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Hydrographic Structure Along 131.5°W in the Eastern Tropical Pacific in July 2003

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Abstract : Conductivity-temperature-depth (CTD) data obtained along a meridional section in the eastern tropical Pacific in July 2003 have been analyzed to identify various water masses, and to examine the hydrographic structure and zonal geostrophic currents in the upper 1000 m. Water mass analysis shows the existence of subtropical and intermediate waters, characterized by layers of subsurface salinity maximum and minimum, originating from both hemispheres of the Pacific. Vertical section of temperature in the upper 200 m shows the typical trough-ridge structure associated with the zonal current system for most of the tropical Pacific. Water with the lowest salinity of less than 33.6 was found in the upper 30 m between 8.5°N and 10.5°N in a boundary zone between the North Equatorial Current and North Equatorial Countercurrent. Temporal changes in water properties observed at 10.5°N over a period of 9 days suggest both the local rainfall and horizontal advection is responsible for the presence of the low-salinity water. Development of a barrier layer was also observed at 10.5°N. In the North Equatorial Current region a local upwelling was observed at 15°N, which brings high salinity and cooler subtropical water to the sea surface. A band of countercurrent occurs in the upwelling region between 13°N and 15°N.

Key words : hydrography, geostrophic zonal flows, eastern tropical Pacific, water masses, short-term variation

1. Introduction

This paper describes the hydrographic structure along a meridional section in the eastern tropical Pacific observed in July 2003. From the viewpoint of oceanography, the tropical Pacific usually lies within 15° to 20° of the equator where the currents are oriented much more east-west as compared to the currents at higher latitudes. The tropics are also characterized by excess heating from the sun and heavy rainfall. Physical oceanography in the tropical Pacific is well described in numerous articles (e.g., Wyrtki and Kilonsky 1984; Tomczak and Godfrey 1994; Talley *et al.* 1999; Godfrey *et al.* 2001), and here we briefly summarize those articles concentrating on temperature and salinity distributions and the circulation in the tropical Pacific since they help to understand the observed hydrographic structure.

Ocean surface temperature (SST) is dominated by excess

heating in the tropics compared with higher latitudes, leading to a large SST difference between the equator and pole (Fig. 1a). The maximum SST is around 28°C or higher in the tropical Pacific. The SST is not uniformly high in the tropical Pacific. A large warm pool is found in the central and western Pacific, while the equatorial cold tongue, that is several degrees cooler than the SST in the west, is obvious in the eastern equatorial Pacific. Wind-induced upwelling in the eastern Pacific is responsible for the cold tongue in the eastern equatorial Pacific. Upwelling of the cold water also occurs at the equator.

The distribution of sea surface salinity (SSS) tends to be zonal, similar to the temperature distribution (Fig. 1b). The SSS distribution is closely associated with precipitation minus evaporation. The saltiest waters are at mid-latitude where evaporation is high. Less salty waters seen near the equator are associated with the ITCZ/SPCZ (Intertropical Convergence Zone/South Pacific Convergence Zone) system. The ITCZ corresponds to a zonal band of low salinity along 5°-10°N. The SPCZ is evident as an extension of the

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Fig. 1. Climatological mean (a) potential temperature and (b) salinity at the sea surface for the world ocean. Adapted from Tomczak and Godfrey (1994).

tropical low salinities from New Guinea to Fiji. Minimum salinities occur in the Gulf of Panama, where salinity drops below 33.0 in the annual mean. This water originates from the North Equatorial Countercurrent, which crosses the Pacific eastward under the heavy rains of the ITCZ and arrives in the east with substantially reduced salinities (Tomczak and Godfrey 1994). Weak currents in the Gulf of Panama expose the water further to the heavy rains. Eventually, the diluted water exits into the westward North Equatorial Current and into the subtropical gyre via the Kuroshio.

