A Numerical Study of the Western Cosmonaut Polynya In a Coupled Ocean-Sea Ice Model

T.G. Prasad  
*University of Southern Mississippi*

Julie L. McClean  
*Naval Postgraduate School*

Elizabeth C. Hunke  
*Los Alamos National Laboratory*

Albert J. Semtner  
*Naval Postgraduate School*

Detelina Ivanova  
*Naval Postgraduate School*

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A numerical study of the western Cosmonaut polynya in a coupled ocean–sea ice model
T. G. Prasad1 and Julie L. McClean2
Department of Oceanography, Naval Postgraduate School, Monterey, California, USA

Elizabeth C. Hunke
Theoretical Division, Los Alamos National Laboratory, Los Alamos, New Mexico, USA

Albert J. Semtner and Detelina Ivanova
Department of Oceanography, Naval Postgraduate School, Monterey, California, USA

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[1] Employing results from a 0.4°, 40-level fully global, coupled ocean–sea ice model, we investigated the role of physical processes emanating from atmosphere, ocean, and ice in the initiation, maintenance, and termination of a sensible heat polynya with a focus on the western Cosmonaut polynya that occurred during May–July 1999. The Cosmonaut polynya first appeared in early May 1999 in the form of an ice-free embayment, transformed into an enclosed polynya on 5–9 July, and disappeared by late July, when the ice from the surrounding regions began to encircle the embayment. Except for the differences in ice concentrations, the time of appearance, size, and shape of the Cosmonaut polynya simulated by the model are in approximate agreement with the Special Sensor Microwave/Imager (SSM/I) observations. Between May and July 1999 the Cosmonaut Sea experienced two synoptic storms, both lasting ~5 days. Followed by the passage of the first storm on 12–19 June, there was a remarkable growth in the size of the embayment by $21 \times 10^3$ km$^2$. Associated with this, the sea surface temperature (SST) rose by 0.15°C, the upward heat flux jumped from 5 to 94 W m$^{-2}$, and a net freshwater flux into the ocean increased by 2 cm d$^{-1}$. By running the model simulation with a 20% wind speed increase, it is demonstrated that the twofold increase in SST and upward heat flux increased the embayment area by $15 \times 10^3$ km$^2$ and decreased the ice concentration by approximately 10% from the control run. A similar, but somewhat weaker wind event that took place on 30 June to 10 July had less influence on the embayment area although the upward heat flux (65 W m$^{-2}$) was comparable to the first event. By examining the vertical displacement of the $-1.6^\circ$C isotherm depth prior to, during, and after these two storms, we demonstrate that the impetus provided by these storms was able to raise the $-1.6^\circ$C isotherm depth by 30 m through wind-driven mixing, making sufficient oceanic heat input from beneath the mixed layer available to prevent freezing and/or delay ice formation while ice in the adjacent regions continued to grow. A sudden shift in the ice drift direction from southwest to northeast (3 July) followed by the second storm, accompanied by large air-sea temperature differences, caused the enclosure of the embayment, subsequent formation of the polynya, and its termination.


1. Introduction

[2] Sea ice plays an important role in the global climate system by influencing regional polar heat and freshwater budgets, surface albedo, and consequently the oceanic and atmospheric circulation. Polynyas are areas of persistent open water or reduced ice concentration surrounded by sea ice [Smith et al., 1990; Morales Maqueda et al., 2004]. Polynyas have been divided into two classes: "sensible
heat” and “latent heat” according to their formation mechanism and maintenance. Sensible heat polynyas are thermally driven. They appear as a result of oceanic sensible heat entering the area of polynya formation in amounts large enough to melt any preexisting ice and prevent the growth of new ice. Latent heat polynyas are mechanically driven, and are created in areas where the ice motion is divergent due to the prevailing winds or oceanic currents (for a review of polynyas, see Morales Maqueda et al. [2004]). Deep ocean sensible heat polynyas constitute 2% of the overall Antarctic winter sea ice cover [Arbetter et al., 2004] and are responsible for the ventilation of warm deep waters [Comiso and Gordon, 1996]. Polynyas are important to climate variability in that they impact the atmospheric circulation, the ice variability, and regional primary production in coastal polynyas [Arrigo and van Dijken, 2003]. Open water within the ice pack is often the location of enhanced exchange of heat and moisture from the ocean to the atmosphere. Thermal plumes of warm, moist air from a recurring polynya produce cloud formations that can achieve great heights. Recurring polynyas suggest consistency in their formation and maintenance, which would be manifested in the evolution of the spatial structure of the sea ice cover. Although, studies of these polynyas have revealed some understanding of the crucial mechanisms, the oceanographic setting relevant to the polynya formation and maintenance is not well understood.

[1] A persistent region of reduced sea ice concentration in the Cosmonaut Sea (Figure 1) was first reported by Comiso and Gordon [1987] who named it the Cosmonaut polynya. Later, with the advent of Special Sensor Microwave/Imager (SSM/I), Comiso and Gordon [1996] documented the spatial and temporal variability of the Cosmonaut polynya from sea ice concentration maps for several years (1987–1993). Recurring polynyas were observed in the eastern and western regions of this sea and were designated eastern and western Cosmonaut polynya (ECP and WCP), respectively. The ECP occurs near Cape Ann (Figure 1) one or more times during winter (July to October) while the WCP occurs west of 45°E in early winter. On occasion, the ECP and WCP occur at the same time and coalesce.

[2] The formation of the ECP in the vicinity of Cape Ann may be due to oceanic forcing [Comiso and Gordon, 1996] or divergent winds [Arbetter et al., 2004; Bailey et al., 2004], or both. From the SSM/I observations, Comiso and Gordon [1996] observed coastal polynyas forming adjacent to Cape Ann that grew in size and extended offshore. Using climatological data, they argued that this offshore location experienced upwelling of warm salty Circumpolar Deep Water resulting from the compression of the westward flowing coastal current and the southern edge of the eastward flowing Antarctic Circumpolar Current via conservation of potential vorticity. This water inhibited sea ice growth resulting in polynya growth. While the vorticity conservation theory can be used to explain the mechanism of ECP formation because of its proximity to Cape Ann (Figure 1), the exact mechanisms causing the WCP formation are unclear and have not been studied. This study will focus on the forcing mechanisms responsible for the preconditioning, formation, and maintenance of the WCP. Arbetter et al. [2004] investigated the processes of formation, maintenance, and decay of a polynya using a 13-year climatology of atmospheric fields. They suggest that atmospheric divergence may play a stronger role than upwelling in initiating the surface divergence of sea ice in this region.

[3] There have been many attempts to model polynyas in the Southern Ocean during the past two decades. These studies have used regional or global models of varying complexity with an active/passive atmosphere or ocean. An excellent review of these and other previous modeling studies of the Weddell polynya are provided by Morales Maqueda et al. [2004]. Bailey et al. [2004] using a regional coupled atmosphere–sea ice model studied the formation mechanisms of the Cosmonaut polynya that occurred during 6–8 August 1988. The size, shape and intensity of their simulated polynya were different from the SSM/I observations (compare their Figures 4 and 5). This model-data discrepancy could be associated with the lack of realistic ocean currents and oceanic heat flux; both of these fields were specified in their simulation. Arbetter et al. [2004] and Bailey et al. [2004] emphasized the importance of the oceanic processes in maintaining the Cosmonaut polynyas, but they were unable to address it directly. It is this issue that we would like to address here.

[4] This builds on prior work, most notably that of Comiso and Gordon [1996], Arbetter et al. [2004], and Bailey et al. [2004]. By using a coupled ocean–sea ice model, we are able to provide direct insight into ocean processes, something the prior studies were unable to do. We employ a coupled ocean–sea ice model of moderately high resolution that includes an active ocean and ice dynamics and thermodynamics. Our preliminary model-data comparisons suggest that the model is capable of simulating the Cosmonaut polynyas for different years. For example, consistent with the SSM/I observations, a WCP occurred in 2002. In this study, we focus on the WCP that occurred during May–July 1999. In the ensuing sections, the Cosmonaut polynya refers to the WCP unless otherwise stated. We chose this period because the Cosmonaut polynya that occurred during May–July 1999 (1) was preceded by the largest embayment in the last two decades, (2) lasted for several weeks between the time it appeared and disappeared, and (3) experienced the passage of two
synoptic storm events, which enabled us to study the response of the upper ocean and sea ice to storm events. The present coupled model with the advantage of having realistic ocean dynamics shows a considerable improvement in simulated polynya structure and variability. We try to address the following questions: (1) What are the mechanisms that initiate and maintain the embayment? (2) What are the mechanisms involved in transforming an embayment into the Cosmonaut polynya? (3) What are the mechanisms leading to its decay?

