Available online at www.sciencedirect.com
ScienceDirect
Deep-Sea Research II 55 (2008) 943–962
DEEP-SEA RESEARCH
PART II
www.elsevier.com/locate/dsr2

Tidal forcing on sea-ice drift and deformation in the western Weddell Sea in early austral summer, 2004

Petra Heil[a,*], Jennifer K. Hutchings[b], Anthony P. Worby[a], Milla Johansson[c], Jouko Launiainen[c], Christian Haas[d,1], William D. Hibler III[b]

[a]*ACE CRC & Australian Antarctic Division, University of Tasmania, Hobart, Australia*
[b]*International Arctic Research Center, University of Alaska, Fairbanks, USA*
[c]*Finnish Institute of Marine Research, Helsinki, Finland*
[d]*Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany*

Accepted 21 December 2007
Available online 2 May 2008

Abstract

Sea-ice drift and deformation in the western Weddell Sea in early austral summer of 2004 are characterised using *in situ* data from a meso-scale array of 24 drifting ice buoys. Horizontal GPS-derived position measurements are available from drifting buoys deployed as part of the *Ice Station POLarstern* [*ISPOL*] experiment for 26 days during late November and December 2004, at various temporal resolutions and spatial accuracies. These data form the basis for sea-ice velocity and deformation measurements across the meso-scale *ISPOL* array and at two remote sites. Analysis of the sea-ice velocities reveals coherence for sea-ice drift at separations of less than 70 km; and a correlation length scale of 60 km. Within the limits of the *ISPOL* array, at larger separations zonal ice drift remains correlated, while meridional ice drift becomes uncorrelated. This together with the east–west gradient in ice velocities indicates the influence of bathymetry, via tidal forcing, on local dynamic processes. Atmospheric forcing also contributes to the sea-ice drift: about 40% of variability in the sea-ice velocity is explained by changes in wind velocity, which is significantly less than other studies have found for the region during winter. Sea-ice deformation has been derived for the overall array and four sub-arrays. There appeared to be no spatial scale dependency of ice deformation, although considerable spatial variability was observed between sub-arrays. The net divergence of the *ISPOL* array was in excess of 30%, with the largest contributions to divergence being from the southern section and along the eastern side of the overall *ISPOL* array. Temporal variability for all deformation parameters is dominated by high-frequency (sub-daily) processes, namely tidal forcing and inertial response. Low-frequency (multiple days) processes, including atmospheric changes, played a secondary role in forcing sea-ice deformation during *ISPOL*.

Keywords: Sea-ice motion; Sea-ice deformation; High-frequency processes; Ocean tides; Inertial response; Weddell Sea; Antarctica

1. Introduction

Observations of sea-ice motion and deformation in the Antarctic are few, particularly from regions that are marked by thick and heavily deformed sea ice, such as the western Weddell Sea. Only a small number of scientific experiments have previously been conducted there. Our knowledge of sea-ice dynamics in that region relies largely on data collected as part of *Ice Station Weddell* [ISW-1], which was deployed during austral autumn 1992, and provided data at the site of the ice camp as well as from five drifting buoys. In ISW-1 the buoys were spaced to resolve the large-scale (in the order of 150 km) sea-ice dynamics (e.g., Geiger et al., 1998a). Further information on sea-ice drift and deformation in the Weddell Sea is available from other buoy deployments (Rowe et al., 1989; Wadhams et al., 1989; Kottmeier et al., 1992; Massom, 1992; Vihma and Launiainen, 1993; Vihma et al., 1996; Uotila et al., 2000).

Previous Weddell Sea expeditions focussed largely on either autumn or winter processes, such as bottom-water formation or surface-flux exchanges (for example, IWS-1

*Corresponding author. Tel.: +61 3 6226 7243; fax: +61 3 6226 7650.
E-mail address: petra.heil@utas.edu.au (P. Heil).
[1]Present address: Department of Earth & Atmospheric Sciences, University of Alberta, Edmonton, Canada.

0967-0645/$ - see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.dsr2.2007.12.026

(e.g., Gordon et al., 1993; Geiger and Drinkwater, 2005); Winter Weddell Gyre Study 1992 (Lemke, 1994)), or on the central and eastern Weddell Sea (Crane and Wadhams, 1996). *Ice Station POLarstern* 2004 was designed to investigate physical and biological processes at the western rim of the Weddell Sea west of 50°W and between 70°S and 65°S during austral spring/summer. It was set up as an ice camp in the western Weddell Sea (Hellmer et al., 2008), by anchoring the R.V. *Polarstern*, host of the *ISPOL* experiment, to a multi-year ice floe, in the following referred to as the *ISPOL* floe. After the encounter of heavy ice *en route* to the proposed deployment site, *ISPOL* was deployed on 27 November 2004 at 68.2°S and 54.8°W. The *ISPOL* floe partly disintegrated on 25 December 2004 requiring the relocation of some of the experiments. *ISPOL* ceased on 01 January 2005 with the departure of the R.V. *Polarstern.*

The intensive buoy deployment during *ISPOL* aimed to resolve meso-scale (in the order of 10–100 km) sea-ice kinematics and deformation of the Antarctic pack ice under early summer conditions. The buoy-derived data provide information on high-frequency (sub-daily) ice motion and deformation that are not resolved by satellite-based sensors. These high-frequency data are crucial to determine the relative importance of tidal forcing and inertial response in the sea-ice motion and deformation fields.

