Shell fluxes of solution-resistant planktonic foraminifers as a proxy for mixed-layer depth

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[1] Shell fluxes of solution-resistant planktonic foraminifera, *G. scitula* and *N. dutertrei*, collected by moored sediment traps, are examined as a possible tool to reconstruct the surface water convection in the past subtropical western North Pacific. Time-series observation reveals that shell fluxes of these two species fluctuate in an opposite sense. When surface water is warmed and well stratified, *N. dutertrei* fluxes reach a maximum. In contrast, *G. scitula* increases in response to the deepening of the mixed-layer. To amplify the response of shell fluxes to climatological variables, the shell flux ratio of *G. scitula* to *N. dutertrei* ($F_{G.sci/N.dut}$) is introduced. The time series $F_{G.sci/N.dut}$ pattern is similar to that of the Monsoon Index (MOI) representing the strength of the East Asian Winter Monsoon. The $F_{G.sci/N.dut}$ is also well correlated with the mixed-layer depth. These correlations allow reconstruction of the ancient MOI and MLD from the faunal ratio. *INDEX TERMS:* 3344 Meteorology and Atmospheric Dynamics: Paleoclimatology; 4267 Oceanography: General: Paleoceanography; 3030 Marine Geology and Geophysics: Micropaleontology. **Citation:** Itou, M., and S. Noriki, Shell fluxes of solution-resistant planktonic foraminifers as a proxy for mixed-layer depth, *Geophys. Res. Lett.*, *29*(17), 1838, doi:10.1029/2002GL014693, 2002.

1. Introduction

[2] Sea surface physical water properties and water column structure are influenced by atmospheric conditions. Wintertime water cooling in the western North Pacific is thought to be predominantly controlled by the East Asian Winter Monsoon, that is, the cold outbreak from the Asian continent [e.g., *Hanawa et al.*, 1988]. This winter monsoon causes subsequent surface water cooling which is followed by the formation of dense surface water and a deep mixed-layer. *Suga and Hanawa* [1995] demonstrated the inverse relationship of the low sea surface temperature to the wintertime monsoon by using the Monsoon Index (MOI) which is defined as the difference in sea level pressure between Irkutsk and Nemuro (Figure 1). As a result of sea surface cooling and subsequent deep mixed-layer development, the North Pacific Subtropical Mode Water is formed [*Masuzawa*, 1969]. The winter mixed-layer deepens to 300−400m at the source area of the North Pacific Subtropical Mode Water from February to March [*Bingham*, 1992].

[3] Recent studies revealed that shell fluxes and abundance of some planktonic species may indirectly respond to mixed-layer development [*Itou et al.*, 2001; *Schiebel et al.*, 2001]. These studies noticed that shell abundance would be controlled by trophic conditions which are closely in conjunction with physical oceanic structures. The percentage of deep-dwelling species in deep-sea sediments is discussed with regard to mixed-layer depth or thermocline thickness [*Martinez*, 1997]. Statistical analysis and approaches dependent on the relative abundance of planktonic foraminifera in sediment cores may mislead when we estimate mixed-layer depths (MLD) because the preferential dissolution of solution-susceptive planktonic foraminifera would change faunal compositions in the North Pacific [*Watkins and Mix*, 1998]. Accordingly, another approach is needed to reconstruct the paleo-MLD in the North Pacific. Solution-resistant *N. dutertrei* is known as a thermocline dwelling species and as one of the important components of the "gyre-margin assemblage", which resides at the edge of the Kuroshio gyre [*Parker*, 1971]. Their habitat depth is closely related to deep chlorophyll maxima [*Fairbanks and Wiebe*, 1980], and their high abundance occurred in stratified water [*Ortiz et al.*, 1995]. In contrast, Globorotaliids are useful genus in reconstructing deep-convection [e.g., *Chen et al.*, 1999]. *Globorotalia scitula* dwells in subsurface and intermediate depths and is regarded as a useful proxy of deep-convection [*Ortiz et al.*, 1996]. To overcome the dissolution problem in reconstructing MLD, we examine these two solution-resistant species which were collected with sediment traps.

