Pergamon

PII: S0967-0645(96)00036-7

Deep-Sea Research II, Vol. 43, No. 4–6, pp. 1095–1132, 1996

0967-0645/96 $15.00 + 0.00

Export flux of particulate organic carbon from the central equatorial Pacific determined using a combined drifting trap–^{234}Th approach

JAMES W. MURRAY,* JENNIFER YOUNG,* JAN NEWTON,*†
JOHN DUNNE,* THOMAS CHAPIN,* BARBARA PAUL*
and JAMES J. McCARTHY‡

(*Received* 31 *October* 1995; *in revised form* 5 *April* 1996; *accepted* 10 *April* 1996)

Abstract—The export flux of particulate organic carbon from the euphotic zone in the central equatorial Pacific was measured using an approach that utilizes ^{234}Th and organic carbon analyses on water column and drifting sediment trap samples. This study was conducted as part of the U.S. Joint Global Ocean Flux Study (U.S. JGOFS) EqPac process study from 12°N to 12°S at 140°W. Samples were collected during the Survey I (February–March 1992) and Survey II (August–September 1992) cruises. The accuracy of drifting sediment traps was evaluated by comparing the measured flux of ^{234}Th with the flux calculated from the deficiency of ^{234}Th relative to ^{238}U in the water column. Calculated ^{234}Th fluxes were corrected for the effects of horizontal and vertical advection. The uncertainties on these ^{234}Th fluxes averaged 39% for Survey I and 20% for Survey II. Comparison of measured and calculated ^{234}Th fluxes revealed evidence for overtrapping, especially in the shallow traps (≤100 m). Measured and calculated ^{234}Th fluxes agreed to within 50% for traps at 150–250 m. Good correlation was obtained between measured fluxes of organic carbon and ^{234}Th except for some shallow samples high in organic carbon, suggesting that ^{234}Th was a good tracer for organic carbon. The flux of particulate organic carbon (POC) was calculated as the product of the calculated flux of ^{234}Th times the organic carbon/^{234}Th ratio in trap samples. Assuming that the organic carbon/^{234}Th ratio in trap samples was representative of sinking particles, we used an average value for the organic carbon/^{234}Th ratio for each station. The variability in the station-averaged POC/^{234}Th ratio ranged from 10% to 30%. The POC fluxes calculated using our combined ^{234}Th-trap approach ranged from 1 to 6 mmol C m^{-2} day^{-1} during Survey I, and from 2 to 30 mmol C m^{-2} day^{-1} during Survey II. The average uncertainty for the POC fluxes was ±60%. Primary and new production integrated to the depth of the 0.1% light level varied by factors of 2–3 for Survey I and Survey II, respectively. The export of particulate organic carbon from the euphotic zone also increased by a factor of 3. The corresponding *e*-ratios (POC export/primary production) ranged from 0.03 to 0.11 for Survey I, and 0.04 to 0.23 for Survey II. Annual average regional rates (10°N–10°S; 90°W–180°E) of new (0.47 Gt C year^{-1}) and particulate export (0.42 Gt C year^{-1}) production were in good agreement, suggesting that, on an annual basis, significant export of DOC need not be invoked to balance new and export production in this region. Copyright © 1996 Elsevier Science Ltd

INTRODUCTION

Upwelling of nutrient-rich water at the equatorial divergence in the Pacific supports a highly productive biological community (Barber and Chavez, 1983). Chavez and Barber (1987) proposed that this region has the potential to contribute as much as 25–50% of global new

*School of Oceanography, Box 357940, University of Washington, Seattle, WA 98195–7940, U.S.A.
†Present address: Washington Department of Ecology, Ambient Monitoring Section, P.O. Box 47710, Olympia WA 98504, U.S.A.
‡Museum of Comparative Zoology, 26 Oxford Street, Harvard University, Cambridge, MA 02138, U.S.A.

production. Paradoxically, this region is also representative of high-nutrient low-chlorophyll (HNLC) regimes, with a biological food-web dominated by small phytoplankton and zooplankton and low ratios of new and export production to primary production. New production, defined as the fraction of primary production driven by input of new nutrients (usually NO_3^-) to the euphotic zone (Dugdale and Goering, 1967), and export production, defined as the fraction of primary production exported as particulate organic carbon (Eppley and Peterson, 1979), are macroscopic variables that characterize the efficiency of carbon and nutrient cycling and particle export from the biological food web. Distinguishing between new and export production is important because they are equal only if: (i) steady state conditions exist and (ii) all the export is in the form of particulate organic carbon.

JGOFS is a study of carbon fluxes in the world's oceans, and measurement of the particulate flux from the euphotic zone is one of the most important fluxes used to characterize upper ocean carbon cycling. Drifting sediment traps are the only direct approach for measuring and collecting the vertical particulate flux. Data collected using this method in the past are consistent with paradigms that the flux decreases with increasing depth, distance from the continental margin and decreasing primary production (Martin *et al.*, 1987; U.S. JGOFS, 1989; Murray *et al.*, 1989; Knauer *et al.*, 1990). Nevertheless, a number of factors have been proposed, such as zooplankton swimmers (Lee *et al.*, 1988; Karl and Knauer, 1989; Michaels *et al.*, 1990), solubilization (Knauer *et al.*, 1990) and hydrodynamics (Gardner, 1980; Gust *et al.*, 1992, 1994), that may bias the results. Even though this approach is one of our most uncertain flux measurements, drifting traps have provided a significant contribution to our understanding of sinking particles in the ocean.

Model-calculated carbon fluxes based on the export flux of ^{234}Th, which is calculated from the deficiency of ^{234}Th relative to ^{238}U, have been proposed both as a method for calibrating traps (Buesseler, 1991) and as an alternative approach to the direct measurement of particulate carbon flux (Eppley, 1989; Buesseler *et al.*, 1992). The approach used to calibrate traps is to compare the measured and calculated ^{234}Th fluxes. Calculating the ^{234}Th flux approach has its own biases including uncertainties in the time variability and transport terms (Buesseler *et al.*, 1992; Wei and Murray, 1992). Nevertheless, in our opinion, ^{234}Th is the best tool we have at present to evaluate the accuracy of drifting sediment traps under field conditions. The approach used to calculate the particulate carbon flux is to multiply the calculated ^{234}Th flux by the $C/^{234}Th$ ratio in sinking particles. This method has additional uncertainty due to variability in the $C/^{234}Th$ ratio in sinking particles as determined by different sampling approaches (Michaels *et al.*, 1994).

U.S. JGOFS recently conducted a Process Study of the carbon cycle in the central equatorial Pacific (EqPac, Murray *et al.*, 1994). Several of the main scientific questions addressed by EqPac dealt with new and export production (Murray *et al.*, 1992). The EqPac goals were to measure new and export production, determine if they were in balance, and determine what controls their value. In addition, our earlier work in the eastern equatorial Pacific (Murray *et al.*, 1989) led to two specific results that we wanted to explore in more detail and see if they held for the central equatorial Pacific as well. The first was that the magnitudes of both new and export production were surprisingly low for the relatively high nutrient concentrations present. The second was that export production was less than new production. This result is consistent with the hypothesis that significant export occurs as dissolved organic carbon.

Few previous chemical or biological data exist from the central equatorial Pacific for El Niño conditions. Based on biological data from 95°W (Barber and Chavez, 1983; Barber and Kogelschatz, 1990) and moored trap fluxes (Dymond and Collier, 1988) during the 1982/1983 El Niño, we predicted that both new and export production would be greatly reduced during El Niño periods. Fortunately, the EqPac study sampled both El Niño and non-El Niño conditions during 1992. The U.S. JGOFS cruises were part of a multi-year international study (U.S. JGOFS, 1990), and when the final data set is complete we should be able to determine how the region responds to interannual variability, including El Niño periods.

In this study we determined the flux of particulate carbon out of the euphotic zone from 12°N to 12°S along 140°W on the EqPac Survey I and II cruises using a combined drifting sediment trap-^{234}Th approach. Our goals were to (i) evaluate the accuracy of drifting traps as a function of latitude and depth by comparing measured and calculated ^{234}Th fluxes, (ii) determine the magnitude of particulate organic carbon export production and its meridional and seasonal variability, (iii) compare export production with primary and new production, and (iv) update the Chavez and Barber (1987) evaluation of the importance of this region for global new production.

SAMPLES AND METHODS

Water column samples for total ^{234}Th were collected at eight depths from the surface to 250 m using CTD-rosette mounted 30-l Go-Flo bottles. These samples were collected shortly after deployment of the drifting traps. ^{234}Th samples were collected at the same depths as the traps to facilitate flux calculations. Shipboard sample processing and beta counting were used for ^{234}Th ($t_{1/2}$ = 24.1 days) to minimize in-growth and decay corrections. Analyses of ^{234}Th were conducted following a combination of the procedures of Anderson and Fleer (1982) and Coale and Bruland (1985). Samples were immediately drawn into 25-l polyethylene cubitainers, spiked with about 30 dpm ^{230}Th ($t_{1/2}$ = 75,000 years) as a yield tracer, 500 mg purified $FeCl_3$ in concentrated HCl (final pH = 1.5), and equilibrated for at least 6 h. They were then neutralized to pH 8 with NH_4OH, and the $Fe(OH)_3$ precipitate was allowed to settle. The overlying water was decanted, and the $Fe(OH)_3$ precipitate was dissolved in 9 N HCl. A series of anion exchange columns (AG 1X8, 100–200 mesh) was used to separate ^{234}Th, ^{210}Pb and ^{210}Po. The ^{210}Pb and ^{210}Po results will be reported elsewhere.

The purified sample of ^{234}Th was electroplated or extracted with TTA/benzene and stippled on stainless steel planchets, wrapped with Al-foil, and beta counted at sea using lead shielded, anti-coincidence gas-proportional counters. All column chemistry, plating and beta counting (105 and 112 samples for Survey I and II, respectively) were completed at sea within 5 days of sample collection. The ^{234}Th activities were decay-corrected to the time of collection. The background of the beta counters at sea was about 0.3 cpm, and the efficiency, which was checked twice a week with standard ^{238}U plates, averaged 60%. All samples were alpha counted after the cruise to determine the yield of ^{230}Th tracer. The ^{230}Th spike was inter-calibrated with Michael Bacon (WHOI). The uncertainty in the activity of ^{234}Th calculated from propagation of the errors for each step in the separation/analytical process was 6.2%. The precision calculated from several replicate samples was considerably better at 2.4%. We use the value of 6.2% for error analysis in this paper (Table 1). The ^{238}U/salinity relationship of Chen *et al.* (1986) (^{238}U dpm $l^{-1} = 0.0686 \times \sigma_t$) was used to calculate

Table 1. *Error estimates for individual data points*

Parameter	Error estimate (%)
Total ^{234}Th	6.2
Dissolved ^{234}Th	6.2
Particulate ^{234}Th	6.2
Total ^{328}U	1.0
Trap ^{234}Th flux	12
Trap organic carbon flux	12
Meridional velocity (v)	50
Vertical velocity (w)	50
New production	30
Trap organic C/^{234}Th	10–30
Log (^{234}Th trap/^{234}Th model)	(log (value + SD) − log(value − SD))/2

water column ^{238}U activities. The uncertainty for ^{238}U calculated from this equation was 1% (Table 1).

Samples for dissolved (<0.45 μm) and particulate (>0.45 μm) ^{234}Th also were collected at the same depths as total ^{234}Th during both survey cruises. Samples for ^{234}Th were collected by pressure filtration (15 psi of N_2) of whole bottle samples through either 142 mm diameter 0.50 μm Nuclepore or 0.45 μm Millipore filters. Nuclepore filters were used when total suspended matter weights were desired. Three bottles (about 90 l) were filtered, and the filters for each depth were combined for a single analysis. These results will be used to discuss particle cycling in a later paper (Dunne *et al.*, in prep.). Here we use the particulate analyses to calculate the C/^{234}Th ratio for background suspended matter. ^{234}Th analyses also were completed on large-volume particulate matter samples collected during Survey II on 1-μm Microquartz filters and 53-μm Nytex prefilter using the *in-situ* large volume pump system (MULVFS) of Bishop *et al.* (1985). MULVFS carbon data are reported by Bishop *et al.* (in prep.). The MULVFS organic carbon/^{234}Th ratios are reported in Dunne *et al.* (in prep.). All dissolved analyses were completed at sea, and the particulate analyses were conducted after the cruise at UW. Particulate samples were digested in warm HNO_3, $HClO_4$ and HF that was spiked with ^{230}Th yield tracer. The analyses then followed the sequence given above for total ^{234}Th. Both dissolved and particulate analyses were assigned the same uncertainty (6.2%) as total ^{234}Th (Table 1).

Water column samples for nutrients, chlorophyll, and particulate carbon and nitrogen were collected at 12 depths with a 24-bottle CTD-rosette from the surface to 400 m during the routine dawn (06:00 h) and dusk (18:00 h) hydrocasts. Samples (4–6 l) for particulate carbon and nitrogen were drawn through silicon tubing with minimum turbulence to reduce possible aggregation of sub-micron into filterable particles (Bishop, 1991; Altabet *et al.*, 1992) and filtered through pre-combusted 25 mm Whatman GF/F filters. Carbon and nitrogen analyses were conducted using a Leeman Labs CEC 440 CHN analyzer. Samples were run with and without removal of $CaCO_3$ by moistening filters with excess H_3PO_4 and drying the acid on the filter. Standards were prepared to cover the range of the samples. All carbon fluxes reported in the paper are for particulate organic carbon.

The flux of particles was sampled using two types of drifting sediment traps, i.e. Lorenzen *et al.* (1983) traps and Knauer *et al.* (1979) particle interceptor trap (PIT) designs. The Lorenzen traps, opaque to prevent photodegradation of pigments, were equipped with

timer controlled closing devices. These traps were deployed with salt tablets at the bottom, but the final salt gradient was unknown. The PITs were constructed from polycarbonate cylinders (area = 0.0039 m^2) and were modified from the original design to contain a 90 mm filter holder at the base and to be trace-metal clean (Murray *et al.*, 1989). The PITs were deployed with a 15-cm thick brine layer (50 ppt above ambient salinity, consistent with U.S. JGOFS, 1989, 1993; Michaels *et al.*, 1994) at the bottom. This layer was the same thickness after recovery. The most recent JGOFS Protocols recommend use of a brine of only 5 ppt in excess (IOC, SCOR, 1994; Gardner and Zhang, in press). Although these traps had different aspect (length to diameter) ratios (PIT = 8:1 and Lorenzen = 5:1), we observed good agreement and good correlation between the log values of the carbon ($r^2 = 0.80$) fluxes at the same depths. The sediment trap arrays were hung with bungi cord on a PVC cross frame and normally deployed for about 48 h at each station. Traps were deployed at 5–7 depths from 50 to 250 m. The most common depths for PIT deployments were 75 m, 100 m, 150 m, 200 m and 250 m. During Survey I the Lorenzen traps were hung 10 m above the PIT multitraps. For Survey II Lorenzen traps with a 8:1 aspect ratio and a 15 cm thick brine layer were hung on the same frames as the PIT traps.

All trap samples were carefully picked using forceps, under 25 power magnification, to remove all recognizable zooplankton specimens (swimmers) (Michaels *et al.*, 1990). Selected combined zooplankton samples were analyzed for ^{234}Th. Several analyses were conducted of total swimmers picked from samples at 100 m. The ^{234}Th content of swimmer material ranged from 0.025 to 0.126 dpm mg^{-1}. If they had not been removed, the ^{234}Th flux associated with swimmers would have ranged from 46 to 244 dpm m^{-2} day^{-1}, or 1.5% to 8% of the total ^{234}Th flux. Both Lorenzen and multitrap samples were filtered through GF/F filters for carbon and nitrogen analyses as described above. Samples for ^{234}Th were collected on 0.45 μm Millipore filters mounted in the bottom of the PITs. ^{234}Th analyses were completed in the lab at UW within 2 months of collection. Some trap solutions also were analyzed for ^{234}Th to check for remineralization. The precision in trap carbon fluxes was 12% as determined from several sets of duplicate and triplicate traps at the same depths (Table 1). The precision for trap ^{234}Th fluxes was less than or equal to this value.

The methods for new production were reported by McCarthy *et al.* (1996). We assign an upper limit uncertainty of 30% to these data (Table 1).

Many comparisons of data in this paper are made at 120 m. This depth was selected at a U.S. JGOFS Science Workshop to be a common depth for reporting fluxes because it was a good approximation of the base of the euphotic zone as defined as the depth of the 0.1% light level using PAR. We make these comparisons at the 0.1% light level because about 10% of the primary production and 20% of the new production occurs between the 1% and 0.1% light levels.

