Observation of cyclone-induced inertial sea-ice oscillation in Fram Strait

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Observation of cyclone-induced inertial sea-ice oscillation in Fram Strait

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[1] In March 2007 the field campaign FRAMZY took place in the region between Spitsbergen and Greenland. One goal of the experiment was the observation of cyclone impact on ice drift by means of autonomous meteorological buoys, deployed on sea ice. On 23 March an intense cyclone, of about 500 km diameter, passed with about 20 m/s from south to north over the ice-covered part of the Fram Strait and induced strong inertial oscillations of the sea ice. Ice-drift velocity fluctuations abruptly increased by a factor of three to values of more than 1 m/s. This was caused by a resonant wind forcing for almost three quarters of the inertial oscillation. Depending on the local ice conditions the oscillations lasted over a two to five days period. The inertial oscillations caused ice drift divergence fluctuations of $\pm 6 \cdot 10^{-6}\ s^{-1}$ and a reduction of ice concentration by up to 11%. **Citation:** Lammert, A., B. Brümmer, and L. Kaleschke (2009), Observation of cyclone-induced inertial sea-ice oscillation in Fram Strait, *Geophys. Res. Lett.*, *36*, L10503, doi:10.1029/2009GL037197.

1. Introduction

[2] The Arctic region, particularly sea ice, is an important part of the global climate system. Sea-ice extent, concentration, thickness, and export react very sensitively to the climate change [*Intergovernmental Panel on Climate Change*, 2007]. The knowledge of the atmospheric and oceanic interaction processes with sea ice is important for the understanding and prognosis of the climate system, and it is also important for the improvement of weather forecast models.

[3] The transport of sea ice is driven by atmospheric and oceanic forcing [*Kimura and Wakatsuchi*, 2000; *Zhao and Liu*, 2005; *Makshtas et al.*, 2007]. For the ice transport from the Arctic Ocean to the North Atlantic the Fram Strait as the main gateway plays a key role [*Rogers et al.*, 2005; *Kwok et al.*, 2004]. Strong temperature contrasts exist between the open water in the eastern part and the sea ice in the western part of Fram Strait. Due to this strong baroclinicity the Fram Strait is a region with a high cyclone occurrence [*Brümmer et al.*, 2000; *Affeld*, 2003]. The impact of cyclones on the ice export in Fram Strait was investigated, e.g., by *Brümmer et al.* [2001], *Affeld* [2003], *Rogers et al.* [2005], and *Schröder* [2005].

[4] In order to increase our observational knowledge of Fram Strait cyclones impact on ice extent, concentration, and export the field experiment FRAMZY 2007 (Framstrassen Zyklonen) was conducted in March/April 2007 as contribution to the International Polar Year (IPY). During the campaign, drift buoys were deployed on the sea ice of the Fram Strait, a research aircraft was employed for detailed atmospheric measurements, and satellite imagery as well as operational model analyses were applied.

[5] In this paper we present measurements of an intense cyclone, which occurred during FRAMZY 2007. The cyclone moved very fast from south to north through the Fram Strait and caused substantial inertial ice-motions lasting for several days. Inertial sea-ice oscillations are a known process both in the Arctic [e.g., *Leppäranta and Hibler*, 1987; *Kwok et al.*, 2003] and the Antarctic [e.g., *Geiger and Perovich*, 2008]. However, to the authors' knowledge no observations of such a strong inertial oscillation in the Arctic have been presented in the literature before. Our observations demonstrate the particular triggering conditions by the cyclone and the consequences for ice divergence and concentration.

2. Data Used in This Study

[6] Our study is mainly based on data of CALIB (compact air launchable ice buoy) buoys manufactured by the Canadian company Metocean. The buoys measure air pressure and temperature. The drift velocity is derived from the buoy position, which is determined by means of the Argos satellite system (see http://www.argos-system.org). The temporal resolution of the data varies between 20 and 90 minutes, depending on the availability of the polar orbiting satellites. For this study, all measurements are interpolated to one-hour resolution.

[7] Buoys were deployed via aircraft at the beginning of March 2007. The main experimental period was from 1 March to 9 April 2007. Figure 1 shows the positions of all 13 buoys on 23 March. The overall drift direction for all buoys in the Fram Strait was towards south-southwest. However, strong velocity differences between the buoys could be observed. Buoys (e.g., B3, B8, B15) in the vicinity of the fast ice on the Greenland shelf ice were moving slowly, in contrast to buoys (e.g., B6, B9, B14) located near the ice edge.

