Glacial conditions in the northern Molucca Sea region (Indonesia)

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ABSTRACT

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Palynological, planktonic foraminiferal and stable isotope data from a sediment core in the northern Molucca Sea have been used to evaluate regional glacial climatic and hydrographic conditions. The palynological record shows that in glacial time the climate was drier than today, indicating a weakened influence of the northwesterly winds at that time.

The drier climatic conditions at glacial time were associated with a higher lapse rate, which, together with a lower sea level, resulted in a large expansion of the Lower Montane oak forests on the nearby island of Halmahera.

Glacial Molucca Sea surface water salinities were probably higher than today, while glacial surface water temperatures might have been close to present-day values. The Deep Chlorophyll Maximum (DCM) layer in the northern Molucca Sea at glacial time was more productive and cooler than today, probably the result of the inflow of cooler and nutrient-enriched Subtropical Lower Water from the Pacific.

The less asymmetrical high-latitude ice coverage at glacial time and the particularly strong increase in the pole to equator thermal gradient on the Northern Hemisphere, provides theoretical evidence that the Intertropical Convergence Zone (ITCZ) shifted equatorwards and oscillated over a more narrow latitudinal range than today. This inferred configuration of the ITCZ at glacial time, however, fails to explain the observed increased aridity in the study area at that time. We propose, therefore, that the drier glacial climatic conditions are related to a possible disturbance in the El Niño Southern Oscillation (ENSO) system.

Introduction

Present-day climatic conditions in the Indonesian archipelago are controlled by the monsoonal circulation which oscillates between southeast Asia and northern Australia.

The response of the monsoonal circulation to

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orbital forcing and glacial conditions is well known in the northern sector of the Indian Ocean (e.g. Van Campo et al., 1982; Fontugne and Duplessy, 1986; Prell and Kutzbach, 1987), but is poorly known in the southeastern sector. Palynological data from northern Australia point to glacial conditions that are distinctly drier than today (e.g. Kershaw, 1986; Van der Kaars, 1991), whereas data from the highlands on Sumatra (Stuijts, 1984), Java (Stuijts et al., 1988) and New Guinea (e.g. Hope, 1976; Walker and Flenley, 1979) suggest glacial temperatures that were lower than today without evidence of drier conditions. Climatic proxy data from marine sediments are restricted

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to the Sulu Basin and suggest increased rainfall at glacial time (Linsley et al., 1985). These few and scattered data provide an incomprehensive picture, and many more climatic proxy data are required to fully portray the response of the monsoonal circulation to glacial climatic conditions in the southeastern sector of the Indian Ocean.

In this paper we discuss the glacial monsoonal system in the eastern Indonesian archipelago at glacial time, by combining published data with a detailed climatic proxy record from the northern Molucca Sea. This proxy record is based on palynological, planktonic foraminiferal, and stable isotope data from a sediment core collected during the Snellius II-Expedition in April 1985 (Figs. 1 and 2).

Climatic and hydrographic setting

Present-day climate in the eastern Indonesian archipelago is controlled by the semi-annual reversal of the wind direction. The northwesterly winds in the northern winter originate in the Northern Hemisphere subtropical high-pressure belt and gather large amounts of moisture while crossing the sea on their way to the Intertropical Convergence Zone (ITCZ), which in the northern winter lies as far south as northern Australia. The moisture-laden air rises in the ITCZ and releases its moisture as rain. Rainfall in Indonesia and northern Australia, therefore, is highest in the northern winter. South of the ITCZ, precipitation decreases rapidly (e.g. Webster and Streten, 1978).

The southeasterly winds in the northern summer originate in the Southern Hemisphere highpressure belt and are relatively dry and cool when blowing over the eastern Indonesian archipelago. On arrival in the ITCZ, which passes over SE Asia in the northern summer, the air rises and sheds its moisture as rain. Highest rainfall in SE Asia, therefore, occurs in the northern summer.

The surface water circulation in the eastern Indonesian archipelago is strongly influenced by the semi-annual reversal in wind direction. There is a strong surface outflow into the Indian Ocean and South China Sea during the SE Monsoon (northern summer; Fig. 3A) causing large-scale upwelling in the eastern Banda Sea and western Arafura Sea (Wyrtki, 1961). Upwelling in this region was confirmed during the Snellius II-Expedition in August 1985 by Zijlstra et al. (1990) and Wetsteyn et al. (1990), who observed a shoaling of the isopycnals in the upper 100–150 m and a thinning of the mixed layer compared to the situation in February 1984. Concomitant primary production was twice as high as during the non-upwelling season (Gieskes et al., 1990).

During the NW Monsoon (northern winter; Fig. 3B), surface water flow in the archipelago is reversed with inflow from the South China Sea (Wyrtki, 1961).

A substantial additional inflow of Pacific surface water through the passage east of Halmahera during the SE Monsoon is suggested by Wyrtki (1958), whereas Schott (1935) and Tchernia (1980) show a strong surface outflow in the same region. Wyrtki (1961) discussed this discrepancy and concluded that the flow pattern of Schott (1935) would require upwelling in the Banda Sea over a much larger area than actually observed. Year-round, north-going surface waters from the Molucca Sea join the southern branch of the Mindanao cyclonic gyre and together they feed the main branch of the Mindanao Current, which forms the root of the Equatorial Counter Current (Fig. 3). The Mindanao gyre is a permanent feature but is intensified in the northeastern sector of the Molucca Sea during the SE Monsoon, when there is a stronger surface water outflow from the Molucca Sea into the Pacific.

