Exxon Valdez Oil Spill
Restoration Project Annual Report

Toward Long-Term Oceanographic Monitoring of the Gulf of Alaska Ecosystem

Restoration Project 01340
Annual Report

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Study History: This project was initiated in Fall 1997 to maintain sampling of temperature and salinity variability at hydrographic station GAK 1 that was begun opportunistically in 1970. With EVOS funding the sampling was upgraded to include moored temperature and conductivity recorders as well as monthly conductivity-temperature-depth (CTD) measurements. Funding has continued since then and a paper is now being prepared that contains the salient findings from this project for submission to a peer-reviewed journal.

Abstract: Interannual variations in Gulf of Alaska shelf temperature and salinity could significantly influence this ecosystem and hence the recovery and restoration of organisms and services affected by the *Exxon Valdez* oil spill. This variability is being quantified from time series at hydrographic station GAK 1, near Seward Alaska, and within the Alaska Coastal Current. Data from this station spans a 32 year period. In addition to maintaining the sampling, this project has extended the value of these time series by developing predictions for the freshwater content, and the baroclinic components of the mass and freshwater transport within the Alaska Coastal Current. The results allow us to hindcast these variables back to 1948 and therefore provide a data set that can be used in retrospective studies of this marine ecosystem. We have also generated a surrogate time series of freshwater runoff for the Gulf of Alaska based on atmospheric sea level pressure differences between Ketchikan and Seward. This surrogate time series allows us to extend the freshwater discharge record back to 1900. This surrogate time series should be of considerable interest to investigators seeking to understand interdecadal climate variability in the Gulf of Alaska. We have also attempted to relate Seward sea level variations to GAK 1 dynamic height variability. This effort has been partially successful but there are other (as yet unidentified) contributions to sea level variability here. Thus at this time, Seward sea level variations cannot be used as a predictor of dynamic height (salinity) variations for the northern Gulf of Alaska.

Key Words: Alaska Coastal Current, temperature and salinity variability, climate variability, Gulf of Alaska

Project Data: Updated periodically and available at Internet site: http://www.ims.uaf.edu/gak1/

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Weingartner, T.J., and S.L. Danielson. 2002. Toward long-term oceanographic monitoring of the Gulf of Alaska ecosystem, *Exxon Valdez* Oil Spill Restoration Project Annual Report (Restoration Project 98340), Alaska Department of Fish and Game, Habitat and Restoration Division, Anchorage, Alaska.

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EXECUTIVE SUMMARY

This annual report summarizes some of the activities and analyses based on the final year of this four-year project. During the past year we successfully deployed and recovered the mooring at station GAK 1. The instruments are now being post-calibrated but preliminary inspections indicates that the data return and quality from the six instruments on this mooring were excellent. We also continued the monthly CTD profiles at this station. The webpage is being updated with these, and other, data sets.

The most significant finding from the past year's data is that temperatures are significantly colder (by 0.5 – 1.5°C) during the first few months of 2002 compared to the corresponding period in 2001. These differences extend throughout the water column (~250m) and are most likely due to the strong cooling that occurred over the Gulf of Alaska during the winter of 2001-02 compared to the winter of 2000-01.

Our analyses over the past year have focussed on interpreting some of the historical data available from GAK 1 with a particular emphasis on developing predictions of monthly anomalies in the freshwater content, and the mass and freshwater transport within the Alaska Coastal Current (ACC). We have also developed a predictive relationship for these variables based on a set of readily available atmospheric indices. Although the predictive skill using these indices is considerably lower than the skill achieved when the GAK 1 data are included, the approach based on environmental indices alone allows us to hindcast these ACC variables as far back as 1948. (Both predictors estimate the baroclinic, geostrophic component of mass and freshwater transport, but not the barotropic component). The hindcasting capability should prove useful in retrospective studies of this marine ecosystem. Furthermore, our results suggest that these important parameters can be monitored in a very cost-effective manner. These analyses continue and benefit from complement data collected from the coastal Gulf of Alaska GLOBEC program in which I am also a PI.

We also find a significant correlation between the monthly anomaly in atmospheric sea level pressure difference between the Seward and Ketchikan, Alaska and Royer's monthly anomalies in Gulf of Alaska discharge. This correlation is valuable because it allows us to extend (by proxy) the discharge anomaly time series for the Gulf of Alaska back to the 1900.

We have continued efforts to relate Seward sea level variations to GAK 1 dynamic height and "local" winds. Both variables explain only a part of this variability and the correlations are not consistent throughout the record. Hypothesized causes for these deviations are propagating shelf waves, large, slowly propagating eddies along the continental slope, and basin-scale barotropic forcing of the Gulf of Alaska gyre.

Introduction

The Gulf of Alaska shelf is subject to large seasonal and interannual variations in meteorological and oceanographic forcing (*Royer*, 1996; 1993), which potentially affect biological production (*Mantua et al.,* 1997). Quantifying this variability and its causes are necessary for understanding the structure of, and changes in, the northern Gulf of Alaska marine ecosystem. Natural physical variability could influence the recovery of many of the marine species and marine services affected by the *Exxon Valdez* oil spill. The information provided by this project should help investigators working in the Gulf of Alaska understand some of the long-term variability in the physical environment. This monitoring project represents a step toward quantifying and understanding this variability by building upon the historical record of temperature and salinity measurements made on the Gulf of Alaska shelf at hydrographic station GAK 1 near Seward, Alaska (**Figure 1**). GAK 1, located on the inner shelf of the northern Gulf of Alaska and within the Alaska Coastal Current, is situated approximately one-third of the distance between the western end of Prince William Sound and Cook Inlet. The fundamental goal of this program is to maintain the ~32-year time series of temperature and salinity at hydrographic station GAK1 so that the magnitude and sources of environmental variability can be quantified and understood. This is being accomplished through a combination of monthly CTD measurements and through yearlong deployments of a mooring containing temperature and conductivity (T/C) recorders. The recorders are deployed at six depths spanning the water column.

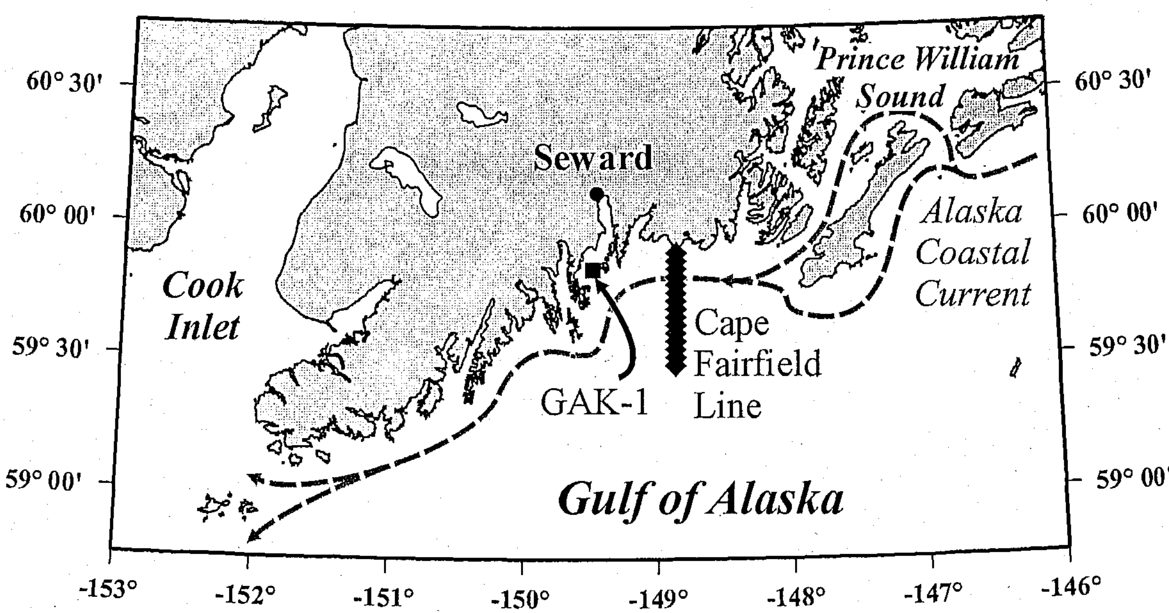

Figure 1. Location map for hydrographic station GAK 1 in the northern Gulf of Alaska.

Objectives

As stated in the original proposal our general objectives are to:

I. Quantify the thermohaline variability on time scales from the tidal to the interdecadal,

II. Interpret existing data so that a better understanding of climate forcing and its effects on this marine ecosystem can be construed,
III. Guide the development of a cost-effective long-term monitoring program, and
IV. Provide information useful for designing process studies necessary to develop ecosystem models for this shelf.