[8] In order to evaluate the synoptic situation in the Fram Strait region we use the six-hourly operational analyses of the ECMWF (European Centre for Medium-Range Weather Forecasts) global model with a 0.25 degree resolution. The ice concentration as well as the extent is taken from satellite observations as best estimate. Here we use sea-ice concentration data derived from the 89 GHz channels of the AMSR-E (Advanced Microwave Scanning Radiometer) instrument on the AQUA satellite [*Kaleschke et al.*, 2001; *Spreen et al.*, 2005, 2008]. The horizontal resolution of the

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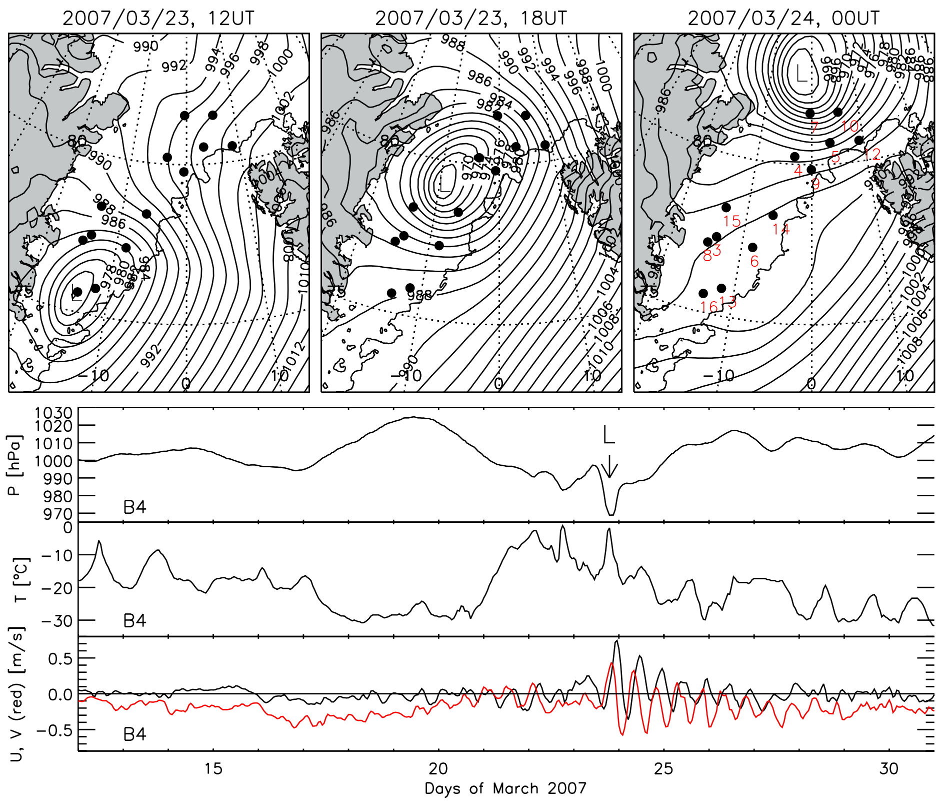

Figure 1. (top) Six-hourly ECMWF sea level pressure analyses and buoy positions for 12 to 24 UT on 23 March 2007. In addition the AMSR-E ice extent averaged for 23 March 2007 is provided in all maps. (bottom) Time series of pressure (P), temperature (T), and drift velocity (U (black) and V (red)) measured by buoy B4 from 12 to 31 March 2007. L marks the cyclone event.

AMSR-E ice concentration is 5 km × 5 km and is, thus, particularly useful for the investigation of mesoscale features. Ice concentration and extent in ECMWF analyses are not significantly different from AMSR-E data.

3. Analysis of Cyclone and Ice Motion

[9] On the west side of a high pressure ridge in a general south-west air flow, three cyclones developed and passed through the Fram Strait from south to north. First one on 21 and second on 22 March were weak and slowly passing cyclones. In the following we concentrate on the third and strongest one of this family on 23 March. Figure 1 shows the sea level pressure analyses of ECMWF for 12, 18, and 24 UT on 23 March 2007. The cyclone passed to the west of most of the buoys through Fram Strait within 12 hours with a mean velocity of about 20 m/s. During this time the cyclone intensified and the core pressure decreased from 974 hPa to 963 hPa. The ECMWF pressure analyses are in agreement with the buoy pressure measurements.

