Exxon Valdez Oil Spill
Long-Term Monitoring Program (Gulf Watch Alaska) Final Report

Long-Term Monitoring of Oceanographic Conditions in the Alaska Coastal Current from Hydrographic Station GAK1

Exxon Valdez Oil Spill Trustee Council Project 16120114-P
Final Report

Thomas J. Weingartner
Seth L. Danielson

Institute of Marine Science
College of Fisheries and Ocean Sciences
University of Alaska Fairbanks
PO Box 757220
2150 Koyukuk Dr.
Fairbanks, AK 99775

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Study History: Hydrographic measurements at GAK1 at the mouth of Resurrection Bay, Alaska began in 1970. Initially the sampling was opportunistic, became more regular in the 1980s and 1990s, and then systematic beginning in 1997 with *Exxon Valdez* Oil Spill Trustee Council support under the following project numbers: 0010100340 (2010), 070340 (2009), 070340 (2008), 070340 (2007), 040340 (2006), 040340 (2005), 040340 (2004), 030340 (2003), 02340 (2002), 1340 (2001), 00340 (2000), 99340 (1999), 98340 (1998). Portions of this final report are also directly relevant to Seward Line Monitoring project 1612114-J and provided input to the 2015 science synthesis report for programs 14120114 and 14120120. This report summarizes briefly the available time series and re-examines a number of trends last reported by the University of Alaska M.S. thesis of Kelly (2015).

Publications from 2012-2016 using GAK1 data include the following. (A complete list of all known publications using GAK1 data is available at http://research.cfos.uaf.edu/gak1/.)

1. Batten, S. D., S. Moffitt, W. S. Pegau, and R. Campbell. 2016. Plankton indices explain interannual variability in Prince William Sound herring first year growth. Fisheries Oceanography 25:420-432.
2. Fedewa, E. J., J. A. Miller, and T. P. Hurst. 2015. Pre-settlement processes of northern rock sole (*Lepidopsetta polyxystra*) in relation to interannual variability in the Gulf of Alaska. Journal of Sea Research 111:25-36. doi:10.1016/j.seares.2015.11.008
3. Kelly, J. 2015. An examination of hydrography and sea level in the Gulf of Alaska. M.S. Thesis, University of Alaska Fairbanks.
4. Stearns, L. A., G. S. Hamilton, C. J. van der Veen, D. C. Finnegan, S. O'Neel, J. B. Scheick, and D. E. Lawson. 2015. Glaciological and marine geological controls on terminus dynamics of Hubbard Glacier, southeast Alaska. Journal of Geophysical Research: Earth Surface 120:1065–1081. doi:10.1002/2014JF003341.
5. Horning, M., and J. A. E. Mellish. 2014. In cold blood: evidence of Pacific sleeper shark (*Somniosus pacificus*) predation on Steller sea lions (*Eumetopias jubatus*) in the Gulf of Alaska. Fishery Bulletin 112:297-310. doi:10.7755/FB.112.4.6
6. Munro, A. R., and C. Tide, editors. 2014. Run forecasts and harvest projections for 2014 Alaska salmon fisheries and review of the 2013 season. Alaska Department of Fish and Game, Special Publication No. 14-10, Anchorage, Alaska, USA.
7. Wang, Y. H. Xue, F. Chai, Y. Chao, J. Farrara. 2014. A model study of the Copper River plume and its effects on the northern Gulf of Alaska. Ocean Dynamics 64:241-258. doi:10.1007/s10236-013-0684-3
8. Eggers, D. M., C. Tide, and A. M. Carroll, editors. 2013. Run forecasts and harvest projections for 2013 Alaska salmon fisheries and review of the 2012 season. Alaska

Department of Fish and Game, Special Publication No. 13-03, Anchorage, Alaska, USA.
9. Evans, W., J. T. Mathis, P. Winsor, H. Statscewich, and T. E. Whitledge. 2013. A regression modeling approach for studying carbonate system variability in the northern Gulf of Alaska. Journal of Geophysical Research: Oceans 118:476–489. doi:10.1029/2012JC008246.
10. Zador, S., editor. 2013. North Pacific Fishery Management Council ecosystem considerations for 2014 for the North Pacific groundfish stock assessment and fishery evaluation report. Resource Ecology and Fisheries Management Division, Alaska Fisheries Science Center, National Marine Fisheries Service, NOAA, Seattle, WA, USA.
11. Janout, M. A., T. J. Weingartner, and P. J. Stabeno. 2013. Air-sea and oceanic heat flux contributions to the heat budget of the northern Gulf of Alaska shelf. Journal of Geophysical Research: Oceans. 118:1807–1820. doi:10.1002/jgrc.20095.
12. Zador, S., editor. 2012. North Pacific Fishery Management Council ecosystem considerations for 2013 for the North Pacific groundfish stock assessment and fishery evaluation report. Resource Ecology and Fisheries Management Division, Alaska Fisheries Science Center, National Marine Fisheries Service, NOAA, Seattle, WA, USA.

Abstract: Hydrographic station GAK1, at the mouth of Resurrection Bay, Alaska, has been sampled for the past 46 years. Initially this sampling was conducted quasi-monthly by ships of opportunity, but beginning in 1998, the sampling has been systematic using both monthly sampling from a small vessel and continuous recording at select depths from an oceanographic mooring. The fundamental goal of this project is to provide high quality, long-term data to quantify and understand monthly, seasonal, interannual and longer period variability of the GOA shelf. This long data set reveals significant trends in temperature and salinity. Shelf waters have warmed by 0.6°C to 1.0°C and shelf stratification has increased due to a reduction in upper ocean salinities and an increase in deep shelf salinity. These salinity changes are due, in part, to an increase in coastal freshwater discharge and a reduction in wind-mixing intensity. In aggregate, these changes can be expected to affect the metabolic rate of some marine species and, through changes in stratification, primary production and perhaps upper trophic level productivity. The GAK1 data set is freely available and has been used in a broad variety of physical and biological oceanographic studies, as well as fisheries investigations and fisheries management decisions. This report summarizes briefly the available time series and re-examines a number of trends last reported by the University of Alaska M.S. thesis of Kelly (2015).

Key words: Alaska Coastal Current, climate,Gulf of Alaska, monitoring, Resurrection Bay, salinity, temperature

Project Data: Data collected include monthly water column conductivity-temperature-depth (CTD) profiles from station GAK1 and hourly CTD measurements from instruments mounted at six discrete depth levels on a year-round mooring. Data are stored in columnar

ASCII text files that are archived by the Alaska Ocean Observing System (AOOS) and at the University of Alaska Fairbanks (UAF).

AOOS Point of Contact: Carol Janzen, janzen@aoos.org, 907-644-6703, AOOS, 1007 W. 3rd Ave. #100, Anchorage, AK 99501; http://portal.aoos.org/gulf-of-alaska.php#metadata/3c4ecb88-6436-4312-8281-ed584e020b0e/project

UAF Point of Contact: Seth Danielson, sldanielson@alaska.edu, 907-474-7834, UAF-CFOS, PO Box 757220, Fairbanks, AK 99775; http://research.cfos.uaf.edu/gak1/.

There are no limitations on the use of the data; however, it is requested that the authors be cited by any subsequent publications that reference this dataset. It is strongly recommended that careful attention be paid to the contents of the metadata file associated with these data to evaluate data set limitations for intended use.

Citation:

Weingartner, T. J. and S. L. Danielson. 2018. Long-term monitoring of oceanographic conditions in the Alaska Coastal Current from hydrographic station GAK1 over 1970-2016. *Exxon Valdez* Oil Spill Long-Term Monitoring Program (Gulf Watch Alaska) Final Report (*Exxon Valdez* Oil Spill Trustee Council Project 16120114-P), *Exxon Valdez* Oil Spill Trustee Council, Anchorage, Alaska.

