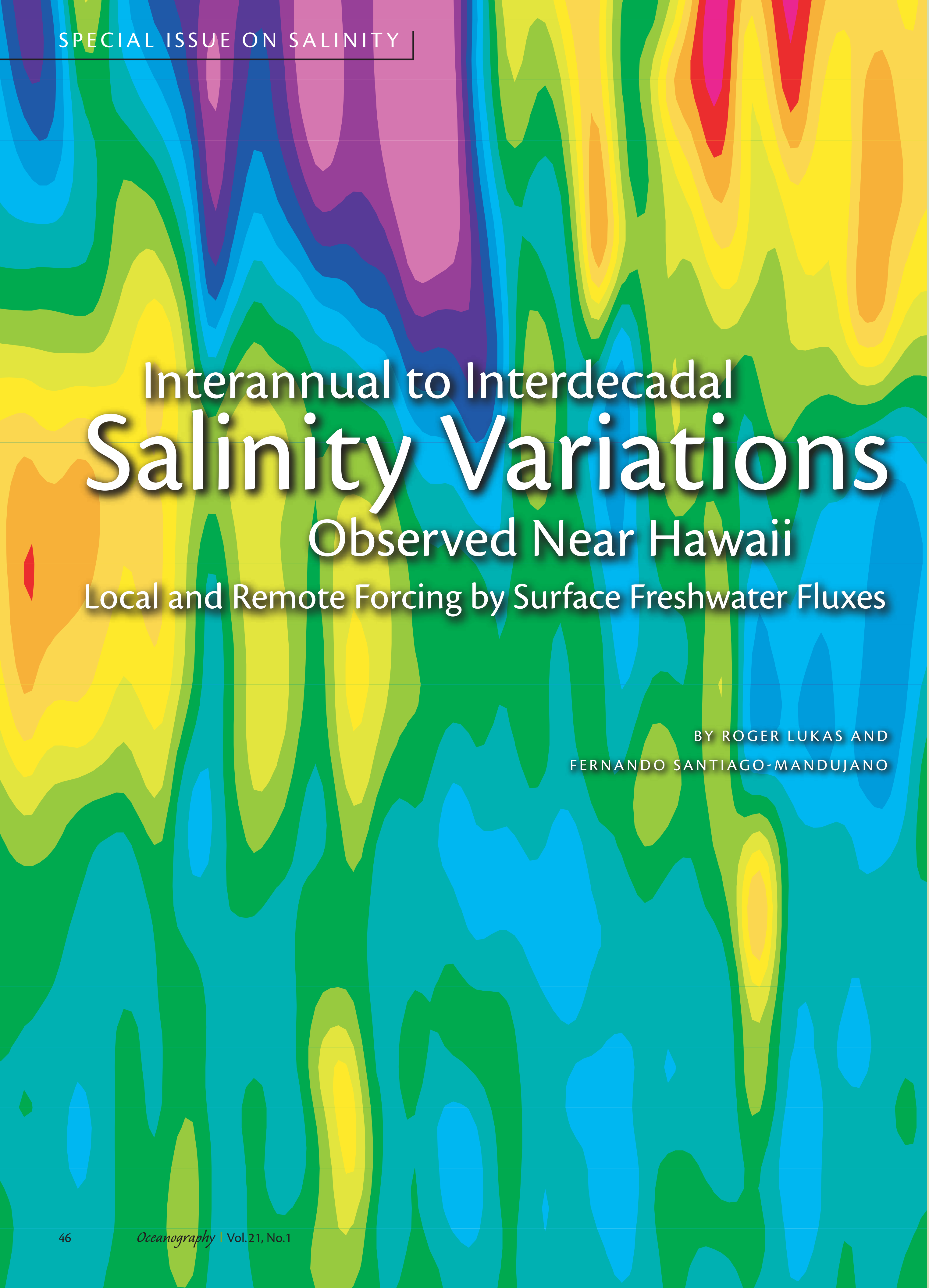

Interannual to Interdecadal Salinity Variations Observed Near Hawaii

Local and Remote Forcing by Surface Freshwater Fluxes

BY ROGER LUKAS AND FERNANDO SANTIAGO-MANDUJANO

Ray Schmitt's introduction to this issue underlines the importance of including the oceanic component of the hydrological cycle in considerations of Earth's climate. Spatial and temporal salinity variations play an important role in diapycnal (across-density-surface) mixing, affecting property distributions and ocean circulation, which may in turn affect the atmosphere through sea-surface temperature.

Unfortunately, the historical distribution of subsurface salinity observations is generally very sparse, especially lacking adequate temporal resolution to confidently study climate cycles and trends. Energetic, high-frequency salinity variations resulting from vertical motions of internal waves must also be resolved or appropriately filtered, or these signals will be aliased into lower frequencies. There are only a handful of deep ocean sites with requisite sustained high-vertical-resolution time series. Among them are the Hawaii Ocean Time-series (HOT) Station ALOHA, and the Bermuda-Atlantic Time series Study (BATS) and *Panulirus* stations off Bermuda (Karl et al., 2001).

