ADCP-referenced geostrophic velocity and transport in the West Spitsbergen Current

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Abstract

During the summer of 2000 and 2002 (June–July) the West Spitsbergen Current (WSC) was investigated by the Institute of Oceanology, Polish Academy of Sciences. CTD and current measurements by a vessel-mounted Acoustic Doppler Current Profiler (ADCP) were performed along three transects perpendicular to the WSC main stream and covering the region from 76°30′N to 78°20′N and from 02°30′E to 15°E. In general, the geostrophic, baroclinic flow patterns and the ADCP-measured currents were found to be in good agreement but measured current velocities were significantly higher than calculated values. This fact supports earlier observations that the barotropic component is dominant in the WSC. Since ADCP has a better spatial resolution than CTD records, the West Spitsbergen Current could be investigated and described in much greater detail than before.

The main stream of Atlantic Water is topographically steered by the continental slope (isobars 800–2000 m) and the complex, multistream structure of the West Spitsbergen Current is clearly visible. The absolutely referenced total geostrophic transport is about three times higher than the estimated value assuming the level of no motion lies at 1000 m.

The complete text of the paper is available in PDF format at http://www.iopan.gda.pl/oceanologia/index.html

1. Introduction

The influence of the GIN Seas (Greenland, Iceland and Norwegian Seas) on climate is well known (Aagaard et al. 1985). This region is crucial for the Arctic circulation as well as for the mass, salt and heat balance. Salt and heat are transported principally through the Fram Strait and Barents Sea. The West Spitsbergen Current (WSC) carries warm, saline Atlantic Waters northwards along the western coasts of Svalbard. The huge amounts of salt and heat they contain are of immense significance to climatic variability, but direct measurements of their transport are still difficult.

One of the key questions concerns the magnitude of barotropic transport in comparison with that of baroclinic transport. Until the 1970s all calculations had been based on CTD data only. The barotropic component of the flow was unknown and the results depended on the choice of reference level. Hopkins (1991) reviewed the transports in the GIN seas. Transport estimates for the WSC ranged between 1 Sv and 11.9 Sv, depending on the location and season of measurements. The first current meter data were described by Aagaard et al. (1973) and demonstrated the large barotropic component in the WSC. Recent transport estimates have been based on the results of measurements by 14 moorings deployed in the Fram Strait for two years during the VEINS project. The results confirmed the large barotropic component, yielding a total annual average northward transport of 6.7 Sv (Woodgate et al. 1998). Further, more detailed analysis of these current meter data by Fahrbach et al. (2001) resulted in an even higher estimate (9.5 Sv) of the volume transport by the WSC.

Recently, a new method of measuring currents by means of the acoustic Doppler current profiler (ADCP) has enabled absolute transport to be estimated with greater reliability. The principal aim of the present paper is the application of ADCP data as a reference for geostrophic transport calculations in the WSC.

2. ADCP and CTD data

During the summer cruises of r/v 'Oceania' in 2000 and 2002 (July 7–13, 2000 and July 5–13, 2002), three CTD-ADCP transects were carried out, covering the area between $76°30'$N and $78°20'$N and from $02°30'$E to $15°$E (Fig. 1). Temperature, conductivity and pressure data were collected using a Seabird 9/11+ CTD probe. A ship-mounted 150-kHz ADCP (RD Instruments) was used to obtain vertical profiles of current speed and direction in the upper layer. The maximum range of ADCP measurements was about 400 m, but for reasons of quality control the maximum depth of the layer analysed was reduced to 150–300 m. The ADCP measurements