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EXECUTIVE SUMMARY

Observations at oceanographic station GAK1 represent one of the longest and most regularly sampled surface-to-seafloor oceanographic time series in the northern North Pacific Ocean. Between 1970 and the late 1990s, measurements consisted of quasi-monthly conductivity-temperature-depth (CTD) vertical profiles. An oceanographic mooring has supplemented observations since the turn of the century with 15-minute and hourly data collected by six temperature-conductivity data loggers that record year-round.

The goal of the GAK1 project is to provide a long-term high-quality reference dataset for the coastal northern Gulf of Alaska (GOA) that enables scientists, students, and resource managers to better understand climatic and ecological conditions, their changes, and the ramifications of change (Fig. 1). Understanding, anticipating, and responding to change requires a stationary frame of reference in the form of long-term in situ observations. Such datasets are the best means to guide our assessments and interpretations of system variability. Untangling the relations between climatic and other drivers of change (e.g., oil spills or fishing regulations) similarly requires long reference time series. Environmental time series data can provide information valuable to the management of fish and shellfish populations and fisheries (Anderson and Piatt 1999, Munro and Tide 2014).

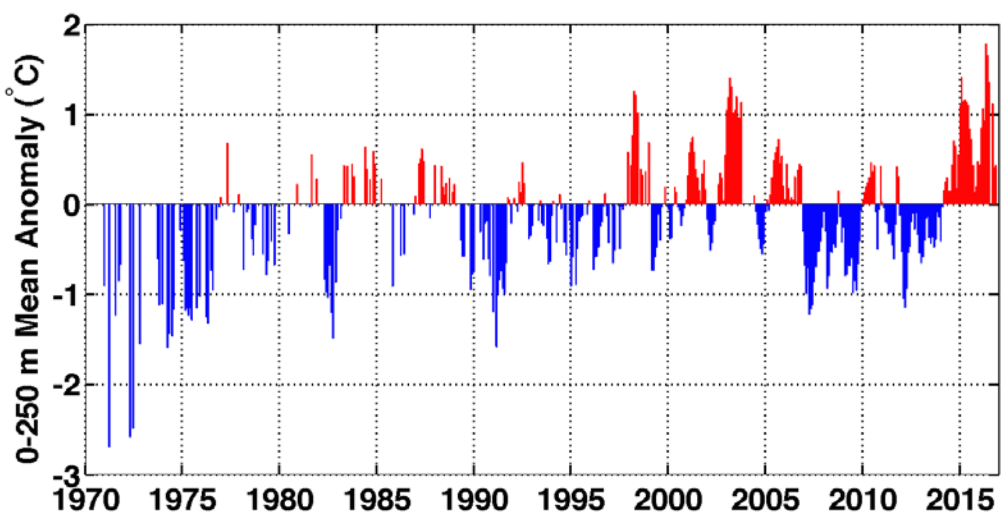

Figure 1. Temperature anomalies from the GAK1 dataset averaged over the entire water column exhibit a long-term trend in warming along with signals associated with the cycles of El Niño, La Niña, and other climate-related phenomena.

No other full water column temperature and salinity time series in the northern GOA exist with comparable data quality, temporal extent, and frequency of sampling. Hence, the GAK1 dataset is the premier reference dataset for evaluating hypotheses that seek mechanistic descriptions of the regional ocean environment and ecosystem. As shown by an ever-increasing number of publications that utilize the GAK1 dataset, the value of this unique time series continues to grow and even accelerate with the passing decades.

The GAK1 dataset is collected under the fundamental hypothesis that oceanic conditions are important to the physical and biological functioning of the GOA ecosystem. To that end, dozens of papers have examined this hypothesis from numerous perspectives (for a comprehensive list, see the GAK1 home page at http://research.cfos.uaf.edu/gak1/). As the chemical and biological datasets begin to catch up (via quality of resolution, duration, and frequency) to the physical measurements we expect that the insights gleaned through interdisciplinary analyses will grow in kind. To date, the 47-year GAK1 time series has helped show:

1. Large interannual differences associated with El Niño and La Niña events, including substantial differences in the spring bloom between these phenomena (Weingartner et al. 2002, Childers et al. 2005).

2. The intimate connection between coastal freshwater discharge and the depth-varying evolution of winter and spring temperatures over the shelf (Janout 2010, Janout et al. 2013).

3. GAK1 provides a reliable index of Alaska Coastal Current (ACC) transports of mass, heat, and freshwater (Weingartner et al. 2005).

4. That GAK1 near-surface salinities are correlated with coastal freshwater discharge from around the GOA (Weingartner et al. 2005).

5. Variations in mixed-layer depth in the northern GOA, which affects primary production (Sarkar 2007).

6. Decadal scale trends in salinity and temperature (Royer 2005, Royer and Grosch 2006, Weingartner et al. 2005, Janout et al. 2010, Kelly 2015).

7. The relationships between temperature and salinity variations and the Pacific Decadal Oscillation and the strength and position of the Aleutian Low (Royer 2005, Weingartner et al. 2005, Janout et al. 2010).

8. That the GAK1 observations can guide understanding of the variability in iron concentrations, a potentially limiting micro-nutrient required by many phytoplankton. Preliminary findings indicate that iron and surface salinity are correlated at least in certain seasons (Wu et al. 2009).

9. Approximately 1000 to 1500 years before present the northern GOA likely experienced a cooler, more sluggish and higher salinity ACC, whereas between 600 and 1000 years before present a stronger Aleutian Low may have driven a stronger and fresher ACC (Hallmann et al. 2011).

10. Ocean acidification (carbonate) system variability (with a focus on sub-seasonal time scales) can be described using multiple linear regression models to predict dissolved

inorganic carbon and total alkalinity using observations of nitrate, temperature, salinity, and pressure (Evans et al. 2013).

11. A decoupling of near-surface and near-bottom waters increased stratification (Kelly 2015) with implications for nutrient resupply to the euphotic zone and long-term changes in shelf productivity.

As shown by Mueter et al. (1994), Mueter (2004), and Spies (2009), these factors affect and relate to many ecosystem processes on the shelf and within both Prince William Sound and Lower Cook Inlet/Kachemak Bay.

INTRODUCTION

The Alaska Coastal Current (ACC) circumscribes the entire inner shelf of the Gulf of Alaska (GOA). Its mean and varying properties reflect the spatially and temporally integrated forcing due to winds, coastal discharge, and air-sea heat exchanges. The current originates on the British Columbian shelf and substantial portions of it circulate through Prince William Sound and lower Cook Inlet and Kachemak Bay before flowing southwestward through Shelikof Strait. The GAK1 hydrographic station (59° 50.7' N, 149° 28.0' W) at the mouth of Resurrection Bay has been shown to be an excellent proxy for the temperature and salinity properties of the ACC (Weingartner et al. 2005). Trends and anomalies at this station are also correlated with those over the mid- and outer shelf, although in general the anomaly magnitudes are larger within the ACC than farther offshore.

