Journal of the Korean Society of Oceanography
Vol. 37, No. 3, pp. 160 — 168 September 2002

# Submarine Cable Measurements of Voltage for Current Monitoring in the Tsushima and in the Tokara Straits

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We have been measuring the voltage differences by using submarine cables in the Tsushima and in the Tokara Straits. The aim of these measurements is to estimate the volume transports of the ocean currents through those straits. In this paper, the voltage differences are compared with the corresponding sea level and air pressure differences between straits. Especially in the Tsushima Strait, the voltage difference is consistent with the air pressure difference as well as the sea level difference.

**Key words:** Tsushima warm current, Kuroshio, Electro-magnetic Induction, Submarine cable valtage

## INTRODUCTION

When seawater as a good conductor flows in the geomagnetic field, voltage difference is induced across the flow. Faraday mentioned this phenomenon soon after discovering his famous law of electromagnetic induction. Several attempts have been made to measure voltage differences across straits for monitoring the ocean currents. Near Japan, other groups have been measuring voltage differences with submarine cables between Hamada and Pusan (Lyu *et al.*, 2001), between Naoetsu and Nakhodka (Palshin *et al.*, 2001), between Okinawa and Taiwan, between Okinawa and Luzon, between Miyake-Jima and Hachijo-Jima, and between Fukushima and Imabetsu in the Tsugaru Strait (Rikiishi et al., 1997). Unfortunately the measurement between Miyake-Jima and Hachijo-Jima has been interrupted by the eruption of Miyake-Jima, and the one between Fukushima and Imabetsu was abandoned because the submarine cable was removed.

The Nippon Telegraph and Telephone West Corporation allowed us to use some submarine cables, which were replaced with optical fiber cables and retired a few years ago, for monitoring the ocean currents. We began to measure the voltage difference between Nogita and Iki on November 1, 1996. Nogita is located in northern Kyushu and about 20 km distant from Fukuoka city.

The brief history of our measurement is shown in Table 1. Fig. 1 shows the locations of submarine cables used for the measurement and the locations of tidal stations of the Hydrographic Department of Japan Coast Guard. At the tidal stations the sea levels and the air pressures are measured. The Kuroshio and a part of the Tsushima Warm Current cross these cables.

## MEASUREMENT

We have been measuring the voltage differences in the Tsushima and in the Tokara Straits by using four submarine cables whose properties are show in Table 2. These cables are no longer in use for the telecommunication. The measuring system at Kagoshima

**Table 1.** History of measurement

| | |
|---|---|
| Nov. 1, 1996 | Nogita-Iki |
| Nov. 10, 1998 | Nogita-Iki-Tsushima |
| Jan. 21, 1999 | Kagoshima-Naze and Kagoshima-Yaku-Shima |
| Sept. 9, 1999 | PC at Kagoshima station failed. |
| May 16, 2000 | PC was replaced. |

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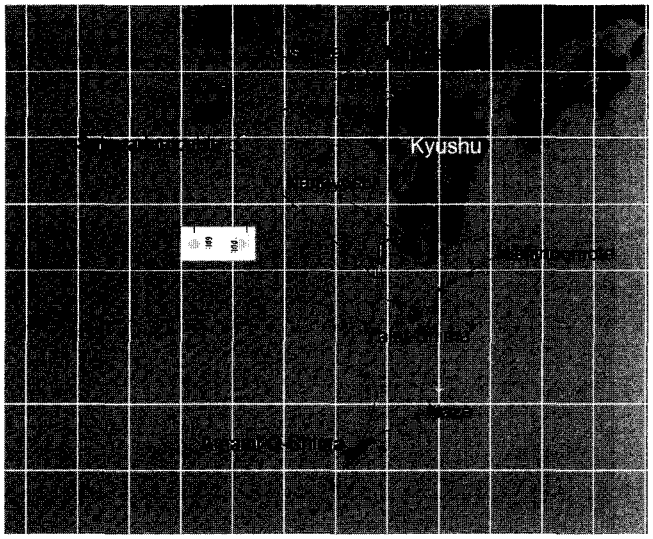


**Fig. 1.** Locations of submarine cables and tidal stations.

**Table 2.** Properties of submarine cables

| Interval | Type | Cable length |
|---|---|---|
| Nogita-Iki | CS-36M-S | 52.709 km |
| Iki-Tsushima | CS-36M-S | 82.046 km |
| Kagoshima-Yaku-Shima | CS-36M-D1 | 204.564 km |
| Kagoshima-Naze | CS-36M-D1 | 470.352 km |

(Nagayoshi) station is shown in Fig. 2. Kagoshima station is located in southern Kyushu and is the termination of the submarine cables from Yaku-Shima and Naze. The voltages are measured every 5 seconds by two digital multimeters (Keithley Model 2000). These multimeters are connected to a PC running under Linux operating system as shown in Fig. 2. Ten minutes average values of the voltages are calculated to reduce high frequency noise and stored in the PC every 10 minutes. We can get the voltage data any time by means of the telephone line. The measuring system at Iki station is similar to this system except that PC is running under the MS-DOS.