Least-squares propagation of uncertainties was used for each individual data point. The estimated error for the important data and parameters used in this paper are summarized in Table 1. Data sets were tested for normal distributions and parameters such as the average, standard deviation, and least-squares regression were calculated using the data or their log transformation as required. For characterizing variability within and between data sets, we have used the non-parametric Mann–Whitney (or Wilcoxon) *U*-test (Rohlf and Sokal, 1969; Sokal and Rohlf, 1981). The test gives the probability, *P*, that the two data groups come from the same population. In discussing our results, we use the statistical convention that the difference between the two groups is considered "significant" if *P* is less than 0.05. If *P* is less than 0.01, the difference between populations is considered "highly significant" (Taylor,

1982). Here, we have used the two-tailed (i.e. more stringent) form to establish difference in either direction.

RESULTS

Samples were collected from 12°N to 12°S along 140°W on the R.V. *Thompson* during EqPac Survey I (TT007; February–March, 1992) and Survey II (TT011; August–September, 1992). Stations were occupied at 12°N, 9°N, 7°N, 5°N, 3°N, 2°N, 1°N, Equator, 1°S, 2°S, 3°S, 5°S and 12°S for 1.5–2.5 day periods during which samples were collected for a complete set of hydrographic, chemical and biological parameters (Murray *et al.*, 1995). Characterization of these sample sites in terms of average values of sea surface temperature and nitrate (Murray *et al.*, 1995), euphotic zone depth (defined as the 0.1% light level calculated from scalar PAR, 400–700 nm) (C. Trees, personal communication, 1994), mixed-layer thickness (depth where density is 0.03 density units greater than at the surface; Gardner *et al.*, 1995), and integrated particulate organic carbon (POC), chlorophyll and primary production (Barber *et al.*, 1996) in the euphotic zone is summarized in Table 2. For perspective, the range of values for integrated POC (135–410 mmol C m^{-2}), integrated chlorophyll (17.51–37.91 mg Chl m^{-2}) and integrated primary production (13.2–149.5 mmol C m^{-2} day^{-1}) are less than those observed during the North Atlantic Spring Bloom (NABE) Process Study (400–1100 mmol C m^{-2}, 35–90 mg Chl m^{-2} and 50–150 mmol C m^{-2} day^{-1}) (Lochte *et al.*, 1993) but greater than those observed at the Hawaii Ocean Time-series (HOT) (0–200 m) for 1991–1992 (340 ± 71 mmol C m^{-2}, 21.9 ± 3.6 mg Chl m^{-2} and 44.5 ± 8.9 mmol C m^{-2} day^{-1}; Karl *et al.*, 1996). In terms of these variables, the EqPac study site was intermediate, both in terms of magnitude and variability, relative to conditions at the North Atlantic (NABE) and North Pacific (HOT) sites. Trends in hydrographic, chemical and biological properties at the equator during these and other EqPac cruises were discussed in more detail in Kessler and McPhaden (1995), Murray *et al.* (1994, 1995), Roman *et al.* (1995), Gardner *et al.* (1995) and D. Foley (personal communication, 1996).

The key data used to calculate the export flux of particulate organic carbon using our combined ^{234}Th-drifting trap approach are given in the Appendix. This Appendix includes all water column concentrations and sediment trap fluxes for ^{234}Th, values of water column ^{238}U calculated from salinity and calculated fluxes of ^{234}Th, and particulate organic carbon with propagated uncertainties (1 SD). The model calculated fluxes include terms for advective transport in vertical and meridional directions. The data are given as a function of depth for stations sampled during Survey I and Survey II. The data for dissolved ^{234}Th, particulate carbon, and ^{234}Th from samples filtered from bottle samples and samples filtered *in situ* using the MULVFS pump system are available in the U.S. JGOFS Data System (http://www1.whoi.edu/jgofs.html). The data will be shown here in subsequent figures.

The measured POC and ^{234}Th trap fluxes during Survey I (TT007) and Survey II (TT011) are shown in Fig. 1(a),(b) and Fig. 2(a),(b). Trap fluxes of POC and ^{234}Th at depths shallower than 150 m were higher and more variable than deeper values. At and above 100 m, POC and ^{234}Th fluxes ranged from about 4 to 40 mmol C m^{-2} day^{-1} and 1000 to 11,000 dpm m^{-2} day^{-1}, respectively. The data do not group well into equatorially symmetric latitude bands. There were no significant meridional bands for carbon. For ^{234}Th we observe that for Survey I the values from 5°N to 1°S were significantly higher, and for Survey II the values from 5°N to 5°S were significantly higher. Overall the populations

Table 2. Summary of hydrographic, chemical and biological parameters that characterize the stations occupied during the EqPac Survey I and Survey II cruises

	Station Deg. latitude	Date First day	SST deg C	Surface NO_3 μmol kg^{-1}	0.1% light depth m	Mixed layer m	Integr. POC mmol C m^{-2}	Integr. Chl mg Chl m^{-2}	Integr. PP mmol C m^{-2} day^{-1}
Survey I	12 N	February 4, 1992	25.95	0.03	118	50	267	20.13	25.5
	9	February 7, 1992	26.63	0.09	116	46	239	19.45	13.2
	7	February 10, 1992	27.71	0.30	119	34	135	23.66	38.0
	5	February 12, 1992	28.48	0.44	—	52	307	21.23	43.9
	3	February 15, 1992	28.60	1.46	133	57	254	23.88	63.0
	2	February 17, 1992	28.42	2.00	132	27	250	27.62	62.4
	1	February 20, 1992	28.48	2.66	—	57	299	23.60	50.9
	0	February 23, 1992	28.41	3.00	150	28	258	25.12	62.8
	1 S	February 27, 1992	28.59	2.83	139	36	241	33.13	82.8
	2	March 1, 1992	28.60	2.78	—	72	240	18.55	48.9
	3	March 3, 1992	28.59	2.82	—	73	390	—	—
	5	March 4, 1992	28.76	2.79	141	59	273	22.84	60.2
	7	March 6, 1992	28.83	2.78	—	39	218	—	—
	9	March 7, 1992	28.87	0.65	—	12	236	—	—
	12	March 8, 1992	28.64	0.17	158	36	194	19.42	33.6
Survey II	12 N	August 11, 1992	28.48	0.38	121	43	244	20.52	29.8
	9	August 14, 1992	28.38	0.20	119	24	237	21.06	23.3
	7	August 17, 1992	28.40	0.19	128	28	183	17.51	22.4
	5	August 19, 1992	28.11	0.28	124	25	288	25.73	46.5
	3	August 22, 1992	27.03	1.52	121	41	297	25.89	57.3
	2	August 25, 1992	24.89	5.05	95	20	410	37.91	149.5
	1	August 27, 1992	24.69	6.24	100	11	361	33.88	105.4
	0	August 29, 1992	24.90	6.14	97	28	265	26.76	92.6
	1S	September 1, 1992	25.56	5.54	109	27	220	—	—
	2	September 3, 1992	25.47	5.89	110	31	300	31.17	100.2
	3	September 6, 1992	25.43	5.13		23	298	36.64	115.2
	5	September 8, 1992	26.00	4.64	117	40	271	30.48	70.7
	7	September 10, 1992	26.68	3.74		34	207	—	—
	9	September 11, 1992	27.30	0.67		76	272	—	—
	12	September 13, 1992	26.47	0.45	147	53	244	20.31	31.1

Each station was occupied for 1.5–2.5 days. The sea surface temperature and surface nitrate are average values for several casts at each station (Murray *et al.*, 1995). The euphotic zone depth (defined as 0.1% light level as calculated from scalar PAR, 400–700 nm) was determined from optical casts conducted at midday (C. Trees, personal communication). The mixed-layer thickness was defined as the depth where the density increased by $\Delta\sigma = 0.03$ (Gardner *et al.*, 1995). The inventories of particulate organic carbon and chlorophyll were integrated to the base of the euphotic zone. The primary production values represent one or the average of two measurements as appropriate (Barber *et al.*, 1996).

did not have normal distributions but were skewed toward lower values. The difference between the total populations for trap carbon flux and ^{234}Th flux between Survey I and Survey II was found to be insignificant.0 >

The water column ratios of total ^{234}Th/^{238}U are shown in Fig. 3; a ratio of 1 represents secular equilibrium. During both cruises there was a deficiency of ^{234}Th from the surface to the depth interval of 100–150 m. The depth of the 0.1% light level (which we use here to define the euphotic zone) falls in this range. The integrated deficiency was larger during Survey II than Survey I. During Survey I there was evidence for 10–20% excess ^{234}Th from 150 m to 250 m, suggesting that some ^{234}Th was released from particles in that depth range. Excess ^{234}Th was also observed at these depths by Bacon *et al.* (1996) during Time Series I and II cruises, which were 20-day occupations of the equator station conducted immediately after the Survey I and II cruises. The very high ^{234}Th/^{238}U ratio at the surface during Survey II was collected in the *Rhizosolenium*-rich patch north of the convergent front observed at 2°N, 140°W (Yoder *et al.*, 1994) due to physical concentration of particles and associated ^{234}Th. This data point was not included in our calculations, but is discussed in Archer *et al.* (submitted).

Calculated ^{234}Th fluxes

Model fluxes of ^{234}Th were calculated as a function of depth and latitude from water column profiles of total ^{234}Th (Appendix). The data are shown as the ratio to ^{238}U in Fig. 3. The model vertical flux of ^{234}Th at each depth was calculated from a mass balance of sources and sinks for total ^{234}Th that included physical transport:

$$\frac{\delta \mathrm{Th}}{\delta t} = {}^{238}\mathrm{U}\lambda_{234} - {}^{234}\mathrm{Th}\lambda_{234} - P - V(\text{advective} + \text{diffusive transport})$$

where ^{238}U and ^{234}Th are expressed as activities (dpm l^{-1}), and λ_{234} is the decay constant for ^{234}Th (=0.0288 day^{-1}). δTh/δt is the time rate of change of the activity of ^{234}Th, P is the particulate ^{234}Th export flux, and V is the sum of advective and diffusive fluxes (all in dpm m^{-2} day^{-1}). Buesseler *et al.* (1995) and Bacon *et al.* (1996) also calculated particulate export fluxes of ^{234}Th from the central equatorial Pacific as part of the EqPac project. We followed a similar approach but differed in the way we did the correction for advective transport. Buesseler *et al.* (1995) collected integrated pump samples (0–100 m) for ^{234}Th from meridional transects (10°N–10°S) at four longitudes (95°, 110°, 125° and 140° W). For comparison with their data they developed a regional 3-D flux model that incorporated seasonal and site specific upwelling and horizontal fluxes. They calculated ^{234}Th fluxes at 100 m which included the influence of upwelling and horizontal advection. They directly measured the zonal and meridional horizontal gradients and had to estimate the vertical gradient and time rate of change. Bacon *et al.* (1996) collected four vertical profiles (0–400 m) of ^{234}Th at the equator over a 2-week period during each Time Series cruise. They used direct measurements of the time rate of change and the vertical gradient but had to neglect the horizontal gradients. They used a 1-dimensional model, which included vertical upwelling. Our 2-dimensional data set consisted of data for total ^{234}Th from 0 to 250 m from 12°N to 12°S at 140°W; thus we were able to calculate the vertical and meridional advective terms as a function of depth but had to rely on constraints of data from Bacon *et al.* (1996) for the time rate of change and Buesseler *et al.* (1995) for the zonal gradients.

For our model calculations of the ^{234}Th flux we assumed steady state (δTh/δt=0).

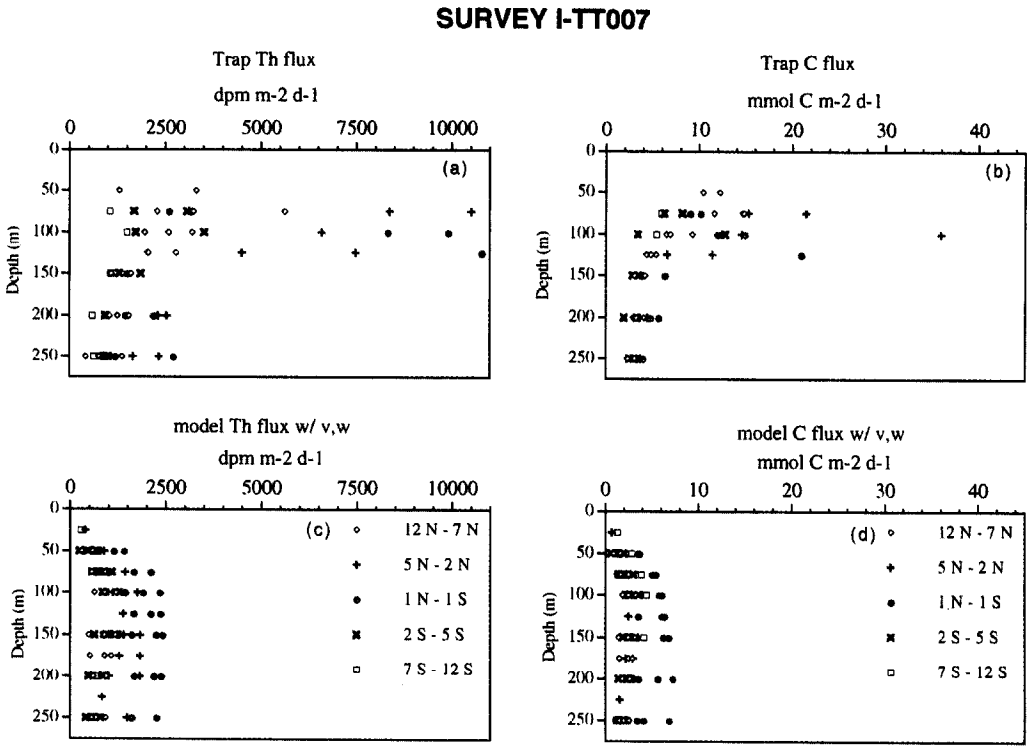

Fig. 1. Summary of measured and model-calculated ^{234}Th and organic carbon fluxes from 0 to 250 m for Survey I of the U.S. JGOFS EqPac Process Study. Survey I was conducted as R.V. *Thompson* cruise TT007 in February–March 1992. Data are symbol and color coded for ease of identification. The red circles are data from 1°N to 1°S, crosses are from 2°N to 5°N and 2°S to 5°S and the boxes are from 7°N to 12°N and 7°S to 12°S. The method used for the model calculations is described in the text. The original data are in the Appendix. (a) Measured trap flux of ^{234}Th (dpm m^{-2} day^{-1}); (b) measured trap flux of particulate organic carbon (mmol C m^{-2} day^{-1}); (c) model-calculated ^{234}Th flux including vertical and meridional advection terms from 5°N to 5°S (dpm m^{-2} day^{-1}); (d) particulate organic carbon flux calculated as the product of the model calculated ^{234}Th flux times the organic carbon/^{234}Th ratio in trap particles (mmol C m^{-2} day^{-1}).

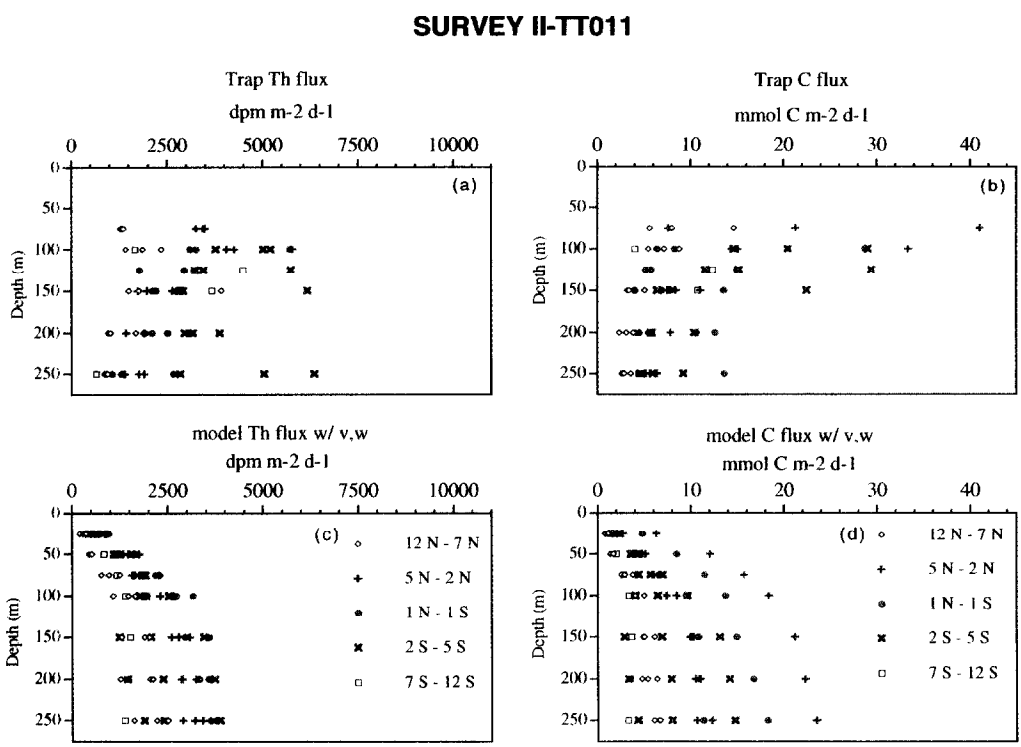

Fig. 2. Summary of measured and model-calculated ^{234}Th and organic carbon fluxes from 0 to 250 m for Survey II of the U.S. JGOFS EqPac Process Study. Survey II was conducted as R.V. *Thompson* cruise TT011 in August–September 1992. Data are symbol and color coded for ease of identification. The red circles are data from 1°N to 1°S, crosses are from 2°N to 5°N and 2°S to 5°S and the boxes are from 7°N to 12°N and 7°S to 12°S. The method used for the model calculations is described in the text. The original data are in the Appendix. (a) Measured trap flux of ^{234}Th (dpm m^{-2} day^{-1}); (b) measured trap flux of particulate organic carbon (mmol C m^{-2} day^{-1}); (c) model-calculated ^{234}Th flux including vertical and meridional advection terms from 5°N to 5°S (dpm m^{-2} day^{-1}); (d) particulate organic carbon flux calculated as the product of the model Th flux times the organic carbon/^{234}Th ratio in trap particles (mmol C m^{-2} day^{-1}).

