



Title	Seasonal variations in planktonic foraminiferal flux and oxygen isotopic composition in the western North Pacific : Implications for paleoceanographic reconstruction
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1 **Seasonal variations in planktonic foraminiferal flux and**
2 **oxygen isotopic composition in the western North Pacific:**
3 **implications for paleoceanographic reconstruction**

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25

26

27 **Abstract**

28 The oxygen isotopic composition ($\delta^{18}\text{O}$) of planktonic foraminiferal shells in seafloor sediment
29 provides information on past surface oceanography. Knowledge of seasonal and depth habitat, as
30 well as the $\delta^{18}\text{O}$ disequilibrium (vital effect), is essential to constrain the interpretation of
31 sedimentary $\delta^{18}\text{O}$. Here, we present a 1-year time series of planktonic foraminiferal shell fluxes and
32 $\delta^{18}\text{O}$ from a sediment trap moored in the northwestern margin of the North Pacific. The vital effect
33 and calcification depth for four species were estimated by comparing shell $\delta^{18}\text{O}$ and the predicted
34 values of equilibrium calcite calculated from temperature and estimated $\delta^{18}\text{O}$ in seawater. Six major
35 species (*Neogloboquadrina incompta*, *Neogloboquadrina dutertrei*, *Neogloboquadrina pachyderma*,
36 *Globigerina quinqueloba*, *Globigerina bulloides*, and *Globorotalia scitula*) constituted 97% of the
37 total foraminiferal flux. Most major species showed large fluxes in June and December,
38 corresponding to periods of the development and disruption of the seasonal thermocline, implying
39 the importance of nutrient injection and/or circulation for foraminiferal fluxes. Additional peaks in *N.*
40 *dutertrei* and *N. pachyderma* were observed in August. The seasonal successions of foraminiferal
41 fluxes corresponded to surface ocean stratification conditions and food availability, which are
42 closely related to circulation of local currents. Vital effect estimations suggest that shells calcified in
43 equilibrium for *G. bulloides* and *N. pachyderma* [sinistral (s)] and with a -0.7‰ offset for *N.*
44 *dutertrei* [dextral (d)], a -1.0‰ offset for *N. incompta* (d), and a -0.3‰ offset for *N. pachyderma* (d).

45 The calculation of flux-weighted $\delta^{18}\text{O}$ values reveals that the sedimentary $\delta^{18}\text{O}$ values of *G.*
46 *bulloides*, *N. dutertrei* (d), and *N. incompta* (d) reflect surface temperature in winter season, and
47 those of *N. pachyderma* (s) and *N. pachyderma* (d) reflect summer and annual mean subsurface
48 temperature, respectively. The shallow calcification depths for the four species suggest that $\delta^{18}\text{O}$
49 between different species ($\Delta\delta^{18}\text{O}$) in the western North Pacific does not work for reconstructing past
50 stratification conditions, unlike in other regions. Rather, the $\Delta\delta^{18}\text{O}$ between *N. pachyderma* (s) and *G.*
51 *bulloides*, *N. dutertrei* (d) or *N. incompta* (d) would provide a proxy for past seasonality.

52

53 *Keywords: planktonic foraminifera, sediment traps, oxygen isotopes, northwestern North Pacific*

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55

56 **1. Introduction**

57 The oxygen isotopic composition ($\delta^{18}\text{O}$) of planktonic foraminifera has been widely used to
58 reconstruct past surface ocean conditions. Because the isotopic fractionation factor between water
59 and carbonate minerals depends on the calcification temperature (e.g., Epstein et al., 1953; McCrea,
60 1950), $\delta^{18}\text{O}$ in fossil foraminifera in seafloor sediments records both past seawater $\delta^{18}\text{O}$ and
61 temperature changes. Knowledge of the seasonal and depth habitats of foraminifera is essential when
62 fossil $\delta^{18}\text{O}$ is used for paleoceanographic reconstruction. Additionally, the difference in $\delta^{18}\text{O}$ among
63 species ($\Delta\delta^{18}\text{O}$) that live different depths or seasonal habitats may give us an opportunity to
64 investigate past stratification (e.g., Mortyn et al., 2002; Mulitza et al., 1997; Rashid and Boyle, 2007;
65 Sagawa et al., 2011; Simstich et al., 2003; Spero et al., 2003) or seasonality (Jonkers et al., 2010).
66 The vertical and seasonal distributions of planktonic foraminifera are strongly affected by regional
67 environmental factors, such as geography, hydrography, and ecosystems (e.g., Fairbanks et al., 1980;
68 Kuroyanagi and Kawahata, 2004; Kuroyanagi et al., 2002; Sautter and Thunell, 1991). The regional
69 environment may also influence the vital effect of the shell $\delta^{18}\text{O}$ (e.g., Niebler et al., 1999), which is
70 defined as offset from the $\delta^{18}\text{O}$ equilibrium value. It is therefore important to constrain the
71 influences of habitat distribution and the vital effect in the fossil $\delta^{18}\text{O}$ records on regional scales.

72 The planktonic foraminiferal species *Neogloboquadrina pachyderma* (Ehrenberg) has been

73 commonly used in paleoceanographic studies of the middle to high latitudes. Temporal variation in
74 the coiling ratio of this species has been interpreted in relation to past environmental changes (e.g.,
75 Thompson and Shackleton, 1980). However, recent genetic studies revealed that the two
76 morphospecies with opposite coiling directions show distinct genetic patterns (Bauch et al., 2003;
77 Darling et al., 2000). Based on the genetic differences and geographic distribution of the
78 morphospecies, Darling et al. (2006) suggested that the right-coiling morphospecies should be
79 recognized as *Neogloboquadrina incompta* (Cifelli). The geographic distribution of *N. pachyderma*
80 and *N. incompta* in surface sediments around the Japanese islands also shows a distinct pattern (Oda
81 and Domitsu, 2009; and references therein). In general, the left-coiling form is dominant in *N.*
82 *pachyderma* and the right-coiling form is dominant in *N. incompta* (Darling et al., 2006; Oda and
83 Domitsu, 2009), accounting for >97% in both species. However, a higher right-coiling ratio (>50%)
84 in *N. pachyderma*, which is distinct from *N. incompta*, was reported from the Holocene sediment of
85 the northwestern margin of the North Pacific (Kuroyanagi et al., 2006). This evidence implies that
86 the coiling direction–based identification method is not applicable to this region. Therefore, added
87 understanding of the habitat preferences and $\delta^{18}\text{O}$ of these morphospecies is essential for
88 paleoceanographic interpretation.

89 This study investigated the seasonal variation in the planktonic foraminiferal flux and $\delta^{18}\text{O}$
90 using a 1-year data series from a moored sediment trap in the northwestern margin of the North

91 Pacific (Fig. 1). The vital effect of $\delta^{18}\text{O}$, calcification depth, and flux-weighted $\delta^{18}\text{O}$ were estimated
92 to better constrain the foraminiferal $\delta^{18}\text{O}$ proxy in paleoceanographic study. Our results revealed that
93 differences in the flux-weighted $\delta^{18}\text{O}$ values among species mainly reflect seasonal flux pattern
94 rather than the calcification depth in the western North Pacific, and the potential of $\Delta\delta^{18}\text{O}$ as a proxy
95 of past seasonality in this region is therefore extended.