Long-term data sets coupled with retrospective analyses are required to address these issues. We have also formulated several project-specific objectives to guide progress toward these generic objectives. Specifically we will:

1. Determine the within-month variance of temperature and salinity at a given depth. This information has been lacking for GAK 1 so it is difficult to determine the significance of a single monthly measurement (as determined from the CTD data) relative to the variability observed within a given month. These basic statistics can be used to estimate the statistical significance of temperature or salinity anomalies observed in the past.
2. Determine the rate of change of water mass properties (temperature and salinity) and the phasing of these changes at different depths. Some of these features might be temporally aliased by the monthly sampling. They need to be resolved to understand the dominant oceanic time scales and the relationship between low-frequency variations (monthly and longer) and shorter period fluctuations (synoptic scale events).
3. Construct statistical relationships between ACC freshwater content and mass and freshwater transport variations based on GAK 1 data and/or other environmental indices.
4. Determine if there is a significant relationship between atmospheric sea level pressure gradients and Gulf of Alaska freshwater discharge.
5. Relate Seward sea level variations to temperature and salinity variability.

Prior annual reports have addressed various aspects of these objectives (*Weingartner,* 1999, 2000, 2001). This annual report describes some preliminary results based on the GAK 1 mooring for the past year. These data were collected at 15-minute intervals beginning at 2130, 3 December 2000 through 2030, 1 March 2002. A more detailed exposition of this program and our results are being prepared for a peer-reviewed publication and so will not be presented here. Instead, we briefly report on the past year's activities and results.

Methods

We collected monthly conductivity-temperature-depth (CTD) data nearly monthly from either the Institute of Marine Science's 25' *Little Dipper* or the *R/V Alpha Helix*. The CTD sensors are calibrated annually by the manufacturer (e.g., Seabird of Bellevue, Washington). Salinities have an accuracy of ~0.01 psu or better and temperatures are accurate to ~0.005°C or better.

The monthly sampling was complemented with quarter-hourly measurements from six temperature/conductivity recorders (Seabird MicroCats; SBE model 37-SM) incorporated in a taut wire, subsurface mooring at GAK1, located at 59° 51.131'N, 149° 29.923'W in 262 m water depth. Instruments were deployed at depths of 30, 60, 100, 150, 200, and 250 m. The mooring was designed to minimize instrument diving when subjected to strong currents. Diving was monitored with a pressure sensor incorporated on the instrument at 30 m depth. The pressure record indicates that the pressure variations were typically ~2 db (or about 2 m) and associated with the principal lunar, semi-diurnal (M_2) tide. However because tidal velocities here are relatively weak (~ 10 cm s^{-1}), the pressure variations are believed to reflect M_2 tidal changes in sea level rather than mooring diving. Current-induced diving appears to have been no greater than about 1 m throughout the record. Biofouling was heavy on the pressure cases of the shallowest (30 m depth) and deepest (~250m depth) instruments although the conductivity cells were clean. Biofouling on the instruments at intermediate depths was negligible. All instruments are currently being calibrated at Seabird and therefore the reported values are tentative. However, overall instrument performance appears to have been excellent and based on past experience we expect that pre- and post-calibration differences will be less than 0.03 psu for salinity and 0.01 for temperature.

Results and Discussion

The following three subsections tie directly to the first two general objectives listed in the "Objectives" section.

Record Length Statistics

We begin with a description of the record length statistics for salinity and temperature summarized in **Table 1** and **Table 2**, respectively. The minimum mean salinity occurs at 30 m depth and the maximum mean salinity occurs at 250 m. The standard deviation, s, is greatest at 30 m ($s = 0.69$ psu) and relatively constant ($s = 0.30$ psu) throughout the rest of the water column. The mean temperature is greatest at 30 m depth and least at 250 m. However, on average the mean temperature difference is small and only differs by ~1°C over the water column. Temperature variance is greatest at the surface and least at the bottom.

At all depths and for both temperature and salinity, the integral time scales are about one month for salinity (43 days at 150 m and 31 days at 50 m) and temperature (28 days at 150 m and 47 days at 30 m). These long integral time scales suggest that the monthly CTD sampling, which constitutes the bulk of the historical salinity data from station GAK 1, are not seriously aliased and therefore captured many (but not all) aspects of the annual cycle. Note that the integral time scales for temperature and salinity differ considerably from the integral time scales for the alongshore flow within the Alaska Coastal Current. *Stabeno et al.* (1995) estimates this to be about 5 – 10 days, which is similar to the integral time scale for the alongshore winds. The wind time scale reflects the influence of storm winds, at periods of several days, on accelerating and decelerating the shelf circulation. The longer time scales for temperature and salinity reflect forcing by the large seasonal changes in solar radiation, freshwater runoff, and wind stress. The winds work to redistribute heat and salt throughout the water column by vertical mixing and/or downwelling, both of which occur relatively slowly. They also force the alongshore circulation, which can modify temperature and salinity properties through advection. Finally, the long integral time scales imply that temperature and salinity are spatially coherent over a vast alongshore extent.

The alongshore coherence is a consequence of several factors. First, the wind field around the gulf is spatially coherent [*Livingstone and Royer*, 1980] because the scales of the storm systems that enter the gulf are comparable to the size of the basin. These same systems affect vertical mixing, precipitation and the radiation balance (primarily through cloud cover). Second, the distributed nature of the runoff entering along the coastal margin of the gulf suggests that buoyant forcing is approximately uniform along the length of the coast. The long integral time scales for

Table 1. Record length statistics for salinity (psu). The integral time scale (τ) and the effective number of degrees of freedom (N_{eff}) are determined from the autocorrelation function with the maximum number of lags being 15% of the record. All values in Tables 1-4 are based upon pre-calibration values, pressure indicated is the nominal instrument pressure.

Pressure (dbar)	Mean (psu)	s (psu)	s^2 $(psu)^2$	Max (psu)	Min (psu)	τ (days)	N_{eff}
30	30.72	0.69	0.47	31.60	27.63	32.45	14.59
60	31.29	0.32	0.10	32.00	29.91	30.85	15.31
100	31.74	0.29	0.08	32.34	30.82	39.63	11.92
150	32.16	0.32	0.10	32.77	31.36	43.20	10.93
200	32.57	0.35	0.13	33.07	31.75	40.29	11.75
250	32.80	0.32	0.10	33.22	31.88	35.33	13.37

Table 2. Record length for temperature (°C). The integral time scale (τ) and the effective number of degrees of freedom (N_{eff}) are determined from the autocorrelation function with the maximum number of lags being 15% of the record.

Pressure (dbar)	Mean (°C)	s (°C)	s^2 $(°C)^2$	Max (°C)	Min (°C)	τ (days)	N_{eff}
30	6.80	2.40	5.74	12.60	3.39	47.32	10.00
60	6.57	1.87	3.48	11.75	3.46	41.35	11.42
100	6.44	1.27	1.61	10.26	3.51	33.62	14.05
150	6.21	0.76	0.58	8.36	4.33	27.56	17.14
200	6.03	0.41	0.17	7.32	4.90	32.92	14.38
250	5.98	0.29	0.08	6.82	5.34	32.65	14.47

temperature and salinity in conjunction with the swift, extensive, and persistent nature of the Alaska Coastal Current imply that thermohaline variations along the Gulf of Alaska coast can be monitored efficiently with only a few coastal sites. Our results suggest that a spatial decorrelation (alongshore) length scale of about 500 km assuming a typical coastal current speed of 10 cm s^{-1} and an integral time scale of 35 days for temperature or salinity. This length scale is relevant to the Gulf Ecosystem Monitoring (GEM) program because it suggests that a few coastal stations, spaced approximately 500 km apart, will capture the major seasonal and interannual variations in temperature and salinity on the inner shelf. *Royer* (1982) estimated that approximately 60% of the freshwater discharge into the Gulf of Alaska originates in Southeast Alaska with the remainder entering the shelf between Yakutat and Prince William Sound. We suggest that an appropriate location for a temperature/salinity monitoring station similar to GAK 1 is on the inner shelf near Yakutat or in Cross Sound where waters from the inside passage of Southeast Alaska flow onto the northeast Gulf of Alaska shelf.

The Annual Cycle

We illustrate the annual salinity cycle by combining data from the mooring for the period December 1999 through March 2002 (**Figure 2**). The seasonal pattern is similar to that described by *Xiong and Royer* (1982) using monthly CTD casts collected over the first ten years of sampling at GAK 1. The annual cycle differs at each depth in terms of both the amplitude and the phasing of the minimum and maximum. Near-surface salinities increase rapidly from fall through early winter and then more gradually through spring. Salinities remain relatively constant into June and then decrease to the annual minimum in October. At 50 m depth, salinity slowly increases from a minimum in November to a maximum in July or August before rapidly declining through fall. For depths at and deeper than 100 m, salinities are a maximum in July or August, decrease into February or March before gradually beginning to increase again.