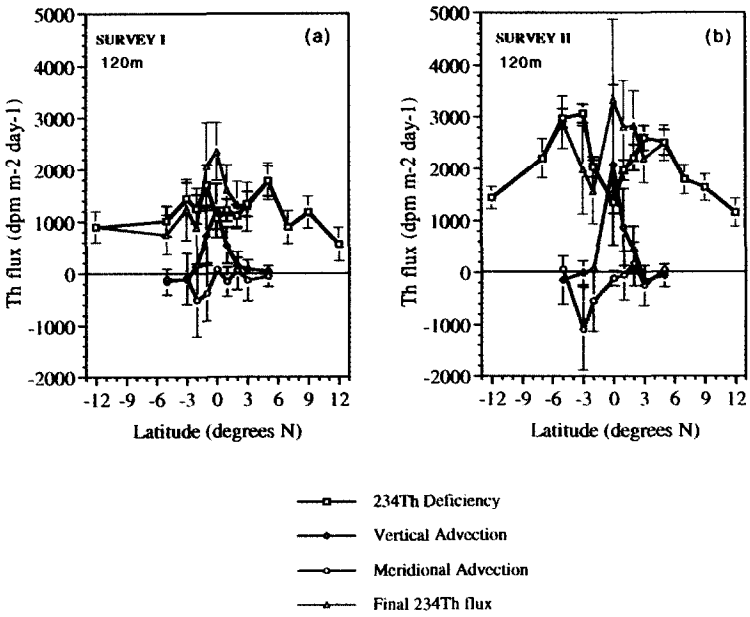

Fig. 4. Model-calculated flux of ^{234}Th at 120 m showing individual terms and final values as a function of latitude (12°N–12°S) for Survey I (TT007) and Survey II (TT011). The individual terms include the flux calculated from the deficiency of ^{234}Th relative to ^{238}U, the correction for vertical advection, and the correction for meridional advection. Error bars are shown for the individual terms and the propagated error is shown for the final ^{234}Th flux.

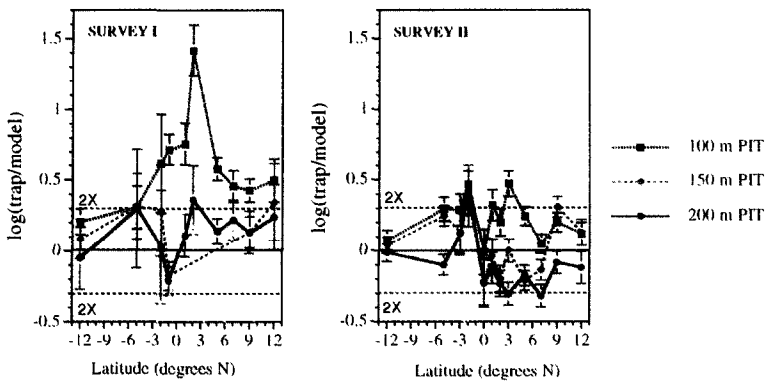

Fig. 5. The log ratio of the measured to the model-calculated fluxes of ^{234}Th for the PIT design traps. Calculations for PITs are shown for depths of 100 m, 150 m and 200 m for Survey I (TT007) and Survey II (TT011). The solid horizontal line at the log ratio of zero represents the point where the observed and trap fluxes are equal. Dashed horizontal lines are also shown for log ratios of 0.3 and −0.3, which represent variations of a factor of two.

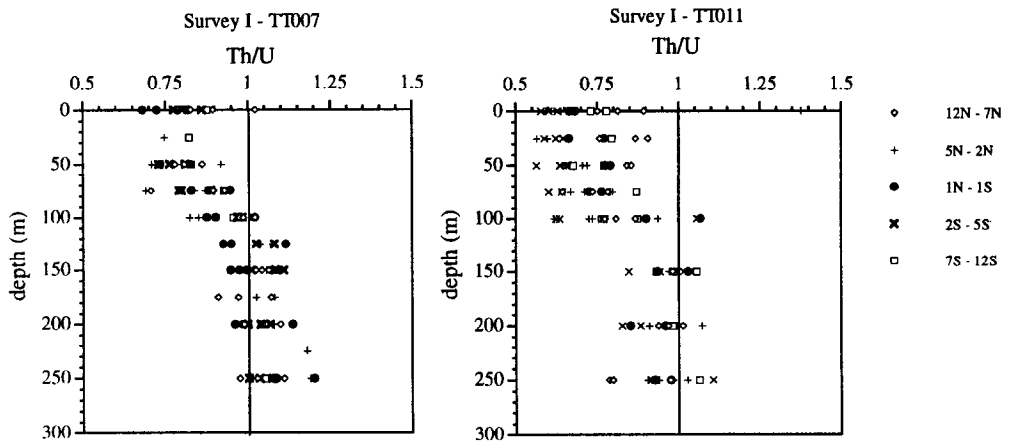

Fig. 3. The ratio of total $^{234}Th/^{238}U$ in the upper water column (0–250 m) during Survey I (TT007) and Survey II (TT011). The vertical line at the ratio of 1 represents secular equilibrium of ^{234}Th with ^{238}U.

Previous studies have shown that the time rate of change needs to be carefully evaluated for each location (Buesseler *et al.*, 1992, 1994). The cruise plan for the EqPac Survey cruises did not allow an opportunity for us to evaluate specifically this term for our data set. Thus we based this assumption on the results by Bacon *et al.* (1996) from the EqPac time-series cruises, which were conducted immediately after each Survey cruise, and by comparison of our results with those of Bacon *et al.* (1996) and Buesseler *et al.* (1995). Bacon *et al.* (1996) conducted four repeat casts for ^{234}Th over a 2-week period and concluded that steady state could be assumed for ^{234}Th. We generally agree with their assessment but note that a tropical instability wave passed the sample site on 13 October 1992 (Roman *et al.*, 1995), and shortly afterward (on 15 October 1992) they observed a 17% increase in total ^{234}Th below 80 m and a 30% increase in model particulate flux at and below 60 m. In addition, we observed that ^{234}Th at the equator and 140°W showed no systematic secular trend between the Survey I, Time Series I and NOAA Survey I or between Survey II, Time Series II and NOAA Survey II (Buesseler *et al.*, 1995). Each set of three cruises occurred within a 2 month time span.

Vertical and horizontal diffusive transport were neglected because they are small relative to the other terms. Zonal currents were large, but zonal advective transport ($u\,d^{234}Th/dx$) also was neglected because the zonal gradients in ^{234}Th, as determined by Buesseler *et al.* (1995), were small. Another approach for estimating the zonal gradient was to assume that the 30% increase in flux observed by Bacon *et al.* (1996) during the passage of the tropical instability wave was representative of horizontal gradients associated with these features. If the length scale associated with these waves is on the order of 1000 km (Yoder *et al.*, 1994), the zonal gradients still can be neglected.

With these assumptions, the particulate ^{234}Th flux (P) was therefore expressed as:

$$P = (^{238}U - ^{234}Th)\lambda_{234} + w\frac{d^{234}Th}{dz} - v\frac{d^{234}Th}{dy}$$

The upwelling (w) and meridional (v) advection velocities (m day^{-1}) as a function of depth were obtained from a 3-dimensional general ocean circulation model configured for

the tropical Pacific Ocean using 3 month average seasonal wind fields for 1992 (Buesseler *et al.*, 1995; Chai *et al.*, 1996). Average winds for March–May 1992 and September–November 1992 were used to simulate currents for Survey I and Survey II. During Survey I the estimated vertical velocity at the equator increased from 0 at the sea surface to a maximum of 266 cm day^{-1} at about 40 m and then decreased to less than 25 cm day^{-1} by 150 m. During Survey II the maximum upwelling increased to 392 cm day^{-1} and was centered at about 50 m. The vertical velocity decreased rapidly north and south of the equator and was negligible at 2°N and 2°S. For both cruises the meridional velocities were to the north and south away from the equator above 50 m and converged toward the equator below 50 m. Currents were more intense during Survey II than Survey I. The meridional gradients for ^{234}Th (δTh/δy) were calculated from our data assuming that activity gradients were linear between stations using a centered difference method when bounding points were available. The vertical gradients (δTh/δz) were calculated assuming linear gradients between vertical discrete data points using the same method.

The approach we followed was to calculate the ^{234}Th deficiency at each depth and then to calculate the proper advection correction terms at the same depth. First we integrated the deficiency from the surface to the depth of interest. Since the ^{234}Th flux was calculated from the difference between the activities of ^{234}Th and ^{238}U, the relative uncertainty was smallest when the deficiency was large. The relative uncertainty increased as the activity of ^{234}Th approached that of ^{238}U. The uncertainty in the integrated flux calculations also increased with depth, but the per cent propagated error actually decreased slightly with depth until the model flux reached its constant value, whereupon the per cent error increased sharply. We illustrate how the per cent propagated error varies with depth when integration begins at the surface using data obtained by averaging the data from all stations on each Survey cruise (Table 3). The per cent error for the ^{234}Th flux calculated from the deficiency only at 150 m was 20% for TT007 and 8% for TT011.

The magnitude of the advective terms relative to the flux calculated from the deficiency alone is shown in Fig. 4. We compare the horizontal and vertical advective terms with the uncorrected and corrected model fluxes at 120 m. The vertical advection term was only

Table 3. The per cent propagated error for the calculated integrated flux of ^{234}Th as a function of depth for Survey I and Survey II. Values given are the average of all stations from 12°N to 12°S along 140°W. The calculations were made assuming that the uncertainty in the ^{234}Th analyses was 6.2%, the uncertainty in the ^{238}U calculations was 1% and the depth was known to ±1 m

Survey I		Survey II	
Depth (m)	Error (%)	Depth (m)	Error (%)
		25	13
50	20	50	9
75	15	75	8
100	14	100	7
150	20	150	8
200	28	200	10
250	45	250	11

important from 1°N to 1°S. At the equator its magnitude can equal the flux calculated from the deficiency alone. The largest positive fluxes are at the equator where upwelling provided a source of ^{234}Th that must be removed by horizontal or vertical export. Upwelling increased the calculated flux at the equator by 100% and for stations within 1° of the equator by about 50%. The negative corrections below 100 m for stations at 2°S and 3°S were due to horizontal advection. All advective transports were small at latitudes higher than 5°N and S and were thus neglected.

The final calculated ^{234}Th fluxes (advection corrected) as a function of depth are shown in Figs 1(c) and 2(c). The values increase from a depth of 25 m to depths of 100–150 m, then decrease slightly with depth. The integrated fluxes at 150 m ranged from 500 to 2400 dpm m^{-2} day^{-1} for Survey I and from 1300 to 3600 dpm m^{-2} day^{-1} for Survey II. The highest values were in the interval of 1°N–1°S. The individual values with the estimated errors propagated to the final uncertainty are given in the Appendix. The average uncertainty for the advection corrected model flux of ^{234}Th was $39 \pm 28\%$ ($n = 89$) for Survey I and $20 \pm 9\%$ ($n = 88$) for Survey II. Histograms of model calculated ^{234}Th were skewed toward lower values. Log transformations gave normal distributions.

Bruland and Coale (1986) calculated particulate fluxes of ^{234}Th from 20°N to 20°S at 160°W for a non-El Niño period (October 1980). Their values showed a well defined maximum at the equator, and ^{234}Th fluxes ranged from about 1800 dpm m^{-2} day^{-1} at the equator to about 500 dpm m^{-2} day^{-1} at 20° N and S. These fluxes are somewhat lower than values given here because they calculated fluxes using surface samples and assumed a 70 m deep mixed-layer for the entire transect. In addition their calculations did not include advection corrections.

DISCUSSION

Our goal in this study was to measure export of particulate organic carbon from the euphotic zone of the central equatorial Pacific (140°W). To accomplish this we utilized a combined drifting trap–^{234}Th approach using traps at multiple depths (5–7) from 50 m to 250 m. Our approach was to (i) assess trap accuracy using ^{234}Th, (ii) establish the viability of ^{234}Th as a tracer of organic carbon, (iii) calculate the particulate export flux of organic carbon and (iv) compare the export flux of organic carbon with primary and new production to evaluate carbon cycling in the euphotic zone of the equatorial Pacific.

Trap accuracy

There have been several previous comparisons of model-derived ^{234}Th fluxes with ^{234}Th fluxes measured with drifting sediment traps. In most cases, the comparison was made at a single depth. Coale and Bruland (1985) found good agreement (within 20–40%) for comparisons of calculated fluxes with relatively shallow (35–65 m) trap samples in the California Current. Buesseler (1991), however, evaluated several literature studies from a range of locations and showed that some comparisons differed by as much as 3–10 times, thus casting doubt on the accuracy of the shallow traps. Buesseler *et al.* (1992) in the North Atlantic during the North Atlantic Bloom Experiment (NABE) and Wei and Murray (1992) in Dabob Bay showed that some of this discrepancy could be due to non-steady-state corrections in the ^{234}Th flux calculation or horizontal fluxes of ^{234}Th not included in the mass-balance equations. Even at a single site the range of results depended on the conditions

at the time of sampling. Buesseler *et al.* (1994) conducted a detailed 3-D study of ^{234}Th distributions around drifting traps at 95 m at the Bermuda Oceanographic Time-series Study (BATS) site in May 1992. The trap fluxes were larger than the model calculated fluxes, and they concluded that traps over-collected during that period. That test was conducted during a low-flux period, and they hypothesized that the traps would under-collect during high-flux periods. Michaels *et al.* (1994) used ^{234}Th data to confirm that, for most of the year at BATS, drifting traps at 150 m under-collected and therefore measured a lower flux than predicted. These studies showed that evaluation of the accuracy of drifting traps in the upper ocean with ^{234}Th is necessary.

A number of assumptions are made when the ^{234}Th flux is calculated, and these need to be considered when trap biases are evaluated. There are three main categories of trap bias: zooplankton (swimmers) that enter the trap to graze on the particulate carbon; solubilization of particulate organic carbon (POC) to dissolved organic carbon (DOC); and hydrodynamic effects that disrupt the efficiency of capture and retention of particles in the trap. No absolute standard exists for identifying and removing extraneous zooplankton from the trap samples. In any event, swimmers are primarily a source of carbon, and our results, and those of Buesseler *et al.* (1995), indicate that swimmers contain negligible amounts of ^{234}Th. Solubilization of POC to DOC was evaluated by analyzing trap solutions for DOC before and after deployment. Short deployments (less than or equal to 2 days) were used to minimize this problem. DOC analyses at sea (E. Peltzer, personal communication, 1994) showed that solubilization of POC was less than 10% of the carbon flux. Similar values also were observed by Hansell and Newton (1994) in Monterey Bay and at Bermuda. 234Th was below detection limits in the trap solutions, thus solubilization in traps was not an important process for ^{234}Th.

The effect of hydrodynamics on trap efficiency is poorly understood. Several lab and field studies that addressed trap dynamics (Gardner, 1980, 1985; Butman, 1986; Butman *et al.*, 1986; Baker *et al.*, 1988; Gust *et al.*, 1992, 1994) have shown that artifacts can be appreciable. In our study we addressed the problem of hydrodynamics using ^{234}Th data (Figs 1, 2 and 4), which was relatively unaffected by biases due to swimmers and solubilization.