## DATA

First we show the voltage difference between Nogita and Tsushima and the sea level difference between Hakata (Fukuoka city) and Izuhara (Tsushima) in Fig. 3. Since there is no tidal station in Iki, we use the voltage difference between Nogita and Tsushima that is the sum of voltage differences between Nogita and Iki and between Iki and Tsushima. The positive voltage corresponds to the north-eastwards current. Both lines in Fig. 3 are 25 hours moving averages. The 25 hours moving average is a kind of lowpass filter and its frequency response is shown in Fig. 4. It seems that the agreement of both data is fairly good in Fig. 3. This may mean that the current is geostrophic and proportional to the sea level difference. The raw data of the voltage between Nogita and Tsushima and the sea level difference between Hakata and Izuhara are shown in Fig. 5. From Fig. 5, it is obvious that the amplitude of the voltage has been gradually decreasing, while the one of the sea level difference is steady. To consider quantitatively, the amplitude gain, which is the ratio of the standard deviation of the voltage to the one of the sea level difference, is shown in Fig. 6. It is considered that the change of conductivity of the seawater causes the change of output voltage since the seawater, seabed and submarine cables compose an electric circuit. For purpose of comparison, average salinity in the East

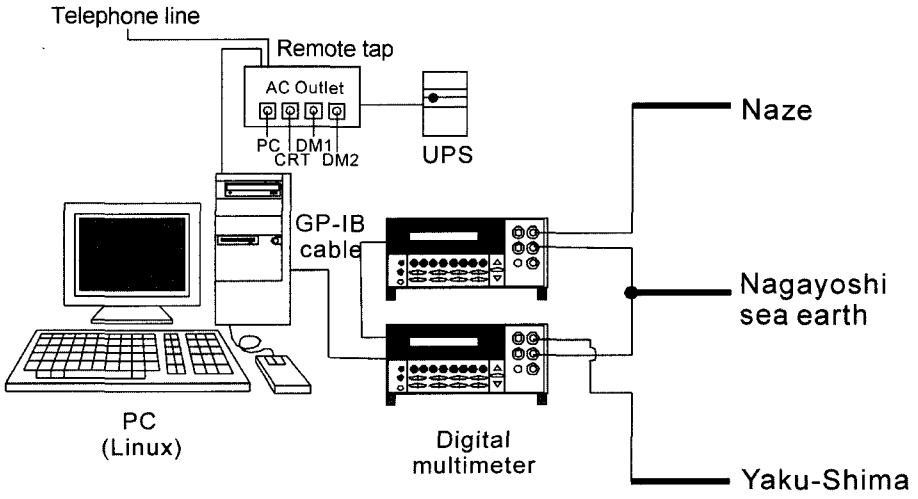


**Fig. 2.** Schematic diagram of measuring system at Kagoshima station.

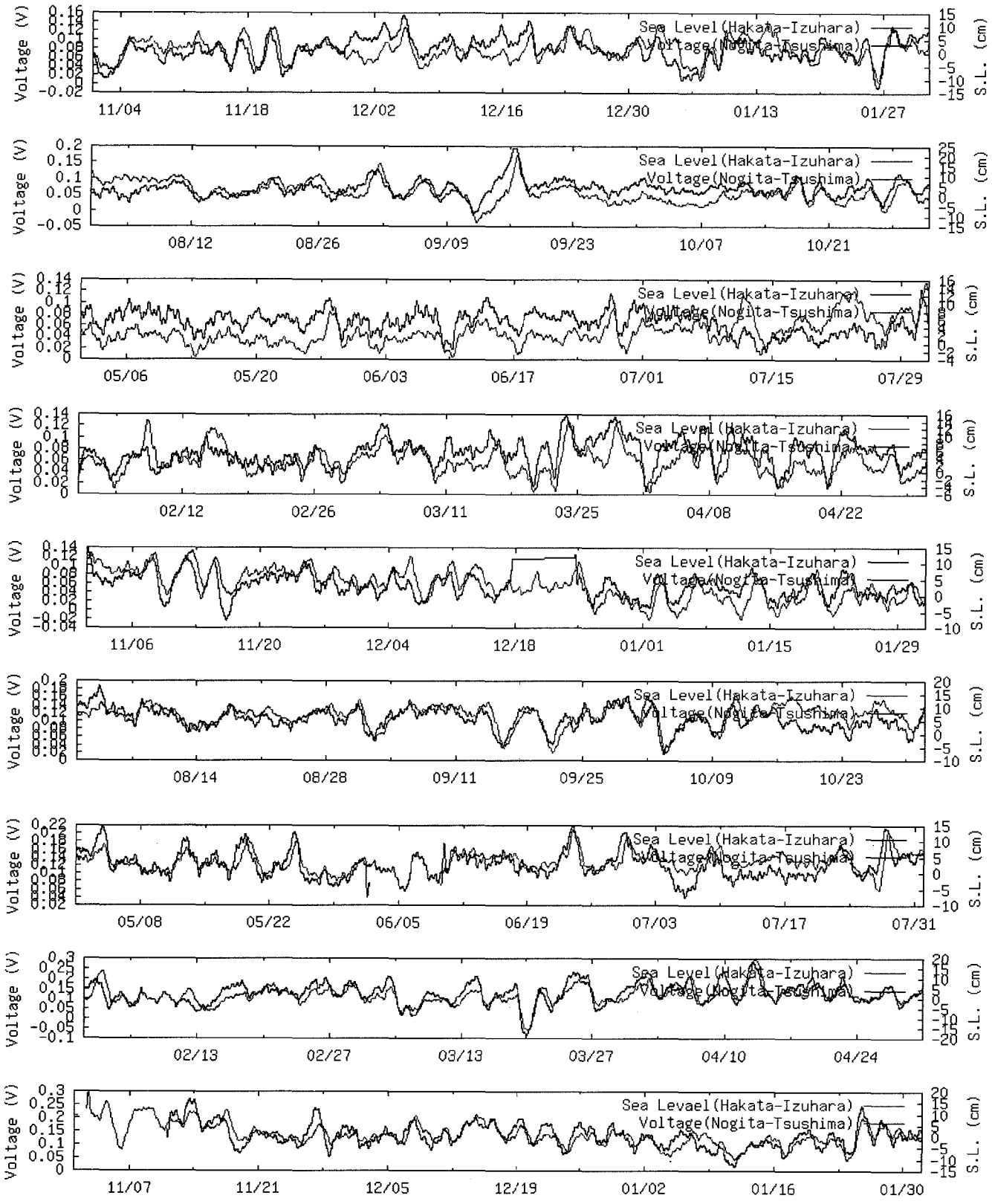


**Fig. 3.** Comparison of voltage between Nogita and Iki (black line) and sea level difference between Hakata and Izuhara (gray line) from Nov. 1998 to Dec. 2000. Both lines show 25 hours moving averages.

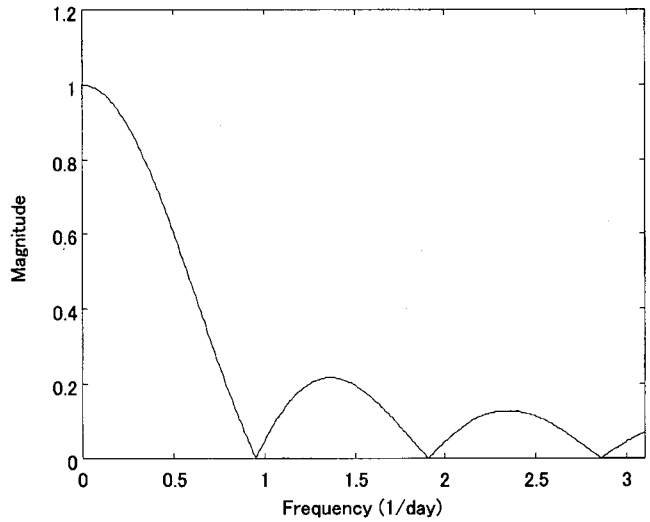


**Fig. 4.** Frequency response of 25 hours moving average filter.

Channel of the Tsushima strait is also shown in Fig. 6 since the salinity is closely related to the conductivity of the seawater. However, it is difficult to conclude that the decrease of the voltage amplitude is due to the change of the salinity from Fig. 6. Though it is difficult to specify the reason for the decrease of the voltage amplitude at present, we suppose the deterioration of submarine cable system have caused this phenomenon.