Station ALOHA, located 100 km north of Oahu, occupies a 10-km-radius circle centered on 22°45′N, 158°W. It is slightly south of the climatological center of the zonally elongated surface salinity maximum of the North Pacific subtropical gyre (see Figure 1b in Schmitt, page 18 this issue). This station has been occupied approximately monthly since October 1988, with support from the National Science Foundation and the State of Hawaii. Each ALOHA cruise plan includes numerous physical and biogeochemical observations (Karl and Lukas, 1996; Karl et al., 2001; annual data reports at www.soest.hawaii.edu/HOT_WOCE); the plans also include a 36-hour period of three-hourly repeat conductivity-temperature-depth (CTD) profiling to 1000 m to help resolve high-frequency phenomena such as baroclinic tides (cf. Chiswell, 1994) and avoid aliasing. Most cruises also call for at least one full-depth (4.8-km) profile. The salinity profiles are calibrated against water samples that are accurate to better than 0.003 and internally consistent at a level of 0.001 (Lukas et al., 2001).

Significant variations in salinity have been observed at Station ALOHA (e.g., Lukas, 2001), but even our 19-year-long time series is too short to adequately capture the longer time scales. We have thus tried to extend our salinity time series back in time. To construct a longer record of surface salinity for the vicinity of Oahu, we joined the HOT cruise-averaged salinity values from 0–4-m depth with the measurements from bucket samples that were obtained off Koko Head, Oahu, from 1956 to 1992 (Murphy et al., 1960; Seckel and Yong, 1977). Koko Head is relatively far from streams flowing to the coastal ocean around Oahu. It also projects into the Molokai Channel, and is thus representative of the deep ocean conditions around Oahu and the northwestward flow of the North Hawaiian Ridge Current (Firing, 1996; Bingham, 1998). Measurements were made weekly at the beginning, and usually twice weekly from 1962 until 1983. From 1983, measurements were made either weekly or twice weekly, but after 1989, sampling was very inconsistent. Fortunately, the later observations overlapped sufficiently with our HOT measurements for us to determine that they compared well.

...the historical distribution of subsurface salinity observations is generally very sparse...

The subsurface salinity observations at Station ALOHA have been placed in an approximate historical context by analyzing the available hydrographic station data (Curry, 1996; Macdonald et al., 2001) taken within a 200-km radius. Only stations in deep water north of the islands were used. The relatively sparse hydrographic sampling in the region prior to HOT makes it necessary to use this large area in order to have enough temporal resolution to contour. Obviously, spatial variability is convolved with the temporal variability, but the effects of that are unknown.

ISOPYCNAL ANALYSIS OF SALINITY ANOMALIES

Salinity, temperature, and pressure are related to potential density by the equation of state. A traditional approach in physical oceanography is to analyze variables on potential density surfaces—potential isopycnals referred to hereafter simply as "isopycnals." This approach effectively filters out the variability of water-mass properties due to vertical displacements ("heaving") of isopycnals by internal waves and Ekman pumping. It does not, however, remove the along-isopycnal advective influences of those waves, which may be important for very-long-period Rossby waves. Along a submerged isopycnal, variations in salinity are compensated by variations in potential temperature, assuming that variations in isopycnal depth are not too large. Such compensated salinity anomalies are dynamically passive, which means that they do not disperse on their own; rather, mixing processes are required to diffuse them. Given the relatively low levels of diapycnal mixing observed in the main thermocline, it is reasonable to expect that variations of salinity on isopycnals will reflect variations of hydrological cycle forcing where the isopycnals are ventilated.

For surface waters in contact with the atmosphere, temperature and salinity are generally determined by surface heat and freshwater fluxes, and by local vertical mixing, all of which have substantial spatial and temporal variations. Fortunately, the ocean mixed layer integrates atmospheric surface forcing in time, thus acting as a low-pass filter in many respects. In addition, Rudnick and Ferrari (1999) show that despite considerable spatial variations in salinity and temperature in the mixed layer, most of the observed variability is density compensated. This compensation results from stirring and diffusion (Ferrari and Paparella, 2003) associated with density-driven flows on relatively short time scales. After these surface waters have been subducted in late winter (Stommel, 1979) and incorporated into the subtropical gyre, the remaining vertical salinity gradients can lead to vertical mixing by salt fingers that meld the new waters into the temperature-salinity relation of the thermocline (Schmitt, 1999).

Following Stommel's (1979) seminal paper on the subduction of wintertime

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mixed layer waters, Luyten et al. (1983) developed the modern thermocline ventilation theory, which Talley (1985) applied to observations to determine the climatological sources of the shallow salinity minimum waters found in the eastern North Pacific. Thus, suitably observed variations in the subsurface ocean climate can be inverted to estimate coherent and persistent patterns of past surface heat and freshwater fluxes (e.g., Huang and Pedlosky, 1999; Huang, 2000; Stammer et al., 2004).

