Continental Shelf Research 28 (2008) 1838–1853

Contents lists available at ScienceDirect

Continental Shelf Research

journal homepage: www.elsevier.com/locate/csr

Fjord–shelf exchanges controlled by ice and brine production: The interannual variation of Atlantic Water in Isfjorden, Svalbard

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ARTICLE INFO

Article history:
Received 19 August 2007
Received in revised form
14 March 2008
Accepted 29 April 2008
Available online 17 May 2008

Keywords:
Fjord–shelf exchange
Hydrography
Atlantic Water
Polynya
Sea ice
Brine-enriched fjord water

ABSTRACT

Exchanges between oceanic and coastal waters are fundamental in setting the hydrography of arctic shelves and fjords. In West Spitsbergen, Atlantic Water from the West Spitsbergen Current exchanges with the seasonally ice-covered waters of the coast and fjords causing a major annual shift in hydrographic conditions. The extent to which Atlantic Water dominates the fjord systems shows significant interannual variability. Hydrographic sections taken between 1999 and 2005 from Isfjorden and the adjacent shelf have been analyzed to identify the causes of the variability in Atlantic Water occupation of the fjord system. By treating the fjord system as a coastal polynya and running a polynya model to quantify the salt release each winter, we conclude that the critical parameter controlling fjord–shelf exchange is the density difference between the fjord water masses and the Atlantic Water. We provide a full dynamical mechanism for the interaction between water masses at the fjord entrance to rationalize the interannual variability.

1. Introduction

The West Spitsbergen Shelf (WSS) is a site where Atlantic, Arctic and glacial waters converge, mix and are exchanged (Saloranta and Svendsen, 2001). Such is the dynamic nature of the shelf that, within an annual cycle, the waters on the shelf and in the adjacent fjords, switch from a state of Arctic dominance (cold and fresh in winter) to one of Atlantic dominance (warm and saline in summer) and back (Svendsen et al., 2002; Cottier et al., 2005). There is also continuous modification of the water masses through heat and mass exchanges with the atmosphere. The majority of the fjord systems along the WSS can be regarded as coastal polynyas (or 'ice factories') due to the prevailing easterly (offshore) winds over Svalbard leading to large heat fluxes in the open water regions in the fjord/polynya (Skogseth et al., 2004, 2005b). Ice formation in the fjords increases the salinity of the local water (LW) masses and the final salinity of the fjords in spring will be determined by the polynya efficiency which is itself a function of the atmospheric forcing. In this paper we examine the seasonal hydrography of Isfjorden, the largest fjord on West Spitsbergen and discuss how variability in the winter polynya dynamics can influence subsequent shelf–fjord exchanges during summer and autumn.

The interest for fjords on Svalbard was first woken by Helland-Hansen and Nansen who, in a pioneer study, discussed the nature and origin of the water in the fjords (Helland-Hansen and Nansen, 1912; Nansen, 1915). Fjords are commonly regarded as the link between the ocean and the land through cross-shelf exchanges and circulation and mixing in the fjords. The oceanic and terrestrial realms set the fjord boundary conditions and fjords respond to variations in these, thus making them susceptible to any changes in the boundary conditions. In addition, arctic fjords may be regarded as an extreme variant of standard fjord concepts as they are subject to intense seasonality through sea ice formation and glacial melt. Hence, the fjords on the west coast of Spitsbergen, which balance Atlantic, Arctic, brine- and fresh-water inputs, are potentially sensitive indicators of environmental change.

Recently, the major effort in studying hydrographic processes in Svalbard's fjords has been focused on Storfjorden (Haarpaintner et al., 2001; Skogseth et al., 2004, 2005b) and the Kongsfjorden–Krossfjorden double fjord system (Svendsen et al., 2002; Cottier et al., 2005). During the last six years a systematic hydrographic observation program of the Isfjorden system and the continental shelf area westward into the West Spitsbergen Current (WSC) has given new insight into the cross-shelf and fjord–shelf exchange mechanisms.

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doi:10.1016/j.csr.2008.04.015

During summer and autumn 2002, the WSS was 'flooded' with Atlantic Water (AW) which then penetrated into the fjord systems around Svalbard (Skogseth et al., 2005b; Cottier et al., 2005). In 2004, blue mussels were rediscovered in the mouth of Isfjorden at Sagaskjæret (Fig. 1), and dating revealed that the majority of this population settled in 2002 due to an increased AW transport in the WSC and the favorable cross-shelf exchange conditions of that year (Berge et al., 2005). Settlement of larvae and their growth to adult mussels at Sagaskjæret in Isfjorden was possible through an increased autumn SST in 2002 that also was evident in 2003 (Berge et al., 2005). The flux of AW into Isfjorden in August and September 2002 was confirmed by the anomalous appearance of the temperate planktonic diatom *Skeletonema costatum* and the mass occurrence of Atlantic cod (*Gadus morhua*) and Atlantic salmon (*Salmo sala*) (Johnsen & Quillfeldt, unpublished).

