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子計劃（四）：台灣東邊黑潮時空變化

Temporal and spatial variations of Kuroshio east of Taiwan

-007

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Abstract

This report illustrates the works have been done for the study of Kuroshio Upstream Dynamics Experiment (KUDEX). A large-scale hydrographic and current velocity survey was performed using the CTD and Ship-board Acoustic Doppler Current Profiler (Sb-ADCP). Applied the principal of geostrophy and referred the average velocity in between 50 and 100m obtained from the Sb-ADCP, the current velocity in the upper 1500m ocean was estimated. The result shows that the Kuroshio was wider and greater influence depth at east of Taiwan (23.5 ^{o}N) than at northern tip of Philippine (18^{o}N) directed to NNW, but the speed remained more or less the same. The transport of Kuroshio increased as its flowed from northern Philippine to Taiwan. The obtained current velocity spatial distribution gave an evidence for the existence of eddy, which inferred from the altimetry.

The historical Sb-ADCP measurements were edited, and the composite of current velocity around Taiwan was obtained. The result provided a chance to examine the integrated current velocity distribution in space around Taiwan. Through the Luzon strait, the intrusion of Kuroshio with the transport of 3Sv. was evident. The zonal sections of current velocity from north to south of Taiwan were investigated. The variability of Kuroshio along the eastern coast of Taiwan was described. The Taiwan Strait current with two peaks was found. The spatial current velocity distribution on the southern East China Sea shelf was described. A manuscript is in preparation.

A subsurface ADCP mooring at southwest of Taiwan was retrieved, but the mooring at Luzon Strait was lost. The obtained current velocity showed the current persistently flowing westward. The variation of moored time series could be related with the propagation of eddy. A further analysis is going on.

1. Introduction:

A quite few oceanic features in the regional sea around Taiwan were found in the last decade. Some of those new features indicated that the oceanic variation around Taiwan could be highly related with the Kuroshio, which originated from the North Equatorial Current (NEC). Since the Kuroshio was formed remotely, it should contain both local and remote characteristics. Without knowing the remote characteristics of Kuroshio, the oceanic variation around Taiwan would not be well understood. For example, the result obtained from the program of Kuroshio Edge Exchange Process (KEEP) indicated that the pathway of Kuroshio had significantly impact on the oceanic characteristics northeast of Taiwan. Tang and Yang (1993) pointed out that the local wind force had little impact on the variation of pathway of Kuroshio. The migration of Kuroshio could be related with the remote forces. To study the characteristics Kuroshio upstream dynamics would be great helpful to explore the oceanic variation around Taiwan.

The promised works of first year in this project are to perform the large-scale hydrographic and current velocity survey using the CTD and Sb-ADCP, and to deploy three self-contained ADCP along the PR20 (defined in World Ocean Circulation Experiment, WOCE). The mooring plan was modified. The moorings were shifted to the southwest of Taiwan to study the interaction of Kuroshio and SCS current. We believe that the current southwest of Taiwan not only has impact on the northern SCS, but also has great influence on the Kuroshio east of Taiwan.

2. Large-scale hydrographic and current velocity survey

Figure 1 shows the cruise track and the CTD stations. The track started from near the coast of Philippine along 18°N to 127°E, then turned northward to 23.5°N and finally turned westward back to the coast of Taiwan. The CTD measurements did every 0.5°. Each profile reached to 1500m. The Sb-ADCP was set as to ping every one second. The current velocity was recorded averaged over 120 pings. The bin interval was 8 m. The transducers were mounted 4m below the water surface and there had one blanket bin length was set immediately beneath the transducers. The shallowest depth obtaining the current velocity was 16m. The range of transducers was around 250m, but slightly change with the sea condition. The GPS continuously provided the ship positions, which were used to compute the ship velocity. The recorded current velocity then was calibrated and aligned using the method of Tang and Ma (1995). Finally, the spatial average was applied to obtained the current velocity at every 15NM.

The current velocity at 16m along the cruise track is shown in Figure 2. At the northern tip of Philippine, the Kuroshio Current flowed mainly to NNW but gradually turned to NNE. Its width and maximum speed were around 100km and 120cm/sec, respectively. A southward countercurrent was seen centered around 123.8°E. East of the countercurrent, the current mainly was westward. The current velocity along 127°E from 18 to 23.5°N was varied, but mainly westward. This result implies that the Kuroshio might be still in the convergent area. Along 23.5°N, the current was westward in 125-127°E. A southward current was seen in 124.3-125°E. West of southward flow, the current velocity was weak until to reach the region of Kuroshio. The Kuroshio Current east of Taiwan had around 150km in width and maximum speed over 150cm/sec. Its direction was mainly NNE or N. The notable difference of Kuroshio Current at northeast of Philippine and east of Taiwan was seen.

Figure 3 shows the anomaly of altimetry, which estimated from the TOPEX/ERS data, on October 15. The figure was provided by Naval Research Laboratory and obtained from the Internet. It showed a cold eddy centered on 17.8°N, 125°E where a cyclonic-like flow field was observed. Such eddy had been observed by Chelton and Schlax (1996), Fu (1991), 鄭世培(1998) etc. It generated in the central Pacific and propagated to the west. The present observation provided an evidence of the existence of eddy, but it also indicated that some of eddies could be artificial. The artificial eddy could be generated owing to the poor spatial resolution of altimetry and incorrect mean field.

Under the assumption of geostrophic approximation, the hydrographic measurement was used to estimate the current velocity perpendicular the cruise track. The mean current velocity at 50-100m obtained from the Sb-ADCP was used to obtain the absolute geostrophic velocity. Pickart and Lindstorm (1994) discussed similar method in detail. The vertical profiles of velocities of Sb-ADCP and absolute geostrophic current are shown in Figure 4. The good agreement indicated that the current was nearly geostrophic. Figure 5 shows the meridional current velocity along 18°N. The upper panel is the velocity measured by the Sb-ADCP, while the lower panel is the calculated absolute geostrophic velocity. The Kuroshio was clearly seen. Its speed had a maximum value, over 120cm/sec, at surface and decreased rapidly with the depth. Below 300m, the current became southward and had a maximum value, over 40cm/sec, around 800m. The width of northward Kuroshio in the upper 300m was around 100km. East of Kuroshio, the current was weak and was mainly southward in the upper layer and northward in the lower layer. The meridional current velocity along 23.5°N, shown in Figure 6, had relative complicated structure than it along 18°N. The Kuroshio became wider and deeper. Its width was over 130km and northward current extended to over 1500m. It is noted that the maximum absolute geostrophic velocity was less at 23.5°N than at 18°N, but this feature was opposite for the velocity measured by the Sb-ADCP. This could be due to that the absolute geostrophic was over smoothed and the absolute geostrophic current was large at the core of Kuroshio. East of Kuroshio, the southward and northward velocity was alternatively seen. In general, the current was weak and mainly southward.

The northward transport associated with Kuroshio increased significantly from 18 to 23.5^{o}N. Obviously, new water was injected into the Kuroshio between the northern tip of Philippine and I-Lan Ridge. There have two potential water sources, South China Sea (SCS) and Western Pacific Waters. If the increase amount of water was originally from the SCS, a net outflow (from SCS to Pacific) in the Luzon Strait is expected. Then, two questions are raised. The first one is that the recent current measurement (Chuang, personal communication) along the Luzon Strait showed that the Kuroshio intruded persistently into the SCS. The outflow water was seen, but its amount could not significantly exceed the amount of intruded Kuroshio water. The other question is where the water comes from to compensate the water flow out through the Luzon Strait. The SCS connects with its surrounding seas through a few either shallow or narrow straits. It is difficult having a significant amount water flow into the SCS from its surrounding seas. The only possible resource for the compensated water is the deep inflow water in the Luzon Strait. The deep inflow water was observed by Wang and Chern (2000, personal communication), but its amount of transport was not known. More likely, the western Pacific water could be the resource for the increased amount of Kuroshio water. The observed velocity showed that the current flowed westward east of Kuroshio. The long-term altimetry obtained from TOPEX/ERS indicated that the westward propagating eddies continuously interacted with the Kuroshio.

Though the observation showed some new results and interesting features, it need to be studied carefully. No firm conclusion could be made in this preliminary report. Continue measurement and study are proposed.

(3) Composite current velocity

The historical Sb-ADCP data is used to study the spatial distribution of current velocity around Taiwan. The data were provided by the Data Bank, National Center for Ocean Research (NCOR) of Taiwan. The Sb-ADCP current velocity data was collected from1991-2000 by 3 Taiwanese research vessels, ORI, II, and III. In general, the Sb-ADCP was set to measure the current velocity every second and then to record the ensemble average velocity every 1-2 minutes. The depth bin was 8 or16m and the range of measurement was from 16m to 320m. The ship location, provided by the Global Positioning System (GPS), was recorded simultaneously with the current velocity. To obtain the composite current velocity, the data were processed as follows. The current velocity was firstly calibrated and aligned using the method same as it of Tang and Ma (1995) and then averaged over 30 minutes. The root mean square (rms) error associated with the calibrated and averaged current velocity data was generally less than $\pm 3.5 cms^{-1}$. The 30-minute averaged current velocities then were linearly interpolated vertically with a 10m intervals and grid horizontally with the size of 0.25^{o}x0.25^{o}. In the above process, an eye examination was applied to discard the questionable data, which such as the data had the large difference between the ship velocities obtained from Sb-ADCP (bottom tracking mode) and GPS estimate, respectively, and it was unable to be corrected by the calibration and alignment. Finally, the data were ensemble averaged in each grid.