Hydrographic measurements at GAK1 began in 1970. Initially the sampling was opportunistic, became more regular in the 1980s and 1990s, and then systematic beginning in 1997 with *Exxon Valdez* Oil Spill Trustee Council (EVOSTC) support. Since then the sampling protocol has included both quasi-monthly conductivity-temperature-depth (CTD) casts and hourly temperature and salinity measurements obtained by moored instruments at 6 depths distributed over the water column. *GAK1 is the only station in the GOA that measures both salinity and temperature year-round over the 250 m deep water column*. Nutrient, chlorophyll, and zooplankton sampling at GAK1 has occurred since 1997 with support from the Seward Line sampling done by the Global Ocean Ecosystems Dynamics program, jointly funded by the National Science Foundation and the National Oceanic and Atmospheric Administration (1997-2004) and more recently by the North Pacific Research Board, Alaska Ocean Observing System, and EVOSTC within the Gulf Watch Alaska program. Over the years, data from GAK1 has been used in over 60 scientific investigations addressing topics in physical and biological oceanography relevant to fisheries management. (A listing of these publications is given on the GAK1 website: http://research.cfos.uaf.edu/gak1/. Additional publications and/or use by private citizens or other entities, of which we are unaware, may also have used these data). This report summarizes briefly the available time series based on both sampling protocols and re-examines a number of trends last reported by the University of Alaska M.S. thesis of Kelly (2015).

OBJECTIVES

The fundamental goal of this project is to provide high quality, long-term data to quantify and understand monthly, seasonal, interannual, and longer period variability of the GOA shelf. This measurement provides the broader temporal and spatial scale perspective that other Gulf Watch Alaska projects and components can turn to for interpreting their data in the context of sub-seasonal, seasonal, interannual, and decadal-scale environmental conditions. Specifically we measure:

1. Temperature and salinity throughout the water column.
2. Near surface stratification which affects phytoplankton bloom dynamics.

METHODS

Sampling includes nominally monthly CTD measurements and year-long, continuous measurements from a subsurface mooring with temperature and conductivity (T/C) recorders placed at depths of 20, 30, 60, 100, 150, 200, and 250 m. The moored instruments and monthly CTD sampling schemes are complementary: the CTD provides high vertical resolution at monthly time scales, and the mooring provides high temporal resolution but at coarser vertical spacing. The monthly CTDs provide redundancy in the event an instrument fails on the mooring.

Vertical profiles are collected using a portable CTD (Seabird SBE-25) from a chartered fishing vessel resident in Seward or the University of Alaska Fairbanks Seward Marine Center vessel the *R/V* Little Dipper. The SBE-25 has an accuracy ~0.01 psu or better for salinity and 0.005 °C for temperature. The moored T/C recorders are SeaBird SBE-37 Microcats and Seabird SeaCat SBE-16 dataloggers. Seabird performs pre- and post-deployment calibrations upon which we determine sensor drift (typically ~0.01°C yr^{-1} and ~0.03, or better, practical salinity unit yr^{-1}). The mooring is recovered and redeployed annually, typically in late winter. Bio-fouling gradually degrades the signal quality of the data, especially ancillary measurements such as chlorophyll-*a* fluorescence, so we strive to deploy the mooring in March or early April (depending upon weather) in order to minimize fouling potential prior to the spring bloom in April or May. Temperature and salinity data are sampled at 15-minute intervals by Microcat instruments and hourly intervals by the SeaCat instruments.

RESULTS

Annual cycles are clearly evident in monthly (Fig. 2A) and daily (Fig. 3A) time series of temperature, salinity, and density, and density profiles closely correspond to the salinity distribution, indicating salinity is the primary driver of density variations in the GOA. (Density contours from the mooring are available at http://research.cfos.uaf.edu/gak1/.) This is also seen in hourly time series from April 2011 – March 2012 (Fig. 4), when density variations mirror salinity changes at all recorded depths.

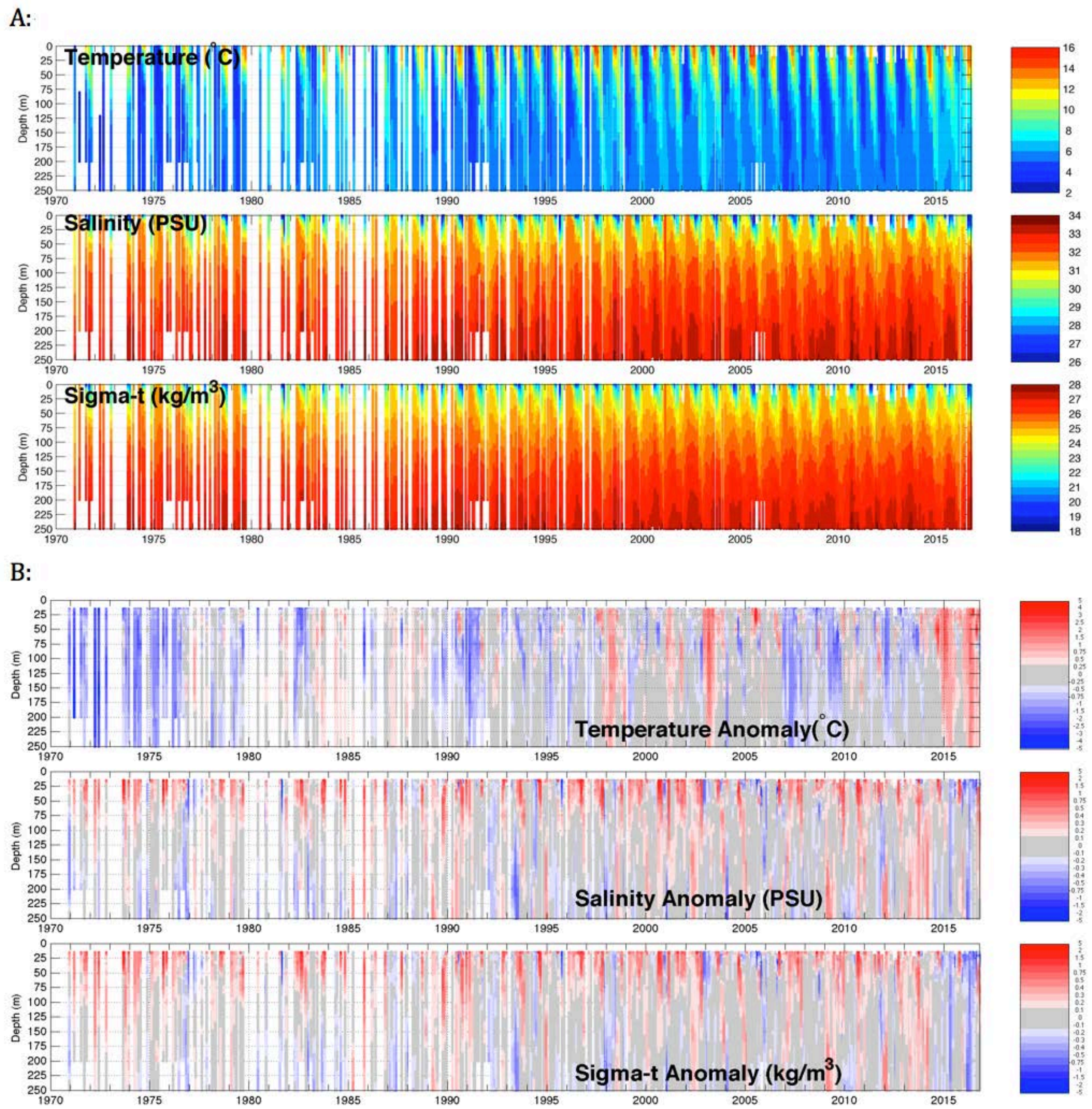

Figure 2. A) Time series of monthly temperature, salinity, and density obtained from GAK1 CTD casts over 1970-2016. B) Corresponding time series of monthly anomalies based on the 2000 – 2016 period of mooring measurements.

