Role of off-shelf to on-shelf transitions for East Antarctic sea ice dynamics during spring 2003

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[1] During austral spring 2003, mesoscale sea ice drift and deformation off East Antarctica were investigated using in situ data from a nine-buoy array. Upon deployment, the array comprised an area of about 4000 km² with a mean ice concentration of 96%. Half-hourly sea ice velocities were coherent across all buoys at zonal (meridional) separations of less than 160 km (70 km). Regional cross-spectral correlation was high at synoptic scales and also at semidiurnal periods off the continental shelf. Atmospheric synoptic-scale forcing explained in excess of 85% of the ice drift variability. This is significantly more than found in the Weddell Sea, where significant ice drift variability is derived from oceanic forcing. Peak frequencies of semidiurnal contributions covaried with latitude and are largely associated with the inertial response. Over the continental shelf, coincident diurnal and semidiurnal variances in ice motion arose from tidal forcing. Net divergence over 37 days resulted in an expansion to 270% of the initial area, although regional ice concentration reduced only slightly. High-frequency processes, namely inertial response and to a lesser degree tidal forcing, dominated the variability of all deformation parameters. In contrast to ice motion, low-frequency processes played a secondary role in sea ice deformation. This high-frequency dominance is similar to what has been found in the Weddell Sea, although many observations there were limited to the continental shelf, where tidal processes dominate. Sea ice motion and deformation were not affected by a seasonal transition, nor did the regional ice characteristics show any signal of seasonal change. Instead, local ice dynamics were strongly influenced by bathymetrically dependent processes.


1. Introduction

[2] The drift of sea ice is largely in response to external forcing, and generally closely associated with large-scale weather systems [Leppäranta, 2005]. Ice motion affects the ice thickness distribution and hence the sea ice mass balance, the thermal energy and the moisture budgets between ocean and atmosphere, and also the freshwater flux at the surface ocean. In this study we provide information on sea ice dynamics at synoptic and shorter timescales during early austral spring, as derived from in situ buoys during the Antarctic Remote Ice Sensing Experiment (ARISE) project.

[3] While offering wide-scale coverage, satellite-derived information on sea ice drift (e.g., Emery et al. [1997], Geiger and Drinkwater [2005], or Kwok [2005]) is acquired at limited spatial resolution, limited spatial and seasonal coverage and low temporal definition. In situ observations of Antarctic sea ice motion and deformation are rare, with most coming from the Weddell Sea, one of the larger embayments, where the life expectancy of drifting buoys is higher than in the narrow belt of seasonal sea ice off East Antarctica or in the Bellingshausen/Amundsen seas. Data on ice dynamics in the Weddell Sea are available from multiple investigations and for different seasons and years, and several large-scale sets of buoy arrays from the Weddell Sea have been analyzed. For example, Massom [1992] used four drifting buoys, deployed during austral autumn and winter 1980, to describe the ice motion and deformation in the western Weddell Sea. He notes a coherent response of the buoys to synoptic-scale forcing at separations over 100 km. Buoys were also deployed as part of Ice Station Weddell during austral autumn 1992. Geiger et al. [1998] found that the sea ice drift there was dominated by low-frequency forcing, while variability in ice deformation peaked at diurnal and semidiurnal frequencies. Observations from the Ice Station PoLarstern (ISPOL) experiment provide detail on mesoscale ice drift and deformation [Heil et al., 2008] during early austral summer 2004. Using 24 buoys on a staggered grid within a mesoscale array, they found that both sea ice motion and deformation experienced largest variability at diurnal and semidiurnal
frequencies. They concluded that synoptic-scale forcing on ice motion was less effective during summer than in autumn and winter.

[4] Buoy deployments off East Antarctica have been fewer, and our knowledge of sea ice deformation there relies largely on data collected as part of two separate austral winter experiments conducted in the 1990s. One of them, a winter experiment off Adélie Land [Worby et al., 1996], provided buoy-derived information on large-scale sea ice drift and deformation [Heil et al., 1998] using a total of 13 buoys, which were deployed in July and August 1995 within a region of 110 km by 110 km. During the austral winter 1999, a further set of drifting sea ice buoys was deployed, this time in the region of the Mertz Glacier Polynya [Lytle et al., 2001] to track the transport of newly forming sea ice within and also out of the polynya region. Most additional in situ information on sea ice motion off East Antarctica is available from other deployments, mostly of individual buoys (e.g., Allison [1981], Allison [1989], or Heil and Allison [1999]).

[5] Sea ice motion is a consequence of external forces onto the ice, which include atmospheric and oceanic forcing, as well as internal stress. Sea ice drift is modified by the effects of the ice’s material properties, specifically its thickness, strength and the local ice concentration [Hibler, 1979]. In addition, ice drift is subject to boundary conditions such as coastline, glaciers, ice tongues, or icebergs. Sea ice is “embedded” in the upper ocean and experiences the transfer of momentum from oceanic surface currents and tidal forcing [Hibler et al., 1998]. Synchronous with the ocean, sea ice responds to atmospheric forcing, both at synoptic scale and at subdaily frequencies (inertial response [McPhee, 1978]). While McPhee [1978] modeled inertially driven ice motion in Arctic pack during summer, he concluded that the inertial response during Arctic winter is less effective as increased sea ice concentration would dampen the free drift of ice floes. In the Antarctic, especially off East Antarctica, the seasonal change in ice dynamic characteristics is less pronounced than for the Arctic. Inertial oscillations have been observed for both ice motion and deformation during the Antarctic autumn and winter [e.g., Geiger et al., 1998; Heil and Allison, 1999]. During the time of thermodynamic ice growth, such high-frequency ice dynamics is especially important as it increases the amount of ice growth [Heil et al., 1998]. This increased ice production affects the ocean properties via brine drainage, and has implications for processes such as the formation of bottom water [Heil and Allison, 1999].

[6] Within the sea ice zone the relative importance of the two identified high-frequency processes varies, both with location and with time, and it is important to separate the two to gain an understanding of their relative contributions as the external forcing mechanisms change. While tidal forcing is clearly linked to high-frequency oceanic processes, the inertial response of the sea ice has no direct high-frequency equivalent in the oceanic or atmospheric spectra [Heil and Hibler, 2002]. Instead, a cascade of energy from low frequencies to subdaily frequencies is required to generate high-frequency variance in the ice motion and deformation. The cascade arises from nonlinear ice dynamics, which is driven by synoptic-scale changes in the atmospheric forcing. This energy transfer to higher frequencies resonates with the inertial response, and becomes trapped near semi-diurnal frequencies.

[7] To investigate these processes, we analyze data from the ARISE field experiment, which was carried out from the RSV Aurora Australis. ARISE provided an opportunity to study East Antarctic ice dynamics during maximum sea ice extent, which is the time when the balance between dynamic and thermodynamic forcings maintains a quasi-stationary ice edge. Compared to other sectors, the East Antarctic sea ice zone occupies only a narrow meridional range of as little as 200 km from the coast at maximum annual ice extent.