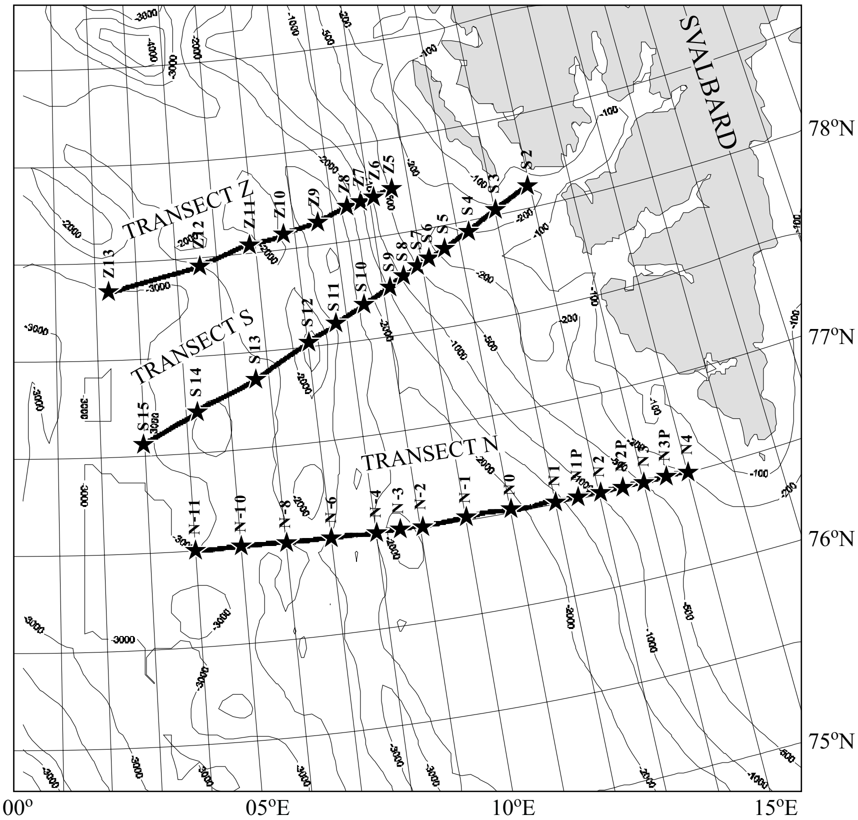

Fig. 1. Map of CTD and VM-ADCP stations during the Arex 2000 and Arex 2002 experiments

do not include the sea surface – in our case this was the 0–16 m layer. The depth bin length was set to 8 m. Data were averaged in 5 minute ensembles equivalent to 0.75 km horizontally at a speed of 5 knots, resulting in a random error in the horizontal velocity component of 0.95 cm s^{-1}. The minimum percentage of good pings in the ensemble was set to 75% and the velocity error to 10 cm s^{-1}.

Most of the measurements were done in regions where the depth was greater than the range of ADCP bottom tracking (c. 500 m), so we had to rely on navigational data as a reference. In this case, the crucial parameter for data quality is the misalignment angle. To solve this problem, transects were run partly in the shelf region, where bottom-track and navigation references were available, and from these data we were able to calculate the misalignment angle. The procedure was repeated for each transect (Osiński 2000). The ship's speed when using navigational reference was determined by GPS. The main source of GPS position error was due to the degradation of GPS signals by the U.S. military. However, this degradation was not working during our cruises, so our measurements were based on a highly accurate navigational data set. For a five-minute ensemble the ADCP-bin error is c. 4 cm s^{-1}, but its value falls to about 1 cm s^{-1} for the average velocity between CTD casts.

To reduce Schuler oscillation, which affects the ship's gyrocompass after any significant acceleration of the vessel (Pollard & Read 1989), the current measurements used in the calculations were made while the ship was sailing at 4 to 6 knots without changing course.

3. Method

Calculations of geostrophic flow from two hydrographic stations are well known (Pond & Picard 1978, Gill 1982) and the usefulness of the method has been demonstrated over the years. In fact, much of our knowledge about oceanic circulation is based on such calculations. This method assumes a balance between the pressure gradient and the Coriolis force and results in the vertical current profile V_R(p) relative to the reference level (level of no motion – LNM).

$$V_R(p) = \left(\frac{g}{f}\right)\frac{\Delta D(p)}{\Delta x}, \tag{1}$$

where g is gravity, $f = 2\Omega \sin\varphi$ is the Coriolis parameter, φ is the latitude and $\Delta D(p)$ is the difference in dynamic height $D(p)$ between two stations separated by a distance Δx. Dynamic heights were calculated from the specific volume anomaly vertical profiles with reference level at 1000 dbar. Corrections for shallower water areas (depth less than 1000 m) were obtained by assuming that the vertical profile of the specific volume anomaly was the same as that of the nearest deep station.

