JOURNAL OF MARINE RESEARCH

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Baroclinic transport in the Gulf of Alaska
Part I. Seasonal variations of the Alaska Current

by Thomas C. Royer[1]

ABSTRACT

Temperature and salinity sections which intersect the Alaska Current are used to determine the baroclinic, geostrophic current on 21 occasions from 1975 to 1977. A sinusoidal curve-fitting technique is applied to these Alaska Current estimates and others available in the literature to statistically test the flow for an annual signal. The mean baroclinic transport relative to 1500 db is estimated to be 9.2×10^6 m³ s⁻¹ with seasonal signal of 1.2×10^6 m³ s⁻¹. The maximum is in March and minimum in September. Maximum speeds in excess of 100 cm s⁻¹ are estimated and, typically, more than 80% of the transport is within 60 km of the shelf break. Thus, near Kodiak Island, the Alaska Current can be considered as a narrow, high speed jet.

A distinctive characteristic of this and many other high-latitude baroclinic flows is that the horizontal density gradient is primarily a function of the horizontal salinity gradient, with the thermal gradient contributing to a lesser degree. For the Gulf of Alaska this salinity gradient could be created through runoff and coastal wind convergence.

1. Introduction

Though frequent baroclinic flow computations of the Alaska Current have been carried out since the 1920's (McEwen *et al.,* 1930; Thompson *et al.,* 1936), direct or indirect calculations of seasonal fluctuations have not previously been made. Recent seasonal hydrographic sections through the Alaska Current and over the adjacent continental shelf now allow the determination of the mean transport and its seasonal variation in the Alaskan Gyre.

The Alaska Current represents the northern limb of the subarctic cyclonic gyre with the southern limb corresponding to the North Pacific Current. According to common nomenclature the westward flowing Alaska Current becomes the Alaska Stream somewhere between 150W and 180W. In this paper, a distinction will not be made between the two names and Alaska Current will refer to the entire westward flow along the northeastern boundary of the Pacific.

General oceanographic conditions in the subarctic North Pacific are addressed in detail by Uda (1963), Dodimead *et al.* (1963) and Favorite *et al.* (1976). Addi-

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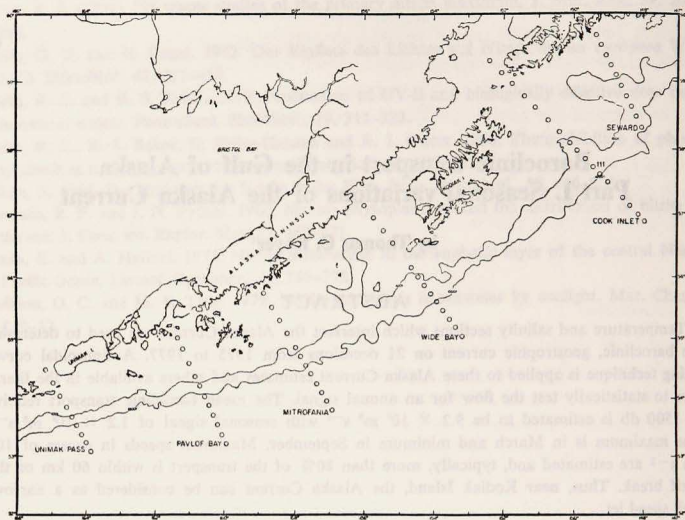
Figure 1. Western Gulf of Alaska with hydrographic station positions used in the OCS surveys.

tional details of the general oceanographic conditions for this region by J. L. Reid (1961; 1965; 1973) indicate a large scale dilution of the surface layers from an excess of precipitation over evaporation in the subarctic. Relative to 1000 db, the surface baroclinic speed in the Alaska Current is about 25 cm s^{-1} with the volume transport estimated to be between 3 and 18 × 10^6 m^3 s^{-1} (Tabata, 1975). For this current near the British Columbia coast, Tabata (1975) determines a transport of 7 × 10^6 m^3 s^{-1} relative to 1000 db and 14 × 10^6 m^3 s^{-1} relative to 3500 db. Fofonoff and Tabata (1966) detect no seasonal changes in this north-ward flow, such as winter intensification. More recently, Reed *et al.* (1980) find no detectable seasonal signal in the Alaskan Stream.