[8] ARISE itself was a detailed survey of sea ice and snow conditions in the region off Wilkes Land [Massom et al., 2006]. An array of sea ice buoys was deployed during ARISE to define a Lagrangian grid of in situ sampling locations in the region. The in situ sampling supported the validation of several new generation satellite-borne cryo-spheric instruments, including the Advanced Microwave Scanning Radiometers (AMSRs) onboard the National Aeronautics and Space Administration’s Aqua and Japan’s Advanced Earth Observing Satellite-II (ADEOS-II). Here we concentrate on the analysis of the ice drift data themselves. We present a characterization of ice motion and deformation in austral spring 2003 from about 105° to 119°E. This characterization includes results of our analysis on frequency-dependent coherence of ice motion at mesoscale separations (of the order of 10 to 100 km). The spatiotemporal variability of the ARISE ice motion is reviewed as well as its response to changes in the atmospheric forcing. We investigate the variance in sea ice motion and deformation, and discuss the likely association of this variance with synoptic-scale atmospheric events and how they may contribute to the significant divergence experienced by the array. Similarly we investigate the individual contributions of inertial and tidally induced ice motion, and how these change relative to the synoptic-scale forcing within a largely unchanged physical framework (i.e., ice concentration and ice thickness) during the lifetime of the array.

2. Methods

[9] During ARISE nine sea ice buoys were deployed in an array in the region near 65°S, 119°E (Figure 1). These buoys were ClearSat-EZ™ 2002 marker buoys from Clearwater Instrumentation, Inc., and provided half-hourly data. The buoys were equipped with Jupiter GPS Engines, with a horizontal accuracy of better than 15 m (at the 90% confidence level). Buoys were transmitted via the CLS Argos system, which operates on satellites in the NOAA series (CLS Argos, User’s manual, available at http://www.argos-system.org/manual, 2007). Air temperature (at approximately 0.5 m above the ice surface) and the snow-ice interface temperature were also measured by the buoys, and transmitted via CLS Argos. Before any analysis, all position and auxiliary data were quality checked, and any erroneous data were removed. Using a weighted polynomial interpolator [Scargle, 1982], the quality-checked data were projected into a equitemporal 0.5 hourly time series with a common time base, ensuring that the inherent high-frequency energy distribution of the sea ice motion was retained.
The buoy array was used to reference eight HEIL ET AL.: SEA ICE DYNAMICS DURING ARISE 2003, 1999]. The data Worby et al. Positions of the ARISE buoys for DOY 269.27 Worby and Allison Aurora Australis by an automatic weather temporal changes in ice conditions using aerial photography occurred with helicopter support to determine spatiotemporal changes of sea ice and snow properties within the buoy sites during ARISE to measure temporal and regional provided guidance for the selection of in situ ice station imagery (spatial resolution 250 m) acquired to derive finer scale information of the sea ice characteristics and zonation.

3. Sea Ice Conditions During ARISE

On the basis of AMSR-E imagery from NASA's Leve11 and Atmospheric Archive and Distribution System, the ice edge in the experimental region was located at about 62.27°S at the beginning of ARISE, and varied during the experiment between 61.80 and 62.87°S, moving northward or southward due to prevailing winds of passing atmospheric systems. Shipboard ice observations commenced at the sea ice edge at 62.40°S, 125.98°E on 23 September 2003 (DOY 266). As the ship sailed on a general north–south transect, three distinct ice zones were observed, namely, the marginal ice zone, inner pack and coastal zone (Figure 3, top). In the north, the marginal ice zone comprised highly inertial response in the sea ice motion and deformation fields [Heil and Hibler, 2002].

The nine buoy deformation array of ARISE operated from DOY 269.27 until DOY 306.83, when buoy C1 (see Figure 1 for the naming convention) in the southwestern corner of the array ceased its transmissions. The longest transmitting buoys were C2 and C3, also deployed along the southern side of the array. The drift trajectories during that time interval and the outline of the ARISE array at DOY 269.27 and DOY 306.83 are shown in Figure 2. This study is limited to the analysis of sea ice motion using data from all nine buoys, and of sea ice deformation using the outer four buoys only. In a follow-on study the full set of buoy data will be used to investigate the presence of any scale dependence for sea ice deformation.

ARISE itself comprised acquisition of numerous in situ as well as ship-based and helicopter-based data to describe the state of the East Antarctic sea ice and the overlying snow cover (see Massom et al. [2006] for details). For our study, we also use a number of in situ and remotely sensed data sets. These include hourly observations of the sea ice conditions from the ship’s bridge using a protocol devised by the Antarctic Sea Ice Processes and Climate (ASPeCt) group [Worby and Allison, 1999]. The data include total and partial ice concentrations, ice and snow types, and ice and snow thicknesses.

Meteorological measurements were collected onboard the RSV Aurora Australis by an automatic weather station at 10 second intervals. Wind velocity was measured at a height of 34 m. Assuming a logarithmic wind profile in a neutral atmosphere [Blackadar, 1962], these were converted to the 10 m reference level, and were corrected for the movement of the vessel. In addition, during ARISE, trained meteorological forecasters conducted 3-hourly observations following World Meteorological Organization (WMO) procedures. The WMO data were used to quality control the 10 second data. To extend the time series of onboard meteorological data, additional information on atmospheric conditions in the region were derived from the NCEP 2 reanalysis data.

We use sea ice concentrations derived from satellite passive microwave sensors, including AMSR-E [Cavaliere and Comiso, 2004](digital media, updated daily), to define the large-scale ice conditions, as well as Moderate Resolution Imaging Spectroradiometer (MODIS) visible channel imagery (spatial resolution 250 m) acquired to derive finer scale information of the sea ice characteristics and zonation.

Figure 1. Positions of the ARISE buoys for DOY 269.27 (triangles). Also shown are the naming conventions for the buoys and bathymetric contours (m). In the inset, the ARISE region is indicated by dark grey area.

[10] The buoys were deployed by helicopter on the 26 September 2003 (day of year (DOY) 269) just before maximum equatorward ice extent in the region. Upon deployment the nine buoys enclosed a region of 100 km zonally and 50 km meridionally, and provided a reference frame for the ARISE field work described by Massom et al. [2006]. The buoy array was used to reference eight experimental boxes of 25 km by 25 km initial dimension [i.e., Worby et al., 2008]. The initial separation between buoys was chosen as a multiple of the spatial grid scale on which satellite-derived products, such as those derived from AMSR-E data, are distributed. The Lagrangian movement of the boxes was derived from the buoy positions, and provided guidance for the selection of in situ ice station sites during ARISE to measure temporal and regional changes of sea ice and snow properties within the buoy array. Revisits of various boxes occurred on numerous occasions with helicopter support to determine spatiotemporal changes in ice conditions using aerial photography and in situ measurements.