Because isopycnals are ventilated farther poleward with increasing depth/density, and because the time-averaged circulation generally weakens with depth, profile time series provide a paleoceanographic perspective on surface conditions at successively distant locations at ever-earlier times in the past. Just as paleoceanographers drill holes in seafloor sediments to develop a proxy time series of past temperatures (and other properties) in the surface waters above, hydrographers working at time-series stations repeatedly drill holes in the ocean with CTDs and rosette samplers to develop a high-resolution record of subsurface water property variations that reflect earlier variations of surface conditions at remote locations, as well as the variations in advection and mixing in between. As with paleoceanographic data, geochemical, ocean circulation, and climate models are needed to interpret the sparse time series and to reconstruct previous variability (e.g., Huang and Pedlosky, 1999). Further, hydrographic time series with high enough temporal resolution can be used in dynamic analyses of the ocean state to strongly constrain previous upstream as well as subsequent downstream conditions (Stammer et al., in press).

Large-scale variations in advection within the subtropical gyre can also occur, due to surface wind stress curl variations and westward-propagating Rossby waves. Such circulation anomalies can advect the mean salinity gradients on isopycnal surfaces, which need to be accounted for in quantitatively estimating the contributions from subduction of surface salinity anomalies. This calculation is very challenging, but dynamic data assimilation has now been successfully used to adjust initial surface-flux estimates to be consistent with observations in the context of a non-eddy-resolving model (Stammer et al., 2004). Douglass et al. (2006) used the corresponding ocean state estimates to study coherent, decadal-time-scale changes in component currents of the North Pacific subtropical gyre.

SALINITY AT STATION ALOHA AND MULTIPLE CONNECTIONS TO THE SURFACE

The Potential Temperature-Salinity Relationship

The mean potential temperature-salinity (θ-S) relationship at Station ALOHA (Figure 1) is characteristic of the North Pacific subtropical gyre (Sverdrup et al., 1942), which is ventilated to a maximum potential density of about

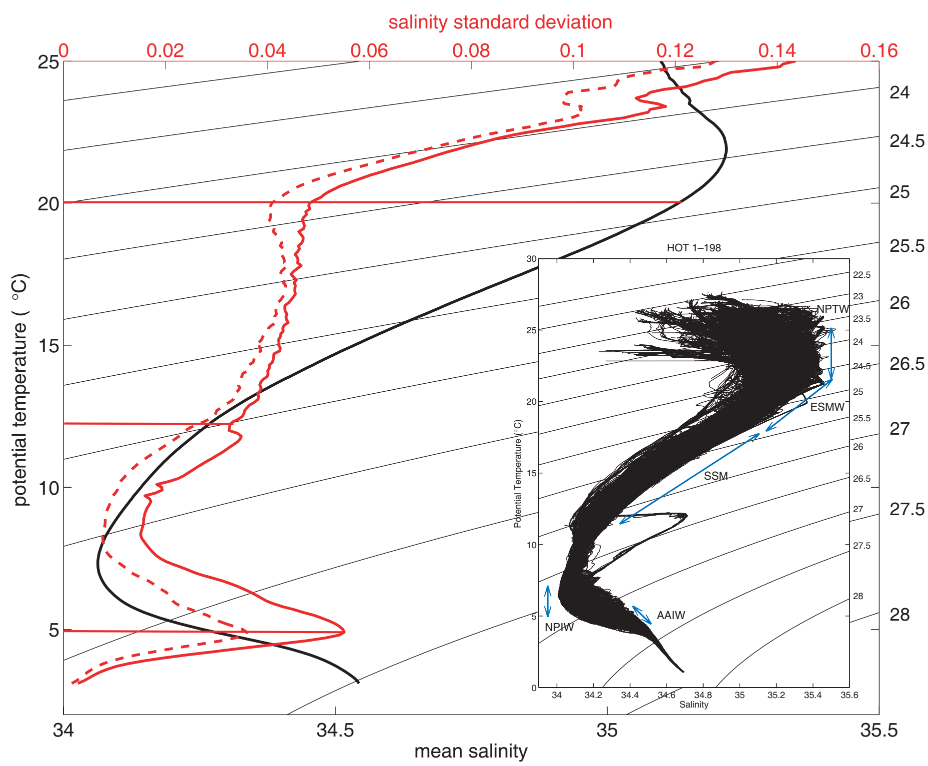

Figure 1. Mean potential temperature-salinity (θ-S) curve (thick black curve) from more than 2600 CTD profiles at Station ALOHA compiled in the inset. Salinity data were averaged within θ intervals of 0.1°C. The standard deviation of salinity within these intervals is given as a function of θ (solid red curve). The dashed red curve indicates the standard deviation of annually averaged salinity. Contours of potential density anomaly are indicated by thin black curves. Horizontal red lines are selected values of θ corresponding to features in the variability curves discussed in the text. The intersection of these lines with the mean θ-S curve gives the approximate potential density for these features.

