Exxon Valdez Oil Spill
Restoration Project Annual Report

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

Restoration Project 98340
Annual Report

This annual report has been prepared for peer review as part of the *Exxon Valdez* Oil Spill Trustee Council restoration program for the purpose of assessing project progress. Peer review comments have not been addressed in this annual report.

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Study History: EVOS funding for this project was initiated in October 1998 and continues through FY99 with this annual report being the first prepared. This work builds upon, indeed continues, measurements of temperature and salinity computed as a function of depth (CTD sampling) at a hydrographic station near Seward (GAK1) that were begun about 29 years ago. Prior to the initiation of this study sampling at GAK1 was nominally monthly and conducted opportunistically from research vessels transiting to and from Seward. Between 1990 and 1995 (DATES) NOAA funding maintained the monthly sampling on a more systematic basis. Funding from EVOS has systematized the sampling even further by supporting an instrumented mooring at GAK 1, which consists of six temperature and salinity sensors deployed at discrete depths throughout the water column. In addition, EVOS funding has maintained the monthly CTD sampling. This project complements additional ecosystem sampling being conducted on the Gulf of Alaska shelf under the auspices of the Northeast Pacific Global Ocean Ecosystem Dynamics (NEP-GLOBEC) Program. The PI is also a participant in this GLOBEC study, which is supported jointly by NOAA and NSF.

Abstract: This project is building upon a 29 years time series of temperature and salinity obtained from hydrographic station GAK 1 on the Gulf of Alaska shelf near Seward. First year results showed El Nino effects. El Nino effects were greatest in winter when temperatures were ~1-2°C above normal throughout the 250 m depth of the water column. The shelf was also fresher than normal because the vertically averaged salinity was about 0.15psu below average. Temperatures began returning to normal by May 1998 but bottom water temperatures were still about 0.5°C above normal through the fall. Upper ocean salinities have also returned toward normal however summer deep-water salinities were slightly above normal. Results from the moored instruments show that most of the variance in temperature and salinity occurs at periods > 1, consequently the integral time scales are long. These results imply that: 1) the historical record of monthly temperatures and salinities do not suffer seriously from temporal aliasing and 2) within the Alaska Coastal Current, much of the temperature and salinity variations are coherent over a broad (~500 km) alongshore region. These findings have important implications for future ocean monitoring.

Key Words: Alaska Coastal Current, Gulf of Alaska shelf, ocean ecosystem monitoring, temperature-salinity variability.

Project Data: Two types of data are available: 1) Monthly temperature and salinity profiles collected by CTD (accessible from website http://www.ims.uaf.edu:8000/gak1/gak1.dat, and 2) hourly measurements of temperature and salinity at 28, 58, 198 and 245 m depth accessible from the PI (weingart@ims.uaf.edu).

<u>**Citation**</u>**:**

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EXECUTIVE SUMMARY

This annual report summarizes the activities and analyses of the first year of this anticipated four-year project. The project goals were largely achieved although the deployment of the first year's mooring was delayed by about 2.5 months. The second year's mooring was deployed on schedule. The results presented are tentative but they reflect the activities and the planned direction of this project. The tentative findings are:

1. Mooring motion and biofouling are negligible so that temperature and conductivity measurements can be reliably made year-round from the GAK 1 mooring. The integral time scales for temperature and salinity are generally quite long (~1 month). This implies that the monthly CTD records that make up the historical GAK 1 record do not suffer severely from temporal aliasing. The results also imply that the alongshore coherence scales of temperature and salinity variability are about 500 km. Hence only 2 – 3 moorings of this type would be needed to sample adequately temperature and salinity variability around the inner shelf of the Gulf of Alaska.
2. The phasing of temperature and salinity changes over depth at GAK 1 as seen from the mooring are consistent with inferences drawn from the historical record. However, some of these changes occur quite rapidly (e.g., at time scales shorter than one month). The surface temperature increase and near-bottom salinity increase in summer are examples of these rapid changes. If these rates of change are typical then monthly sampling alone cannot adequately resolve them. The onset of these changes presumably varies from year-to-year and could have ecological importance, such as in the evolution of the surface mixed layer and the delivery of nutrient-rich deep water to the shelf.
3. The within-month variance is less than the interannual variance from winter through mid-summer and probably no greater than the interannual variance in late summer and fall. Longer time series (currently underway) will be required to statistically test this result.
4. The 0-50 db dynamic height change between April and September, 1983 tracks the 20-day low-pass filtered change in Seward sea level. The result implies that the sea level change reflects thermosteric effects. About two-thirds of this affect is due to salinity and one-third to temperature. The results imply that changes in summer sea level could be a proxy for freshening and heating rates and the change in freshwater and heat content over the summer. If, so then historical sea level records might be useful in retrospective studies of ocean climate conditions around the Gulf of Alaska.
5. The unusually high summer and fall 1997 temperatures (2-3°C above normal) were limited to the upper 60 m of the water column. The cause is likely associated with the abnormally low cloud cover, which would allow increased solar radiation to reach the sea surface over the Gulf of Alaska.
6. The winter of 1998 exhibited abnormally high temperatures (1-2°C above normal) over the *whole* water column and unusually low salinity (~0.15 psu below normal on vertical average). We suggest that both the atmosphere (with above normal air temperatures and a greater atmospheric moisture content) and ocean (advection from lower latitudes) likely contributed to these differences).

7. The 29-year long monthly CTD sampling indicates that monthly temperature and salinity anomalies are inversely correlated with one another in the upper 100m. A testable hypothesis that emerges from this result is that:

    Warm, low-salinity winters are due to an anomalously high atmosphere-ocean moisture flux and an anomalously low ocean-atmosphere heat flux. Warm, low-salinity summers are due to increased air temperatures and solar radiation and greater runoff from the quasi-permanent mountain snowpacks ringing the coast.

This project is closely connected to the ongoing GLOBEC program of which this PI is also involved. As the GLOBEC data set matures we will be better able to understand the mechanisms responsible for change at GAK 1 and the relation between the inner shelf (GAK 1) and outer shelf.

Introduction:

The Gulf of Alaska experiences large seasonal and interannual variations in meteorological and oceanographic forcing (Royer, 1996; 1993) which affects 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 EVOS investigators working in the Gulf of Alaska analyze progress in recovery and restoration progress within the context of the long-term variability of the physical environment. This monitoring project represents a step toward this capability 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**).

This annual report describes the first year's accomplishments and ongoing efforts of what is anticipated to be a four-year program. Since many of the analyses are still underway and some of the results and conclusions are tentative only. However, they are meant to offer a glimpse into the program and the direction in which we anticipate the research proceeding.

Objectives:

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

1. quantify the thermohaline variability on time scales from the tidal to the interdecadal,
2. interpret existing data so that a better understanding of climate forcing and its effects on marine ecosystems can be construed,
3. guide the development of a cost-effective long-term monitoring program, and
4. provide information useful for designing process studies necessary to develop ecosystem models for this shelf.

Our contention is that long-term data sets are required to address these issues completely. A fundamental requirement of this program is to continue the 29-year time series of temperature and salinity at hydrographic station GAK1. This was done with a combination of monthly CTD measurements and through yearlong deployments of a mooring containing temperature and conductivity (T/C) recorders. We have also formulated several project-specific objectives to guide our progress toward our generic objectives. Specifically we want to:

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 with 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. Determine how variance in temperature, salinity and dynamic height are distributed over depth and seasonally, e.g., determine if distinct vertical "modes" of variability exist and how these modes vary in time.
4. Assuming that the temperature/conductivity recorders provide a useful estimate of dynamic height, then determine the joint effects on Seward sea level of dynamic height and winds. Over what time-scales are these variables coherent with one another and with Seward sea-level?

Methods:

We collected 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 sensors on the CTDs used were calibrated annually by the manufacturer (e.g., Seabird of Bellevue, Washington). In addition, field checks were made on the conductivity sensor from bottle salinities collected during the cast. The bottle samples are analyzed on the salinometer at the Seward Marine Center. Salinities have an accuracy of ~0.01 or better and temperatures are accurate to 0.005°C or less.

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. Details on the mooring are summarized in **Table 1**. As originally planned the mooring was to be deployed in November-December 1997, but delays at the manufacturer's and weather resulted in the late March deployment. The mooring was recovered in early December 1998 and an identical one deployed at the same location. (There will be a time gap between the first and second years' data of less than 8 hours). The first years' mooring also included a prototype OSMO chemical sampler, deployed at ~30 m depth, which is owned and under development by scientists at the Monterey Bay Research Institute. The OSMO sampler was not a part of this EVOS-supported work but has potential for use in ecosystem monitoring. Results from the sampler are still being examined and are not discussed herein.

The thermistors on two of the MicroCats provided faulty data throughout the deployment period. Seabird discovered the problem during instrument post-calibration and the manufacturer has replaced these sensors. Unfortunately reliable salinity data cannot be obtained without accurate temperature data. Hence there was effectively no data obtained from the instruments at 98 and 150 m depth. The remaining sensors all performed well.