[11] Apart from furnishing a reference frame for several ARISE projects, the buoys also provided mesoscale data on sea ice kinematics of the pack ice early in the Antarctic spring. Furthermore, the buoy data contained subdaily and also true daily information on Lagrangian ice motion and deformation, both of which are not resolved by satellite sensors. These high-frequency data are crucial to distinguish between atmospheric and oceanic forcing as well as to determine the relative importance of tidal forcing and
deformed ice composed of small to medium cake ice and brash. The Antarctic Divergence, where the large-scale surface winds and ocean currents change direction, was located just north of 64.50°S, and coincided with a change in the floe size distribution to vast floes separated by large open water areas or extensive thin ice leads. Floes in this zone exhibited consolidated ridges, and the thickness of level ice often exceeded 0.7 m. South of 65.00°S and over the continental shelf, the ice comprised vast level floes and little open water or newly formed sea ice.

Mean snow thickness in the ARISE study region was 0.36 m over rough sea ice and 0.17 m over smooth sea ice [Worby et al., 2008]. The vast floes to the south of 65.00°S were covered with snow in well developed dunes, with a largely east–west orientation, suggesting that the sea ice floes had moved en masse for some time. Snow accumulation during ARISE occurred during several blizzards, including those experienced during the field phase on the 4 (DOY 277), 9 (DOY 282), and 15 October 2003 (DOY 288). During those three events, wind speeds were in excess of 28 m s⁻¹, peaking at 46 m s⁻¹. The winds were from the southeast at the peak of the storms, turning northwest soon after the first two events (Figure 4b).

The ASPeCt observations from ARISE show that the majority of the observed floes consisted of deformed sea ice. In general, the deformed ice itself was formed from level ice with typical thicknesses of 0.2 to 0.4 m. Ridges of about 1.5 to 2.0 m height were typical for the region, and covered an average of 24% of the floe area. The mean thickness of level ice in the region was 0.45 m and that of deformed ice was 0.82 m. ASPeCt-derived ice concentration values are between 95 and 100% up to 14 October 2003 (DOY 287) (Figure 4e), after which the vessel departed westward from the experimental region to resupply Casey Station (66.3°S, 110.5°E). AMSR-E provides continuous data over the buoy array. In late September 2003, the mean ice concentration in the area enclosed by the buoy array was 96% and decreased to 89% by early November 2003, by which time the array center had moved to 64.73°S, 112.03°E.

In situ observations as well as AMSR-E imagery suggest that the buoy array remained within the relatively uniform inner pack for the first three and a half weeks after deployment. At this time, the transition to the marginal ice zone was about 100 km north of the array, and a shear zone separated the inner pack from the fast ice to the south (Figure 3, top). By about mid October the southern part of the buoy array had traversed the shear zone, which separated buoys B1 and C1–C3 along the southern edge from the remainder of the buoys. Near coincident with this transition, the whole region underwent a rapid change in the last third of October 2003, due to a change in wind direction that also corresponded to a breakup of the fast ice to the south (Figure 3, bottom). The ice concentration in the region reduced and floe sizes decreased with the distribution becoming dominated by smaller ice floes (Figure 3, bottom).

4. Results: Sea Ice Drift During ARISE

The ARISE buoys were deployed south of the Antarctic Divergence on medium sized ice floes within
Figure 3. MODIS images [Hall et al., 2007](digital media, updated daily) of the sea ice off East Antarctica in the general region of ARISE for (a) 25 September 2003 (DOY 268) and (b) 21 October 2003 (DOY 294).
the westward flowing Antarctic Coastal Current. The buoys initially drifted to the northwest, undergoing considerable short-term deviations from their average drift trajectory (Figure 2), before turning west. The ARISE array remained in the westward drift over the lifetime of the buoys, even though they underwent some cyclonic excursions to the north associated with the passage of synoptic low-pressure systems.

Half-hourly zonal and meridional sea ice velocities (Figure 5) were derived by upstream differencing of the 30 min position data. The overall velocity error associated with the ARISE buoy data was 0.008 m s\(^{-1}\). Over the array, the mean ice velocity for the interval from DOY 269.27 to 306.83 varied between -0.13 and +0.01 m s\(^{-1}\) for the zonal component and between -0.01 and +0.01 m s\(^{-1}\) for the meridional component. The mean sea ice speed varied between +0.15 and +0.19 m s\(^{-1}\) over the buoy array. Zonal velocities were all net westward and peaked at +0.85 m s\(^{-1}\) (buoy A1). The net meridional velocity direction, on the other hand, was more varied. Buoys A2, A3, and B3 exhibited a net northward drift, while the others showed net southward drift. Meridional velocities peaked at +0.53 m s\(^{-1}\) (northward, buoy A3). Zonal variability of the sea ice velocity was dominated by midday excursions from the mean, while such deviations were not clearly visible in the trace of the meridional velocity. Both velocity components were modulated by high-frequency variability, often at semidiurnal and to a lesser degree at diurnal periods.

There was a clear zonal gradient in sea ice velocity over the array. The drift rate of sea ice along the western flank of the array exceeded the rate along the eastern side by more than 20%. There was also a meridional gradient across the array, with the ice drift along the northern side exceeding that along the southern flank by 10%. Observational evidence of the ocean surface velocity during the voyage suggested that the high sea ice velocities along the southwestern edge of the buoy array were driven by the surface expression associated with a narrow westward oceanic jet. The jet coincided with the location of the strongest gradient of topography over the shelf break [Whitworth et al., 1998; Nicol et al., 2000].

To investigate the ARISE ice motion field more fully we analyzed the velocity cross correlation between buoy pairs and the velocity variance across the array, derived the associated meander coefficients, assessed the atmospheric driving force on the sea ice velocity, and investigated the sea ice drift in the frequency domain including their cross-spectral characteristics. Results are given in sections 4.1–4.5.

4.1. Spring Velocity Cross Correlation and Variance off East Antarctica

To characterize the sea ice motion off East Antarctica, the correlation length scale has been defined using the ARISE data. Correlation coefficients have been derived for the component and the total horizontal velocity traces using all 36 permutations of buoy pairs. The correlation length is
Figure 5. (a) Zonal and (b) meridional velocity components of the ice drift as measured using the nine buoy ARISE array.
defined here as the minimum distance between two buoys, for which the correlation coefficient drops below 0.6. During ARISE, separations between individual buoys in pairs varied from 24 to 189 km. On the basis of all buoy data, the zonal velocity components from the various buoys correlate well with each other (mean $R^2 = 0.89$). On the other hand, the meridional velocities show lower spatial coherence (mean $R^2 = 0.61$). While the horizontal correlation coefficients for individual buoy pairs dropped below 0.6 at separations in excess of 140 km, zonal velocities remained highly correlated ($R^2 \geq 0.75$) across the array at all separations. On the other hand, meridional velocities, at separation lengths larger than 62 km, were not well correlated ($R^2 \leq 0.60$). This relatively low-correlation length scale in the meridional velocity component was most likely due to the southern buoys crossing south into and then over the ocean jet at the shelf break. As a result, the northern buoys were left within the deep ocean regime, where the ice drift is primarily affected by passing synoptic systems, while the southern part of the array drifted over the continental shelf break and onto the shelf proper, where it was exposed to intensified tidal forcing and moved within the limits of the slope current. Nevertheless, all buoys remained within the westward flowing coastal current, hence the zonal correlation remained high for all buoy pairs.