The alias of the high frequency fluctuations of current velocity was noted. The data points in each grid less than 4 (2 hours current measurement), the ensemble average was not performed and not shown. By assume the amplitude of semi-diurnal tidal current velocity, which was most significant high frequency fluctuation around Taiwan, the rms of alias could be reached 17cm/s. The alias would not considerable influence the feature of composite current velocity.

Figure 7 shows the current velocity at 20m around Taiwan. The Kuroshio directed to the NNW after it left Luzon. Over the central Luzon Strait, the main stream of Kuroshio gradually turning to northward and then to NNW-ward, but a part of Kuroshio intruded into the SCS through the central portion of Luzon Strait. It is noted that the SCS water flowed out of SCS along the western coast of Luzon. This outflow water partially injected into the Kuroshio and partially bent to northwest re-flowing into the SCS. Either the intruded Kuroshio or northwestward SCS current gradually became more westward. Then, they were blocked by the shelf break, partially flowed along the shelf break to the southern opening of Taiwan Strait. The eastward flow at southern opening of Taiwan was mainly re-injected into the Kuroshio through the southern tip of Taiwan, but it had a portion of water flowing into the Peng-Hu Channel. This northward current could have considerable impact on the Taiwan Strait current. The Kuroshio east of Taiwan flowed along the coast to the north. Its width was around 150km and its maximum speed was around 120cm/s. The Kuroshio gradually became more eastward as it flowed over the I-Lan Ridge. As left the Taiwan, the Kuorshio basically flowed along the shelf break. Portion of its water intruded into the ECS through around North Mein-Hwa Canyon. There has a weak or even no flow region north of Taiwan, where had been intensively studied in the project of Kuroshio Edge Exchange Process (KEEP) (Chern and Wang (1989), Liu et al (1992), Chuang (1994)). In fact, this region had the Kuroshio Countercurrent (Chuang et al 1993) and the cyclonic eddy (Tang et al 1999), which formed due to the intruded subsurface Kuroshio water. Since the eddy or countercurrent migrated from time to time, the current was cancelled each other during the process of ensemble average. Therefore, the composite current velocity in the region was weak. The outflow of Taiwan Strait spilt into two branches (Chern and Wang 1992). One flowed along the coast of Taiwan injecting into the Kuroshio.

The other flowed to the north into the shelf of ECS. It seems that the Taiwan Strait flow originated from both the current through the Peng-Hu Channel and the current along the Mainland China coast. No southward Mainland China coast current, which was reported by many previous studies, was found. This could be the southward current only found in winter, but the present data set had less data in winter than summer.

Taking slice from the north Luzon to southern Taiwan, the vertical-meridional section of current velocity along the Luzon Strait is shown in Figure 8. The V was mainly positive (northward) except at the regions close to both ends. The positive and negative U was seen alternatively. From Luzon to 20°N, the U was generally weak. The large westward flow was found around the central Luzon Strait, where the water is deep, while the large eastward current was seen north of 21.25°N. The integration of U was 3.3Sv. Although the earlier studies showed the Kuroshio flow in, but also flow out the Luzon Strait and even the SCS current flow out of SCS, the present results indicates that the net transport of water through the Luzon Strait was from the Pacific into SCS. The intrusion of Kuroshio, then, is confirmed.

The zonal-vertical sections of current velocity from south to north along the Taiwan were examined. 3 section at 22, 24, 26°N are shown in Figure 9, 10, and 11, respectively. At the southern tip of Taiwan, the current velocity section along 22°N showed that the Kuroshio had two peaks, which were at east and west of Lan-Yu, respectively. The double peaks feature was identified using the hydrographic measurement by the preceding studies (Chern and Wang 1992), but its formation was quite controversial. The topography, such as the existence of Lan-Yu, could spill the Kuroshio into two branches. The outflow of SCS also could be one of the reasons. Since the present data presented more integration feature in space, we found that the Kuroshio was fragmental after it left Luzon, but it gradually re-unified as approaching the coast of Taiwan. The double feature could be related with the re-unification of Kuroshio. It is noted that a sub-surface countercurrent was found near the coast of Taiwan. The moored time series current velocity (Joe Wang, 2001, personal communication) showed that such countercurrent could be surfacing in October-January. The U in the Taiwan Strait was eastward but weak. The V was negative and positive at east and west of 120°E, respectively. This result agreed with the findings of Lin and Tang (2001), which inferred anti-cyclonic flow pattern was often found at the southern opening of Taiwan Strait.

Further to the north, the zonal-vertical section of current velocity south of I-Lan Ridge (Figure 10) showed that the Kuroshio had more solid construction. It had only one velocity peak and had greater speed and influence depth than the previous one. The Kuroshio flowed essentially northward. The U was weak. Again, a sub-surface countercurrent was found near the coast, but it was quite weak. In the Taiwan Strait, the V was mainly positive. The maximum V was at the central-east of Strait. It had two peaks, one at surface and the other at bottom. The near bottom's peak was also observed by the bottom-mounted ADCP. Near the Mainland China coast, the V was negative. It could be a part of the Mainland China Coast Current in winter. The U also had a negative peak at bottom. On the sides of peak, the U became positive. The zonal vertical section of current velocity at 26°N, limit to the insufficient data, the vertical –zonal section of current velocity did not include the Kuroshio. The V on the shelf of ECS was mostly northward, and its vertical gradient was weak. East of 124°E, the V was negative. This southward current could be a part of returning flow of intruded Kuroshio. The U was predominantly positive. It was weak west of 123°E and large east of 123°E. Again, the strong eastward current could be related with the intruded and returned Kuroshio.

The above description of the composite current velocity is brief. More detail explanation will be stated in the prepared manuscript, which is planed to be submitted to the Continental Shelf Research in the next 1 or 2 months.

(4) Moorings at southwest of Taiwan

The characteristics of oceanic variation southwest of Taiwan was quite controversial and drew a lot of attentions of local oceanographic community in the recent years. The early theory believes that the northeasterly monsoon drove the Kuroshio intruding into the SCS while the southwesterly monsoon caused the SCS flow out the SCS (Wyrtki 1961). This theory became suspicious since it did not agreed with the observed current velocity. Where the intruded Kuroshio goes or how it interacts with the SCS flow is quite vague. Such question has to be properly addressed in order to study the Kuroshio dynamic east of Taiwan. It is also import for the study of Taiwan Strait Current. Therefore, we changed our original plan shifted our mooring array from PR20 to the region southwest of Taiwan.

Three moorings, 2 subsurface ADCP and one surface mooring with T-chain and RCM current meters, were proposed to deployed. Figure 12 shows the mooring locations. This array had been reduced since the insufficient instrument, but it nearly completed in the on-going measurement. The one in the Luzon Strait was lost and the one of surface mooring is still in the water. No data have been retrieved from these two mooring. Figure 13 shows the recorded current velocity (U, V) at 30, 100, and 200m. The thin lines represent the hourly velocities and the bold lines represent the 36-hour low-pass filtered velocities. The 36-hour low-pass filtered U was mainly negative, westward, while the 36-hour low-pass filtered U was alternatively positive and negative. This result agreed with the composite current velocity, in general. The westward current could be related with the intrusion of Kuroshio or the SCS current returned from the Luzon Strait. The alternate change of V could be caused by the passage of eddies. The high-frequency fluctuations were primarily the semi-diurnal and diurnal tidal, and inertia currents. The diurnal tidal current was larger than the semi-diurnal tidal current. The observed current velocity indicated the importance of baroclinity in this region.

A MS degree student, 劉怡茹，is working on the measurement. More complete result should be stated in her thesis.

(5) On-going mooring work

Three subsurface ADCP moorings, at KA1, KA2, and KA3, were deployed since last October. The one in the Luzon Strait would be cancelled since the poor mooring survived rate. The current was large over the entire water column. The mooring line underwent a tremendous drag force. The advice of international mooring expert had been searched. No proper solution had been received. The three moorings in the water plan to be retrieved in April. Then, a part of these moorings would be deployed east of Taiwan to join with the study of Dr. Joe Wang.

Reference

Chelton, D. B., and M. G. Schlax (1996) Global observation of Oceanic Rossby waves. *Science*, **272**, 234-238.

Chern, C. S., and J. Wang (1992) The influence of Taiwan Strait waters on the circulation of the southern East China Sea *La mer*, **30**, 223-228.

Chern, C. S., and J. Wang (1989) On the water masses at northern offshore area of Taiwan. *Acta Oceanogr. Tawanica*, **22**, 14-32.

Chuang, W. S., H. W. Li, T. Y. Tang and C. K. Wu (1993) Observations of the countercurrent on the inshore side of the Kuroshio northeast of Taiwan. *J. Oceanogr.*, **49**, 581-592.