There were two concerns we had prior to the deployment of the mooring. First, biological growth, if severe, could foul the conductivity sensor and corrupt these data. To inhibit fouling we applied a biocide on the inlet ports to the conductivity cell. We found substantial growth only on the 28 m and 245 m instruments where it was confined to the outside of the instrument housing. Hence the conductivity cell was relatively clean. The absence of significant accumulated growth on a mooring deployed throughout the spring and fall blooms is encouraging because it suggests that reliable conductivity measurements can be made from moorings deployed year-round here. Second, was the potential influence of mooring motion due to high-speed currents on the data. Mooring motion causes the instruments to "dive", or to be submerged below the intended measurement depth due to strong currents. In regions of strong vertical temperature or salinity gradients the "diving" effectively contaminates the data record. To assess this problem we installed a pressure sensor on the uppermost MicroCat to monitor pressure variations throughout the deployment period. These data indicated that the mean depth of the instrument was 27 m and that it ranged between 24.6 and 30.2 m. Most of the depth changes were associated with the M_2 tide (12.42 hour period). These changes are small and suggest that mooring motion was negligible. Of course pressure variations influence the determination of salinity, however for our purposes these effects are negligible and so were not included.

Results and Discussion:

Temperature and salinity time series measured from the mooring and at each depth are shown in **Figure 2**. The data have been filtered to remove tidal fluctuations at diurnal and shorter periods. Note also that the ordinate scales change for each series in order to highlight changes at the depth of interest. There are a number of depth dependent features apparent in these time series. First, the ranges for temperature and salinity were greatest at the surface and diminish with depth. Second, timing of temperature and salinity changes varied throughout the water column. For example, temperatures increased gradually from ~5.0°C in April to ~9.0°C in mid-July, and more rapidly to ~12-13°C by late July. Surface temperatures began a steady decrease in late September and reached ~7.0°C by the end of November. Temperature trends at 58-m depth tracked those at the surface but with an approximate one-month lag. For example, maximum temperatures occurred in late August and the fall cooling began in mid-October. Deep (198 and 245-m depth) temperatures evolved quite differently from those near the surface. Temperatures decreased from April through July and thereafter slowly increased.

At 27-m depth, the salinity decreased slowly from April through July, and then more rapidly beginning in early August until it reached a minimum in late September. Thereafter salinity gradually increased. At 58-m depth, salinity was fairly constant through late August and decreased through fall. At both 27 and 58-m depth these gradual salinity variations were punctuated by 5-10 day fluctuations between August and October. These fluctuations reflect either passage of frontal systems associated with wind and/or flow instability processes within the Alaska Coastal Current, which flows through GAK 1. Instabilities represent a potentially important mechanism for the vertical flux of subsurface water into the surface layer. Because these deeper waters have higher nutrient concentrations than the surface waters, the instabilities could be important to late summer and fall biological production.

The seasonal evolution of salinity in the deep water is quite different. At 248-m depth, salinity increased rapidly by about 0.8 through April, remained constant through May, and slowly increased through June. There then was a relatively abrupt increase by about 0.5 over a 10-day period in early July to the maximum observed value of ~33.3. Thereafter salinities decreased slowly. Salinity changes at 198-m depth evolved similarly although much more gradually than those at 248-m depth.

The impression gleaned from these time series is that temperature and salinity changes in the deep water were not in-phase (and perhaps not even correlated) with those in the upper 50 m. An alternative approach to examine this is to compute the empirical orthogonal functions (EOFs) of these data. Because we are missing the mid-depth data sets we have computed the EOFs from density time series collected from a mooring, (labeled CF in **Figure 1**) ~30 km east of GAK1 between April and October 1983. (Johnson et al.; 1988) previously discussed these data although their EOFs were based on monthly values and included the forcing effects represented by time series of winds and discharge.) Here we focus only on the EOFs computed from the density data. (The mechanisms responsible for these changes are an ongoing effort of this study and will be addressed when a more complete data is available later on in the project.) The EOFs shown here were calculated from the eigenvalues and eigenfunctions of the cross-correlation matrix of density data collected at 5m, 50m, 70m, 110m, and 175m. The results are shown in **Figure 3**. Roughly 95% of the total variance can be represented by the first three modes. Mode 1, which accounts for ~60% of the total variance, primarily represents coherent fluctuations in the upper 100 m of the water column. This follows because the amplitude of the mode at 175-m depth is less than one-third that of the amplitudes at 70-m and shallower depths. Mode 2 accounts for about 20% of the total variance and represents fluctuations at the bottom. In agreement with the discussion relative to **Figure 2**, the first two modes also suggest that variability in the deep water is uncorrelated with that in the upper 50 m.

The monthly means and standard deviations for temperature and salinity for each instrument on the GAK 1 mooring are listed in **Table 2**. These variance estimates represent intramonthly variability. The variance changes seasonally and with depth; it tends to be greatest at the surface and from mid-summer through early fall. For temperature, in the upper 60 m of the water column, the maximum variance occurs in summer and the minimum variance occurs in April. For salinity, in the upper 60 m of the water column, the maximum variance occurs in early fall and the minimum variance also in May. We have also computed the integral time scale based on the autocorrelation function for each of the records. Although there is considerable variability throughout the water column with time scales ranging from 9 – 47 days, the integral time scales were typically about one month. Statistically these results imply that there are few "effective" degrees of freedom within a month, perhaps 3 at most.

The long integral time scales imply that most of the variability occurs at low frequencies. This is evident in **Figure 4**, which shows the spectra for water density in variance preserving form. At each depth most of the variance occurs at frequencies < 0.001 cph (i.e., at periods > 1 month). In fact, with the relatively short time series (7 months) available from the moored instruments we cannot resolve the low frequencies very well. However, the results show that there was little variance at 198- and 245-m depth at periods <1 month. There is some variance at higher frequencies, specifically at 5-10 day periods and at the M_2 tidal period, but the variance at these periods is roughly an order of magnitude less than the variance at low frequencies. The long integral time scales and the highly advective nature of the Gulf of Alaska shelf suggest that temperature and salinity variations at Seward are probably coherent over a broad alongshore distance. The integral time scales in conjunction with the .2 m s^{-1} speeds typical of the upper 100 m of the Alaska Coastal Current suggest an alongshore coherence scale length of about 500 km (or roughly the distance between Yakutat and Seward).

Table 3 shows the monthly means and standard deviations computed from the GAK1 monthly CTD data over the 28-year time series at approximately the same depths as the instruments listed in **Table 2**. The variances in **Table 3** are estimates of interannual variability. In general, the interannual variability exceeds the intramonthly variability. A more statistically rigorous comparison of these differences will be deferred until we have a full year's worth of data at all instrumented depths. Further, the integral time scale results suggest that this comparison will have to be done using seasonal data so that sufficient degrees of freedom are available for comparing variances with an F-test. However, an important (and comforting) preliminary result is that the intramonthly variances are less than the monthly variances computed from the archived data. This implies that interannual signals are large and not masked by within month variability. This relation particularly holds for the winter and spring months and deeper depths.

The monthly CTD data are further summarized in **Figures 5a-c**, which is essentially a climatology showing the mean monthly temperature, salinity, and density at standard depths. (Note that the temperature axis on Figure 5a is inverted to reflect that increasing temperature causes a decrease in density, which is plotted in Figure 5c. These plots are an update of those prepared by Xiong and Royer (198) and are based on the 29-year time series of GAK 1 measurements. Many of the features seen from the mooring data, especially the seasonal evolution of heating, cooling, freshening, and salinization, the depth dependent phasing of annual minima and maxima are all evident in this figure. Thus the structure of the thermohaline evolution at GAK 1, as inferred from the moored instruments was similar to the climatology portrayed in **Figures 5a-c**. The climatology suggests that the freshening observed between April and September occurs within the upper 75 m while the deep salinity increase extends from the bottom up to ~100-m depth. Because salinity is the primary determinant of density at this location, monthly changes in density track those for salinity. The out-of-phase differences in density through these months have important implications for the seasonal evolution of dynamic height. (Dynamic height is a function of vertically integrated density referenced to an arbitrary depth. It has units of energy and represents the work required to "lift" a water parcel through a vertical distance against the opposing force of gravity. A change of one dynamic centimeter [dyn. cm] is nearly identical numerically to 1 cm.) **Figure 5d** shows the mean monthly dynamic height for the 0-50 db, 0-100 db, and 100 – 200 db layers. Dynamic height increases by ~10 and ~14 dyn. cm for the 0-50 db 0-100 db layer between April and September. The 4 dyn. cm increase for the 50-100 db layer, however, is offset by the ~4 dyn. cm decrease over the 100-200 db layer during this time. Hence there is effectively no dynamic height change between the 50-200 db layer over this time period.

