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Estimation of vertical mixing in the upper ocean at Station P from chlorofluorocarbons

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ABSTRACT

Vertical mixing (K_v) in the upper ocean is estimated from chlorofluorocarbons (CFC's) F-11 and F-12 data collected on 5 cruises (1982, 1985, 1992, 1993, 1995) near Station P (50N, 145W). A one-dimensional advection-diffusion model was fitted to the data from each cruise to estimate vertical mixing (K_v) and upwelling velocity (w). With constant K_v and w , the average value of K_v and w was $0.4 \pm 0.1 \text{ cm}^2 \text{ s}^{-1}$ and $1.2 \pm 0.4 \text{ m yr}^{-1}$ respectively for the depth range 0–900 m below the base of the mixed layer. This case produced K_v values that increased with time, and modeled CFC concentrations that were higher than observed in the upper 200 m and lower than observed in the deeper water (200–900 m). Both of these conditions are consistent with K_v values that increased with depth. Fitting the one-dimensional advection-diffusion model to the data with K_v inversely related to the buoyancy frequency reduced the model-data misfit by 40%, produced consistent estimates of K_v for all cruises and reduced the systematic differences in the model data misfits. From this model K_v and w at the base of the mixed layer were $0.15 \pm .04 \text{ cm}^2 \text{ s}^{-1}$ and $0.5 \pm 0.15 \text{ m yr}^{-1}$, respectively. The results strongly supported a K_v that increased with depth. Modeled anthropogenic CO_2 penetration at Station P with the inverse buoyancy frequency scaling of K_v , produced results consistent with the observed anthropogenic CO_2 penetration inferred from ΣCO_2 , alkalinity and apparent oxygen utilization measurements.

1. Introduction

The distribution of tracers in the ocean depends on isopycnal and diapycnal processes. Recently, the magnitude of vertical mixing (K_v) has been the subject of debate. Historically, K_v has been assigned a value of the order of $1 \text{ cm}^2 \text{ s}^{-1}$ (Munk, 1966). This magnitude of K_v has invoked a simple conceptual model of the ocean circulation where cold dense water is formed in high latitudes; this water sinks and moves equatorially, upwelling in mid and low latitudes. In the mid and low latitudes, the temperature profile is maintained by the balance between upwelling cold water and downward mixing of heat from the surface. However, it has long been recognized that ocean circulation is more complicated than this. Furthermore, measurements of the turbulent fluctuations of heat and velocity at scales of a few millimeters have implied a much smaller K_v (order of magnitude of $10^{-1} \text{ cm}^2 \text{ s}^{-1}$ in the upper 1000 m). If K_v is of $O(10^{-1} \text{ cm}^2 \text{ s}^{-1})$, then the structure of the thermocline is

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determined by the wind forcing. The determination of the magnitude of K_v is necessary for understanding and modeling climate change, contaminant dispersal in the ocean and ocean productivity.

Another area of uncertainty in K_v is its depth dependency. Gargett and Holloway (1984) proposed that K_v was inversely related to buoyancy frequency, which produced K_v values that increased with depth. However, the dissipation measurements of Gregg (1989) did not find this buoyancy frequency scaling, rather they suggested K_v was constant with depth. As discussed by Gargett (1984) and Stommel and Arons (1960), a depth-dependent K_v has important dynamical consequences on ocean circulation. Under the assumption that the density field in the pycnocline (away from boundary regions) is maintained by the balance between upwelling (w) and K_v , Gargett (1984) showed that a K_v which was inversely related to buoyancy frequency (N) produced an upwelling velocity that increased with depth. Assuming geostrophic balance in the deep ocean, the vorticity equation is

$$\beta v = f \frac{\partial w}{\partial z}. \quad (1)$$

If w increases with depth ($\partial w / \partial z < 0$), this would produce flow toward the equator in the intermediate water (Gargett, 1984). The poleward motion required by the Stommel and Arons (1960) model would be restricted to the bottom boundary layer where vertical velocity decreased with depth ($\partial w / \partial z > 0$).

Anthropogenic tracers (e.g., tritium and chlorofluorocarbons, CFC's) in the ocean provide a means of quantifying K_v and investigating its depth structure. For example, Rooth and Ostlund (1972) used the temperature and tritium profiles from the Sargasso Sea to obtain an upper bound estimate on K_v . Their approach used the observed exponential decrease of temperature and tritium with depth in the upper ocean to derive an empirical equation from the advection-diffusion equations that gave an upper bound estimate of K_v which was independent of advection. Applying this technique to the Sargasso Sea data, they calculated an upper bound on K_v of $0.23 \text{ cm}^2 \text{ s}^{-1}$ in the 200–1000 m depth range. Gammon *et al.* (1982) used CFC measurements from the northeast Pacific Ocean to estimate K_v . They fitted a one-dimensional advection diffusion model to the temperature and CFC profiles and estimated a K_v value of $1.3 - 1.4 \text{ cm}^2 \text{ s}^{-1}$ in the open ocean. Ledwell *et al.* (1993) used the rate of diapycnal spreading of a patch of an artificial tracer, sulfur hexafluoride (SF_6), injected at 310 m in the North Atlantic, to determine K_v in the upper ocean. By measuring the spread of SF_6 six months after the initial injection, they determined a K_v value of $0.11 \pm 0.02 \text{ cm}^2 \text{ s}^{-1}$.