[7] The paper is organized as follows. A brief description of the coupled ocean–sea ice model and the forcing fields are provided in section 2. We present the evolution of the Cosmonaut polynya that occurred between May and July 1999 using SSM/I sea ice concentrations and relate the atmospheric forcing fields to the timing of the observed polynya in section 3. Model experiments are discussed in section 3.1. The role of ice and oceanic forcing in initiating, maintaining and terminating the embayment/polynya are discussed respectively in sections 4 and 5. This is followed by a discussion (section 6) and summary (section 7) of the results.

2. Coupled Ocean–Sea Ice Model

The simulation was performed with an ocean–sea ice coupled model developed at Los Alamos National Laboratory, forced by realistic atmospheric reanalysis data. Detailed documentation for the ocean and ice models is given by Smith and Gent [2002], Hunke and Lipscomb [2004], Hunke et al. [2004], and other publications referenced below.

The Parallel Ocean Program (POP) [Smith et al., 1992; Dukowicz et al., 1993, 1994] is a z-coordinate ocean model featuring an implicit free surface; it solves the primitive equations for temperature, salinity and the horizontal velocity components. The K-profile parameterization (KPP) [Large et al., 1994] provides vertical mixing of momentum and tracers, while convective adjustment occurs through a high vertical diffusion coefficient done implicitly in time. Horizontally, friction is biharmonic with a coefficient of \(10^{-2}\) m\(^2\) s\(^{-1}\). The ocean model provides sea surface temperature, salinity, currents, and slope as well as a freezing or melting potential to the ice model. The freezing temperature is salinity-dependent.

The Los Alamos Sea Ice Model (CICE) features the elastic-viscous-plastic ice dynamics of Hunke and Dukowicz [1997, 2002] and the energy conserving thermodynamics model of Bitz and Lipscomb [1999], with a nonlinear vertical salinity profile. A new incremental remapping scheme [Lipscomb and Hunke, 2004] is used for horizontal advection, and mechanical redistribution of ice is accomplished through an energy-conserving ridging scheme based on Thorndike et al. [1975]. There are four layers of ice and one layer of snow in each of five ice thickness categories. Surface fluxes and temperatures are computed separately for each category and merged on the basis of the fractional area covered by that category. Prognostic variables for each thickness category include ice area fraction, ice volume, ice energy in each vertical layer, snow volume and energy, and surface temperature. The ice model provides a freshwater flux, net heat flux and ice-ocean stress to the ocean model. Details pertaining to the CICE model are given by Hunke and Lipscomb [2004].

The ice and ocean models are coupled through a driver that also reads atmospheric data from files and prepares the data for use by the other components. The driver merges ice and ocean quantities on the basis of the ice area fraction in cells where there is less than 100% ice coverage. The ice-ocean model runs as a single executable; the driver and ice model use a time step of 30 minutes, while the ocean model takes 48 leapfrog time steps and 3 averaging time steps each day. The ice model exchanges information with the driver once each time step, the ocean model once per day. Additional information about the ice-ocean coupled model configuration is given by Hunke et al. [2004].

The model runs on a nonuniform, general curvilinear grid in which the North Pole has been moved smoothly into North America. For the simulations described here, we use a 0.4°, 900 × 601 global mesh with 40 vertical ocean levels. The horizontal grid spacing in the Cosmonaut polynya region (40°E, 65°S) is 18–23 km. A blended bathymetry from Smith and Sandwell [1997], the International Bathymetric Chart of the Arctic Ocean (IBCAO) [Jakobsson et al., 2000], and the British Antarctic Survey (BEDMAP) [Lythe et al., 2001] products is used.

The model is forced with surface boundary conditions primarily from the National Center for Environmental Prediction (NCEP)—National Center for Atmospheric Research (NCAR) reanalysis data [Doney et al., 2002]. A combination of daily and monthly fields is employed to estimate the surface momentum, heat, and freshwater fluxes using bulk formulae of Large et al. [1997]. Daily fields of wind stress, air temperature, air density and specific humidity are derived from the NCEP-NCAR reanalysis data. Monthly downward shortwave radiation and cloud fraction come from the International Satellite Cloud Climatology Project (ISCCP) [Rossow and Schiffer, 1991]. Monthly mean precipitation data are taken from the Microwave Sounding Unit (MSU) and Xie-Arkin climatology [Xie and Arkin, 1997]. All forcing fields are interpolated to the nominal 0.4° mesh prior to model integration. The model was initialized from the Navy’s Modular Ocean Data Assimilation System (MODAS) 1/8-degree January climatology [Fox et al., 2002] outside of the Arctic and the University of Washington’s Polar Hydrography winter climatology in the Arctic. The model is initialized with a uniform ice thickness of 2 m, was spun up for 20 years starting in 1979 (1979–1998), and was then run for a further 4 years (1999–2002). The model output is analyzed for the year 1999.

3. Cosmonaut Polynya 1999

Sequences of daily SSM/I derived sea ice concentration are used to depict the evolution of the Cosmonaut polynya during 1999. These daily maps averaged for selected 5-day periods (5–9, 10–14, 15–19 and 25–29) from May to July 1999 are displayed in Figure 2. While we employ the SSM/I sea ice concentration generated using the NASA Team algorithm [Markus and Cavalieri, 2000] for model-data comparisons, a comparison of this with that generated using the Bootstrap algorithm shows some differences. The NASA Team algorithm underestimates the ice
concentration by 5–10% when compared to the Bootstrap method in some regions. The uncertainty can be up to 35% in the new ice regions because of differences in the SSM/I algorithms (see Comiso and Steffen [2001] for detailed comparisons). The reason for using the NASA Team algorithm here is that during winter, polynyas are often covered with thin ice, which can be detected as ice in the NASA Team algorithm. Nevertheless, the two techniques produced almost identical Cosmonaut polynya during May–July 1999. In the ensuing sections, we use the term “embayment” for an open ocean area surrounded by (or at least three sides) sea ice (as in a bay) and the term “polynya” after the embayment is completely enclosed by sea ice. The Cosmonaut polynya that evolved during May–July 1999 was preceded by the formation of an embayment. An embayment of ice-free water started to form at about 38°E, 67°S in May 1999 (Figure 2) and persisted for several weeks. This is indicated by a v-shaped dip in the sea ice extent at 38°E, 67°S. In fact, its existence was apparent in the SSM/I maps during 25 April. The size of the embayment progressively became larger until 5–9 July, when ice began to encircle the feature, causing the formation of the Cosmonaut polynya on 10–20 July with an apparent center around 40°E, 65°S. A rapid increase in the size of the embayment occurred in mid-June: the width of the embayment along 65°S (based on 10% contour) jumped from 70 km on 10 June to 645 km on 15 June and dropped to 352 km on 1 July. The polynya reached a southwest-northeast oriented near-elliptical shape on 5–9 July. Thereafter, its size continued to decrease until its complete disappearance on 29 July 1999. After the polynya became enclosed on 5–9 July, its size decreased at a rate faster than its formation. It is interesting to note that this region was ice-free for more than two months in late fall and early winter.

