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Short Contribution

On Geostrophic Reference Levels in the Bering Sea Basin

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Various data sets in the deep Bering Sea are examined in an effort to find suitable reference levels for geostrophic transport computations. Because of the lack of other data, classical methods are used: mainly vertical structure of differences in geopotential (method of Defant) and mass conservation. In the western Bering Sea, maximum transports are usually, but not always, obtained by using reference levels near the bottom. In the central region, there is considerable variability, both spatial and temporal, in the depth of the most suitable reference level, which varies from ~500 to at least 1500 db. The variations seem to be related to depth of inflow in the passes, to near-surface salinity gradients, and to features such as upward movement of water or well-developed eddies.

1. Introduction

The existence of considerable spatial complexity in Bering Sea circulation has been known for decades (Ohtani, 1973; Kinder *et al.*, 1975; Sayles *et al.*, 1979). Much temporal variability is also suggested by these and other studies, and one case of Lagrangian chaos was found in drifter data along the eastern slope (Reed and Stabeno, 1990). It is reasonable though to derive a schematic of large-scale circulation, as shown in Fig. 1, with the warning that many departures from this state occur. The Alaskan Stream provides the source waters for at least the upper 1 km of the deep basin; the major inflow is through Near Strait, with appreciable transport through Amchitka Pass, and significant flow at times through Amukta and Buldir passes (Favorite, 1974; Stabeno and Reed, 1994). The cyclonic flow around the basin (Bering Slope Current and Kamchatka Current) is present in various climatologies.

There have been only a few efforts to determine suitable reference levels for geostrophic flow computations. Hughes *et al*. (1974) compared one-day trajectories (from drogued buoys) with baroclinic shear in the western Bering Sea and suggested suitable reference levels in most cases between 700 and 3000 m. Kinder *et al.* (1975) used similar methods in the central region and inferred reference levels in the range 800–1800 m. On the other hand, data from a year-long mooring at 995 m in the Bering Slope Current indicated that 500 m was a suitable reference level (Schumacher and Reed, 1992). The climatological hydrocast data in Sayles *et al*. (1979) suggest that >80% of the geopotential relief is above 1400 m.

It might be argued that the Bering Sea is so rife with eddies that efforts to derive mean circulation are futile. In general, this is not so with the data examined here, and meaningful transports are derived after consideration of appropriate reference levels. The present study is thus an effort to examine baroclinic reference levels in the deep basin of the Bering Sea (the area >1000 m in Fig. 1), with emphasis on the region east of 180°. It will be shown that there is

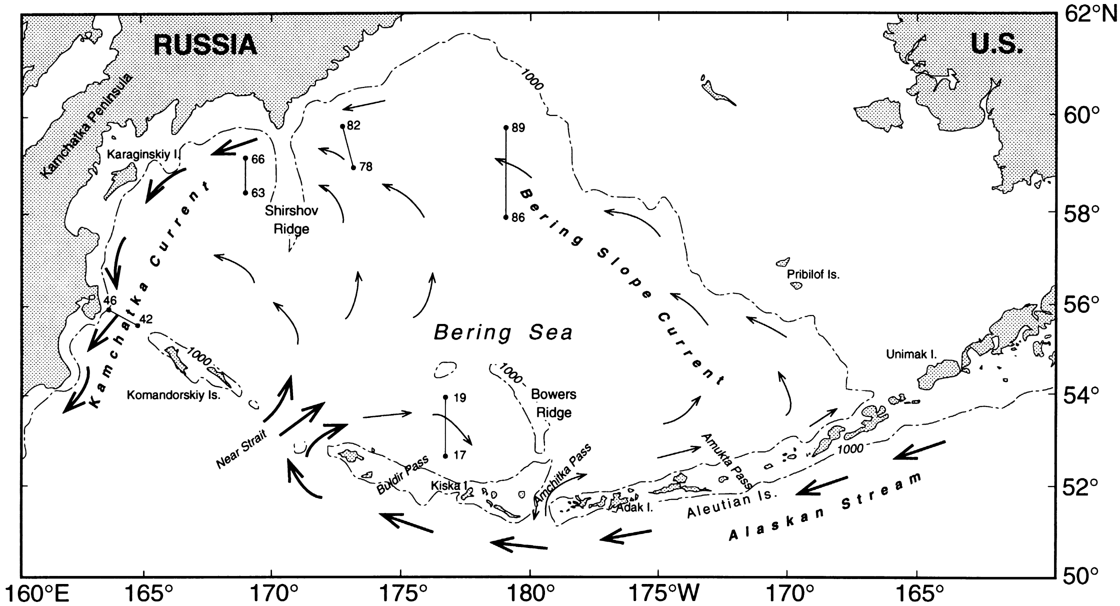

Fig. 1. Schematic of mean circulation in the Bering Sea basin (modified from Stabeno and Reed (1994)). Major currents, topographic features, and the 1000-m isobath are indicated. The line segments, with end-point stations, represent locations where volume transports were computed (see Table 1) from data taken in August 1991.

