheric forcing environments (i.e., experiments #2, #11, #13 and #18 with red color), the SICs typically reach a maxima in March and a secondary peak ice in May (except experiment #13). The results show that experiment #18 (non-Odden atmosphere with climatological ocean) has the largest SIC of 65%, while experiment #11 has 40% SIC in March. Experiments #2 and #13 show results having low SIC (<20%) response to these simulations during March to May.

Experiment #4, with Odden wind field simulation shows a SIC maxima (~40%) in March, and are especially prominent among atmospheric forcing in April and May, indicating the wind effect is involved to driving sea ice variability in this season. The SIC responses to the atmospheric forcing experiments #3 – #9 have similar time variability to that in non-Odden experiment #11, but downward longwave radiation, air temperature and specific humidity have slightly more contribution to SIC than occurs in the non-Odden experiment. Shortwave, air density and precipitation have minor effects during the April to June period.

The individual Odden atmospheric forcings have a limited effect on SIC variability in January and February ice formation. From March through May, the primary SIC responses (30% – 40%) are to wind (experiment #4) and sea surface currents (experiment #15) with a secondary response (20% – 30%) to downward longwave radiation (experiment #5), air temperature (experiment #3) and shortwave radiation (experiment #6). These seem to play important roles in producing and maintaining the sea ice formation till the end of April. SIC starts to decline after May. At this time the SIC response to air temperature and longwave radiation become as large as that to wind and
sea surface currents, indicating that air temperature and longwave radiation are important in the ice melting processes during this period. The results suggest that in Odden sea ice formation period, the dynamic effects are more important than thermodynamic effects. When sea ice starts to melt, the thermodynamic forcing becomes increasingly important.

5.5.1.2 Mean ice thickness

Figure 5.30b shows the annual trends of mean ice thickness in response to the 18 experiments. In experiments #1, #10, #12 and #17, the results generally agree with that in the SIC results showing the highest thickness (1.3m) in April. Experiments #10 and #17 have the thickest sea ice accumulation ~1.3m in April, while experiments #1 and #12 have the sea ice much thinner than ~0.4m during the same period. The thickness in full non-Odden environment experiments are highly variable. Experiment #18 has the highest thickness of ~1.0m in April and 0.8m in May, while experiment #11 has the thickness of about 0.7m in April and 0.5m in May. Meanwhile, experiments #2 and #13 have ice thicknesses that are relatively thinner than 0.2m.

In experiments #3 to #9, the temporal patterns are similar to that of experiment #11. Relatively low thickness (~0.3m) occurs in April except in response to the wind parameter (experiment #4). In the wind experiment, the thickness starts at 0.3m in January, reached its maximum value (0.7m) in April, and declined to zero by August, which indicates the Odden wind field can efficiently maintain the ice compared to other meteorological parameters. Downward longwave radiation, air temperature, and specific humidity create somewhat thicker ice between April and August than occurs in non-
Odden experiments, suggesting that Odden atmospheric forcing can help to maintain the ice thickness against melting after March. Shortwave radiation, air density and precipitation produce the ice thickness responses that are lower than that in experiment #11, showing their minor contributions with this time.