2. Alaska Current transports

Two different sets of Alaska Current transport data are used in this study; the first is a historical data set and the second set consists of recently acquired (1974-1979) data. A summary of historical Alaska Current baroclinic transports (0/1500 db) by Favorite *et al.* (1976) is available for transects from 155W to 179E. The set consists of 24 transport estimates from 1965 to 1970. Some transports represent

seasonal estimates while others are for specific months. The transports range from
13.9×10^6 m³ s⁻¹ for March 1966 to 5.1×10^6 m³ s⁻¹ in July 1968. The
second set of Alaska Current transports are determined from hydrographic tran-
sects occupied from 1975 to 1977 under the Outer Continental Shelf Environ-
mental Assessment Program (OCSEAP) using sections from Kodiak Island to
Unimak Pass (see Fig. 1). This set of transports consists of 21 transects from
148W to 166W (see Table 1).

These lines, approximately orthogonal to the coast, begin about ten kilometers
offshore, terminating at depths greater than 1500 m. The lines near Kodiak are
specifically designed to measure the Alaska Current with closely spaced stations
in deep water. For positions on the indicated grid (Fig. 1), temperature and salinity
or conductivity versus depth were obtained to within 10 m of the bottom or 1500
m whichever was less. These STD/CTD measurements were field calibrated using
discrete salinity and temperature measurements. Seasonal coverage was attempted
but not achieved (see Table 1).

Because irregular sampling and limited data do not lend themselves to anomaly
determination or spectral analysis, the monthly means are used to create an
annual transport cycle. For some months, no observations are available while
others have an abundance of measurements (see Table I). A sinusoidal least
squares fit is made to the annual transport cycle. This fit forces a symmetric
annual cycle with maxima and minima separated by six months. A mean ampli-
tude, phase and F-statistic of the fit are estimated for each cycle. The F-statistic
is used to measure the appropriateness of the annual cycle in the data, that is,

Table 1. Distribution of Hydrographic Sections.

Section		J	F	M	A	M	J	J	A	S	O	N	D
Cook Inlet	1975									X		X	
(7)	1976				X			X				X	
	1977			X								X	
Wide Bay	1975									X		X	
(5)	1976				X			X					
	1977											X	
Mitrofania	1975									X		X	
(5)	1976				X			X			X		
	1977												
Pavlof Bay	1975									X		X	
(2)	1976												
	1977												
Unimak Pass	1975									X		X	
(2)	1976												
	1977												

can a significant amount of the observed transport variations be accounted for by an annual cycle?

Using only the historical transports (Favorite *et al.*, 1976), the least squared sinusoidal fit technique gives a mean transport of 9.2×10^6 m³ s⁻¹ and an annual signal amplitude of 1.2×10^6 m³ s⁻¹ (see Table 2). With this fit, the maximum transport occurs in February with the minimum in August. The time of the peak transport differs from the time of year (December-January) suggested by Favorite and Ingraham (1977) and Reid and Mantyla (1976). The analysis of variance of the regression about this annual cycle yields an F-statistic of 2.0 which implies that this is an actual annual response and not random noise with a probability of $>50\%$.

Using only the OCSEAP transport measurements, least squares sinusoidal curve fit yields a mean of 9.7×10^6 m³ s⁻¹ and annual amplitude of 1.4×10^6 m³ s⁻¹ (Table 2); very similar to the results from the Favorite *et al.* (1976) data. However, these estimates have a phasing that places the maximum transport in June and minimum in December; a phase shift of four months from the earlier estimate. The F value of 6.3 indicates that the probability is greater than 80% that the hypothesis of an annual signal is true. The combined set of Alaska Current transports from Favorite *et al.* (1976) and OCSEAP have a mean of 9.5×10^6 m³ s⁻¹ and annual amplitude of 1.4×10^6 m³ s⁻¹ with a maximum in March and minimum in September. The associated probability for an annual cycle is $>90\%$.