Mixed layer waters in the northeastern sector of the Molucca Sea are warm and low-saline (Tchernia, 1980). Van Riel et al. (1957) report a temperature of 29°C and a salinity of 34‰ at Station 284 (May 1939), which is close to site K12. The yearaverage depth of the mixed layer in the region is 60 m (Wyrtki, 1961). The thermocline water is Subtropical Lower Water, which originates north and south of the subtropical convergences in the North and South Pacific, respectively, and is transported into the eastern Indonesian archipelago by the equatorial currents (Wyrtki, 1961). The core of this Subtropical Lower Water spreads throughout the archipelago at depths between 100 and 200 m. The phosphate gradient within this watermass is steep. The core of the Subtropical Lower Water in



Fig. 1. Map of the eastern Indonesian archipelago and location of core K12.

the northeastern Molucca Sea is located at about 150 m (Wyrtki, 1961) and has a salinity of 34.8% and a temperature of 18° C (Van Riel et al., 1957; Station 284).

Lowered salinities between 500 and 1000 m (Van Riel et al., 1957, Station 284) reveal the presence of intermediate water. This intermediate water has the properties of the North Pacific Intermediate Water which originates near the polar front (Wyrtki, 1961; Van Aken et al., 1988). Pacific Deep Water fills the Molucca Basin below about 1000 m and ventilates the various deep basins in the region; only the basins south of the Banda Sea are filled with deep water from the Indian Ocean. Thus, the eastern Indonesian archipelago (including the Molucca Basin) is filled primarily with



Fig. 2. Lithology of core K12 and position of samples and AMS radiocarbon dates. The oxygen isotope record is based on the planktonic foraminifer *Globigerinoides ruber*. Numbering of isotopic events is after SPECMAP (Pisias et al., 1984). Ages (in 1000 yr B.P.) for identified isotopic events are given in parentheses and are based on interpolation between radiocarbon dates.

water from the Pacific, mainly because sea level in the western Pacific is higher than in the northeast Indian Ocean (Wyrtki, 1961).

Material and methods

Core K12 was taken in the northeastern sector of the Molucca Basin, some 50 km north of the island of Halmahera $(02^{\circ}41'20''N-127^{\circ}44'10''E)$,

from a depth of 3510 m (Fig. 1). The Molucca Basin is connected to the Pacific via a 2000 m deep sill between the island of Morotai and the Philippines, and with the Sulawesi Basin via a 270 m deep sill between Sulawesi and the Philippines. An 1880 m deep sill west of the island of Obi separates the Molucca Basin from the Banda Basin.

Core K12 recovered 533 cm of greenish clays with some intervening turbiditic layers of detritical



Fig. 3. Surface water transport through the Indonesian archipelago in August (3A) and February (3B) after Wyrtki, 1961. NEC = North Equatorial Current; ECC = Equatorial Courter Current; SEC = South Equatorial Current; MC = Mindanao Current.

sand and silt (Fig. 2). Carbonate values are low and vary between 8 and 11%. Biogenic components consist of foraminifers, radiolarians and diatoms. Foraminifers are well-preserved, indicating that the lysocline lies below 3510 m, which accords with the reported lysocline depth of 4100 m in the adjacent West Pacific (Berger et al., 1976) and of 3800 m in the nearby Sulu Basin (Linsley et al., 1985).

Fifty-two samples were taken at 10 cm intervals from core K12 avoiding turbiditic layers. A survey of all samples indicated that 28 samples were sufficiently rich in pollen and spores to perform a meaningful quantitative analysis. This analysis included the counting (per subsample of 2 cc) of more than 100 pollen grains and associated spores from slides that were counted completely. Samples were prepared following standard techniques (hydrochloric acid 20%, warm sodium phosphate 20%, sodium phosphate 10%, heavy liquid separation using a bromoform–alcohol mixture with a density of 2.0), and stained with safranin. *Lycopodium* marker spores were added to establish the pollen concentration of the sediment. Slides were mounted with glycerol-jelly and the cover slips were sealed with paraffin.

Planktonic foraminifers were counted in all samples. Counts are based on splits of 200-500 specimens from the larger than 150 μ m fraction using an Otto microsplitter. All specimens were hand-picked, mounted on microslides and identified.

Forty-seven samples were used for oxygen and carbon isotope analyses. About 30 specimens of the planktonic foraminiferal species *Globigerinoides ruber* per sample were ultrasonically cleaned to remove adhering particles and roasted under vacuum at 350°C for two hours. The CO₂ was extracted by reacting foraminiferal carbonate in 100% orthophosphoric acid at 50°C. The CO₂ samples, obtained after two on line distillation steps to purify the CO₂, were analysed in a V.G. Sira 9 triple collector mass spectrometer. The results are listed in Table 1. The analytical precision for δ^{18} O and δ^{13} C values are ± 0.01 and ± 0.06 , respectively.

TABLE 1

Stable isotope data from core K12

Sample	Depth	Age	δ ¹⁸ 0	δ ¹³ C
number	(cm)	(years)	G.ruber	G.ruber
•	 	45/		
1	2.75	154		
2	17.75	430	-2.02	0.96
5	27 75	902 157/	-2.30	1 20
4 F	21.13	1004	-2.24	1.20
5	31.13	2000	-2.30	1 30
7	44.75	3008	-2.33	1.62
8	77.75	4294	-1.90	1.46
9	87.75	4846	-2.52	1.12
10	97.75	5398	-1.33	1.74
11	106.75	5895		
12	117.75	6502	-2.71	1.13
13	127.75	7054	-2.90	0.94
14	137.75	7606	-2.61	1.36
15	147.75	8158	-2.59	0.79
16	157.75	8710	-2.69	0.85
17	167.75	9175	-2.45	0.64
18	177.75	9640	-2.06	0.80
19	206.75	10990	-1.51	0.99
20	216.75	11516	-1.51	0.89
21	226.75	12042	-1.51	1.10
22	236.75	12568	-1.13	1.25
23	246.75	13094	-1.14	1.01
24	251.75	13357	-0.66	1.34
25	266.75	14146	-0.80	0.92
26	276.75	14672	-1.31	0.65
27	286.75	15198	-0.52	1.20
28	296.75	15724	-1.27	0.83
29	306.75	16250	-0.82	0.84
30	316.75	16776	-0.40	1.07
31	326.75	17302	-0.81	1.07
32	334.50	17710	-0.89	1.01
33	336.00	17789	-0.66	1.12
34	346.75	18354	-0.97	1.05
35	356.75	18880	-0.49	0.98
36	366.75	19406		
37	376.75	19932	-1.10	0.99
38	385.75	20420		4 70
39	395.75	20933	-1.38	1.38
40	405.25	21420	-0.48	1.55
41	415.25	21933	-0.84	1.52
42	423.23	22440	-1 17	1 01
43	433.23	22939	-1.06	1 17
44 15	443.63	23412	- 1.00	1.15
45	465 25	23903 24498	-1.16	1.02
47	475.25	25011	-0.72	1.29
48	485.25	25524	-1.16	1.23
49	495.75	26063	-0.52	1.03
50	505.75	26576	-1.22	1.06
51	515.75	27100	-1.32	1.05
52	528.25	27741	-1.29	1.05

