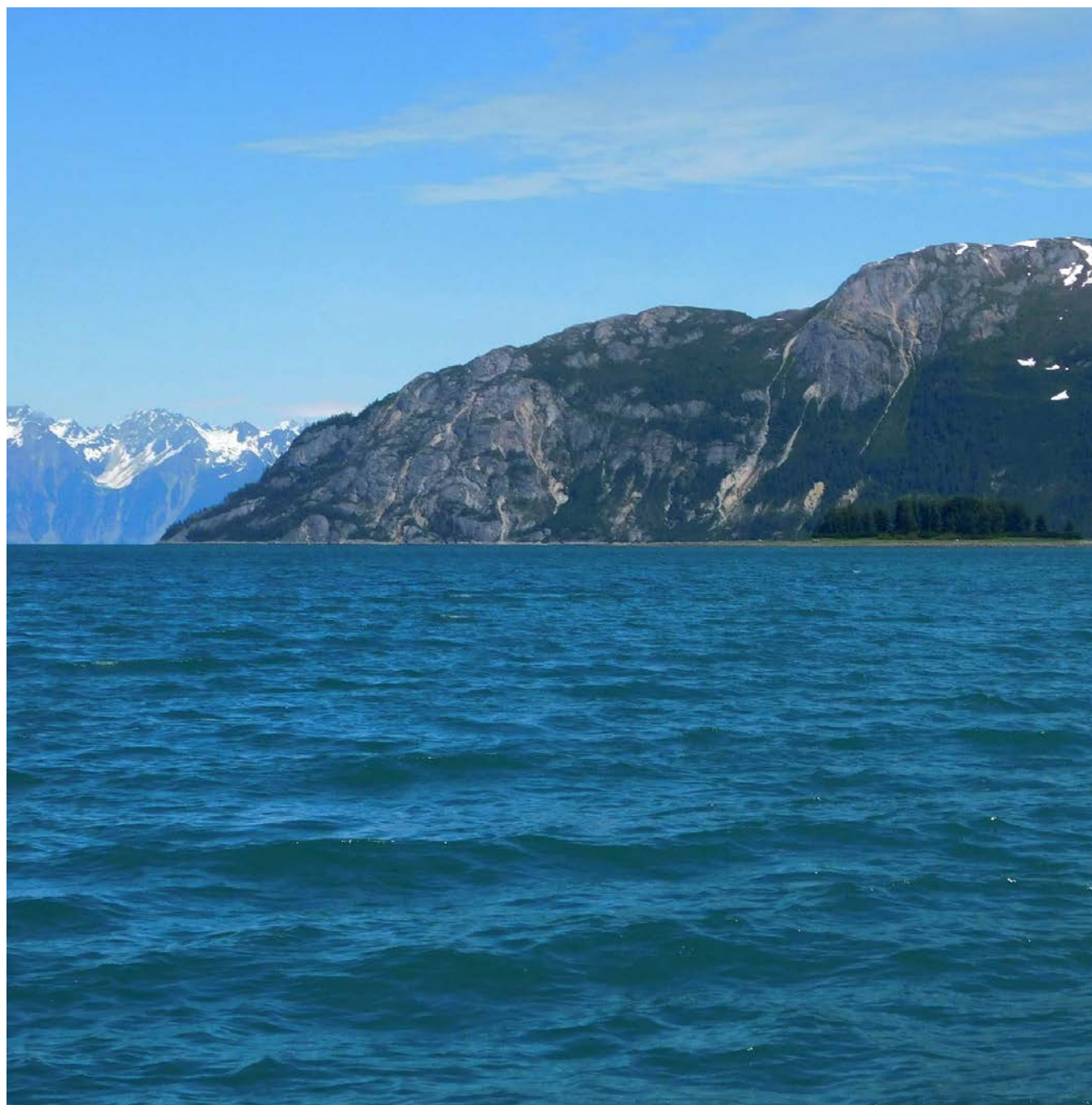




Glacier Bay Oceanographic Monitoring Program Analysis of Observations, 1993-2016





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Sandy Cove south shore at evening dusk.
Photo courtesy of Seth Danielson

ON THE COVER

Geikie Inlet, Glacier Bay, June 2016.
Photo courtesy of Seth Danielson

Glacier Bay Oceanographic Monitoring Program Analysis of Observations, 1993-2016

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Executive Summary

The Glacier Bay oceanographic monitoring data archive period of record (1993-2016) is newly analyzed in this report. As with the preceding report (Danielson 2012) covering 1993-2009, this document serves as a reference manual for thermal and haline oceanic conditions at fixed-location sampling stations throughout the bay. The mean annual cycle is characterized at each station throughout the water column using monthly averages. Monthly climatological hydrographic cross-sections show how the mean water column structure varies along the length of the fjord. Removing the climatology from each station's individual records generates monthly anomalies that are evaluated for trends and fluctuations occurring over seasonal to inter-annual time scales.

The dominant hydrographic signal for the 2010-2016 monitoring time period was a transition from relatively cool waters over 2007-2013 to a 2014-2016 marine heat wave, which drove average water temperatures throughout the bay to approximately 1.5 °C higher than normal. The warming was accompanied by a strong freshening that was equivalent to the addition of 3 km³ of fresh water to the bay, or a continuous excess of 50 m³ s⁻¹ of runoff over two years. Biological consequences of this relatively long-lived warming and freshening are still mostly unknown, but effects may be felt for years to come.

Some stations exhibit statistically significant increasing or decreasing trends (significance determined at the 95% confidence level) over the period of record at particular depths, but these trends are not yet large and ubiquitous enough to be detected unambiguously everywhere. At least some of these trends are driven by the unusually warm conditions of 2014-2016. A Monte Carlo bootstrapped variance analysis is used to anticipate the duration of sampling needed to detect trends of various magnitudes. Given the frequency of observations, the observed standard deviations, and the magnitude of long-term trends observed elsewhere in the Northeast Pacific, we expect to be able to detect a climate-driven warming trend at most stations with 20-50 years of sampling.

Comparison of the anomaly time series with large-scale climate indices such as the Pacific Decadal Oscillation (PDO) and the El Niño Southern Oscillation (ENSO) indicates that these modes of variability are clearly detectable in the waters of Glacier Bay, but they account for only a relatively modest fraction (<25%) of the total variance. Covariations with hydrographic observations from oceanographic station GAK1 (located in the northern coastal Gulf of Alaska near Seward, at the mouth of Resurrection Bay) are weak and generally not statistically significant. Hence, the Glacier Bay and GAK1 Resurrection Bay time series are both important records that contribute to our comprehensive understanding of coastal Gulf of Alaska oceanic conditions.

Ocean current measurements from moored current meters are analyzed for tidal and subtidal flows. The results provide estimates of tidal harmonic parameters for 35 tidal constituents at nine mooring sites. The velocity data provide context for the Glacier Bay hydrographic fields and they are important contributors to the overall character of the fjord's physical environment and its marine ecosystem.

The nature of the bay's physical and chemical hydrography changes from the southern portions of the fjord, where positive heat anomalies tend to accompany negative salt anomalies, to the northern reaches of the fjord where cool temperatures are associated with fresher waters derived from melting glacier ice. Analysis of the density structure on

either side of Sitakaday Narrows suggests that renewal of deep fjord waters occurs most readily between November and May, while renewal of intermediate depth waters likely occurs in summer months. It is clear that many factors affecting conditions on seasonal to inter-annual time scales are the result of processes occurring at sub-seasonal time scales locally within Glacier Bay. We provide recommendations for future oceanographic research directions that will lead to a deeper understanding of the bay's oceanography, with applications to both management needs and public education.

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I am indebted to Michael Bower, Brendan Moynahan, Lisa Etherington, Philip Hooe, Jim Lawler, and many other NPS personnel for their support and enduring encouragement to discover all Glacier Bay has to offer. Bill Johnson's clear guidance on the development, maintenance, and continued application of the oceanography protocol is greatly appreciated. This Glacier Bay oceanography report is the first with data additions that fall entirely after the implementation of OC2010.1 and it reaps many benefits of this still relatively new protocol. Most of all, I thank Lewis Sharman and Craig Murdoch for their steadfast reliability in continuing to the field work, and all other cruise participants who have contributed to this ever-growing data collection.

Data collections at oceanographic station GAK1 are supported by the Exxon Valdez Oil Spill Trustee Council through the Gulf Watch Alaska program <http://www.gulfwatchalaska.org/>.

Introduction

Background

Glacier Bay National Park and Preserve (GLBA; Figure 1) hosts an unusual combination of remote and untouched wilderness, continually evolving biological, glacial, and geological systems, a highly productive marine ecosystem, and the institutional infrastructure necessary to carry out and maintain long-term scientific monitoring and research programs. Two critical components of the park's mission include implementing the necessary scientific monitoring and research that are needed to properly administer the park's assets, and informing the visiting public about the park's ecology, history and importance. This report summarizes scientific findings from the 2010-2016 Southeast Alaska Network (SEAN) inventory and monitoring (I&M) program for the oceanography component.

This report is a reference manual for each of the monitoring stations' physical properties. Analyses and graphical depictions depict typical conditions and their fluctuations in time. The approach allows us to understand similarities between stations as well as differences that define each station's and region's unique attributes. The now 24-year record provides a robust climatology from which we compute monthly anomalies. The analysis does not attempt to incorporate historical Glacier Bay measurements (prior to 1993); however, these early data are used to describe and examine typical seasonal conditions in Glacier Bay and the adjoining Gulf of Alaska.

Oceanographic research expeditions in Glacier Bay first occurred in the mid-1960s, and the modern era of regular observations using high-accuracy conductivity-temperature-depth (CTD) instrumentation began in 1993. Early work focused on basic characterization of the fjord's circulation (although without the

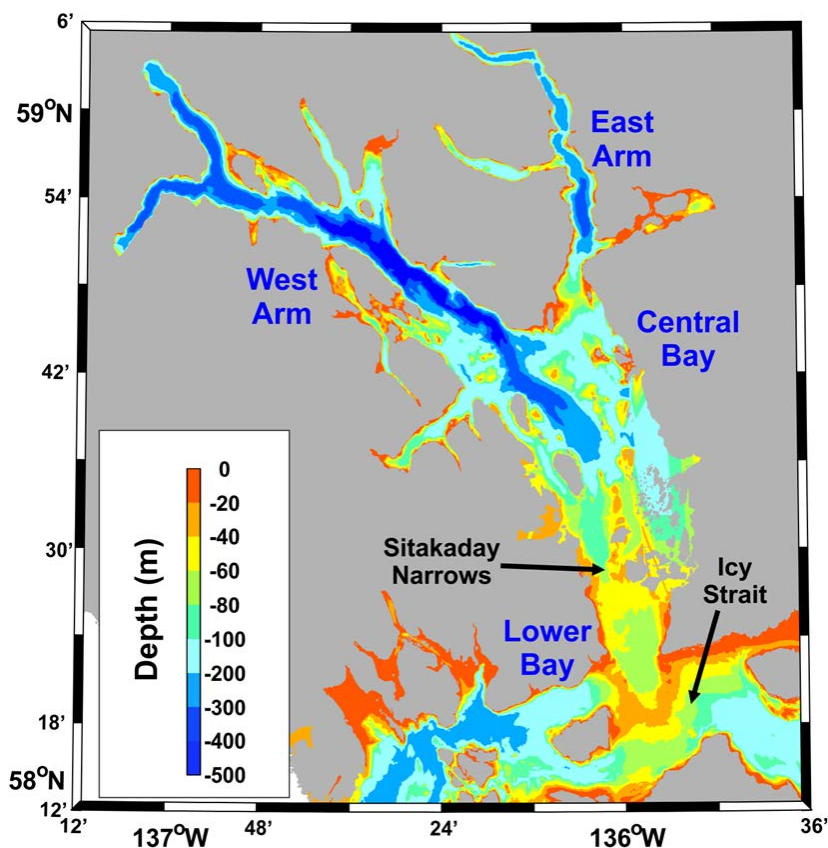


Figure 1. Map of Glacier Bay National Park and Preserve with insets to show location with respect to Alaska (above, top) and bathymetric map of Glacier Bay proper (above) showing the four primary monitoring regions (blue type). Note the non-linear depth scale.

benefit of direct current measurements) and seasonal property distributions (Pickard 1967, Matthews and Quinlan 1975). Matthews (1981) concluded that deep-water renewal takes place primarily between November and April, but a more recent report by Hooe and Hooe (2002) suggests that deep-water renewal events may occur episodically at any time of year. This issue remains pertinent today because understanding the underpinning of Glacier Bay's marine ecosystem dynamics requires a mechanistic description of the processes controlling the influx of nutrient-rich water and its subsequent residence time, utilization rates, and return pathways.

Regular oceanographic monitoring began in 1993, and these measurements documented inter-annual variability of the near-surface and sub-surface temperature and salinity fields. Oceanographic monitoring efforts in Glacier Bay were formalized with a sampling protocol that called for seasonal (quarterly) observations (Hooe et al. 2003). Following a 2006 program review (Etherington 2006), the National Park Service (NPS) Inventory and Monitoring Program committed to continuing the oceanographic sampling, and a subsequent 2009 protocol working group discussed program intent, implementation, and available resources (see Appendix E of Danielson et al. 2010). Following the template of Oakley et al. (2003), the original protocol was updated by Danielson et al. (2010), distributed for peer review, and published as protocol OC2010.1 (Danielson et al. 2010) and subsequently updated as OC2014.1 (Johnson and Sharman 2014). OC2010.1 more closely aligned the oceanography sampling effort with the program objectives listed in Etherington (2006). The most substantive changes from Hooe et al. (2003) to OC2010.1 and OC2014.1 include the following:

1. a reduction of the spatial resolution of sampling except in mid-summer (July) and mid-winter (December/January),
2. an increase of the temporal resolution at a select subset of seven stations between March and October,
3. the addition of one deep (150 m bottom depth) station outside of the fjord and the removal of two stations in Geikie Inlet and one in lower Muir Inlet, and
4. the implementation of a more fully automated and standardized system of data processing, error checking, and archiving.

OC2014.1 adds the new role of Data Steward, methods for maintaining backup instruments, references to the latest software, extended documentation, and numerous updates to process details. Data deliverables are essentially unchanged from OC-2010.1 and are fully compatible with the dataset processed under OC2010.1. OC2014.1 went into service at the beginning of the 2013 cruise year.

There now exist sufficient data in the monitoring record to enable comparisons to other long-term datasets and climate indices; comparisons to these other time series are used in this report to help place the Glacier Bay measurements into a broader regional context within the greater Northeast Pacific and within a global climate context with respect to large-scale climate indices. We expect that variability of Glacier Bay's property fields respond to local, regional, and global drivers. Comparisons to other time series help us identify pertinent linkages.

Despite the extensive research carried out within and near Glacier Bay over the course of the last century, there are relatively few process-oriented studies or publications that focus on the specific mechanisms controlling Glacier Bay's marine physics and marine ecosystem dynamics. Studies of the lower trophic levels (microbes, phytoplankton, and zooplankton) are particularly lacking.

While the basic oceanography of Glacier Bay is now relatively well described, and we are able to assess the monitoring time series for statistically significant trends, inter-annual variations and climate perturbations, there remain many important unanswered questions about this system.

The thriving marine ecosystem that supports unusually high concentrations of marine mammals and seabirds remains one of the main park attractions. We know that retreating tidewater glaciers over the last few hundred years have made this marine habitat newly accessible to wildlife, but we still do not fully understand the factors that today renew the euphotic zone with new nutrients; nor do we know whether these processes operate within a relatively stable range of extremes or if someday soon the system will again transform its character and ecosystem. Could the bay possibly become even more productive than it is presently, or is it already operating at or near some peak carrying capacity? Could changes in glacial discharge potentially alter the oceanographic structure of the bay so as to

reduce the overall productivity? The GLBA I&M oceanography program will help us document, describe, and understand whatever future changes this remarkable system will eventually experience. As time unfolds, our understanding of the mechanistic controls that regulate the system will improve, and we may find that we are eventually able to reasonably anticipate some of these future changes.

Regional Environmental Setting

Glacier Bay's physical environment—which fundamentally supports all biological components of the marine ecosystem—responds strongly to atmospheric forcing that is driven both by the influence of Aleutian Low storms (e.g., Figure 2) that propagate into the NE Gulf of Alaska, and the local meteorology of the fjord itself. Environmental variations measured by the Glacier Bay observations are driven by local atmospheric and oceanographic processes and by external influences, including climate variability and regional weather. In this section we review known processes that exert influence on Glacier Bay's oceanographic conditions.

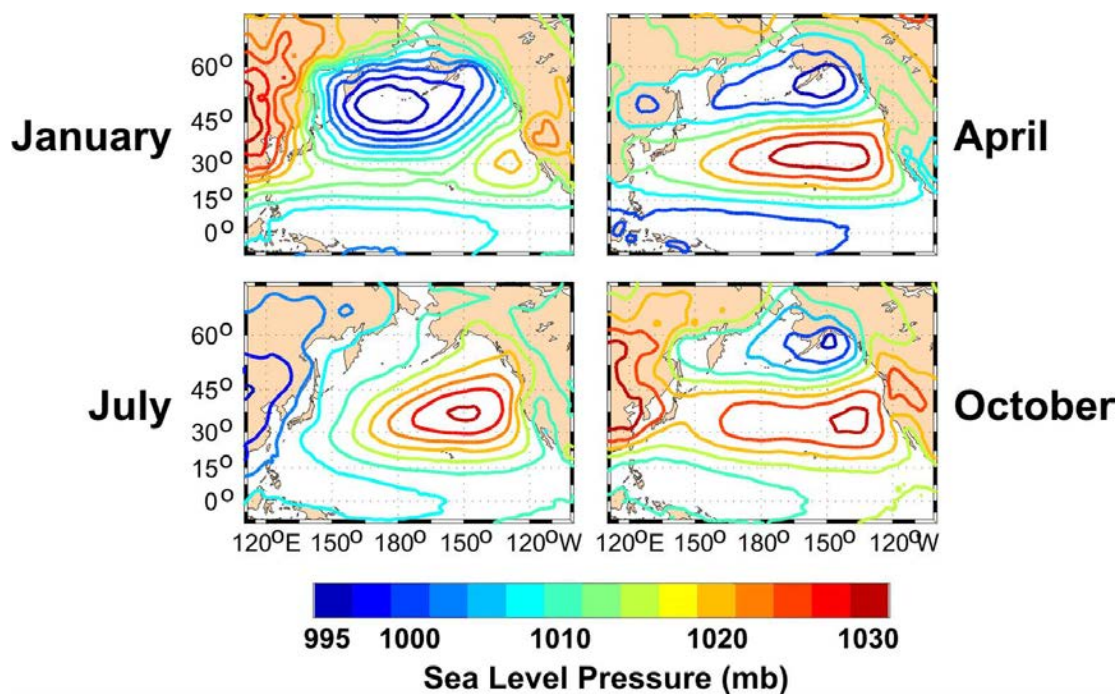


Figure 2. Mean atmospheric pressure at sea level contours for the North Pacific in January, April, July and October. The Aleutian Low atmospheric pressure system (blue colors) dominates the eastern Gulf of Alaska in winter, spring, and fall months; the North Pacific High atmospheric pressure system (red colors) dominates during summer months. Data from the NCEP/NCAR Reanalysis II (Kalnay et al. 1996).

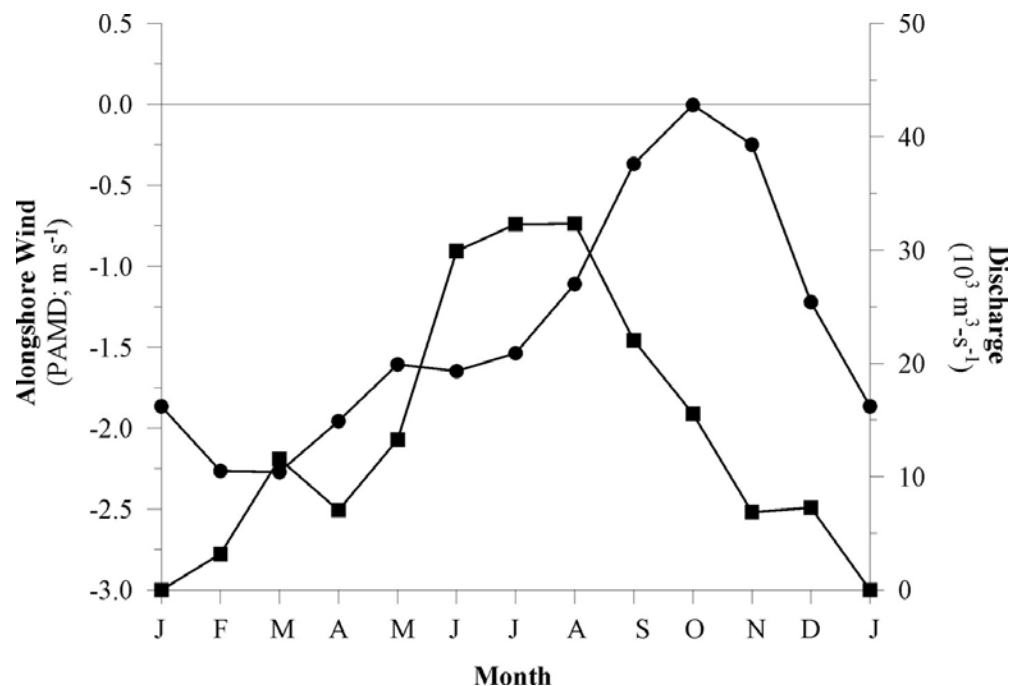
The meteorology and oceanography comprise a closely coupled system of interactions that also depend on the terrestrial geomorphology, hydrology, and cryosphere dynamics and feedbacks. Etherington et al. (2004) found that seasonal anomalies of near-surface temperature and salinity are related to anomalies in local day length, air temperature, and precipitation. Hill et al. (2009) showed that the strong seasonal discharge cycle (average range of 300-1,000 $\text{m}^3 \text{s}^{-1}$) is likely modulated by different discharge cycles from high-elevation vs. low-elevation watersheds, with peak discharge events reaching as high as 15,000 $\text{m}^3 \text{s}^{-1}$ due to new precipitation and melting of the seasonal snowpack. Matthews and Quinlan (1975) focused on the role of glacial ice meltwater in maintaining the high levels of salinity stratification. Freshwater effects are not confined to the bay's physics: Hood et al. (2008) provide estimates of dissolved and particulate carbon and nutrient loads in Southeast Alaska runoff.

Glacier Bay and the greater Gulf of Alaska are strongly impacted by the position and strength of storms associated with the Aleutian Low, a pattern of relatively low

atmospheric pressure that extends over much of the sub-Arctic North Pacific Ocean for much of the year (Figure 2). The Aleutian Low (assessed within the mean sea level pressure field) reflects the tendency of individual (synoptic) low pressure storm systems to propagate from the western North Pacific northeastward into the Bering Sea or eastward into the Gulf of Alaska. The sea level pressure (SLP) varies spatially and synoptically, seasonally, and inter-annually in time. On a seasonal basis in the Gulf of Alaska, the North Pacific High dominates in summer, while the Aleutian Low dominates in winter (Figure 2). The variability in these patterns directly impacts eastern Gulf of Alaska coastal waters. For example, cold continental air (arctic air masses) on a winter storm's northern/western flanks can be advected over the coastal region in mid-winter. Winds associated with Aleutian Low storm systems' southern flank carry warm and moist air masses from the subtropical Pacific Ocean toward Southeast Alaska, resulting in high precipitation rates and relatively elevated temperatures.

Figure 3 (squares, left axis) shows the magnitude and sign of the downwelling

Figure 3. Annual cycle of the northeastern Gulf of Alaska along-coast wind velocity (squares; left axis) measured at Middleton Island, and the coastal fresh water discharge (circles, right axis), after Royer (1982). Note that the discharge cycle is representative of the entire northeastern Gulf of Alaska; timing of local discharge in Glacier Bay likely varies somewhat. Reproduced from Weingartner et al. (2005). PAMD is the National Weather Service designator for the meteorological station on Middleton Island.



wind in the northeastern Gulf of Alaska, computed as a function of the along-coast wind speed. This component of the wind forcing helps drive the Alaska Coastal Current (ACC) because strong downwelling wind stresses help keep the fresh ACC plume confined relatively close to shore. By driving the plume on-shore, the oceanic horizontal (cross-shore) density gradient increases, thereby accelerating the ACC in the along-shore direction. Thus, advective connections (ACC strength and location) along the eastern Gulf of Alaska coastal zone are also modulated by the wind field, which is set up by the position and strength of the Aleutian Low's storm systems.

Warm air temperatures also contribute to melt of the high-altitude snowpack, so we may expect a cascade of consequences to follow shifts in the wind strength and/or direction that accompany changes in the Aleutian Low. For example, temperatures drive the terrestrial freeze/thaw cycles, which along with precipitation subsequently determine the volume of coastal fresh water discharge from land into the ocean. This runoff (Figure 3, circles, right axis) feeds the

ACC (Figure 4), which is a wind- and buoyancy-driven nearshore current that serves as an important nearshore habitat and advective pathway (Weingartner et al. 2005, Stabeno et al. 2016). In cross section, the ACC manifests as a low-salinity wedge of water that is bounded by the coast and tapers offshore. Its structure changes seasonally as a function of the coastal discharge and the surface wind stress. The ACC serves as a seasonally varying reservoir of fresh water that eventually is dispersed downstream (westward along the coast) and offshore. Strongly stratified low-salinity coastal waters inhibit vertical mixing and so reduce entrainment of sub-pycnocline nutrients into the euphotic zone where primary producers are dependent upon nutrients for growth and reproduction. In addition to tidal energy, Aleutian Low winds provide energy for mixing (breakdown of density stratification) and advection.

Local conditions in Glacier Bay are modulated by the global climate, which evolves under the influence of numerous modes of atmospheric and oceanographic processes. Major climate indices that track the temporal evolution of some

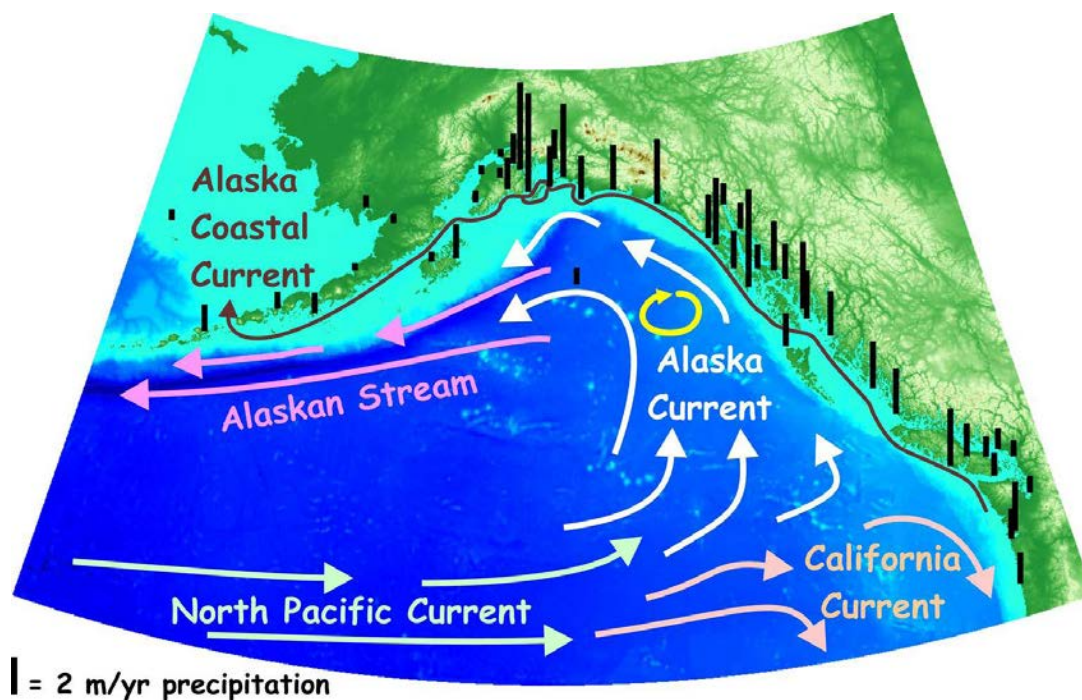


Figure 4. Idealized circulation map showing annual precipitation rates (vertical bars) and the large-scale oceanic circulation features in the Gulf of Alaska. Topographic elevations are shaded in green to brown; bathymetric depths are shaded in blue. Reprinted from Weingartner et al. (2005).

of these fluctuations are depicted in Figure 5: the Pacific Decadal Oscillation (PDO) sea surface temperature index, the North Pacific Gyre Oscillation (NPGO) sea level height index, the El-Niño Southern Oscillation (ENSO) sea surface temperature index, and the Pacific-North American (PNA) sea level pressure index.

The PDO is the leading mode of North Pacific sea surface temperature (SST) variability (Mantua et al. 1997). It exhibits decadal-scale and multi-decadal scale temporal variability, and its spatial pattern

shows that the western North Pacific fluctuates in an out-of-phase relation to the coastal Gulf of Alaska and the eastern equatorial Pacific (Figure 6).

The NPGO is the second dominant pattern of sea surface height variability in the North Pacific Ocean (Figure 7), and its spatial structure shows a three-pole pattern in the eastern North Pacific, with the Gulf of Alaska and the ocean region adjacent to California and Mexico fluctuating in phase with each other and an out-of-phase center situated between the

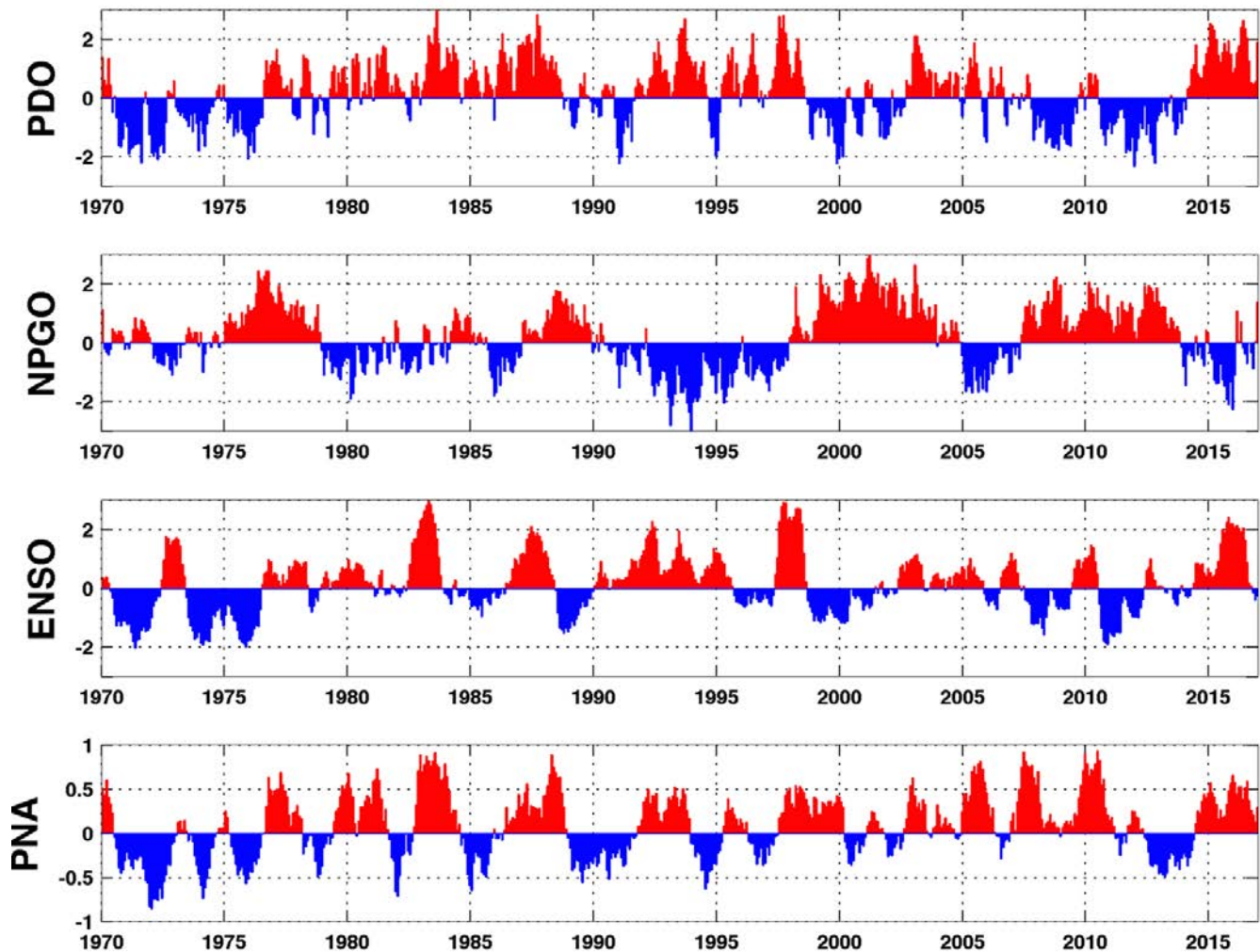


Figure 5. Normalized monthly anomalies since 1970 of the following major climate indices: the Pacific Decadal Oscillation (PDO; data from <http://jisao.washington.edu/pdo/PDO.latest>) sea surface temperature index, the North Pacific Gyre Oscillation (NPGO; data from <http://www.o3d.org/npgo/npggo.php>) sea level height index, the El-Niño Southern Oscillation (ENSO; multivariate ENSO index data from <http://www.esrl.noaa.gov/psd/enso/mei/table.html>) sea surface temperature index, and the Pacific-North American (PNA; data from <https://www.ncdc.noaa.gov/teleconnections/pna/>) sea level pressure index. They are shown as normalized standard anomalies: each record is transformed by removing the monthly mean value and dividing by the standard deviation so that each resultant index has a mean of zero, unity standard deviation, and no associated units. The PNA record has been further smoothed with an 11-month running average filter.

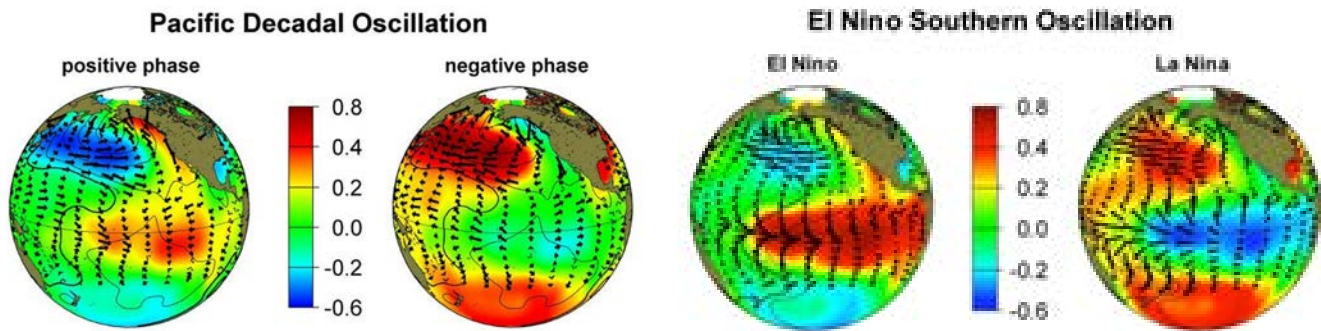


Figure 6. Spatial structure of the PDO (left two panels) and ENSO (right two panels) modes of SST variability. Colors depict the SST anomaly, vectors depict wind stress anomalies, and contours denote structure of the SLP field. Images from <http://jisao.washington.edu/pdo/>.

two (DiLorenzo et al. 2008). The NPGO is closely correlated with salinity and nitrate fluctuations along the southern Gulf of Alaska Line P section (Figure 7). Nitrate is an important macronutrient that often limits marine primary productivity in the North Pacific.

ENSO (Figure 6 right panels) is a tropical climate mode of variability with dominant fluctuations in the 3-5 year time frame. Development of El-Niño conditions triggers atmospheric teleconnections along

the eastern North Pacific, and atmospheric modal patterns result in oceanic temperature fluctuations observed from the equator to the northern Gulf of Alaska. While the ENSO and PDO patterns are similar in shape, the locations where the largest amplitude fluctuations occur are different, their spectral contents differ, and the associated wind stress patterns differ.

Whereas the PDO, NPGO, and ENSO are all measures of oceanic variability, the PNA (Figure 8) reflects atmospheric

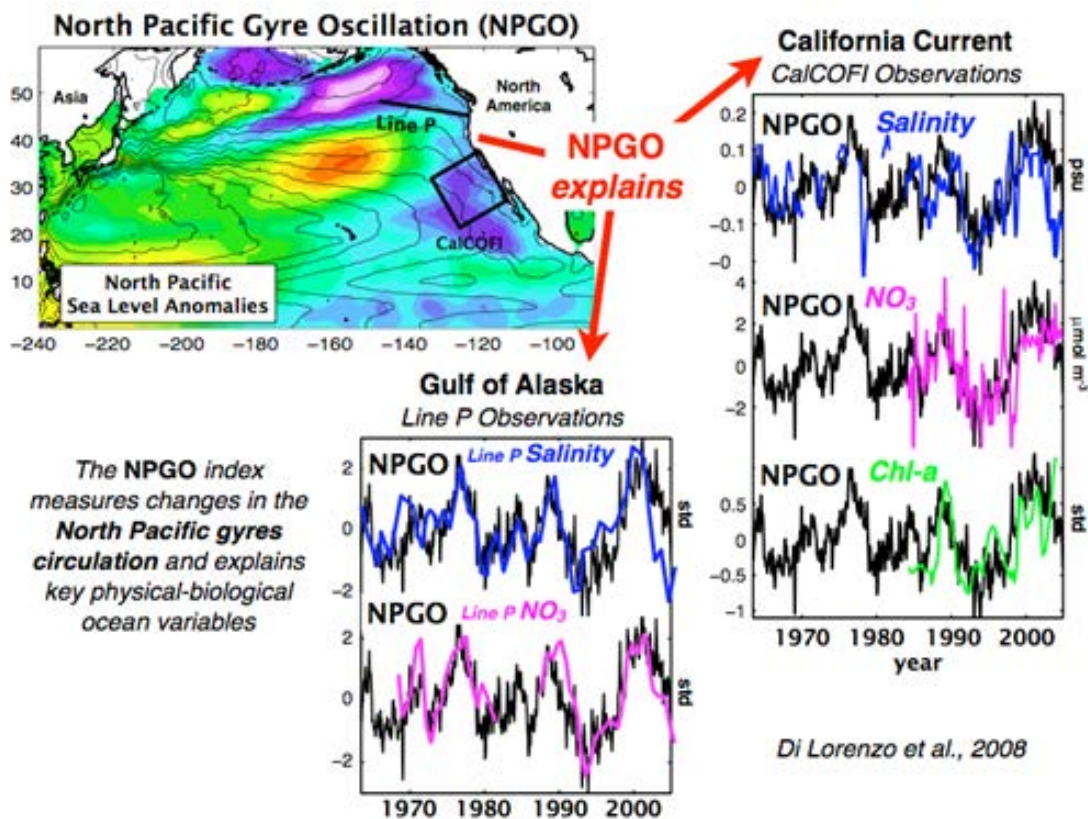


Figure 7. Spatial pattern of the NPGO (upper left) along with time series of salinity, nitrate, and chlorophyll fluorescence fluctuations along Line P (lower) and in the CalCOFI (California Cooperative Oceanic Fisheries Investigations) observation area (right). Image from <http://www.o3d.org/npgo/>.

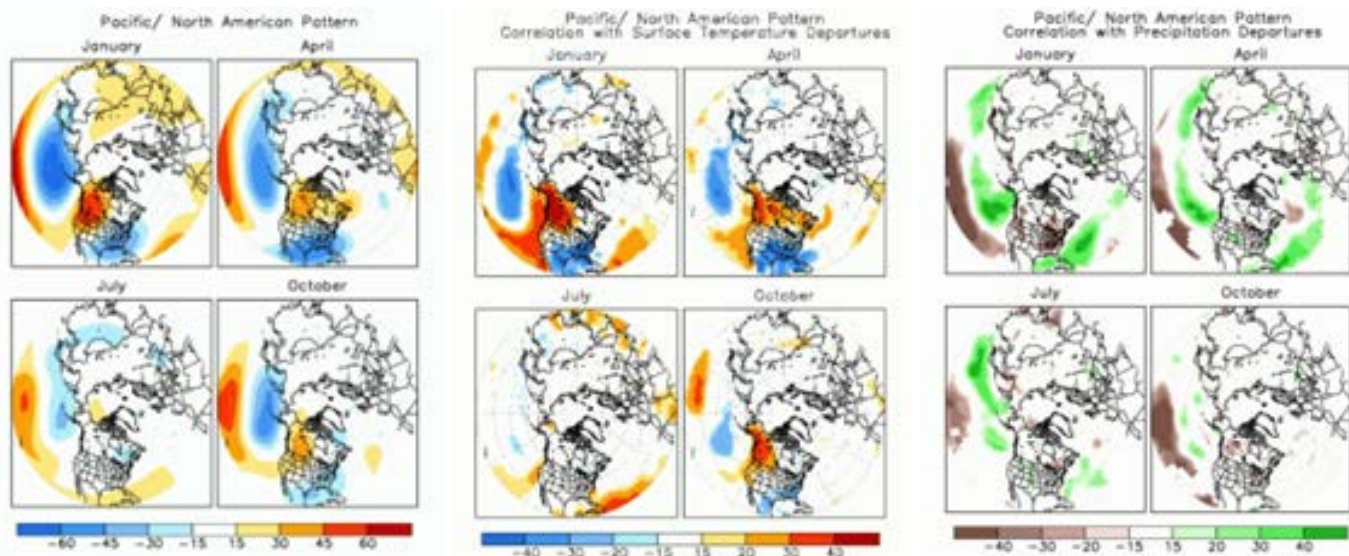


Figure 8. Maps for January, April, July, and October of the PNA pattern (left) and its correlation with temperature (center) and precipitation (right). Images downloaded from: <http://www.cpc.ncep.noaa.gov/data/teledoc/pna.shtml>.

conditions more directly: it is the second leading mode of atmospheric pressure variability in the northern hemisphere, normally evaluated at the 700 mbar level (van den Dool et al. 2000). The PNA exhibits much higher frequency variability than the oceanic indices. The PNA is closely related to the North Pacific (NP) index, which is the average of the sea level pressure over the box delimited by (30 – 65 °N, 160 °E – 140 °W) and so is a measure of the strength of the Aleutian Low over

its normal winter location (Figure 2). The PNA's pattern depicts opposing phases centered over the northern North Pacific and the continental United States (Figure 8). The location and strength of Aleutian Low storm systems are the North Pacific manifestation of the PNA, and so they control or impact advection of air masses, cloud cover, precipitation rates, and air temperatures, along with oceanic wind-driven mixing and wind-driven circulation fields.

Methods

Detailed background information, objectives, sampling rationale, sampling design, field procedures, equipment lists, reporting requirements, and data handling algorithms are documented in OC2010.1; we provide a brief overview below. Previous studies (e.g., Etherington et al. 2007) identified four primary biophysical domains within Glacier Bay (Figure 9):

1. **Lower Bay** stations are in Sitakaday Narrows, over the entrance sill of the fjord and in Icy Strait (00-03, 24);
2. **Central Bay** stations (04, 05, 13-15) are north of the sill in the widest portion of the fjord;
3. **East Arm** stations (16-20) extend into Muir Inlet;
4. **West Arm** stations (06-12 and 21) extend into Tarr Inlet.

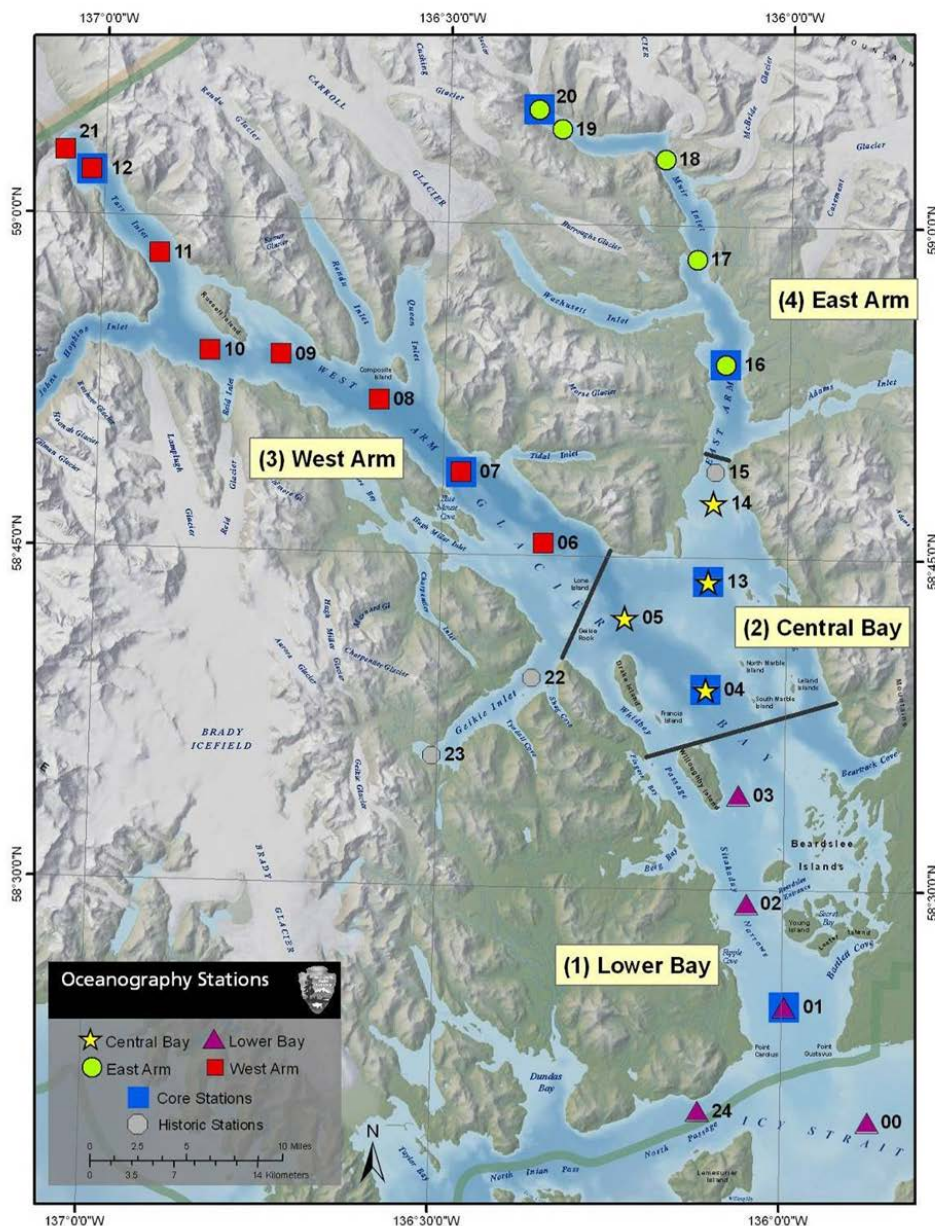


Figure 9. Oceanographic sampling station locations are depicted with numbers and symbols. The four primary domains—separated by solid black lines—are delimited with different station symbols. Stations comprising the core station set are shown within dark blue squares. Blue background shading depicts bathymetric depths, with darker (lighter) colors corresponding to deeper (shallower) waters.

Sampling and Field Protocol

The NPS Glacier Bay CTD makes direct measurements of pressure, temperature, conductivity, chlorophyll fluorescence, dissolved oxygen (DO), photosynthetically available radiation (PAR), and optical backscatter (OBS). Derived values from these measurements yield water column profiles of depth, salinity, density, chlorophyll-a concentration, and turbidity. The sampling plan includes CTD profiles at (1) the “full” station set twice per year: mid-summer (July) and mid-winter (December or January), and (2) the “core” station set in March, April, May, June, August, September, and October. The full station set includes Stations 00-14, 16-21, and 24; the core station set includes Stations 01, 04, 07, 12, 13, 16, 20, and 24. Stations 15, 22, and 23 are no longer sampled. The monthly samples from March through October ensure that the program resolves seasonal signals during the most biologically active period of the year. The higher density sampling in mid-summer and mid-winter ensures that locally isolated ecosystem changes can also be evaluated by this program in the future.

The sampling instrumentation employed in the monitoring effort is a SeaBird Instruments, Inc. 19+V2 CTD data logger. Accuracy of the SeaBird temperature probe is better than 0.005 °C, sufficient for documenting Glacier Bay’s highly variable coastal environment, where horizontal and vertical gradients are often quite large. Salinity (derived from the conductivity, pressure and temperature measurements), temperature, and pressure are used to compute water density; these three parameters form the basis of the physical system monitoring carried out in this program.

Prior to each CTD downcast, the instrument is allowed to equilibrate just below the surface for two minutes before initiating the vertical profile. The CTD is lowered at ~60 m/min (1 m/s) in the

uppermost 50 m and at ~100 m/min (1.7 m/s) for depths below 50 m. Note that samples taken before 2009 employed a shorter surface soak period and did not implement the slower near-surface descent rate.

Ancillary sensors on the CTD (photosynthetically available radiation [PAR], fluorescence, optical backscatter [OBS], and dissolved oxygen [DO]) provide information about biologically important parameters. The ancillary parameters are less easily assessed in the integrative or time series approaches employed in this document because of the various qualifications associated with each measurement. For example, PAR levels are impacted by the time of day, clouds, and sampling vessel shadows. Fluorescence, turbidity and oxygen measurements are not calibrated with in-situ seawater analyses and so provide at best relative levels of each parameter. Different species of phytoplankton can have different responses to activation by fluorometers operating at different wavelengths, so stations that host different phytoplankton species assemblages may provide different profiles that are not solely related to the concentration of fluorescing phytoplankton or chlorophyll-a concentrations. The relative values are useful measures, but care must be taken to view them in proper context and with an understanding of their limitations. Comparisons of chlorophyll-a fluorescence among seasons and years are limiting for the same reasons. Furthermore, some of these parameters exhibit highly non-linear seasonal responses (e.g., spring bloom timing or coastal discharge suspended sediment load) that are highly susceptible to temporal aliasing. This report devotes relatively little attention to these secondary measurements.

Processing, Verification, and Archiving

The CTD data are processed using the SeaBird, Inc. (2010) SBE Data Processing algorithms as described in OC2010.1 (Danielson et al. 2010) and more recently OC2014.1 (Johnson et al. 2014). Data are processed in 1-m bins between the surface and the deepest attained depth level. The processing follows the manufacturer recommendations for algorithm settings and is fully automated, including the generation of vertical profile plots of all parameters immediately following a cruise. Visual inspection of the profiles immediately after the cruise by the program manager ensures algorithm and measurement fidelity. Annual calibrations of the CTD at the instrument manufacturer's calibration facility quantifies sensor drift and bounds the accuracy of the measurements. The processed data are either verified for inclusion within the database or additional steps are taken to address problematic profiles as needed.

The oceanographic program protocol (OC2014.1 and previously OC2010.1), reports, and data are available at the NPS Southeast Alaska Network (SEAN) I&M website: http://science.nature.nps.gov/im/units/sean/OC_Main.aspx. Original calibration coefficients, raw data, and processed data are archived online; verified and final 1-m data are uploaded to the NPS database for permanent storage. Archived material also includes field log sheets and legacy copies of the sampling protocol.

1993-2008 Data Reprocessing

In 2010, the SEAN I&M program undertook a complete re-processing of all past Glacier Bay oceanographic data collected between 1993 and 2008 following the procedure described in OC2010.1. This reprocessing was warranted because of a number of problems identified in the historic database, including portions of

fields appearing in the wrong columns, mis-coded latitude/longitude position data, and erroneous constant values in measurement fields. As a test case, all data from 2008 were re-processed using (intermediate but unpublished) protocol OC2009.1 (Danielson et al. 2009). Comparing results from the original and re-processed, we found that the OC2009.1 processing resulted in a noticeably cleaner dataset, with fewer T/C/S spikes and fewer density inversions. Additionally, all temperature records from two entire CTD downloads were found to be listed with 0.000 °C readings in the legacy dataset. For these reasons, we concluded that a re-processing of all historical data was warranted. The reprocessing ensures that all data collected since 1993 have been handled similarly to the degree possible. Some measurement differences will always exist: early cruises did not employ pumped conductivity cells and employed a shorter surface soak time, for example. Allowances were made in the processing algorithms to accommodate these special cases.

Sampling Coverage

Sampling extends over 1993 to 2016, with a variety of measurement parameters and frequencies (Figure 10). For field sampling and data processing, the shift from the Hooke et al. (2003) protocol to OC2009.1 was implemented in March 2009. Historic data (1993-2009) were re-processed following OC2010.1. Other oceanographic data for Glacier Bay, which are not part of this database, are archived within the National Ocean Data Center (NODC) World Ocean Database-2009 (WOD09; Boyer et al. 2000).

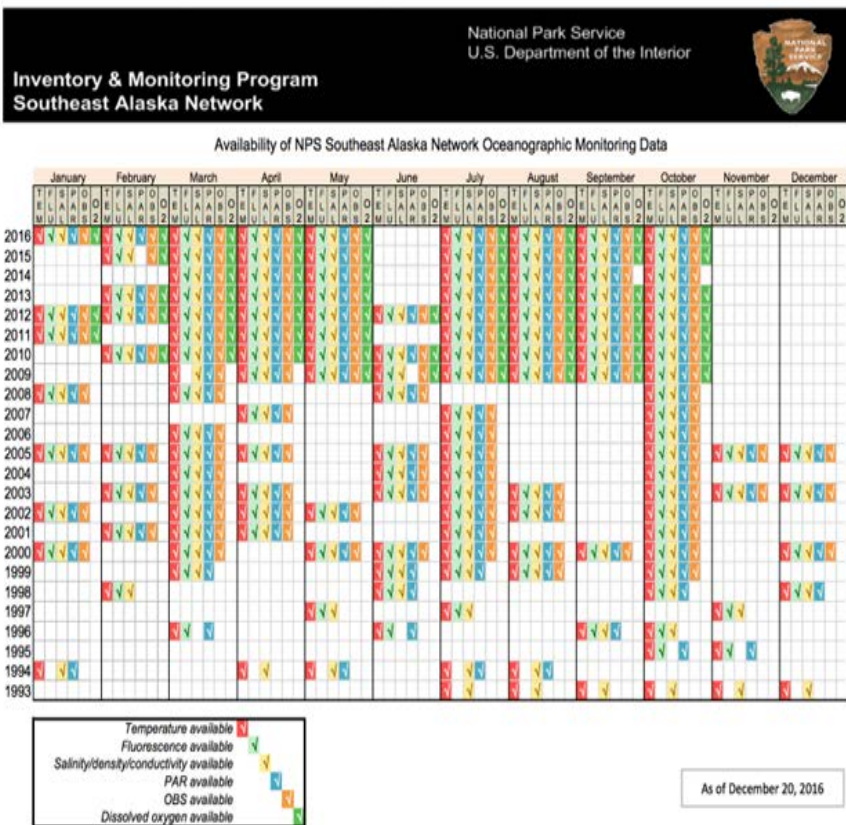


Figure 10. Sampling coverage from 1993-2016, depicting sample month and measurement type as denoted by the legend.

Analytical Techniques

Data are processed using the manufacturer's SBE Data Processing software (SeaBird, Inc. 2010) and then imported into the MATLAB computing environment (MATLAB and Statistics Toolbox Release 2017b, The MathWorks, Inc., Natick, Massachusetts, United States) for graphical visualization and statistical analyses. Station-specific climatologies are generated by creating monthly means for each station and at each depth level, after linearly interpolating between any data gaps in the middle of the water column. Monthly anomalies are generated at each station and at each depth level by subtracting the corresponding monthly climatology from each monthly profile.

Analyses include mathematical means, standard deviations, univariate regressions using Pearson's correlation coefficient, and best-fit linear trends using a sum of square error criteria. We search for correlative

relations between the Glacier Bay data and other time series using the Pearson's correlation and the p-value appropriate for $N-2$ degrees of freedom where N is the number of unique monthly observations. This approach is somewhat sensitive to auto-correlations and the presence of outliers. We employ standard anomalies that are normalized to unity variance and zero mean, and unscaled anomalies that retain units of the original parameter. Harmonic analysis of the tidal current ellipse constituents are computed using the MATLAB T_Tide toolbox (Pawlowicz et al. 2003).

Other Data Sources

Meteorological data from the National Weather Service station in Gustavus, Alaska (station ID 25322/703670) were downloaded from the National Climate Data Center on 24 April 2017. Data spanned spanning 1976-2016, although records prior to July 1987 were sparse.

Data were assessed for stuck sensor and other faulty readings; questionable data were eliminated.

Hydrographic data from the World Ocean Database were downloaded from the National Ocean Data Center (NODC) 2009 archive (WOD09; Boyer et al. 2009). These data were visualized using the Ocean Data View software package.

Sea surface temperature data were assembled using the Extended Reconstructed Sea Surface Temperature (ERSST) compilation version 3 (Smith et al. 2010), see <https://www.ncei.noaa.gov/access/metadata/landing-page/bin/iso?id=gov.noaa.ncdc:C00833>

Sea surface temperature anomaly maps are from NOAA's Center for Environmental Prediction (NCEP) at http://www.emc.ncep.noaa.gov/research/cmb/sst_analysis/

Ocean current data was collected in Glacier Bay by the National Ocean Service's (NOS) Center for Operational Oceanographic Products and Services (CO-OPS). Data was downloaded from <https://tidesandcurrents.noaa.gov/products.html>

Hydrographic data at station GAK1 in the northern Gulf of Alaska is collected by the University of Alaska Fairbanks with support from the Exxon Valdez Oil Spill Trustee Council. Data is available from: <https://nga.lternet.edu/data-overview/signature-datasets/>

Hydrographic data from profiling floats in the NE Pacific were accessed from Roemmich and Gilson (2009) and available from https://sio-argo.ucsd.edu/RG_Climatology.html

Results

The results section is ordered as follows. We first examine local atmospheric conditions and their relation to the general oceanography of Glacier Bay, including placing the seasonally varying hydrographic structure of the bay into a regional context. We follow this with an examination of long-term inter-annual variability across the bay as a whole, including the 2014-2016 Pacific Marine Heatwave. A statistical analysis examines the sampling protocol through the lens of detectable trends. These are followed by brief summaries of conditions in each of the four main Bay domains (c.f. Figure 9), and a correlation analysis that documents

co-variability (or lack thereof) relative to known large-scale modes of variability. The results section concludes with an analysis of tidal and subtidal currents measured by a suite of oceanographic moorings.

Local Atmospheric Conditions

The annual solar cycle drives air temperature and light seasonality, the biosphere's growing season, and ocean-atmosphere heat exchanges. A monthly climatology of the annual temperature and wind cycles recorded at the National Weather Service Gustavus, AK Automated Surface Observing Systems (ASOS) weather station is shown in Figure 11.

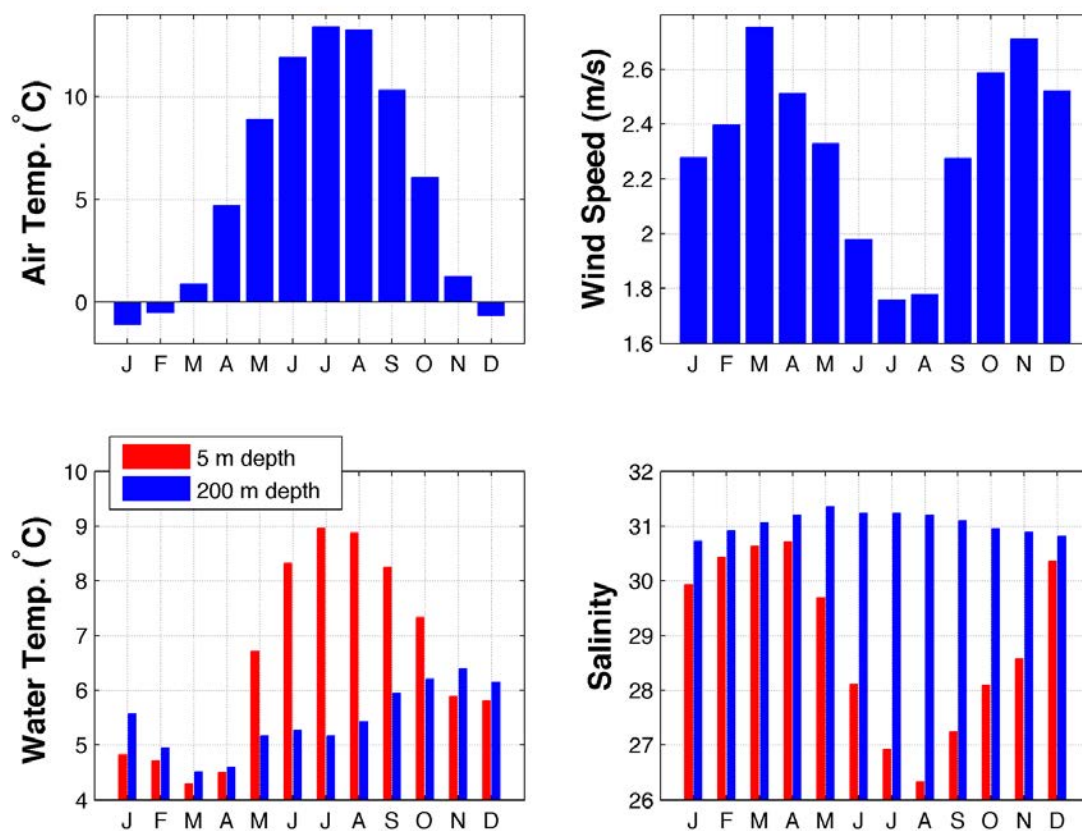


Figure 11. Monthly climatology of atmospheric conditions recorded at Gustavus, AK over 1993-2016 (top row) and mean monthly T and S values from the Central Bay sub-region (at GLBA Station 04) averaged over 0-10 m (red) and 195-205 m (blue) depth strata (bottom row).

During summer months, the ocean gains heat directly from incoming solar radiation; during winter months, the ocean loses heat to the atmosphere through cooling induced by long-wave radiative heat loss. The maximum monthly mean air temperature (13.4 °C) occurs in July and is in phase with the summer SLP maximum. However, the minimum air temperature (-2.3 °C) in January lags behind the SLP fall minimum, showing that the annual cycles of heating/cooling and storminess do not progress in tight synchrony with each other. Likewise, the oceanic temperatures do not share identical timing with the air temperatures: the maximum near-surface water temperature at Station 04 occurs in July-August, and the minimum occurs in March-April. At 200 m depth, maximum water temperatures are observed in November; minimum temperatures are in phase with those at the surface.

The Glacier Bay oceanographic time series extends 1993-present so we compiled monthly air temperature anomalies over this time period (Figure 12). No record-length trend is detectable in this time series but inspection shows that low-frequency fluctuations lie behind the dominant high-frequency variability.

Precipitation peaks in early fall (September) and reaches an annual minimum in late spring and early summer (April-June). Thus, coastal discharge is reduced during the winter months due to freezing temperatures between December and February and low precipitation rates following the end of winter. In contrast, near-surface salinities at Station 04 are at their annual minimum prior to the peak in precipitation; this demonstrates the importance of snow and glacier ice melt to the marine fresh water budget. Salinities increase through the winter: maximum salinity occurs in April, near the time of minimum water temperature. At 200 m depth, maximum salinities occur in May (shortly after the temperature minimum); minimum salinity at depth occurs in January.

Wind speeds exhibit a bimodal structure showing peak speeds in fall (November) and late winter (March) that induce strong mechanical mixing of the near-surface waters. The oceanic cycle of stratification (see Hydrographic Structure section below) offers varying levels of resistance to mixing between these two maxima: October closely follows the period of maximum water column stratification of late summer while March represents the

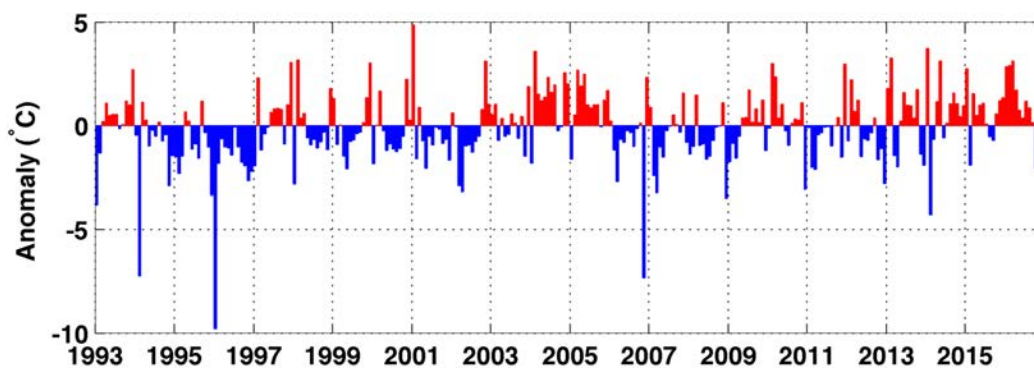


Figure 12. Monthly air temperature anomalies recorded in Gustavus, AK, 1993-2016.

time of minimum stratification because it follows strong winter wind mixing, convective cooling, and reduced levels of coastal discharge.

Together, the panels of Figures 3 and 11 show that the relative timings of the atmospheric and terrestrial inputs are only loosely coupled to oceanic conditions, leading us to conclude that internal ocean dynamics and other external (local or regional) atmospheric processes also must play important roles in setting the seasonal character of Glacier Bay waters.

While oceanographic conditions within Glacier Bay depend in part on local weather and dynamics, the fjord is also connected to the marine waters of Southeast Alaska: Icy Strait and Chatham Strait to the south and east, and Cross Sound and the Gulf of Alaska to the west. Shallow subsurface sills and the narrow entrance limit exchange of fjord and adjacent waters. Based on numerical model experiments, Hill et al. (2009)

conclude that waters of Glacier Bay primarily communicate with waters from the Cross Sound region to the west, rather than from the east.

Using data from the World Ocean Database 2009 archive (WOD09; Boyer et al. 2009), we construct a transect that extends from the central Gulf of Alaska to the northern reaches of Glacier Bay to show hydrographic differences between late winter/early spring (Figure 13) and late summer/early fall (Figure 14). Note that these two figures are generated from non-synoptic data spanning multiple years, so care must be taken in their interpretation. Since seasonal cycles likely dominate over inter-annual variability, we expect that these sections are probably at least representative of typical inter-seasonal changes. A large apparent discontinuity (but possibly a sampling artefact caused by inter-annual variability) is observed in the winter/spring season thermal field, showing Glacier Bay temperatures at the

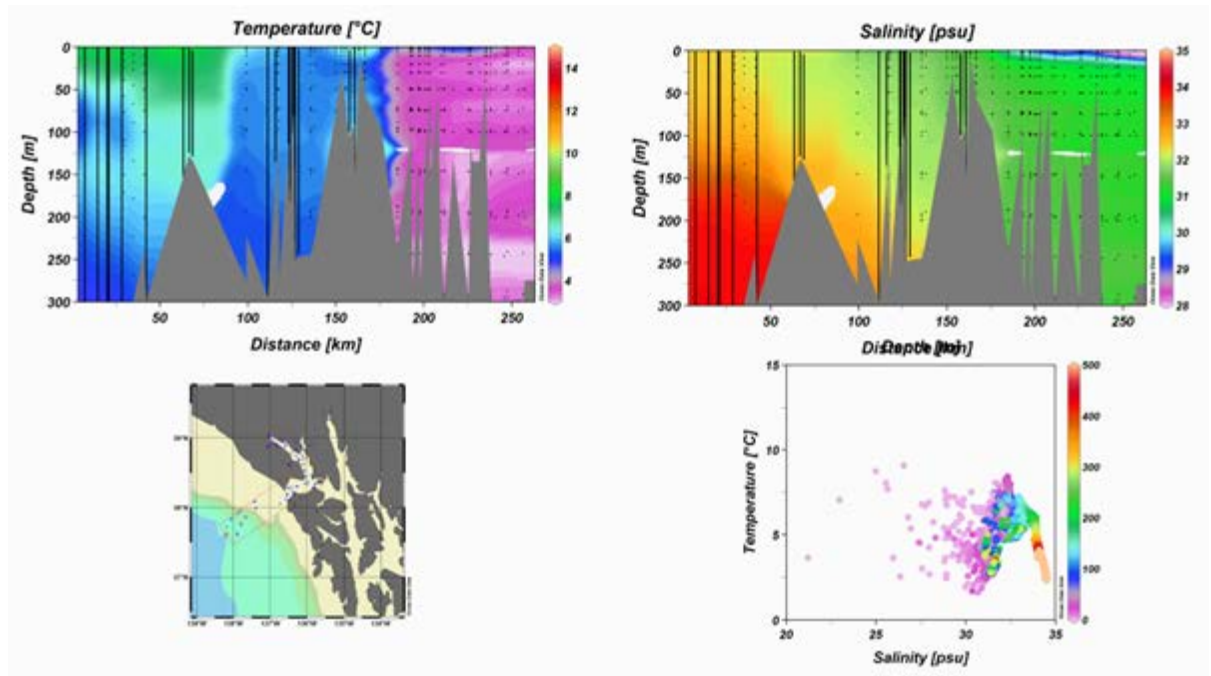


Figure 13. Late winter/early spring ocean conditions (March to May) between the Gulf of Alaska and the northwestern reaches of Glacier Bay. The cross-sections are oriented with the farthest offshore sites at 0 km and upper Bay fjord stations beyond 250 km. The mouth of the Glacier Bay fjord lies at ~160 km. Note the separation of the fjord stations from the offshore stations on the T-S diagram. Black dots and vertical lines on the cross-sections denote locations of data used in the figure. T-S diagram points are colored by depth (m). Data are extracted from Boyer et al. (2009).

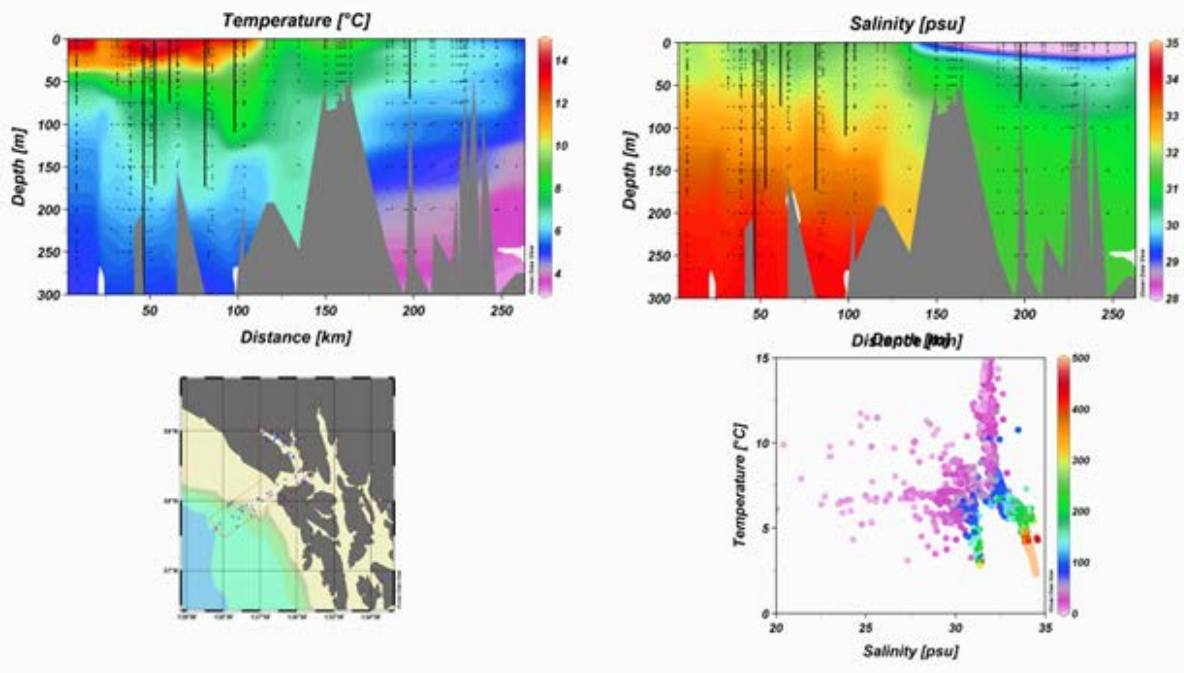


Figure 14. As in Figure 13 for late summer/early fall (August to September).

end of winter to be appreciably colder north of the main entrance sill than to the south for the data shown here.

