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Distribution of Pelagic Blue-green Algae in the North Pacific Ocean*

Ryuzo MARUMO** and Osamu ASAOKA***

Abstract: The distribution of pelagic blue-green algae, especially of *Trichodesmium thiebautii*, was investigated on the basis of the collection of the *Hakuhō Maru* Cruise KH-69-4 along 155°W (50°N-15°S) in the North Pacific Ocean from September to November 1969.

(1) Five species were identified: *Trichodesmium thiebautii* (most predominant), *T. erythraeum*, *Oscillatoria* sp., *Katagnymene spiralis* and *Richelia intracellularis*.

(2) *T. thiebautii* was most abundant in the western North Pacific central water and abundant next to it in the equatorial water, but it did not occur in the subarctic water.

(3) *T. thiebautii* was ubiquitously distributed in the lower layer of 100-200 m in the equatorial water, though not in a large quantity.

(4) *T. thiebautii* inhabited only the water warmer than 20°C. In its main habitat, nitrate and nitrite were almost zero, but ammonia and phosphate were present. There was not found any correlation between its occurrence and the salinity.

(5) Blue-green algae were generally thinly populated in the water rich in diatoms.

1. Introduction

Trichodesmium red tide is a very striking phenomenon in the tropical and subtropical waters, and it has been reported by many authors (in the Pacific Ocean, MOSELY, 1892; MURRAY, 1895; YONGE, 1930; DELSMAN, 1939; MOHLER, 1941; KING, 1950; TSUJITA, 1956; SATO, PARANAGUÁ and ESKINAZI, 1963; WOOD, 1963; BOWMAN and LANCASTER, 1965). However, only a little is known on usual or non-blooming distributions (in the Pacific, AIKAWA, 1942; MARUMO, 1957; NAGASAWA and MARUMO, 1967), although *Trichodesmium* inhabits ubiquitously the tropical and subtropical waters in the Pacific Ocean almost throughout the year, constituting an important part of phytoplankton communities in the surface layer of these waters.

The investigation of productivity, metabolism and biogeography was carried out in the North Pacific and the equatorial area on board the *Hakuhō Maru*, Ocean Research Institute, University of Tokyo, during the period from September to November 1969 (MARUMO ed., 1970) (Figure 1). The present paper deals with the vertical and geographical distributions of pelagic blue-green algae, mainly of *Trichodesmium*, on the basis of the collections obtained in the water from 50°N to 15°S along 155°W and around 15°S during the said cruise, and gives discussions on their distribution and environments.

The authors express their hearty thanks for kind assistance and cooperation given by the scientists and crew members aboard the *Hakuhō Maru* on the Cruise KH-69-4.

2. Materials and methods

(1) Net samples

In order to investigate the geographical distribution of pelagic blue-green algae, 150-0-m vertical hauls were taken with Norpac net (45 cm in mouth diameter, 180 cm in filtering cloth length and 0.1 mm in mesh aperture) at 19 stations along 155°W (MARUMO ed., 1970) (Figure 1). Filament number of blue-green algae was counted and expressed for 1-m^2 water

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** Ocean Research Institute, University of Tokyo, Minamidai, Nakano-ku, Tokyo, 164 Japan

*** Meteorological Research Institute, Koenji-kita, Suginami-ku, Tokyo, 166 Japan

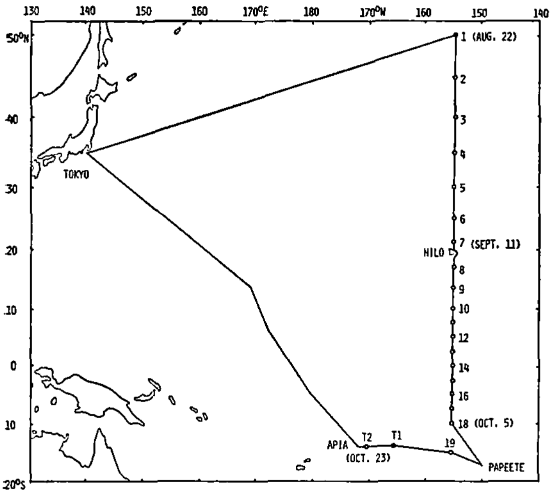

Fig. 1. Sampling stations.

column, and diatom cell number was also counted for comparison.