Chronology of core K12

The chronology of core K12 is primarily based on oxygen isotope stratigraphy. The oxygen isotope stratigraphy, which relies on correlation with radiocarbon-dated or orbitally-tuned oxygen isotope profiles, is based on the assumption that ice volume is the dominant factor controlling changes in foraminiferal δ^{18} O values and that the ice volume signal is globally synchronous within the mixing time of the oceans (ca. 1000 years). Salinity effects, however, may locally modify the shape of the profiles.

The dominant feature in the oxygen isotope profile of core K12 (Fig. 2) is the large upward decrease in δ^{18} O values between 250 and 150 cm which corresponds to the last deglaciation. The Younger Dryas cold event between 11 and 10 kyr (Fairbanks, 1989), which has been identified near the study area by Linsley and Thunell (1990), is not recorded in core K12 due to insufficient resolution over this interval of time (Fig. 2). This insufficient resolution is caused by a turbiditic layer, which was avoided during sampling. The classical two step deglaciation signal in δ^{18} O profiles, therefore, merges into one single step between 250 and 150 cm.

Four AMS radiocarbon dates on monospecific samples of *Globorotalia menardii-tumida* (Table 2) were used to refine the chronology of core K12. Calculated accumulation rates between these AMS radiocarbon dates are extremely uniform varying between 19 and 21.5 cm/kyr. These accumulation rates have been used to estimate ages for individual samples (Table 1). Sample ages for the upper part of the core were estimated, assuming that the top of the core has an age of zero.

The refined chronology based on AMS radiocarbon dates furthermore assisted in numbering various isotopic events after SPECMAP (Pisias et al., 1984; Martinson et al., 1987).

Palynological results

The palynological results are summarized in Fig. 4. This figure shows a cumulative abundance plot of 5 vegetational groups together with individual abundance plots of the *Lithocarpus-Casta*-

nopsis group, Mangroves, Palmae, and fern spores. Also shown is the pollen concentration (= total number of pollen per cc). The composition of the 5 vegetational groups and the scores of individual taxa are given in Table 3.

Since core K12 lies only 50 km north of Halmahera and the wind and surface currents facilitate pollen transport from Halmahera to the core location, it seems likely to assume that the majority of the pollen grains found in core K12 is derived from Halmahera itself. The low scores of long-distance transported *Nothofagus brassii* and *Eucalyptus* type pollen grains (Table 3) support this assumption, because these taxa are not present on Halmahera (Van Steenis and Van Balgooy, 1966; Walter and Straka, 1970).

The cumulative abundance plot of the 5 vegetational groups shows a change in dominance between the Lower Montane forest group and the Tropical (coastal) Lowland group at about 270 cm which level has an interpolated age of 14 kyr B.P. (Fig. 4). The dominance of the Lower Montane forest elements compared to the Tropical (coastal) rainforest elements before 14 kyr B.P. and the reversed conditions thereafter, indicate that the Tropical rainforests on Halmahera were largely replaced by Lower Montane oak forests at glacial time. This suggests that the average boundary between both vegetational zones, which presently lies at 650 m, was significantly lower at glacial time.

The low-lying average boundary between the Lower Montane oak forests and Tropical (coastal) rainforests on Halmahera at glacial time suggests cooler glacial climatic conditions at high altitudes. Cooler glacial conditions at high altitudes, however, do not explain the strongly reduced percentages of fern spores in the glacial section of core K12 (Fig. 4). According to Van Waveren (1989) fern spores are abundant in surface sediment samples but almost absent in air samples from this region indicating that fern spores are largely transported by rivers and ocean currents. The strongly reduced percentages of fern spores in the glacial section of core K12, therefore, suggest a reduction in either the fern cover or the runoff on Halmahera. Both options, however, would indicate drier climatic conditions on Halmahera at glacial time.

At first sight, drier glacial conditions seem to be

TABLE 2

AMS	radiocarbon	dates fro	om core	K12	(uncorrected	for	reservoir	age)
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Sample ^a	code ^b	Depth ^c	δ ^{13d}	Age ^e
name	no	cm	0/00	yr BP
K12P1-5;57-58.5	UtC-1205	157.75	0.10	8710 (120)
K12P1-4;7-8.5	UtC-1204	206.75	0.80	10990 (160)
K12P1-3;86-87.5	UtC-1209	385.75	1.26	20420 (160)
K12P1-1;19-20.5	UtC-1210	515.75	1.32	27100 (400)

^a Sample identification; material is calcite.

^b Code number of Van de Graaff Laboratorium, Rijksuniversiteit Utrecht, The Netherlands.

^c Depth below sea-floor.

^d δ^{13} -values measured at Earth Sciences Department, Rijksuniversiteit, Utrecht. ^e Age in years before present (BP) determined from measured ¹⁴C activity by means

of AMS.