96

97 **2. Oceanographic setting**

98 The surface water around the study site is characterized by high seasonal variability due to the
99 coexistence of the Oyashio Current and the Tsugaru Warm Current (TGC; Fig. 1). The Oyashio
100 Current is a western boundary current of the Western Subarctic Gyre of the North Pacific that
101 transports cold, fresh surface water. The Oyashio Current off the southeastern coast of Hokkaido
102 bifurcates into the first branch of the Oyashio and the coastal Oyashio Water (Kono et al., 2004). The
103 TGC is relatively warm and saline ($>6\text{ }^\circ\text{C}$ and ~ 34.0) (Hanawa and Mitsudera, 1986) and it
104 originates from the Tsushima Warm Current (TWC), which is formed by mixing of the Kuroshio
105 water and the coastal water in the East China Sea. Changes in the relative influence of these currents
106 produce strong seasonality in surface conditions. The first branch of the Oyashio Current reaches its
107 southernmost latitude in late winter to early spring and its northernmost latitude in late summer to
108 autumn (Yasuda, 2003). The influence of the TGC on the study site increases in summer and autumn

109 (Hanawa and Mitsudera, 1986).

110 Monthly mean vertical profiles of temperature, salinity, and density during the period

111 corresponding to trap deployment, from May 2002 to May 2003, are shown in Fig. 2a–c.

112 Temperature and salinity data were obtained from the National Centers for Environmental Prediction

113 (NCEP) Global Ocean Data Assimilation System (GODAS) (Behringer and Xue, 2004). The

114 temperature and salinity of the upper 200 m in March were nearly constant and fell within the range

115 of about 2°C and 0.02, respectively, due to vertical mixing. Summer surface temperature reaches

116 ~20°C and a steep thermocline develops at 20–40 m. The similarity of the density and temperature

117 profiles suggests primary control by temperature, as expected with low variation in annual salinity

118 (Fig. 2b).

119

120 **3. Materials and Methods**

121 **3.1. Samples**

122 A time-series sediment trap (model SMD21-6000; Nichiyu-giken-kogyo Ltd., Tokyo, Japan)

123 was deployed at 350 m water depth (~620 m above the seafloor) at 41°33.8'N, 141°52.0'E. The

124 sediment trap has a collection area of 0.5 m² with 21 cup collectors and was moored for 1 year from

125 June 2002 to June 2003. Each sample represents a collection period of 11–30 days, with most being

126 14 days (Kawahata et al., 2009). The sample treatments were conducted following a method

127 described in Kawahata et al. (1998). Prior to trap deployment, the sampling bottles were filled with
128 filtered seawater (0.45 μm pore size) containing a 3% formalin solution buffered with sodium borate
129 to retard microbial activity in the trapped sample. After recovery, samples were stored at 2–4°C.
130 They were filtered through a 1-mm mesh to remove zooplanktonic swimmers. The <1-mm fraction
131 was split into 64 aliquots. Major components of trap samples were reported by Kawahata et al.
132 (2009).

133

134 **3.2. Analytical Methods**

135 Planktonic foraminifera were wet sieved into two size fractions (125–250 μm and >250 μm),
136 picked after drying, and identified for faunal abundance analysis. In this study, the taxonomic criteria
137 followed Parker (1962), Saito et al. (1981), and Hemleben et al. (1989). $\delta^{18}\text{O}$ measurements were
138 derived from four planktonic foraminiferal species: *Globigerina bulloides*, *Neogloboquadrina*
139 *dutertrei* [dextral (d)], *N. incompta* (d), and *N. pachyderma* [dextral and sinistral (s)]. Identified
140 foraminiferal shells (125–250 μm) were cleaned with a wet brush under a microscope before being
141 measured. Ten specimens were ideally used for each measurement, but approximately half of the
142 samples contained <10 shells (2–9 specimens). Measurements were obtained using an isotope mass
143 spectrometer (Finnigan MAT 253; Thermo Fisher Scientific Inc.) connected to an automated
144 preparation system (Kiel Carbonate device IV) at Hokkaido University. Measured results were

145 calibrated with the NBS-19 standard, which was analyzed in the same sequence, and expressed in
146 the VPDB scale. The analytical error was $\pm 0.06\%$.

147

148 **3.3. Calculation of isotopic equilibrium and flux-weighted $\delta^{18}\text{O}$ values**

149 The predicted $\delta^{18}\text{O}$ value of equilibrium calcite was calculated using the $\delta^{18}\text{O}$ temperature
150 scale of Kim and O'Neil (1997):

$$151 \quad \delta_{\text{c}} = \frac{4.64 - \sqrt{21.53 - 0.36 \times (16.1 - T)}}{0.18} + \delta_{\text{w}} \quad (1)$$

152 where T is temperature ($^{\circ}\text{C}$) and δ_{c} and δ_{w} are $\delta^{18}\text{O}$ values of carbonate and the ambient water,
153 respectively, relative to the VPDB. We chose this $\delta^{18}\text{O}$ temperature scale because the calibrated
154 temperature range (10-40 $^{\circ}\text{C}$) corresponds to that of natural variability. When we discuss the vital
155 effect offset, it is reasonable to compare the measured values against the equilibrium $\delta^{18}\text{O}$ values
156 based on the inorganic precipitation relationship (Kim and O'Neil, 1997) rather than the values based
157 on field and laboratory relationships for specific foraminiferal taxa (e.g., Bemis et al., 1998; von
158 Langen et al., 2000) or mollusks (e.g., Epstein et al., 1953). Monthly mean temperature and salinity
159 data at 10-m depth intervals from 5 m to 303 m were obtained from a $1^{\circ} \times 1^{\circ}$ gridded dataset of the
160 NCEP GODAS (Fig. 2a, b). Unfortunately, the GODAS has no temperature and salinity data for a
161 grid including the mooring site centered at 41 $^{\circ}10'\text{N}$, 141 $^{\circ}30'\text{E}$; therefore, average values were
162 calculated from three adjacent grids (Fig. 1b). Seawater $\delta^{18}\text{O}$ was estimated using the linear

163 relationship proposed by Oba and Murayama (2004) between salinity and δw in the
164 Kuroshio-Oyashio mixed water region along the eastern coast of the Japanese islands:

$$165 \quad \delta w = 0.521 \times S - 17.955, \quad (2)$$

166 where δw is $\delta^{18}\text{O}$ of seawater (VSMOW) and S is salinity. The δw is converted to the VPDB scale
167 by subtracting 0.27‰ (Hut, 1987). The vertical distribution of the predicted $\delta^{18}\text{O}$ record inversely
168 resembles that of temperature (Fig. 2), suggesting that the predicted $\delta^{18}\text{O}$ is controlled mainly by
169 temperature.

170 To constrain the effect of the seasonal foraminiferal flux in the fossil $\delta^{18}\text{O}$ record,
171 flux-weighted $\delta^{18}\text{O}$ values (King and Howard, 2005; Kuroyanagi et al., 2011) were calculated for
172 each species using the following equation:

$$173 \quad \text{Flux-weighted } \delta^{18}\text{O value} = \sum_{i=1}^n (\text{flux}_i \times \delta^{18}\text{O}_i) / \text{total flux} \quad (3)$$

174 where flux_i and $\delta^{18}\text{O}_i$ are the shell flux and $\delta^{18}\text{O}$ value for each species (125–250 μm size fraction).