In the vertical, the most rapid change in temperature occurs in the thermocline in the upper 500 m. The lower boundary of the tropical thermocline is roughly given by the 14°C isotherm, below which temperature gradients are much less pronounced (Wyrski and Kilonsky 1984). The vertical thermal structure in the western equatorial Pacific is characterized by a thick surface layer of approximately 100 m deep with temperature higher than 28°C. On the other hand, the surface layer is shallower, and so colder water and thermocline are found closer to the surface in

Fig. 2. Mean distribution of (a) zonal geostrophic flow U (cm/s) relative to 1000 db, (b) temperature T ($^{\circ}\text{C}$), and (c) salinity between Hawaii and Tahiti (about 150°W and 160°W) in the upper 400 m. Adapted from Wyrski and Kilonsky (1984).

the central and eastern equatorial Pacific. Temperature reaches about 1.2°C in the abyssal tropical Pacific. As the initial temperature and salinity of all ocean water are set at the sea surface, water colder than 18°C comes from higher latitudes. The coldest waters flow northward from the Antarctic region and fill the Pacific below 1000 m to 1500 m. The North Pacific does not produce any deep water, and the deepest waters in the Pacific come from the Antarctic (Weddell and Ross Seas) and the Greenland Sea in the North Atlantic. As it takes about 500 years for these deep waters to reach the depths of the North Pacific, waters in the deep Pacific have a very narrow range of temperature and salinity due to the mixing.

Mean annual cross-equatorial hydrographic structure in the upper 400 m between 20°S and 20°N show that the thermocline comes closest to the sea surface near 9°N at the northern flank of the NECC, and a trough near 5°N at its southern flank (Fig. 2, Wyrski and Kilonsky 1984). The thermocline spreads towards the equator due to the equatorial undercurrent. North of 10°N the sharp tropical thermocline begins to deepen poleward and spreads. The

salinity distribution shows that surface salinity increases both southward and northward toward the subtropical high-salinity cell in the North and South Pacific from the region of lowest salinity (34.3) at around 10°N associated with the NECC. Subsurface salinity maxima in the thermocline at depths between 100 and 150 m represent the cores of the high-salinity waters of the subtropical origin. The northern salinity maximum at 20°N is situated near the middle of the thermocline and penetrates to about 10°N. A salinity minimum lies below the high-salinity tropical waters and above the core layer of the North Pacific Intermediate Water (NPIW). The salinity minimum rising from 400 m at 20°N to 100 m near 10°N originates at the sea surface in the eastern and central North Pacific and is brought southward and westward by the eastern limb of the subtropical gyre (Wyrki and Kilonsky 1984).

2. Data

CTD (conductivity-temperature-depth) data through the water column were collected on board R/V Onnuri in the northeastern tropical Pacific between July 16 and July 26, 2003 with a SeaBird SBE 911 plus CTD system. The CTD measurements were made along a 131.5°W meridian between 4.5°N and 17°N at every 0.5° intervals. CTD was lowered to 1000 m (200 m) depth at 1° interval from 16°N (16.5°N) to 6°N (4.5°N). Full-depth CTD casts were made at 17°N, 10.5°N, and 5°N. The CTD measurements started at 10.5°N on July 7, and stations in the northern half from

10.5°N to 17°N were occupied until July 17. R/V Onnuri, then, steamed back to 10.5°N, and CTD measurements were conducted every 2 hours at 10.5°N from July 18 to July 19 to look at the short-term variability of hydrographic structure. After the one-day stay at 10.5°N, southern stations were occupied until July 26.

Downcast CTD data were processed, binned in to 1 m depth bin, and parameters derived using the SeaBird SEASOFT software package, except for the alignment time constant for salinity, and the thermal anomaly amplitude and constant, which were determined using the obtained data. Temperature and salinity sensors were post-calibrated at SeaBird after the observations.

3. Results

Water masses

Potential temperature (θ)-salinity (S) diagrams for all shallow stations and for three full-depth stations at 5°, 10.5°, and 17°N are shown in Fig. 3. Surface waters on the survey line can be grouped into three categories: warm ($\theta > 28.0^\circ\text{C}$) and relatively high-salinity ($S > 34.4$) surface water south of 6°N, warm ($> 28.0^\circ\text{C}$) and low-salinity ($S < 34.0$) surface water between 6°N and 14.5°N, and relatively cold ($27.0^\circ\text{C} < \theta < 28.0^\circ\text{C}$) water north of 15.5°N.

