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Extreme Water Mass Anomaly Observed in the Hawaii Ocean Time-series

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Abstract. Extremely anomalous water mass properties, with deviations as high as 35σ, were observed in the thermocline during January 2001 at the Hawaii Ocean Time-series site north of Oahu. The spatial distribution of the anomalous waters is consistent with a submesoscale vortex with radius ~20-30 km, possibly a remnant of a mesoscale eddy. The most plausible source location of the anomalous waters is offshore of Mexico near Baja California. Given the southwestward subtropical gyre circulation, it is unlikely that these waters were transported directly westward to Hawaii. Unusual northward transport of Equatorial Waters along the coast by the 1997-98 El Niño event, and subsequent transport southwestward in the core of a mid-thermocline eddy is more plausible. El Niño modulation of eddy transport and diffusion of water mass properties may substantially impact biological productivity in the low-nutrient North Pacific subtropical gyre.

Observations

High-resolution profiles of temperature, salinity, dissolved oxygen and fluorescence obtained during the 122nd cruise (14-19 January 2000) of the Hawaii Ocean Time-series (HOT; Karl and Lukas, 1996) reveal the most extreme water mass anomalies observed since the project began in October 1988. These anomalies are evident between 300 and 550 m (potential density ~25.5-26.7 kg m^{-3}) when compared to a typical set of profiles from the HOT cruise one-month prior (Fig. 1). Departures from the mean of the first 11 years of observations reach more than 0.6 psu in salinity, 2.7°C in potential temperature, and -180 μmol/kg in dissolved oxygen near 400 m (26.3 kg m^{-3}). The chloropigment concentration estimated from fluorescence measurements also exhibits a dramatic increase.

These water mass anomalies are obviously extreme: One indication is that dissolved oxygen was virtually depleted (3.9 μmol kg^{-1}) in the region of the maximum anomaly, highly atypical of the subtropical gyre. Another indication is that a potential temperature inversion of more than 0.2°C, compensated by salinity, was observed in the main thermocline between 354 and 390 m. When normalized by the corresponding standard deviations on isopycnal surfaces from the first 11 years of observations, the anomalies exceed 35σ in temperature and salinity, and –20σ in dissolved oxygen (Fig. 2). A Gaussian distribution of water mass properties is characteristic of most density levels in the HOT observations, and the probability of observing a feature of this magnitude is virtually zero. It is more difficult to estimate a probability of observing such extreme water mass characteristics in the lower portion of the feature because isopycnals near the salinity minimum (~500 m) are non-Gaussian and highly skewed due to episodic high-salinity, low-oxygen intrusive features that have been associated with submesoscale eddies (Kennan and Lukas, 1996). We have observed conditions at this site on 122 separate occasions over 12 years, so the probability is certainly less than 1%.

Our observations are robust. We use redundant temperature, conductivity and oxygen sensors on our Sea-Bird 9/11+ CTD system so that we can detect instrumental misbehavior. The accuracy and precision of our measurements are at the limit of technology (Table 1). The anomalous water mass persisted over our routine 36–hour period of time-series CTD profiling at Station ALOHA (22°45'N, 158°W). Similar water mass anomalies were observed in profiles at 10 other locations within 44 km of ALOHA (not shown).

Interpretation

Spatial Structure

The spatial structure of the anomalous water mass is needed to determine the dynamics responsible for its appearance. Additional CTD profiles were obtained near Station ALOHA after the anomaly was discovered to estimate its spatial scale. They were sufficient to suggest that a spatially coherent core of anomalous water was located roughly 8 km west of Station ALOHA with a radius of about 10 km. The signature of the water mass anomaly was clearly present, though much weaker, at locations as far as 36 km from the center. Finestructure indicative of active mixing is apparent in profiles outside of the core. Time was not available to sample to the north and southeast of the core, so we cannot be sure that this is an isolated vortex rather than an elongated filament, nor can we be sure that we measured the peak anomalies. It does seem likely that the anomaly is associated with a submesoscale vortex.

Source waters and pathway

The source region for these anomalous waters was located by constructing approximate climatological mean distributions of potential temperature, salinity, and dissolved oxygen for isopycnal surfaces in the main thermocline for the Pacific Ocean from the World Ocean Atlas (Levitus and Boyer, 1994). The average distributions of salinity and dissolved oxygen (Fig. 3), on the 26.3 kg m^{-3} isopycnal surface on which the maximum anomalies occurred at Station ALOHA, are consistent with the hypothesis that the waters observed during HOT-122 derive from the general region south and west of Baja California. This assumes that the peak anomalies that we observed at ALOHA are undiluted by mixing during their transport to Hawaii. If we missed the peak value in the core of the anomalous water mass, or if the core was significantly eroded by mixing along its pathway, then the source waters were saltier and located further to the south, irrespective of the east-west location of the source region (Fig. 3).

We further constrain the source region to within about 200 km south and west of the southern tip of Baja California by exploiting the significant negative salinity anomaly near 25.8 kg m^{-3} (Fig. 2), and the fact that the distribution of salinity on this isopycnal is quite different from that on 26.3 kg m^{-3}. Given the relatively strong smoothing used by Levitus and Boyer (1994), a more precise location of the source waters is not possible.