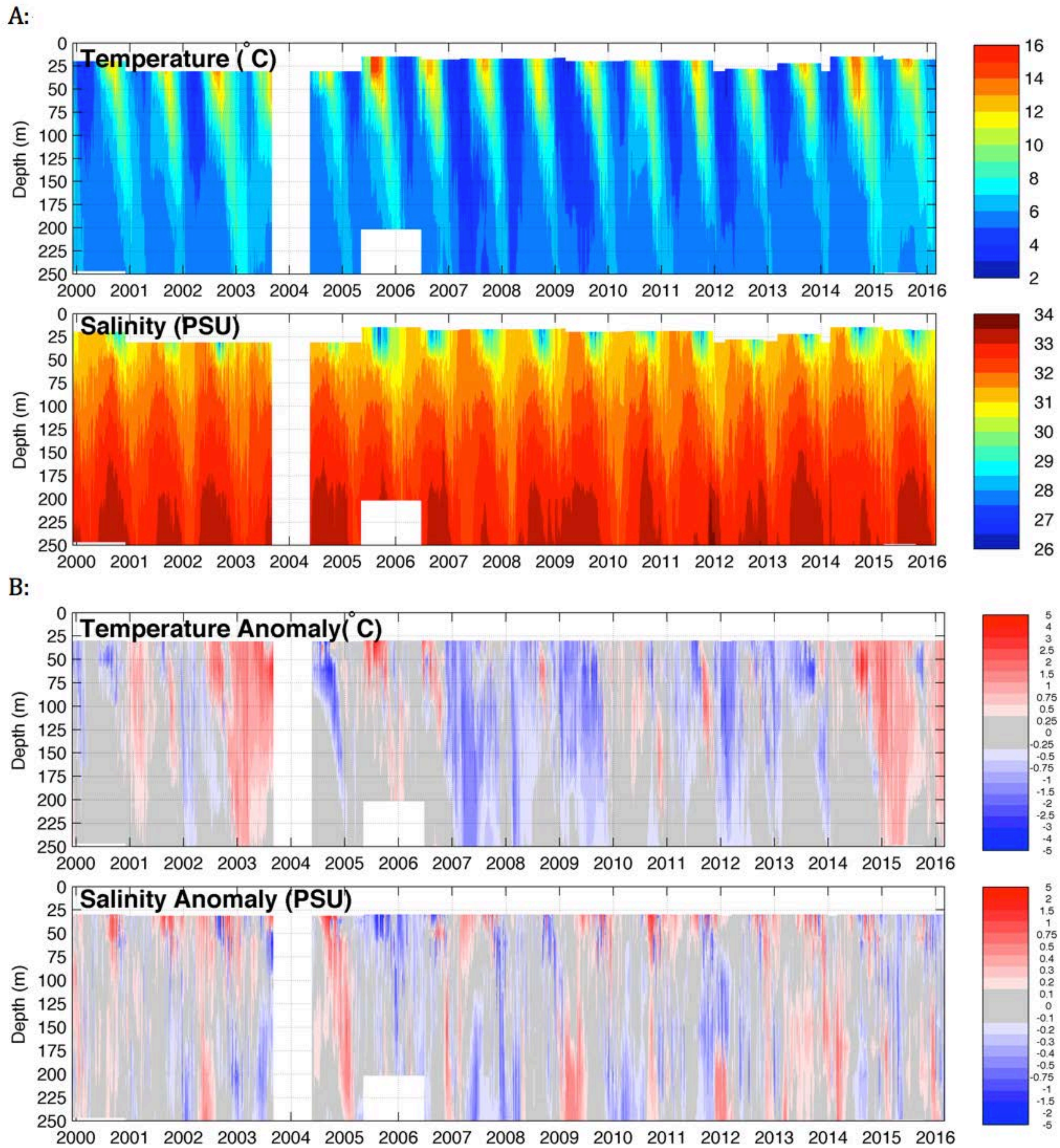

Figure 3. A) Time series of daily temperature and salinity obtained from the GAK1 mooring since 2000. B) Corresponding time series of anomalies.

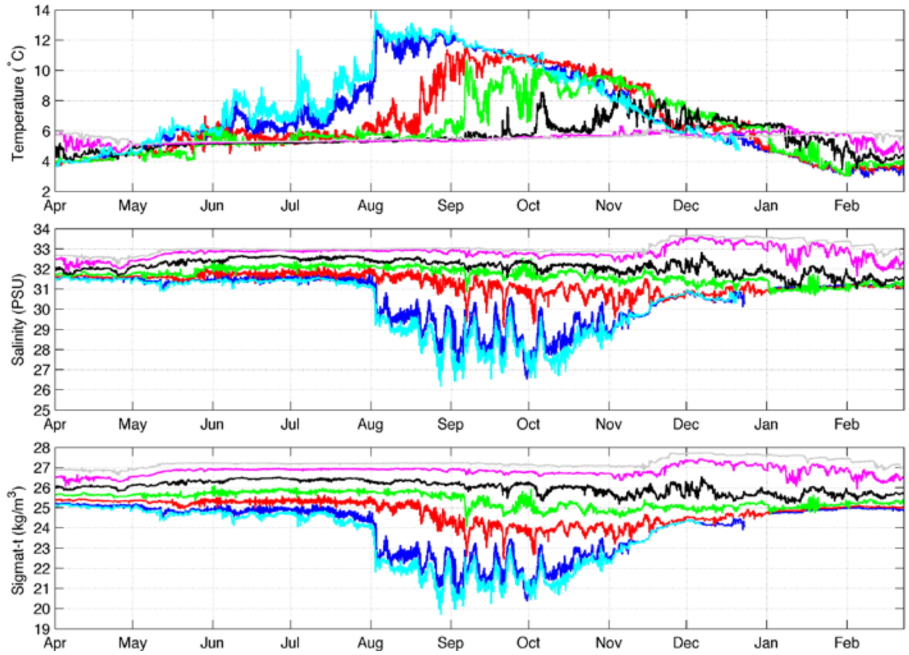

Figure 4. Time series of hourly temperature (top), salinity (middle), and density (sigma-t; bottom) at 20 (cyan), 30 (blue), 60 (red), 100 (green), 150 (black), 200 (magenta), and 250 m (gray) from the GAK1 mooring from April 2011 – March 2012.

Note that over the 1970 – 2016 period, the coldest waters (Fig. 2B) occurred through the first pentad of the 1970s. Thereafter temperatures warmed in association with the mid-1970s regime shift (Hare and Mantua 2000). The only other noteworthy cooling events occurred in 1991 and 2007 – 2013. The extended period of cool years late in the record was replaced by the very warm waters of 2014 – 2016, which in addition to a very strong 2015 El Niño included the recent North Pacific "blob" or "marine heat wave" (Bond et al. 2015).

Data reveal long-term trends in temperature and salinity at the surface, and averaged between 0 – 100 m and 100 – 200 m (Fig. 5). These trends are based on the monthly anomalies determined from the CTD data set between 1970 and 2014 (Kelly 2015). For clarity of presentation, the monthly anomalies were smoothed with a 25-month running mean before being plotted with trend lines. All trends are significant at the 95% level, except that for salinity between 0 and 100 m depth, which is significant at the 90% confidence level.