2. Methods

[4] Foraminiferal tests were collected by moored time-series sediment traps at Sta. B located at 40°30′N 144°30E in 1000+/−300 m water depth from October 1994 to May 1998 (Figure 1). Each mooring consisted of a cone-shaped type HX-10 sediment trap with 13 time-series cup collectors, which can be replaced at 14- to 35-day open/close intervals, and a baffled area of 0.196m^2. Each collector cup was filled with filtered sea water mixed with a buffered formalin solution. Each sample was wet sieved, then dried at 60°C. The size fraction larger than 210 μm was used in this study because of difficulty in identifying juvenile forms of both *G. scitula* and *N. dutertrei*.

[5] Periodical hydrographic observations near Sta. B were conducted by Japan Meteorological Agency (JMA). The CTD and chlorophyll data are available at bottle depths of 0m, 10m, 20m, 30m, 50−200m in 25m steps, 250m, and

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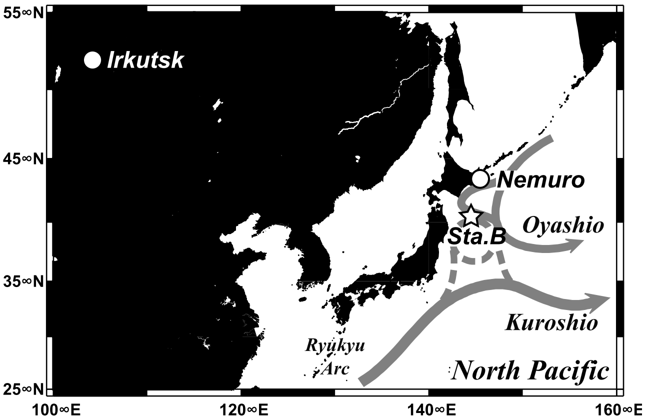

Figure 1. Location map of sediment trap mooring site, Sta. B.

300m–1000m in 100m steps. Mixed-layer depth (MLD) was estimated using the *Levitus* [1982] definition, i.e., the shallowest depth at which potential density is 0.125 higher than at the sea surface. The MLD was estimated from bottle data by interpolation. Since the water shallower than 10m was probably disturbed by the Research Vessel while water sampling, we do not consider a MLD shallower than 10m.

[6] Data on monthly averaged sea level pressure is provided by JMA [*Geophysical Review*, 1994–1998]. The MOI is calculated by subtracting sea level pressure of Nemuro from that of Irkutsk. This index is a significant index particularly in winter, and a high MOI indicates strong wind coming from the Asian continent.

3. Results and Discussion

3.1. Water Properties and Shell Flux Patterns

[7] The study site is located in the mixed water region where the Kuroshio and Oyashio meet. Saline Kuroshio-originated Water and less saline Oyashio Water are complexly mixed with each other. The Oyashio Water appears to have been predominant in spring and summer. The Kuroshio-originated Water was distributed at Sta. B primarily in winter. The physical property of this water was relatively uniform from surface to 50–470m due to intensive surface sea water cooling and subsequent water convection (Figure 2a). This uniformity was observed, more or less, in every winter. The MLD remarkably developed to more than 400m in February 1996.

[8] Concentration and depth distributions of chlorophyll *a* and phaeophytin (hereafter, we refer to these pigments as ''chlorophyll'') was associated with surface water structure. The transition of the chlorophyll distribution pattern is illustrated in Figure 2b.

[9] *Neogloboquadrina dutertrei* is the frequent species in subtropical-tropical faunas [*Bé and Tolderlund*, 1971]. Shell fluxes of *N. dutertrei* increased when the warm surface water prevailed at Sta. B (Figures 2a and 3a). *Neogloboquadrina dutertrei* shell fluxes particularly increased when the sea surface temperature exceeded 18°C. The peak flux maximum of *N. dutertrei* was observed in July 1996 when the highest temperature (>20°C) was recorded. This is consistent with the fact that peak abundance of *N. dutertrei* is found in a temperature range of 16–24°C [*Bé and Tolderlund*, 1971].