In this paper, we estimate K_v in the upper ocean from CFC data collected near Station P (50N, 145W). We re-examine the Station P data used in the Gammon *et al.* (1982) study and additional data collected in 1985, 1992, 1993 and 1995. Model fits to the CFC data produced K_v values less than $1 \text{ cm}^2 \text{ s}^{-1}$ in the upper ocean which are significantly less than the value determined by Gammon *et al.* (1982) but consistent with turbulence measurements (Gregg, 1989) and the value determined from the tracer release experiment (Ledwell

et al., 1993). Our model fits to the CFC data supports a K_v value that increases with depth. The observed CFC profiles are consistent with a K_v value that is inversely related to the buoyancy frequency. In Section 2 we describe the CFC data used in this study. In Section 3, we calculate estimates of K_v and investigate a depth-dependent K_v . Section 4 discusses and summarizes the results of this study.

2. Data collection and analysis

Temperature and CFC data collected near Station P are available from five cruises: Dec. 1980 (Gammon *et al.*, 1982), May 1985, Feb. 1992, Mar. 1993, and April 1995. For these cruises, water samples and CTD measurements were obtained using a General Oceanics Rosette holding 23 10-L Niskin PVC samplers and a Guildline Model 8737 CTD. Two pairs of reversing digital thermometers and a digital pressure sensor were used to check CTD measurements. For each of these cruises, replicate profiles of temperature and CFC's were made and used to calculate the experimental precision of the data. Replicate temperature samples had experimental precision of $\pm 0.01^\circ\text{C}$.

Water samples for CFCs F-11 ($\text{C Cl}_3 \text{ F}$) and F-12 ($\text{C Cl}_2 \text{ F}_2$) were drawn in 100 mL glass syringes following the procedures described by Gammon *et al.* (1982). Samples were analyzed by gas chromatography with an electron capture detector following the procedure of Bullister and Weiss (1988). To calibrate the CFC measurements, a laboratory gas standard was used which, prior to the cruise, was calibrated against a gas standard prepared by Bullister's laboratory. Calibration curves were done prior to each cast with additional analysis of the gas standard performed hourly to monitor drift in detector sensitivity.

The deepest water sample on the cast was used to determine a CFC blank correction for cast because the deep water of the subarctic Pacific should be completely free of CFCs (Watanabe *et al.*, 1994). The deep water measurements of F-11 and F-12 from each cast were subtracted from the shallower measurements. The F-11 blank correction varied between 0.001 and 0.12 pmol kg^{-1} and the F-12 blank correction varied between 0.001 and 0.06 pmol kg^{-1} . From the observed variability in the deep water CFC measurements, the blank correction was assigned an error of $\pm 0.05 \text{ pmol kg}^{-1}$ for both F-11 and F-12 for all cruises. The repeated casts at Station P during each cruise were used to determine the measurement precision. The precision of the CFC concentrations from replicate samples were about $\pm 5\%$ for both F-11 and F-12. The total uncertainty in the CFC measurements were assigned the value of $\pm(5\% + 0.05) \text{ pmol kg}^{-1}$.

3. Optimal estimates of K_v and w from CFC and temperature profiles

a. One-dimensional advection diffusion model

The depth profiles of the CFC data provide information on K_v and w in the upper ocean. In the vicinity of Station P, horizontal gradients of CFCs are weak (Fig. 1). Scale analysis using the observed horizontal and vertical gradients showed that the measured CFC profiles are dominated by vertical processes. This motivates the fitting of a time-dependent

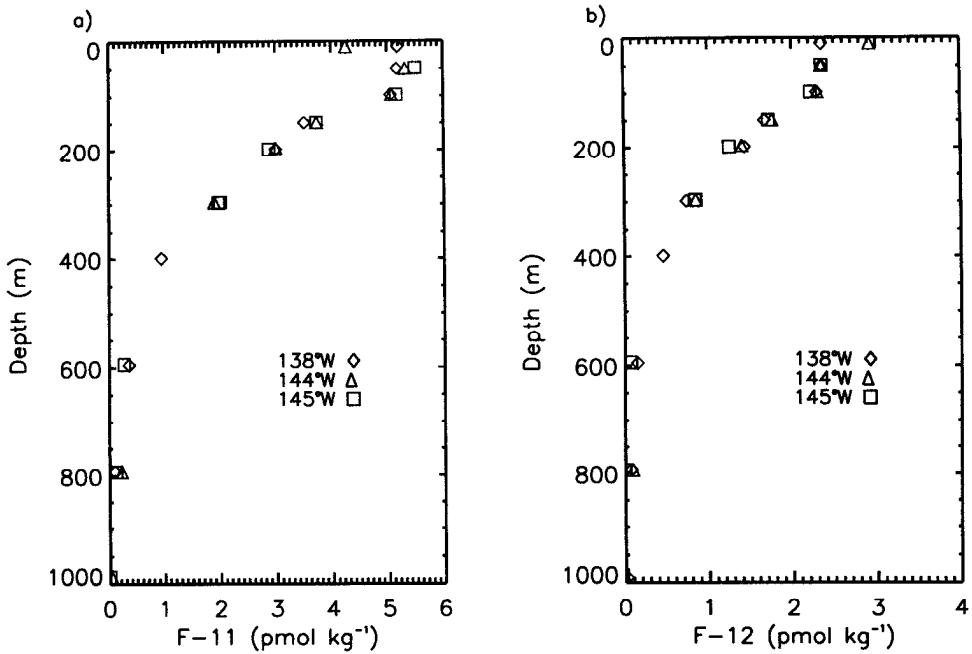


Figure 1. Vertical profiles of (a) F-11 and (b) F-12 collected at 3 stations along latitude 50N; Station P is at 145W.

one-dimensional advection-diffusion model to the CFC profiles to determine K_v and w . The time-dependent one-dimensional advection-diffusion equation is

$$\frac{\partial c}{\partial t} - w \frac{\partial c}{\partial z} - K_v \frac{\partial^2 c}{\partial z^2} - \frac{\partial K_v}{\partial z} \frac{\partial c}{\partial z} = 0 \quad (2)$$

where rate of change in CFC concentration with time $\partial c/\partial t$, is a function of time (t) and depth (z), and K_v and w are depth-dependent vertical mixing and upwelling velocity, respectively. The model is forward-integrated using the prescribed evolution of $\partial c/\partial t$ in the mixed layer to obtain the CFC profile below the mixed layer.

