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 FY01 with this annual report being the third produced. This work builds upon, indeed continues, measurements of temperature and salinity determined as a function of depth (CTD sampling) at a hydrographic station (GAK1) near Seward that were begun about 30 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 NOAA funding maintained the monthly on a more systematic basis. Funding from EVOS has systematized the sampling even further by supporting an instrumented mooring at GAK 1, which consistes of six temperature/conductivity recorders 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 NSF and NOAA.

Abstract: This project is building upon a 30-year time series of temperature and salinity obtained from hydrographic station GAK1 on the Gulf of Alaska shelf near Seward. Results from the past year suggest that beginning in the winter of 2001 there is a modest freshening (~0.25 psu) within the upper 100m of the Alaska Coastal Current and a modest warming (0.75^{o}C)over the entire water column. The salinity anomaly corresponds to an anomalous freshwater standing stock on the shelf of about 0.8 m. The source(s) of these anomalies are not known but are subject to continuing investigation.

The mooring data show that both salinity and temperature have integral time scales of about 1 month at all depths. These time scales suggest an alongshore spatial decorrelation length scale of about 500 km assuming a typical speed of 10 cm s^{-1} for the Alaska Coastal Current. This length scale is relevant to the ecosystem monitoring design considerations because it suggests that only a few (3 – 4) temperature and salinity monitoring stations are needed to monitor these parameters along the coast of the Gulf of Alaska.

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

Project Data: All of the data are being archived and are accessible from the web. The address is: http:/www.ims.uaf.edu/gak1/

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EXECUTIVE SUMMARY

This annual report summarizes some of the activities and analyses based on the third year of this four-year project. The project goals were and are being achieved. We successfully deployed a mooring at station GAK 1, which contained six temperature/conductivity recorders in December 1999. The mooring was recovered in December 2000 and replaced with a new mooring with identical instrumentation. Data return and quality from the six instruments on the 1999 – 2000 mooring were excellent. We also continued the monthly CTD profiles at this station. The webpage is being updated with these data sets. During the past year some of our results were presented at the Eastern Pacific Ocean Conference held in September 2000 in Sidney, BC. Preliminary analyses reported herein focus on the mooring data and comparisons between the mean winter shelf conditions and those observed in 2001.

Our results suggest that the GAK 1 mooring be augmented with an additional temperature/conductivity recorder at 10 m depth. This 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. The additional instrument is consistent with the long-range goals of the Gulf Ecosystem Monitoring (GEM) program now under development.

In our original proposal we suggested that empirical orthogonal functions (EOFs) might provide a useful description of temperature and salinity variations. We find that while they yield a statistically convenient way to describe the vertical variations in the temperature and salinity of the water column on the inner shelf, the EOFs lack a physically meaningful interpretation. While the EOFs are not useful descriptors of the seasonal cycle, they may prove to be useful in interpreting vertical patterns in salinity and temperature anomalies. A more physically useful interpretation can be obtained by analyzing the mooring data by least squares harmonic fits at the annual, semi-annual, and quarter-annual periods. The phase and amplitude information from these fits might be useful in quantifying interannual variability on this shelf if this mooring is maintained under the GEM program.

The results suggest that relative to the long-term mean, the winter of 2001 is slightly warmer (by about 0.75 C) over the entire water column and moderately fresher within the upper 100 m. The origin(s) of these anomalies will be investigated in the coming months.

Introduction:

The Gulf of Alaska experiences large seasonal and interannual variations in meteorological and oceanographic forcing (*Royer*, 1993) which probably affects biological production (*Mantua et al.,* 1997). Quantifying the oceanographic variability and its causes are necessary in order to understand 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. It should also be useful to investigators involved in the Gulf Ecosystem Monitoring (GEM) Program. The monitoring program discussed herein 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 station lies on the inner shelf of the northern Gulf of Alaska, within the Alaska Coastal Current, approximately one-third of the distance between the western end of Prince William Sound and Cook Inlet. A fundamental goal of this program is to continue the 30-year time series of temperature and salinity at hydrographic station GAK1. This is being done through a combination of monthly CTD measurements and through yearlong deployments of a mooring containing six temperature and conductivity (T/C) recorders that span the water column.

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 marine ecosystems 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 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 the seasonal and vertical distribution of variance in temperature, salinity and dynamic height. That is, determine if distinct vertical "modes" of variability exist and how these modes vary in time.

Prior annual reports have addressed various aspects of the general objectives (I – IV) as well as the specific objectives listed above (*Weingartner,* 1999, 2000). This report describes some preliminary results from the third year of this project and focuses on the data from the mooring at GAK1. These data (34,941 records) were collected at a quarter-hour sampling rate from 2130, 3 December 1999 through 2030, 1 December 2000 (all times are Greenwich Mean Time). This interim report does not include results from additional analyses that are underway. These analyses include: a) relating time series of Seward sea level to the GAK 1 mooring results, b) a discussion of longer period temperature and salinity variations at GAK 1, and c) ongoing efforts to relate Gulf of Alaska coastal precipitation measurements to sea level pressure patterns. Results from these efforts will be presented in the final report.

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 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 psu or better and temperatures are accurate to 0.005^{o}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^o 51.131'N, 149^o 29.923'W in 262 m water depth. Our procedure has been to deploy the T/C recorders for a period of one year, recover the mooring and replace it with an identical mooring with containing freshly calibrated instruments. The mooring discussed herein was deployed in December 1999 and recovered in December 2000. Instruments were deployed at depths of 20, 50, 91, 143, 195, and 247 m. The mooring was designed to minimize instrument diving when subjected to strong currents. Diving of the surface instrument was monitored with a pressure sensor incorporated on the instrument at 20 m depth. Pressure variations were typically ~2 db (e.g., ~ 2 m) and associated with the principal lunar, semi-diurnal (M_2) tide. The tidal velocities here are unlikely to exert significant drag on this mooring given our design. Hence the pressure variations reflect M_2 tidal changes in sea level and not instrument diving induced by tidal currents. Current-induced diving appears to have been no greater than ~1 m throughout the record. Although the pressure case of the shallowest instrument (20 m depth) was encrusted by biological growth, the conductivity cell remained clean. Biofouling of the deeper instruments was negligible. Overall instrument performance was excellent, with pre- and post-calibration differences being *less than* 0.03 psu for salinity and 0.01 for temperature.

Results and Discussion:

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 20 m depth and the maximum mean salinity occurs at 247 m. The variance is greatest at 20 m and decreases rapidly through the upper water column, at 50 m depth the variance is only 20% of the variance at 20 m depth. Below 91 m, the variance is approximately uniformly distributed with depth and is an order of magnitude smaller than the variance at 20 m depth. The mean temperature is greatest at 20 m depth and least at 247 m. However, the mean temperature gradient is small; only 1.5^{o}C over the water column. The variance in temperature variance is largest at the surface, and decreases by a factor of 100 by the bottom.

Although the variance differs considerably over the water column, the integral time scales for both variables and all depths are very similar. These are about one month for both salinity (a maximum of 37 days at 20 m and a minimum of 21 days at 50 m) and temperature (27 days at 143 m and 45 days at 20 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 that the historical data adequately describe the annual cycle. 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 days, which is similar to the integral time scale for the alongshore winds. Hence the integral time scales for the currents reflect the passage of storm systems at periods of several days. The winds accelerate or decelerate the shelf circulation and therefore force current fluctuations at similar time scales. 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. 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 scale 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 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 only a few coastal stations, spaced approximately 500 km apart, are needed to capture the major seasonal and interannual variations in temperature and salinity on the inner shelf.