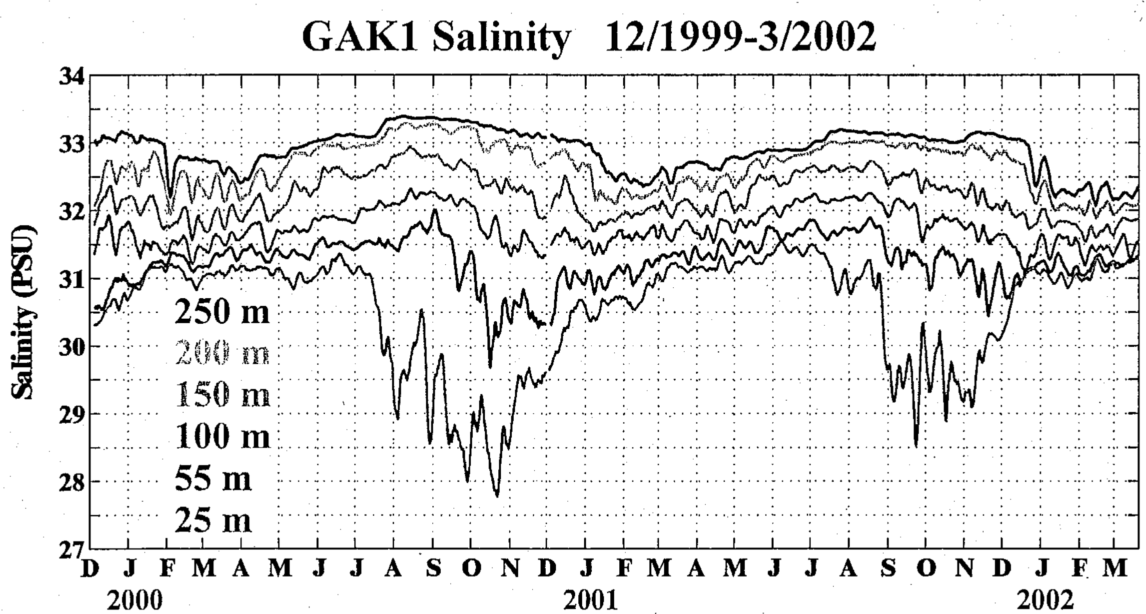

Figure 2. Time series of salinity at each depth from the GAK 1 mooring (December 2, 1999 – March 21, 2002)

Salinity differences between depths are proportional to the vertical density gradient because salinity primarily affects water density in the Gulf of Alaska. Thus, the data shown in **Figure 2** indicates that vertical stratification is a minimum in winter and early spring and a maximum in September. As seen in the salinity time series the transition to minimal vertical stratification occurs rather suddenly in each winter. (The transition is most evident in the time series at 250 m depth and occurred abruptly in February 2000, mid-January 2001, and January 2002.) During the transition, deep salinities decrease by ~0.25 – 0.75 psu over approximately a 10-day period. This seasonally important and rapid change would not be captured by the monthly CTD casts, but requires the dense temporal sampling afforded by the T/C recorders. In the wake of these transitions the water column is weakly stratified until April or May with the stratification slowly building again. The large salinity differences observed between the topmost two instruments in summer and fall suggests that our measurements are not sufficiently adequate to capture the vertical stratification in the upper ocean during this time. A better estimate of upper ocean stratification would be achieved by adding an additional instrument near the surface. We recommend that an additional instrument be incorporated in the mooring at ~15 m depth with the next shallowest instrument located at 30 m depth.

There is also a distinct seasonal cycle in the monthly variance (**Table 3**). At 25 m and 55 m depth, the monthly salinity variance is larger in summer and fall when the upper ocean stratification is strong and smaller in winter and spring when the stratification is weak. At depths greater than or

Table 3. Monthly means, standard deviations (s), maxima, and minima for salinity. Bold-faced values correspond to maximum and minimum monthly means for the period of record. Red (blue) values correspond to minimum (maximum) means and standard deviations.

	12/00	1/01	2/01	3/01	4/01	5/01	6/01	7/01	8/01	9/01	10/01	11/01	12/01	1/02	2/02	3/02
30 dbar																
Mean:	30.26	30.58	30.75	31.13	31.17	31.27	**31.43**	31.18	30.84	**29.53**	29.55	29.77	30.84	31.01	31.10	31.23
s:	0.37	0.17	0.19	0.10	0.10	0.07	0.08	0.27	0.52	0.66	0.53	0.44	0.32	0.10	0.13	0.07
Max:	30.83	30.97	31.21	31.29	31.42	31.50	31.60	31.57	31.41	30.72	30.92	30.44	31.23	31.22	31.34	31.31
Min:	29.53	30.11	30.35	30.85	30.95	31.07	31.25	30.45	29.09	27.63	28.51	28.90	30.05	30.72	30.89	31.04
60 dbar																
Mean:	**30.92**	31.00	31.13	31.34	31.38	31.53	31.68	31.71	**31.72**	31.30	31.22	31.00	31.00	31.18	31.19	31.24
s:	0.30	0.20	0.18	0.11	0.12	0.14	0.10	0.10	0.16	0.23	0.28	0.36	0.21	0.13	0.12	0.05
Max:	31.30	31.46	31.50	31.59	31.64	31.82	31.90	31.92	32.00	31.77	31.73	31.57	31.30	31.60	31.42	31.35
Min:	29.91	30.53	30.65	31.12	31.17	31.31	31.41	31.51	31.13	30.28	30.07	30.12	30.38	30.91	30.96	31.13
100 dbar																
Mean:	31.59	31.53	31.64	31.71	31.71	31.87	32.08	**32.17**	32.16	31.98	31.84	31.66	31.40	31.52	**31.39**	31.48
s:	0.14	0.17	0.15	0.15	0.15	0.11	0.10	0.06	0.09	0.22	0.12	0.16	0.22	0.15	0.12	0.15
Max:	31.85	31.83	31.90	32.06	31.99	32.10	32.25	32.34	32.30	32.24	32.11	31.91	31.75	31.71	31.62	31.78
Min:	31.29	30.93	31.21	31.28	31.37	31.60	31.84	32.03	31.84	31.44	31.34	30.82	30.91	31.14	31.10	31.23
150 dbar																
Mean:	32.18	31.83	31.98	32.07	32.08	32.30	32.50	32.62	**32.63**	32.48	32.33	32.17	31.92	31.84	**31.67**	31.84
s:	0.22	0.10	0.08	0.12	0.17	0.22	0.10	0.04	0.09	0.13	0.10	0.17	0.16	0.10	0.12	0.07
Max:	32.59	32.03	32.15	32.28	32.36	32.60	32.68	32.71	32.77	32.72	32.62	32.61	32.31	32.13	31.88	31.95
Min:	31.76	31.56	31.79	31.76	31.78	31.89	32.28	32.52	32.34	32.12	32.10	31.86	31.53	31.59	31.36	31.69
200 dbar																
Mean:	32.77	32.29	32.24	32.38	32.41	32.62	32.79	32.96	**33.02**	32.96	32.88	32.88	32.57	32.13	**32.02**	32.06
s:	0.12	0.22	0.07	0.12	0.12	0.15	0.05	0.06	0.03	0.06	0.06	0.11	0.28	0.16	0.12	0.06
Max:	32.96	32.80	32.42	32.58	32.57	32.82	32.85	33.05	33.06	33.07	33.00	33.05	32.93	32.51	32.31	32.15
Min:	32.33	31.85	32.11	32.02	32.04	32.29	32.67	32.82	32.91	32.78	32.74	32.50	31.96	31.88	31.75	31.89
250 dbar																
Mean:	33.04	32.69	32.44	32.61	32.69	32.83	32.90	33.11	**33.15**	33.11	33.03	33.13	32.90	32.37	32.29	**32.23**
s:	0.04	0.20	0.07	0.12	0.08	0.05	0.02	0.08	0.02	0.03	0.03	0.04	0.27	0.21	0.14	0.07
Max:	33.17	33.03	32.58	32.75	32.82	32.92	32.98	33.22	33.19	33.16	33.09	33.18	33.11	32.84	32.52	32.37
Min	32.92	32.33	32.28	32.18	32.46	32.71	32.85	32.96	33.09	33.03	32.97	33.02	32.19	32.08	31.88	32.10

equal to 150 meters, the variability is largest in the winter months and smallest in the summer months. The increased variability in winter at depth is presumably a reflection of increased mixing.

The seasonal variability is largely described by the first fivr harmonics fit to the 25 months of salinity data. The computed amplitudes and phases are plotted in **Figure 3** as a function of time and depth.