Figure 13 shows that, in general, late winter waters are weakly stratified within the fjord, having been exposed to months of reduced runoff (due to accumulation of the snowpack field through the winter), convective cooling, and vigorous wind- and topographically induced mixing. Water temperatures are cold (2.5-4.5°C), and salinities vary little at depth ($S \sim 31$), although a shallow (<25 m thick) low-salinity plume can extend south from the head of the fjord even at the end of winter; not all terrestrial discharge ceases in the winter. Offshore waters are weakly stratified ($\Delta T < 3^\circ\text{C}$; $\Delta S < 1.5$) over the upper 300 m at this time of year with most of the stratification occurring near ~150 m depth.

In contrast, the end-of-summer thermal gradient over the upper 300 m of the central Gulf water column increases to $\Delta T \sim 10^\circ\text{C}$ (the salinity gradient increases slightly to $\Delta S \sim 2$), and most of the stratification occurs in the upper 50 m of the water column (Figure 14). Inside the fjord at the end of summer, the water is only moderately thermally stratified ($\Delta T < 4^\circ\text{C}$), but the salinity stratification can be extremely large in the upper 50 m ($\Delta S \sim 5-20$).

Against the above introductory background of the regional climate, oceanography, and its drivers, we next turn to the SEAN I&M oceanographic measurements, beginning with a description and analysis of the Northeast Pacific “marine heat wave” of 2014-2016.

2014-2016 Marine Heat Wave

In January 2014, ocean temperatures of the northeastern Pacific Ocean had warmed to an incredible four standard deviations above normal (Freeland 2014), a heat anomaly that was dubbed “the Blob” in the popular press. A combination of unusual winter atmospheric conditions (Bond et al. 2014) along with a “failed” 2014-2015 El Niño that was followed by a very strong El Niño in 2015-2016 (third-strongest recorded to date by some metrics) all contributed to a spatially and temporally extensive warm water anomaly that has impacted not only the Gulf of Alaska basin but also the adjacent continental shelf, the Bering Sea shelf and the Arctic (Figure 15).

The recent elevated oceanic temperatures were associated with the warmest year on record for many coastal Alaskan communities (Walsh et al. 2017), and the 2016 ocean surface temperatures were the highest recorded over 1900-2016 based on a reconstruction of past surface temperatures from ships logs, satellites, and other observations (Figure 16). The heat wave has been identified as a contributing factor to many disruptions in the marine environment (Walsh et al., 2017), including a massive 2015-2016 Common Murre die-off, widespread toxic algae blooms and paralytic shellfish poisoning events, and sea star wasting disease. Changes in the zooplankton

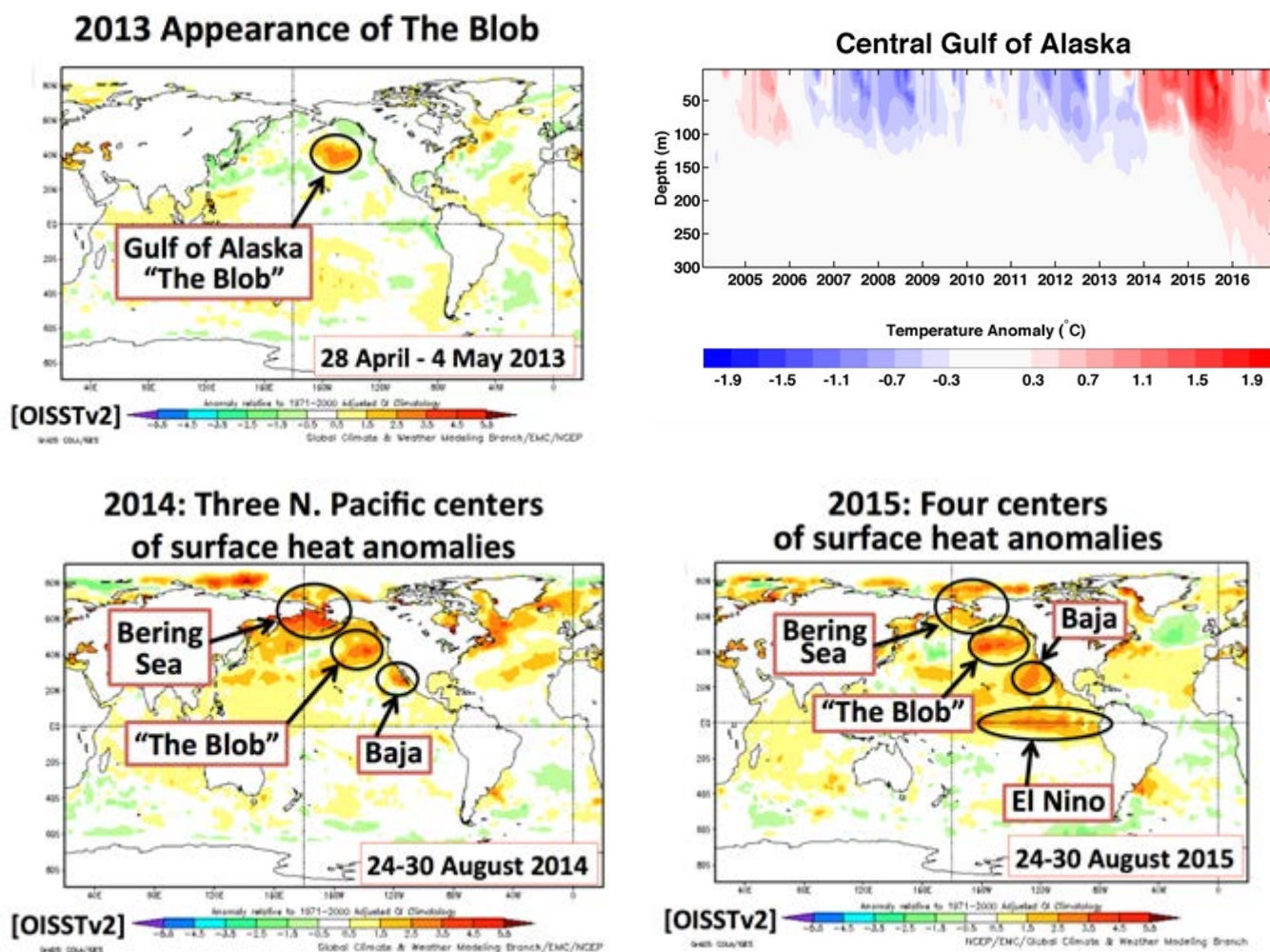


Figure 15. Evolution of the eastern Pacific marine heat wave with snapshots of the sea surface temperature anomaly from spring 2013 (upper left), late summer 2014 (lower left), and late summer 2015 (lower right). Upper right panel shows the time-depth evolution of the temperature anomaly averaged over the deep Gulf of Alaska (45-55 °N, 155-135 °W). Data in the upper-right panel are from Roemmich and Gilson (2009). Maps were downloaded from http://www.emc.ncep.noaa.gov/research/cmb/sst_analysis/ and subsequently annotated by the author.

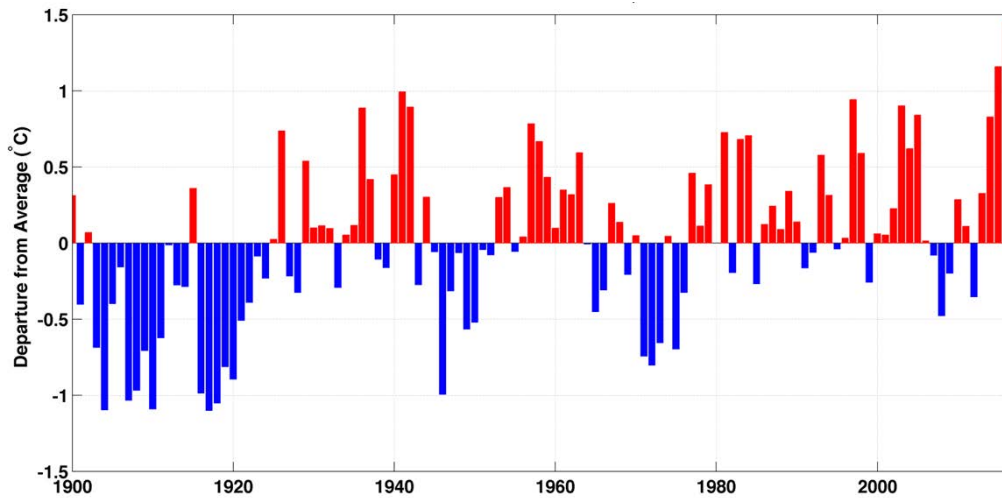


Figure 16. 1900-2016 annual average sea surface temperature anomalies over the Gulf of Alaska integrated over 55-62 °N and 160-120 °W. Data from ERSSTv3.

community structure were also observed, whereby species more typically associated with southerly latitudes were found in higher abundances in the Gulf of Alaska (Kintisch 2015, Peterson et al. 2016).

Oceanographic station GAK1 (Figure 17) is located at the mouth of Resurrection Bay, near Seward, Alaska, in 270 m water depth. Data are collected by researchers from the University of Alaska Fairbanks. GAK1 is the longest-running time series of coastal temperature and salinity profiles in coastal Alaska, and its data have been incorporated into numerous oceanographic studies,

ecosystem assessments, and fisheries forecast algorithms (see <http://www.ims.uaf.edu/gak1>). The average surface-to-bottom temperature anomaly at GAK1 is shown in Figure 17. The record depicts a gradual warming from the cool years in the first half of the 1970s to the present, culminating with the very warm (nearly 2 °C) anomaly in 2016.

The marine heat wave was clearly observed by the Glacier Bay oceanographic monitoring program (Figure 18). Like the central Gulf of Alaska (Figure 16) and at station GAK1 (Figure 17), Glacier Bay experienced relatively

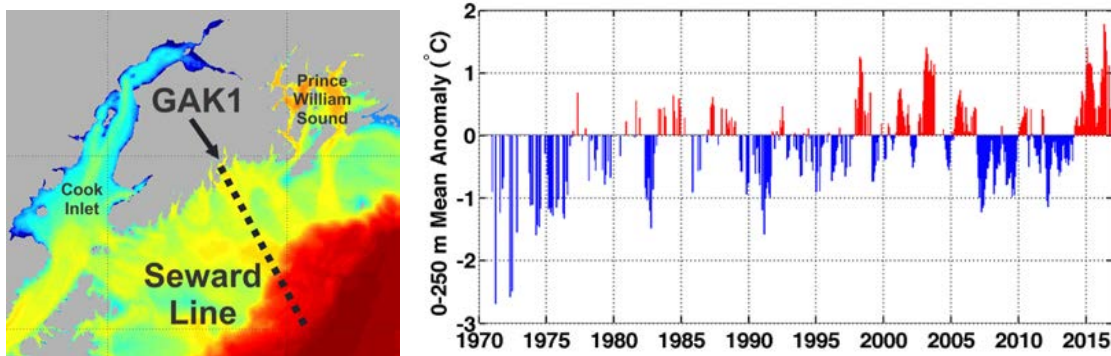


Figure 17. Left: Map of the northern Gulf of Alaska and Gulf Watch Alaska hydrographic monitoring stations of the Seward Line; GAK-1 is the Seward Line station closest to the coast. Right: Water column mean monthly temperature anomaly from oceanographic station GAK-1 on the inner Gulf of Alaska shelf over 1970 - 2016. Data from <http://www.ims.uaf.edu/gak1>. Note the correspondence between the GAK1 warm and cool intervals and the warm and cool intervals shown in Figure 16.

cool waters over most of 2007-2013. A number of warm events stand out in both the GLBA and GAK1 datasets, including the massive 1997-1998 El Niño, the 2003-2004 El Niño, and the 2014-2016 marine heat wave that include another very large El Niño. There is no statistically significant warming trend for the integrated record shown in Figure 18. Air temperature anomalies inside Glacier Bay (Figure 12) do not exhibit the same cool-warm phasing over the past ten years, showing that oceanic processes are very important and possibly dominant in driving seawater temperatures in the bay.

The marine heat wave in Glacier Bay was accompanied by large negative salinity anomalies, shown in Figure 19. A salt balance shows that this freshening (from approximately +0.2 to -0.2 over the

course of two years) is equivalent to an accumulation of 3 km³ of fresh water to the bay, or an excess terrestrial discharge of at least 50 m³ s⁻¹ of freshwater. We are not yet able to discern whether this addition came solely from within the Glacier Bay watershed, if part of this could be due to altered volume exchanges over the sill, or if the freshening was advected in from Icy Strait. Inspection of the thermohaline anomaly fields shows that the temperature and salinity anomalies extend from the surface to the seafloor. Given the strength and role of the stratification, the importance of mixing over the Sitakaday Narrows sill (Figure 13), and the nature of mid-depth and deeper renewals, it seems likely that these signals are primarily driven from outside of Glacier Bay proper.

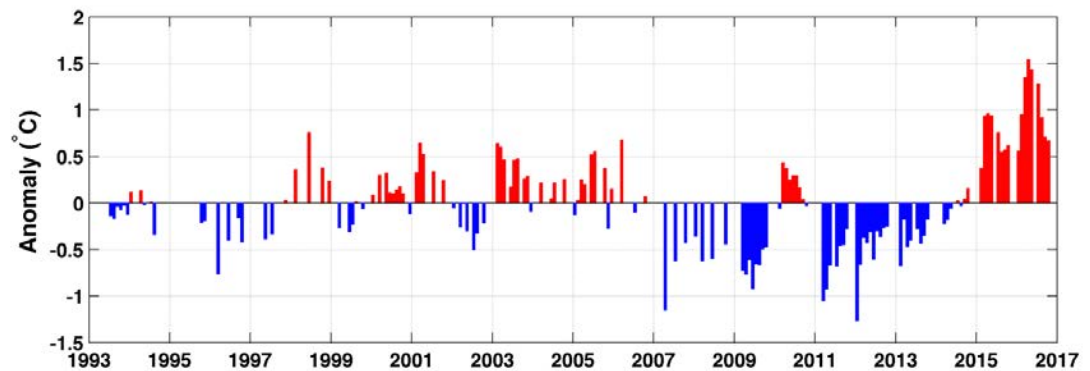


Figure 18. Surface-to-bottom mean monthly temperature anomaly averaged over all occupied Glacier Bay standard stations 1993-2017.

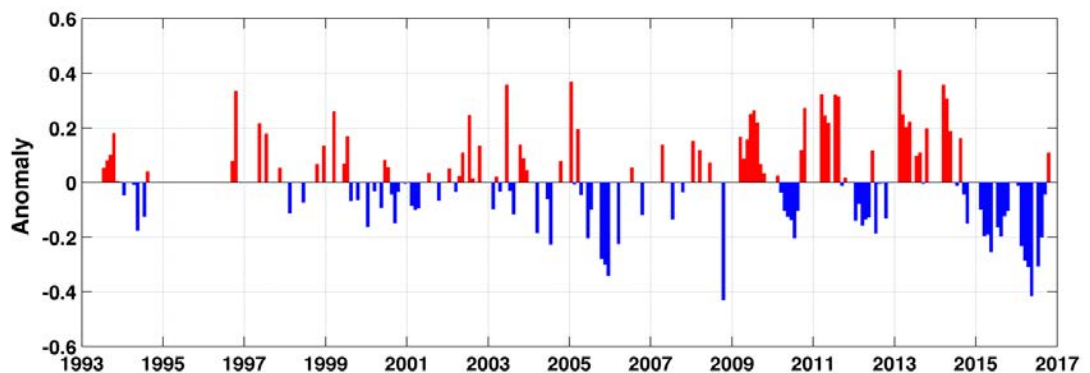


Figure 19. Surface-to-bottom mean monthly salinity anomaly averaged over all occupied Glacier Bay standard stations 1993-2017.

Mean Hydrographic Structure

In this section, we examine the spatial structure of Glacier Bay's hydrography and its variability in time.

The mid-winter and mid-summer mean water column structure along the length of Glacier Bay (Figure 13) shows that highest salinities at both times of year are found over and south of the shallow sill at the southern end of the fjord. At both times of year salinities at 40 m depth at stations 24 and 01 are higher than any salinity found 150 m below the surface north of the sill. In January, the water column over the sill is nearly homogeneous, but in summer even water mixing associated with the swift tidal currents (see the Ocean Currents section, below) here are not able to fully overcome the density stratification. The strongest stratification occurs at ~10-30 m depths in winter and over 0-15 m depths in summer (Figure 20).

Temperatures are lowest in the northernmost reaches of the fjord closest to the source of the fresh and cold glacier meltwaters. Warmest temperatures are found at depth during winter and in the surface waters of the Central Bay during summer.

Detecting Temporal Trends

Shifts in environmental conditions can trigger fundamental reorganizations (e.g., crossing tipping points) in marine ecosystems (e.g., Anderson and Piatt 1999). Informed management of GLBA waters should include assessments of long-term trends and other changes over time, and the SEAN Vital Signs oceanographic monitoring program is designed to document such variations. Of particular interest are trends that extend over many years and decades because such features are persistent enough to impact many generations of marine life.

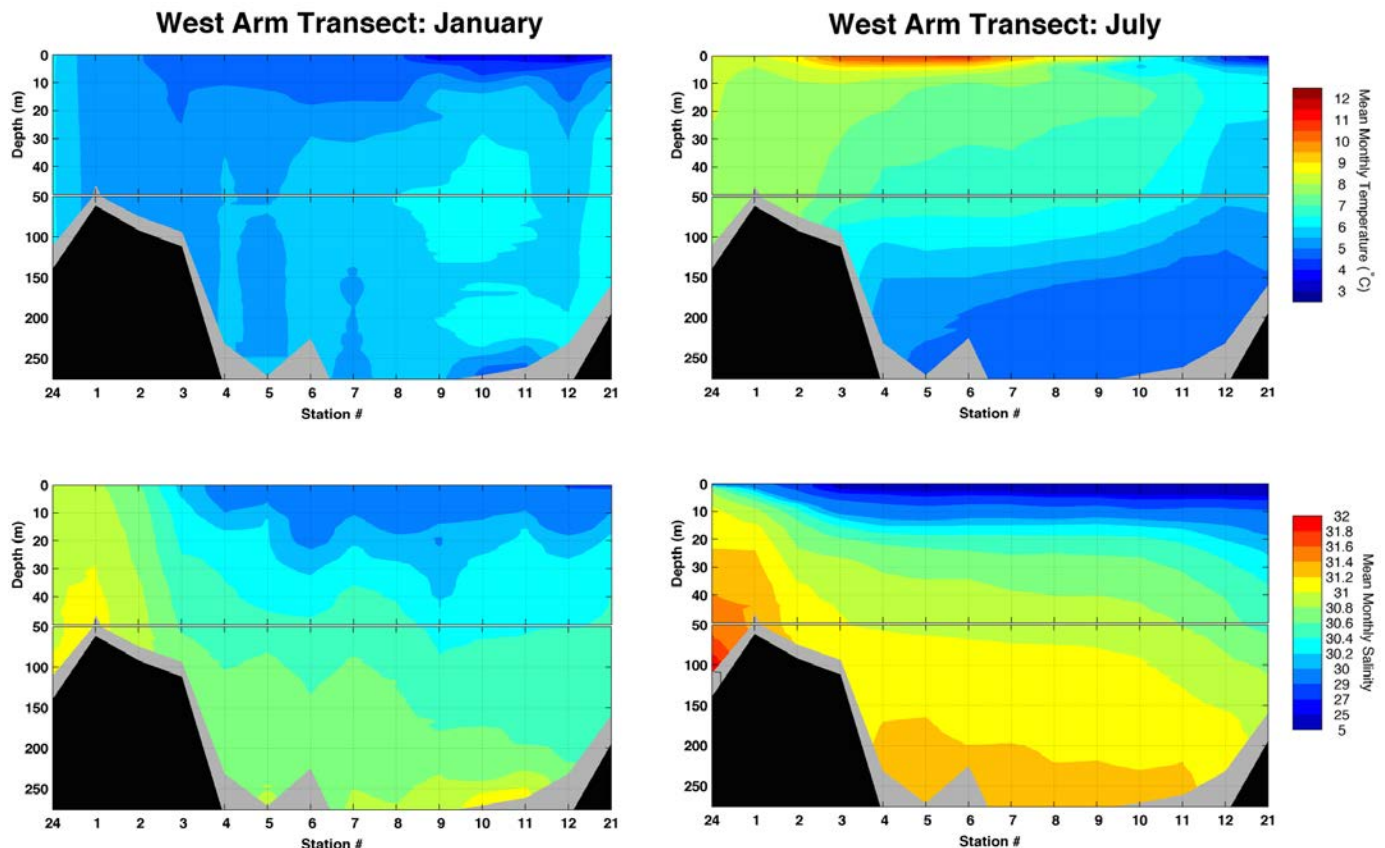


Figure 20. Climatological cross-sections using the 1993-2016 period of record data from Icy Strait up into Tarr Inlet for January (left) and July (right).

Under assumptions of normally distributed anomalies and knowledge of the standard deviations as shown in Figure 21, we can reasonably anticipate the length of time that would be required to detect environmental trends of various magnitudes given the existing oceanographic sampling protocol (the I&M Vital Signs program samples some stations nine times per year and other stations just twice per year). We follow a bootstrap approach (Efron and Tibshirani 1993), generating in total over 15,000,000 random time series, each having varying duration, trend, number of samples per year, and standard deviation (Table. 1. For each of these synthetic time series we evaluate whether the imposed trend is detectable at the 95% and 99% confidence

levels. Results of these bootstrap computations are shown in Figure 22.

The bootstrap integrations can be interpreted by comparing these results to the observations. Removing the monthly climatology, we compute the standard deviation (σ) of the resulting monthly anomalies (Figure 21). Standard deviations are largest for both temperature and salinity in the upper 10 m at most stations, with $\sigma_{\text{temperature}}$ typically between 0.4 and 1.0 °C, and σ_{salinity} typically between 0.4 and 2. Below 20 m depth, standard deviations for both parameters are smaller than near the surface, mostly the range of 0.4 to 0.6 °C for temperature, and 0.1 to 0.4 for salinity. The very shallow depth of the largest deviations reflects the shallow mixed layer

Figure 21. West Arm cross-section of temperature (left) and salinity (right) standard deviations. The standard deviations are computed using temperature and salinity anomalies, where the annual monthly climatology has been removed. Note the non-linear color scale.

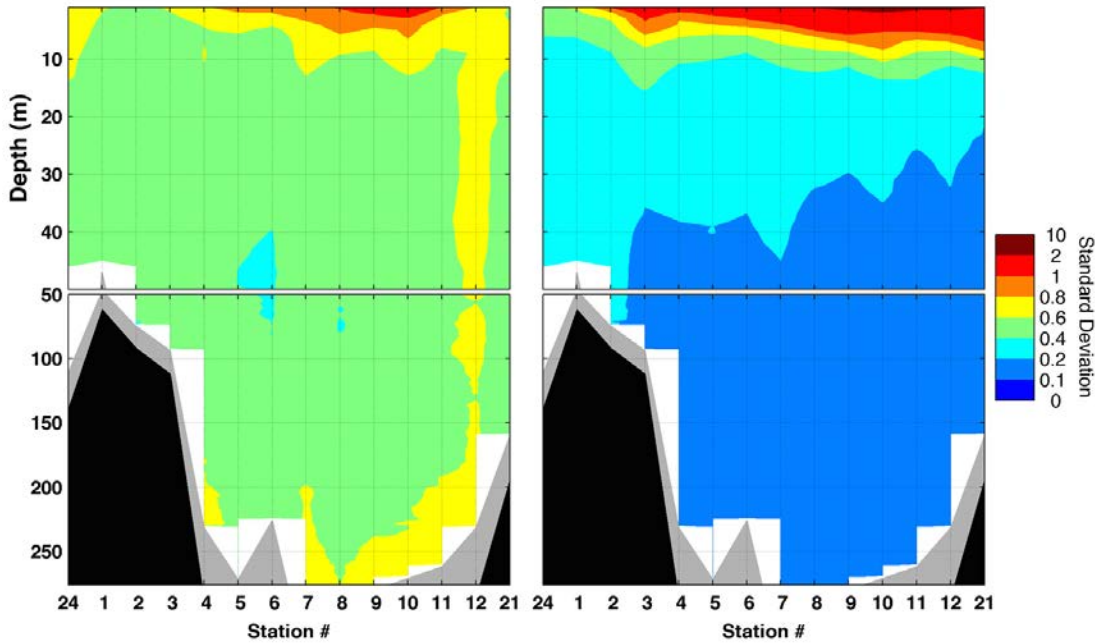


Table 1. Integration parameters for estimating the duration of sampling required to detect statistically significant long-term changes. Each integration was repeated 1,000 times.

Parameter	Value
Duration of record (years)	1 to 100
Samples per year (number)	2 & 9
Magnitude of temperature or salinity trend (°C yr ⁻¹ or PSU yr ⁻¹)	0.001, 0.01, 0.1, & 1.0
Standard Deviation (σ , °C or PSU)	0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0, 2.0, 3.0, 4.0, 5.0, 6.0, 7.0, 8.0, 9.0, & 10

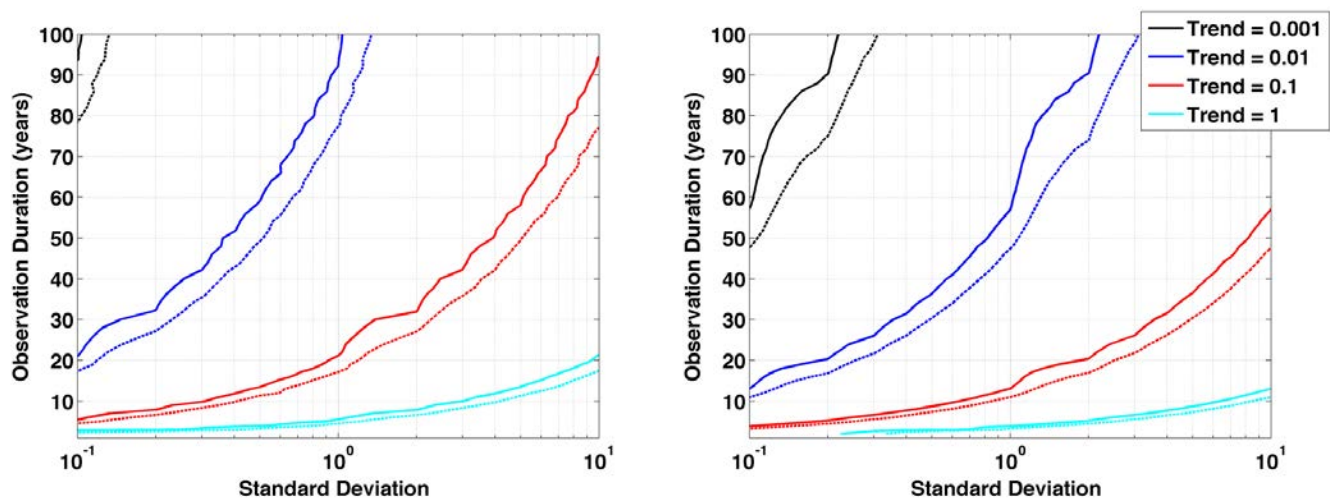


Figure 22. Contours showing the duration of time required to detect a trend at the 95% (dotted lines) and 99% (solid lines) confidence levels for standard deviations between 0.1 and 10 sample units and for a monitoring program that samples a station twice per year (left) and nine times per year (right). Line colors black, blue, red, and cyan denote detectable trends (yr^{-1}) of 0.001, 0.01, 0.1 and 1.0, respectively. Refer to Figure 15 for observed Glacier Bay standard deviations, which are mostly between 0.4 and 1.0 C for temperature and between 0.1 and 2 for salinity.

depth and the importance of the near-surface stratification in isolating the waters that lie below.

Figure 22 reveals that larger trends (0.1 to 1 yr^{-1}) are more quickly detectable, and that the length of time is relatively short (1-8 yr) from between being able to identify a significant trend at the 95% confidence level to detection at the 99% confidence level. Smaller trends (0.001 to 0.01 yr^{-1}) are less quickly identifiable and also require more time (5-20 yr) to move from a 95% confidence level to 99% confidence.

Nearly five decades of hydrographic sampling at station GAK1 in the northern Gulf of Alaska have revealed a statistically significant warming ($\sim 0.02 \text{ C yr}^{-1}$) and freshening (0.014 yr^{-1}) at the sea surface (Kelley 2015). Assuming that we may find a similar magnitude of change in Glacier Bay, Figure 22 suggests that such a warming could be detectable in the Glacier Bay hydrographic data with approximately 20 to 50 years of sampling at nine times per year. With 24 years of data in the time series (although not all years have had 9 sampling expeditions), it would appear that the times series length is on the

cusp of being able to reveal statistically significant multi-decadal trends, although the entire record does not have fully nine samples per year. A near-seafloor increasing salinity trend at GAK1 of $\sim 0.002 \text{ yr}^{-1}$ suggests that subsurface salinity changes in Glacier Bay will take additional decades of sampling to detect. Small trends at depth may be quite important for the Glacier Bay ecosystem, however, because the expected salinity-nitrate relations dictate that trends in the salinity and the density stratification could affect the nutrient supply to primary producers.

In this report we do identify a number of statistically significant trends over the 1993-2016 period of record (see Appendix A). The warming trends are consistent with those observed in the 47-year record from station GAK1. The very large positive temperature anomalies of the 2013-2016 North Pacific marine heat wave may be driving the significance of some of these relations, and a few “normal” or “cool” years in a row could tip the results back into the realm of only marginal significance.

Lower Bay Summary

Station 01 (Figure 23; cf. Figure 9) lies over the shallow, strongly mixed regime of the main sill at the entrance to Glacier Bay. Massively energetic tidal currents provide a nearly continual source of turbulence that erodes the density stratification. Tidal rips near promontories like Point Carolus can cause choppy and white-capped waters even in the absence of wind forcing, an example of which was observed with coincident vessel-based current measurements that recorded

current speeds exceeding 2.5 m s^{-1} in June 2016 (Danielson unpubl. obs.). Because of the strong mixing that takes place over this sill, the annual phasing of maximum and minimum temperatures near the surface and near the seafloor are nearly in phase with one another, and surface temperatures remain relatively cool in comparison to the more highly stratified stations farther north in the fjord. Salinities at Station 01 are greatest near the seafloor in May, having increased throughout late fall and all of winter. Maximum salinity

GLBA Station 01

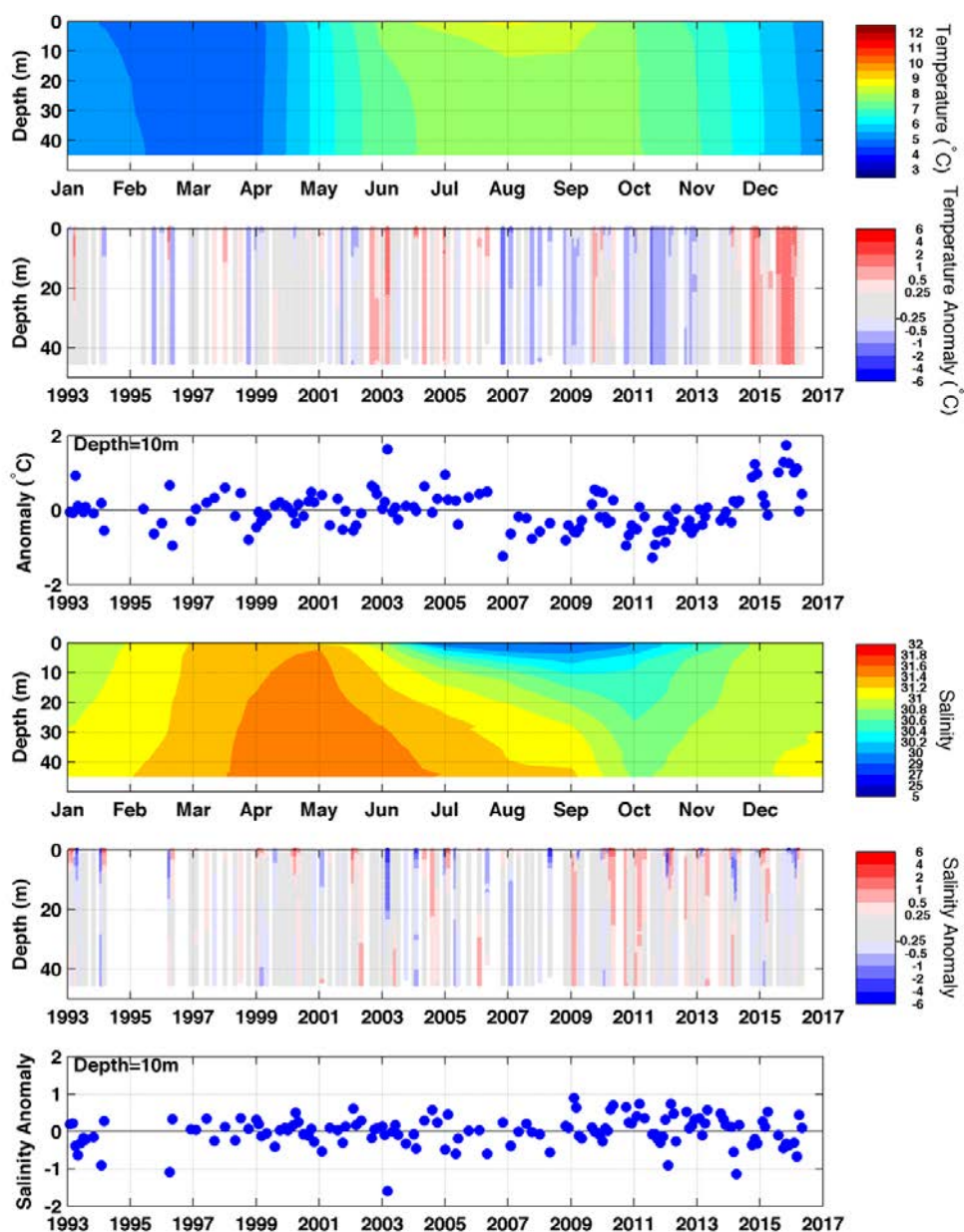


Figure 23. Station 01 temperature fields (upper three panels) and salinity fields (lower three panels). For each set of three, the panels show (from top bottom): the mean monthly cross-section, anomaly profiles through time for all depths, and monthly anomaly time series at 10 m below the surface.

at Station 24, however, occurs at the end of summer. This oddly offset relation is likely influenced by the tides, stratification, and the wind field over the greater Gulf of Alaska. Salinities at much deeper stations farther north in the Bay do not attain the highest salinities observed at Lower Bay sites. The recent marine heat wave is clearly seen as full-water column heat anomalies over 2014, 2015, and 2016.

Central Bay Summary

The mean annual cycles of temperature and salinity at Station 04 (Figure 24; cf.

Figure 9) show that Central Bay waters remain stratified in salinity throughout the year, and that the phasing of temperature and salinity maxima and minima vary with depth. For example, the maximum temperature occurs in July at the surface, but at 200 m the maximum temperature occurs in November (see Appendix A figures for depths below 50 m). Minimum temperatures across the water column occur in March. Maximum salinities occur in April at the surface and in May at 200 m depth, while minimum salinities occur

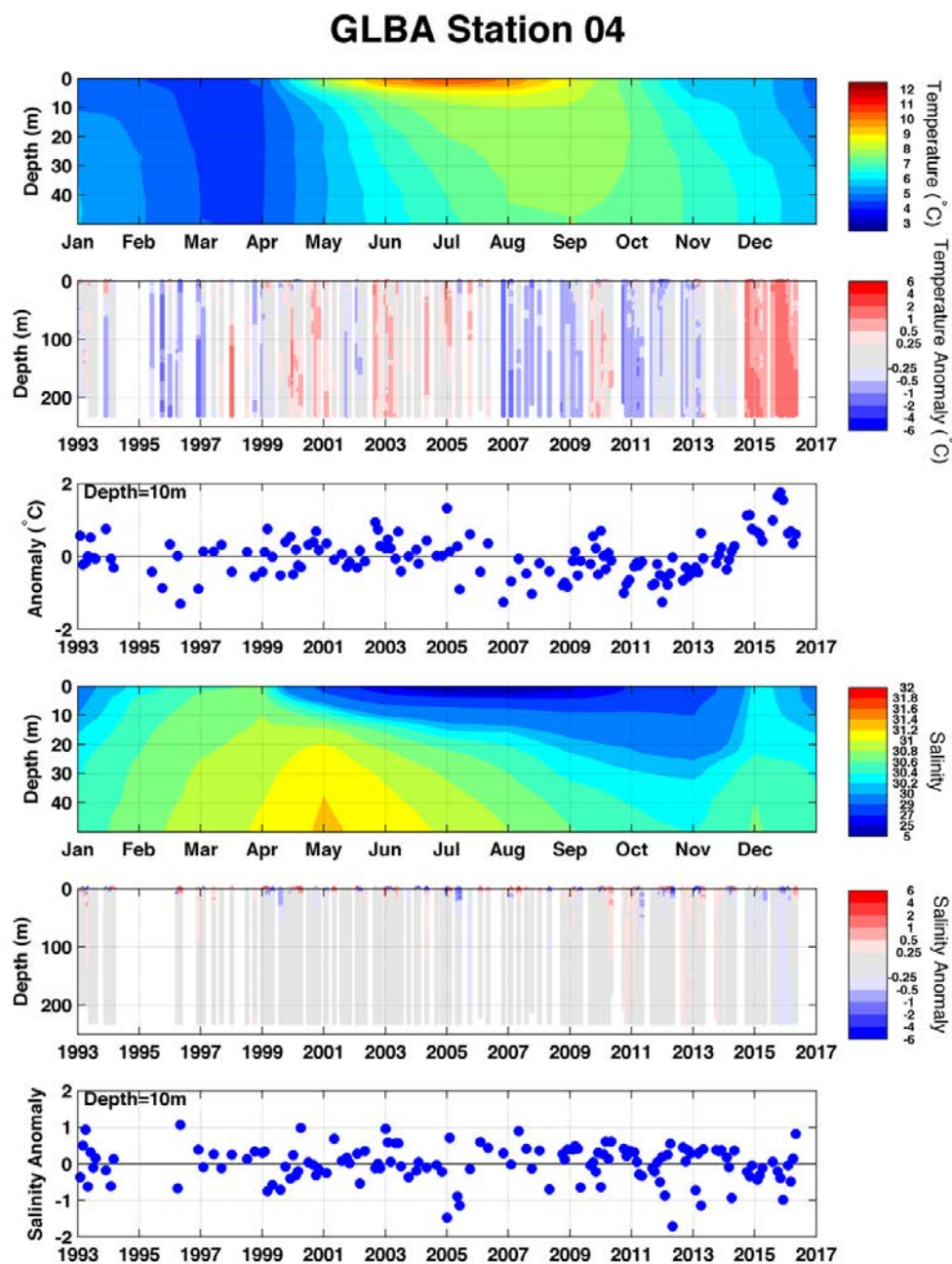


Figure 24. Station 04 temperature fields (upper three panels) and salinity fields (lower three panels). For each set of three, the panels show (from top to bottom): the mean monthly cross-section over the upper 50 m only, anomaly profiles through time for all depths, and monthly anomaly time series at 10 m below the surface.

in August at the surface and January at 200 m depth. These relations highlight how the upper and lower portions of the central bay water column respond out of phase and in response to different forcing mechanisms and at different times of year. For example, surface cooling and wind-induced mixing erode the upper layer stratification in fall, but tidally induced mixing at the seafloor in the Lower Bay sets up a density structure that allows Central Bay waters to renew in winter and spring.

West Arm Summary

Located at the head of the West Arm, the shallow observations at Station 12 (Figure 25; cf. Figure 9) show that near the glacial terminus, mean water temperatures never exceed 8°C, maximum temperatures normally occur at sub-surface depths, and the water column is strongly stratified by a surface freshwater lens between May and October. As at the other stations in the Bay, the largest and longest-lived temperature anomaly occurs over 2015-2016. Glacial melt is responsible for large-magnitude

GLBA Station 12

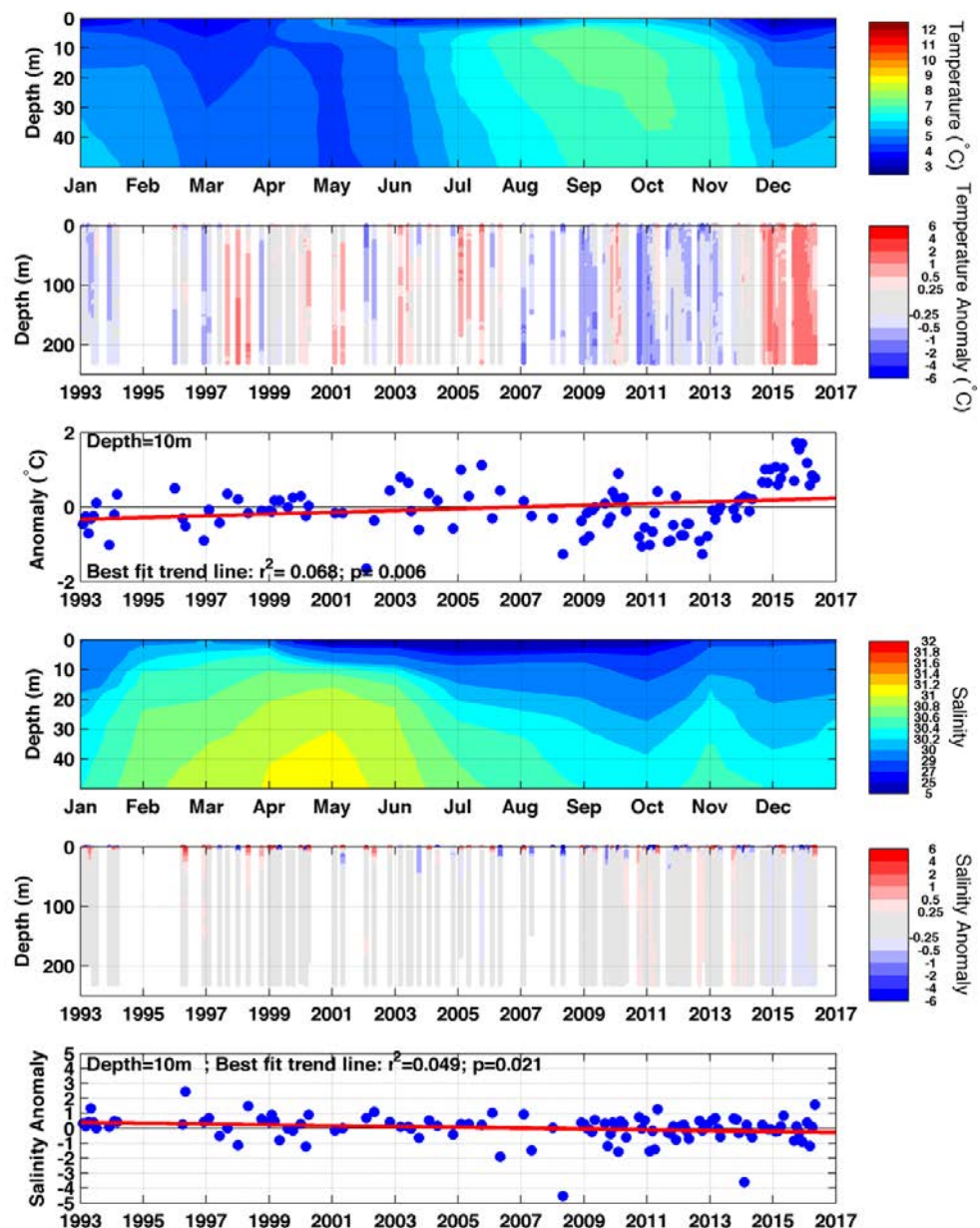


Figure 25. Station 12 temperature fields (upper three panels) and salinity fields (lower three panels). For each set of three, the panels show (from top to bottom): the mean monthly cross-section over the upper 50 m only, anomaly profiles through time for all depths, and monthly anomaly time series at 10 m below the surface.

salinity anomalies (also see Figure 21). As with stations farther south inside the bay, the maximum subsurface salinities at Station 12 occur in late spring. Hence, there is little to no lag time for renewal waters to permeate from the sill to the farthest-north reaches of the bay. Near-surface waters exhibit a statistically significant freshening trend over 1993-2016 that is accompanied by a statistically significant warming trend.

East Arm Summary

Located at the northern end of the East Arm, Station 20 (Figure 26; cf. Figure 9) exhibits similar annual cycles, strength of stratification, and anomaly patterns to those observed at Station 12. The near-surface salinity anomalies exhibit strong fresh and salty signals, indicating that the timing and/or magnitude of the glacial discharge can vary appreciably in different years. Some instances of salinity anomalies with magnitude greater than ± 1 exhibit opposite-sign anomalies lying at different

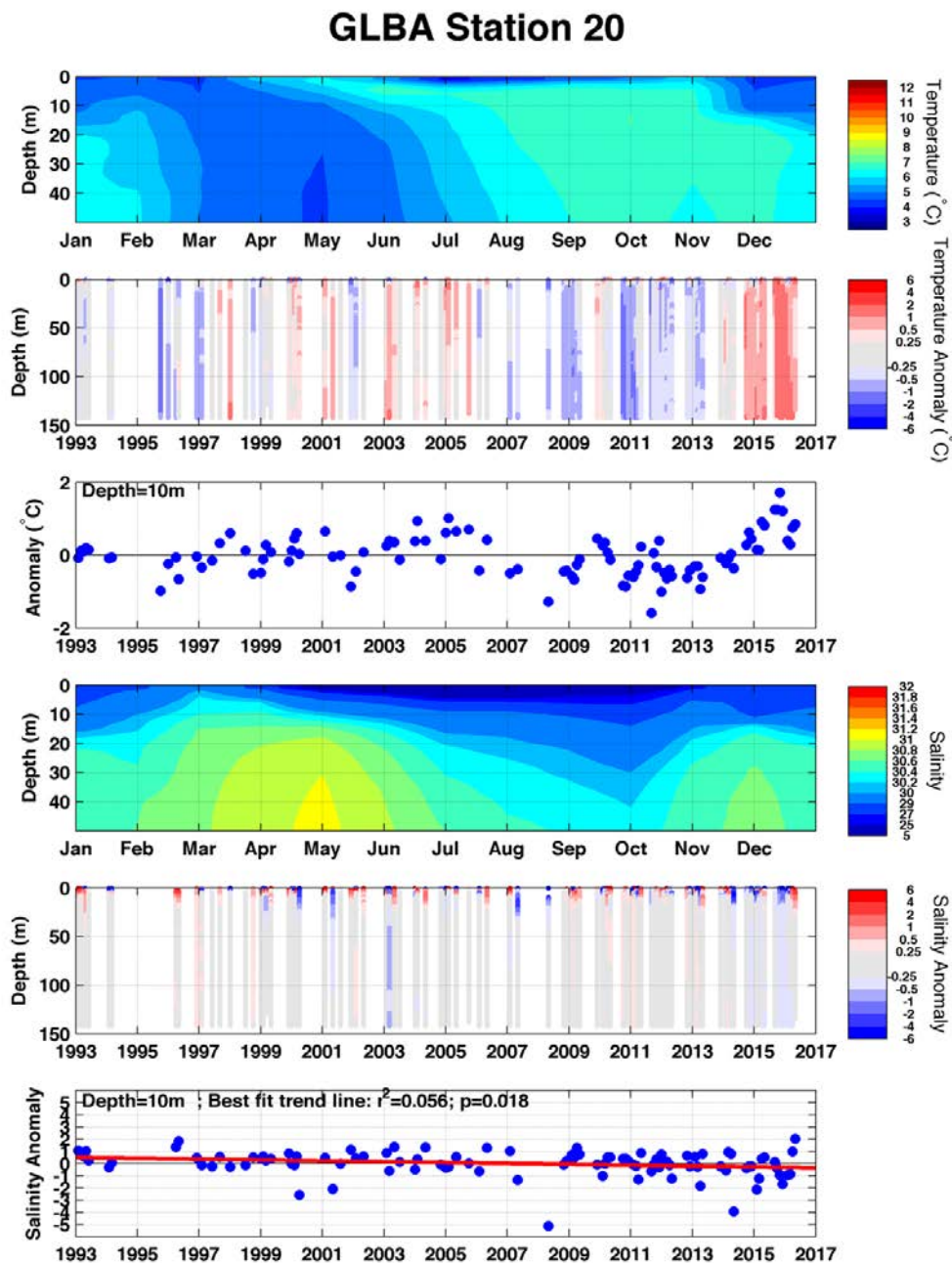


Figure 26. Station 20 temperature fields (upper three panels) and salinity fields (lower three panels). For each set of three, the panels show (from top to bottom): the mean monthly cross-section over the upper 50 m only, anomaly profiles through time for all depths, and monthly anomaly time series at 10 m below the surface.

depths within the top 10 m, suggesting that runoff plume dynamics that govern the depth and strength of the ice melt pycnocline are affected by mixing with deeper, more saline water. For example, in the first three samples of 1999, a fresh anomaly lies over a more saline anomaly: the surface salinity is lower than normal, and just below this the waters are saltier than normal. The situation is reversed in 2001 when the surface waters are anomalously salty, while waters down to 25 m depth are fresher than usual. In the latter case it is possible that fresh runoff has been mixed downward and/or experienced lateral advection.

Hydrographic Anomalies: Thermohaline Co-variations

The relation of temperature (T) and salinity (S) anomalies with respect to each other at all stations for surface (0 m; Figure 27) and subsurface (100 m; Figure 28) depths are shown in Figures 20 and 21. At 100 m depth all stations show a statistically significant negative relation between T and S: warm and fresh anomalies co-occur, as do cold and salty anomalies. This relation is consistent with our expectation and understanding that warm atmospheric anomalies are associated with enhanced atmospheric advection of warm, moist air to the region, which results in higher rates

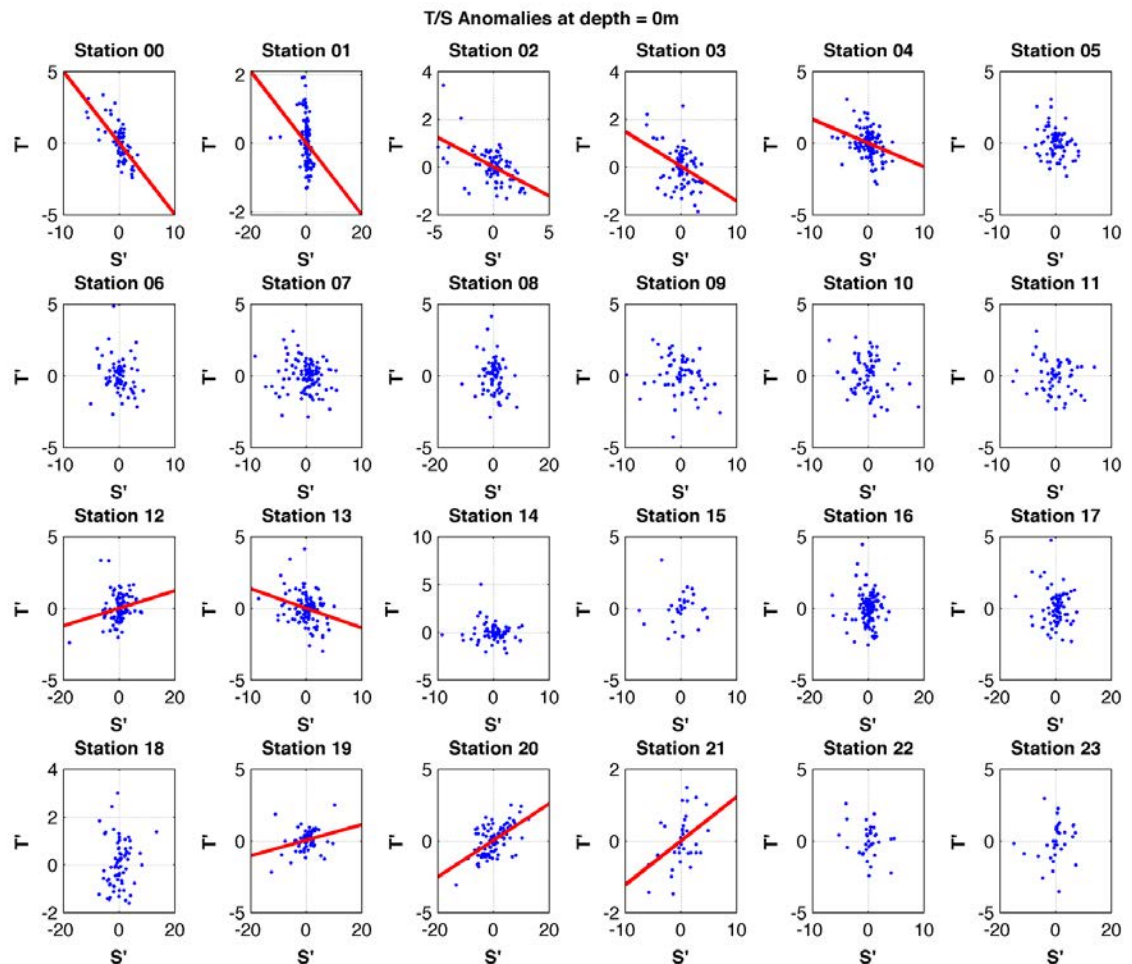


Figure 27. Anomalies of temperature (T') vs. anomalies of salinity (S') at 0 m depth for all stations. Significant relations at the 95% level are shown with a red best-fit linear trend line. Each panel is individually scaled to fit the range of observed anomalies. Note that the sign of the trend line is different for the stations in the Lower Bay and Central Bay (00 through 04 and 13) versus stations at the head of the fjord (12, 19, 20, and 21).

of precipitation, snowpack and glacial melt, and coastal runoff. The negative T/S slope is also found in near surface measurements of Stations 00-04 and 13. Most other near-surface measurements show no significant relation, but Stations 12, 19, 20, and 21 (the four stations closest to the heads of the West Arm and East Arm inlets) depict a positive relation, whereby cool water temperature anomalies are associated with fresh anomalies. This shows that near the fjord upper reaches the temperature and salinity dynamics are governed more strongly by glacial melt: melting glacier ice releases cold, fresh water. This signal is also clearly seen in

the mean hydrographic section shown in Figure 20.

From inspection of the anomaly time series shown above (and those in the Appendices), it is clear that deeper anomaly signals tend to extend across multiple stations and depth levels, whereas shallower anomalies are more tightly confined to the fjord extremes.

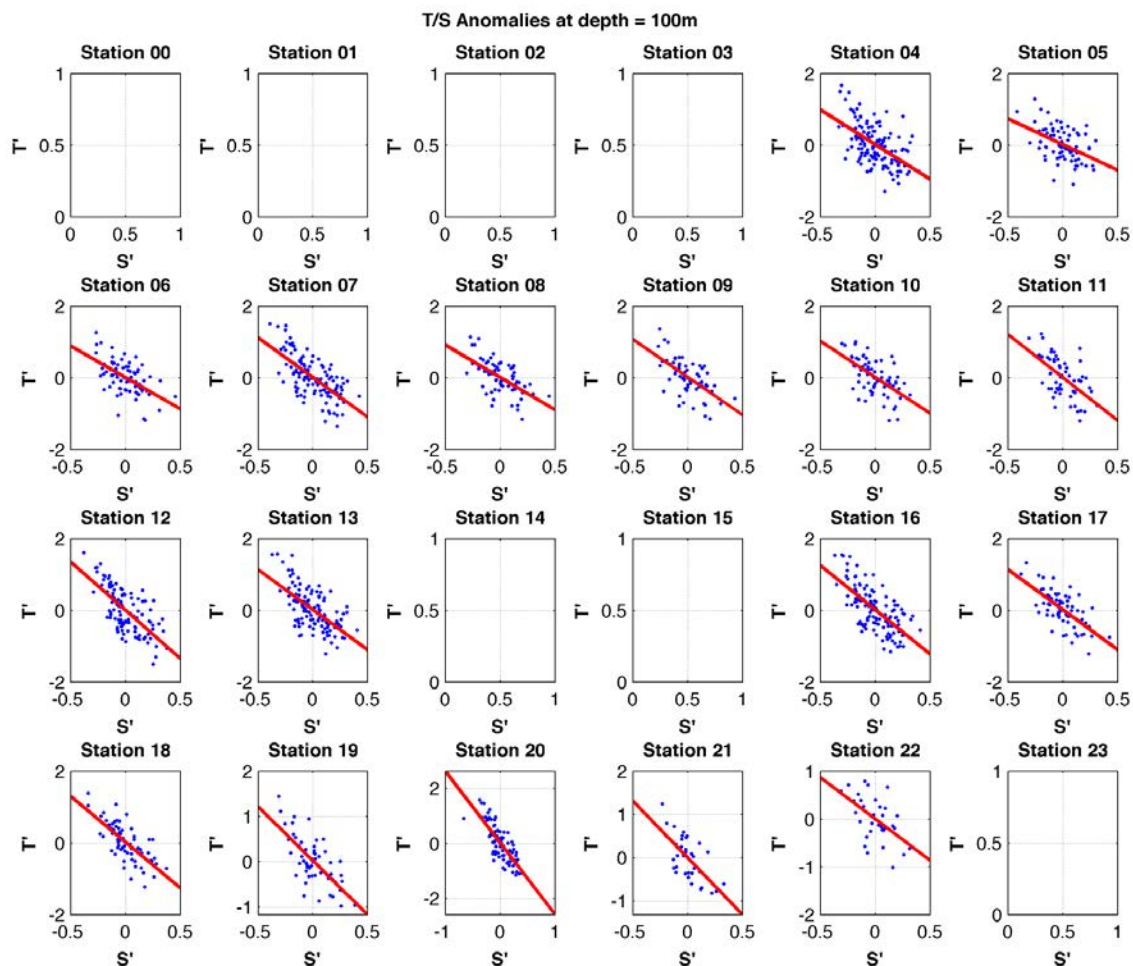


Figure 28. Anomalies of temperature (T') vs. anomalies of salinity (S') at 100 m depth for all stations. Significant relations at the 95% level are shown with a red best-fit linear trend line. Note that each panel is individually scaled to fit the range of observed anomalies. Blank panels denote stations that have no observations at 100 m depth.

Hydrographic Anomalies: Origins

To investigate possible origins of thermal and haline anomalies in Glacier Bay, we regress monthly anomalies of the observed data against anomalies of weather records (recorded at the Juneau airport), climate indices (Figure 9), and observations of temperature and salinity recorded at oceanographic station GAK1. We highlight Station 20 for these comparisons (Figure 29) because it is located at the upper reaches of the bay, and exhibits correlated anomalies at both the surface and 100 m depth (Figures 27 and 28) but with opposite sign of the relation at these two depth levels. For this analysis we select T and S observations from a near-surface depth

level and a sub-surface depth level. We plot regression lines only for relations that exhibit a statistically significant relation at the 95% confidence level ($p \leq 0.05$). Results of identical correlations for all other stations are provided in Appendix B.

Of the atmospheric variables, we find significant (but weak) correlations between the Juneau air temperature anomalies and both temperature and salinity anomalies (both shallow and deep), but no significant correlations between the hydrographic and wind speed anomalies. The atmospheric pressure variable exhibits a few significant relations with near-surface measurements, but they are not consistent across stations or parameters. Air temperature affects

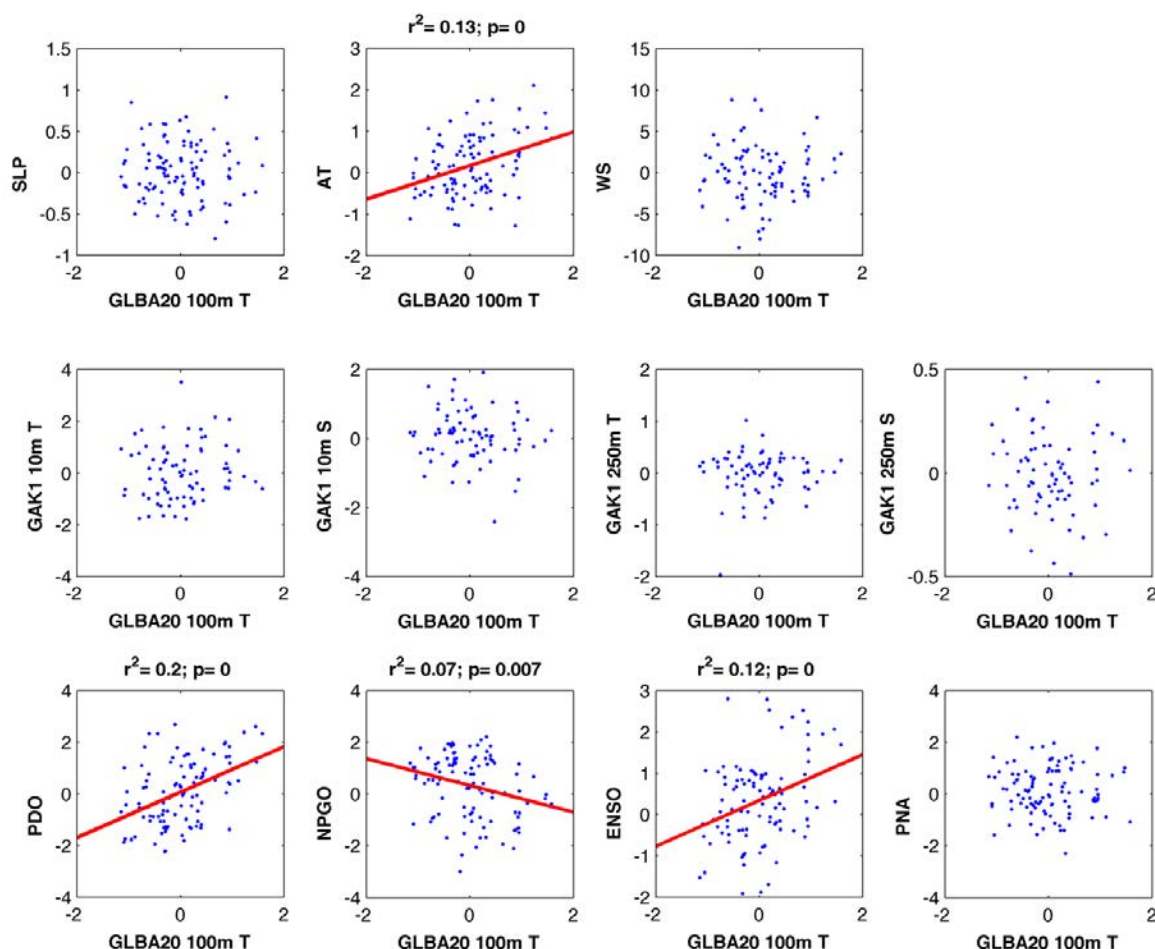


Figure 29. Scatter plots of Station 20 temperature anomalies at 100 m depth against eleven atmospheric, oceanographic and climate time series. Top row shows the relation to the Juneau sea level pressure (SLP), air temperature (AT), and wind speed (WS). Middle row shows the relation to 10 m and 250 m depth temperatures (T) and salinities (S). Bottom row shows the relation to the PDO, NPGO, ENSO, and PNA climate indices. Red lines denote linear regressions significant at the 95% confidence level or better; the statistical fit is described by the r^2 and p values.

snow melt and ice melt, and air-sea heat fluxes, which in turn can influence oceanic temperatures and salinities.

We find no consistent relations between anomalies of temperature or salinity between the Glacier Bay and oceanographic station GAK1. This finding shows that the GAK1 and GLBA monitoring programs are both important for our ability to characterize the coastal thermohaline variability along the entire Gulf of Alaska coast. This finding is consistent with the along-shore length scale appropriate to advection of anomalies within the ACC. With an ACC characteristic speed of 20 cm s^{-1} , the relevant length scale is approximately 500 km. Glacier Bay and Resurrection Bay are separated by 800 km.

In contrast, consistent relations between temperatures at this station are found, and they are in phase with fluctuations of the PDO and ENSO indices, and out of phase with the NPGO index. In all three of these cases, the fraction of total variance explained by the regression is small or modest ($\leq 25\%$). However modest the strength of co-variability, it does reveal that Glacier Bay is coherent with and sensitive to these well-known broad-scale modes of climate variability.

These results show more consistent correlations between the various variable sets than in the prior (2011) GLBA oceanography monitoring 5-year report (Danielson 2011). We note that the number of significant relations has jumped considerably since the last report in this series: in 2011 we found 11 significant correlations; in this report we find four times this number as a consequence of increasing degrees of freedom in the analyses. The present analysis adds seven years of data, representing nearly a third of the entire time series.

In aggregate, the impression that we get from these regressions is that Glacier

Bay waters respond strongly to local processes, but the regional and global-scale factors also play a role in determining the sign and magnitude of the observed anomalies. The clearest example of this is in the case of the 2014-2016 marine heat wave that manifested not only as warm temperatures in the coastal Gulf of Alaska but also across much of the northeastern Pacific Ocean including the Bering Sea and on into the Arctic. Additional work is needed to evaluate other processes not considered here, such as the role of ocean circulation response to wind forcing over the continental shelf and within the Southeast Alaska archipelago. Although we can account for a portion of the in situ variability, the majority of variance in both temperature and (especially) salinity remains unexplained.

Ocean Currents

The National Ocean Service's (NOS) Center for Operational Oceanographic Products and Services (CO-OPS) program deployed six current meter moorings in Glacier Bay in August 2008 and three moorings in May 2010 (Table 2; Figure 30). The 2008 instruments were deployed for slightly longer than one month, and the 2010 instruments were deployed for about three months. With the 6-minute recording intervals employed on these moorings, even a 1-month record can resolve 35 tidal constituents, and the dominant barotropic tidal components are quite accurately determined. On the other hand, subtidal flows computed from these records should be interpreted only as relatively brief duration snapshots of the mean flow and not necessarily well representative of any seasonal or annual long-term means. Nonetheless, both the tidal and subtidal water velocity data recorded by these moorings can be valuable for helping to interpret the SEAN I&M oceanography monitoring hydrographic data, planning field experiments, studying processes that depend on ocean circulation, and evaluating numerical circulation models.

Table 2. Summary of current meter mooring deployments, including the mooring name, location, geographic coordinate, water depth, deployment date, and number of hours in each data record.

Mooring	Location	Latitude (°N)	Longitude (°W)	Water Depth (m)	Depl. Year	Depl. Month	Depl. Day	# Samples (hr)
SEA0845	Icy Strait, Eastern North Passage	58.3182	-136.1179	115	2008	8	5	875
SEA0846	West of Point Gustavus	58.3842	-135.9528	73.6	2008	8	5	876
SEA0847	West of Beardslee Islands	58.4671	-136.0345	68.3	2008	8	7	866
SEA0848	Mouth of Muir Inlet	58.726	-136.1133	134	2008	8	6	874
SEA0849	West of Drake Island	58.6763	-136.2861	157	2008	8	6	753
SEA0850	Hugh Miller Inlet	58.7494	-136.3733	110	2008	8	6	895
SEA1002	Entrance to Glacier Bay - East	58.3824	-135.9462	66.4	2010	5	19	2,147
SEA1003	Entrance to Glacier Bay - Center	58.3821	-135.9767	70.9	2010	5	19	2,165
SEA1004	Entrance to Glacier Bay - West	58.3828	-136.0155	62.1	2010	5	19	2,145

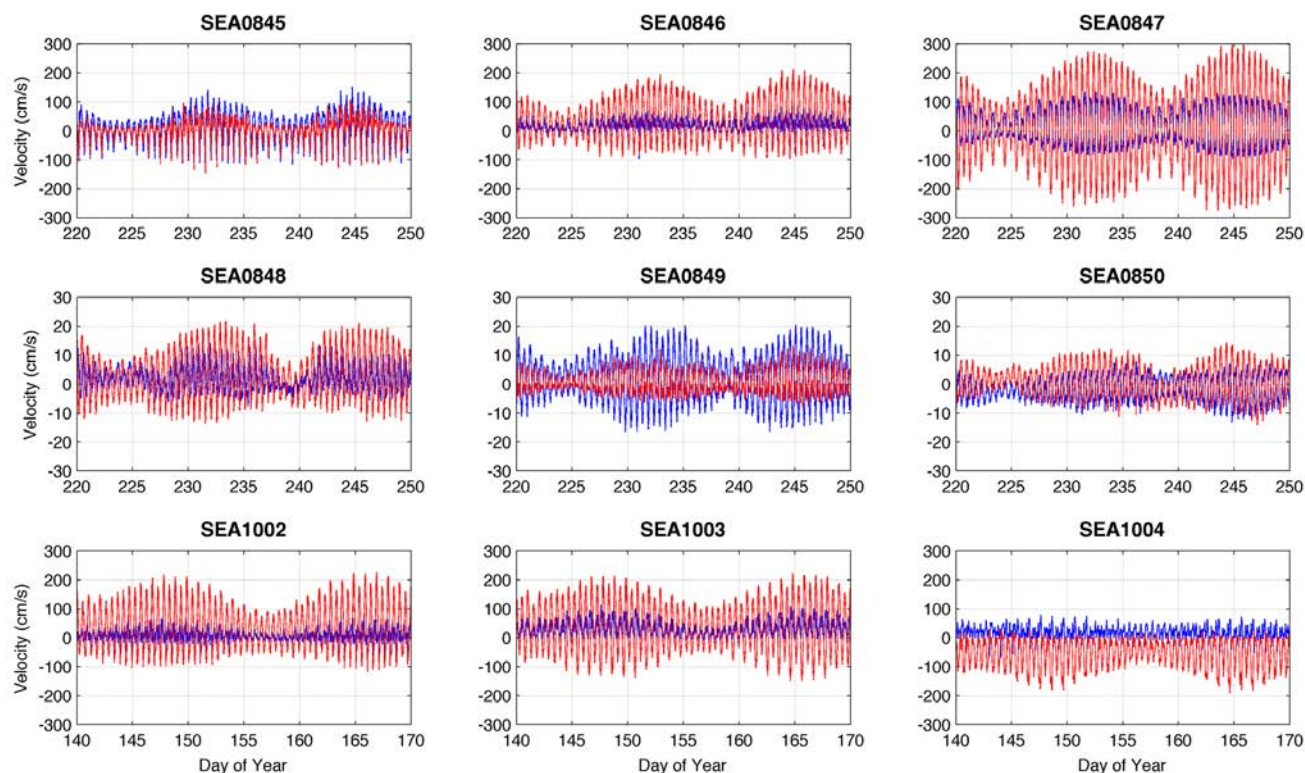


Figure 30. Thirty days of vertically averaged current velocity records from the nine mooring deployments. Blue traces show the east-west (U) component and red traces show the north-south (V) component. Note the difference in vertical scale for the middle row panels. C.f. Table 2 for deployment parameters.