At Sts. 19, T1 and T2 in the equatorial water, samplings were also made from different subsurface layers shown in Table 1 with a closing type of Norpac net, in order to study the ecology of *Trichodesmium* inhabiting lower layers.

(2) Water samples

Five-hundred ml of sea water were obtained with Van Dorn samplers from the standard layers down to 200 m at 13 stations along 155°W and fixed by adding 10-ml neutralized formalin. The sample water was filtered through a Milipore filter HA (24 mm in diameter), and salts were removed by linsing with 1 % formalin distilled water. Thereafter, it was dried during more than 5 hours at room temperature. This filter paper was prepared into a permanent slide by using Cargille's immersion oil B.

Filament number of blue-green algae was counted and expressed per liter of sea water. Cell number is expressed more appropriately than filament number as the index of standing crop of phytoplankton, since a cell is the fundamental unit of organisms, but the cell counting of *Trichodesmium* was hardly practiced in the case of cell division.

3. Results

(1) Distribution of pelagic blue-green algae along 155°W

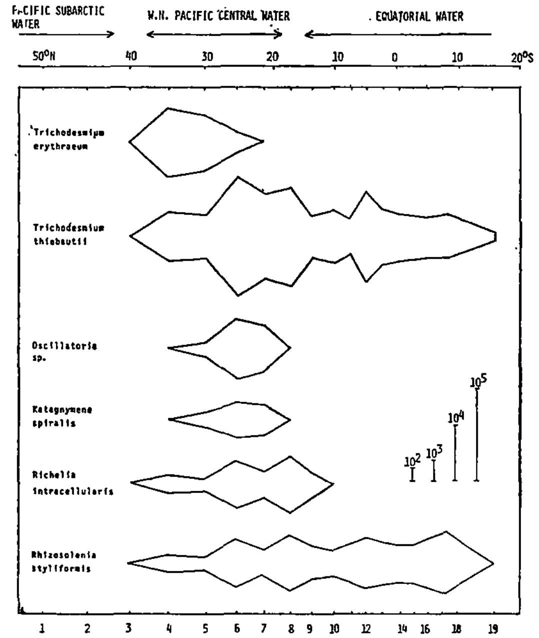

Fig. 2. Distribution of blue-green algae (filament/m^2) and *Rhizosolenia styliformis* (cell/m^2) from net samples along 155°W.

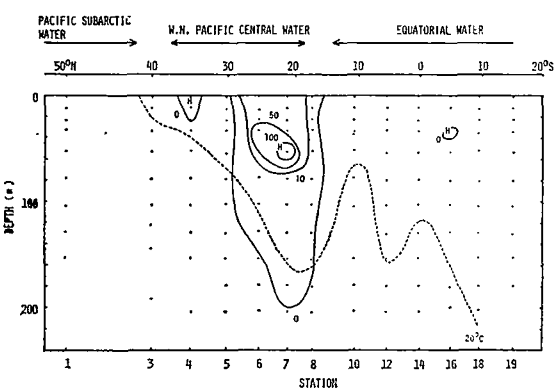

Fig. 3. Distribution of *Trichodesmium thiebautii* (filament/l) from water samples along 155°W.

(a) Net samples (Figure 2)

Species of blue-green algae identified are as follows:

Trichodesmium thiebautii GOMONT
Trichodesmium erythraeum EHRENBERG
Oscillatoria sp.
Katagnymene spiralis LEMMERMANN
Richelia intracellularis SCHMIDT

T. thiebautii was most abundant among blue-green algae, being mainly distributed in the western North Pacific central water, and not at all found in the Pacific subarctic water. *T. erythraeum*, *Oscillatoria* sp. and *K. spiralis* inhabited the western North Pacific central water, but not the Pacific subarctic water and the equatorial water, and the distributional patterns of these species were somewhat different each other. *R. intracellularis* was endophytic to all of *Rhizosolenia styliformis* cells collected at Sts. 4-9 in the western North Pacific central water and to a half number of cells of this diatom collected at St. 10, while this blue-green alga was never found in *Rhizosolenia* cells collected from the equatorial water in which this diatom was ubiquitously distributed. *R. intracellularis* was also endophytic to *Rhizosolenia acuminata* and *R. cylindrus* and epiphytic to *Chaetoceros compressus*. *R. intracellularis* was found in cells of *Rhizosolenia styliformis* (SMAYDA, 1966; WIMPENNY, 1966) and in *Rhizosolenia hebetata* f. *semispina* (MARGALEF, 1957).