Figure 2. SSM/I-derived sea ice concentrations (100% = 1) for the Cosmonaut Sea region (Antarctic) showing the Cosmonaut polynya 1999, which is preceded by an embayment during May–July 1999. These maps are averaged for selected 5-day periods, 5–9, 10–14, 15–19, and 25–29.
14 June and 29 June to 2 July 1999. storm events during this period, and they occurred on 9–

April and July is 7.8 m s

fields are averaged in the polynya region (38°–46°E, 66°–

was moderate (450 km). The average concentration during this

period reached the lowest value (40–50%) in the embay-

ment followed by a gradual increase in concentration (50–

60%). The polynya became completely surrounded by

ice on 9 July. In the following sections, the result from

this model run is treated as the control run (CR). While the

model successfully simulated the evolution of the Cosmo-

naut polynya in terms of its size, shape and time of

appearance, some discrepancies exist between the model

and SSM/I observations: (1) overall, the simulated con-

centration in the polynya region was higher by

50% relative to the SSM/I data (Figure 2). The spatial extent of 10%

concentration in SSM/I is in reasonable agreement with the

model’s 60% concentration contour until 10 July. Daily

snapshots showed an almost closed polynya on 10 July,

consistent with the SSM/I data. However, an embayment of

reduced ice concentration persisted from mid-July through

early August, with no evidence for a closed polynya similar

to that in the SSM/I observations. From 10–14 June

through 15–19 June, significant increases in open water

and embayment area are obvious in both SSM/I and model

concentrations. The zonal width of the embayment com-

puted on the basis of the 60% contour along 65°S was

~9.6° (450 km). The average concentration during this

period was moderate (~8 m s

and the direction was north-

easterly. The occurrence of many moderate, but short-
lived, wind events are seen throughout the period and

they occurred roughly around 20 April, 2, 4, 10, and 16 May,

2, 20, and 25 June, and 23 July. A significant reduction in

ice concentration (15–19 June, Figure 2) after the passage

of the first storm event suggests a relationship between

them. From early July, the wind speed showed a gradually

decreasing trend and the wind direction shifted from

northeast to southwest on 5 July. It is possible that such a

shift in the wind direction may have resulted in an advec-
tion of ice into the embayment region causing the enclosure

of the embayment. However, an examination of the average

air temperature in the polynya region (Figure 3c) indicates

an alternate mechanism leading to its enclosure. A sharp

reduction in air temperature from early to middle July may

have increased the ice growth and subsequent closure of the

embayment. Also included in Figure 3c is the downward

longwave radiative heat flux, which is a function of air

temperature and cloud fraction. Positive longwave heat flux

indicates surface warming. The corresponding longwave

heat flux showed a reduction of 75 W m

period. In the following sections, we identify the role of

each forcing mechanism involved in the formation, main-
tenance, and decay of the embayment and polynya.

3.1. Model Experiments

3.1.1. Control Run

Model derived ice concentrations for the same period are plotted in Figure 4; these will be compared with the

SSM/I data. Superposed is the 10% ice concentration contour from the SSM/I data. Outside of the polynya region, the model ice concentration is in good agreement with the

SSM/I with differences being under 10%. In the polynya region, there is an overall bias in ice concentration by

~50%. Except for this bias, the formation of the Cosmo-
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this model run is treated as the control run (CR). While the

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appearance, some discrepancies exist between the model

and SSM/I observations: (1) overall, the simulated con-

centration in the polynya region was higher by

50% relative to the SSM/I observations: (2) the closure of the

polynya and its termination after 10 July were not consis-
tent with the SSM/I fields.

[17] The wind speed will likely have a strong impact on

the temporal and spatial variability of the area of the

polynya and embayment. In addition, the wind speed

affects the sensible and latent heat fluxes at the air–sea

interface, thus the sea ice growth rate. In addition to

CR, four perturbation experiments have been performed to

examine the effects of surface winds, surface air tempera-
ture and sea ice dynamics on the formation and mainte-
nance of the Cosmonaut polynya and their details are

summarized in Table 1. Their comparison with the CR will

provide further insight into the mechanisms governing the

formation of an embayment and polynya. The first, two

perturbation experiments examine the role of surface wind

speed (Experiment 1 (EXP1)) and direction (EXP2). Their

details are summarized in Table 1. To explore the effect of

surface winds on the Cosmonaut polynya, an integration is

conducted with a 20% increase of the surface wind speed

Figure 3. Area-averaged (a) wind speed (m s

1. There are indications of two

storm events during this period, and they occurred on 9–
14 June and 29 June to 2 July 1999.

these periods, throughout May and June the wind speed

in the polynya region (38°–46°E, 66°–

63°S, see box in Figure 4). The average wind speed between

April and July is 7.8 m s

1). There are indications of two

storm events during this period, and they occurred on 9–
14 June and 29 June to 2 July 1999.
The wind speed change is restricted to the region 54°W - 105°E, 79°S - 53°S covering the entire Weddell Sea and Cosmonaut Sea regions. Since divergence in the sea ice has been shown to be well correlated with the wind field divergence, wind direction would be an influencing factor controlling the polynya formation. To quantify its relationship with the Cosmonaut polynya, EXP2 will be conducted with the sign of the wind components reversed. In EXP3, the model is run with the ice dynamics terms turned off, so that the sea ice experiences only thermodynamic changes and does not move. All model simulations are started with January 1999 ocean and ice state taken from CR and integrated through a complete year. EXP4 tested the effect of the air temperature on the closure of the embayment and will be discussed in section 4.2.

3.1.2. Experiment 1

The ice concentrations from EXP1, shown in Figure 5 when the wind speed was increased by 20%, clearly demonstrate the role of surface winds on polynya structure and maintenance. Except in the Cosmonaut polynya region, the overall ice concentrations showed no significant changes from the control run (CR). In the Cosmonaut polynya region, significant reduction in ice coverage was observed. 

![Figure 4](image)

**Figure 4.** Same as Figure 2, but simulated ice concentration from the control run (CR), in which no forcing fields are altered. Except for the differences in ice concentrations, the size, shape, and time of appearance of the embayment and polynya are in reasonable agreement with the SSM/I observations. Superposed is the 10% (0.1 ice fractional area) contour from the SSM/I (repeated in Figures 5 and 6). The ocean and ice fields are averaged in the polynya region (38° - 46°E, 66° - 63°S, see box) and presented in the following sections.

<table>
<thead>
<tr>
<th>Table 1. Model Experiments</th>
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<tbody>
<tr>
<td><strong>Parameter</strong></td>
</tr>
<tr>
<td>20% + wind speed</td>
</tr>
<tr>
<td>Ice dynamics off</td>
</tr>
<tr>
<td>$T_{air}(July) \Rightarrow T_{air}(June)$</td>
</tr>
</tbody>
</table>
concentrations occurred, agreeing better with the SSM/I observations. An opening of an embayment can be easily identified in early May in the Cosmonaut Sea region (38°–46°E, 65°–67°S). A sharp increase in open water area occurred on 15–19 June, when the concentration reached a minimum value of 20% (80% open water). The zonal width of the embayment computed on the basis of 60% contour along 65°S was about 14.8° (694 km). The embayment persisted until the 5–9 July period when it became surrounded by ice. The average concentration was about 40% when the polynya was formed and it was approximately 70% when the Cosmonaut polynya disappeared. The appearance of a well developed Cosmonaut polynya in the model (5–9 July) occurred approximately 5 days earlier than in the SSM/I (10–14 July). A similar time discrepancy was also obvious during the period of polynya disappearance. For example, the ice distribution was nearly uniform during 15–19 July in the Cosmonaut polynya region indicating that the polynya was completely closed in contrast to the SSM/I observations, which clearly showed a polynya at this time.

3.1.3. Experiment 2

In Experiment 2, the sign of the wind components were reversed ($u = -u$, $v = -v$). The ice concentration from Experiment 2 depicted in Figure 6 clearly revealed that the ice production and reduction are strongly controlled by the wind direction. The resulting ice concentration did not contain a well-developed embayment and polynya. Overall, the ice concentration was higher than CR in the Cosmonaut Sea region. A conspicuous region of reduced ice concentration hugging the coast in Experiment 2 resembled a coastal polynya. Obviously, changes in wind direction affected the polynya formation through changes in atmospheric divergence, which drive the sea ice and ocean divergence and hence the oceanic upwelling maintaining the polynya. The impact of changes in wind direction on the dynamics and thermodynamics of the sea ice is discussed in section 4.2.

3.1.4. Experiment 3

The model is run with the ice dynamics terms turned off (EXP3), so that the sea ice experiences only thermodynamic changes and does not move. A comparison of the sea ice concentration between EXP3 (Figure 6) and
CR (Figure 4) clearly demonstrates that the sea ice dynamics are a key determinant of the Cosmonaut polynya. There was an overall reduction in sea ice concentration in EXP3 compared with CR. In contrast to CR, EXP3 failed to reproduce the pattern of polynya formation in July. However, the ice concentration clearly indicated an opening of the embayment from early May, and it persisted until 15 May, agreeing better with the SSM/I and EXP1. While the reduced ice concentrations in the Cosmonaut Sea region suggest its continued existence, the size and strength of the embayment showed weakening. In particular, a reduction in ice concentration and an increase in the embayment area associated with the passage of the first storm event (15–19 June) seen in CR were weakened in EXP3. This was followed by a sudden decline in the area of the embayment, eventually leading to its termination earlier than July.