One month of vertically averaged velocity records are shown for each mooring site in Figure 30. At all sites the tidal velocities greatly overwhelm the subtidal flows. Maximum recorded speeds south of Sitakaday Narrows are an order of magnitude larger than current speeds north of the sill. Peak instantaneous speeds approach 3 m s^{-1} at site SEA0847 and can exceed 2 m s^{-1} at all of the other stations in and near the entrance to Glacier Bay, except for Station SEA0845 in Icy Strait between Lemesurier Island and the mainland.

Record-length mean (subtidal) flows (Figure 31) show that the waters tend to enter Glacier Bay on the eastern side of the entrance and flow out on the western

side of the entrance. Despite the outflow location and direction, it appears that the mean flow direction at the North Passage site is eastward and onto the sill. The flow magnitude here does not appear large enough to compensate for the inflowing transport observed on the eastern side of the entrance, suggesting that waters entering Glacier Bay likely are drawn from both the west and the east sides of the Icy Strait sill.

Following Pawlowicz et al. (2003) we compute tidal current ellipse parameters associated with each of the barotropic (vertically averaged) currents from these moorings (e.g., Figure 30). We focus our attention here (Table 3) on the two dominant semi-diurnal M_2 and S_2

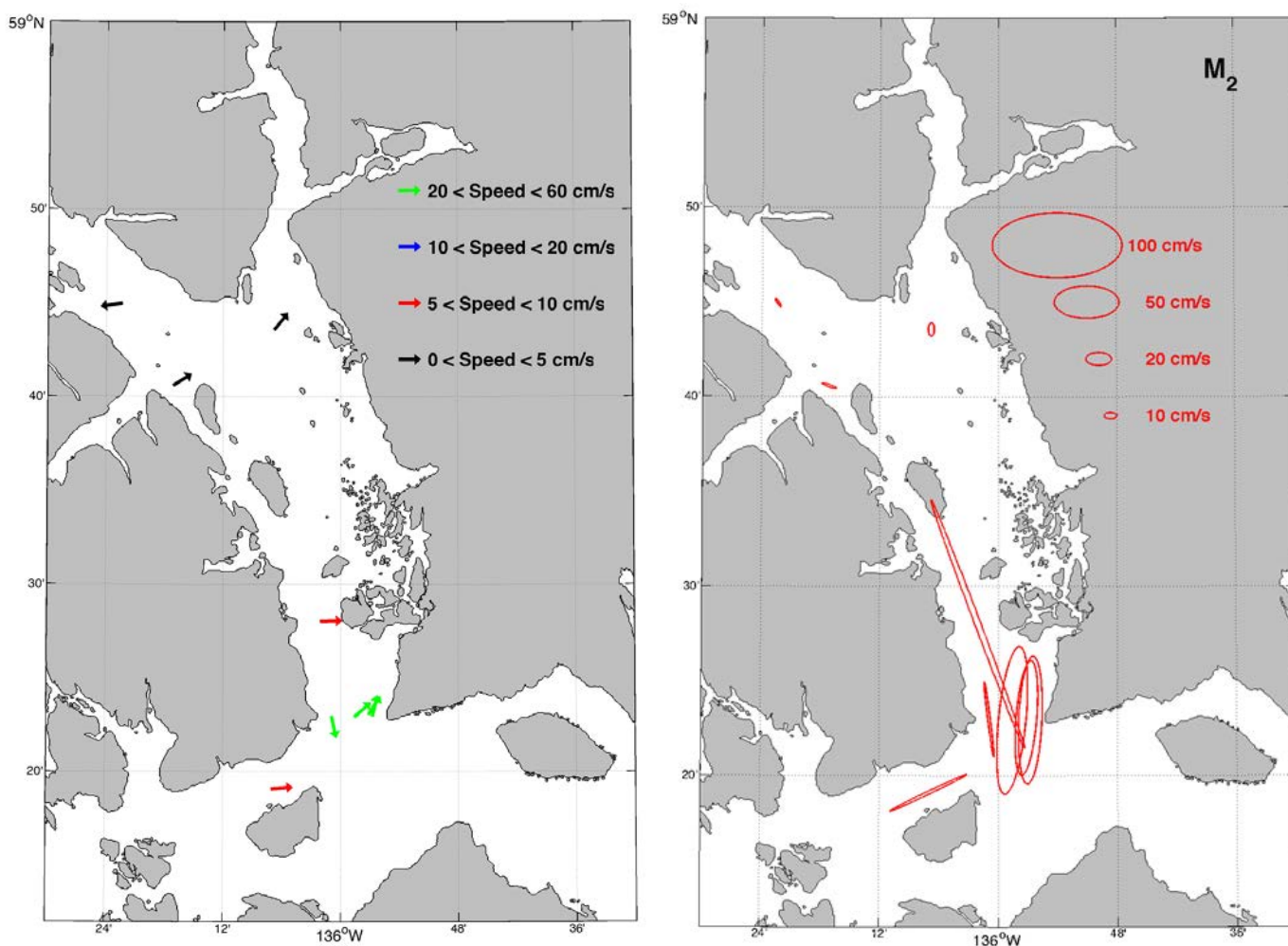


Figure 31. Mean vertically averaged subtidal currents (left), with arrows showing the net direction of the record-length flows at each mooring site and colors denoting the mean current speeds. Tidal current ellipses (right) are for the dominant semi-diurnal M_2 constituent. C.f. Table 2 for deployment parameters.

Table 3. Tidal current harmonic parameters computed from the mooring sites shown in Figure TC1. Abbreviations: MAJ = Semi-major axis (cm/s), MIN = Semi-minor axis (cm/s), INC = Inclination (degrees True); GPH = Greenwich Phase (degrees); E denotes error estimate for each parameter.

Constituent	Mooring	MAJ	MAJE	MIN	MINE	INC	INCE	GPH	GPHE
M_2	SEA0845	65.7	4.5	2.4	4.3	25.44	3.6	165.45	4.06
M_2	SEA0846	88.7	1.7	16.2	2.0	85.21	1.16	212.63	1.13
M_2	SEA0847	203.4	3.8	-4.5	2.2	110.62	0.66	214.26	1.29
M_2	SEA0848	10.0	0.9	-4.4	0.7	88.92	5.1	184.86	5.54
M_2	SEA0849	11.5	0.3	-1.5	0.3	161.04	1.77	201.31	1.76
M_2	SEA0850	8.4	0.3	1.8	0.2	125.42	1.63	207.76	1.8
M_2	SEA1002	98.4	2.4	18.2	0.8	87.4	0.64	210.43	1.42
M_2	SEA1003	114.2	2.3	21.4	1.0	84.19	0.59	215.12	1.11
M_2	SEA1004	58.4	1.4	-1.7	1.1	97.2	1.01	192.05	1.44
S_2	SEA0845	26.3	4.7	-1.6	3.9	29.61	8.64	184.85	9.76
S_2	SEA0846	37.0	1.6	9.2	1.9	90.02	2.86	246.91	2.6
S_2	SEA0847	86.9	3.9	-0.8	2.5	111.61	1.66	254.96	2.69
S_2	SEA0848	4.5	0.8	-2.2	0.7	100.54	13.42	227.79	14.22
S_2	SEA0849	5.0	0.3	-0.8	0.3	161.76	3.88	246.55	4.45
S_2	SEA0850	3.1	0.2	0.9	0.2	123.99	4.88	258.82	4.92
S_2	SEA1002	28.4	2.0	6.8	0.9	89.2	2.55	243.29	4.58
S_2	SEA1003	33.3	2.1	8.8	0.9	90.39	2.17	260.4	3.56
S_2	SEA1004	18.7	1.4	2.3	1.1	110.18	3.6	259.45	4.16
K_1	SEA0845	6.2	1.7	0.2	1.4	35.83	12.93	143.49	14.51
K_1	SEA0846	10.4	0.5	4.9	0.5	93.17	4.38	168.6	3.79
K_1	SEA0847	23.8	0.7	-0.4	0.6	112.07	1.27	196.23	1.76
K_1	SEA0848	0.8	0.1	0.3	0.1	98.27	15.04	254.2	12.88
K_1	SEA0849	0.9	0.1	0.1	0.1	159.28	8.5	176.06	10.94
K_1	SEA0850	0.5	0.1	0.0	0.2	148.39	22.51	173.94	14.56
K_1	SEA1002	11.7	1.0	5.5	0.8	96.77	5.71	154.58	7.45
K_1	SEA1003	18.0	0.8	6.5	0.8	107.16	3.56	196.63	3.36
K_1	SEA1004	13.9	1.1	-1.3	0.8	101.34	2.9	200.64	4.85
O_1	SEA0845	3.1	1.7	-0.2	1.3	17.94	26.37	96.75	27.08
O_1	SEA0846	6.1	0.5	3.5	0.5	90.42	7.8	129.92	7.5
O_1	SEA0847	16.5	0.7	-0.6	0.6	115.52	1.88	167.03	2.38
O_1	SEA0848	0.6	0.1	0.0	0.2	105.15	14.95	232.96	11.81
O_1	SEA0849	0.7	0.1	0.1	0.1	163.51	11.89	180.3	14.42
O_1	SEA0850	0.3	0.2	0.2	0.1	125.16	53.12	135.33	64.33
O_1	SEA1002	5.5	0.9	3.5	0.7	76.02	17.8	95.98	20.65
O_1	SEA1003	10.7	0.8	4.9	0.8	114.98	5.67	180.82	6.04
O_1	SEA1004	9.3	1.3	-1.4	0.9	107.94	4.72	180.25	6.66

tides (with periods of 12.42 and 12.00 hr, respectively) and the two dominant diurnal K_1 and O_1 tides (with periods of 23.93 and 25.82 hr, respectively), recognizing that appreciable variance remains at the other tidal frequencies. At all sites, the M_2 tidal currents are 2-3 times larger in magnitude than the next largest constituent. See Appendix D for the tidal ellipse parameters at all resolved frequencies.

From the nine mooring sites, tidal currents are found to be swiftest over the shallow and narrow passage leading into Sitakaday Narrows (SEA0847), but the largest mean flows were observed at the mooring sites that stretch from west to east across the entrance to Glacier Bay (Figure 31). The tidal ellipse at SEA0847 is also highly rectilinear, as are the ellipses of SEA0847 and SEA1004, while other sites in the broader Lower Bay exhibit more rotation.

The harmonic analysis results can be used to predict or hindcast the barotropic tidal current speed and direction at any given

time in the past or future and thus are valuable for planning field experiments or interpreting past collected data in relation to the phase of the tide and the direction of the flow. We note that with sufficient knowledge of the tidal currents at each station and the lateral structure of the physical hydrography it would be possible to estimate and remove a portion of the variability contained within the shipboard hydrography that is due to tidal advection. This approach could possibly be used to lower the standard deviation associated with the monthly hydrographic anomalies and subsequently increase the sensitivity of a trend analysis to small-magnitude signals. Some tidal effects will remain difficult or impossible to remove, such as those caused by long periods (e.g., 18-yr tides), baroclinic (stratified) tides, and very high frequency (tidally generated internal waves) effects. Each of these will continue to impart signals (noise) into the hydrographic anomalies and potentially obscure decadal-scale trends.

Discussion and Conclusions

This report reviews measurements made to date by the Glacier Bay oceanographic monitoring program, with particular focus on observations from 2010 through 2016. A special section analyzes and summarizes current meter mooring data collected by the National Ocean Service (NOS) in 2008 and 2010. The report is intended to provide an accessible manual interpreting Glacier Bay oceanography at the monitoring stations and provide context for the observations with respect to the regional Northeast Pacific atmospheric and oceanographic conditions.

Appendices provide station-by-station depictions of the primary physical data on a seasonal basis and over the period of record, along with additional depictions of the hydrography and the tidal analyses. The existing SEAN I&M Oceanographic Monitoring program continues to build on a unique and increasingly valuable oceanographic dataset. The record length is now long enough that indications of multi-decadal trends are beginning to emerge, and we are gaining a better understanding of the range of variability and the factors that control it.

Like much of the rest of the sub-Arctic, density in Glacier Bay is primarily a function of salinity rather than temperature (Carmack, 2007). Highest densities at all depths at Station 04 occur in May; peak density over the sill at Station 01 occurs in April. The annual minimum in density at 45 m depth occurs first at Station 01 in October and then at Station 04 in November. The Station 04 density minimum at 45 m depth is in November but at 250 m depth in January. The surface density at Station 04 is always lower than that at Station 00 (outside Glacier Bay proper in Icy Strait, not shown). Monthly mean densities in January, March, and April over the sill achieve greater density than waters at much greater depths within the fjord (note the blue trace in the bottom

panel of Figure 32 crosses the black and gray traces); this is in close agreement with Matthews' (1981) assessment.

We continue to learn about the timing, location, and rate of deep-water renewals in the Bay. The observations suggest that the fjord's deep-water renewal is particularly prone to occur between December and April because in these months the near-bottom density over the sill exceeds the density at 100 m depth north of the sill and the pressure gradient force will tend to draw the shallow waters over the sill down into the Bay. With waters not in hydrostatic balance we might expect that waters inflowing on the flood tide will seek an equilibrium depth as they advect (and mix) on their way into the fjord. The strong tides will naturally freshen the near-bottom salinities over the course of the year until the following season in which densities at the sill are again higher than densities found at depth in the Bay.

Valle-Levinson and Wilson (1994) show that strong barotropic forcing over a sill leads to asymmetry of the advection of the gradient field and that the tidal prism mediates cross-sill exchange, rather than the primarily hydraulic control expected in fjords with weaker forcing. The model of Hill (2007) exhibits semidiurnal excursions on the order of 20 km in the lower bay, so advection of density by the tides may well introduce Icy Strait and Lower Bay waters into and north of the sill region where gravity flows can then exert control. We note also that Hill et al. (2009) analyzed the currents of a barotropic numerical model and found net northward flux into the Bay in the center of Sitakaday Narrows and net outflow at the margins. This is partially influenced by the net outflow required to balance the terrestrial discharge and the subsurface waters that this transport entrains. This structure also suggests the importance of station

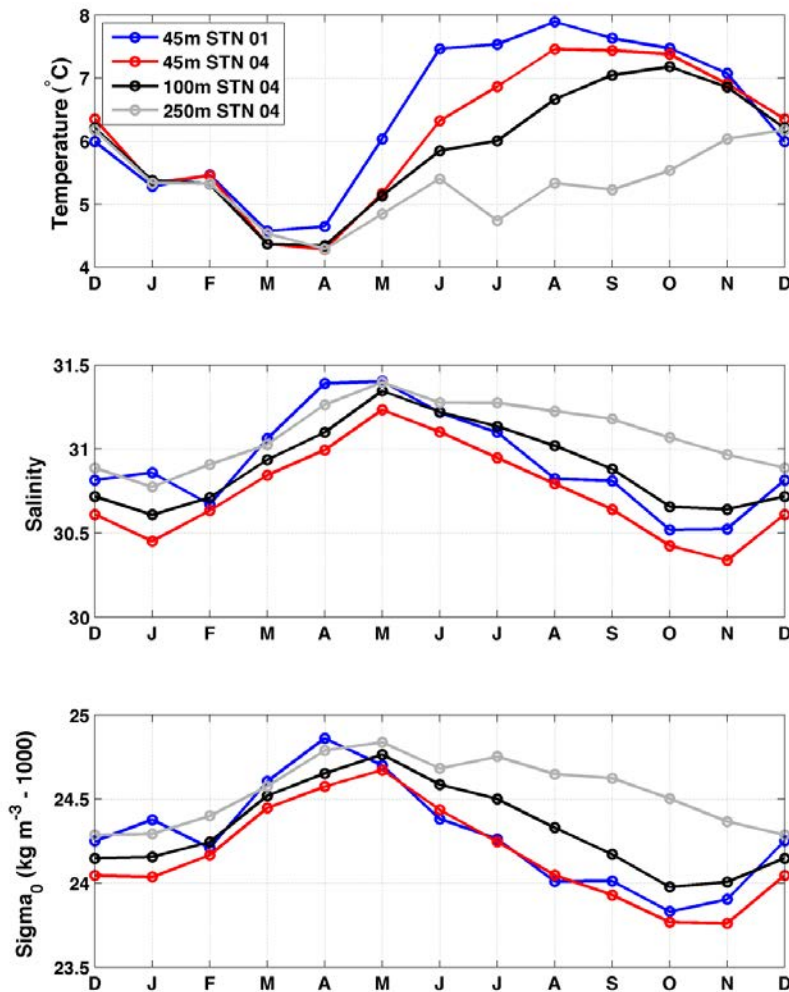


Figure 32. Mean monthly time series of temperature (top), salinity (middle), and density (sigma-0, bottom) for 45 m (red and blue), 100 m (black) and 250 m (gray) depth strata at Stations 01 and 04.

location and the small-scale structures that are not resolved by the oceanographic monitoring program. The NOS current meter moorings were sparsely located but indicated net northward flow on the eastern side of the sill and net southward flow on the western side. This contrast between the models and the observations deserves further investigation. Inspection of satellite imagery also suggests surface inflow on the eastern side of the East and West Arms and surface outflow on the west sides of these Arms.

Near-surface (<40 m depth) waters south of the sill remain denser at all times of year than the corresponding waters north of the sill, so the stratification tendency is to promote regular surface estuarine exchange year-round, despite the strong mixing at the sill. It is possible that inflow

during summer and fall months (June to October) occurs at intermediate depths. Bernoulli suction could pull waters from below the sill depth (perhaps on each tidal cycle) up to the sill, but we lack sufficient measurements deeper than the sill depth in Icy Strait to assess the importance of this mechanism.

The anomaly panels of Figures 23-26 depict some signals that are confined to the near-surface, some signals that are found only at depth, and some signals that extend nearly uniformly across the water column. These latter signals suggest the influence of external forcing upon the Glacier Bay system because waters entering the Bay over the sill have more direct communication with the deeper waters than with surface waters in highly stratified locations. Surface and deep waters within

the bay are largely isolated from one another for much of the year due to high levels of upper water column vertical stratification. Near-surface temperature and salinity anomalies are more likely locally forced phenomena resultant from wind, high/low rates of heating/cooling, freshening/salinization associated with the cloud cover anomalies (and associated incoming solar radiation anomalies), and precipitation anomalies (and subsequent terrestrial discharge anomalies).

The strong temperature anomaly observed at depth in late 1997 and early 1998 is the footprint of the record-strength El-Niño conditions of that year. El-Niño triggers atmospheric teleconnections that transmit equatorial climate signals to the extratropics. Such waves can displace the thermocline, resulting in a temporary increase of temperatures as the trough of the signal passes. The signal is barotropic (operates across the entire depth of the water column), but the surface waters are more strongly influenced by and connected to local conditions so the wave is strongly observed only at depth. The propagation time for this signal to reach Alaskan waters is on the order of half a year after the El-Niño disturbance impinges upon the eastern equatorial Pacific shoreline. This signal was also observed at depth at oceanographic station GAK1; Royer (2005) attributes the temperature increase to anomalous advection of the along-shelf temperature gradient found in the eastern Gulf of Alaska.

The cold and salty anomalies of late 2006-2009 were also observed by Janout et al. (2010) and represented a temporary return to colder and saltier conditions that had not been seen in the Gulf of Alaska since the early 1970s. This signal is particularly apparent at 200 m depth where a prolonged period of relatively fresh conditions from 1999-2006 contrasts with the subsequent saltier period. The

shift from cold to warm conditions in the greater Gulf of Alaska was coincident with a large-scale reorganization of the marine ecosystem: crab and shrimp stocks crashed in the late 1970s, and the fishery was replaced by a pelagic fishery (Anderson and Piatt, 1999).

Given the large apparent net production that takes places in Glacier Bay (inferred from the high density of marine mammals and birds that are supported within this relatively small region), the primary production of the Bay must have some consistent source of nutrient supply. Because the renewal of deep-waters within the Bay likely occurs primarily during the winter and spring months, much of this exchange takes place when there is not sufficient light to enable rapid phytoplankton growth. Figure 32 shows that waters outside of the Bay above the sill depth are able to replace deep-waters between November and May and that intermediate waters could also exchange during summer months. Waters below the sill depth could likely replace deep-waters inside the fjord at any time of year. Certainly the nutrients fueling new production at the end of winter are dependent upon the periodic resupply of deep-waters. However, as this nutrient supply is drawn down over the course of the spring, where do the new nutrients come from to continue to provide for production during the summer months?

Possible mechanisms for nutrient resupply include the turbulence generated by direct frictional drag over the seafloor, remineralization, and the interplay between frontal systems, stratification, advection, and bottom topography. One example of the latter mechanism would be that of internal wave-breaking. In an estuary that hosts a combination of strong tidal currents and large variations in bathymetric depth, one might expect that internal wave generation would exert influence on the resulting character of

the density field and cross-pycnocline (diapycnal) mixing. Internal waves may be triggered at each of the multiple sills found within Glacier Bay; it is less clear where the internal waves might propagate to and subsequently break, or whether stationary waves may be generated. However, these sites of turbulent wave-breaking could create persistent hotspots for biological production. Whether nutrient resupply is due primarily to enhanced mixing due to frictional drag in shallow waters, or to internal wave dynamics, is presently unknown.

Research Recommendations

A comprehensive mechanistic understanding of Glacier Bay physical dynamics and its mediation of the ecosystem remains elusive. Some gaps in knowledge can be at least framed through application of theory, conceptual models, and numerical modeling. Progress on others will require an observational effort that goes beyond the existing ship-based monitoring program. The most direct route to a fuller understanding is through a series of targeted process studies that can sequentially target important knowledge gaps.

Examples of such efforts are listed below. Some of these could be addressed with just one or two seasons of targeted process study measurements; others would require multiple years. Some could be addressed with moored instrumentation; others are better investigated with shipboard surveys, autonomous surface or underwater vehicles, towed instruments, or a combination of all. A common thread is the need to better understand locally driven oceanographic variability in contrast to variability driven by remote forcing. By working toward a better understanding of the topics listed below, the NPS will be in a better position to interpret the data collected by the ongoing oceanographic monitoring program and apply the monitoring data to management needs.

Focal questions and topics that could inform future investigations and improve our understanding of the Glacier Bay oceanographic functioning include the following:

1. **Sub-seasonal oceanic variability:** The GLBA oceanographic monitoring program documents seasonal changes in water column properties. However, processes that occur on time scales of minutes, hours, and up to a few days may be the most important in determining the overall character of the oceanic habitat that supports the marine ecosystem. We know very little about the magnitude of temperature, salinity, nutrient, and current fluctuations on time scales shorter than that of the nominally monthly monitoring.
2. **Remote forcing:** To what degree are oceanographic fluctuations in the greater Gulf of Alaska and within Icy Strait, Cross Sound, and Chatham Strait felt within Glacier Bay? Do winds over the greater Gulf of Alaska influence exchanges over the Sitakaday Narrows sill? Does wind influence the physical or chemical characteristics of exchanged waters, or the total volume transport?
3. **Glacier meltwaters:** What is the importance of tidewater glaciers and discharge of ice melt to the Glacier Bay marine ecosystem? With increasing planetary temperatures and net glacial ablation, might we expect a change in the fjord's near-surface physical hydrography, the subsurface stratification, or the associated chemical hydrography and biological components of the ecosystem? What is the role of submarine meltwater discharge in structuring and supporting near-glacier ecosystem?
4. **Deep-water renewal:** What sets the depth of subsurface water renewals in the Bay, and what controls the thermohaline, nutrient, and oxygen properties of these waters?
5. **Stratification:** What drives variability in the end-of-winter stratification? Do differences in stratification observed in February or March impact the sub-

sequent spring bloom strength or the makeup of the primary or secondary producer communities? Some scientific studies suggest that future runoff from precipitation will continue to increase due to an accelerated hydrological cycle. How might this change affect primary productivity?

6. **Nutrient dynamics and primary productivity:** Where and when does nutrient delivery to the euphotic zone take place that supports primary production, and what are the primary sources? Is it primarily fed by turbulent mixing from tides or are there regions of wind-driven upwelling that can spur mid-summer blooms? Is bottom friction or breaking internal waves more important? Is net production more dependent on the resupply of nutrients to deep depths over the course of the winter, or is it more dependent upon the resupply of nutrients to an intermediate layer on an ongoing basis through the summer? What is the relative importance of new versus regenerated production in Glacier Bay?
7. **Secondary production:** With a few notable exceptions (e.g., Park et al. 2004, Arimitsu et al. 2016, Stemmler in prep.), the lower trophic level component of the Glacier Bay ecosystem has not been very thoroughly described. What is the relation between the zooplankton communities in Glacier Bay, Icy Strait, Cross Sound, and the Gulf of Alaska shelf? To what degree does Glacier Bay serve as a refugium for relic cold-climate species?
8. **Ocean acidification:** The park has invested in two ocean acidification (OA) studies over the last decade. At the same time, the network of OA studies in Alaskan waters has greatly increased in number. Should the Park also maintain an OA monitoring program as part of the oceanography vital sign? What might this look like?
9. **Role of internal waves:** In a 2016 field experiment, trains of internal waves were observed in Glacier Bay (Daniel-

son unpubl. obs.). While their overall impact on the ecosystem still remains unknown, there are implications for turbulence-mediated nutrient resupply to the euphotic zone and prey aggregations that may benefit both lower and upper trophic level consumption. Many unresolved questions remain: do soliton-like features propagate, or are they stationary? Are they triggered on every tidal cycle, or is there a special combination of tidal current speed and stratification that allows their generation?

10. **Cross-program synthesis efforts:** Results from a variety of park research projects and monitoring programs address specific hypotheses and monitoring questions, but there remains untapped potential for extracting new knowledge from existing data. Synthetic analyses, workshops, and development of conceptual models offer means to leverage prior investments into new products that inform both the public and park management.

There are many possible approaches to tackling any of the above research topics. Two types of mooring programs should be considered if the NPS decides that any of the above questions should be addressed: (1) incorporating a permanent fixed-location mooring into the monitoring program, and (2) undertaking process-studies with short-term mooring arrays deployed over months to years in order to answer specific research questions. Moored observations from either type of program would add value to the ongoing shipboard CTD observations by placing the monitoring measurements within a fuller spatial-temporal context and would add substantial value to both the measurements collected in the past and the measurements still to be taken in the future.

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Appendix A: Time-depth Sections of Temperature and Salinity: Mean Seasonal Cycle and Anomalies

The pages of Appendix A contain station-by-station depictions of temperature (on the left) and salinity (on the right). The top two panels show monthly mean contours of each parameter over 0-50 m depth and then 50 m to the bottom or 225 m, whichever is shallower. The third panel from the top shows the monthly anomaly versus depth. The bottom three panels show single-depth anomalies at 10 m, 100 m, and 200 m below the surface. Shallow stations not reaching the greater depths have panels that are left blank (Figures A1 - A46).

GLBA Station 00

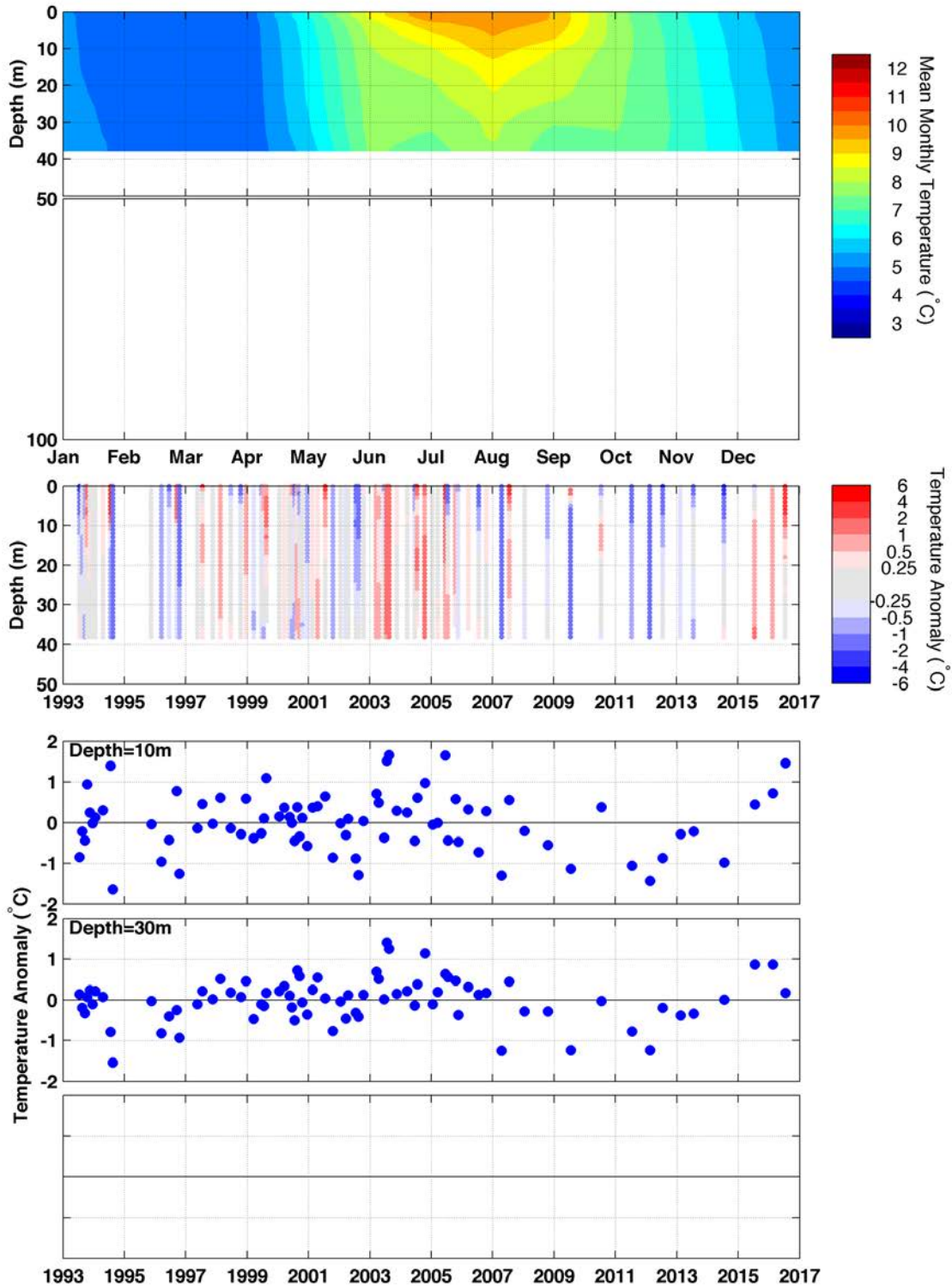


Figure A1. GLBA Station 00 temperature fields. The top two panels show monthly mean contours of temperature over 0-50 m depth and then 50 m to the bottom or 225 m, whichever is shallower. The third panel from the top shows the monthly anomaly versus depth. The bottom three panels show single-depth anomalies at 10 m, 100 m, and 200 m below the surface. Shallow stations not reaching the greater depths have panels that are left blank.

GLBA Station 00

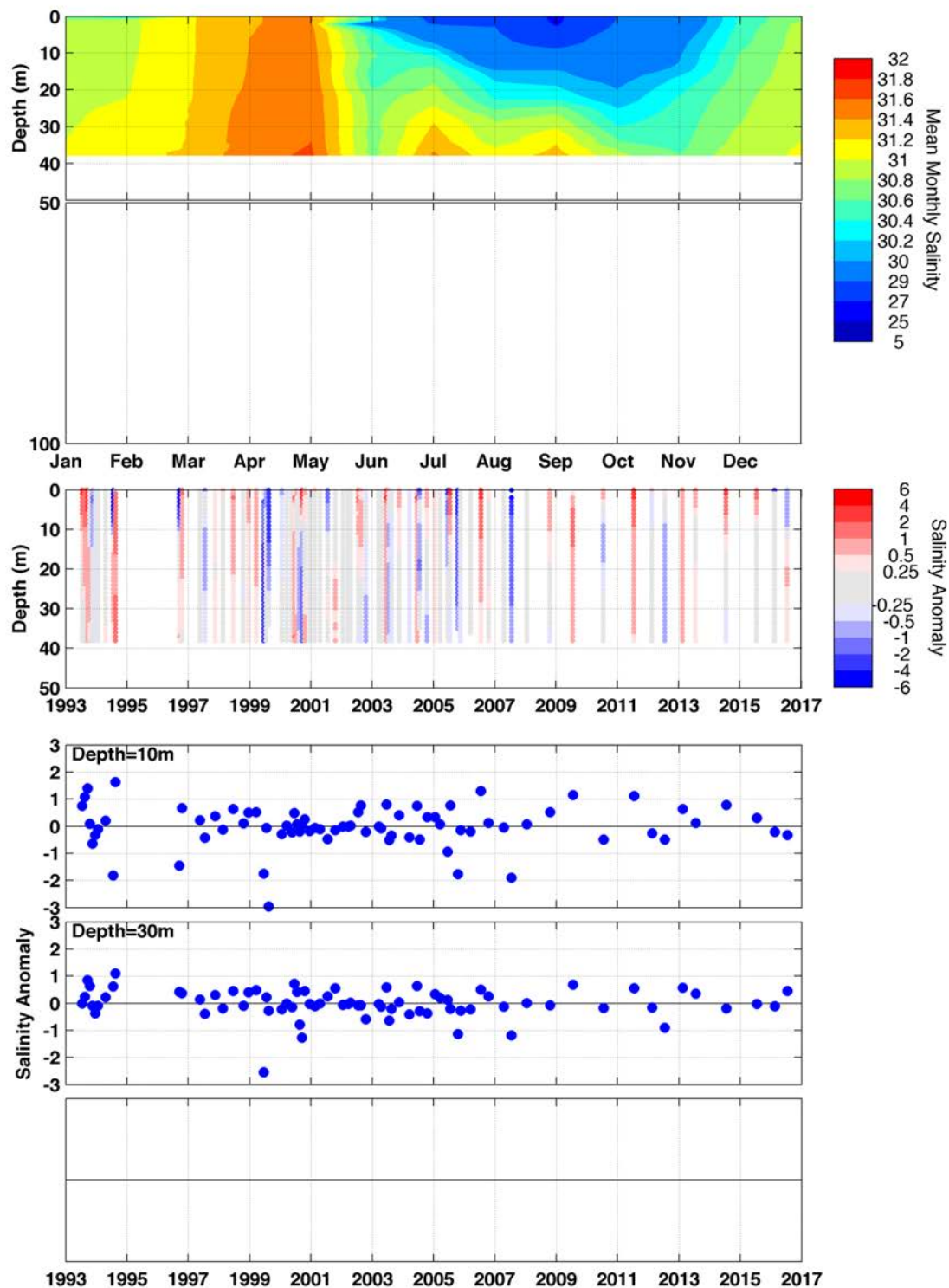


Figure A2. GLBA Station 00 salinity fields. The top two panels show monthly mean contours of salinity over 0-50 m depth and then 50 m to the bottom or 225 m, whichever is shallower. The third panel from the top shows the monthly anomaly versus depth. The bottom three panels show single-depth anomalies at 10 m, 100 m, and 200 m below the surface. Shallow stations not reaching the greater depths have panels that are left blank.

GLBA Station 01

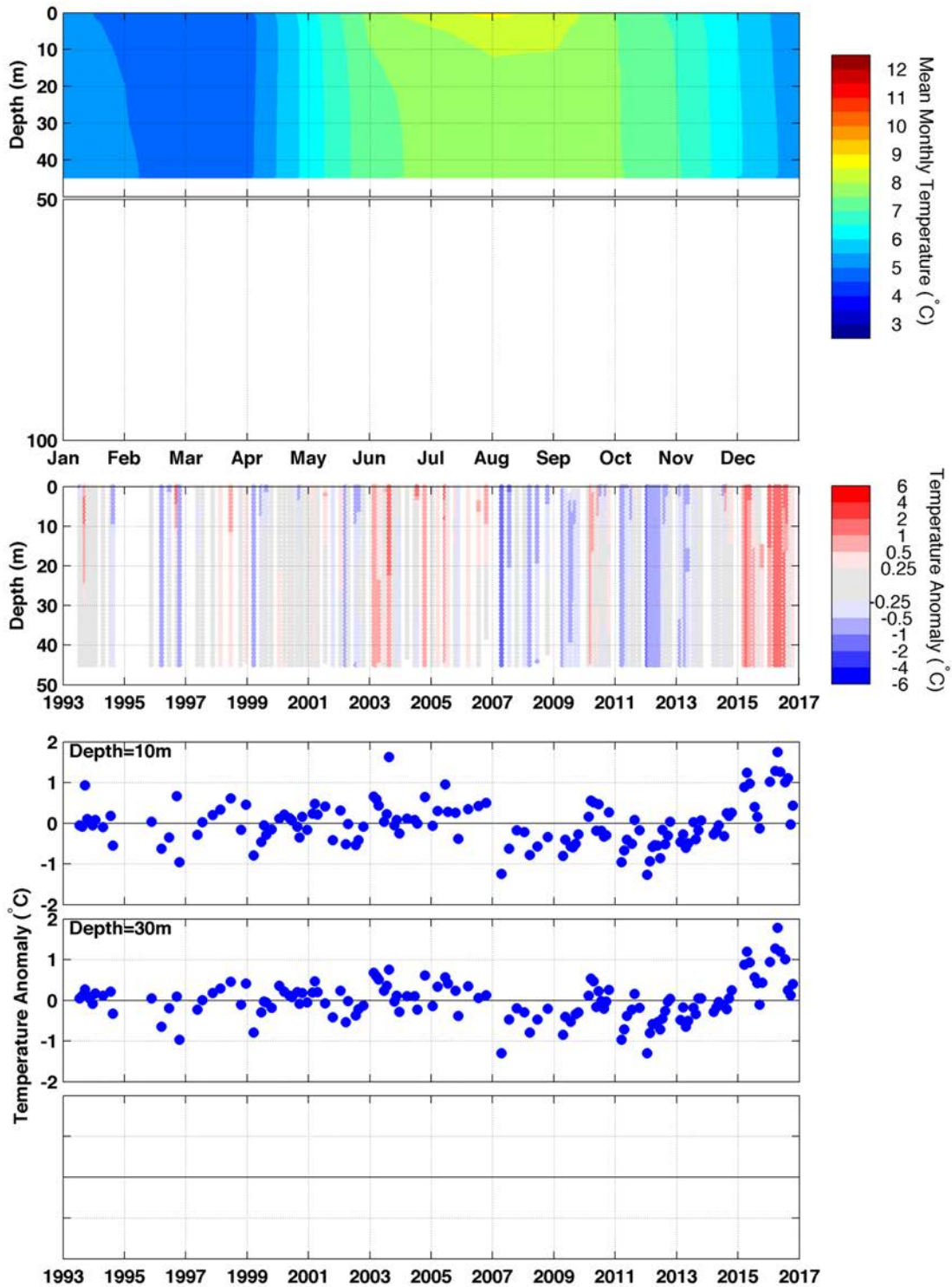


Figure A3. GLBA Station 01 temperature fields. The top two panels show monthly mean contours of temperature over 0-50 m depth and then 50 m to the bottom or 225 m, whichever is shallower. The third panel from the top shows the monthly anomaly versus depth. The bottom three panels show single-depth anomalies at 10 m, 100 m, and 200 m below the surface. Shallow stations not reaching the greater depths have panels that are left blank.

GLBA Station 01

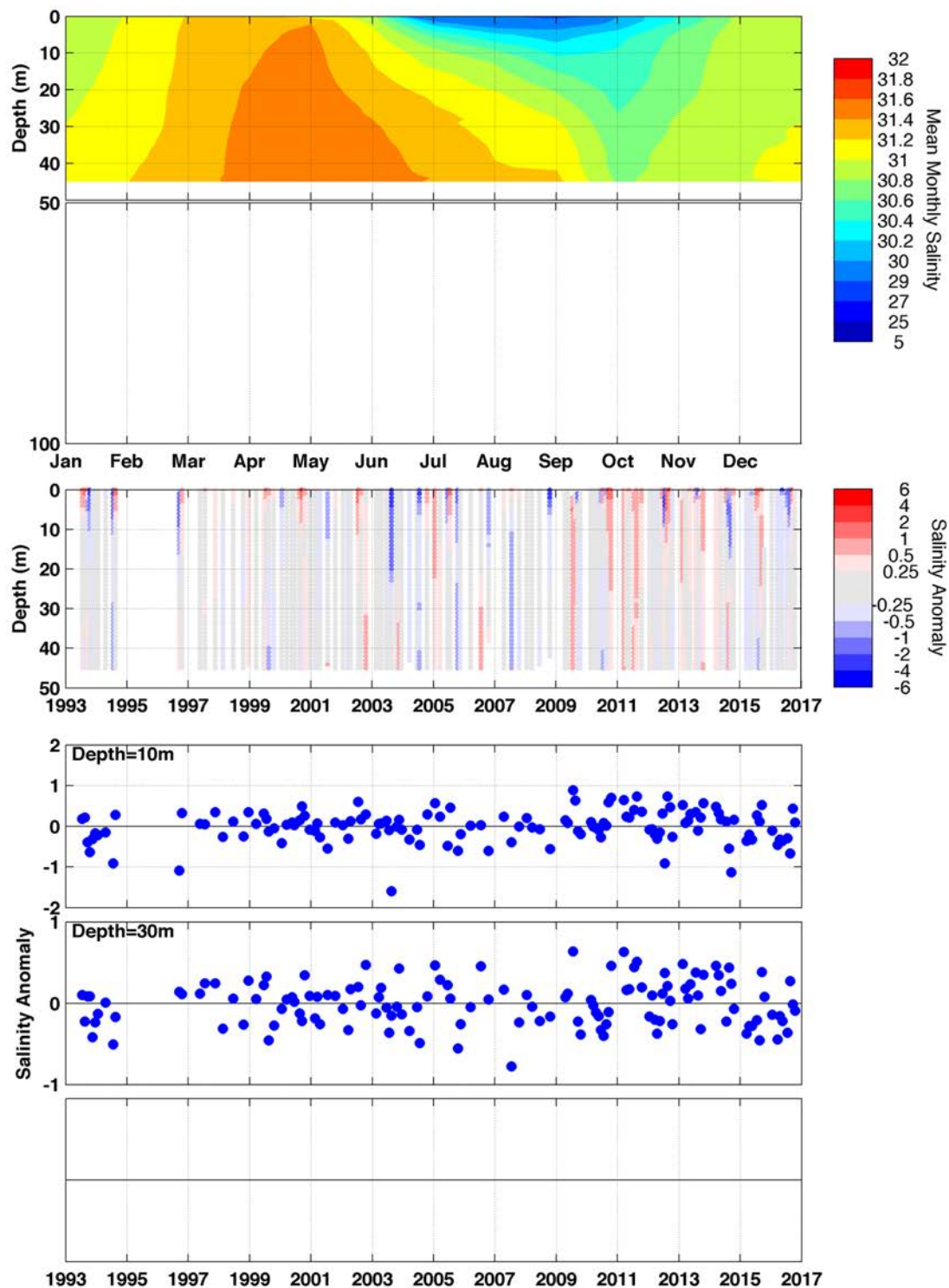


Figure A4. GLBA Station 01 salinity fields. The top two panels show monthly mean contours of salinity over 0-50 m depth and then 50 m to the bottom or 225 m, whichever is shallower. The third panel from the top shows the monthly anomaly versus depth. The bottom three panels show single-depth anomalies at 10 m, 100 m, and 200 m below the surface. Shallow stations not reaching the greater depths have panels that are left blank.

GLBA Station 02

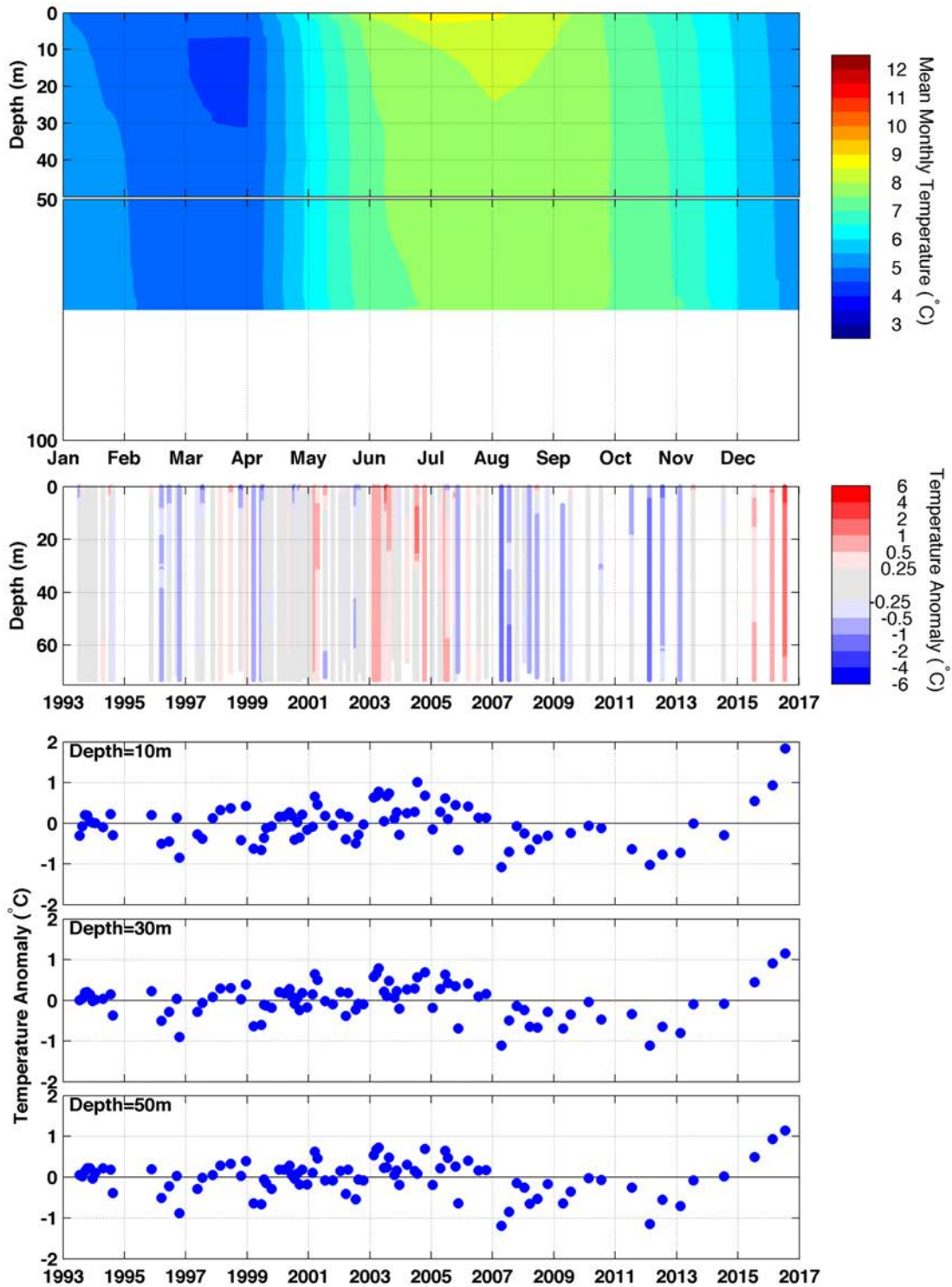


Figure A5. GLBA Station 02 temperature fields. The top two panels show monthly mean contours of temperature over 0-50 m depth and then 50 m to the bottom or 225 m, whichever is shallower. The third panel from the top shows the monthly anomaly versus depth. The bottom three panels show single-depth anomalies at 10 m, 100 m, and 200 m below the surface. Shallow stations not reaching the greater depths have panels that are left blank.

GLBA Station 02

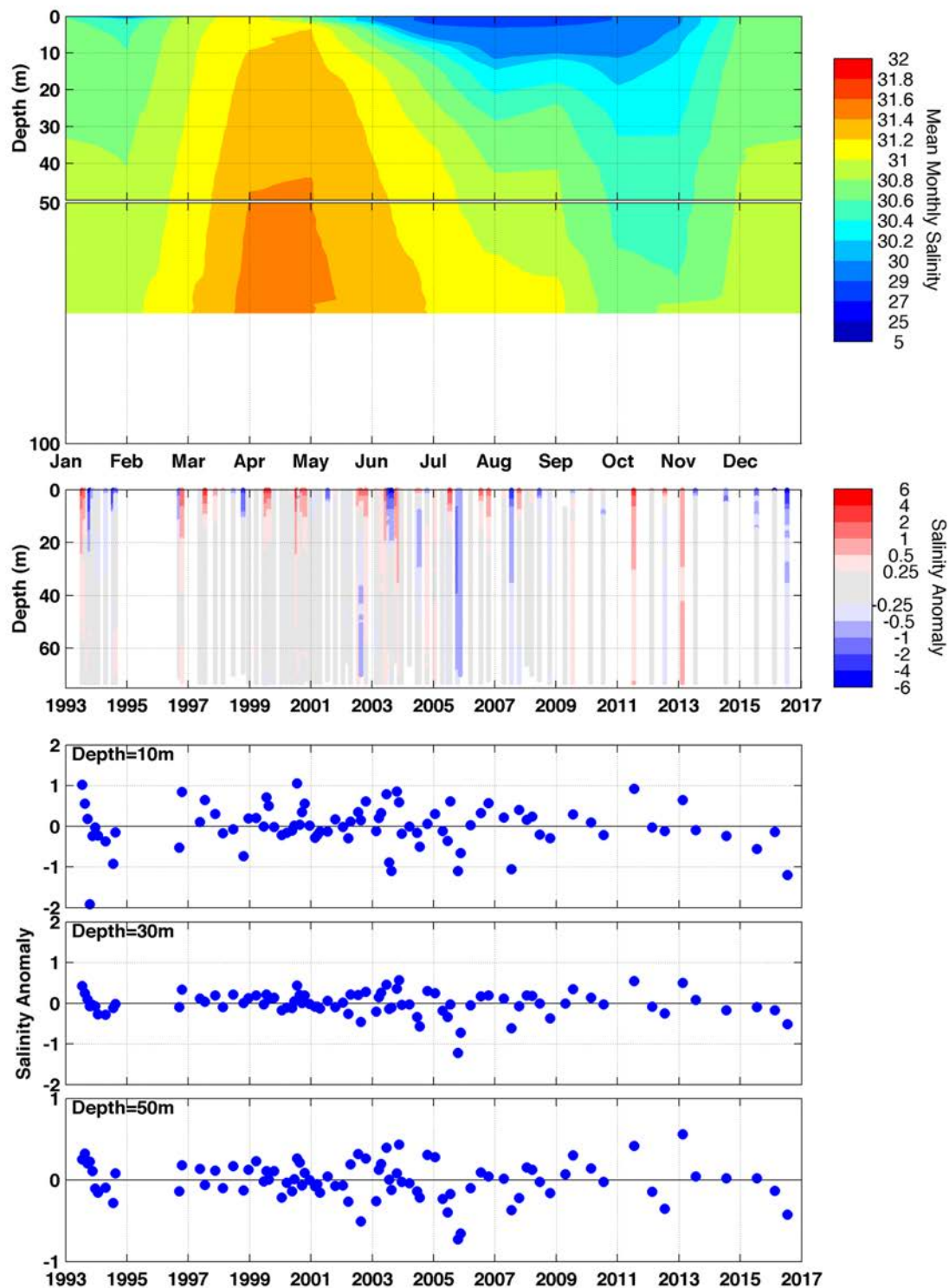


Figure A6. GLBA Station 02 salinity fields. The top two panels show monthly mean contours of salinity over 0-50 m depth and then 50 m to the bottom or 225 m, whichever is shallower. The third panel from the top shows the monthly anomaly versus depth. The bottom three panels show single-depth anomalies at 10 m, 100 m, and 200 m below the surface. Shallow stations not reaching the greater depths have panels that are left blank.

GLBA Station 03

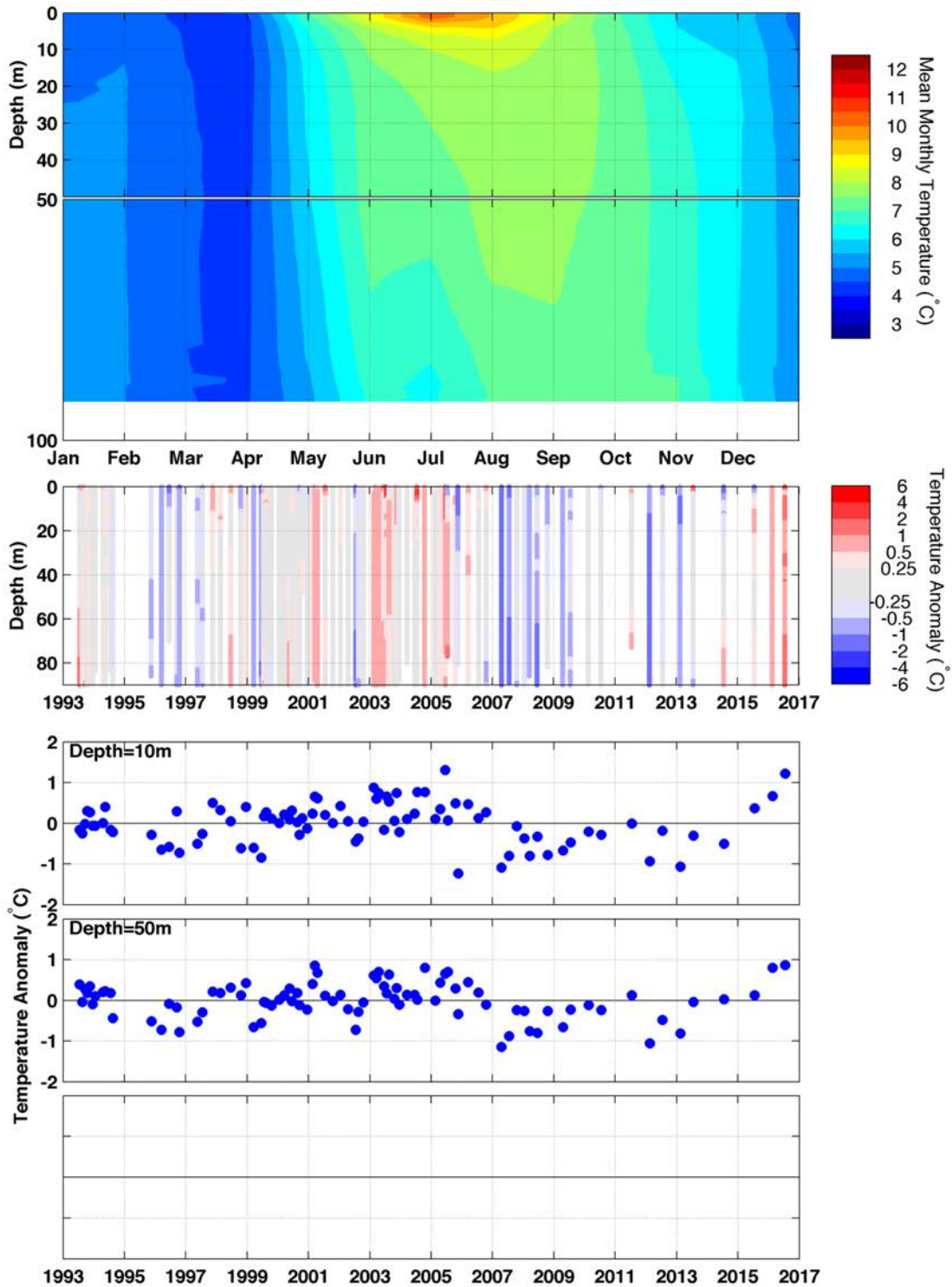


Figure A7. GLBA Station 03 temperature fields. The top two panels show monthly mean contours of temperature over 0-50 m depth and then 50 m to the bottom or 225 m, whichever is shallower. The third panel from the top shows the monthly anomaly versus depth. The bottom three panels show single-depth anomalies at 10 m, 100 m, and 200 m below the surface. Shallow stations not reaching the greater depths have panels that are left blank.

GLBA Station 03

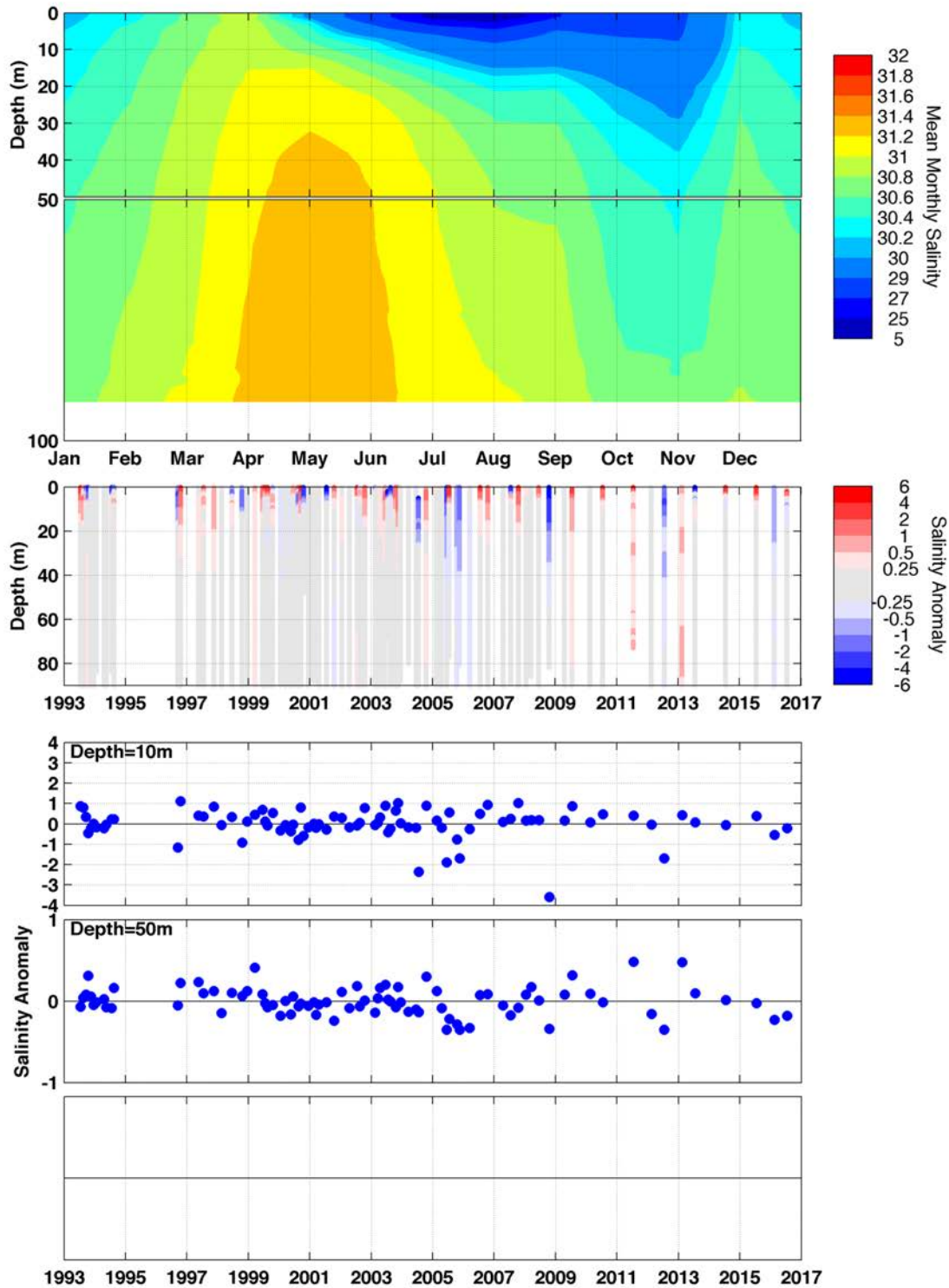


Figure A8. GLBA Station 03 salinity fields. The top two panels show monthly mean contours of salinity over 0-50 m depth and then 50 m to the bottom or 225 m, whichever is shallower. The third panel from the top shows the monthly anomaly versus depth. The bottom three panels show single-depth anomalies at 10 m, 100 m, and 200 m below the surface. Shallow stations not reaching the greater depths have panels that are left blank.

GLBA Station 04

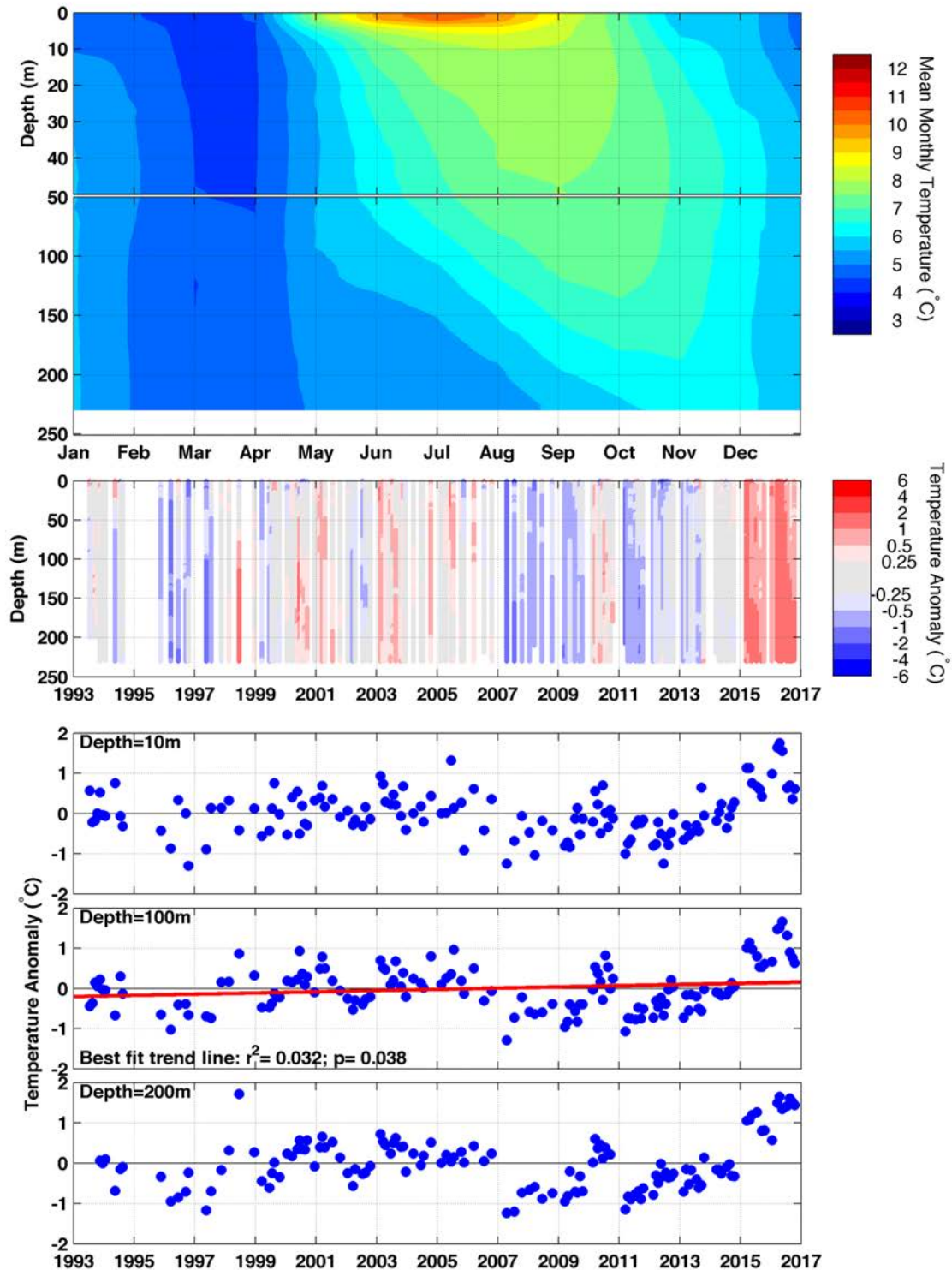


Figure A9. GLBA Station 04 temperature fields. The top two panels show monthly mean contours of temperature over 0-50 m depth and then 50 m to the bottom or 225 m, whichever is shallower. The third panel from the top shows the monthly anomaly versus depth. The bottom three panels show single-depth anomalies at 10 m, 100 m, and 200 m below the surface. Shallow stations not reaching the greater depths have panels that are left blank.

GLBA Station 04

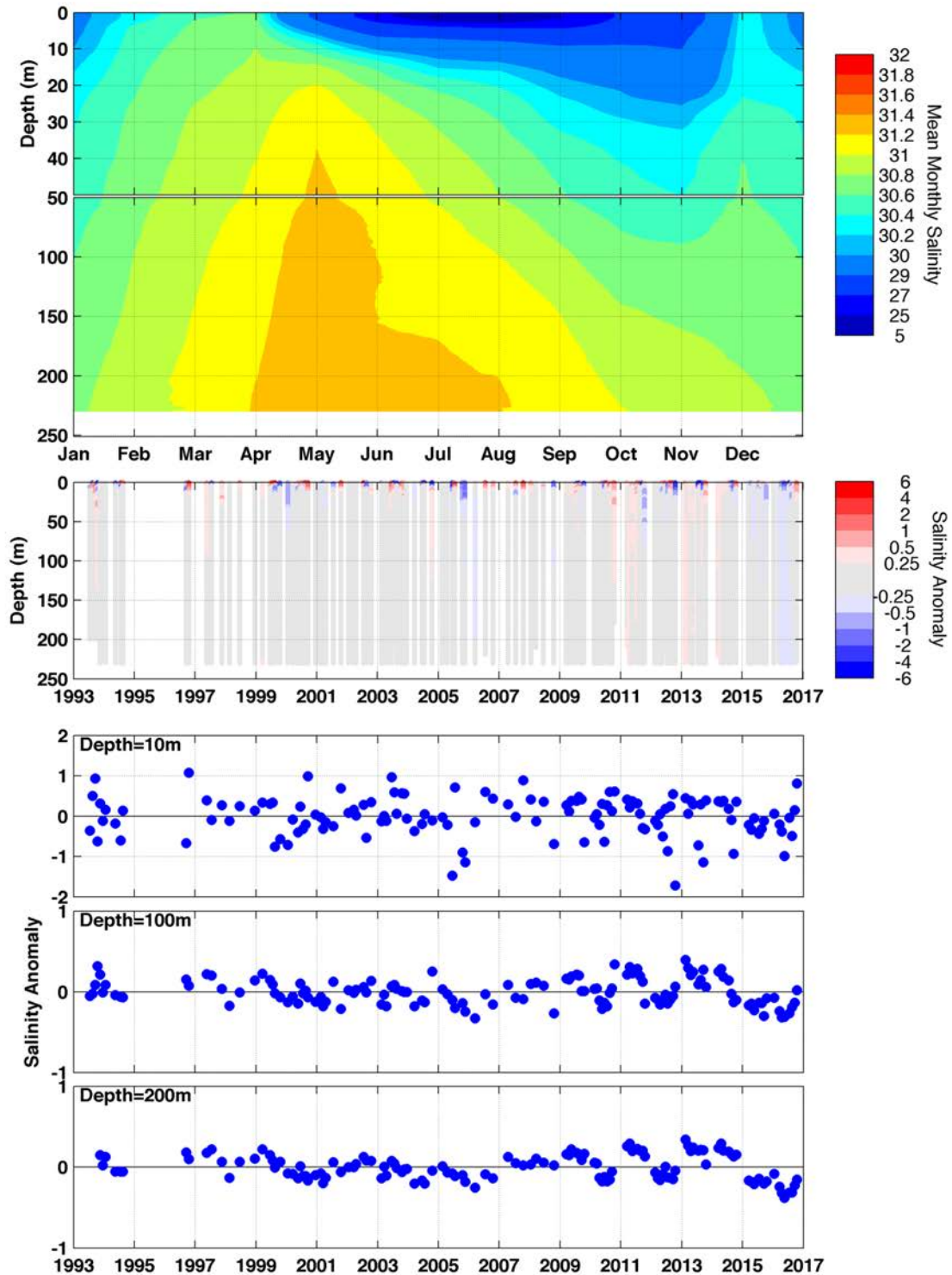


Figure A10. GLBA Station 04 salinity fields. The top two panels show monthly mean contours of salinity over 0-50 m depth and then 50 m to the bottom or 225 m, whichever is shallower. The third panel from the top shows the monthly anomaly versus depth. The bottom three panels show single-depth anomalies at 10 m, 100 m, and 200 m below the surface. Shallow stations not reaching the greater depths have panels that are left blank.

GLBA Station 05

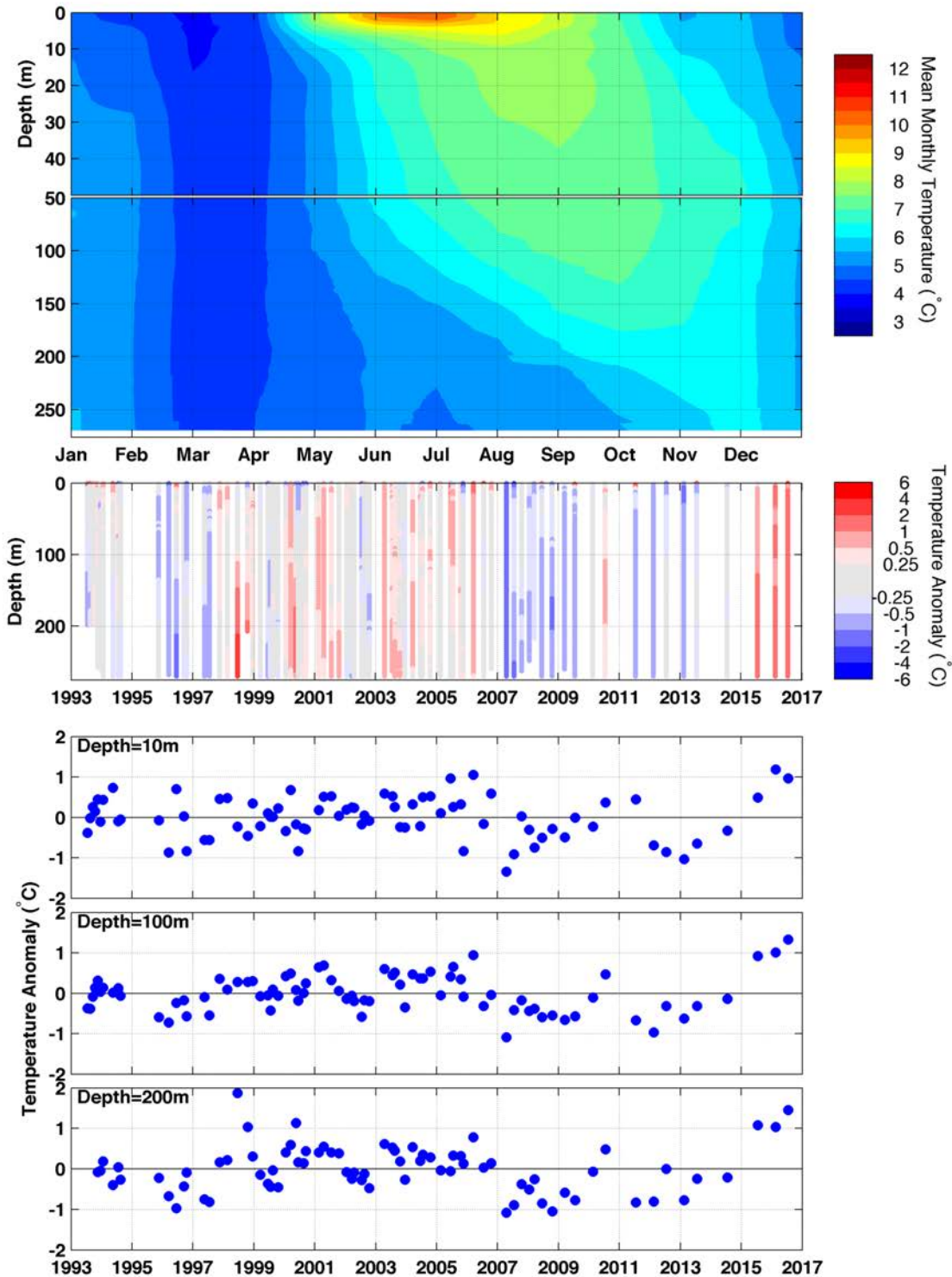


Figure A11. GLBA Station 05 temperature fields. The top two panels show monthly mean contours of temperature over 0-50 m depth and then 50 m to the bottom or 225 m, whichever is shallower. The third panel from the top shows the monthly anomaly versus depth. The bottom three panels show single-depth anomalies at 10 m, 100 m, and 200 m below the surface. Shallow stations not reaching the greater depths have panels that are left blank.