Second we show the air pressure difference between Hakata and Izuhara and the voltage difference between Nogita and Tsushima in Fig. 7. The air pressure difference is mean daily value and the voltage difference is same as in Fig. 3. It seems that the agreement of both data is fairly good in Fig. 7 as well as in Fig. 3. This agreement may mean that the Tsushima Warm Current in the East Channel is strongly affected by the air pressure difference or the corresponding wind. Moreover, the comparison of the

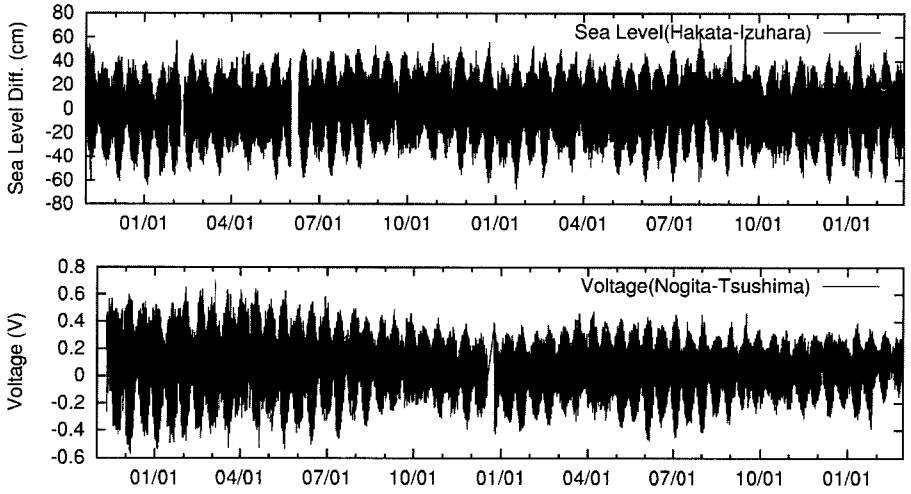


**Fig. 5.** Time-series of voltage between Nogita and Tsushima and sea level difference between Hakata and Izuhara from Nov. 1998 to Feb. 2001 (raw data).

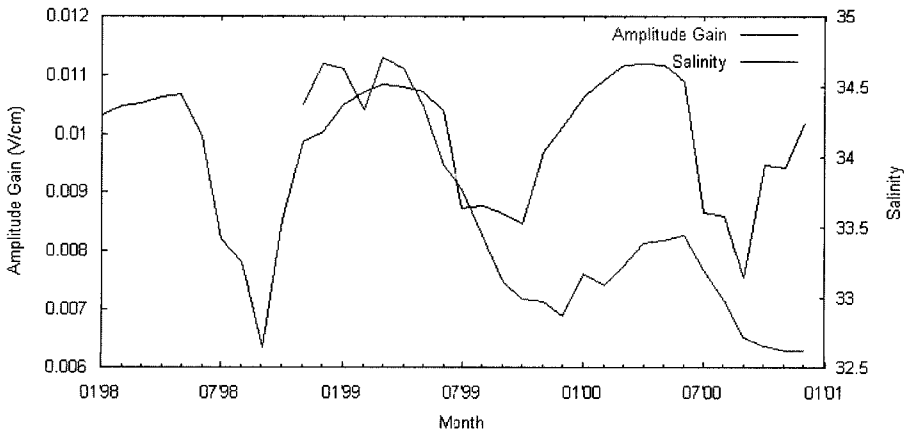


**Fig. 6.** Voltage amplitude gain between Hakata and Tsushima (gray line) and mean salinity in the East Channel of the Tsushima Strait (black line).