26.8 kg m^{-3}, while denser waters derive from Southern Hemisphere sources and downward diffusion. The water masses present in the upper kilometer at ALOHA are the North Pacific Tropical Water (NPTW), the Eastern North Pacific Subtropical Mode Water (ESMW), the Shallow Salinity Minima (SSM), the North Pacific Intermediate Water (NPIW), and the Antarctic Intermediate Water (AAIW). NPTW is formed in the central subtropical gyre near the subtropical fronts where it is subducted and advected to ALOHA (Suga et al., 2000), where it presents as a subsurface salinity maximum (Figure 1) between 24.3 and 24.7 σ_θ (mean depths of 100–140 m). Interannual variations associated with El Niño-Southern Oscillation (ENSO) sometimes result in NPTW formation at Station ALOHA, with the most saline waters occurring in the surface mixed layer. Also subject to considerable interannual variability, the fresher ESMW is formed in the region 25–30°N, 135–140°W (Hautala and Roemmich, 1998; Hosoda et al., 2001), influencing Station ALOHA in the density range 24–25.4 σ_θ. The ESMW and the NPTW compete for dominance at ALOHA.

SSM waters are formed at the surface in the area 35–50°N, 145–160°W in the density range 25.1–26.2 σ_θ, and then are carried by the California Current and the North Equatorial Current to Hawaii (Tsuchiya, 1982; Yuan and Talley, 1992). Because SSM waters are found above the pronounced salinity minimum of the NPIW at Station ALOHA, they simply bridge the range of salinity from the NPIW to the salinity maximum of the NPTW. Complex subsurface interactions along the western boundary of the North Pacific are thought to form NPIW (Talley, 1993), which is then carried within the lowest portions of the subtropical gyre to ALOHA (Reid, 1965; Kennan and Lukas, 1996). AAIW is formed in the mid-latitude southwest Pacific and carried across the equator along the western boundary (Tsuchiya, 1991) where it turns into the interior of the North Pacific around 10–12°N and mixes with the NPIW above (Reid, 1965; Kennan, 1993).

Salinity variability observed on isopycnals at ALOHA (Figure 1) decreases sharply from the surface layer through the salinity maximum (S_{max}) near 24.5 σ_θ, but then decreases less noticeably between 24.8 σ_θ and 26 σ_θ. Variations among annual averages account for most of the salinity variability over these upper portions of the water column, while seasonal variations and eddies account for a significant fraction of variability between 26.0 σ_θ and 27.1 σ_θ (Bingham and Lukas, 1996). A minimum in variability is found near 26.5 σ_θ. Variability then increases downward through the NPIW centered at 26.8 σ_θ and into the AIW centered near 27.2 σ_θ. This region of enhanced variability is subject to intrusive finestructure (Kennan and Lukas, 1996), but considerable longer-term variability is evident as well, which may be due to meridional migrations of intermediate water-mass boundaries found near Hawaii (Hamann and Swift, 1991).

There are only a handful of deep ocean sites with requisite sustained high-vertical-resolution time series.

Cycles and Trends in Selected Layers

Surface Mixed Layer

El Niño and the Pacific Decadal Oscillation (PDO) markedly affect rainfall patterns over the North Pacific Ocean (Lukas, 2001). The combined effect of these two climate signals on rainfall near Hawaii during 1998 was very significant; a prolonged drought associated with the PDO was exacerbated by the mature phase of the 1997–1998 El Niño event. Because the time scales associated with these climate perturbations are relatively long, the accumulated impact of the rainfall anomalies on upper ocean salinity was quite pronounced.

From late 1997 through 1998, upper ocean salinity (Figure 2a) at Station ALOHA increased rapidly by about 0.5, resulting in the saltiest conditions since the start of our observations in 1988. In fact, this high-salinity anomaly was unprecedented in the 50-year-long record of upper-ocean salinity near Oahu. The duration of the unusually salty conditions was also remarkable, lasting through 2003. A comparable salinity increase was observed during the 1969/70 winter, coinciding with mature El Niño conditions. However, that change simply returned salinity levels to near average from anomalously fresh conditions. During the mature phase of the 1982/83 El Niño, a similarly rapid increase of salinity occurred. While there were fresh anomalies prior to that event, they were not nearly as strong as during 1968. The 1982/83 event also left high-salinity anomalies in its wake, diminishing over the next two years.