[25] Similar to the mean ice velocity, the variance of the zonal velocity component exceeded that of the meridional velocity component (Figure 6). The velocity variances exhibited a gradient from the northeast to the southwest over the ARISE array. This gradient was most pronounced for the meridional variance, which was largest at the northernmost sites. The zonal velocity variances exhibited only a small gradient across the array, with zonal variances in the east slight smaller than in the west. In the north of the array, the ratio of the zonal to the meridional variance was 1:0.65, and reducing toward the south and west.

[26] To explore the spatial distribution of the velocity variances, we compared the spatial distribution of sea ice speed to the ice concentration at each site. As discussed in section 2, the buoy array overlays a shear zone. Ice concentrations to the south of the shear zone were slightly lower (by 3 to 5%) than those further to the north (Figure 6). These relatively uniform ice concentrations are unlikely to contribute to the spatial distribution of the ice velocity variances. We believe that the dominance of the zonal movement over the meridional in the southern region of the array, associated with the westward ocean slope jet, explains the change of shape of the velocity variance ellipses.

Figure 6. Variance ellipses of the sea ice velocity from DOY 269.27 to 306.83, shown at the respective mean positions (as labeled). Contours of mean sea ice concentration over the same interval are derived using AMSR-E data.
4.2. Spring Meander Coefficients off East Antarctica

The extent to which the sea ice motion deviated from a straight path is examined using the meander coefficient, which relates the overall translation of a particle to its net translocation. By definition, a meander coefficient of one implies that a particle moved along a straight line, while a high meander coefficient indicates an erratic trajectory [e.g., Massom, 1992]. The meander coefficient is a function of the time interval over which it is being calculated and also depends on the sampling frequency of the position data. To investigate the sea ice motion across the ARISE buoy array, we analyzed the common time interval from DOY 269.27 to 306.83, and used half-hourly positions to derive the mean-der coefficient for each buoy.

The distribution of meander coefficients varied across the ARISE array, with the lowest values in the southwest of the array, and larger values toward the north-east (Figure 7). Meander coefficients varied by a factor of two across the array, largely mirroring the results of our velocity variance analysis. Overall, the derived meander coefficients were low, indicating that the drifting sea ice observed here was part of a single large-scale forcing system, namely, the westward coastal current.

Meander coefficients for the ARISE array were also calculated for hourly data to enable comparison with those derived for other studies. There was less than 0.1% change in each of the meander coefficients using hourly instead of half-hourly buoy data. We note that although meander coefficients from the different experiments cannot be directly compared because of the differences in buoy deployment duration, it is informative to analyze the ARISE meander coefficients in the light of those derived previously. Unpublished hourly data from buoys deployed over the continental shelf in the region off the Mertz Glacier Polynya around 66°S, 145°E during 15 days in austral winter of 1999 exhibited similarly low meander coefficients. Earlier data from the westward coastal current west of the Mertz Glacier Polynya, around 65°S, 140°E, show hourly meander coefficients between 1.4 and 1.8 for a 15-day interval in August 1995 [Heil and Allison, 1999]. On the other hand, hourly meander coefficients derived for the western Weddell Sea over a 26-day interval in December 2004 were significantly larger [Heil et al., 2008], varying from 4.4 over the continental shelf break to 9.7 on the shallower continental shelf. Different durations and seasonality of the sea ice drift data are likely to account for the slight discrepancy in East Antarctic meander coefficients between those calculated for ARISE and those derived for winters 1995 and 1999. The relatively high meander coefficients found for ISPOL region during austral summer 2004 were a reflection of the high contribution of tidally driven motion relative to the mean drift at that location. There the sea ice moved with the ocean tides forth and back.
over the continental slope, deviating from its mean drift path. During ARISE, on the other hand, the presence of the ocean jet along the shelf break prevented the repeated on-shelf to off-shelf movement of the sea ice, aligning the sea ice to a more direct drift path.

### 4.3. Atmospheric Forcing

[30] Mean sea ice drift is driven by the atmospheric forcing as well as by the ocean surface current field [e.g., Thorndike and Colony, 1982; Budd, 1986], which is itself driven by a combination of wind-driven and geostrophically forced currents, with short-term deviations due to a combination of Ekman pumping and topographic steering [Budd, 1986]. At synoptic timescales, the sea ice drift is largely directly driven by the atmosphere. Here we used 10 m wind velocities derived from the vessel’s meteorological data to investigate the relationship between sea ice and the lower atmosphere during ARISE. The ratio of wind speed to ice drift depends on whether the sea ice is in free drift, readily following changes in the atmospheric forcing, or if it is under compression subject to internal stress. [31] Because the RSV Aurora Australis moved within the ARISE region, we analyzed the ratio of sea ice drift to wind speed separately for three time intervals, limiting the analysis to times when the RSV Aurora Australis was within 25 km of a given sea ice buoy. Half-hourly meteorological point data were used. A mean ratio for the interval from DOY 269.5 to 279.5 was 0.021 (±0.005). The mean ratios of sea ice drift to wind speed between the three segments are in good agreement to each other, with the mean correlation being R² = 0.91 over all three intervals. The ice drift to wind speed ratio derived here was at the lower end of the range of previous observations in the general region. For example, Worby et al. [1996] identified a mean ratio of sea ice drift to wind speed of 0.025 (relative to winds at the 10 m level) for winter pack ice off the East Antarctic. During ARISE, the divagation angle describing the angle between wind direction and sea ice drift, varied between 5.7 and 8.3° over the three segments, while the mean was at 6.8° with the sea ice drifting to the left of the wind direction. This agrees well with previous observations taken in the region. [32] Using Fourier analysis of the atmospheric parameters derived from the ship’s meteorological data, we derived the typical timescales at which atmospheric forcing peaked during the experiment. Surface winds and pressure spectra had most of their variance associated with frequencies of 0.09 to 0.33 cycles d⁻¹. This frequency range is associated with the passage of low-pressure systems [Jones and Simmonds, 1993]. For surface winds or air pressures there was little variance in the high-frequency end of the spectrum, which includes diurnal or semidiurnal processes.