Chuang, W. S., and W. D. Liang (1994) Seasonal variability of intrusion of the

Kuroshio watter across the continental shelf northeast of Taiwan. *J. Oceanogr.* **50**, 531-542

Fu, Z., J. Hu and G. Yu (1991) Seawater flux through Taiwan Strait. *Chin. J. Oceanol. Limnol.,* **9**, 232-239.

Liu, K. K., G. C. Gong, C. Z. Shyu, S. C. Pai, C. L. Wei, S. Y. Chao (1992) Response of Kuroshio upwelling to the onset of the northeast monsoon in the sea north of Taiwan: observations and a numerical simulation. *J. Geophys. Res.*, **97**, 12511-12526.

Pickart, R. S., and S. S. Lindstrom (1994) A comparison of techniques for referencing geotrophic velocities. *J. Atoms. Oceanic Technol.*, **11**, 814-824

Tang, T. Y. and Y. J. Yang (1993) Low frequency current variability on the shelf break northeast of Taiwan. *J. Oceanogr.*, **49**, 193-210.

Tang, T. Y. and J. C. Ma (1995) A note on the accuracy of shipboard ADCP on Ocean Researcher 1. *Acta Oceanogr. Tawanica,* **34**, 71-81.

Tang, T. Y., Y. Hsueh,, Y. J. Yang, and J. C. Ma (1999) Continental slope flow northeast of Taiwan. *J. Oceanogr.* **29**, 1353-1362

Wang, J., and C. S. Chern (1988) On the Kuroshio Branch in the Taiwan Strait during wintertime. *Prog. Oceanogr.*, **21**, 469-491.

Wang, J., and C. S. Chern (1992a) On the deflection of a rotational, baroclinic jet by an angular coast with application to the branching of currents southwest of Taiwan. *Acta Oceanogr. Taiwanica,* **29**, 18-33.

Wang, J., and C. S. Chern (1992b) On the distribution of bottom cold water in the Taiwan Strait during summertime. *La mer.*, **34**, 246-257.

Wyrtki, K. (1961) Physical oceanography of the southeast Asian water, NAGA report vol. 2, Scientific results of marine investigations of the South China Sea and Gulf of Thailand. Scripps Institution of Oceanography, La Jolla, CA.

王胄、陳慶生 (2000) 對黑潮入侵南海過程的一些觀查與看法. *臺灣海洋學刊*, **38**, 129-151

鄭世培 (1998) 西北太平洋的表面環流. 國立臺灣海洋研究所碩士論文, pp 102.