[10] The substantial increases of *N. dutertrei* fluxes seem to have been concurrent with surface water stratification (Figures 2a and 3a). When surface water was stratified, the deep chlorophyll maximum (DCM), which is defined as the chlorophyll concentration maximum at subsurface water, was almost simultaneously observed (Figures 2b and 3a). In contrast, very small numbers of *N. dutertrei* were observed when surface waters were completely mixed. *Ravelo et al.* [1990] revealed the peak distribution depth of *N. dutertrei* collected by MOCNESS tows corresponded to the DCM. Our time-series sediment trap results reconfirmed the interpretations derived from previous MOCNESS tow studies [e.g., *Ortiz et al.*, 1995]. Accordingly, the increase of *N. dutertrei* fluxes is considered to be associated with shoaling of the MLD.

[11] The shell flux pattern of *G. scitula* attained maxima during winter, apparently out of phase with that of *N. dutertrei* (Figure 4). *Globorotalia scitula* shell fluxes increased from October, and reached maxima between December and February. *Itou et al.* [2001] suggested that *G. scitula* fluxes increased in response to the enhanced downward transport of fine suspended organic matters due to surface water convection during winter. In winter 1995/96, the increment of *G. scitula* shell fluxes corresponding with the extreme deepening of the MLD is clearly documented (Figures 2a and 3b). *Globorotalia scitula* production seems to have been enhanced when a high chlorophyll concentration level of >1.0 g/L was documented at 100m water depth. Therefore, *G. scitula* increased in response to deepening of the mixed-layer though food availability is the primary factor determining production of this species as

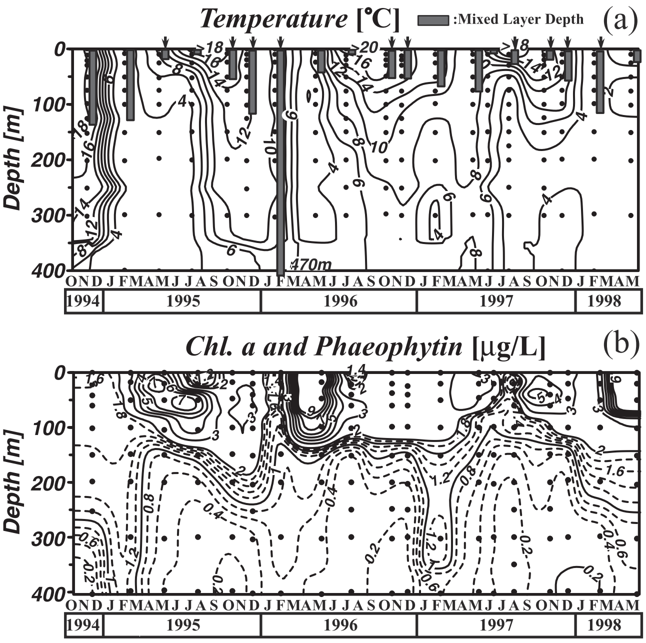

Figure 2. Temporal variations in (a) temperature, shaded bars indicate the mixed-layer depth, and (b) chlorophyll concentration at Sta. B. Mixed layer depths indicated by downward arrows in mid-panel are compared with foraminiferal flux ratio in Figure 5.