Gammon *et al.* (1982) applied the one-dimensional model to 1980 Station P data to estimate depth-independent values of K_v and w . Our study will re-apply the model to their 1980 data and four additional datasets but in a way that reduces the sensitivity of K_v to the blank correction.

The work of Gammon *et al.* (1982) demonstrated that F11 and F12 were insufficient to uniquely determine K_v and w . To resolve the two unknowns, we fitted the steady-state version of Eq. (2) to the measured temperature profiles. The observed temperatures profile displayed exponential decreases with depth (Fig. 2a). For a constant K_v and w , the steady-state temperature profile decreases exponentially to an asymptotic value (T_0) with depth scale equal to the K_v/w . From the observations, the asymptotic temperature (1.6°C)

was determined from the y-intercept of the plot of vertical temperature gradient versus temperature. In contrast, Gammon *et al.* (1982) set the asymptotic temperature to observed temperature at 1000 m (3.0°C). This incorrectly assumed that the vertical temperature gradient was zero at 1000 m and gave too small a temperature depth scale of 300 m. With an asymptote temperature of 1.6°C we calculated a temperature depth scale of 900 ± 100 m (Fig. 2b).

b. Optimal fits to the CFC profiles

i. Cost function. For given values of K_v and w , the model CFC concentrations are determined by forward-integrating (2) from 1946 to the time of the cruise using prescribed CFC concentrations in the mixed layer. To integrate (2), we used a 4th order Runge-Kutta adaptive time-stepping scheme with 50 m finite differencing in the vertical direction. One independent estimate of K_v and w was made from the F-11 and F-12 data from each cruise. The optimal solution for K_v and w was found by minimizing the following cost function (J)

$$J = \frac{1}{N} \sum_{i=1}^N \left(\frac{c_i^* - c_i}{0.05c_i + 0.05} \right)^2 \quad (3)$$

where N is the number of samples, c^* is the measured CFC concentrations and c is the modeled CFC concentrations. The cost function was computed using F-11 and F-12 measurements from 0 to 1000 m below the mixed layer. Each term in the cost function was normalized by the estimated uncertainty in the measure concentration. Hence, the greater the relative uncertainty of an observation the less influence the observation has on the optimal solution. By computing the model-data misfit using (3), the optimal solution will not be biased by uncertain low CFC concentrations found in the deep water. In contrast, the semi-log fit used by Gammon *et al.* (1982) is extremely sensitive to the low and uncertain CFC concentrations from the deep water. With the semi-log fit, one tends to rely heavily on deeper and less precise measurements than the more accurate shallow measurements which make the fitting procedure very sensitive to the blank correction.

The two CFC measurements are not significantly independent to resolve both K_v and w (Gammon *et al.*, 1982) and the depth scale computed from the temperature profile was used to set K_v/w (Fig. 2b). To determine the optimal values of K_v , we used the modified Powell conjugate search direction method to iteratively search for the minimum value of J (Press *et al.*, 1992).

ii. Mixed layer CFC concentrations. To forward-integrate the model requires the evolution of CFC concentrations in the mixed layer. We assumed that the CFC concentrations in the mixed layer tracked the evolution of CFC concentrations in the atmosphere, with mixed layer being 100% saturation with the atmosphere concentration. The assumption is valid because the mixed layer response time is short (1 month) (Gammon *et al.*, 1982) relative to the atmospheric growth rate ($\tau > 6$ yr). This is supported at Station P by mixed layer CFC