Changes in nearshore dynamic height are sometime reflected in sea level variations (this influence is also referred to as the thermosteric or more simply, the steric effect). On annual and shorter time scales sea level responds to tides, winds, and water density and atmospheric pressure variations. On longer time scales tectonic effects can also alter sea level. Royer (1979) first suggested that there was a relationship between dynamic height, freshwater, and sea level. We collected the Seward sea level data for 1998, with the intent of examining the relation between sea level change and the thermohaline structure at GAK 1. We intended to correct the sea level data for the effects of atmospheric pressure using measurements from a weather package in Seward. Unfortunately, that package was destroyed in a storm and we are seeking alternate pressure data sets to apply this correction. However **Figure 6** shows the direction of our investigation. It shows the, demeaned, atmospheric-pressure corrected and 20-day lowpass filtered time series of sea level at Seward. It also shows two linear least squares fits; one fit over the 1 April – 30 September period and the other from 1 April –31 October. The sea level and associated fits show a sea level rise from April through October. That rise occurs when downwelling favorable winds, which cause coastal sea levels to rise are weak. Average winds are weak during this time period so that the change in sea level is largely a function of upper ocean water density changes. We have also plotted the actual 0-50 db dynamic height at GAK 1 as well as the "adjusted" dynamic height. The adjustment is applied as follows. Using the least squares fit we predicted the sea level on April 5 (which corresponds to the first point in our dynamic height data set for this time period). The difference between the predicted sea level and the actual dynamic height (~10 cm or dyn. cm) was then used to offset each additional dynamic height measurement. The succeeding points tend to track the sea level curve quite well; especially those in early June and September. The relationship breaks down in late October as sea level rises but dynamic height decreases. We account for this by noting that strong downwelling winds intensified in late October. These winds would elevate sea level and perhaps mix saltier water into the upper 50 m. This mixing would lower dynamic height over this depth interval. Hence the results suggest that a reasonably good relationship between sea level and dynamic height can be obtained during this season.

The results suggest that historical sea level records could serve as a proxy for the summertime freshwater content of the Gulf of Alaska shelf. This follows because ~70% of the 0-50 db change in dynamic height between April and October is due to salinity. The sea level records could potentially reveal two important pieces of information. The first is the seasonal rate of freshening, which is given by the slope of the linear least squares fit. The second is the total change in sea level between spring and early fall, which is proportional to the freshwater volume on the Gulf of Alaska shelf. These data have biological relevance since the rate of freshening should be correlated with increasing stratification and the total freshwater content could be a signature of climate variability that affects precipitation and/or melting rates of the glaciers and snowfields bordering the Gulf of Alaska. We believe that freshwater variability could substantially affect this marine ecosystem (and perhaps that of the southeast Bering Sea as well because waters from the Gulf of Alaska shelf flow into the Bering Sea). However, it is difficult to obtain reliable runoff, precipitation, snowfall, and glacial mass balance measurements in this rugged and remote region. Few streams are routinely gauged and many of those that are have very small watersheds. Precipitation measurements are also few and possibly subject to local orographic effects. Indeed the terrestrial hydrologic sampling around the gulf is sparse and there is some uncertainty as to how regionally representative these measurements. In contrast, shelf salinities are the integrated response to freshwater runoff over a broad region. The ocean effectively filters out local effects. While absolute values of runoff might be difficult to determine relative differences between years could be discernible. We emphasize that our results are tentative and that considerably more analyses are required before sea level data can be confidently applied in the manner suggested. However, if the approach proves successful then an ocean environmental monitoring station at Yakutat or Sitka would be recommended because both locations front the shelf, each is at least 500 km distant from Seward, and both have a long historical sea level base. One could simply "calibrate" the sea level records over a period of several years with ocean density measured from a mooring similar to that described herein. In principle, with more than one site available would allow calculating the net freshwater influx between coastal locations.

The unusual ocean conditions of fall 1997 – winter 1998

As a final set of results we show two different aspects of the anomalous ocean conditions in the Gulf of Alaska that commenced in summer 1997 and continued through winter 1998. These we summarize in **Figures 7 and 9**. **Figure 7** shows the mean October profile and ± one standard deviation for temperature and salinity profile at GAK 1 along with the profiles measured in October 1997. **Figure 9** is the corresponding set of plots for April 1998. The October 1997 data indicates abnormally warm water (~2°C above normal) within the upper 60 m of the water column. Temperatures below that depth and salinities over the whole water column are well within one standard deviation. That the warming is confined to the upper ocean only suggests that the cause is due to abnormally high incoming short wave solar radiation and/or anomalously low wind speeds (which entrains cooler subsurface water into the surface layers).

We have examined wind records from several NOAA buoys from around the Gulf of Alaska and find no compelling evidence that wind speeds were below normal. However, satellite measurements of outgoing longwave radiation along 58°N and between 140°W and 160°W (essentially the northern Gulf of Alaska) show unusually high and persistent values through summer and early fall 1997 in comparison to other years in this decade (**Figure 8**). The longwave radiation flux is an indicator of cloud cover. Low values correspond to cold "surface" temperatures or cloud tops while high values correspond to warm surfaces such as the ocean in summer. Thus we conclude that the anomalous surface temperatures in summer and fall 1997 were primarily a response to enhanced solar heating.

The April 1998 data set (**Figure 9**) shows that temperatures throughout the entire water column were 1-2 °C above normal. The warming was also associated with a freshening throughout the upper 200 m. The vertically averaged salinity in April 1998 was about 0.15 psu less than the mean salinity at GAK 1 for this month. To shift the mean GAK 1 April salinity profile to match the April 1998 profile implies an immense anomalous freshwater influx equivalent to mixing an additional 1.5 m of freshwater over the entire water column. The source of this anomalous freshening (and warming) is not immediately clear to us, although several mechanisms could be contributing. First, the westward alongshore winds in October were stronger than normal and would have promoted onshore and downward transport of relatively warm and fresh surface waters. The alongshore winds were near normal in November and December but unusually strong in January and February. At this time of the year surface water temperatures are usually colder than normal so that enhanced downwelling would also tend to flush warm subsurface waters offshore. Thus we believe that the strong downwelling favorable winds in October are consistent with the observations but those of early winter are not. A preliminary examination of weather records from around coastal Alaska suggests warmer than normal air temperatures from fall 1997 through early winter 1998. Above average air temperatures in winter would have two consequences. First, warm winter air temperatures would inhibit the sensible and latent heat flux from the ocean to the atmosphere. This is consistent with our finding that the average rate of heat loss from the ocean between October 1997 and April 1998 was 90 W m^{-2}., whereas the average value based on changes in heat content at GAK 1 between October and April is about 230 W m^{-2}. Second, warmer air temperatures imply a higher saturation vapor pressure, or that the atmosphere can carry more moisture. Thus precipitation rates were probably higher during this winter than in an average winter. Moreover, because air temperatures were warmer more of the precipitation would have been delivered as rainfall than as snow. Snow is stored through winter in the surrounding mountains and its contribution to discharge is felt during the summer upon melting. If rainfall occurs in winter it likely enters the ocean shortly thereafter via coastal discharge (Royer, 198). Finally, above average ocean temperatures and lower than normal salinities were observed along the coast of British Columbia during this time period (Carmack, pers. comm.) which is upstream of GAK 1 and within the path of the prevailing ocean circulation. Hence, it is likely that the unusually warm and fresh winter water was at least partially associated with ocean advection.

Other findings

Our efforts during the first year of this project have mainly focussed on the collection and analysis of the data collected under EVOS support. However, we have also undertaken some preliminary retrospective analyses using the historical data. One intriguing result of this activity is shown in **Table 4,** which is a matrix of correlation coefficients between temperature and salinity as a function of depth. The table is based on the complete GAK 1 data record and the annual cycle was removed prior to computing the correlations. The results indicate that temperature and salinity are inversely correlated within the upper water column. A logical hypothesis is that warm winters tend to be wetter because the atmosphere has a higher moisture content and ocean to atmosphere heat loss is reduced. The inverse relation holds in summer also because we expect warmer summers to have a greater glacial or snowmelt contribution. These are easily testable hypothesis with available atmospheric data and we will begin this in the 1999 and 2000. There is also a strong positive correlation between salinities at 100-200 m depth and surface temperatures. This is an interesting finding for which we have no satisfactory hypothesis. Nevertheless we will continue to examine these historical data seeking additional structures that they might contain. We will examine the data using singular value decomposition (SVD) multivariate approach (in contrast to EOFs, which operate on a single variable), which will establish the dominant modes of temporal and vertical covariance. Those modes might correspond to particular atmospheric fields such as the strength and location of the Aleutian Low and North Pacific High, moisture content, winds, air temperatures, etc. The SVD analysis might also provide insight as to the cause of the positive correlation between deep salinities and surface temperature.

Conclusions

The results thus far lead to the following conclusions.

8. Mooring motion and biofouling are negligible so that temperature and conductivity measurements can be reliably made year-round from the GAK 1 mooring.
9. The integral time scales for temperature and salinity are generally quite long (~1 month). This implies that the monthly CTD records that make up the historical GAK 1 record do not suffer severely from temporal aliasing. The results also imply that the alongshore coherence scales of temperature and salinity variability are about 500 km. Hence only 2 – 3 moorings of this type would be needed to sample adequately temperature and salinity variability around the inner shelf of the Gulf of Alaska.
10. The phasing of temperature and salinity changes over depth at GAK 1 as seen from the mooring are consistent with inferences drawn from the historical record. However, some of these changes occur quite rapidly (e.g., at time scales shorter than one month). The surface temperature increase and near-bottom salinity increase in summer are examples of these rapid changes. If these rates of change are typical then monthly sampling alone cannot adequately resolve them. The onset of these changes presumably varies from year-to-year and could have ecological importance, such as in the evolution of the surface mixed layer and the delivery of nutrient-rich deep water to the shelf.
11. The within-month variance is less than the interannual variance from winter through mid-summer and probably no greater than the interannual variance in late summer and fall. Longer time series (currently underway) will be required to statistically test this result.
12. The 0-50 db dynamic height change between April and September 1983 tracks the 20-day low-pass filtered change in Seward sea level. The result implies that the sea

level change reflects thermosteric effects. About two-thirds of this affect is due to salinity and one-third to temperature. The results imply that changes in summer sea level could be a proxy for freshening and heating rates and the change in freshwater and heat content over the summer. If, so then historical sea level records might be useful in retrospective studies of ocean climate conditions around the Gulf of Alaska.