Fig. 4. Pollen diagram for core K12 showing percentages of the various vegetational groups and parts of its selected elements. Fern species are calculated as percentage of total pollen count.

•		'																											
SAMPLE TAXA	-		, ,	_		0	5	-	9	۹ ~	20	22	23	25	27	29	31	34	36	38	40	42	4	4	48	8	52	VEGETATIONAL GROUPS	r
Podocar pus Dacrycar pus Dacrydium Phyllocladus	5 5 7 7 J		0 11 7 11	404v		- + - ~	0 1	4 -	3 - 0 - 0 - 0 - 0 - 0 - 0 - 0 - 0 - 0 -	0 4 10	9 15	3 30	25 6 6	8 - 0 - 13	12 5 4	9 ° ° °		7 0 0 0	= = - •	4 ~ 4 4	• - = =	80 80 m 77	o + 2 2	9 2 2 3		s 2 4 1		Upper-Mid Montane	1
Lithocar pus-Castanopsis Araucaria-Agathis	- 4	<u>a 1</u>		E 2		18 2		3	5 1 2	د : د :	3	3	18	31	32	64 4		78 5	84	4 4	34	45 2	38	61	21	6 42	5 30	Lower Montane	T
Palmae Eugenia Rubiaceae	- 0 22	800	8 - 0	5-0	200	0 6 0	4	8 - 0	0	9 T	∞ ⊂ ⊂	2 F 0	• • •	e 4 0	~ ~ ~ ~	- • •	- ~ 0	- 0 0	- 0 -	0 0 0	400	- ~ -	500	4-0	0 0 7	e - 0	0		T
Sapindaceae-Sapotaceae Urticaceae-Moraceae Ilex	4 ~ 0	0 7 0	0 10 10		~ ~ ~ ~	- 7 4		• • •	- 19 0	~ - O	m - 0	s - 0	~	0 2 -	0 1 0	007		0	0 7 0	0 7 -	- 0 0	- 0 0	~ o o	- 0 0	m o o	0 77 -			
Engelhardtia Terminalia Fuchechia	0 0 m		000	·	~ ·	-0*			004	0 ~ ~	0 - 4	- 0 -	- 0 ^	000	o o -	-07	- • -		• • -	o o -	- 0 0		00~	o o -	<i>.</i>	0 0 V	000		
Macaranga-Mallotus Austroburus-Diseiliaria	~ ~ c	· ~ -	. ~ 0	4 -		. o		~ · ·		- o -	Ξ ο	~ 0	4 0	0	4 -	~ ~ 0	- 0	5 0	0	- 0		4 0	- 0	. n -				Tropical (coastal) Lowland	
Excoecaria	00				0.				0 1	- ~	00			• • •	0 -	0 -			00		• • •	• • •	0 0						
Ericaceae		. o -							••-			• • •	• • •			c			• • -) - c		- c					c		
Proteaceae	· • ·				, ,							• - •	000	000	000				• • •										
Gunnera Pandanus	- 0 :	ə m -								000	v - c	00-			000	- • -	- o c		- 0 ^										······
Olea Balidaceae-Gryrostemonaceae	- -	- 0			-				••	• •	00	- 0	00	00	• •	- 0	- 0	0 0	10		- 0	00	- 0	- 0		- 0			
Barringtonia Brownlowia Rhizophoraceae Sonneratia	-0	- 0 6 7	0	- 12 0 0	000 0	0 10	0.0 1 0	5 10 0	- 2 0 - 1	2 2	0000	0 0 0 0	~ ~ 0 0	0 0 ~ -	0000	0000	0000	0 7 0 0	0000	0 7 0 0	0 0 ⁰ 0	00	0000	0040	0040	0000	0 - 4 0	Mangrove	1
Casuaria Cyperaceae Gramineae Compositae		4 - ~ -	m − 4 0	- 4 5 2	4 - 6 -	0 0 0 0			L 1 4 0	0-00		4 1 1 0	0 - 1 - 0	~ - % O	4 - 4 0	9 4 0 0	0 ~ ~ ~	4010	0 m m 0	- ~ ~ ~	0	e - 20		0 1 0 2	r es -	* ~ - O	4040	Grassiand - Woodland	Т
Eucalyptus Nothofagus brassii		- 0	- ~	0 0		- -			- 0	0 m	5 0	- ~	5 0		00	- ~			- 0	00	0 7	00	• •	00	0 2	0	0	Long-distance transport	
Other Angiosperms Pteridophyta	11 1761	14 951	11 1501	12 1612	11 1225	19 1 1142 1	147	10 1	859 1	220 11	3 14	6 69	10	13 11 746	12 542	16 709	13 343	14 205	16 371	8 481	9 612	8 587	11 662	12 1512	10 1055	10 1046	9 897		

Numbers of pollen taxa and fern spores per pollen count in 28 samples from core K12. Samples a and b are additional samples not belonging to the regular set of samples

TABLE 3

in conflict with the expansion of Lower Montane oak forests on Halmahera at glacial time, since the main components of these forests, Lithocarpus and Castanopsis, require a humid climate. Soepadmo (1972), however, reports on a number of exceptions. For instance Castanopsis buruana, which grows on the Moluccas, locally survives in SW Ceram in secondary forests during the long dry period in the northern summer, while Lithocarpus sundaicus occurs on some mountain summits and slopes in central and east Java under drier than average conditions. These examples suggest that the expansion of the Lower Montane oak forest to lower altitude on Halmahera at glacial time may have resulted from high-altitude cooling under overall drier climatic conditions.

Middle to Upper Montane forests are less tolerant to drier conditions since typical representatives flourish only under very humid conditions (Walter, 1985). Any potential expansion of the Middle to Upper Montane forests on Halmahera at glacial time due to high-altitude cooling, therefore, may have been supressed by increased aridity, resulting even in a slight reduction of the Middle to Upper Montane forest elements in the glacial section of core K12 (Fig. 4).