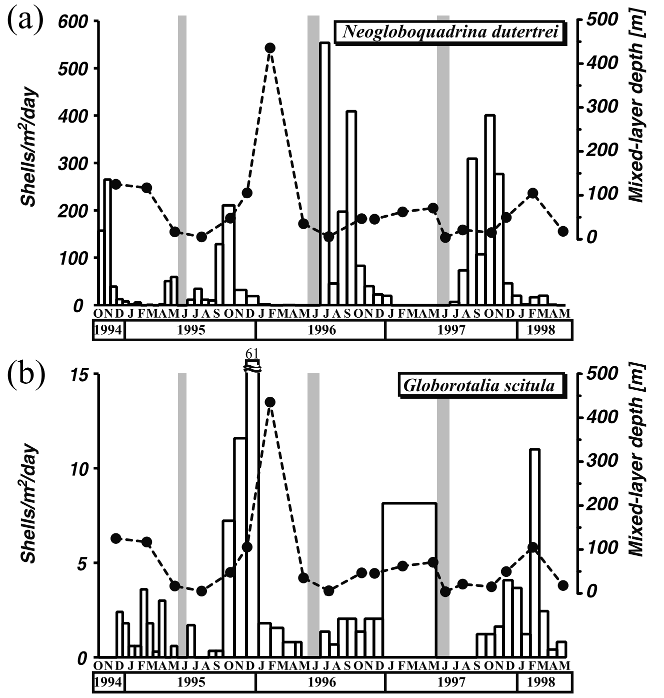

Figure 3. Shell flux patterns of (a) *N. dutertrei* and (b) *G. scitula*. The mixed-layer depths (m) are superimposed. Shaded areas indicate hiatuses.

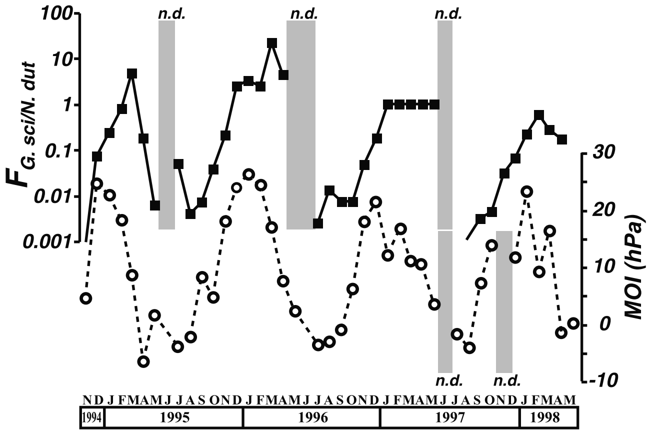

Figure 4. Monthly averaged flux ratio of *G. scitula* versus *N. dutertrei* on a logarithmic scale (upper panel). Time series of monthly mean monsoon index (MOI) [*Japan Meteorological Agency*], given as the difference in sea level pressure at Nemuro from that at Irkutsk (lower panel), given as the difference in sea level pressure at Nemuro from that at Irkutsk (Figure 1).

well as *N. dutertrei*. As illustrated in Figures 2a and 3b, *G. scitula* is produced mostly in winter while the surface water is well cooled and the mixed-layer deepens.

3.2. Shell flux ratio of *G. Scitula* to *N. Dutertrei*

[12] Here, we examine the relationship of the foraminiferal flux ratio to the monsoon index (MOI) which represents the strength of the East Asian Winter Monsoon [*Hanawa et al.*, 1989]. Positive MOI prevails for about 5 months during winter (Figure 4). The MOI maxima consistently appeared in December and January. A cold and strong westerly wind blows from the Asian continent when the MOI is high [*Hanawa et al.*, 1989]. The strongest MOI may be the cause for the extremely deep mixed-layer during the winter of 1995/96 (Figures 2a and 4). During winter of 1996/97 and 1997/98, the MOI was moderate.

[13] To assess the response of foraminiferal fluxes to climatological variables quantitatively, a new parameter, the shell flux ratio (denoted as $F_{G.sci/N.dut}$), is introduced. Since the monthly MOI mean is reported, the $F_{G.sci/N.dut}$ is converted to a monthly average for comparison. The $F_{G.sci/N.dut}$ clearly shows winter maxima, and these maxima seem to be delayed more than one month from MOI maxima (Figure 4). A correlation coefficient (r^2) between $F_{G.sci/N.dut}$ and MOI during the same month is 0.30. On the other hand, at one month, two month and three month lags, the corresponding values are 0.75, 0.68 and 0.35, respectively. In the subtropical North Pacific, the deepest mixed-layer is observed from January to March [*Suga and Hanawa*, 1990]. The westerlies in the mid-latitude North Pacific are strengthened between November and January [*Namias and Born*, 1974], the same as the MOI. The deepest mixed-layer seems to lag more than one month from the highest MOI (Figures 2a and 4). The oceanic mixed-layer responds to atmospheric forcing events on a timescale of days to months [*Wallace et al.*, 1990]. Using weekly data, *Deser and Timlin* [1997] estimated that the 2–3 week timescale may be a reflection of forcing by atmosphere on the ocean mixed-layer in the North Pacific. The required time for cooling of the sea surface water and the subsequent development of the mixed-layer by strengthened cold westerly winds may explain a substantial part of the one or two month lags of $F_{G.sci/N.dut}$ from the MOI. Also, planktonic foraminifers do not correspond to hydrographic changes immediately, but need a certain time to reproduce and to grow [e.g., Hemleben et al., 1989] to a size of >210μm, which is the size-class used in this study.