The mean depth of the 26.3 kg m^{-3} isopycnal surface (Fig. 4) reveals the eastern half of the North Pacific subtropical gyre, shoaling from about 380 m north of Oahu, to less than 200 m near the coast of Mexico. The geostrophic flow that corresponds to this isopycnal is generally southward and westward offshore of Mexico. (Maps of acceleration potential [cf. Huang and Qiu, 1994] are similar to the topography of the main thermocline in this region.)

It seems unlikely that the anomalous water mass observed north of Oahu during January 2001 was transported almost due westward across the prevailing southward flow of the California Current and the west-southwestward flow of the North Equatorial Current (NEC). If the anomalous waters are indeed associated with a long-lived vortex, the speed of their transport depends on the size of the vortex (Dewar and Meng, 1995). A submesoscale vortex moves with the large-scale flow (approximately 0.02 m s^{-1} on this surface), while a mesoscale eddy is also subject to a westward "beta" drift of perhaps 0.01-0.02 m s^{-1}. The trajectory of the anomalous water mass would also have depended on the actual large-scale flow, which almost surely was anomalous due to the strong El Niño and La Niña forcing during 1997-2000.

Hypotheses

We hypothesize that the salty, oxygen-depleted waters normally found south of Baja California in the pycnocline were first transported northward along the coast by unusually strong northward flows in the California Undercurrent (cf. Badan-Dangon et al. 1989) during the very intense 1997-98 El Niño event, with some portion subsequently transported offshore in one of the ubiquitous eddies within the California Current. Castro et al. (2001) show that the California Undercurrent normally transports waters of the eastern tropical North Pacific northward, mixing with the southward-flowing California Current. This is consistent with the results of Gregg (1975), who found intrusive features near Baja California associated with the interleaving of warm and salty northward-flowing Equatorial Water and the cool, fresh, southward-moving California Current. The frequency of such intrusions was observed to decrease with distance offshore.

TOPEX altimetry shows a large and rapid increase of sea level along the North American coastline in early 1997, sustaining into early 1998, when a sharp upwelling signal occurs returning sea level to near normal (Qiu, 2001). The northward-propagating El Niño signal reaches high latitudes, although there is a dramatic reduction in magnitude near 20°N, the southern extent of Baja California. Further to the south, Zamudio et al. (2001) observed and modeled the northward-propagating, downwelling coastal Kelvin waves associated with the onset of the 1997-98 El Nino, showing that the surge in northward flow destabilized the coastal circulation and generated numerous anticyclonic eddies. Roemmich and Gilson (2001) show a modulation of mesoscale eddies by the 1997-98 ENSO cycle, and importance of such diffusive heat flux to the mean heat budget.

If we suppose that the eddy observed at ALOHA was spun up in early 1997 near the coast at 30°N, our observation of its remnants north of Oahu in January 2001 would require a propagation speed of about 0.035 m s^{-1}, which is not unreasonable considering the mean flow, possible influences of ENSO on the large-scale circulation, and the potential contribution of beta drift. Virtual drifter trajectories in a 3-layer, high resolution nonlinear model of the Pacific Ocean forced by observed winds indicate that this hypothesis is plausible (Qiu, personal communication, 2001).

Conclusions

An extreme water mass anomaly observed north of Hawaii originated near the southern tip of Baja California. An indirect route including advection northward along the west coast of North America during the 1997-98 El Niño seems to be required. If this El Niño/eddy hypothesis is correct, we might expect that other such extreme, but small-scale, water mass anomalies exist presently in the central North Pacific. If so, quantification of the impact of interannually varying extreme eddy transports and diffusion on water mass property and ecosystem variations in the North Pacific subtropical gyre will be important.

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Figure 1. Potential temperature (θ), salinity (S), dissolved oxygen (O_2), and chloropigment (Chl) profiles from Station ALOHA during HOT cruises 121 (black lines) and 122 (colored lines).

Figure 2. HOT-122 profiles of potential temperature, salinity and dissolved oxygen normalized by their corresponding long-term standard deviations on isopycnal surfaces.

Figure 3. Maps of mean dissolved oxygen (top) and salinity (bottom) on the 26.3 kg m^{-3} isopycnal surface estimated from the Levitus and Boyer (1994) climatology. Contour intervals are 20 μmol kg^{-1} and 0.1 psu. The location of the Hawaii Ocean Time-series station ALOHA is indicated by a +, the location of mean water mass properties matching those of the submesoscale eddy is indicated by a ✇.

Figure 4. Map of the depth (m) of the mean isopycnal surface of 26.3 kg m^{-3}. Symbols are as in Fig. 3.

Table 1: Accuracy and precision of temperature, salinity, and dissolved oxygen for HOT CTD profiles (Lukas et al., 2001).