The reduction of the Lower Montane forest elements following the last glacial maximum and the concomitant increase in Tropical (coastal) Lowland elements, and fern spores suggest the return to higher temperatures at high altitudes and wetter climatic conditions. The sudden increase in the Mangrove group at 10 kyr B.P. (190 cm) is coincident with a second phase of rapid sea level rise, associated with meltwater pulse IA of Fairbanks (1989). This second phase of rapid sea level rise possibly resulted in the final drowning of the shelf area and the formation of tidal flats which allowed the rapid expansion of mangrove forests along the shoreline of Halmahera. Mangrove forests were present before 10 kyr B.P. but on a much smaller scale, possibly as fringe vegetation along the shoreline of the exposed shelf area.

The increase in palm pollen grains at 5 kyr B.P. (80 cm) coincides with the onset of a slow-down in the post-glacial sea level rise (Fairbanks, 1989), which may have resulted in the establishment of a

stable palm vegetation, either as beach vegetation or in the backswamps behind mangrove forests.

Pollen numbers per cc are elevated in the glacial section of core K12 with a distinct peak between 350 and 330 cm (Fig. 4), which corresponds to the Last Glacial Maximum (LGM) at about 18 kyr B.P. Pollen flux rates (not shown) reveal a similar pattern with more than 300 pollen cm^{-2} yr⁻¹ during the LGM and less than 100 pollen cm^{-2} yr^{-1} before and thereafter. We believe that such a great difference cannot exclusively be the result of variations in pollen production. We do, however, acknowledge that there was a limited increase in the area of vegetated exposed shelves in response to sea level lowering at glacial time. More importantly, pollen flux rates in marine sediments generally decrease exponentially with increasing distance from the shore (Short et al., 1989). The high pollen numbers and flux rates during the LGM, therefore, may well reflect the low sea level at that time, which reduced the distance of the northern shoreline of Halmahera to the core site by some 40%. At present this distance amounts to about 50 km. Pollen numbers and flux rates decreased rapidly after the Last Glacial Maximum, when sea level began to rise and the distance to shore increased.

Thus, it appears that core K12 reveals a fairly detailed record of vegetational change on Halmahera during the past 27,000 years with major changes being controlled by changes in high-altitude temperature, precipitation and sea level. Average glacial climatic conditions were drier and cooler at higher altitudes than those of today. Lower mean annual temperatures are also reported from the highlands on Java (Stuijts, 1984), New Guinea (Hope, 1976; Walker and Flenley, 1979), and Sumatra (Maloney, 1981; Newsome and Flenley, 1988; Stuijts et al., 1988), but in contrast to Halmahera, there is no clear palynological evidence of drier climatic conditions in these regions.

Planktonic foraminiferal results

The planktonic foraminiferal fauna from core K12 is diverse and characteristic of low-latitude oceanic regions with a well-developed Deep Chlorophyll Maximum (DCM) layer (Fairbanks et al.,

1980; Ravelo et al., 1990). The percentages of individual species are given in Table 4, while the abundances of species showing systematic changes are plotted in Fig. 5.

The fauna in the glacial section (below 270 cm) is characterized by elevated percentages of *Neogloboquadrina dutertrei* (Plate I, 1–6) and dextrally coiled *Neogloboquadrina pachyderma* (Plate I, 7–14) together with reduced percentages of *Globigerinoides ruber*, *Globigerinoides sacculifer* and *Globigerinella equilateralis*. Reversed faunal conditions exist above 270 cm. The 270 cm level, which has an interpolated age of 14 kyr B.P., thus, marks a level of major change in the planktonic foraminiferal record from the northern Molucca Sea.

Neogloboquadrina dutertrei feeds exclusively on phytoplankton (Hemleben et al., 1989), which, in the tropical ocean, is highly abundant in permanent Deep Chlorophyll Maximum (DCM) layers. High abundances of Neogloboquadrina dutertrei are, therefore, associated with a DCM layer (Fairbanks et al., 1980; Ravelo et al., 1990), which develops when the thermocline lies above or near the light compensation depth. The DCM layer may be a seasonal or a permanent feature, which is fueled with new nutrients by cross-isopycnal or along-isopycnal mixing (e.g. Hayward, 1987). The continuous presence of substantial numbers of Neogloboquadrina dutertrei in core K12 indicates that the upper part of the thermocline in the northern Molucca Sea resided consistently above the light compensation depth, either seasonally or permanently, during the past 27,000 years. The substantial numbers of dextrally coiled Neogloboquadrina pachyderma in the glacial section of core K12 is remarkable at these low latitudes. Dextrally coiled Neogloboquadrina pachyderma is a cool-water morphotype of Neogloboquadrina dutertrei (Arikawa, 1983), which, just as Neogloboquadrina dutertrei, feeds exclusively on phytoplankton (Hemleben et al., 1989). Probably these cool-water morphotypes also exploited the food sources associated with the DCM layer, which implies that glacial temperatures at the base of the euphotic layer were lower than today. The higher average numbers of Neogloboquadrina dutertrei and Neogloboquadrina pachyderma in the glacial section of core K12 furthermore suggest an increased phytoplankton production in the DCM layer at glacial time.

Higher numbers of *Neogloboquadrina dutertrei* and dextrally coiled *Neogloboquadrina pachyderma* are also reported from glacial sediments in the Sulu Sea by Linsley et al. (1985), who explained the higher glacial abundances of *Neogloboquadrina dutertrei* by lowered glacial surface water salinities. Their conclusion is based on the wide-spread assumption that *Neogloboquadrina dutertrei* is a low-salinity indicator. This assumption, however, is no longer tenable since it has been wellestablished that highest abundances of *Neogloboquadrina dutertrei* occur in the subsurface thermocline where phytoplankton productivity is at a maximum (Fairbanks et al., 1980; Ravelo et al., 1990).