### 4.4. Frequency Analysis

[33] The drift of sea ice may be presented in either the time or frequency domain. The Fourier transformation allows one to step from the time domain to the frequency domain and vice versa, while conserving the total power contained in the signal (Parseval’s theorem [Press et al., 1990]). Applying the linear Fourier transformation to our sea ice data allowed us to analyze how much variance was contained in frequency bands that can be associated with physical forcing mechanisms. We applied a fast Fourier transform (FFT) to our velocity data, to derive the power spectral density, which presented the variance abundance across the frequency spectrum. As our data were in the form of a discrete time series, we used a Hamming window [Press et al., 1990] in the time domain to minimize frequency leakage.

[34] As described above, sea ice dynamics is forced via a number of physical processes, which occur within specific bands in the frequency domain. For example, variability of extratropical cyclones, and hence changes in the distribution of surface pressure and winds, peak at frequencies around 0.12 to 0.33 cycles d⁻¹ [Jones and Simmonds, 1993]. Processes at shorter periods, which may exert force on the sea ice, are ocean tides and the inertial response, both of which occupy well defined frequency bands. Diurnal tides combine to peak around 1 cycle d⁻¹ and semidiurnal tides combine to peak around 1.93 cycles d⁻¹. The inertial response is due to the embedding of the sea ice within the upper ocean layer [i.e., McPhee, 1978; Heil and Hibler, 2002]. The frequency at which the sea ice exhibits an inertial response is a function of its latitude. In the ARISE region the inertial response occurs at about 1.82 cycles d⁻¹. On the basis of the half-hourly velocities, the Nyquist frequency associated with ARISE data was 24 cycles d⁻¹, sufficient to investigate the high-frequency processes affecting the sea ice dynamics.

[35] To increase our confidence in the derived frequency spectra, we split the finite time series into three overlapping intervals [Press et al., 1990]. We calculated the overall distribution of power spectral density as the normalized sum over all realizations, hence increasing the likelihood that the derived frequency spectrum converged toward the true distribution. The length of our time series allowed a resolution of frequencies as low as 0.04 cycles d⁻¹ (or periods as long as 21 days), which includes the frequencies at which synoptic-scale variability occurs within the atmospheric forcing. Given the length of the ARISE time series and its half-hourly sampling rate, we calculated the power spectral density over 512 frequency bins.

[36] For all nine buoys, the power spectral density associated with the zonal velocity exceeded that of the meridional by a factor of three to ten (Figure 8). The zonal sea ice velocities consistently showed a dominant low-frequency peak coinciding with a signal period of 3.5 to 5.3 days (or with frequencies of 0.19 to 0.28 cycles d⁻¹), coinciding with the peak identified in the spectra of the surface winds and pressure. A local maximum at around 0.55 day (or 1.83 cycles d⁻¹) was a consistent feature at all sites. In addition, the sites B1 and C1 to C3 exhibited a power spectral peak around 1.03 days (or 0.97 cycles d⁻¹). In contrast, for the meridional ice velocity at the ARISE sites, the power spectral density in the low-frequency band (period of 3.5 to 5.3 days) was of about equal magnitude to that in the semidiurnal frequency band. There was little variance of a diurnal signal in the meridional velocities. We interpret variance at periods of about 3.5 to 5.3 days as synoptic-scale forcing. As the ARISE buoys remained at all times north of the critical latitude, where the tidal frequency equals the local inertial frequency, we interpret variance at periods of about 1.03 days as the diurnal ocean tidal forcing. Power at semidiurnal periods could either be associated with half-daily oceanic tides or the inertial response of sea
ice to external forcing. The inertial period in the ARISE region is too close to that of the half-daily oceanic tides (M2 with a period of about 12.4 h; S2 with a period of about 12.0 h) to distinguish using the FFT method. Instead, a complex Fourier analysis is required to separate the relative contributions of these two semidiurnal mechanisms.

[37] In the complex spectral analysis, velocities within a two-dimensional plane are expressed as a combination of their clockwise and anticlockwise motion. Applying this and the knowledge that the ocean tides and the inertial response have different complex characteristics, we can distinguish between the two processes despite their near identical energy distribution over frequency. First, the inertial response in the Southern Hemisphere is strictly anticlockwise. Second, tidal motion describes a full ellipse every cycle, and can be separated into a barotropic (or clockwise in the Southern Hemisphere) and a baroclinic (or anticlockwise in the Southern Hemisphere) motion [Robertson et al., 1998].

[38] The anticlockwise and clockwise spectra for the sea ice velocity at the nine buoy locations are shown in Figure 9. As with the Fourier analysis discussed above, the bulk of the variance for sea ice motion during the experiment was found at low frequencies (0.19 to 0.28 cycles d\(^{-1}\)). This is in good agreement with the findings of our analysis of surface winds (section 4.3), confirming that the low-frequency variance in sea ice motion is strongly associated with synoptic-scale atmospheric forcing. In the anticlockwise spectrum a secondary peak occurred at semidiurnal frequencies for several buoy locations (A1–A3 and B2–B3). In the anticlockwise, spectrum variance associated with the diurnal band was generally low compared to that in the semidiurnal band. The oceanic tidal forcing gives rise to variances of similar magnitude at both the diurnal and the semidiurnal frequencies. Hence, the lower amplitude of the diurnal variance relative to the semidiurnal variance gives evidence that the semidiurnal variations are not due to tidal forcing, but rather the inertial response of the sea ice. At sites B1, C1, and C2, the variance in the anticlockwise semidiurnal band was similarly low to that in the diurnal band, indicating the absence of inertial response at those sites. It is noteworthy that, in the clockwise spectrum, semidiurnal and diurnal signals were low, except at B1, C1, and C2. The amount of variance associated with semidiurnal processes in the anticlockwise spectrum varied from 6 to 32% of that associated with low-frequency processes, while in the clockwise spectrum the high-frequency variance was less than 4% of that associated with low-frequency processes.

4.5. Sea Ice Deformation During Austral Spring 2003

[39] The sea ice deformation within the ARISE array was assessed by analysis of the differential kinematic parameters (DKPs, following Massom [1992] and Wadhams et al. [1989]). The four constituent DKPs were derived assuming that sea ice can be represented as a homogeneous continuum. Following Kirwan [1975] and Molinari and Kirwan [1975], the sea ice divergence (D), vorticity (V), shear deformation (S) and normal deformation (N) are functions...
of the strain components. To avoid any effect of the long-term drift, the kinematic parameters are calculated relative to the centroid of the ARISE array. Here only the sea ice deformation derived from the outer four buoys in the array, which on deployment enclosed an area of just over 4000 km$^2$, is discussed.

The ARISE array deformed significantly over the course of its deployment. While deformation occurred to some degree at all times, the bulk occurred in the second half of the experiment during two major events. During the initial 12 days the buoys moved largely uniformly, and ice deformation at all sites showed clear semidiurnal fluctuations. Then, about two weeks after deployment, the ice movement was characterized by differential motion, resulting in a net lengthening of the southern and western boundaries of the array. While all sea ice within the array drifted to the west (Figure 10), we observed a shear zone in east–west direction extending through the southern part of the array. The sea ice in the southwestern section of the array exhibited net southward movement, while that in the northern and eastern parts of the array showed net northward movement. This shear zone agreed with the gradient of the sea ice motion, with highest velocities during the experiment occurring along the southern edge of the array and to a lesser degree also at the western array edge.