ORI-CR564 CTD Stations

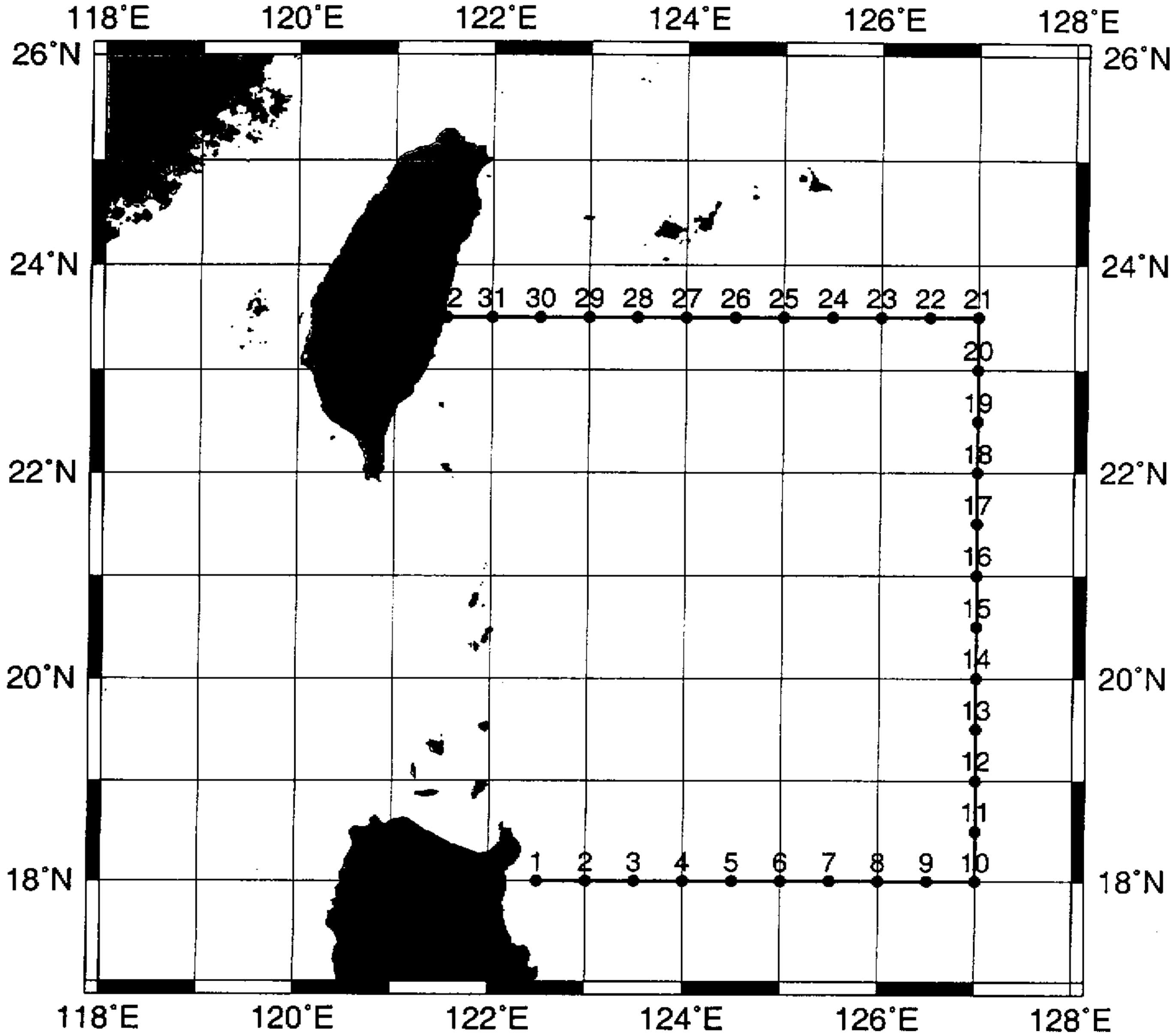


fig. 1

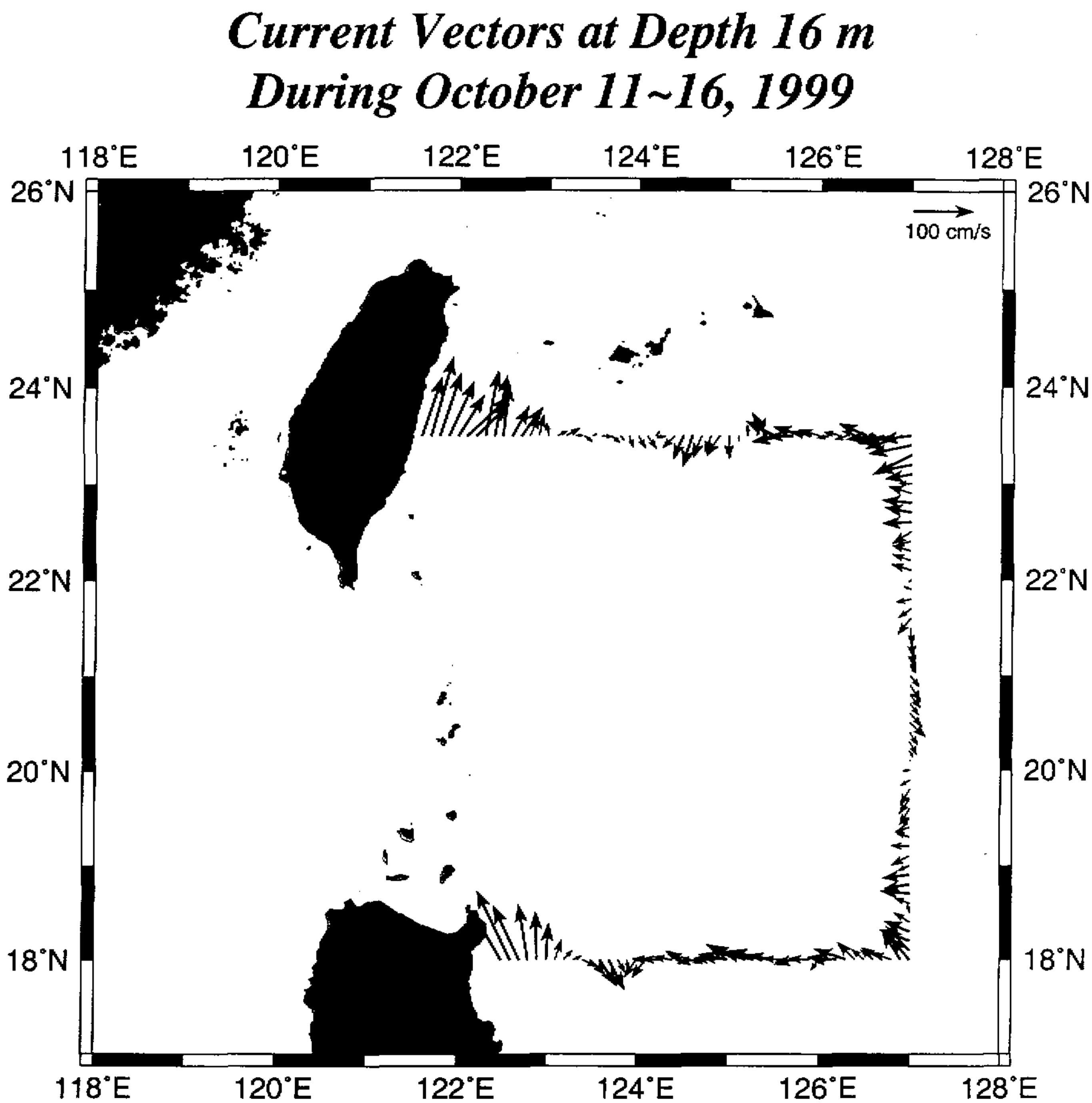
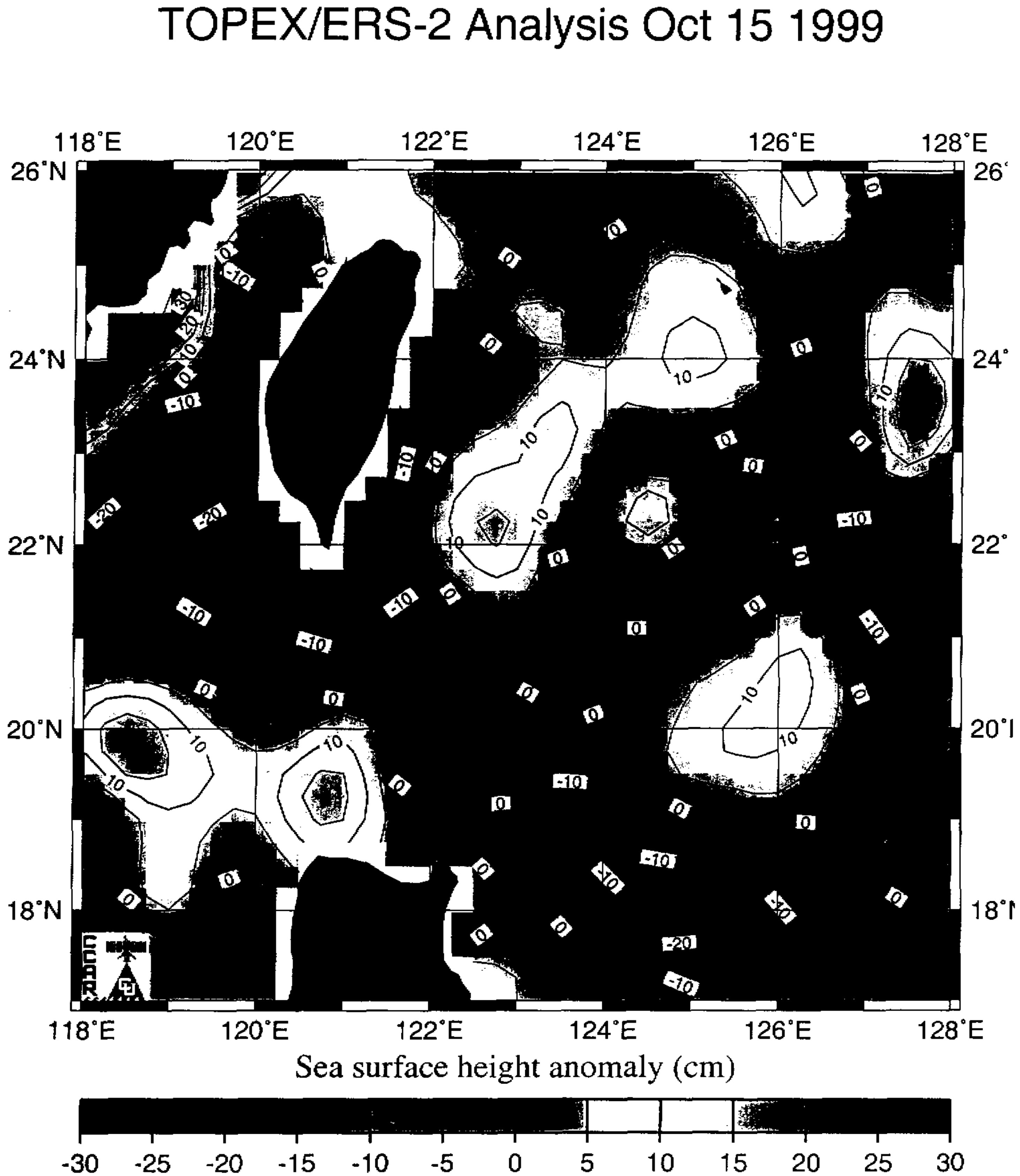

Current Vectors at Depth 16 m
During October 11~16, 1999
118°E
120°E
122°E
124°E
126°E
128°E
26°N
24°N
22°N
20°N
18°N
100 cm/s

fig. 2



TOPEX/ERS-2 Analysis Oct 15 1999
118°E
120°E
122°E