The elevated percentages of *Neogloboquadrina* dutertrei and dextrally coiled *Neogloboquadrina* pachyderma in glacial sediments from the northern Molucca Sea and Sulu Sea, thus, indicates that the DCM layer in these regions was more productive and experienced lower temperatures at glacial time than today. Simultaneously, cross-isopycnal mixing and associated eutrophication of the mixed layer might have reduced the oligotrophic mixed layer species.

The source of dextrally coiled *Neogloboquadrina* pachyderma types is somewhat puzzling. Expatriated individuals may have been imported from the Pacific by the equatorial currents, whereafter they found a suitable habitat in the DCM layer in the northern Molucca Sea and Sulu Sea at glacial time. An alternative explanation is that part of the in situ population of *Neogloboquadrina dutertrei* changed into *Neogloboquadrina pachyderma* when the temperature of the thermocline water decreased at glacial time. Such an in situ change in morphology is conceivable since *Neogloboquadrina pachyderma* belong to one biogeographic cline (Arikawa, 1983).

Glacial surface water temperature and salinity in the northern Molucca Sea

The results of the oxygen isotope analyses of the surface dwelling planktonic foraminifer *Globi*gerinoides ruber are plotted versus time in Fig. 6, Percentages of planktonic foraminiferal taxa per split in µg samples. Samples 11, 36 and 42 are deleted because of possible sorting effects

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PLATE I



Age (¹⁴C years) x 1000

Fig. 6. δ^{18} O record for *Globigerinoides ruber* from the northern Molucca Sea (dashed) and the Sulu Sea (solid) plotted versus time. The Sulu Sea record is from ODP Site 769A (Linsley and Thunell, 1990).

using the ages for individual samples of Table 1. Added to Fig. 6 is the oxygen isotope record for *Globigerinoides ruber* in ODP Site 769A from the Sulu Sea (Linsley and Thunell, 1990).

The difference in δ^{18} O values between the Holocene and the last glacial maximum in the Sulu Sea nearly equals the ice volume effect of 1.25‰ for the last glacial-interglacial transition, which is based on a glacio-eustatic sea level fall of 120 m (Fairbanks, 1989) and a 0.011% change in δ^{18} O per 1 m sea level change (Fairbanks and Matthews, 1978). This implies that glacial surface water temperatures and salinities in the Sulu Sea were not demonstrably different from modern values. The glacial-interglacial δ^{18} O change in the northern Molucca Sea, on the other hand, exceeds the ice volume effect. For the last glacial maximum (around 18 kyr B.P.) northern Molucca Sea δ^{18} O values are enriched by about 0.8‰, compared to those from the Sulu Sea. Consequently, surface waters in the northern Molucca Sea during the last glacial maximum must have been either 3°C cooler (using the paleotemperature equation of Shackleton, 1967), or 1.5-1.9‰ saltier (using the δ^{18} O vs S relation for the modern eastern equatorial Pacific of Craig and Gordon, 1965), or some combination of the two.

Which of the two parameters, temperature or salinity, was the main contributor is difficult to ascertain, but there is some evidence that the $\delta^{18}O$ enrichment in the northern Molucca Sea during the last glacial maximum reflects primarily a surface water salinity change. Modern salinity values in the northern Molucca Sea are low (34‰, Wyrtki, 1961) because of the large excess of rainfall over evaporation. Glacial climatic conditions in the northern Molucca Sea region, however, were drier as concluded earlier in this paper from a substantial reduction in fern spores in the glacial section of core K12. Palynological evidence from northern Australia also points to drier glacial conditions (Kershaw, 1986; Van der Kaars, 1991), suggesting that the entire eastern Indonesian archipelago experienced a drier climate at glacial time than that at present. Drier glacial conditions must have resulted in a decrease in the excess of precipitation over evaporation, producing glacial surface water salinities that were higher than at present in the northern Molucca Sea. Glacial-interglacial surface water temperature differences of no more than

PLATE I

^{1-6.} Neogloboquadrina dutertrei (D'Orbigny). Core K12, sample 6, 44-46 cm.

^{7-14.} Neogloboquadrina pachyderma (Ehrenberg). Core K12, sample 47, 474-476 cm.

1°C, inferred for the region by CLIMAP (1981) and Moore et al. (1980), also suggest that the excess δ^{18} O enrichment in the northern Molucca Sea of 0.8‰ during the last glacial maximum is primarily salinity driven.

Thus, it appears that the δ^{18} O enrichment in the northern Molucca Sea at glacial time primarily resulted from higher surface water salinities due to a reduced excess of precipitation over evaporation at glacial time. Glacial surface water temperatures on the other hand were probably close to modern values.

Lapse rate and altitude of the Lower Montane forests on Halmahera at glacial time

The calculated present-day change of air temperature with height (lapse rate) in the eastern Indonesian archipelago of 0.6°C per 100 m, is based on an air temperature at mean sea level of 28°C (Terada and Hanzawa, 1984) and a position of the snowline in New Guinea of 4600 m (Bowler et al., 1976). The lapse rate during the last glacial maximum could be calculated in a similar way provided we would know the air temperature at mean sea level and the position of the snowline in New Guinea during the last glacial maximum. A reliable estimate of the glacial lapse rate will reveal whether or not the glacial-interglacial change in altitude of the Lower Montane oak forest on Halmahera is sufficient to explain the substantial increase of Lower Montane forest elements in the glacial section of core K12.

Present-day differences between sea surface water temperatures and air temperatures at mean sea level are negligible in the eastern Indonesian archipelago (Terada and Hanzawa, 1984). This would imply that the sea surface water temperature during the last glacial maximum is a good approximation of the air temperature at mean sea level at that time. Present-day annual mean surface water temperature and air temperature at mean sea level are close to 28°C (Terada and Hanzawa, 1984). Since sea surface water temperatures during the last glacial maximum were probably close to modern values, air temperatures at mean sea level at that time were probably close to 28°C as well. With a full glacial snowline in New Guinea being 1000–1500 m lower than at present (Loffler, 1972; Bowler et al., 1976), the glacial lapse rate must have been somewhere between 0.75 and 0.87° C per 100 m during the last glacial maximum.