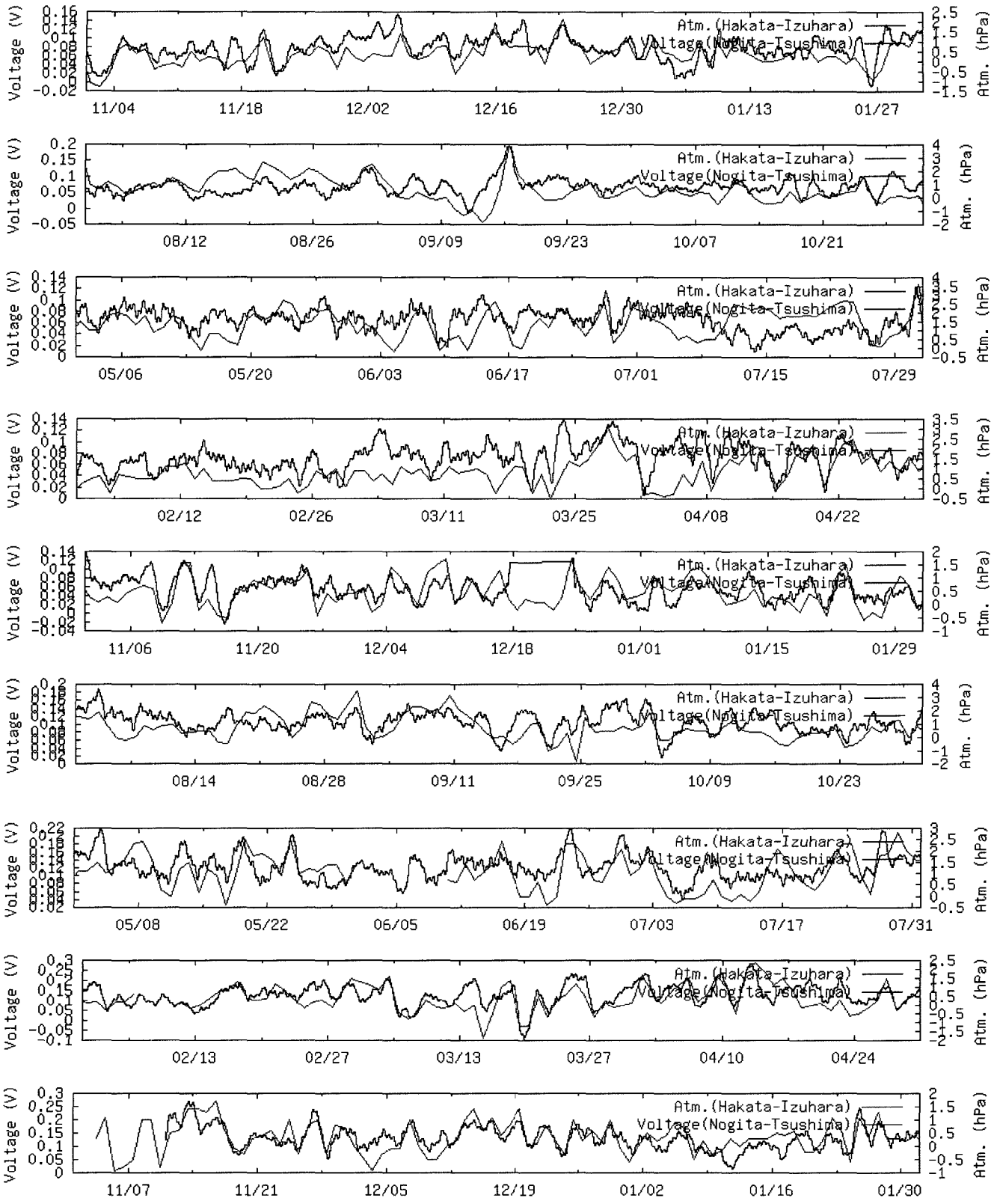


**Fig. 7.** Comparison of voltage between Nogita and Tsushima (black line) and air pressure difference between Hakata and Izuhara (gray line) from Nov. 1998 to Jan. 2001.