An explanation for the lower confidence level for the annual cycle determined from the Favorite *et al.* (1976) transports is their nonuniform sampling. In contrast, the OCSEAP transects are designed for the purpose of estimating Alaska Current transports and in most cases were repeated, whereas the Favorite *et al.* (1976) data are not. (The lower F value, 5.2, but greater probability [$>90\%$] of the combined set is due to the increased degrees of freedom.)

Table 2. Fitted annual transports, 0/1500 db.

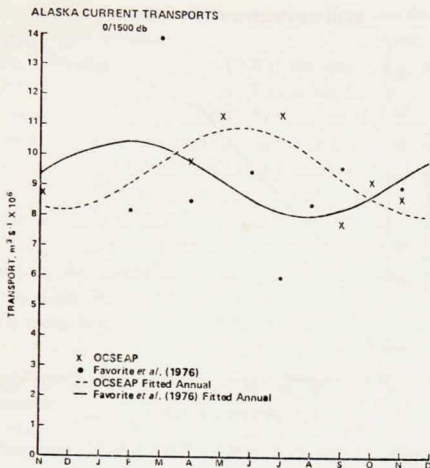| Source	Mean x 10⁶ m³ s⁻¹	Annual amplitude x 10⁶ m³ s⁻¹	Maximum	Minimum	*F*
Favorite, Dodimead and Nasu (1976)	9.2	1.2	Feb	Aug	2.0
OCSEAP	9.7	1.4	June	Dec	6.3
Combined	9.5	1.4	March	Dec	5.2
With Reed *et al.* (1980) 1978 transports	9.2	1.2	March	Sept	5.6 $>90\%$

Figure 2. Alaska Current transports with annual cycle fitted.

For any given month, the range of transports is larger than the annual signal which implies that year-to-year variations could override the seasonal cycle (Fig. 2). However, a seasonal reversal in the general cyclonic circulation of the Alaska Gyre as suggested in Bogdanov (1963) is not supported by these data. It is not surprising that other attempts to describe an annual transport have failed or given erroneous results. As previously mentioned, Reed et al. (1980) find no seasonal signal in the 0/1500 db baroclinic transport near Kodiak. Their data set has some points in common with the OCSEAP data used in this analysis. However, using only their transports, the annual current fit has an F value of 0.88 for their unadjusted transports and 0.49 for their adjusted transports. Adjusted transports refer to corrections in the geopotential in water depths less than the reference level. The maximum in their annual signals occur in April and June respectively. If the hypothesis to be tested is whether there is an annual signal in these data, it cannot be accepted or rejected with a confidence above 25% using only their data. When the transports of Reed et al. (1980) are included with those of Favorite et al. (1976) and other OCSEAP data, the hypothesis of the existence of an annual signal has a greater than 90% probability of being correct (Table 2) and does not differ significantly from the other results from the subsets.

The spatial variability of the Alaska Current can best be determined from the most frequently repeated section near Cook Inlet. From that section, it can be seen that slightly more than 80% of the Alaska Current transport is within 60 km

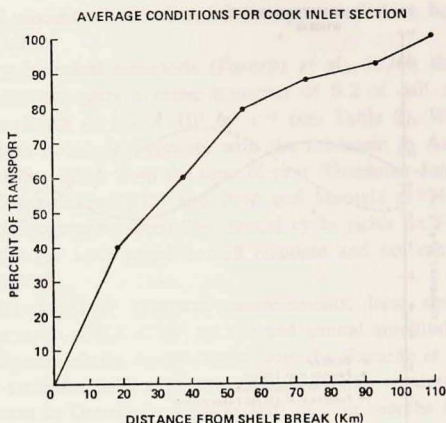AVERAGE CONDITIONS FOR COOK INLET SECTION

Figure 3. Averaged baroclinic transport for Cook Inlet. Distance measured from Station 111 (see Figure 1).

of the shelf break near Kodiak Island (Fig. 3). The seven transports used in this estimate are from the Cook Inlet section where the section extends into the Gulf of Alaska at which point the isopycnals become approximately parallel to the 1500 db surface. Favorite and Ingraham (1977) estimate that 75% of the transport is within 50 km of this shelf break in May 1972.