considerable variability (both spatial and temporal) in the most suitable reference levels. In some cases, it is possible to link the variations to specific mechanisms.

2. Methods and Data

Long-term current measurements in the deep Bering Sea are generally lacking; also, there are inadequate data to use beta-spiral or inverse methods for determining baroclinic reference levels. Hence one is forced to either use the deepest common level, which will be shown to be invalid in some places at times, or resort to other techniques. Certain classical methods are available, however. Fomin (1964) used the method of Defant near the Kuril Islands, and Stramma (1984) used it for a region in the northeast Atlantic; both obtained plausible, unambiguous results. This method is used here to select levels based on the existence of vertical zones of nearly constant horizontal differences (between stations) of geopotential anomaly. In conjunction with examination of geopotential differences, mass conservation is used as a constraint where feasible, and observed property distributions were examined. Geopotential differences, of course, only provide information on the baroclinic component of flow.

When using geopotential anomaly difference curves to specify reference levels, it is quite helpful to have an estimate of the error in the differences. According to Wooster and Taft (1958), the standard error (at 95% confidence limits) of the difference in the 0/1000-db anomaly between two stations is ~±0.011 dyn m for bottle-cast data with salinity titrations; it is only ~±0.001 dyn m for CTD (conductivity, temperature, depth) data, however. Using only CTD data, the criterion of vertical zones with differences that vary by 0.002 dyn m or less is used in selecting reference levels.

Only synoptic data (from seven NOAA cruises, 1971–1993) that clearly resolved substantial flows are used. First, a detailed data set from the north slope of the Aleutian Islands is analyzed. Next, some data from deep casts in the western Bering Sea are examined. Finally, less comprehensive data from the central basin are used. My objective is not to derive climatological transports or *a* level of no motion. Instead, it is to demonstrate methods and their value, show the considerable spatial and temporal variability in reference levels, and attempt to ascertain mechanisms for the observed conditions.

3. North Side of the Central Aleutians, September 1993

Figure 2 presents various dynamic topographies from data taken during 6–12 September 1993 (Reed and Stabeno, 1994). The sea surface topography, referred to 500 db (Fig. 2(a)), indicates northward flow in eastern and central Amchitka Pass and a southward branch on the western side. Some of the northward flow continued northward, but the rest turned eastward along the north side of the Aleutians. This latter flow then turned northward, moved southward off Atka Island, and then turned eastward, with counterclockwise rotation east of 172°W.

The topography at 1000 db, referred to 500 db (Fig. 2(b)), reveals weaker relief than at the sea surface but shows a continuous eastward flow along the north slope of the Aleutians that was especially well-developed near 176°W. On the other hand, there is an indication of westward flow near 171°W and a southward tendency east of Bowers Ridge. The topography at 500 db, referred to 1000 db (Fig. 2(c)), indicates northward flow east of the ridge and eastward flow north and east of Amukta Pass but a *westward* flow along the north slope of the Aleutians. I present evidence below that there was a variable reference (minimum-velocity) layer over this area; a 500-db level was optimum along the north slope from 174 to 178°W but not near Bowers Ridge or offshore east of ~174°W.

Figure 3 presents plots of the geopotential anomaly differences in the vertical (method of Defant) between various stations from this cruise. Most of the plots have zones of relatively constant maximum difference at intermediate depths; horizontal shear decreases both above and below the maxima, indicating unidirectional flow if an intermediate depth is taken as the reference level. A level of ~500 db is also supported by vertical sections of properties which show little slope in isolines near this depth. The exceptions to this pattern are for station pairs 29–33, 60–61, 61–64, and 64–65. Thus levels of no motion are taken as follows: 500 db for the three north-south sections near 174, 176, and 178°W and 1000 db for the others.