The Annual Cycle

The annual salinity cycle is illustrated using the mean monthly values and standard deviations shown in **Figure 2a** and tabulated in **Table 3**. 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. At 20m depth, the salinity increases from ~30.5 psu in December to ~31 psu in January and then remains constant through June. Thereafter salinity decreases to the annual minimum of ~29 psu in October and then increases to ~29.5 in November. At 50 m depth, salinity slowly increases from December (30.8 psu) through August (31.4 psu) and then declines to the annual minimum of ~30.4 psu in November. At or below 91 m, salinities decrease from December through February or March, then increase to a maximum in August, before slowly decreasing through fall.

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 2a** indicates that vertical stratification is a minimum in winter and early spring and a maximum in September. However, the large salinity differences observed between 20 and 50 m depth from July through November indicates that our measurements are not 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 10 m depth and that the instrument at 20 m be re-deployed at 30 m depth.

The within month variability (as given by the standard deviations) also differs among the measured depths (**Figure 2a, Table 3)**. At 20 m depth, the variability is relatively constant from December through June but is a factor of 3-4 larger from July through October when the vertical stratification is greatest. At and below 143 m, the variability is largest from January through March and smallest in mid-summer. Note that the vertical bars representing the monthly standard deviations rarely overlap between depths. This suggests that the instrument distribution is close to optimal (with the near-surface being the exception) and that we are not oversampling the water column.

The seasonal variability is largely described by fitting the data to the annual, semi-annual, and quarter-annual periods. The predicted amplitudes are plotted in **Figure 3** as a function of time and depth. The phase is indicated in the same figure by means of diamonds that show the time of the maximum salinity and the circles that show 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, with a node at about 91 m depth. Here, the amplitude is a minimum (~0.8 psu) and the phase patterns differ above and below this depth. For example, for all depths greater than or equal to 91 m the minimum salinities occur in March and the maximum in September, e.g., 6 months apart. This suggests that forcing at the annual period governs salinity changes below about 100 m. Above 91 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. 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 vertical phase differences are also reflected in the structure of the empirical orthogonal functions (EOFs) computed from the correlation matrix of the salinity data and shown in **Figure 4 a, b, c, and d**. This technique decomposes data distributed through time and at discrete stations into discrete modes (e.g., *Kutzbach*, 1967). The modes result from an eigenanalysis of the correlation matrix computed from the data and the analysis decomposes the total variance into mutually orthogonal modes. For each mode the analysis produces an eigenvector, a temporal amplitude function, and an eigenvalue. The eigenvalues represent the fraction of the total system variance explained by a single mode. The eigenvector describes how the amplitude of a given mode varies in space and the time amplitude function describes how the particular mode varies in time.

The first salinity mode, which accounts for 63% of the total variance, captures the out-of-phase relationship between 20 m depth and depths greater than or equal to 91 m. (The amplitude of this eigenvector is a minimum at 50 m depth). The time function for the first EOF mode is clearly dominated by the annual cycle and it describes the surface freshening and deep salinity increase that occurs in summer and early fall. The second EOF captures 26% of the total variance and has largest amplitudes at 20 and 50 m depth. This mode primarily describes the salinity increase in the upper layer in fall.

The mean monthly temperatures along with their standard deviations are shown in **Figure 2b** and **Table 4**. As with 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^{o}C and occurs at 20m depth and the minimum temperature range is <1^{o}C and occurs at 247 m depth. At 20 and 50 m depth, temperatures decrease from December, reach their respective minima in February (20 m) or March (50 m), and their maxima in August (20 m) or September (50 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 (**Figure 2b, Table 4)**. At 20 m depth, the variability is maximum in June, which is when the water column begins to stratify and surface temperatures are rapidly increasing. At greater 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 either rapidly warming or cooling due to the seasonal propagation of these signals through the water column.

The seasonal variability is summarized in **Figure 5** which is based upon least squares harmonic fits to the data at the annual, semi-annual, and quarter-annual periods. The phase information shows that the annual period dominates at the surface (the minimum and maximum temperatures are separted by 6 months). This is consistent with warming and cooling by radiation and exchange of heat between the ocean and atmosphere. The vertical phase patterns suggest downward propagation of the heating (and cooling) cycle due to 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 are set at the surface and their propagation time scales depend upon water column mixing rates. Vertcial mixing is governed by the wind velocity and by the stratification, which is primarily a function of salinity.

The EOFs for temperature are shown in **Figures 6a, b, c, and d.** The first two modes explain most (89%) of the temperature variance. The first EOF, which accounts for about 50% of the variance, has largest amplitudes between 20 and 150 m depth and represents the annual cycle of heating and cooling at these depths. The second mode accounts for 39% of the variance and describes the out-of-phase component of the annual temperature cycle between the surface and bottom. It describes a cooling mode at the surface and a warming mode at the bottom.

Although the temperature and salinity EOFs imply that the water column has a simple vertical structure in a statistical sense, the eigenvectors do not lend themselves to a simple physical interpretation. The reason for this is that EOFs provide a useful representation of standing wave phenomena, but fail to simply describe propagating waves. As shown in **Figures 3** and **5**, the GAK 1 temperature and salinity annual cycles have different phases at different depths indicating that these changes propagate through the water column. In this sense, the harmonic analyses provide a far more physically appealing interpretation than the EOFs. Moreover, the amplitude and phase information constructed from the moored data might be useful indices of interannual variability on the Gulf of Alaska shelf. These parameters will reflect the integrated effects of the various parameters that control vertical mixing, dilution, heating, and cooling.

Shorter-period variations

Time series of salinity and temperature for each depth are shown in **Figures 6** (salinity) and **7** (temperature). While the monthly and seasonal variations discussed above are evident in these time series, the shorter-period (< 1 month) fluctuations are illustrated in these figures. Indeed, many of the shorter period fluctuations reflect the processes that lead to the seasonal changes. As stated above, many of the fluctuations are not uniformly distributed throughout the records, but instead vary in both time and depth. For example, the largest short period salinity and temperature variations occur near the surface (above 91 m) in summer and fall. These variations mostly reflect wind-mixing events that temporarily displace or erode the pycnocline in summer and lead to its gradual erosion in fall. The largest salinity and temperature variations in deep water occur in late fall and winter. We draw particular attention to the large salinity fluctuations that occur between February and April below 91 m depth. These begin in late January/early February and are most apparent in the records at 195 and 247 m depth. At the latter depth, the salinity first decreases by ~1 psu over a week-long period before increasing by ~0.8 psu. Similar changes occurred at 195m depth. These salinity changes imply the addition of nearly 0.4 m of freshwater to the deepest 50 m of the water column. This freshwater is supplied by downwelling and/or vertical mixing from the surface layer. The early February event coincided with minimum water column stratification. Following this event, deep salinities gradually decreased through early April. However, salinities between 50 and 143 m increased at this time. These differences probably reflect vertical mixing in which salt is diffused into the near-surface layers of the shelf. *Ruehs* (2001) finds that nutrients and salinity are positively correlated so that the observed salinity increase in the upper layers implies nutrient replenishment.