13. The unusually high summer and fall 1997 temperatures (2-3°C above normal) were limited to the upper 60 m of the water column. The cause is likely associated with the abnormally low cloud cover, which would allow increased solar radiation to reach the sea surface over the Gulf of Alaska.
14. The winter of 1998 exhibited abnormally high temperatures (1-2°C above normal) over the *whole* water column and unusually low salinity (~0.15 psu below normal on vertical average). We suggest that both the atmosphere (with above normal air temperatures and a greater atmospheric moisture content) and ocean (advection from lower latitudes) likely contributed to these differences).
15. The 29-year long monthly CTD sampling indicates that monthly temperature and salinity anomalies are inversely correlated with one another in the upper 100m. A testable hypothesis that emerges from this result is that:

    Warm, low-salinity winters are due to an anomalously high atmosphere-ocean moisture flux and an anomalously low ocean-atmosphere heat flux. Warm, low-salinity summers are due to increased air temperatures and solar radiation and greater runoff from the quasi-permanent mountain snowpacks ringing the coast.

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Table 1. Summary of GAK1 mooring specifics. The mooring was located at 59 51.131'N, 149 29.923'W in 262 m water depth. Sampling interval was 15 minutes.

Depth (m)	Start Time	End Time	Comments
27	1215 March 22, 1998	1145 November 30, 1998	Polychaete fouling on case, sensors clean, 24479 records
58	1215 March 22, 1998	1145 November 30, 1998	negligible growth, 24479 records
98	1215 March 22, 1998	1145 November 30, 1998	Negligible growth, temp. sensor failed, data bad
148	1215 March 22, 1998	1145 November 30, 1998	Negligible growth, temp sensor failed, data bad
197	1215 March 22, 1998	1145 November 30, 1998	Negligible growth, 24479 records
245	1215 March 22, 1998	1145 November 30, 1998	Slight Bryozoan fouling, sensors clean, 24479 records

Table 2. The monthly means and standard deviations (in parentheses) at each depth for temperature (°C; 1st row) and salinity (psu; 2nd row). The values were computed from the data collected from the GAK 1 mooring in 1998. The last column contains the integral time scale (τ).

Depth (m)	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**τ (days)**
27	5.39 (.17)	6.30 (.34)	7.43 (.42)	10.07 (1.71)	11.67 (.35)	11.81 (.29)	10.13 (.71)	8.02 (.74)	46
	31.08 (.12)	30.85 (.11)	30.91 (.16)	30.59 (.30)	30.16 (.35)	28.98 (.66)	29.13 (.72)	29.49 (.55)	33
58	5.55 (.17)	6.39 (.50)	7.06 (.42)	7.28 (.36)	8.67 (.68)	10.90 (.42)	10.39 (.41)	8.92 (.64)	47
	31.27 (.14)	31.22 (.16)	31.42 (.09)	31.49 (.11)	31.48 (.14)	31.04 (.38)	30.99 (.36)	30.92 (.28)	9
197	6.36 (.15)	6.13 (.11)	6.06 (.05)	5.86 (.07)	5.84 (.11)	5.95 (.05)	6.17 (.13)	6.54 (.34)	14
	32.36 (.28)	32.59 (.08)	32.85 (.11)	33.20 (.09)	33.27 (.04)	33.17 (.15)	32.99 (.13)	32.81 (.15)	30
245	6.20 (.24)	5.91 (.07)	6.05 (.05)	5.71 (.09)	5.73 (.03)	5.81 (.05)	5.92 (.06)	6.11 (.10)	18
	32.44 (.16)	32.56 (.03)	32.85 (.13)	33.29 (.13)	33.32 (.03)	33.24 (.04)	33.13 (.06)	32.88 (.10)	34

Table 3. The monthly means and standard deviations (in parentheses) at each depth for temperature (°C; 1st row) and salinity (psu; 2nd row). The values were computed from the historical record of monthly CTD casts at GAK 1.

Depth (m)	**Apr** (n = 31–33)	**May** (n = 29-31)	**Jun** (n = 30-34)	**Jul** (n = 17-22)	**Aug** (n = 12-16)	**Sep** (n = 23–26)	**Oct** (n = 26-29)	**Nov** (n = 24-28)
30	4.18 (.75)*	5.46 (.78)	6.94 (.95)	9.71 (1.39)	11.17 (1.45)	11.41 (.90)	9.84 (1.19)	7.43 (.91)
	31.37 (.29)	31.32 (.29)	31.27 (.28)	30.85 (.38)	30.27 (1.06)	30.18 (.53)	29.32 (.68)	29.74 (.33)
50	4.29 (.79)*	5.30 (.83)	6.26 (.95)	7.37 (.85)	8.60 (1.38)	9.46 (1.40)	9.85 (.90)	8.29 (.65)
	31.52 (.24)	31.47 (.24)	31.56 (.18)	31.49 (.19)	31.30 (.34)	31.35 (.37)	30.88 (.53)	30.64 (.41)
200	5.17 (0.9)*	5.38 (.52)	5.25 (.61)	5.35 (.38)	5.63 (.33)	5.48 (.43)	5.67 (.49)	6.03 (.43)
	32.27 (.24)	32.55 (.20)	32.70 (.22)	32.99 (.25)	33.06 (.21)	32.99 (.16)	33.02 (.19)	32.79 (.21)
250	5.47 (.70)	5.54 (.37)	5.36 (.53)	5.44 (.36)	5.56 (.34)	5.46 (.43)	5.61 (.49)	5.72 (.25)
	32.56 (.26)	32.78 (.26)	32.88 (.26)	33.13 (.30)	33.16 (.22)	33.16 (.13)	33.22 (.16)	33.06 (.14)

Table 4. Correlation coefficients for temperature (row) versus salinity (columns) as a function of depth based on monthly measurements at GAK 1. For example, the temperature at 10 m depth (2nd row) is inversely correlated with a magnitude of .71 with salinity at 0m (1st column). Significant negative values are italicized and significant positive values are boldfaced. Significance tests were conducted at the α = 0.01 level.

Depth	**0 m**	**10 m**	**20 m**	**30 m**	**50 m**	**75 m**	**100 m**	**150 m**	**200 m**	**250 m**
0m	*-0.70*	*-0.55*	*-0.42*	*-0.32*	-0.09	0.12	***0.25***	***0.37***	***0.19***	0.03
10 m	*-0.71*	*-0.64*	*-0.52*	*-0.40*	-0.12	0.10	***0.22***	***0.38***	***023***	0.08
20 m	*-0.71*	*-0.7*	*-0.58*	*-0.44*	-0.13	0.12	***0.24***	***0.40***	***0.27***	0.12
30 m	*-0.71*	*-0.76*	*-0.66*	*-0.52*	*-0.19*	0.09	***0.22***	***0.40***	***0.28***	***0.16***
50 m	*-0.56*	*-0.71*	*-0.70*	*-0.66*	*-0.39*	-0.11	0.01	***0.28***	***0.23***	0.12
75 m	*-0.33*	*-0.45*	*-0.49*	*-0.58*	*-0.55*	*-0.27*	*-0.20*	0.05	0.10	0.02
100 m	*-0.23*	*-0.32*	*-0.37*	*-0.47*	*-0.58*	*-0.42*	*-0.26*	-0.03	0.04	-0.04
150 m	*-0.19*	*-0.24*	*-0.23*	*-0.28*	*-0.46*	*-0.46*	*-0.36*	*-0.19*	-0.06	-0.09
200 m	-0.14	*-0.23*	*-0.2*	*-0.22*	*-0.35*	*-0.39*	*-0.36*	*-0.20*	-0.01	-0.03
250 m	*-0.17*	*-0.23*	*-0.18*	*-0.18*	*-0.28*	*-0.34*	*-0.34*	*-0.24*	-0.05	0.06