However, this method has two serious disadvantages: (i) the velocity profile is related to an arbitrarily assumed level of no motion which in most cases is unknown, and (ii) it comprises only the baroclinic component of the geostrophic velocity; the barotropic component is still unknown unless the measured absolute geostrophic velocity at any depth is given. Note that different authors variously define the terms 'barotropic' and 'baroclinic'. Sometimes 'barotropic' refers to the vertically averaged velocity, sometimes it refers to the velocity at the bottom (just above the Ekman layer); at other times it is the surface velocity, while deviations from this value are treated as the baroclinic part. For the purpose of the present paper, the geostrophic current is made up of two components: a barotropic component, due to the uniform tilt of the pressure surface so that the velocity is independent of depth, and a baroclinic flow caused by density variations. Thus, from our calculations based on CTD data we have obtained only the baroclinic part of the geostrophic current.

The absolute geostrophic velocity at any given depth can be measured with current meters, which does not seem to be a useful solution owing to the poor spatial resolution; the alternative is the use of ADCP (Picard & Lindstrom 1994, Cokelet et al. 1996). This latter method gives a better solution because the quasi-continuous measurement between CTD casts allows the mean velocity to be computed at a selected depth. A combination of CTD and ADCP measurements along three transects allows the absolute perpendicular to transect velocity in the WSC to be computed. The absolute ADCP-referenced velocity, $V_{\mathrm{abs}}(p)$, is equal to (Meinen et al. 2000):

$$V_{\mathrm{abs}}(p) = V_R(p) + (V_{\mathrm{ADCP}} - < V_R(p) >), \tag{2}$$

where

V_R(p) – the vertical profile of the calculated baroclinic velocity,

$< V_R(p) >$ – the calculated baroclinic velocity averaged in the 50–150 m layer,

V_{ADCP} – the averaged ADCP measured velocity, which is defined by the formula:

$$V_{\mathrm{ADCP}} = \frac{1}{X_2 - X_1} \times \frac{1}{Z_2 - Z_1} \int\limits_{X_1}^{X_2} \int\limits_{Z_1}^{Z_2} V dx dz \tag{3}$$

where X_1 and X_2 are the locations of two adjacent CTD stations, Z_1=50 m, Z_2 =150 m, V – ADCP measured velocity.

The depth range 50–150 m was chosen as the layer where ADCP consistently provided accurate data during both cruises and where the ageostrophic signal is sufficiently weak.

The main source of errors in this method is the unknown impact of ageostrophic velocities, such as those of drift currents, tides, internal waves or inertial oscillations. All ageostrophic velocities are treated as errors when the ADCP-referenced method is used.

In general, waves and winds were light to medium during the cruises. The prevailing wind speeds were less than 5 m s^{-1} (av. 4.3 m s^{-1} max. c. 8 m s^{-1}) in 2000 and less than 7 m s^{-1} (av. 6.1 m s^{-1}, max. c. 48 m s^{-1}) in 2002. Assuming the drag coefficient $C_D = 1.4 \times 10^{-3}$, and the ratio of the surface current V_0 to wind speed W to be (Pond & Picard 1978)

$$\frac{V_0}{W} = \frac{0.0127}{\sqrt{\sin(\varphi)}}, \tag{4}$$

we estimated the maximum depth of the Ekman layer at c. 35 m, well above the chosen layer. A prolonged period of strong winds along transect N in 2000 was rejected.

At the moment the ADCP data are not detided; however, tides cannot be completely discarded. Measurements during the VEINS project revealed tidal currents up to 7–10 cm s^{-1} on the West Spitsbergen slope (Woodgate et al. 1998). Tidal velocities are considerably lower in deep regions and do not produce a significant error in the ADCP data, although their contribution to the measured flow field remains unknown.

It is difficult to estimate the accuracy of ADCP-referenced geostrophic velocities, but we assumed their value to be of the order of 5 cm s^{-1}, taking all possible sources of errors into consideration. This is for an individual ADCP ensemble. Assuming no correlation between ensembles for transect N (about 300 ensembles), for instance, implies an uncertainty of c. 0.3 cm s^{-1}. This means that we estimated the total transport accurate to 2 Sv, 1.5 Sv, 1 Sv for transects N, S, and Z respectively.