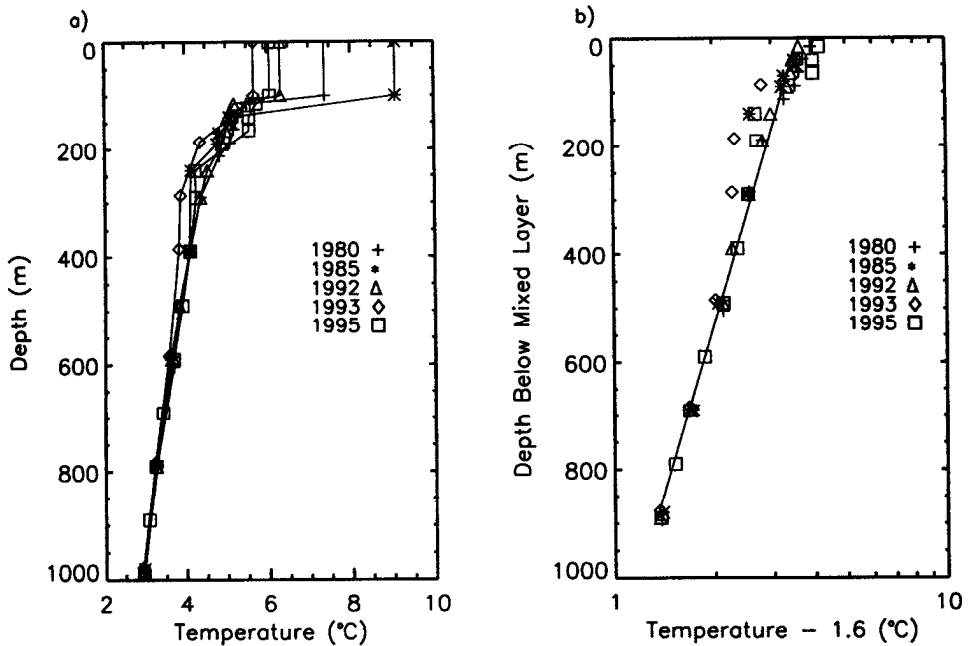


Figure 2. (a) Vertical temperature ($^{\circ}\text{C}$) profile from data near Station P (50N, 145W). (b) Fit of exponential depth scale to the vertical temperature profile in (a). The calculated exponential depth scale was 900 ± 100 m.

concentrations that were at equilibrium with the atmospheric CFC concentrations (i.e. 100% saturation for the mixed layer CFC concentrations).

Atmospheric concentrations of F-11 and F-12 increased exponentially from 1948 to 1977 with characteristic growth rates of 6.7 and 9.6 yr^{-1} respectively (Gammon *et al.*, 1982). After 1978, the growth rate of both these CFCs decreased (Elkins *et al.*, 1993). From 1978–1995 we used the observed CFC concentrations in the mixed layer, adjusted to a constant temperature of 6°C (average temperature when the mixed layer is deepest) to determine the evolution of CFC concentrations in the mixed layer (Fig. 3). The prescribed growth rate of CFCs in the mixed layer at Station P were consistent with growth rates of CFC in the atmosphere (Elkins *et al.*, 1993) which showed a reduction in atmospheric growth rates from the 1980's to the 1990's of more than 50% and 25% for F11 and F12 respectively.

For the 1980 data it was acceptable to use the transient steady-state solution presented by Gammon *et al.* (1982) because the atmospheric growth rates of the CFCs were still adequately approximated by exponential growth. However, for the later cruises the reduced atmospheric growth rate of CFCs required a forward model to compute the CFC's profile using prescribed mixed layer CFC concentration.

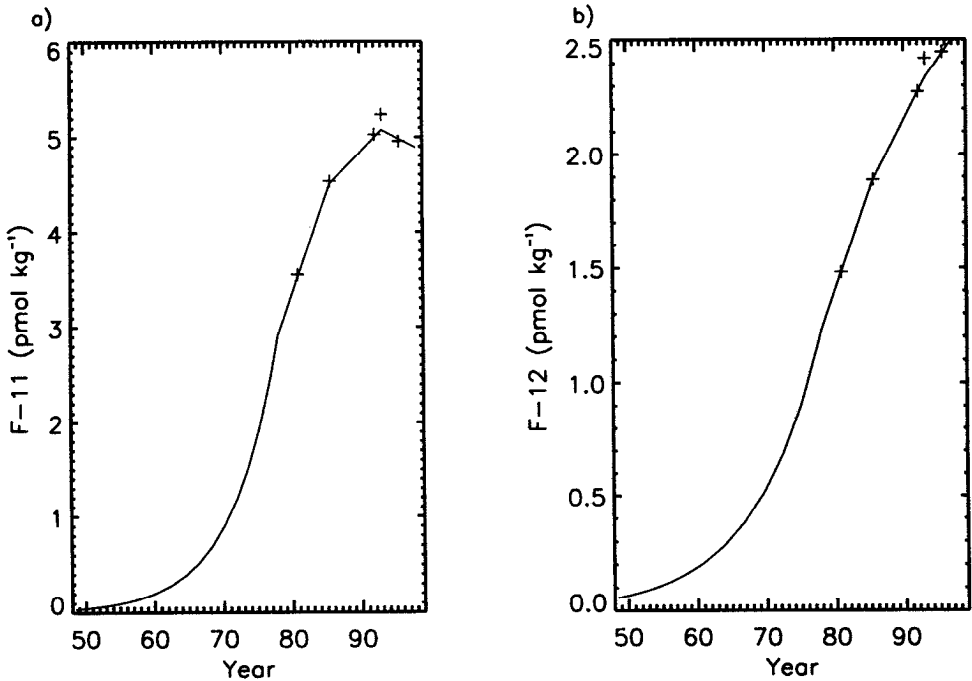


Figure 3. Evolution of CFC's in the mixed layer: (a) F-11 and (b) F-12.

iii. *Constant K_v and w .* For case 1, the CFC data from each cruise were fitted with a depth-independent K_v and w (Table 1). From the 5 cruises, the average values for K_v and w are small, $0.4 \text{ cm}^2 \text{ s}^{-1}$ and 1.2 m yr^{-1} respectively. The value of K_v displayed a significant increase with time. This does not reflect K_v increasing with time but rather K_v increasing with depth. With time, the CFC's penetrate deeper into the mixed layer and are influenced by K_v in the deeper water and this produces an increase in the computed K_v value with time. The misfits between the modeled CFC concentrations and the observed concentrations

Table 1. Case 1, optimal depth-independent estimates of estimates K_v and w from the CFC's and temperature profiles.