Layers of the subsurface salinity maximum due to subtropical waters originating from both hemispheres of the Pacific can be seen. The core of the salinity maximum ($S=34.904$) occurs at shallower depth (103 db), and hence

Fig. 3. Potential temperature-salinity relationships (a) in the upper 1000 m, and (b) for three full-depth stations at 5°N (red), 10.5°N (black), and 17°N (blue). Red, black, and blue lines in Fig. 3(a) are for CTD stations located south of 10.5°N, at 10.5°N, and north of 10.5°N, respectively.

Fig. 4. Vertical sections of (a) potential temperature θ ($^{\circ}\text{C}$), (b) salinity, (c) potential density σ_{θ} (kg/m^3), and (d) zonal geostrophic flow U (cm/s) relative to 1000 db in the upper 200 m. Positive U denotes the eastward flow.

has a higher θ of 21.251°C at 17°N as compared to the high salinity core to the south. At 5°N , the core layer ($S=34.945$) is situated at 147 db with θ of 13.647°C (see also Fig. 4).

Below the salinity maximum, two salinity minima occur at 17°N : a shallow salinity minimum at 197 db with θ of 13.017°C and salinity of 34.213, and deep salinity minimum at 482 db with θ of 7.524°C and salinity of

34.481 (see also Figs. 4, 5). On the other hand, only one salinity minimum layer occurs to the south at 10.5°N and 5°N . The salinity minimum at 5°N occurs at 836 db with θ of 5.590°C and salinity of 34.551. Hence it is cooler and saltier than the deep salinity minimum at 17°N . The salinity minima are due to the spreading of intermediate waters originating from both hemispheres in the Pacific. The density (σ_{θ}) of the deep salinity minimum at 17°N is

Fig. 5. Vertical sections of (a) potential temperature θ ($^{\circ}\text{C}$), (b) salinity, (c) potential density σ_{θ} (kg/m^3), and (d) zonal geostrophic flow U (cm/s) relative to 1000 db in the upper 1000 m. Positive U denotes the eastward flow.

26.94 kg/m^3 similar to σ_{θ} of the NPIW, which has a narrow σ_{θ} range centered at $26.7\text{--}26.9 \text{ kg/m}^3$ (Talley 1993). The salinity minimum at 5°N has a much higher σ_{θ} of 27.25 kg/m^3 , and arises from the northward spreading of the Antarctic Intermediate Water (AAIW). The northward spreading of the AAIW can be traced to about 6°N , and the AAIW has relatively higher dissolved oxygen content (DO) as compared to that of the northern intermediate

water (Wyrki and Kilonsky 1982). The vertical section of DO clearly shows the southward spread of the AAIW (Fig. 6).

Below the deep salinity minima, temperature decreases and salinity increases. Near the seabed the θ - S diagram at three full-depth stations merges into a single water mass called the Pacific Deep Water (Tomczak and Godfrey 1994), whose origin is both the Antarctic region and the

Fig. 6. Vertical sections of (a) potential temperature θ ($^{\circ}\text{C}$), (b) salinity, (c) potential density σ_{θ} (kg/m^3), and (d) un-calibrated dissolved oxygen content (ml/l) below 500 m.

North Atlantic. The Pacific Deep Water has θ of 1.062–1.093 $^{\circ}\text{C}$ and salinity of 34.690 with corresponding σ_{θ} of 27.79 kg/m^3 .

Vertical sections

Warm surface water with θ higher than 28.0 $^{\circ}\text{C}$ occupies upper 30 m–60 m depth in the NECC south of 9 $^{\circ}\text{N}$. Its thickness is reduced to the north between 10.5 $^{\circ}\text{N}$ –12.5 $^{\circ}\text{N}$ in the NEC, and increases again to the north to 14 $^{\circ}\text{N}$, where the geostrophic currents are directed to the east (Fig. 4). Surface temperature in July 2003 was about 1 $^{\circ}\text{C}$ higher than that of July 1999 (Shin *et al.* 2004). July of 2003 was a normal period according to the Oceanic Niño

Index (ONI) based on SST anomalies in the Niño 3.4 region (5 $^{\circ}\text{N}$ –5 $^{\circ}\text{S}$, 120 $^{\circ}$ –170 $^{\circ}\text{W}$) (http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/). On the other hand, CTD data were obtained during the La Niña period in July 1999. The SST anomalies were 0.3 $^{\circ}\text{C}$ in July 2003, and –0.9 $^{\circ}\text{C}$ in July 1999 according to the ONI.