The volume transports, using these reference levels, are shown in Fig. 4(a). The net northward transport through Amchitka Pass was 2.8×10^6 m^{3}s^{-1} (Reed and Stabeno, 1994); 1000 db (near bottom) was used as a reference level. The section near 176°W had a smaller transport than those immediately east and west of it, but the geostrophic flow (Fig. 2(a)) indicates that some of the water from the west moved north of station 45. Note that the transports of the upper 1000-db layer between stations 29–33, 60–64, and 64–65 were referred to 1000 db (indicated by asterisks in Fig. 4(a)), in agreement with results in Fig. 3, rather than 500 db as for the three north-south sections between 174 and 178°W. The transport between stations 60 and 64 (3.5×10^6 m^{3}s^{-1}) is in excellent agreement with the sum of transports between stations 29 and 33 (1.5×10^6 m^{3}s^{-1}), stations 46 and 50 (1.3×10^6 m^{3}s^{-1}), and the flow through Amukta Pass (0.8×10^6 m^{3}s^{-1}), or a total of 3.6×10^6 m^{3}s^{-1}. It is also apparent from the streamlines in Fig. 2(a) that this is the pattern of flow and that the northward flow between stations 29 and 33 moved east and entered the section between stations 60 and 64. Thus mass conservation can provide a powerful constraint in the selection of reference levels. Conversely, when flow is referred to a constant