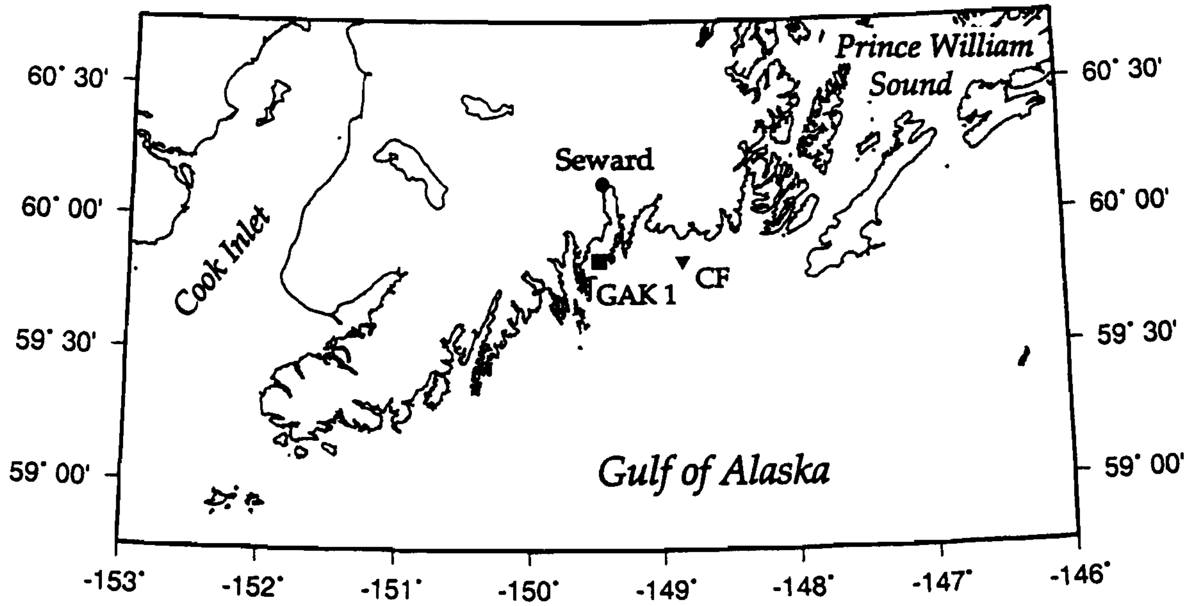


Figure 1. Location map of the northern Gulf of Alaska showing the position of hydrographic station GAK 1 and the mooring CF deployed in 1983.

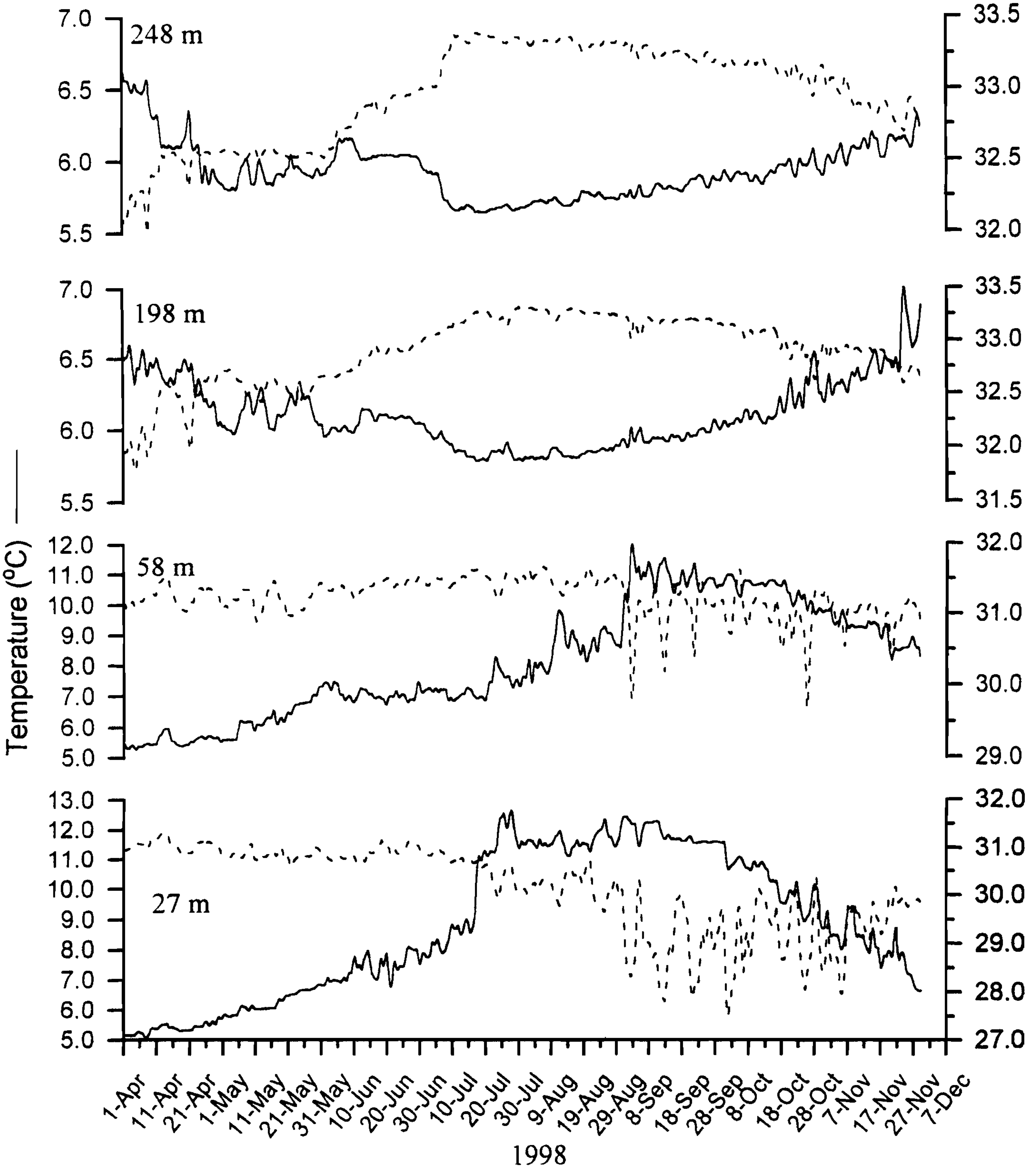


Figure 2. Lowpass filtered time series of temperature and salinity at the GAK 1 mooring.

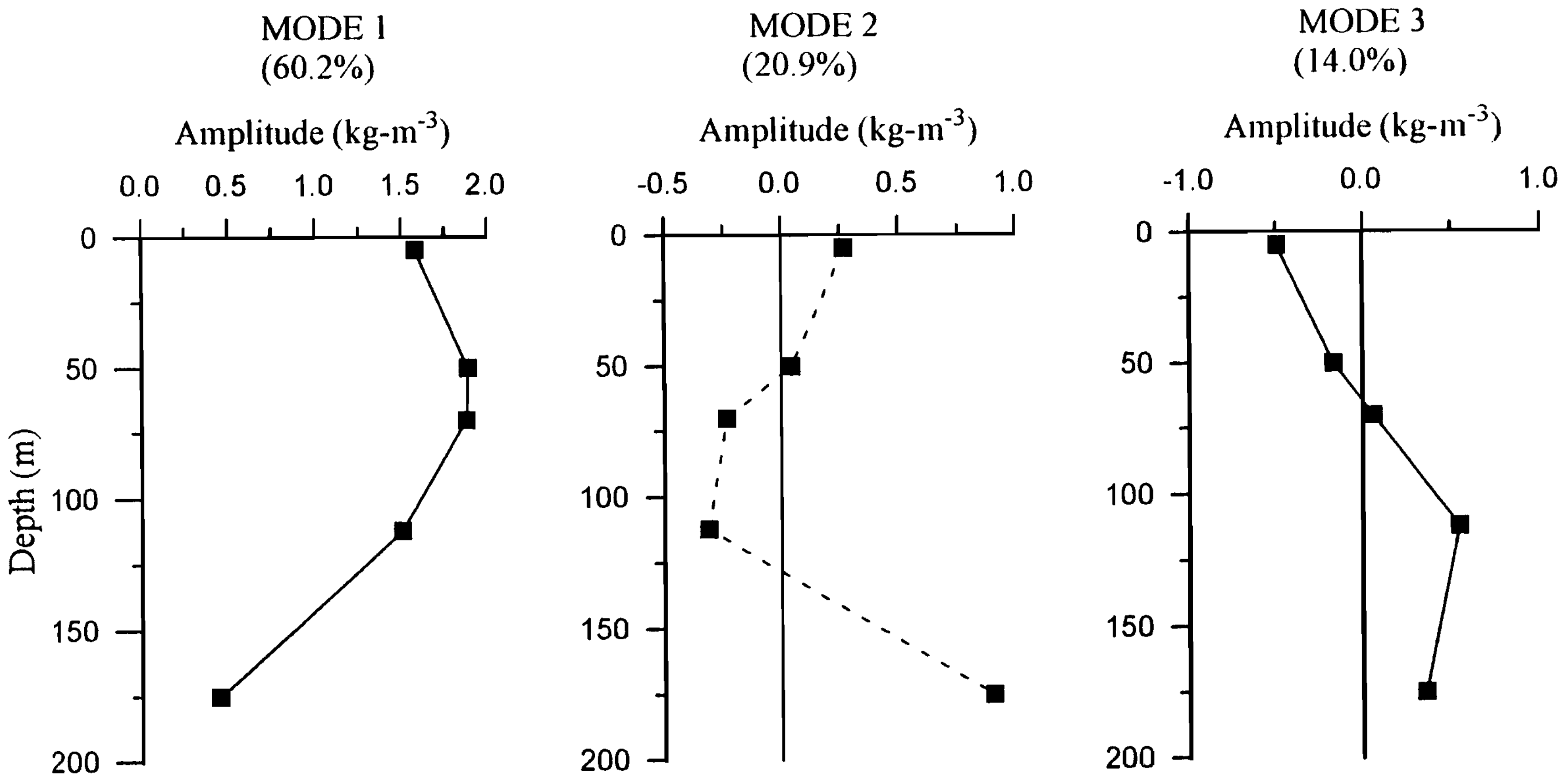


Figure 3. The first three EOF modes of water density at the Cape Fairfield mooring computed from lowpass filtered data collected between April and October 1993.