124°E
126°E
128°E
26°N
24°N
22°N
20°N
18°N
Sea surface height anomaly (cm)
-30
-25
-20
-15
-10
-5
0
5
10
15
20
25
30

fig. 3

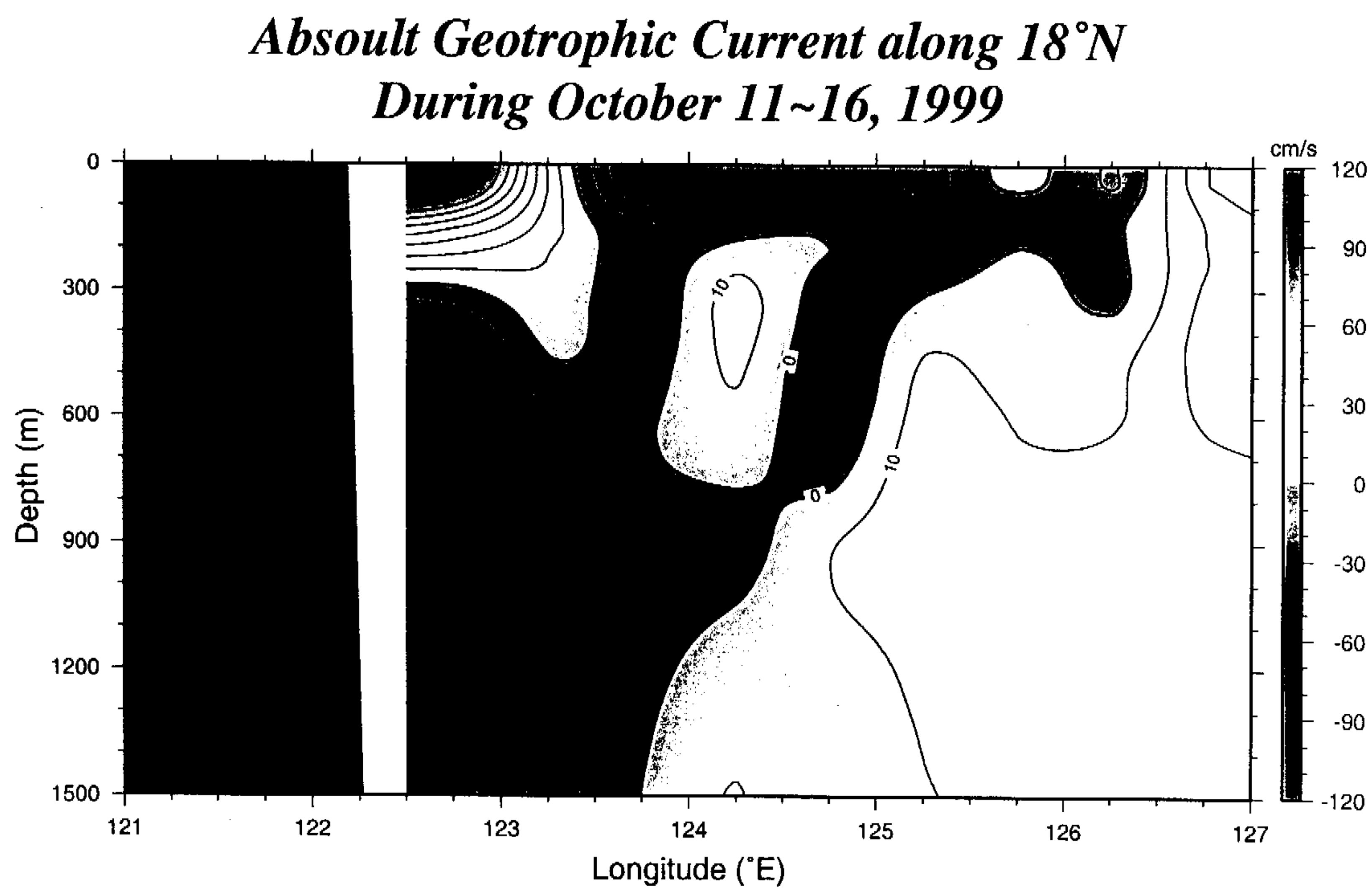

Absoult Geotrophic Current along 18°N
During October 11~16, 1999
Depth (m)
0
300
600
900
1200
1500
121
122
123
124
125
126
127
Longitude (˚E)
10
0
cm/s
120
90
60
30
-30
-60
-90
-120