Assessment of trap accuracy was done by comparing measured and modeled fluxes of ^{234}Th. The difference between the populations of ^{234}Th in trap samples was found to be statistically insignificant between Survey I and Survey II. The difference between the populations of modeled ^{234}Th fluxes for different cruises, on the other hand, were highly significant. For example, the calculated ^{234}Th flux, interpolated to the depth of the euphotic zone at 120 m, for Survey II was 1.8 ± 0.7 times higher than the calculated ^{234}Th flux for Survey I. Comparison of modeled with observed ^{234}Th trap fluxes (Figs 1 and 2) showed that model fluxes shallower than 150 m were much less than the trap observations. Fluxes deeper than 150 m were comparable. For both Survey I and Survey II, ^{234}Th in traps was significantly higher than ^{234}Th calculated from the model at 75 m and 100 m. The difference was highly significant at both depths during Survey I. At 250 m during Survey I, the model ^{234}Th was significantly higher than the ^{234}Th in the traps, with the level of significance being at the boundary of $P = 0.05$. All other comparisons (150 m, 200 m, and 250 m) gave a null result. There was variable equatorial banding in the data set. For Survey I, an equatorial zone of 5°N–1°S was significantly higher in terms of both trap and modeled ^{234}Th. For Survey II, the equatorial zone of 5°N–5°S had higher fluxes for both.

The log ratio of the trap flux to model flux for three depths (100 m, 150 m, 200 m) from

12°N to 12°S is shown in Fig. 5. During Survey I, the ratios were significantly higher than one at all depths (Table 4). The average ratios at 150 m, 200 m and 250 m were 1.59 ± 0.60, 1.43 ± 0.51 and 1.41 ± 0.57, respectively. During Survey II, the ratios were significantly higher than 1 only at 100 m (cruise average $= 1.80 \pm 0.65$) and significantly less than 1 at 200 m (average $= 1.01 \pm 0.70$) and 250 m (average $= 0.80 \pm 0.60$). Note that even though the linear averages are close to 1.0, the data are not normally distributed and log values must be used for statistical evaluation. The ratio at 150 m gave a null result. The general agreement of trap to model ^{234}Th flux to better than a factor of 2 below 150 m (Survey I) and 100 m (Survey II) suggests that trap biases are less important at those depths. At shallower depths, the measured trap fluxes are significantly larger than the model fluxes, suggesting over-trapping of ^{234}Th (Fig. 5). Overall, there is evidence for over-trapping, but there are few ocean fluxes that can be measured by two totally independent methods and give such good agreement.

Deployment of traps at several depths is necessary to determine the depths of good agreement. If we had only deployed traps at 100 m we would have only reported highly

Table 4. Ratio of measured to model calculated fluxes of ^{234}Th for PIT design traps at 100 m, 150 m, 200 m, and 250 m for Survey I and Survey II. Average and standard deviations are given for each depth for each cruise

	100 m	150 m	200 m	250 m
Survey I				
12 N	3.13	2.25	1.74	0.62
9	2.68	1.37	1.35	1.36
7	2.86		1.65	1.48
5	3.77		1.40	1.57
2	26.38		2.29	1.95
1	5.81		1.31	1.68
−1	5.20	0.67	0.61	0.53
−2	4.14	1.94	1.08	1.16
−5	2.05	2.07	2.01	2.43
−12 S	1.61	1.22	0.89	1.27
Average	3.47	1.59	1.43	1.41
SD	1.40	0.60	0.51	0.57
Survey II				
12 N	1.32	1.36	0.76	0.53
9	1.59	2.07	0.82	0.38
7	1.13	0.74	0.48	0.41
5	1.76	0.62	0.67	0.66
3	2.99	1.01	0.50	0.43
2	1.60	0.66	0.59	0.52
1	2.11	0.93	0.76	0.73
0	0.98	0.61	0.59	0.28
−2	2.95	2.34	2.67	1.51
−3	1.96	1.37	1.33	2.10
−5	1.98	1.79	0.79	1.64
−12 S	1.20	2.41	2.16	0.47
Average	1.80	1.33	1.01	0.80
SD	0.65	0.68	0.70	0.60

significant over-trapping. While over-trapping was observed at 150 m and 200 m its significance was much reduced. Many previous studies of carbon fluxes using drifting traps have reported a decreasing flux with depth (e.g. Martin *et al.*, 1987; Betzer *et al.*, 1984). These observations are consistent with existing paradigms that particle flux decreases with depth. However, our results suggest that some of this decrease could be due to over-trapping by shallow traps. In spite of the uncertainties in this approach, it is our opinion that ^{234}Th is the best tool available for the evaluation of the accuracy of drifting traps. Based on this work we recommend that JGOFS drifting sediment trap studies should be conducted at multiple depths and include ^{234}Th analyses on both water column and trap samples.

^{234}Th as a tracer for carbon export

The flux of ^{234}Th has been proposed as a tracer for particulate carbon export from the euphotic zone. Eppley (1989) suggested that this flux can be calculated from the residence time of ^{234}Th and the inventory of POC in the euphotic zone. For the approach used in this paper (see also Buesseler *et al.*, 1992, 1995; Bacon *et al.*, 1996) we do not need to assume that the residence times of organic carbon and ^{234}Th are equal. This approach only requires knowledge of the flux of ^{234}Th and the organic carbon/^{234}Th ratio in sinking particles. This approach is similar to that of Eppley (1989) but distinguishes between sinking and suspended particles.

Several previous studies have determined the organic carbon/^{234}Th ratio in trap samples. Buesseler *et al.* (1992) calculated ratios of 2.4–7.4 μmol dpm^{-1} for traps at 150 m and 300 m during the North Atlantic Bloom Experiment (NABE). An average value of 2.8 μmol dpm^{-1} was calculated using 80 m trap data from the eastern equatorial Pacific (Murray *et al.*, 1989). Buesseler *et al.* (1994) and Michaels *et al.* (1994) reported values ranging from 2.1 to 9.6 μmol dpm^{-1} for traps (97 m and 150 m) at the BATS site.

Alternate approaches are to collect particulate samples by whole-bottle filtration of water column samples and with *in-situ* pump devices. In this study we compared the organic carbon/^{234}Th ratios on trap samples with ratios obtained by both additional sampling approaches. Two additional studies were conducted using *in situ* pump samples during EqPac. Buesseler *et al.* (1995) collected integrated samples from 0 to 100 m in two size classes during the NOAA EqPac meridional survey cruises from 175°W to 95°W. For the whole region studied they found that small particles (>0.7 μm) had organic carbon/^{234}Th ratios ranging from about 2 to 4 μmol dpm^{-1}. The ratio in large particles (>53 μm) tended to be lower, ranging from approximately 0.5 to 2.5 μmol dpm^{-1}. The higher ratios for both particle sizes tended to be in the eastern part of their study region (east of 125°W). The range of values they observed from 12°N to 12°S at 140°W was smaller, averaging about 2.0 for particles >0.7 μm and 1.0 for particles >53 μm. Buesseler *et al.* (1995) suggested the organic carbon/^{234}Th ratio was larger for small particles because biological production tended to produce fresh particles with high organic carbon and low ^{234}Th and that biological grazing resulted in utilization of organic carbon, while ^{234}Th is retained. Bacon *et al.* (1996) used a similar pump-sampling approach during the EqPac time series cruises (Time Series I and II) at the equator and 140°W. They observed that the organic carbon/^{234}Th ratio in the >53 μm particles decreased with depth from values of 1.3–6.2 μmol dpm^{-1} at 20 m to 0.6 μmol dpm^{-1} at 200 m.

We first analyzed our data to evaluate whether ^{234}Th was a tracer for organic carbon. The relationship between ^{234}Th and organic carbon fluxes in the drifting trap samples is shown in

Fig. 6. Log transformations were used because histograms of both trap carbon and ^{234}Th fluxes were skewed towards lower values. The relationship for the log transformed data was linear over the whole range for both Survey I ($r = 0.88$) and Survey II ($r = 0.69$); however, the slope was steeper for Survey II than Survey I because a few samples (mostly from depths < 100 m) had anonymously high organic carbon contents. This may be due to formation of sinking biogenic particles that have not reached sorptive equilibrium with ^{234}Th. When the high flux points were removed, the difference between cruises was no longer significant.

The organic carbon/^{234}Th ratios were examined for depth trends. During Survey I no significant difference was found between shallow and deep traps. During Survey II the difference between shallow and deep traps was significant only when using a one-tailed test. When the two cruises were taken together for a composite comparison, the result was still significant using the one-tailed test. The r-values obtained from linear least-squares regressions were used to determine the statistical significance of the depth trend of C/Th in traps at each individual station (Taylor, 1982). The regressions were only significant for three stations, all during Survey II. These were 2°N ($r = 0.90$, $n = 5$), 3°S ($r = 0.91$, $n = 5$) and 5°S ($r = 0.96$, $n = 5$). At all other stations the organic carbon/^{234}Th ratio was characterized best by an average value.

Because of the statistical similarity of the data sets for the two cruises, we considered using a single grand average organic carbon/^{234}Th ratio for all carbon flux calculations. The average C/Th ratio for the entire data set was 3.18 ± 1.78 (56%), while the averages for Survey I and Survey II were 2.72 ± 1.07 (39%) and 3.57 ± 1.78 (50%), respectively. Closer

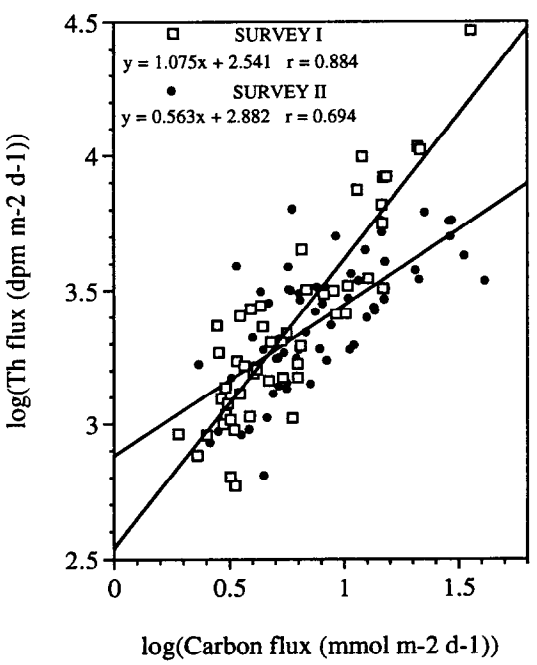

Fig. 6. Relationship between measured trap fluxes of particulate organic carbon and ^{234}Th. Log values are plotted because the histograms of both POC and ^{234}Th flux are skewed toward lower values. There is a good correlation between the particulate organic carbon and ^{234}Th fluxes on each cruise.

examination of the data set indicated that the standard deviation for all individual stations (except the three with significant depth trends) was considerably better (10–30%). The average organic carbon/^{234}Th ratio for each station (with 1 SD error bars) shows meridional structure in the organic carbon/^{234}Th ratio (Fig. 7) for which we do not have an obvious explanation, but which we don't want to obscure. Because of this we decided to use an average organic carbon/^{234}Th ratio for each station rather than the average for the entire data set or for each individual cruise.

The organic carbon/^{234}Th ratios in trap samples are compared with the ratios for particles collected using other sampling approaches in Fig. 8. The comparisons were made for depth intervals of 0–50 m, 75–100 m and 125–250 m. The results are only compared for Survey II because ^{234}Th for MULVFS samples was not measured for Survey I. The ratios for particles obtained using whole-bottle filtration (0.45 μm) were generally high and varied with latitude and depth. The ratios for samples from 0–50 m ranged from 2.6 to 12.5 μmol dpm^{-1} and had a pronounced maximum centered at the equator (Fig. 8(a)). The ratios decreased in the 75–100 m to 125–250 m intervals but remained higher than obtained using other sampling approaches. There was less systematic meridional structure for bottle samples in the deeper intervals. Two size classes of particles ($<$ 1–53 μm and $>$ 53 μm) were collected using the

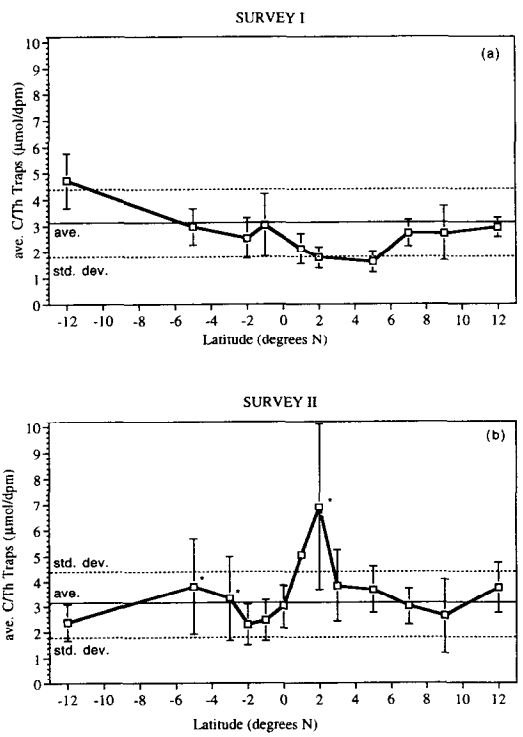

Fig. 7. Ratios of organic carbon/^{234}Th for Survey I (a) and Survey II (b). An average value is given for each station. Error bars are shown for each station average and range from 10 to 30%. Stations with an asterisk had a significant depth trend and their standard deviations are larger than the rest of the stations. All other stations showed no significant trend with depth. The mean and standard deviation for the entire data set are shown in each figure.

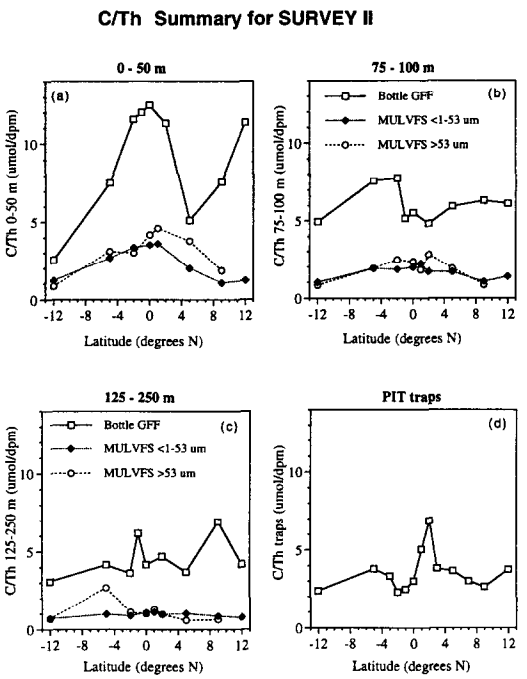

Fig. 8. Comparison of the particulate organic carbon/^{234}Th ratios for whole bottle filtration, MULVFS and drifting trap samples. Bottle and MULVFS samples are compared for depth intervals of 0–50 m (a), 75–100 m (b) and 125–250 m (c). The values for the drifting traps (d) represent station averages (0–250 m). The bottle samples were filtered through GF/F filters. Ratios are given for MULVFS samples filtered in series through 1 μm Quartz and 53 μm Nytex filters.

MULVFS. Surprisingly, there were no significant differences between the ratios for these two size classes. Buesseler *et al.* (1994) and Bacon *et al.* (1996) observed higher ratios in smaller size particles. The organic carbon/^{234}Th ratios on all MULVFS samples ranged from about 0.5 to 4.5 μmol dpm^{-1}. There was a broad equatorial maximum for 0–50 m (Fig. 8(a)) and 75–100 m (Fig. 8(b)). These values were in the same range as the > 53 μm *in situ* pump samples collected by Buesseler *et al.* (1994) and Bacon *et al.* (1996). The station averaged organic carbon/^{234}Th ratios in our trap samples ranged from 2.5 to 7.0 μmol dpm^{-1} (Fig. 8(d)), about 3 times higher than the ratios observed on MULVFS large particles (> 53 μm). It is generally agreed that particles from bottle samples and < 1.0–53 μm MULVFS are small and should not contribute directly to the sinking flux.

Two explanations are possible for the differences observed in the organic carbon/^{234}Th ratios in the trap and > 53 μm MULVFS samples: (i) the ratios are high for trap samples because of high organic carbon due to zooplankton "swimmer" contamination, or (ii) the ratios are low for pump samples because they do not accurately collect sinking particles or because organic carbon is removed from the samples when they are rinsed with distilled water to remove seasalt. Variations in the organic carbon/^{234}Th ratio are the main source of differences between our organic carbon fluxes and those of Buesseler *et al.* (1995) and Bacon *et al.* (1996).