175

176 **4. Results**

177 **4.1. Seasonal fluxes**

178 Fluxes in major components of trapped particles are reported by Kawahata et al. (2009) (Fig.
179 3a–e). In general, major components showed higher fluxes during three periods: June–July 2002,
180 October 2002–January 2003 (maximum in December), and April–May 2003. Total foraminiferal

181 shell flux (TFF) ranged from 2 to 2032 shells m⁻² day⁻¹ during the mooring period (Fig. 3f). Most
182 (89%) of the TFF was composed of small individuals (125–250 μm). Seasonal variation in TFF
183 differed slightly from that of other biogenic components. Higher TFFs were observed in June,
184 August, and December 2002 and a small peak was observed in late May. Two peaks in June and
185 December corresponded to higher fluxes for other biogenic components. However, a TFF peak
186 observed in August was not accompanied by other components, which showed minimum fluxes at
187 this time. Another difference is that the increase in TFF starting in late May 2003 lagged behind that
188 of biogenic opal and organic matter. The beginning of the TFF increase also lagged behind that of
189 carbonate flux, suggesting differences in biological response between foraminifera and
190 coccolithophores.

191 A total of 14 planktonic foraminiferal species were found at this site. The fauna consisted
192 mainly of the temperate and subpolar species *N. incompta*, *N. dutertrei*, *N. pachyderma*, *Globigerina*
193 *quiqueloba*, *G. bulloides*, and *Globorotalia scitula*, which had relative abundances of 25.7%, 25.4%,
194 22.8%, 15.1%, 4.1%, and 3.7%, respectively. These six species made up more than 97% of annual
195 TFFs (>125 μm). The seasonal fluxes for *G. bulloides*, *N. incompta*, and *G. quiqueloba* exhibited
196 bimodal peaks: late spring–summer (May–June) and early winter (December; Fig. 4). An additional
197 peak in August was significant for *N. dutertrei* and *N. pachyderma*. *Globorotalia scitula* had a
198 prominent peak around August–September only. To evaluate differences in seasonal variation

199 between right- and left-coiling individuals, we examined the coiling ratios of *N. incompta*, *N.*
200 *dutertrei*, and *N. pachyderma*. *N. incompta* and *N. dutertrei* had high right-coiling ratios throughout
201 the sampling period (both annual mean values were 87%). In contrast, left-coiling individuals were
202 dominant in *N. pachyderma* (mean right-coiling ratio was 42%). Both coiling directions in all three
203 species had similar seasonal flux patterns; weak positive correlations were found between right- and
204 left-coiling fluxes ($r = 0.37, 0.44, \text{ and } 0.58$ in *N. incompta*, *N. dutertrei*, and *N. pachyderma*,
205 respectively).

206

207 **4.2. Measured shell $\delta^{18}\text{O}$ and predicted $\delta^{18}\text{O}$ equilibrium value**

208 Because the foraminiferal flux varied significantly with seasons, about half of the samples
209 consist of less than 10 specimens per measurement. In order to assess the representativeness of the
210 $\delta^{18}\text{O}$ measurement with a small number of foraminiferal tests, we conducted replicate analyses using
211 samples that contained enough foraminiferal tests. Figure 5 shows the results of the replicate
212 analyses of *N. pachyderma* (s) and *N. pachyderma* (d). Each measurement consists of 4-13
213 specimens with mostly less than 10 specimens. The results show that the reproducibility is generally
214 less than $\pm 0.3\text{‰}$ (1σ). This is much smaller than the seasonal $\delta^{18}\text{O}$ variations (Fig. 6), confirming the
215 reliability of $\delta^{18}\text{O}$ measurements with a small number of tests.

216 Measured shell $\delta^{18}\text{O}$ values for four species showed seasonal variation, with lighter values

217 obtained during summer and heavier values during winter and spring (Fig. 6). The $\delta^{18}\text{O}$ for all
218 species was minimal in October, whereas the timing of the maximum value differed among species.
219 More enriched values were observed in May for *G. bulloides* and *N. pachyderma* (s), in March for *N.*
220 *incompta* (d), in late December for *N. pachyderma* (d), and in late June and February–March for *N.*
221 *dutertrei*.

222 Predicted $\delta^{18}\text{O}$ values for equilibrium calcite calculated using GODAS temperature and
223 salinity data showed clear seasonal succession, especially at shallower depths (Fig. 6). The seasonal
224 amplitudes were 3.5‰ at 5 m, 0.6‰ at 105 m, and <0.3‰ at >155 m, reflecting larger temperature
225 variation at shallower depth. The predicted $\delta^{18}\text{O}$ values at the end of winter were maximal and
226 homogeneous for the upper 75 m due to deepening of the mixed layer. Minimum values at shallower
227 depths (<15 m) were seen in August and September, whereas those at deeper depths (>25 m) lagged
228 behind until October or November. This finding is explained by seasonal changes in the vertical
229 thermal structure (Fig. 3g). The warming of surface water during summer produces strong
230 stratification, which prevents subsurface warming in this season. Stratification decays gradually
231 starting in October until isothermal conditions are achieved by late winter / early spring.

232 Measured shell $\delta^{18}\text{O}$ values for four species showed seasonal variation, with lighter values obtained
233 during summer and heavier values during winter and spring (Fig. 5). The $\delta^{18}\text{O}$ for all species was
234 minimal in October, whereas the timing of the maximum value differed among species. More

235 enriched values were observed in May for *G. bulloides* and *N. pachyderma* (s), in March for *N.*
236 *incompta* (d), in late December for *N. pachyderma* (d), and in late June and February–March for *N.*
237 *dutertrei*.

238 **5. Discussion**

239 **5.1. Seasonal flux variations**

240 As mentioned above, the general seasonal patterns of the major foraminiferal species included
241 two large maxima in summer (May–August) and early winter (December) and a small, broad
242 maximum around autumn. In particular, *N. incompta* (both coiling directions), *G. quinqueloba*, and *G.*
243 *bulloides* had almost the same seasonal peaks (May–June and December). These peak periods are
244 consistent with the development and disruption of thermoclines (Fig. 3g), corresponding to periods
245 before and after the TGC-dominant interval. Therefore, these results suggest that similar factors
246 control seasonal fluxes in these three species (i.e., nutrients, light, food availability and/or water
247 column structure). Similar seasonal flux patterns of *G. quinqueloba* and *G. bulloides* were also
248 observed in the western North Pacific (Kuroyanagi et al., 2008). Concurrent increases with biogenic
249 components (Fig. 3) and neritic radiolarian fluxes (Itaki et al., 2008) suggest that these species
250 respond to nutrient-rich water. The supply of nutrients by vertical mixing and/or from coastal water
251 might increase primary production and subsequent planktonic foraminiferal production.

252 *Neogloboquadrina dutertrei* (both coiling directions) showed a relatively large flux peak in

253 August. Hilbrecht (1997) reported two populations of *N. dutertrei*, tropical and subtropical. Plankton
254 tow experiments also showed bimodal peaks in the abundance of *N. dutertrei* (at ~18°C and 8°C)
255 around Japan (Kuroyanagi and Kawahata, 2004). Therefore, it is suggested that different populations
256 contribute to bimodal distribution in seasonal flux at this site. The maximum flux in summer was
257 reported from a sediment trap study at offshore site Sta. B (Fig. 1) (Itou and Noriki, 2002). In
258 contrast, the Japan Sea sediment trap showed a distinct peak of this species in November–December
259 (Park and Shin, 1998). These results suggest that the mid-summer and early winter peaks represent
260 the Pacific and Japan Sea populations, respectively.

