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 ~15 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 North American coast during the 1997-98 El Niño event, and subsequent transport southward in the core of a California Undercurrent eddy is more plausible. El Niño modulation of eddy transport and diffusion of water mass properties may substantially impact the mean distribution of properties in the 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 as high salinity, high temperature, low oxygen, and elevated fluorescence between about 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^-1 in dissolved oxygen near 400 m (26.3 kg m^-3). The chloropigment concentration inferred from fluorescence measurements also exhibits a dramatic increase. The anomalous water mass persisted over our routine 36-hour period of time-series CTD profiling at Station ALOHA (22°45'N, 158°W).

Eleven additional CTD profiles were obtained near Station ALOHA after the anomaly was discovered to estimate its spatial structure. Maximum water-mass anomalies were measured roughly 10 km southwest of ALOHA. Time was not available to sample adequately to the north and south of this location, 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. The signature of the water mass anomaly was clearly present, though very much weaker, 36 km southwest of this apparent core. The apparent radius is about 15 km (Fig. 2), although this estimate may be biased low. Finestructure indicative of active mixing is apparent in profiles along the edges of the feature.

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. The HOT site has been sampled 122 times over 12 years and water-mass properties on most density levels display a Gaussian distribution. The intermediate salinity minimum (~500 m) is an exception, having a highly skewed distribution due to episodic salty, oxygen-poor intrusions associated with submesoscale eddies [Kennan and Lukas, 1996]. When normalized by the corresponding standard deviations on isopycnal surfaces from the first 11 years of observations, the anomalies exceed 35σ in salinity (temperature statistics are nearly identical for isopycnal analysis) and -20σ in dissolved oxygen (Fig. 3).

Interpretation

Spatial Structure

It seems likely that the anomaly is associated with a submesoscale vortex (SCV; [McWilliams, 1985]). The Burger number B=(Nh/fL)^2, where N is the buoyancy frequency, h is the scale height of the feature, f is the Coriolis parameter, and L is the horizontal scale length, compares the strength of rotation to stratification in a vortex. A circulation feature with B=O(1) is in the regime of SCV dynamics. For the observed feature, B=1.1. Because the water-mass anomaly signature may be somewhat smaller than the dynamical signature [McWilliams, 1985], and because any transect of a circular feature is likely to underestimate its radius, B is probably somewhat smaller.

We were unable to unambiguously detect the density anomaly associated with the vortex and thus could not make any dynamic computations based on its spatial structure. Energetic baroclinic tides are often present at ALOHA [Karl and Lukas, 1996]. These were removed in a least squares sense from the 36-hour burst sampling at Station ALOHA for HOT-121 and HOT-122 to give the relatively robust mean stratification profiles in Fig. 1. A slight weakening of the stratification is seen surrounding the depth of maximum anomalies, which would suggest anticyclonic circulation. However, the stratification anomaly is not large relative to the typical cruise-to-cruise variation. Subtracting the baroclinic tide from the stations in the section across the eddy did not result in a sufficiently noise-free eddy signal, possibly because the spatial variation in tidal phase may be of comparable scale to that of the eddy, and non-tidal internal waves are certainly present.
Source waters and pathway

The source region for these anomalous waters was located by constructing approximate climatological mean distributions of 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 for the 26.3 kg m$^{-3}$ isopycnal surface (Fig. 4) 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. 4a).

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. 3), 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 neither possible nor warranted.

The mean depth of the 26.3 kg m$^{-3}$ isopycnal surface (Fig. 4c) 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-south-westward flow of the North Equatorial Current (NEC). If the anomalous waters are indeed associated with a long-lived vortex, their translation speed 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 anom-
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 Undercurrent [Garfield et al., 1999]. 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.

A large and rapid increase of sea level propagated northward along the North American coastline in early 1997, sustaining into early 1998, when a sharp upwelling signal returned sea level to near normal. Large changes in circulation, water-mass properties and biology associated with this event were observed along the coast of California [Schwing et al., 1997; Lynn et al., 1998]. 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 Niño, showing that the surge in northward flow destabilized the Mexican coastal circulation and generated numerous anticyclonic eddies. Roemmich and Gilson [2001] show a modulation of mesoscale eddies by the 1997-98 ENSO cycle, and the 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 during January 2001 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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References

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**Figure 4.** Maps of mean dissolved oxygen (a), salinity (b) and depth (c) for the 26.3 kg m⁻³ isopycnal surface estimated from the Levitus and Boyer (1994) climatology. Contour intervals are 20 μmol kg⁻¹, 0.1 psu and 25 m. 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 ©. The hypothesized pathway of the anomalous waters is given by the arrow in (c).


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