Surface salinity observations through the 1990s are too sparse to directly reconstruct the spatial structure of the high-salinity anomalies that were observed at Station ALOHA. The Consortium for Estimating the Circulation and Climate of the Ocean (ECCO) used the MIT ocean circulation model, the National Centers for Environmental Prediction/National Center for Atmospheric Research reanalysis surface fluxes, and various ocean observations to produce a dynamically consistent ocean state estimation for the period starting with the 1992 launch of the TOPEX/Poseidon altimetric satellite mission (Stammer et al., 2004). Because the surface fluxes were also included in the state estimation, some of their well-known biases were minimized. The resulting surface salinity anomalies for 1998–2001, relative to the 1992–2003 mean, are shown in Figure 3. Coherent, large-scale anomalies of both signs are seen during this period, with those around Hawaii connecting to salty

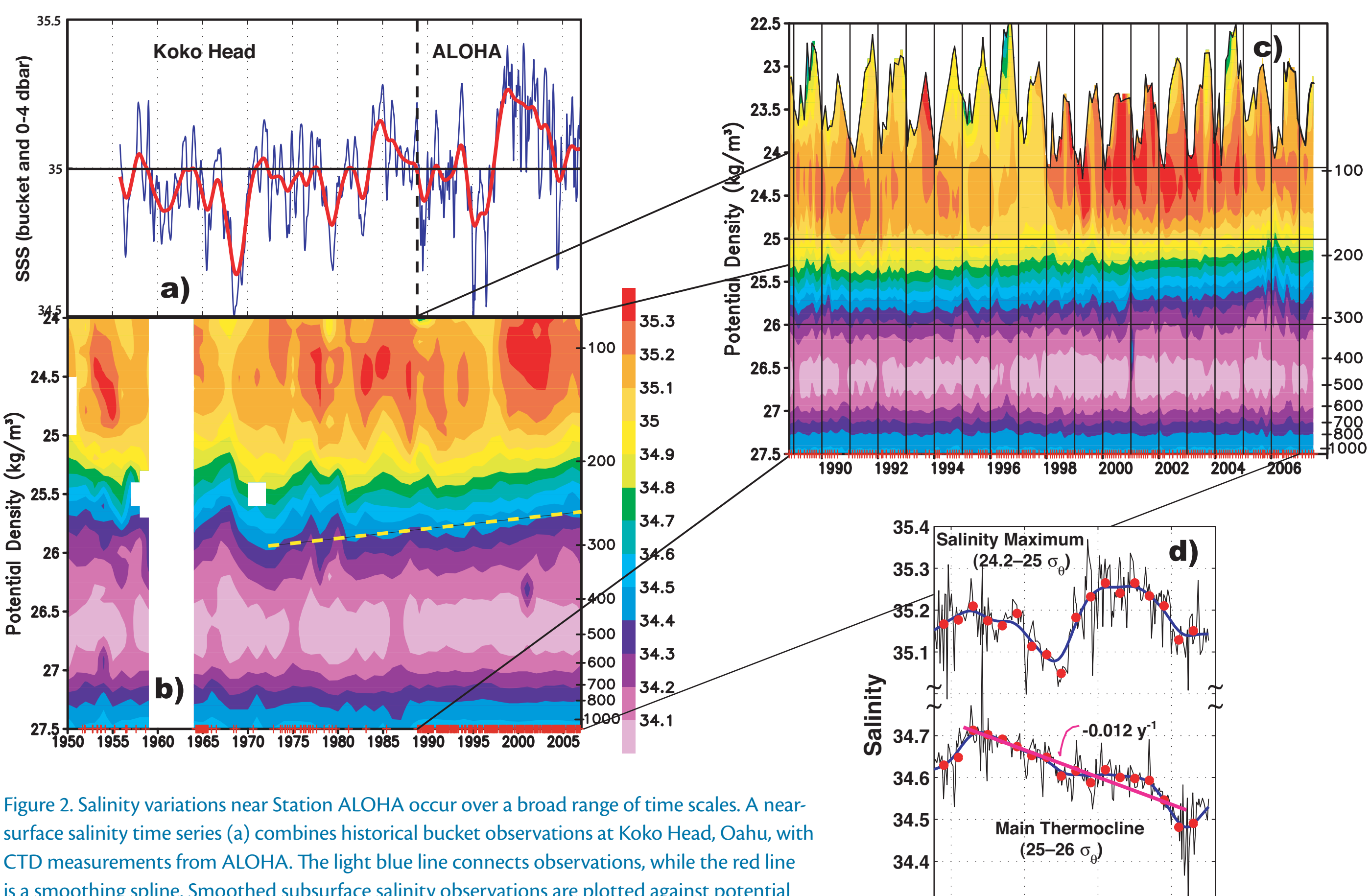

Figure 2. Salinity variations near Station ALOHA occur over a broad range of time scales. A near-surface salinity time series (a) combines historical bucket observations at Koko Head, Oahu, with CTD measurements from ALOHA. The light blue line connects observations, while the red line is a smoothing spline. Smoothed subsurface salinity observations are plotted against potential density (b), combining available historical hydrographic station data (Curry, 1996; Macdonald et al., 2001) taken within a 200-km radius with annually averaged salinity profiles from HOT. Times of individual stations are indicated by red tick marks. The long-term average depths of selected isopycnals are indicated along the right-hand axis. The dashed yellow line indicates an apparent decrease in the potential density of neighboring isohalines. HOT observations at ALOHA are expanded in (c) showing details of variability. The thin black line indicates the density of the surface mixed layer. Time series of salinity averaged over potential density in the region of the salinity maximum and in the mid-thermocline (d) indicate systematic variations over nearly two decades. Black lines connect cruise-averaged data, while red dots are annual averages. The blue lines are smoothing splines.