261 Right-coiling *N. pachyderma* showed a large peak in August that decreased until January with
262 moderate fluctuations. In contrast, the left-coiling variety exhibited a large peak around June–August
263 and a small peak around December. Darling et al. (2006) reported an aberrant sinistral morphotype
264 of the dextral genotype in the North Atlantic. Although the distribution of genotypes is not known
265 for the western North Pacific, 1) the higher right-coiling ratio (42%) than at the boundary of the
266 North Atlantic (3%) and 2) a weak positive correlation ($r = 0.58$) between coiling types (Kuroyanagi,
267 2006) suggest that most individuals were probably dextral morphologically and genetically. Seasonal
268 flux patterns for both coiling patterns of *N. pachyderma* differed from those of other major species.
269 This finding supports the hypothesis that this species inhabits a different environment or that
270 different factors control its fluxes. In particular, the lack of a prominent peak in August for *N.*

271 *incompta* (both coiling directions) strongly suggests that it is distinct from *N. pachyderma*, at least in
272 the western North Pacific. This suggestion is supported by the different vertical distributions of these
273 species around the Japanese islands (Kuroyanagi and Kawahata, 2004).

274 *Globolotalia scitula* had a prominent peak in the stratified summer season. Sediment trap
275 results from Sta. B (Fig. 1) showed the maximum flux of this species in winter and early spring, with
276 a minimum in summer (Itou et al., 2001). The seasonality difference between the two neighboring
277 sites suggests that temperature and stratification are not major controlling factors because
278 hydrographic conditions at intermediate depth are uniform at this scale. A common feature of the two
279 sediment trap results is the rapid increase in *G. scitula* corresponding to a decline in particulate
280 organic matter (POM) (Fig. 3). The sinking particles during the low POM period consist of
281 disaggregated fine particles. Such particles have lower sinking speeds and are more likely to be
282 preyed upon by deep dwellers (Itou et al., 2001). Longer duration in surface productivity at Sta. B
283 probably delayed the increase in *G. scitula* until winter.

284

285 **5.2. Estimation of vital effect on shell $\delta^{18}\text{O}$**

286 The $\delta^{18}\text{O}$ of planktonic foraminiferal shells is often offset from the equilibrium value, the
287 so-called vital effect. The vital effect includes disequilibria induced by ontogeny, respiration (Spero
288 and Lea, 1996), photosynthesis of symbionts (Spero and Lea, 1993), calcification and growth rates,

289 and carbonate chemistry (Spero et al., 1997). Because the influence of these factors on shell $\delta^{18}\text{O}$
290 largely depends on species, the magnitude of the vital effect differs among species (Niebler et al.,
291 1999). In this study, the vital effects for four species were estimated by comparing measured $\delta^{18}\text{O}$ to
292 predicted values.

293 Expansion of the depth of the mixed layer in January–March resulted in homogeneous
294 predicted $\delta^{18}\text{O}$ values for the upper 75 m (Fig. 6). If foraminiferal shells are calcified in this
295 well-mixed water, the disequilibrium can be calculated as an offset of measured $\delta^{18}\text{O}$ from the
296 predicted value. However, the calculation using $\delta^{18}\text{O}$ values from January–March was problematic.
297 The measured $\delta^{18}\text{O}$ values in February–March were comparable to those in December for all species
298 (Fig. 6). This result did not follow the predicted $\delta^{18}\text{O}$ values, which showed a continuous increase
299 until March. The discrepancy implies that shell $\delta^{18}\text{O}$ did not reflect the surface condition during this
300 period. Such discrepancies were also observed in the sediment traps moored in the subarctic North
301 Pacific (Kuroyanagi et al., 2011), the western South Pacific (King and Howard, 2005), and the
302 western subpolar North Atlantic (Jonkers et al., 2010) during small foraminiferal flux periods.
303 Therefore, we attribute these lighter $\delta^{18}\text{O}$ values to survival of the early winter population without
304 additional calcification in cold water as suggested by Jonkers et al. (2010). We decided to use $\delta^{18}\text{O}$
305 values from December and January to calculate the vital effect for the following reasons. First, the
306 predicted $\delta^{18}\text{O}$ for the upper 45 m was relatively homogeneous (Fig. 6). Second, all species analyzed

307 here calcify at depths < 45 m, which was deduced from the large seasonal amplitude (>1‰) in shell
308 $\delta^{18}\text{O}$. An amplitude > 1‰ was seen only in predicted $\delta^{18}\text{O}$ values for the upper 45 m. The shallower
309 calcification depth is supported by the concordant timing of the minimum value between measured
310 and predicted $\delta^{18}\text{O}$ at shallower depths (Fig. 6). Third, all species showed maximum fluxes during
311 this period, indicating that the shells trapped during this period were certainly calcified at this time.
312 The average predicted $\delta^{18}\text{O}$ value for the upper 45 m in December and January was 1.2‰. The
313 offsets from this predicted value were 0.0‰ for *N. pachyderma* (s) and *G. bulloides*, -0.3‰ for *N.*
314 *pachyderma* (d), -0.7‰ for *N. dutertrei*, and -1.0‰ for *N. incompta* (d) (Table 1).

315 Previous estimates of the vital effect have not been consistent. For instance, the vital effect for
316 the most frequently reported species, *N. pachyderma* (s), has ranged from ± 0.0 to -1.3‰. Our result
317 is consistent with the estimation of Jonkers et al. (2010), which was obtained from a sediment trap
318 moored in the western North Atlantic. However, other studies reported negative offsets. Ortiz et al.
319 (1996) reported a -0.7‰ offset from California. Simstich et al. (2003) reported -0.9 and -1.0‰
320 offsets for encrusted and non-encrusted specimens, respectively, in the Nordic Seas. An offset of
321 -1.0‰ was also reported from the Arctic Ocean (Bauch et al., 1997), the Okhotsk Sea (Bauch et al.,
322 2002), the Southern Ocean (Mortyn and Charles, 2003), and the western Subarctic Gyre (Kuroyanagi
323 et al., 2011). A much larger offset of -1.3‰ was reported from the Arctic Ocean (Volkman and
324 Mensch, 2001). As discussed in Kuroyanagi et al. (2011), the $\delta^{18}\text{O}$ temperature scale for calculating

325 the predicted $\delta^{18}\text{O}$ is an important factor. In this study, as in Jonkers et al. (2010), the $\delta^{18}\text{O}$
326 temperature scale of Kim and O'Neil (1997) was used because its calibrated temperature range (10,
327 25, and 40°C) corresponds to the temperature of the upper layer at this site. In contrast, other
328 high-latitude studies used the scale of O'Neil et al. (1969), which is calibrated down to 0°C. These
329 scales have different values, especially in the low temperature range. When calculated using the
330 scale of O'Neil et al. (1969), the vital effect for *N. pachyderma* (s) was -0.4‰ .