3.2. Open Water Area

We computed the total area of open water and average concentrations in the region 38°–46°E, 63°–66°S from EXP1, EXP2 and EXP3 and compared them with CR in Figure 7a. The SSM/I derived average ice concentration is shown in Figure 7b. These fields show large differences. The time series plots show a gradual decrease (increase) in open water area (ice concentration) from early May until 10 June, typical for winter conditions. From 10 June to mid-July, the open water area increased significantly in EXP1 in comparison with CR. For example, when the first storm event peaked on 15 June, the open water area jumped from $53 \times 10^3$ km$^2$ (12 June) to $88 \times 10^3$ km$^2$ (20 June) yielding $35 \times 10^3$ km$^2$ in 8 days in EXP1, while it was only $21 \times 10^3$ km$^2$ in CR. In response to the first storm event, both SSM/I and CR ice concentration showed a 15% reduction. The SSM/I concentration began to increase abruptly from early July 1999 at a rate of 3.4% d$^{-1}$, indicating the termination of the Cosmonaut polynya. From 15 July onward, the average EXP1 concentration (and area of open water) was identical to the CR, which suggests that wind speed has negligible effect on the sea ice growth rate during this period. A second peak of

Figure 6. Same as Figure 4, but from EXP2 (top two rows) and EXP3 (bottom two rows). EXP2 is run with the sign of the wind components reversed ($u = -u$, $v = -v$), and EXP3 is run with the ice dynamics (elastic-viscous-plastic) [Hunke and Dukowicz, 1997] turned off. For clarity, only selected periods are shown. The importance of ice dynamics is obvious from June in EXP3, when the embayment began to weaken significantly, which eventually caused its termination. EXP2 failed to contain an embayment and polynya, which demonstrates that ice convergence-divergence are the key processes determining the evolution of the embayment/polynya.
open water area that occurred in response to the second storm event in EXP1 was less pronounced in CR.

4. Sea Ice Fluxes

4.1. Sea Surface Temperature, Heat, and Freshwater Fluxes

[22] An important aspect of the Cosmonaut polynya 1999 was that the region remained ice-free for several weeks beginning in early May while ice continued to grow in the adjacent regions (Figure 2). We can envisage such a condition occurring via (1) upward oceanic heat flux, (2) advection of ice away from the formation region by the action of surface wind or ocean currents, (3) upwelling and mixing associated with the passage of synoptic storms, and/or (4) a combination of two or more of these processes.

[23] Time series of sea surface temperature (SST) (Figure 8a), fluxes of heat (Figure 8b) and freshwater (Figure 8c) from the four model runs (CR, EXP1, EXP2, and EXP3) are presented in Figure 8. These fields are averaged over the polynya region (38°–46°E, 66°–63°S). Overall, the SST showed a gradual decrease from early May to 25 May, and it then remained close to a near-freezing (−1.75°C) condition until 10 June. Thereafter, the SST rose quickly to −1.6°C and fell back to −1.75°C on 20 June. A similar event also occurred between 30 June and 10 July. These two events are clearly associated with the passage of synoptic storms. The wind stress presented in Figure 3 confirms the occurrence of such events. Thus the upwelling and mixing are the likely mechanisms leading to the warm SST during the periods of strong winds. This is further elucidated in section 5.3. The sea surface salinity (SSS, psu) from CR (Figure 8c) progressively increased at a rate of $5.4 \times 10^{-3}$ psu d$^{-1}$ during the entire period. A small drop in SSS by 0.03 psu occurred during the storm periods. Also evident in Figure 8a are intermittent periods of somewhat mild SST warming during May, which is more pronounced in EXP1 but absent in EXP2. Both EXP1 and EXP3 generated higher SSS in early May, causing the opening of an embayment. However, a lack of increase in SST during the storm events prematurely terminated the embayment in EXP3.

[24] The time series of net heat flux (W m$^{-2}$) across the ice-ocean interface (from the ice model) for the Cosmonaut polynya region is displayed in Figure 8b. Positive (negative) values indicate heat flux from the ice (ocean) to the ocean (ice). A substantial jump in heat flux from the ocean to the ice occurred during the period of strong winds, which is consistent with the SST. The first event generated a heat flux of $\sim 85$ W m$^{-2}$ into the ice while the second produced a flux of $\sim 60$ W m$^{-2}$. The bursts of upward heat flux promoted enhanced ice melting and inhibited further ice growth in the embayment region. The release of freshwater into the ocean due to melted ice is illustrated in Figure 8c. There is 2 cm d$^{-1}$ freshwater flux
into the ocean during the period of the first storm event. This freshwater input in turn stabilized the water column by increasing the stratification. Throughout the period, EXP2 and EXP3 heat flux remained under 25 W m\(^{-2}\), which is in agreement with CR and EXP1 except during the storm periods. The impact of increased wind speed (EXP1) was evident only during the strong wind conditions although the pattern of SST between CR and EXP1 was not the same. Although the wind stress magnitude was the same in both CR and EXP2, the wind direction altered the ice/ocean divergence and hence the upward heat flux. The wind reversal in EXP2 lead to dramatic changes in heat flux because of oceanic downwelling, which is discussed in section 5.3. Except during the storms, a net loss of freshwater flux by the ocean via ice formation increased the SSS progressively. What is clear from this analysis is that the significant reduction in ice concentration and increase in the embayment area that occurred during 15–19 June (Figure 4) was primarily driven by the upward heat flux and associated SST warming. The impact of the second event on the embayment area, however, was somewhat mitigated by the reversal of the ice drift and larger air-sea temperature differences, which aided rapid ice growth (see sections 4.2 and 4.4).

Clearly, the exchange of heat between the ocean and ice plays a vital role in the maintenance of the embayment, particularly those associated with the storms, which can provide ample upward heat flux to keep the region ice-free for several weeks. Inclusion of such realistic oceanic heat flux (which is often prescribed as a spatially uniform heat flux) in the future coupled atmosphere–sea ice models would certainly improve the polynya simulation. Parkinson [1983] specified a spatially uniform 25 W m\(^{-2}\) ocean heat flux for the simulation of the Weddell polynya. This value agrees with our estimate except during the strong wind conditions. In an attempt to simulate the Cosmonaut polynya that occurred on 6–8 August 1988, Bailey et al. [2004], using a coupled atmosphere–sea ice model, performed several numerical experiments with vertical ocean heat flux values varying from 15 W m\(^{-2}\) to 200 W m\(^{-2}\). They noted a sharp reduction in ice concentration in the polynya region when the heat flux was set uniformly to 15 W m\(^{-2}\), except for a patch of 200 W m\(^{-2}\) centered within the polynya region. This extreme heat flux can be attained under the action of strong winds; for example, during the Antarctic Zone Flux Experiment (ANZFLUX) in July and August 1994, upward heat fluxes exceeding 100 W m\(^{-2}\) were observed in the eastern Weddell Sea [McPhee et al., 1996]. Thus the significant contribution of heat flux induced by the storms should be represented accurately in coupled atmosphere–sea ice models, rather than by a spatially uniform constant value.

### 4.2. Ice Growth and Melting

There are number of factors that influence ice growth/melt processes such as oceanic heat flux, ice drift and deformation, wind, and air temperature. Time series of area-averaged congelation (Figure 9a), frazil (Figure 9b) ice growth rates, and basal ice melt (Figure 9c) from CR, EXP1, EXP2 and EXP3 are plotted in Figures 9. These fields represent the average growth/melt rate per unit ice area. The congelation ice growth occurs thermodynamically by freezing onto an existing ice bottom. It should be noted that the bias in the ice concentration within the polynya affects the relative importance of frazil and congelation ice growth in the simulation because frazil forms in open water, while congelation ice forms at the base of the existing ice. The rate of congelation ice growth is much larger than the frazil ice growth during the entire period. The occurrence of strong winds on 10–15 June and 1–5 July were characterized by a prolonged period (~5 days) of no ice growth. The former period was followed by a rapid increase in embayment area on 15–19 June (Figure 4) while the latter event had little influence on the embayment area. It was during these periods that the highest rate of basal ice melting (2.5 cm d\(^{-1}\)) occurred in the Cosmonaut Sea region (Figure 9c). This suggests that even small changes in ocean temperature (~0.2°C, Figure 8a) can have significant impacts on the basal melt rate. During the first event, a heat flux of ~85 W m\(^{-2}\) (Figure 8b) from the ocean to ice yielded a basal melt rate of 2.5 cm d\(^{-1}\).