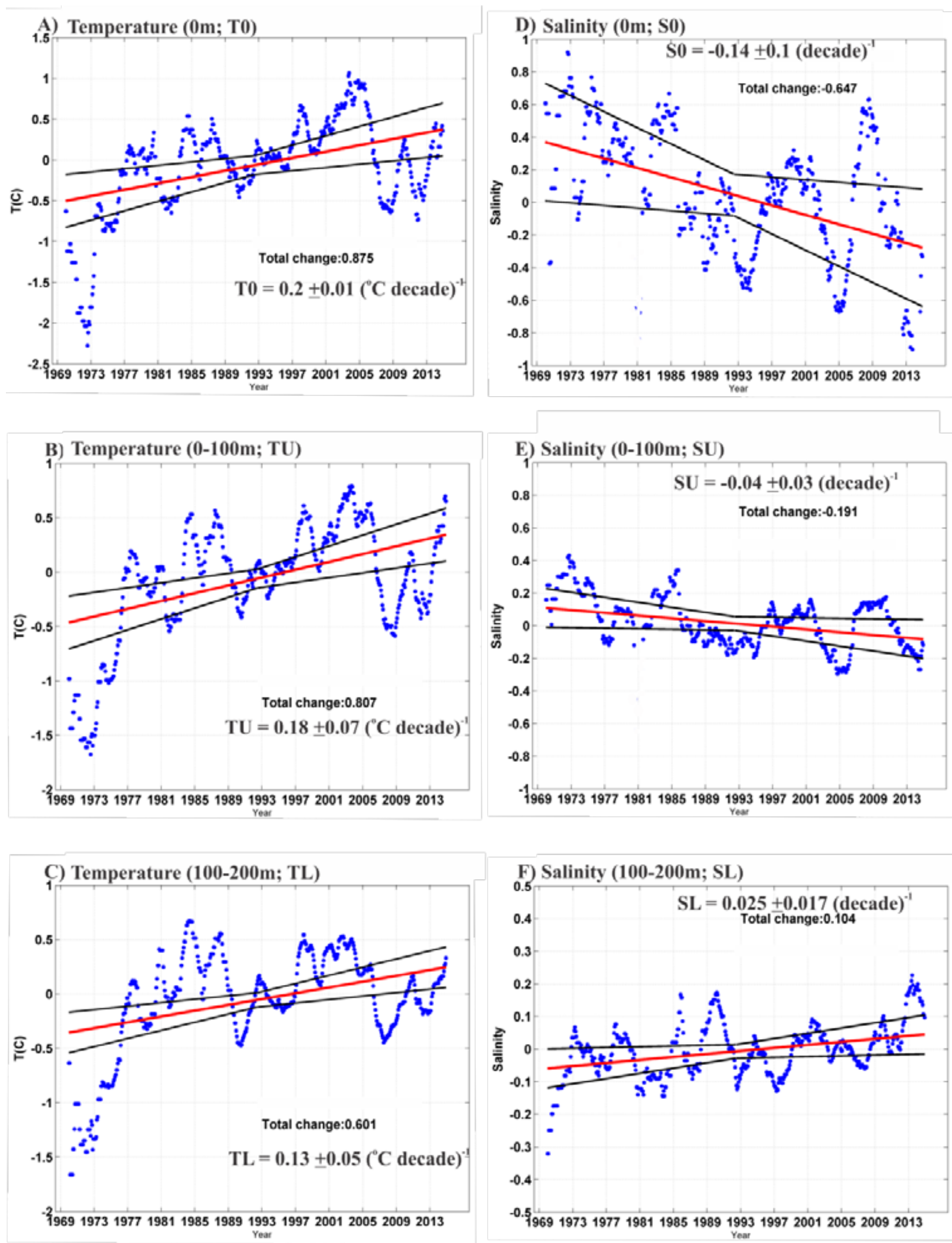

Figure 5. Long-term linear trends in monthly anomalies of temperature at the A) surface (T0), B) 0 – 100 m (TU), and C) 100 – 200 m (TL). Long-term linear trends in monthly anomalies of salinity at the D) surface (S0), E) 0 – 100m (SU), and F) 100 – 200 m (SL). All regressions are significant at the 95% level, except for SU, which is significant at the 90% level. Blue dots are the monthly anomalies smoothed with a 25-month running mean.

The results indicate that the GOA shelf has warmed by ~1.0 °C in the upper 100 m and by ~0.6 °C between 100 and 200 m in the last 46 years. Salinity has decreased by ~0.6 psu at the surface and by ~0.2 psu over the upper 100 m. In contrast, the salinity between 100 and 200 m depth has increased by ~0.1 psu. These contrasting changes in salinity between the upper and lower layers of the shelf imply that the vertical stratification of the water column has increased substantially since the early 1970s.

There is no trend in the alongshore wind stress component (Fig. 6, top panel); therefore the deep salinity increase is not associated with changes in the alongshore wind stress. Of interest is that the meridional component of the wind stress does show a significant decrease (becomes more northerly; Fig. 6, middle panel). This change is most prominent after 1995 and is associated with a change in the meridional position of the Aleutian Low (Danielson et al. 2014).

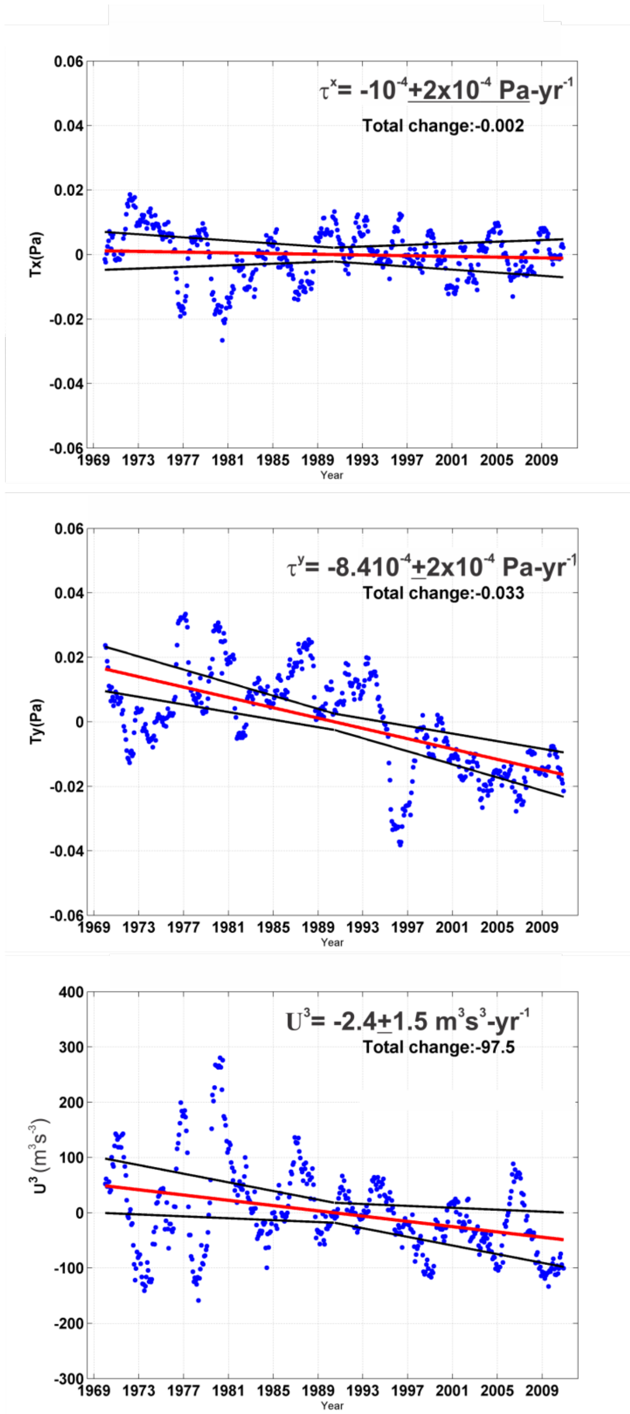

Figure 6. Long-term linear trends in monthly anomalies of the along-(τ^x; top panel) and cross-shore (τ^y; middle panel) wind stresses and wind speed cubed, U^3 (bottom panel). All regressions are significant at the 95% level, except for τ^x, which is not significant. Blue dots are the monthly anomalies after smoothing with a 13-month running mean. Anomalies have been smoothed with a 2.5-year low-pass filter.