GLBA Station 05

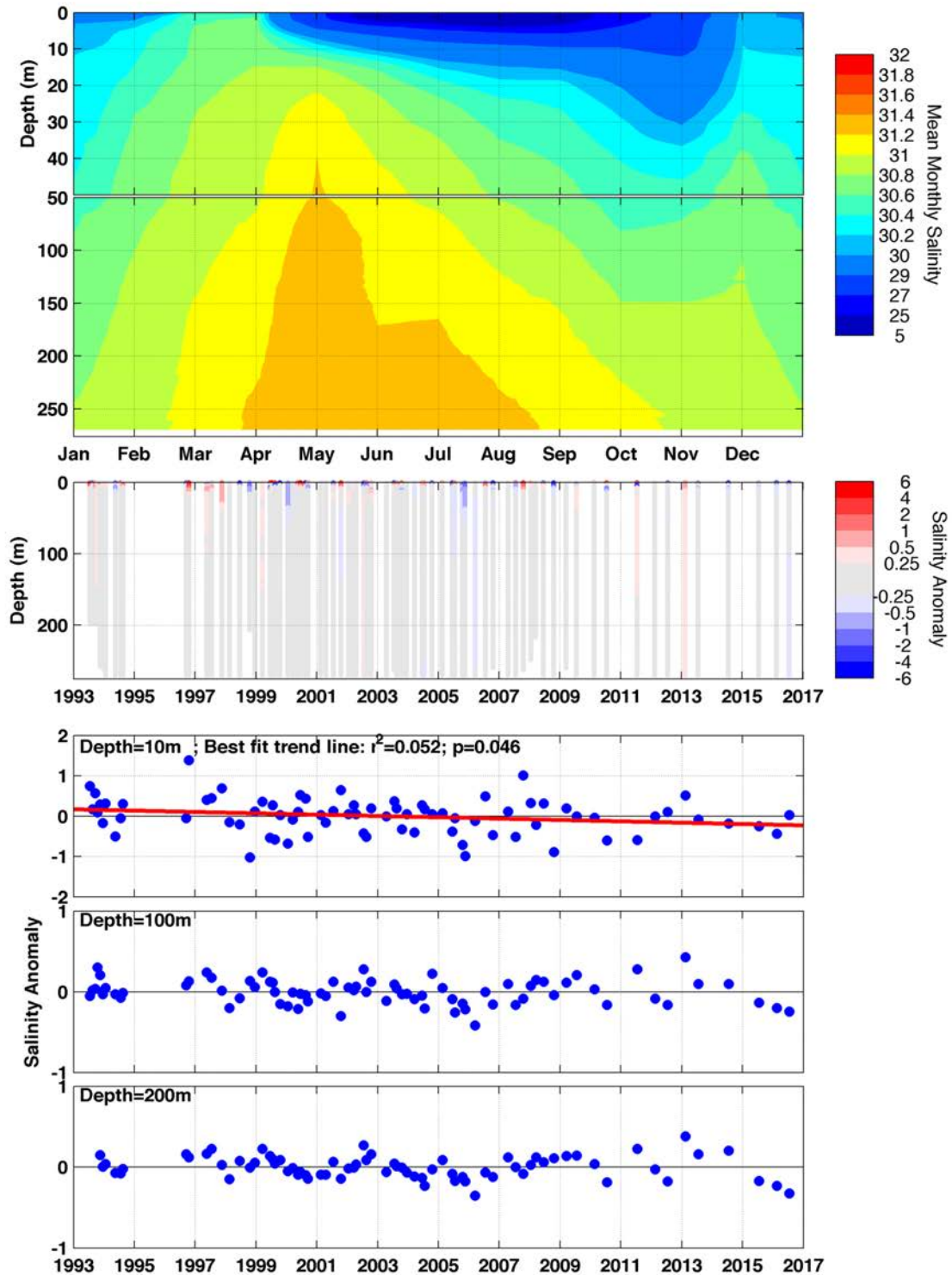


Figure A12. GLBA Station 05 salinity fields. The top two panels show monthly mean contours of salinity over 0-50 m depth and then 50 m to the bottom or 225 m, whichever is shallower. The third panel from the top shows the monthly anomaly versus depth. The bottom three panels show single-depth anomalies at 10 m, 100 m, and 200 m below the surface. Shallow stations not reaching the greater depths have panels that are left blank.

GLBA Station 06

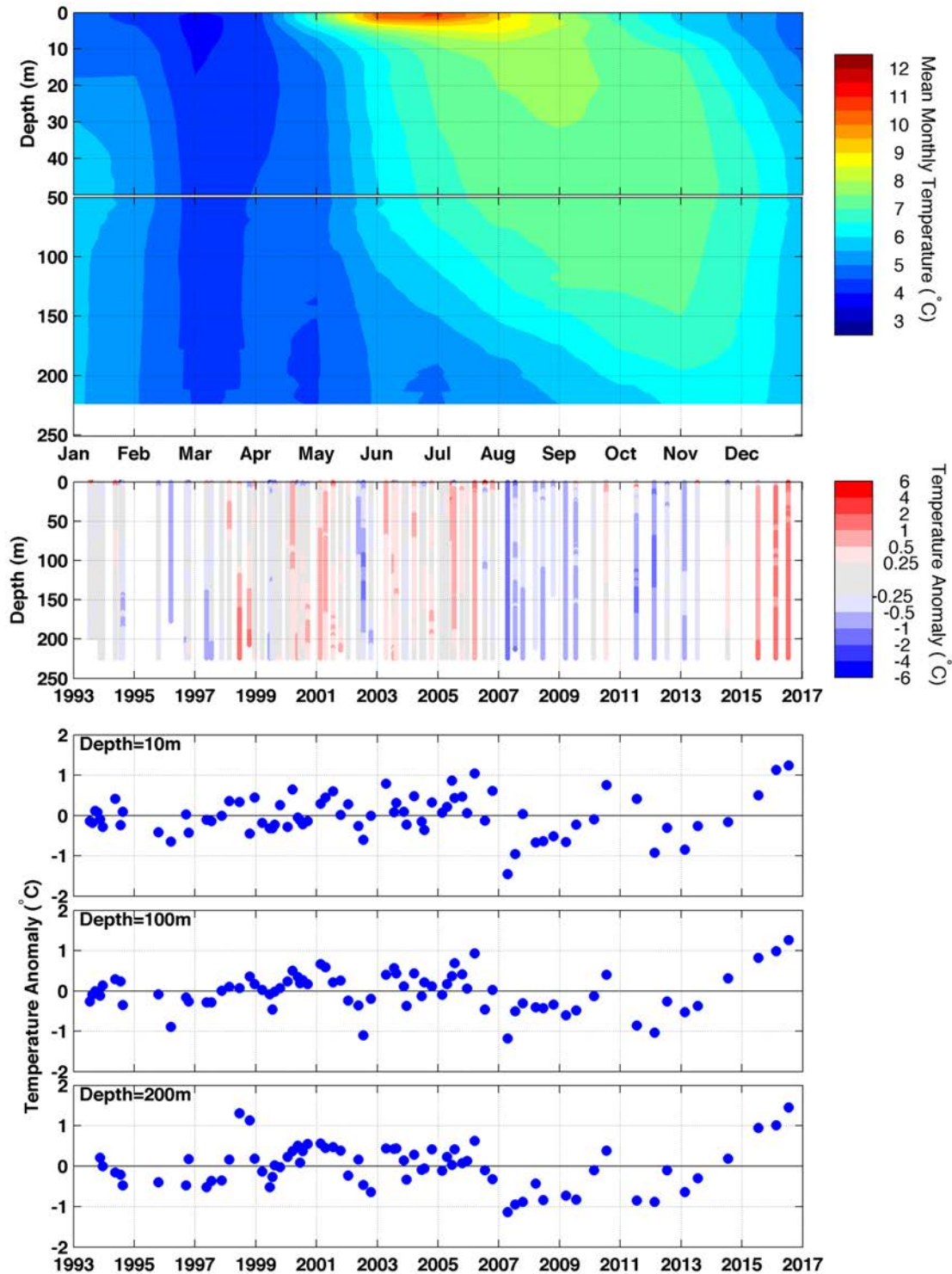


Figure A13. GLBA Station 06 temperature fields. The top two panels show monthly mean contours of temperature over 0-50 m depth and then 50 m to the bottom or 225 m, whichever is shallower. The third panel from the top shows the monthly anomaly versus depth. The bottom three panels show single-depth anomalies at 10 m, 100 m, and 200 m below the surface. Shallow stations not reaching the greater depths have panels that are left blank.

GLBA Station 06

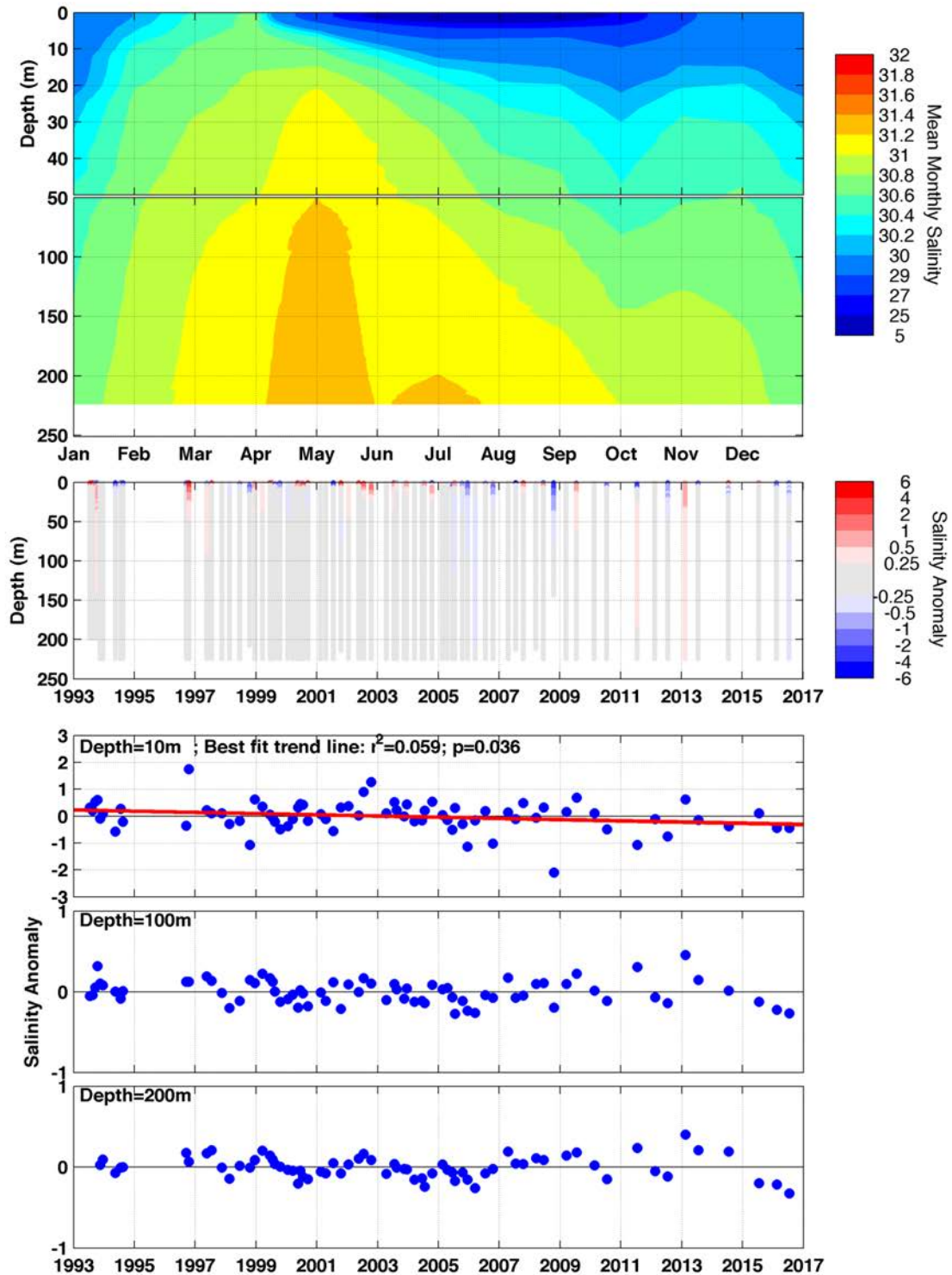


Figure A14. GLBA Station 06 salinity fields. The top two panels show monthly mean contours of salinity over 0-50 m depth and then 50 m to the bottom or 225 m, whichever is shallower. The third panel from the top shows the monthly anomaly versus depth. The bottom three panels show single-depth anomalies at 10 m, 100 m, and 200 m below the surface. Shallow stations not reaching the greater depths have panels that are left blank.

GLBA Station 07

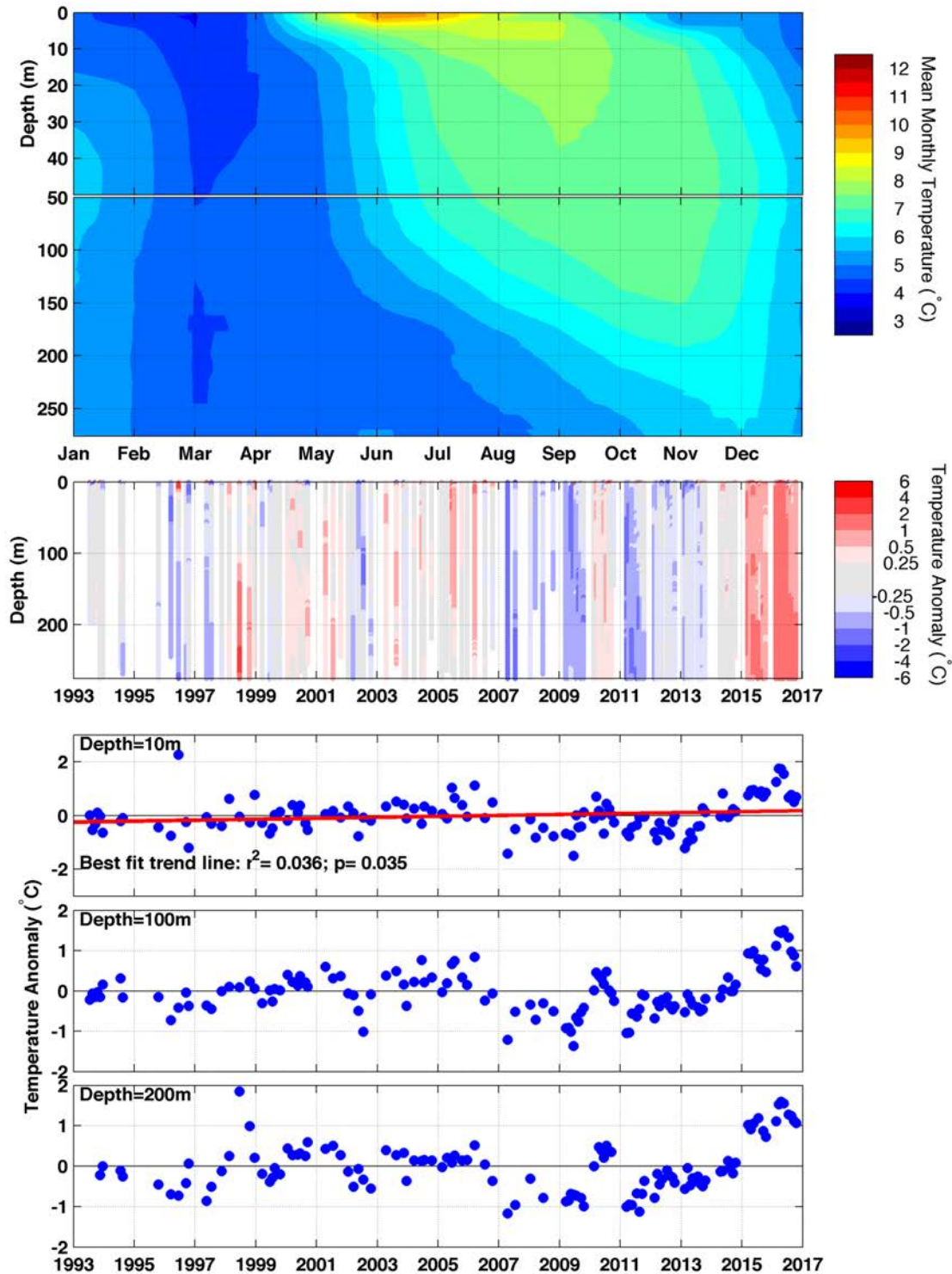


Figure A15. GLBA Station 07 temperature fields. The top two panels show monthly mean contours of temperature over 0-50 m depth and then 50 m to the bottom or 225 m, whichever is shallower. The third panel from the top shows the monthly anomaly versus depth. The bottom three panels show single-depth anomalies at 10 m, 100 m, and 200 m below the surface. Shallow stations not reaching the greater depths have panels that are left blank.

GLBA Station 07

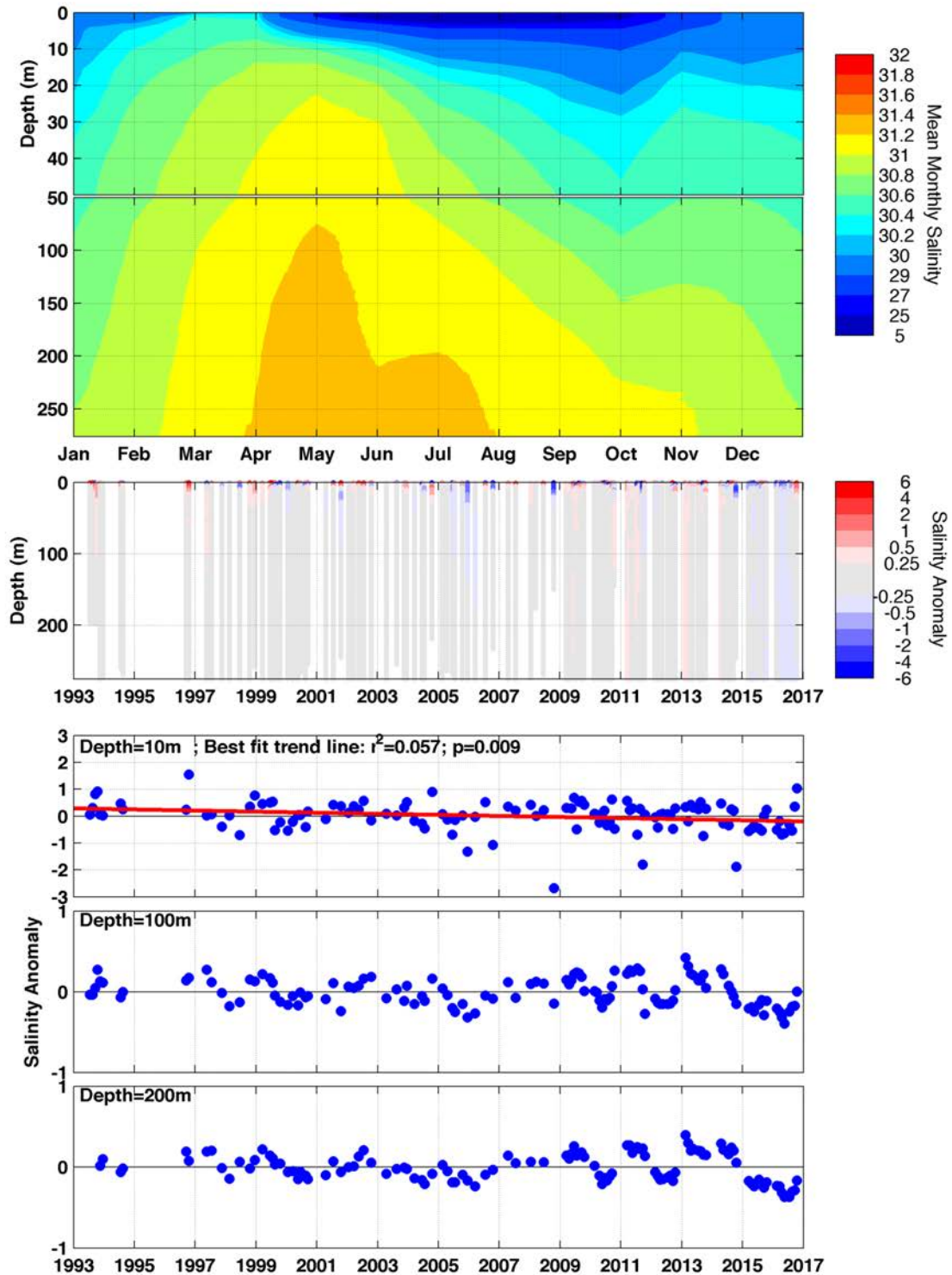


Figure A16. GLBA Station 07 salinity fields. The top two panels show monthly mean contours of salinity over 0-50 m depth and then 50 m to the bottom or 225 m, whichever is shallower. The third panel from the top shows the monthly anomaly versus depth. The bottom three panels show single-depth anomalies at 10 m, 100 m, and 200 m below the surface. Shallow stations not reaching the greater depths have panels that are left blank.

GLBA Station 08

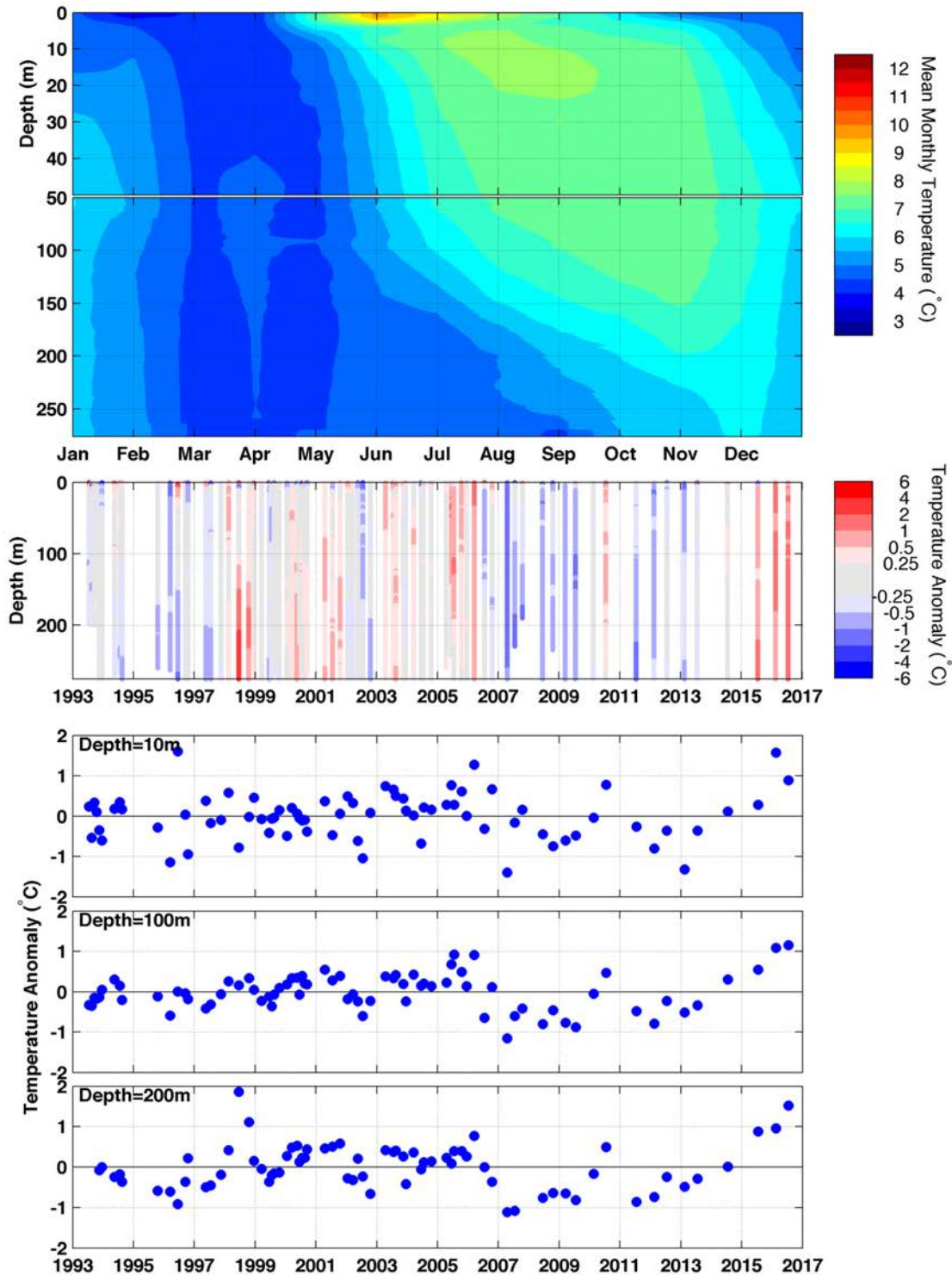


Figure A17. GLBA Station 08 temperature fields. The top two panels show monthly mean contours of temperature over 0-50 m depth and then 50 m to the bottom or 225 m, whichever is shallower. The third panel from the top shows the monthly anomaly versus depth. The bottom three panels show single-depth anomalies at 10 m, 100 m, and 200 m below the surface. Shallow stations not reaching the greater depths have panels that are left blank.

GLBA Station 08

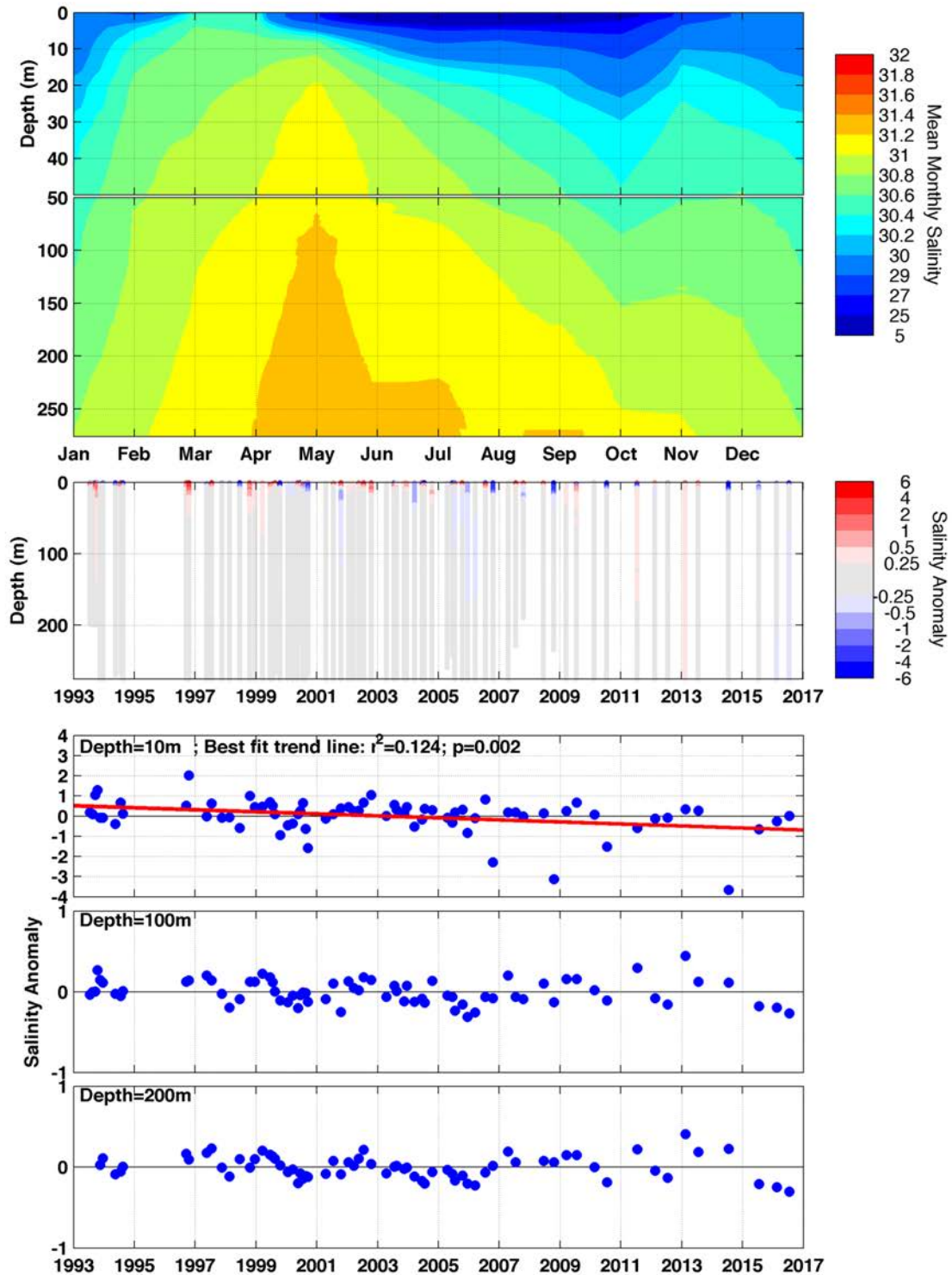


Figure A18. GLBA Station 08 salinity fields. The top two panels show monthly mean contours of salinity over 0-50 m depth and then 50 m to the bottom or 225 m, whichever is shallower. The third panel from the top shows the monthly anomaly versus depth. The bottom three panels show single-depth anomalies at 10 m, 100 m, and 200 m below the surface. Shallow stations not reaching the greater depths have panels that are left blank.

GLBA Station 09

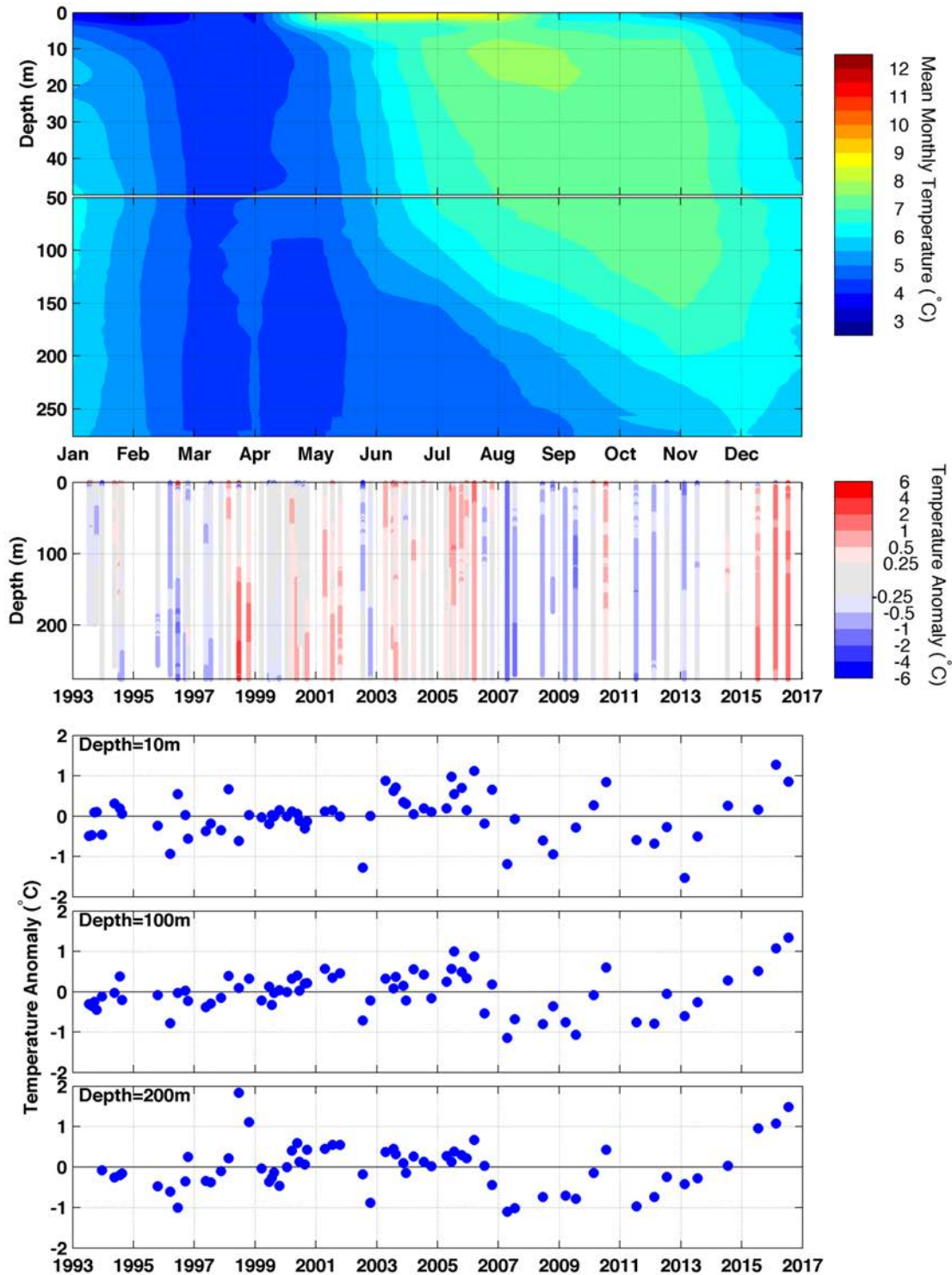


Figure A19. GLBA Station 09 temperature fields. The top two panels show monthly mean contours of temperature over 0-50 m depth and then 50 m to the bottom or 225 m, whichever is shallower. The third panel from the top shows the monthly anomaly versus depth. The bottom three panels show single-depth anomalies at 10 m, 100 m, and 200 m below the surface. Shallow stations not reaching the greater depths have panels that are left blank.

GLBA Station 09

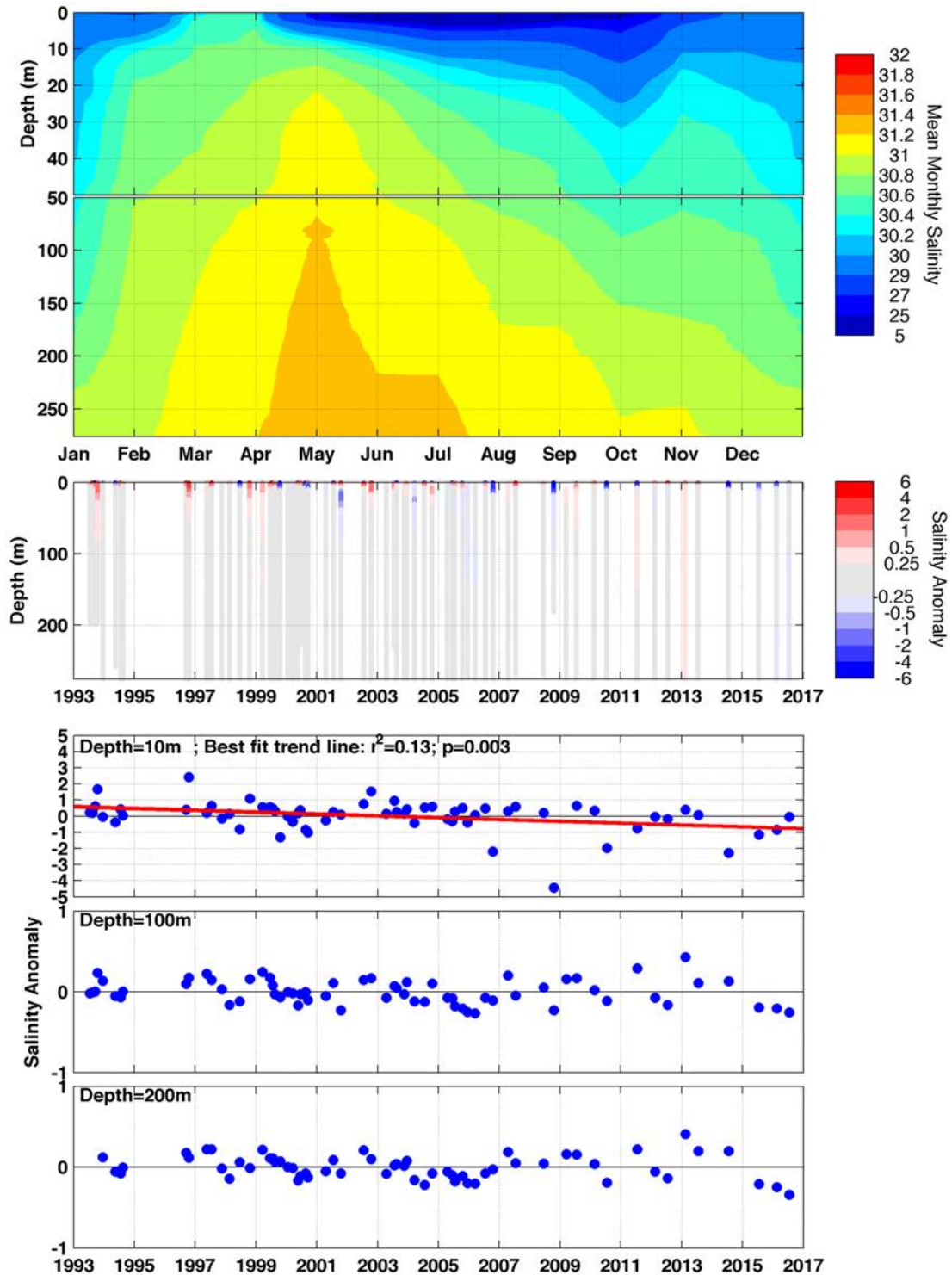


Figure A20. GLBA Station 09 salinity fields. The top two panels show monthly mean contours of salinity over 0-50 m depth and then 50 m to the bottom or 225 m, whichever is shallower. The third panel from the top shows the monthly anomaly versus depth. The bottom three panels show single-depth anomalies at 10 m, 100 m, and 200 m below the surface. Shallow stations not reaching the greater depths have panels that are left blank.

GLBA Station 10

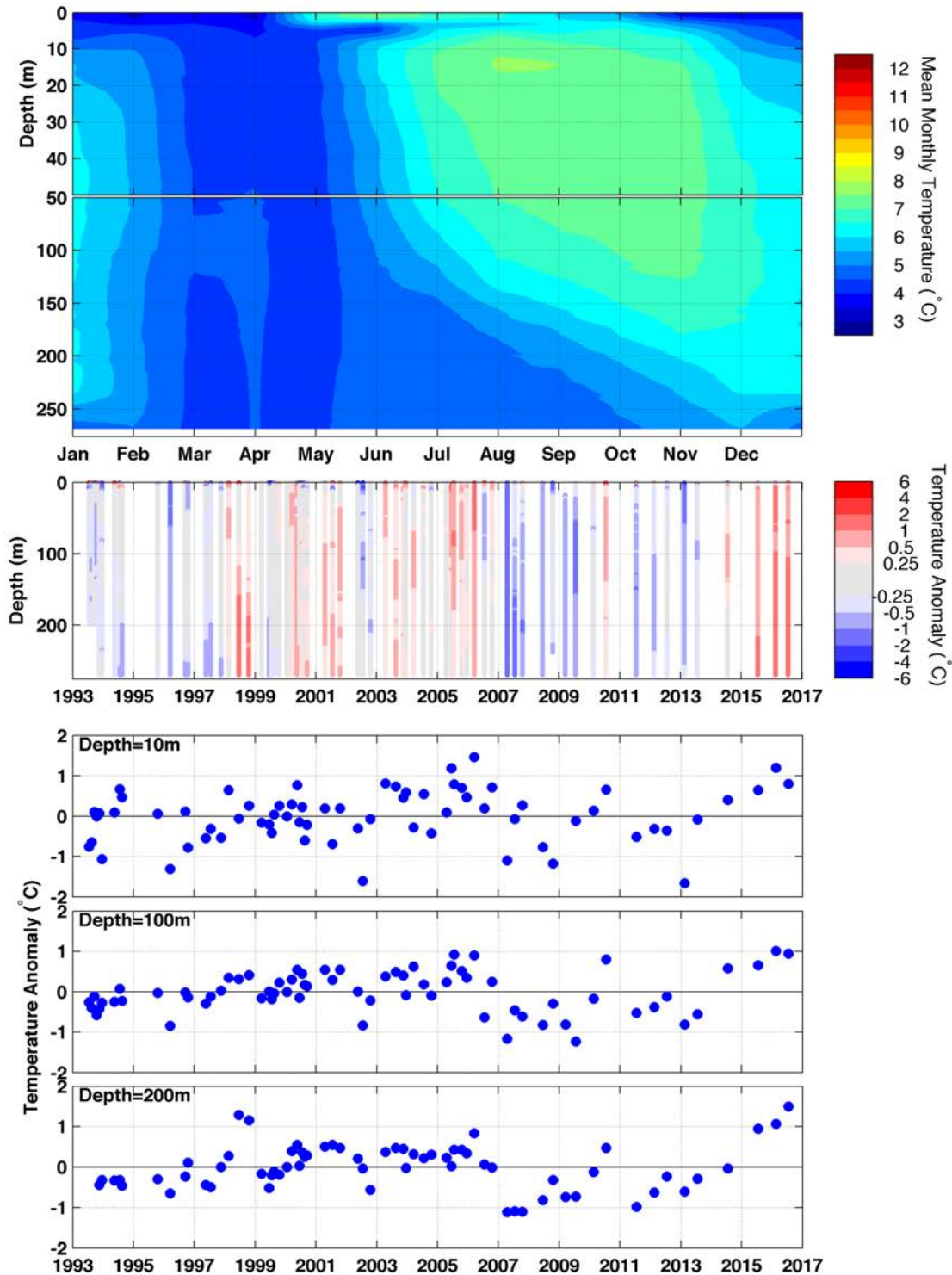


Figure A21. GLBA Station 10 temperature fields. The top two panels show monthly mean contours of temperature over 0-50 m depth and then 50 m to the bottom or 225 m, whichever is shallower. The third panel from the top shows the monthly anomaly versus depth. The bottom three panels show single-depth anomalies at 10 m, 100 m, and 200 m below the surface. Shallow stations not reaching the greater depths have panels that are left blank.

GLBA Station 10

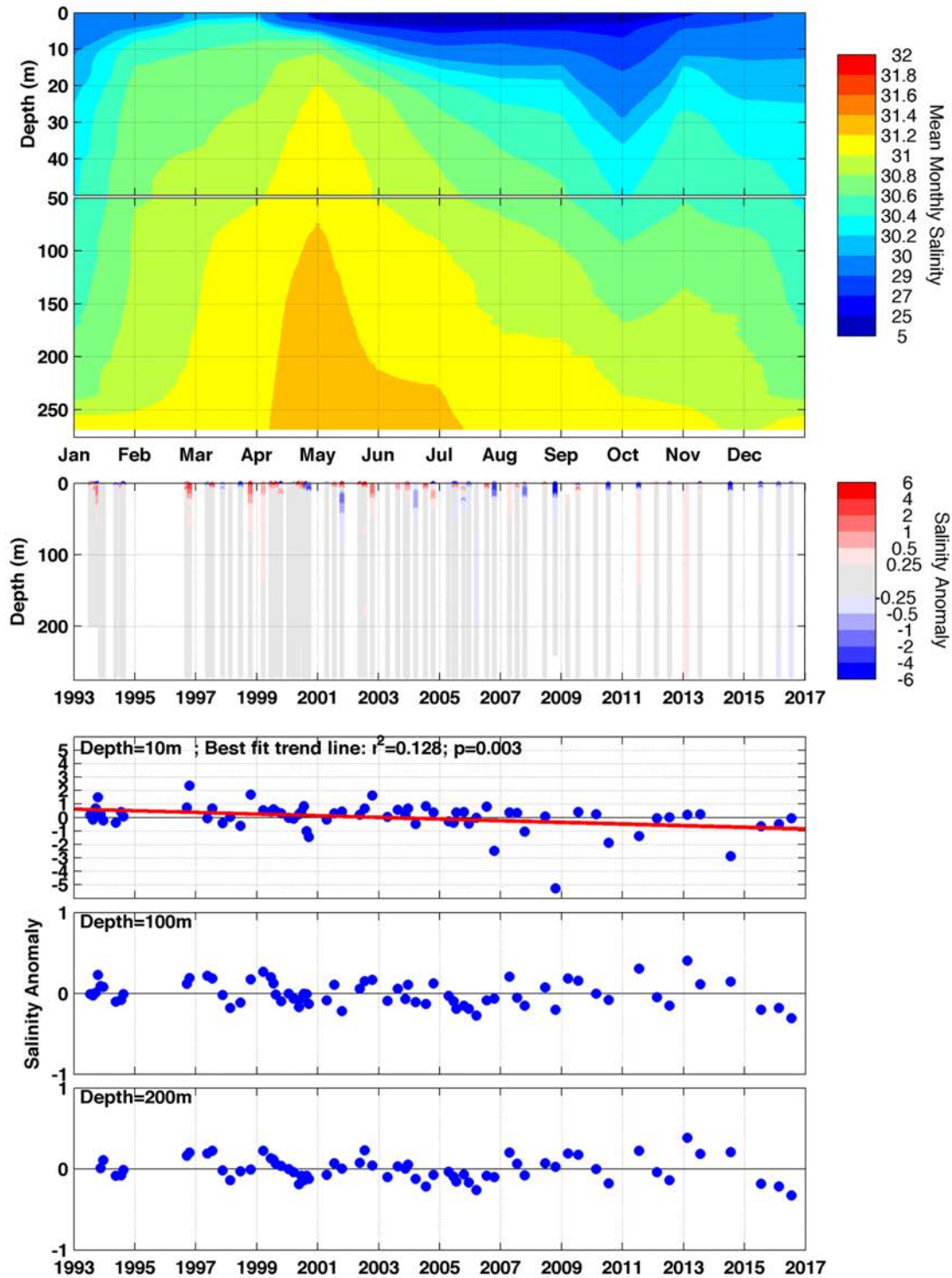


Figure A22. GLBA Station 10 salinity fields. The top two panels show monthly mean contours of salinity over 0-50 m depth and then 50 m to the bottom or 225 m, whichever is shallower. The third panel from the top shows the monthly anomaly versus depth. The bottom three panels show single-depth anomalies at 10 m, 100 m, and 200 m below the surface. Shallow stations not reaching the greater depths have panels that are left blank.

GLBA Station 11

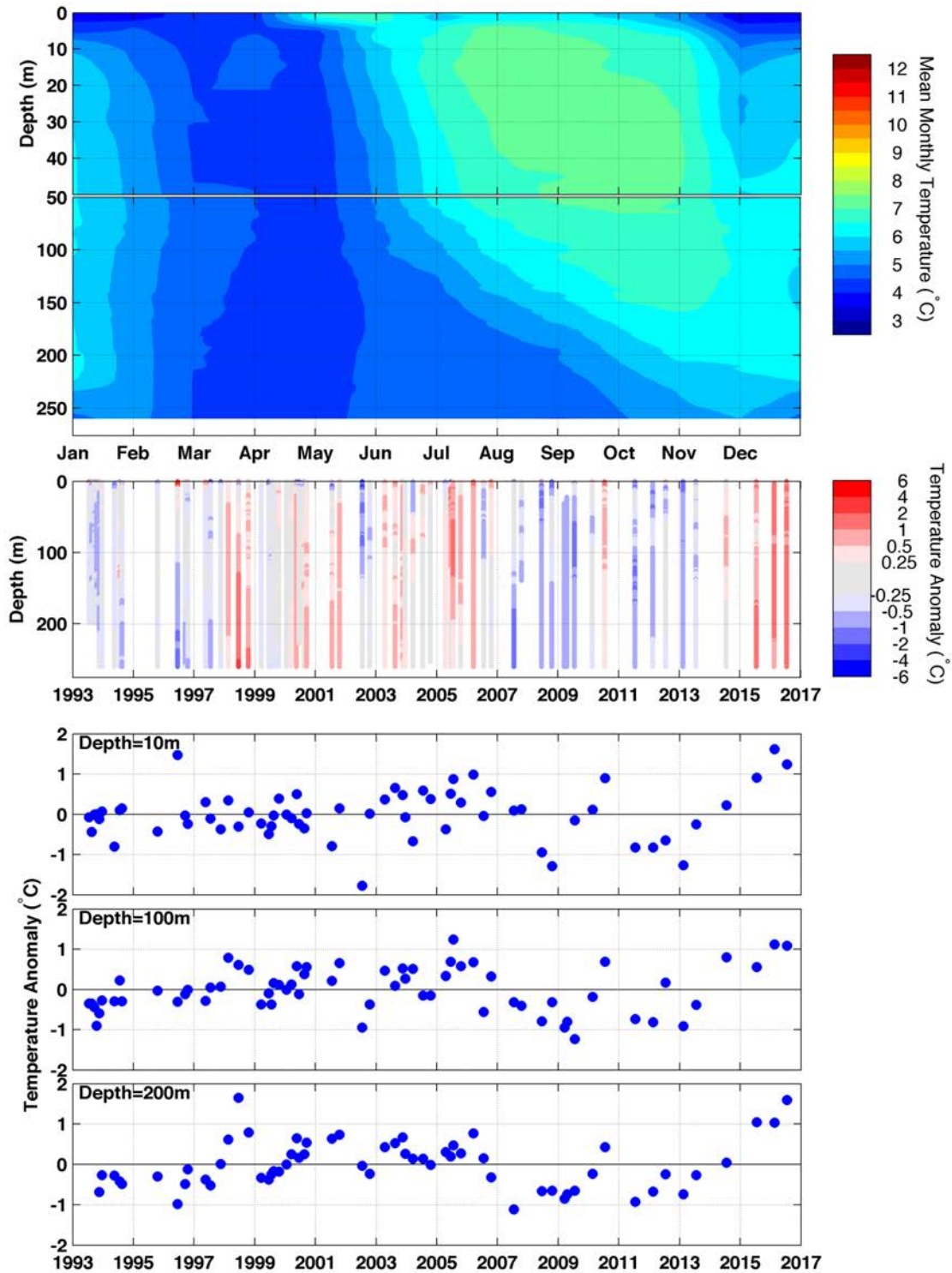


Figure A23. GLBA Station 11 temperature fields. The top two panels show monthly mean contours of temperature over 0-50 m depth and then 50 m to the bottom or 225 m, whichever is shallower. The third panel from the top shows the monthly anomaly versus depth. The bottom three panels show single-depth anomalies at 10 m, 100 m, and 200 m below the surface. Shallow stations not reaching the greater depths have panels that are left blank.

GLBA Station 11

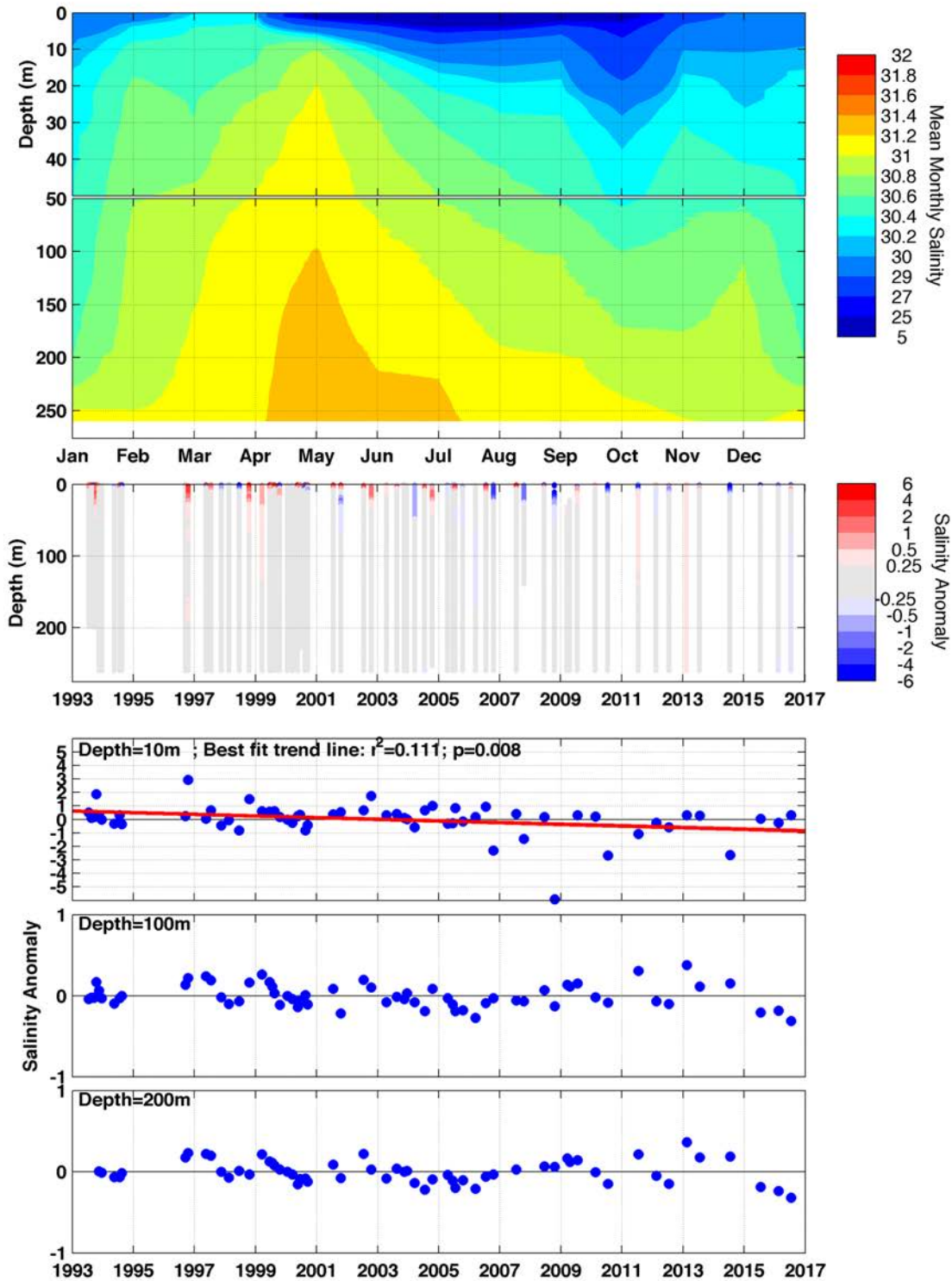


Figure A24. GLBA Station 11 salinity fields. The top two panels show monthly mean contours of salinity over 0-50 m depth and then 50 m to the bottom or 225 m, whichever is shallower. The third panel from the top shows the monthly anomaly versus depth. The bottom three panels show single-depth anomalies at 10 m, 100 m, and 200 m below the surface. Shallow stations not reaching the greater depths have panels that are left blank.

GLBA Station 12

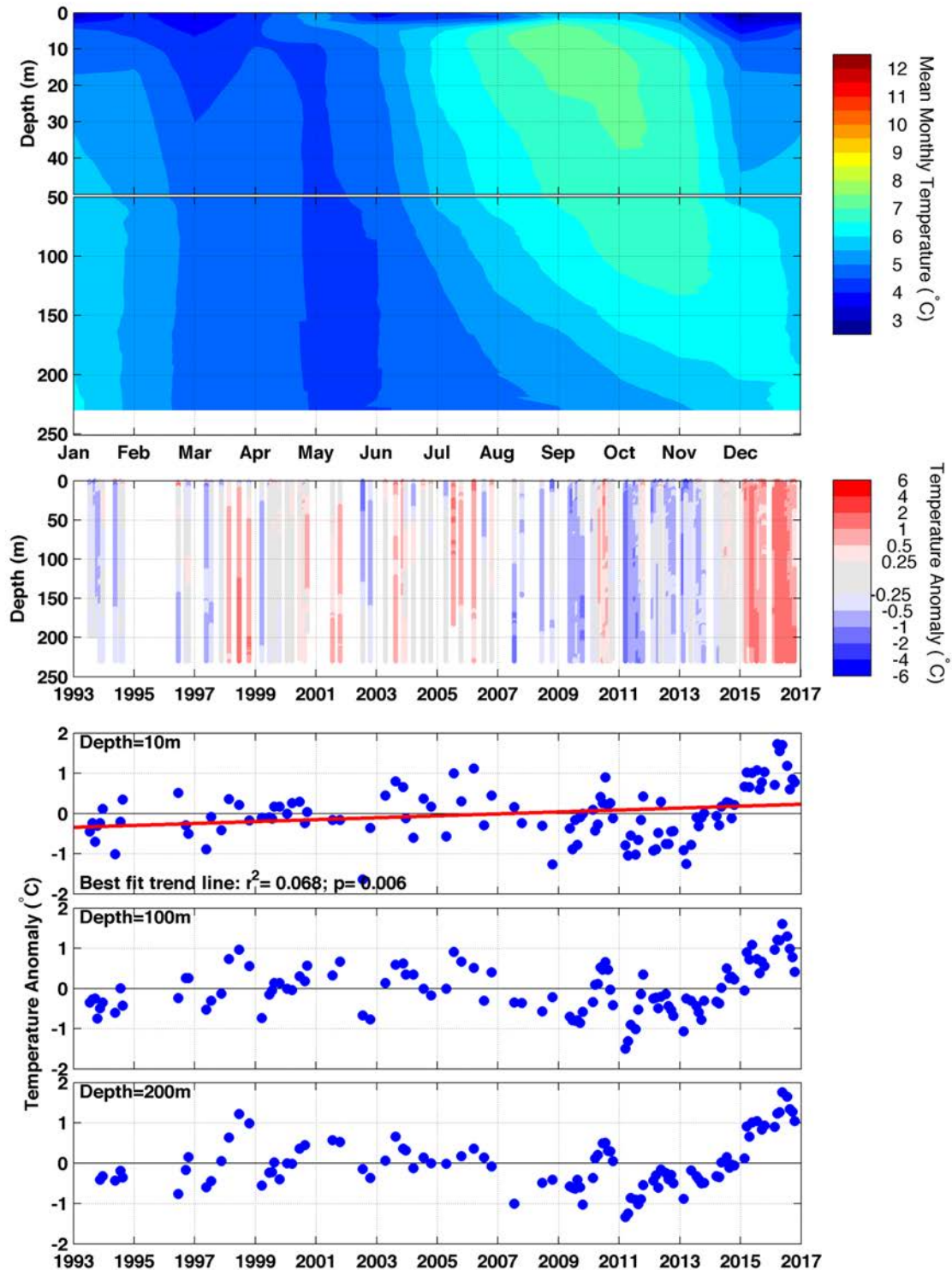


Figure A25. GLBA Station 12 temperature fields. The top two panels show monthly mean contours of temperature over 0-50 m depth and then 50 m to the bottom or 225 m, whichever is shallower. The third panel from the top shows the monthly anomaly versus depth. The bottom three panels show single-depth anomalies at 10 m, 100 m, and 200 m below the surface. Shallow stations not reaching the greater depths have panels that are left blank.

GLBA Station 12

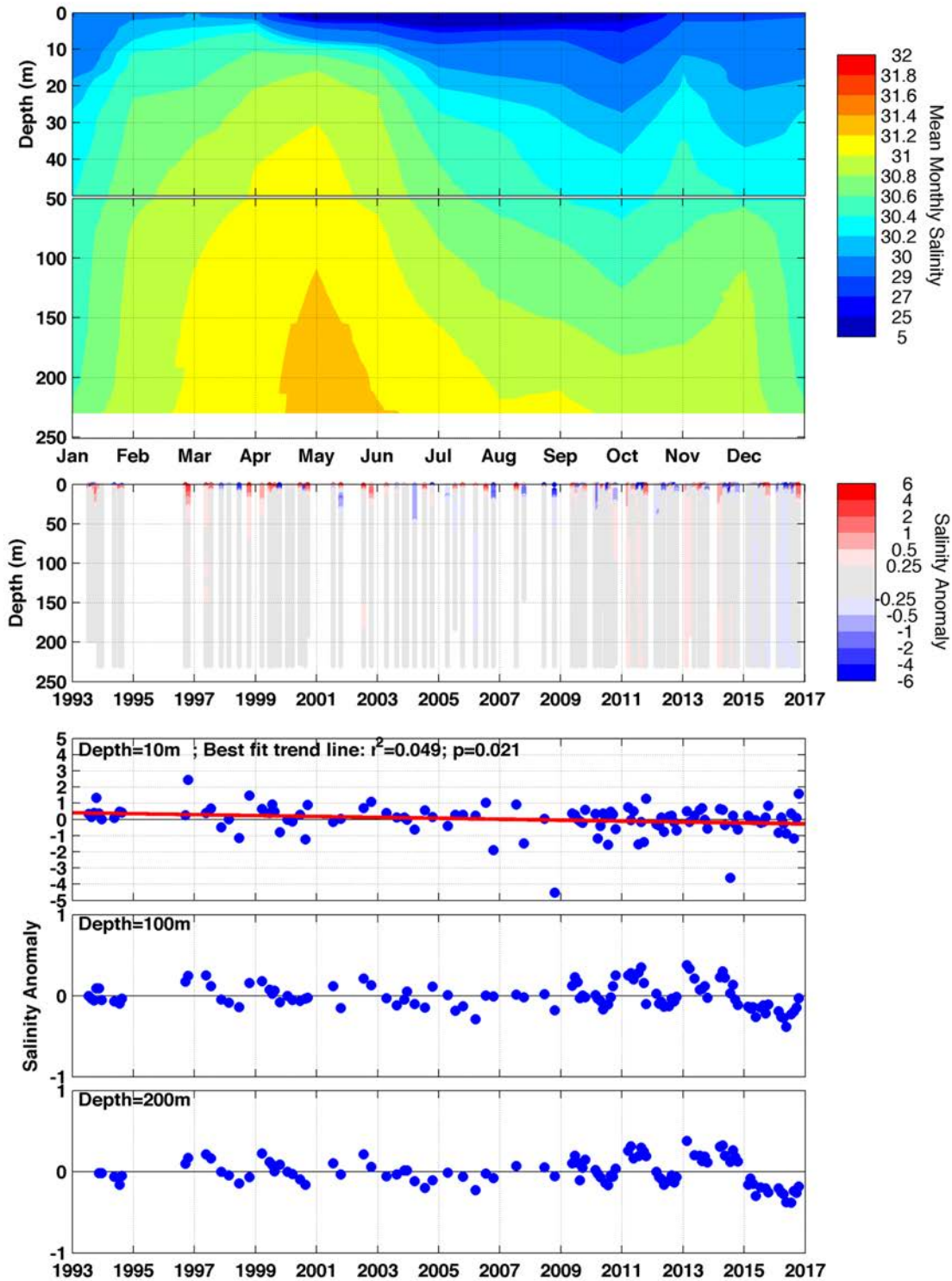


Figure A26. GLBA Station 12 salinity fields. The top two panels show monthly mean contours of salinity over 0-50 m depth and then 50 m to the bottom or 225 m, whichever is shallower. The third panel from the top shows the monthly anomaly versus depth. The bottom three panels show single-depth anomalies at 10 m, 100 m, and 200 m below the surface. Shallow stations not reaching the greater depths have panels that are left blank.

GLBA Station 13

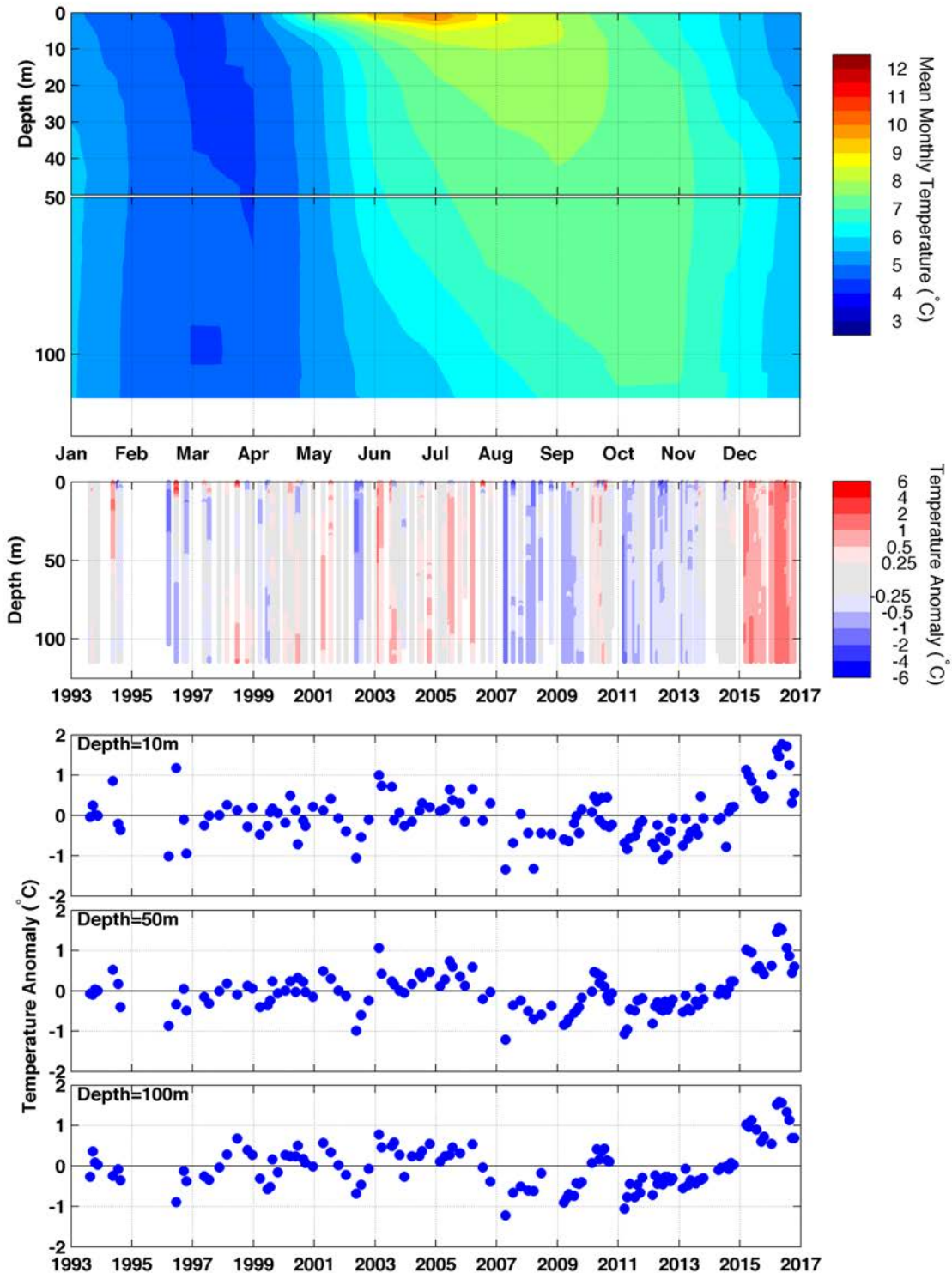


Figure A27. GLBA Station 13 temperature fields. The top two panels show monthly mean contours of temperature over 0-50 m depth and then 50 m to the bottom or 225 m, whichever is shallower. The third panel from the top shows the monthly anomaly versus depth. The bottom three panels show single-depth anomalies at 10 m, 100 m, and 200 m below the surface. Shallow stations not reaching the greater depths have panels that are left blank.

GLBA Station 13

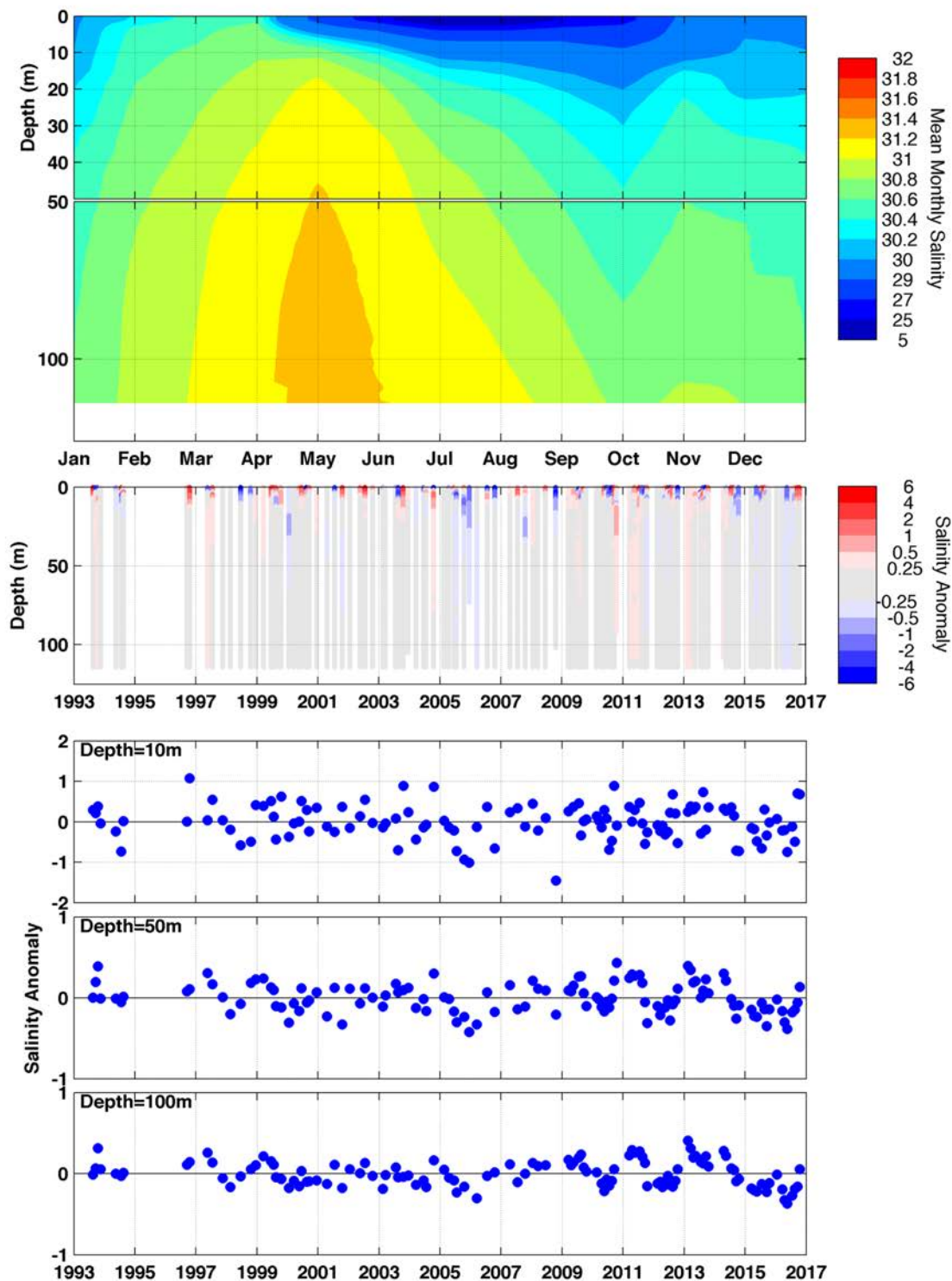


Figure A28. GLBA Station 13 salinity fields. The top two panels show monthly mean contours of salinity over 0-50 m depth and then 50 m to the bottom or 225 m, whichever is shallower. The third panel from the top shows the monthly anomaly versus depth. The bottom three panels show single-depth anomalies at 10 m, 100 m, and 200 m below the surface. Shallow stations not reaching the greater depths have panels that are left blank.