(b) Water samples (Figure 3)

T. thiebautii appeared around Sts. 6 and 7, showing a distributional pattern almost similar with that obtained from net samples. The filament number was 10-50/l in the upper 30-m layer, and it reached to its maximum of about 100/l at about 50-m depth, and then decreased remarkably with depth. *Oscillatoria* sp. amounted to 6 filaments/l at 20-m depth and 2 filaments at 50-m depth of St. 6. *K. spiralis* was

Table 1. Colony number of *Trichodesmium thiebautii* GOMONT collected with Norpac closing net in the equatorial area.

Station	Location	Hauling layer (m)	Water volume filtered (m^3)	Total colony number collected	Colony/10 m^3
19	14°59′S	0- 75	12	0	0
	155°00′W	75-150	12	0	0
		150-240	14	4	2.9
		0- 50	8	0	0
T1	14°38′S	50-100	8	0	0
	165°29′W	100-200	16	1	0.6
		100-200(1)	160	10	0.6
		0- 80	13	0	0
		80-120	6	1	1.7
T2	14°00′S	80-160(1)	130	14	1.1
	170°15′W	120-160	6	1	1.7
		160-200	6	1	1.7
		150-250(2)	32	2	0.6

Hauling was repeated 10 times for (1) and 2 times for (2).

Table 2. Morphological comparison between specimens of *Trichodesmium thiebautii* GOMONT from the subsurface layer at St. 19 and those from the surface layer at St. T1.

		Specimens from subsurface layer	Specimens from surface layer
Colony	Shape	bundle or sphere	bundle
	Color	yellow-greyish	greenish, yellow-greyish
	Filament number	100, 140, 160	few (ca. 40)
	Filament length	1500 μ	2500 μ
	Constriction between cell	absent	rarely weakly present
Cell	Width	6 μ	9 μ
	Ratio of height to width	4-8 : 1	2 : 1
	Cell wall	very weak	not so weak

4 filament/l at 0-m depth of St. 6.

(2) *Trichodesmium* in the lower layer

The inhabitation of *Trichodesmium* in the lower layer was examined on the basis of collections obtained with Norpac closing net at Sts. 19, T1 and T2 around 15°S (Figure 1 and Table 1).

Trichodesmium colony occurred in 8 of 10 subsurface samples between 80- and 250-m depths (27°-19°C in temperature) at these stations. Such an occurrence means that this alga inhabited fairly ubiquitously the lower layers of the equatorial water, though the colony was not so numerous, 0.6-2.9 per 10 m^3 (Table 1). On the contrary, in vertical hauls in the upper layer at these stations there was not found any *Trichodesmium* colony large enough to be examined with naked eyes, although a fairly large number of *T. erythraeum* and a small number of *T. thiebautii* were collected by a horizontal tow with a long distance at 1 m below the surface at St. T1.

Referring to WILLE (1908), UMEZAKI (1961), NAGASAWA and MARUMO (1967) and SOURNIA (1968), these subsurface specimens were identified as *Trichodesmium thiebautii* according to the following morphological characters (Table 2 and Figure 4), but the cells of these specimens are remarkably elongated compared with those of the individuals usually inhabiting the surface layer.

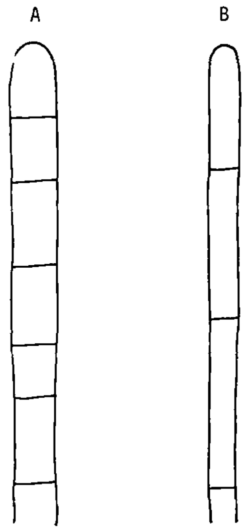

Fig. 4. *Trichodesmium thiebautii.*
A: specimen from the surface layer, 9 μ in width.
B: specimen from the subsurface layer, 6 μ in width.

Cell is about 6 μ in width, cell height being 4-8 times as large as width. Filament is 1,500 μ in length, and mostly not straight but slightly curved, appearing soft hairs. Cell wall is very weak and not constricted between cells. Colony is yellow-greyish. The shape of colony is various, from bundle to sphere. The central part of the colony is mostly cemented by mucous substances, but filaments are easily separated by fixing with formalin. A colony involves 100, 140 or 160 filaments. *T. thiebautii* filaments consisting of elongated cells with the width of 5 μ were found also in 125-m layer at St. 7.

