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Is Ekman pumping responsible for the seasonal variation of warm circumpolar deep water in the Amundsen Sea?

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ABSTRACT

Ekman pumping induced by horizontally varying wind and sea ice drift is examined as an explanation for observed seasonal variation of the warm layer thickness of circumpolar deep water on the Amundsen Sea continental shelf. Spatial and temporal variation of the warm layer thickness in one of the deep troughs on the shelf (Dotson Trough) was measured during two oceanographic surveys and a two-year mooring deployment. A hydrographic transect from the deep ocean, across the shelf break, and into the trough shows a local elevation of the warm layer at the shelf break. On the shelf, the water flows south-east along the trough, gradually becoming colder and fresher due to mixing with cold water masses. A mooring placed in the trough shows a thicker and warmer layer in February and March (late summer/early autumn) and thinner and colder layer in September, October and November (late winter/early spring). The amplitude of this seasonal variation is up to 60 m. In order to investigate the effects of Ekman pumping, remotely sensed wind (Antarctic Mesoscale Prediction System wind data) and sea ice velocity and concentration (EASE Polar Pathfinder) were used. From the estimated surface stress field, the Ekman transport and Ekman pumping were calculated. At the shelf break, where the warm layer is elevated, the Ekman pumping shows a seasonal variation correlating with the mooring data. Previous studies have not been able to show a correlation between observed wind and bottom temperature, but it is shown here that when sea ice drift is taken into account the Ekman pumping at the outer shelf correlates with bottom temperature in Dotson Trough. The reason why the Ekman pumping varies seasonally at the shelf break appears to be the migration of the ice edge in the expanding polynya in combination with the wind field which on average is westward south of the shelf break.

1. Introduction

According to the Intergovernmental Panel on Climate Change (IPCC, 2013), the West Antarctic Ice Sheet (WAIS) is the largest source of uncertainty in predictions of future sea level rise over the 50–200 year time horizon. The WAIS has experienced a pronounced mass loss in recent decades (Bindschadler, 2006; Rignot et al., 2008; Paolo et al., 2015). This melting of ice into the ocean impacts biogeochemical cycles (Menviel et al., 2010), biological productivity (Hawkings et al., 2014), sea level (Dutton et al., 2015), and sea ice formation (Rignot and Jacobs, 2002). The most rapidly changing region of the West Antarctic is the Amundsen Sea, where the intrusion of relatively warm Circumpolar Deep Water (CDW) onto the continental shelf (Walker et al., 2007; Jenkins et al., 2010; Wåhlin et al., 2010, 2013; Arneborg et al., 2012; Jacobs et al., 2012) may be the reason for observed recent thinning of the floating ice shelves along the coast (e.g. Paolo et al., 2015).

After intruding onto the continental shelf, CDW is modified by mixing with colder water masses, after which it is referred to as modified CDW (MCDW). In situ observations of MCDW flowing towards the ice shelves have been obtained from the deep troughs that connect the outer shelf to the inner shelf basins, e.g. in the north-western branch of the Pine Island Trough (Walker et al., 2007; Assmann et al., 2013), in the main Pine Island Trough (Nakayama et al., 2013; Jacobs et al., 2011) and in the Dotson Trough (Wåhlin et al., 2010, 2013; Arneborg et al., 2012; Ha et al., 2014) (Fig. 1). The temporal variability in Dotson Trough is considerable (Arneborg et al., 2012; Wåhlin et al., 2013; 2015; Ha et al., 2014). On time scales

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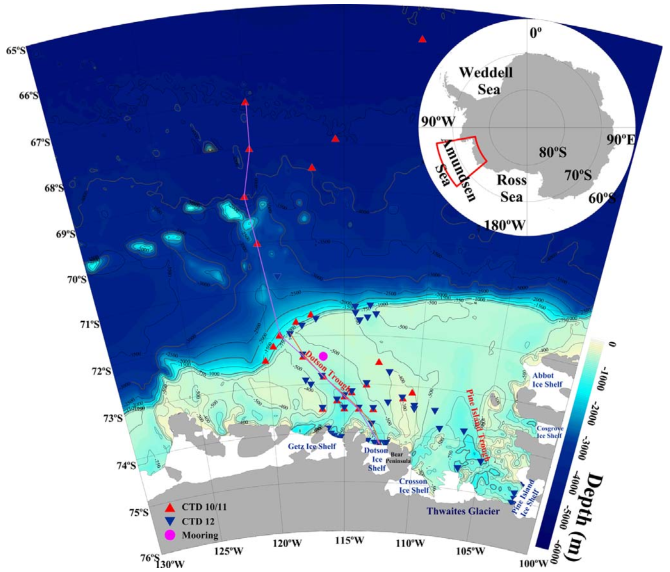