While a more extensive measurement program is required to understand the hypothesized mixing, it represents a critical mechanism by which biological production is maintained on this shelf. The deep turbulent mixing in late fall and winter would mix the nutrient-rich deep water that is advected onto the shelf in summer up into the surface layer 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 247 and 195 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. We contend that the strongest mixing occurred from February to mid-April 2000.

Finally, we note that the salinity time series suggest that the upper portion of the water column was slightly fresher in late November 2000 than in early December 1999. While these differences partially reflect the seasonal cycle, the monthly hydrographic data from GAK 1 during the winter of 2001 suggests an anomalously modest warming of the entire water column and a freshening of the upper 100 m. This is suggested in **Figure 7**, which compares the mean GAK 1 temperature and salinity profiles with those collected in April 2001. Temperatures were approximately 0.75^{o}C warmer in April 2001 compared to the mean. These differences are 4 –5 times greater than the within-month standard deviation computed from the mooring data. They are approximately the same as one standard deviation in April temperatures computed from the historical record. While the difference is within one standard deviation of the monthly mean, the difference is consistently positive throughout the water column suggesting that the observed warming reflects interannual variability and not random sampling error. The mean salinity difference over the upper 100 m is about –0.23 psu (April 2001 being fresher than the mean). The difference is about twice the magnitude of the within-month standard deviation, but equivalent to about one standard deviation as determined from the monthly mean computed over the entire GAK 1 record. The lower salinity within the upper 100 meters of the water column in April 2001 represents an anomalous freshwater content of about 0.8 m.

Conclusions

We recommend that the GAK 1 mooring be augmented with a temperature/conductivity recorder at 10 m depth. This 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.

While the EOF analysis provides a statistically convenient way to describe the vertical variations in the temperature and salinity of the water column on the inner shelf, they lack a physically meaningful interpretation. A more useful interpretation can be obtained by analyzing the results of harmonic fits to the mooring data. The phase and amplitude information from these fits might be useful in quantifying interannual variability on this shelf.

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 only a few coastal stations, spaced approximately 500 km apart, are needed to capture the major seasonal and interannual variations in temperature and salinity on the inner shelf.

Relative to the long-term mean, the data suggest a modest warming over the entire water column and a modest freshening within the upper 100 m in winter 2001. The origin(s) of these anomalies will be investigated in the coming months.

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Table 1. Annual 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.

Pressure (db)	Mean (psu)	s (psu)	s^2 $(psu)^2$	Max (psu)	Min (psu)	τ (days)	N_{eff}
20	30.34	1.01	1.02	31.56	27.18	37.10	9.74
50	31.20	0.44	0.20	32.19	28.91	20.85	17.33
91	31.75	0.30	0.09	32.41	30.92	28.54	12.66
143	32.29	0.35	0.12	32.98	31.40	36.96	9.77
195	32.77	0.35	0.13	33.33	31.83	36.43	9.92
247	33.03	0.27	0.07	33.41	31.88	36.50	9.90

Table 2. Annual statistics for temperature (^oC). 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	Mean	S	S	Max	Min	τ (days)	N_{eff}
20	7.35	3.06	9.36	13.62	3.34	45.22	7.99
50	6.42	2.00	4.01	11.42	3.50	43.42	8.32
91	6.10	1.35	1.81	9.75	3.84	36.10	10.01
143	5.92	0.75	0.57	8.26	4.47	26.55	13.61
195	5.84	0.42	0.18	7.45	5.15	27.49	13.14
247	5.80	0.33	0.11	6.63	5.21	33.54	10.77

Table 3. Monthly means, standard deviations (s), maxima, and minima for salinity. Bold-faced values correspond to minimum monthly means (and standard deviations) and underlined values correspond to maximum monthly means (and standard deviations).

Pressure	12/99	1/00	2/00	3/00	4/00	5/00	6/00	7/00	8/00	9/00	10/00	11/00
20												
Mean	30.56	31.01	31.05	31.09	31.13	30.99	31.19	30.60	29.58	28.89	**28.56**	29.41
s	0.18	0.17	0.15	0.08	**0.07**	0.11	0.14	0.59	0.77	0.72	0.59	0.32
Max	30.95	31.23	31.40	31.29	31.31	31.22	31.56	31.32	31.03	30.57	30.13	29.98
Min	30.21	30.58	30.69	30.89	30.86	30.67	30.68	29.29	27.53	27.18	27.51	28.58
50												
Mean	30.80	31.08	31.25	31.31	31.37	31.36	31.50	31.51	31.66	31.44	30.55	**30.50**
s	0.24	0.16	0.11	0.11	0.10	0.08	**0.07**	0.10	0.16	0.40	0.59	0.27
Max	31.42	31.32	31.47	31.53	31.58	31.58	31.68	31.81	32.06	32.19	31.53	31.27
Min	30.35	30.71	31.03	31.11	31.19	31.23	31.35	31.21	31.18	30.54	28.91	29.76
91												
Mean	31.68	31.50	31.46	31.54	31.65	31.73	31.87	32.04	32.21	32.16	31.73	**31.46**
s	0.24	0.20	0.14	0.11	0.16	0.09	**0.05**	0.08	0.10	0.08	0.24	0.18
Max	32.02	31.93	31.67	31.85	31.92	32.03	31.99	32.21	32.41	32.35	32.12	31.84
Min	30.99	31.12	31.12	31.26	31.29	31.54	31.77	31.76	31.95	31.97	31.10	30.92
143												
Mean	32.13	32.04	**31.83**	31.87	32.00	32.24	32.56	32.60	32.84	32.70	32.42	32.18
s	0.19	0.18	0.17	0.16	0.15	0.15	0.10	0.10	**0.06**	0.09	0.13	0.20
Max	32.53	32.39	32.10	32.22	32.34	32.52	32.72	32.85	32.98	32.90	32.72	32.48
Min	31.69	31.47	31.40	31.54	31.65	31.95	32.22	32.41	32.71	32.55	32.10	31.78
195												
Mean	32.51	32.63	32.32	**32.31**	32.39	32.78	32.94	33.03	33.25	33.21	33.01	32.84
s	0.24	0.20	0.24	0.17	0.16	0.12	**0.03**	0.10	0.05	0.06	0.14	0.13
Max	32.89	32.95	32.65	32.60	32.63	32.93	33.02	33.28	33.33	33.33	33.25	33.03
Min	31.88	32.21	31.83	31.96	32.04	32.44	32.86	32.88	33.11	33.03	32.73	32.41
247												
Mean	33.08	33.04	32.67	**32.62**	32.68	32.91	33.09	33.17	33.37	33.34	33.23	33.12
s	0.10	0.08	0.24	0.13	0.15	0.08	0.04	0.11	**0.01**	0.02	0.06	0.05
Max	33.19	33.15	32.92	32.77	32.90	33.03	33.13	33.37	33.41	33.39	33.32	33.22
Min	32.79	32.58	31.88	32.25	32.35	32.75	32.95	33.06	33.33	33.29	33.09	32.98

Table 4. Monthly means, standard deviations (s), maxima, and minima for temperature. Bold-faced values correspond to minimum monthly means (and standard deviations) and underlined values correspond to maximum monthly means (and standard deviations).