In addition to the organic carbon/^{234}Th ratios, there are many differences between the

composition of particulate samples collected using water bottles versus samples filtered *in situ*. *In situ* pump samples are systematically lower in particulate organic carbon (Dunne *et al.*, in prep.; H. Ducklow, personal communication, 1994), chlorophyll (our unpublished data and C. Lee, personal communication, 1994) and suspended calcite concentrations (Balch and Kilpatrick, 1996). MULVFS samples are higher in ^{234}Th than bottle samples (Dunne *et al.*, in prep.). Thus MULVFS samples have a low organic carbon/^{234}Th ratio for two reasons. They are low in organic carbon and high in ^{234}Th relative to bottle samples. The origin of the disagreement between *in situ* pump and bottle filtered samples is unclear but must be due to how the samples are collected, processed and stored. As there is no absolute standard for particulate concentrations, or compositions, this controversy is unresolved.

POC flux calculated from ^{234}Th

Few previous measurements of the vertical flux of POC from the upper water column of the equatorial Pacific have been made. Betzer *et al.* (1984) made mass flux measurements using drifting-traps deployed at 900 m between 12°N and 6°S at 153°W. Assuming their mass fluxes were at the upper limit of 100% organic matter, then the flux at 900 m at the equator was 1.8 mmol C m^{-2} day^{-1}. Murray *et al.* (1989) measured POC fluxes at the base of the euphotic zone (80–100 m) in the eastern equatorial Pacific (85°) using drifting traps. Directly measured fluxes ranged from 4.9 to 5.8 mmol C m^{-2} day^{-1}. The measured ^{234}Th fluxes were 1.5 to 3.3 times larger than calculated values for these relatively shallow traps, and correction for this apparent over-trapping resulted in POC fluxes of 1.5–3.5 mmol C m^{-2} day^{-1}. For comparison, the power function describing the composite open ocean VERTEX flux data predicts a flux of about 4 mmol C m^{-2} day^{-1} at 100 m (Martin *et al.*, 1987). Najjar *et al.* (1992) used a phosphorus-based model of nutrient cycling and an ocean general circulation model to estimate particulate export fluxes of 5 to 16 mmol C m^{-2} day^{-1} for the average equatorial Pacific.

The model flux of POC for EqPac Survey I and II was calculated using the equation:

$$\text{Model POC flux} = \text{Model } ^{234}\text{Th flux} \times (\text{trap POC flux/trap } ^{234}\text{Th flux})$$

This equation can be viewed in two ways. On one hand it is a calculation of the POC flux from the ^{234}Th flux with the assumption that the C/Th ratio of sinking particles is approximated by the values of the sediment trap samples. If it is rearranged, as shown below, it describes a correction of the measured trap POC flux for bias assuming ^{234}Th is an accurate calibrator of trap efficiency.

$$\text{Model POC flux} = \text{trap POC flux} \times (\text{model } ^{234}\text{Th flux/trap } ^{234}\text{Th flux})$$

The model POC fluxes for Survey I and Survey II (Figs 1(d) and 2(d)) can be compared with measured POC fluxes (Figs 1(b) and 2(b)).

The uncertainties for the organic carbon flux at each depth (Appendix) average about ±60%. These uncertainties come from three sources; the error for calculating the ^{234}Th flux from the water column deficiency relative to ^{238}U (about ±30%), the advective fluxes (about ±100%), and the organic carbon/^{234}Th ratio in sediment trap samples (about ±30%).

During Survey I most model POC fluxes were between 1 and 6 mmol C m^{-2} day^{-1} and

varied little with depth or latitude. The trap carbon flux was significantly higher than the modeled carbon flux at 75 m, 100 m and 250 m. The difference was highly significant at 75 m and 100 m. During Survey II, the values were larger and more variable, ranging from 2 to 30 mmol C m^{-2} day^{-1}. Trap carbon fluxes were not significantly higher than modeled carbon fluxes at any depth using the two-tailed test. The difference between the populations of modeled organic carbon flux, between the two survey cruises, was highly significant.

The fluxes calculated for 120 m (approximately the depth of the euphotic zone) (Fig. 9) show that meridional variability was greater and that the highest fluxes occurred from 1°N to 1°S zone for Survey I and from 2°N to 5°N for Survey II. Our data are consistent with the hypothesis that export production was lower during the El Niño conditions of Survey I. Reduced export flux during El Niño conditions is consistent with changes that occurred in the food-web during that period. For example, the phytoplankton size distribution was dominated by smaller phytoplankton during Survey I than Survey II (Landry *et al.*, 1996; Bidigare and Ondrusek, 1996). There was a higher abundance of large phytoplankton cells, particularly diatoms, during Survey II. Mesozooplankton biomass also increased during Survey II, but their grazing impact actually decreased (Dam *et al.*, 1995; Zhang *et al.*, 1995). Both primary production and phytoplankton growth rates were higher during Survey II, but microzooplankton plus mesozooplankton grazing accounted for most of this production during both periods. Thus, the lower export during Survey I and higher export during Survey II is consistent with food web arguments (Landry *et al.*, in press). Karl *et al.*

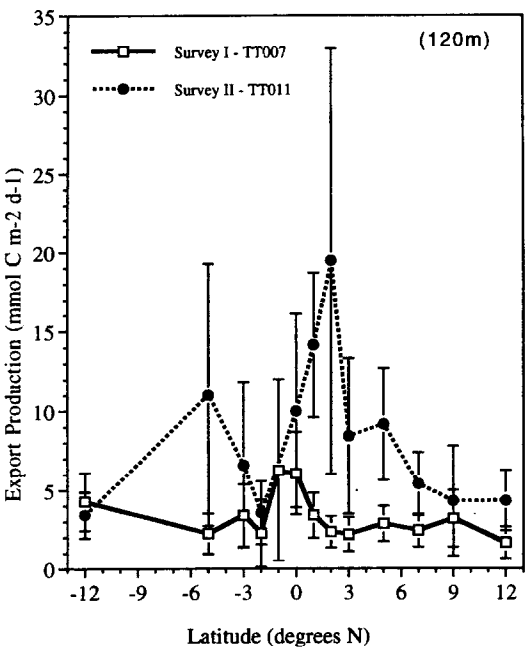

Fig. 9. Export fluxes of particulate organic carbon at 120 m for Survey I and Survey II (with propagated error bars) for EqPac Survey I and Survey II. Fluxes were calculated as the product of the model ^{234}Th flux times the particulate organic carbon/^{234}Th ratio in drifting trap samples. The individual data are given in the Appendix.

(1996) also observed a 30% reduction in particulate carbon export flux during the 1991–1992 El Niño at the HOT station in the North Pacific central gyre, which he attributed to changes in the structure of the biological food web. Thus, El Niño conditions may result in a basin scale reduction in export flux in the North Pacific.

These magnitudes are somewhat different from the POC fluxes calculated using the ^{234}Th method by the other two related EqPac studies. Buesseler *et al.* (1995) calculated POC fluxes for April 1992 that ranged from 4–5 mmol C m^{-2} day^{-1} at the equator to 1–2 mmol C m^{-2} day^{-1} at 12°N and 12°S along 140°W. In the September–October 1992, period, however, they had no data within 5° of the equator at 140°W. Bacon *et al.* (1996) calculated vertical profiles of the POC fluxes at the equator and 140°W for the two EqPac Time Series cruises. Their calculated fluxes increased from zero at the sea surface to maximum values of 1.5–3.5 mmol C m^{-2} day^{-1} at 60–80 m and then decreased to 1–1.5 mmol C m^{-2} day^{-1} at 200 m. The mean values were about 50% higher during Time Series II than Time Series I. The range of ^{234}Th fluxes calculated in our study is similar to those calculated by Buesseler *et al.* (1995) and Bacon *et al.* (1996), so most of the differences in the calculated POC fluxes are due to different values used for the organic carbon/^{234}Th ratio in sinking particles.

Luo *et al.* (1995) used a similar approach with different isotopes of thorium (^{228}Th and ^{230}Th). They estimated POC export fluxes from the euphotic zone to be 0.6–1.3 mmol C m^{-2} day^{-1} during Survey I and 1.5–5.0 mmol C m^{-2} day^{-1} during Survey II. The thorium flux was converted to carbon using POC analyses on MULVFs samples.

Migrating zooplankton are an alternative vertical pathway for export of organic carbon. For example, Dam *et al.* (1995) concluded that the downward flux of respiratory carbon associated with diel-vertical zooplankton migration was potentially a significant contribution to the carbon export at the BATS site near Bermuda. Their estimated respiratory carbon flux ranged from 18 to 70% of the POC flux. Similar calculations by X. Zhang and H. Dam (personal communication, 1996) suggest that migrator-driven respiratory carbon fluxes are much smaller in the central equatorial Pacific, perhaps only 0–5% of the POC flux.

While there are not many historical data for shallow traps for comparison, we can compare our fluxes with those obtained using deep moored traps deployed during EqPac. The fluxes of organic carbon out of the euphotic zone presented here are at least an order of magnitude larger than the annual average carbon fluxes to deep moored traps. Fluxes to traps between 2200 m and 3500 m varied from 0.33 mmol C m^{-2} day^{-1} at the equator to 0.08 mmol C m^{-2} day^{-1} at 12°N,S (Honjo *et al.*, 1995). The decrease in flux from the euphotic zone to the deep moored traps is due to disaggregation, solubilization and respiration.

Comparison with primary and new production

There have been few comparisons of new and export production in the world's oceans. One comparison was our own work in the eastern equatorial Pacific (Murray *et al.*, 1989) where we observed *f*-ratios (defined as the nitrate uptake rate divided by the sum of the nitrate plus ammonium uptake rates) ranging from 0.17 to 0.29. The *e*-ratio (defined as the POC flux at the base of the euphotic zone divided by primary production) ranged from 0.14 to 0.38. At three out of four stations the particulate export flux was less than new production, suggesting that some export occurred as DOC. Unfortunately the errors on

those fluxes were poorly constrained. Modeling studies by Bacastow and Maier-Reimer (1991) and Najjar *et al.* (1992) suggested that dissolved organic carbon (DOC) was a significant form of carbon exported from the central equatorial Pacific. Measurements in that region have been scarce. Dugdale *et al.* (1992) and Pena *et al.* (1992) reported similar values as Murray *et al.* (1989) for *f*-ratios in the central equatorial Pacific, but export production had not been measured until the EqPac Process Study.

The particulate carbon export production for each Survey I and Survey II station is compared with primary production (Barber *et al.*, 1996) and new production (McCarthy *et al.*, 1996) in Table 5. For this paper, primary and new production were integrated to the base of the euphotic zone (which we define as the depth of 0.1% *I*) and are reported as mmol C m^{-2} day^{-1}. The values given for primary production were determined from on deck ^{14}C incubations of water samples collected from the same water bottle used for the ^{15}N–NO_3 uptake experiments. The values differ slightly from those of Barber *et al.* (1996), for *in situ* incubations, because they were collected from different samples; but the trends are the same. Primary production varied from low values of 25–30 mmol C m^{-2} day^{-1} at 12°N and 12°S for both survey cruises to maximum values of 84 mmol C m^{-2} day^{-1} at 1°S during Survey I and 154 mmol C m^{-2} day^{-1} at 2°N during Survey II. The values for new

Table 5. Summary of integrated chlorophyll, primary production, new production, and particulate organic carbon export flux at the base of the euphotic zone (defined as the depth of 0.1% I_o) for EqPac Survey I (TT007) and Survey II (TT011). The new production values for Stations 7 and 11 of TT011 were integrated to 1% I_o. Primary production and new production were determined using the same samples incubated on deck

Cruise	Survey I — TT007											
Station	1	2	3	4	5	6	7	8	9	10	12	15
Latitude	12N	9N	7N	5N	3N	2N	1N	Eq	1S	2S	5S	12S
Chlorophyll (integrated to 0.1% I_o, mg m^{-2})	20.1	19.4	23.7	21.2	23.9	27.6	23.6	25.1	33.1	18.6	22.8	19.4
Primary Production (PP) (integrated to 0.1% I_o, mmol C m^{-2} day^{-1})	24.7	23.3	30.2	41.4	46.2	61.3	46.6	60.1	84.5	64.5	67.9	34.8
New Production ($\rho_{NO_3} \times 6.6$) (integrated to 0.1% I_o, mmol C m^{-2} day^{-1})	7.9	3.8	3.2	5.1	5.9	7.9	3.0	3.6	4.8	9.2	6.6	7.9
POC Export Flux (at 120 m) (mmol C m^{-2} day^{-1})	1.7	3.2	2.4	2.9	3.4	2.4	3.4	6.1	6.3	2.3	2.2	4.3
$e\left(\frac{\text{POC Export Flux}}{\text{PP}}\right)$(%)	7	14	8	7	5	4	7	10	7	4	3	12
$f\left(\frac{\text{New Production}}{\text{PP}}\right)$(%)	32	16	11	12	13	13	6	6	6	14	10	23

Cruise	Survey II — TT011												
Station	1	2	3	4	5	6	7	8	9	10	11	12	15
Latitude	12N	9N	7N	5N	3N	2N	1N	Eq	1S	2S	3S	5S	12S
Chlorophyll (integrated to 0.1% I_o mg m^{-2})	20.5	21.1	17.5	25.7	25.9	37.9	—	33.9	26.8	31.2	36.6	30.5	20.3
Primary production (PP) (integrated to 0.1% I_o, mmol C m^{-2} day^{-1})	29.8	25.4	19.2	48.1	64.8	154.5	—	102.6	84.2	117.8	99.9	102.3	33.9
New Production ($\rho_{NO_3} \times 6.6$) (integrated to 0.1% I_o, mmol C m^{-2} day^{-1})	—	5.3	6.6	6.6	4.7	33.0	23.1 (1%)	19.1	9.2	13.9	17.8 (1%)	7.9	1.8
POC export flux (at 120 mm) (mmol C m^{-2} day^{-1})	4.3	4.3	5.4	9.2	8.4	19.5	14.2	10.0	—	3.6	6.6	11.0	3.4
$e\left(\frac{\text{POC Export Flux}}{\text{PP}}\right)$(%)	15	17	28	19	13	13	—	10	—	3	7	11	10
$f\left(\frac{\text{New Production}}{\text{PP}}\right)$(%)		21	34	14	7	21	—	19	—	12	18	8	5

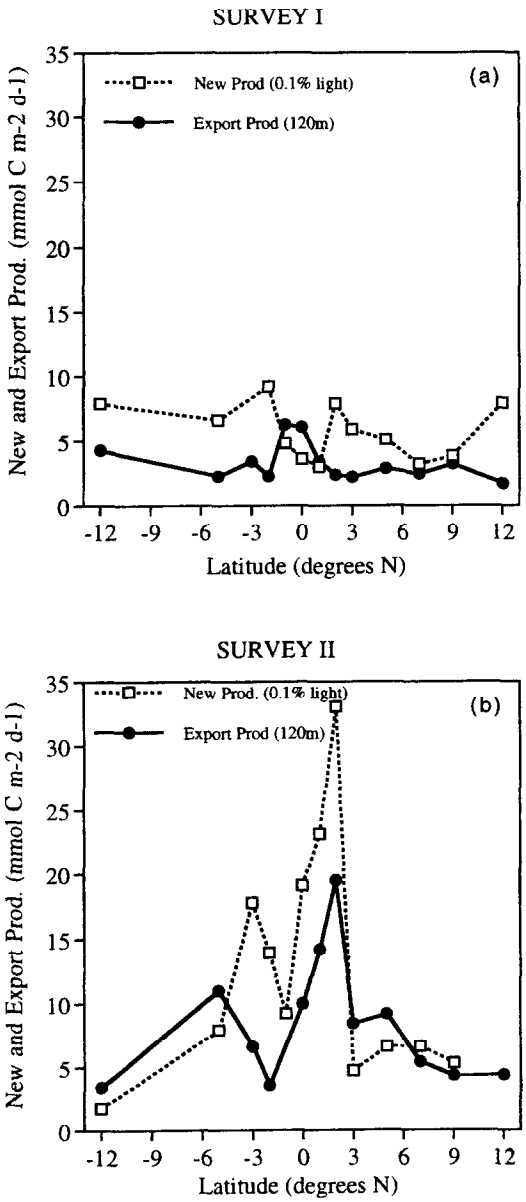

Fig. 10. Comparison of new production and particulate carbon export for Survey I(a) and Survey II(b). New production values are for the depth of 0.1% light level and are expressed in carbon units calculated assuming carbon/nitrogen fixation ratio of 6.6. Particulate organic carbon fluxes are for the depth of 120 m. The error bars for the POC fluxes were shown in Fig. 9. The uncertainty for new production is assumed to be 30%.

production were calculated for a daily basis using two to three separate 4-h deck incubations for different parts of the daily cycle. Nitrate uptake rates were converted to carbon new production by multiplying the nitrate uptake rate (ρ_{NO_3}) by a constant C/N uptake ratio of 6.6 (Redfield *et al.*, 1963). The new production values given here are slightly higher than those reported in McCarthy *et al.* (1996), which were integrated to the 1% light level. New production varied little with latitude during Survey I and was significantly higher during Survey II, especially from 2°N to 3°S (Fig. 10). POC export fluxes, interpolated to 120 m, are compared with the new production in Fig. 10; export production values average about 60% and are given in the Appendix. The uncertainty for new production was estimated to be about 30%.