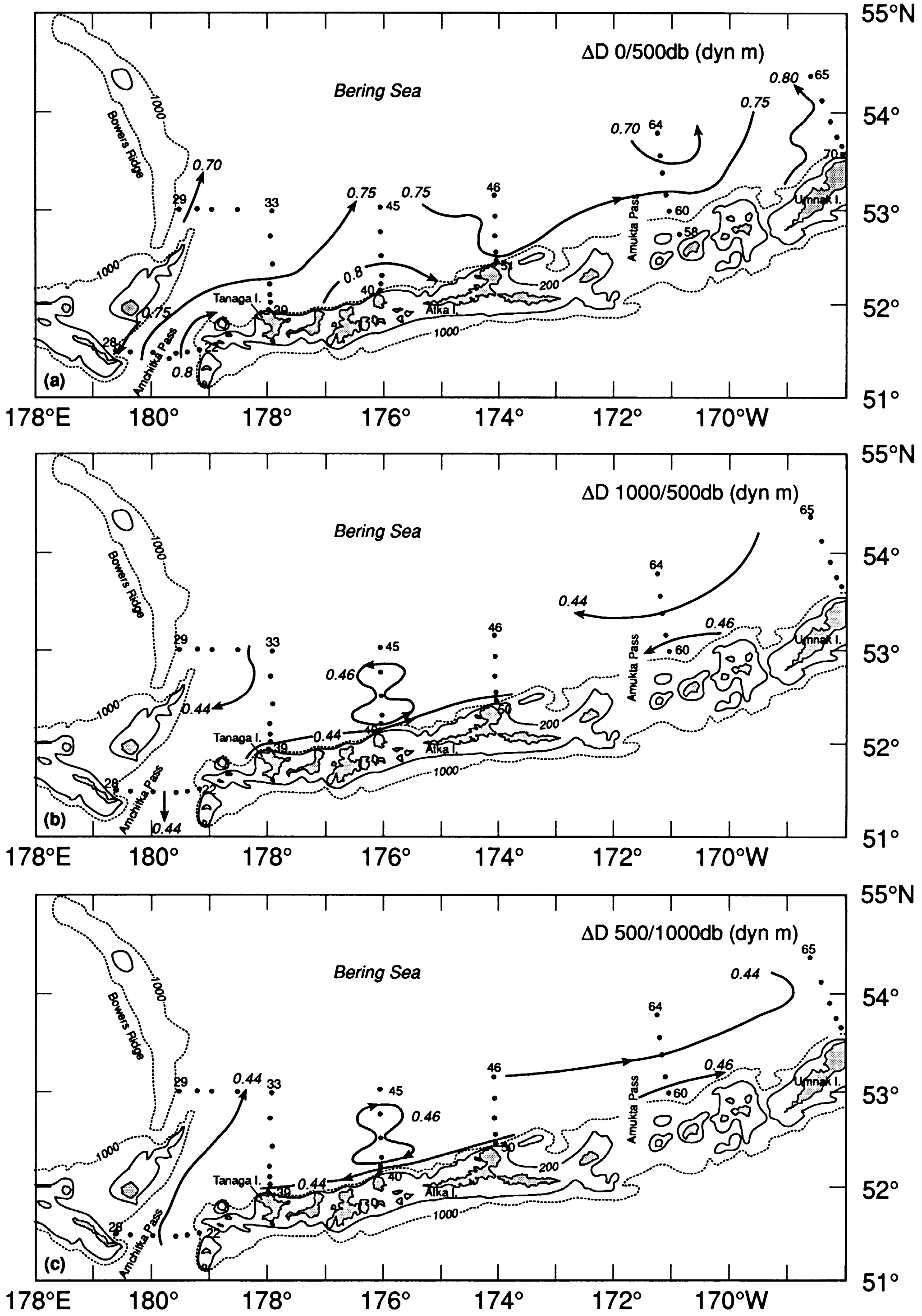

Fig. 2. Geopotential topography (in dyn m) of (a) the sea surface referred to 500 db, (b) the 1000-db surface referred to 500 db, and (c) the 500-db surface referred to 1000 db, September 1993. The 200- and 1000-m isobaths are shown.