5.5.1.3 Sensible heat flux

The time series of sensible heat flux response in the 18 experiments are presented in Figure 5.30c. The sensible heat response has similar time tendencies in full Odden atmospheric environment experiments increasing from January, reaching maximum values (~ 20 W m⁻²) in April and dropping to zero in July. Similar patterns occur in experiments #10 and #17, which is consistent with the SIC and thickness results shown before. The full non-Odden experiments (#2, #11 and #18) have the largest sensible heat flux with 25 W m⁻² in experiment #18, 17 W m⁻² in #11, and 8 W m⁻² in March. The sensible heat flux has low correlation with the climatological atmospheric and the Odden/non-Odden oceanic forcing conditions (experiments #12 – #16), but has high correlation with the combination of the Odden/non-Odden atmospheric and the climatological oceanic conditions in experiment #18 implying that the climatological atmospheric forcing could dilute the atmospheric effects. Moreover, positive sensible heat flux in experiment #10 (solid blue line) is always larger than that in experiment #11 (solid red line) during February to June indicating that under Odden conditions, ice gains more sensible heat from the air than in non-Odden conditions, to balance the energy budget.
The sensible heat flux in air temperature experiment #3 is negative in January (-1 W m\(^{-2}\)) and April (-2 W m\(^{-2}\)), but reaches its maximum value (+ 6 W m\(^{-2}\)) in February and its temporal pattern matches that of non-Odden conditions in experiment #11, suggesting a limited role in producing sensible heat flux. The sensible heat flux in the wind experiment (#4) remains around 14 W m\(^{-2}\) from January to the beginning of April and then drops down to 0 in middle of July, which is very similar to the patterns in experiments #10 and #17 (Odden conditions), reflecting the strong correlation between wind and sensible heat flux described in Equation 5.2.1. The rest of experiments #5 – #9 have similar trends of the sensible heat flux to that in experiments #11. The sensible heat flux in longwave radiation (#5) and specific humidity (#8) experiments have larger responses than that to experiments #10 and #17 in the beginning of March implying the effects of the climatological oceanic forcing. This response is also larger to experiment #11 in February to August, while shortwave (experiment #6), air density (experiment #7) and precipitation (experiment #9) have lower sensible flux responses to non-Odden atmosphere and oceanic forcing. These results indicate that, in the non-Odden environment, the sensible heat is sensibly influenced by the Odden longwave and specific humidity variability in this period, especially in the end of February and the beginning of the March. Overall, during February and March, high responses show the importance of Odden downward longwave radiation and specific humidity related to the sensible heat flux in the ice growth period. After reaching the largest sea ice in April, the wind parameter begins to dominate the sensible heat flux variability.
5.5.1.4 Latent heat flux

The annual cycle of latent heat flux responses to the 18 experiments is shown in Figure 5.30d. Experiments #1, #10 and #17 have very similar time variations of latent heat feedbacks with positive values before March, negative values in April and May, and back close to zero by June until the end of the year. During January to March, the surface has less SIC (20% ~ 60% in Figure 5.30a) and thinner ice (0.2 ~ 0.9m in Figure 5.30c) than occurs in April and May (60% ~ 80% with 0.9 ~ 1.3m). The surface with lower air temperature has minor downward latent heat flux involved in melting or evaporating processes even the sea ice keeps expanding. In April, the surface is covered by about 80% SIC with 1.3m thickness. The latent heat flux turns toward the atmosphere with freezing and condensation processes associated with ice formation. After April, the latent heat flux has an upward trend and back to the positive after June as the latent heat flux changes in sign, associated with melting ice.

The Odden air temperature (experiment #3) and specific humidity (# 8) have opposite tendencies in the relation of the latent heat flux. In Equation 5.2.4.1, the specific humidity is directly associated with the variability of latent heat flux. Meanwhile, the downward longwave radiation (experiment #5), air density (#7) and wind (#4) have minor influence on the flux. The response to wind increases to its highest value (3 W m\(^{-2}\)), close to that of air temperature during April. It implies that the wind is a main forcing involved in the ice maximum stage. In conclusion, the latent heat is strongly affected by air temperature, specific humidity and wind forcing, especially in the high sea ice formation period.
5.5.1.5 The u component of sea ice velocity

The changes of the u component of the sea ice velocity are displayed in Figure 5.30e. Before April, the experiments with full Odden atmospheric forcing (i.e., experiments #1, #10 and #17) have the opposite trends to the full non-Odden atmospheric forcing experiments (i.e., experiments #2, #11 and #18). The Odden experiments show the SIMs have a strongly easterly advection after the middle of January till June, especially in February (~ -10 cm s⁻¹) which has the same trend as the Odden wind experiment (#4). This simulation was forced by Odden wind with other non-Odden parameters, and the u-component of SIM agrees with that the strong Odden wind driven effects. The other atmospheric parameters (experiments #3, #5 – #9) show the same trends as full non-Odden experiment meaning they have a minor effect on the u-component of SIM. In the experiments with climatological atmospheric but Odden/non-Odden oceanic forcing, the SIM u-component shows a westerly direction most of the time. It is not compatible with the full Odden experiment results indicating the low relationship between them.