Low-salinity surface waters with S less than 34.0 widely distribute in the mixed layer between 8 $^{\circ}\text{N}$ –16.5 $^{\circ}\text{N}$ except for high salinity surface water at 15 $^{\circ}\text{N}$, where the local upwelling occurs. The lowest salinity with S less than 33.5 occurs in the upper 30 m between 8.5 $^{\circ}\text{N}$ –10 $^{\circ}\text{N}$, which occupies the northern parts of the NECC and the southern parts of the NEC. The water can be either advected by the

NECC from a pool of low-salinity water in the western Pacific or by the NEC from the eastern tropical Pacific, where an even larger pool of lower salinity water exists (see Fig. 1b). The latter origin seems to be more probable considering the salinity value of less than 33.5.

The thermocline comes closest to the sea surface near 8.5°N at the northern flank of the NECC. The thermocline deepens and spreads to the south towards the southern flank of the NECC, and also to the north of 8.5°N. The thermocline between 13.5°N and 17°N has an upper and a lower branch. The high-salinity core ($S > 34.8$) of the northern subtropical origin is found in the middle of the thermocline between 50 m and 150 m north of 14°N. Below it a salinity minimum ($S < 34.4$) can be seen rising from about 220 m at 17°N to 100 m near 15°N. Subsurface isotherms colder than 20°C have a ridge structure at 15°N associated with the upwelling of the salinity minimum layer. The upwelling of the salinity minimum layer brings the overlying high-salinity subtropical water of the North Pacific origin upwards, resulting in cooler and saltier surface water at 15°N than surface waters found just north and south of 15°N.

Below the thermocline, temperature decreases gradually. Deep isotherms deepen to the north in the NEC region between 8°N–13°N, and then shoal rather rapidly between 13°N–15°N. The density distribution resembles that of temperature. The salinity distribution well shows the existence and layering of salty subtropical waters and less saline intermediate waters originating in both the south and north Pacific.

The NPIW, characterized by a distinct layer of salinity minimum with S less than 34.5, occupies 400–700 m depths north of 14°N (Fig. 5). It can be traced as far south as 10°N by an extension of low-salinity water with S less than 34.54 but with higher σ_θ around 27.2 kg/m³ than the definition of the NPIW (Fig. 6). The NPIW is characterized by low DO, and the influence of the AAIW, which is comparably high in DO, can be seen south of 10°N below 700 m. The AAIW has a lower θ and higher S as compared to those of NPIW.

A layer of high-salinity water ($S > 34.7$) is found in the upper 400 m south of 14°N. The highest salinity occurs at the southernmost station at 5°N, where salinity is even higher than 34.9. The high-salinity core is a trace of the southern subtropical water, which partially sinks to the top of the thermocline during winter, spreads toward the equator, and enters the core of the Equatorial Undercurrent (Wyrski and Kilonsky 1984). On its way south, the southern subtropical water mixes with low-salinity water coming

from the north, and the mixed waters are upwelled near the equator or depressed below the undercurrent. The thickness of water having S higher than 34.7 narrows at around 6°N, and broadens again to the south (Fig. 5). The high-salinity water south of 6°N has relatively higher DO compared to that of the high-salinity water north of 6°N (not shown), suggesting the latter is older southern subtropical water.

Zonal geostrophic currents

CTD observations were taken at every 1° intervals only to a depth of 1000 db, and geostrophic speeds relative to 1000 db are calculated. The selection of 1000 db as a reference level is thought to be a reasonable choice (Wyrski and Kilonsky 1984). The calculated zonal flows are shown in Figs. 4, 5. In general, strong flows with speeds higher than 20 cm/s are confined to upper 100 m depth.

The NECC flows eastward south of 9°N. It splits into two branches and the southern branch is stronger and has a deeper structure. The deepening of the velocity core seems to be related to the connection of the NECC with the northern subsurface countercurrent which lies beneath the South Equatorial Current. A weak subsurface westward flow occurs below 200 m depth between the two branches of the NECC between 6°N and 7°N, which is also evident in the mean zonal geostrophic flow patterns calculated by Wyrski and Kilonsky (1984) (see Fig. 2). The weak subsurface countercurrent was also observed between 5°N and 6°N in July, 1999 (Shin *et al.* 2004).