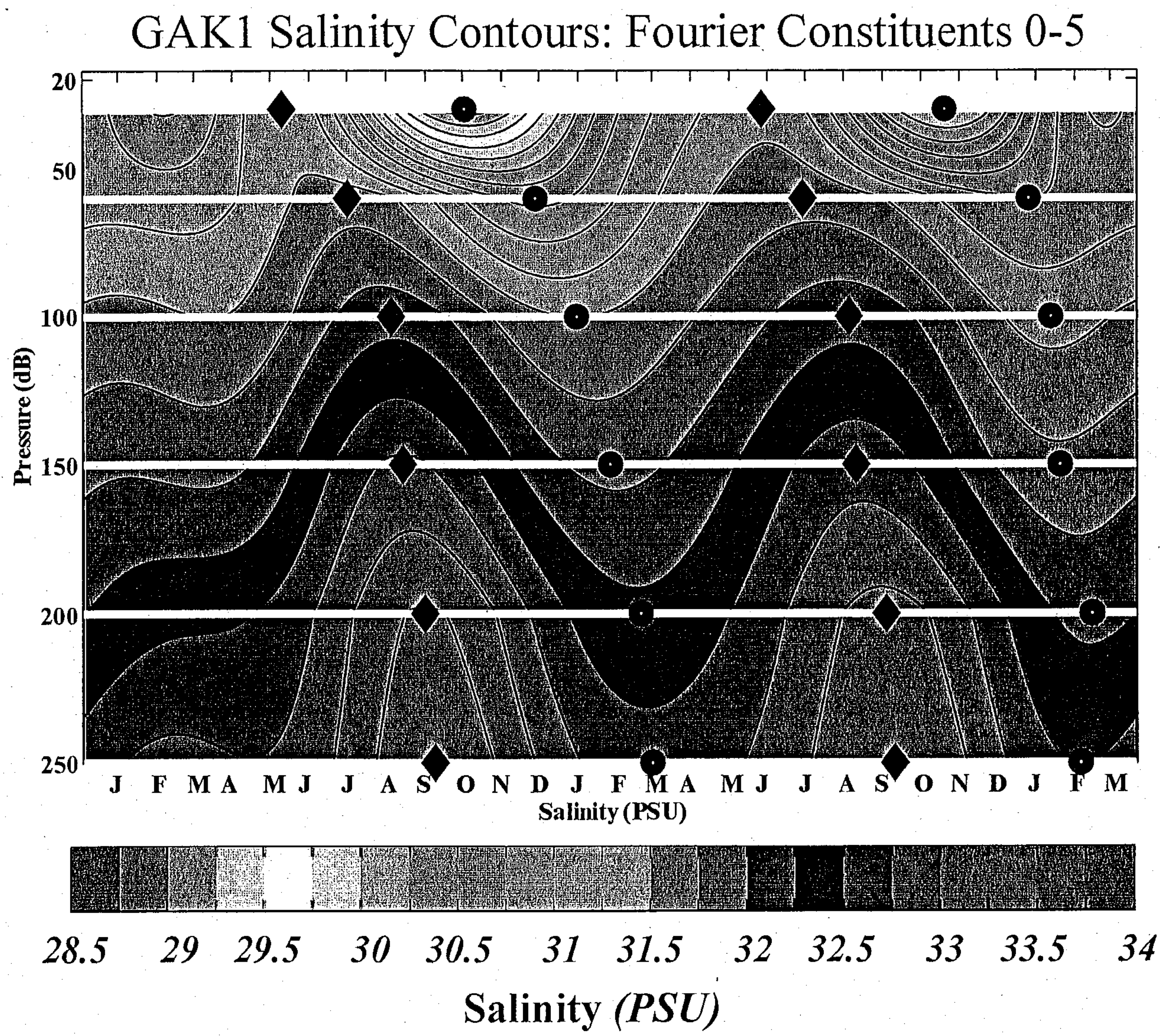

Figure 3. Salinity amplitude computed from a harmonic fit to the annual, semi-annual, and quarter-annual periods contoured as a function of time and depth for both years. Phase information is reflected by the solid diamonds that show the time of maximum salinity at a given depth and the solid circles that show the time of minimum salinity.

The phase is indicated by diamonds that correspond to the maximum salinity at a given and the circles correspond to the time of the minimum salinity. The phase information shows that the annual salinity cycles are *nearly* out-of-phase between the surface and deeper layers. The amplitudes are minimal (~0.8 psu) at 55 and 100 m depth and the phase differs above and below this depth interval. For example, for depths greater than or equal to 100 m minimum salinities occur in winter and maximum salinities in summer, e.g., ~6 months apart. This suggests that forcing at the annual period largely governs salinity changes below about 100 m (with the exception of the rapid transitions discussed above). Above 100 m, the minimum and maximum salinities occur within a few months of each other indicating a more complex set of forcing mechanisms at the surface. The differences in phase between the shallowest and deepest sections of the water column reflect the influence of different physics in controlling the seasonal evolution of salinity on the Gulf of Alaska shelf. At the surface, salinity variations are primarily influenced by the annual cycle in coastal freshwater discharge and wind mixing. Discharge is a maximum in fall and a minimum in winter, while winds reach maximum strength in winter. Near surface salinity increases through winter and early spring as deep, saline water is mixed upward. Surface freshening commences in summer as winds diminish and runoff increases. Seasonal variations in deep salinity are largely influenced by the annual cycle in the alongshore winds. Maximum salinities occur in summer when downwelling winds are weaker and upwelling-favorable winds occur more frequently. These result in salty, nutrient-rich water migrating onto the inner shelf from the shelfbreak. In winter, the deeper layers freshen because of strong vertical wind mixing and increased coastal downwelling. Both effects mix fresh water downward (and saltier, nutrient-rich water upward).

The deep mixing represents a potentially important mechanism by which the nutrient-rich deep water that is advected onto the shelf in summer is carried into the surface layers in time for the spring bloom. The bloom appears to occur in April or May on the Gulf of Alaska shelf [*Whitledge*, pers. comm., 2001]. If this is so, then vernal nutrient levels might result from a two-stage pre-conditioning process occurring over the several months prior to the spring bloom. The first stage occurs in summer and is related to the onshelf movement of saline, nutrient-rich, bottom water. The arrival of this water is evident in the salinity time series at 250 and 200 m depth. Salinity increases at first rapidly in mid-April, more gradually through July, and very abruptly again in late July. The source of this water is along the continental slope (which lies about 150 km south of GAK 1). The temperature/salinity properties of this deep water are identical to the properties of the halocline of the Gulf of Alaska. Hence, the inner shelf communicates directly with the deep basin through this annual deep-water renewal. Presumably, the quantity of nutrients (and salt) carried onshore depends upon the summer wind field and the properties of the slope source water that contributes to this inflow. The second step occurs in fall and winter and depends on turbulence. Current instabilities, downwelling-induced convection, and diffusion accomplish the vertical mixing. However, the extent of this mixing depends upon the seasonally varying stratification and the vertical and horizontal velocity structure of the ACC. Each of these mechanisms probably varies from year-to-year suggesting that spring nutrient concentrations will do so as well.

The annual temperature cycle is shown in **Figure 4** using the mooring data for both years. Similar to salinity, the annual temperature cycle differs at each depth both in terms of the amplitude and the phasing of the minimum and maximum. The maximum temperature range is ~8°C at the uppermost instrument and the minimum temperature range is <1°C at 250 m depth. Above 60 m depth, temperatures decrease from December, reach minima in February (25 m) or March (55 m), and maxima in August (25 m) or September (55 m). At deeper depths, the annual minima are attained in March or April and the maxima between November and February.

The within month variability (as given by the standard deviations) also differs among the measured depths (**Table 4**). At 30 m depth, the variability is a maximum in June, coincident with maximum stratification and when surface temperatures are rapidly increasing. At the other depths the maximum monthly variability occurs in late fall and or early winter. As discussed below these are times when the deeper portions of the water column are warming or cooling due to the seasonal propagation of these signals through the water column.