fig. 4

Meridional Current along 18°N During October 11~16, 1999

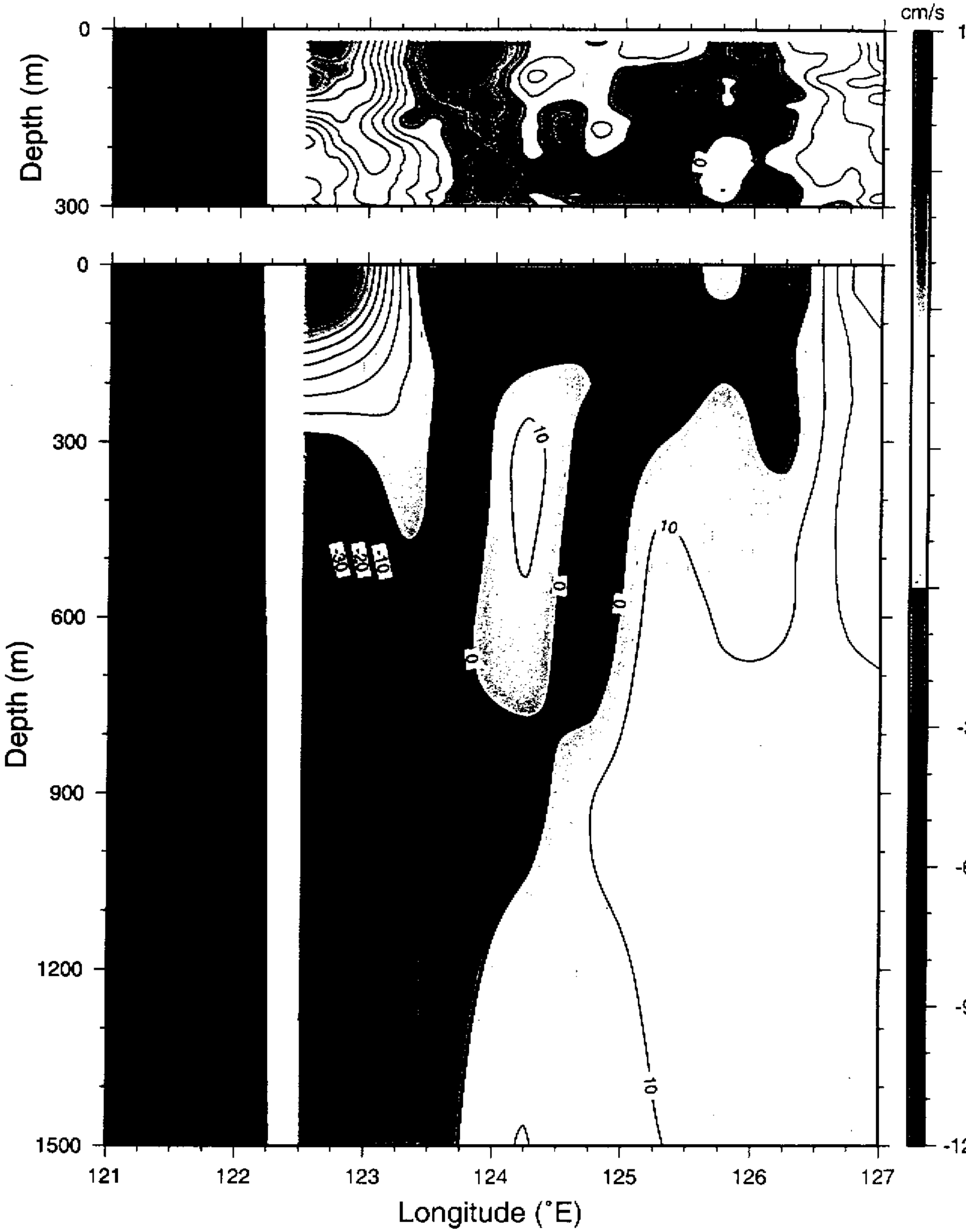


fig. 5

Meridional Current along 23.5°N During October 11~16, 1999

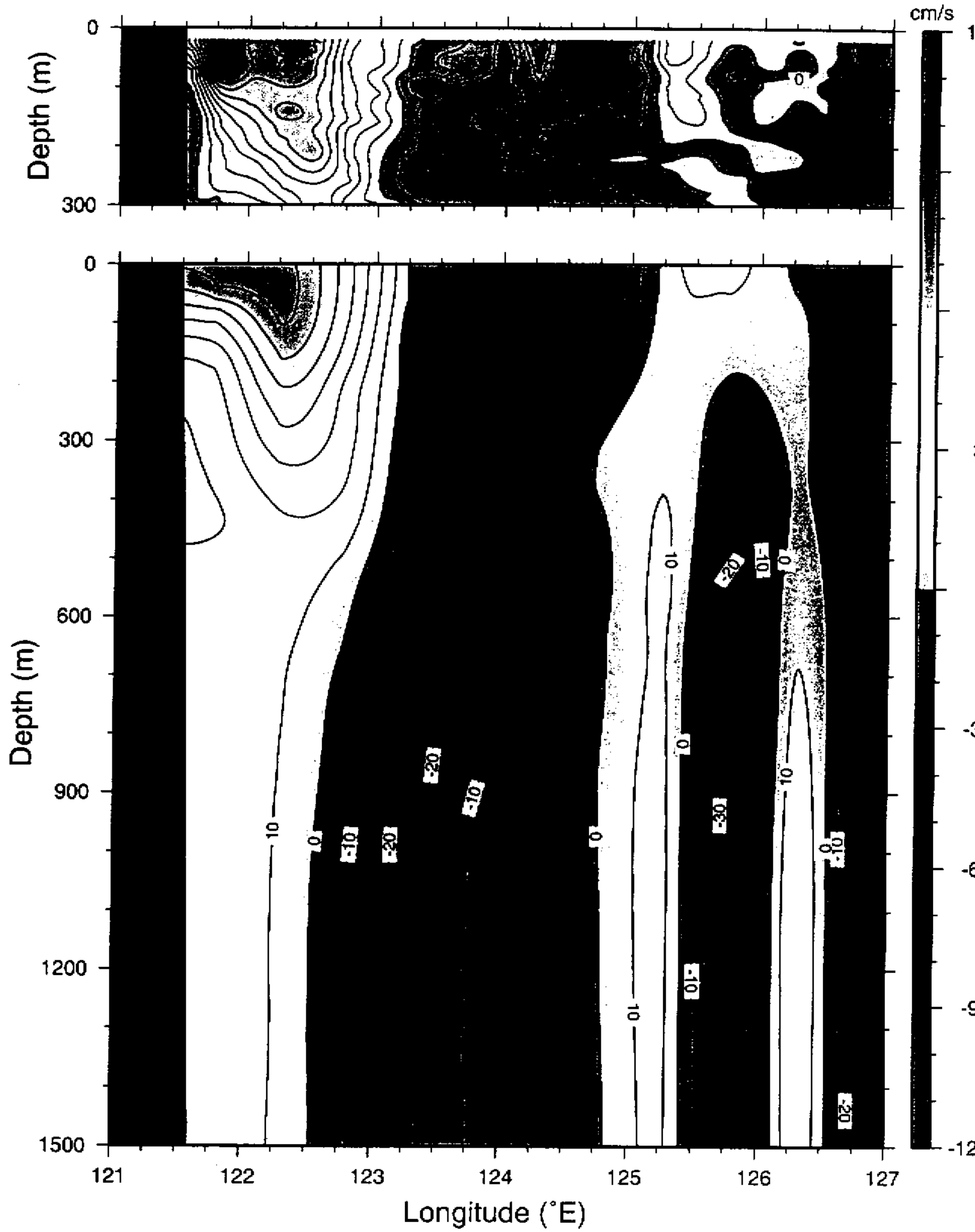


fig. 6

Composite Current Velocity Vectors at 20 m
SBADCP: 1991~2000

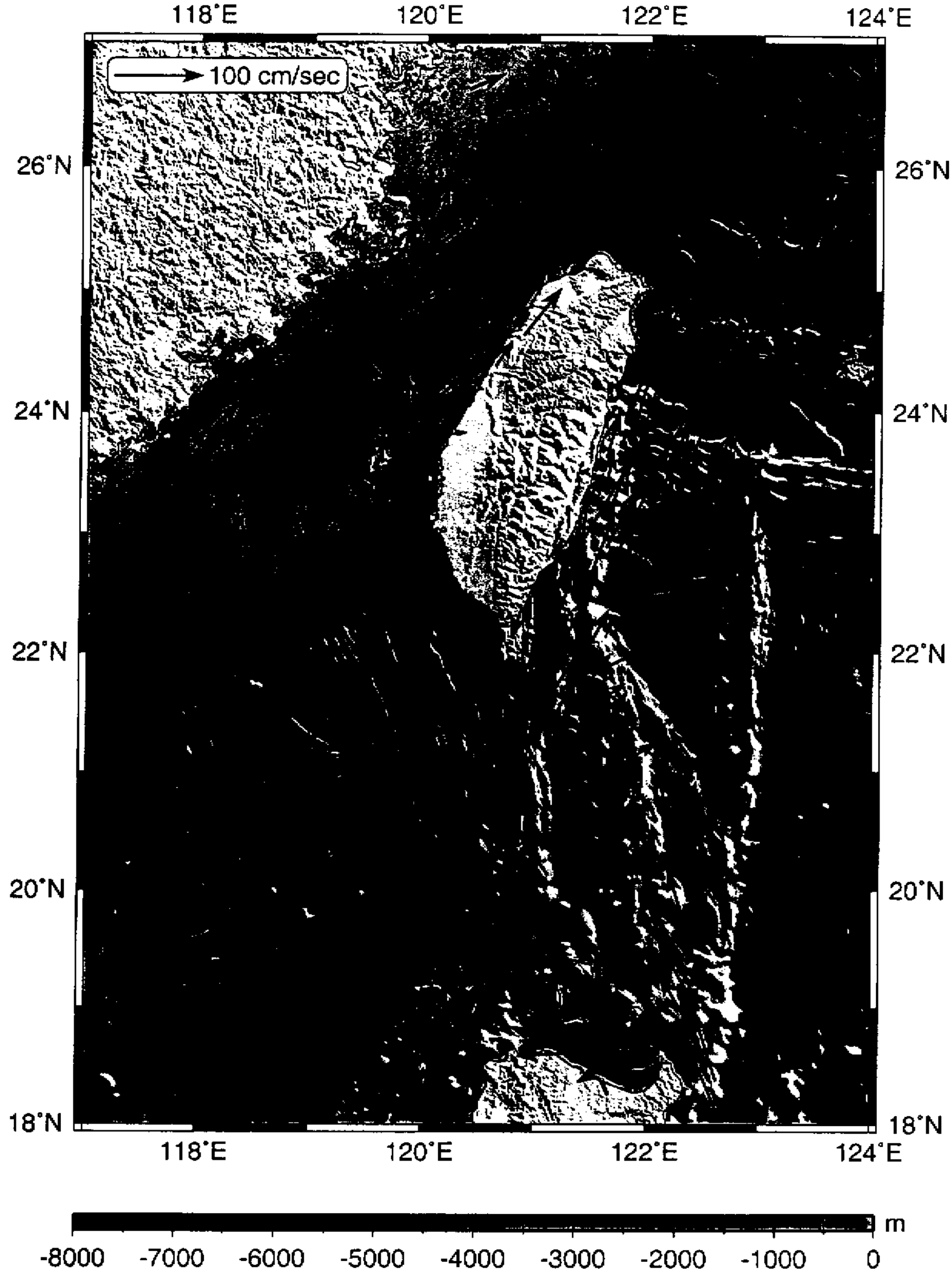


fig. 7

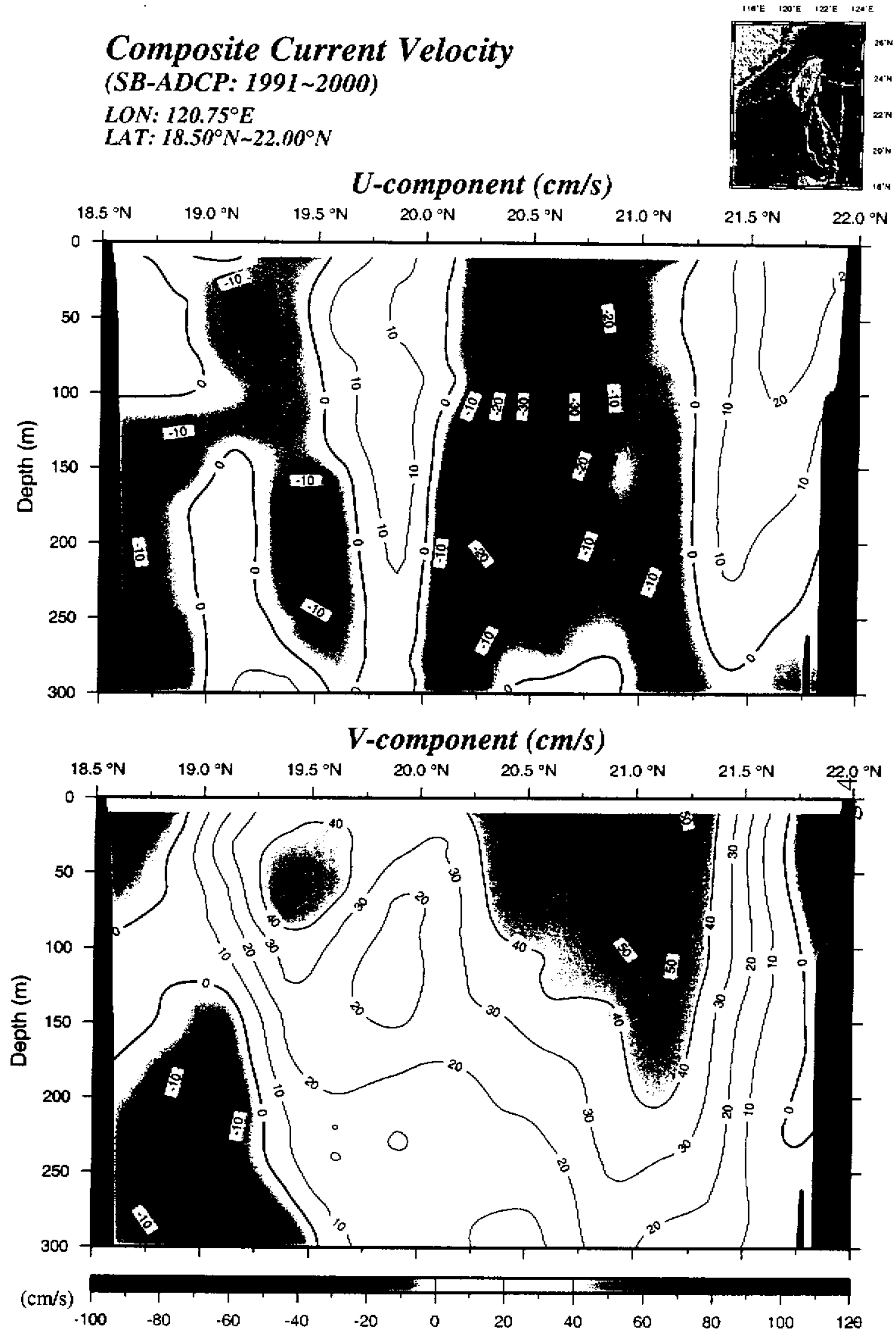

Composite Current Velocity
(SB-ADCP: 1991~2000)
LON: 120.75°E
LAT: 18.50°N~22.00°N
U-component (cm/s)
V-component (cm/s)
18.5 °N
19.0 °N
19.5 °N
20.0 °N
20.5 °N
21.0 °N
21.5 °N
22.0 °N
Depth (m)
0
50
100
150
200
250
300
(cm/s)
-100
-80
-60
-40
-20
0
20
40
60
80
100
120