The closure of the embayment began on 5 July, when the congelation ice growth at the bottom of the existing ice increased rapidly. The congelation ice growth jumped from a zero value on 5 July to 1.1 cm d\(^{-1}\) on 17 July. This occurred during a period of southwesterly winds, when the ice had a net northeasterly drift to the northwestern side of the embayment. Also there was a close relationship between air temperature (Figure 3c) and the congelation ice growth from 5 July to late July. Thus the southwesterly winds in this region not only caused the ice to drift northwest but also carried very cold continental air. The embayment rapidly refreezes because of the enormous temperature difference between the atmosphere (~−25°C) and the ocean (~−1.8°C).

From late May to early July, the congelation ice growth in EXP1 and EXP2 remained quite similar. EXP1 formed more frazil ice because of greater open water areas (allowing greater ocean cooling), while congelation ice growth depended on both the ocean temperature and the existing ice cover. Since these are fairly similar in CR and EXP1, the congelation growth rates are similar. Centered on mid-May, EXP1 revealed slower congelation ice growth than CR and EXP2. Basal melting rates during the periods of strong winds differed significantly; EXP1 produced the highest melting rate (>4.5 cm d\(^{-1}\)) while EXP2 and EXP3 yielded <0.5 cm d\(^{-1}\) owing to the differences in SST and net heat flux from the ocean to the ice (Figure 8) among the four model runs.

Although the rapid congelation ice growth during July correlated well with the air temperature, it is unclear whether the rapid decline of air temperature accelerated the closure of the embayment and the subsequent formation of the polynya. To address this issue, we performed an additional model experiment (EXP4) in which the July air temperature was replaced with that from June thereby eliminating the sharp drop in air temperature so that the model was run for July 1999 (with June 1999 air temperature). The air temperature used in EXP4 and CR and the corresponding congelation ice growth are plotted in Figure 9d. The apparent reduction of congelation ice growth rate in EXP4 from CR clearly demonstrated that the air temperature was partly accountable for the rapid growth seen in CR. The sea ice concentrations from EXP4 (figure not presented) suggest that differences in air temperature...
between CR and EXP4 had negligible impact on the embayment shape and did not affect the closure of the embayment. Therefore we argue that the advection of ice from the east following the second storm event was responsible for the closure of the embayment.

### 4.3. Turbulent Heat Fluxes

The time series of latent (Figure 10a) and sensible (Figure 10b) heat fluxes from the atmosphere to the ice from CR, EXP1, and EXP2 are shown in Figure 10. Throughout the period, sensible heat flux was positive, which indicates colder sea ice underneath warm air temperatures. The sensible heat flux gradually increased from early May and persisted until early July with a jump (40 W m$^{-2}$) during the period of strong winds in mid-June. A sharp reduction in sensible heat flux by 40 W m$^{-2}$ from early July to mid-July corresponded in part to the weakening of the wind speed. This reduction was also in part associated with the drop in air temperature (Figure 3c). The latent heat flux that showed an overall downward trend with values ranging between +10 and −10 W m$^{-2}$ was much smaller than the sensible heat flux in the polynya region. The latent heat flux also showed a gradual decrease from early July to mid-July consistent with the sensible heat flux.

The wind speed affects the sensible and latent heat fluxes at the air–sea ice interface, thus affecting the sea ice growth rate. By comparing the sensible heat flux from the three model runs, it is demonstrated that increasing the wind speed by 20% in EXP1 did not alter the sensible heat flux except that it was diminished by 5 W m$^{-2}$ in May and July relative to CR. This clearly suggests that the differences in ice concentrations among the three model experiments cannot be explained by the sensible heat flux. Again, a somewhat small difference in latent heat flux in EXP1 (∼4 W m$^{-2}$) relative to that in CR and EXP2 had little effect on the sea ice growth/melt. Thus the ice melted at the bottom rather than at the top.

### 4.4. Ice Drift and Deformation

The ice drift is dependent primarily upon wind stress and secondarily upon water stress. The ice typically drifts at 2–3% of the wind speed and to the left of the wind direction (southern hemisphere). The time series of the zonal and meridional components of ice velocity are presented from CR in Figure 11a. Overall, the ice drifted southwestward during June with two peaks coinciding with the passage of the synoptic storms. During these periods, ice velocities accelerated from near zero to more than 20 cm s$^{-1}$. The strong west or southwestward ice drift during these...
periods may have contributed to the retreat of the ice edge and the enlargement of the embayment. Following the second event, the direction of the ice drift changed from southwest to northeast causing the ice pack located to the east of the embayment to advect toward the north or the northeast. The eastward advection of ice in concert with colder air temperatures triggered the closure of the embayment and the subsequent formation of the Cosmonaut polynya. The ice concentration during 5–9 July from the model (Figure 4) and SSM/I (Figure 2) clearly indicated that the closure of the embayment started from the western side of the embayment, thus supporting the idea that reversal of the ice drift contributed partly to the closure of the embayment.

Sea ice deformation drives changes in the distribution of ice thickness through the creation of leads, where new ice can grow. The time series of ice divergence and shear in the CR for the Cosmonaut polynya region are shown in Figure 11b. Overall, the nature of the deformation showed a random pattern consistent with free drift conditions and low ice strength. When ice drifted eastward or northeastward on 15–25 May, the advection of thicker pack ice into the region increased the ice strength (150 N m$^{-1}$, Figure 11c) by compacting the ice distribution. There were two periods of large ice divergence in June; the first event occurred in early June and the second one after the first storm event (after 10 June). The compressive ice strength (Figure 11c) showed its lowest value from early June to early July indicating that the ice was generally less compact. During the second storm event (early July) the wind direction shifted from northeast to southwest. This caused a weak divergence of ice, which lasted longer than the first event and an ice convergence occurred thereafter. At the time when closure began in early July until the time it terminated on 30 July, the ice strength jumped sharply from 0 to 500 N m$^{-1}$. When the ice drifted northeastward (which occurred during 20–30 May and 5–10 July), the ice strength markedly increased, particularly during the latter period. The shear deformation is much larger than the divergence, as is usually the case. In general, periods of large shear coincided with ice convergence. While the ice was diverging at about 2% d$^{-1}$ during mid-June, the shear rate was $\sim$4% d$^{-1}$. The shear deformation peaked around 25 June (12% d$^{-1}$), and it remained relatively low after 5 July.

### 4.5. Area-Volume Tendency Terms

The sea ice area and volume tendencies due to dynamic and thermodynamic processes for the Cosmonaut Sea region are shown in Figure 12. The thermodynamic processes include all growth and melt terms and the dynamic processes include ice advection and ridging. The thermodynamic processes dominated the dynamic processes.
heat from the ocean to the atmosphere.

1999. Negative values of net heat flux indicate the loss of

net heat flux (W m$^{-2}$) during April–July 1999. The increased input of heat from beneath the mixed layer during storm mixing can be substantial in polynya intensification processes. For example, a significant increase in the embayment area (and decrease in ice concentration) occurred after the first storm event (10–14 June, Figure 4). It is, however, unclear what mechanisms kept this region ice-free and prevented it from closing and freezing for a prolonged period of time. Therefore characterizing the role of oceanic setup is important for understanding the evolution of the embayment and the Cosmonaut polynya.

5. Role of Oceanic Forcing

In the preceding sections, we discussed the role of ice forcing on the initiation and maintenance of the Cosmonaut polynya that occurred during May–July 1999. While the model results are strongly suggestive of the influence of the winds on the occurrence of the Cosmonaut polynya, it may also be influenced by the atmospheric (synoptic) forced local oceanic responses through Ekman divergence or mixing. An important aspect of the eddy potential vorticity argument of Comiso and Gordon [1996] is that eddies that shed from instabilities in the Antarctic Divergence could become a source of heat because of upwelling or local divergence. This contribution, however, cannot be addressed with an eddy-permitting model. Comiso and Gordon [1996] suggested that the heat provided from the upwelled circumpolar deep water was sufficient to maintain an ice-free region in the ECP. The increased input of heat from beneath the mixed layer during storm mixing can be substantial in polynya intensification processes.