There is no convenient measure of accuracy for field estimations of new production. In McCarthy *et al.* (1996) new production calculated from uptake rates of nitrate, nitrite, and ammonium agrees well with estimates based upon nitrate uptake rates and an assumed C/N assimilation ratio of 6.6. The actual measure of isotope enrichment accruing in particulate matter during an ^{15}N incubation experiment is highly precise. Nutrient concentration values upon which isotopes enrichment are based are precise within a few per cent. Replicate uptake experiments agree within 4%, and in a large enclosure the measured rates of nitrate uptake and differences between initial and final nitrate concentration over 6 h experiments also agree within 4% (unpublished data). For full euphotic zone and full day computations of new production, and regional extrapolation of these values, there are additional sources of error. The three time points during a day from which daily new production values are computed are not necessarily from the same water. Moreover, while distinct day–night differences in rates of new production have been observed (McCarthy *et al.*, 1996) this difference is a function of nitrogen sufficiency and available light. Hence day-to-day variations in incident irradiation are an additional source of error. If we were to assume that the rate measurements for primary production are without error, and that the ratio of carbon and nitrogen incorporation averaged over any full day should always be 6.6, then daily departures from this value provide a crude estimate of error for rates of new production. Such calculations would indicate a 15–30% error in new production rates during the two EqPac surveys.

The fraction of primary production exported as POC (defined here as the *e*-ratio) ranged from 3% to 11% for Survey I and 4% to 23% for Survey II (Fig. 11). The fraction of primary production due to NO_3 uptake (defined here as the *f*-ratio) was significantly larger in most cases (Fig. 11).

Both new and export production were higher during Survey II than Survey I (Fig. 10). This trend is consistent with our initial hypothesis that these fluxes would be lower during El Niño warm periods such as occurred during Survey I because temperature, nutrient and mixing conditions favored a shift in the biological community toward smaller phytoplankton. When comparing magnitudes of new and export production, the most important observation is how good their agreement actually is. There are some significant differences, however. During Survey I, new production was higher than export production and the difference was "highly significant". During Survey II, however, the null result was reached. Comparing only 2°N to 3°S for Survey II, new production was higher than export production and the result was "highly significant". McCarthy *et al.* (1996) observe that the rates of new production during the 1992 warm period (Survey I) were similar to the historical data, whereas the high values of new production during Survey II appear anomalous, perhaps due to alterations in the biological community structure following El

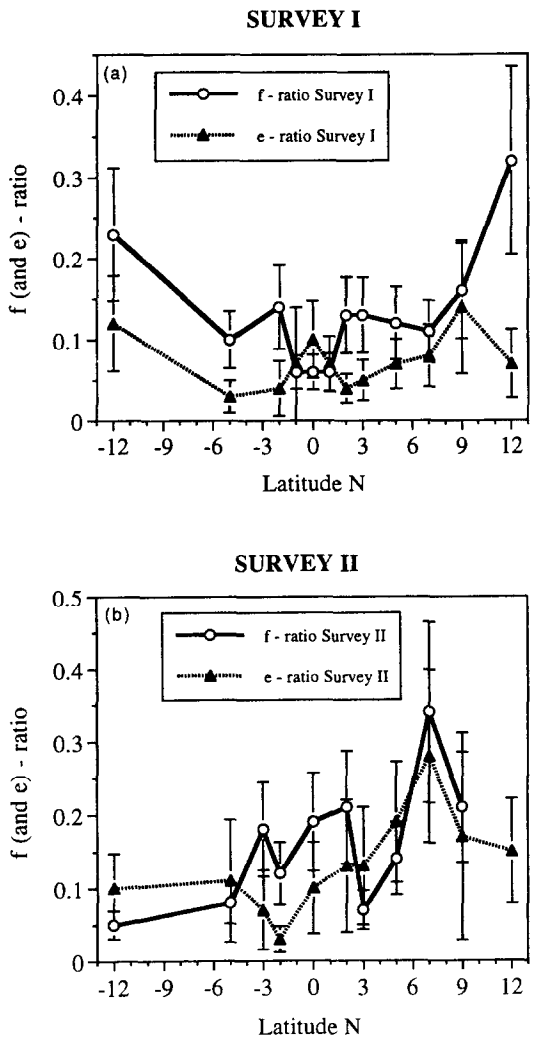

Fig. 11. *f*- and *e*-ratios for Survey I(a) and Survey II(b) calculated using the results in Fig. 10 and Table 5. The *f*-ratios were calculated as new production (in carbon units)/primary production. The *e*-ratio was calculated as POC flux at 120 m/primary production.

Niño periods. Evaluation of this hypothesis for export production is not possible because there were virtually no previous measurements of POC export from this region.

At most stations, the POC export flux was less than new production. Assuming steady state, we hypothesize that new production not exported in the particulate form is potentially exported in the dissolved form. Thus we define the difference between new production (in carbon units) and the POC export flux as the potential DOC export flux. Potential DOC flux is plotted versus latitude for Survey I and Survey II in Fig. 12. For all cases where export production is greater than new production (e.g. potential DOC flux is negative), new production falls within the error of the export production. The patterns are different between the two cruises. For Survey I, the values between 1°N and 1°S overlap with zero,

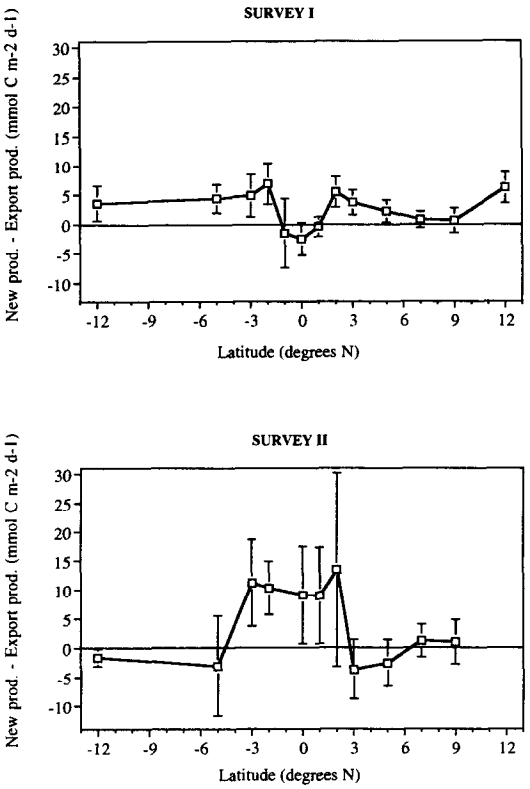

Fig. 12. Difference between new production (in carbon units) at the depth of 0.1% light level and the export flux of particulate organic carbon at 120 m. Propagated error bars are shown. The error on the POC fluxes was shown in Fig. 9 and ranged from 10 to 30%. New production was assumed to have an uncertainty of $\pm 30\%$.

and positive values exist to the north and south. The highest significant potential DOC fluxes appear to be in the off-equatorial zones of 2°N–5°N and 2°S–12°S. For Survey II there is a well-defined region from 2°N to 3°S with significant potential DOC production. The potential DOC flux averages $11.2 \pm 7.2\,\mathrm{mmol\,C\,m^{-2}\,day^{-1}}$ (or 50% of new production). The meridional sections of DOC for Survey I and Survey II are consistent with the hypothesis that there is DOC export from the equatorial zone (Peltzer and Hayward, 1996). Both show low surface DOC values of about $60\,\mathrm{mmol\,kg^{-1}}$ at the equator increasing to about $80\,\mathrm{mmol\,kg^{-1}}$ at 10° N and S. Peltzer and Hayward (1996) calculate DOC export fluxes ranging from 4 to $13\,\mathrm{mmol\,C\,m^{-2}\,day^{-1}}$ for four cruises to this region.

Regional fluxes

Regional estimates of equatorial new production based upon models and field observations are discussed in McCarthy *et al.* (1996). There are many distinct differences between the two EqPac surveys in properties observed and rates measured,

as is evident above in data for new and export production. Some of these may be explained as related to the El Niño event, while others are more elusive. Taken together, however, the results of the two EqPac surveys might be considered representative of a year with an El Niño event. Thus, in the following analysis, averages for our entire data set are compared with estimations of new production for this region published by Chavez and Barber (1987).

Chavez and Barber (1987) estimated a total new production of 0.85 Gt C year^{-1} for the 10°N–10°S and 90°W–180° region (area = 1.3×10^{13} m^2) by multiplying an *f*-ratio (0.5), approximated from the Eppley and Peterson (1979) relationship, times measured rates of primary production. While Chavez and Barber suggested that this assumed *f*-ratio value may have been conservative, direct measurements of new production and *f*-ratios (Dugdale *et al.*, 1992; Pena *et al.*, 1992) and work undertaken during the EqPac study (McCarthy *et al.*, 1996) indicate that *f*-ratios for this equatorial region average only 0.1–0.14. Hence, a new calculation based upon the rates of primary production measured by Chavez and Barber and the more recently measured *f*-ratios would yield estimated rates of new production 70–80% lower that those computed by Chavez and Barber (1987).

Applying our averages for measured rates of new production over the 12°N–12°S meridional extent of the EqPac Surveys to the 1.3×10^{13} m^2 area used by Chavez and Barber (1987), new production for the equatorial region is estimated to be 0.47 Gt C year^{-1}. The reason that this rate is about half that estimated by Chavez and Barber (1987), when the measured *f*-ratio is about one quarter that which they assumed, is because rates of primary production observed earlier in this region by Chavez and Barber (1987) were only half the average rate observed during the two EqPac surveys (1.9 vs 3.8 Gt C year^{-1}).

Using the EqPac data presented here, and the area given above, we calculate a POC export of about 0.42 Gt C year^{-1}. Comparison of this export value with our best estimate of new production given above, 0.47 Gt C year^{-1}, shows surprising agreement. The measurements upon which both of these calculations are based are subject to errors that are difficult to estimate with a high degree of confidence. They are, however, completely independent calculations and unlikely to share any specific bias. Thus, while the individual survey data discussed above indicate imbalances within and between the two surveys, the average values for the entire study suggest that significant export of DOC need not be invoked to balance new and export production for this region.

Acknowledgements—Many people helped with this research, but we wish to especially thank R. Bidigare and W. Peterson who were regular members of the drifting trap deployment/recovery team on the R.V. *Thompson*. We are also grateful to all scientists and crew who helped to search for the array lost at the equator during Survey I. J. Bishop provided the MULVFS samples for ^{234}Th analyses. The revised manuscript benefited from constructive comments by L. Balistrieri, M. Bacon, K. Buesseler, D. Karl, and T. Michaels. This research was supported by NSF grant no. 9022466. School of Oceanography Contribution Number 2162. U.S. JGOFS Contribution Number 227. Musical inspiration provided by Bonnie Raitt.

REFERENCES

Altabet M. A., J. K. B. Bishop and J. J. McCarthy (1992) Differences in particulate nitrogen concentration and isotopic composition for samples collected by bottles and large volume pumps in Gulf Stream warm core rings and the Sargasso Sea. *Deep-Sea Research*, **39**, S405–S417.

Anderson R. F. and A. P. Fleer (1982) Determination of natural activities of thorium and plutonium in marine particle material. *Analytical Chemistry*, **54**, 1142–1147.

Archer *et al.* (submitted) A meeting place of great ocean currents: Shipboard observations of a convergent front at 2N in the Pacific. *Deep-Sea Research II.*

Bacastow R. and E. Maier-Reimer (1991) Dissolved organic carbon in modeling oceanic new production. *Global Biogeochemical Cycles*, **5**, 71–85.

Bacon M. P., J. K. Cochran, D. Hirschberg, T. R. Hammar and A. P. Fleer (1996) Export flux of carbon at the equator during the EqPac time-series cruises estimated from ^{234}Th measurements. *Deep-Sea Research II*, **43**, 1133–1153.

Baker E. T., H. B. Milburn and D. A. Tennant (1988) Field assessment of sediment trap efficiency under varying flow conditions. *Journal of Marine Research*, **46**, 573–592.

Balch W. M. and K. Kilpatrick (1996) Calcification rates in the equatorial Pacific along 140W. *Deep-Sea Research II*, **43**, 971–993.

Barber R. T. and F. P. Chavez (1983) Biological consequences of El Niño. *Science*, **222**, 1203–1210.

Barber R. T. and J. E. Kogelschatz (1990) Nutrients and productivity during the 1982/1983 El Niño. In: *Global ecological consequences of the* 1982/1983 *El Niño–Southern Oscillation*, P. W. Glynn, editor, Elsevier, Oxford, U.K., pp. 21–53.

Barber R. T., M. P. Sanderson, S. T. Lindley, F. Chai, J. Newton, C. C. Trees, D. G. Foley and F. P. Chavez (1996) Primary productivity and its regulation in the equatorial Pacific along 140°W. *Deep-Sea Research II*, **43**, 933–969.

Betzer P. R., W. J. Showers, E. A. Laws, C. D. Winn, G. R. DiTullio and P. M. Kroopnick (1984) Primary productivity and particle fluxes on a transect of the equator at 153W in the Pacific Ocean. *Deep-Sea Research*, **31**, 1–11.

Bidigare R. R. and M. E. Ondrusek (1996) Spatial and temporal variability of phytoplankton pigment distributions in the central equatorial Pacific Ocean. *Deep-Sea Research II*, **43**, 809–833.

Bishop J. K. B. (1991) Getting good weight. In: *Marine particles: analyses and characterization*, D. Hurd and D. W. Spencer, editors, American Geophysical Union, pp. 229–234.

Bishop J. K. B., D. Schupack, R. M. Sherrell and M. Conte (1985) A multiple-unit large-volume *in situ* filtration system for sampling oceanic particulate matter in mesoscale environments. In: *Mapping strategies in chemical oceanography*, A. Zirino, editor, Advances in Chemistry Series No. 209, The American Chemical Society, pp. 155–175.

Bishop J. K. B., M. Fleisher and S. Ingalls (in prep.) Paradox of particles: Biogeochemical response of large and small particles to ENSO forcing during the JGOFS equatorial Pacific Survey Cruises.

Bruland K. W. and K. H. Coale (1986) Surface water ^{234}Th/^{238}U disequilibrium: spatial and temporal variations of scavenging rates within the Pacific Ocean. In: *Dynamic processes in the chemistry of the upper ocean*, J. D. Burton, P. G. Brewer and R. Chesselet, editors, Plenum, New York, pp. 159–172.

Buesseler K. O. (1991) Do upper-ocean sediment traps provide an acurate record of particle flux? *Nature*, **353**, 420–423.

Buesseler K. O., M. P. Bacon, J. K. Cochran and H. D. Livingston (1992) Carbon and nitrogen export during the JGOFS North Atlantic bloom experiment estimated from ^{234}Th:^{238}U disequilibria. *Deep-Sea Research*, **39**, 1115–1137.

Buesseler K. O., A. F. Michaels, D. A. Siegel and A. H. Knap (1994) A three dimensional time-dependent approach to calibrating sediment trap fluxes. *Global Biogeochemical Cycles*, **8**, 179–193.

Buesseler K. O., J. A. Andrews, M. C. Hartman, R. Belastock and F. Chai (1995) Regional estimates of the export flux of particulate organic carbon derived from thorium-234 during the JGOFS EqPac program. *Deep-Sea Research II*, **42**, 777–804.

Butman C. A. (1986) Sediment trap biases in turbulent flows: results from a laboratory flume study. *Journal of Marine Research*, **44**, 645–693.

Butman C. A., W. D. Grant and K. D. Stolzenbach (1986) Predictions of sediment trap biases in turbulent flows: a theoretical analysis based on observations in the literature. *Journal of Marine Research*, **44**, 601–644.

Chai F., S. T. Lindley and R. T. Barber (1996) Origin and maintenance of a high nitrate condition in the equatorial Pacific. *Deep-Sea Research II*, **43**, 1031–1063.