GLBA Station 14

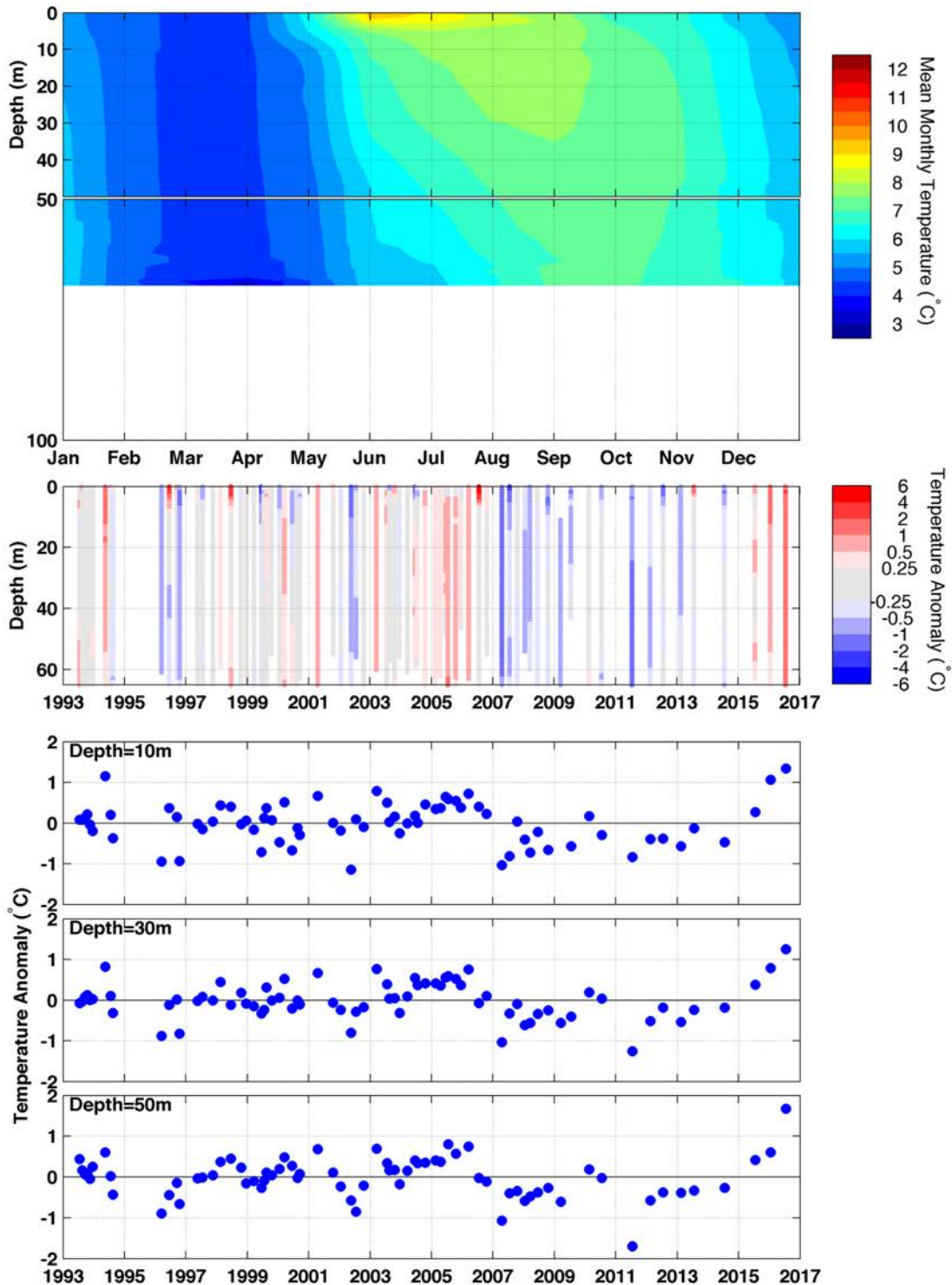


Figure A29. GLBA Station 14 temperature fields. The top two panels show monthly mean contours of temperature over 0-50 m depth and then 50 m to the bottom or 225 m, whichever is shallower. The third panel from the top shows the monthly anomaly versus depth. The bottom three panels show single-depth anomalies at 10 m, 100 m, and 200 m below the surface. Shallow stations not reaching the greater depths have panels that are left blank.

GLBA Station 14

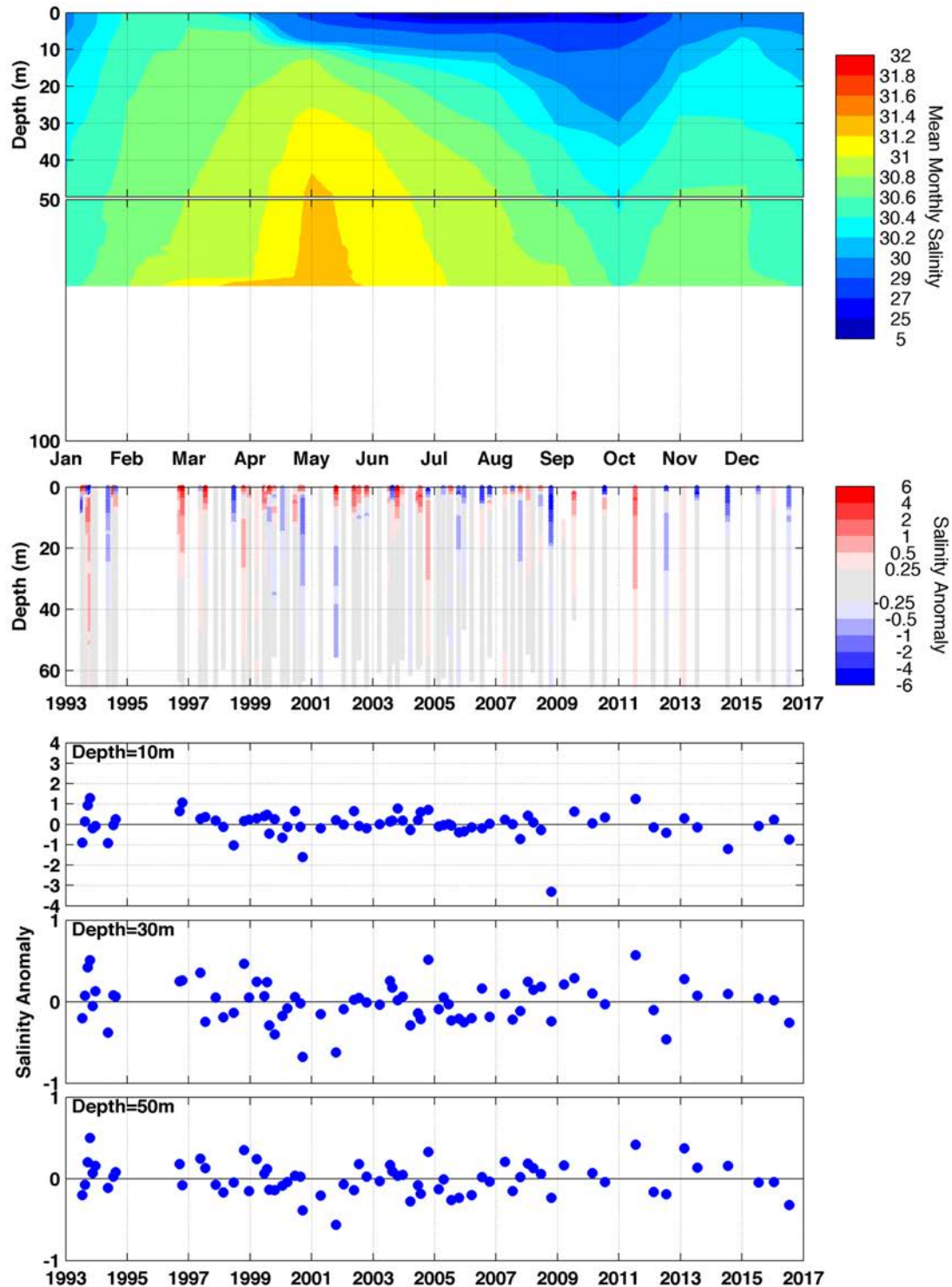


Figure A30. GLBA Station 14 salinity fields. The top two panels show monthly mean contours of salinity over 0-50 m depth and then 50 m to the bottom or 225 m, whichever is shallower. The third panel from the top shows the monthly anomaly versus depth. The bottom three panels show single-depth anomalies at 10 m, 100 m, and 200 m below the surface. Shallow stations not reaching the greater depths have panels that are left blank.

GLBA Station 16

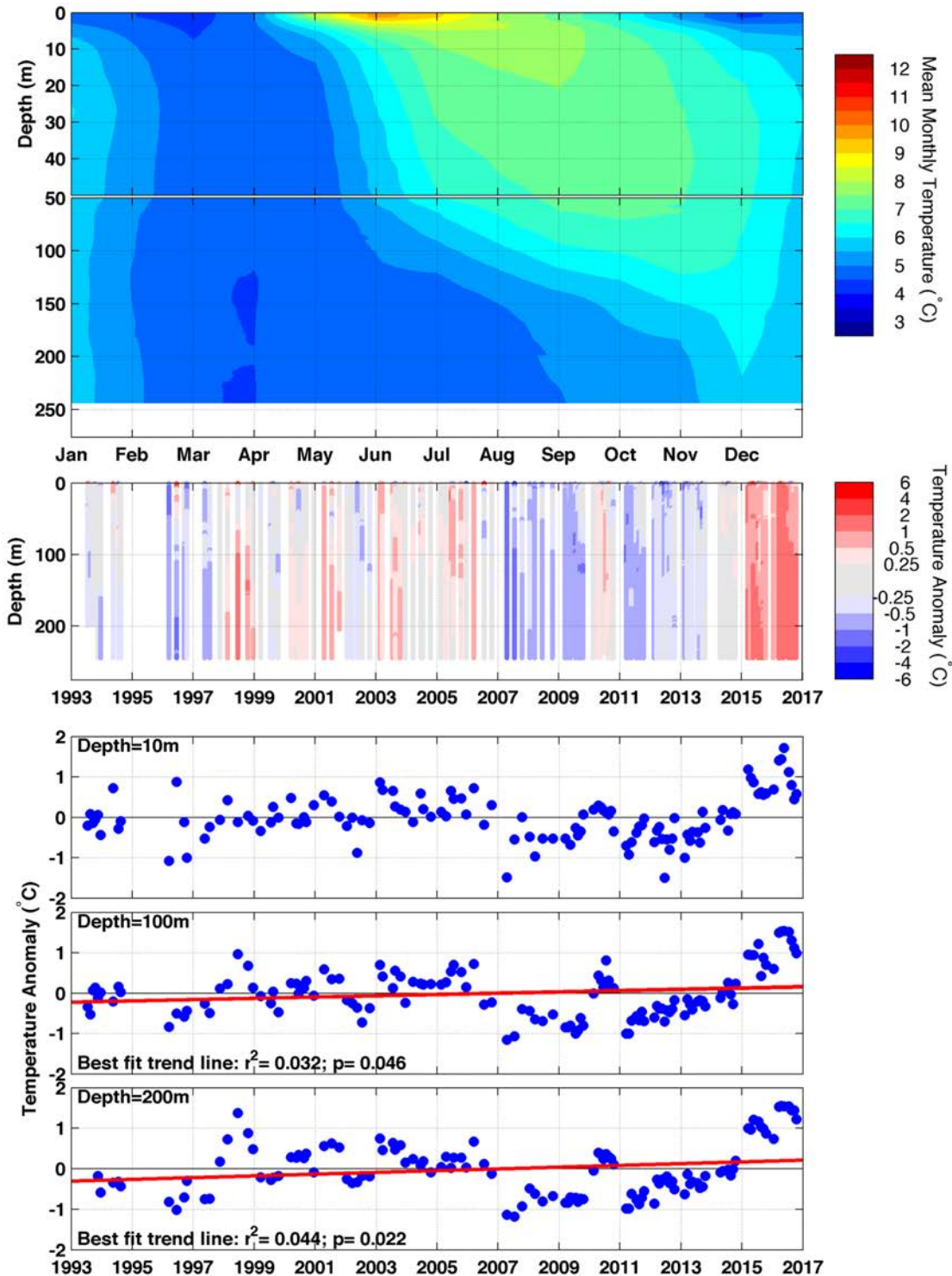


Figure A31. GLBA Station 16 temperature fields. The top two panels show monthly mean contours of temperature over 0-50 m depth and then 50 m to the bottom or 225 m, whichever is shallower. The third panel from the top shows the monthly anomaly versus depth. The bottom three panels show single-depth anomalies at 10 m, 100 m, and 200 m below the surface. Shallow stations not reaching the greater depths have panels that are left blank.

GLBA Station 16

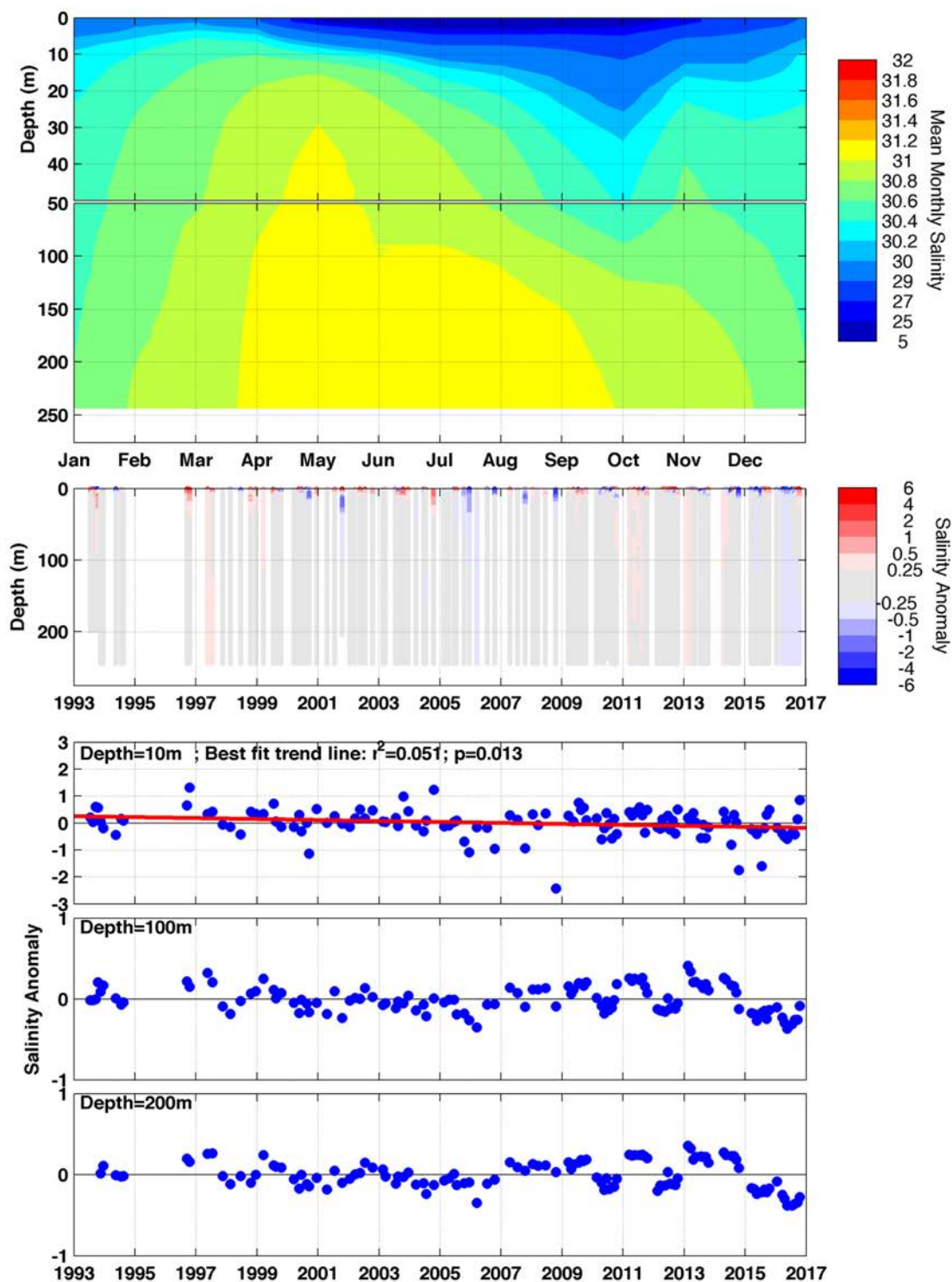


Figure A32. GLBA Station 16 salinity fields. The top two panels show monthly mean contours of salinity over 0-50 m depth and then 50 m to the bottom or 225 m, whichever is shallower. The third panel from the top shows the monthly anomaly versus depth. The bottom three panels show single-depth anomalies at 10 m, 100 m, and 200 m below the surface. Shallow stations not reaching the greater depths have panels that are left blank.

GLBA Station 17

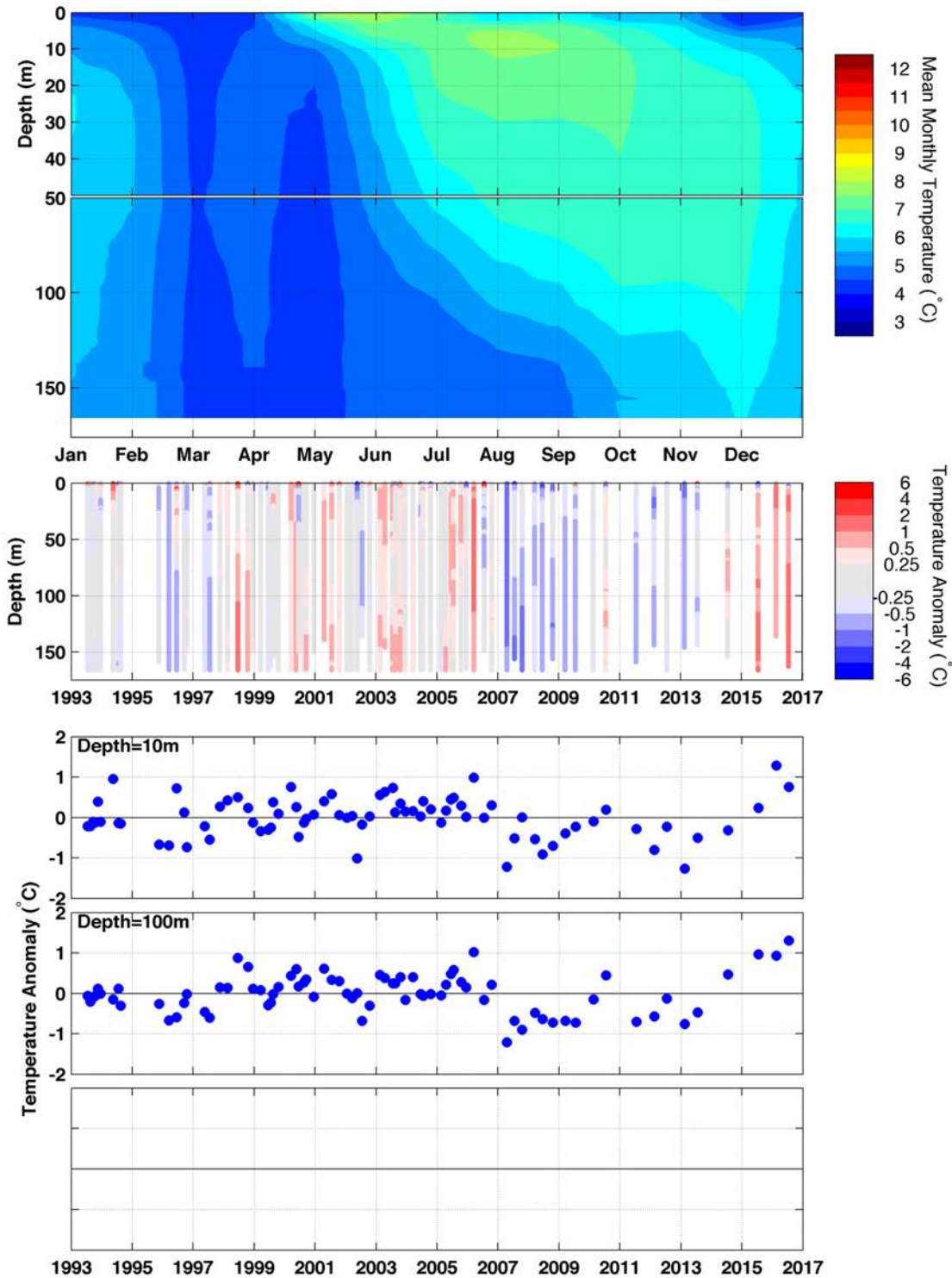


Figure A33. GLBA Station 17 temperature fields. The top two panels show monthly mean contours of temperature over 0-50 m depth and then 50 m to the bottom or 225 m, whichever is shallower. The third panel from the top shows the monthly anomaly versus depth. The bottom three panels show single-depth anomalies at 10 m, 100 m, and 200 m below the surface. Shallow stations not reaching the greater depths have panels that are left blank.

GLBA Station 17

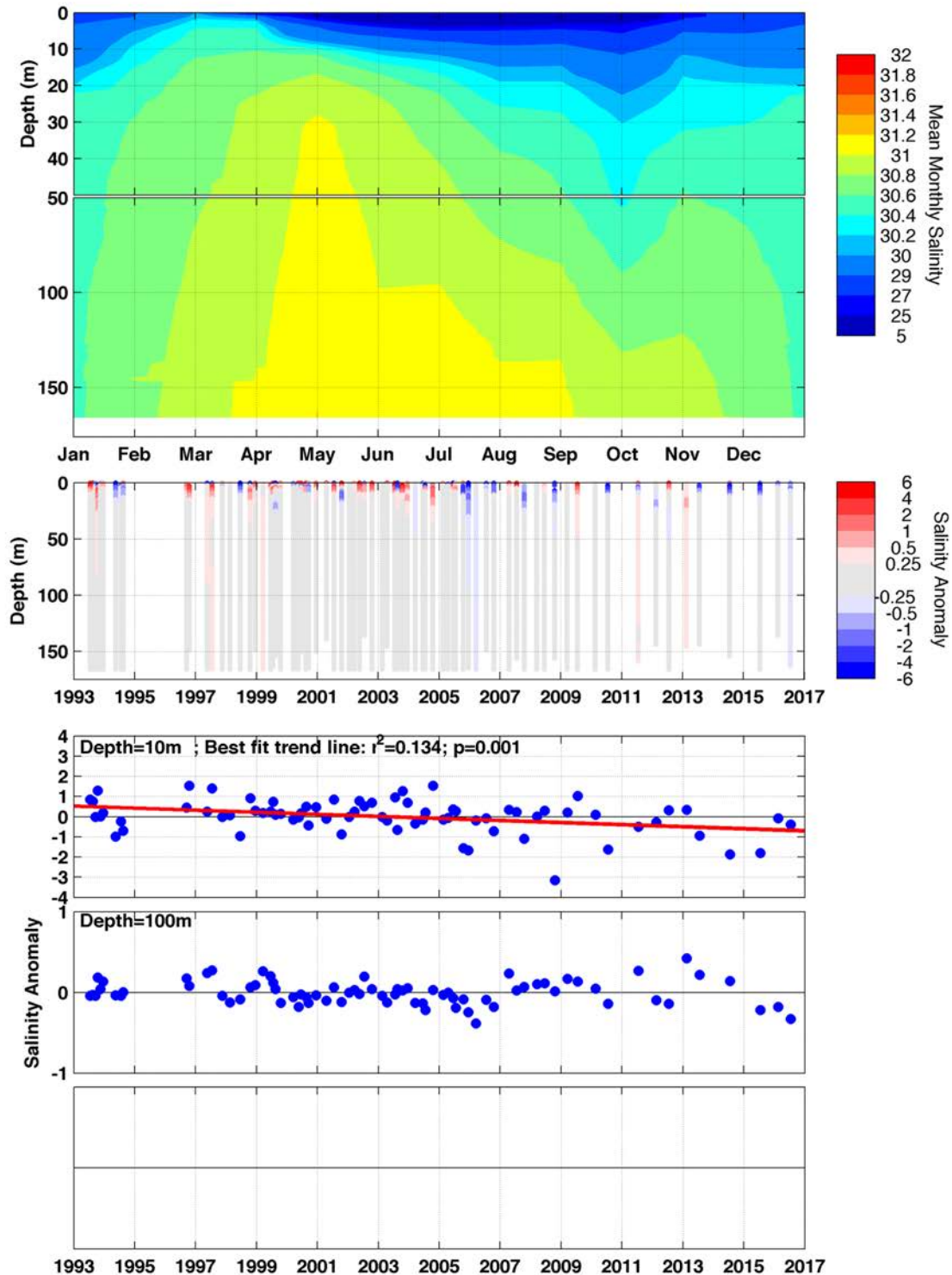


Figure A34. GLBA Station 17 salinity fields. The top two panels show monthly mean contours of salinity over 0-50 m depth and then 50 m to the bottom or 225 m, whichever is shallower. The third panel from the top shows the monthly anomaly versus depth. The bottom three panels show single-depth anomalies at 10 m, 100 m, and 200 m below the surface. Shallow stations not reaching the greater depths have panels that are left blank.

GLBA Station 18

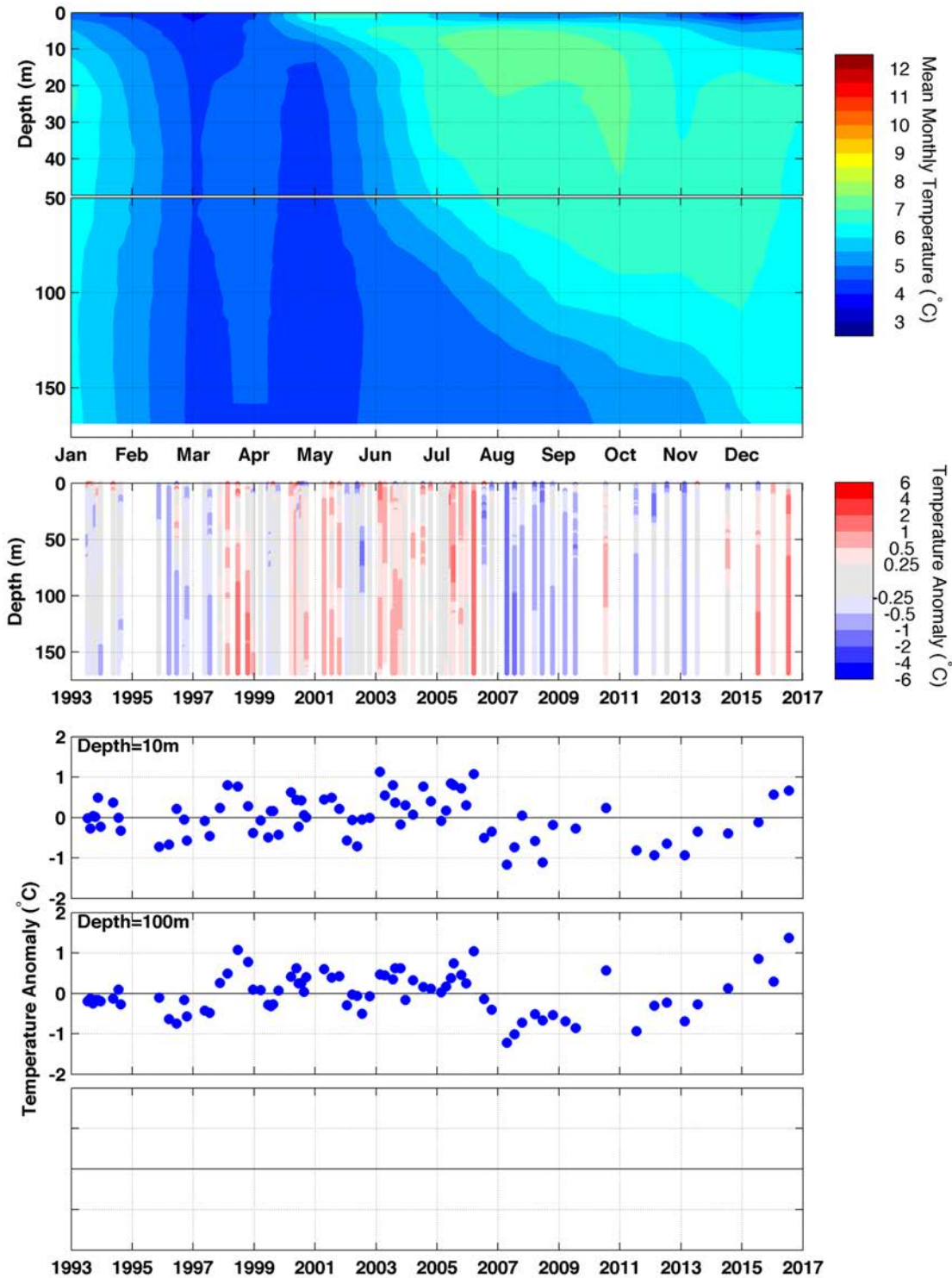


Figure A35. GLBA Station 18 temperature fields. The top two panels show monthly mean contours of temperature over 0-50 m depth and then 50 m to the bottom or 225 m, whichever is shallower. The third panel from the top shows the monthly anomaly versus depth. The bottom three panels show single-depth anomalies at 10 m, 100 m, and 200 m below the surface. Shallow stations not reaching the greater depths have panels that are left blank.

GLBA Station 18

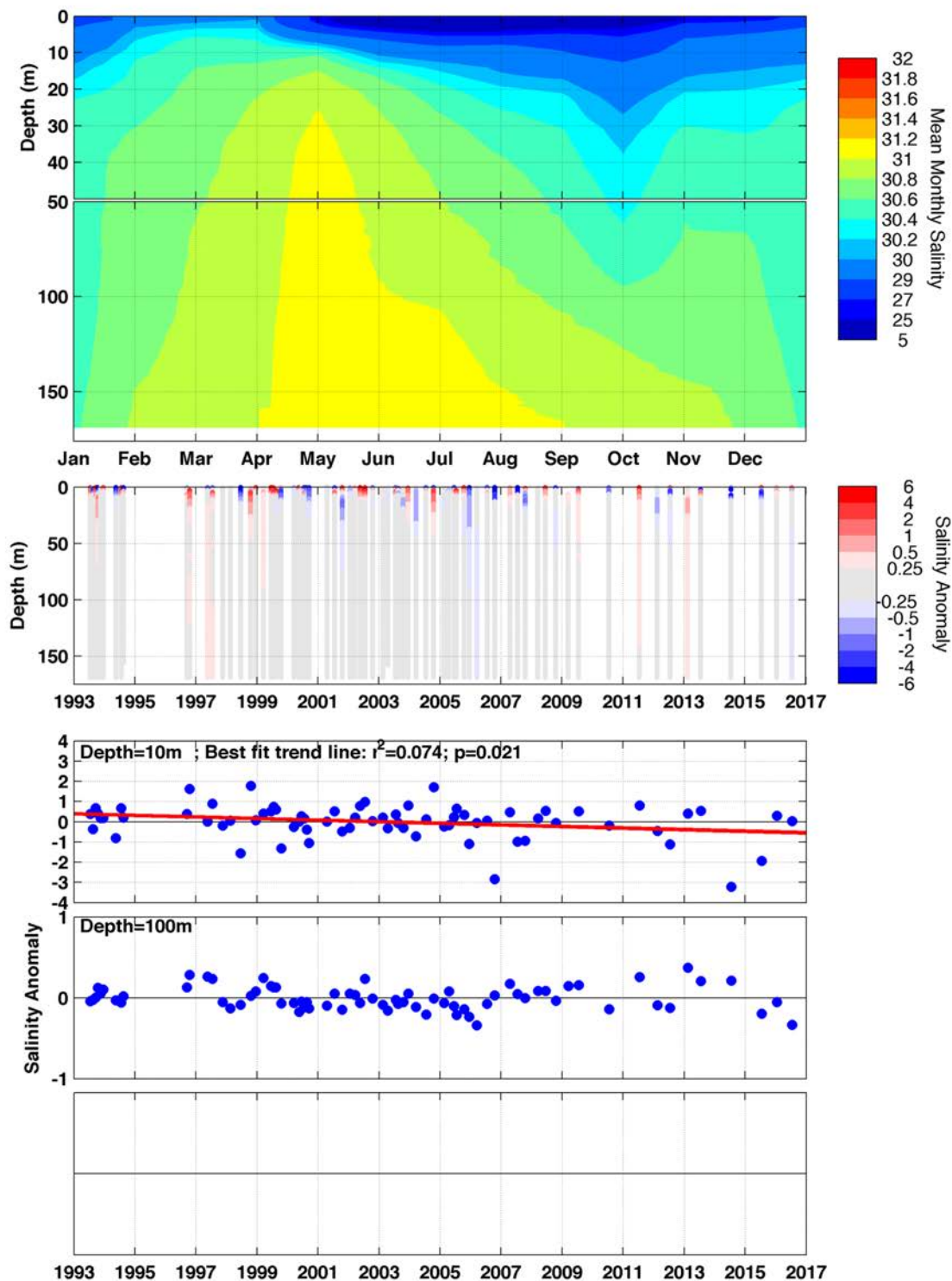


Figure A36. GLBA Station 18 salinity fields. The top two panels show monthly mean contours of salinity over 0-50 m depth and then 50 m to the bottom or 225 m, whichever is shallower. The third panel from the top shows the monthly anomaly versus depth. The bottom three panels show single-depth anomalies at 10 m, 100 m, and 200 m below the surface. Shallow stations not reaching the greater depths have panels that are left blank.

GLBA Station 19

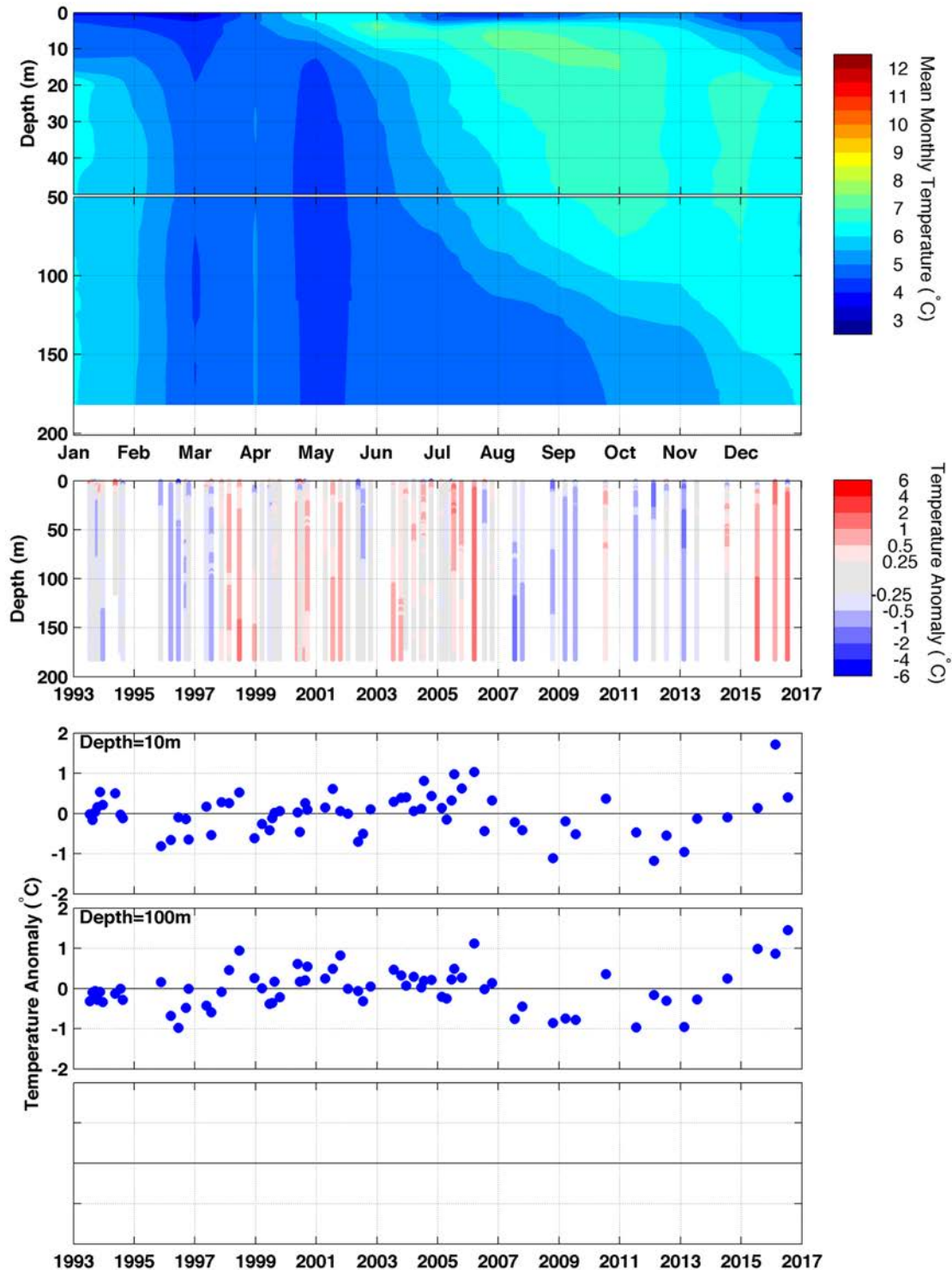


Figure A37. GLBA Station 19 temperature fields. The top two panels show monthly mean contours of temperature over 0-50 m depth and then 50 m to the bottom or 225 m, whichever is shallower. The third panel from the top shows the monthly anomaly versus depth. The bottom three panels show single-depth anomalies at 10 m, 100 m, and 200 m below the surface. Shallow stations not reaching the greater depths have panels that are left blank.

GLBA Station 19

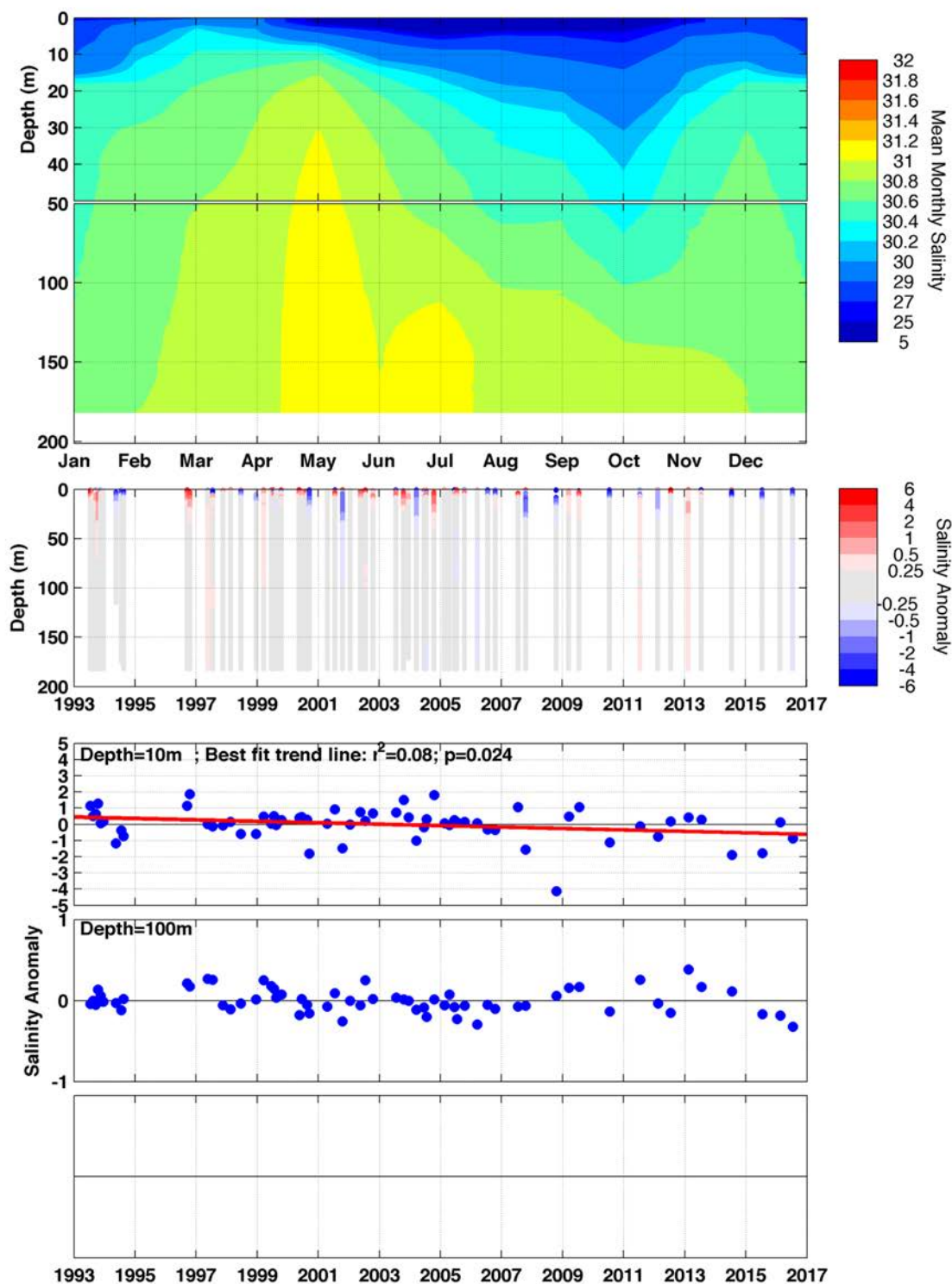


Figure A38. GLBA Station 19 salinity fields. The top two panels show monthly mean contours of salinity over 0-50 m depth and then 50 m to the bottom or 225 m, whichever is shallower. The third panel from the top shows the monthly anomaly versus depth. The bottom three panels show single-depth anomalies at 10 m, 100 m, and 200 m below the surface. Shallow stations not reaching the greater depths have panels that are left blank.

GLBA Station 20

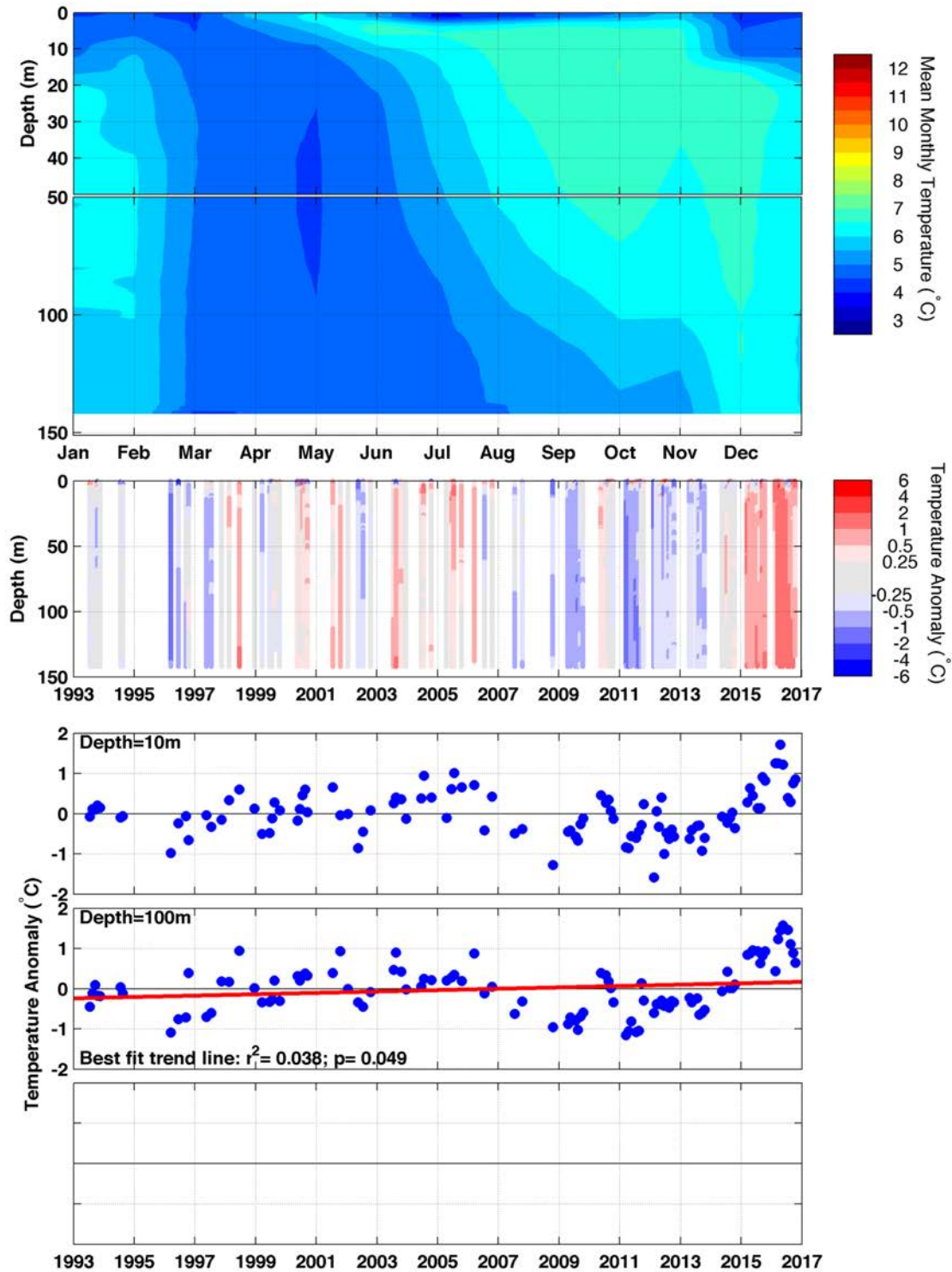


Figure A39. GLBA Station 20 temperature fields. The top two panels show monthly mean contours of temperature over 0-50 m depth and then 50 m to the bottom or 225 m, whichever is shallower. The third panel from the top shows the monthly anomaly versus depth. The bottom three panels show single-depth anomalies at 10 m, 100 m, and 200 m below the surface. Shallow stations not reaching the greater depths have panels that are left blank.

GLBA Station 20

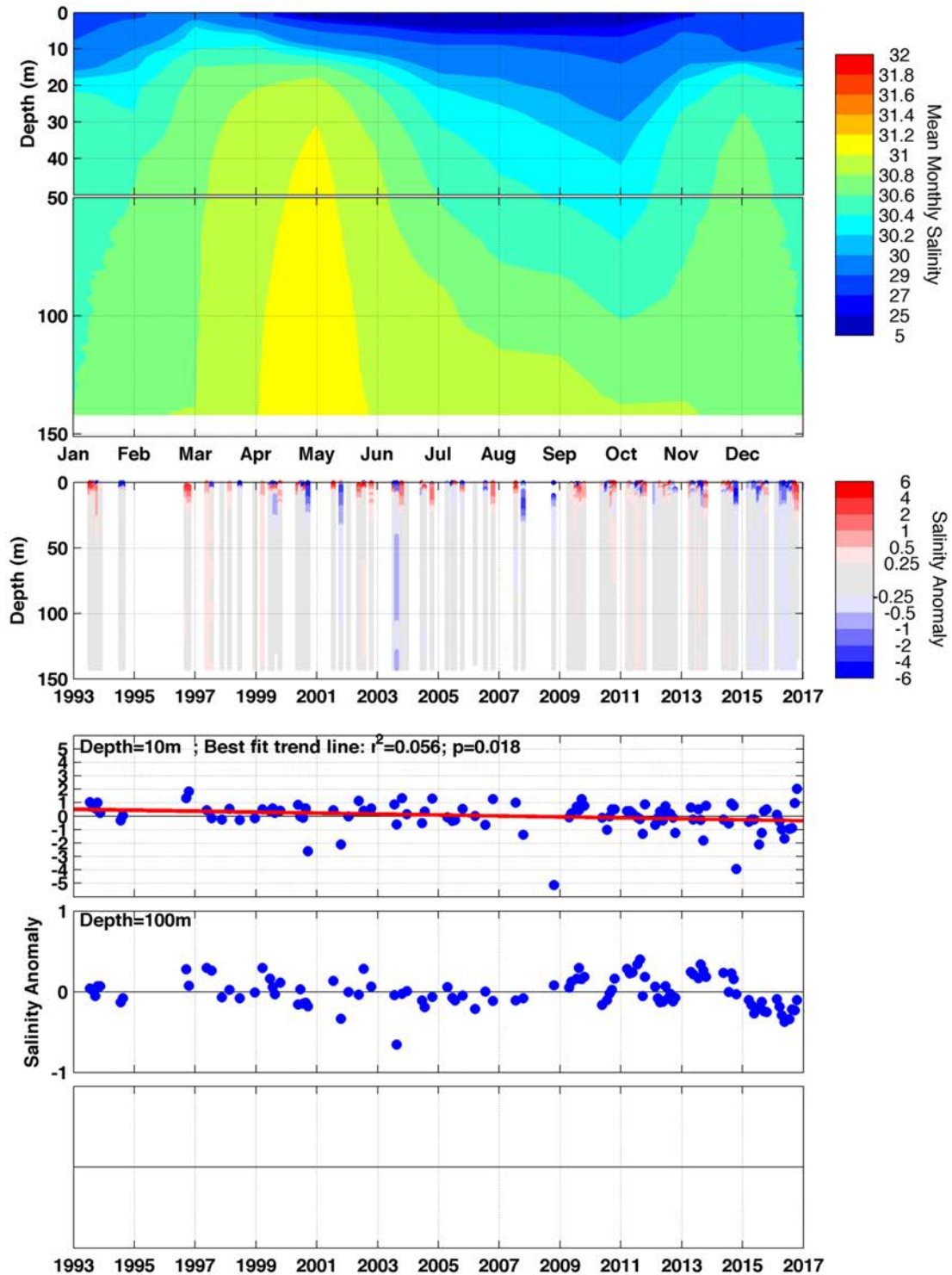


Figure A40. GLBA Station 20 salinity fields. The top two panels show monthly mean contours of salinity over 0-50 m depth and then 50 m to the bottom or 225 m, whichever is shallower. The third panel from the top shows the monthly anomaly versus depth. The bottom three panels show single-depth anomalies at 10 m, 100 m, and 200 m below the surface. Shallow stations not reaching the greater depths have panels that are left blank.

GLBA Station 21

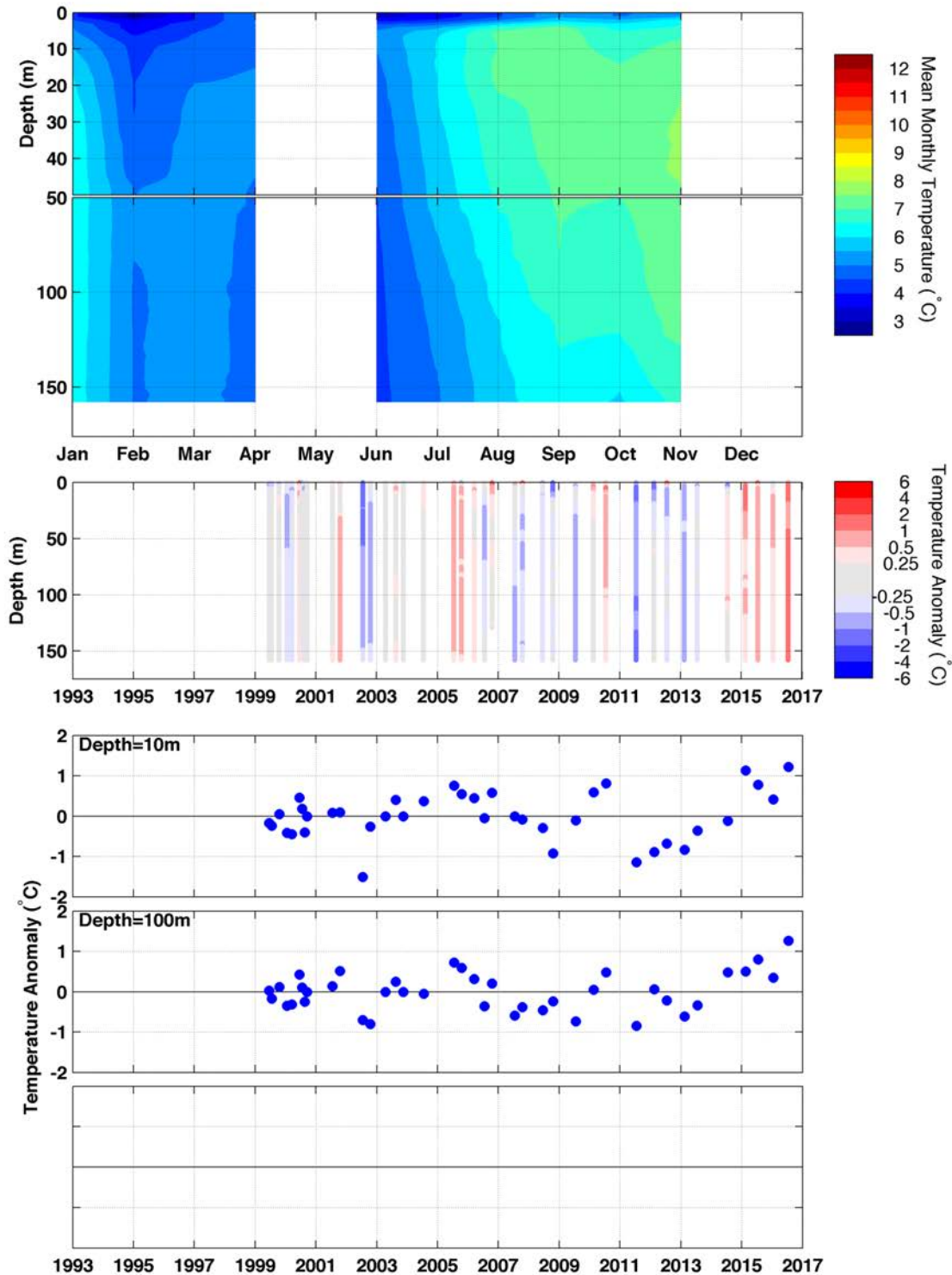


Figure A41. GLBA Station 21 temperature fields. The top two panels show monthly mean contours of temperature over 0-50 m depth and then 50 m to the bottom or 225 m, whichever is shallower. The third panel from the top shows the monthly anomaly versus depth. The bottom three panels show single-depth anomalies at 10 m, 100 m, and 200 m below the surface. Shallow stations not reaching the greater depths have panels that are left blank.

GLBA Station 21

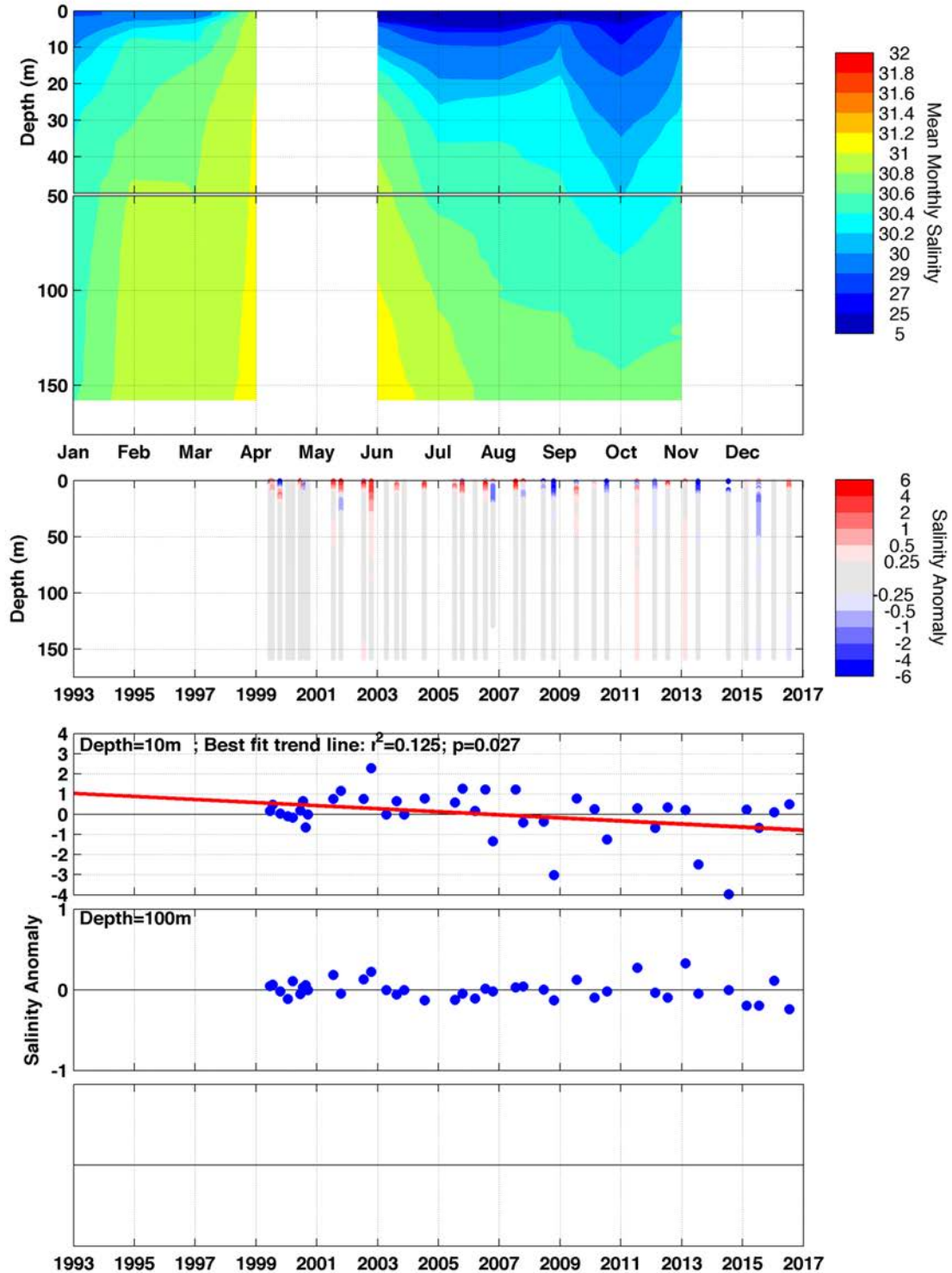


Figure A42. GLBA Station 21 salinity fields. The top two panels show monthly mean contours of salinity over 0-50 m depth and then 50 m to the bottom or 225 m, whichever is shallower. The third panel from the top shows the monthly anomaly versus depth. The bottom three panels show single-depth anomalies at 10 m, 100 m, and 200 m below the surface. Shallow stations not reaching the greater depths have panels that are left blank.

GLBA Station 22

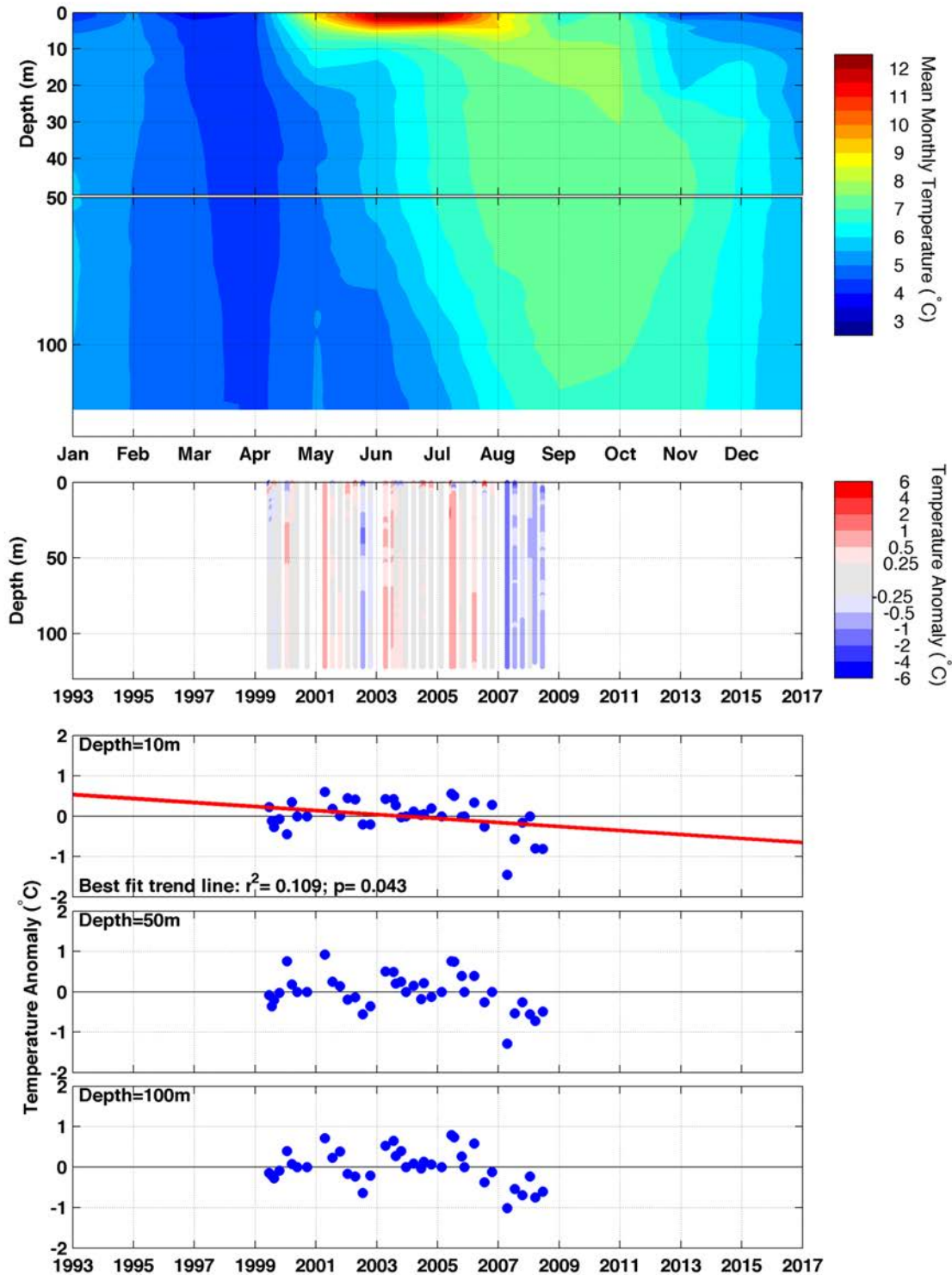


Figure A43. GLBA Station 22 temperature fields. The top two panels show monthly mean contours of temperature over 0-50 m depth and then 50 m to the bottom or 225 m, whichever is shallower. The third panel from the top shows the monthly anomaly versus depth. The bottom three panels show single-depth anomalies at 10 m, 100 m, and 200 m below the surface. Shallow stations not reaching the greater depths have panels that are left blank.

GLBA Station 22

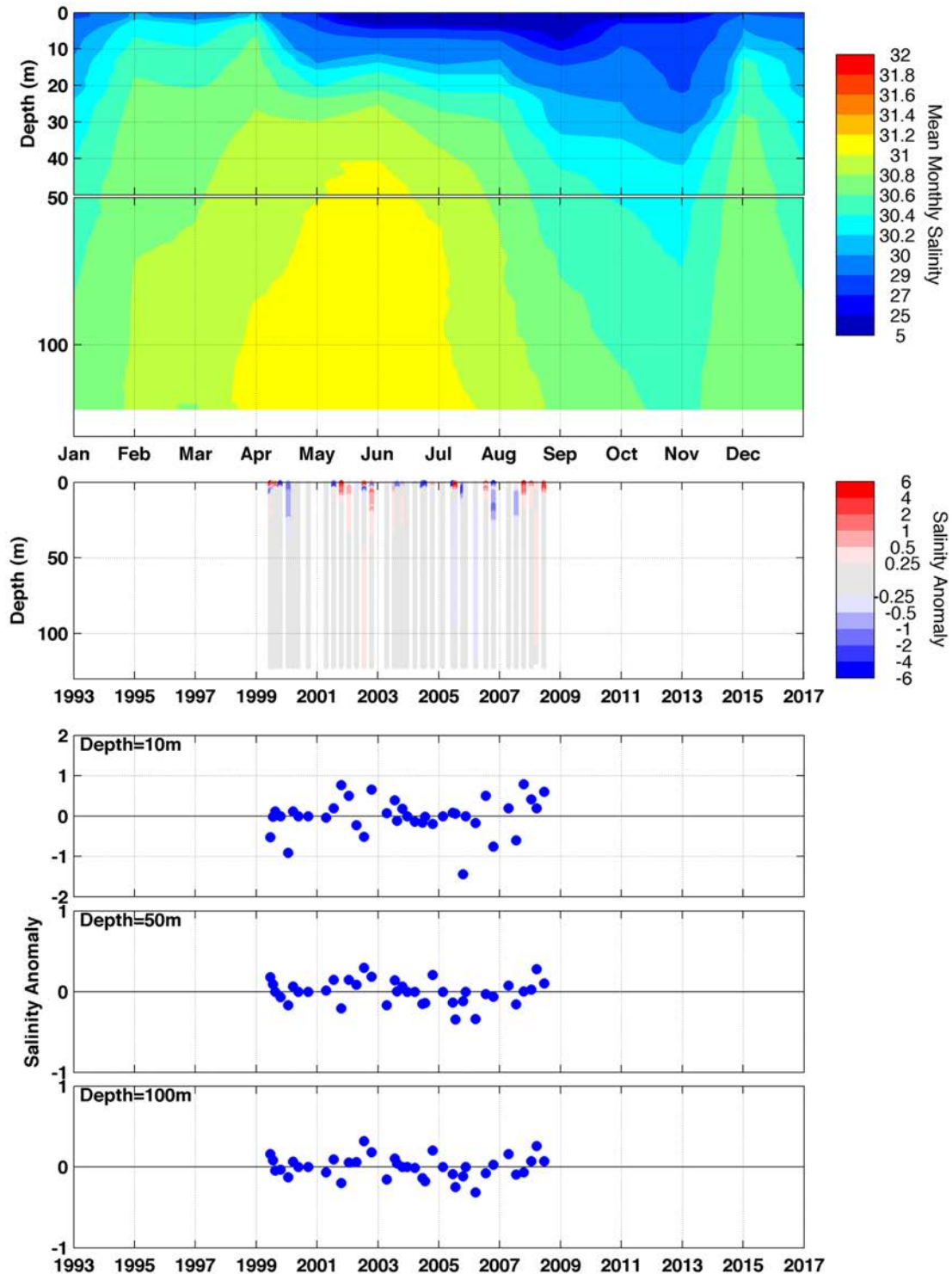


Figure A44. GLBA Station 22 salinity fields. The top two panels show monthly mean contours of salinity over 0-50 m depth and then 50 m to the bottom or 225 m, whichever is shallower. The third panel from the top shows the monthly anomaly versus depth. The bottom three panels show single-depth anomalies at 10 m, 100 m, and 200 m below the surface. Shallow stations not reaching the greater depths have panels that are left blank.

GLBA Station 24

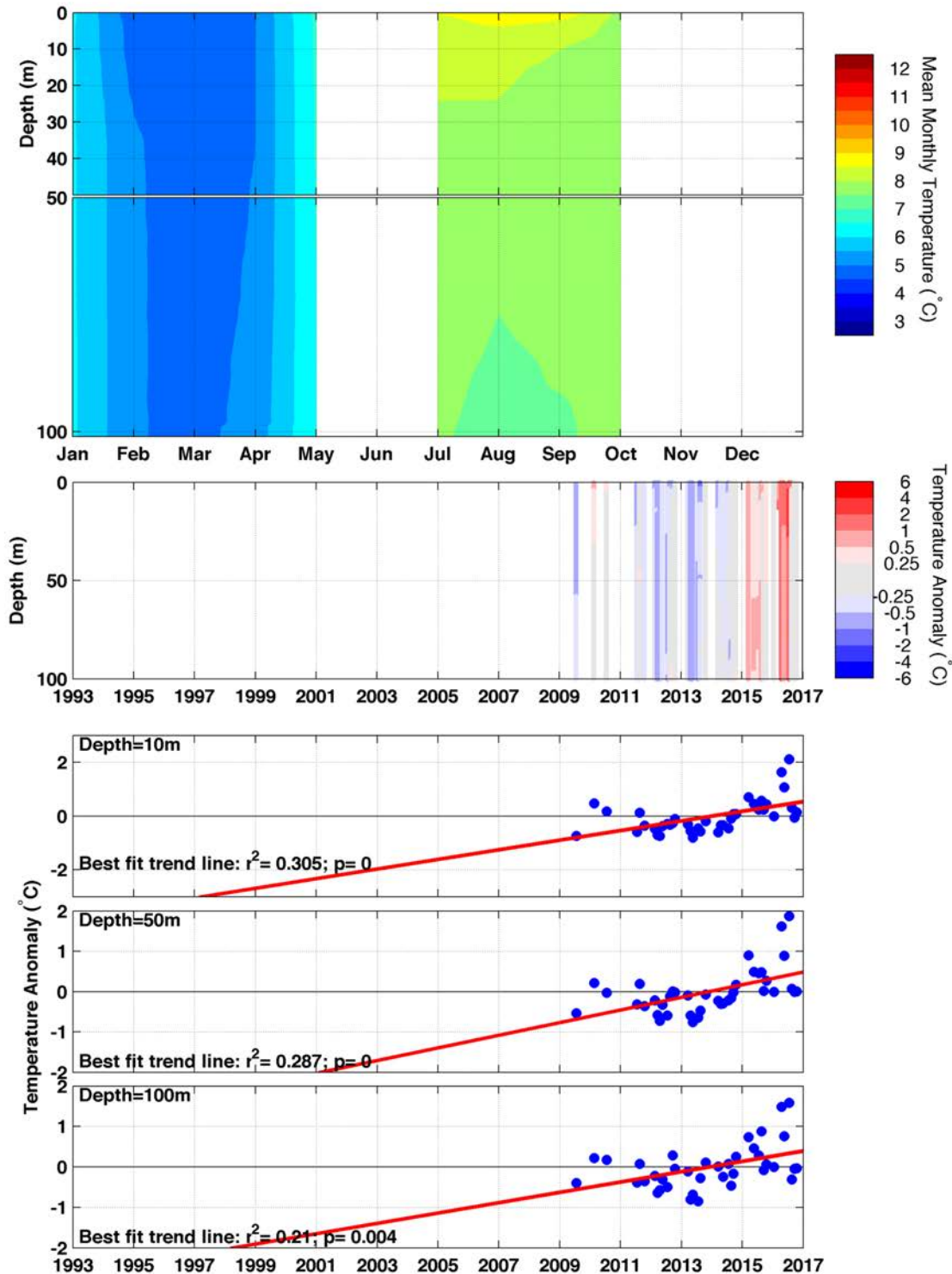


Figure A45. GLBA Station 24 temperature fields. The top two panels show monthly mean contours of temperature over 0-50 m depth and then 50 m to the bottom or 225 m, whichever is shallower. The third panel from the top shows the monthly anomaly versus depth. The bottom three panels show single-depth anomalies at 10 m, 100 m, and 200 m below the surface. Shallow stations not reaching the greater depths have panels that are left blank.