Pressure	**12/99**	**1/00**	**2/00**	**3/00**	**4/00**	**5/00**	**6/00**	**7/00**	**8/00**	**9/00**	**10/00**	**11/00**
20												
Mean	5.39	4.13	**3.86**	3.98	4.57	6.15	8.35	10.59	12.24	11.81	9.37	7.40
s	0.38	0.31	0.31	**0.16**	0.31	0.51	1.44	0.79	0.67	0.44	0.92	0.37
Max	6.40	4.84	4.56	4.42	5.44	6.99	10.66	12.07	13.62	12.71	11.54	8.09
Min	4.67	3.38	3.34	3.66	4.00	4.97	5.89	9.52	10.85	10.82	7.70	6.55
50												
Mean	5.84	4.30	**4.23**	4.27	4.63	5.40	6.12	6.89	7.67	9.80	9.60	8.17
S	0.43	0.36	0.25	**0.15**	0.18	0.28	0.51	0.51	0.61	0.99	0.47	0.50
Max	6.93	5.52	4.76	4.59	5.01	6.03	7.47	8.75	9.93	11.42	10.58	9.36
Min	5.01	3.61	3.50	3.98	4.27	4.87	5.24	5.98	6.19	6.93	8.27	7.12
91												
Mean	6.89	5.14	**4.61**	4.61	4.92	5.33	5.75	6.01	6.28	6.85	8.46	8.49
s	0.55	0.71	0.25	0.16	**0.14**	0.23	0.15	0.18	0.24	0.39	0.64	0.34
Max	8.21	6.45	4.98	5.00	5.28	6.24	6.08	6.46	6.96	7.62	9.75	9.20
Min	5.90	3.94	3.84	4.20	4.62	4.99	5.41	5.64	5.85	6.18	7.24	7.89
143												
Mean	6.91	5.99	5.17	**5.03**	5.20	5.57	5.68	5.82	5.72	6.01	6.58	7.51
s	0.33	0.51	0.27	0.20	0.15	0.17	**0.07**	**0.09**	**0.07**	0.14	0.33	0.47
Max	7.83	6.70	5.60	5.40	5.51	5.97	5.96	6.05	5.99	6.25	8.01	8.26
Min	5.99	4.61	4.47	4.56	4.87	5.23	5.58	5.65	5.63	5.72	5.93	6.58
195												
Mean	6.84	6.45	5.78	5.50	**5.48**	5.54	5.58	5.63	5.64	5.70	5.86	6.19
S	0.21	0.15	0.24	0.14	0.09	0.03	**0.02**	0.04	**0.02**	0.04	0.12	0.23
Max	7.45	6.72	6.09	5.76	5.66	5.62	5.62	5.71	5.68	5.80	6.20	7.03
Min	6.53	5.90	5.30	5.15	5.21	5.46	5.53	5.55	5.58	5.64	5.70	5.88
247												
Mean	6.42	6.51	5.96	5.72	**5.44**	5.53	5.64	5.66	5.61	5.64	5.72	5.84
s	0.14	0.06	0.20	0.10	0.11	0.08	**0.02**	0.04	**0.02**	**0.02**	0.04	0.06
Max	6.63	6.59	6.40	5.92	5.63	5.61	5.67	5.72	5.71	5.70	5.82	6.02
Min	6.11	6.33	5.39	5.44	5.21	5.34	5.61	5.56	5.59	5.61	5.66	5.73

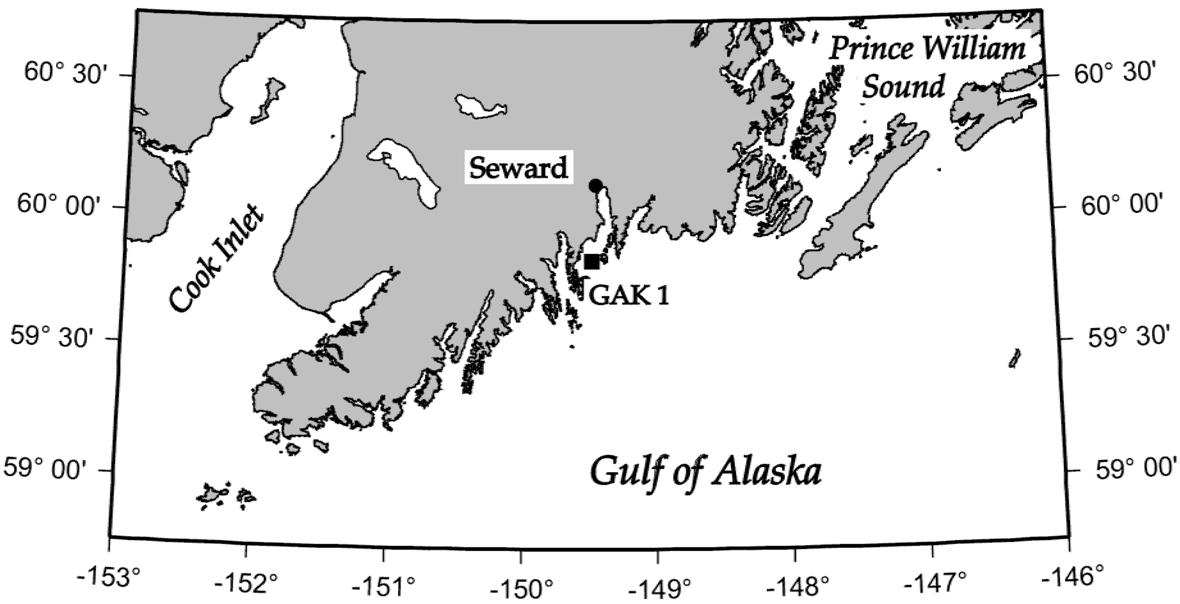

Figure 1. Location map for hydrographic station GAK 1 in the northern Gulf of Alaska.