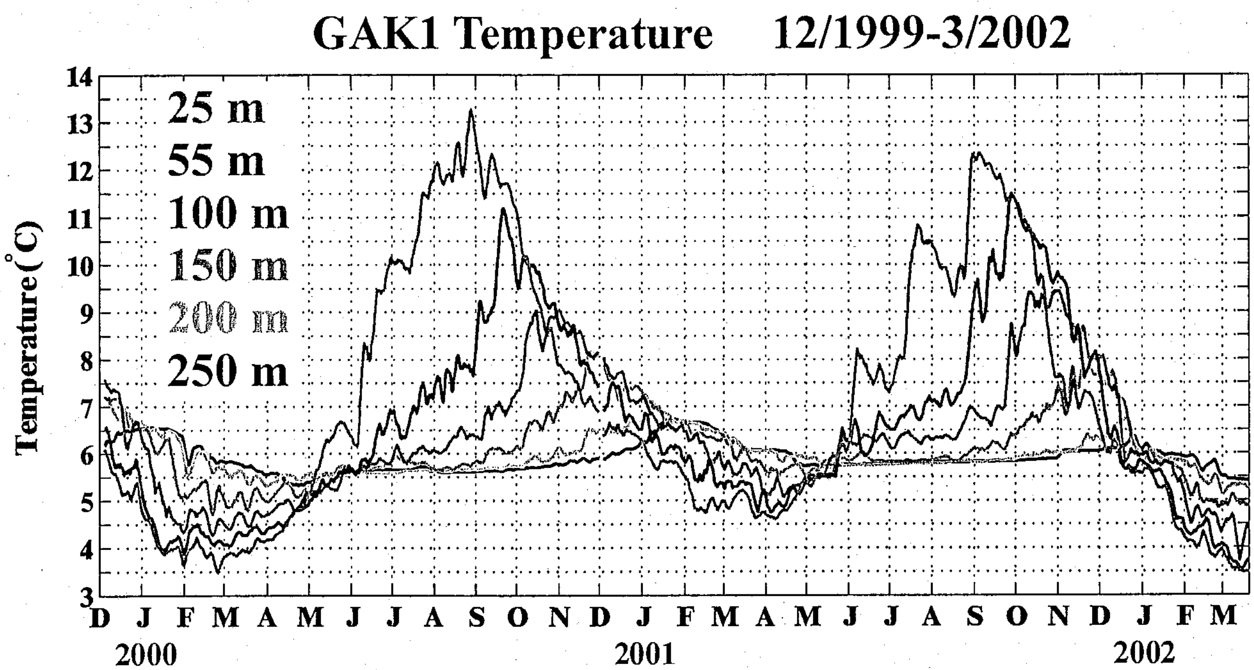

Figure 4. Time series of temperature at each depth from the GAK 1 mooring (December 2, 1999 – March 21, 2002).

The seasonal variability in temperature based the first five harmonics fit to the two years of data is shown in **Figure 5**. The phase information shows that the annual period dominates at the surface (the minimum and maximum temperatures are separated by 6 months) consistent with warming and cooling by radiation and heat exchange between the ocean and atmosphere. The phase patterns suggest downward propagation of the heating (and cooling) cycle consistent with vertical mixing. The downward flux of heat from the surface occurs over a four-month period between September and January. However, the downward propagation of the cooling signal occurs over a two-month period between February and April. Both the heating and cooling signals originate at the surface and their propagation times depend upon water column mixing rates. The wind velocity and the stratification govern these rates. Because winds are strongest and stratification weakest in winter, the cooling signal propagates with depth more rapidly in winter than does the warming signal in fall.

Table 4. Monthly means, standard deviations (s), maxima, and minima for temperature. Bold-faced values correspond to maximum and minimum monthly means for the period of record. Red (blue) values correspond to minimum (maximum) monthly means and standard deviations.

	12/00	1/01	2/01	3/01	4/01	5/01	6/01	7/01	8/01	9/01	10/01	11/01	12/01	1/02	2/02	3/02
30 dbar																
Mean:	6.46	5.82	4.97	4.93	4.90	5.73	7.60	9.31	10.18	**11.87**	9.79	7.22	5.88	5.10	4.03	**3.59**
s:	0.19	0.21	0.28	0.22	0.29	0.34	0.56	1.36	0.90	0.36	1.25	0.42	0.34	0.49	0.19	0.15
Max:	6.98	6.34	5.77	5.27	5.63	6.66	8.42	11.37	12.46	12.60	11.42	8.13	6.70	5.76	4.40	3.99
Min:	5.96	5.29	4.49	4.51	4.47	4.87	5.94	7.13	8.98	11.07	7.36	6.35	5.37	4.26	3.66	3.39
60 dbar																
Mean:	6.99	6.25	5.58	5.25	5.03	5.70	6.41	6.81	7.45	10.01	**10.47**	8.59	6.17	5.30	4.29	**3.74**
s:	0.42	0.37	0.36	0.27	0.22	0.40	0.39	0.28	0.65	1.05	0.54	0.80	0.61	0.46	0.23	0.20
Max:	8.10	7.30	6.46	6.04	5.45	6.78	7.35	7.74	9.47	11.75	11.47	10.07	8.01	5.88	4.81	4.19
Min:	6.38	5.73	4.92	4.65	4.62	5.31	5.69	6.31	6.67	7.52	9.34	7.19	5.39	4.32	3.82	3.46
100 dbar																
Mean:	7.49	6.70	6.12	5.59	5.27	5.72	6.29	6.29	6.48	7.16	**9.04**	8.57	6.77	5.71	4.68	**4.35**
s:	0.35	0.28	0.33	0.28	0.18	0.35	0.12	0.15	0.26	0.75	0.62	0.53	0.88	0.26	0.25	0.39
Max:	8.38	7.43	6.86	6.40	5.76	6.48	6.65	6.60	7.22	9.11	10.26	9.70	8.22	6.23	5.20	4.90
Min:	6.79	6.21	5.28	4.97	4.86	5.41	6.07	6.01	6.14	6.40	7.48	7.86	5.60	4.86	4.13	3.51
150 dbar																
Mean:	7.44	6.84	6.39	5.98	5.65	5.77	5.88	5.84	5.91	6.18	6.79	**7.52**	6.99	5.81	5.06	**4.96**
s:	0.24	0.29	0.14	0.24	0.14	0.13	0.07	0.02	0.08	0.16	0.34	0.45	0.68	0.15	0.27	0.19
Max:	8.06	7.42	6.79	6.48	6.03	6.04	6.09	5.89	6.15	6.68	7.74	8.36	8.10	6.25	5.71	5.28
Min:	6.95	6.39	6.13	5.49	5.35	5.47	5.77	5.79	5.78	5.91	6.04	6.44	5.70	5.51	4.33	4.48
200 dbar																
Mean:	6.54	**6.81**	6.56	6.17	5.94	5.78	5.75	5.78	5.82	5.84	5.97	6.16	6.43	5.91	5.52	**5.27**
s:	0.16	0.17	0.11	0.15	0.10	0.09	0.01	0.02	0.02	0.03	0.07	0.20	0.29	0.09	0.22	0.11
Max:	7.24	7.32	6.70	6.52	6.11	5.96	5.80	5.80	5.85	5.94	6.11	6.98	7.12	6.16	5.89	5.45
Min:	6.27	6.53	6.31	6.01	5.58	5.66	5.72	5.75	5.78	5.79	5.85	5.93	5.80	5.67	4.90	4.94
250 dbar																
Mean:	6.04	6.55	**6.59**	6.14	5.95	5.73	5.76	5.80	5.81	5.82	5.86	6.03	6.14	6.01	5.77	**5.45**
s:	0.10	0.19	0.08	0.10	0.14	0.02	0.01	0.01	0.01	0.01	0.02	0.04	0.12	0.09	0.15	0.06
Max:	6.27	6.82	6.69	6.41	6.07	5.80	5.78	5.82	5.84	5.84	5.91	6.06	6.53	6.22	5.97	5.61
Min:	5.83	6.17	6.33	6.05	5.67	5.69	5.74	5.77	5.80	5.82	5.83	5.88	5.91	5.90	5.38	5.34