4. Results

Distributions of the potential temperature, salinity and potential density along transect N in 2002 are an illustrative example of the warm and salty Atlantic waters (Fig. 2). The WSC is evident in the upper 700 m layer, characterised by the highest temperature and salinity values (max. temperature 6.7°C in 2000 and 7.2°C in 2002; max. salinity 35.13 PSU in 2000 and 35.12 PSU in 2002). The main core of the WSC is topographically steered along the continental slope (between isobaths 800–2000 m) between km 240 and 255 of the transect (Fig. 3). A second stream, further to the west, flows over the Knipovich Ridge and is noticeable between km 100 and 120 of the transect. The temperature and salinity of this western branch are a little lower than the values recorded in the main stream.

The observed velocities are similar within the main core of the WSC along all sections (40–55 cm s^{-1}), whereas within the western stream of the WSC they decrease northwards (Fig. 4). The recirculating branch of the WSC near the Hovgaard fracture zone is located between transects S and Z, and carries c. 2.7 Sv of water (Table 1).

The strongest currents over the continental slope in 2000 were recorded along transect Z. The highest velocity of the northward current, measured there by ADCP, was in excess of 55 cm s^{-1}. The maximum speed of the southward flow (41 cm s^{-1}) was measured along transect N. The situation changed slightly in 2002 when the highest velocity of the northward current was measured along transect N (55 cm s^{-1}). The pulsating character of the investigated current could probably explain this difference.

The ADCP-referenced geostrophic circulation agrees in a general sense with that obtained by referring geostrophic flows to 1000 m (Figs. 3 and 4) but the currents are stronger and deeper. Defining the negligible velocity