5.5.1.6 The v component of sea ice velocity

The time variation of the Odden wind experiment (#4; Figure 5.30f) on the SIM v-component is very similar to that in experiments #1, #10 and #17 (i.e., full Odden atmospheric forcing experiments). The importance of the wind driven forcing is apparent, as with the u-component. The easternmost model Odden sea ice has strong northerly
advection starting from January and changes to weak southerly flow in the beginning of February. The SIM returns to northerly and reaches its highest value of about -11 cm s$^{-1}$ in April.

The rest of experiments show the similar annual time variations in the sea ice v component. They have mostly southerly sea ice velocity with highest values in March (4 cm s$^{-1}$) that gradually change to near zero closely matching the outcome of SIM activity in non-Odden events. Combining the u- and v-components together, Odden SIM is strongly associated with the wind driven effect. From February to April, SIM is added by direction changes from southeasterly to northeasterly during the period of ice growth. The non-Odden ice motions are southerly in February, April and May.
Figure 5.29: The selected domain of the model Odden region is based on the highest SIC difference in the Greenland Sea shown in Figure 5.6i.
Figure 5.30: The annual trends of variables in model Odden region. (a) SIC, (b) ice thickness, (c) sensible heat flux, (d) latent heat flux, (e) the u component of ice velocity, and (f) the v component of ice velocity.
Figure 5.30 continued
Figure 5.30 continued
5.5.2 Analysis of a larger model Odden area

According to Comiso et al. (2001), who used satellite data to track the Odden sea ice variability in 1997, Odden sea ice variability generally occurs in an area between 20°W and 8°E, and between 70° and 76°N. The purpose of this section is to evaluate a larger Odden realm to see the time variation of the model output parameters. Comparison can be made then to results for the eastern most area of Odden model ice results in the previous section. The domain selected to analyze its physical parameters are shown in Figure 5.31 and are referred to as the extended or larger Odden region.

5.5.2.1 Sea ice concentration (SIC)

The SIC variations for the 18 experiments are shown in Figure 5.32a. To identify details of the small variations among the experiments, Figure 5.32a only displays SIC values greater than 70% occurring from January to May. The SIC has the largest coverage from February to April, which is generally consistent with observational studies. Experiments #10 and #17 have the largest SIC (> 95%) in March and April larger than in other experiments. It suggests that the SIC variability is strongly correlated with atmospheric forcing similar to results of the model Odden region described in section 5.5.1.1.

The SIC in experiment #18 with Odden atmospheric forcing and climatological oceanic background forcing shows a SIC maximum of ~ 96% in March that quickly declines to lower than 85% in April and May. The SICs for the series of climatological atmospheric forcing with individual oceanic forcing experiments (i.e., experiments #12 to
yield the same results to that in the model Odden region, indicating that the sea
surface current has larger impact on SIC than sea surface slope between Odden and non-
Odden experiments. Experiment #12 has a very similar SIC temporal distribution to that
in experiment #18, even though the SIC is ~ 5% lower than that in experiment #18. Wind
field simulation (#4) shows large SIC (90%) in April, which is higher than that in
experiment #11 suggesting the wind driven effects are important at peak SIC.

The SIC responses to atmospheric forcing experiments #3 – #9 have similar time
variability to that in non-Odden experiment #11, except that downward longwave
radiation, air temperature and specific humidity have slightly more contribution to SIC
than occur in the non-Odden experiments. Generally speaking, in January ice formation is
larger for non-Odden forcing than for Odden and the individual Odden atmospheric
forcing has a limited effect on the SIC variability. From March through April, results
show the primary SIC response to wind (experiment #4) with a secondary response to the
thermodynamic forcing experiments including downward longwave (experiment #5), air
temperature (experiment #3), and specific humidity (experiment #8). When ice is melting
in May, the wind effect is reduced, and the thermodynamic effects become important in
ice retreat. The result is similar to that in the smaller eastern Odden area.