Maximum baroclinic current speeds are significantly higher than those presented by Roden (1969) or Tabata (1975) (~25 cm s^{-1}). Speeds in excess of 100 cm s^{-1} are determined from the OCSEAP data while Favorite and Ingraham (1977) compute a maximum speed of 98 cm s^{-1}. Since geostrophic transport computations are independent of the horizontal distance between the density observations, the good agreement between recent and earlier transports and the poor agreement between recent and earlier current speeds is consistent with the coarse grid sampling used in the earlier studies. The recent spacing of about 18 km might even be too great to resolve important details of the flow. For example, no seasonal shift in the position of the Alaska Current is detectable from our data.

Further details of the transport for the Cook Inlet section and the adjacent upstream section (Seward) and downstream section (Wide Bay) support the concept of maximum transport in the Alaska Current between April and July (Table 3). No section has a maximum transport in winter regardless of the reference level used. The small transports for the Seward section are a consequence of that section not containing the entire Alaska Current. Conversely, as previously

mentioned, the Cook Inlet and Wide Bay station locations are desgined specifically to measure Alaska Current transport.

Annual transport fluctuations for the 0/200 db interval in the three sections account for 38-46% of the annual transport fluctuation for the 0/1500 db interval. The 0/100 db transport lags the 100/200 db transport by about one month for all sections. However, the 200/1000 db transport is in phase with the 0/100 db transport with the exception of the Wide Bay section where it lags the upper layer (0/100 db) transport by a month. The only apparent reversal in the Alaska transport takes place in the 1000/1500 db layer on the Seward section where a slight reversal ($<1 \times 10^6$ m^3 s^{-1}) is predicted for autumn.

For a comparison, the harmonic fit computational routine is applied to 35 sections across the Gulf Stream from 1932 to 1977 (Worthington, 1977). The Gulf Stream has a mean transport of 76.4×10^6 m^3 s^{-1} and a seasonal amplitude of 6.5×10^6 m^3 s^{-1} with its maximum in March. The hypothesis that an annual signal exists can be stated with a confidence of greater than 80%. While the Gulf Stream's seasonal current fluctuation is much larger than the fluctuation for the Alaska Current, the Alaska Current's fluctuation is a much larger percentage of the mean flow. That is, the Gulf Stream varies seasonally by 8.5% of the mean, where the Alaska Current varies by 13.0%.

3. Forcing mechanisms of the Alaska Current

The Alaska Current undergoes a transition from an eastern boundary current along the west coast of North America (Veronis, 1973), into a zonal current in the northern Gulf of Alaska (Thomson, 1972). Near Kodiak Island, the current behaves as a western boundary current. To the west of Kodiak Island, the current returns to a zonal flow along the southern coast of the Aleutians. Because it can serve as return flow for the subarctic North Pacific gyre, its transport could be dependent on atmospheric forcing over the entire North Pacific basin. The seasonal variations in the North Pacific circulation are not yet well known nor is the response of the ocean to seasonal atmospheric forcing. In addition, the regional seasonal response to such forcing is not known and could be more complex than

Table 3. Mean transports ($\times 10^6$ m^3 s^{-1}) $\pm$ amplitude of the annual variation (time of annual maximum).