Fig. 1. Map of study area with the CTD stations and the mooring indicated. Red and blue triangles show the CTD stations during the 2010/11 and 2012 Araon expeditions, respectively. The purple circle indicates the mooring station (February, 2010–2012). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

shorter than a week, the velocity is characterized by strong barotropic fluctuations that correlate with zonal winds at the shelf break (Wåhlin et al., 2013, 2016; Kalén et al., 2015). The wind drives a clockwise barotropic circulation in the area (Ha et al., 2014; Kalén et al., 2015) and can also set up resonant Rossby waves (Wåhlin et al, 2016). In addition to these short-term fluctuations, there is a persistent south-eastward baroclinic flow of dense warm water (Arneborg et al., 2012) connected to the thickness and density of the warm bottom layer (Wåhlin et al., 2013). However, neither the baroclinic flow nor the bottom temperature correlates with the wind (Wåhlin et al., 2013). This is in contrast to what is seen in model results (e.g. Thoma et al., 2008; Steig et al., 2012) where eastward winds at the shelf break are responsible for transporting warm salty water onto the shelf, a mechanism that has been observed to occur in the Eastern part of the shelf break (Wåhlin et al., 2012). However, since the observed summertime maximum in warm layer thickness in Dotson Trough is not related to any maximum in the eastward winds, it is unlikely that eastward winds alone force the MCDW into the Dotson Trough.

Previous studies that examined the correlation between wind stress and observations of the layer of MCDW in Dotson Trough (Wåhlin et al., 2013) have not accounted for the effect of a sea ice cover, which affects the surface stress. The surface stress induced by a (wind-forced and moving) sea ice cover depends strongly on ice characteristics, and either increased or decreased upwelling or downwelling, compared to an ice-free environment, may result from the presence of the ice (Leppäranta and Omstedt, 1990; Häkkinen, 1986; Carmack and Chapman, 2003; Yang, 2006; Schulze and Pickart, 2012). Very thick ice can take the role of the Ekman layer and veer sharply compared to the wind direction (even more than 45°), while thin ice follows the surface currents. For example, Häkkinen (1986) studied downwelling/upwelling in the marginal ice zone, using a two-dimensional coupled ice-ocean model. The model showed that horizontally homogenous westward winds produced upwelling at the sea ice zone (north of ice edge) and downwelling at the open ocean (south of ice edge) due to the difference between air-ice and air-ocean momentum fluxes. Using satellite and in situ buoy data from the Arctic Ocean, Yang (2006) showed a seasonal variation of heat and salt fluxes induced by Ekman pumping in the Beaufort Sea, and Schulze and Pickart (2012) found that the seasonal variation in upwelling in the Beaufort Sea, induced by the temporal variation of sea ice condition (open water, partial ice and full ice).

Our objective is to examine the combined effect of wind and sea ice drift on the thickness of the layer of MCDW in the western Amundsen continental shelf region, and more specifically to examine if it can explain the seasonal variation of the CDW layer that is observed. This is done by calculating the ocean surface stress, and Ekman pumping, from satellite-derived winds and sea ice drift and comparing these to hydrographic surveys and mooring time series from the Dotson Trough in the Amundsen Sea.

2. Materials and methods

Two oceanographic surveys were conducted by the IBRV *Araon* from 21 December 2010 to 23 January 2011, and from 31 January to 20 March 2012 (Fig. 1). A total of 30 and 52 CTD stations were occupied during the surveys in 2011 and 2012, respectively. At each station, a CTD (SBE 911+) hydrocast was conducted to measure profiles in temperature, pressure, and conductivity. The conductivity sensors were calibrated by Sea-Bird before and after the cruises and salinities were further checked at regular depths by an Autosal

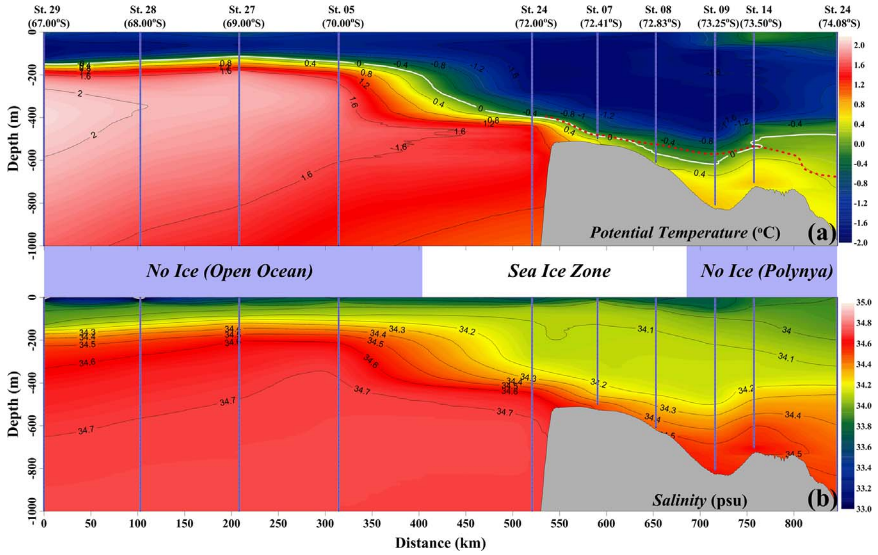

Fig. 2. Cross sections of (a) potential temperature and (b) salinity during the 2011 cruise along a transect from 67° S (left) to the Dotson Ice shelf front (right). Red dashed line in (a) shows the 0 °C isotherm during the 2012 cruise. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)