fig. 8

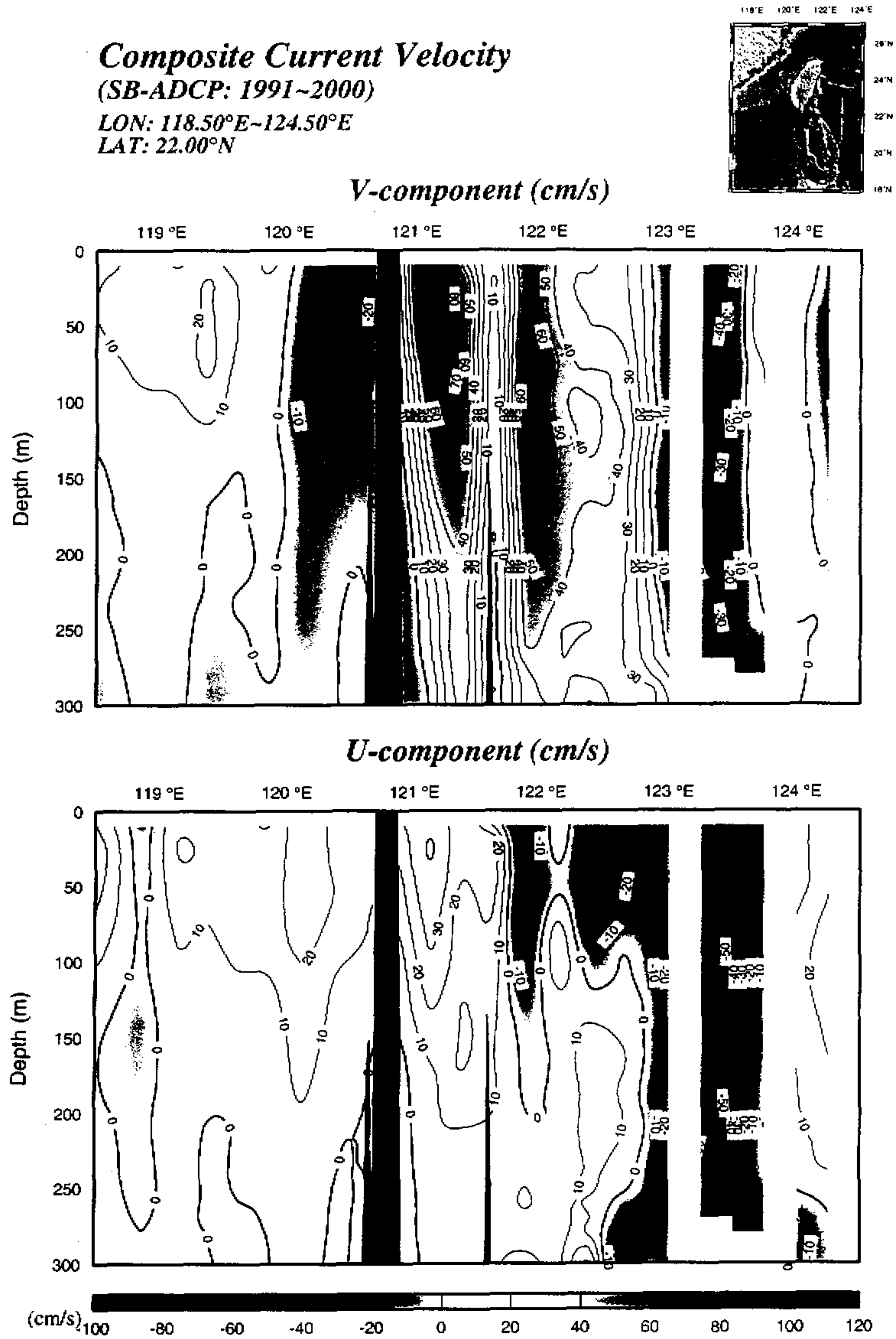
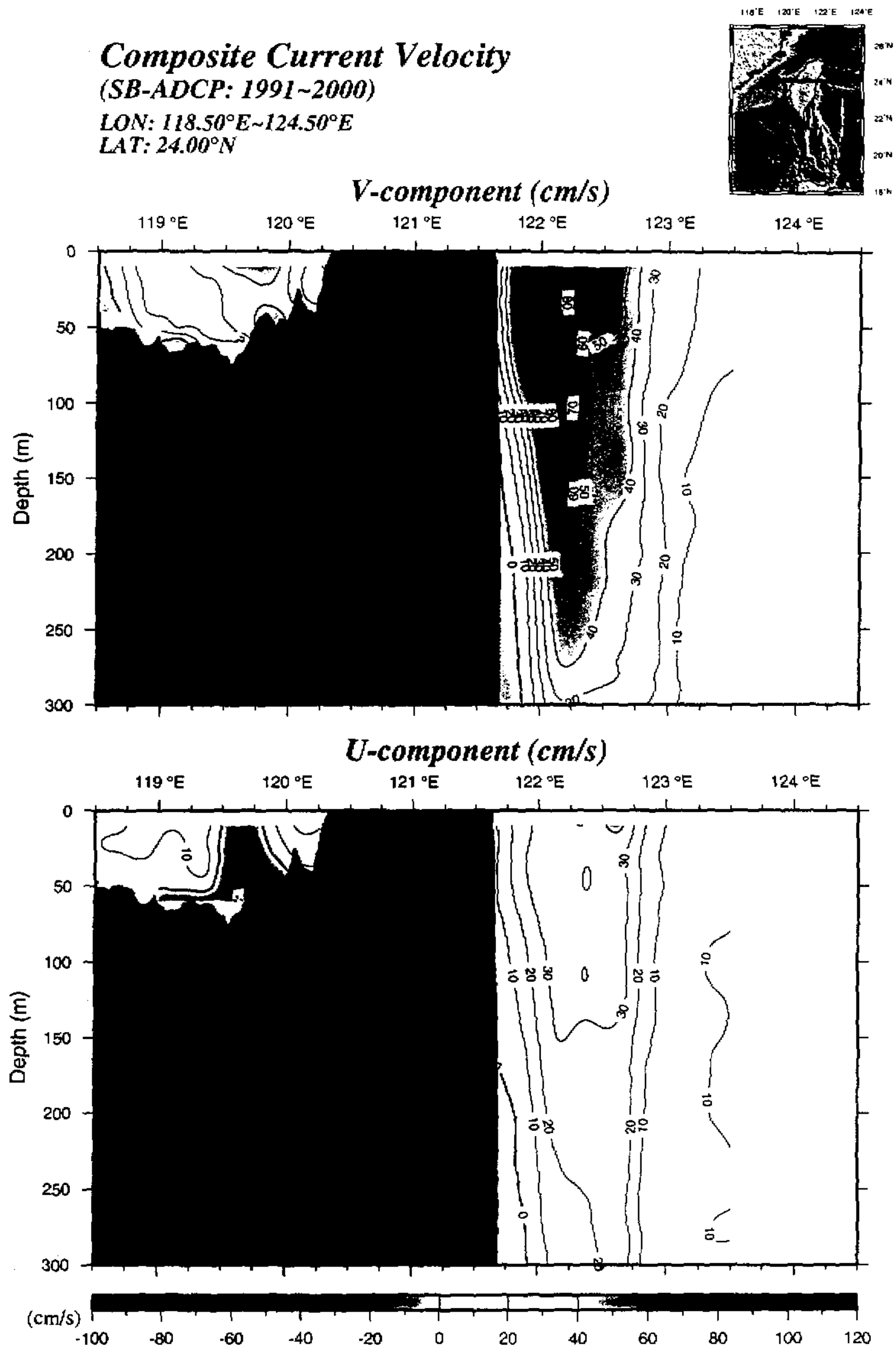

Composite Current Velocity
(SB-ADCP: 1991~2000)
LON: 118.50°E~124.50°E
LAT: 22.00°N
V-component (cm/s)
119 °E
120 °E
121 °E
122 °E
123 °E
124 °E
Depth (m)
0
50
100
150
200
250
300
U-component (cm/s)
(cm/s)
-100
-80
-60
-40
-20
0
20
40
60
80
100
120

fig. 9



Composite Current Velocity
(SB-ADCP: 1991~2000)
LON: 118.50°E~124.50°E
LAT: 24.00°N
V-component (cm/s)
119 °E
120 °E
121 °E
122 °E
123 °E
124 °E
Depth (m)
U-component (cm/s)
(cm/s)

fig. 10

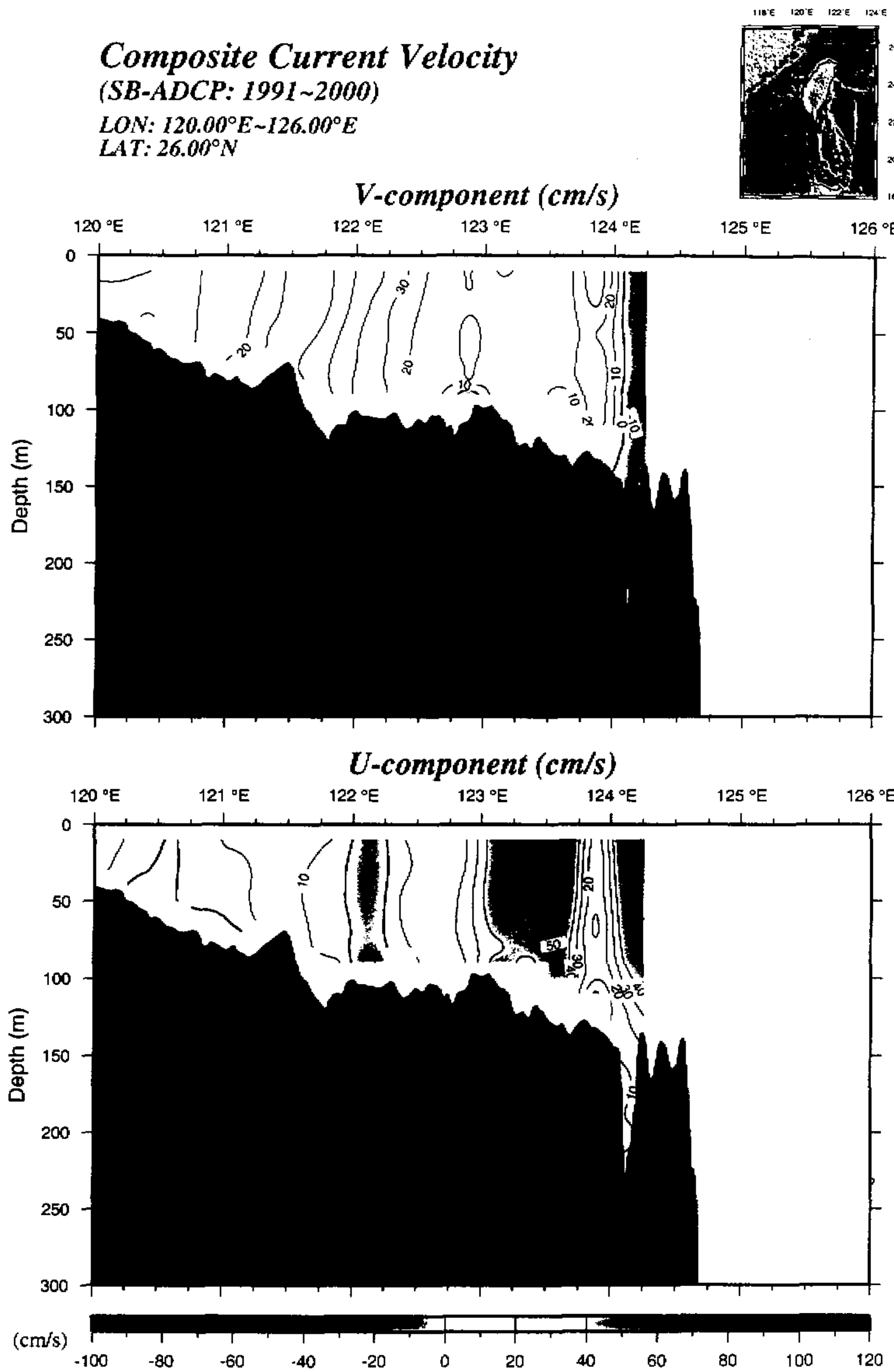

Composite Current Velocity
(SB-ADCP: 1991~2000)
LON: 120.00°E~126.00°E
LAT: 26.00°N
V-component (cm/s)
120 °E
121 °E
122 °E
123 °E
124 °E
125 °E
126 °E
Depth (m)
0
50
100
150
200
250
300
U-component (cm/s)
(cm/s)
-100
-80
-60
-40
-20
0
20
40
60
80
100
120