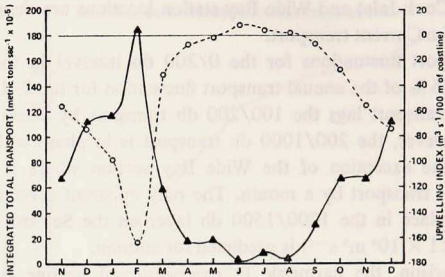| Pressure interval	Seward	Cook Inlet	Wide Bay
0/ 100	0.82 ± .10 (May)	1.94 ± .34 (July)	2.11 ± .46 (May)
100/ 200	1.48 ± .08 (April)	1.49 ± .41 (June)	1.46 ± .66 (April)
200/1000	1.20 ± .69 (May	4.87 ± 1.90 (July)	3.75 ± 2.39 (June)
1000/1500	.08 ± 0.10 (May)	0.61 ± .40 (Aug)	0.53 ± .23 (May)
0/1500	2.89 ± 1.08 (May)	0.07 ± 2.72 (July)	7.82 ± 2.43 (April)

Figure 4. Average annual intergrated total transport at 55W, 145N (solid) and upwelling index at 60W, 149N (dashed) from sea level atmospheric data (1974-1979).

the open ocean wind-force response. These complexities might be a consequence of large horizontal current shears associated with the intense narrow flow, interaction of the flow with horizontal boundaries and the transient nature of the forcing winds.

A measure of the seasonal variation of the regional wind field can be obtained from the integrated total transport at 55N, 145W and upwelling index at 60N, 149W (Fig. 4), as determined from sea level atmospheric pressure data by National Marine Fisheries Service at Fleet Numerical Weather Central, Monterey, California. Both representations have an annual maximum in February and minimum in June. Because the sinusoidal fit forces the maximum and minimum values to be separated by six months, the fitted data has its maximum in January and its minimum in June. The F-statistic for these fits has a confidence interval of greater than 99.9%.

Thermohaline effects can act in concert with the wind forcing to drive the circulation. Unlike baroclinic currents at lower latitudes in the world's oceans, the Alaska Current is associated with a horizontal salt gradient rather than a thermal gradient. Typically, about 2/3 of the horizontal density gradient is the consequence of spatial salinity variations. For comparison, the Gulf Stream's thermal portion of the horizontal density gradient is about twice its salinity contribution. More importantly the direction of the two gradients are the same in the Alaska Current but oppose one another in the Gulf Stream. That is, salinity and temperature gradients contribute to the cyclonic sense of flow in the Gulf of Alaska, whereas the coastal dilution on the east coast of the United States contributes to a southward flow counter to the northward flowing Gulf Stream.

The seasonal influx of fresh water into the Gulf of Alaska is a possible mechanism by which the horizontal salinity gradient is maintained and hence might affect the Alaska Current. This influx primarily takes place at the coast as

runoff with maximum in fall and minimum in winter (Royer, 1981). Details of fresh water injection into the Alaska Current are presently not well known, except that near Kayak Island it appears that a portion of this fresh water enters the Alaska Current. That island forces a southward displacement of the coastal current across the very narrow (<25 km) shelf. This band of fresh water retains its identity at the surface for hundreds of kilometers downstream and is observed in hydrographic sections near Kodiak (Favorite and Ingraham, 1977) and in satellite infrared images which can detect sea surface temperature gradients (Royer and Muench, 1977). The surface temperature gradients are created from uniform surface heating of water with different vertical density structures. Therefore, west of Kayak Island the Alaska Current can be identified as a band of low salinity surface water and surface temperature contrasts.

The fresh water driving mechanism for the Alaska Current could be analogous to the thermocline depth variations causing transport variations in the Gulf Stream (Worthington, 1977). Instead of the thermocline, the halocline is the important dynamic feature in the Gulf of Alaska because of the greater importance of salinity in determining the density of cold water. The halocline depth variations between onshelf and offshelf water masses could cause the variations in Alaska Current transport. The halocline depth depends on both fresh water discharge and wind stress through convergences and divergences. Instead of the poleward deepening of the thermocline, as suggested by Worthington (1977) for the Gulf Stream, there is a poleward deepening of the halocline in the Gulf of Alaska.