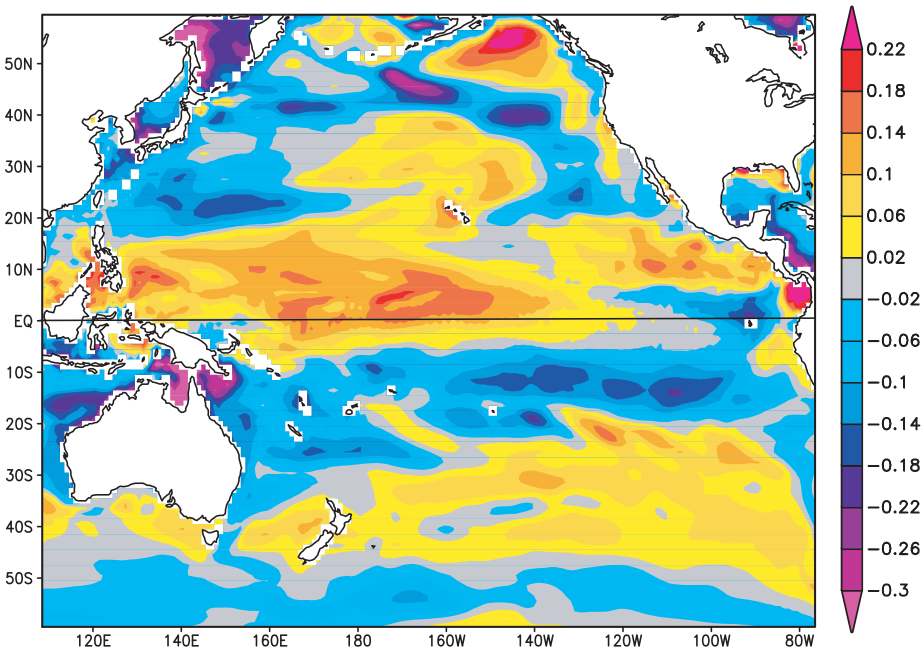

Figure 3. Sea-surface salinity anomalies (color bar) for 1998–2001 relative to the 1992–2001 average from the Consortium for Estimating the Circulation and Climate of the Ocean (ECCO) reanalysis of Stammer et al. (2004). Note the large spatial scales of the anomalies.

surface waters across the tropical Pacific. The salinity anomalies near Hawaii are only about half the magnitude observed in Figure 2a, although much of the difference is due to the different base periods for computing anomalies. While the error characteristics for surface salinity in the ECCO reanalysis are not well known, the four-year average in Figure 3 qualitatively reflects estimated rainfall anomalies in the National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center Merged Analysis of Precipitation data set (not shown), in which the accumulated rainfall deficit for 1998–2001 was more than 0.5 m around Hawaii, and more than 3 m in the equatorial western Pacific and the Intertropical Convergence Zone area in the central tropical Pacific.

An impact of this strong hydrological forcing of the surface mixed layer was to reduce the oceanic sink for CO_2 (Dore et al., 2003). Because the partial pressure of carbon dioxide (pCO_2) is a per-unit-mass quantity and is thus affected by changes in ocean salinity, the large mixed layer salinity anomalies at ALOHA following the 1997/98 ENSO event measurably increased pCO_2, thus reducing the effectiveness of the upper ocean in absorbing atmospheric CO_2. Additionally, biological changes during this period had an impact on the upper-ocean carbon budget, also contributing to a weakening of the CO_2 sink.

The biogeochemical responses to the combined interannual and decadal physical climate forcings show significant differences at Station ALOHA for the regimes before and after 1997/98 (Corno et al. 2007; paper in progress by Robert Bidigare, University of Hawaii, and colleagues on alteration of ecosystem structure in the subtropical North Pacific by climate-forced changes in nitrate flux). In addition to the greatly increased salinity, cooling of the mixed layer contributed comparably to a net density anomaly as large as 0.5 kg m^{-3}. The higher surface-layer density resulted in weaker stratification below the mixed layer, which allowed deeper penetration of winter mixing events. Impacts of this variability on nutrient and planktonic light levels in turn appears to have influenced the composition of the plankton assemblage, resulting in changes in rates of primary productivity, export, and, therefore, carbon sequestration in the North Pacific subtropical gyre.