Cruise	Vertical mixing, K_v , ($\text{cm}^2 \text{ s}^{-1}$)	Vertical Velocity, w , (m yr^{-1})	Misfit
1980	0.28	0.95	2.4
1985	0.29	0.95	12.7
1992	0.36	1.2	3.2
1993	0.52	1.7	1.7
1995	0.47	1.6	8.9
Average	0.4	1.2	
Standard deviation	0.1	0.4	

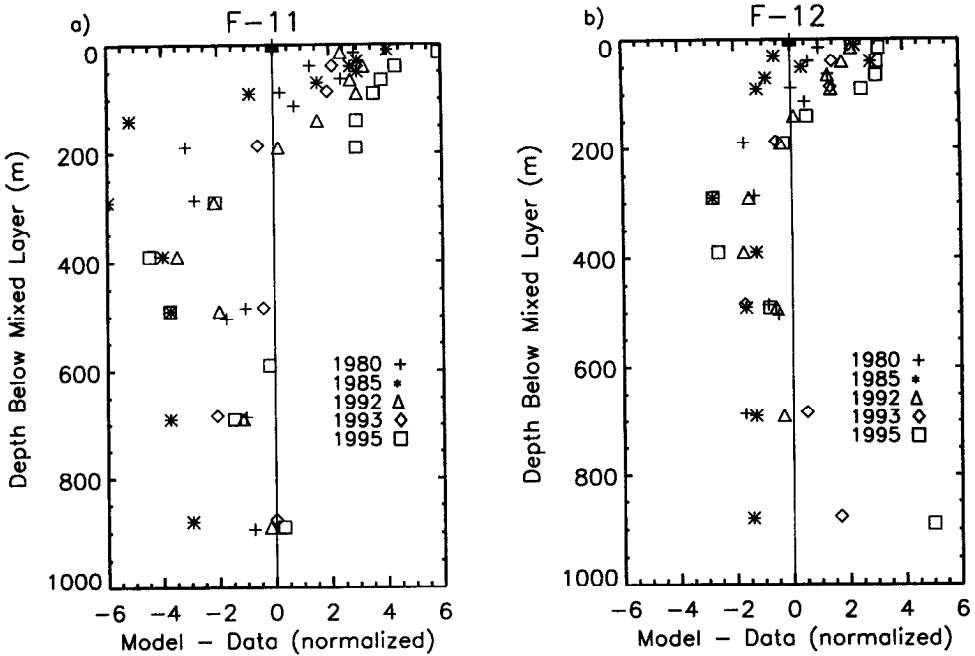


Figure 4. Case 1 model-data-misfits for (a) F-11 and (b) F-12.

displayed a systematic pattern (Fig. 4). The modeled CFCs are too high in the upper 300 m and too low below 400 m. This pattern further supports the increase in K_v with depth.

iv. Depth-dependent K_v and w . For case 2, K_v was assumed to be a depth-dependent function related to the inverse buoyancy frequency (N) (Gargett and Holloway, 1984)

$$K_v = aN^{-1}. \quad (4)$$

The smoothed average N and N^{-1} for the 5 cruises are shown in Figure 5. We used the CFC profiles to determine a in (4). The temperature profile provides additional information on the K_v and w . For a depth-dependent K_v , the one-dimensional advection diffusion equation for temperature is

$$w \frac{\partial T}{\partial z} + \frac{\partial K_v}{\partial z} \frac{\partial T}{\partial z} + K_v \frac{\partial^2 T}{\partial z^2} = 0. \quad (5)$$

Combining the first two terms on the rhs gives

$$w_a \frac{\partial T}{\partial z} + K_v \frac{\partial^2 T}{\partial z^2} = 0 \quad (6)$$

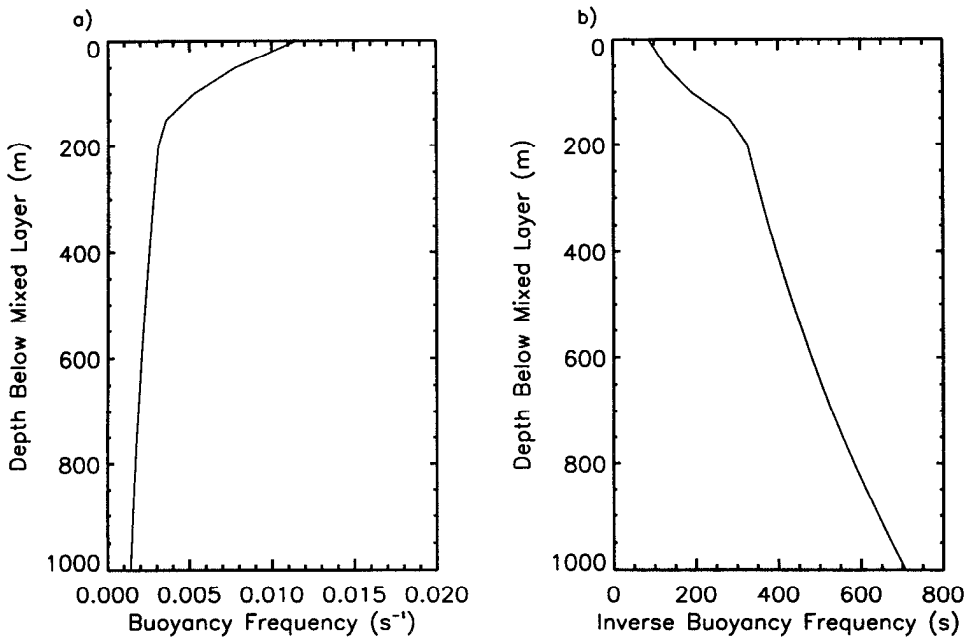


Figure 5. Smoothed averaged (a) buoyancy frequency and (b) inverse buoyancy frequency at Station P.

where the K_v/w_a equals the observed temperature depth scale. With K_v varying with the inverse buoyancy frequencies, all 5 cruises produced consistent results (Table 2, Fig. 6). At the base of the mixed layer, K_v was less than half the value determined for case 1. The depth varying optimal solutions for K_v and w differed from case 1 by significantly reducing the model-data misfit (Table 2) and reducing the systematic depth dependence in the model-data misfit (Fig. 7). The modeled CFC concentrations in case 2 decreased in the upper part of the water column and increased in the deeper part of the water column from that of case 1.