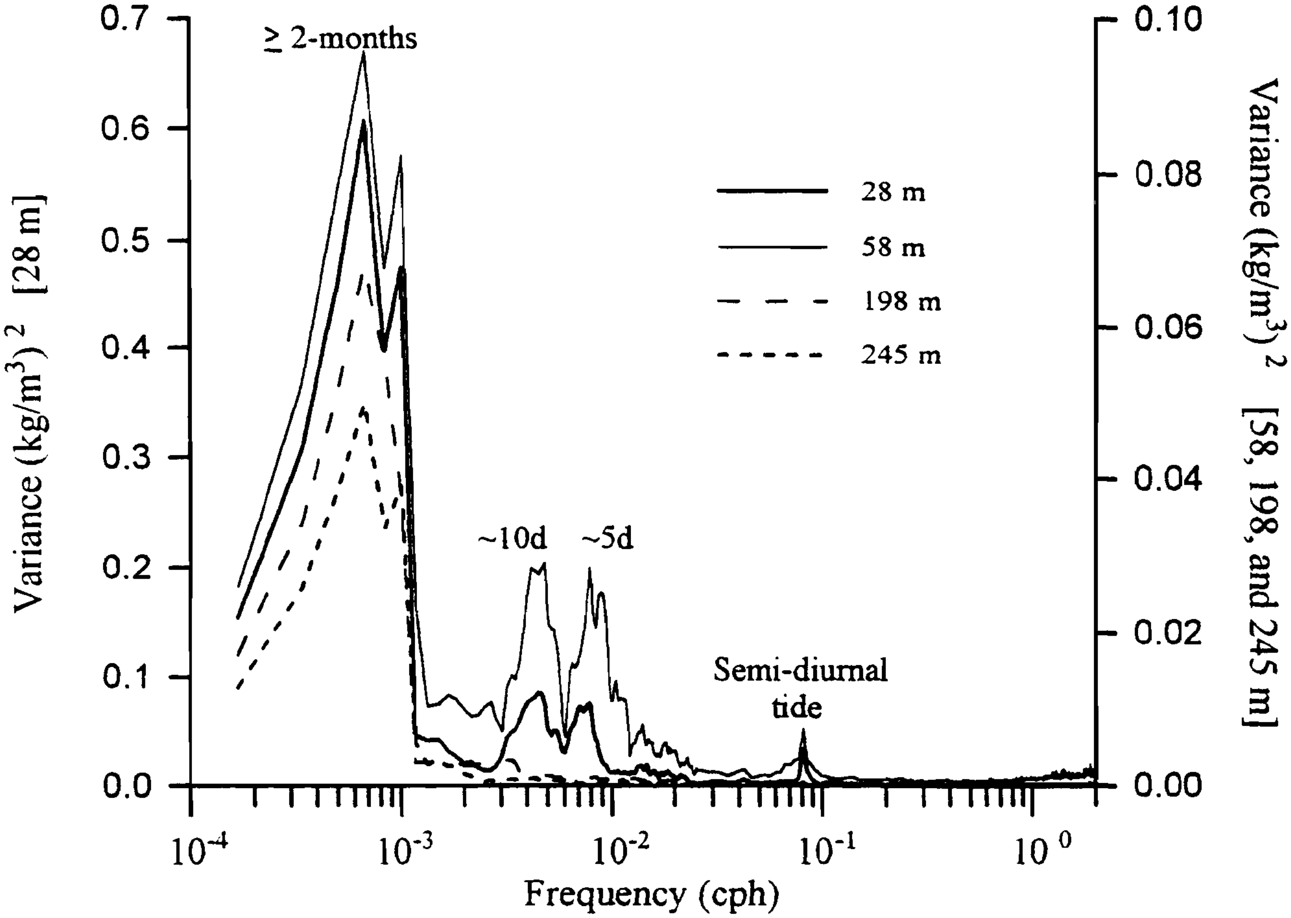


Figure 4. Variance preserving spectra of water density at GAK 1 based on 15-minute samples between March 20 and December 1, 1998

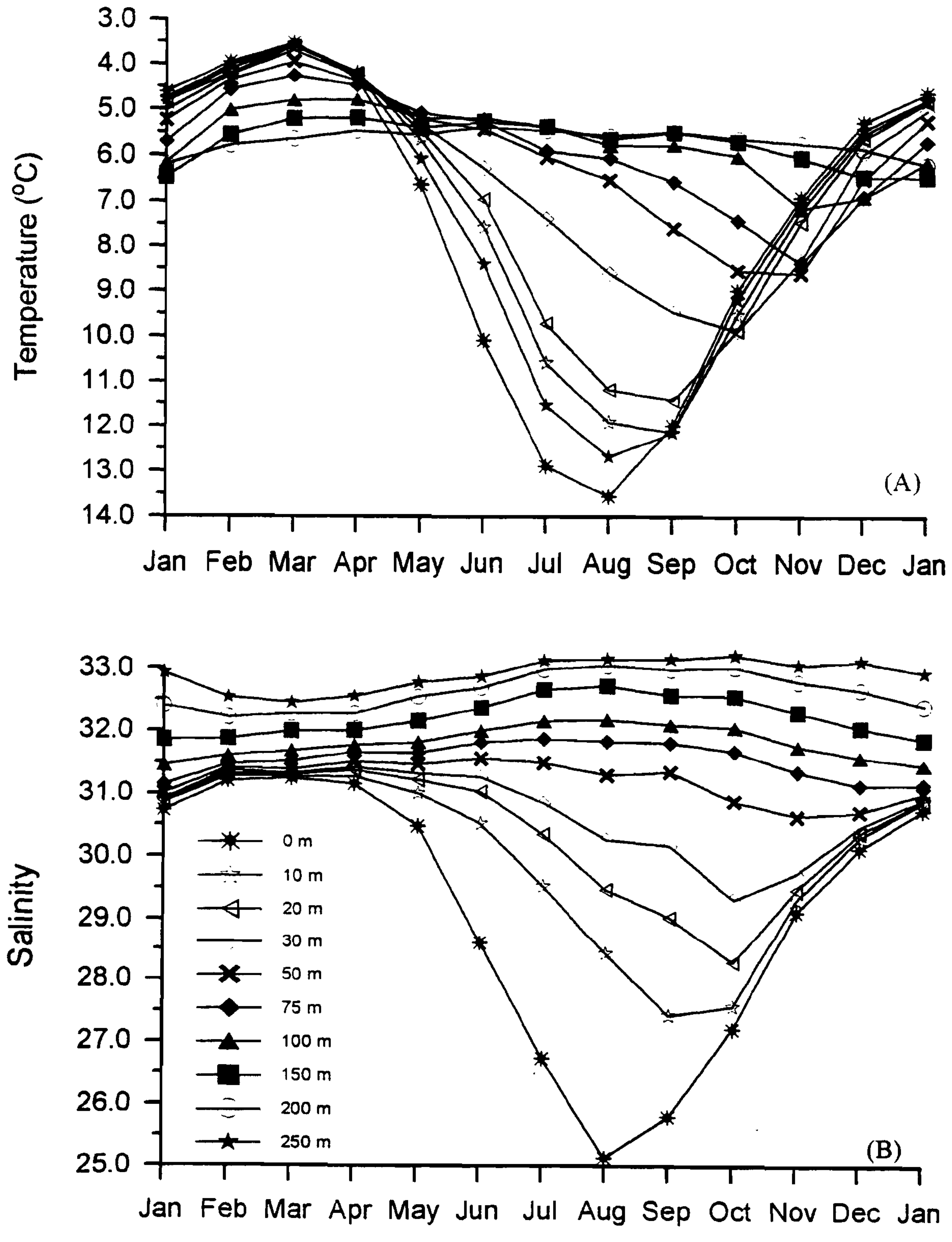


Figure 5. Mean monthly a) temperature, b) salinity, c) density and d) dynamic height over indicated portions of the water column.