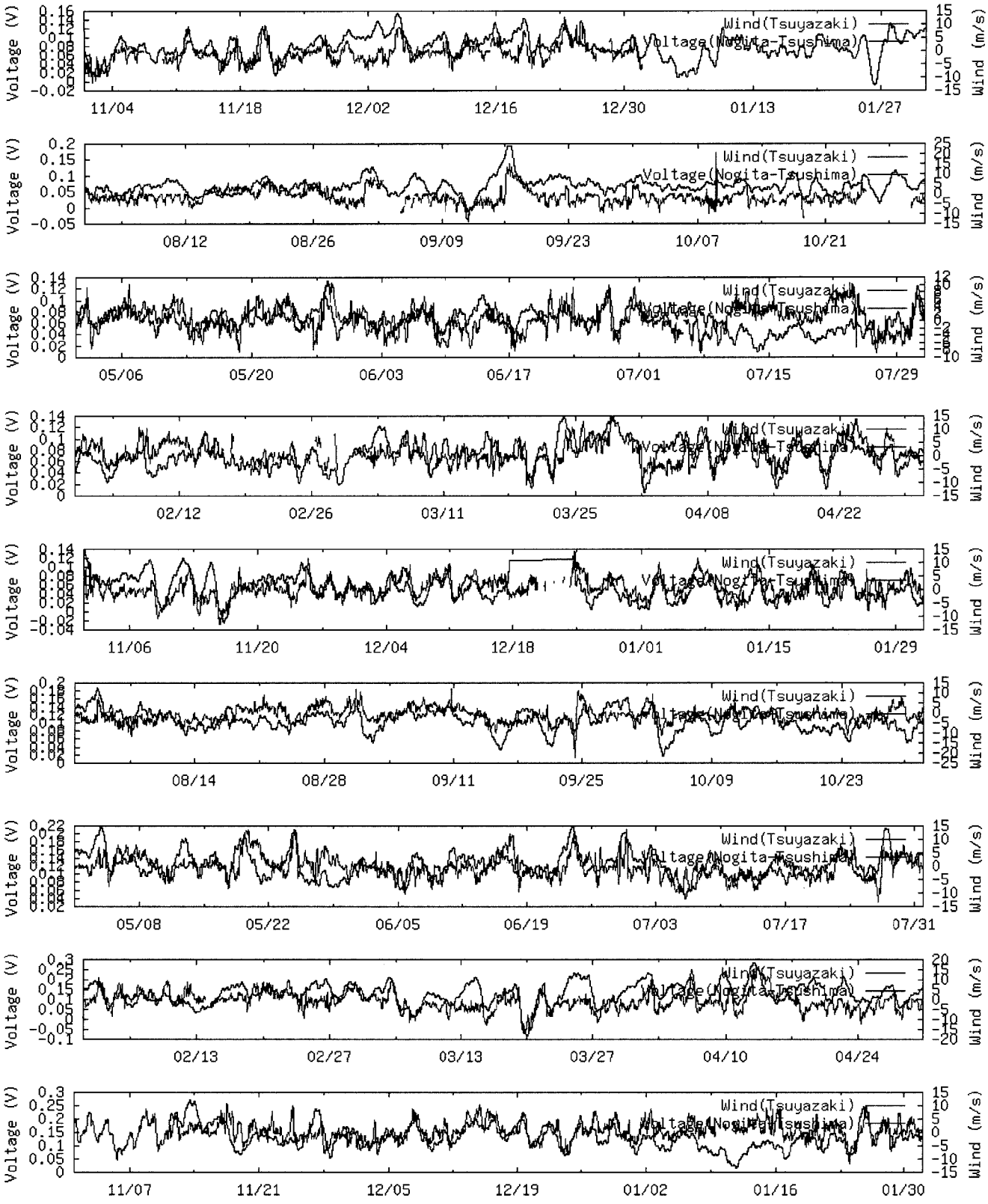


**Fig. 8.** Comparison of voltage between Nogita and Tsushima (black line) and wind speed (south-west component) at Tsuyazaki station (gray line) from Nov. 1998 to Dec. 2000.