331 Another possibility is a difference in morphotype and/or genotype. *Neogloboquadrina*
332 *incompta* has often been classified as the *N. pachyderma* dextral form. Darling et al. (2006)
333 suggested that the left- and right-coiling forms of *N. pachyderma* should be identified as *N.*
334 *pachyderma* and *N. incompta*, respectively. However, both of these species have coiling forms. For
335 our sediment trap samples, the sinistral and dextral forms of *N. pachyderma*, *N. incompta*, and *N.*
336 *dutertrei* were identified separately; the sinistral form accounted for 42%, 23%, and 23% of the
337 species, respectively. Comparing the $\delta^{18}\text{O}$ values for two species from identical sediment trap cups,
338 the values of *N. incompta* were ~ 0.7 and 0.6‰ lighter than those of *N. pachyderma* for sinistral ($n =$
339 3) and dextral ($n = 12$) forms, respectively. These results suggest that the two species have different
340 depth habitats and/or vital effects. If one identifies *N. pachyderma* and *N. incompta* only by coiling
341 direction, the relative abundance of the two species significantly affects mean isotope values. The
342 genetic difference may also influence shell $\delta^{18}\text{O}$ values. Bauch et al. (2003) reported two genotypes

343 for *N. pachyderma* (d) in the Nordic Sea, and their $\delta^{18}\text{O}$ values had a systematic offset that may have
344 been due to the vital effect. Although the genotype data for *N. pachyderma* in the western North
345 Pacific have not yet been reported, the genotype of *N. pachyderma* (d) in the eastern North Pacific is
346 distinct from that in the Atlantic (Darling et al., 2006). Therefore, differences in morphotype and/or
347 genotype between the basins are clear candidates for geographical divergence of the vital effect.

348 The vital effects for the other species are also influenced by other factors, as discussed above.
349 The values estimated in this study generally agree with those from the literature, as summarized in
350 Niebler et al. (1999), and we provide new data on *N. incompta* (d). Significant differences in the
351 vital effect between two morphospecies (right- and left-coiling) of *N. pachyderma*, as well as
352 between the right-coiling forms of *N. pachyderma* and *N. incompta*, suggest that $\delta^{18}\text{O}$ measurements
353 based on incorrect identification of these species may be a source of bias when estimating
354 paleoceanographic conditions.

355

356 **5.3. Estimation of calcification depths**

357 Calcification depths were estimated by comparing vital effect–corrected $\delta^{18}\text{O}$ values with
358 predicted $\delta^{18}\text{O}$ values (Fig. 6). *Globigerina bulloides* $\delta^{18}\text{O}$ tracked to 45 m in June–August and to
359 25–35 m in October–January, with deeper values in May (Fig. 6a). Similar variation was seen in *N.*
360 *pachyderma* (s) (Fig. 6d). The $\delta^{18}\text{O}$ values of *G. bulloides* and *N. pachyderma* (s) were positively

361 correlated ($r = 0.92$). Such seasonal $\delta^{18}\text{O}$ variations suggest changes in the calcification depth in
362 response to physical or biological conditions. The large $\delta^{18}\text{O}$ changes eliminate the possibility of
363 calcification at a specific temperature because this minimizes the amplitude of seasonal $\delta^{18}\text{O}$. Rather,
364 biological conditions such as food availability probably constrained calcification depth. The
365 chlorophyll maximum at PH-1 (41°30'N, 142°00'E), which is an observational station of the Japan
366 Meteorological Agency near the study site, was ~20–30 m from May–July 2002 and 50 m from
367 April–May 2003 (Fig. 3h) (Japan Meteorological Agency, 2002, 2003). The estimated calcification
368 depths of *G. bulloides* and *N. pachyderma* (s) fell immediately below the chlorophyll maximum
369 during high-chlorophyll periods. Such vertical distributions for these species were also reported
370 around the study site using depth-discrete plankton tow experiments (Kuroyanagi and Kawahata,
371 2004) and agree with the observation that the abundance of many foraminiferal species corresponds
372 to the deep chlorophyll maximum (Fairbanks and Wiebe, 1980).

373 The vital effect–corrected $\delta^{18}\text{O}$ values for *N. incompta* (d), *N. dutertrei* (d), and *N.*
374 *pachyderma* (d) indicate calcification at 25–35-m depths throughout the year (Fig. 6b, c, e). The
375 habitat depth of *N. dutertrei* is often observed in the mixed layer to thermocline depth (e.g.,
376 Fairbanks et al., 1982; Fairbanks et al., 1980). This is also the case at the study site, where the
377 thermocline developed from 15–45 m (Fig. 2). The plankton tow experiment conducted in May–June
378 2002 showed a shallower habitat depth for *N. incompta* than for *N. pachyderma* (Kuroyanagi and

379 Kawahata, 2004). This feature was also observed in our early summer results, but is not applicable
380 for all seasons.

381

382 **5.4. Paleoceanographic implications**

383 Our sediment trap experiment revealed significant seasonal variation in shell flux and $\delta^{18}\text{O}$ in
384 the western North Pacific. The uneven distribution of foraminiferal flux implies that
385 paleoceanographic records obtained from fossil foraminiferal $\delta^{18}\text{O}$ trend toward specific seasons.
386 Because the sedimentary $\delta^{18}\text{O}$ should reflect the weighted average of flux variation, flux-weighted
387 $\delta^{18}\text{O}$ values were calculated using equation (3) (Table 1). The flux-weighted value of 1.0‰ for *G.*
388 *bulloides* obviously reflects a large flux peak centered in December (Fig. 6a). If shells captured in
389 February and March are assumed to be survivors of early winter calcified tests, as discussed above,
390 the cumulative fluxes of the late autumn and early winter calcified shells exceeds 66% of the total
391 flux. The flux-weighted values (vital effect–corrected) for *N. dutertrei* (d) and *N. incompta* (d) were
392 1.1 and 1.2‰, respectively. These values also reflect larger fluxes centered in December, as for *G.*
393 *bulloides* (Fig. 6b, c). The cumulative fluxes from November to February reached 71% and 67‰ for
394 each species. Therefore, the sedimentary $\delta^{18}\text{O}$ values for three species, *G. bulloides*, *N. dutertrei* (d),
395 and *N. incompta* (d), record surface temperatures mainly in early winter with species-specific vital
396 effect offsets.

397 The case of *N. pachyderma* is more complicated owing to broad flux peaks. The
398 flux-weighted value for *N. pachyderma* (s) was 1.4‰. Measured $\delta^{18}\text{O}$ values for June–August and
399 December–March were around 1.4‰ (Fig. 6d). The cumulative fluxes of the former and latter
400 periods account for 58% and 28% of the total flux, respectively, indicating that the sedimentary $\delta^{18}\text{O}$
401 value of this species reflects surface temperature primarily in summer and secondarily in early winter.
402 The flux-weighted value for *N. pachyderma* (d) was 0.8‰. The prominent peak in August accounts
403 for 18.4% and the broad peak in October–January accounts for 63% of the total flux. The broad
404 distribution of shell flux suggests that the sedimentary $\delta^{18}\text{O}$ value indicates mean annual temperature
405 at 25–45 m.

406 The sedimentary $\Delta\delta^{18}\text{O}$ of foraminiferal species, according to differences in habitat depth or
407 season, is often used to deduce past ocean stratification conditions or seasonality. The estimated
408 calcification depths for the four species examined in this study ranged from 25 to 45 m (Table 1).
409 Small divergences in calcification depths suggest that the sedimentary $\Delta\delta^{18}\text{O}$ does not provide a
410 proxy for past stratification in this region, unlike other areas (e.g., Southern Ocean) where depth
411 habitat differences are large enough between species that stratification changes can be deduced
412 (Mortyn and Charles, 2003; Mortyn et al., 2002). The only candidate for a temperature recorder at
413 intermediate depth is *G. scitula*. Although the $\delta^{18}\text{O}$ for this species was not provided in this study
414 because of discontinuous occurrence during the sampling period, the examination of depth habitat

415 and shell chemistry by Itou et al. (2001) suggested *G. scitula* as an intermediate depth indicator. If
416 one combines the $\delta^{18}\text{O}$ values of *G. scitula* and *N. pachyderma* (s), which primarily reflect summer
417 subsurface and surface temperature, respectively, $\Delta\delta^{18}\text{O}$ may provide a proxy for summer
418 stratification. In contrast to the calcification depth, the seasonal flux differences among species are
419 observed. The difference in seasonal preference of *N. pachyderma* (s) from other species may
420 provide a seasonal contrast for surface to subsurface water in the western North Pacific. Namely, the
421 $\Delta\delta^{18}\text{O}$ between *N. pachyderma* (s) and other winter species [*G. bulloides*, *N. dutertrei* (d), and *N.*
422 *incompta* (d)] possibly records a contrast between summer and early winter. This study revealed that
423 the seasonal variation of foraminiferal flux was strongly affected by the regional oceanographic
424 variations. Therefore, added modern perspectives on a regional basis will help in more precise
425 paleoceanographic reconstructions.