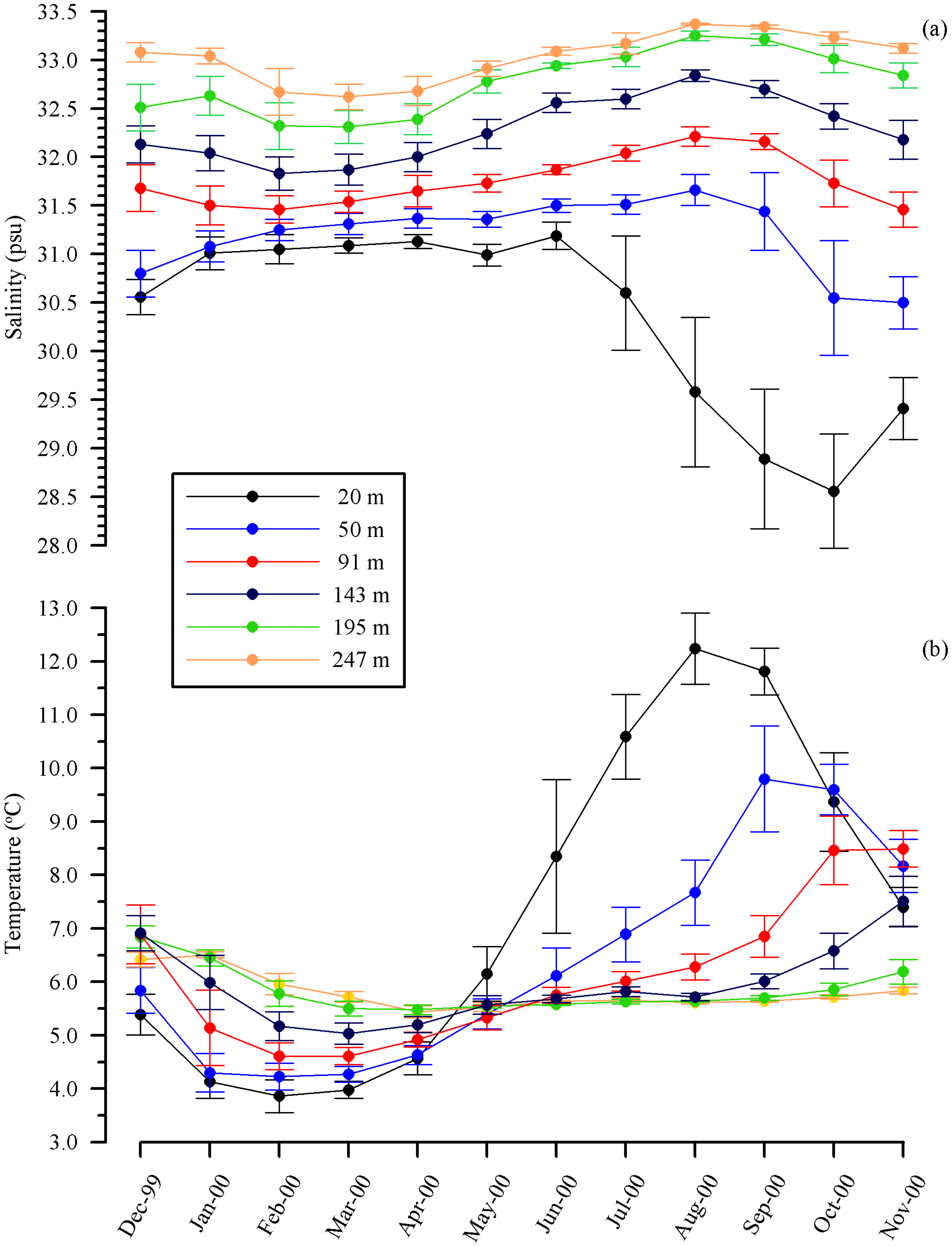

Figure 2. Mean monthly (a) salinity and (b) temperature at GAK 1 as measured at the depths of the temperature/conductivity recorders.

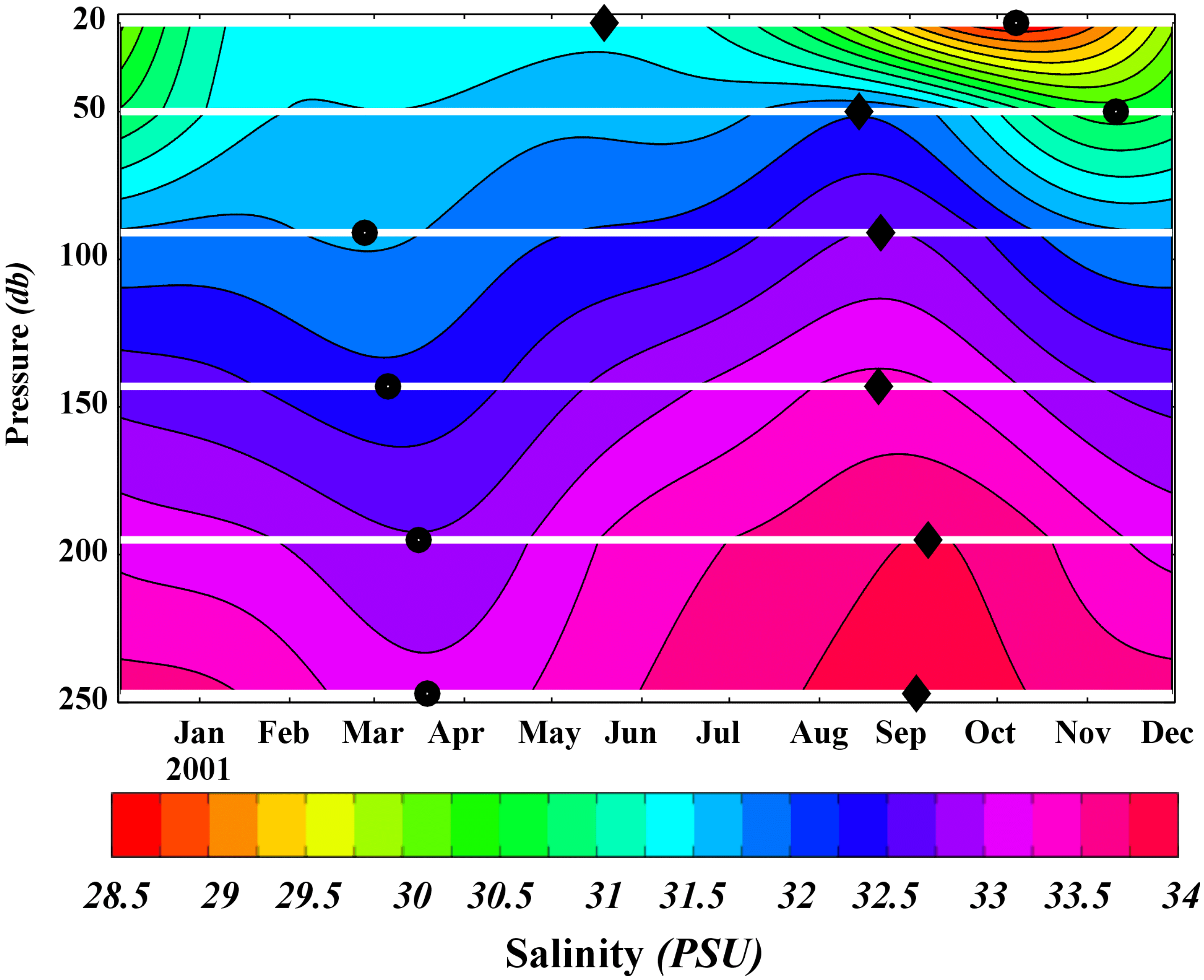

Figure 3. Salinity amplitude computed from a harmonic fit to the annual, semi-annual, and quarter-annual periods contoured as a function of time and depth. Phase information is reflected by the solid diamonds that show the time of maximum salinity at a given depth and the solid circles that show the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