[14] It is essential to examine how the $F_{G.sci/N.dut}$ is related to the MLD. The examined species sometimes disappeared and did not always coexist, and in addition, since the water data was not frequently taken, not all the $F_{G.sci/N.dut}$ were compared with the MLD. Only ten $F_{G.sci/N.dut}$ data points have been compared with the MLD data.

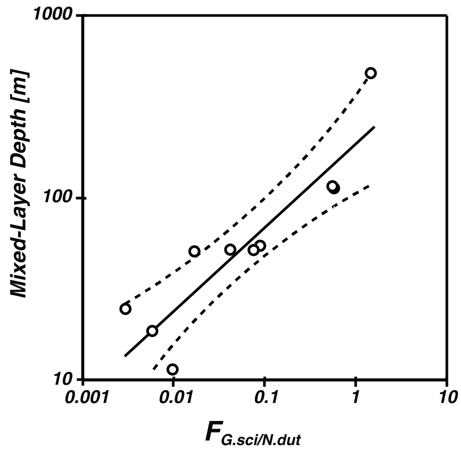

Figure 5. The relationship between mixed-layer depth and flux ratio of *G. scitula* to *N. dutertrei*. Dotted lines represent the 95% interval estimate for equation (1).

Despite small sample size, the $F_{G.sci/N.dut}$ is correlated to the MLD (Figure 5), and the MLD-$F_{G.sci/N.dut}$ relationship is described as follows:

$$\mathrm{MLD} = 194 \cdot \left(F_{G.sci/N.dut}\right)^{0.46}$$
$$r^2 = 0.82, n = 10, p < 0.01 \qquad (1)$$

This relationship implies the utility of the $F_{G.sci/N.dut}$ as a recorder of paleo-MLD within the examined depth range, i.e., from 11m to 470m.

[15] Assemblages of foraminifers in surface sediments display an average production possibly integrated over several years. Accordingly, the annual production of the two species has to be converted to the winter production before applying the equation (1) to sediment cores. Data obtained in the last three time deployments (June 1995 to May 1998) were examined to determine a factor which converts an annual flux ratio to that for winter. In this calculation, shell fluxes in June are estimated by averaging those of May and July. Substantial part of *G. scitula* (73.8%) occurred in winter (here, winter is defined from November to March). On the other hand, the percentage of *N. dutertrei* flux in winters was 14.1% of the annual production. By assuming that above percentage of winter production was constant in the geological time scale, the MLD during winter is determined by substituting conversion factor in equation (1). The conversion factor of 5.23 is calculated by dividing $(73.8/100)_{G.\ scitula}$ by $(14.1/100)_{N.\ dutertrei}$. This conversion, based on use of different seasonal production ratios of different species, can be valid because the summer water column structure contains a memory of the wintertime ocean-atmosphere interaction [*Suga and Hanawa*, 1995]. Then $F_{G.sci/N.dut}$ for winter is expressed as follows:

$$\mathrm{MLD_{winter}} = 194 \cdot \left(5.23 \cdot F_{G.sci/N.dut}\right)^{0.46} \qquad (2)$$

[16] To test the validity of equation (2), we applied it to core top sediments in the Rykyu Arc region, in the northwest Pacific. By substituting data presented by *Ujiie and Ujiie* [2000] to equation (2), winter MLD of 93 m in the Rykyu Arc region is estimated. The mean MLD observed at the Ryukyu Arc region in November, December, January, February and March are 72m, 105m, 101m, 85m and 78m, respectively (Hydrographic data are available from the Japan Oceanographic Data Center, Online Service System at http://www/jodc.go.jp/online_hydro.html). The good agreement of the calculated-MLD with the observed-MLD indicates equation (2) is applicable to the deep sea sediment.

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