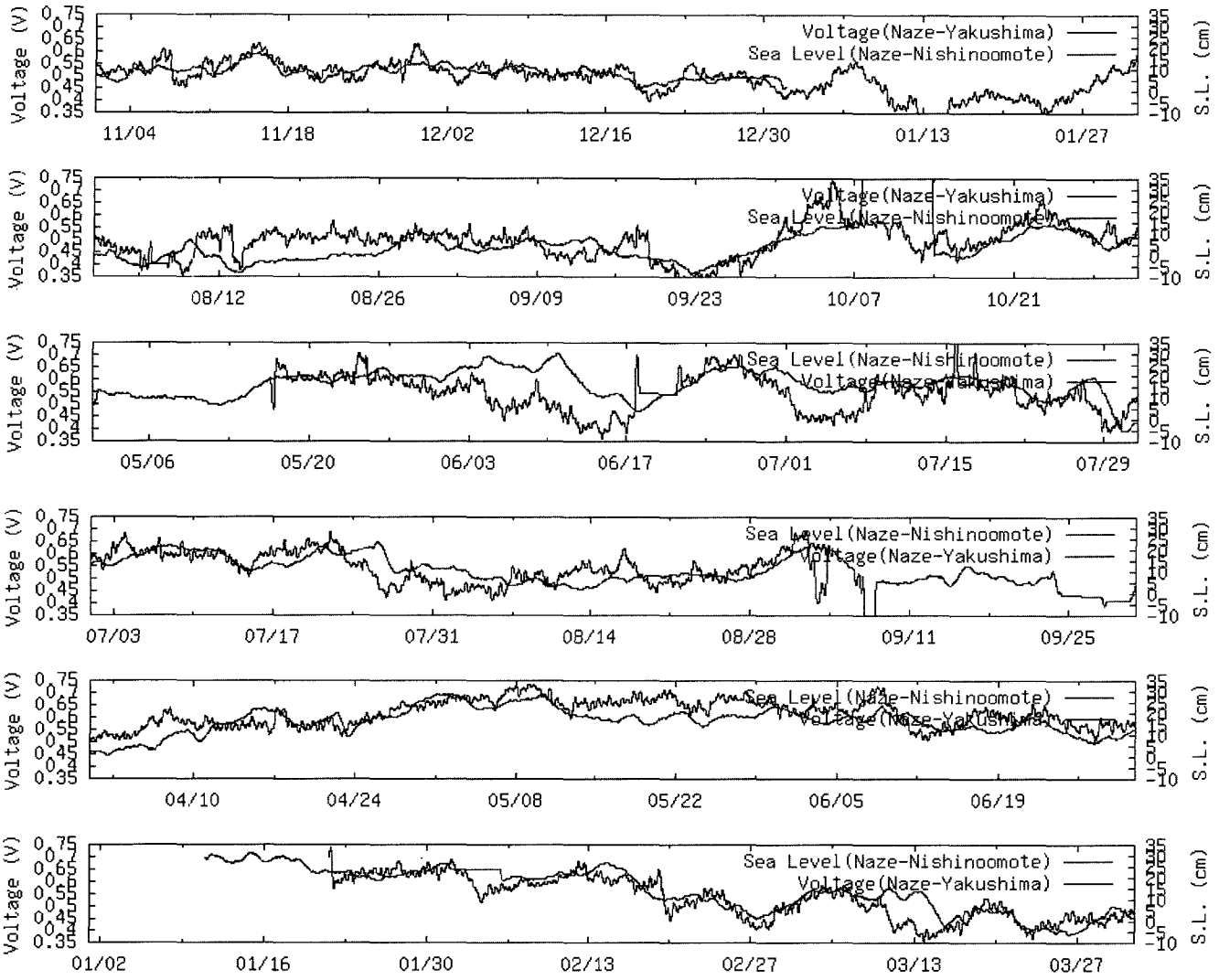


**Fig. 9.** Comparison of voltage between Naze and Yaku-Shima (black line) and sea level differences between Naze and Nishinoomote (gray line). Lower three figures are from Jan. to Sept. 1999, and upper three figures are from May to Dec. 2000.

voltage between Nogita and Tsushima and the wind speed measured at Tsuyazaki station of RIAM is show in Fig. 8. The wind speed shown in Fig. 8 is the south-west component, which is parallel to the flow direction of the Tsushima Warm Current. Tsuyazaki station is a marine observation tower and 17 km north of Hakata tidal station.

Third we show the sea level difference between Nishinoomote and Naze and the voltage difference between Naze and Yaku-Shima in Fig. 9. Nishinoomote is located in southern Tane-ga-Shima that is an island near Yaku-Shima. There are no data from September 4, 1999 to May 15, 2000 because of the failure of the PC at Kagoshima station. We are measuring voltage differences between Kagoshima and Yaku-Shima and between Kagoshima and Naze as shown in Fig. 1, however, it is doubtful that the voltage of the sea earth at Kagoshima station corresponds to the ground since it is shared with a relay equipment of optical fiber submarine cables operating actively. To eliminate the uncertainness of the sea earth at the Kagoshima station, we use the voltage difference between Naze and Yaku-Shima, which is calculated by subtracting the voltage difference between Kagoshima and Naze from the one between Kagoshima and Yaku-Shima. Both lines in Fig. 9 are 25 hours moving averages. The agreement of both data is not so bad in Fig. 9.