5.5.2.2 Mean sea ice thickness

Figure 5.32b presents the time variability of mean sea ice thickness for all
experiments in the larger Odden region. Unlikely SIC, all experiments have very similar
timing patterns; a peak in April and lowest value in September. In the simulation of the
full non-Odden atmospheric and oceanic forcing (experiment #11), the ice thickness has the largest response to the air temperature (experiment #3), downward longwave radiation (experiment #5), and the specific humidity (experiment #8), while the other atmospheric forcing has a small impact on thickness from February to September, indicating that thermodynamic forcing is mainly affecting sea ice thickness variability. The results in the series of oceanic forcing (i.e., experiments #12 – #16) shows the largest ice thickness is about 0.6m (experiment #13) in May, which is later but much lower than the 1.4m (experiment #11), and 1.2m (experiment #10) results for April. It implies that the ocean environment might provide a negative effect on sea ice thickness. The Odden air temperature, longwave radiation and specific humidity can give positive feedbacks to ice thickness, while the Odden wind effect and ocean forcing have negative effects on ice thickness. Thus, the full Odden atmospheric and oceanic forcing experiment (#10) shows thinner sea ice than that in the full non-Odden atmospheric and oceanic forcing experiment (#11) in this region.

5.5.2.3 Sensible heat flux

The annual cycle of sensible heat flux feedback in the 18 experiments is shown in Figure 5.32c. The sensible heat feedbacks to full non-Odden atmospheric forcing environment (experiments #2, #11, and #18) have downward trends from 30 W m\(^{-2}\) to near zero during January to May. An upward trend for full Odden atmospheric forcing environment (experiments #1, 10, and #17) starts from 10 W m\(^{-2}\) in January, reaches a maximum of 20 W m\(^{-2}\) before declining to near zero in May. Two peaks of sensible heat
occur in response to specific humidity (experiment #8) and downward longwave radiation (experiment #5) and appear in January (> 40 W m\(^{-2}\)) and March (~30 W m\(^{-2}\)). Meanwhile the response to air temperature (experiment #3) has two lowest values with -40 W m\(^{-2}\) in January and -20 W m\(^{-2}\) in April. The relatively high responses in experiments #8 and #5, and the lower response in #3 indicate the strong correlations between sensible heat and these parameters consistent with results in section 5.5.1.3. The lowest sensible heat response to the air temperature experiment with a rising trend indicates that the vertical temperature gradient is increased in the colder Odden air temperatures and the surface releases sensible heat to the atmosphere (negative sign). When air temperature increases from January to June, the upward sensible heat also decreases, or even changes sign to positive when the vertical temperature gradient is small enough. Combining the effects from air temperature, specific humidity and longwave radiation by May and June, the sensible heat is positive all the time suggesting the model atmosphere has a sensible heat flux is transported from atmosphere to the surface.

5.5.2.4 Latent heat flux

Figure 5.32d presents the time series of latent heat flux response to the 18 experiments. Generally, most of the latent heat time sequence has a pattern of downward latent flux (positive sign) all the time except in May. As in the results of the eastern most model Odden region in Figure 5.30d, a primary positive response is to air temperature (experiment #3) with largest magnitudes in January (+38 W m\(^{-2}\)) and April (+25 W m\(^{-2}\))
and a secondary response to longwave radiation (experiment# 5) in January (+ 14 W m\(^{-2}\)) and March (10 W m\(^{-2}\)). During the same time, the response to the specific humidity (experiment #8) has lowest magnitudes with -25 W m\(^{-2}\) in January, and -20 W m\(^{-2}\) in April, respectively. The results are similar to those shown in Figure 5.30d for the eastern most Odden region, but latent heat flux the magnitudes are larger due to the analysis domain covers an area with large FMA air temperature forcing differences between Odden and non-Odden years (Figure 5.5), with similar extremes in longwave radiation and specific humidity (Figures 5.2a, c, and g, and 5.3a, c, and g). The latent heat is strongly associated with the above three meteorological parameters. Limited differences occur between the full Odden and non-Odden forcing simulations (i.e., experiments #10 and #11) just as in the easternmost model Odden region, which has the largest downward latent heat flux of \(\sim +5\) W m\(^{-2}\) in March, and upward flux of \(\sim -5\) W m\(^{-2}\) in May implying the surface evaporating and freezing processes involved in different seasons.