fig. 11

Moorings location

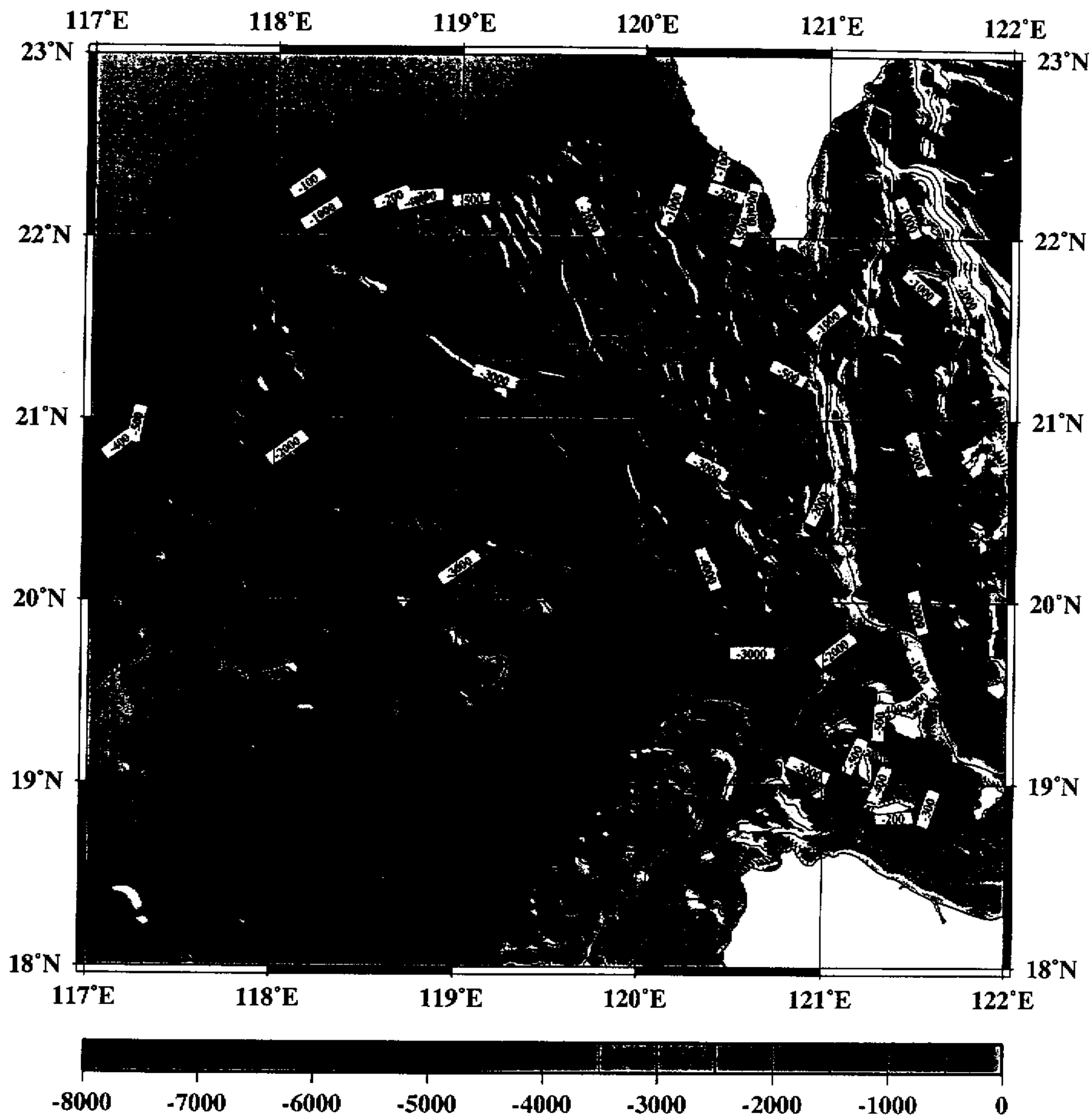


fig. 12

Velocity (cm/s)

Lon:118° 37.936′ E *Station:KA1*

Lat: 20° 23.008′ N

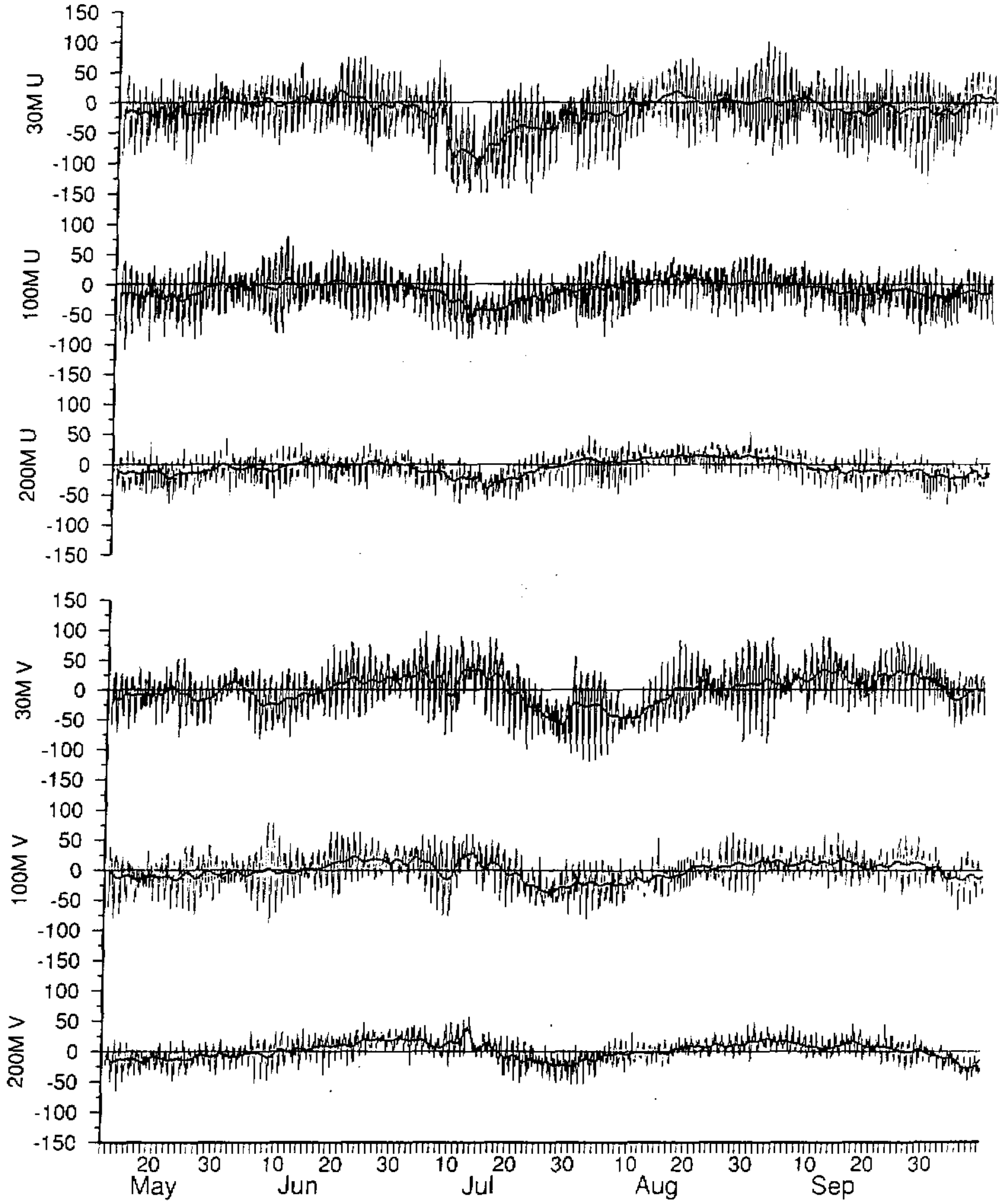


fig. 13