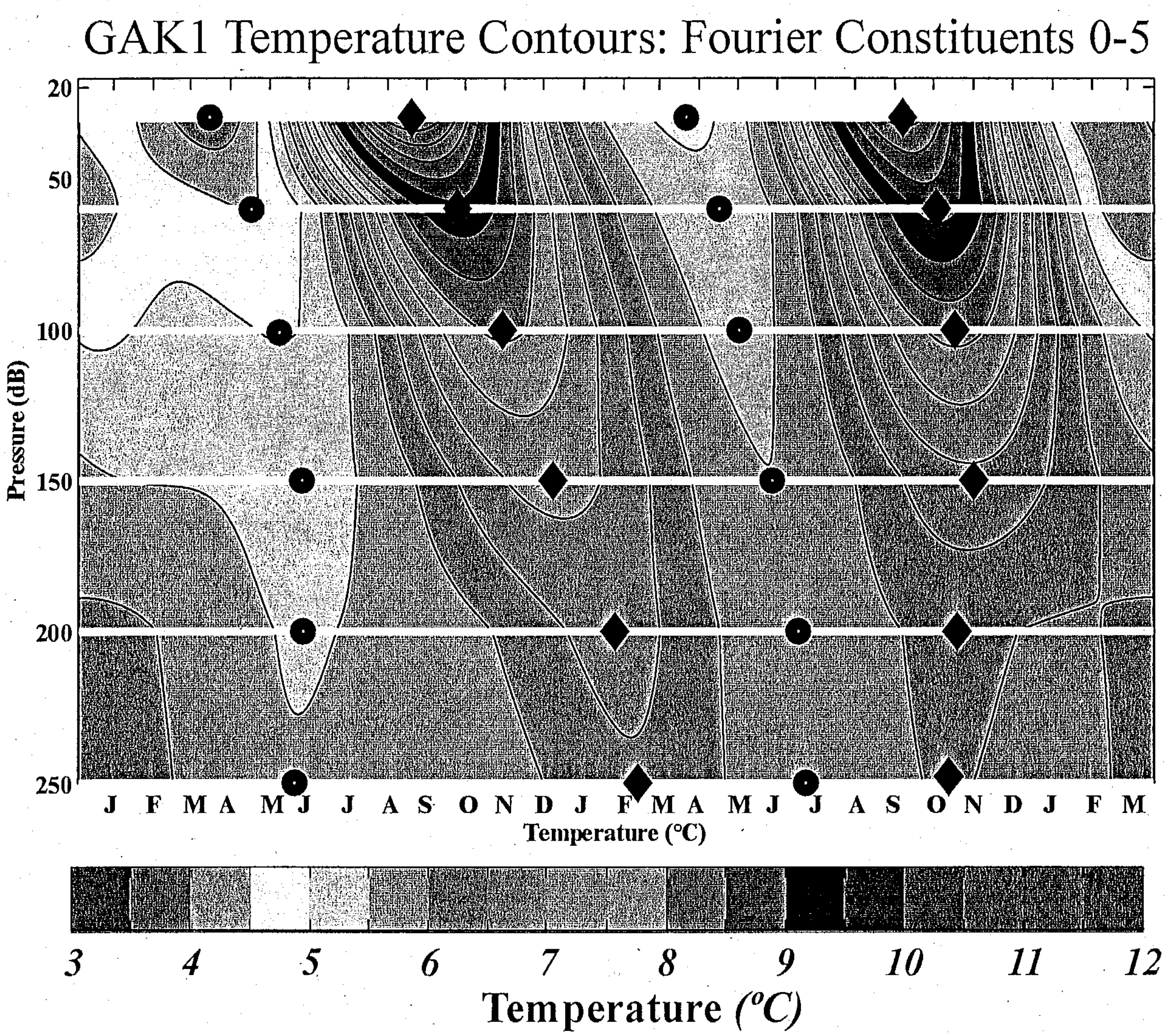

Figure 5. Temperature amplitude computed from a harmonic fit to the annual, semi-annual, and quarter-annual periods contoured as a function of time and depth for both years. Phase information is reflected by the solid diamonds that show the time of maximum temperature at a given depth and the solid circles that show the time of minimum temperature.

Towards Predictability

While the GAK 1 time series provide useful information on temperature and salinity variations on the inner Gulf of Alaska shelf, we are attempting to expand the utility of these measurements by predicting transport variability in the Alaska Coastal Current. We have done this by combing the GAK 1 CTD casts with measures of the baroclinic mass and freshwater transports across the Cape Fairfield Line (**Figure 1**). The Cape Fairfield data set consists of 75 occupations of this line many of which were obtained in the 1980s and the remainder collected more recently as part of the GLOBEC program. We have combined all the transects and computed an annual cycle climatology and monthly anomalies of ACC: 1) fresh water content (FWC), 2) baroclinic transport

(BCT), and 3) fresh water transport (FWT). In order to predict these anomalies, we constructed a multiple linear regression using GAK1 vertical profiles and other monthly environmental time series as the independent variables. We have generated two regressions; one based on the GAK 1 data and the environmental indices as the independent variables and another based using only the environmental indices. By not using GAK 1 data we hoped to develop a statistical model that would hindcast these anomalies back to 1948.

Table 5 Monthly data sets, abbreviation used in text, starting date, data source, and URL of the time series used in the regression models described in the text.

DATA SET	ID	START YEAR	SOURCE	DATA SET URL
GAK1 Vertical Profiles	GAK1	1970	UAF/IMS	http://www.ims.uaf.edu/gak1/
Seward Sea Level	SSL	1964	GLOSS	http://www.pol.ac.uk/psmsl/psmsl_individual_stations.html
Middleton Island Winds	MI	1978	UAF/IMS	http://137.229.40.69/stations/703430.html
Fresh Water Discharge	FWD	1931	UAF/IMS	http://www.ims.uaf.edu/gak1/
Sea Level Pressure	SLP	1948	CDC	http://www.cdc.noaa.gov/cdc/data.nmc.reanalysis.html
Net Shortave Radiation	SWR	1948	CDC	http://www.cdc.noaa.gov/cdc/data.nmc.reanalysis.html
Net Longwave Radiation	LWR	1948	CDC	http://www.cdc.noaa.gov/cdc/data.nmc.reanalysis.html
North Pacific Index	NPI	1899	NCAR	http://www.cgd.ucar.edu/~jhurrell/np.html
Southern Oscillation Index	SOI	1882	CPC	http://www.cpc.ncep.noaa.gov/data/indices/index.html
Northern Oscillation Index	NOI	1948	PFEL	http://www.pfeg.noaa.gov/products/PFEL/modeled/indices/NOIx/noix_download.html
Pacific Decadal Oscillation	PDO	1900	JISAO	http://tao.atmos.washington.edu/data_sets/pdo/

To create the regression, we assembled the monthly mean anomalies of the time series listed in **Table 5**. (The table also contains the Internet sites from which we obtained these time series.) The time series selected include local, regional, and large-scale Pacific climate indices. The local measurements are GAK 1, Seward sea level (SSL), and Middleton Island winds (MI). Middleton Island is a small island located on the shelf about 100 km south of Prince William Sound. The island is small and has little relief so that it should represent the outer shelf wind field. The regional Gulf of Alaska indices are Royer's freshwater discharge (FWD) and Gulf of Alaska sea level pressure (SLP), short-wave radiation (SWR), long-wave radiation (LWR) averaged over the area within 50°N to 60°N and 160°W to 130°W (but excluding points over land) and the North Pacific Index (NPI). The large-scale variables are the Southern Oscillation Index (SOI), Northern Oscillation Index (NOI) and the Pacific Decadal Oscillation (PDO). Two other time series that were considered but did not show up as significant in the analysis are the Upwelling Indices from around the gulf and the Arctic Oscillation Index. The GAK 1 variables used are temperature, salinity, and dynamic height at the standard oceanographic depths: 0m, 10m, 20m, 30m, 50m, 75m, 100m, 150m, 200m and 250m. Months with multiple occupations of the Cape Fairfield line or GAK1 CTD casts have been averaged together to form mean monthly values. All time series have had the annual cycle removed by subtracting the monthly mean and then were normalized to have unit standard deviation and mean zero. We expected that different dynamics are operating in different seasons so we constructed a separate regression model for each of the following periods: March-May, June-August, September-October, and November-December, with between 7 and 17 Cape Fairfield transects available for each time period. (February and January are not included as there was only one Cape Fairfield transect occupied during these months.)

The number of independent variables is large and many are highly correlated with one another. In order to make the problem more tractable, we reduced the number of independent variables accordingly. First, we computed the correlation between our independent anomaly time series with the FWC, FWT, and BCT (dependent) anomaly time series. Independent time series that were not significantly correlated with the dependent variables were discarded. Second, we computed the principal components (PC) of the remaining time series. These are orthogonal to one another, thus each PC can be considered a new, independent variable. In order to gain insight on the physical connections between the PCs used in the regression model and the dependent variable, we correlated each independent variable with the PC time series to determine which independent variable was contributing to a particular PC.

The regression result for FWT is shown in **Figure 6** (the results for BCT and FWC are similar). The model accounts for ~74% of the variance in the FWT anomaly. The mean of the residuals (unexplained by the model) is 3400 m^3-s^{-1}. This amounts to ~10% of the mean monthly FWT in the ACC (~30000 m^3-s^{-1}). The magnitude of the mean residual is 47% of the mean magnitude of the FWT anomalies. Future error analyses will include comparing the error in predictions of the FWT, BCT, and FWC from the ACC based on data gathered during the 2001 GLOBEC field season. We will make predictions for these months based on the regression model as it presently stands. Thus the error analysis will be made on observations that have not been included in the construction of the model. A more complete description of these results will be provided in our paper. By excluding the GAK1 time series from the model we can extend model hindcasts to 1948. Although our results are statistically significant the uncertainty associated with a specific hindcast event is nearly twice as large as that based on predictions that include the GAK 1 data. While the uncertainty in a hindcast is considerably larger in this case, we do have the ability to hindcast these important variables in a statistically meaningful sense. The hindcast results could prove valuable in retrospective studies of ecosystem variability on this shelf. Moreover, the difference in models clearly underscores the value of the GAK 1 data in monitoring this ecosystem.