The GAK1 measurements permit us to consider the causes, temporal evolution, and consequences of the changing shelf stratification. Inter-annual variability of the inner shelf thermal and haline stratification fields is appreciably large. In the winter of 2006-2007 (right panels of Fig. 7) deep mixing was associated with anomalously strong heat loss from the ocean to the atmosphere (in November 2006 and March 2007) and lower than average terrestrial runoff in the fall of 2007. In stark contrast, the winter of 2000-2001 (left panels of Fig. 7) had higher than average heat fluxes into the ocean and higher than average runoff. The more typical 2000-2001 winter finished with appreciably stronger water column stratification that was the result of both fresher and cooler water near the surface and warmer temperatures near the seafloor. Note (as shown previously) that the density field closely mirrors that of salinity. Cooling over 2006-2007 was associated with anomalously strong atmospheric heat losses in fall and late winter and below average fall coastal runoff. The weak runoff and oceanic heat losses weakened the winter stratification and allowed the late cooling to penetrate throughout the water column. Consequences of this dynamic are potentially important for the shelf ecosystem because of altered thermal regulation of metabolic rates and through the redistribution of subsurface nutrients as the water column de-stratifies.

The 25-month running means of the monthly anomalies indicate substantial low-frequency

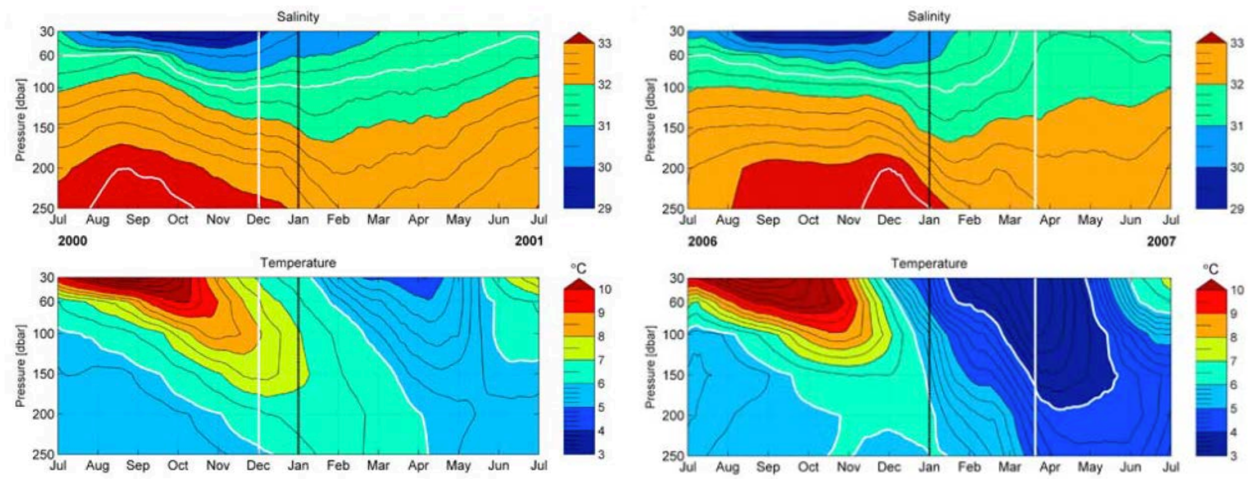

Figure 7. Salinity (top) and temperature (bottom) from July 2000 – June 2001 (left) and July 2006 – June 2007 (right). Reproduced from Janout et al. (2010).

variability in the hydrographic properties (Fig. 5). Variability at these long time scales is most likely due to basin-wide, hemispheric, or global processes. Several decadal-scale fluctuations in climate have been previously linked to low-frequency, hydrographic forcing in the GOA. These include the Pacific Decadal Oscillation (PDO, Mantua et al. 1997) and the El Niño and La Niña events of the equatorial Pacific as gauged by the Southern Oscillation (SOI) index. The PDO is the first empirical orthogonal mode of North Pacific sea surface temperature anomalies (SSTA). Its characteristic signal is approximately decadal and includes out-of-phase SSTA between the northwestern and northeastern Pacific Ocean. Fluctuations in the SSTA patterns also coincide with fluctuations in the intensity and position of the Aleutian Low. El Niño and La Niña events are initiated in the equatorial

Pacific but are linked by atmospheric and oceanic teleconnections to the North Pacific Ocean and GOA.

The North Pacific Gyre Oscillation (NPGO) is the second empirical orthogonal mode in sea surface height variability (Di Lorenzo et al. 2008, Di Lorenzo et al. 2013) and is significantly correlated with salinity, nutrients, and chlorophyll-*a* variations in the California Current and the GOA basin (specifically along Line P).

Royer and Grosch (2006) previously related GAK1 hydrographic variability to the PDO and SOI. We updated their results and find that the PDO index explains ~38% of the temperature variance but less than 15% of the salinity and discharge variance. In all cases, the maximum correlation occurs with the PDO index leading these variables by from 2 – 3 months. The SOI index explains ~20% of the temperature variance and leads the temperature signal by 8 – 9 months. The SOI index is maximally correlated with salinity when leading by 6 – 7 months but explains less than 10% of the salinity variability. The NPGO was uncorrelated with either temperature or salinity. This last result suggests that the inner shelf of the GOA is not responding to the GOA basin signatures associated with the NPGO.

GAK1 also provides important information about oceanic advection and its consequences on the inner GOA shelf. Salinity and dynamic height (computed from temperature, salinity, and pressure) at GAK1 are significant predictors of the ACC baroclinic mass transport (M_{bc}), the along-shore fresh water transport (FWT_W), and the fresh water content (FWC) (Table 1). Significance was tested at $p<0.05$ using the F-statistic determined from an analysis of variance of the regression. There are 31 degrees of freedom for November–May and 10 for June–August. R^2 is the fraction of the variance explained by the regression. The 95% confidence interval on the slope is given in parentheses. Hence, we can use the GAK1 CTD profile data as imperfect but useful proxies of the ACC.

Table 1. Relation of monthly anomalies of salinity at 30 m (S30) and 50 m (S50) depth and dynamic height over 0-200 m depth as measured at GAK1 with respect to ACC baroclinic mass transport (M_{bc}), the along-shore fresh water transport (FWT_W) and the fresh water content (FWC). Reproduced following Weingartner et al. (2005).

Dependent Variable	Independent Variable	Months	R^2	Slope
M_{bc}	*S30*	Nov-May	0.47	0.69 (.28)
M_{bc}	*S50*	Jun-Aug	0.72	-0.85 (.43)
M_{bc}	*DH200*	Jun-Aug	0.86	0.93 (.30)
FWT_W	*S30*	Nov-May	0.62	0.79 (.23)
FWT_W	*DH200*	Nov-May	0.39	-0.63 (.29)
FWT_W	*DH200*	Jun-Aug	0.63	0.79 (.50)
FWC	*DH200*	Nov-May	0.73	0.85 (.20)

DISCUSSION

The GAK1 data collected over the past 5 decades supports previous findings of a long-term trend in warming over the GOA shelf, an increase in deep (>100 m) salinities, and a decrease in upper ocean (0 – 100 m) salinities. The latter finding is in agreement with the long-term trend toward increasing discharge throughout the GOA (Hill et al. 2015, Beamer et al. 2016). These results have important biological implications. A warming environment should affect metabolic activities of a host of marine species, although it remains unclear what the ramifications of these changes will be on the ecosystem as a whole. Note that the temperature trends are slightly lower than those reported by Royer and Grosch (2006). The differences are associated with anomalous cooling over 2007-2013.