Table 2. Case 2, optimal depth-dependent estimates of K_v and w at the base of the mixed layer for the CFC and temperature profiles.

Cruise	Vertical mixing ($\text{cm}^2 \text{s}^{-1}$)	Vertical velocity (m yr^{-1})	Misfit
1980	0.15	0.51	1.1
1985	0.09	0.29	5.5
1992	0.15	0.50	1.4
1993	0.19	0.64	1.0
1995	0.17	0.56	6.5
Average	0.15	0.50	
Standard deviation	0.04	0.15	

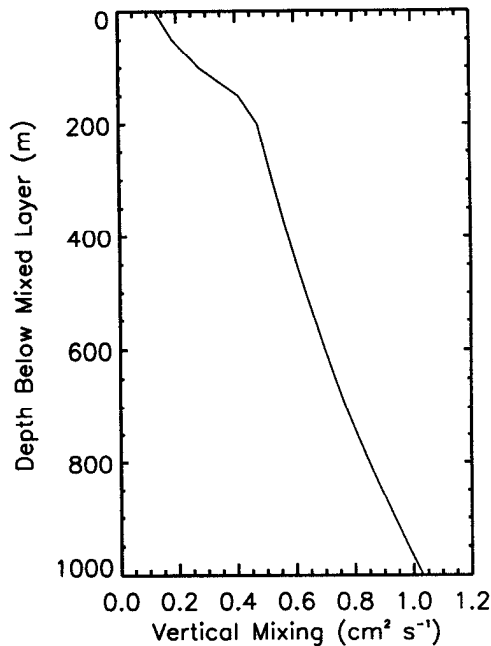


Figure 6. Averaged depth-dependent K_v , determined from the 5 cruises.

4. Discussion and summary

The analysis of CFC and temperature profiles from near Station P produced small values of K_v and w . Optimal fits to the CFC data with a one-dimensional advection-diffusion model with constant K_v gave average K_v and w values of $0.4 \pm 0.1 \text{ cm}^2 \text{ s}^{-1}$ and $1.2 \pm 0.4 \text{ m yr}^{-1}$. Our average value of K_v was significantly smaller than the $1 \text{ cm}^2 \text{ s}^{-1}$ value proposed by Munk (1966). However, our fits to the CFC profiles produced K_v values that increased with time and modeled CFC concentrations that were too high in the upper 300 m and too low below 400 m. These two features implied that K_v increased with depth. Using the assumption proposed by Gargett and Holloway (1984) that K_v was inversely related to the buoyancy frequency, produced optimal solutions that significantly reduced the model-data differences, removed the systematic depth dependence in the model-data misfit and produced consistent estimates of K_v for all 5 cruises. The model results strongly supported the assumption that K_v increased with depth. The assumption that K_v was related to N^{-1} was consistent with the CFC profiles but it does not negate another functional relationship for K_v , which increases with depth.

The magnitude of the estimated K_v profiles does suggest that vertical mixing in the open ocean interior is driven by vertical instability caused by internal waves. The energy requirements for K_v can be supplied by internal waves. K_v appears to be a local process and the advection of boundary-mixed water into the ocean interior (Ivey, 1987; Ivey and Nokes, 1989) is not required at Station P.

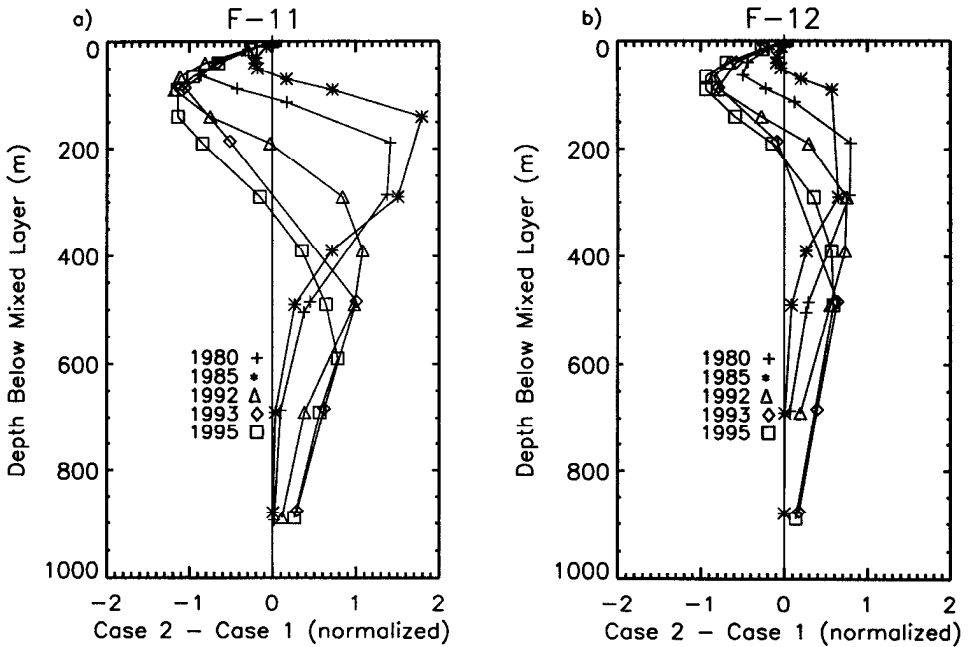


Figure 7. Case 2 model-data-misfits for (a) F-11 and (b) F-12.