In the following sections, we attempt to address (1) the preconditioning that leads to the formation of the embayment, (2) divergence of ocean currents and upwelling, and (3) wind-driven mixing associated with the passage of synoptic storms. Since SSM/I and model ice concentration already showed an opening of the embayment on 1 May, it is implied that the first appearance of the embayment can be traced back to April. So in the following sections, the focus will be placed on the period April through July rather than May–July.

5.1. Ocean Currents

Although the dominant driving force on the sea ice is the wind, ice can also undergo small changes because of the ocean currents. The area-averaged ocean surface currents (5 m, cm s$^{-1}$) for both area and volume tendency terms. Except during the period of storm events, the ice area and volume showed an overall increase primarily due to the thermodynamic processes. A significant reduction in the area and volume of ice during the storm periods was driven by the thermodynamic processes, which is consistent with ice/ocean heat flux and SST. There were three periods in May (5, 11, and 21 May) during which the thermodynamic contribution to the area fell to a near-zero value. The SST (and heat flux) during these periods clearly showed a mild jump (Figures 8a and 8b) although it was much weaker than that associated with the storm events. However, such contributions could provide sufficient heat to prevent ice formation in the region. It is interesting to note that the dynamic and thermodynamic contributions are of equal magnitude but opposite sign around the second event. This led to little change in the ice concentration. After the closure of the embayment on 5 July, both dynamic and thermodynamic processes appeared to have less impact on the ice area while their contributions to the volume increase were significant. This is consistent with the increased rate of congelation ice growth, which is driven by the colder air temperatures. Thus the large air-sea temperature difference together with dynamic processes via the advection of ice by the ocean currents or winds on 5–10 July led to the closure of the embayment. The volume and area change due to thermodynamic processes from EXP3 are depicted in Figure 12c. By comparing these fields between CR and EXP3, it is demonstrated that the sea ice dynamics play an important role in the maintenance of the embayment. In the absence of ice dynamics, the decreasing ice area and volume due to thermodynamic processes as a consequence of the storm events, did not take place.

Figure 13. Area-averaged (a) zonal (solid line) and meridional (dotted line) ocean surface currents (5 m, cm s$^{-1}$) and (b) net heat flux (W m$^{-2}$, solid line), sensible heat flux (W m$^{-2}$, dash-dotted line), surface heat due to ice melt (W m$^{-2}$, dash-dotted line), and longwave heat flux (W m$^{-2}$, dash-dot-dotted line) from the ocean model (CR) in the polynya area (38°–46°E, 66°–63°S) during April–July 1999. Negative values of net heat flux indicate the loss of heat from the ocean to the atmosphere.
newly formed ice by ocean currents before they could form continuous ice cover, (2) the upward heat flux following the passage of storms, and (3) a combination of both processes.

The question remains, what ocean currents accomplish this removal of ice from the embayment region? We began to answer this by investigating the spatial pattern of ocean surface currents from CR, which is depicted in Figure 14 for 24 April, 13 June, 2 July, and 10 July 1999 from CR. Shaded regions indicate SSM/I-derived sea ice concentrations during 30 April (Figure 14a), 15 June (Figure 14b), 5 July (Figure 14c), and 10 July 1999 (Figure 14d). An eastward flowing Antarctic Circumpolar Current (ACC) to the north of the Antarctic Convergence (65°S) and a southwestward flowing coastal current to the south are evident. The coastal current keeps the embayment open via advection of ice southwestward (Figures 14a–14c), and reversal of the coastal current triggered the closure of the embayment (Figure 14d).

The generally east-northeasterly winds in this region induce a south-southwestward ice drift and carry relatively warm moist air from the open ocean. The sea ice is continually removed southwestward from the embayment region owing to the action of prevailing winds and ocean.
The rate of ice transport by the coastal current exceeds the relatively slow ice growth. To the northwest of the embayment, the eastward advection of ice into the embayment region was restricted because of the weak surface currents. Thus the embayment remained open for several weeks partly because of the divergence of ice by the coastal currents coincident with weak ice growth. An overall reduction in wind speed in the coastal region from early July weakened the coastal currents and ice divergence. At the same time, a dramatic reversal of the winds from northeast to southwest advected ice eastward into the embayment region. This, coincident with the large temperature difference between the ocean and atmosphere resulted in the closure of the embayment.

The role of coastal currents in initiating and maintaining the embayment can be explained by comparing the surface currents simulated by CR with EXP2 and EXP3. With the ice dynamics turned off in EXP3, one obtains the ocean currents from direct atmosphere-ocean wind stress forcing, but they might be quite different from the currents in the CR where the ice also affects the currents. Figure 15 shows the May and June monthly mean ocean surface currents from CR and EXP3. In May, both CR and EXP3 did produce nearly identical southward flowing coastal currents in the embayment region (box). This suggests that the ice had little effect on the ocean currents in the advection of ice away from the embayment region. However, the ocean currents were different in June: the strong southwestward coastal current that developed in CR was nearly absent in EXP3. Thus the ice velocity in CR actually accelerated the ocean currents in the embayment region. In the absence of the ice velocity in EXP3, the ocean currents evolved as a result of direct atmospheric-ocean wind stress forcing. Thus it is the combined action of sea ice drift and ocean currents that is responsible for the advection of ice away from the embayment region. The drag between the ice and ocean therefore plays an important role in the ice distribution and the embayment/polynya mechanisms. In EXP2, the removal of sea ice from the embayment region was affected by the reversal of the southwestward flowing

Figure 15. Monthly mean surface ocean currents (cm s\(^{-1}\)) from CR and EXP3 for (a) May (CR), (b) May (EXP3), (c) June (CR), and (d) June (EXP3). Location of the model average sea ice extent as indicated by the 10% and 60% ice concentration is also included (contour). The structure of the current within the box is compared in the text.
coastal currents (figures not shown). In contrast to CR, the northeastward coastal currents in EXP2 advected ice into rather than out of the embayment region thereby preventing the embayment from opening. The continued movement of ice away from the coast by the northeastward coastal currents in EXP2 opened an ice-free region along the coast of Antarctica (Figure 6).

5.2. Heat Fluxes

Upward heat transfer can occur through vertical mixing of heat from deeper water or through upward advection of heat by such mechanisms as wind-driven upwelling, making sufficient oceanic heat available to erode the underside of the ice cover. Once open, the polynya will rapidly lose heat to the atmosphere but the source of warmer water may be sufficient to prevent freezing. If not, the original advective currents may carry away newly formed ice crystals before they can form continuous ice cover. The time series of net heat flux (NHF, W m\(^{-2}\)), sensible heat flux (SHF, W m\(^{-2}\)), surface melt heat flux (SMHF, W m\(^{-2}\)) and longwave heat flux (LWF, W m\(^{-2}\)) averaged for the polynya region (38°–46°E, 66°–63°S) from the ocean model are shown in Figure 13b. Except during storm periods, the exchange of heat between the ocean and atmosphere differs from that between the ocean and the ice (compare Figures 8b and 13b). This difference is largely due to the longwave heat flux. Local changes in wind speed, particularly those associated with the passage of synoptic storm events, caused a rapid loss of heat to the atmosphere from 25 to 100 W m\(^{-2}\) within a few days. It is remarkable that this peak value of heat loss at the height of the first storm event (100 W m\(^{-2}\)) in June was comparable with that during 20 April, when the entire region was mostly ice-free. From mid-April to 7 June, as the ice was forming in the embayment, the heat loss to the atmosphere decreased gradually. The sensible heat flux, which was under 10 W m\(^{-2}\) prior to the embayment closure (5 July), was not a significant contributor to the net heat flux. The surface heat flux due to ice melt jumped from 10 to more than 50 W m\(^{-2}\) during the passage of the storms.