During the first 17 days, there was little net change in the shape of the ARISE array. While there was little change in area in the first 11 days after deployment, the area enclosed by the array (Figure 11) increased to 270% of its initial size during the array’s 37 days deployment. At the same time, the open water fraction (derived from AMSR-E ice concentrations) in the region nearly trebled to 12%, suggesting that significant new ice growth took place in the pack during October 2003. This is in agreement with ship-based observations, which show that the surface air temperature at that time was well below freezing point, the sea surface temperature remained near the freezing point, and 20 to 40% of the total ice concentration was new or young grey ice.

The time series of sea ice divergence for the nine buoy array shows a quiescent interval from DOY 269 to 276, when the divergence amplitude rose from 2 to 5 × 10$^{-6}$ s$^{-1}$ (Figure 12). The divergence magnitude settled back to lower values when sharp but intense signals were observed in shear and normal deformation. These coincided with the creation of the shear zone through the ARISE array, which persisted for the remainder of the experiment. During this time, net divergence remained positive, which resulted in an increase in enclosed array area by about 15%. From DOY 282, and coinciding with increased winds (Figure 4b), the divergence amplitude increased again (to about 3.5 × 10$^{-6}$ s$^{-1}$). At this time, the vorticity showed a net cyclonic rotation. From DOY 289 onward the amplitude of the DKPs increased to about 0.3 × 10$^{-5}$ s$^{-1}$ and again from DOY 296, when the amplitude of the parameters reached in excess of 1.6 × 10$^{-5}$ s$^{-1}$. This almost tenfold increase in magnitude of the DKPs coincided with a major blizzard event. Before DOY 279 and from DOY 281, the sea ice...
DKPs observed over the ARISE array oscillated with a period of half a day.

Initially, all four parameters remained relatively low (on the order of $10^{-8} \text{ s}^{-1}$). About 10 days after deployment (DOY 278), there was a rapid oscillation in vorticity from anticyclonic to cyclonic. This was followed by a minor peak in normal deformation, and increased positive shear deformation over a 22-h interval. Overall, the four DKPs are of similar magnitude, and changes in magnitude are linked between all the four parameters, with one often leading the others.

5. Discussion

During ARISE, observations captured sea ice dynamics with maximum separations of 189 km between individual buoys. As such, the ARISE array drifted within a...

**Figure 10.** Net directional sea ice translation (black arrows) for the ARISE array averaged over the interval DOY 269.27 to 306.83, originating at the mean position of each buoy in the array. The buoy deployment positions are shown as black stars. See Figure 1 for naming of the initial buoy arrangement.

**Figure 11.** Time series of the area enclosed by the nine buoy ARISE array from DOY 269.27 to 306.83. Dashed lines indicate the occurrence of major storms in the region of the buoy array. Meteorological data after the vessel’s departure on DOY296 are from NCEP-2 reanalysis.
Figure 12. Time series of the differential kinematic parameters for the ARISE array derived using data from the four corner buoys A1, A3, C1, and C3: (a) divergence, (b) shear deformation, (c) normal deformation, and (d) vorticity. Positive vorticity indicates anticlockwise motion. Dashed lines indicate the occurrence of major storms in the region of the buoy array. Meteorological data after the vessel’s departure on DOY296 are from NCEP-2 reanalysis.
single synoptic-scale atmospheric regime, and its drift reflected the dominance of atmospheric forcing on the sea ice. In excess of 65% of the variance in the ice motion was directly associated with the synoptic-scale forcing. Tidal forcing was significantly less effective, contributing to less than 8% of the variance in the ice motion. Tidal activity was largely limited to the southwestern part of the buoy array, which mostly drifted over or near the continental shelf. Tidal forcing was largely negligible in the northern and eastern sections of the array, where the ice drifted over deep water off the continental slope. Notably, the ice drift over the deep water exhibited a significant subdaily contribution from the inertial response, which reduced as the ice moved into shallower regions. On the other hand, variability in differential ice motion was largely driven by the inertial response, with additional contributions from the synoptic-scale atmospheric forcing.

5.1. Oceanic Modulation of Atmospheric Forcing on the Sea Ice

Our results present evidence that the bathymetry of the ARISE region gives rise to the anisotropic character of the velocity variance and also of the distribution of power spectral density. The large-scale setting around the study region includes an ocean bathymetry, where depth decreases from the north to the south. Upon deployment, the continental slope was just to the south of the southern edge of the ARISE array. Ocean depths at the deployment sites of buoys C1, C2, and C3 were close to 1000 m, and ranged between 2000 and 3000 m at those of the other buoys. To the west of the array, east of Law Dome (Figure 6), the continental shelf extends further to the north than in the initial ARISE region, encouraging the movement of part of the ARISE array over the slope onto the continental shelf. Following Middleton and Humphries [1989], tidal forcing at the surface ocean, and hence on the embedded sea ice, is largest over shallow waters as well as in the vicinity of major topographic gradients, such as near sea mounts or along the continental shelf slope. Elevated variances for the zonal velocities at frequencies near 0.97 cycles d\(^{-1}\) and near 1.83 cycles d\(^{-1}\) at the southernmost sites and near B1 agree well with this. During the course of their respective drifts these buoys were largely located near or above the continental shelf. In contrast, the northern and northeastern part of the array, where the ice remained over deeper water, did not show substantial diurnal variance.

On the other hand, there is an inverse distribution of semidiurnal contributions to the velocity variance, that is not matched by diurnal variances. This variance, due to inertially induced ice motion, was observed at the northern sites (A1–A3 and B2–B3), where the ice remained over deeper water. The semidiurnal variance associated with the inertial response was about five to eight times stronger than the variance due to diurnal or semidiurnal tidal forcing. Little inertially induced variance was observed at the continental slope or over the continental shelf. This may be an unexpected result as both in situ and remotely sensed data show that, in general, ice concentrations over the shelf were slightly lower than north of the continental slope. However, the existence of a strong and persistent oceanic surface jet originating at the shelf break is responsible for the anisotropic character of the velocity variance at southwestern sites of the ARISE array (e.g. Figure 6). The effect of this surface current is also reflected in the very low meander coefficients encountered at the far southwestern sites. To the north away from this unidirectional fast current, the sea ice was, despite slightly higher ice concentrations, free to deviate from the mean drift. This in turn may have contributed to the high levels of observed semidiurnal variance (Figure 9), which is linked to synoptic-scale variance through the upward propagation of a nonlinear energy cascade in the frequency spectrum [Heil and Hibler, 2002]. This finding is in agreement with those derived from previous observations of sea ice drift off East Antarctica [e.g., Heil et al., 1998], where a significant inertial response of the sea ice near 65\(^{\circ}\)S, 140\(^{\circ}\)E has been identified in austral winter.