The deep salinity increase is somewhat surprising. That increase reflects exchanges with the basin, which occurs most prominently on an annual basis with the seasonal relaxation in alongshore wind stress (Royer 1975, Weingartner et al. 2005). This is evident in the salinity data shown in Figure 2a and at 200 and 250 m depths in the middle panel of Figure 4 (as an example of a particular year). We therefore examined the long-term trend in alongshore wind stress, $\tau^x = \rho_a C_D U \vec{U}$ where ρ_a is the air density, C_D is a drag coefficient, U is the wind speed, and $\vec{U}$ is the zonal wind component. We have also examined changes in the cross-shore wind stress ($\tau^y = \rho_a C_D U \vec{V}$, where $\vec{V}$ is the meridional component of the wind.) Two other possible mechanisms are responsible for the deep salinity increase. The first is simply associated with a decrease in vertical mixing efficiency. This would be brought about by an increase in discharge (as observed) and/or a change in wind speeds. In particular, vertical mixing is proportional to $U^3$and? U^3 has significantly decreased through time so that wind-driven mixing has decreased over the shelf in the past 40 years (Fig. 6). The last mechanism potentially involved in the deep salinity increase is a change in the salinity of the waters bathing the outer edge of the GOA continental slope. Such changes could be assessed using the plethora of ARGO floats that have been deployed in the GOA basin over the past 15 years. This effort is beyond the scope of the present work, but worth undertaking in the future.

Of particular significance is that the GOA shelf is undergoing a substantial change toward increasing stratification. This increase appears to be a response to surface freshening due to increased coastal freshwater discharge, a reduction in wind mixing, and an increase in deep salinity. The reasons for the deep salinity increase are uncertain. The increase may simply be related to a decrease in vertical mixing efficiency due to the combined increase in discharge and decrease in wind speed. It does not appear to be related to changes in the along-shore wind stress that would induce changes in the position of the shelf break front that separates fresher shelf waters from saltier slope waters. There may be other pathways by which slope waters intrude on the shelf involving topographically-induced exchanges, but these potential mechanisms are not obvious. Finally, the deep salinity increase could be related to increasing salinities within the GOA basin and along the GOA continental slope, but this mechanism remains to be explored.

The sustained change in stratification has potentially tremendous implications on the GOA marine ecosystem. This change could not have been detected without the long-term monitoring at GAK1. The biological implications of such a change could have substantial ecosystem and economic affects for the GOA. Detecting and quantifying such changes requires sustained ecosystem monitoring.

We have continued to monitor the GOA shelf manifestation of the “warm blob” heat anomaly documented by Bond et al. (2015) over the GOA basin. The GAK1 data indicates that this anomaly first appeared on the shelf in the fall of 2014. The warm anomaly amounted to ~3°C and first appeared in late summer of 2014 in the upper 50 – 75 m of the water column. It then spread throughout the entire water column in the winter of 2015 with depth averaged temperature anomalies being ~2°C. The winter warming anomaly was accompanied by a freshening throughout the water column, which resulted in depth-averaged salinity anomalies of -0.3 to -0.4 psu. Both temperature and salinity anomalies persisted and were present again in the beginning of 2016.

Other reasons to monitor the inner GOA shelf relate to understanding along-shelf advection and its influence on the transport of heat, fresh water, nutrients, and a variety of plankton types. The GAK1 measurements provide suitable proxies for assessing these transports with seasonally varying relations between the transport and the hydrographic properties (Weingartner et al. 2005). Remotely sensed altimeter data also offers an opportunity to assess flows along the continental shelf and slope regions.

CONCLUSIONS

Our major finding is that the GOA shelf has been warming over the past 4.5 decades by nearly 1°C within the upper 100 m and by 0.6°C between 100 and 200 m. These temperature changes have been accompanied by a salinity decrease of ~0.2 psu in the upper 100 m and by a salinity increase of ~0.1 psu at 100 to 200 m. The net result of these changes has been an increase in stratification over the shelf. The upper ocean freshening is associated with higher coastal discharge and increased melting rates of coastal mountain glaciers. The deep salinity increase may be associated with enhanced stratification and a reduction in the rate of wind mixing and/or changes in the properties of the slope waters that annually replenish the deep shelf waters. To investigate this possibility would require assembly of historical temperature and salinity data from the basin and slope and the ~decadal-long ARGO float profiling data set that is continuing across the global ocean.

These trends in ocean physical conditions would not have been detected without long-term monitoring such as the GAK1 data set, which is now entering its 47th year.

ACKNOWLEDGEMENTS

The authors thank the many captains, crews, and technicians on board vessels that have gone to GAK1 for mooring turnarounds and CTD profiles since 2012 and before. In the last 5 years these include Mike Brittain on the *M/V* Dora, Billy Pepper on the *R/V* Tiglax, Andy Schroeder on the *M/V* Island C, Rollins Apperson and Edward de Castro on the *R/V* Little Dipper, and the *R/V* Sikuliaq. We extend our gratitude to Seward Marine Center technicians Phyllis Schumacher and Steven Hartz and especially David Leech and Peter Shipton for continuing the GAK1 sampling from year to year and in all seasons. The views expressed here are our own and do not necessarily represent those of the *Exxon Valdez* Oil Spill Trustee Council.

LITERATURE CITED

Anderson, P. J., and J. F. Piatt. 1999. Community reorganization in the Gulf of Alaska following ocean climate regime shift, Marine Ecology Progress Series 189:117-123.

Batten, S. D., S. Moffitt, W. S. Pegau, and R. Campbell. 2016. Plankton indices explain interannual variability in Prince William Sound herring first year growth. Fisheries Oceanography 25:420–432. doi:10.1111/fog.12162

Beamer, J., D. F. Hill, A. Arendt, and G. Liston. 2016. High-resolution modeling of coastal freshwater discharge and glacier mass balance in the Gulf of Alaska watershed. Water Resources Research. doi:10.1002/2015WR018457

Bond, N. A., M. F. Cronin, H. Freeland, and N. Mantua. 2015. Causes and impacts of the 2014 warm anomaly in the NE Pacific. Geophysical Research Letters 42:3414-3420. doi:10.1002/2015GL06306

Childers, A. R., T. E. Whitledge, and D. A. Stockwell, 2005. Seasonal and interannual variability in the distribution of nutrients and chlorophyll-a across the Gulf of Alaska shelf: 1998–2000, Deep Sea Research Part II 52:193–216. doi:10.1016/j.dsr2.2004.09.018

Danielson, S. L., T. W. Weingartner, K. Hedstrom, K. Aagaard, R. Woodgate, E. Curchitser, and P. Stabeno. 2014. Coupled wind-forced controls of the Bering–Chukchi shelf circulation and the Bering Strait through- flow: Ekman transport, continental shelf waves, and variations of the Pacific–Arctic sea surface height gradient. Progress in Oceanography http://dx.doi.org/ 10.1016/j.pocean.2014.04.006.

Di Lorenzo E., N. Schneider, K. M. Cobb, K. Chhak, P. J. S. Franks, A. J. Miller, J. C. McWilliams, S. J. Bograd, H. Arango, E. Curchister, T. M. Powell, and P. Rivere. 2008. North Pacific Gyre Oscillation links ocean climate and ecosystem change. Geophysical Research Letters 35:L08607. doi:10.1029/2007GL032838.