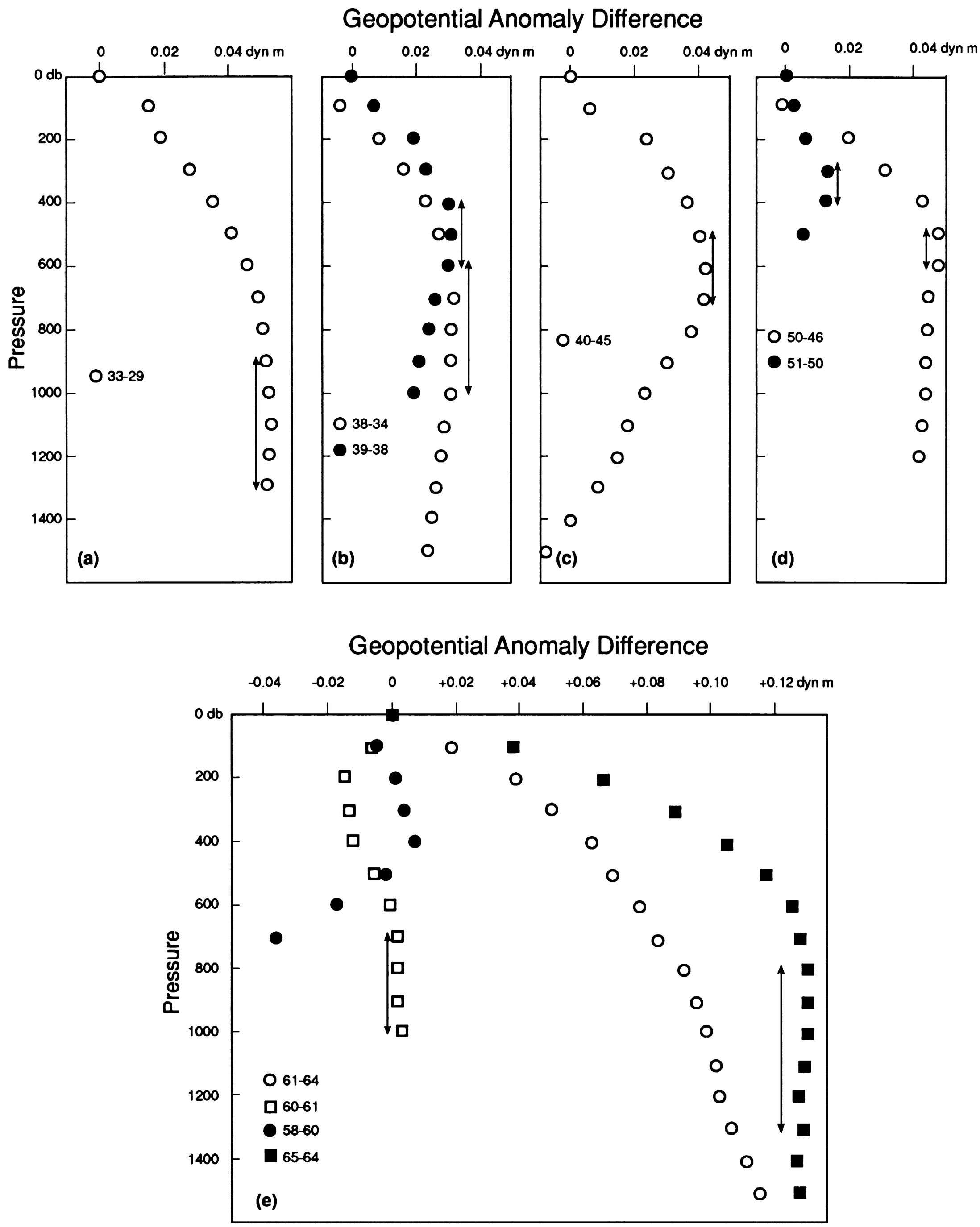

Fig. 3. Vertical plots of the difference in geopotential anomaly (in dyn m) between stations as indicated, September 1993. The vertical lines with arrows indicate zones where the differences were constant to 0.002 dyn m or less.

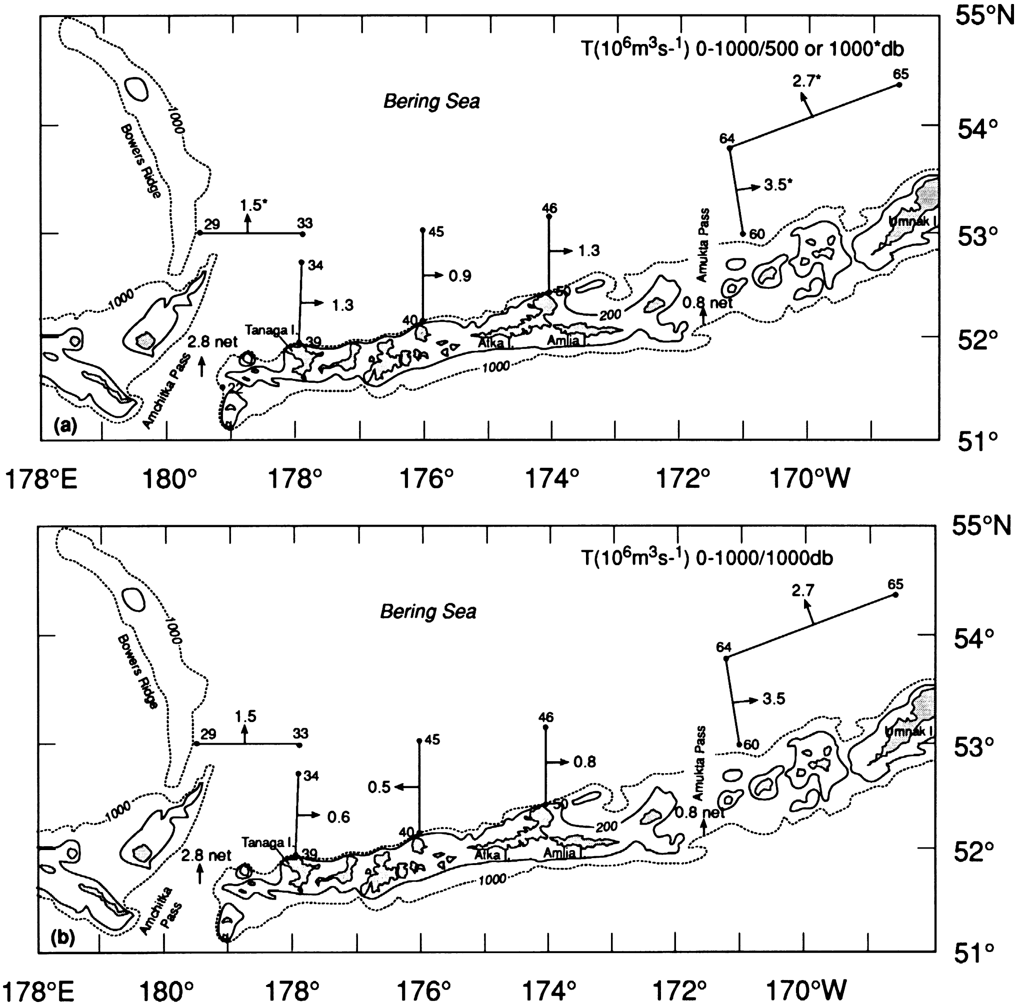

Fig. 4. (a) Computed volume transport (10^6 m^3s^{-1}) of the upper 1000-db layer, referred to 500 db for the three north-south sections (stations 34–39, 40–45, and 46–50) but referred to 1000 db (indicated by asterisks or stars) for the other three sections (stations 29–33, 60–64, and 64–65). (b) Computed volume transport of the upper 1000-db layer, referred to 1000 db for all sections. The net transports in Amchitka and Amukta passes were referred to near-bottom levels.