A higher lapse rate at glacial time is very likely, since the combined effect of globally lower average atmospheric temperatures and regionally drier climatic conditions must have resulted in a lower moisture content of the air, and thus in a reduced heat-capacity.

The average boundary between the Lower Montane forests and Tropical (coastal) rainforests is at present at an elevation of 650 m, but must have been substantially lower at glacial time when the Lower Montane oak forests appear to have dominated the vegetation on Halmahera. This boundary reached its lowest position during the last glacial maximum when the Lower Montane forests on Halmahera had their maximum expansion. Figure 7 compares the present-day position of the boundary between the Lower Montane oak forests and the Tropical (coastal) rainforests on Halmahera with that calculated for the last glacial maximum, using a glacial lapse rate of 0.8°C/100 m and air temperature at mean sea level of 28°C. This figure shows a lowering of the floral boundary from 650 m above present-day sea level to 500 m above glacial sea level, which implies a downward shift by 270 m. Such a shift would be sufficient to explain the substantial expansion of the Lower Montane forests on Halmahera at glacial time.

Discussion

The present study shows evidence of increased aridity in the northern Molucca Sea at glacial time. Also the Banda Sea region (Van der Kaars, 1991) and northeast Australia (Kershaw, 1986) experienced drier glacial climatic conditions. Java and Sumatra, on the other hand, lack clear palynological evidence of drier glacial climatic conditions (Stuijts, 1984; Stuijts et al., 1988) and the same seems to hold true for the Sulu Sea where glacial/interglacial surface water salinities remained unaltered (Linsley and Thunell, 1990). Thus, it seems that glacial aridity was primarily restricted to the eastern Indonesian archipelago and northern Australia. The causative mechanism of this must be



Fig. 7. Present-day and glacial position of the average boundary between Lower Montane forests and Tropical (coastal) rainforests on Halmahera. The lowering of the floral boundary from 650 m above present-day sea level to 500 m above glacial sea level implies a downward shift by 270 m.

somehow related to weakened influence of the wet northwesterly winds, which at present bring substantial rainfall in the region.

Modern earth is in a more or less unipolar mode of glaciation since more than 90% of all ice is stored on the Southern Hemisphere, at and around Antarctica. Glacial/interglacial differences in ice cover at and around Antarctica are negligible, but are enormous on the Northern Hemisphere (CLIMAP, 1981). Substantial ice growth on the Northern Hemisphere at glacial time resulted in a more symmetrical ice cover on both hemispheres than today. The degree of asymmetry in the cryosphere determines the dislocation of the average position of the ITCZ with respect to the geographic equator. The large degree of asymmetry in the present-day ice cover forces the present-day ITCZ to an average position of about 10°N of the geographic equator. Expansion of ice at glacial time steepened pole to equator thermal gradients, especially on the Northern Hemisphere. This would drive the ITCZ southward, to a position close to the geographic equator. Such a southward shift (by some 10° lat.) is also suggested by the results of a simulation study by Lautenschlager and Herterich (1989) of the ice age climate. Also, the latitudinal range covered by the present-day atmospheric Hadley cell could have decreased at glacial time. Latitudinal narrowing of the Hadley cell would have restricted the yearly oscillation to a more narrow latitudinal range than today and intensified the subtropical high-pressure belts and the associated trade winds. Intensification of the subtropical high-pressure belts and increased trade wind activity is suggested by Manabe and Hahn (1977) and Flohn (1981), but is not evident from the ice-age climate reconstruction of Lautenschlager and Herterich (1989).

The present-day yearly oscillation of the ITCZ in Australasia is larger than anywhere else in the world. This large N-S amplitude results from the build-up of strong low pressure cells over southeast Asia and northern Australia in summer and illustrates the high sensitivity of this region to differential heating. Massive growth of Northern Hemisphere ice and the permanent ice cover on the Tibetan plateau (Singh and Agrawal, 1976), preventing substantial heating during the glacial summer, would have resulted in a particularly large equatorward shift in the average position of the ITCZ in the northern glacial summer. This would imply that the northernmost reach of the ITCZ (northern summer) would be considerably closer to the geographic equator than at present, whereas the southernmost position of the ITCZ (northern winter) would be roughly comparable to that of today. The inferred position and yearly oscillation of the ITCZ at glacial time, however, would fail to explain the observed increased aridity in the eastern Indonesian archipelago, which suggests the interference of a hitherto unnoticed mechanism. We tentatively propose that this mechanism is related to a possible disturbance in the El Niño Southern Oscillation (ENSO) system, since it is known that this system causes periodical failure of the wet NW Monsoon in the eastern Indonesian archipelago (e.g. Rasmussen and Wallace, 1983). The CLIMAP (1981) reconstruction of a cooler glacial eastern Pacific does not seem to endorse the inferred ENSO-explanation for our observations. Note, however, that the CLIMAP (1981) results for the eastern Pacific are based on a limited number of data-points, and we suggest that further study is required to determine whether, and to what extent, the ENSO system was influenced by glaciation.

The record of *Neogloboquadrina dutertrei* in core K12 points to the consistent presence of a seasonal or year-round Deep Chlorophyll Maximum (DCM) layer in the northern Molucca Sea during the past 27,000 years. Augmented numbers of *Neogloboquadrina dutertrei* and the presence of dextrally coiled *Neogloboquadrina pachyderma* in the glacial section of core K12 suggest increased production and lower temperatures in the DCM

layer of the northern Molucca Sea at glacial time. Similar conditions seem to have prevailed in the Sulu Sea at glacial time, since the pattern of neogloboquadrinids in the Sulu Sea (Linsley et al., 1985) is similar to that in core K12. Glacial production in the DCM layer may have been increased either by shoaling of the thermocline, or by increased nutrient concentrations in the thermocline water.