Thermocline

In the salinity maximum (24.2–25 σ_θ, ~ 80–160 m), a bit more than one cycle of an oscillation with an approximately 10-year period and ~ 0.1 amplitude has been observed (Figure 2d). The isopycnals in this range are found at the surface from within a few hundred kilometers north of ALOHA to about 30°N. Due to the different spatial patterns associated with El Niño and the PDO, the isopycnals are subject to increasing decadal (decreasing interannual) freshwater forcing with distance poleward from Hawaii (Lukas, 2001). Combined with an advective lag that increases with depth to about 3.8 years at 25 σ_θ, the surface layer and upper thermocline waters at ALOHA exhibit salinity anomalies that are sometimes in phase and sometimes out of phase (Figure 2c).

It is interesting to note that the decadal variation in the upper thermocline leads the weaker variation in the mid-thermocline (Figure 2d) by ~ 1.3 years, based on a regression analysis. This lag is consistent with the increased advective time scale on the deeper isopycnals (Figure 4). The smaller amplitude of the decadal salinity signal in the deeper layer (0.03 vs. 0.07; see Figure 2d) likely reflects the greater integral effects of mixing along longer and slower trajectories. Large, sustained salinity anomalies have only occurred on isopycnals lighter than 26.2 σ_θ (Figure 4) at ALOHA to date. This is consistent with the model results of Stammer et al. (in press).

In the main thermocline (25–26 σ_θ, 160–310 m), the dominant feature is a trend with a ~ 0.2 salinity decrease from 1991 through 2005 (Figure 2d, Figure 4). The associated density-compensated temperature decrease is 1°C. The 15-year-long freshening trend in the mid-pycnocline may be part of much longer cycle, or may reflect secular changes in precipitation at higher latitudes. Analysis of sparse hydrographic observations around ALOHA prior to the start of HOT suggests that this trend may have started in the early 1980s, or possibly in the 1970s (see dashed yellow line in Figure 2b). Wong et al. (2001) showed that this layer freshened between the 1960s and 1985 along 24°N at the longitudes surrounding ALOHA. Recent observations at ALOHA suggest that the trend is reversing, but it is not clear whether this is simply due to the influence of the decadal variations that are superimposed on the longer-term trend.

Variations in precipitation have been quantitatively related to large-scale variations of the North Pacific storm track (Nakamura et al., 1997; Nakamura et al., 2002), and qualitatively to salinity at ALOHA through subduction and subsequent advection of the associated

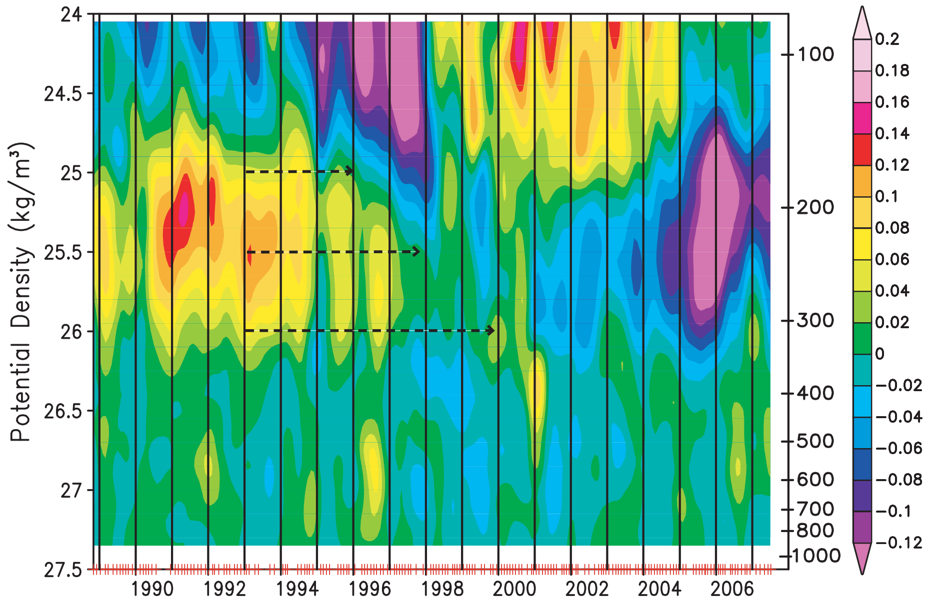

Figure 4. The smoothed deviations of salinity (color bar) from their long-term monthly averages observed at Station ALOHA, as a function of potential density. Times of HOT cruises are indicated by red tick marks. The transit time from the point of subduction to ALOHA is indicated by black arrows for selected isopycnals. These are based on climatological geostrophic currents and isopycnals computed from the World Ocean Atlas 2001 (Conkright and Boyer, 2002). The feature centered at 26.5 σ_θ in early 2001 is a submesoscale eddy that carried waters from Baja California to ALOHA (Lukas and Santiago-Mandujano, 2001).