4. Discussion

(1) Filament number of *Trichodesmium*

According to water samples collected along 155°W, *Trichodesmium* was generally very scarce, being absent in most stations and less than 10^2/l in filament number even at Sts. 6 and 7 with the highest population. In comparison with other results obtained by the same water sampling method, *Trichodesmium* inhabited more abundantly the waters which are not purely oceanic but tend to somewhat neritic characteristics by mixing with coastal waters. For example, the filament number of *T. thiebautii* was 10^2-10^3/l in the Kuroshio water around Okinawa in August 1966 (MARUMO and ASAOKA, unpublished) and in May 1971 (MARUMO ed., 1972), and 10^2-10^4/l in most stations of the Celebes, Sulu and South China Seas in May-June 1972 (MARUMO, unpublished).

The filament number in net samples collected along 155°W was also very few, about $10^5/m^2$ in the western North Pacific central water and much less, 10^3-$10^4/m^2$, in the equatorial water. The former value is in the same order as the concentration, $10^5/m^2$ obtained at the weather station T, 29°N, 135°E, in the Kuroshio water in summer (MARUMO, KITOU and ASAOKA, 1954), and it is much smaller than that, 10^6-$10^7/m^2$, in the eastern coastal water of Philippines in summer (NAGASAWA and MARUMO,

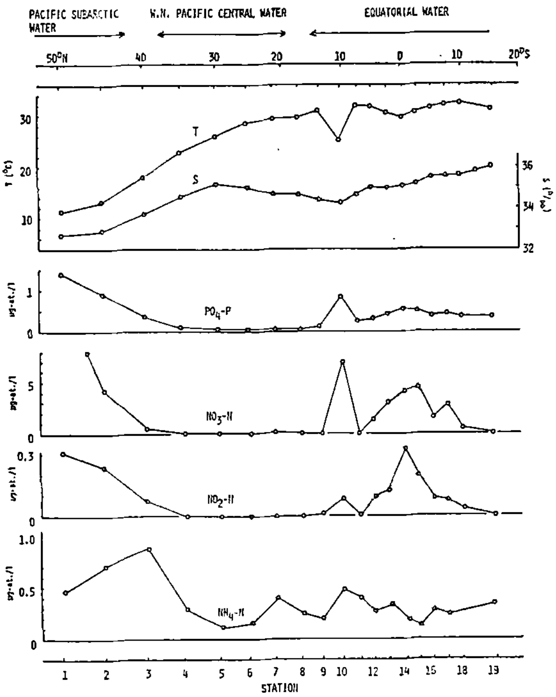

Fig. 5. Distributions of the mean values of temperature, salinity and nutrient salts in the upper 100-m layer along 155°W.

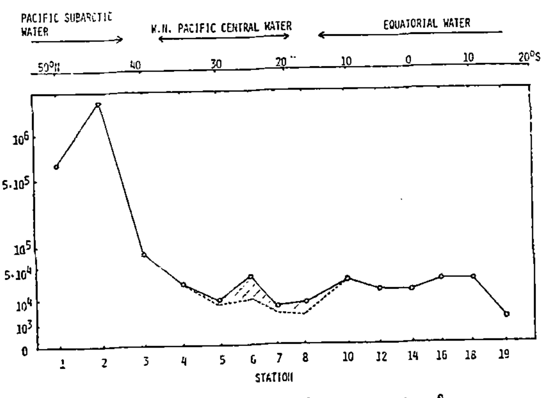

Fig. 6. Diatom cell number in 1-m^2 water column down to 150 m from net samples along 155°W. Shaded area shows cell number of *Hemiaulus hauckii*.

1967).

(2) Relation between *Trichodesmium* abundance and environmental factors

T. thiebautii abundance was remarkably different in respective water masses along 155°W. However, it is not possible to elucidate what kind of factors will leadingly control *Trichodesmium* distribution and abundance in these waters, though it may be generally considered that the important factors will be the propagation of *Trichodesmium* itself, the transportation by ocean current (FARRAN, 1932) and the mechanical accumulation by local water movements or waves in the surface layer especially on the occasion of red tide phenomenon (TSUJITA, 1956).