426

427 **6. Summary**

428 In this study, we investigated the seasonal variation in foraminiferal flux and $\delta^{18}\text{O}$ using a
429 1-year data set from a moored sediment trap in the northwestern North Pacific. The TFF had three
430 distinct peaks centered in June, August, and December. Six major species (*N. incompta*, *N. dutertrei*,
431 *N. pachyderma*, *G. quinqueloba*, *G. bulloides*, and *G. scitula*) constituted 97% of the TFF. All species
432 except *G. scitula*, which had only one prominent peak in August, showed higher fluxes in June and

433 December. Additional peaks in August were observed for *N. dutertrei* and *N. pachyderma*. The
434 seasonal successions of foraminiferal fluxes correspond to surface ocean stratification and food
435 availability, which are closely related to local current circulation. Comparison of seasonal $\delta^{18}\text{O}$
436 variations in foraminiferal shells with predicted values, calculated using temperature and $\delta^{18}\text{O}$ of
437 seawater, revealed species-specific vital effects and calcification depths. The vital effect estimations
438 suggest that shells calcified in equilibrium for *G. bulloides* and *N. pachyderma* (s) and with a -0.7‰
439 offset for *N. dutertrei* (d), a -1.0‰ offset for *N. incompta* (d), and a -0.3‰ offset for *N. pachyderma*
440 (d). Differences in seasonal flux pattern and the vital effect between *N. pachyderma* (d) and *N.*
441 *incompta* (d) suggest that separation of these species only by coiling direction is a source of bias in
442 the estimation of paleoceanographic conditions in this region. The flux-weighted $\delta^{18}\text{O}$ values suggest
443 that sedimentary $\delta^{18}\text{O}$ in three species [*G. bulloides*, *N. dutertrei* (d), and *N. incompta* (d)] mainly
444 record temperatures in the surface layer in early winter, with species-specific vital effect offsets. The
445 sedimentary $\delta^{18}\text{O}$ values of *N. pachyderma* (s) and (d) record summer subsurface and mean annual
446 subsurface temperatures, respectively. The surface calcification of the four species implies the
447 potential to reconstruct past seasonality, in particular via $\Delta\delta^{18}\text{O}$ between *N. pachyderma* (s) and *G.*
448 *bulloides*, *N. dutertrei* (d) or *N. incompta* (d). The prominent peak in summer for *G. scitula* implies
449 that the $\delta^{18}\text{O}$ difference compared to the subsurface species *N. pachyderma* (s) may provide a proxy
450 for summer surface stratification.

451

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460

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596

597 Figure captions

598 Figure 1. Maps showing the study site and surface current systems in the western North Pacific. (a)

599 Major surface currents in the study region. The rectangle with broken line indicates the
600 area shown in the inset. (b) The locations of the sediment trap used in this study and
601 reference site Sta. B. Three rectangles are 1°×1° grids of NCEP GODAS used for the
602 predicted $\delta^{18}\text{O}$ calculation in Fig. 2 and Fig. 6. TWC: Tsushima Warm Current, TGC:
603 Tsugaru Warm Current.

604 Figure 2. Seasonal variation in temperature (a), salinity (b), potential density (c), and predicted

605 oxygen isotopic composition ($\delta^{18}\text{O}$) of equilibrium calcite (d) for the upper 200 m. The

606 temperature and salinity data are averages of three grids in Fig. 1 obtained from the

607 National Centers for Environmental Prediction Global Ocean Data Assimilation System

608 (Behringer and Xue, 2004). The predicted $\delta^{18}\text{O}$ values were calculated using the equation

609 of Kim and O'Neil (1997) (see text for details).

610 Figure 3. Flux variation in major components of sediment trap samples. Fluxes in (a) total mass, (b)

611 lithogenics, (c) biogenic opal, (d) organic matter, (e) carbonate, and (f) total foraminifera.

612 (g) Temperature variation to 200 m water depth during the mooring period (data from the
613 Global Ocean Data Assimilation System). (h) Variation in chlorophyll-*a* concentration for
614 the upper 100 m measured at station PH-1 (41°30'N, 142°00'E) on 27 April 2002, 19 July
615 2002, 5 October 2002, 2 December 2002, 8 February 2003, 2 May 2003, and 4 August
616 2003 by the Japan Meteorological Agency. Vertical white lines indicate observational dates
617 during the mooring period. The data are temporally interpolated to intervals of one week
618 with the surface tool in the Generic Mapping Tools. Data for (a)–(e) are from (Kawahata et
619 al., 2009). Sample cup numbers are shown in (a).

620 Figure 4. Flux variation in total foraminifera and the six major species. The two morphospecies of
621 *Neogloboquadrina pachyderma*, *N. incompta*, and *N. dutertrei* are shown in separate
622 panels. Dark and light colors represent shell sizes > 250 μm and 125–250 μm , respectively.

623 Figure 5. The results of $\delta^{18}\text{O}$ replicate analyses. Each data point consists of 4–13 specimens with
624 mostly less than 10 specimens. The $\delta^{18}\text{O}$ are normalized by subtracting average values for
625 the purpose of comparison. The standard deviations (1σ) are shown on the right side of
626 each data.

627 Figure 6. Seasonal variation in oxygen isotopes (dots) and shell flux (bars) for (a) *Globigerina*
628 *bulloides*, (b) *Neogloboquadrina incompta* (dextral), (c) *N. dutertrei* (dextral), (d) *N.*
629 *pachyderma* (sinistral), and (e) *N. pachyderma* (dextral) of small shell size (125–250 μm).

630 The vital effect–corrected oxygen isotopic composition ($\delta^{18}\text{O}$) values are also shown in (b),
631 (c), and (e). Lines show seasonal variation of the predicted $\delta^{18}\text{O}$ values for the upper ~300
632 m. Error bars in (d) and (e) show the standard deviation (1σ) of replicate analyses.
633
634

635

636 Table 1. The estimations of vital effect, depth habitat, and flux-weighted $\delta^{18}\text{O}$ value.

Species	Vital effect (‰)	Estimated depth habitat (m)	Flux-weighted $\delta^{18}\text{O}$ value (‰)
<i>G. bulloides</i>	0.0	~45 (Jun-Aug) 25-35 (Oct-Jan)	1.0
<i>N. dutertrei</i> (d)	-0.7	25-35	1.1*
<i>N. incompta</i> (d)	-1.0	25-35	1.2*
<i>N. pachyderma</i> (d)	-0.3	25-35	0.8*
<i>N. pachyderma</i> (s)	0.0	35-45 (Jun-Aug) ~35 (Oct-Jan)	1.4

637 * vital effect corrected (see section 5.4)

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639

Figure 1 Sagawa et al.