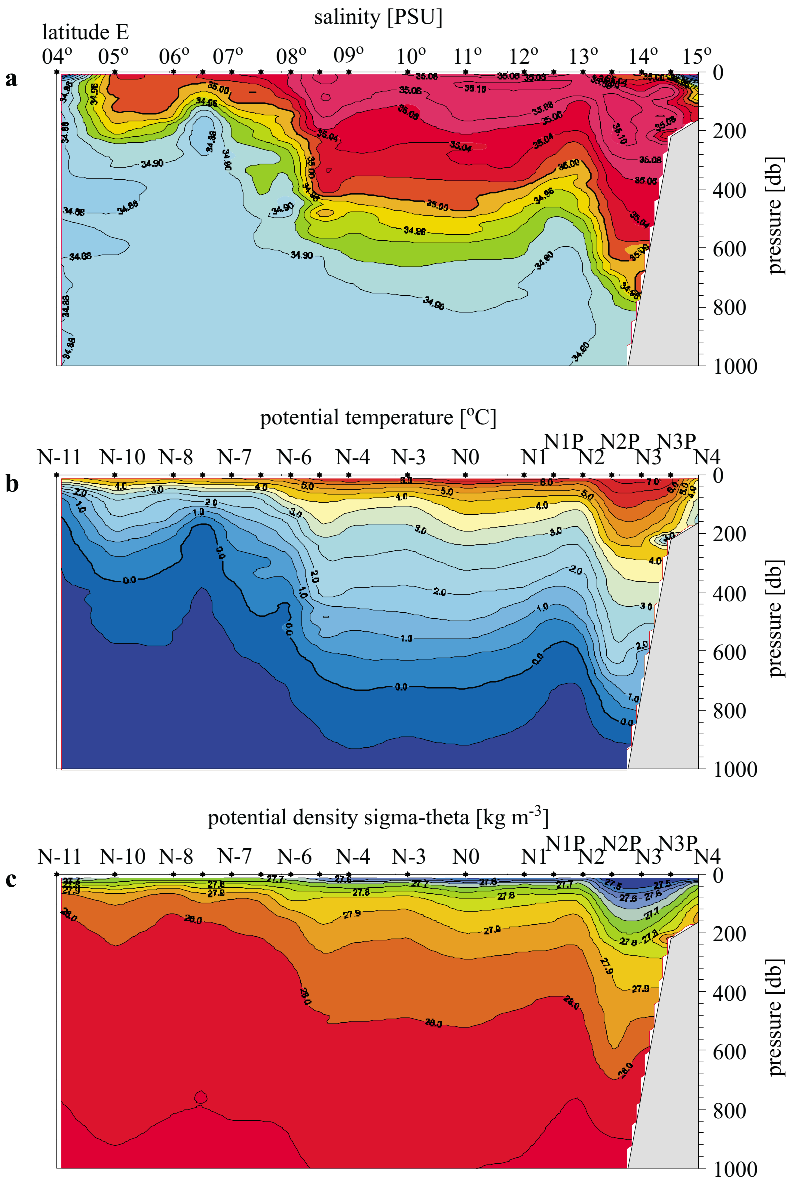

Fig. 2. Distribution of salinity (a), potential temperature (b) and potential density (c) along transect N in 2002 (5–7 July)

gradient as $\frac{dV}{dz} < 10^{-5}\text{s}^{-1}$, we found that baroclinic currents persisted below 1700 m. Baroclinic velocities in the upper layer are higher than barotropic ones, but the former decrease very rapidly with depth. Thus, at depths of a few hundred metres, the barotropic component prevailed in the geostrophic flow. In 2000 barotropic velocities of about 2 cm s^{-1} were

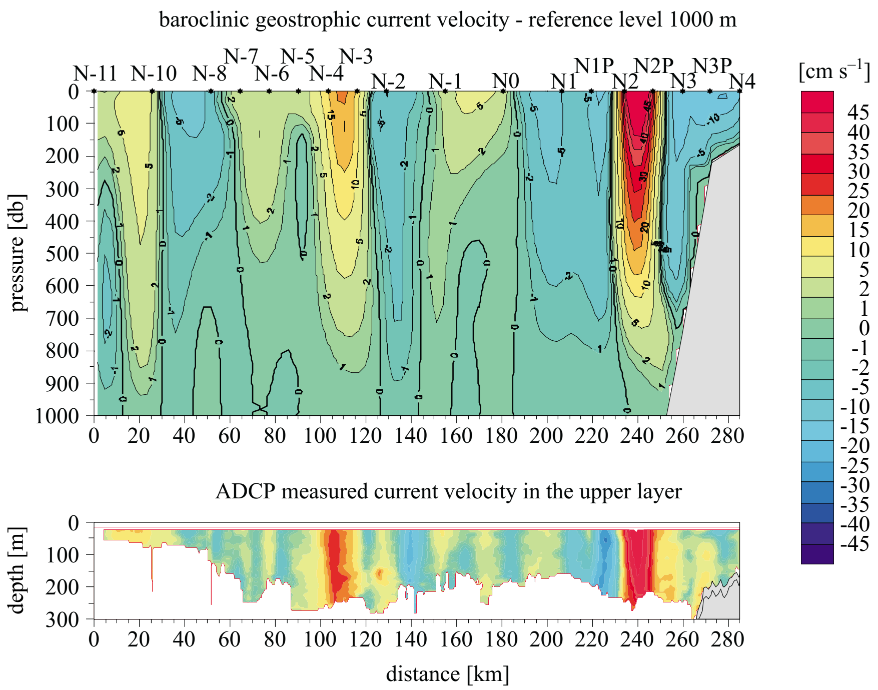

Fig. 3. Baroclinic geostrophic (upper Fig.) and ADCP-measured (lower Fig.) currents along transect N in 2002

Table 1. ADCP-referenced (T_{abs}) and calculated baroclinic geostrophic (T_R) volume transports in 2000 and 2002

	ADCP-referenced transport T_{abs}			Calculated baroclinic transport T_R		
Year	Northward [Sv]	Southward [Sv]	Net [Sv]	Northward [Sv]	Southward [Sv]	Net [Sv]
			TRANSECT N			
2000	17.8	8.7	9.1±2	6.5	3.8	2.7
2002	14.1	5.0	9.1±2	5.6	2.3	3.3
			TRANSECT S			
2000	15.7	7.2	8.5±1.5	4.0	1.2	2.8
2002	17.8	9.1	8.7±1.5	2.9	1.4	1.5
			TRANSECT Z			
2000	10.5	4.6	5.9±1	3.6	1.6	2
2002	14.5	8.6	5.9±1	3.7	1.5	2.2