Royer's discharge time series extends from 1930 through the present. This is barely long enough to assess interdecadal scale variability in the gulf. We have explored the possibility of extending this data set to the beginning of the 20th century by correlating Royer's Gulf of Alaska discharge time series with the Trenberth's Northern Hemisphere sea-level pressure (1899-2002) data set (*Trenberth and Paolino*, 1980). We evaluated pairs of points around the Gulf of Alaska and computed correlations of sea level pressure difference to the FWD time series (both monthly anomalies). We chose sea level pressure difference (rather than pressure itself) because the pressure difference can be related to geostrophic wind vector. We hypothesized that pressure differences that corresponded to southerly airflow should correlate with anomalously high runoff. Because our focus is on low-frequency variations and because both time series are noisy we lowpass filtered the data with a 36-month second order Butterworth filter. We computed correlations between all points

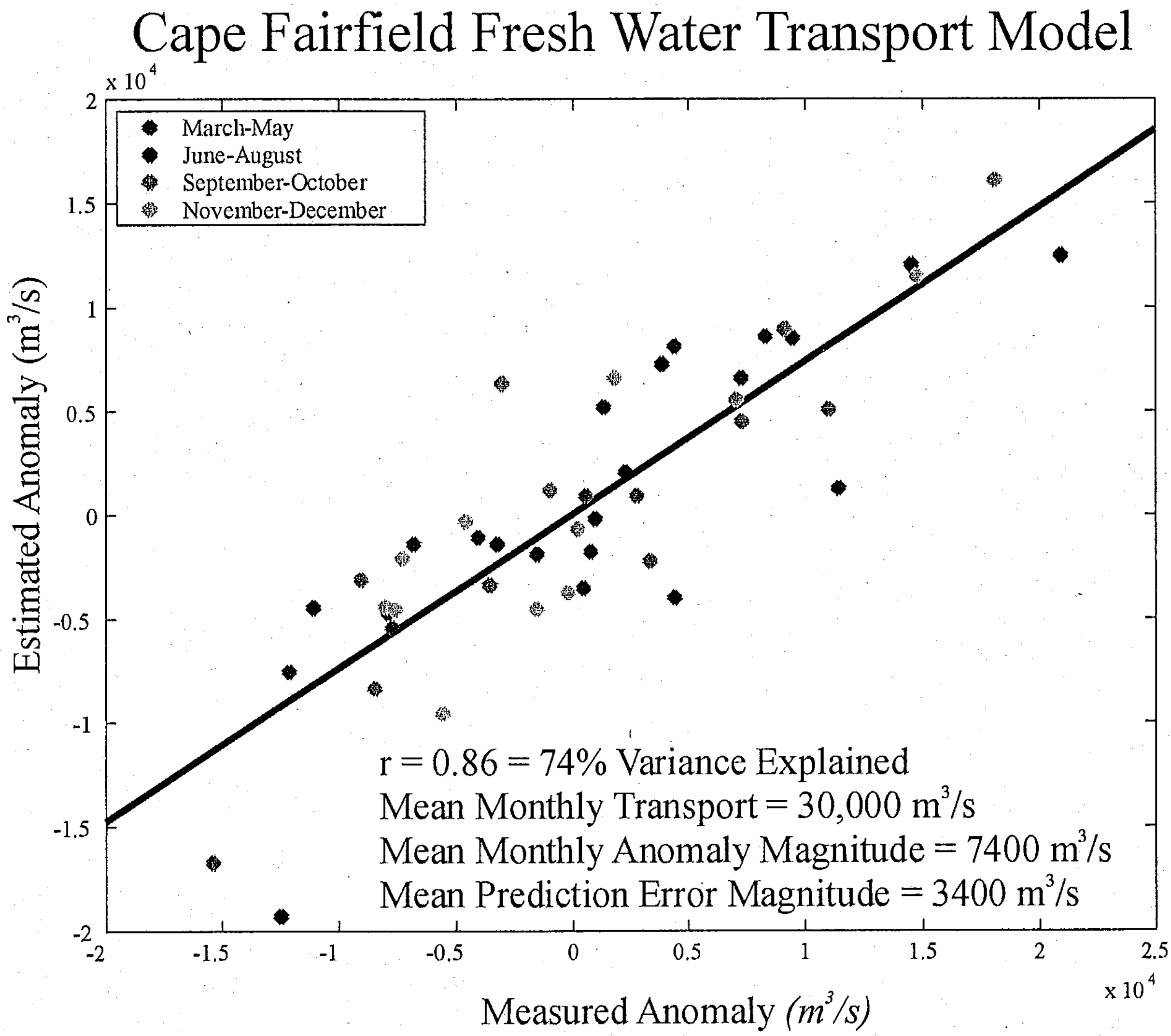

Figure 6. Regression between the predicted freshwater transport anomaly within the ACC along Cape Fairfield and the observed anomaly.

within our grid and found the highest correlation (r = +0.70, significant at the 99% level) between the two grid points nearest to Ketchikan (55 N, 130 W) and Seward (60 N, 150 W). If the difference in sea level pressure between Ketchikan and Seward is positive ($\Delta SLP_{KS} > 0$) then discharge is anomalously high. Under these conditions the geostrophic winds are from the southwest and therefore should advect warm, moist air into the Gulf of Alaska. **Figure 7** provides a comparison between the smoothed anomaly time series for ΔSLP_{KS} and FWD. Spectral analyses (not shown) show that the dominant modes of variability occur at 8 and 15 years periods in the ΔSLP_{KS} record. The largest negative anomaly in ΔSLP_{KS} occurred during the first decade of the 1900s, which implies that runoff was anomalously low during these years. We also found no significant correlation between the time series of ΔSLP_{KS} and the PDO, but a significant correlation between ΔSLP_{KS} and the NPI time series (r = -0.53). However, this correlation is not consistent throughout the record because there are periods when the NPI and ΔSLP_{KS} are strongly correlated and in-phase and other periods when the relationship is out-of-phase. We will look at this more closely in the future in an effort to understand why this correlation is inconsistent.

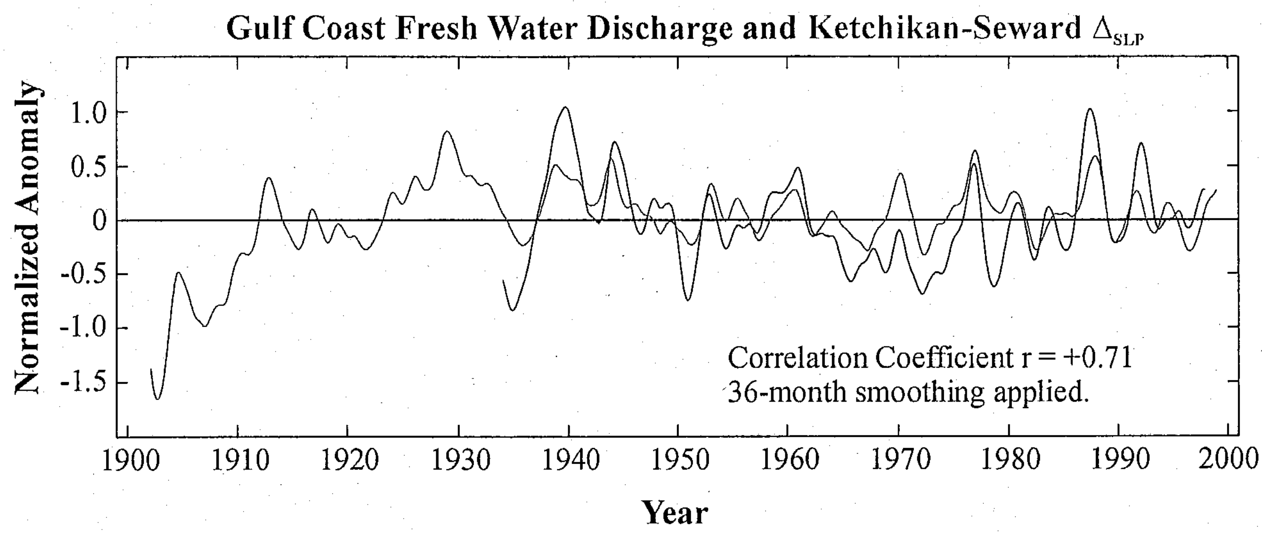

Figure 7. Time series of 36-month low pass filtered monthly freshwater discharge anomaly (blue) and the monthly anomaly in the atmospheric sea level difference between Seward and Ketchikan.