	Accuracy	Precision
Temperature (°C)	0.0014	0.0002
Salinity	0.003	0.001
Oxygen (μmol kg^{-1})	3	0.35

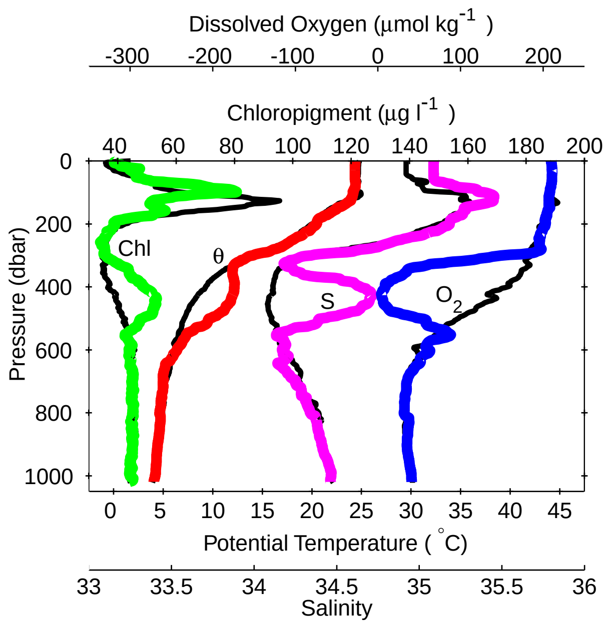


Figure 1

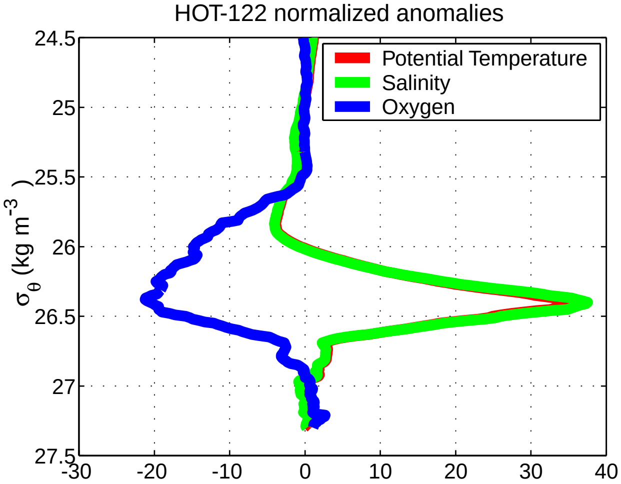
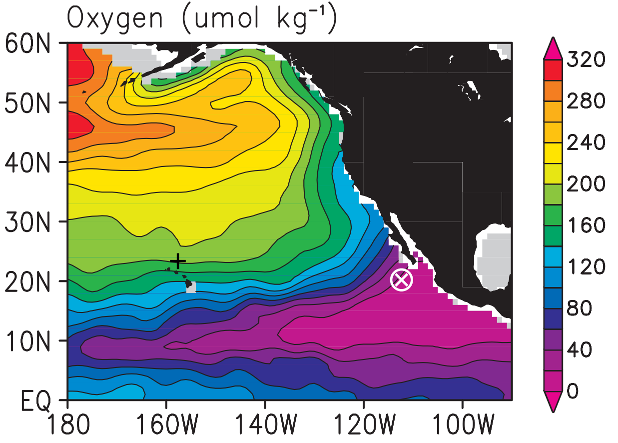


Figure 2



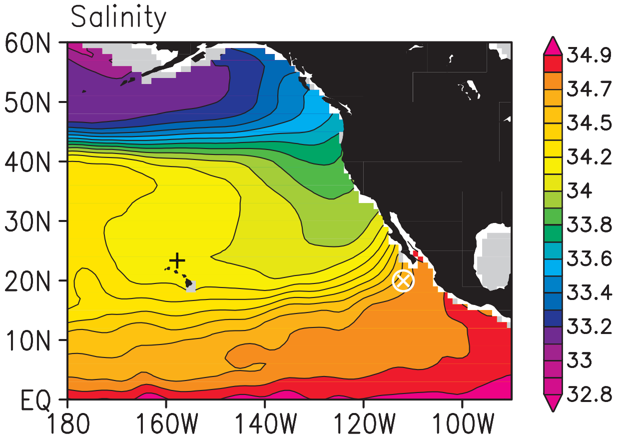


Figure 3

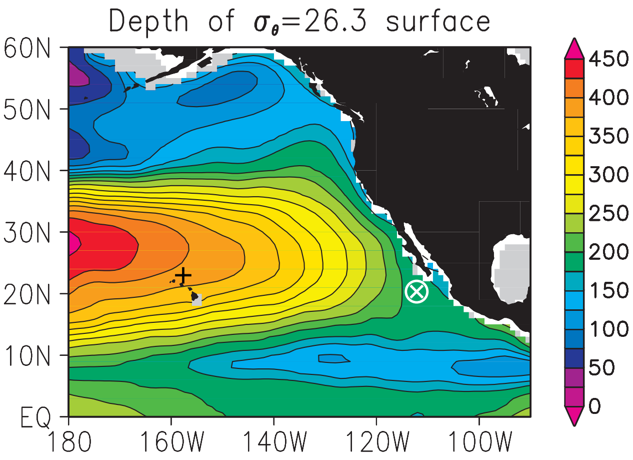


Figure 4