5.3. Upwelling and Mixing

What might be the mechanisms responsible for the increased oceanic heat flux during the storm events? We argue that with the impetus provided by the storm and the resulting wind-driven vertical mixing increase the heat input from beneath the mixed layer. To demonstrate this, we examine the vertical displacement of the \(-1.6^\circ\)C isotherm depth (D\(_{-1.6}\)) prior to, during, and after each of the two storms discussed earlier. We have chosen this isotherm...
because it best represents the vertical mixing owing to its proximity to the surface through outcropping into the surface mixed layer. The sequences of $D_{1.6}$ along 65°S for the two storm periods are depicted in Figures 16a and 16b, respectively. Prior to the first event (10–16 June 1999, Figure 16a), on 11 and 12 June, $D_{1.6}$ was located at 27 m in the Cosmonaut polynya region. The isotherm outcropping into the surface layer occurred during 13–15 June, that is, between 12 and 13 June, the isotherm was displaced vertically by 25 m. By 18 June, $D_{1.6}$ had returned to its original position of 27 m where it was located prior to the event. During the second event (1–9 July 1999), the location of $D_{1.6}$ remained close to 27 m prior to the event with an exception that its position slightly deepened in the eastern half of the polynya region. As the storm was strengthening, the isotherm continued its upward displacement until it reached the surface by 3–4 July. On 8 July the isotherm returned to the original depth of 30 m. The region that experienced near-surface warming due to the action of strong winds extended zonally from 38° to 46°E, roughly 376 km.

[45] Clearly, the storm-induced oceanic upward heat flux and warmer SST (Figures 16a and 16b) provided sufficient heat to erode the underside of the ice cover and contributed to the strengthening of the Cosmonaut polynya. However, the presence of warmer water in this region can be seen during the nonstorm periods beginning in early April. Sequences of $D_{1.6}$ plotted in Figure 16c for April–May clearly demonstrate this. Between 35° and 45°E, the presence of warmer water, as evidenced by the surfacing of $D_{1.6}$ from early April to 8 May, was sufficient to prevent freezing and/or delay ice formation while ice growth continued in the surrounding regions. The existence of this warmer water in the Cosmonaut Sea led to preconditioning for the embayment formation.

[46] If the thermocline is sufficiently shallow, upward heat transfer can occur through vertical mixing (primarily wind-driven) of heat from deeper water or through upward advection of heat by wind-driven upwelling. To examine the nature of the thermocline variability in the Cosmonaut Sea region, we show sequences of the 0°C isotherm depth from early April to late July 1999 in Figure 16d. The shoaling of the thermocline by more than 60 m between 35° and 45°E from adjacent regions indicates upwelling. Throughout the period, as the winter season progressed, the depth of the thermocline was gradually deepening, except during the periods of strong winds. For example, the isotherm deepened from 20 to 55 m between April and July. Surface warming can occur only when conditions are favorable for near-surface mixing. During April, when the thermocline was sufficiently shallow (20 m), winds with moderate speeds were able to vertically mix the water column so that the region remained warmer. On the other hand, when the thermocline was relatively deeper in June, more energy was required for mixing the water column.

[47] The thermocline depth, upwelling and upward heat flux through vertical mixing are closely related, so both atmospheric and oceanic forcing effects can be substantial in the processes governing the lifecycle of polynyas in the Cosmonaut Sea. Therefore it is expected that any changes in the atmospheric forcing would have a significant effect on the thermal fields and hence the oceanic upwelling that maintains the polynya. A comparison of the upper ocean thermal fields and vertical velocity from the three model experiments provided further insights regarding the polynya mechanisms. The vertical distribution of the temperature (upper 150 m) from CR, EXP1, EXP2 and EXP3 for April and June 1999 (Figure 17 (top)) shows interesting changes in the thermocline pattern. The corresponding vertical velocity (m d$^{-1}$) for June 1999 is depicted in Figure 17 (bottom). West of 45°E, both CR and EXP1 indicated upwelling of warm water at a rate of $>0.2$ m d$^{-1}$ ($2.3 \times 10^{-4}$ cm s$^{-1}$), which agrees with the ECP upwelling rate of $2.6 \times 10^{-4}$ cm s$^{-1}$ [Comiso and Gordon, 1996]. The shoaling of the thermocline due to oceanic upwelling preconditioned the surface for embayment formation. When the wind components were reversed (EXP2), the region experienced oceanic downwelling (instead of upwelling), which in turn yielded relatively colder SSTs in the Cosmonaut Sea ($>35°$–45°E) during April. Further depression of the thermocline (induced by downwelling) during June in this region coincident with a deep mixed layer ($>60$ m) inhibited the upward heat flux through vertical mixing.

[48] While the downwelling mechanism can be used to explain the absence of large upward heat fluxes during the storm wind events in EXP2 (Figure 8), obviously the same mechanism is not applicable for that in EXP3. The upper ocean thermal structure and upwelling are not likely to be affected by the absence of ice dynamics in EXP3. To examine this, we show vertical sections of temperature and vertical velocity from EXP3 during June 1999 in Figure 17. As expected, no significant changes are evident in the upwelling intensity or the location of the mixed layer depth compared to CR. Thus the upward heat flux differences between EXP3 and CR during the periods of strong winds are not caused by the upwelling. Rather, it is the difference in wind-driven vertical mixing that is responsible for the large heat flux differences. Lack of ice movement in EXP3 prevented the upward heat flux through leads opened by ice advection and vertical mixing. In principle, the ocean model computes all the terms (advective and diffusive as well as horizontal and vertical differences); but they are not saved for later analysis.

6. Discussion

[47] Employing results from a 0.4° fully global, coupled ocean-ice model we investigated the physical processes responsible for the initiation, maintenance and termination of the Cosmonaut polynya with a focus on the recent 1999 polynya. In this particular year, the Cosmonaut polynya first appeared on 25–30 April 1999 in the form of an
embayment and began to enclose and undergo the transformation into a well-developed polynya on 5–9 July, which disappeared by late July. Except for the differences in ice concentrations, the time of appearance, size and shape of the Cosmonaut polynya simulated by the model are in good agreement with the SSM/I observations. The mechanisms underlying the occurrence of polynya in the Cosmonaut Sea can be explained by a combination of wind-driven mechanisms and warm water upwelling. The presence of warm water in the region (35°–45°E, 66°–68°S) prevents sea ice from forming, causing an opening of the embayment in late April. This warm water results from wind-driven mixing whereby warmer subsurface water that is located at shallow depths can easily be mixed with overlaying cold waters under moderate wind conditions. The occurrence of a moderate wind event on 16–26 April coincident with a shallow thermocline (as indicated by depth of 0°C isotherm in Figure 16d) initiated the surface warming, which in turn inhibited ice formation. Obviously, stronger wind events would significantly increase the upward heat flux and would most likely contribute to the enlargement of the embayment.

Figure 17. Monthly mean vertical sections of temperature from CR, EXP1, EXP2, and EXP3 for (top) April and (middle) June 1999 along 65°S. Contour interval is 0.4°C. The shoaling of the isotherms between 35° and 45°E (CR and EXP1) indicates upwelling of warmer Circumpolar Deep Water (CDW), which provides sufficient heat to maintain the embayment and polynya. Wind reversal in EXP2 deepened the thermocline via oceanic downwelling. The red lines indicate the mixed layer depth (meters) based on 0.5°C temperature gradient criteria. (bottom) Monthly mean vertical velocity (m d⁻¹) from CR, EXP1, EXP2, and EXP3 for the month of June 1999 along 65°S.
Figure 18. (a) Latitude-time plot of SST (°C, shaded) and 0°C isotherm depth (meters, contours) along 40°E. Also shown in Figure 18a is the average SST (dotted line) in the polynya region (38°–46°E, 66°–63°S). (b) Zonal (dotted line) and meridional (solid line) heat fluxes (×10^{-6} °C s^{-1}) averaged in the polynya region. Contour interval for SST is 0.2°C, and that for isotherm depth is 50 m with 40 and 25 m contours appended. Positive zonal (meridional) heat flux values indicate eastward (northward) transport of heat. Arrows indicate storm-induced SST warming.

by subsequent melting. There were two strong wind events (synoptic storms) during our study period and they occurred respectively in mid-June and early July 1999. Both periods indicated strong upward fluxes of ~75 W m^{-2} heat from the ocean, ~2 cm d^{-1} freshwater flux from ice to ocean, and ~0.2°C SST increase (Figure 8).