### 5.5.2.5 The u component of sea ice velocity

The time change of the u component of the sea ice velocity in the 18 experiments is shown in 5.5.4. The experiments with full Odden atmospheric forcing experiments #1, #10 and #17 have, through March, opposite trends to the full non-Odden atmospheric forcing experiments (i.e., experiments #2, #11 and #18). The easterly SIMs in Odden experiments are increased with time to the maximum \(-16\) cm s\(^{-1}\) in February, decrease and change to reach the westerly maximum about \(6\) cm s\(^{-1}\) in July. After July, the trend of u-component SIMs declines until the end of the year. For the non-Odden experiments, the
SIMs decrease the easterly speed from -20 cm s$^{-1}$ to -1 cm s$^{-1}$ in January, and increase the speed from -1 cm s$^{-1}$ to 18 cm s$^{-1}$ in February. After March, the u-component of sea ice advection decreases its speed and change the direction in June. Starting in July, the trends of the non-Odden experiments are almost the same as that of Odden experiments until November indicating little differences in model forcing. The trends in all experiments are generally the same as that in the easternmost model Odden region. It is found that the u-component of SIM in the Odden wind field (#4) and sea surface current experiments (#15) has the same time trend as the Odden-like experiments, which suggests that the SIMs are strongly associated with wind and sea surface current effects in this area. The magnitudes of u-component are slightly more negative (easterly) in this larger area than in the easternmost model Odden area. In January, March and April the winds are more easterly in non-Odden than in Odden years, consistent with observational studies.

5.5.2.6 The v component of sea ice velocity

In the v component of sea ice velocity annual cycle (Figure 5.5.4f), the SIM responses in all experiments have northerly motions. There are only small v-component differences between Odden and non-Odden experiments suggesting that the v component of SIM has low response to the Odden and non-Odden environments in this spatial domain (Figure 5.31). The SIM in wind (#4) and ocean current experiments (#15) also have the similar trends with these experiments indicating their high association with SIM advection in both extremes. The non-Odden winds in this larger area remain northerly
throughout all months while they become southerly in the small easternmost region (Figure 5.30f).
Figure 5.31: The selected domain of the model Odden region is based on 1997 Odden ice feature shown in Comiso et al. (2001).
Figure 5.32: The annual trends of variables in model Odden region. (a) SIC, (b) ice thickness, (c) sensible heat flux, (d) latent heat flux, (e) the u component of ice velocity, and (f) the v component of ice velocity.
Figure 5.32 continued
Figure 5.32 continued
CHAPTER 6: CONCLUSIONS AND FUTURE WORK

6.1 Discussions and conclusions

The primary goal of this study was to investigate Odden sea ice response to specific atmospheric and oceanic environments, and the seasonal interactions among atmosphere, sea ice and ocean surface in the Greenland Sea area. In order to tackle this, 18 experiments were designed to examine a 26 years (1979 – 2004) of atmospheric and oceanic input data by using the National Center for Atmospheric Research (NCAR) Community Climate System Model 3.0 (CCSM3). To limit the complicated dynamic forcing effects from the ocean circulations, the M configuration of CCSM3 with a simple slab model was chosen to use in this research.