In this paper the focus is on the characterisation of ice motion and deformation in the Weddell Sea during early summer. Data from spatially staggered *ISPOL* buoy arrays provide information on the relationship between spatial scale and magnitude of sea-ice motion (see Section 4) and of differential kinematic parameters (DKPs) (see Section 5) at the meso-scale and smaller. This, together with a buoy deployed about 100 km to the north, allows us to test the linearity of scale effects. Furthermore, our investigation of tidal forcing versus inertial response is critical to defining summer sea-ice drift and deformation in the western Weddell Sea. *ISPOL* buoys provide sea-ice data for a region where the inertial response may amplify the semidiurnal tidal forcing.

This work presents our analysis of the variance in sea-ice velocity, including the effective translation and the dependency on local bathymetry; and results from our investigation of the relative strength of tidal forcing and inertial response on sea-ice motion and deformation. In our ongoing analysis of the *ISPOL* buoy data we will investigate fracture patterns, which can be interpreted as sites of recurrent ice deformation events (Hibler and Schulson, 1997), and explore how to improve the description of sea-ice kinematics in numerical models via rheological parameterisations (e.g., Geiger et al., 1998b; Hibler and Schulson, 2000). Preliminary results suggest that this is especially relevant in view of changes in sea-ice rheology in response to compaction, shear and tension. Furthermore, data derived from the *ISPOL* deformation array have already supported the interpretation of observations on the early summer evolution of the floe-size distribution (Steer et al., 2008).

2. Sea-ice conditions during *ISPOL*

The ice conditions in the region of the *ISPOL* buoy array were influenced by three ice regimes: second-year ice from the central Weddell Sea in the east, largely uniform first-year ice from the region of the Filchner-Ronne Ice Shelf in the centre, and heavily deformed first- or second-year ice in the west (Hellmer et al., 2006). Across those types, ice thickness typically varied from 0.9–1.8 m (first-year ice), 2 m (second-year ice) to 3–5 m (deformed ice) (Hellmer et al., 2006). Deformed ice was characterised by consolidated ridges of about 1.0 m height, which covered 10–20% of the surface. The sea ice in the vicinity of *ISPOL* was covered, on average, by 0.3 m of cold old snow. Helicopter-borne electromagnetic ice thickness soundings in combination with *in situ* snow-thickness measurements showed that the overall ice and snow thickness reduced by 0.1–0.2 m during the *ISPOL* experiment, mainly due to a reduction of the snow layer. The majority of *ISPOL* buoys were deployed on medium to large floes within the zone of first-year ice. *In situ* observations show that in the vicinity of *ISPOL* sea ice covered in excess of 90% of the ocean surface. This is in good agreement with ice concentration data derived from *AMSR-E* imagery (obtained from the NSIDC, USA), which show close to 100% sea-ice concentrations in the region of the *ISPOL* array at the end of November 2004.

3. The *ISPOL* buoy array

This study of sea-ice deformation during *ISPOL* was made possible by four institutes sharing their resources: the Australian Antarctic Division [AAD], the Alfred Wegener Institute [AWI], the Finnish Institute of Marine Research [FIMR], and the International Arctic Research Center [IARC]. Starting on the 28 November 2004, 26 drifting buoys were deployed on the sea ice to the southwest of the *ISPOL* drifting ice station. Twenty-four buoys were arranged in a triangular array with side length of approximately 76 km. However, two of these failed to operate: AWI 14955 and IARC-D; incidently both were deployed at site D (see Fig. 1 for naming convention of buoy deployment sites). In addition, one FIMR buoy (site Y) was deployed near the R.V. *Polarstern* to the north-east of the buoy array. It was equipped with numerous meteorological sensors in support of a study of air-ice fluxes and heat balance. A second buoy (site X) outside the deformation array had been deployed 100 km north of the deformation array to provide information on ice drift and meteorological conditions for analysis of synoptic-scale events. For information on buoy types and position accuracy see Appendix A.

Most of the *ISPOL* buoys were deployed on the 28 November 2004 (day-of-year [DoY] 333), using two