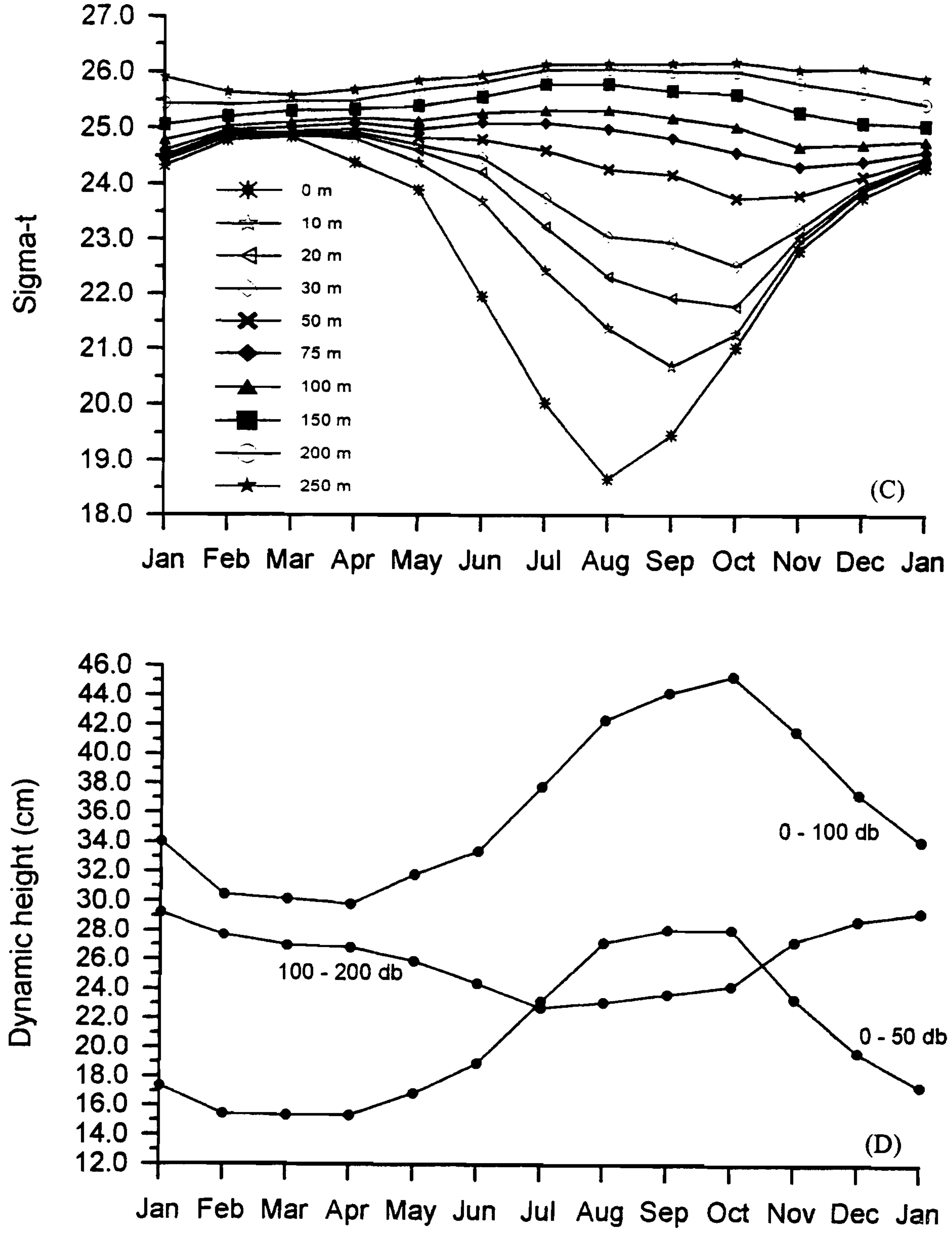


Figure 5 c,d (cont.)

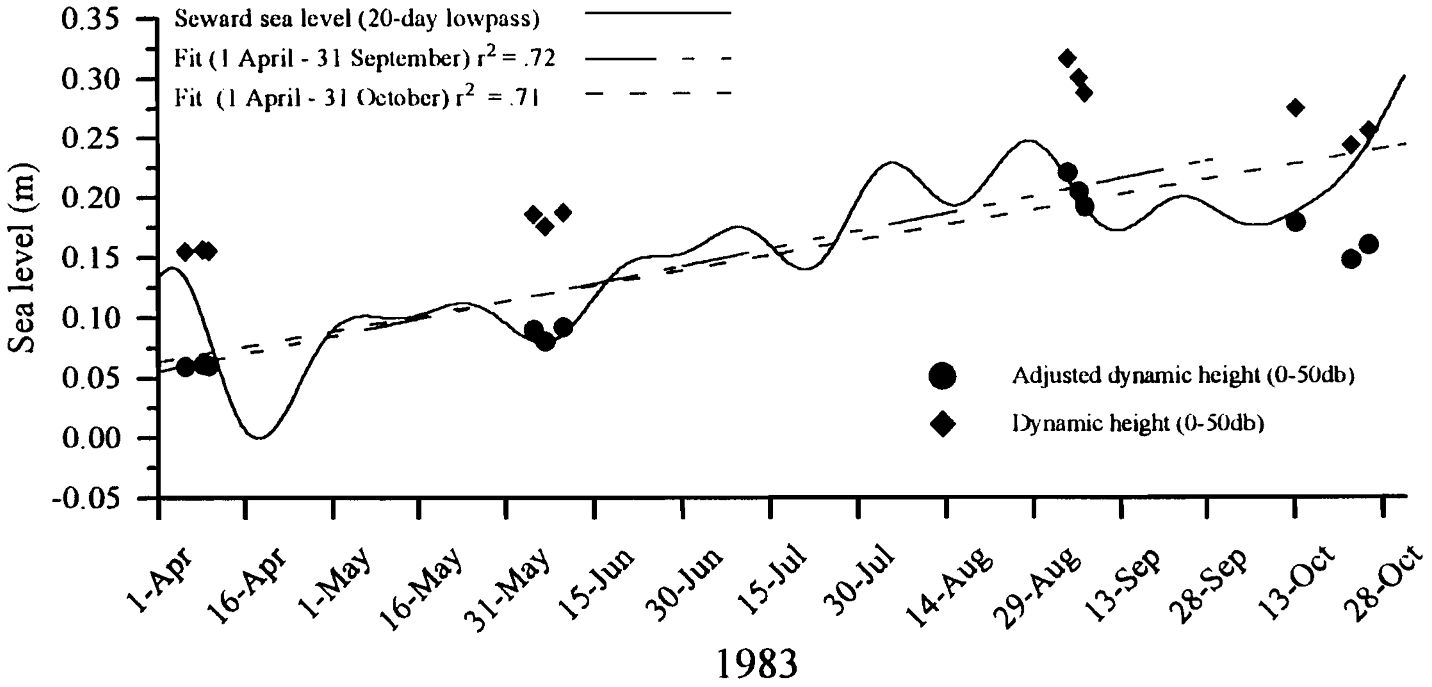


Figure 6. Comparison between demeaned, 20-day lowpass filtered Seward sea level (corrected for atmospheric pressure) and GAK 1 0-50 db dynamic height. Linear fits to the Seward sea level curve are also plotted.