By integrating with 26 years of NCEP/NCAR Reanalysis data as atmospheric and CCSM3 oceanic forcing, the SIC simulation in the control run shows a high positive SIC variability at the far east and southeast side of an area shown by observational data to be the typical Odden region in the Greenland Sea. PCA and RPCA methods were applied to the 26 year control run output to analyze and evaluate the capability of this simple model to reproduce the Odden sea ice variations. The Labrador Sea is out of phase with the Odden variability, which is consistent with the results from the observations and the patterns derived from HadISST data reported by Rogers and Hung (2008). This compatible result suggests that although oceanic dynamic mechanisms are excluded (e.g.,
ocean circulation) within the slab ocean model, the M configuration still has the ability to reproduce and simulate the Odden sea ice fairly well.

The 18 model experiments are designed to evaluate the model response to forcing of various types during a single year (e.g., Odden in 1997, and non-Odden in 1994) as well as combinations of 26 year climatological atmospheric and oceanic forcing (Table 4.2). In the seasonal spatial distributions, the model does a reasonable job in capturing the Odden characteristics under the full Odden/non-Odden atmospheric and oceanic parameter experiments in FMA and MJJ. During these two seasons, in the Greenland Sea, the highest positive SIC and ice thickness differences between Odden and non-Odden environments are located along a southwest/northeast area between 10°W and 5°E, and between 67° and 75°N, and as such the so-called model Odden is a little southeastward of the typical Odden area in observational studies. In this region, the relatively high positive response in SIC and ice thickness was strongly associated with the effects of wind, air temperature, downward longwave, and oceanic currents.

The sensible and latent heat fluxes are also examined by the 18 experiments. The results show that they are strongly correlated with temperature difference between air and surface, the initial u-component wind field, downward longwave radiation, and specific humidity, which are defined in Equations 5.2.3 and 5.2.4.1. With full Odden/non-Odden forcing integrations in FMA, the positive sensible heat difference between Odden and non-Odden simulations suggests that the non-Odden air temperature is warmer than that in Odden condition although both are warmer than the surface. Combining the effects of air temperature, specific humidity and longwave radiation, the sensible heat still shows
positive values indicating the sensible flux is transported from air to ice surface in the Odden scenario. The minor negative latent heat difference east of positive flux area in FMA (Figure 5.9), is associated with the variations of air temperature (Figure 5.2a), density (Figure 5.2f), and specific humidity (Figure 5.2g) between Odden and non-Odden background forcing conditions. The FMA positive latent heat difference area is replaced by a negative values in MJJ suggesting most of the Greenland Sea under Odden conditions has more downward latent heat toward the surface associated with condensation than occurs in the non-Odden year, but it releases more latent heat to the atmosphere inducing freezing in MJJ. The sea ice velocity response to full Odden/non-Odden forcing shows that strong northeasterly SIM (sea ice motion) differences occur with a low velocity difference on its west side, which introduces accumulation of the sea ice on the Odden region in FMA and MJJ. In other experiments, the results show that SIM always has high correlation with the Odden wind forcing and sea surface currents.

In the annual cycle of the easternmost model Odden region, the wind driven effect appears to be a primary forcing associated with Odden ice events (Figures 5.30e, f and 5.32e, f). This result has the good agreement with previous observational studies by Shuchman et al. (1998), Wadhams and Comiso (1999), Comiso et al. (2001), and Rogers and Hung (2008). The wind driven effects are associated not only with the SIC and thickness accumulations, but also the interactions of sensible heat and latent heat fluxes between the air and surface, which allows the surface to exchange energy with the atmosphere to freeze/melt the ice during the Odden ice growing/retreat months. The time variability of SIM has close agreement with that of the wind direction indicating the high
association between wind and SIM. Shuchman et al. (1998) and Rogers and Hung (2008) pointed out that westerly flow can bring in the cold air to help the Odden ice development, while the northeasterly or easterly flow can decay Odden sea ice. The model SIM in the easternmost Odden region (Figure 5.29) changes from northwesterly to northeasterly associated with the SIC and thickness grow from January to June, but changes direction to southwesterly with the Odden ice retreat. During this period, the second important forcing is from sea surface current, while the downward longwave, specific humidity, and air temperature are of lesser importance to the Odden ice extension.