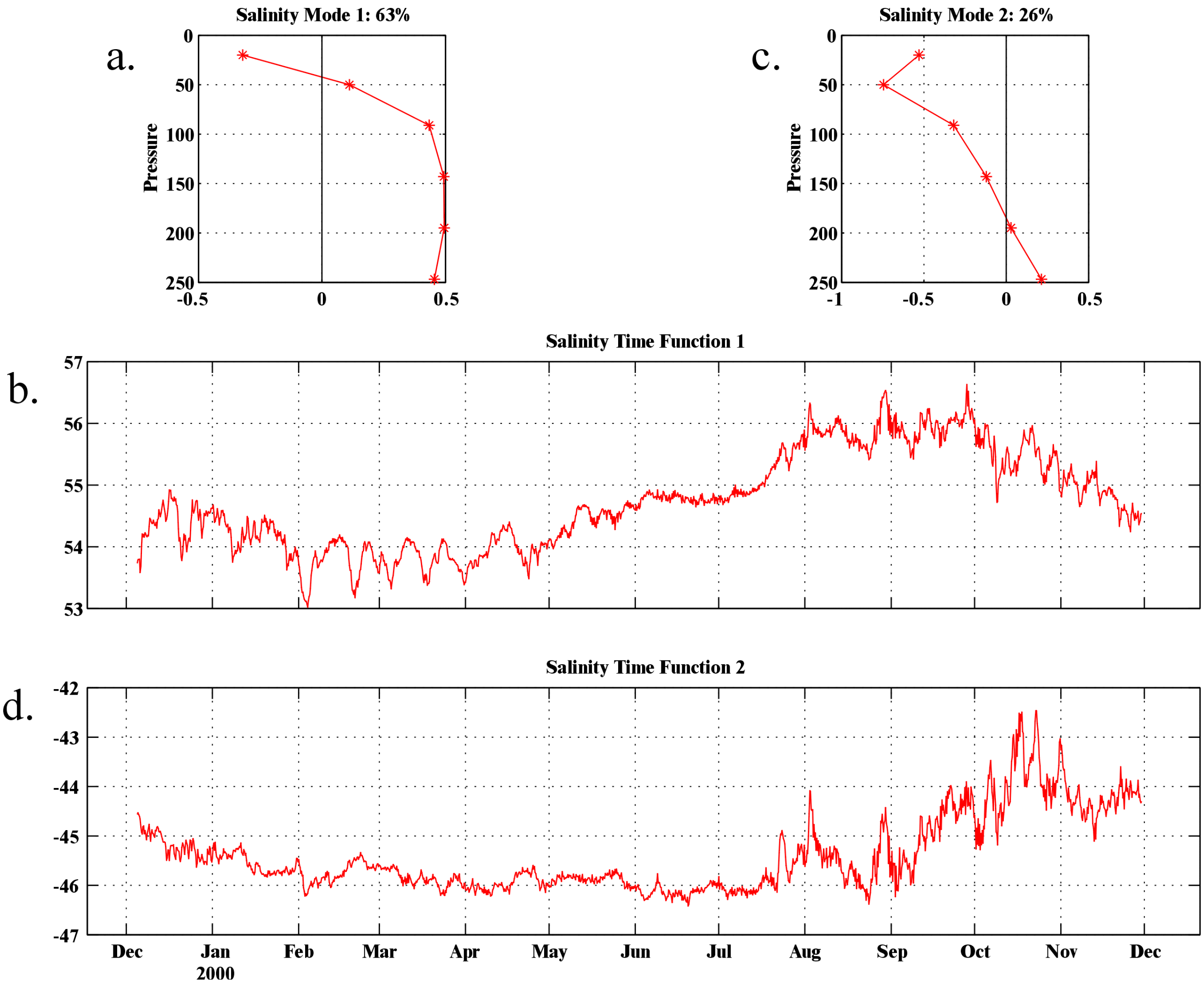

Figure 4. Empirical orthogonal function (EOF) analysis for salinity. a) the first eigenvector, b) the first time amplitude function, c) the second eigenvector, and d) its corresponding time amplitude function.

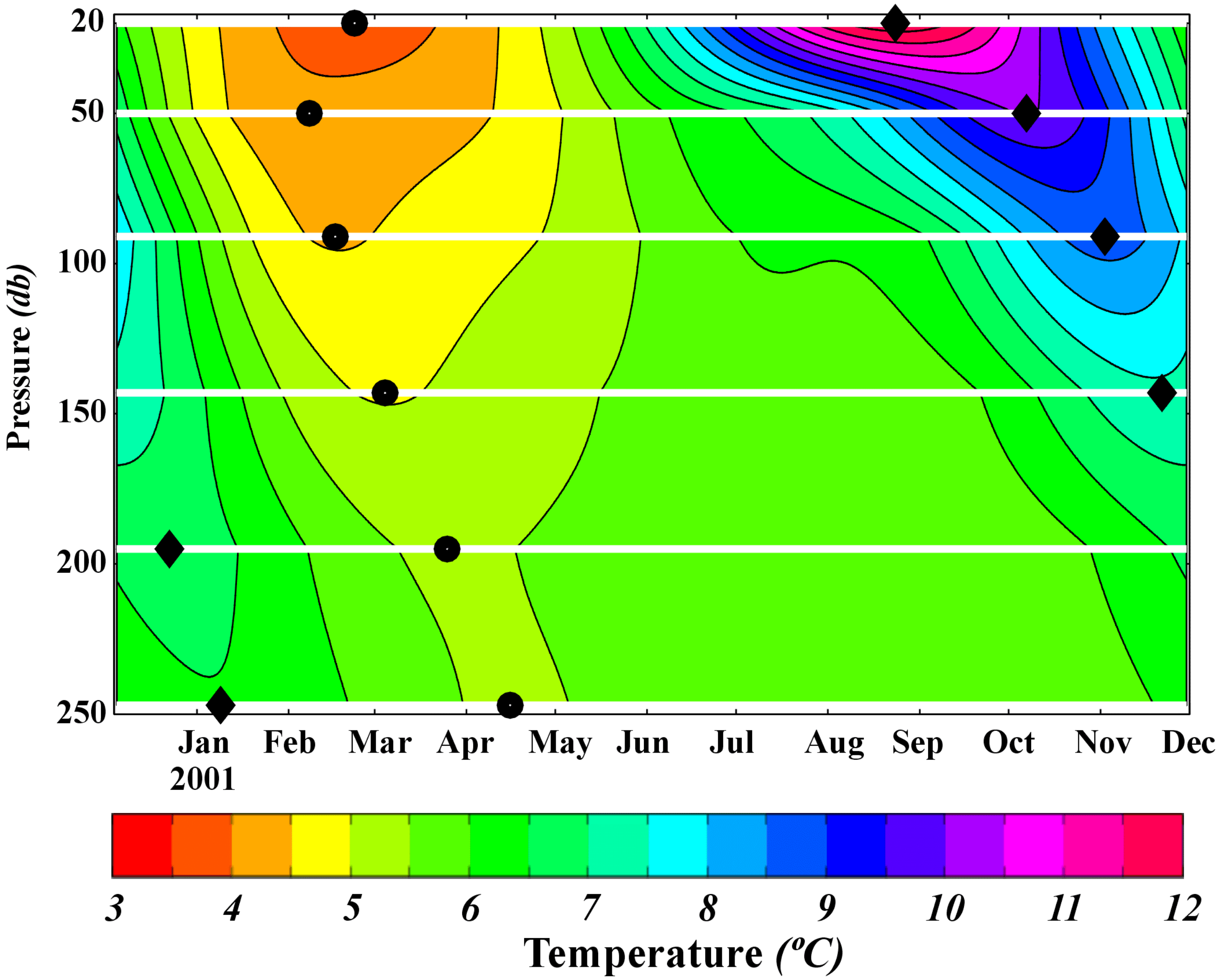

Figure 5. Temperature amplitude computed from a harmonic fit to the annual, semi-annual, and quarter-annual periods contoured as a function of time and depth. Phase information is reflected by the solid diamonds that show the time of maximum temperature at a given depth and the solid circles that show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