[10] Figure 1 shows the time series of air pressure, temperature, and drift velocity of buoy B4 in the northern part of the Fram Strait as an example. Until 20 March the east-west component (U) of the ice drift varied between −0.1 and 0.1 m/s and the north-south component (V) between −0.4 and 0.0 m/s. On 23 March the pressure decreased rapidly to a minimum of 968 hPa indicating the passage of the third cyclone. At this moment strong oscillations of the U and V drift component were initiated ranging between −0.3 and 0.7 m/s and between −0.6 and 0.4 m/s, respectively.

[11] All buoys experienced the effect of this pressure minimum and the ice drift changed to be dominated by high-frequency oscillations. In Figure 2 the hourly drift vectors are given starting on 23 March, 06 UT for all buoys, sorted from southwest to northeast (bottom to top). In addition the ECMWF 10m wind vector, interpolated to buoy positions, is given every six hours. Figure 2 demonstrates (a) the clockwise oscillation drift of all buoys, (b) the in-phase wind forcing at the first 6 to 8 hours of the oscillation, (c) the time shift of oscillation onset from south to north in accordance with the propagation speed of the cyclone, and (d) the general increase of wind speed and oscillation amplitude with the intensifying cyclone. Probably depending on the local ice conditions around the buoy and the local amplitude of the wind forcing the ice oscillations lasted for different periods between two and five days.

[12] It is known that cyclones are able to induce inertial oscillations of the sea ice due to the wind stress on the ice-ocean mixing layer [e.g., *Pease et al.*, 1995; *Hibler et al.*, 2006]. Inertial oscillations (in the northern hemisphere) are clockwise rotations, in contrast to tidal oscillation, which can rotate clockwise or counter-clockwise. The inertial-oscillation period T at 8°N is 11.82 hours and thus close to the semidiurnal M2 tide. In Fram Strait the tide changes between clockwise and counter-clockwise on a small horizontal scale due to the bathymetry, and the maximum tidal velocity is almost one order of magnitude

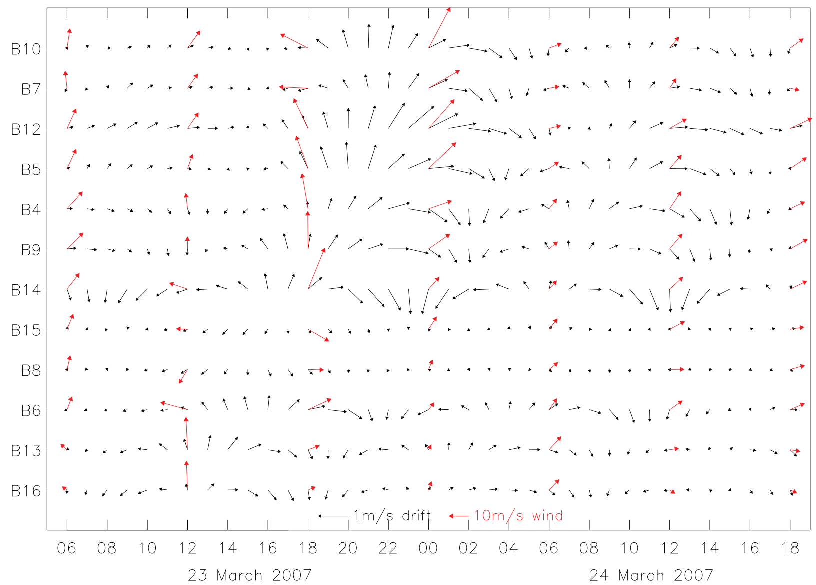

Figure 2. Time sequence of drift vector of buoys (given in Figure 1) from southwest to northeast (one hour resolution, black) for the time interval 23 March, 06 UT to 24 March, 18 UT. In addition 10m wind vectors, interpolated from ECMWF operational analyses to buoy positions (six hour resolution, thick gray) are plotted.

smaller than the buoy drift-velocity (E. Taguchi, personal communication, 2009). Due to the track of the cyclone on the western side of the buoy array, its propagation speed, its horizontal scale, and its strong pressure gradient, the ice oscillation was resonantly forced by the in-phase change of wind direction. The buoys experienced wind from east first, followed by wind from south, and finally wind from west in the cause of the cyclone passage (see Figure 2).