The excess of zonal over meridional variance in all spectra (Figure 8) is a striking feature of the ice drift during ARISE. Variance spectra of the two horizontal components of the surface wind do not show any directional preference. Although there are no concurrent oceanographic velocity data, we suggest that the dominant westward ocean currents are not only responsible for the strong westward ice motion but also for the increased zonal variance across the frequency spectrum. The oceanic regime in the region consists of the westward coastal current and of the intense westward jet stream along the continental slope [Nicol et al., 2000]. Alongshore, in our case east–west, flow speeds of the jet stream exceed those present on the nearby continental shelf [Middleton, 2006]. The westward jet is not only a preferred pathway for drifting icebergs but, as our data show, it also efficiently carries sea ice to the west and out of the region. Hence, the mean westward ice drift identified here is reflected in the zonally dominant low-frequency variance (Figure 8), even though the atmospheric forcing contributes equally to the zonal and meridional low-frequency variance.

To summarize, the sea ice drift during the spring of 2003 was dominated by atmospheric forcing, while oceanic contributions not only included tidal forcing but also gave rise to anisotropic character of the ice drift as the sea ice moved within two (westward) ocean regimes. The contribution of tidal forcing was generally less than that of the inertial response, and was limited to locations within close proximity of the continental shelf. The inertial response, derived from atmospheric forcing, exerted the largest influence on the sea ice drift at short (daily or less) timescales. The contribution of the wind-induced forcing to the sea ice drift was similar to that found in previous studies.

5.2. Bathymetric Imprint on Correlation Length Scales

Regarding correlation length scales, a horizontal dichotomy dominated the region, with the meridional velocities decorrelating at relatively short separations, while the zonal velocities remained correlated within the spatial limits of the ARISE array. The two-dimensional horizontal velocity showed a correlation length scale of 140 km. To determine whether the decorrelation identified here was due to discrete events (such as strong wind episodes) or if it provides a general representation of the ice drift in the region, the correlation length scales have also been derived for intervals shorter than the ARISE interval (DOY 269-27 to 306.83). These shorter intervals (8 days) were chosen both to include and exclude discrete forcing events. Zonal
velocities remained highly correlated during all shorter intervals. There is little difference in the correlation length scales identified, with meridional velocities decorrelating (R² ≤ 0.6) at 60 km and 66 km for intervals including and excluding discrete forcing events, respectively. This gives evidence that the correlation length scale identified from the ARISE data is independent of individual forcing events such as strong winds. To emphasize, the decorrelations identified here are not due to the ice breakup during spring. Instead, the derived correlation length scales provide a regional characterization of sea ice drift around the time of maximum annual ice extent.

[50] To explore the processes contributing to the decorrelation of sea ice velocities, cross-spectral correlations [i.e., Jenkins and Watts, 1969; Naidu, 1996] have been derived for all possible permutations of buoy pairs. For all buoy pairs, the cross-spectral correlations were high (R² ≥ 0.8 at the 95% significance level) at synoptic scale, while few buoy pairs also exhibited high cross-spectral correlation at semidiurnal periods. In detail, semidiurnal cross-spectral correlations showed a dependency on bathymetry underneath the buoy pairs, with semidiurnal correlations being confined to buoy pairs off the continental shelf (Figure 13).

5.3. East Antarctic Sea Ice Deformation During Spring

[51] Well-defined changes in sea ice deformation across the ARISE region, in general, coincided with the occurrence of wind speeds in excess of 35 m s⁻¹. At times of high wind speed, the wind direction veered from predominantly westerly to predominantly easterly, giving rise to a reversal in direction of the sea ice vorticity. Notably, changes in divergence during those events were usually delayed by up to 36 h.

[52] The net divergence of the outer ARISE array was dominated by the high velocity differential of the pack ice along the northern and the eastern edges of the array relative to the remainder. The shear deformation of the outer ARISE array was largely a response to the lateral stresses encountered along the southern edge and the southwestern corner of the array. As such, the shear deformation was strongly influenced by the position of the oceanic slope jet relative to the array. Both effects became most pronounced with the passage of the first storm after the on-shelf transition of the southwestern array section (Figure 12).

[53] Temporal variability in all four DKPs over the outer ARISE array was largely dominated by high-frequency changes, with twice-daily modulations often oscillating between positive and negative values for all four DKPs for most of the ARISE interval. Fourier analysis of the DKPs (Figure 14) exemplified the dominance of the semidiurnal variance associated with all four parameters. In contrast to the analysis of the ARISE sea ice velocities themselves, power spectral density at low frequencies, including multiday and at diurnal frequencies, were of lesser importance for the sea ice deformation during ARISE 2003. Variance associated with multiday periods, as prevalent for the sea ice velocity, was effectively damped out, while semidiurnal variance dominated. This can only be explained by the energy propagation to higher frequencies, as none of the tangible external forcing mechanisms showed high-frequency variability across the complete ARISE array. This is in agreement with Heil and Hibler [2002], who identified a nonlinear cascade of energy when analyzing the frequency distribution of Arctic sea ice deformation.

5.4. ARISE Sea Ice Dynamic in the Antarctic Context

[54] Although there have been a number of drifting buoy deployments off Antarctica (see section 1), there have been relatively few drifting buoy arrays. The first sea ice buoys in the Southern Ocean were deployed in the Weddell Sea in 1979, and this region experienced the highest intensity of Antarctic buoy deployments. Numerous studies covered the Weddell Gyre, as well as subregions of the Weddell Sea [e.g., Massom, 1992]. The buoy data showed that sea ice drift over the continental shelf or near the shelf break typically followed bathymetric contour lines [Limbert et al., 1989], hence providing evidence of topographic steering similar to that found during ARISE. Furthermore, for the Weddell Sea the observations showed that the ice motion depends on the regional ice concentration [Rowe et al., 1989]. The meridional pack ice extent in the Weddell Sea is typically up to 1000 km during austral winter and spring, compared to the meridional extent of about 330 to 410 km off East Antarctica during ARISE [Gloersen et al., 1992]. In consequence, the full latitudinal breadth of the East Antarctic sea ice is generally exposed to the same synoptic-scale atmospheric forcing, overwriting any dependencies on the local ice concentration, as seen during ARISE.
At long timescales, the ice motion variance in the Weddell Sea is largely a function of large-scale atmospheric forcing and the oceanic circulation associated with the Weddell Gyre [Uotila et al., 2000], and of tidal motion and inertial response at daily and shorter timescales. Variance in the ice motion over the continental shelf in the western Weddell Sea appears to be dominated by diurnal and semidiurnal tidal forcing [Rowe et al., 1989; Geiger et al., 1998]. Variance of early austral summer drift near the continental shelf during ISPOL (average ice concentration