At Station P, it is unlikely that the observed CFC distributions are the result of isopycnal processes and not diapycnal ones (Gammon *et al.*, 1982). An empirical technique presented by Rooth and Ostlund (1972) provides an upper bound estimate of K_v , independent of advection (i.e. no simplification of the ocean physics is required). We used the upper bound estimate of K_v to validate the K_v determined by the one-dimensional advection diffusion model. The limitation in using the upper bound estimate of K_v is that it is only applicable where temperature and CFC display exponential depth profiles (Rooth and Ostlund, 1972) (0–100 m below mixed layer). If the two tracers displayed exponential depth profiles, a coupled equation can be written which does not include advective terms. For temperature (T) and a CFC tracer (C) with depth scale H_T and H_C respectively, the coupled equation is

$$\phi_t = (\mu^2 - \mu) \left[K_v \left(\frac{\partial \theta}{\partial z} \right)^2 + K_h (\nabla_h \theta)^2 \right] \tag{7}$$

where $\theta = \ln(T - T_0)$, $\phi = \ln(C)$ and $\mu = H_T/H_C$. Defining $H_T \approx |\partial \theta / \partial z|^{-1}$ and $L_T \approx |\nabla_h \theta|^{-1}$ as the characteristic vertical and horizontal length scales in the thermocline, one can write (1) as (Rooth and Ostlund, 1972)

$$\phi_t = (\mu^2 - \mu) \left[\frac{K_v}{H_T^2} + \frac{K_h}{L_T^2} \right]. \tag{8}$$

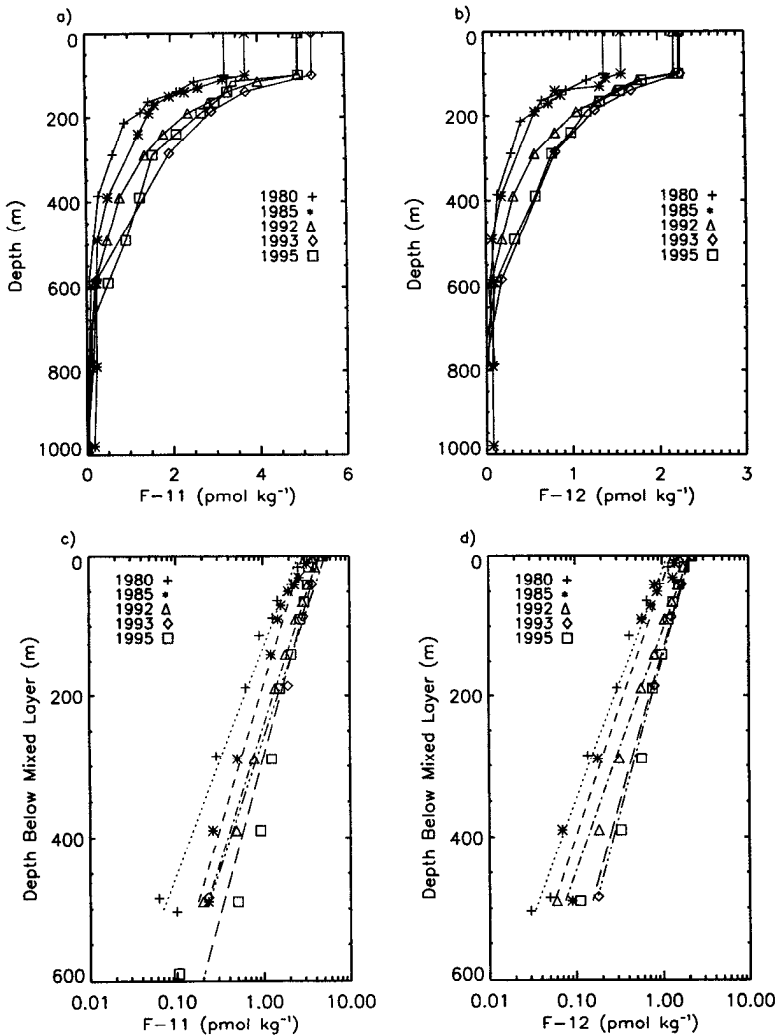


Figure 8. Vertical profiles of (a) F-11 and (b) F-12 from data near Station P. The exponential depth scale fitted to the (c) F-11 data and (d) F-12 data. The computed depth scales are summarized in Table 3.

The local rate of change, ϕ_t , balances the effective diffusion rate independent of advective effects and boundary conditions. The temperature data from Station P displayed an exponential decrease with depth ($H_T = 900 \pm 100$ m) to an asymptotic value of 1.6°C (Fig. 2b). The CFC data also showed an exponential decrease in concentration with depth (Fig. 8). For the 1980 cruise, ϕ_t is set to the observed 1948–78 atmospheric increase (Table 3). For the 1985, 1992, 1993 and 1995 cruises, ϕ_t is estimated from the measured CFC concentrations in the mixed layer normalized to a constant mixed layer temperature of

Table 3. Upper bound estimate of K_v for 0–100 m below the base of the mixed layer.