Chavez F. R. and R. T. Barber (1987) An estimate of new production in the equatorial Pacific. *Deep-Sea Research*, **34**, 1229–1243.

Chen J. H., R. L. Edwards and G. J. Wasserburg (1986) ^{238}U, ^{234}U and ^{232}Th in seawater. *Earth and Planetary Science Letters*, **80**, 241–251.

Coale K. H. and K. W. Bruland (1985) ^{234}Th:^{238}U disequilibria within the California Current. *Limnology and Oceanography*, **30**, 22–33.

Dam H. G., M. R. Roman and M. J. Youngbluth (1995) Downward export of respiratory carbon and dissolved inorganic nitrogen by diel-migrant mesozooplankton at the JGOFS Bermuda time-series station. *Deep-Sea Research*, **42**, 1187–1197.

Dugdale R. C. and J. J. Goering (1967) Uptake of new and regenerated forms of nitrogen in primary productivity. *Limnology and Oceanography*, **12**, 196–206.

Dugdale R. C., F. P. Wilkerson, R. T. Barber and F. P. Chavez (1992) Estimating new production in the equatorial Pacific Ocean at 150W. *Journal of Geophysical Research*, **97**, 681–686.

Dunne J. P., J. W. Murray, J. Young, L. S. Balistrieri and J. Bishop (submitted) ^{234}Th and particle cycling in the central equatorial Pacific. *Deep-Sea Research II*.

Dymond J. and R. Collier (1988) Biogenic particle fluxes in the equatorial Pacific: evidence for both high and low productivity during the 1982–1983 El Niño. *Global Biogeochemical Cycles*, **2**, 129–137.

Eppley R. W. (1989) New production: history, methods and problems. In: *Productivity of the ocean: Present and past* (Dahlem Workshop), W. H. Berger, V. Smetacek and O. Wefer, editors, Wiley, New York, pp. 85–97.

Eppley R. W. and B. J. Peterson (1979) Particulate organic matter flux and planktonic new production in the deep ocean. *Nature*, **282**, 677–680.

Gardner W. D. (1980) Sediment trap dynamics and calibration: A laboratory evaluation. *Journal of Marine Research*, **38**, 17–39.

Gardner W. D. (1985) The effect of tilt on sediment trap efficiency. *Deep-Sea Research*, **32**, 349–361.

Gardner W. D. and Y. Zhang (in press) The effect of brine on the collection efficiency of cylindrical particle traps. *Aquatic Sciences*.

Gardner W. D., S. P. Chung, M. J. Richardson and I. D. Walsh (1995) The oceanic mixed-layer pump. *Deep-Sea Research II*, **42**, 757–776.

Gust G., R. H. Byrne, R. E. Bernstein, P. R. Betzer and W. Bowles (1992) Particle fluxes and moving fluids: experience from synchronous trap collections in the Sargasso Sea. *Deep-Sea Research*, **39**, 1071–1983.

Gust G., A. F. Michaels, R. Johnson, W. G. Dueser and W. Barber (1994) Mooring line motions and sediment trap hydrodynamics: *in situ* intercomparison of three common deployment designs. *Deep-Sea Research*, **41**, 831–858.

Hansell D. A. and J. A. Newton (1994) Design and evaluation of a "swimmer"—segregating particle interceptor trap. *Limnology and Oceanography*, **39**, 1487–1495.

Honjo S., J. Dymond, R. Collier and S. J. Manganini (1995) Export production of particles to the interior of the equatorial Pacific Ocean during the 1992 EqPac experiment. *Deep-Sea Research II*, **42**, 831–870.

IOC, SCOR (1994) Protocols for the Joint Global Ocean Flux Study (JGOFS) Core Measurements. IOC Manuals and Guides No. 29, 170 pp.

Karl D. M. and G. A. Knauer (1989) Swimmers: A recapitulation of the problem and a potential solution. *Oceanography*, **2**, 32–35.

Karl D. M., J. R. Christian, J. E. Dore, D. V. Hebel, R. M. Letelier, L. M. Tupas and C. D. Winn (1996) Seasonal and interannual variability in primary production and particle flux at Station ALOHA. *Deep-Sea Research II*, **43**, 539–568.

Kessler W. S. and M. J. McPhaden (1995) The 1991–1993 El Niño in the central Pacific. *Deep-Sea Research II*, **42**, 295–334.

Knauer G. A., J. H. Martin and K. W. Bruland (1979) Fluxes of particulate carbon, nitrogen and phosphorus in the upper water column of the northeast Pacific. *Deep-Sea Research*, **26**, 97–108.

Knauer G. A., D. G. Redalje, W. G. Harrison and D. M. Karl (1990) New production at the VERTEX time-series site. *Deep-Sea Research*, **37**, 1121–1134.

Landry M. R., J. Kirshtein and J. Constantinou (1996) Abundances and distributions of picoplankton populations in the central equatorial Pacific from 12°N to 12°S, 140°W. *Deep-Sea Research II*, **43**, 871–890.

Landry M. R., R. T. Barber, R. R. Bidigare, F. Chai, K. H. Coale, H. G. Dam, M. R. Lewis, S. T. Lindley, J. J. McCarthy, M. R. Roman, D. K. Stoecker, P. G. Verity and J. R. White (in press) Iron and grazing constraints on primary production in the central equatorial Pacific: An EqPac synthesis. *Limnology and Oceanography*.

Lee C., S. G. Wakeham and J. I. Hedges (1988) The measurement of oceanic particle flux—Are "swimmers" a problem? *Oceanography*, **1**, 34–36.

Lochte K., H. W. Ducklow, M. J. R. Fasham and C. Stienen (1993) Plankton succession and carbon cycling at 47°N; 20°W during the JGOFS North Atlantic Bloom Experiment. *Deep-Sea Research*, **40**, 91–114.

Lorenzen C. J., N. A. Welschmeyer, A. E. Copping and M. Vernet (1983) Sinking rates of organic particles. *Limnology and Oceanography*, **28**, 766–769.

Luo S., T.-L. Ku, M. Kusakabe, J. K. B. Bishop and Y.-L. Yang (1995) Tracing particle cycling in the upper ocean with ^{230}Th and ^{228}Th: an investigation in the equatorial Pacific along 140°W. *Deep-Sea Research II*, **42**, 805–830.

Martin J. H., G. A. Knauer, D. M. Karl and W. W. Broenkow (1987) VERTEX: carbon cycling in the northeast Pacific. *Deep-Sea Research*, **34**, 267–285.

McCarthy J. J., C. Garside, J. L. Nevins and R. T. Barber (1996) New production along 140°W in the equatorial Pacific during and following the 1992 El Niño event. *Deep-Sea Research II*, **43**, 1065–1093.

Michaels A. F., M. W. Silver, M. M. Gowing and G. A. Knauer (1990) Cryptic zooplankton "swimmers" in upper ocean sediment traps. *Deep-Sea Research*, **37**, 1285–1296.

Michaels A. F., N. R. Bates, K. O. Buesseler, C. A. Carlson and A. H. Knap (1994) Carbon-cycle imbalances in the Sargasso Sea. *Nature*, **372**, 537–540.

Murray J. W., J. N. Downs, S. Strom, C.-L. Wei and H. W. Jannasch (1989) Nutrient assimilation, export production and ^{234}Th scavenging in the eastern equatorial Pacific. *Deep-Sea Research*, **36**, 1471–1489.

Murray J. W., M. W. Leinen, R. A. Feely, J. R. Toggweiler and R. Wanninkhof (1992) EqPac: A process study in the central equatorial Pacific. *Oceanography*, **5**, 134–142.

Murray J. W., R. T. Barber, M. R. Roman, M. P. Bacon and R. A. Feely (1994) Physical and biological controls on carbon cycling in the equatorial Pacific. *Science*, **266**, 58–65.

Murray J. W., E. Johnson and C. Garside (1995) A U.S. JGOFS Process Study in the equatorial Pacific (EqPac): Introduction. *Deep-Sea Research II*, **42**, 275–293.

Najjar R. G., J. L. Sarmiento and J. R. Toggweiler (1992) Downward transport and fate of organic matter in the ocean: simulations with a general circulation model. *Global Biogeochemical Cycles*, **6**, 45–76.

Peltzer E. T. and N. A. Hayward (1996) Spatial and temporal variability of total organic carbon along 140°W in the equatorial Pacific Ocean in 1992. *Deep-Sea Research II*, **43**, 1155–1180.

Pena M. A., W. G. Harrison and M. R. Lewis (1992) New production in the central equatorial Pacific. *Marine Ecology Progress Series*, **80**, 265–274.

Redfield A. C., B. H. Ketchum and F. A. Richards (1963) The influence of organisms on the composition of seawater. In: *The sea*, vol. 2, M. N. Hill, editor, Wiley-Interscience, New York, pp. 26–77.

Rohlf F. J. and R. R. Sokal (1969) *Statistical tables*, W. H. Freeman and Co., New York, Table CC, pp. 176–177.

Roman M. R., H. G. Dam, A. L. Gauzens, J. Urban-Rich, D. G. Foley and T. D. Dickey (1995) Mesozooplankton variability on the equator at 140°W during the JGOFS EqPac study. *Deep-Sea Research II*, **42**, 735–755.

Sokal R. R. and F. J. Rohlf (1981) *Biometry*, W. H. Freeman and Co., New York, pp. 387–395.

Taylor J. R. (1982) *Introduction to error analysis*. University Science Books, pp. 199–201.

U.S. JGOFS (1989) Sediment Trap Technology and Sampling. Planning Report No. 10, U.S. JGOFS Planning Office, Woods Hole, MA, 94 pp.

U.S. JGOFS (1990) Report of a workshop on equatorial Pacific process studies, Tokyo, April 1990. Report no. 8 JGOFS, Scientific Committee for Ocean Research, 75 pp.

U.S. JGOFS (1993) Bermuda Atlantic Time-Series Study-Methods Manual, Version 3. U.S. JGOFS Planning Office, Woods Hole, MA, 108 pp.

Wei C.-L. and J. W. Murray (1992) Temporal variations of ^{234}Th activity in the water column of Dabob Bay: Particle scavenging. *Limnology and Oceanography*, **37**, 296–314.

Yoder J. A., S. G. Ackleson, R. T. Barber, P. Flament and W. M. Balch (1994) A line in the sea. *Nature*, **371**, 689–692.

Zhang X., H. G. Dam, J. R. White and M. R. Roman (1995) Latitudinal variations in mesozooplankton grazing and metabolism in the central tropical Pacific during the EqPac study. *Deep-Sea Research II*, **42**, 695–714.

APPENDIX

Water column activities (dpm l^{-1}) *of total* ^{234}Th *and* ^{238}U, *measured sediment trap fluxes of* ^{234}Th (dpm m^{-2} day^{-1}) *and organic carbon* (mmol C m^{-2} day^{-1}) *and model calculated fluxes of* ^{234}Th *(advection terms included) and particulate organic carbon with propagated uncertainties*

Stn	Lat.	Long.	Depth	Total ^{234}Th	^{238}U	C trap flux	Th trap flux	Model Th flux	Th error	Model C flux	C error
Survey I — TT007											
1	11.98	140.08	0	2435	2383	nd	nd	nd	nd	nd	nd
1	11.99	140.08	50	1922	2383	10.41	3301	294	156	0.86	0.47
1	11.99	140.08	75	2174	2431	11.61	2281	552	173	1.62	0.55
1	11.98	140.08	100	2471	2421	6.48	1961	627	192	1.84	0.61
1	11.98	140.08	125	nd	2417	4.80	2029	nd	nd	nd	nd
1	11.98	140.08	150	2569	2417	3.05	1083	482	260	1.42	0.78
1	11.98	140.08	175	2215	2438	nd	nd	508	273	1.49	0.82
1	11.99	140.08	200	2411	2442	3.19	1040	599	285	1.76	0.87
1	11.98	140.08	250	2377	2440	2.82	415	667	331	1.96	1.00
2	9.01	140.09	0	1963	2377	nd	nd	nd	nd	nd	nd
2	9.01	140.09	50	2046	2377	12.20	1292	535	146	1.45	0.68
2	9.01	140.09	75	1709	2424	14.80	3222	911	162	2.47	1.04
2	9.01	140.09	100	2372	2437	6.87	3190	1191	178	3.23	1.33
2	9.01	140.09	125	nd	2443	4.32	2771	nd	nd	nd	nd
2	9.01	140.09	150	2545	2445	4.16	1600	1166	248	3.16	1.39
2	9.01	140.09	175	2613	2445	nd	nd	1069	263	2.89	1.32
2	9.01	140.09	200	2682	2444	2.91	1243	923	279	2.50	1.22
2	9.01	140.09	250	2708	2444	2.29	764	562	335	1.52	1.08
3	7.06	140.02	0	2158	2414	nd	nd	nd	nd	nd	nd
3	7.06	140.02	50	1884	2422	nd	nd	571	147	1.56	0.50
3	7.06	140.02	75	2268	2442	14.66	5621	827	166	2.25	0.62
3	7.06	140.02	100	2407	2444	9.25	2580	903	185	2.46	0.68
3	7.06	140.02	125	nd	2440	5.34	2050	nd	nd	nd	nd
3	7.06	140.02	150	2493	2437	nd	nd	889	252	2.42	0.82
3	7.06	140.02	175	2369	2443	nd	nd	895	266	2.44	0.86
3	7.06	140.02	200	2401	2445	4.03	1546	938	279	2.56	0.90
3	7.06	140.02	250	2510	2444	3.04	1369	922	328	2.51	1.01
4	5.05	140.02	0	1767	2429	nd	nd	nd	nd	nd	nd
4	5.05	140.02	50	1718	2428	nd	nd	880	200	1.42	0.48
4	5.05	140.02	75	1674	2428	15.30	8361	1434	211	2.32	0.67
4	5.05	140.02	100	2466	2443	14.58	6585	1747	225	2.82	0.80
4	5.05	140.02	125	nd	2445	6.53	4501	nd	nd	nd	nd
4	5.05	140.02	150	2394	2444	nd	nd	1825	284	2.95	0.87
4	5.05	140.02	175	2497	2438	nd	nd	1829	297	2.95	0.88
4	5.05	140.02	200	2443	2439	3.53	2540	1821	310	2.94	0.89
4	5.05	140.02	250	2903	2442	2.79	2333	1487	361	2.40	0.84
5	3.01	139.99	0	1961	2438	nd	nd	nd	nd	nd	nd
5	3.01	139.99	25	1820	2438	nd	nd	393	70	0.67	0.20
5	3.01	139.99	50	1944	2438	nd	nd	728	307	1.24	0.60
5	3.01	139.99	75	2122	2439	nd	nd	944	321	1.60	0.67
5	3.01	139.99	100	2071	2440	nd	nd	1216	332	2.07	0.75
5	3.01	139.99	125	2533	2445	nd	nd	nd	nd	nd	nd
5	3.01	139.99	150	2594	2459	nd	nd	1402	361	2.38	0.84
5	3.01	139.99	175	2655	2458	nd	nd	1283	372	2.18	0.82
5	3.01	139.99	225	2893	2455	nd	nd	826	418	1.54	0.88