Di Lorenzo, E., V. Combes, J. E. Keister, P. T. Strub, A. C. Thomas, P. J. S. Franks, M. D. Ohman, J. C. Furtado, A. Bracco, S. J. Bograd, W. T. Peterson, F. B. Schwing, S. Chiba, B. Taguchi, S. Hormazabal, and C. Parada. 2013. Synthesis of Pacific Ocean climate and ecosystem dynamics. Oceanography 26:68–81. http://dx.doi.org/10.5670/oceanog.2013.76.

Eggers, D. M., C. Tide, and A. M. Carroll, editors. 2013. Run forecasts and harvest projections for 2013 Alaska salmon fisheries and review of the 2012 season. Alaska Department of Fish and Game, Special Publication No. 13-03, Anchorage, Alaska, USA.

Evans, W., J. T. Mathis, P. Winsor, H. Statscewich, and T. E. Whitledg. 2013. A regression modeling approach for studying carbonate system variability in the northern Gulf of

Alaska. Journal of Geophysical Research: Oceans 118:476–489. doi:10.1029/2012JC008246.

Fedewa, E. J., J. A. Miller, and T. P. Hurst. 2015. Pre-settlement processes of northern rock sole (*Lepidopsetta polyxystra*) in relation to interannual variability in the Gulf of Alaska. Journal of Sea Research 111:25-36. http://dx.doi.org/10.1016/j.seares.2015.11.008

Hallmann, N., B. R. Schöne, G. V. Irvine, M. Burchell, E. D. Cockelet, and M. R. Hilton. 2011. An improved understanding of the Alaska coastal current: the application of a bivalve growth temperature model to reconstruct freshwater-influenced paleoenvironments. Palaios 26:346e363.

Hare, S. R., and N. J. Mantua, 2000. Empirical evidence for North Pacific regime shifts in 1977 and 1989. Progress in Oceanography 47:103–145.

Hill, D. F., N. Bruhis, S. E. Calos, A. Arendt., J. Beamer. 2015. Spatial and temporal variability of freshwater discharge into the Gulf of Alaska. Journal of Geophysical Research 120:634-646.

Horning, M., and J. A. E. Mellish. 2014. In cold blood: evidence of Pacific sleeper shark (*Somniosus pacificus*) predation on Steller sea lions (*Eumetopias jubatus*) in the Gulf of Alaska. Fishery Bulletin 112:297-310. doi:10.7755/FB.112.4.6

Janout, M. A., T. J. Weingartner, T. C. Royer, and S. L. Danielson. 2010. On the nature of winter cooling and the recent temperature shift on the northern Gulf of Alaska shelf. Journal of Geophysical Research: Oceans 115:C05023. doi:10.1029/2009JC005774

Janout, M. A., T. J. Weingartner, and P. J. Stabeno. 2013. Air-sea and oceanic heat flux contributions to the heat budget of the northern Gulf of Alaska shelf. Journal of Geophysical Research: Oceans 118:1807-1820. doi:10.1002/jgrc.20095

Munro, A. R., and C. Tide, editors. 2014. Run forecasts and harvest projections for 2014 Alaska salmon fisheries and review of the 2013 season. Alaska Department of Fish and Game, Special Publication No. 14-10, Anchorage, Alaska, USA.

Kelly, J. 2015. An examination of hydrography and sea level in the Gulf of Alaska. M.S. Thesis, University of Alaska Fairbanks, Alaska, USA

Mantua, N. J., S. R. Hare, Y. Zhang, J. M. Wallace, and R. C. Francis. 1997. A Pacific interdecadal climate oscillation with impacts on salmon production. Bulletin of the American Meteorological Society 78:1069-1079.

Mueter, F. J., B. L. Norcross and T. C. Royer. 1994. Do cyclic temperatures cause cyclic fisheries? Canadian Special Publication of Fisheries and Aquatic Sciences 121:119-129.

Mueter, F. J. 2004. Gulf of Alaska - Marine Ecosystems of the North Pacific. PICES Special Publication 1:153-175.

Royer, T. C. 1975. Seasonal variations of waters in the northern Gulf of Alaska. Deep-Sea Research 22:403-416.

Royer, T. C. 2005. Hydrographic responses at a coastal site in the northern Gulf of Alaska to seasonal and interannual forcing. Deep-Sea Research Part II-Topical Studies in Oceanography 52:267-288.

Royer, T. C., and C. E Grosch. 2006. Ocean warming and freshening in the northern Gulf of Alaska. Geophysical Research Letters. 33:L16605. DOI:10.1029/2006GL026767

Sarkar, N. 2007. Mixed layer dynamics along the Seward Line in the northern Gulf of Alaska, Doctoral dissertation, Old Dominion University, Norfolk, VA, USA.

Stearns, L. A., G. S. Hamilton, C. J. van der Veen, D. C. Finnegan, S. O'Neel, J. B. Scheick, and D. E. Lawson. 2015. Glaciological and marine geological controls on terminus dynamics of Hubbard Glacier, southeast Alaska. Journal of Geophysical Research: Earth Surface. 120:1065–1081. doi:10.1002/2014JF003341

Wang, Y., H. Xue, F. Chai, Y. Chao, J. Farrara. 2014. A model study of the Copper River plume and its effects on the northern Gulf of Alaska. Ocean Dynamics 64:241-258. doi:10.1007/s10236-013-0684-3

Weingartner, T., B. Finney, L. Haldorson, P. Stabeno, J. Napp, S. Strom, R. Brodeur, M. Dagg, R. Hopcroft, A. Hermann, S. Hinckley, T. Royer, T. Whitledge, K. Coyle, T. Kline, E. Lessard, D. Haidvogel, E. Farley, and C. Lee. 2002. The Northeast Pacific GLOBEC Program: Coastal Gulf of Alaska. Oceanography Magazine 15:30-35.

Weingartner, T. J., S. L. Danielson, and T. C. Royer. 2005. Freshwater variability and predictability in the Alaska Coastal Current, Deep Sea Research Part II 52:169–191. doi:10.1016/j.dsr2.2004.09.030

Wu, J., A. Aguilar-Islas, R. Rember, T. Weingartner, S. Danielson, and T. Whitledge. 2009. Size-fractionated iron distribution on the northern Gulf of Alaska, Geophysical Research Letters 36:L11606. doi:10.1029/2009GL038304

Zador, S., editor. 2012. North Pacific Fishery Management Council ecosystem considerations for 2013 for the North Pacific groundfish stock assessment and fishery evaluation report. Resource Ecology and Fisheries Management Division, Alaska Fisheries Science Center, National Marine Fisheries Service, NOAA, Seattle, Washington, USA.

Zador, S., editor. 2013. North Pacific Fishery Management Council ecosystem considerations for 2014 for the North Pacific groundfish stock assessment and fishery evaluation report. Resource Ecology and Fisheries Management Division, Alaska Fisheries Science Center, National Marine Fisheries Service, NOAA, Seattle, Washington, USA.

OTHER REFERENCES

University of Alaska Fairbanks GAK1 home page: http://research.cfos.uaf.edu/gak1/

Gulf Watch Alaska GAK1 web site:
http://www.gulfwatchalaska.org/monitoring/environmental-drivers/gulf-of-alaska-mooring-gak1-monitoring/

AOOS Gulf of Alaska Data Portal GAK1 data archive: http://portal.aoos.org/gulf-of-alaska.php#metadata/3c4ecb88-6436-4312-8281-ed584e020b0e/project