The circulation response of the Indian Ocean to wind and thermohaline forcing (Cox, 1970) is a reasonable approximation of the situation in the Gulf of Alaska. Both basins possess open southern boundaries and large seasonal variations in wind forcing. The seasonal cooling effect on density caused by upwelling in the Indian Ocean is analogous to the downwelling effect on salinity and density in the Gulf of Alaska. Cox, using an analogue between wind-current responses and electrical circuit theory, concludes that the current response to wind forcing should result in the current being 90° out of phase with the wind, that is, current lags the wind by three months, similar to electrical current lagging the voltage by 90°. Since the observed currents in the Indian Ocean are nearly in phase with the wind, Cox attributes this to cooling effects, similar to the addition of resistance to an electrical circuit, which will change both the amplitude and phase of the response. The Somali Current accelerates with coastal upwelling and/or coastal cooling, whereas the Alaska Current could accelerate with coastal downwelling and/or coastal dilution. The surface dilution in fall and its subsequent interaction with the Alaska Current is similar to spring cooling in the Somali Current; both of these density modifications tend to bring the wind and current into phase. For example, the Somali Current is found to be trailing the wind stress by less than a month which agrees with the theoretical work of Lighthill (1969). A serious

difference between the Indian Ocean and the Gulf of Alaska is the latitude and thus planetary vorticity, since the Cox model is nearly centered on the equator and the Gulf of Alaska is at about 55N. The baroclinic response time has been speculated to increase with latitude for interior portions of the ocean (Veronis and Stommel, 1956), which alters the amplitude-phase relationship. However, the response at coastal boundaries might be more rapid, thus offsetting the predicted delayed response in the high latitude region of the Gulf Alaska.

4. Conclusions

The Alaska Current has a mean baroclinic transport 9.2×10^6 m³ s⁻¹ relative to 1500 db, which is higher than that given by Sverdrup *et al.* (1942) (5×10^6 m³ s⁻¹). The probability is greater than 90% that a seasonal transport response of the Alaska Current exists. The seasonal transport amplitude is estimated to be 1.2×10^6 m s⁻¹ (about 13% of the mean). The maximum current lags the maximum wind stress by one to three months and occurs in late spring. Interannual variations are often larger than this seasonal signal. The current speeds are much greater (>100 cm s⁻¹) than previously determined because, while the current transport is slightly greater than previous estimates, the current width ($\cong 60$ km) is much less.

Horizontal salinity gradients are a dominant feature of this current and fresh water discharge affects this transport. Dilution along the right-hand side of the flow and shallower water to the right are opposite to those conditions found with the major ocean currents associated with subtropical gyres. The topographic control of this current is therefore dissimilar to those other currents since a stable topographic condition occurs only along the northern zonal boundary and current reversals and/or eddies are likely to occur elsewhere.

The large annual forcing by wind stress and fresh water appears to be capable of producing a situation where both of these energies are stored in the density field and released throughout the year, as suggested for the Indian Ocean by Holland (1975). The fresh water influx at the outer, coastal boundary in the Gulf of Alaska enhances the offshore density gradient. Low pressure atmospheric systems produce a coastal convergence of low density surface water and downwelling, which also enhances the offshore density gradient. These two processes will accelerate the cyclonic circulation by altering the density field. If the decay time of the collapse of the density field is great compared to the forcing event, the effects of seasonal forcing or other events might persist for months or even years. The evidence of a seasonal circulation for the Gulf of Alaska presented in this paper could have a phase shift of some multiple of 2π radians in it.

The baroclinic flow will be augmented by the barotropic response which should have the same direction under winter conditions. The response time of this baro-

tropic response is less than the baroclinic response, and coupling between these modes can occur through topographic interactions. Better delineation of the non-baroclinic flow responses to seasonal forcing could be accomplished with direct current measurements.

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