(a) Temperature

Water temperature seems to limit primarily *Trichodesmium* propagation. This alga appeared only in the western North Pacific central water with temperatures higher than 20°C as shown in Figure 3. It was never collected even by net sampling in the subarctic waters with temperatures below 20°C (Figures 2 and 5). The occurrence of *Trichodesmium* in the subsurface layer is also limited to the water of 20°C or slightly warmer (Table 1).

At the weather station T, 29°N, 135°E, in the Kuroshio water, *Trichodesmium* filament decreased in number, about one-tenth, in the water of about 20°C at 25 m from December to March, compared with that in the water warmer than 24°C at 25 m from June to October (MARUMO, KITOU and ASAOKA, 1954). In the Sargasso Sea, *Trichodesmium* occurred abundantly only during the summer and fall seasons when surface temperature was above 25°C (DUGDALE, MENZEL and RYTHER, 1961). Thus, the temperature below 20°C is generally unfavourable to the propagation or inhabitation of *Trichodesmium*, though an exception of *Trichodesmium rubescens* was reported in the cold water at latitude 57°S south of New Zealand by WOOD (1965).

(b) Salinity

The Pacific subarctic water where *Trichodesmium* was not found is very low in salinity as well as in temperature, but except for this water there is no correlation between *Trichodesmium* abundance and salinity in this investigation (Figure 5). SATO, PARANAGUÁ and ESKINAZI (1963) reported that *T. erythraeum* may multiply in the high-temperature and high-salinity conditions. By EHRENBERG (1830) and KING (1950) *Trichodesmium* favours coastal waters, except for brackish water. Thus, any conclusive discussion is not yet given as to salinity preference of *Trichodesmium*.

(c) Nutrients

Except for ammonia, nutrient salts such as nitrate, nitrite and phosphate were remarkably poor in the western North Pacific central water, nitrate being zero at Sts. 4, 5 and 11, and nitrite being zero at Sts. 4, 5, 6, 7, 8 and 11 (Figure 5). Thus, the high density of *Trichodesmium* well corresponds to poor nutrient salts. By DUGDALE, MENZEL and RYTHER (1961), a noticeably dense population of *T. thiebautii* appeared in the surface water of the Sargasso Sea during the period of nutrient impoverishment. GOERING, DUGDALE and MENZEL (1966) pointed out that nitrogen fixation by *Trichodesmium* seems to supplement inorganic nitrogen available for this algae, and it is generally accepted that this process occurs in association with nitrogen-fixing microbes in the sea. In this study, the occurrence of *Trichodesmium* in the western North Pacific central water, which is extremely poor in nitrate and nitrite but contains a certain quantity of ammonia, suggests that ammonia and molecular nitrogen will be its important source of inorganic nitrogen. As emphasized by GOERING, DUGDALE and MENZEL (1966), moreover, the importance of nitrogen fixation in the primary productivity lies in the fact that it means a new income of nitrogen into the marine ecosystem in the tropical and subtropical waters.

According to the observation on the uptake of inorganic phosphorus by *Trichodesmium* bloom, the content in the sea water was decreased from 0.4 μg atoms P/1 to nil (RAMAMURTHY and SESHADRI, 1966). In our study, inorganic phosphate was very poor, 0.03–0.07 μg atoms P/1 in the dense area of *Trichodesmium* population in the western North Pacific central water, but never nil.

(d) Chlorophyll *a*

The content of chlorophyll *a* was not especially high in the upper layer of the western North Pacific central water with the high density of *Trichodesmium* in the present cruise (TAKAHASHI, SATAKE and NAKAMOTO, 1972). This seems to indicate that such a small degree of *Trichodesmium* standing crop does not largely contribute to the total chlorophyll *a* content in the sea. The fairly high content of chlorophyll *a* at Sts. 6 and 7 may have resulted not from *Trichodesmium*, but mainly from remarkable abundance of diatoms such as *Hemiaulus hauckii*. However, *Trichodesmium* sometimes occupies the major part of total chlorophyll *a* in the surface water of the Sulu, Celebes and South China Seas (MARUMO, unpublished).