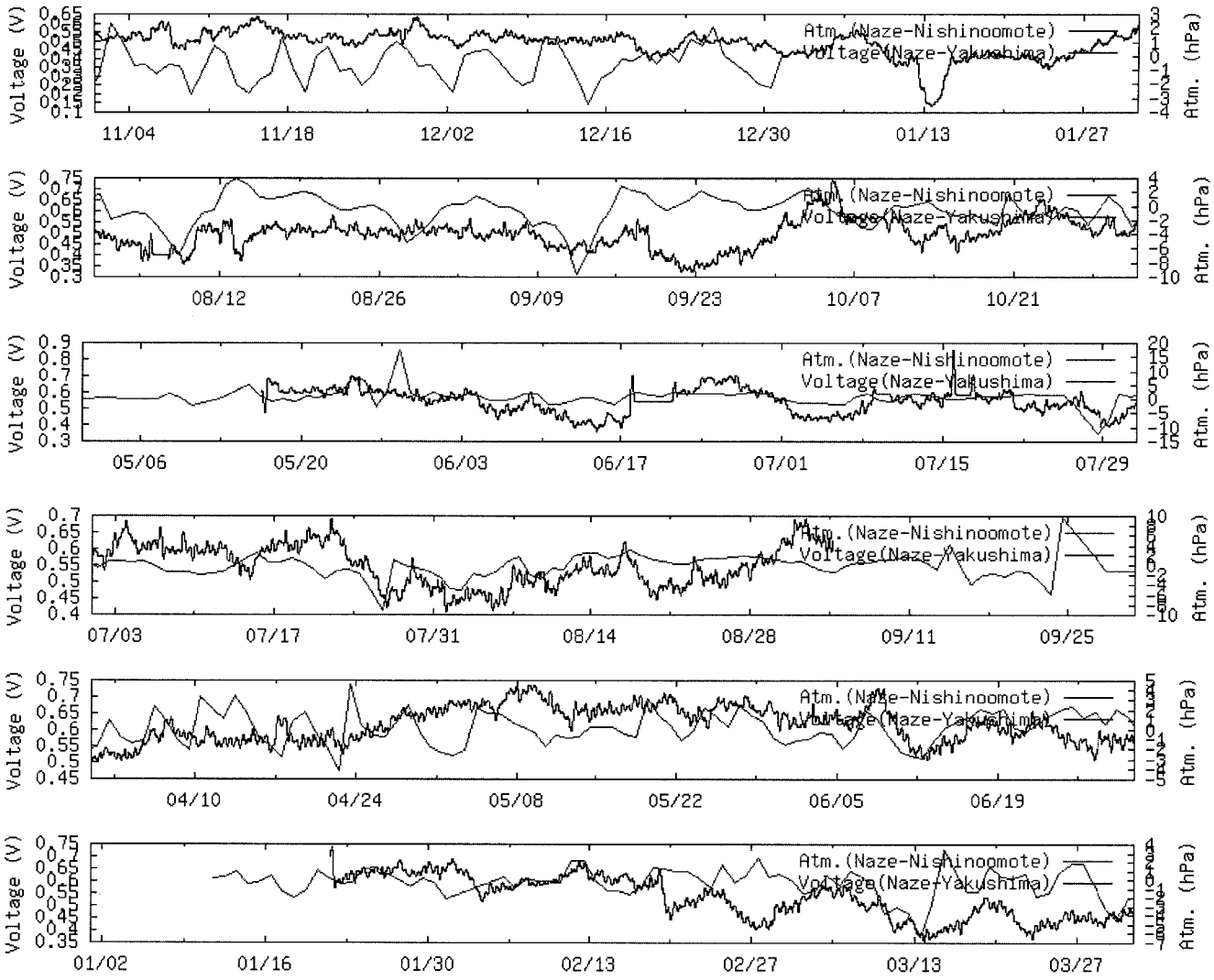


**Fig. 10.** Comparison of voltage between Naze and Yaku-Shima (black line) and air pressure difference between Naze and Nishinoomote (gray line). Lower three figures are from Jan. to Sept. 1999, and upper three figures are from May to Dec. 2000.

Last we show the comparison between the air pressure difference between Nishinoomote and Naze and the voltage difference between Naze and Yaku-Shima in Fig. 10. The voltage data are same as in Fig. 9 and the air pressure data are mean daily values. It seems that the Kuroshio is affected by the air pressure difference or the corresponding wind same as in the Tsushima Strait.

## CONCLUSION

By comparing the voltage data with the sea level and the air pressure differences, we showed that the voltage data reflect the ocean current signal very well and have a correlation with the air pressure difference. However, the circuit, which is composed of the submarine cable, the seawater, and the seabed, may be a time-varying system. Therefore more study is needed to estimate the volume transports from the voltage difference between the straits.

On our web site http://amami.riam.kyushu-u.ac.jp/~hashimot/index-e.html, our voltage data are shown and updated every day.

## ACKNOWLEDGEMENTS

This research has been supported by a grant of the Ministry of Education, Culture, Sports, Science and Technology, Japan. We would like to thank the Nippon Telegraph and Telephone West Corporation for the free loan of the submarine cables, the Hydrographic Department of Japan Coast Guard for supplying the data of

the tidal stations, Prof. A. Masuda and Mr. M. Ishibashi at RIAM Kyushu University for supplying the wind data of Tsuyazaki station, and Mr. M. Yoshida at Fukuoka Fisheries and Marine Technology Research Center for supplying the salinity data in the Tsushima Strait.

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Manuscript received April 11, 2001
Revision accepted August 20, 2002
Editorial handling: Yign Noh