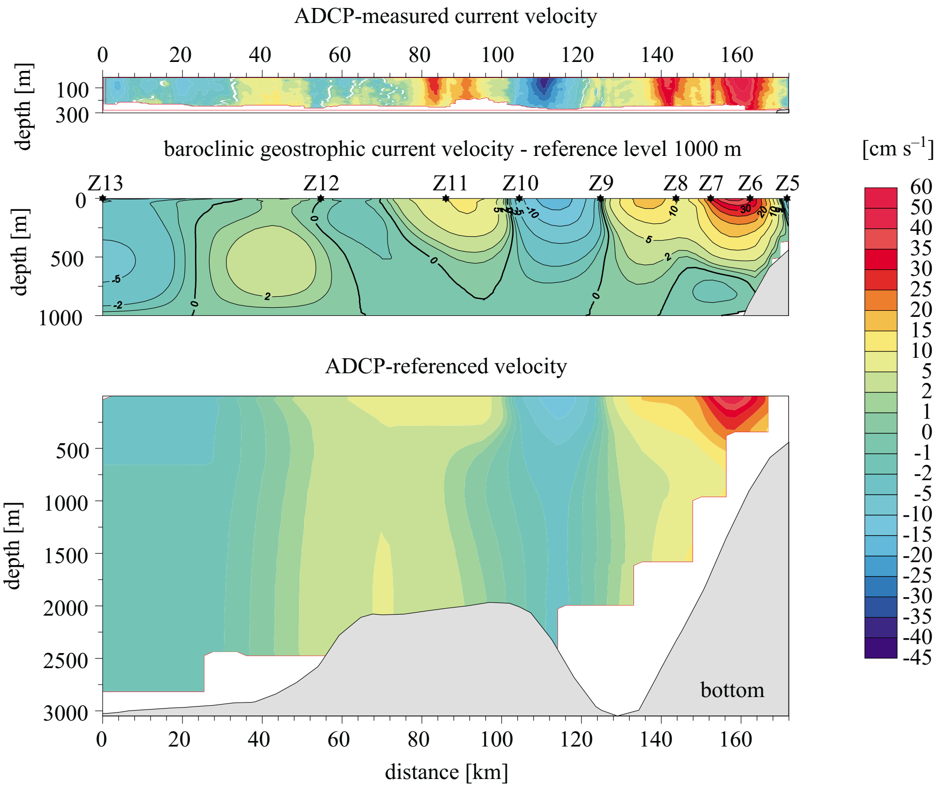

Fig. 4. ADCP-measured (upper Fig.), baroclinic geostrophic (middle Fig.) and ADCP-referenced (lower Fig.) currents along transect Z in 2002

observed along transect N, west of the Knipovich Ridge. Although the absolute value of the barotropic component was not great, the barotropic and baroclinic transports in that region were of the same order.

In general, the pattern of ADCP-measured currents is similar to the calculated current field (Fig. 3) but measured velocities are about 2–5 times higher except for the flow over the continental slope. There, ADCP-measured currents are less than 0.25 times higher than the calculated values (the difference is less than 10 cm s^{-1}), which suggests that baroclinic forces are stronger than barotropic forces in this narrow region (about 10–40 km).

5. Conclusion

ADCP provides fresh opportunities to estimate the absolute current field and volume transports: this is the prime achievement of this research. The highest transport values were found along transect N, and were lower along the more northerly transects. The total ADCP-referenced transport was about three times as high as that calculated assuming LNM at 1000 m (Table 1). Comparison of the transports suggests that barotropic volume transport is significantly larger than baroclinic transport in the WSC. However, it has to be stressed that within the upper layer, of great significance for heat and salt transport, baroclinic transport is still comparable to barotropic transport. Transect Z lies along roughly the same line as the chain of moorings deployed during the VEINS experiment (Woodgate et al. 1998, Fahrbach et al. 2001). Our estimates confirmed the VEINS results, which yielded much higher volume transports than those given in earlier studies.

ADCP has demonstrated its usefulness for the calculation of the absolute transport. Estimated total volume transports represent instantaneous values, hence they are slightly higher than the average transport based on long-term measurements with current meters. It is obvious that the main disadvantage of ADCP measurements lies in the fact that they produce only snapshots of the current field. On the other hand, their high horizontal resolution does help to analyse the current structure in considerable detail.

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