[48] The embayment evolved as a consequence of the wind-driven mixing and southward advection of warm water by the ocean currents. We explain these processes by showing a latitude-time plot of SST (shaded) and depth of the 0°C isotherm (Contours) along 40°E (Figure 18a) and averaged zonal and meridional heat flux (°C s^{-1}) in the polynya region (38°–46°E, 66°–63°S) (Figure 18b) from CR. Also shown in Figure 18a is the average SST in the polynya region (dotted line). Because of the proximity of the thermocline to the surface north of 67°C, the mixing of warm water from below can be triggered by moderate wind speed events. With the temperature increasing northward from the polynya region, advection of warm water southward by coastal currents is likely to extend the warming further south. The southward meridional heat flux (~5 × 10^{-6} °C s^{-1}) associated with a moderate wind speed event on 16–26 April (Figure 18b) and a corresponding SST warming (Figure 18a) in the polynya region support our view that the advection of warm water from the north did occur during this period (see arrow in Figure 18a). This opened an ice-free region during 25–30 April as indicated by a dip in the sea ice extent (Figure 14a). A sharp increase in southward heat flux (~8 × 10^{-6} °C s^{-1}) occurred in concert with the two large storm events. The depth of the thermocline is important in determining the location of the ice edge and upward heat flux. For example, an abrupt descent of the thermocline south of ~67°S limited the embayment location to the north of 67°S. The northward heat transport (~5 × 10^{-6} °C s^{-1}) followed by the second storm event (31 June to 5 July) triggered closure of the embayment.

[49] It is, however, unclear whether the source of the storm-induced warming was sufficient to prevent freezing and the embayment from closing for several weeks. If not, the advective currents may have carried away newly formed ice before it could form continuous ice cover. Prior to the enclosure of the embayment (5–9 July), the general north-easterly winds advected sea ice southwestward from the southern edge of the embayment. This process prevented the embayment from closing and its area increased significantly during the period of strong wind events owing to sea ice divergence and melting. The southwestward flowing coastal currents (ocean) to the southeast of the polynya also advected ice away from the embayment region. The changes in wind direction in early July (from northeast to southwest), which is manifested in the sea ice velocity (Figure 11a), led to the enclosure of the embayment from the western side of the embayment, eventually causing the formation of the polynya. The coastal current markedly weakens following the second storm event in early July and disappears thereafter (6 July). A dramatic increase in growth rate of congelation ice (0.8 cm d^{-1}) that occurred from 5 July 1999 onward contributed to the further closing and termination of the polynya. The colder air emanating from the Antarctic continent by the prevailing winds was accountable for the sharp increase in the congelation ice growth. Thus the shifting wind not only favors the convergence of sea ice but also brings colder air from the south, causing sea ice growth, which leads to the termination of the polynya.

[50] Two model experiments were carried out to understand the role of wind speed and wind direction on the size and shape of the Cosmonaut polynya. Significant reduction in ice concentrations (increases in open seawater) in the Cosmonaut Sea regions occurred when the wind speed was increased by 20%. In contrast, when the wind stress components were reversed, the Cosmonaut polynya failed to develop. The differences in oceanic and ice fields simulated by these experiments and the control run delineated the processes responsible for the polynya evolution. A comparison of the vertical distribution of the temperature from CR, EXP1 and EXP2 clearly demonstrates the important role of atmospheric divergence. For example, by increasing the wind speed by 20%, the intensity of the upwelling increased (Figure 17). If wind action is strong, the doming of isotherms associated with the upwelling in the Cosmonaut Sea region promotes surface warming through turbulent vertical mixing. The role of wind speed is evident during the passage of the two storms with SST, heat and freshwater fluxes being approximately double that from CR. The reversal of the wind components in EXP2 replaced the oceanic upwelling with downwelling, causing a deep mixed layer depth. In the absence of a shallow mixed layer and upwelling, the actions of strong winds were
unable to vertically mix warm subsurface waters with colder surface waters. As a result the SST, heat and freshwater fluxes remained close to the values corresponding to the non-event period.

[51] An additional experiment with no ice dynamics (EXP3) revealed the complex nature of interactions between the ice, ocean and atmosphere. The enhancement of upward heat flux through leads opened by ice advection during the storm events did not occur owing to lack of ice dynamics. As a result, the embayment became closed and prematurely disappeared in mid-June. Because of the absence of ice in the polynya region in April, the ice dynamics were insignificant in initiating the embayment opening. The two wind experiments (EXP1 and EXP2) have secondary effects on the nature of the embayment and polynya. An increase in wind speed by 20% eventually caused a much faster retreat of the ice edge and a larger increase in the embayment area. The removal of the sea ice from the embayment region was particularly affected by the reversal of the southwestward flowing coastal currents (to the south of the embayment) in EXP2. As a result, sea ice is being moved into rather than out of the embayment region thereby preventing the embayment from opening. Although the magnitude of the wind stress components in CR and EXP2 were the same, differences in the direction of the wind stress generated significant changes in the sea ice distribution in the Cosmonaut Sea region.

[52] Although our simulations reasonably agree with the observed nature of the Cosmonaut polynya, discrepancies between the simulated and observed sea ice concentrations are evident. Overall, the simulated ice concentrations are found to be higher than the observations. Part of this discrepancy can be associated with the model forcing fields. The frequency of the forcing fields particularly the wind stress plays a major role in mixing the upper ocean especially under free ice drift conditions. Forcing the model with 6-hourly fields (rather than daily used here) are likely to improve the ice distribution in the Antarctic. The model is also found to be less successful in reproducing the recurring ECP that forms off of Cape Ann during the later part of the winter. There are, however, regions of reduced ice concentration in our simulation that resembled the ECP (e.g., 15–20 September 1999), but their size, shape and time of appearance do not agree with the SSM/I data. It is likely the ocean current biases are causing the mismatch; these will be further investigated with an eddy-resolving (0.1°) coupled ocean-ice model in the near future.

7. Summary and Conclusions

[53] The depth of the thermocline is important in determining the location of polynyas and upward heat fluxes. A shallow thermocline is generally vulnerable to atmospheric forcing so that the warmer water from below can be moved to the surface through wind-driven vertical mixing or upwelling. Given the ocean conditions shown in Figure 17, it is not surprising that the winds with moderate speed can easily create new open water areas (leads) where rapid upward heat flux can occur. This ocean heat is being used not only to prevent the ice formation in the polynya region but also for subsequent melting. The preconditioning that leads to the opening of an embayment is as follows: the arrival of a moderate storm event (wind speed > 12 m s−1) on 16–23 April led to increased wind-driven mixing. The shallow thermocline in this region (for example, D1.6 between 35° and 45°E was located at 15 m, Figure 16c) provided sufficient upward heat flux (warming) through wind-driven vertical mixing, thereby inhibiting further ice growth. This resulted in an embayment of an ice-free region. The embayment is maintained by two processes: (1) a significant increase in upward heat flux during the storm events, which increased the embayment area and (2) continued advection of ice away from the embayment region by prevailing northeasterly winds. The embayment closed primarily because of the advection of ice into the embayment region from the west and southwest by southwesterly winds and secondarily because of increased ice growth associated with the arrival of the colder continental air temperatures that were carried by the prevailing winds. The latter process is likely to play a negligible role in the polynya formation (after the embayment is closed) and its disappearance as suggested by EXP4. The fact that the model failed to simulate the complete closure of the polynya and its disappearance raises the question; what processes exactly caused its termination?

[54] Because of the close relationship between the occurrence of the strong wind events and the embayment/polynya formation, the frequency of cyclone activity in the Antarctic region has a strong impact on the climate through coupled air–sea ice interaction processes. The passage of synoptic wind systems and associated changes in ocean temperature and heat flux contribute to the thinning of the ice cover due to the combined effects of surface and basal ice melting. So an increasing trend in cyclone activity in the Antarctic could have a potential impact on the thickness of the ice and therefore on the heat and freshwater budgets. A model with fully three-way coupled system would be required to study the feedback mechanisms between the atmosphere, ice and the ocean. The present modeling study advances our existing knowledge of the mechanisms of polynya formation and provides a framework for future modeling effort to achieve a 3 way coupled system that can be used for climate prediction.

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E. C. Hunke, Climate, Ocean and Sea Ice Modeling Project, Los Alamos
National Laboratory, Los Alamos, NM 87545, USA. (eclare@lanl.gov)

D. Ivanova and A. J. Semtner, Department of Oceanography, Naval
Postgraduate School, Monterey, CA 93943, USA. (dpivanov@nps.edu; 
sbert@nps.edu)

T. G. Prasad, Department of Marine Science, University of Southern
Mississippi, Stennis Space Center, MS 39529, USA. (thoppil@nrlssc.navy. mil)