Stn	Lat.	Long.	Depth	Total ^{234}Th	^{238}U	C trap flux	Th trap flux	Model Th flux	Th error	Model C flux	C error
5	3.01	139.99	250	2639	2454	nd	nd	602	429	1.15	0.87
6	2.08	139.92	0	1912	2443	nd	nd	nd	nd	nd	nd
6	2.08	139.92	50	2244	2444	nd	nd	570	378	1.02	0.71
6	2.08	139.92	75	2053	2450	21.47	10510	747	398	1.33	0.77
6	2.08	139.92	100	2015	2450	35.94	29333	1112	419	1.98	0.87
6	2.08	139.92	125	2630	2449	11.42	7478	1376	437	2.46	0.96
6	2.08	139.92	150	2675	2445	nd	nd	1309	452	2.33	0.96
6	2.08	139.92	200	2646	2458	4.41	2312	1008	488	1.80	0.96
6	2.08	139.92	250	2489	2454	3.67	1653	848	519	1.51	0.99
7	1.13	140.05	0	2021	2463	nd	nd	nd	nd	nd	nd
7	1.13	140.05	50	2021	2463	nd	nd	649	348	1.38	0.83
7	1.13	140.05	75	2038	2463	8.99	3157	1012	391	2.15	1.01
7	1.13	140.05	100	2156	2463	14.86	8313	1431	439	3.04	1.24
7	1.13	140.05	125	2728	2448	20.93	10783	1652	475	3.50	1.39
7	1.13	140.05	150	2388	2452	nd	nd	1600	488	3.39	1.39
7	1.13	140.05	200	2357	2455	5.62	2183	1666	519	3.53	1.46
7	1.13	140.05	250	2639	2455	3.92	2701	1604	547	3.40	1.48
8	0.00	140.06	0	1775	2453	nd	nd	nd	nd	nd	nd
8	0.00	140.06	50	2023	2464	nd	nd	1409	399	3.63	1.62
8	0.00	140.06	75	2338	2471	nd	nd	2100	474	5.41	2.23
8	0.00	140.06	100	2522	2473	nd	nd	2339	516	6.03	2.46
8	0.00	140.06	125	2346	2472	nd	nd	2355	535	6.07	2.50
8	0.00	140.06	150	2460	2472	nd	nd	2406	545	6.20	2.55
8	0.00	140.06	200	2795	2461	nd	nd	2185	576	5.63	2.44
8	0.00	140.06	250	2952	2456	nd	nd	1589	608	4.10	2.11
9	−1.02	140.16	0	1673	2459	nd	nd	nd	nd	nd	nd
9	−1.02	140.16	50	1805	2460	nd	nd	1133	338	3.44	1.70
9	−1.02	140.16	75	2185	2476	10.15	2593	1655	381	5.02	2.29
9	−1.02	140.16	100	2231	2475	11.97	9900	1903	412	5.77	2.59
9	−1.02	140.16	125	2299	2486	nd	nd	2094	426	6.36	2.82
9	−1.02	140.16	150	2349	2481	6.30	1495	2235	436	6.78	2.98
9	−1.02	140.16	200	2422	2459	4.69	1456	2376	468	7.21	3.17
9	−1.02	140.16	250	2663	2455	3.11	1191	2253	500	6.84	3.09
10	−2.02	140.13	0	1972	2458	nd	nd	nd	nd	nd	nd
10	−2.02	140.13	50	1992	2458	nd	nd	236	530	0.60	1.36
10	−2.02	140.13	75	1944	2460	8.17	3062	563	544	1.43	1.45
10	−2.02	140.13	100	2401	2484	12.76	3513	848	560	2.15	1.57
10	−2.02	140.13	125	2570	2509	nd	nd	nd	nd	nd	nd
10	−2.02	140.13	150	2491	2466	2.84	1853	956	585	2.42	1.66
10	−2.02	140.13	200	2551	2458	1.90	917	851	612	2.16	1.69
10	−2.02	140.13	250	2460	2456	2.51	909	781	637	1.98	1.73
11	−3.00	140.02	0	1909	2464	nd	nd	nd	nd	nd	nd
11	−3.00	140.02	50	1798	2464	nd	nd	714	388	1.97	1.19
11	−3.00	140.02	75	1970	2467	nd	nd	1085	400	2.99	1.36
11	−3.00	140.02	100	2415	2489	nd	nd	1289	412	3.55	1.48
11	−3.00	140.02	150	2779	2509	nd	nd	1162	456	3.20	1.52
11	−3.00	140.02	200	2625	2459	nd	nd	853	493	2.35	1.50
11	−3.00	140.02	250	2635	2457	nd	nd	605	526	1.67	1.52
12	−5.05	140.00	0	2129	2474	nd	nd	nd	nd	nd	nd
12	−5.05	140.00	50	1887	2474	nd	nd	458	239	1.36	0.78
12	−5.05	140.00	75	2197	2474	6.25	1682	749	252	2.23	0.91
12	−5.05	140.00	100	2447	2492	3.40	1721	841	266	2.50	0.98

Stn	Lat.	Long.	Depth	Total ^{234}Th	^{238}U	C trap flux	Th trap flux	Model Th flux	Th error	Model C flux	C error
12	−5.05	140.00	125	2697	2498	nd	nd	nd	nd	nd	nd
12	−5.05	140.00	150	2738	2529	3.50	1297	628	297	1.87	0.98
12	−5.05	140.00	200	2483	2482	3.32	952	474	348	1.41	1.08
12	−5.05	140.00	250	2544	2458	2.98	1000	412	390	1.23	1.19
15	−12.03	135.00	0	2197	2510	nd	nd	nd	nd	nd	nd
15	−12.03	135.00	25	2060	2510	nd	nd	274	77	1.30	0.46
15	−12.03	135.00	50	2080	2515	nd	nd	592	108	2.80	0.80
15	−12.03	135.00	75	2374	2564	5.96	1052	817	135	3.86	1.06
15	−12.03	135.00	100	2451	2567	5.40	1493	926	160	4.38	1.22
15	−12.03	135.00	150	2751	2562	3.87	1068	874	242	4.13	1.46
15	−12.03	135.00	200	2643	2540	3.34	588	664	306	3.14	1.60
15	−12.03	135.00	250	2633	2507	3.20	635	499	357	2.36	1.76
Survey II — TT011											
1	12.01	140.03	0	2138	2394	nd	nd	nd	nd	nd	nd
1	12.01	140.03	25	2076	2394	nd	nd	206	76	0.77	0.35
1	12.01	140.03	50	2070	2423	nd	nd	447	107	1.68	0.60
1	12.01	140.03	75	1889	2415	14.64	1283	763	129	2.86	0.91
1	12.01	140.03	100	2105	2429	7.14	1414	1068	148	4.00	1.21
1	12.01	140.03	150	2456	2443	5.06	1759	1292	220	4.84	1.54
1	12.01	140.03	200	2479	2447	3.85	955	1260	279	4.73	1.64
1	12.01	140.03	250	1922	2446	2.60	853	1615	321	6.05	2.02
2	8.97	139.97	0	1786	2381	nd	nd	nd	nd	nd	nd
2	8.97	139.97	25	2160	2386	nd	nd	295	72	0.78	0.47
2	8.97	139.97	50	2015	2395	nd	nd	513	104	1.35	0.79
2	8.97	139.97	75	1561	2429	5.60	1357	961	124	2.53	1.42
2	8.97	139.97	100	1848	2392	8.79	2342	1469	140	3.86	2.15
2	8.97	139.97	150	2399	2443	3.40	3914	1892	208	4.97	2.78
2	8.97	139.97	200	2291	2443	2.33	1676	2033	266	5.34	3.01
2	8.97	139.97	250	1949	2444	2.82	939	2498	307	6.57	3.69
3	7.01	139.91	0	1944	2390	nd	nd	nd	nd	nd	nd
3	7.01	139.91	25	1815	2398	nd	nd	370	70	1.11	0.34
3	7.01	139.91	75	1772	2410	7.98	1319	1249	152	3.76	1.00
3	7.01	139.91	100	1962	2429	5.46	1854	1646	167	4.95	1.27
3	7.01	139.91	150	2387	2435	3.22	1492	2017	229	6.07	1.59
3	7.01	139.91	200	2368	2447	3.07	1016	2108	283	6.34	1.73
3	7.01	139.91	250	2382	2446	3.56	912	2211	329	6.65	1.86
4	5.01	139.83	0	1651	2426	nd	nd	nd	nd	nd	nd
4	5.01	139.83	25	1599	2426	nd	nd	584	109	2.15	0.68
4	5.01	139.83	50	1566	2430	nd	nd	1227	166	4.51	1.30
4	5.01	139.83	75	1626	2432	7.61	3260	1796	194	6.60	1.82
4	5.01	139.83	100	1763	2438	15.08	4057	2304	212	8.46	2.29
4	5.01	139.83	150	2453	2438	8.42	1733	2785	273	10.23	2.79
4	5.01	139.83	200	2327	2439	7.85	1913	2857	321	10.49	2.91
4	5.01	139.83	250	2509	2444	6.37	1901	2891	363	10.62	3.01
5	2.90	140.21	0	1591	2425	nd	nd	nd	nd	nd	nd
5	2.90	140.21	25	1367	2425	nd	nd	699	182	2.67	1.21
5	2.90	140.21	50	1709	2425	nd	nd	1338	250	5.12	2.11
5	2.90	140.21	75	1928	2441	21.25	3484	1567	286	6.00	2.47
5	2.90	140.21	100	1515	2454	14.44	5786	1933	315	7.40	2.98
5	2.90	140.21	150	2298	2458	7.49	2637	2598	368	9.94	3.92
5	2.90	140.21	200	2235	2458	5.64	1427	2877	402	11.00	4.33

Stn	Lat.	Long.	Depth	Total ^{234}Th	^{238}U	C trap flux	Th trap flux	Model Th flux	Th error	Model C flux	C error
5	2.90	140.21	250	2217	2455	5.18	1388	3207	432	12.27	4.81
6-A	2.12	140.24	0	1572	2461	nd	nd	nd	nd	nd	nd
6-A	2.12	140.24	25	1632	2461	nd	nd	916	239	6.31	3.37
6-A	2.12	140.24	50	1769	2461	nd	nd	1750	390	12.05	6.23
6-A	2.12	140.24	75	1959	2460	41.07	3440	2281	452	15.71	7.96
6-A	2.12	140.24	100	1806	2460	33.39	4261	2665	470	18.35	9.15
6-A	2.12	140.24	150	2386	2458	11.04	1976	3072	524	21.15	10.51
6-A	2.12	140.24	200	2362	2458	10.55	1901	3237	551	22.29	11.07
6-A	2.12	140.24	250	2307	2456	6.19	1762	3414	575	23.50	11.66
6-B	2.27	140.87	0	3347	2432	nd	nd	nd	nd	nd	nd
6-B	2.27	140.87	25	1462	2451	nd	nd	866	214	5.96	3.15
6-B	2.27	140.87	50	1611	2460	nd	nd	1764	350	12.15	6.16
6-B	2.27	140.87	75	1747	2460	41.07	3440	2566	412	17.67	8.72
6-B	2.27	140.87	100	2292	2449	33.39	4261	2934	449	20.20	9.92
6-B	2.27	140.87	150	2312	2459	11.04	1976	2972	541	20.47	10.25
6-B	2.27	140.87	200	2634	2458	10.55	1901	2993	569	20.61	10.38
6-B	2.27	140.87	250	2414	2456	6.19	1762	2896	595	19.94	10.17
7	1.14	140.01	0	1639	2463	nd	nd	nd	nd	nd	nd
7	1.14	140.01	25	1634	2463	nd	nd	942	269	4.75	1.36
7	1.14	140.01	50	1911	2463	nd	nd	1671	417	8.43	2.11
7	1.14	140.01	75	1786	2462	nd	nd	2263	509	11.41	2.57
7	1.14	140.01	100	2209	2453	28.69	5716	2709	582	13.66	2.94
7	1.14	140.01	125	nd	2449	14.95	2940	nd	nd	nd	nd
7	1.14	140.01	150	2296	2455	13.52	2729	2948	712	14.87	3.60
7	1.14	140.01	200	2095	2457	12.59	2501	3309	730	16.6	93.69
7	1.14	140.01	250	2396	2456	13.59	2653	3612	747	18.2	23.78
8	0.21	139.90	0	1679	2463	nd	nd	nd	nd	nd	nd
8	0.21	139.90	25	1899	2464	nd	nd	643	355	1.94	1.20
8	0.21	139.90	50	1948	2466	nd	nd	1249	665	3.76	2.26
8	0.21	139.90	75	1887	2471	nd	nd	2177	913	6.55	3.31
8	0.21	139.90	100	2625	2458	6.38	3097	3149	1061	9.48	4.16
8	0.21	139.90	125	nd	2461	5.15	1770	nd	nd	nd	nd
8	0.21	139.90	150	2524	2452	6.81	2198	3575	1221	10.76	4.76
8	0.21	139.90	200	2353	2453	5.50	2094	3558	1234	10.71	4.78
8	0.21	139.90	250	2276	2456	4.60	1057	3759	1245	11.31	4.91
9	1.08	139.96	0	nd	2468	nd	nd	nd	nd	nd	nd
9	1.08	139.96	25	nd	2468	nd	nd	nd	nd	nd	nd
9	1.08	139.96	50	nd	2467	nd	nd	nd	nd	nd	nd
9	1.08	139.96	75	nd	2489	nd	nd	nd	nd	nd	nd
9	1.07	139.95	100	nd	2499	8.28	3257	nd	nd	nd	nd
9	1.07	139.95	125	nd	2485	5.72	3206	nd	nd	nd	nd
9	1.07	139.95	150	nd	2478	3.99	2108	nd	nd	nd	nd
9	1.07	139.95	200	nd	2458	4.44	1902	nd	nd	nd	nd
9	1.07	139.95	250	nd	2456	4.90	1300	nd	nd	nd	nd
10	−2.19	140.16	0	1426	2471	nd	nd	nd	nd	nd	nd
10	−2.19	140.16	25	1450	2471	nd	nd	798	90	1.83	0.66
10	−2.19	140.16	50	1571	2472	nd	nd	1542	128	3.54	1.25
10	−2.19	140.16	75	1946	2503	nd	nd	1916	205	4.40	1.58
10	−2.19	140.16	100	2657	2516	14.61	5213	1767	325	4.05	1.58
10	−2.19	140.16	125	nd	2476	11.56	3454	nd	nd	nd	nd
10	−2.19	140.16	150	2555	2461	6.43	2918	1244	503	2.86	1.51
10	−2.19	140.16	200	2031	2458	5.71	3878	1450	529	3.33	1.67

Stn	Lat.	Long.	Depth	Total ^{234}Th	^{238}U	C trap flux	Th trap flux	Model Th flux	Th error	Model C flux	C error
10	−2.19	140.16	250	2273	2457	4.68	2844	1889	551	4.33	1.95
11	−3.22	140.26	0	1544	2461	nd	nd	nd	nd	nd	nd
11	−3.22	140.26	25	1585	2459	nd	nd	448	172	1.49	0.94
11	−3.22	140.26	50	1383	2456	nd	nd	1098	230	3.65	1.97
11	−3.22	140.26	75	1480	2465	nd	nd	1701	293	5.66	2.98
11	−3.22	140.26	100	1574	2480	20.47	3773	1930	429	6.42	3.50
11	−3.22	140.26	125	nd	2508	15.16	3231	nd	nd	nd	nd
11	−3.22	140.26	150	2327	2468	8.07	2825	2066	697	6.88	4.13
11	−3.22	140.26	200	2171	2458	5.86	3175	2378	717	7.92	4.60
11	−3.22	140.26	250	2716	2457	9.20	5042	2399	737	7.99	4.67
12	−5.11	140.00	0	1485	2467	nd	nd	nd	nd	nd	nd
12	−5.11	140.00	25	1536	2467	nd	nd	587	170	2.23	1.27
12	−5.11	140.00	50	1618	2466	nd	nd	1161	293	4.41	2.44
12	−5.11	140.00	75	1576	2458	nd	nd	1838	356	6.98	3.70
12	−5.11	140.00	100	1534	2459	29.03	5015	2531	375	9.61	4.95
12	−5.11	140.00	125	nd	2466	29.41	5749	nd	nd	nd	nd
12	−5.11	140.00	150	2125	2509	22.47	6179	3452	386	13.11	6.62
12	−5.11	140.00	200	2494	2486	10.41	2961	3731	421	14.17	7.16
12	−5.11	140.00	250	2253	2460	5.946	3573	8744	531	4.71	7.45
13	−7.01	138.49	0A	1805	2473	nd	nd	nd	nd	nd	nd
13	−7.01	138.49	0B	1925	2473	nd	nd	nd	nd	nd	nd
13	−7.01	138.49	50-A	1662	2473	nd	nd	nd	nd	nd	nd
13	−7.01	138.49	50-B	1672	2473	nd	nd	nd	nd	nd	nd
13	−7.01	138.49	100-A	1907	2474	nd	nd	nd	nd	nd	nd
13	−7.01	138.49	100-B	1888	2474	nd	nd	nd	nd	nd	nd
13	−7.01	138.49	150-A	2490	2530	nd	nd	nd	nd	nd	nd
13	−7.01	138.49	150-B	2357	2530	nd	nd	nd	nd	nd	nd
15	−11.93	134.95	0	1844	2529	nd	nd	nd	nd	nd	nd
15	−11.93	134.95	25	2009	2529	nd	nd	433	72	1.03	0.35
15	−11.93	134.95	50	1947	2529	nd	nd	829	103	1.97	0.63
15	−11.93	134.95	75	2220	2549	nd	nd	1156	128	2.74	0.86
15	−11.93	134.95	100	2236	2560	4.04	1663	1391	151	3.30	1.03
15	−11.93	134.95	125	nd	2565	12.37	4482	nd	nd	nd	nd
15	−11.93	134.95	150	2701	2560	10.73	3663	1522	167	3.61	1.13
15	−11.93	134.95	200	2481	2525	4.32	3135	1453	246	3.45	1.17
15	−11.93	134.95	250	2649	2490	4.45	643	1370	305	3.25	1.20