remote mixed-layer salinity anomalies (Lukas, 2001). The average speed along geostrophic streamlines computed from historical hydrographic station data yield a lag of ~ five years from subduction on the 25.5 σ_θ surface in the central North Pacific to Station ALOHA. In Figure 5, the magnitude of the 15-year linear trend in precipitation is given for the period starting in 1986, five years before the trend at ALOHA in Figure 2d. The region of greatest precipitation increase is in the central North Pacific, spanning the climatological late winter outcropping of the 25–26 σ_θ surfaces from about 170°E to 160°W. This pattern is similar to the decadal freshwater flux pattern of Lukas (2001), and is suggestive of persistent storm-track variations (Nakamura et al., 2002). The implied density-compensating freshening and cooling under the North Pacific storm track are consistent with the phasing of the density-compensated salinity anomalies observed at Station ALOHA.

CONCLUSIONS

Quantitative understanding of the salinity variations at ALOHA in relation to surface forcing, advection, and mixing is actively being pursued. Stammer et al. (in press) have compared ECCO dynamic analyses with HOT observations (that have not been assimilated), and use the MIT 1° model adjoint to understand the sources of salinity variability that are observed in the mid and upper thermocline. The model was also used to track water parcels forward and backward in time. Stammer et al. (in press) conclude that surface salinity anomalies subducted in the central

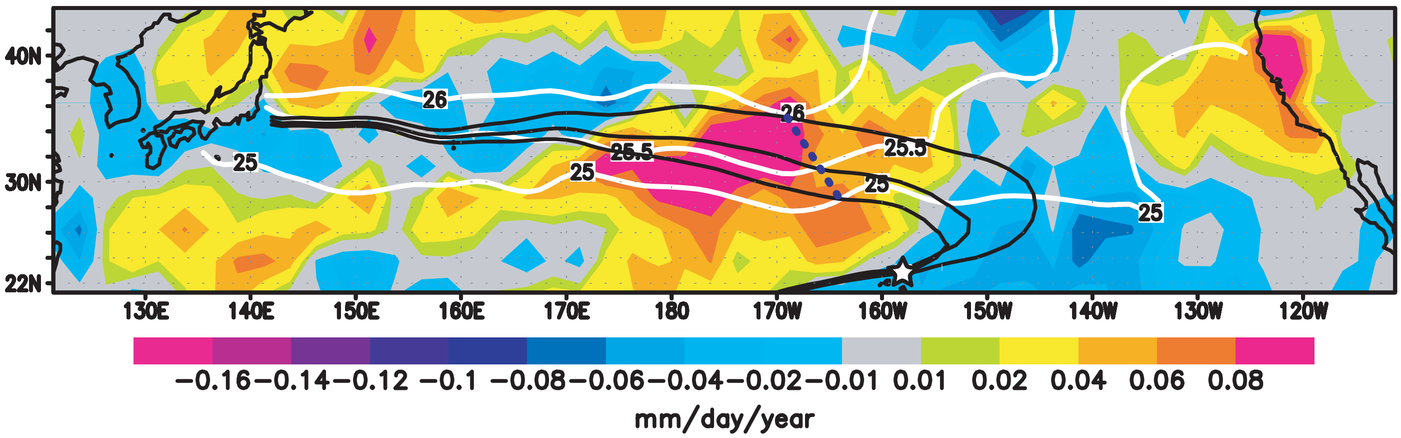

Figure 5. Linear trends (color bar) in January–March total precipitation for the period 1986–2001. Units are mm d^{-1} y^{-1}. Data are from the NOAA Climate Prediction Center Merged Analysis of Precipitation product (Xie and Arkin, 1997). White lines indicate mean March surface locations of selected isopycnals. Black lines indicate mean geostrophic streamlines that intersect Station ALOHA (white star) on the 25, 25.5, and 26 σ_θ surfaces. The dashed blue line connects mean ventilation locations for 25–26 σ_θ.

North Pacific are being advected to ALOHA, explaining a large fraction of the salinity anomalies observed in the upper and mid thermocline. Anomalous advection of the background salinity gradients dominate on time scales up to a year. On longer time scales, along-isopycnal advection by the mean flow is dominant.

Variations of surface forcing, from annual through multidecadal time scales, are important both in the formation of water masses found at Station ALOHA (e.g., Lukas, 2001; Nakamura and Kazmin, 2003) and for variations in their advective transport (Huang and Qiu, 1994; Huang and Russell, 1994). The dominant time scales of water-mass variability at ALOHA increase from interannual to multidecadal with depth from the surface through the main pycnocline. This observation is consistent with the idea that deeper variations are influenced from more distant regions than those at shallow depths, and mixing processes have more time to act along water parcel trajectories to reduce along-isopycnal variability associated with the shorter time scales.

Quantitative understanding of the salinity variations at ALOHA in relation to surface forcing, advection, and mixing is actively being pursued.

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