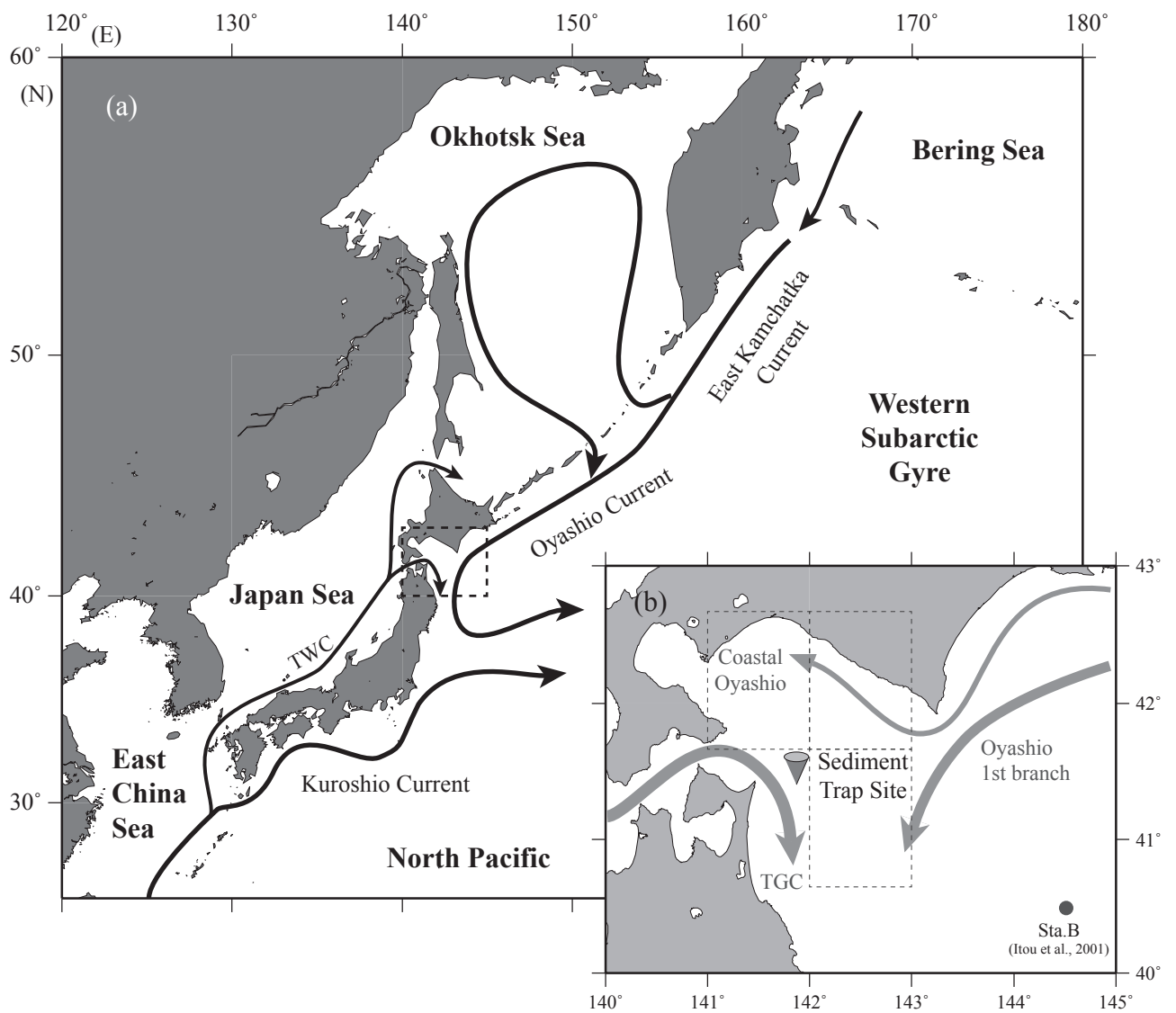


Figure 2 Sagawa et al.

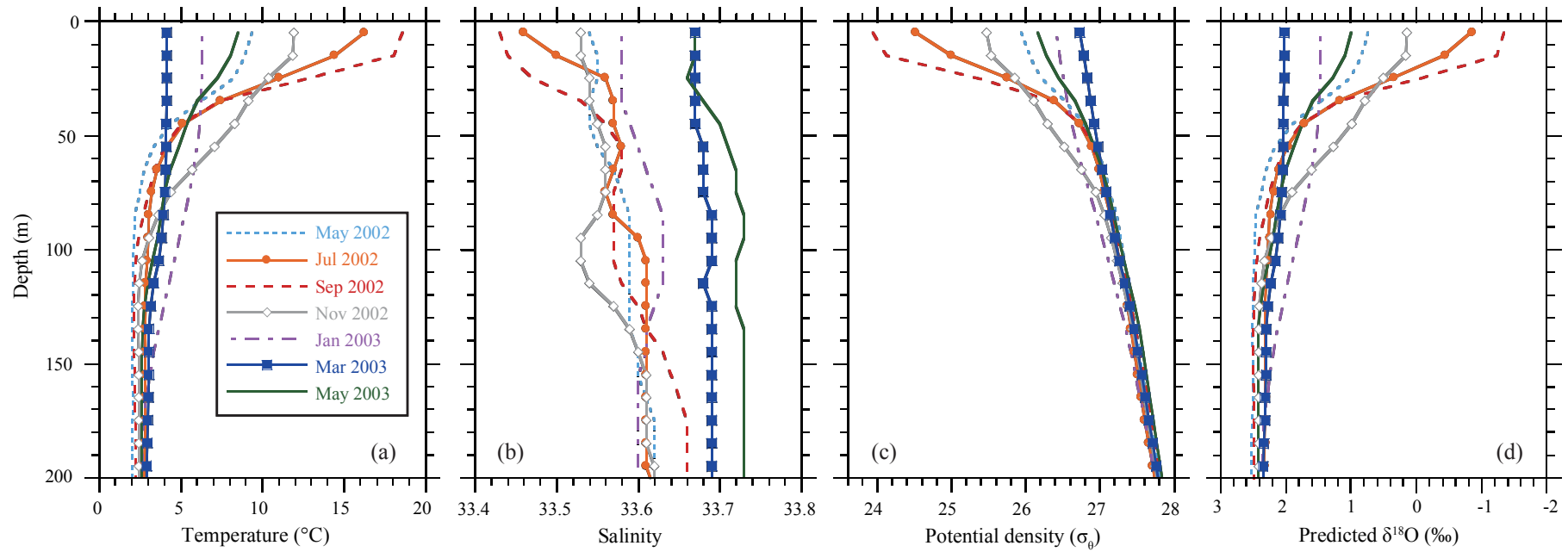


Figure 3 Sagawa et al.