1000-db level (Fig. 4(b)), the transports on the sections between 174 and 178°W are too small to balance the inflow. And the section at 176°W even has *westward* transport as a result of the tendency shown in Fig. 2(c).

The exact mechanism for the establishment of an intermediate reference level on the three sections between 174 and 178°W is not entirely clear but may be related to the structure of flow in Amchitka Pass. Although the northward flow there generally had horizontal shear increasing downward to the bottom (~1000 db), stations 23–24 had a structure that implied an intermediate reference level was most suitable, thus producing both upper-ocean and near-bottom northward flow. Furthermore, property distributions (such as temperature at sigma-*t* density surfaces) above and below 500 db suggest continuity of flow from stations 23–24 along the northern slope and across the three north-south sections between 174 and 178°W. Near 1000 db though, the water along the slope, especially at station 40, was denser (by ~0.04 sigma-*t* units) than at its source (stations 23–24), perhaps as a result of upward motion or rising water.

4. Western Bering Sea, August 1991

This synoptic data set had sections that crossed the Kamchatka Current; the transports, referred to 1500 db, along the current were approximately constant but were weaker than normal because of weak inflow through Near Strait (Reed *et al*., 1993). There were a few deep stations which allow one to examine baroclinic structure throughout the water column; segments of the sections with deep end-point stations are shown in Fig. 1. I wish to stress that these segments did not generally extend across the Kamchatka Current and mass conservation cannot be used as a constraint as in the previous section. These results are useful because they indicate that baroclinic structure is generally quite deep in the western basin.

Data from the section in Kamchatka Strait (stations 42–46), plus those from the easternmost one (stations 86–89), are the only observations here that suggest intermediate reference levels are more suitable than levels near the bottom (Table 1). In Kamchatka Strait, the reference level giving maximum transport sloped from 1000 db in the central strait (stations 42–44) to near-

Table 1. Comparison of volume transports, above the various reference levels indicated, in the western Bering Sea, August 1991. Directions of flow are as indicated: E (eastward), S (southward), and W (westward).

Stations	Reference level (db)	Volume transport (10^6 m^{3}s^{-1})	Transport ratios (1000/1500 db or 1500 db/bottom)
17–19	1000	6.4E	—
	1500	10.5E	0.61
	4000	17.1E	0.61
42–46	1000	2.6S	—
	1500	3.1S	0.84
	variable*	5.0S	0.62
63–66	1000	2.0W	—
	1500	3.2W	0.62
	3000	5.4W	0.59
78–82	1000	4.4W	—
	1500	6.5W	0.68
	3000	11.3W	0.58
86–89	1000	1.6W	—
	1500	1.8W	0.89
	1400 (0–3500 db)	3.3W	0.55

*Referred to 1000 db (stas. 42–44, 0–4000 db) and 3000 db (stas. 44–46).

bottom (3000 db) on the western side (stations 44–46). This tendency is apparent from the sigma-*t* slopes which had a weak reversal below ~1000 db between stations 42 and 44 (Reed *et al.*, 1993; Fig. 5). At station 89, the upper water was warmer, fresher, and had a higher geopotential anomaly than at station 86; below ~1400 db, however, the trend reversed, as a result of the deep-water properties. If the bottom is used as a reference level here, the resulting transport above is 0.5×10^6 m^{3}s^{-1} *eastward*, rather than the plausible 3.3×10^6 m^{3}s^{-1} westward (Table 1).

Stations 17–19 spanned an eastward flow northwest of Kiska Island (Fig. 1). The transports (Table 1) were the largest in the entire data set. This result is deceiving, however, because the data used were in an eddy whose southern side was not well resolved (Reed *et al.*, 1993); thus all of this large transport was clearly not moving eastward into the central Bering Sea. The large values, however, suggest that eddy-like features may reach deep into the water column.

It is of interest to examine the transport ratios in Table 1. Except for the southernmost two sections, there was an increase in the 1000/1500-db transport ratios toward the east across Shirshov Ridge. This is in general agreement with the typical high values shown below in the

Table 2. Comparison of volume transports, above the various reference levels indicated, in the central Bering Sea, during various years. Directions of flow are as indicated: E (eastward), N (northward), NE (northeastward), NW (northwestward), and S (southward).