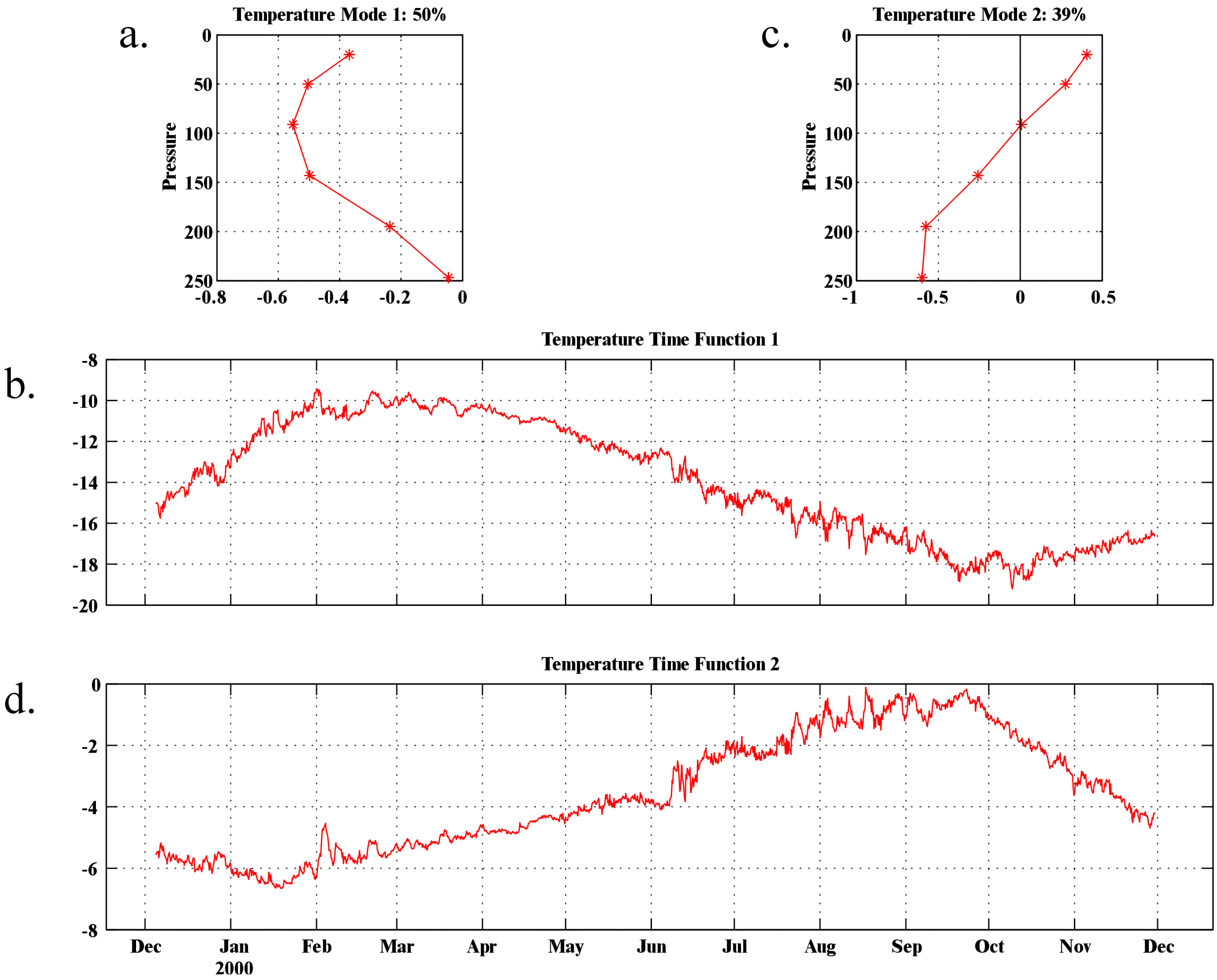

Figure 6. Empirical orthogonal function (EOF) analysis for temperature. a) the first eigenvector, b) the first time amplitude function, c) the second eigenvector, and d) its corresponding time amplitude function.

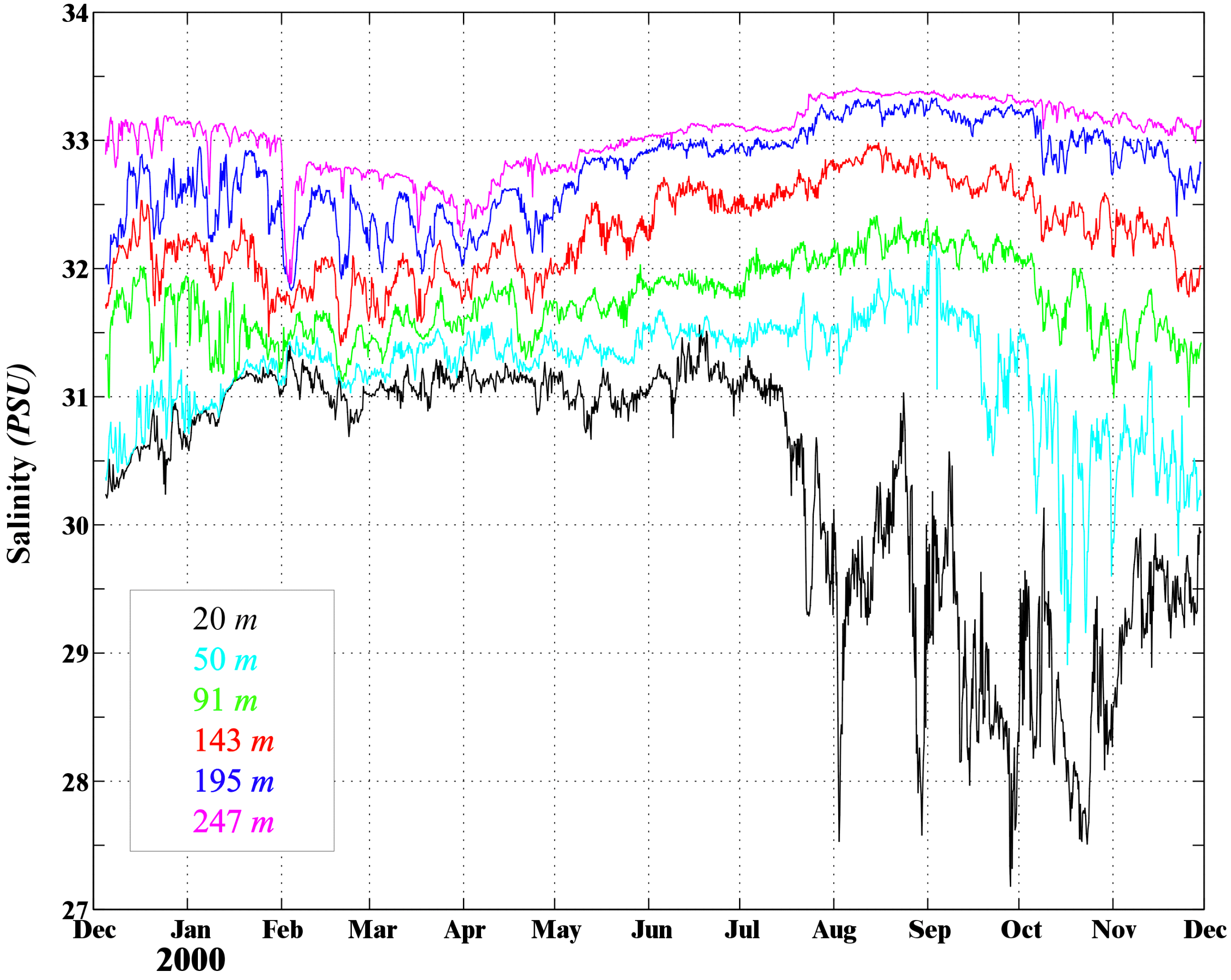

Figure 7. Time series of salinity at each depth from the GAK 1 mooring.