Figure 14. Frequency spectra of the sea ice divergence (in semilogarithmic presentation) for the array of the four outer buoys during ARISE (DOY 269.27 to 306.83): (a) divergence, (b) shear deformation, (c) normal deformation, and (d) vorticity. The scale at 11.5 cycles d^{-1} presents the 95% confidence interval.
of 94%) was largely forced from diurnal tidal motion, with lesser contributions by semidiurnal tidal forcing and inertial response [Heil et al., 2008]. Because of the different geographical setting off East Antarctica, the ARISE velocity variance of sea ice motion did not show oceanic signatures at multidially scales. Instead multidially variability in ice motion are largely explained by atmospheric forcing. Nevertheless, ice moving within the oceanic “jet stream” was strongly affected by its translational character, although the residence time of ice floes within this jet were too short to be reflected in the velocity variance. Similar to the Weddell Sea, all ARISE ice motion off East Antarctica showed some variance due to the inertial response, with sea ice over the continental shelf also being subject to variance due to the tidal forcing. In contrast to data from ISPOL, the ARISE data indicate that the East Antarctic sea ice did provide a medium that effectively allowed the transfer of energy from lower (i.e., multidaily) frequencies toward semidiurnal frequencies, with significant effects on the sea ice characteristics in the region, as discussed earlier.

Few buoy data have been analyzed for regions outside the Weddell Sea or off East Antarctica. Geiger and Perovich [2008] report on ice motion in Marguerite Bay (Bellingshausen Sea) during austral spring 2002, with one buoy deployed deep in the pack and the other about 110 km further north. There, the ice motion was dominated by synoptic-scale atmospheric forcing and topographic steering, although both drift trajectories showed intervals of strong high-frequency oscillations, which were shown to be inertial. Changes in the drift characteristics were linked to the seasonal transition of the ice pack, associated with the disintegration of the sea ice cover. Ice drift west of the Antarctic Peninsula [Geiger and Perovich, 2008] showed similarities to that off East Antarctica with regard to the pronounced effect of the occurrence of an inertial signal in the ice motion, although this high-frequency signal was more persistent off East Antarctica.

In the Weddell Sea, DKPs are largely related to the atmospheric forcing [Crane and Wadhams, 1996; Massom, 1992; Wadhams et al., 1989; Heil et al., 2008], with additional input due to tidal motion and inertial response [Geiger et al., 1998; Heil et al., 2008], especially for ice over the continental shelf or near the shelf break. Differential ice dynamics in the northeastern Weddell Sea (at 100 to 300 km separation) during austral spring 1989 was dominated by vorticity and to a lesser degree by shear and normal deformation [Crane and Wadhams, 1996]. At that time, ice concentration in the region was at or above 95%. Toward the end of this time series, the ice concentration dropped below 93% and the divergence magnitude increased to values similar to the other three differential parameters. Crane and Wadhams [1996] showed that variance in the vorticity was directly related to changes in the surface air pressure, i.e., storms.

Using all buoy data available for the Weddell Sea, Kottmeier et al. [1996] found that inhomogeneous occurrence of tidal motion and inertial response over the continental shelves determines the variability in the ice divergence. During austral winter in the western Weddell Sea, the variance of the DKPs, especially of the ice divergence, was dominated by semidiurnal input [Geiger et al., 1998]. Variance in the DKPs during early austral summer in the western Weddell Sea was driven by subdaily processes, namely, tidal forcing and inertial response [Heil et al., 2008]. These findings compare well with those from ARISE and prior investigations [Heil et al., 1998] of differential ice motion off East Antarctica. There, the semidiurnal processes dominate, with the inertial response driving variance in the DKPs in the regions off the continental shelf, while contributions of the tidal forcing are mostly limited to sea ice over the continental shelf.

6. Conclusions

[59] The ARISE buoy array was deployed near 65°S, 119°E in what was a region of uniform sea ice drift at the time. However, around two weeks after deployment, the surface winds associated with the passage of a low-pressure system shifted the array to the south. Consequently, the south-western part of the array traversed a narrow but fast flowing westward oceanic jet, a near-stationary feature along the continental shelf break. This gave rise to the creation of a shear zone within the array. Subsequently, the sea ice in the south-western part of the array exhibited increased high-frequency variance in its drift, due to oceanic tidal forcing at diurnal and semidiurnal frequencies, while the inertial response remained the dominant factor for high-frequency variance in the northeastern part of the array. Horizontal dichotomy dominated the correlation length scales in the region. Decorrelation of the meridional ice velocities took place at separation scales in excess of 62 km, while zonal ice velocities remained correlated at even the greatest separation scales achieved within the array. The decorrelation of meridional velocities was likely to be driven by bathymetrically controlled flow at the ocean surface, with the ARISE array integrating across two bathymetric regimes.

[60] Variance in the ARISE ice motion was dominated by large-scale multiday processes. Sea ice deformation, derived over the outer perimeter of the array, was dominated by net divergence over the lifetime of the ARISE array. The bulk of variance in the ice deformation occurred at semidiurnal frequencies, with little variation between the four kinematic parameters.

[61] The strong influence of atmospheric forcing on the sea ice drift has been identified in the spectral analysis of the ARISE sea ice velocities. Sea ice motion exhibited most of its variance at the same frequencies at which the atmospheric forcing occurred during the experiment. In excess of 85% of the variability in the sea ice velocity was explained by atmospheric forcing. Furthermore, we were able to identify a secondary effect of the atmospheric forcing on the sea ice, namely, the initiation of an inertial response by the sea ice. Tidal excitation of the sea ice was limited to locations over shallow ocean bathymetry. On the basis of our analysis, we conclude that sea ice dynamics during ARISE 2003 was subject to an energy cascade from lower (multiday) frequencies toward high (semidiurnal) frequencies.

[62] While we found in principle agreement between sea ice drift and deformation during ARISE with those from other Antarctic regions, the East Antarctic sea ice dynamic sets itself apart. ARISE has shown a marked effect of atmospheric forcing on the ice velocity variance, but little
dependence of oceanic forcing on the velocity variance. The overriding effect of synoptic-scale atmospheric events is felt across the full breadth of the East Antarctic sea ice zone, and generally reflected in the heavy modification of the regional ice edge location, floe size distribution, ice concentration and net translation. Because of the recurrence of the atmospheric forcing all through the austral winter and spring season, the effects of the spring transition on the East Antarctic sea ice tend to be mitigated compared to other Antarctic regions. The strongest similarity between the results from ARISE and those reported from the Weddell Sea can be found in the DKPs. The variance in the DKPs is dominated by high-frequency processes, which are generally driven by semidiurnal tidal forcing for ice over the continental shelf or by the inertial response for ice off the shelf. Several experiments, including ARISE, have shown the dominating contribution by the inertial response on the sea ice off East Antarctica during austral winter and spring.

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