In this study we develop the discussions of Cottier et al. (2005) and argue that local ice production and the resulting volume and density of brine-enriched water forming during winter is a key physical mechanisms that enables AW to penetrate into Isfjorden in the following summer and autumn. Annual hydrographic measurements between 1999 and 2005 in the Isfjorden system and adjacent shelf are interpreted using a polynya model to simulate the winter densification of water masses (Haarpaintner et al., 2001; Skogseth et al., 2004). We assess the effectiveness of this approach by comparing the model results to hydrographic data from Billefjorden, the innermost side-fjord of Isfjorden (Fig. 1). Billefjorden has a sill-depth of about 50 m, and retains the locally produced brine water from the previous winter. In this respect it is an integrator and archive of winter conditions and will be used to discuss the interannual variations in ice production and salt release.

The focus of this paper will be to identify the key hydrographic processes and characteristics that determine the interannual variability in penetration and vertical distribution of AW in Isfjorden, particularly those conditioning processes related to winter sea ice formation. We will discuss in detail the contrasting conditions in 2002 and 2003 where AW occupied the whole water column on the shelf in both years but the degree of AW occupation in Isfjorden was substantially greater in 2002 than in 2003.

2. The Isfjorden system

2.1. Regional setting

Spitsbergen is the largest island in the Arctic archipelago of Svalbard. The archipelago is situated between 76°N and 81°N and

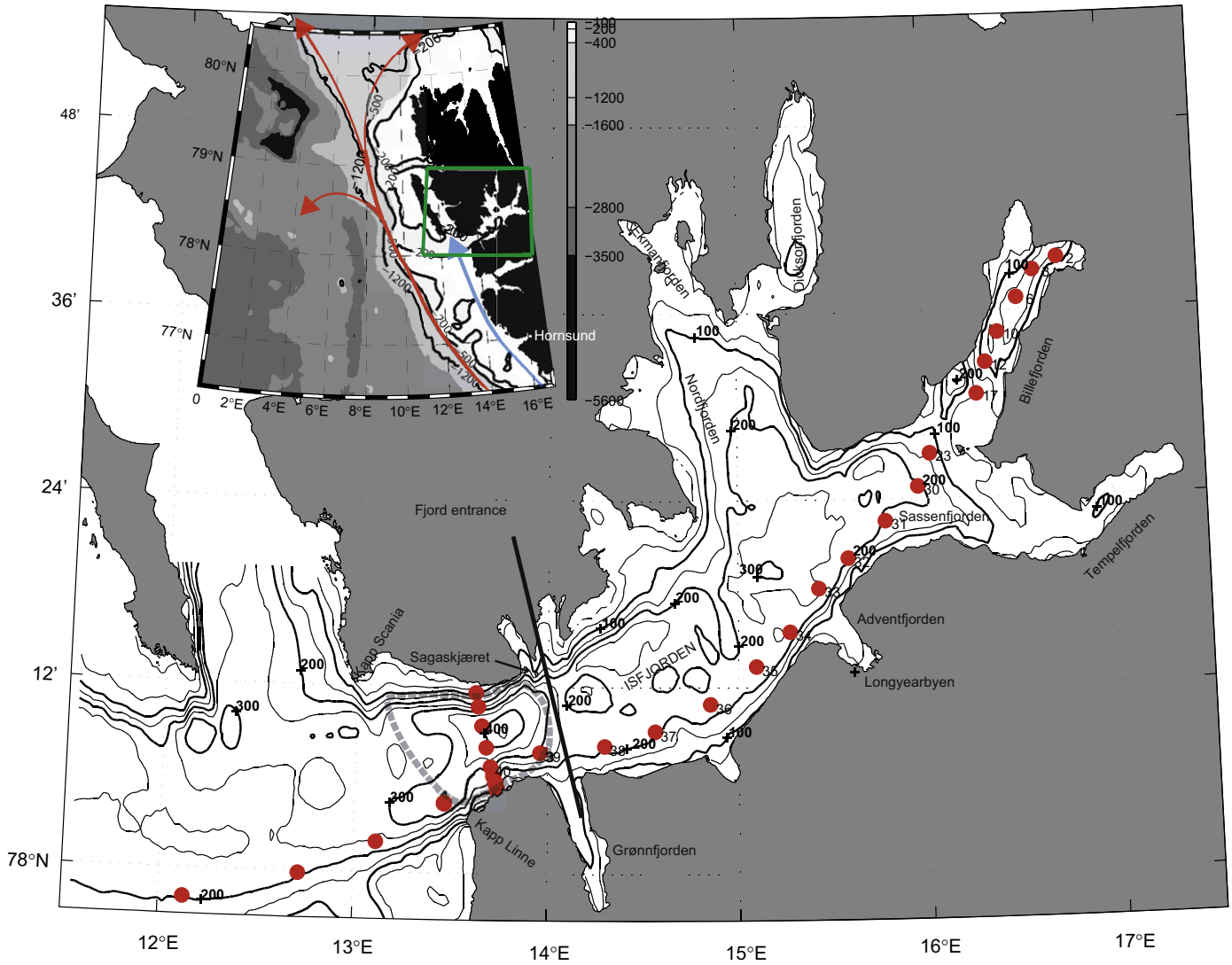

Fig. 1. Map of the Isfjorden system with an inserted map of West Spitsbergen showing the Isfjorden Trough from the slope break towards Isfjorden (green box). Hydrographic stations are marked with red circles and define the along-fjord (A) and cross-fjord (X) sections. The gray dashed line defines the mouth area of the fjord system that is connected to the Trough, while the black line crossing the fjord defines the entrance to Isfjorden.