The NEC flows westward north of 9°N, and is disrupted by an eastward flow between 13°N and 15°N where the branching of the thermocline and upwelling occurred (Fig. 4). The NEC south of 13°N is stronger and deeper in structure as compared to the NEC north of 15°N. Two velocity cores occur in the southern NEC, and the shallow northern core between 10.5°N and 11°N has the strongest speed higher than 60 cm/s. Mean zonal geostrophic flows showed the split of the NEC with a stronger southern branch (Wyrski and Kilonsky 1984). The split was dictated by a weak westward flow at around 15°N, where most mesoscale eddies appear (Wyrski 1982). The present calculation, however, shows that the split is due to the strong (max. speed > 30 cm/s), wide, and deep countercurrent.

Short-term variability at 10.5°N

Repeated CTD observations were made in the upper 200 m at 10.5°N, two times on July 9 and one-day continuous observations during July 18 and 19 at every two hours. After the completion of the continuous observations, CTD

Fig. 7. Vertical profiles of (a) potential temperature, (b) salinity, and (c) potential density on July 9 (blue) and on July 18 (red).

was again lowered to near the seabed. This full-depth CTD data at 10.5°N were used in preparation of Figs. 4–6.

Remarkable changes in the upper hydrographic structure took place at 10.5°N over a period of 9 days. Comparisons of CTD data taken on July 9 and 18 indicate that freshening and warming of the surface water had occurred over 9 days (Fig. 7). Surface salinity was lowered by greater than 0.3, temperature increased by about 0.4°C , and the associated density change was about 0.4 kg/m^3 . Surface salinity was less than 33.6 from 2:30 to 4:30 on July 18 and increased to a value higher than 33.6 afterwards (Fig. 8).

Those changes also include the variation of mixed layer depth. On July 9, the depth of the top of the thermocline (h_T), where the vertical gradient of temperature is 0.05°C/m following the definition of Lukas and Lindstrom (1991, LL hereafter), is 58 m. On the other hand, the mixed layer depths (MLD , MLD_T , MLD_S) are 25 m based on LL's definition, above which less saline and slightly warm water occupies the surface layer. Shoaling of the MLD had also occurred, and iso-layers (MLD_T , MLD_S) and the depths of the top of the thermo- and halocline (h_T , h_S) had all become shallower as compared to those on July 9. The MLD, defined by the density difference, was 9 m thick on July 18, and determined by salinity stratification. The isothermal layer (MLD_T) became deeper than the MLD on July 18. Temperature decreased and both density and salinity increased on July 18 for waters located below the MLD and the near-isothermal layer on July 9. The main halocline, where the vertical change of salinity was the greatest, occurred in a salinity range between 34.0 and

34.6 on July 9. In the time-depth isopleth for salinity, 34.0 isohaline was situated at about 60 m depth on July 9 and at about 30 m on July 18 (Fig. 8). The depth change for the 34.6 isohaline, however, was minimal.

The salt-stratified region that determines the MLD has been called the “barrier layer” (Godfrey and Lindstrom 1989) because the stability associated with that region resists mixing over the deeper isothermal layer. The barrier layer occurs in tropical regions of Pacific, Atlantic, and Indian Oceans, and the barrier thickness in the eastern tropical Pacific between 120° – 130°W , 0° – 10°N is about 0–25 m (Sprintall and Tomczak 1992). Heavy local precipitation is responsible for maintaining the barrier layer in the western equatorial Pacific (Lukas and Lindstrom 1991; Sprintall and Tomczak 1992).

In the present data, the barrier layer of 9 m thick was formed on July 18 because of the influence of the low-salinity surface water which is also slightly warmer than the underlying saltier water. The thickness of the MLD and the isothermal layer (MLD_T) were identical on July 9. An examination of the TRMM (Tropical Rainfall Measuring Mission) data indicates there had been 74 mm of total rainfall between July 10 and July 18 at 10.5°N (Fig. 9). The rainfall was high on July 9 at the time of CTD survey at 10.5°N , and the total amount of rainfall becomes 97 mm between July 9 and July 18. Neglecting the evaporation and horizontal advection, it requires about 98 mm of rainfall in order for salinity of a 10 m-thick layer to be lowered by 0.33 from 33.85 to 33.52. It is about the same amount of the observed rainfall between July 9 and 18,

Fig. 8. Time (LT)-depth isopleths for (a) potential temperature θ ($^{\circ}\text{C}$), (b) salinity, and (c) potential density σ_{θ} (kg/m^3) at 10.5°N .