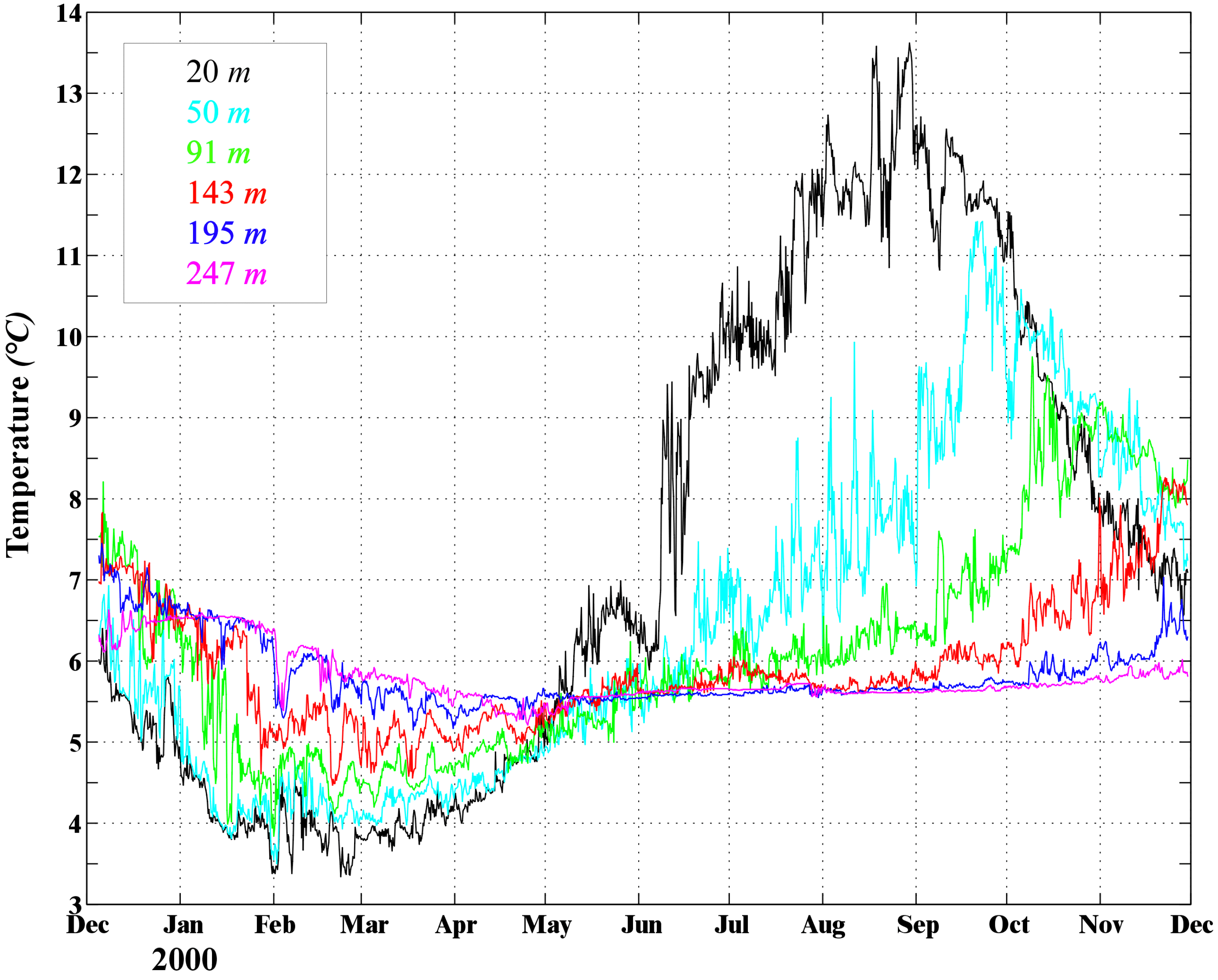

Figure 8. Time series of temperature at each depth from the GAK 1 mooring.

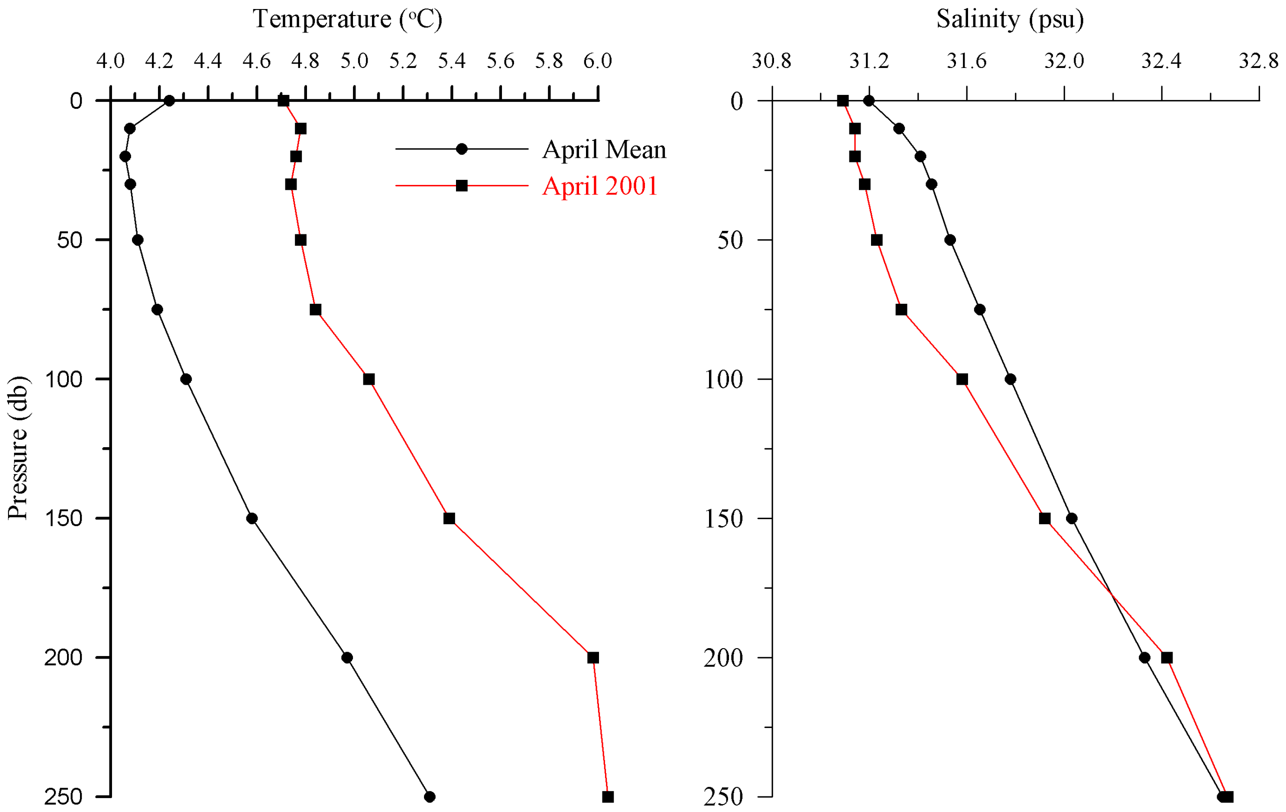

Figure 9. Comparison of vertical temperature and salinity profiles at GAK1 for April 2001 (solid square) and the long-term mean April profile (solid circles).