Finally, we have been working on attempts to relate Seward sea level variability with GAK 1 dynamic height and Gulf of Alaska (MI) winds. Our hope was that we might be able to use sea level variations from around the gulf as a proxy for the nearshore dynamic height (or vertically integrated salinity, which accounts for most of the dynamic height variability). We have examined the correlations for the two years of moored data from GAK 1. Our results are ambiguous for although the correlations are high among these variables, there are times when the relationship does not hold. **Figure 8** shows the time series of predicted Seward sea level predicted from a multiple linear regression between GAK 1 dynamic height and Middleton Island winds. The figure also includes the residuals (observed minus predicted response), which can have amplitudes as large as the sea level signal. The reasons for these are not known. Candidate mechanisms include remotely forced shelf waves that propagate counterclockwise around this shelf, the occasional passage of large (~150 km diameter) eddies propagating along the continental slope, and/or a basin scale barotropic response to wind stress curl variations. All of these can be assessed. For example, in the future we will examine the coherence in sea level between Yakutat and Seward to determine the possible influence of shelf waves on sea level. The coherence and phase structure of these time series should guide us on the possible role of shelf waves in sea level variability. We will also examine sea surface height anomalies determined from satellite altimetry to identify slope eddies. Work underway suggests that these occur annually and so we will require a fairly long time series of observations to establish possible relationships in a statistically meaningful way. Additional guidance on this issue could be obtained from carefully constructed numerical simulations. The large-scale barotropic response of the basin to wind forcing is beyond the scope of this program and would best be examined using numerical models.

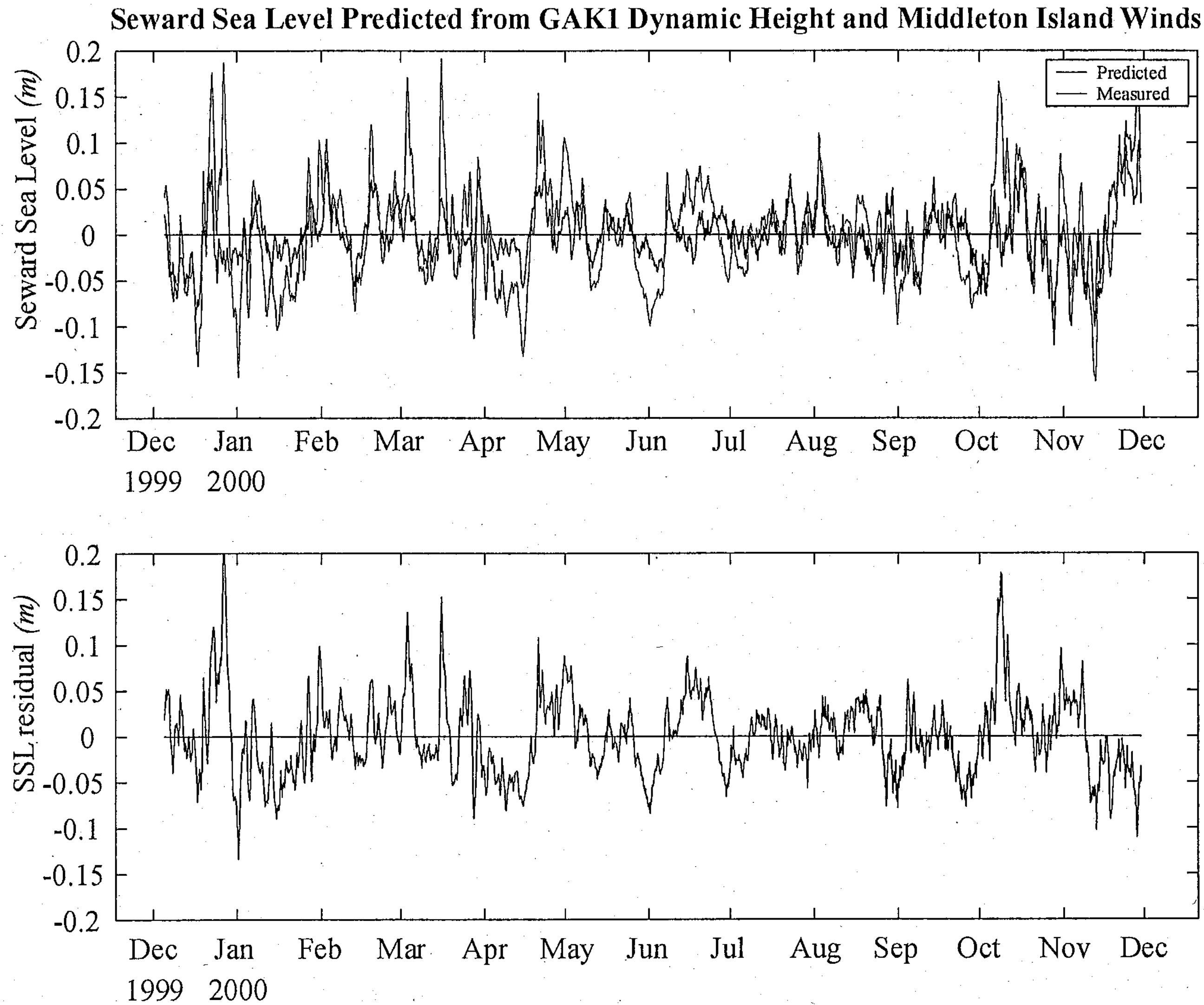

Figure 8. Time series of predicted and measured Seward sea level (upper panel) and the difference between these two series (lower panel). The prediction is based on a multiple linear regression of Seward sea level on GAK 1 dynamic height and Middleton Island winds. Teach time series was filtered with a 35-hour lowpass filter and the sea level was corrected for the inverse barometer effect.

Conclusions

We have made some significant advances this past year in our ability to predict important parameters relevant to the Gulf of Alaska ecosystem, particularly with respect to predicting anomalies in the baroclinic component of the mass and freshwater transports and the freshwater content in the ACC. These predictions have been made with and without the data from GAK 1. While predictions using the GAK 1 data are superior (less error) to those in which GAK 1 is not used, the latter afford the possibility of hindcasting the these variables back to 1948. We feel that this result further enhances the utility of the GAK 1 measurements. These measurements can be made relatively inexpensively and therefore are an ideal component to a long-term monitoring program. We have also found a significant correlation between atmospheric sea level pressure differences between Seward and Ketchikan and the Gulf of Alaska discharge record. This relationship allows us to extend (by proxy) the discharge record back to 1900. Efforts to relate temperature and salinity variability at GAK 1 to Seward sea level are compromised by unknown factors that could include remote forcing. At least two of these factors can be easily assessed with additional data (large offshore eddies and remotely forced shelf waves), whereas the local sea level response to basin-wide barotropic forcing needs to be addressed with a numerical model.

We also recommend that the GAK 1 mooring be augmented with a temperature/conductivity recorder at 15 m depth. The additional instrument would provide a better estimate of the upper ocean stratification, particularly in spring at the onset of the spring bloom. The instrument should include a fluorometer so that the timing of the spring bloom on the inner shelf can be monitored.

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Literature Cited

Mantua, N.J., S. R. Hare, Y. Zhang, J. M. Wallace, and R.C. Francis, A Pacific interdecadal climate oscillation with impacts on salmon production, *Bull. Am. Met. Soc.,* 78: 1069-1079, 1997.

Royer, T. C., High-latitude oceanic variability associated with the 18.6 year nodal tide, *J. Geophys. Res.*, **98**: 4639-4644, 1993

Royer, T. C., Coastal freshwater discharge in the Northeast Pacific, *J. Geophys. Res., 87*, 2017-2021, 1982.

Stabeno, P.J., R. K. Reed, and J. D. Schumacher, The Alaska Coastal Current: coninuity of transport and forcing, *J. Geophys. Res., 100*, 2477-2485, 1995.

Trenberth, K. E. and D.A. Paolino, Jr. 1980. The Northern Hemisphere Sea Level Pressure data set: Trends, errors, and discontinuities. *Mon. Weather Rev.* 108: 855-872.

Weingartner, T. 2001. Toward long-term oceanographic monitoring of the Gulf of Alaska ecosystem, *Exxon Valdez* Oil Spill Restoration Project Annual Report (Restoration Project 98340), Alaska Department of Fish and Game, Habitat and Restoration Division, Anchorage, Alaska.

Weingartner, T. 2000. Toward long-term oceanographic monitoring of the Gulf of Alaska ecosystem, *Exxon Valdez* Oil Spill Restoration Project Annual Report (Restoration Project 98340), Alaska Department of Fish and Game, Habitat and Restoration Division, Anchorage, Alaska.

Weingartner, T. 1999. Toward Long-Term Oceanographic Monitoring of the Gulf of Alaska Ecosystem, *Exxon Valdez* Oil Spill Restoration Project Annual Report (Restoration Project 98340) Alaska Department of Fish and Game, Habitat and Restoration Division, Anchorage, Alaska.