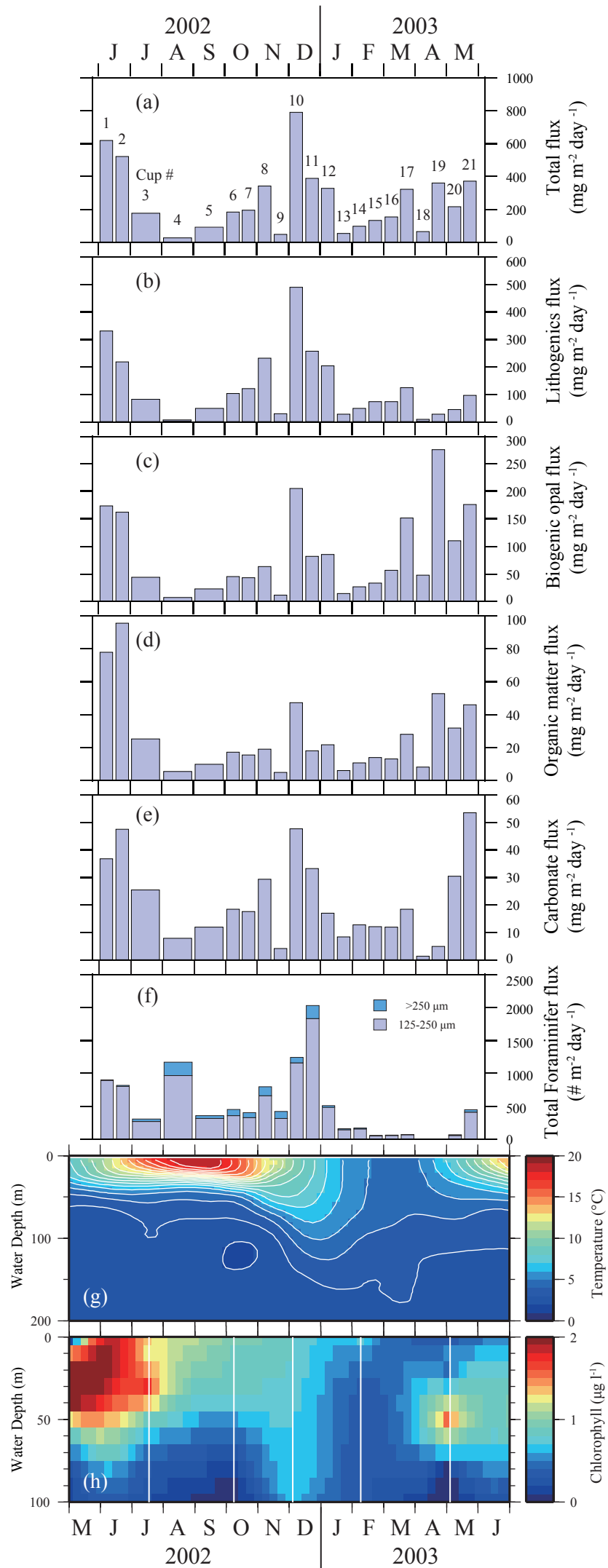


Figure 4 Sagawa et al.

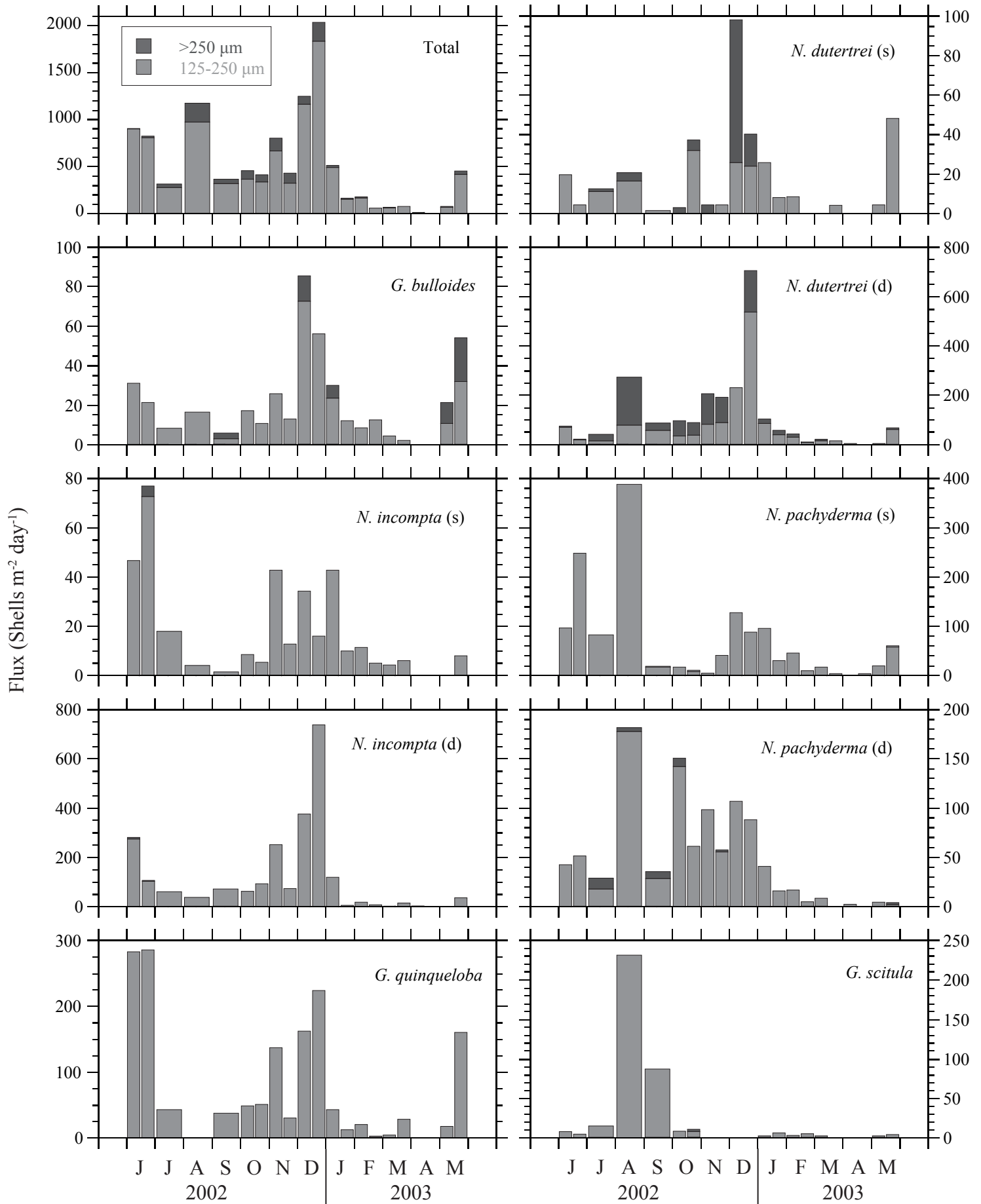


Figure 5 Sagawa et al.

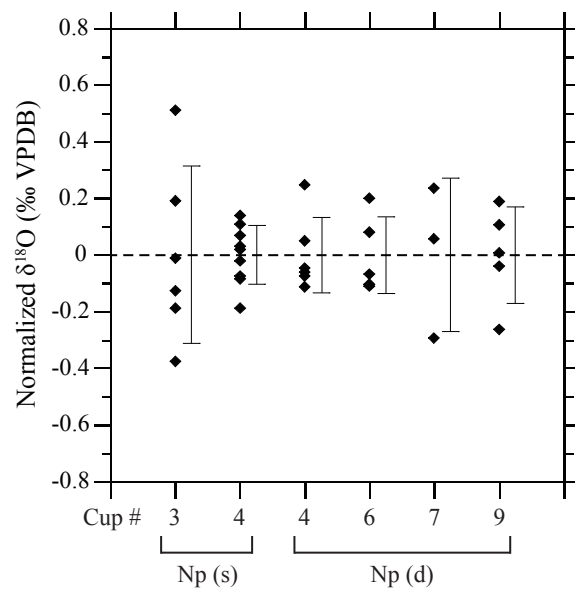


Figure 6 Sagawa et al.