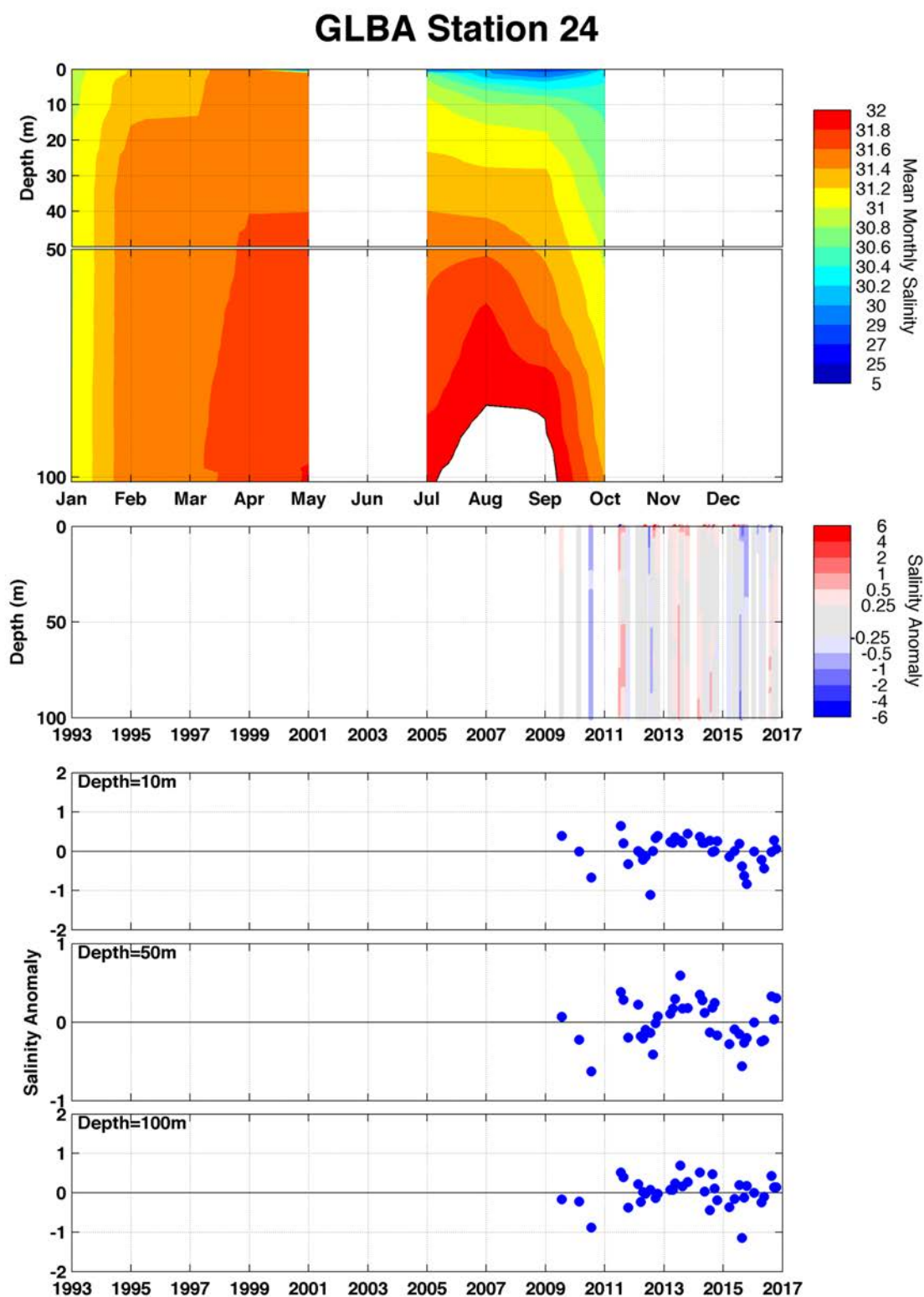


Figure A46. GLBA Station 24 salinity fields. The top two panels show monthly mean contours of salinity over 0-50 m depth and then 50 m to the bottom or 225 m, whichever is shallower. The third panel from the top shows the monthly anomaly versus depth. The bottom three panels show single-depth anomalies at 10 m, 100 m, and 200 m below the surface. Shallow stations not reaching the greater depths have panels that are left blank.

Appendix B: Scatterplots of Glacier Bay Thermal and Haline Anomalies Versus Climate Index, Local Weather, and GAK1 Anomalies

Figures B1 - B16 show scatter plots of temperature (T) and salinity (S) anomalies against eleven atmospheric, oceanographic and climate time series. Top row shows the relation to the Juneau sea level pressure (SLP), air temperature (AT), and wind speed (WS). Middle row shows the relation to 10 m and 250 m depth temperatures (T) and salinities (S). Bottom row shows the relation to the PDO, NPGO, ENSO and PNA climate indices. Red lines denote linear regressions significant at the 95% confidence level or better; the statistical fit is described by the r^2 and p values.

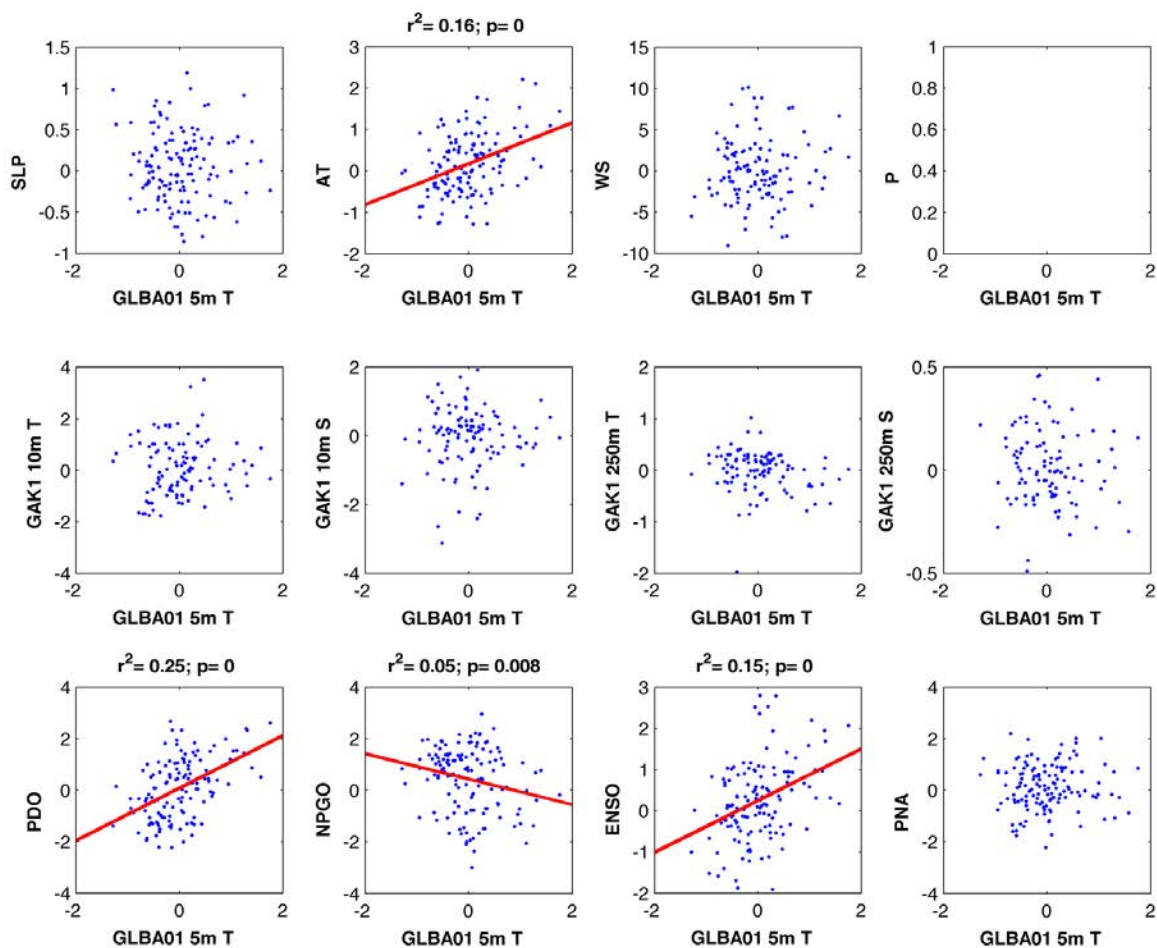


Figure B1. GLBA Station 01 scatter plots of temperature (T) anomalies at 5 m of depth against eleven atmospheric, oceanographic and climate time series. Top row shows the relation to the Juneau sea level pressure (SLP), air temperature (AT), and wind speed (WS). Middle row shows the relation to 10 m and 250 m depth temperatures (T) and salinities (S). Bottom row shows the relation to the PDO, NPGO, ENSO and PNA climate indices. Red lines denote linear regressions significant at the 95% confidence level or better; the statistical fit is described by the r^2 and p values.

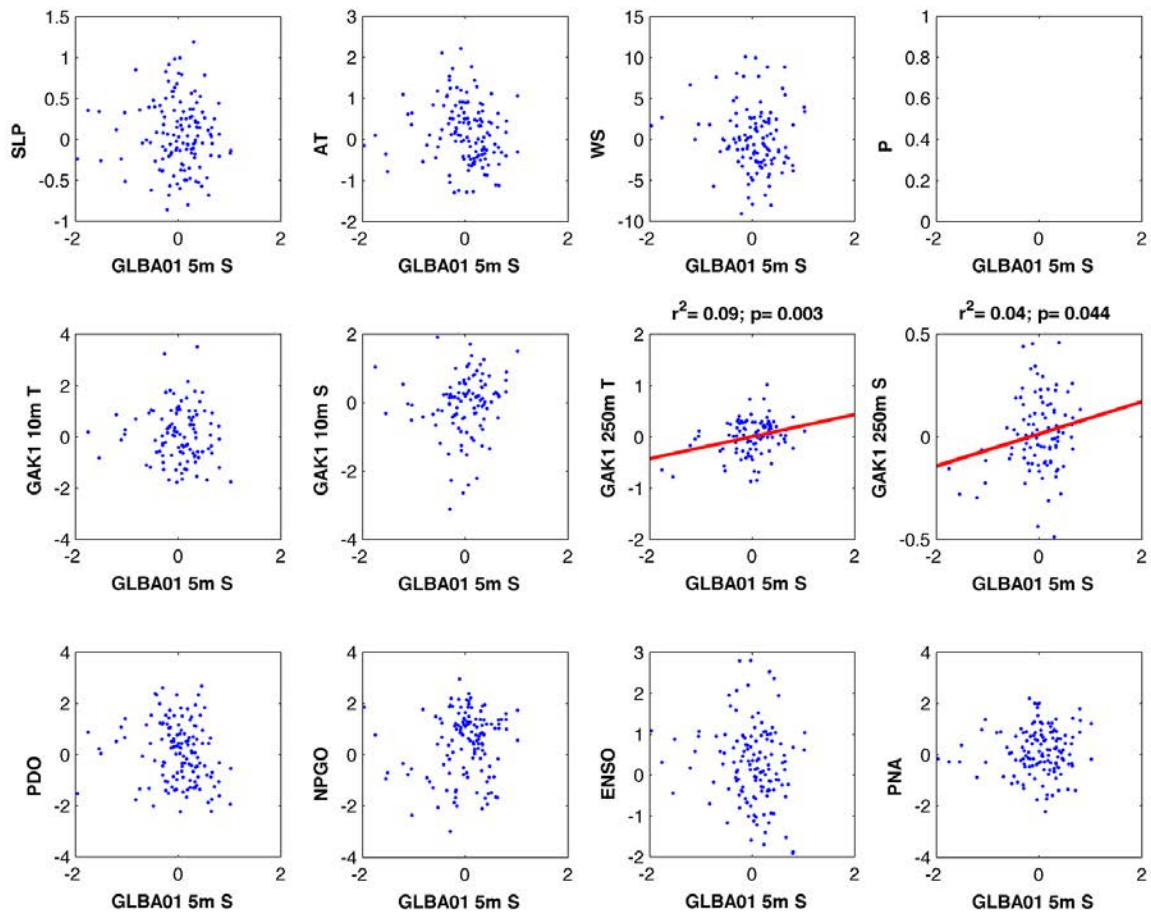


Figure B2. GLBA Station 01 scatter plots of salinity (S) anomalies at 5 m of depth against eleven atmospheric, oceanographic and climate time series. Top row shows the relation to the Juneau sea level pressure (SLP), air temperature (AT), and wind speed (WS). Middle row shows the relation to 10 m and 250 m depth temperatures (T) and salinities (S). Bottom row shows the relation to the PDO, NPGO, ENSO and PNA climate indices. Red lines denote linear regressions significant at the 95% confidence level or better; the statistical fit is described by the r^2 and p values.

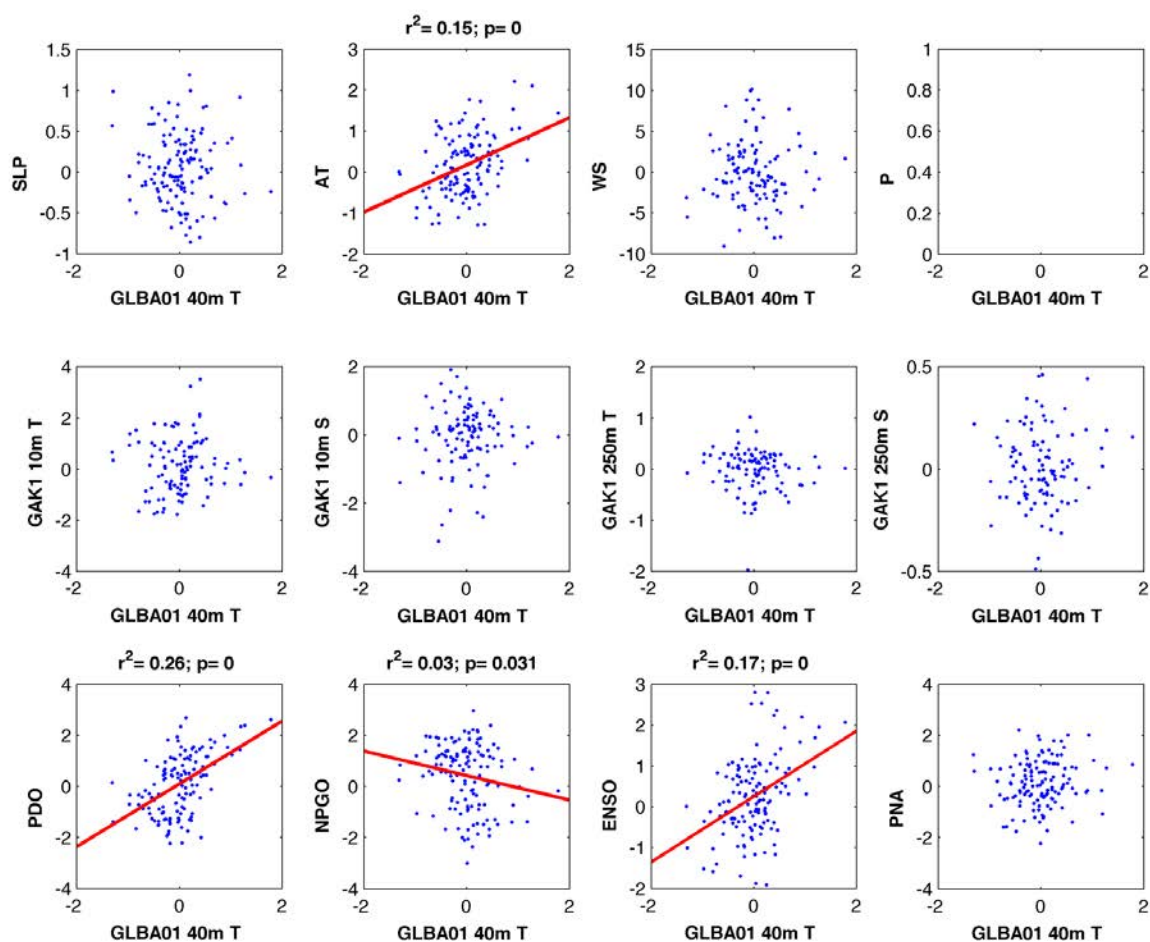


Figure B3. GLBA Station 01 scatter plots of temperature (T) anomalies at 40 m of depth against eleven atmospheric, oceanographic and climate time series. Top row shows the relation to the Juneau sea level pressure (SLP), air temperature (AT), and wind speed (WS). Middle row shows the relation to 10 m and 250 m depth temperatures (T) and salinities (S). Bottom row shows the relation to the PDO, NPGO, ENSO and PNA climate indices. Red lines denote linear regressions significant at the 95% confidence level or better; the statistical fit is described by the r^2 and p values.

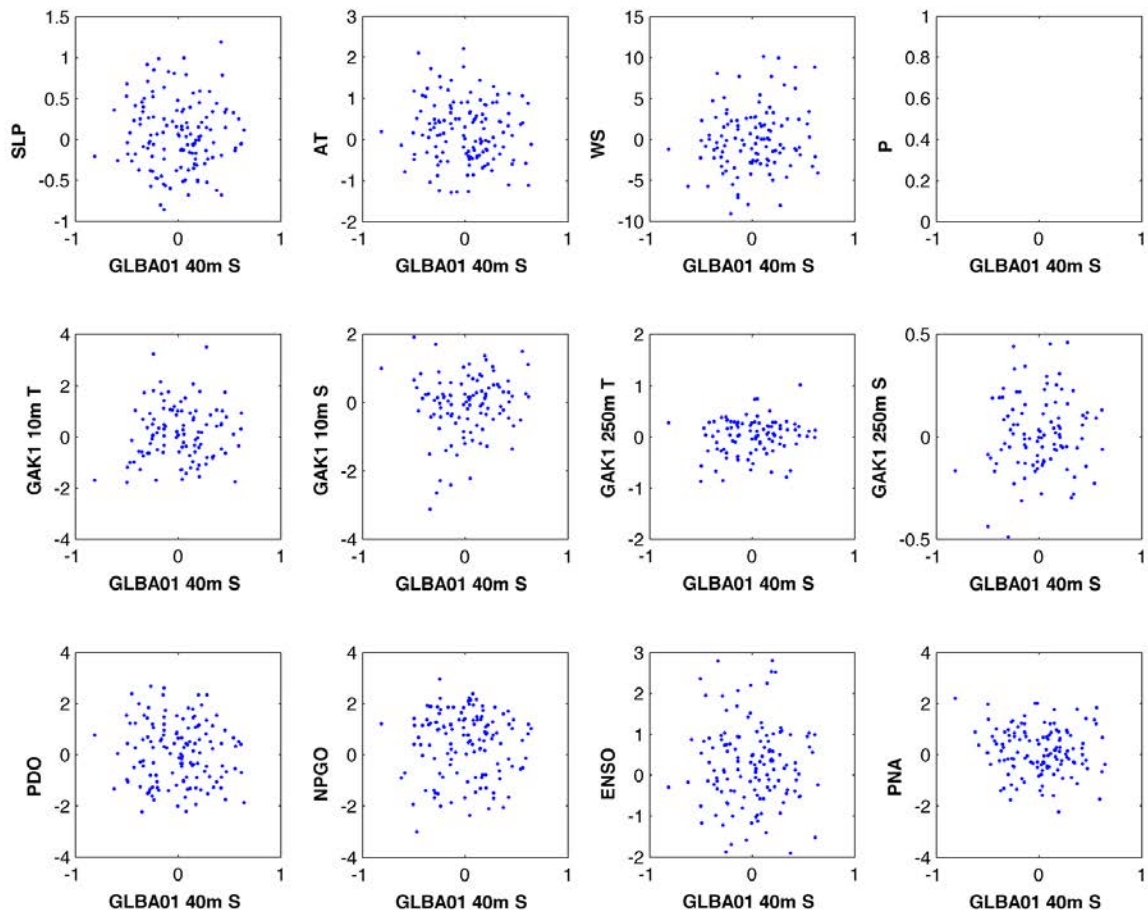


Figure B4. GLBA Station 01 scatter plots of salinity (S) anomalies at 40 m of depth against eleven atmospheric, oceanographic and climate time series. Top row shows the relation to the Juneau sea level pressure (SLP), air temperature (AT), and wind speed (WS). Middle row shows the relation to 10 m and 250 m depth temperatures (T) and salinities (S). Bottom row shows the relation to the PDO, NPGO, ENSO and PNA climate indices. Red lines denote linear regressions significant at the 95% confidence level or better; the statistical fit is described by the r^2 and p values.

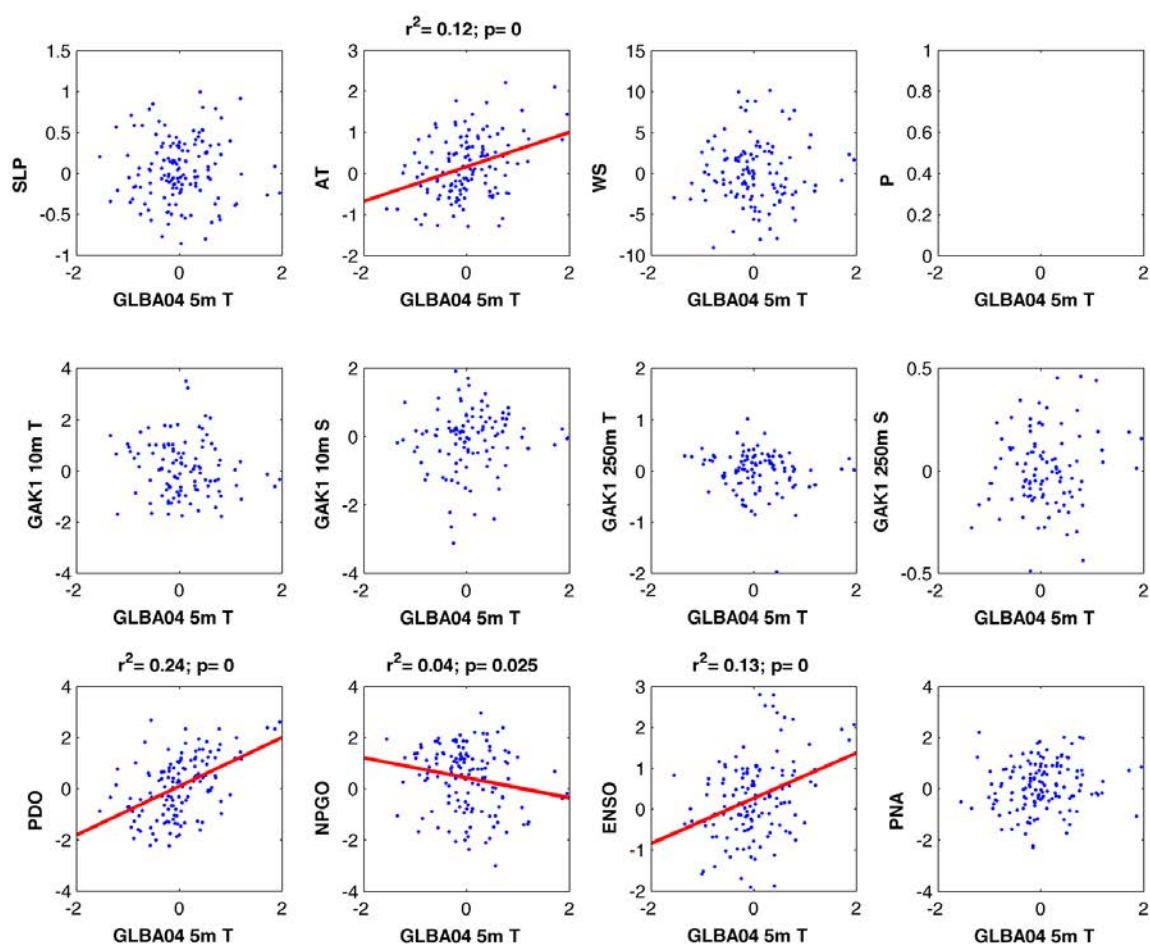


Figure B5. GLBA Station 04 scatter plots of temperature (T) anomalies at 5 m of depth against eleven atmospheric, oceanographic and climate time series. Top row shows the relation to the Juneau sea level pressure (SLP), air temperature (AT), and wind speed (WS). Middle row shows the relation to 10 m and 250 m depth temperatures (T) and salinities (S). Bottom row shows the relation to the PDO, NPGO, ENSO and PNA climate indices. Red lines denote linear regressions significant at the 95% confidence level or better; the statistical fit is described by the r^2 and p values.

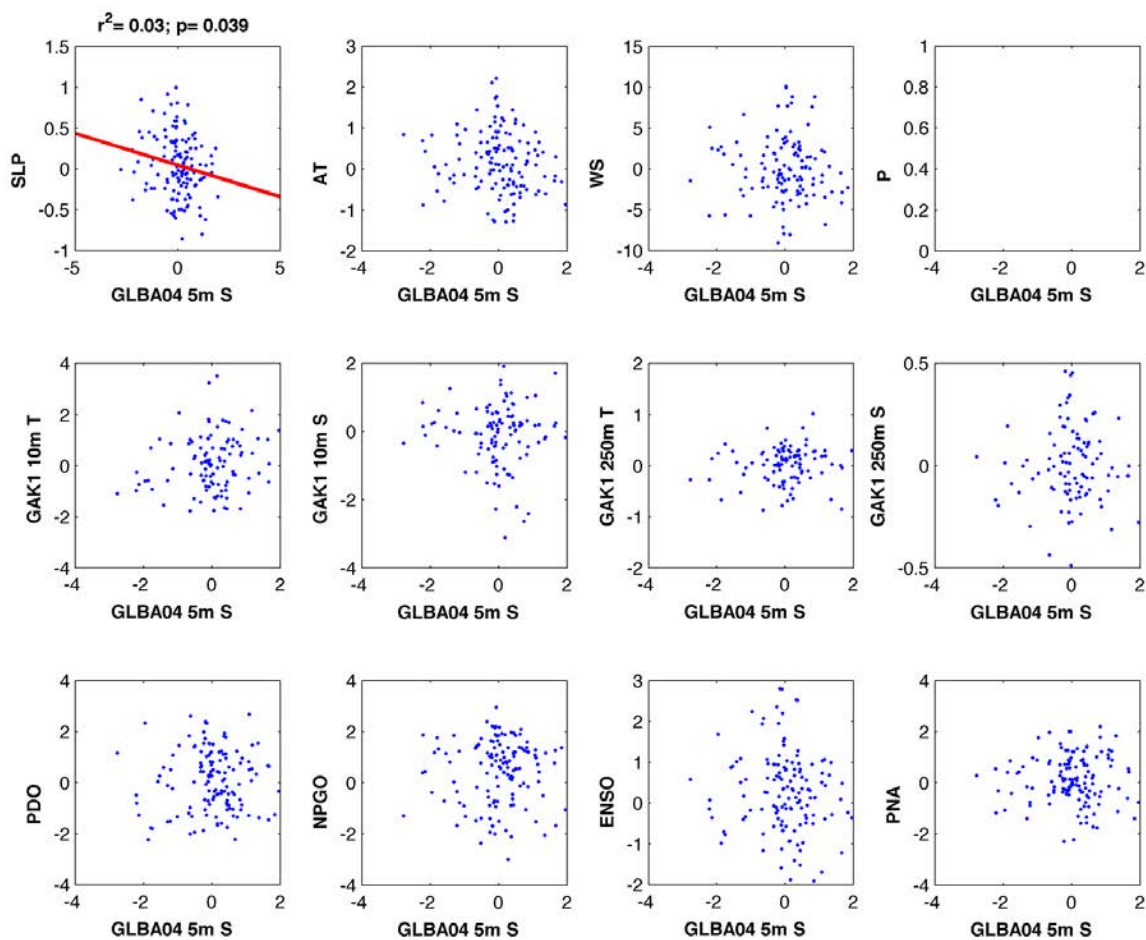


Figure B6. GLBA Station 04 scatter plots of salinity (S) anomalies at 5 m of depth against eleven atmospheric, oceanographic and climate time series. Top row shows the relation to the Juneau sea level pressure (SLP), air temperature (AT), and wind speed (WS). Middle row shows the relation to 10 m and 250 m depth temperatures (T) and salinities (S). Bottom row shows the relation to the PDO, NPGO, ENSO and PNA climate indices. Red lines denote linear regressions significant at the 95% confidence level or better; the statistical fit is described by the r^2 and p values.

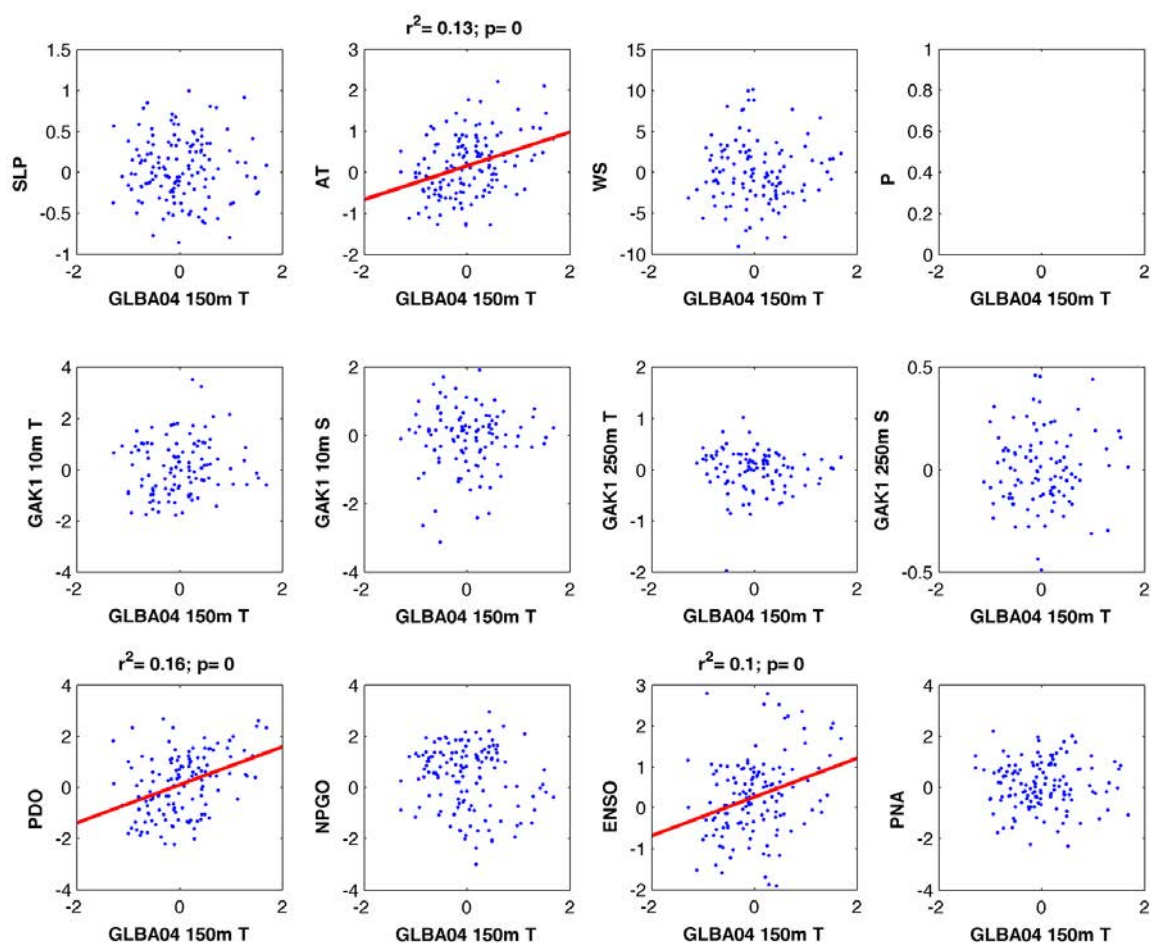


Figure B7. GLBA Station 04 scatter plots of temperature (T) anomalies at 150 m of depth against eleven atmospheric, oceanographic and climate time series. Top row shows the relation to the Juneau sea level pressure (SLP), air temperature (AT), and wind speed (WS). Middle row shows the relation to 10 m and 250 m depth temperatures (T) and salinities (S). Bottom row shows the relation to the PDO, NPGO, ENSO and PNA climate indices. Red lines denote linear regressions significant at the 95% confidence level or better; the statistical fit is described by the r^2 and p values.

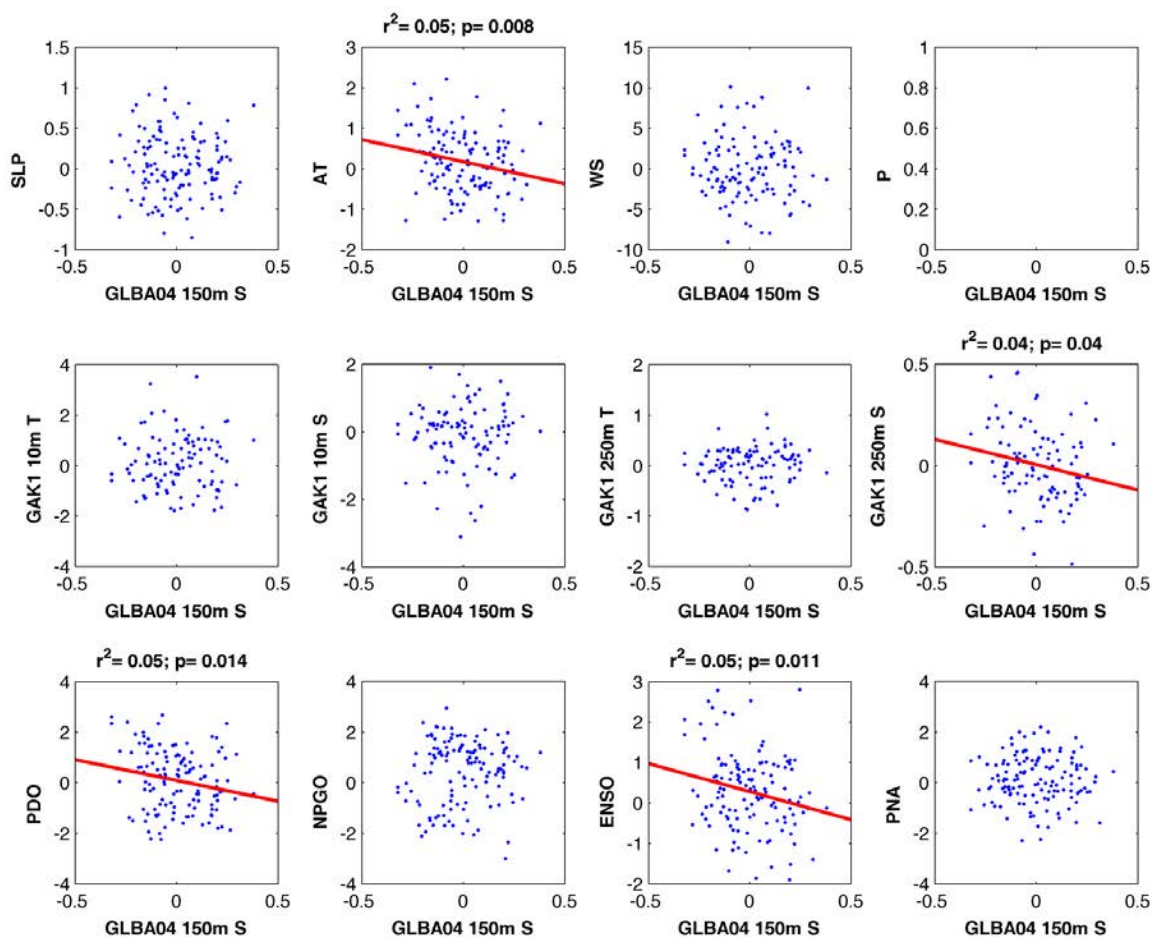


Figure B8. GLBA Station 04 scatter plots of salinity (S) anomalies at 150 m of depth against eleven atmospheric, oceanographic and climate time series. Top row shows the relation to the Juneau sea level pressure (SLP), air temperature (AT), and wind speed (WS). Middle row shows the relation to 10 m and 250 m depth temperatures (T) and salinities (S). Bottom row shows the relation to the PDO, NPGO, ENSO and PNA climate indices. Red lines denote linear regressions significant at the 95% confidence level or better; the statistical fit is described by the r^2 and p values.

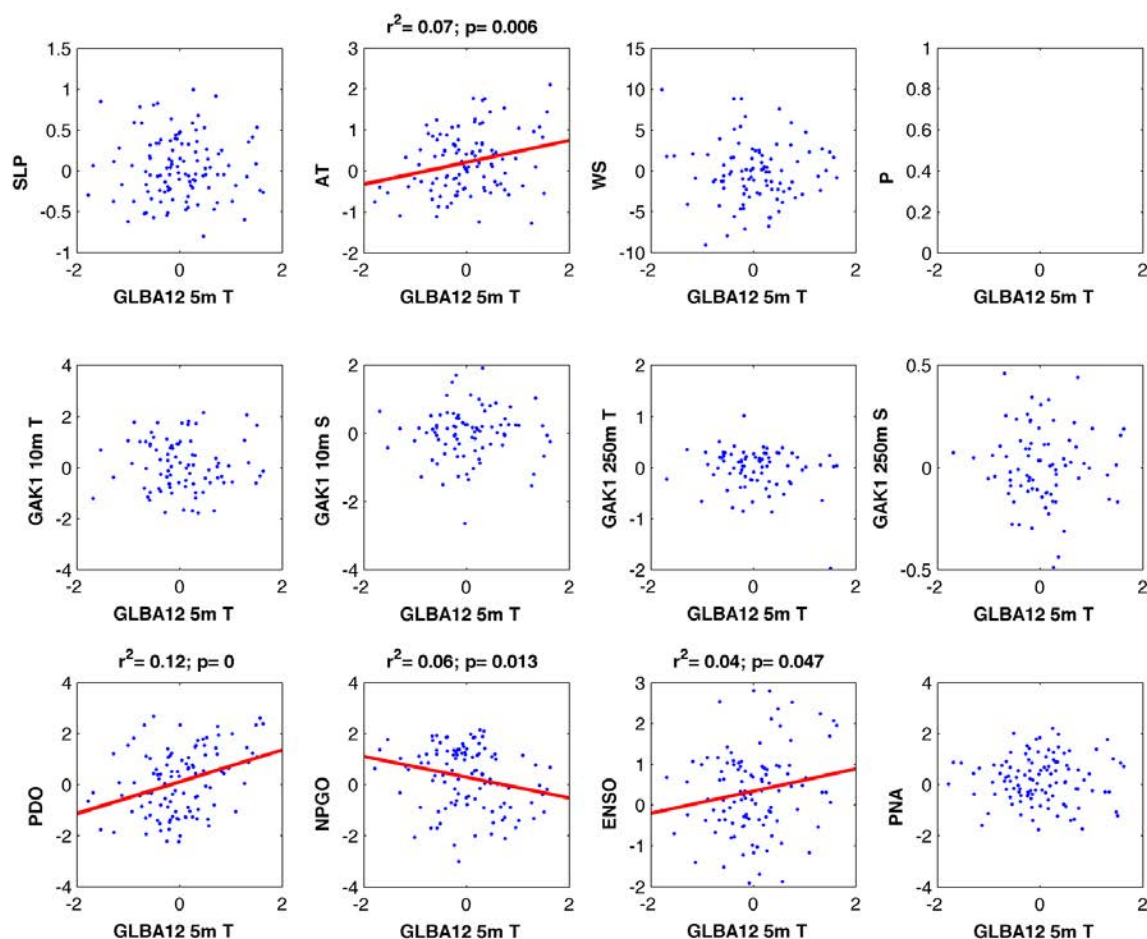


Figure B9. GLBA Station 12 scatter plots of temperature (T) anomalies at 5 m of depth against eleven atmospheric, oceanographic and climate time series. Top row shows the relation to the Juneau sea level pressure (SLP), air temperature (AT), and wind speed (WS). Middle row shows the relation to 10 m and 250 m depth temperatures (T) and salinities (S). Bottom row shows the relation to the PDO, NPGO, ENSO and PNA climate indices. Red lines denote linear regressions significant at the 95% confidence level or better; the statistical fit is described by the r^2 and p values.

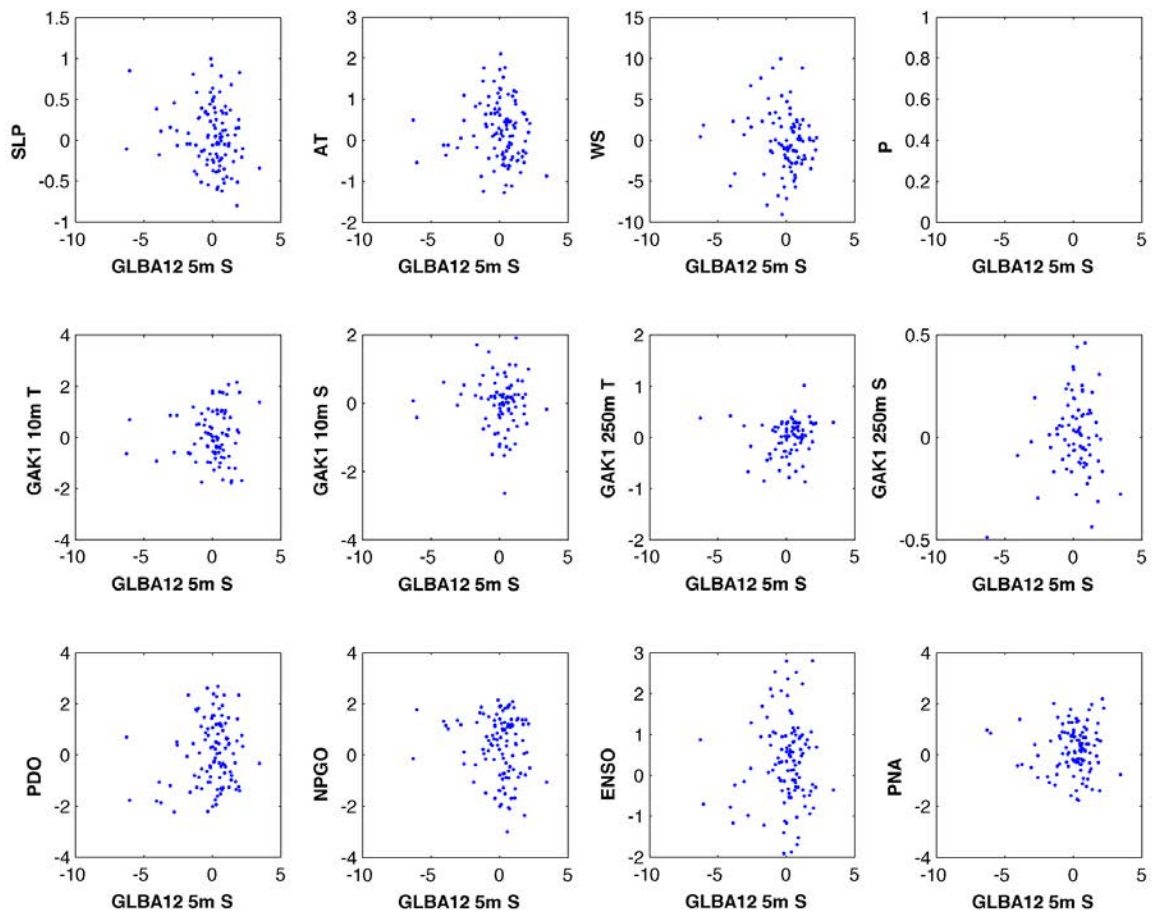


Figure B10. GLBA Station 12 scatter plots of salinity (S) anomalies at 5 m of depth against eleven atmospheric, oceanographic and climate time series. Top row shows the relation to the Juneau sea level pressure (SLP), air temperature (AT), and wind speed (WS). Middle row shows the relation to 10 m and 250 m depth temperatures (T) and salinities (S). Bottom row shows the relation to the PDO, NPGO, ENSO and PNA climate indices. Red lines denote linear regressions significant at the 95% confidence level or better; the statistical fit is described by the r^2 and p values.

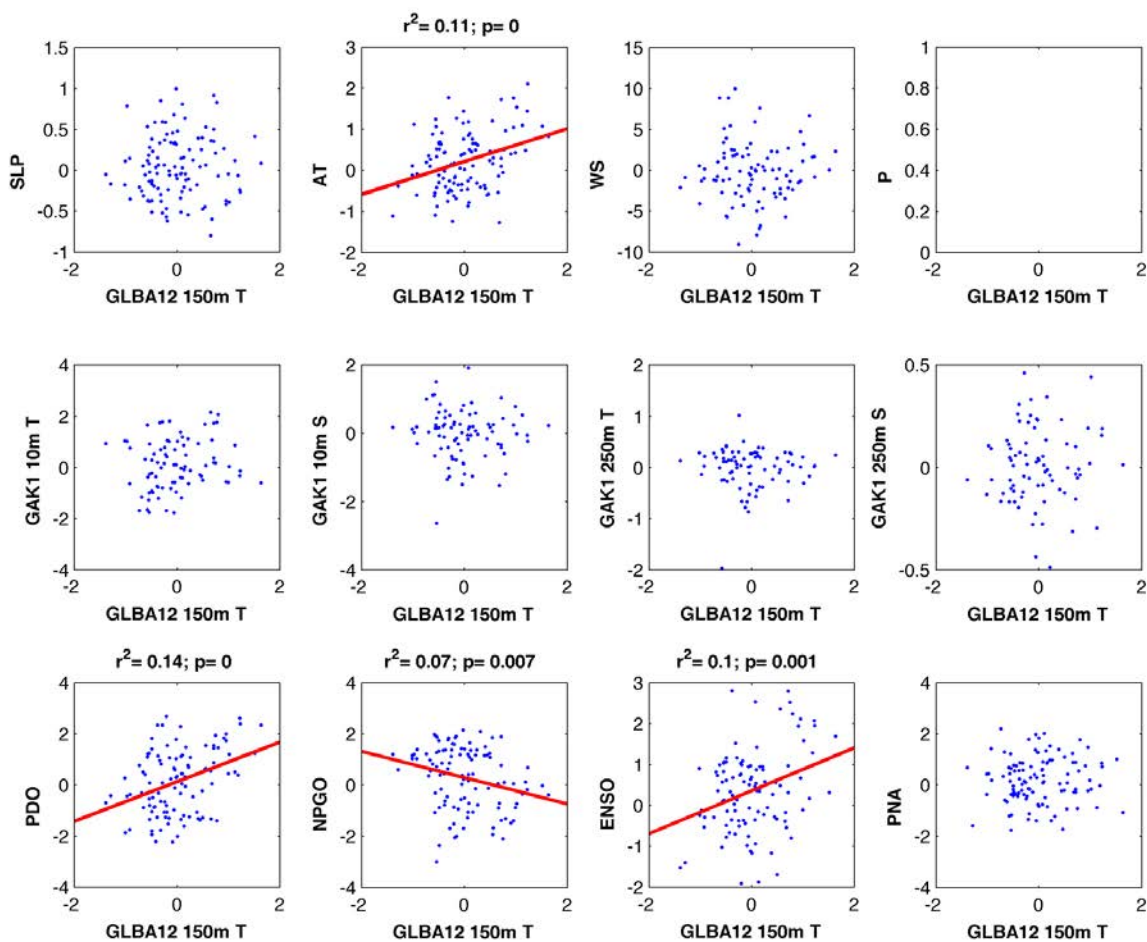


Figure B11. GLBA Station 12 scatter plots of temperature (T) anomalies at 150 m of depth against eleven atmospheric, oceanographic and climate time series. Top row shows the relation to the Juneau sea level pressure (SLP), air temperature (AT), and wind speed (WS). Middle row shows the relation to 10 m and 250 m depth temperatures (T) and salinities (S). Bottom row shows the relation to the PDO, NPGO, ENSO and PNA climate indices. Red lines denote linear regressions significant at the 95% confidence level or better; the statistical fit is described by the r^2 and p values.

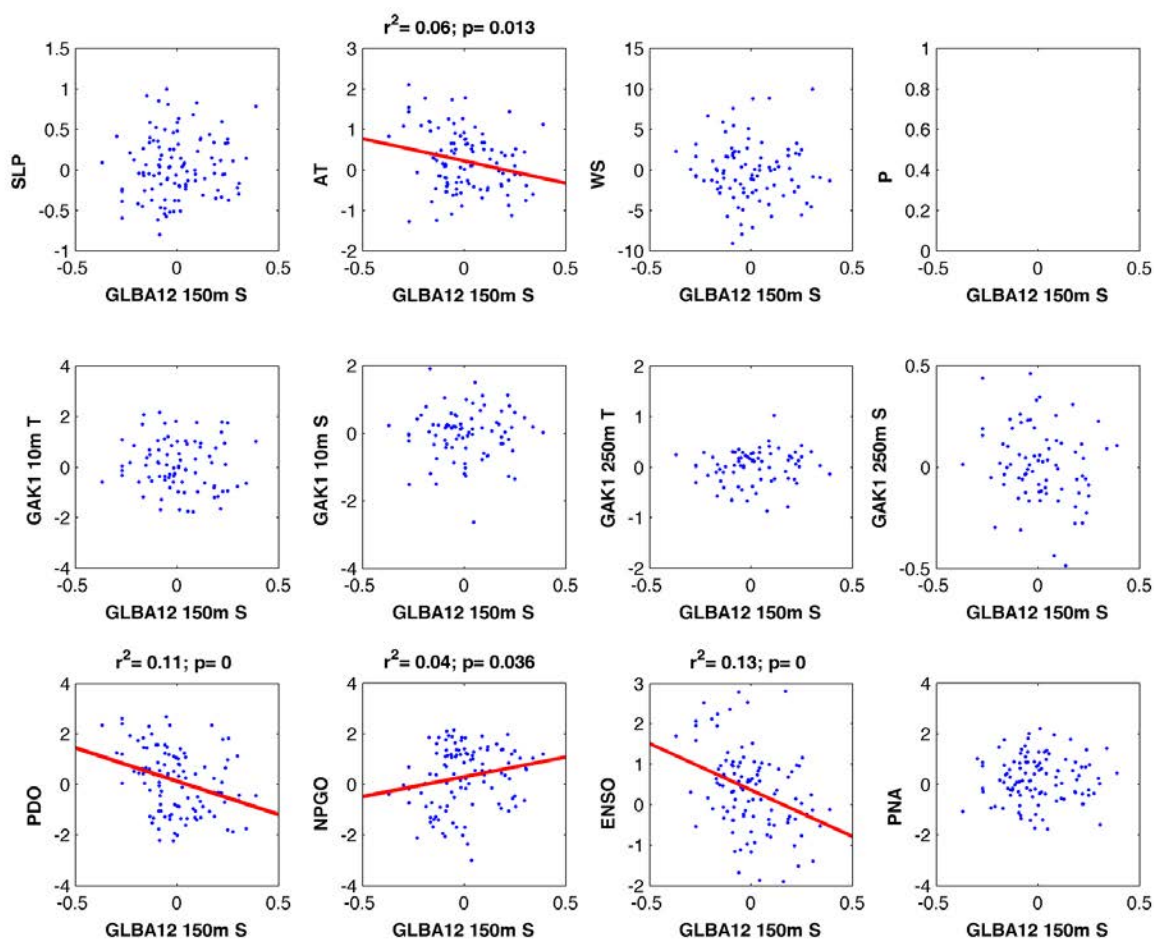


Figure B12. GLBA Station 12 scatter plots of salinity (S) anomalies at 150 m of depth against eleven atmospheric, oceanographic and climate time series. Top row shows the relation to the Juneau sea level pressure (SLP), air temperature (AT), and wind speed (WS). Middle row shows the relation to 10 m and 250 m depth temperatures (T) and salinities (S). Bottom row shows the relation to the PDO, NPGO, ENSO and PNA climate indices. Red lines denote linear regressions significant at the 95% confidence level or better; the statistical fit is described by the r^2 and p values.

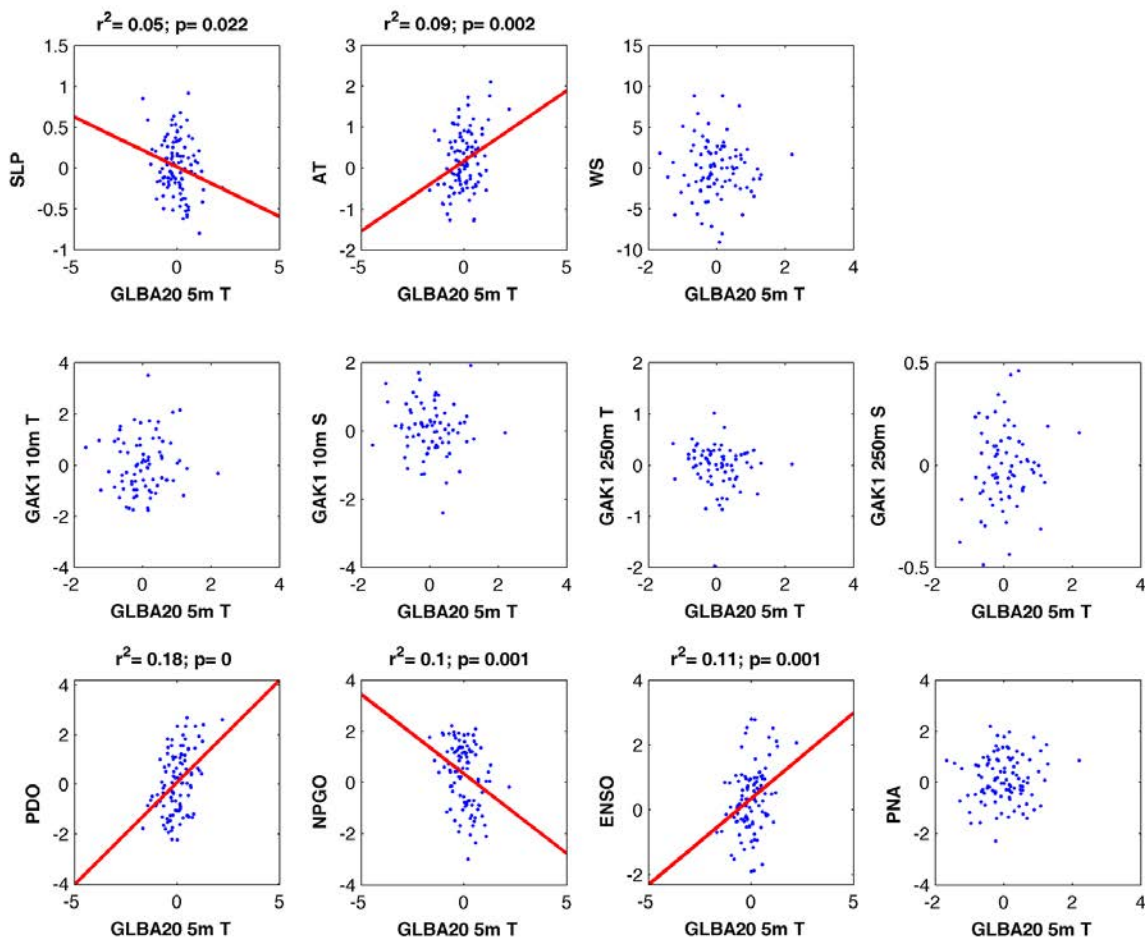


Figure B13. GLBA Station 20 scatter plots of temperature (T) anomalies at 5 m of depth against eleven atmospheric, oceanographic and climate time series. Top row shows the relation to the Juneau sea level pressure (SLP), air temperature (AT), and wind speed (WS). Middle row shows the relation to 10 m and 250 m depth temperatures (T) and salinities (S). Bottom row shows the relation to the PDO, NPGO, ENSO and PNA climate indices. Red lines denote linear regressions significant at the 95% confidence level or better; the statistical fit is described by the r^2 and p values.

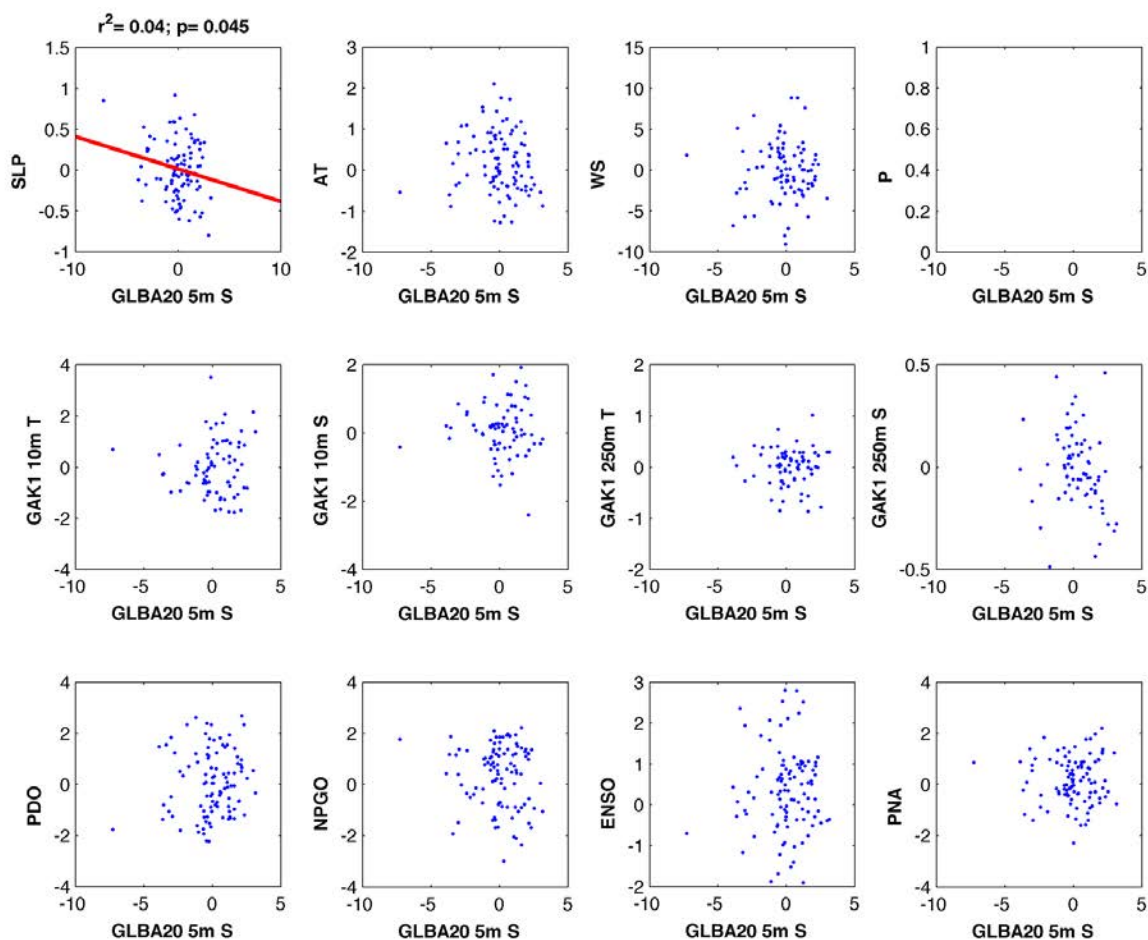


Figure B14. GLBA Station 20 scatter plots of salinity (S) anomalies at 5 m of depth against eleven atmospheric, oceanographic and climate time series. Top row shows the relation to the Juneau sea level pressure (SLP), air temperature (AT), and wind speed (WS). Middle row shows the relation to 10 m and 250 m depth temperatures (T) and salinities (S). Bottom row shows the relation to the PDO, NPGO, ENSO and PNA climate indices. Red lines denote linear regressions significant at the 95% confidence level or better; the statistical fit is described by the r^2 and p values.

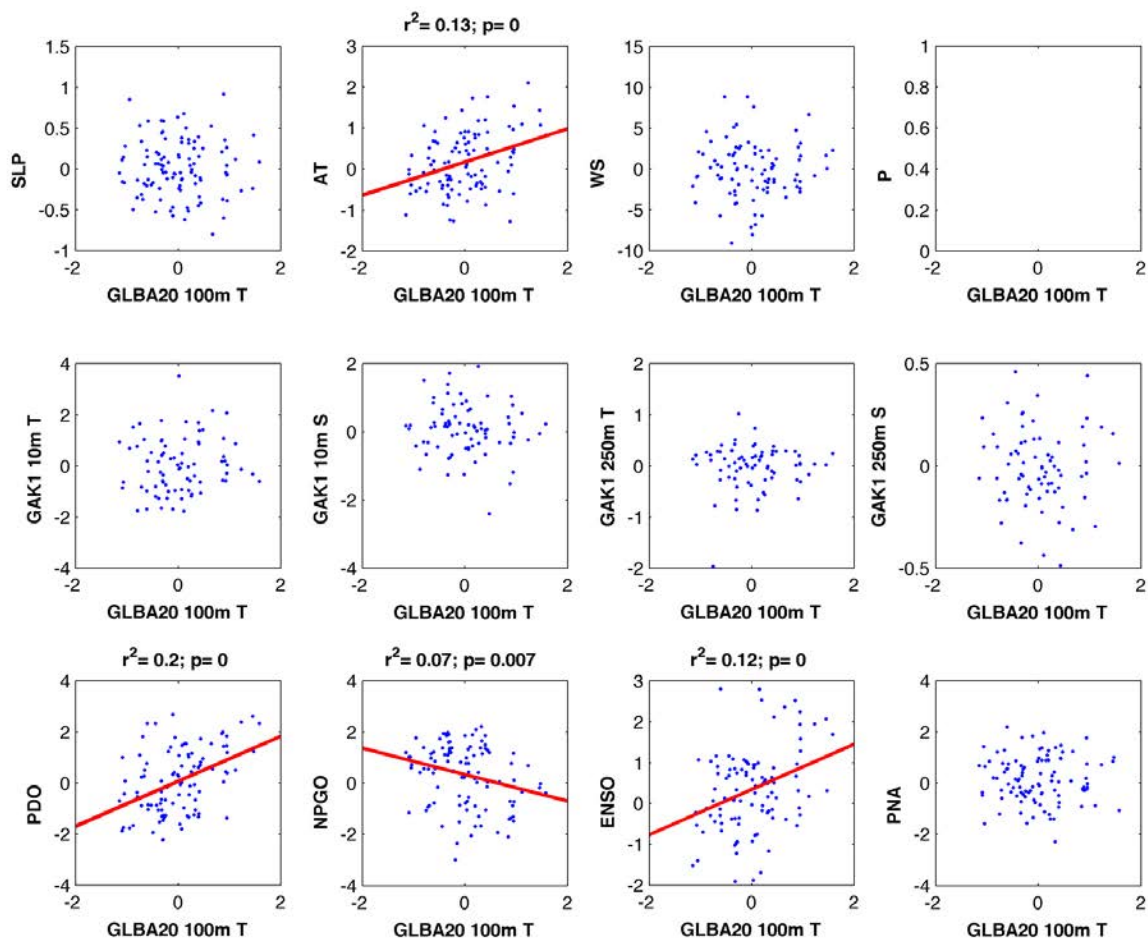


Figure B15. GLBA Station 20 scatter plots of temperature (T) anomalies at 100 m of depth against eleven atmospheric, oceanographic and climate time series. Top row shows the relation to the Juneau sea level pressure (SLP), air temperature (AT), and wind speed (WS). Middle row shows the relation to 10 m and 250 m depth temperatures (T) and salinities (S). Bottom row shows the relation to the PDO, NPGO, ENSO and PNA climate indices. Red lines denote linear regressions significant at the 95% confidence level or better; the statistical fit is described by the r^2 and p values.

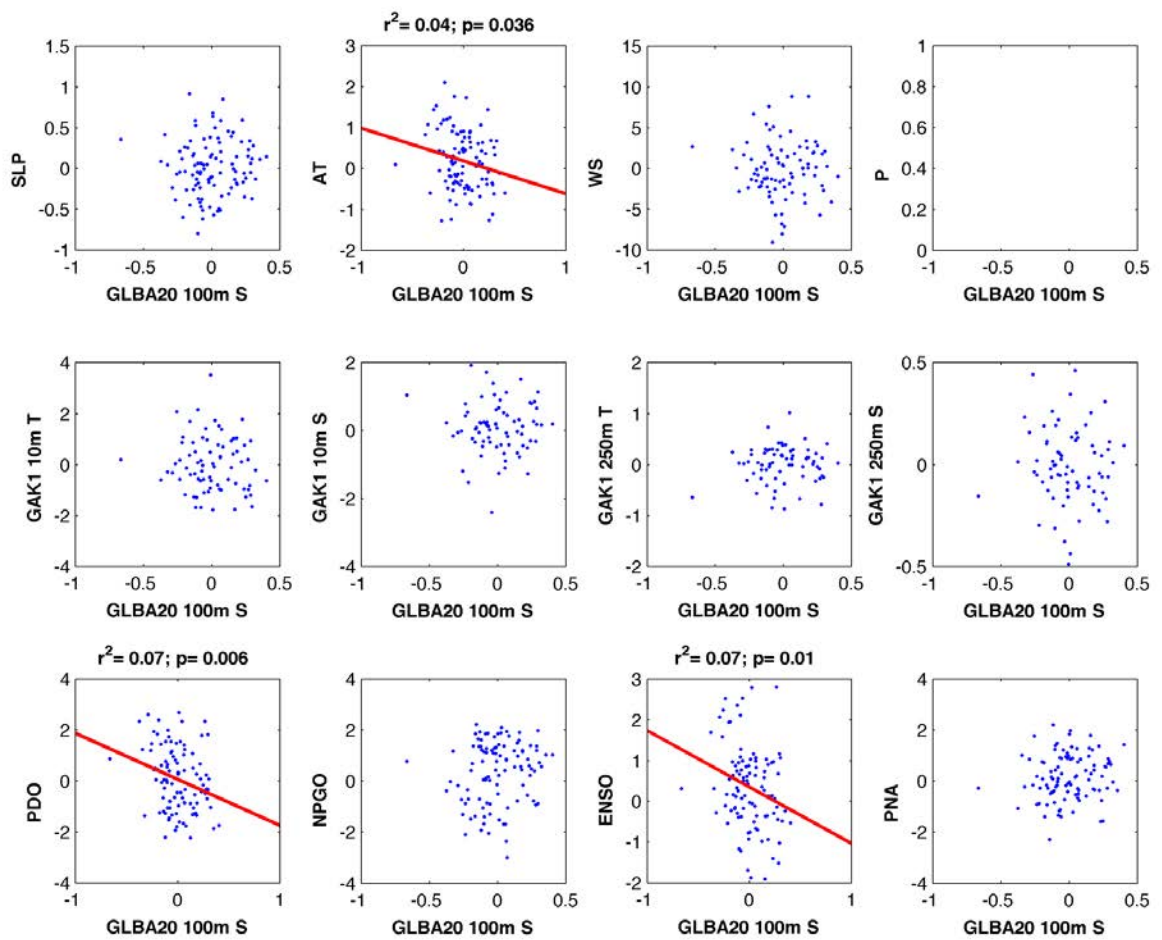


Figure B16. GLBA Station 20 scatter plots of salinity (S) anomalies at 100 m of depth against eleven atmospheric, oceanographic and climate time series. Top row shows the relation to the Juneau sea level pressure (SLP), air temperature (AT), and wind speed (WS). Middle row shows the relation to 10 m and 250 m depth temperatures (T) and salinities (S). Bottom row shows the relation to the PDO, NPGO, ENSO and PNA climate indices. Red lines denote linear regressions significant at the 95% confidence level or better; the statistical fit is described by the r^2 and p values.

Appendix C: Monthly Mean Vertical Cross-sections for the Transect Extending from Icy Bay to the Head of the East Arm

Appendix C shows climatological cross-sections of temperature and salinity using the 1993-2016 period of record data from Icy Strait up into Tarr Inlet (West Arm) and into Muir Inlet (East Arm; Figures C1- C24).