[13] To separate the inertial oscillation from the tidal M2 oscillation, a spectral analysis of the drift velocity was performed. Figure 3 shows the power spectra of the ice-drift vector for several buoys for 8 days intervals before (12 to 19 March) and during (22 to 29 March) the oscillation event. Negative cycles per day (cpd) imply clockwise (inertial or tidal), positive cpd correspond to counter-clockwise (only tidal) rotation. Before the cyclone event, the buoy drift spectra show relative maxima at 2 cpd and −2 cpd, both representing the M2 tide, due to the tidal changes on the above-mentioned small horizontal scale. By contrast during the event a peak at −2 cpd dominates the spectra of all buoys, whereas the spectral values at 2 cpd have the same magnitude as before but show no local maxima. For this reason we can conclude that the maximum at −2 cpd is the additional effect of the inertial oscillation.

[14] The impact of the cyclone-induced inertial oscillation on the ice conditions is demonstrated in Figure 4. It shows the hourly positions of buoys B4, B5, and B7, forming the blue triangle, for the time interval from 12 to 31 March and, in addition, two other buoy triangles (red and green) at the beginning and end of this time interval. Figure 4 illustrates the different drift velocities of the three buoys, the different drift behavior before and after 23 March, as well as the shape changes of the buoy triangles with time. The temporal variation of the divergence of the buoy triangle B4-B5-B7 is also displayed in Figure 4, as an example. Until 23 March the divergence varied in the range from -2 to $+2 \cdot 10^{-6}\ s^{-1}$. On 23 March, at the time of the cyclone event, the divergence fluctuations increased by a factor of 3 to values between -6 to $+6 \cdot 10^{-6}\ s^{-1}$. Since the strong oscillations of the buoy drift propagate with the moving cyclone from south to north, the oscillations at different locations are not in phase and cause the buoy triangle to become smaller and larger with a period of about 12 hours. An impact on the sea-ice concentration appears obvious but cannot be captured with the same high temporal resolution by the

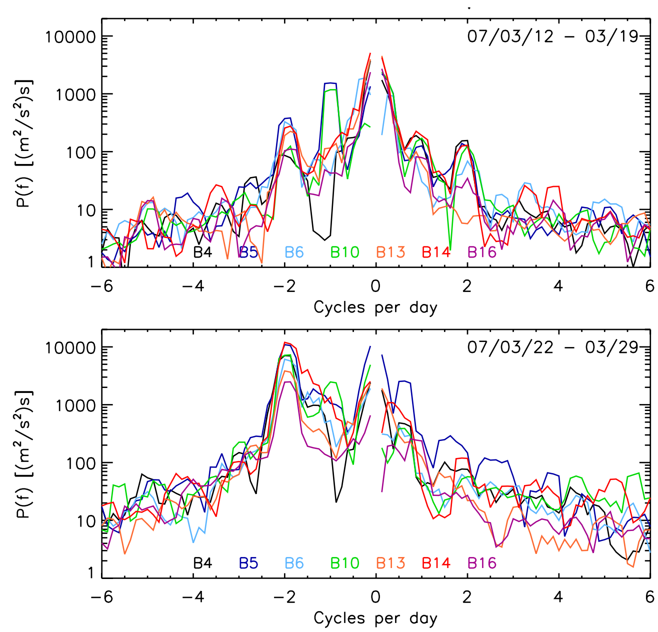

Figure 3. (top) Power spectra P(f) of drift vector for selected buoys for time interval before oscillations (12–19 March). Negative (positive) cycles per day means clockwise (counter-clockwise) drift vector rotation. (bottom) Power spectra P(f) of drift vector of selected buoys for the time interval during oscillations (22–29 March).