	Date	Temperature depth scale (m)	CFC depth scale (m) 0–100	Temporal scale (yr)	K bounds ($\text{cm}^2 \text{s}^{-1}$)
F12	1980	900	99	9.6	0.36
	1985	900	88	12	0.23
	1992	900	132	21	0.31
	1993	900	167	22	0.49
	1995	900	164	23	0.45
F11	1980	900	94	6.7	0.47
	1985	900	94	12	0.26
	1992	900	130	23	0.27
	1993	900	150	24	0.36
	1995	900	180	26	0.49
Average					0.36
Standard deviation					0.10

6°C (Table 3). The effective diffusion calculated from the temperature and CFC's in the depth range 0–100 m below the CFC mixed layer averaged to $0.36 \pm 0.10 \text{ cm}^2 \text{ s}^{-1}$ (Table 3). This value is greater than the average K_v value of $0.30 \text{ cm}^2 \text{ s}^{-1}$ for the 200 m below the mixed layer. The consistency between the average K_v and the upper bound K_v estimates supports the application of the one-dimensional advection diffusion model at Station P.

Our estimated values of K_v and w have important consequences on the supply of nutrients to the euphotic zone at Station P. Miller *et al.* (1991) estimated the vertical transfer of nitrate through the halocline into the euphotic zone in the eastern subarctic Pacific to be 0.6 and $1.6 \text{ mmol m}^{-2} \text{ d}^{-1}$ for the vertical diffusive and vertical advective fluxes respectively. From the K_v and w values calculated in our study, the nitrate supply is reduced to 0.3 and $0.2 \text{ mmol m}^{-2} \text{ d}^{-1}$ for the vertical diffusive and vertical advective fluxes respectively. The factor of four reduction in the supply of nitrate to the mixed layer reduces the nitrate utilization in the euphotic zone calculated by Miller *et al.* (1991) from 3.1 to $1.4 \text{ mmol m}^{-2} \text{ d}^{-1}$. This emphasizes that accurate estimates of the vertical supply of nitrate to the euphotic zone are critical to accurately calculating the nitrate utilization in the euphotic zone and estimating the rate of new production.

The one-dimensional advection-diffusion model calibrated with the temperature and CFC profiles was used to model the penetration of anthropogenic CO_2 at Station P. Atmospheric CO_2 displayed an exponential increase with a characteristic time-scale, τ , of 41 years. Chen (1993) provided a method for calculating anthropogenic CO_2 penetration from ΣCO_2 and alkalinity measurements. The application of this method required some caution (Chen, 1982), however the method did provide a crude estimate of anthropogenic CO_2 penetration to $\pm 8 \mu\text{M}$. Using ΣCO_2 and alkalinity measurements from the 1992 Station P cruise (C. S. Wong unpublished data report), we calculated the anthropogenic CO_2 penetration (Fig. 9). The model penetration of anthropogenic CO_2 for case 1 and 2 are

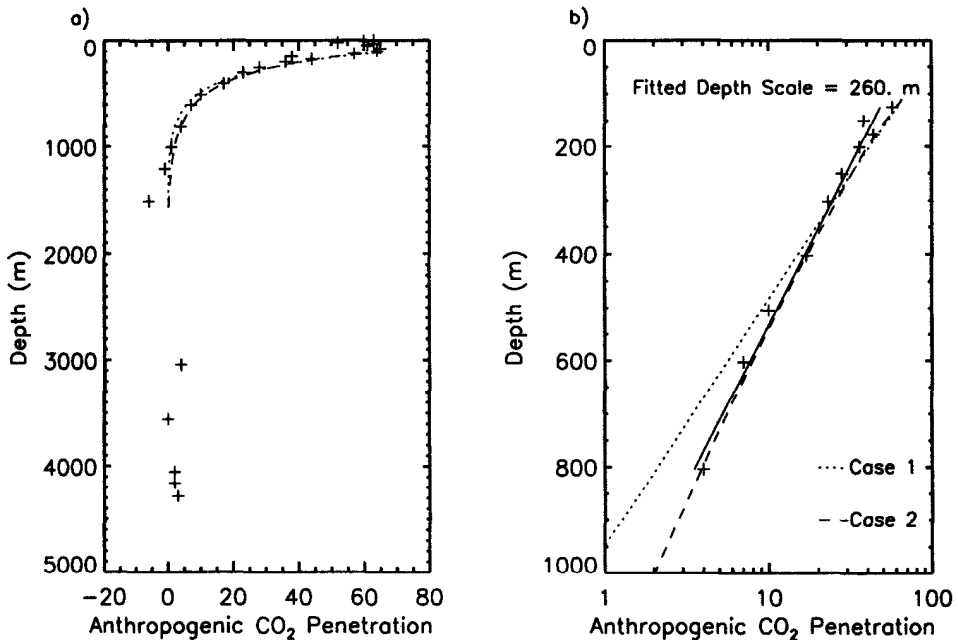


Figure 9. (a) Anthropogenic CO₂ penetration (Chen, 1987) at Station P calculated from the 1992 cruise; (b) Modeled anthropogenic CO₂ penetration for depth independent K_v (case 1) and depth-dependent K_v (case 2).

shown in Figure 9. A depth-dependent K_v (case 2) produced a better fit to the observed anthropogenic CO₂ penetration in the upper 400 m than case 1. Below 400 m, the accuracy of the calculated anthropogenic CO₂ severely limited the usefulness of the data and made it difficult to assess the performance of the two cases. The use of a depth-dependent K_v did increase the penetration of anthropogenic CO₂ into the ocean.

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