East Arm Transect: January

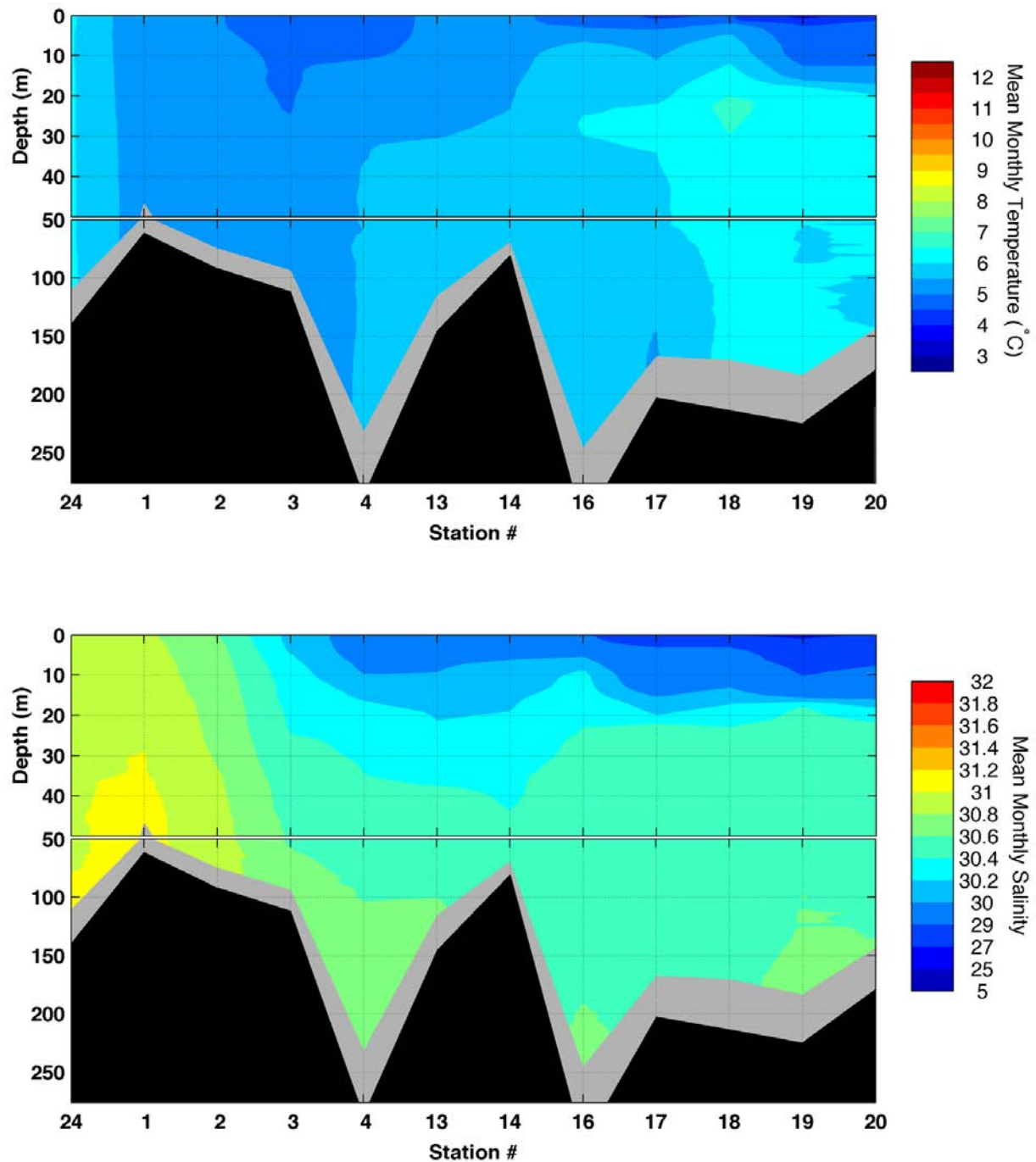


Figure C1. January climatological cross-sections of temperature (A) and salinity (B) using the 1993-2016 period of record data in Muir Inlet (East Arm).

East Arm Transect: February

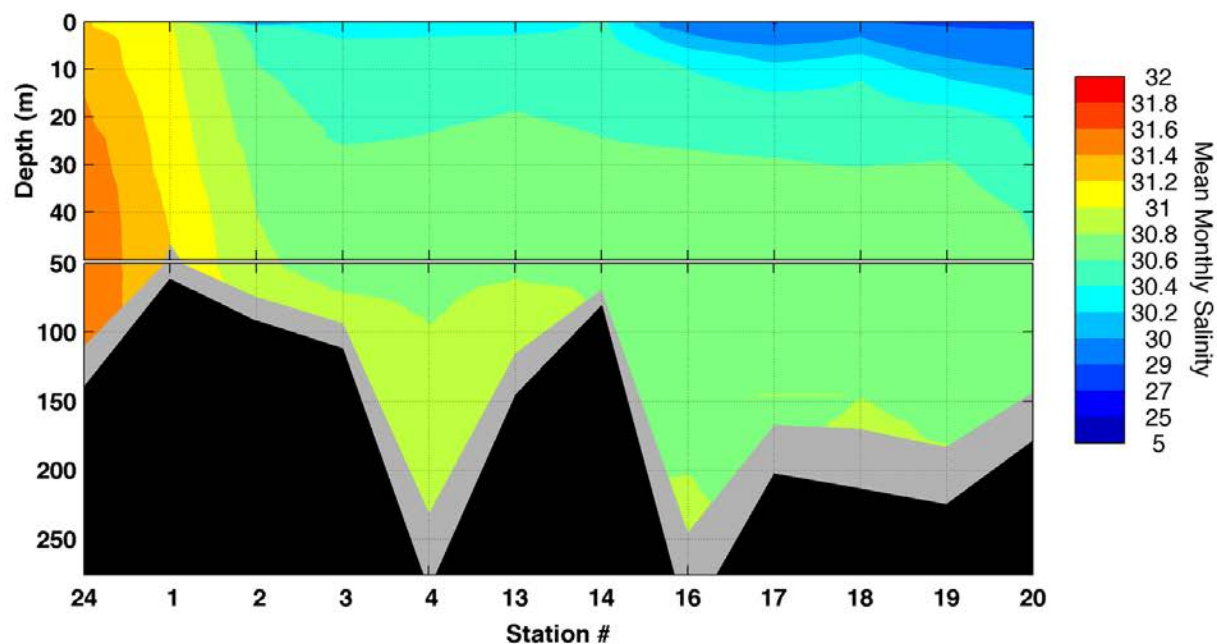
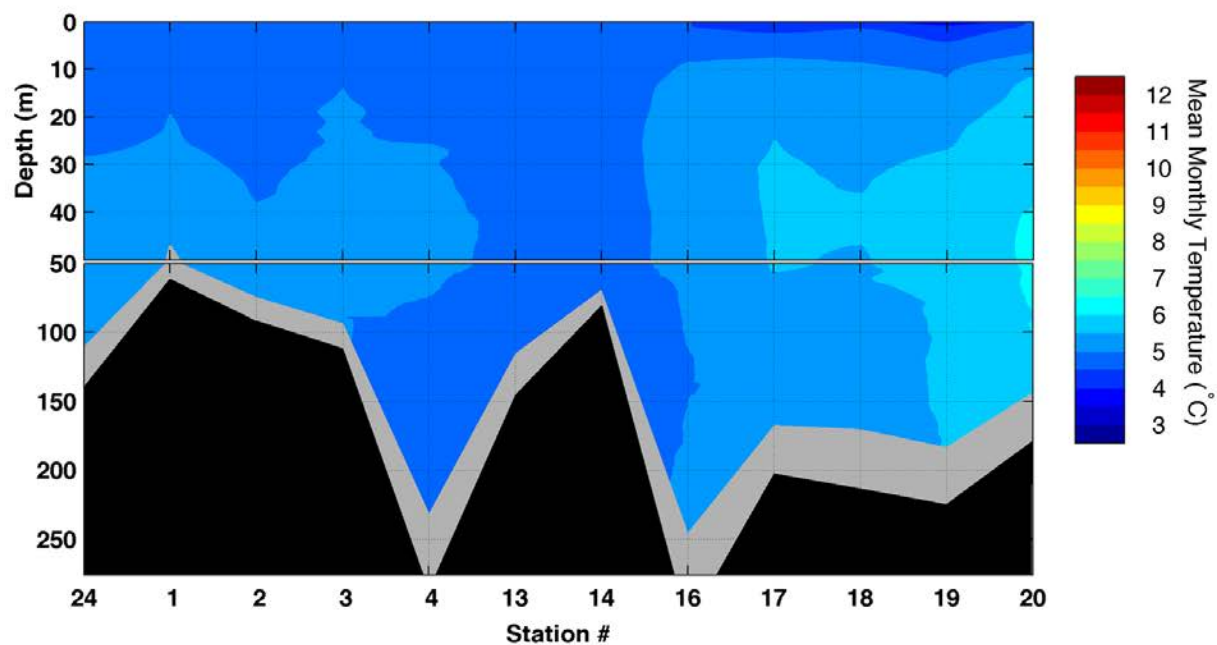


Figure C2. February climatological cross-sections of temperature (A) and salinity (B) using the 1993-2016 period of record data in Muir Inlet (East Arm).

East Arm Transect: March

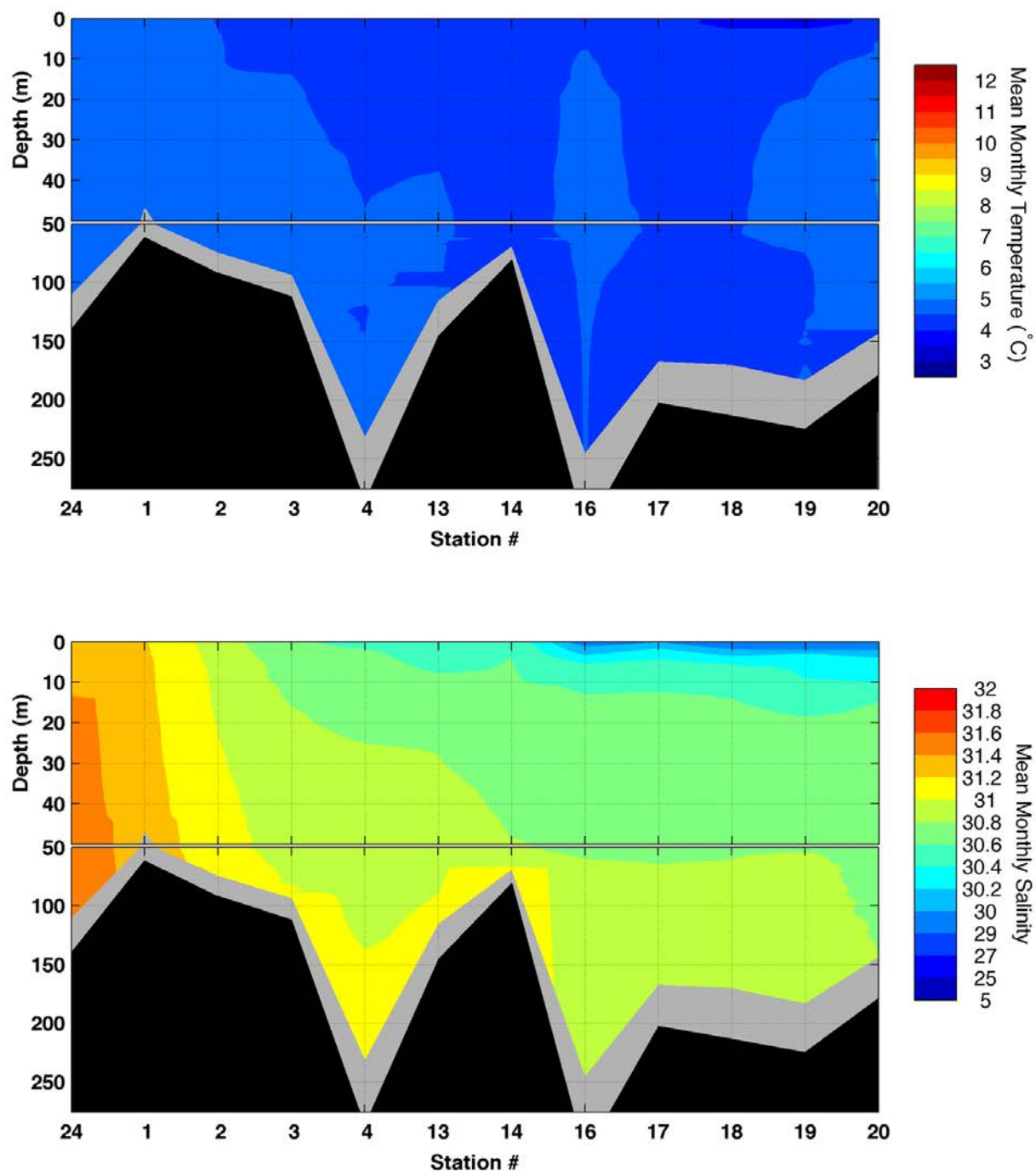


Figure C3. March climatological cross-sections of temperature (A) and salinity (B) using the 1993-2016 period of record data in Muir Inlet (East Arm).

East Arm Transect: April

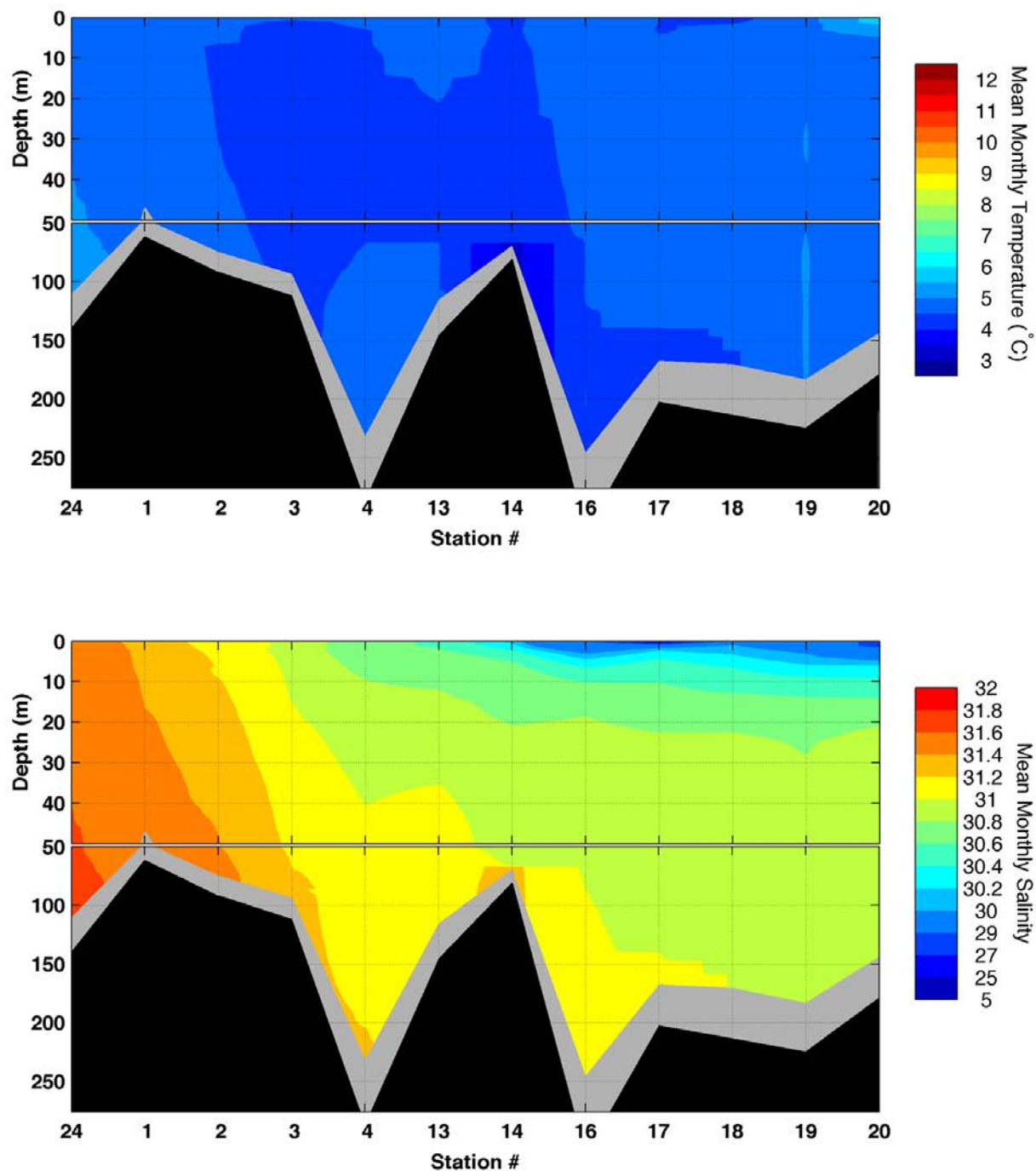


Figure C4. April climatological cross-sections of temperature (A) and salinity (B) using the 1993-2016 period of record data in Muir Inlet (East Arm).

East Arm Transect: May

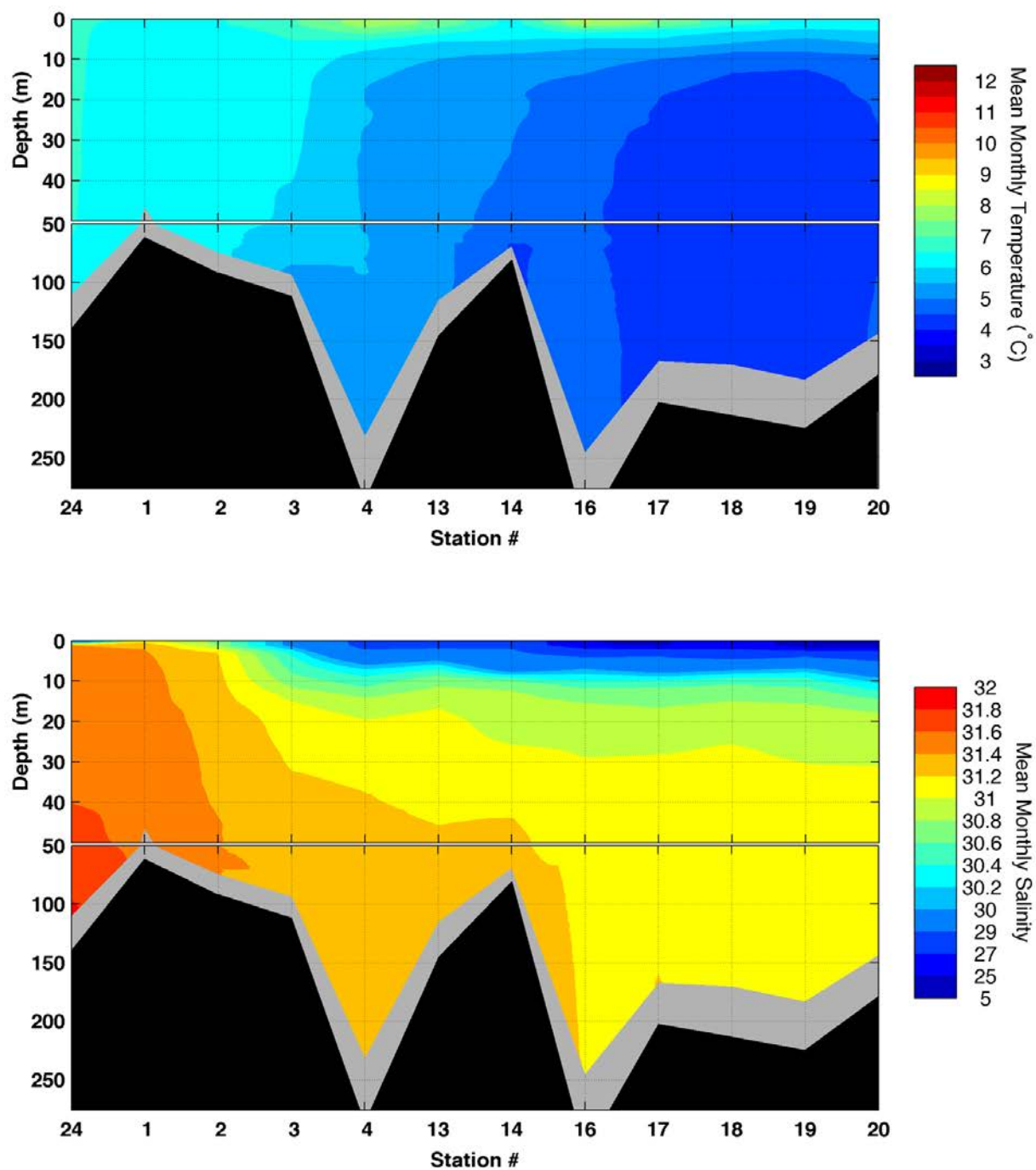


Figure C5. May climatological cross-sections of temperature (A) and salinity (B) using the 1993-2016 period of record data in Muir Inlet (East Arm).

East Arm Transect: June

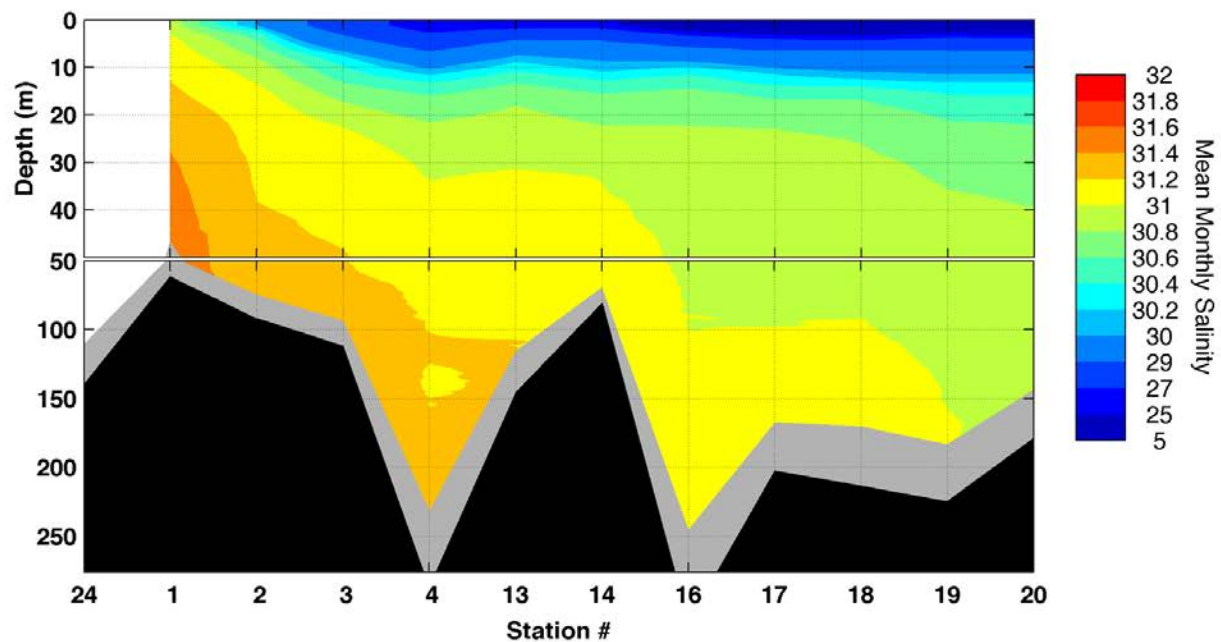
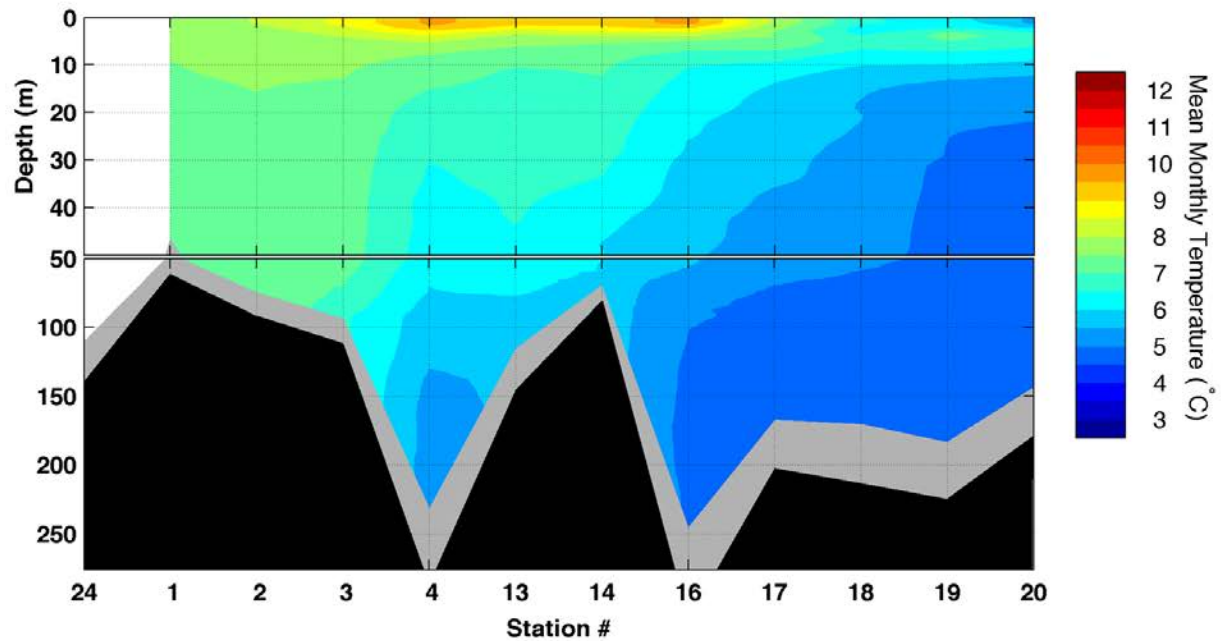


Figure C6. June climatological cross-sections of temperature (A) and salinity (B) using the 1993-2016 period of record data in Muir Inlet (East Arm).

East Arm Transect: July

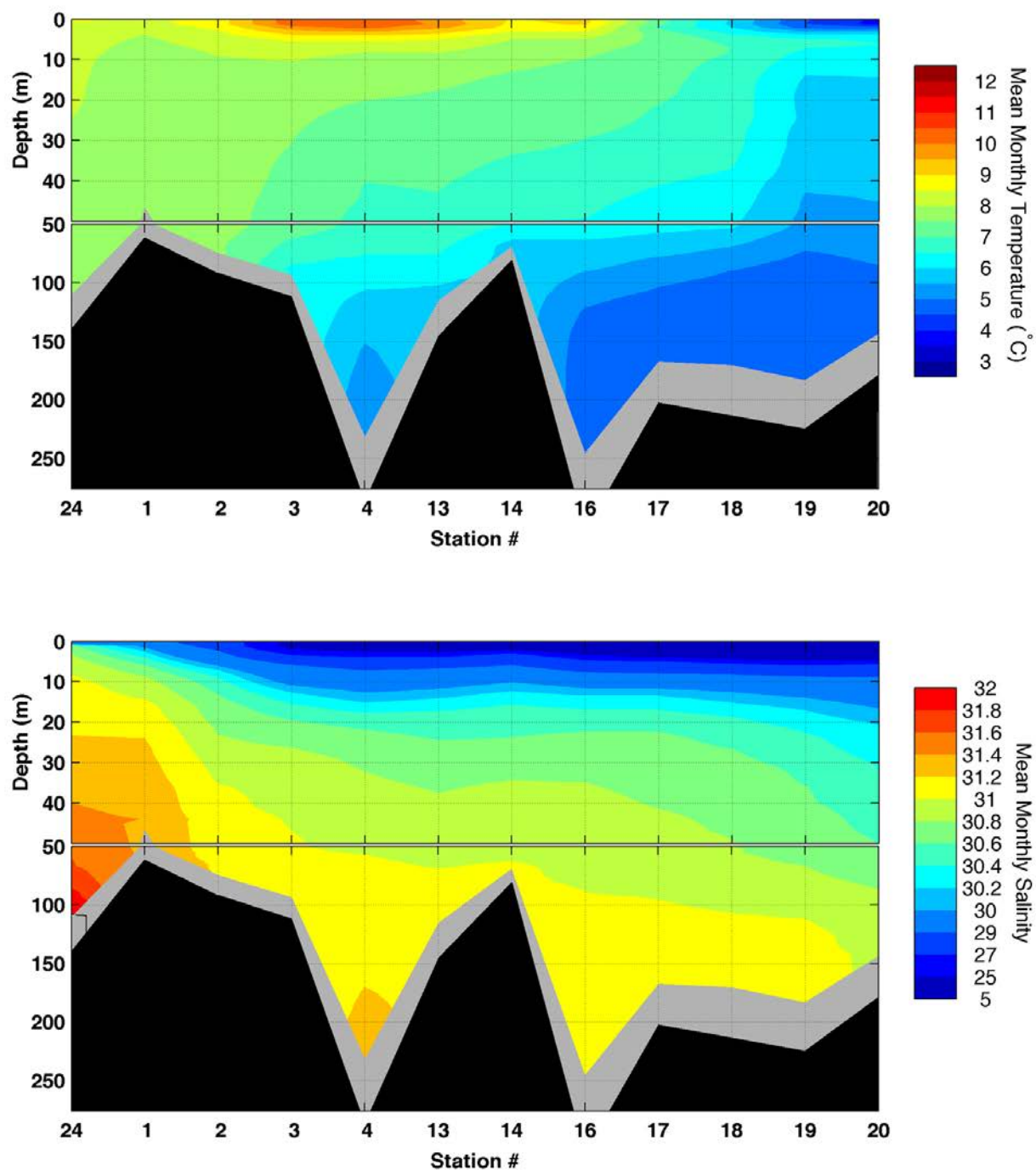


Figure C7. July climatological cross-sections of temperature (A) and salinity (B) using the 1993-2016 period of record data in Muir Inlet (East Arm).

East Arm Transect: August

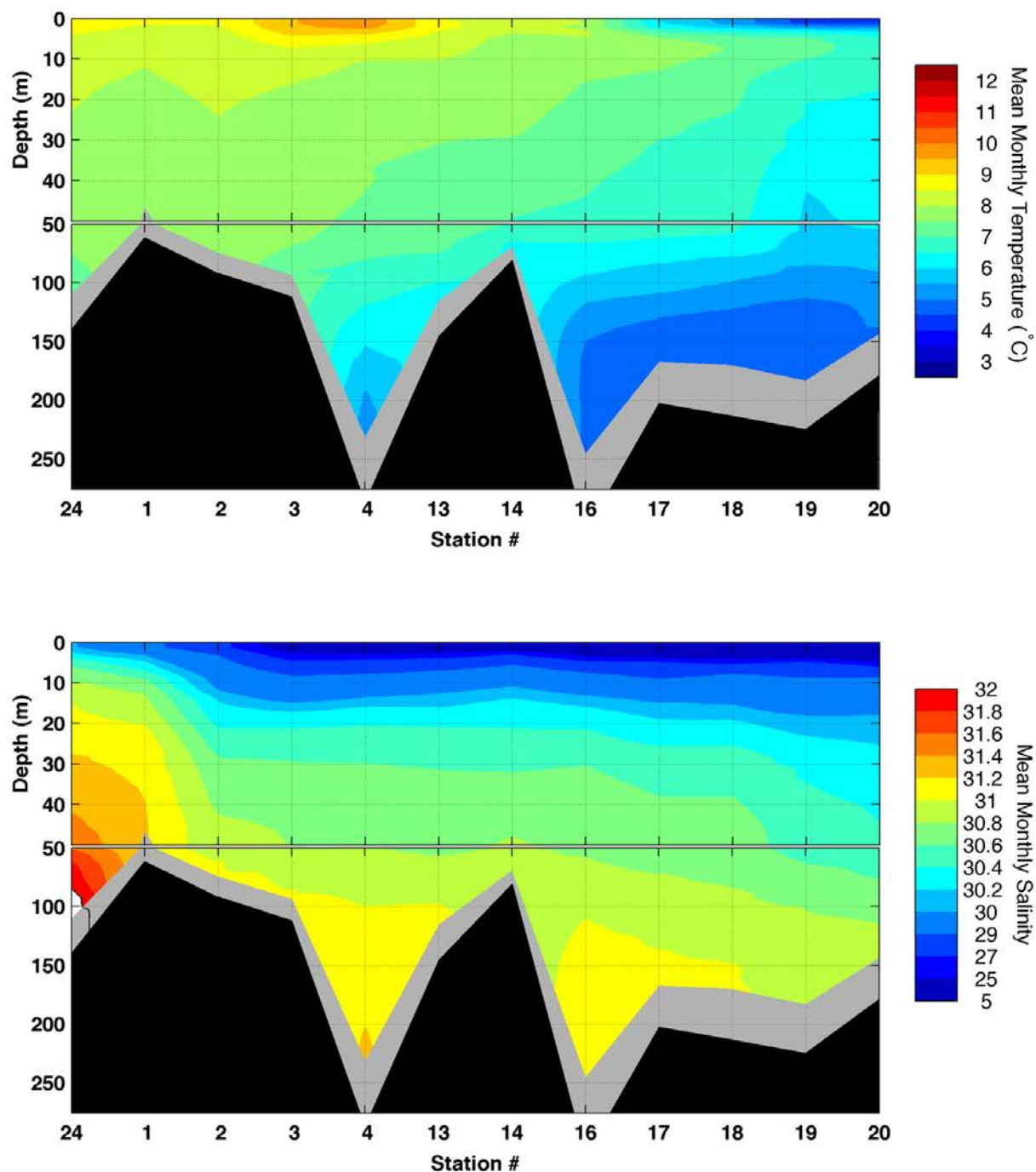


Figure C8. August climatological cross-sections of temperature (A) and salinity (B) using the 1993-2016 period of record data in Muir Inlet (East Arm).

East Arm Transect: September

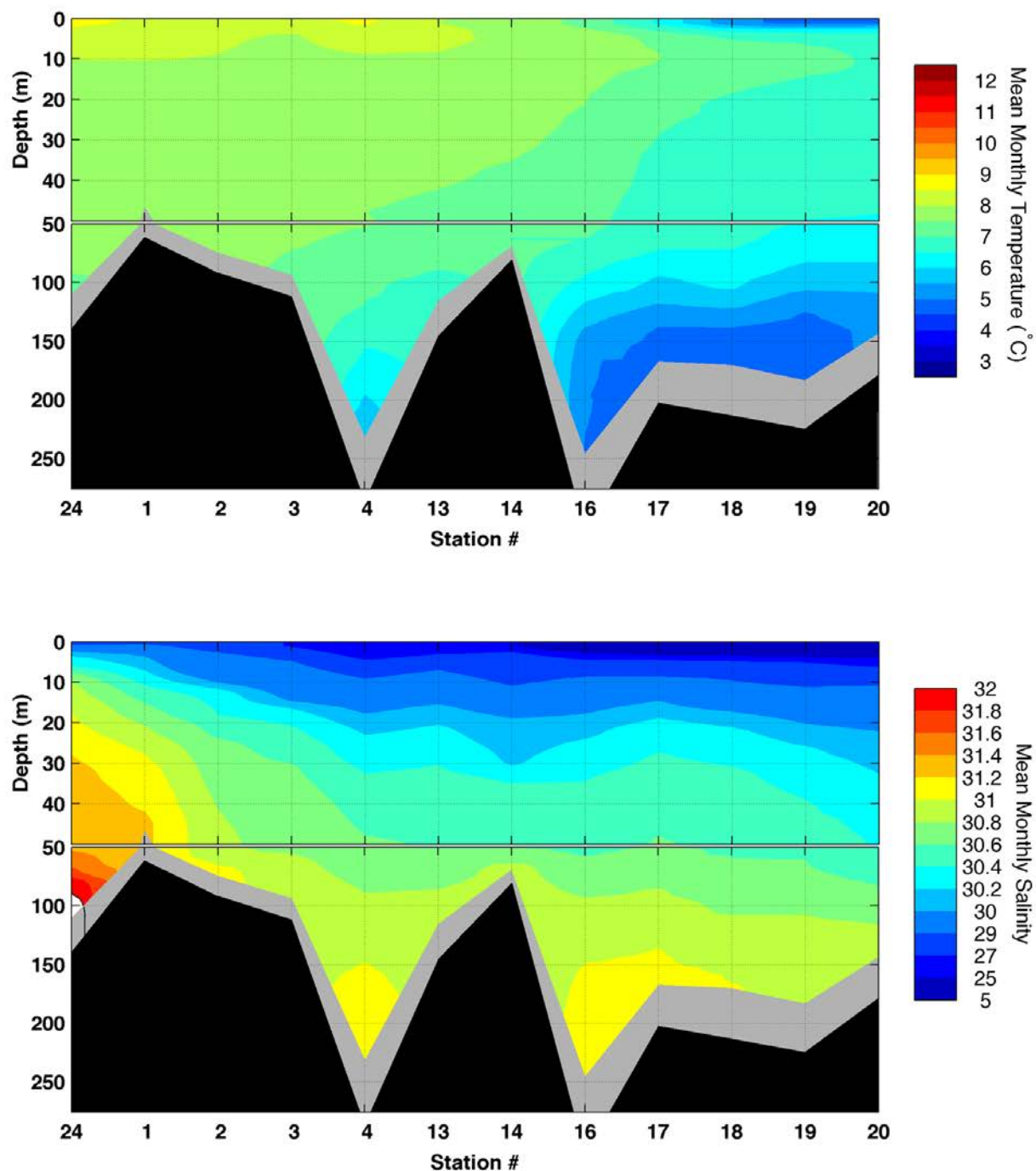


Figure C9. September climatological cross-sections of temperature (A) and salinity (B) using the 1993-2016 period of record data in Muir Inlet (East Arm).

East Arm Transect: October

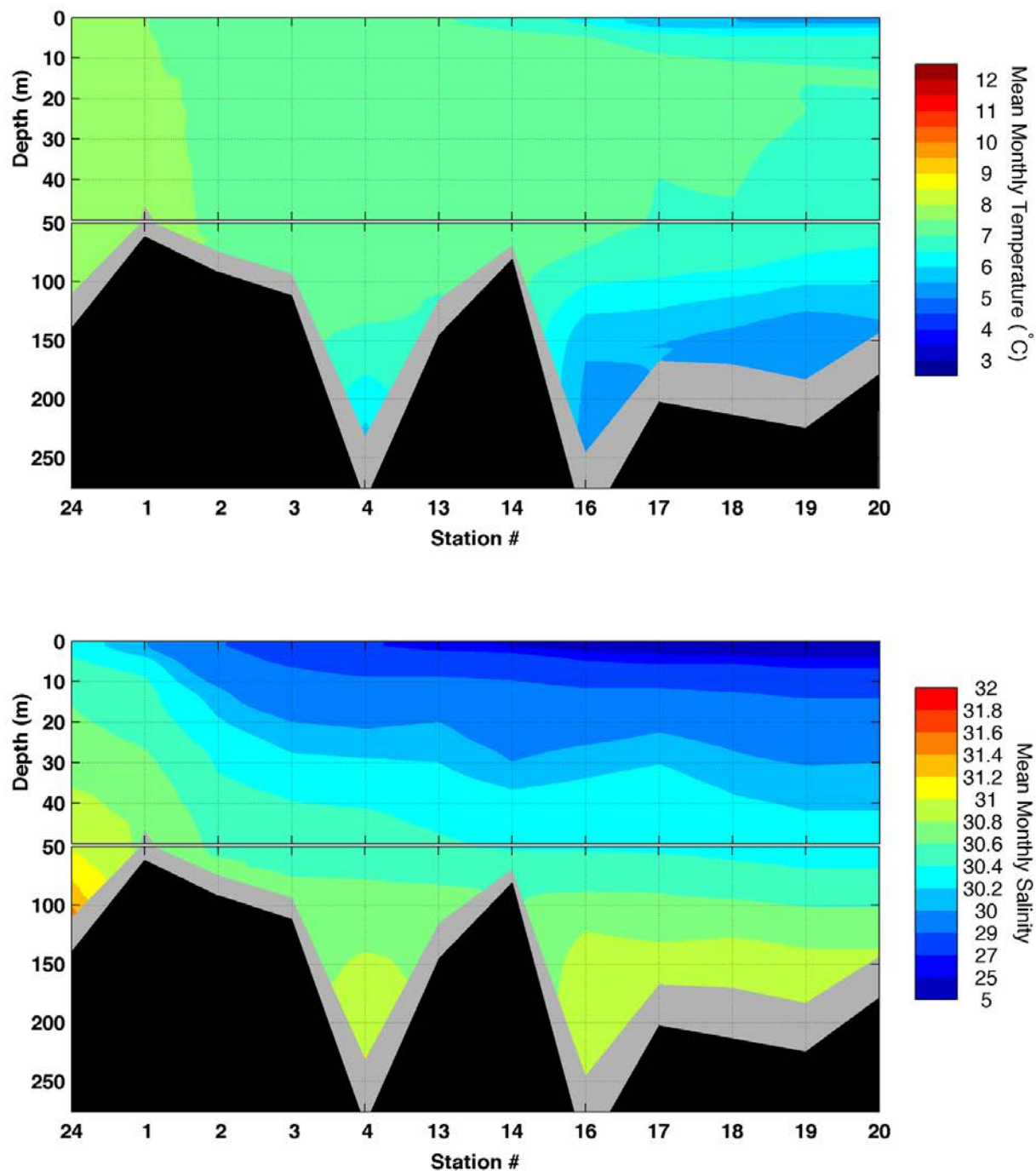


Figure C10. October climatological cross-sections of temperature (A) and salinity (B) using the 1993-2016 period of record data in Muir Inlet (East Arm).

East Arm Transect: November

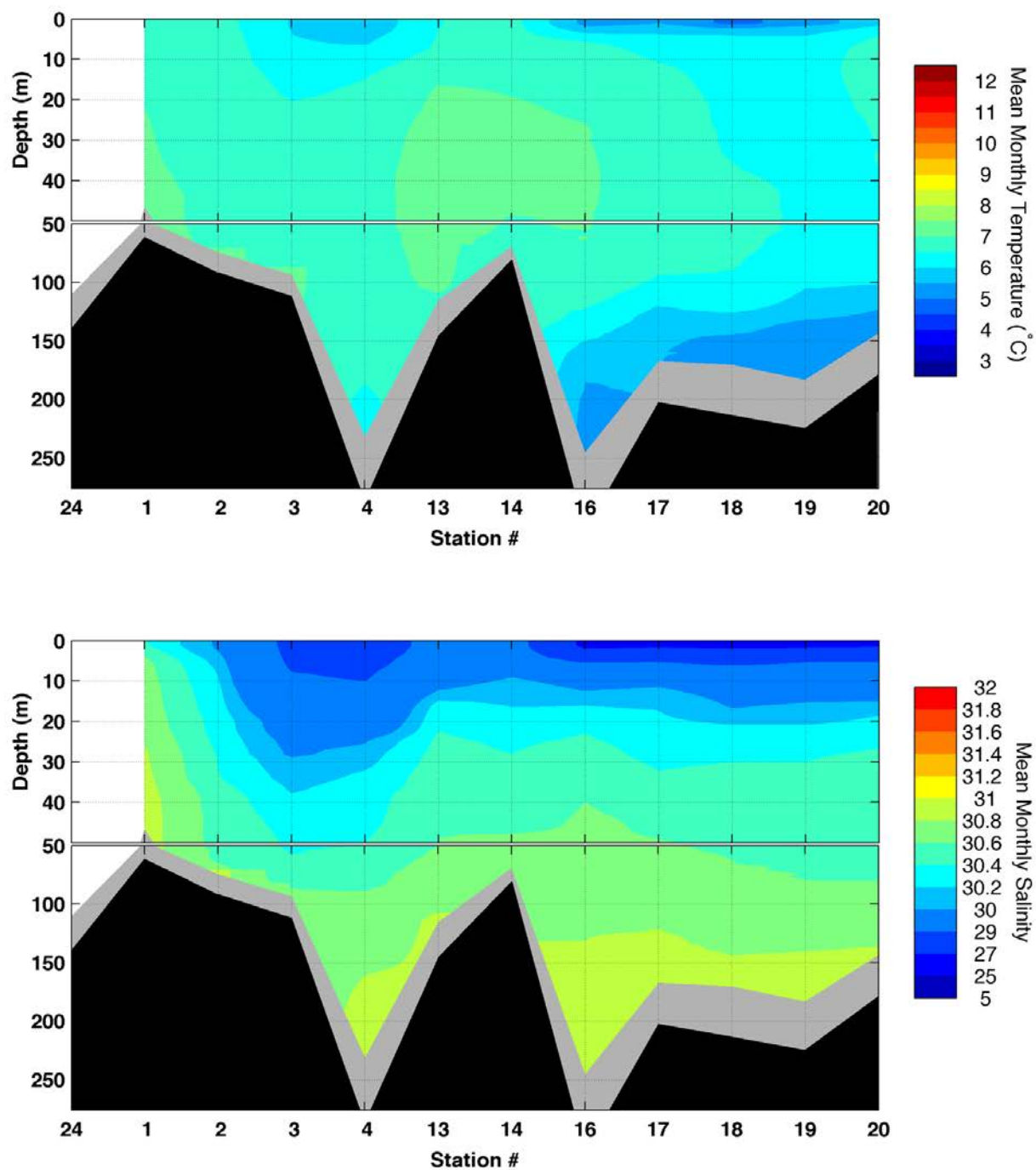


Figure C11. November climatological cross-sections of temperature (A) and salinity (B) using the 1993-2016 period of record data in Muir Inlet (East Arm).

East Arm Transect: December

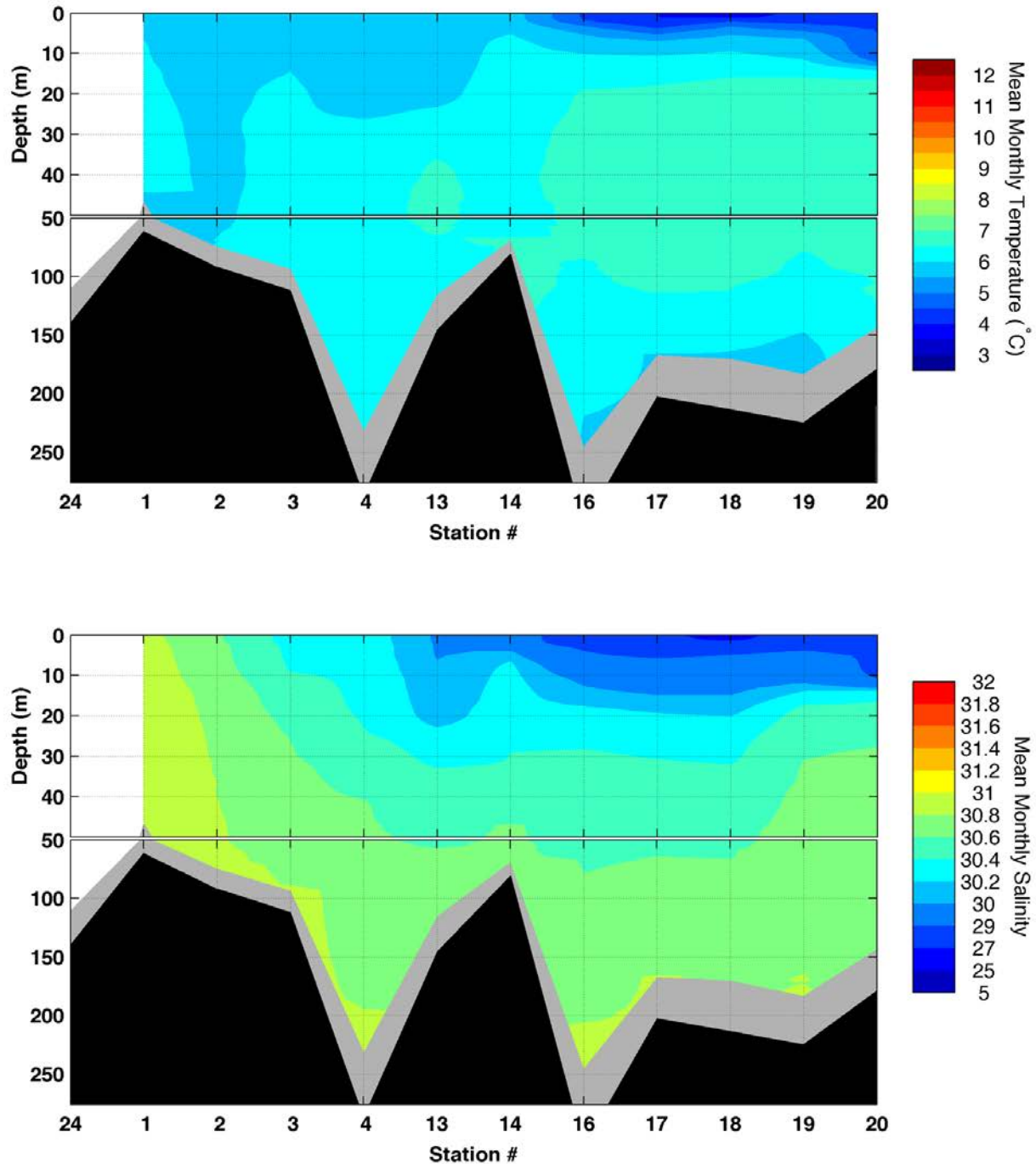


Figure C12. December climatological cross-sections of temperature (A) and salinity (B) using the 1993-2016 period of record data in Muir Inlet (East Arm).

West Arm Transect: January

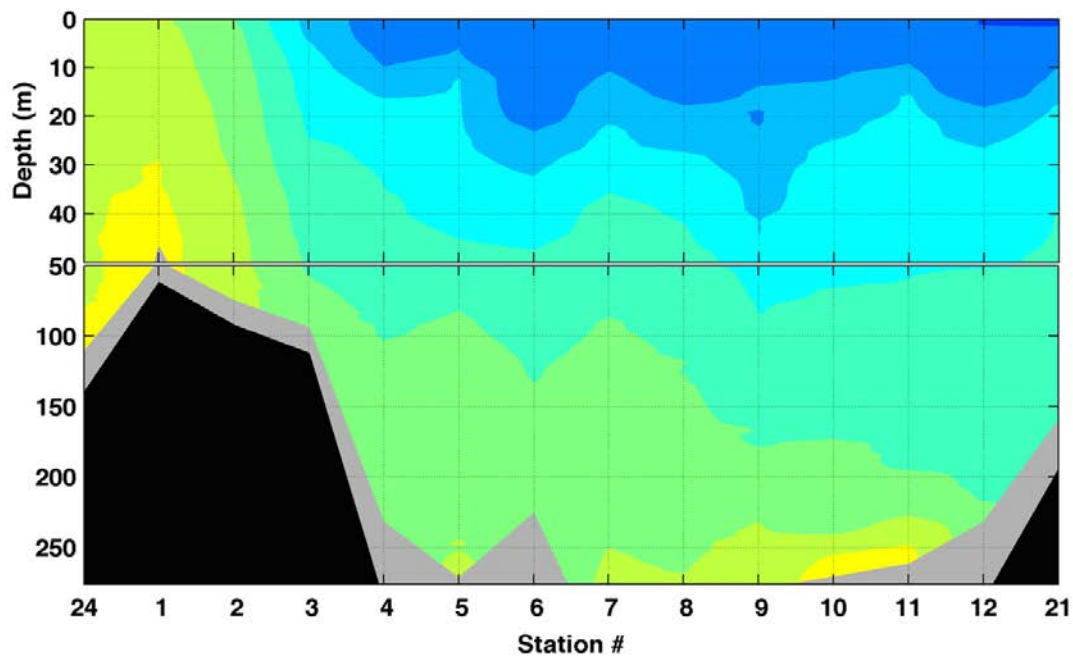
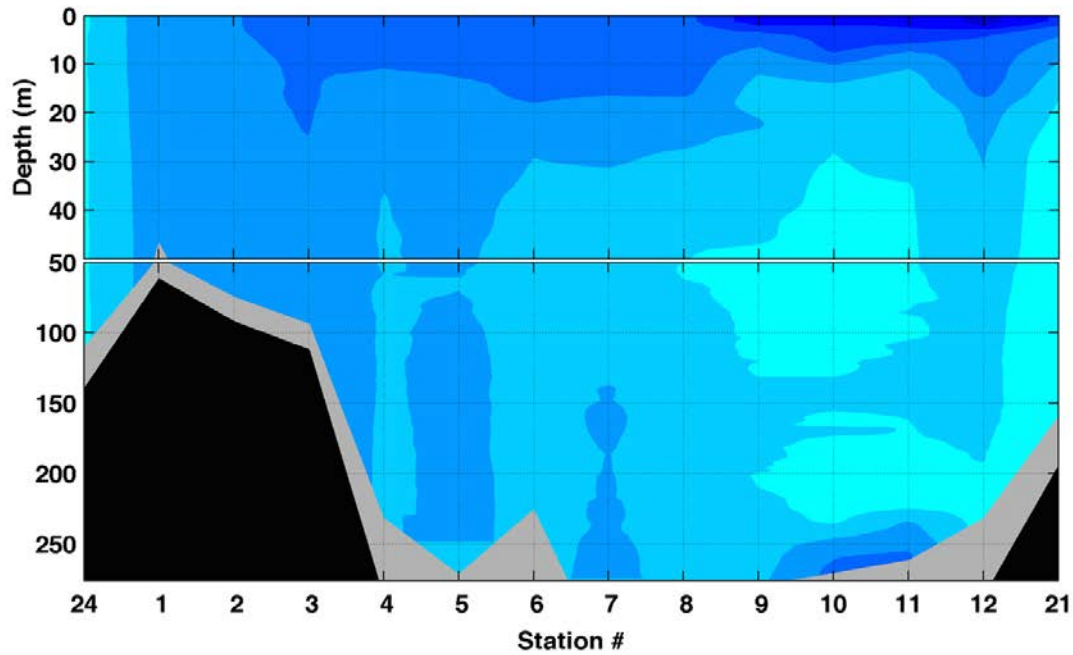


Figure C13. January climatological cross-sections of temperature (A) and salinity (B) using the 1993-2016 period of record data from Icy Strait up into Tarr I.

West Arm Transect: February

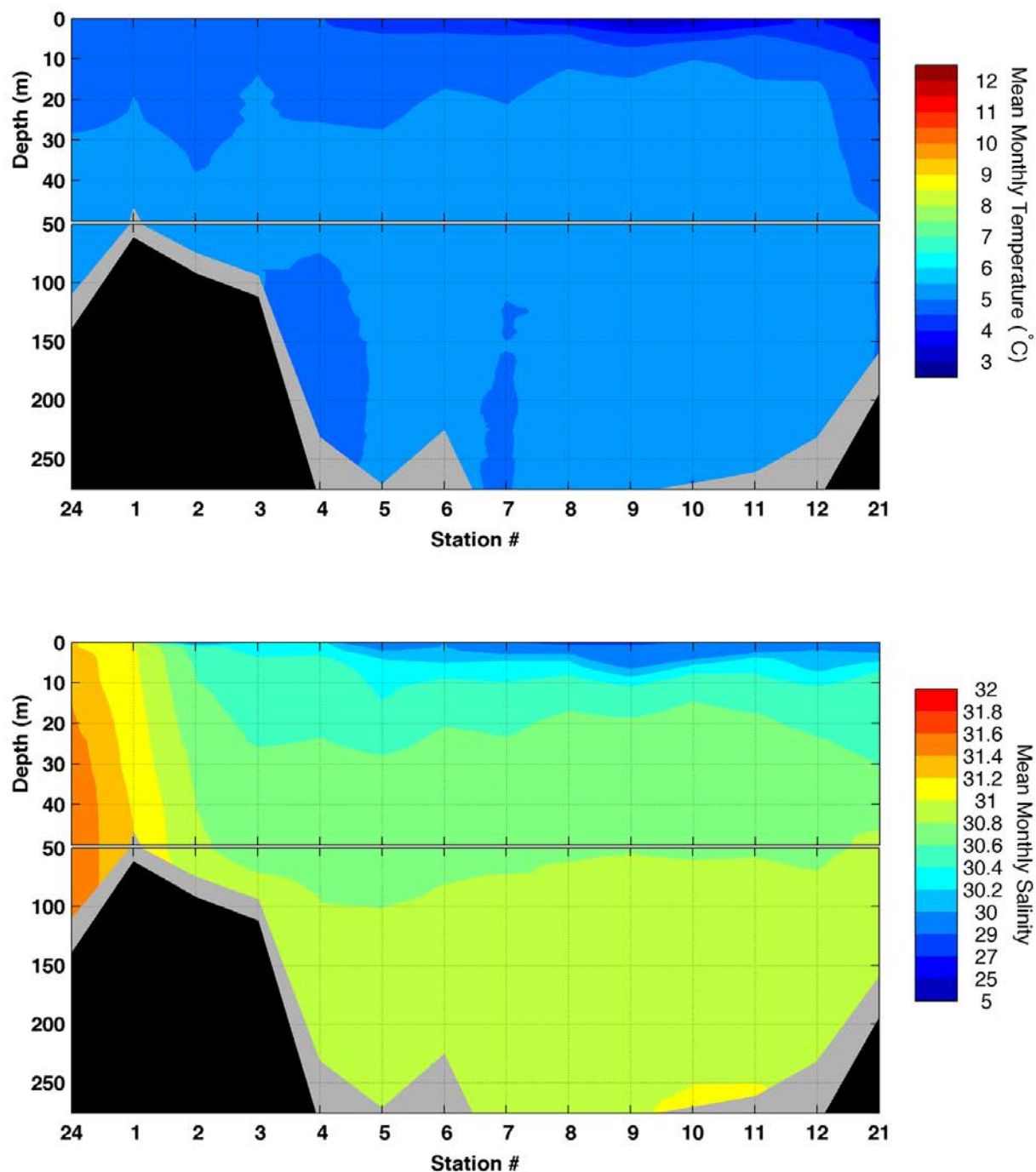


Figure C14. February climatological cross-sections of temperature (A) and salinity (B) using the 1993-2016 period of record data from Icy Strait up into Tarr I.

West Arm Transect: March

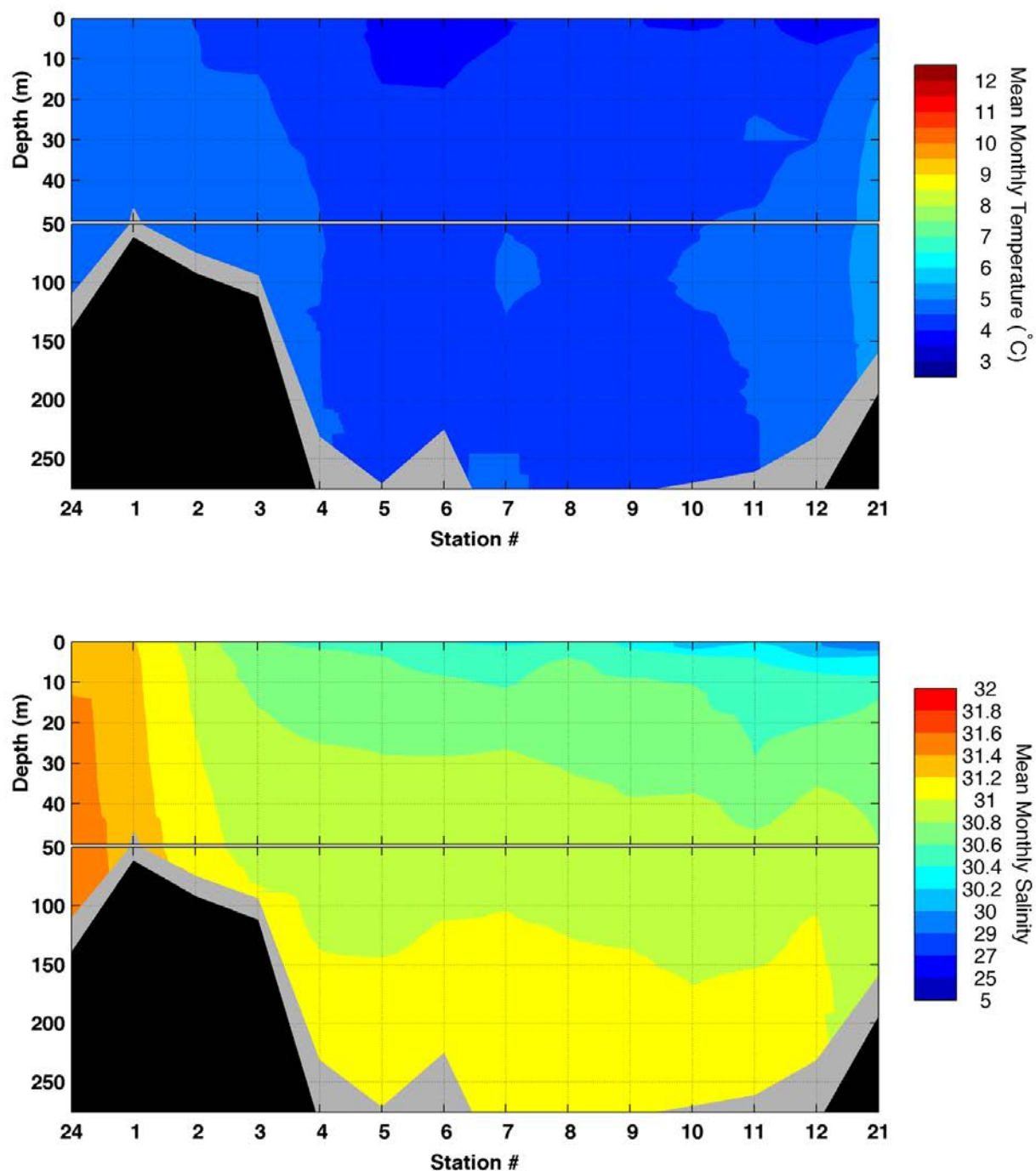


Figure C15. March climatological cross-sections of temperature (A) and salinity (B) using the 1993-2016 period of record data from Icy Strait up into Tarr I.

West Arm Transect: April

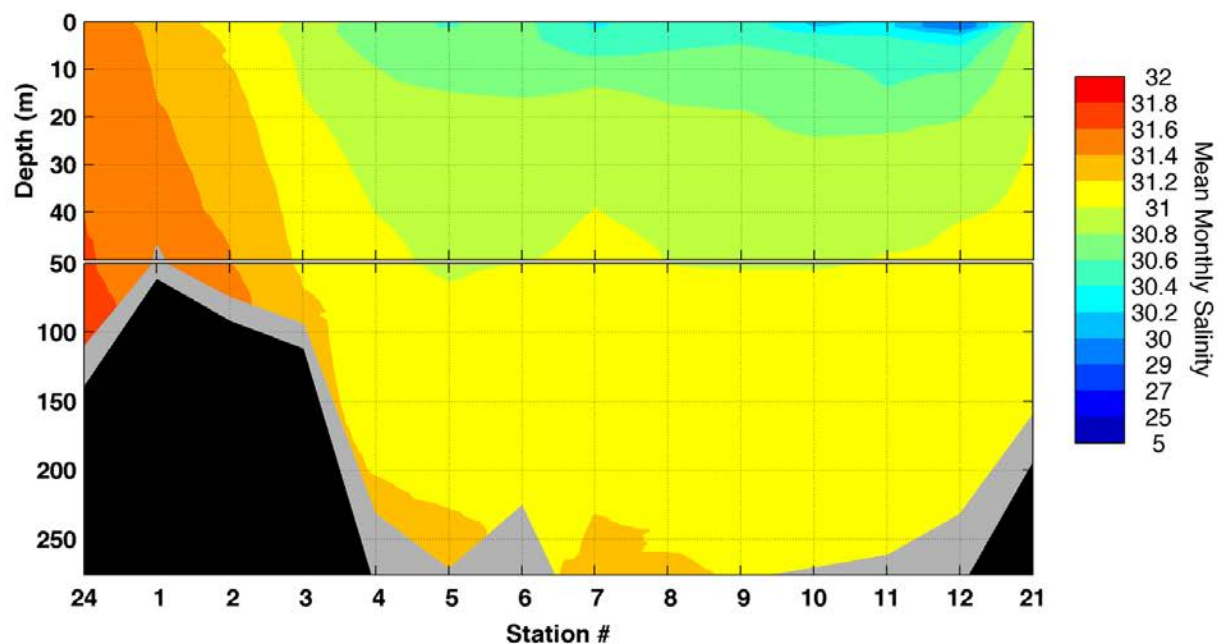
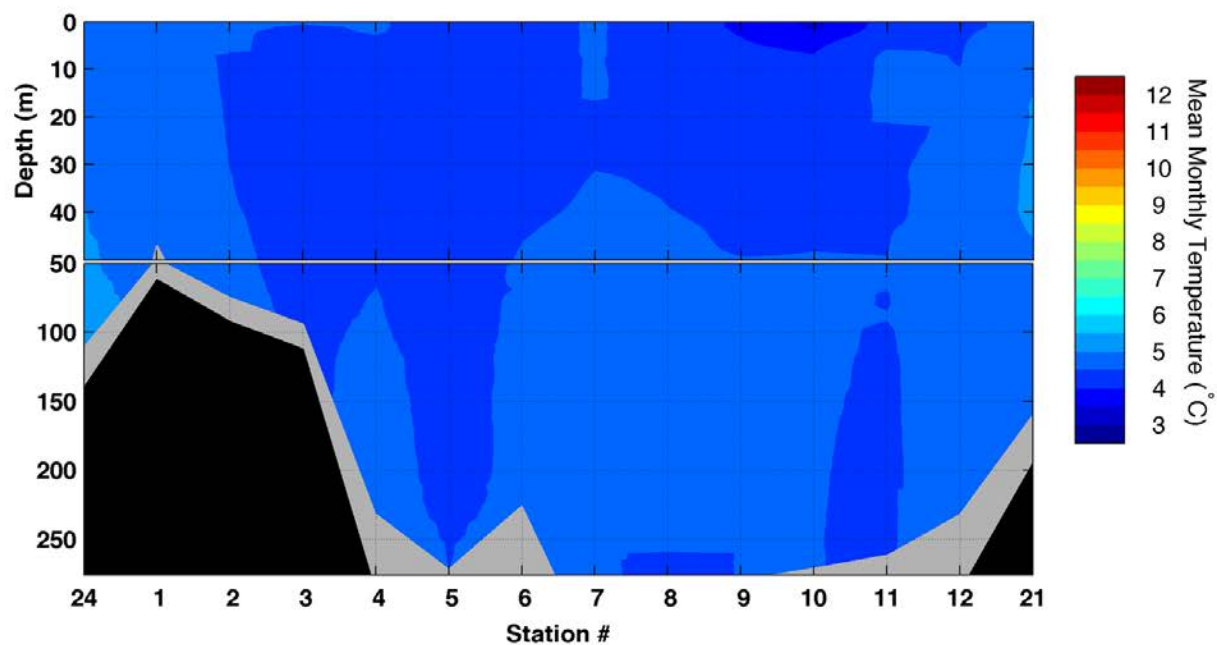


Figure C16. April climatological cross-sections of temperature (A) and salinity (B) using the 1993-2016 period of record data from Icy Strait up into Tarr I.

West Arm Transect: May

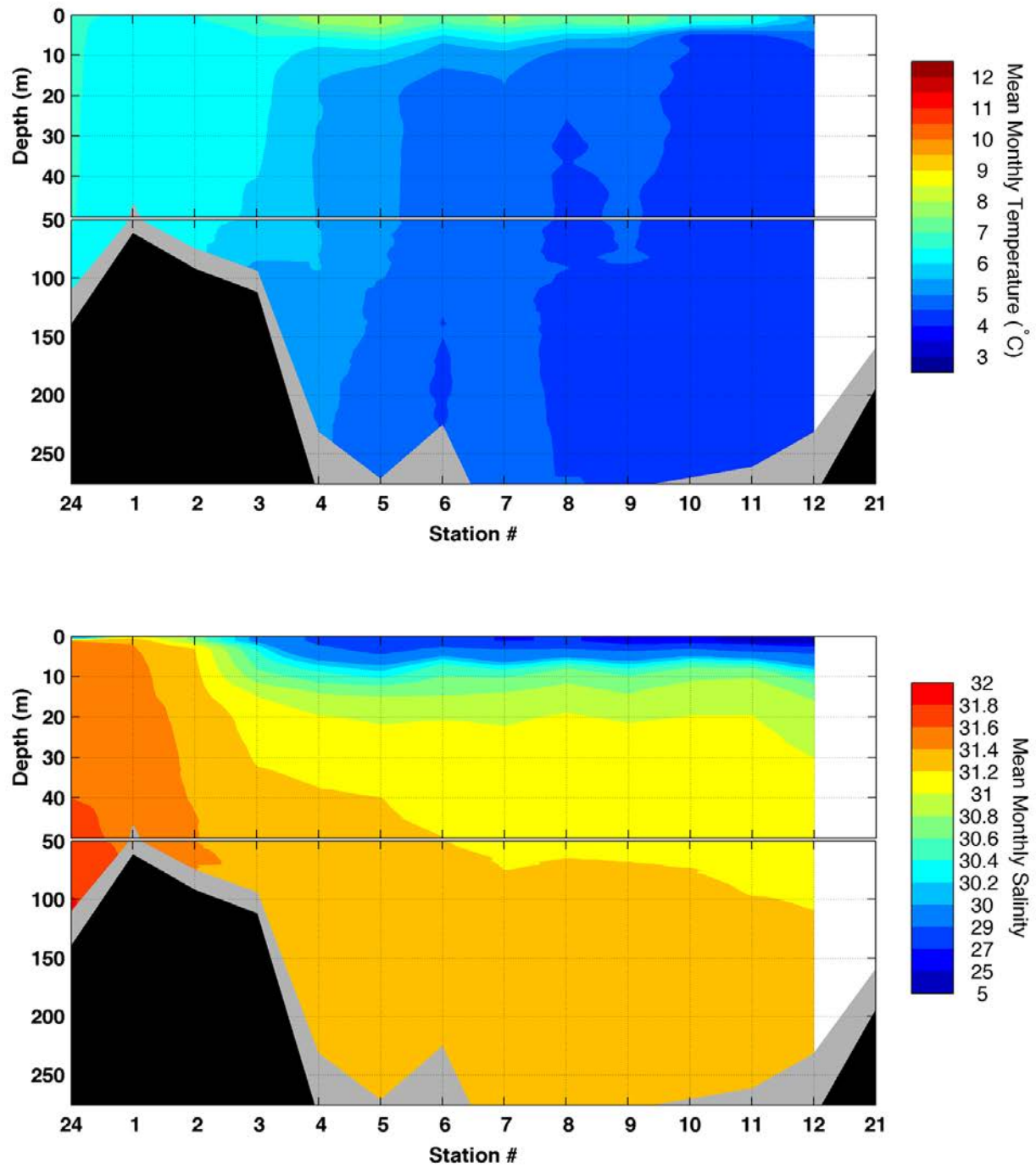


Figure C17. May climatological cross-sections of temperature (A) and salinity (B) using the 1993-2016 period of record data from Icy Strait up into Tarr I.

West Arm Transect: June

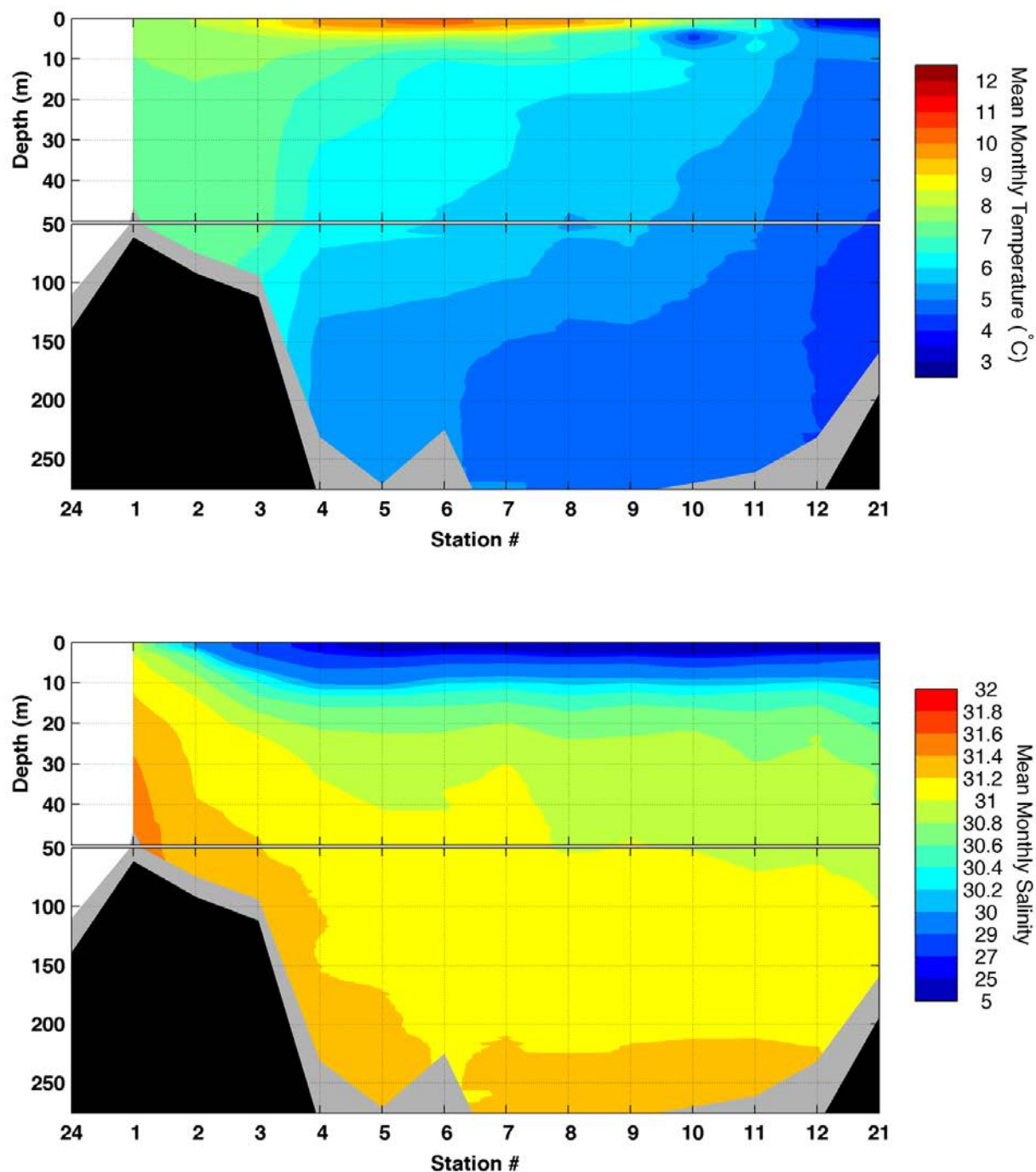


Figure C18. June climatological cross-sections of temperature (A) and salinity (B) using the 1993-2016 period of record data from Icy Strait up into Tarr I.