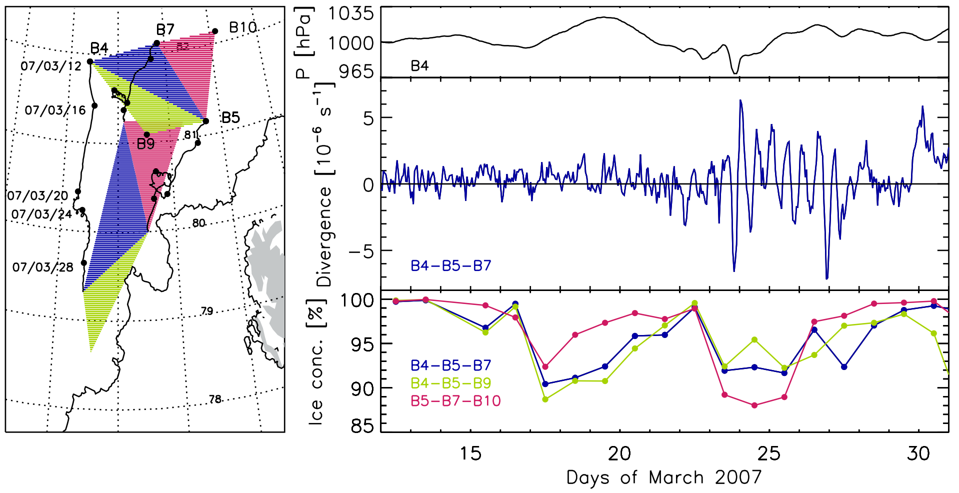

Figure 4. (left) Hourly positions of buoys B4, B5, and B7 from 12 to 31 March 2007 with marks every 4 days. Buoy triangles B4-B5-B7 (blue), B4-B5-B9 (green), and B5-B7-B10 (red) at 12 and 31 March 2007. Black line gives the AMSR-E ice-extent for 23 March 2007. (right) Hourly pressure (P) measured by buoy B4, hourly ice-drift divergence for buoy triangle B4-B5-B7, and daily mean sea-ice concentration from AMSR-E measurements for buoy triangles on the left from 12 to 31 March 2007.

AMSR-E satellite measurements. Satellite overpasses are available only from 09 to 15 UT and sea-ice concentration from individual overpasses may have a 5% error. Thus, daily averaged ice concentrations, areal averaged over each triangle (see map), are presented in Figure 4. The time series show decreases of ice concentration between 7 and 11% from 22 to 24 March. In all triangles the ice concentration increases within two to four days after its minimum concentration to values observed before the event, probably mainly due to refreezing at low air temperature (below −20°C). The second ice-concentration minimum on 17 March is not aligned with increased divergence fluctuations. It occurred when a trough extending from a low over Barents Sea passed from northeast to southwest through Fram Strait on 16/17 March and a cold-air outbreak began (see Figure 1). This explains the slow increase of ice concentration till 20 March 2007.

4. Summary and Conclusions

[15] During the Fram Strait Cyclone Experiment FRAMZY 2007 autonomous meteorological ice drift buoys were used among other instrumentation for the measurement of cyclones and their impact on sea ice. On 23 March 2007 an intense cyclone passed from south to north over the ice-covered part of the Fram Strait. Due to the scale (diameter D around 500 km), the high propagation velocity (U = 20 m/s), and the strong pressure gradient (4 to 6 hPa/100 km), the cyclone's wind field forced an inertial ice oscillation resonating for almost three quarters of the first oscillation period. Owing to the cyclone track over the buoy array, almost all buoys experienced this oscillation. Generally, a passing cyclone can resonantly force an inertial oscillation only on the right side of its track (in northern hemisphere) and at most for three quarters of the period if the condition $D/U \approx 0.75\,T$ is fulfilled. This was nearly the case here. The onset of oscillation propagated from south to north with the same velocity as the cyclone propagation. The divergence fluctuated with the same period as the drift velocity. AMSR-E satellite data show that the cyclone-induced inertial oscillation led to a decrease in sea-ice concentration in the range from 7 to 11%. The ice concentration increased again after the inertial oscillation event, probably due to refreezing. Thus, the event leaves newly frozen areas with lower ice thickness and lower albedo. Other buoy campaigns in Fram Strait and inner Arctic should be analysed with respect to strong oscillation events, since there is no statistics of such phenomena so far. However, such studies are only possible with a high temporal resolution of the measurements as was the case here. Cyclone statistics for the Arctic could be used to evaluate the occurrence frequency of those cyclones fulfilling the above-mentioned condition of diameter and propagation speed, and thus, could be able to induce strong inertial oscillations. Inertial ice oscillation is a small-scale process, the role of which should not be underrated for Arctic climate, similar to the role of tides [e.g., *Holloway and Proshutinsky*, 2007].

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