(3) Comparison of the distribution of *Trichodesmium* and diatoms

Three water masses were clearly characterized by diatom communities obtained by net sampling; the main components were *Chaetoceros atlanticus*, *Corethron criophilum* and *Thalassiothrix longissima* in the Pacific subarctic water, *Hemiaulus hauckii* in the western North Pacific central water and *Chaetoceros atlanticus* v. *neapolitana*, *Planktoniella sol*, *Rhizosolenia bergonii* and *Thalassiothrix delicatula* in the equatorial water. Diatom concentration was distributed in the manner just reverse to *Trichodesmium* density (Figure 6). Namely, diatoms were densest in the Pacific subarctic water, next to it in the equatorial water with upwellings around 10°N and the equator, and poor in the western North Pacific central water except St. 6. It is very noticeable that *Hemiaulus hauckii* generally inhabits the water poor in nutrients together with *Trichodesmium* not only in the present study but also in other observations taken by the authors in the Pacific.

(4) Geographical distribution of *Trichodesmium*

Trichodesmium distribution is considered to depend not only upon multiplication limited by environmental factors such as temperature, salinity, nutrients and other trace elements *in situ*, but also upon water movement such as transportation by a large-scale ocean current or mechanical accumulation by a small-scale surface current or wave, especially in the case of red tide phenomenon. Actually, the inhibitation of *Trichodesmium* in the sea will be formed as the result of combined processes of the multiplication of organisms themselves and the mechanical water movement.

According to AIKAWA (1942), Desmo-plankton mainly composed of *Trichodesmium* is distributed only in the western part of the Kuroshio area south of Japan in winter, and it extends its habitat eastwards and covers all areas of the Kuroshio south of Japan in summer. *Trichodesmium* is a useful indicator organism of the Kuroshio oceanic water, when it encounters the coastal water. According to FARRAN (1932), *T. thiebautii* is not an endemic inhabitant in the northern part of the Atlantic, but it visits very frequently the waters south of Ireland and to the mouth of the English Channel, and he is of opinion that this alga does not multiply in these cold waters.

(5) Vertical inhabitation of *Trichodesmium*

In the present study *Trichodesmium* specimens were often collected from subsurface layers of 100–200 m. These were alive and appeared yellow-greyish and the photosynthetic activity was rather high, according to Dr. Y. FUJITA, Ocean Research Institute (personal communication). *Trichodesmium* colony was found from 75-m depth in the tropical Atlantic (GOERING, DUGDALE and MENZEL, 1966). The large filament number of *T. thiebautii*, 987/1, was obtained from 100-m depth in the East China Sea (MARUMO and ASAOKA, unpublished).

Trichodesmium filament was collected from the surface skin water, although it seems to be not so active (MARUMO, TAGA and NAKAI, 1971).

T. erythraeum and *T. thiebautii* were attached to the surface of benthic organisms collected from the sea bottom with the depth of 25–30 m (FELDMANN, 1932). According to his opinion these algae are separated from the bottom when the sea is rough, and they float up to the surface to make red-tide phenomenon. MARUMO and KAMADA (1973) reported that there were found a large number of *T. thiebautii* and a small number of *T. erythraeum* attached to oil globules floating in the Kuroshio surface water near Taiwan.

Thus, the habitat of *Trichodesmium* is remarkably diverse; this alga is found in different depths from the surface skin layer down to about 200 m, though mostly in the layer upper than 50-m depth, and occasionally attached to benthic organisms and floating substances. Unfortunately, however, our present knowledge is too incomplete to discuss the meaning of their existence in different habitats from the viewpoint of their life history and ecology.

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北太平洋の浮遊性藍藻の分布

丸茂隆三，朝岡　治

要旨：白鳳丸 KH-69-4 次航海（1969年9～11月）で，北太平洋の 155°W（50°N-15°S）において，浮遊性藍藻，とくに *Trichodesmium thiebautii* の分布を調べた．

（1）次の5種の藍藻が出現した．*Trichodesmium thiebautii*（最も卓越），*T. erythraeum*, *Oscillatoria* sp., *Katagnymene spiralis*, *Richelia intracellularis*.

（2）*T. thiebautii* は西部北太平洋中央水で多く，赤道水でこれにつぎ，亜寒帯水には出現しなかった．

（3）*T. thiebautii* は赤道域の 100-200 m の下層に，量的には少ないが，普遍的に分布していた．

（4）*T. thiebautii* は 20°C 以上の水に生息していた．その主分布域では硝酸塩と亜硝酸塩はほとんどゼロであったが，アンモニア塩はかなり多く，リン酸塩はごく少量存在した．本種の出現と塩分とにはとくに相関関係は認められなかった．

（5）一般に藍藻現存量の大きい海域では，珪藻現存量は小さかった．