Fig. 9. Daily rainfall at 10.5°N , 131.5°W in July 2003 from $1^{\circ}\times 1^{\circ}$ TRMM (Tropical Rainfall Measuring Mission) data.

but is about 30% higher than the observed rainfall between July 10 and 18. The horizontal advection, however, cannot be neglected (see Fig. 4), and both the local rainfall and horizontal advection appear to be responsible for the observed short-term change in upper hydrographic structure.

The low-salinity water with S less than 33.6 occupies the surface layer between 8.5°N and 10.5°N (see Fig. 4). The minimum salinity ($S < 33.2$) occurs at 8.5°N . As this low-salinity band is located in the boundary between the NECC and NEC, the origin of the low-salinity water can be either from the west or from the east. The observed low-salinity value, however, suggests its origin from the east. A band of low-salinity water was also observed in

Table 1. Various layer depths for a CTD station at 10.5°N on July 9 and 19. The criteria used for the calculating the various layer depths are based on those in Lukas and Lindstrom (1991).

	Definition	July 9	July 19
MLD (m)	$\Delta\sigma_\theta = 0.01 \text{ kg/m}^3/\text{m}$	25	9
MLD _T (m)	$\Delta\theta = 0.025^\circ\text{C}/\text{m}$	26	13
MLD _S (m)	$\Delta S = 0.01 / \text{m}$	25	9
h _T (m)	$\Delta\theta = 0.05^\circ\text{C}/\text{m}$	58	23
h _S (m)	$\Delta S = 0.02 / \text{m}$	26	12

the boundary between the NECC and NEC during the La Niña period in July 1999 (Shin *et al.* 2004).

4. Summary

CTD data obtained along 131.5°W between 4.5°N and 17°N in July 2003 have been used to identify various water masses, and to examine the hydrographic structure and zonal geostrophic currents in the upper 1000 m. Surface waters are less saline ($S < 34.0$) and relatively warm in the NECC region as compared to those in the NEC region. Water mass analysis shows the cores of salinity maxima due to high-salinity subtropical waters in both hemispheres, and cores of salinity minima due to the influence of the AAIW and NPIW. A shallow salinity minimum layer also occurs below the northern subtropical water and above the NPIW. Below the AAIW and NPIW, temperature decreases and salinity increases to become the Pacific Deep Water, which has a range of temperature (θ) of 1.062–1.093°C and salinity of 34.690 with corresponding σ_θ of 27.79 kg/m³. The northern subtropical water is found in the middle of the thermocline between 50 m and 150 m north of 14°N. The shallow salinity minimum layer above the NPIW can be seen rising from about 220 m at 17°N to 100 m near 15°N. The upwelling of the salinity minimum layer also lifts the overlying northern subtropical water, resulting in cooler and saltier surface water at 15°N than surface waters found north and south of 15°N. A countercurrent occurs in the upwelling region between 13°N and 15°N.

The NPIW has a higher temperature and lower salinity and DO than the water properties of the AAIW. The NPIW influence can be traced as far south to 10°N. The AAIW, which is comparably high in DO, is found south of 10°N below 700 m.

The vertical section of temperature shows the trough-ridge structure associated with the zonal current system typical for most of the tropical Pacific. The thermocline

comes closest to the sea surface near 8.5°N at the northern flank of the NECC. It deepens and spreads towards the southern flank of the NECC, and to the north to the NEC region.

Lowest-salinity water with salinity less than 33.6 was found in the upper 30 m between 8.5°N and 10.5°N in a boundary zone between the NEC and NECC. Temporal changes in water properties observed at 10.5°N over a period of 9 days suggest both the local rainfall and horizontal advection are responsible for the presence of the low-salinity water. A large pool of low-salinity surface water with salinity less than 34.0 exists in the eastern tropical Pacific, and the low-salinity surface water is thought to be advected by the NEC. Development of a barrier layer of about 9 m thick was also observed at 10.5°N.

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