Stations	Date	Approx. location	Reference level (db)	Volume transport (10^6 m^{3}s^{-1})	Transport ratios (500/1000 db or 1000/1500 db)
76–80	Jun. 1971	54°N	500	1.7N	—
		166–168°W	1000	1.4N	1.21
4–8	Oct. 1986	52–54°N	1000	6.0E	—
		176°W	1500	8.1E	0.74
52–56	Nov. 1986	55–56°N	1000	5.6NW	—
		174–175°W	1500	8.0NW	0.70
1–6	Jun. 1987	52–53°N	1000	3.1E	—
		176°W	1500	3.5E	0.89
5–9	Mar. 1988	54°N	1000	5.8NE	—
		168–169°W	1500	4.6NE	1.27
14–17	Mar. 1988	54°N	1000	1.8NE	—
		167–168°W	1500	1.4NE	1.29
65–67	Mar. 1988	54–55°N	1000	3.0NW	—
		168°W	1500	3.0NW	1.00
26–30	Sep. 1992	53–55°N	1000	3.0E	—
		176°E	1500	4.4E	0.68
6–8	Sep. 1992	53°N	1000	3.2S	—
		178–179°W	1500	4.5S	0.71
2–4	Sep. 1992	52–53°N	1000	2.9E	—
		177°W	1500	3.4E	0.85

central basin, which implies a relatively shallow circulation there in agreement with the major inflow to the central basin being through relatively shallow Amchitka Pass (Favorite, 1974). The 1500-db/bottom transport ratios were ~0.6, which is actually larger than in the western Alaskan Stream, where values are ~0.4–0.5 (Warren and Owens, 1988; Onishi and Ohtani, 1993). Finally, the relatively large transport between stations 78 and 82 resulted from this segment of the section crossing nearly all of the Kamchatka Current, whereas there was appreciable flow inshore of the two downstream segments (stations 63–66 and 42–46; Reed *et al.*, 1993; Fig. 7).

5. Central Bering Sea Basin, Various Years

The results presented in this section show variation in reference levels that is both spatial and temporal in nature. Although the individual sections are synoptic, they are limited in comparison with the September 1993 data, however, and constraints such as mass conservation cannot generally be used. Since use of a reference level in the zone of maximum horizontal difference of geopotential anomaly will yield unidirectional flow, which seems very likely, and maximum transports, it is reasonable to assume that the larger values are the most realistic.

Results from the ten sections (from five cruises) in Table 2 indicate that three had maximum transports when referred to intermediate levels (500 or 1000 db) rather than maximum cast depths (1000 or 1500 db). These shallow flows were all associated with strong near-surface salinity gradients. The fall 1986 flows were deep and relatively large and were part of a cyclonic, gyre-like feature. Stations 26–30 in September 1992 were near stations 17–19 in August 1991 (Table 1); the later section had less than half the transport of the earlier one, however. Thus large temporal, as well as spatial changes, occur.

6. Conclusions

In the western Bering Sea basin, the baroclinic circulation is normally quite deep. This is plausible because the upper-ocean inflow can extend to ~2000 m in Near Strait, and there is bottom water inflow below ~3500 m in Kamchatka Strait (Reed *et al.*, 1993). On the other hand, inflow to the central basin appears to be largely limited to the east of Bowers Ridge, where the deepest passes are Amchitka (1000–1200 m) and Amukta (300–400 m). The reference levels appear to vary between ~500 db and at least 1500 db.

Of the 16 sections shown in Fig. 4 and Table 2, four, five, and seven had optimum reference levels at 500, 1000, and 1500 db or greater, respectively. The shallow levels appeared to be caused by relatively shallow inflows through various passes and perhaps by alteration of geopotential slopes below 500 db by rising water at the north slope of the Aleutians. Three of the seven cases with reference levels of 1500 db or greater occurred in regions of well-developed cyclonic curvature offshore; the others seemed to result from moderately deep flow in Amchitka Pass or from extensions of flow across Bowers Ridge.

It is apparent that no single level of no motion, invariant over space and time, can be used in the Bering Sea basin. In the absence of direct current measurements and comprehensive data for inverse methods, one can employ classical methods with each data set. The vertical structure of horizontal geopotential shear (method of Defant), aided by mass conservation and property distributions, can yield plausible results.

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