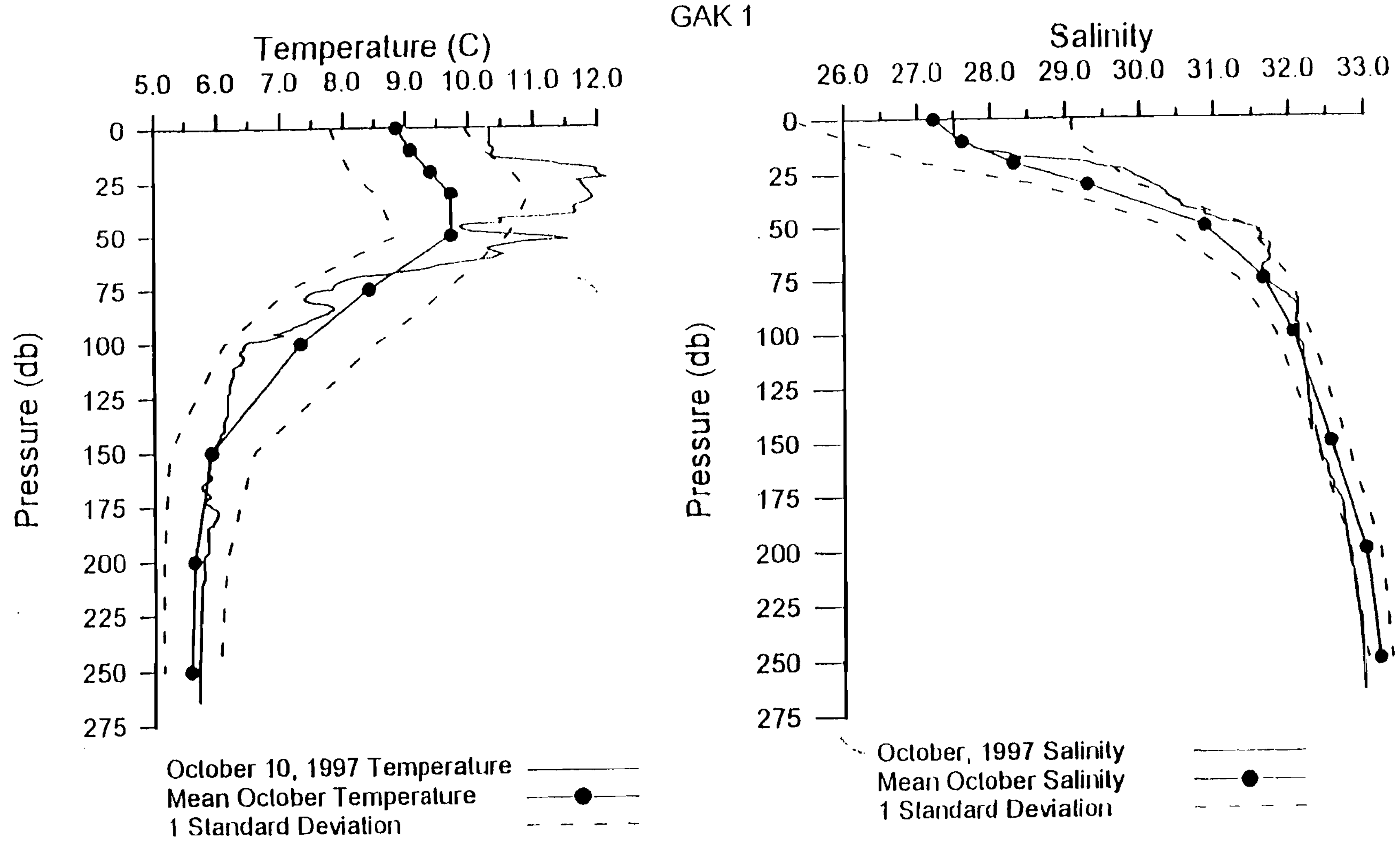
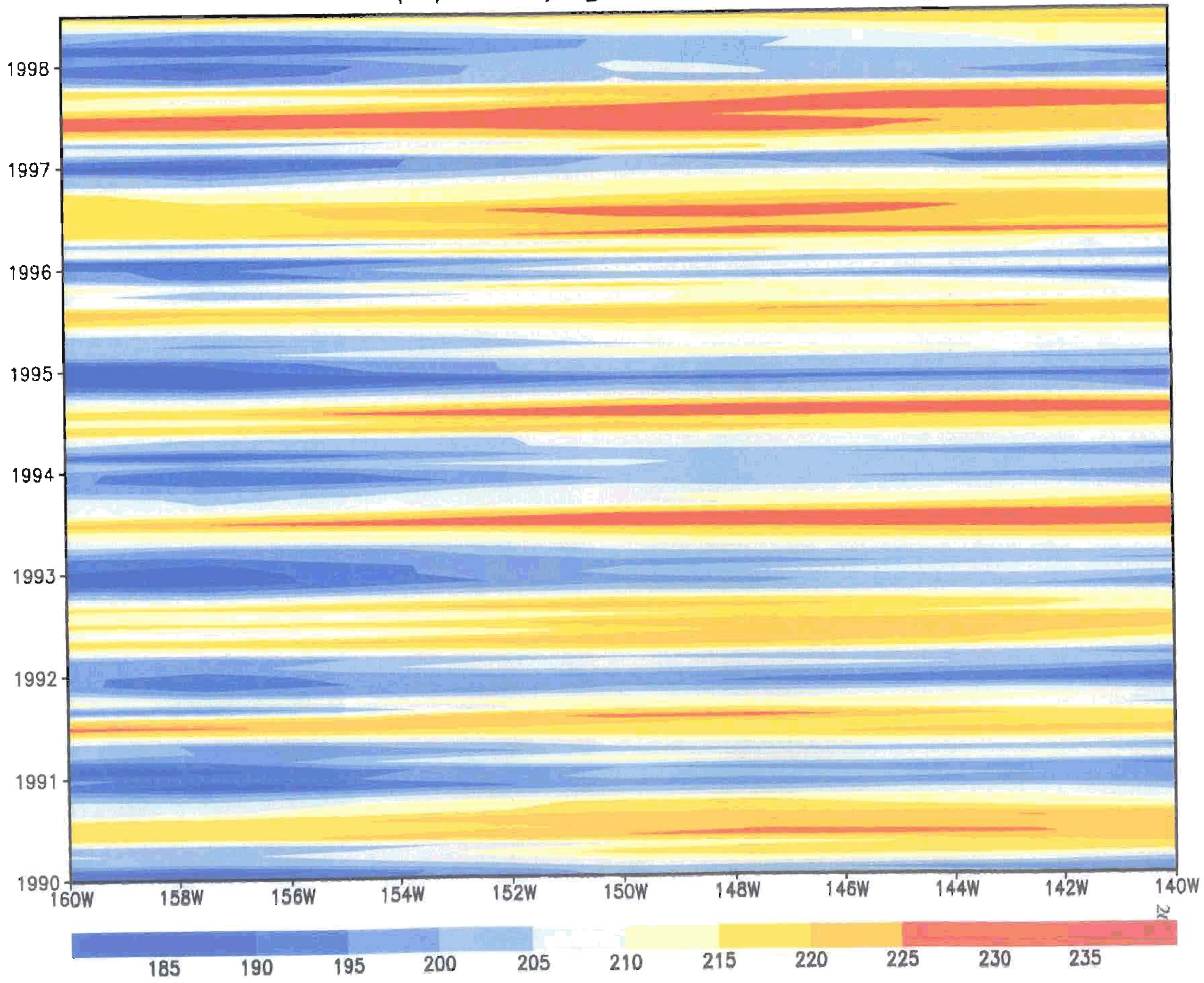


Figure 7. Comparison between mean (+/- one standard deviation) October and October, 1997 temperature and salinity profiles at GAK 1.

Figure 8. Time (vertical axis) and longitude (horizontal axis) of monthly outgoing longwave radiation (OLR) along 58°N in the Gulf of Alaska between 1990 and 1998

OLR (W/m^2) [58N, 140-160W]



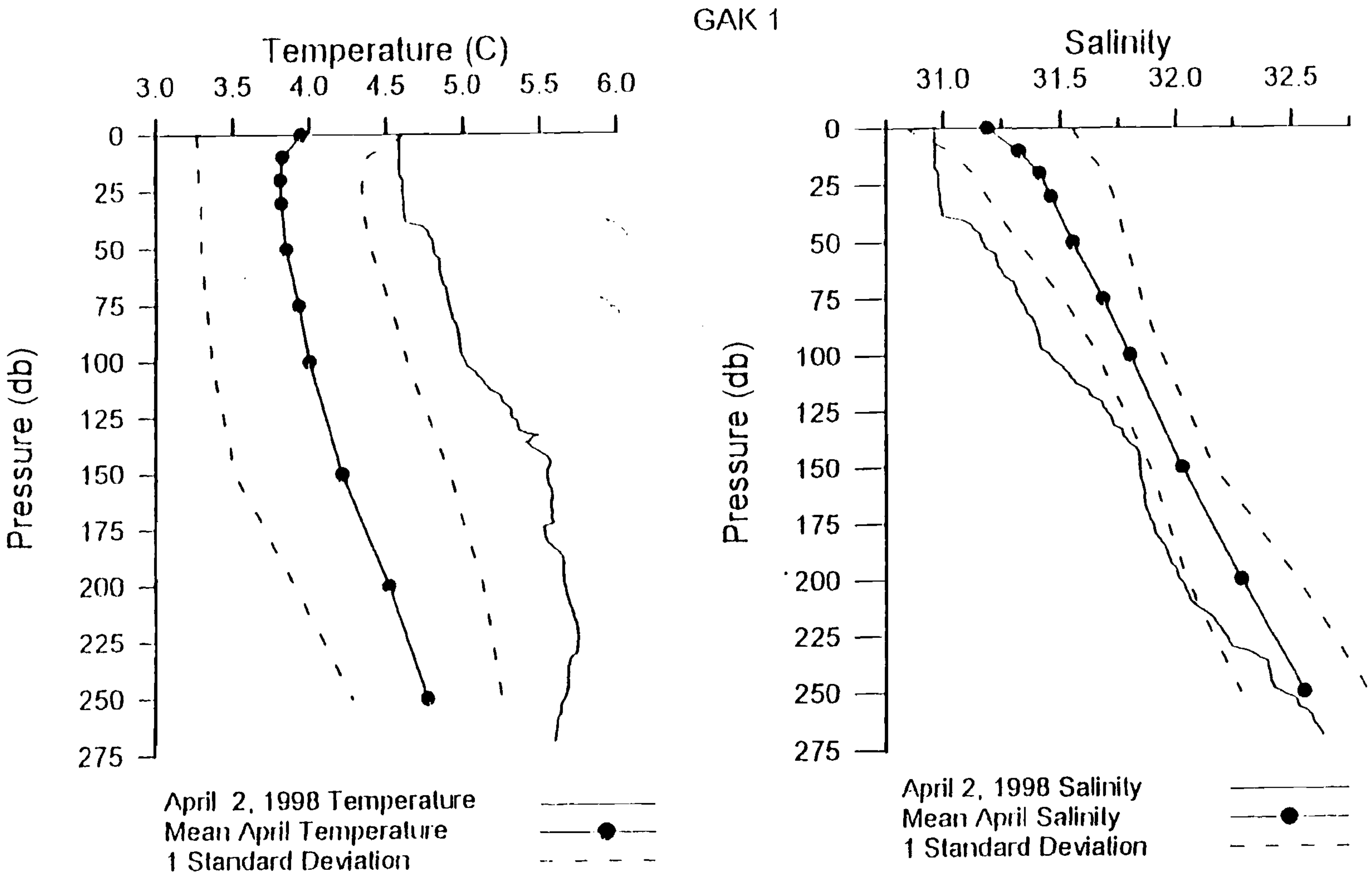


Figure 9. Comparison between mean (+/- one standard deviation) April and April, 1998 temperature and salinity profiles at GAK 1.