Shoaling of the thermocline within the euphotic layer would cause an extension of the DCM layer into shallower water with higher light intensities enhancing primary production in the DCM layer and thus the chlorophyll concentration at depth. This relationship between shoaling of the thermocline and increased production in the DCM layer is reported by Gieskes and Kraay (1986) and by Herbland et al. (1985) from the equatorial Atlantic, and is suggested as well by Gieskes et al., (1990) from the Banda Sea, where upwelling during the northern summer causes a distinct shoaling of the thermocline. Present-day upwelling in the Banda Sea is driven by the prevailing southeasterly winds in the northern summer (Wyrtki, 1958). Since the influence of southeasterly trade winds was probably stronger at glacial time (Manabe and Hahn, 1977; Flohn, 1981), glacial upwelling conditions and concomitant shoaling of the thermocline in the eastern Indonesian archipelago may have prevailed over a much larger area than today. A shoaling of the thermocline might also explain the lower temperatures in the DCM layer of the northern Molucca Sea and Sulu Sea, as inferred from the substantial numbers of dextrally coiled Neogloboquadrina pachyderma in glacial sediments from these regions.

An alternative explanation for the increased production in the DCM layer at glacial time is based on the assumption that the depth of the thermocline at glacial time was similar, but that the nutrient concentration of the thermocline water was higher than today. Thermocline water in the Indonesian archipelago originates as Subtropical Lower Water in the Pacific between 165°E and 165°W at 25°N (Wyrtki, 1961). A rise in the nutrient concentration of glacial Subtropical Lower Water may have resulted from increased export production in the western equatorial Pacific, or from increased time of exposure to steady

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export production. The change in Pacific circulation, from its present-day estuarine mode to an anti-estuarine mode at glacial time (e.g. Shackleton and Duplessy, 1985; Berger, 1987) suggests an increase in average surface water salinity in the Pacific at glacial time, whereas surface water temperatures were lower in the source area of the Subtropical Lower Water (CLIMAP, 1976). Higher glacial surface water salinities and lower temperatures would probably stimulate the formation of Subtropical Lower Water and, thus, the inflow of younger thermocline water in the Indonesian archipelago. Thus, increased exposure of Subtropical Lower Water to steady export production seems highly unlikely. The only other possibility to increase the nutrient concentration of the inflowing glacial Subtropical Lower Water, therefore, is by increasing the export production in the western equatorial Pacific. There is evidence of increased glacial export production in the eastern equatorial Pacific (e.g. Adelseck and Anderson, 1978; Pedersen, 1983; Lyle et al., 1988) but little is known about the fertility history of the western equatorial Pacific. Increased glacial export production in the western equatorial Pacific, however, could have been brought about by increased trade wind activity at glacial time. The inflowing Subtropical Lower Water at glacial time could not only have been enriched in nutrients but could also have been cooler than today, due to lower glacial surface water temperatures in its source area (CLIMAP, 1976).

Summarizing, there are two alternative models to explain the increased production and lower temperatures in the DCM layer in the northern Molucca Sea and Sulu Sea at glacial time. The first one claims an extension and intensification of the present-day upwelling conditions in the Banda Sea due to an increased influence of the southeasterly winds in the region at glacial time. The second model claims the inflow of cooler and nutrientenriched thermocline water in the Molucca Sea and Sulu Sea at glacial time, which requires increased export production in the western equatorial Pacific. The second model is preferred here since it is doubtful whether the increased glacial upwelling in the first model was sufficiently large to cause a shoaling of the thermocline in the northern Molucca Sea and Sulu Sea.

The pattern of neogloboquadrinids indicates that the temperature and production in the DCM layer reached present-day values at about 14 kyr B.P., which in terms of the second model would mark the inflow of warmer and nutrient-depleted Subtropical Lower Water at the beginning of the last deglaciation. The change in properties of the inflowing Subtropical Lower Water at 14 kyr B.P. may be due to a rapid decrease in the equator to pole thermal gradient and associated weakening of the trade winds, at the beginning of the last deglaciation.

Conclusions

(1) The palynological record in the northern Molucca Sea shows that glacial climatic conditions in the study area were drier than today. Although the expansion of ice and increased pole to equator thermal gradients at glacial time presumably changed the average position and yearly oscillation of the ITCZ, these changes most probably did not result in an increased aridity in the study area. We, therefore, assume that the drier climatic conditions at glacial time were related to a possible disturbance in the ENSO system. Increased precipitation in the study area began shortly after the last glacial maximum while present-day values were reached at about 14 kyr B.P.

(2) Molucca Sea surface water salinities were probably higher at glacial time than they are today. Glacial surface water temperatures probably were close to modern values.

(3) The calculated lapse rate for the region at glacial time was higher than today. Estimates vary between $0.75-0.87^{\circ}$ C per 100 m versus 0.6° C per 100 m at present. The higher glacial lapse rate was probably due to drier air and globally lowered temperatures at glacial time. The higher glacial lapse rate induced high-altitude cooling and concomitant expansion of the Lower Montane oak forests on the nearby island of Halmahera at glacial time. The Lower Montane forests retreated rapidly to higher altitudes between 18 and 14 kyr B.P., probably as a result of a rapidly decreasing lapse rate.

(4) The planktonic foraminiferal record indicates increased production and decreased temperatures in the DCM layer at glacial time. Two models are presented to explain these glacial conditions in the DCM layer. The model we prefer claims the inflow of cooler and nutrient-enriched Subtropical Lower Water from the West Pacific into the Molucca Sea at glacial time. Present-day conditions in the DCM layer were attained at about 14 kyr B.P. resulting from a rapid decrease in the equator to pole thermal gradient and an associated decrease in the trade wind intensity at the beginning of the last deglaciation.

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