In the melting season (i.e., May-June-July), the wind driven effects become weaker, while the thermodynamic effects such as downward longwave radiation, specific humidity, and air temperature become more important implying that the North Hemisphere receives more solar radiation and tends to apply it to melting of sea ice. The upward latent heat flux decreases from April to the end of May, and is slightly positive until August as the air is warmer than the ocean.

The time evolution of the larger model Odden region (Figure 5.31) has SIC maximum values (95%) in Odden conditions generally consistent with observations, which is higher than the maximum SIC (80%) in easternmost model Odden region. The wind driven effects are associated with the ice expanding and growth in the formation season, while the thermodynamic parameters (e.g., air temperature, longwave radiation and specific humidity) become more important in ice melt season consistent with the results in easternmost model Odden region. Opposite these results, the mean thickness
has consistent trends in 18 experiments but it shows that the ice in the larger Odden area is thicker in the non-Odden case than in the Odden environment in April. Moreover, in this area, the air temperature and downward longwave radiation are the primary effects on annual variability of ice thickness, which is different from that in the easternmost Odden region. In the annual variation of sensible heat and latent heat fluxes in the larger model Odden region, the annual time variations are similar to that in the easternmost model Odden area. The results show that in Odden conditions, the surface receives downward directed sensible heat and little latent fluxes in the ice growth season. The amount of these downward fluxes declines in the melt season, which is consistent with results for the easternmost model Odden region.

Time variability of the u- and v-component of SIM shows compatible results with that of the easternmost model Odden region. The Odden sea ice is accumulated by increasing northerly motion with decreasing easterly SIM between February and April, and withdrawn by decreasing northerly with increasing westerly SIM from May to July, which is strongly associated with the wind and sea surface current effects.

### 6.2 Future work

The model used in this research is the M configuration of CCSM3 with a simple slab ocean model, which only contains the ocean thermodynamic effects interacting with atmospheric data and a land component model. Although this model can reasonably simulate the Odden ice feature, clarifying the interactions between each mechanism and
the Odden feature would better be done with an active ocean model applied in the simulations. The active ocean model can provide a tool to evaluate the effects from the horizontal and vertical ocean circulation, which can verify the effects of the Jan Mayen Current (Hurdle 1986; Burke et al. 1992; Brandon and Wadhams 1999) and potentially the vertical convection (Budéus et al. 1998; Shuchman et al. 1998; Aagaard and Carmack 1989; Roach et al. 1993; Rudels 1990; Toudal and Coon 2001).

The salinity is another important factor that can induce and affect the Odden sea ice formation. The Great Salinity Anomaly (GSA) event occurred in the late 1960s and was observed to be associated with the heavy sea ice extent at that time. Aagaard and Carmack (1989), Deser et al (2001) and Rogers and Hung (2008) pointed out the linkages between salinity and Odden ice activity, but details of its effect on ice formation still remain unknown. Since the surface salinity is defaulted to a constant in the M configuration, the salinity effect is absent in the simulations. This problem can be solved by using an active ocean model. The simulations by an active ocean model will be able to calculate the salinity rejected from the sea ice, and also evaluate the heat flux and fresh water interactions under the sea ice, which can provide a view to see the processes of sea ice freezing and melting.

The importance of wind driven forcing related to Odden sea ice variability has been indicated and shown in many previous studies and in this research. The atmospheric flows are strongly associated with the sea level pressure (SLP) connected with the North Atlantic Oscillation (NAO) and Arctic Oscillation (AO) in Arctic and subarctic regions. Thus, it is important to discover the linkages between Odden ice activities and the NAO.
and AO. According to the studies from Wadhams and Comiso (1999), Comiso et al. (2001) and Shuchman et al. (1998), the Odden sea ice and NAO are correlated about $r = +0.4$, which is opposite in sign to that found by Rogers and Hung (2008) with correlation $r = -0.38$. Since, the NAO is directly affected by the storm frequency in the Nordic Sea area, it will directly or indirectly impact the air temperature and the ice formation/decay. It is also important to address this topic and to understand the linkage between the Odden sea ice feature and atmospheric circulation related to the global climate change.
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