West Arm Transect: July

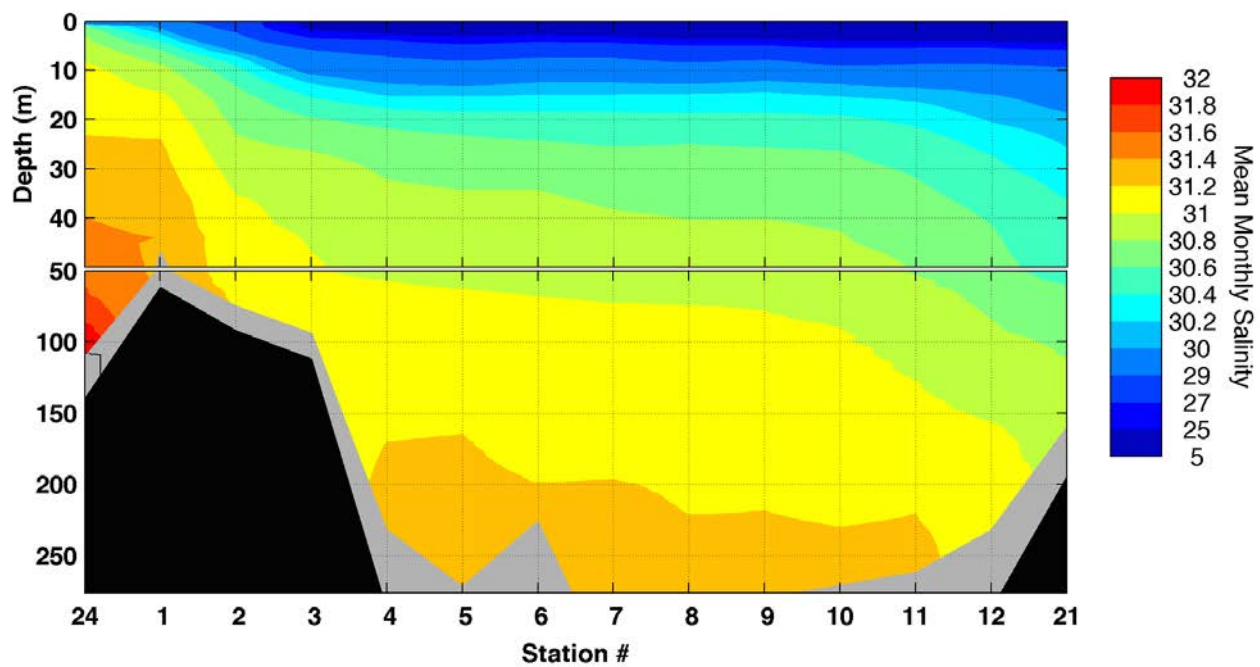
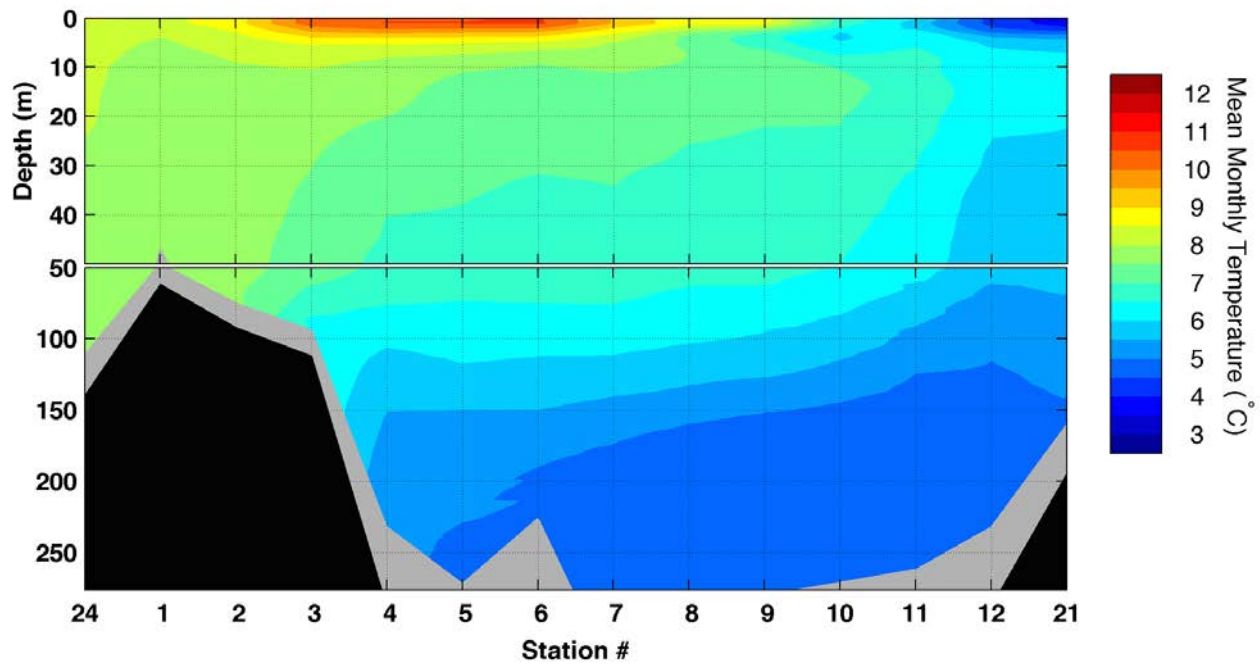


Figure C19. July climatological cross-sections of temperature (A) and salinity (B) using the 1993-2016 period of record data from Icy Strait up into Tarr I.

West Arm Transect: August

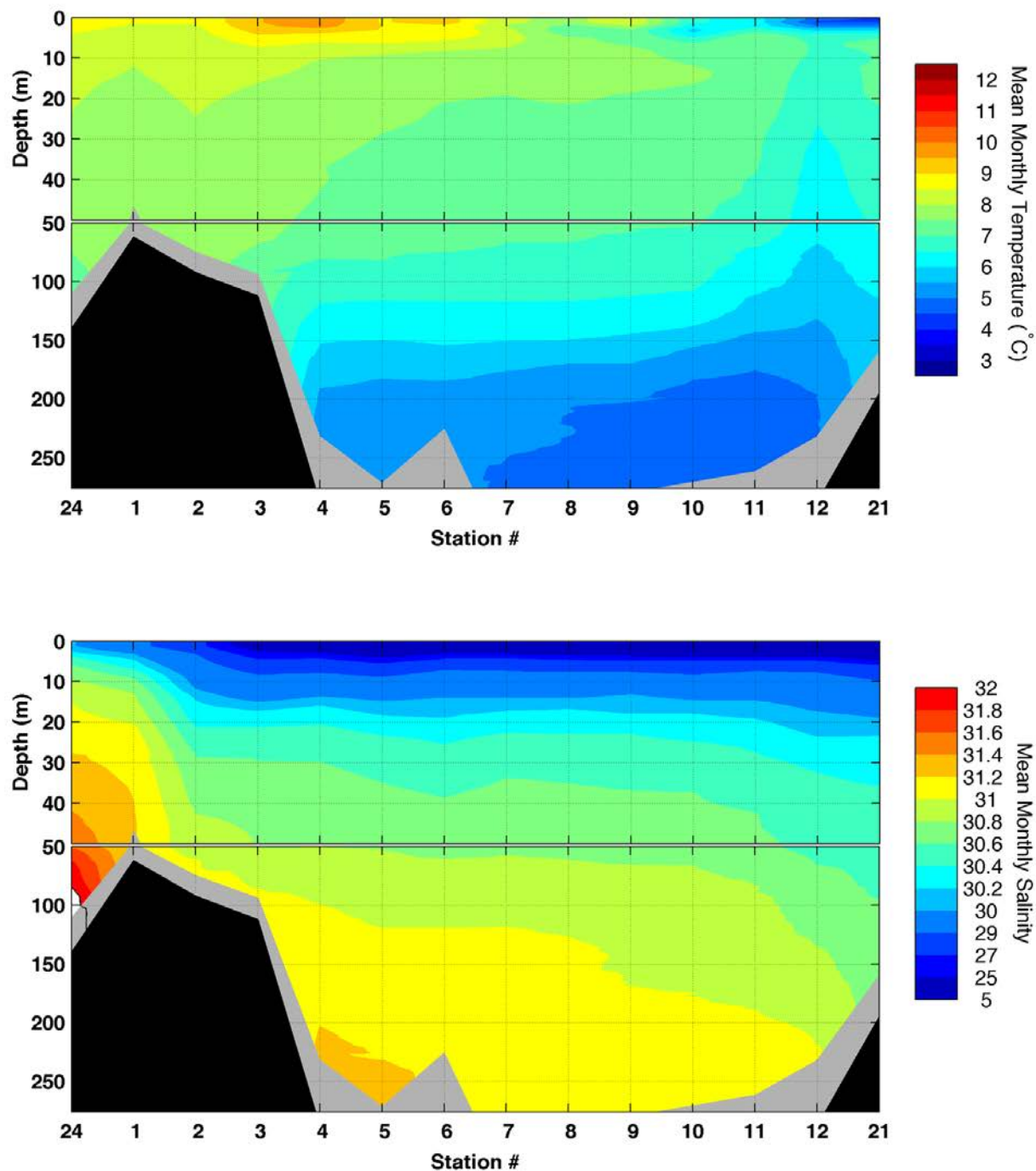


Figure C20. August climatological cross-sections of temperature (A) and salinity (B) using the 1993-2016 period of record data from Icy Strait up into Tarr I.

West Arm Transect: September

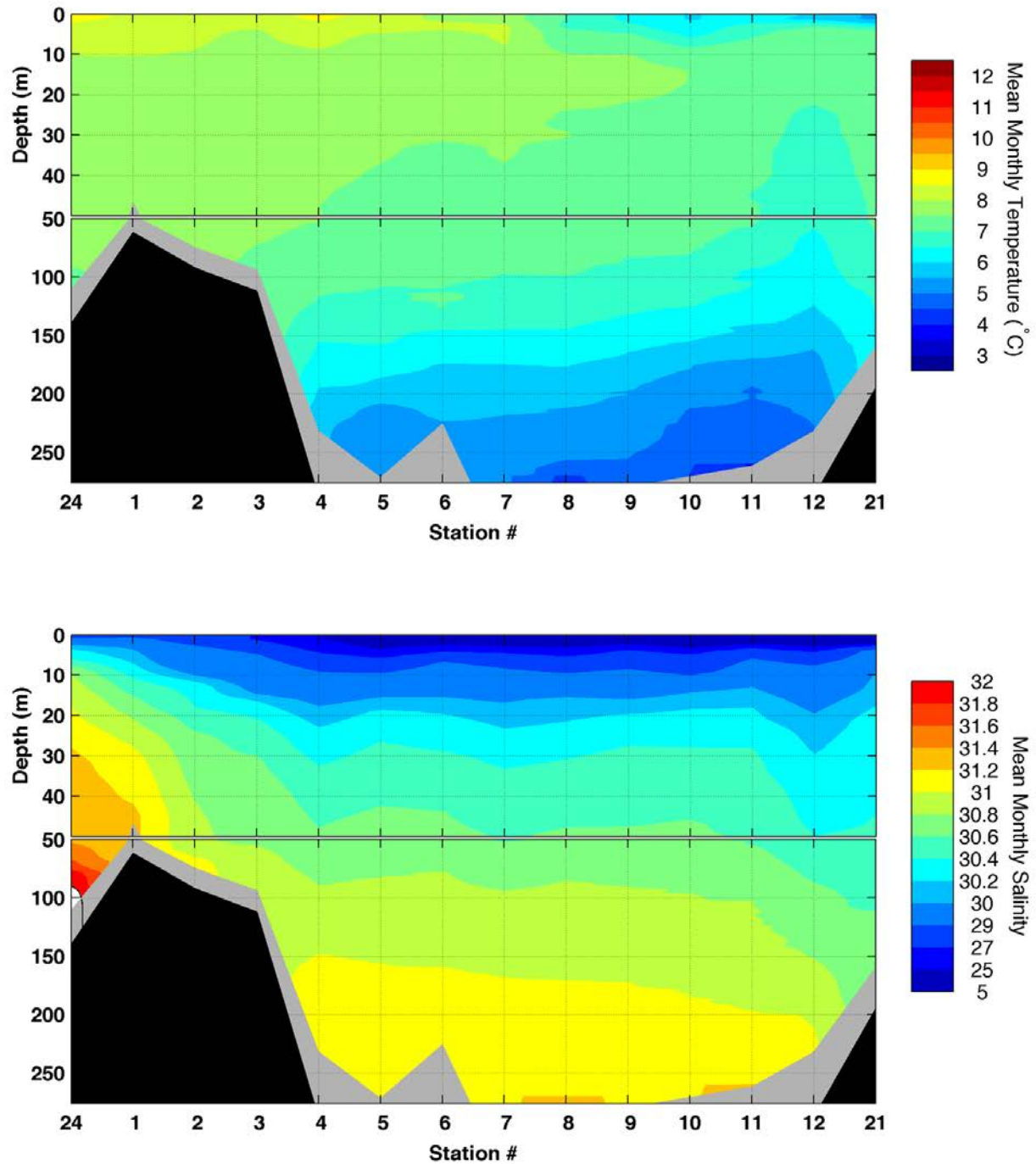


Figure C21. September climatological cross-sections of temperature (A) and salinity (B) using the 1993-2016 period of record data from Icy Strait up into Tarr I.

West Arm Transect: October

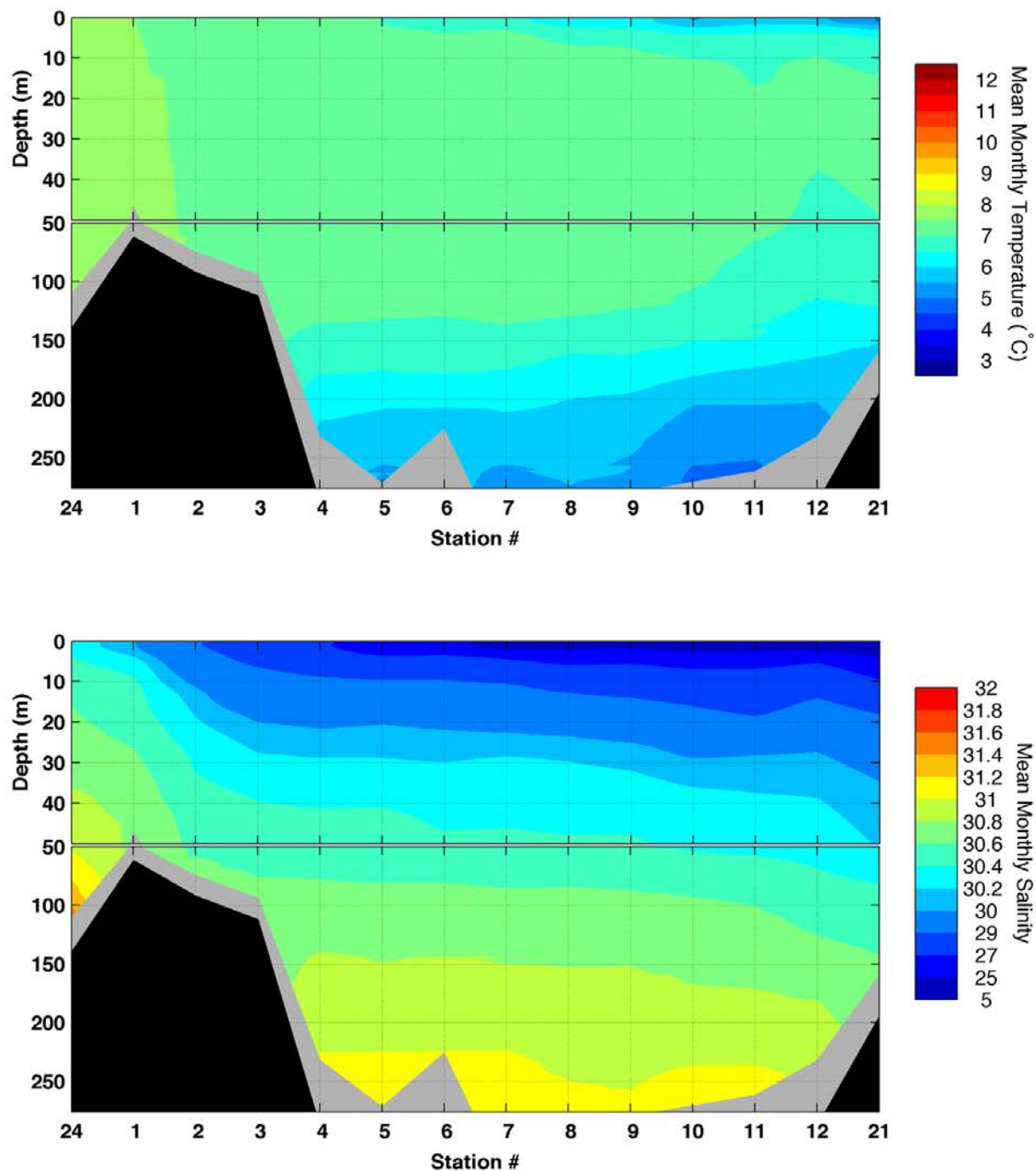


Figure C22. October climatological cross-sections of temperature (A) and salinity (B) using the 1993-2016 period of record data from Icy Strait up into Tarr I.

West Arm Transect: November

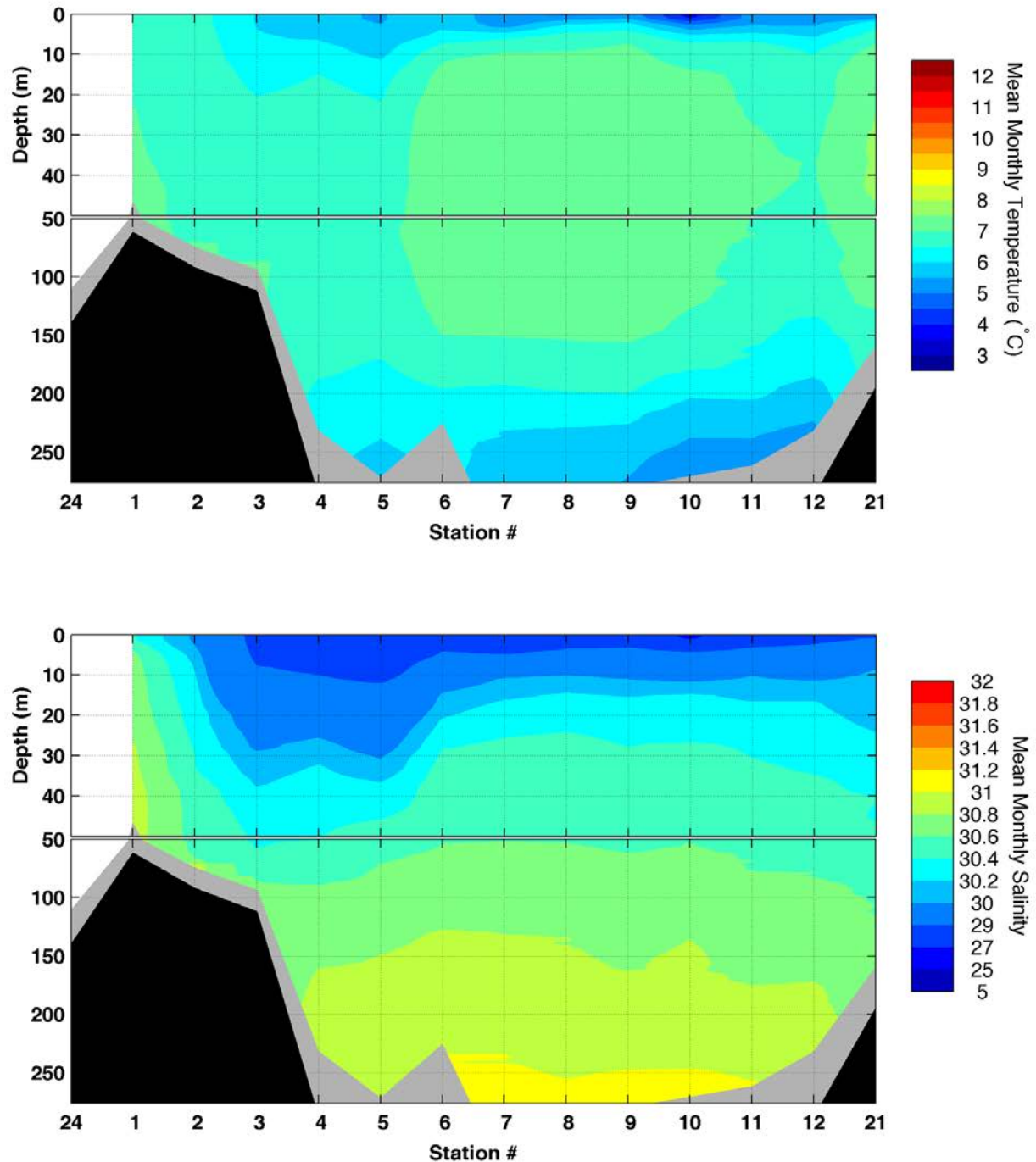


Figure C23. November climatological cross-sections of temperature (A) and salinity (B) using the 1993-2016 period of record data from Icy Strait up into Tarr I.

West Arm Transect: December

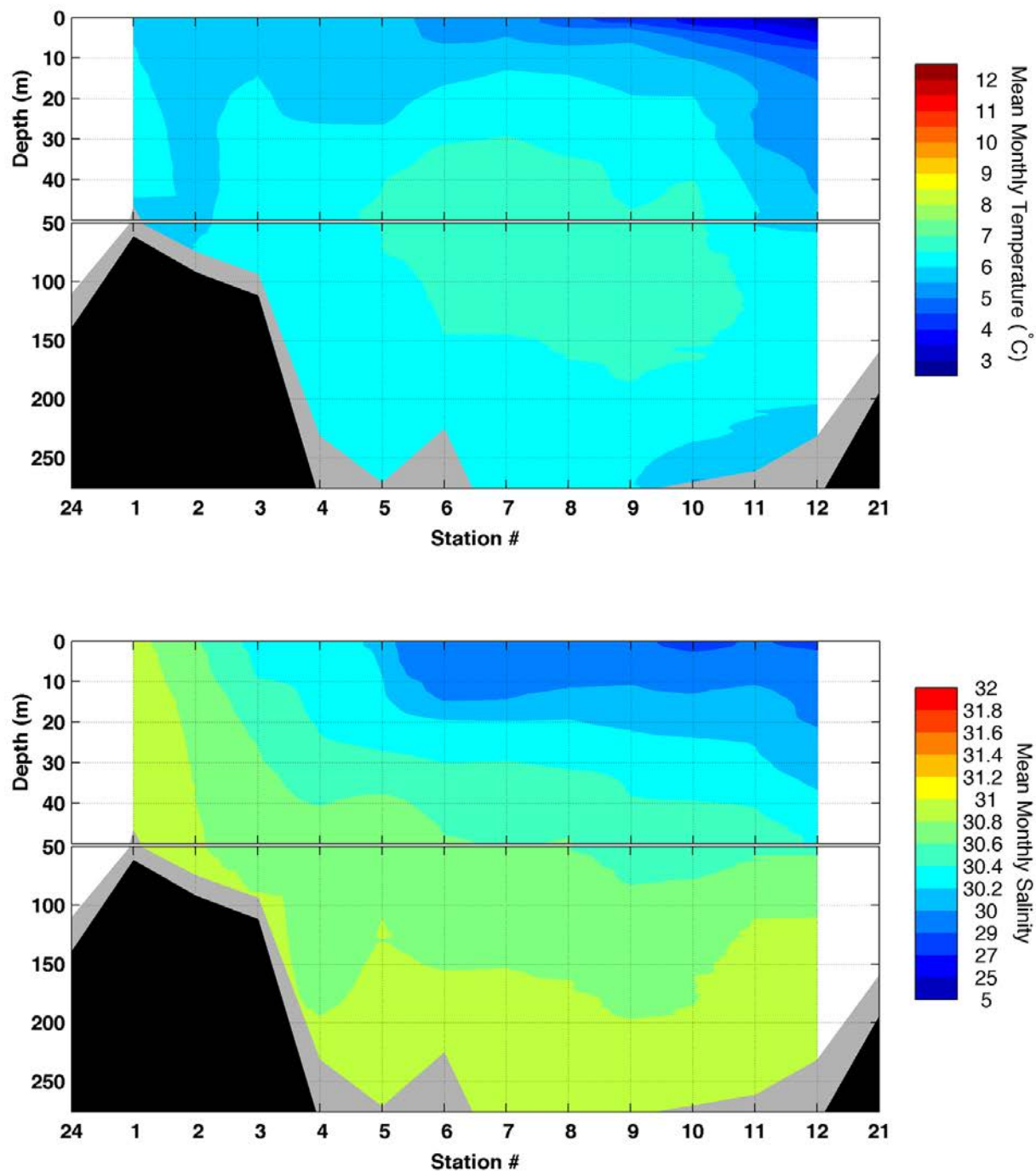


Figure C24. December climatological cross-sections of temperature (A) and salinity (B) using the 1993-2016 period of record data from Icy Strait up into Tarr I.

Appendix D: Current Meter Mooring Tidal Analyses

Tables D1 - D9 show the results of current meter mooring harmonic analyses for the 35 resolved tidal constituents.

Notes

- Asterisks (*) denote constituents that are resolved with a 2:1 signal to noise ratio or better.
- All records are sampled at 6 minute intervals.
- Greenwich phase computed with nodal corrections applied to amplitude and phase relative to center time.
- Rayleigh criterion for all computations is set to 1.0.
- Dominant constituent M2 is highlighted with bold type.

Abbreviations and Units

- emaj, emin, einc, epha = 95% error estimates for the major, minor, inclination and phase parameters
- freq = frequency (hr⁻¹)
- inc = tidal ellipse inclination (°T)
- major = tidal ellipse semi-major axis (cm s⁻¹)
- minor = tidal ellipse semi-minor axis (cm s⁻¹)
- nob = number of observations
- ngood = number of good observations
- pha = Greenwich phase (°)
- pred = predicted
- snr = signal to noise ratio
- tide = Tidal constituent name
- var, var(xp), var(xres) = variance, variance explained, variance residual

Table D1. Tidal current harmonic parameters computed from mooring site SEA0845. Abbreviations: major = Semi-major axis (cm/s), minor = Semi-minor axis (cm/s), inc = Inclination (degrees True); pha = Greenwich Phase (degrees); e denotes error estimate for each parameter.

nobs = 9116, ngood = 9115, record length (days) = 37.98

start time: 05-Aug-2008 21:54:00

x0= 9.25, x trend= 0

var(x)= 2388.4648 var(xp)= 2104.4461 var(xres)= 286.8893

percent var predicted/var original= 88.1 %

y0= 1.69, x trend= 0

var(y)= 1110.3218 var(yp)= 754.5712 var(yres)= 392.286

percent var predicted/var original= 68.0 %

tide	freq	major	emaj	minor	emin	inc	einc	pha	epha	snr
*MM	0.0015122	3.618	0.457	0.038	0.61	34.93	10.19	31.90	6.19	63
*MSF	0.0028219	16.566	0.468	0.770	0.62	38.78	1.86	43.61	1.83	1.3e+03
ALP1	0.0343966	1.657	1.332	0.221	1.36	109.11	67.25	331.87	54.27	1.5
*2Q1	0.0357064	3.341	1.381	0.100	1.46	57.89	25.53	194.10	23.03	5.9
Q1	0.0372185	1.427	1.126	-0.088	1.17	57.54	66.20	5.90	61.32	1.6
*O1	0.0387307	3.132	1.313	-0.175	1.31	17.93	28.94	96.90	27.69	5.7
NO1	0.0402686	1.257	2.019	0.377	2.24	59.55	122.92	310.81	31.01	0.39
*K1	0.0417807	6.213	1.414	0.192	1.59	35.83	14.72	143.63	13.59	19
J1	0.0432929	0.873	1.095	0.189	0.88	30.28	84.26	80.74	103.51	0.64
*OO1	0.0448308	2.458	1.174	0.044	1.30	54.33	32.04	30.59	25.93	4.4
UPS1	0.0463430	0.868	0.908	0.480	0.84	91.90	98.66	42.94	101.15	0.91
EPS2	0.0761773	2.671	2.911	-0.049	3.35	87.63	109.02	1.66	93.85	0.84
*MU2	0.0776895	14.912	4.247	1.993	4.21	39.15	16.30	14.50	13.68	12
*N2	0.0789992	12.684	4.133	-1.179	4.15	31.47	18.89	114.16	19.17	9.4
*M2	0.0805114	65.683	4.691	2.431	4.05	25.44	3.42	165.70	3.65	2e+02
L2	0.0820236	1.384	2.330	0.494	2.23	43.54	114.98	304.15	148.49	0.35
*S2	0.0833333	26.322	4.126	-1.554	4.29	29.62	9.22	185.10	8.63	41
ETA2	0.0850736	1.993	1.968	0.853	2.16	59.34	85.88	58.70	87.12	1
*MO3	0.1192421	3.666	2.260	0.627	1.81	44.86	35.82	110.50	35.02	2.6
M3	0.1207671	0.676	1.842	-0.076	1.42	157.78	111.56	123.00	171.43	0.13
*MK3	0.1222921	4.483	2.016	0.450	2.10	46.45	29.51	145.59	24.86	4.9
*SK3	0.1251141	3.951	2.395	0.864	1.75	64.96	27.71	138.53	42.56	2.7
MN4	0.1595106	6.730	5.038	1.912	5.21	75.01	63.73	118.57	48.75	1.8
*M4	0.1610228	15.581	4.699	1.528	4.59	53.42	18.13	160.52	20.78	11
SN4	0.1623326	2.266	3.262	0.558	3.63	85.14	115.25	178.40	116.68	0.48
*MS4	0.1638447	14.109	5.135	3.493	4.43	59.28	20.90	180.77	19.97	7.6
S4	0.1666667	5.297	3.931	3.259	3.79	89.69	75.74	186.15	86.42	1.8
2MK5	0.2028035	2.340	2.513	0.586	2.37	68.28	62.44	215.57	90.90	0.87
2SK5	0.2084474	1.898	2.333	0.906	2.32	157.56	106.62	220.27	95.62	0.66
2MN6	0.2400221	4.819	4.281	1.898	4.20	20.01	64.28	53.77	76.48	1.3
*M6	0.2415342	6.893	4.097	4.777	4.22	163.25	78.55	246.11	98.20	2.8
*2MS6	0.2443561	8.315	3.648	6.860	3.91	32.77	94.82	161.17	96.24	5.2
*2SM6	0.2471781	6.669	4.260	3.198	4.52	37.95	57.04	171.18	60.42	2.5
3MK7	0.2833149	1.167	1.446	0.284	1.56	89.19	90.41	275.37	126.10	0.65
*M8	0.3220456	3.487	2.364	1.379	2.53	57.68	52.11	141.17	55.63	2.2

total var= 3498.7866 pred var= 2859.0173; percent total var predicted/var original= 81.7%

Table D2. Tidal current harmonic parameters computed from mooring site SEA0846. Abbreviations: major = Semi-major axis (cm/s), minor = Semi-minor axis (cm/s), inc = Inclination (degrees True); pha = Greenwich Phase (degrees); e denotes error estimate for each parameter.

nobs = 9125, ngood = 9125, record length (days) = 38.02

start time: 05-Aug-2008 23:00:00

x0= 19.3, x trend= 0

var(x)= 382.1085 var(xp)= 285.0538 var(xres)= 102.2287

percent var predicted/var original= 74.6 %

y0= 29.4, x trend= 0

var(y)= 4362.0603 var(yp)= 4245.7257 var(yres)= 114.6847

percent var predicted/var original= 97.3 %

tide	freq	major	emaj	minor	emin	inc	einc	pha	epha	snr
*MM	0.0015122	6.321	0.206	1.488	0.27	56.83	3.13	38.45	1.96	9.4e+02
*MSF	0.0028219	18.123	0.173	0.351	0.27	61.03	0.95	45.15	0.61	1.1e+04
*ALP1	0.0343966	1.196	0.447	-0.002	0.48	70.38	20.46	156.81	22.50	7.1
*2Q1	0.0357064	1.663	0.441	0.666	0.39	44.41	16.44	80.98	20.00	14
*Q1	0.0372185	0.666	0.452	0.280	0.44	1.93	54.20	336.95	49.72	2.2
*O1	0.0387307	6.120	0.510	3.518	0.50	90.42	6.97	129.92	7.56	1.4e+02
*NO1	0.0402686	2.784	0.989	0.479	0.97	78.03	19.30	332.33	20.21	7.9
*K1	0.0417807	10.364	0.451	4.946	0.48	93.17	4.08	168.60	4.15	5.3e+02
*J1	0.0432929	1.129	0.437	-0.002	0.46	48.22	20.31	67.30	23.81	6.7
*OO1	0.0448308	1.918	0.414	0.817	0.38	36.08	15.87	18.72	14.16	21
*UPS1	0.0463430	0.819	0.303	0.722	0.28	99.97	108.63	80.02	107.85	7.3
EPS2	0.0761773	1.280	1.254	0.415	1.12	62.91	90.88	1.23	86.32	1
*MU2	0.0776895	5.717	2.189	1.300	1.69	22.49	20.11	29.92	19.86	6.8
*N2	0.0789992	14.641	1.831	3.985	2.13	87.87	8.86	169.98	7.25	64
*M2	0.0805114	88.697	1.836	16.162	1.93	85.21	1.36	212.63	1.19	2.3e+03
L2	0.0820236	0.985	1.104	-0.556	0.99	43.78	96.28	282.69	108.43	0.79
*S2	0.0833333	36.962	1.618	9.226	1.88	90.02	3.08	246.91	2.93	5.2e+02
ETA2	0.0850736	0.506	0.802	0.353	0.74	67.59	137.27	139.91	137.50	0.4
*MO3	0.1192421	3.811	1.706	0.776	1.49	70.99	26.39	166.67	26.51	5
M3	0.1207671	1.625	1.726	0.147	1.43	97.22	59.66	324.72	65.21	0.89
*MK3	0.1222921	2.417	1.506	0.549	1.73	47.52	49.07	153.96	47.08	2.6
SK3	0.1251141	1.314	1.266	0.351	1.35	51.14	77.39	159.59	94.64	1.1
*MN4	0.1595106	3.277	2.107	-0.644	1.09	82.78	21.22	85.78	41.00	2.4
*M4	0.1610228	7.756	2.408	-1.403	1.16	71.74	10.24	131.46	16.06	10
SN4	0.1623326	1.812	2.037	-0.274	1.03	83.32	27.97	119.65	78.55	0.79
*MS4	0.1638447	7.498	2.286	-1.457	1.10	78.02	9.25	163.16	20.09	11
*S4	0.1666667	2.969	1.899	0.353	1.26	66.10	26.30	197.05	42.59	2.4
2MK5	0.2028035	0.830	1.166	-0.286	0.93	66.71	57.40	289.10	134.42	0.51
2SK5	0.2084474	0.473	1.321	0.152	0.74	76.75	51.81	13.45	166.36	0.13
2MN6	0.2400221	1.120	1.597	0.846	1.43	45.53	118.77	80.31	120.77	0.49
*M6	0.2415342	2.604	1.653	1.513	1.64	163.54	71.39	258.26	62.34	2.5
*2MS6	0.2443561	3.910	1.697	2.577	2.08	176.23	61.44	311.43	57.47	5.3
2SM6	0.2471781	2.274	1.701	0.877	1.58	37.70	59.77	150.79	60.43	1.8
3MK7	0.2833149	0.687	0.923	0.241	0.78	84.25	82.66	337.01	117.11	0.55
*M8	0.3220456	2.487	1.368	0.621	1.41	44.35	33.79	298.75	40.44	3.3

total var= 4744.1687 pred var= 4530.7795; percent total var predicted/var original= 95.5 %

Table D3. Tidal current harmonic parameters computed from mooring site SEA0847. Abbreviations: major = Semi-major axis (cm/s), minor = Semi-minor axis (cm/s), inc = Inclination (degrees True); pha = Greenwich Phase (degrees); e denotes error estimate for each parameter.

nobs = 9026, ngood = 9025, record length (days) = 37.61
start time: 07-Aug-2008 01:18:00
x0= 8.8, x trend= 0
var(x)= 2810.6089 var(xp)= 2738.1178 var(xres)= 64.6957
percent var predicted/var original= 97.4 %
y0= -0.556, x trend= 0
var(y)= 18834.2085 var(yp)= 18595.2469 var(yres)= 123.9586
percent var predicted/var original= 98.7 %

tide	freq	major	emaj	minor	emin	inc	einc	pha	epha	snr
*MM	0.0015122	1.203	0.285	-0.571	0.29	152.52	19.81	148.40	18.18	18
*MSF	0.0028219	1.753	0.305	0.668	0.28	102.47	9.98	199.27	12.38	33
*ALP1	0.0343966	0.720	0.449	0.124	0.59	161.30	58.01	216.97	51.43	2.6
*2Q1	0.0357064	0.965	0.575	-0.025	0.49	116.74	29.79	55.72	39.41	2.8
*Q1	0.0372185	2.918	0.660	-0.087	0.56	119.72	11.00	148.93	11.86	20
*O1	0.0387307	16.485	0.687	-0.609	0.54	115.52	2.23	167.03	2.05	5.8e+02
NO1	0.0402686	1.441	1.217	-0.404	0.86	100.57	46.38	241.94	75.59	1.4
*K1	0.0417807	23.813	0.773	-0.372	0.56	112.07	1.67	196.23	2.00	9.5e+02
*J1	0.0432929	1.566	0.651	-0.229	0.50	117.46	18.39	187.61	24.50	5.8
*OO1	0.0448308	1.852	0.581	-0.328	0.46	109.65	13.51	240.83	20.53	10
UPS1	0.0463430	0.587	0.458	0.138	0.35	60.77	41.46	188.00	57.38	1.6
EPS2	0.0761773	2.176	3.074	0.358	2.01	109.56	46.10	274.94	96.48	0.5
*MU2	0.0776895	6.149	3.283	-1.679	2.76	116.58	26.83	283.86	36.43	3.5
*N2	0.0789992	31.744	4.224	0.658	2.83	112.73	4.30	186.06	7.41	56
*M2	0.0805114	203.42	3.762	-4.469	2.29	110.62	0.64	214.26	1.07	2.9e+03
L2	0.0820236	3.942	2.975	-0.185	1.75	103.14	21.83	225.83	47.30	1.8
*S2	0.0833333	86.929	3.545	-0.756	2.36	111.61	1.61	254.96	2.96	6e+02
ETA2	0.0850736	0.950	1.626	0.061	1.13	108.85	50.35	322.48	134.76	0.34
*MO3	0.1192421	1.506	0.840	-0.813	0.89	40.24	55.18	49.79	53.19	3.2
*M3	0.1207671	2.549	1.304	0.044	0.88	107.32	19.66	314.37	28.72	3.8
*MK3	0.1222921	2.859	0.916	-0.976	1.00	137.63	24.06	242.24	24.49	9.7
SK3	0.1251141	0.822	0.768	0.046	0.77	146.92	77.55	40.23	73.15	1.1
MN4	0.1595106	2.761	1.953	-0.594	2.01	61.43	57.26	347.79	52.62	2
*M4	0.1610228	12.255	2.050	-3.663	2.58	53.18	14.31	29.46	13.73	36
SN4	0.1623326	2.068	1.717	-1.741	1.97	94.31	125.76	40.93	103.87	1.5
*MS4	0.1638447	8.444	2.269	-1.696	2.00	48.49	16.00	71.74	16.05	14
S4	0.1666667	1.219	1.455	-0.027	1.73	88.82	133.02	161.24	94.10	0.7
2MK5	0.2028035	1.375	1.316	0.333	1.29	130.99	75.23	143.91	82.74	1.1
2SK5	0.2084474	0.515	1.001	0.068	1.05	153.46	99.12	63.21	156.59	0.26
*2MN6	0.2400221	2.730	1.881	0.004	1.62	132.38	37.79	103.60	45.30	2.1
*M6	0.2415342	7.980	2.160	-0.922	1.72	123.48	11.87	152.33	15.45	14
*2MS6	0.2443561	8.948	2.086	-1.224	1.59	125.98	11.83	190.76	12.49	18
*2SM6	0.2471781	2.630	1.667	0.255	1.52	127.65	38.34	232.42	41.67	2.5
*3MK7	0.2833149	1.082	0.711	-0.556	0.66	162.93	56.37	186.99	68.15	2.3
M8	0.3220456	1.270	0.954	-0.425	0.88	19.31	50.71	305.57	55.76	1.8

total var= 21644.8174 pred var= 21333.3647; percent total var predicted/var original= 98.6 %

Table D4. Tidal current harmonic parameters computed from mooring site SEA0848. Abbreviations: major = Semi-major axis (cm/s), minor = Semi-minor axis (cm/s), inc = Inclination (degrees True); pha = Greenwich Phase (degrees); e denotes error estimate for each parameter.

nobs = 9107, ngood = 9107, record length (days) = 37.95

start time: 06-Aug-2008 19:48:00

x0= 1.66, x trend= 0

var(x)= 15.0085 var(xp)= 11.6198 var(xres)= 3.9037

percent var predicted/var original= 77.4 %

y0= 2.3, x trend= 0

var(y)= 59.7418 var(yp)= 56.7358 var(yres)= 4.0372

percent var predicted/var original= 95.0 %

tide	freq	major	emaj	minor	emin	inc	einc	pha	epha	snr
*MM	0.0015122	0.955	0.040	-0.395	0.07	91.85	5.82	31.40	4.02	5.8e+02
*MSF	0.0028219	2.057	0.044	0.255	0.08	62.99	2.18	60.78	1.64	2.2e+03
*ALP1	0.0343966	0.195	0.132	0.020	0.13	15.08	34.87	120.86	46.47	2.2
*2Q1	0.0357064	0.198	0.129	-0.037	0.10	8.28	35.13	288.09	46.69	2.4
Q1	0.0372185	0.095	0.102	0.036	0.11	132.61	89.14	199.14	89.49	0.86
*O1	0.0387307	0.567	0.127	-0.010	0.14	105.15	14.05	232.96	13.39	20
NO1	0.0402686	0.259	0.232	0.157	0.21	31.81	88.29	104.46	80.87	1.2
*K1	0.0417807	0.849	0.124	0.347	0.17	98.27	14.58	254.20	12.08	47
J1	0.0432929	0.111	0.095	-0.101	0.10	2.66	122.04	241.05	147.29	1.3
*OO1	0.0448308	0.153	0.097	-0.083	0.11	118.05	66.52	151.02	60.73	2.5
UPS1	0.0463430	0.055	0.072	0.027	0.08	167.60	95.15	132.52	129.80	0.58
EPS2	0.0761773	0.253	0.487	0.025	0.46	14.43	123.51	290.51	141.39	0.27
MU2	0.0776895	0.505	0.547	-0.044	0.64	17.81	102.21	255.59	97.52	0.85
N2	0.0789992	0.948	0.740	-0.391	0.67	92.27	59.25	144.92	70.21	1.6
*M2	0.0805114	9.985	0.760	-4.352	0.71	88.92	5.62	184.86	6.44	1.7e+02
L2	0.0820236	0.444	0.451	-0.336	0.43	105.94	112.90	234.83	113.43	0.97
*S2	0.0833333	4.493	0.650	-2.156	0.61	100.54	13.77	227.79	13.04	48
ETA2	0.0850736	0.295	0.362	-0.087	0.35	108.48	79.57	85.83	101.51	0.66
MO3	0.1192421	0.132	0.125	-0.101	0.14	126.72	103.01	233.04	107.50	1.1
M3	0.1207671	0.126	0.128	-0.005	0.14	54.21	94.51	13.42	93.54	0.97
*MK3	0.1222921	0.317	0.171	-0.111	0.15	7.10	35.43	21.25	39.90	3.5
SK3	0.1251141	0.092	0.135	-0.058	0.12	61.85	127.61	339.42	121.17	0.46
*MN4	0.1595106	0.713	0.283	-0.369	0.29	100.03	40.81	16.51	39.04	6.3
*M4	0.1610228	1.584	0.272	-0.723	0.31	100.21	14.28	66.18	13.99	34
SN4	0.1623326	0.130	0.233	0.010	0.22	104.25	127.74	108.90	136.07	0.31
*MS4	0.1638447	1.118	0.255	-0.493	0.27	99.76	20.54	124.96	20.42	19
S4	0.1666667	0.197	0.239	0.034	0.23	5.33	93.78	351.10	102.09	0.68
2MK5	0.2028035	0.168	0.135	-0.009	0.13	9.13	55.02	63.16	60.14	1.5
2SK5	0.2084474	0.078	0.123	-0.011	0.11	168.79	84.88	236.86	156.18	0.4
2MN6	0.2400221	0.103	0.110	0.014	0.11	21.66	70.38	174.60	85.38	0.89
*M6	0.2415342	0.414	0.154	-0.022	0.15	109.40	19.89	125.99	19.52	7.2
*2MS6	0.2443561	0.454	0.137	0.006	0.14	126.25	15.97	168.62	16.88	11
*2SM6	0.2471781	0.226	0.123	-0.086	0.12	137.27	46.18	219.25	42.09	3.4
3MK7	0.2833149	0.050	0.088	-0.011	0.08	117.93	126.64	152.45	147.50	0.32
M8	0.3220456	0.133	0.103	-0.069	0.10	5.03	71.36	86.64	71.82	1.7

total var= 74.7503 pred var= 68.3556; percent total var predicted/var original= 91.4 %

Table D5. Tidal current harmonic parameters computed from mooring site SEA0849. Abbreviations: major = Semi-major axis (cm/s), minor = Semi-minor axis (cm/s), inc = Inclination (degrees True); pha = Greenwich Phase (degrees); e denotes error estimate for each parameter.

nobs = 7898, ngood = 7897, record length (days) = 32.91
start time: 06-Aug-2008 22:24:00
x0= 1.1, x trend= 0
var(x)= 68.4282 var(xp)= 65.1405 var(xres)= 3.2732
percent var predicted/var original= 95.2 %
y0= 0.661, x trend= 0
var(y)= 12.5743 var(yp)= 10.6847 var(yres)= 1.9336
percent var predicted/var original= 85.0 %

tide	freq	major	emaj	minor	emin	inc	einc	pha	epha	snr
MM	0.0015122	0.226	1.082	0.192	0.39	144.15	25.07	176.69	199.78	0.044
MSF	0.0028219	0.594	1.068	-0.303	0.43	157.39	35.78	329.03	125.77	0.31
ALP1	0.0343966	0.124	0.105	-0.077	0.11	105.57	96.83	0.86	92.44	1.4
2Q1	0.0357064	0.145	0.127	-0.065	0.10	11.41	62.68	50.53	75.44	1.3
Q1	0.0372185	0.155	0.128	-0.055	0.10	152.61	53.09	216.56	68.70	1.5
*O1	0.0387307	0.675	0.131	0.118	0.12	163.51	9.82	180.40	13.16	26
NO1	0.0402686	0.127	0.193	-0.078	0.18	169.09	104.62	96.97	158.36	0.43
*K1	0.0417807	0.897	0.164	0.090	0.13	159.28	9.03	176.18	9.89	30
J1	0.0432929	0.133	0.114	-0.000	0.11	174.71	48.04	154.09	64.64	1.4
OO1	0.0448308	0.030	0.078	-0.020	0.08	23.51	119.37	331.35	178.08	0.15
UPS1	0.0463430	0.058	0.077	0.013	0.07	38.80	81.32	282.83	106.13	0.57
EPS2	0.0761773	0.247	0.260	0.028	0.28	11.15	78.70	333.02	86.67	0.9
*MU2	0.0776895	0.672	0.320	0.107	0.29	124.93	29.58	259.11	31.99	4.4
*N2	0.0789992	1.636	0.313	-0.145	0.34	159.09	10.90	157.65	11.89	27
*M2	0.0805114	11.455	0.316	-1.541	0.32	161.04	1.85	201.56	1.82	1.3e+03
*L2	0.0820236	0.397	0.254	0.016	0.23	16.48	39.98	131.01	38.93	2.4
*S2	0.0833333	5.009	0.324	-0.757	0.29	161.76	3.71	246.86	3.82	2.4e+02
ETA2	0.0850736	0.168	0.185	0.071	0.15	3.21	79.62	315.38	90.13	0.83
*MO3	0.1192421	0.404	0.158	-0.188	0.13	87.03	26.47	16.56	35.82	6.5
*M3	0.1207671	0.354	0.162	-0.158	0.19	149.70	44.13	303.17	39.29	4.8
MK3	0.1222921	0.187	0.135	-0.056	0.15	35.56	64.72	68.04	58.97	1.9
SK3	0.1251141	0.160	0.146	-0.085	0.13	46.86	70.10	142.62	77.73	1.2
MN4	0.1595106	0.348	0.385	0.078	0.24	70.60	41.71	358.93	69.63	0.82
*M4	0.1610228	1.435	0.426	0.018	0.30	77.26	10.74	69.70	16.93	11
SN4	0.1623326	0.191	0.282	0.008	0.22	83.40	55.40	86.13	120.32	0.46
*MS4	0.1638447	1.229	0.401	0.209	0.26	67.42	14.27	116.49	20.79	9.4
S4	0.1666667	0.273	0.317	0.057	0.25	87.98	52.44	195.24	91.36	0.74
2MK5	0.2028035	0.071	0.134	-0.018	0.14	128.82	110.38	34.66	131.72	0.28
2SK5	0.2084474	0.045	0.122	0.027	0.12	52.57	127.81	115.08	225.18	0.14
*2MN6	0.2400221	0.205	0.136	0.030	0.14	67.15	54.25	355.36	45.95	2.3
*M6	0.2415342	0.279	0.128	0.240	0.12	0.89	95.09	344.07	106.63	4.7
*2MS6	0.2443561	0.589	0.149	0.220	0.15	89.78	18.32	131.67	16.31	16
2SM6	0.2471781	0.182	0.140	0.065	0.13	67.23	58.45	155.57	57.04	1.7
3MK7	0.2833149	0.056	0.117	-0.043	0.09	43.62	135.70	78.08	174.27	0.23
M8	0.3220456	0.174	0.138	0.027	0.13	130.43	52.81	359.09	52.54	1.6

total var= 81.0024 pred var= 75.8252; percent total var predicted/var original= 93.6 %

Table D6. Tidal current harmonic parameters computed from mooring site SEA0850. Abbreviations: major = Semi-major axis (cm/s), minor = Semi-minor axis (cm/s), inc = Inclination (degrees True); pha = Greenwich Phase (degrees); e denotes error estimate for each parameter.

nobs = 9312, ngood = 9311, record length (days) = 38.80

start time: 06-Aug-2008 21:18:00

x0= -1.66, x trend= 0

var(x)= 14.6904 var(xp)= 13.3502 var(xres)= 1.3412

percent var predicted/var original= 90.9 %

y0= -0.213, x trend= 0

var(y)= 28.73 var(yp)= 24.6612 var(yres)= 3.8459

percent var predicted/var original= 85.8 %

tide	freq	major	emaj	minor	emin	inc	einc	pha	epha	snr
*MM	0.0015122	0.583	0.059	-0.179	0.18	165.46	22.62	163.82	10.08	97
*MSF	0.0028219	1.211	0.191	-0.362	0.11	117.69	6.63	38.10	9.07	40
ALP1	0.0343966	0.118	0.119	-0.058	0.14	168.51	110.36	169.95	68.55	0.98
2Q1	0.0357064	0.094	0.177	0.021	0.06	71.46	24.84	178.88	119.64	0.28
Q1	0.0372185	0.141	0.140	0.121	0.08	76.64	91.51	99.60	166.52	1
*O1	0.0387307	0.282	0.175	0.183	0.13	125.16	52.72	135.33	76.85	2.6
NO1	0.0402686	0.364	0.357	0.136	0.13	99.29	24.73	356.18	79.75	1
*K1	0.0417807	0.531	0.137	0.025	0.19	148.39	25.32	173.94	12.32	15
J1	0.0432929	0.066	0.108	-0.053	0.07	61.04	57.06	265.65	168.64	0.37
OO1	0.0448308	0.143	0.180	-0.020	0.07	110.69	21.54	281.47	70.17	0.64
UPS1	0.0463430	0.088	0.124	-0.018	0.06	116.27	31.71	288.40	108.12	0.51
EPS2	0.0761773	0.200	0.217	0.002	0.17	94.66	51.91	272.09	63.97	0.85
*MU2	0.0776895	0.489	0.244	0.100	0.22	110.06	25.54	240.47	31.38	4
*N2	0.0789992	1.382	0.260	0.252	0.24	129.30	10.89	175.14	10.75	28
*M2	0.0805114	8.377	0.246	1.795	0.24	125.42	1.81	207.76	2.00	1.2e+03
L2	0.0820236	0.222	0.188	-0.023	0.16	109.06	44.29	177.72	52.55	1.4
*S2	0.0833333	3.147	0.250	0.914	0.23	123.99	5.03	258.82	4.43	1.6e+02
*ETA2	0.0850736	0.217	0.151	0.056	0.14	126.30	41.57	338.66	50.15	2.1
MO3	0.1192421	0.124	0.096	-0.045	0.10	130.01	59.22	0.11	65.08	1.7
M3	0.1207671	0.133	0.123	0.039	0.11	96.65	67.33	303.62	76.29	1.2
MK3	0.1222921	0.118	0.109	-0.000	0.10	70.74	51.93	329.92	64.80	1.2
SK3	0.1251141	0.021	0.085	0.003	0.07	165.74	137.77	261.60	201.98	0.062
*MN4	0.1595106	0.274	0.139	-0.144	0.13	126.32	50.22	28.51	47.80	3.9
*M4	0.1610228	0.990	0.156	-0.573	0.15	112.65	15.63	71.31	14.46	41
*SN4	0.1623326	0.198	0.126	-0.125	0.12	175.91	75.90	57.52	84.49	2.5
*MS4	0.1638447	0.748	0.152	-0.450	0.15	103.56	21.94	129.10	19.57	24
S4	0.1666667	0.143	0.128	-0.067	0.11	35.22	72.57	278.41	76.69	1.2
2MK5	0.2028035	0.095	0.083	-0.011	0.09	121.62	62.61	116.87	71.08	1.3
2SK5	0.2084474	0.064	0.083	0.038	0.06	22.19	108.38	92.52	105.21	0.61
2MN6	0.2400221	0.123	0.106	-0.103	0.12	108.75	114.22	134.50	110.47	1.4
*M6	0.2415342	0.430	0.101	-0.237	0.12	116.70	26.11	151.20	27.31	18
*2MS6	0.2443561	0.392	0.130	-0.209	0.12	144.65	30.98	191.74	30.36	9.1
2SM6	0.2471781	0.085	0.106	-0.009	0.09	178.91	84.29	229.47	107.35	0.64
3MK7	0.2833149	0.057	0.059	-0.015	0.06	4.35	88.91	306.30	83.05	0.93
*M8	0.3220456	0.108	0.073	0.038	0.08	126.77	63.27	3.16	50.84	2.2

total var= 43.4203 pred var= 38.0114; percent total var predicted/var original= 87.5 %

Table D7. Tidal current harmonic parameters computed from mooring site SEA1002. Abbreviations: major = Semi-major axis (cm/s), minor = Semi-minor axis (cm/s), inc = Inclination (degrees True); pha = Greenwich Phase (degrees); e denotes error estimate for each parameter.

nobs = 21840, ngood = 21839, record length (days) = 91.00

start time: 19-May-2010 19:36:00

x0= 7.53, x trend= 0

var(x)= 443.6475 var(xp)= 305.6259 var(xres)= 136.9995

percent var predicted/var original= 68.9 %

y0= 30.4, x trend= 0

var(y)= 5939.2636 var(yp)= 5757.4241 var(yres)= 178.1532

percent var predicted/var original= 96.9 %

tide	freq	major	emaj	minor	emin	inc	einc	pha	epha	snr
*MM	0.0015122	5.098	2.126	-0.348	1.31	61.36	13.73	43.43	23.99	5.8
*MSF	0.0028219	8.562	2.142	-0.068	1.28	64.42	7.64	46.34	12.86	16
ALP1	0.0343966	0.814	0.753	0.071	0.65	153.34	76.42	332.63	67.49	1.2
2Q1	0.0357064	0.809	0.758	0.310	0.63	55.24	76.47	11.25	69.34	1.1
Q1	0.0372185	0.774	0.799	-0.017	0.61	67.17	58.97	168.41	73.09	0.94
*O1	0.0387307	5.474	1.084	3.474	0.87	76.02	17.27	95.98	17.72	26
NO1	0.0402686	0.677	0.588	0.275	0.62	30.75	86.18	4.73	74.98	1.3
*K1	0.0417807	11.738	1.008	5.541	0.70	96.77	5.56	154.58	6.71	1.4e+02
J1	0.0432929	1.198	0.860	0.933	0.67	81.28	85.25	88.17	100.63	1.9
*OO1	0.0448308	1.012	0.684	0.190	0.57	66.98	39.44	299.84	44.82	2.2
UPS1	0.0463430	0.650	0.593	-0.172	0.58	63.19	69.04	162.13	71.97	1.2
EPS2	0.0761773	1.589	1.389	0.783	1.11	51.15	62.98	8.51	87.81	1.3
*MU2	0.0776895	7.655	2.179	2.859	1.21	68.26	11.57	54.78	17.44	12
*N2	0.0789992	17.219	2.369	4.016	0.93	89.93	3.70	183.37	7.85	53
*M2	0.0805114	98.438	2.378	18.164	0.80	87.40	0.68	210.43	1.17	1.7e+03
*L2	0.0820236	4.642	2.405	0.597	1.83	53.91	24.81	275.29	29.44	3.7
*S2	0.0833333	28.411	2.244	6.754	0.96	89.20	2.11	243.29	4.74	1.6e+02
ETA2	0.0850736	0.788	1.078	0.489	0.88	130.96	74.34	286.20	162.75	0.53
*MO3	0.1192421	2.498	1.225	-0.349	0.97	60.30	22.18	147.98	28.86	4.2
M3	0.1207671	1.590	1.200	-0.203	0.79	75.20	30.33	346.44	47.25	1.8
*MK3	0.1222921	3.232	0.913	-1.243	1.17	29.26	26.55	156.83	23.51	13
SK3	0.1251141	1.512	1.145	0.394	0.75	70.37	35.57	122.87	51.62	1.7
*MN4	0.1595106	6.024	1.613	-2.398	1.16	95.41	16.02	84.78	18.30	14
*M4	0.1610228	17.123	1.814	-6.097	1.32	98.27	4.95	121.50	6.50	89
*SN4	0.1623326	3.324	1.373	-0.118	1.31	76.98	22.37	118.04	32.49	5.9
*MS4	0.1638447	11.221	1.605	-3.798	1.07	96.32	8.28	153.01	10.12	49
*S4	0.1666667	2.241	1.524	0.126	1.20	85.11	31.12	193.64	44.97	2.2
*2MK5	0.2028035	1.877	0.735	-0.217	0.94	97.98	33.42	245.30	28.21	6.5
2SK5	0.2084474	0.626	0.692	-0.236	0.62	17.92	77.46	197.20	123.41	0.82
*2MN6	0.2400221	2.594	0.941	0.684	1.00	144.65	24.65	246.16	24.09	7.6
*M6	0.2415342	4.936	0.942	0.790	1.03	147.03	13.34	273.01	11.69	27
*2MS6	0.2443561	4.662	0.930	1.258	1.03	152.58	13.76	311.12	13.63	25
2SM6	0.2471781	1.052	0.838	0.902	0.78	82.09	101.75	250.16	120.14	1.6
*3MK7	0.2833149	1.716	0.710	0.063	0.53	96.59	17.90	343.00	23.56	5.8
*M8	0.3220456	2.538	0.761	-1.193	0.82	110.48	25.65	97.38	24.51	11

total var= 6382.9111 pred var= 6063.0499; percent total var predicted/var original= 95.0 %

Table D8. Tidal current harmonic parameters computed from mooring site SEA1003. Abbreviations: major = Semi-major axis (cm/s), minor = Semi-minor axis (cm/s), inc = Inclination (degrees True); pha = Greenwich Phase (degrees); e denotes error estimate for each parameter.

nobs = 22017, ngood = 22017, record length (days) = 91.74
start time: 19-May-2010 20:12:00
x0= 29, x trend= 0
var(x)= 645.1163 var(xp)= 545.1783 var(xres)= 98.2718
percent var predicted/var original= 84.5 %
y0= 26.1, x trend= 0
var(y)= 7844.6549 var(yp)= 7698.792 var(yres)= 145.8664
percent var predicted/var original= 98.1 %

tide	freq	major	emaj	minor	emin	inc	einc	pha	epha	snr
*MM	0.0015122	6.708	1.438	-0.152	1.94	14.38	18.45	36.98	13.17	22
*MSF	0.0028219	11.178	1.500	0.076	2.44	9.58	10.30	48.15	7.55	56
ALP1	0.0343966	0.922	0.718	-0.040	0.71	6.13	55.71	188.08	57.48	1.6
2Q1	0.0357064	1.106	0.851	-0.284	0.66	23.71	51.35	325.95	50.09	1.7
*Q1	0.0372185	2.033	0.804	0.398	0.83	87.78	24.63	174.00	24.43	6.4
*O1	0.0387307	10.695	0.865	4.941	0.85	114.98	5.66	180.82	6.13	1.5e+02
*NO1	0.0402686	1.061	0.647	-0.163	0.58	152.35	36.56	200.13	42.30	2.7
*K1	0.0417807	18.008	0.867	6.514	0.83	107.16	3.10	196.63	3.06	4.3e+02
*J1	0.0432929	1.386	0.738	-0.261	0.85	147.65	35.03	216.28	34.10	3.5
*OO1	0.0448308	0.940	0.606	-0.637	0.53	100.97	84.80	193.40	70.84	2.4
UPS1	0.0463430	0.490	0.586	-0.038	0.51	66.59	75.73	173.73	83.31	0.7
*EPS2	0.0761773	1.951	1.261	0.527	1.69	161.47	72.15	169.70	45.78	2.4
*MU2	0.0776895	5.561	1.025	1.803	2.29	169.59	25.87	195.05	14.96	29
*N2	0.0789992	21.792	2.512	5.164	0.94	90.60	3.54	200.63	6.25	75
*M2	0.0805114	114.23	2.345	21.363	1.02	84.19	0.63	215.12	1.12	2.4e+03
*L2	0.0820236	3.822	1.988	-3.341	1.66	74.40	94.24	196.91	115.81	3.7
*S2	0.0833333	33.319	1.940	8.801	1.04	90.39	2.04	260.40	4.04	2.9e+02
ETA2	0.0850736	1.067	1.213	-0.090	1.01	123.69	49.47	299.42	94.35	0.77
*MO3	0.1192421	2.867	0.848	-0.048	0.59	148.41	14.70	300.95	18.30	11
*M3	0.1207671	1.225	0.820	-0.632	0.70	145.73	54.48	206.17	57.65	2.2
*MK3	0.1222921	5.701	0.763	1.845	0.79	125.37	10.64	298.48	9.94	56
SK3	0.1251141	0.491	0.622	0.242	0.57	163.88	95.57	298.73	115.85	0.62
*MN4	0.1595106	5.660	1.787	-1.081	0.86	102.58	9.36	350.73	18.26	10
*M4	0.1610228	16.759	1.695	-4.829	0.79	102.41	3.28	14.97	5.82	98
SN4	0.1623326	1.615	1.169	-1.042	0.99	53.38	78.60	26.04	97.68	1.9
*MS4	0.1638447	9.313	1.684	-1.499	0.83	93.09	5.27	49.50	10.58	31
S4	0.1666667	0.912	1.220	-0.228	0.77	67.54	53.47	73.06	108.68	0.56
*2MK5	0.2028035	4.169	0.999	-1.707	0.97	46.97	16.95	159.17	16.95	17
2SK5	0.2084474	0.174	0.692	-0.067	0.72	149.96	137.62	304.53	213.40	0.063
*2MN6	0.2400221	3.729	1.304	-1.129	1.09	66.81	19.83	169.42	22.30	8.2
*M6	0.2415342	7.745	1.332	-2.096	1.11	82.03	8.77	188.21	9.94	34
*2MS6	0.2443561	5.890	1.243	-2.233	0.91	78.46	11.15	225.44	14.96	22
2SM6	0.2471781	0.747	0.979	-0.161	0.74	75.69	70.31	290.69	94.59	0.58
*3MK7	0.2833149	1.379	0.637	0.009	0.71	62.12	32.77	261.92	25.91	4.7
*M8	0.3220456	3.142	0.869	0.244	0.56	77.70	10.19	317.32	14.37	13

total var= 8489.7712 pred var= 8243.9702; percent total var predicted/var original= 97.1 %

Table D9. Tidal current harmonic parameters computed from mooring site SEA1004. Abbreviations: major = Semi-major axis (cm/s), minor = Semi-minor axis (cm/s), inc = Inclination (degrees True); pha = Greenwich Phase (degrees); e denotes error estimate for each parameter.

nobs = 21817, ngood = 21817, record length (days) = 90.90

start time: 19-May-2010 21:00:00

x0= 12.3, x trend= 0

var(x)= 391.6295 var(xp)= 261.5848 var(xres)= 130.0679

percent var predicted/var original= 66.8 %

y0= -55, x trend= 0

var(y)= 2455.9757 var(yp)= 2290.5852 var(yres)= 165.9842

percent var predicted/var original= 93.3 %

tide	freq	major	emaj	minor	emin	inc	einc	pha	epha	snr
*MM	0.0015122	5.157	1.610	0.548	1.29	87.44	14.82	212.19	15.69	10
*MSF	0.0028219	9.140	1.443	-0.964	1.20	80.49	9.11	226.92	9.83	40
ALP1	0.0343966	0.781	0.770	0.497	0.79	168.18	106.85	170.72	77.15	1
2Q1	0.0357064	1.188	1.105	0.161	0.69	102.63	33.49	200.72	62.40	1.2
Q1	0.0372185	1.422	1.131	-0.005	0.65	101.60	31.75	155.15	46.60	1.6
*O1	0.0387307	9.281	1.303	-1.379	0.81	107.94	5.10	180.37	7.14	51
NO1	0.0402686	0.503	0.529	-0.023	0.66	10.08	137.03	269.58	84.59	0.9
*K1	0.0417807	13.894	1.229	-1.334	0.82	101.34	3.46	200.76	4.92	1.3e+02
*J1	0.0432929	1.596	1.030	0.149	0.76	101.60	28.15	221.64	39.61	2.4
*OO1	0.0448308	1.332	0.768	-0.375	0.60	114.50	27.80	140.01	42.99	3
UPS1	0.0463430	0.389	0.618	-0.095	0.64	174.80	131.62	221.52	193.35	0.4
*EPS2	0.0761773	2.466	1.565	-0.621	0.99	115.48	28.03	217.63	35.96	2.5
*MU2	0.0776895	7.812	1.466	-1.838	1.07	124.09	9.49	217.45	10.25	28
*N2	0.0789992	12.773	1.498	-0.227	1.15	106.70	4.97	193.27	6.46	73
*M2	0.0805114	58.403	1.583	-1.674	1.16	97.20	1.04	192.29	1.37	1.4e+03
*L2	0.0820236	8.275	2.058	-1.812	1.46	114.03	10.36	129.77	12.24	16
*S2	0.0833333	18.693	1.365	2.330	1.01	110.20	3.24	259.75	4.06	1.9e+02
ETA2	0.0850736	1.336	1.097	-0.011	0.87	99.17	33.40	294.61	54.62	1.5
*MO3	0.1192421	5.338	1.143	-0.603	1.14	149.50	13.16	332.91	11.38	22
*M3	0.1207671	2.192	1.077	-0.296	1.07	148.13	29.48	225.58	31.35	4.1
*MK3	0.1222921	4.470	1.212	0.591	1.06	178.56	13.90	325.40	13.63	14
SK3	0.1251141	1.201	0.968	0.639	0.87	59.61	74.23	257.77	84.75	1.5
*MN4	0.1595106	4.938	1.443	1.822	1.65	35.66	21.62	187.33	23.47	12
*M4	0.1610228	13.122	1.588	7.121	1.62	21.40	10.27	163.79	11.41	68
*SN4	0.1623326	1.876	1.323	-1.394	1.26	116.28	94.68	308.03	90.85	2
*MS4	0.1638447	5.784	1.412	3.130	1.67	67.38	27.84	274.19	24.26	17
*S4	0.1666667	1.947	1.216	0.006	1.60	80.09	51.99	19.73	45.84	2.6
*2MK5	0.2028035	5.212	2.092	-1.100	1.44	118.47	20.03	44.25	26.44	6.2
2SK5	0.2084474	0.564	1.322	-0.056	1.29	160.21	95.77	240.50	152.10	0.18
*2MN6	0.2400221	5.487	1.405	-0.118	1.34	123.46	15.59	59.55	14.13	15
*M6	0.2415342	10.615	1.357	2.848	1.32	129.72	8.28	60.85	7.87	61
*2MS6	0.2443561	7.112	1.328	0.904	1.39	137.93	11.64	116.23	10.42	29
2SM6	0.2471781	1.300	1.253	-0.246	1.14	127.22	63.79	256.95	60.25	1.1
*3MK7	0.2833149	2.423	1.144	-0.195	1.25	44.78	28.52	69.55	26.56	4.5
*M8	0.3220456	4.228	0.909	2.664	0.80	17.83	23.86	75.64	26.58	22

total var= 2847.6052 pred var= 2552.17; percent total var predicted/var original= 89.6 %

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