Temporal and spatial variation of the conversion factor from the motion-induced voltage to the transport

K. Rikiishi, H. Matsuda, M. Michigami,
rikiishi@, hidekazu@, michigam@cc.hirosaki-u.ac.jp
Faculty of Science and Technology, Hirosaki University, Hirosaki 036-8561, Japan

Y. Hashimoto
hashimot@riam.kyushu-u.ac.jp
Research Institute for Applied Mechanics, Kyushu University, Kasuga 816-8580, Japan

１. Introduction

Motion of the seawater in the geomagnetic field induces the voltage as predicted by the theory of electro-magnetic induction. The motion- induced voltage increases with velocity or volume transport, and then it is possible to monitor time variation of an ocean current by measuring the cross-stream voltage using a submarine cable. Western part of the North Pacific is one of the best regions in the world to apply such a method, because there are many islands that are connected by telephone cables with each other. As of July 2000, 12 cables are being used to monitor temporal variation of the ocean currents around Japanese Islands.

Theoretical basis for this method was established by, for example, Longuet-Higgins et al. (1954). When the current is vertically and horizontally uniform, the theory is rather straightforward and the voltage is directly related with the velocity or volume transport. If the current is horizontally uniform but varies with depth, then the voltage is related with the vertical mean velocity. Horizontal structure of the current, both in the cross- and down- stream directions, modifies the voltage, but its effects are believed to be generally small provided that the cable covers a relatively short distance. The voltage is also affected by the resistivity of the seawater and the seabed. Accordingly, the voltage may vary with increasing temperature or salinity of the seawater, and its magnitude depends on the electric structure of the seabed or earth's crust.

However, precise information on the seabed conductivity and the horizontal and vertical structures of the current is not generally available a priori. It is therefore difficult to predict the magnitude of motion-induced voltage. Under these circumstances, it is reasonable to compare observations of the voltage with those of the transport so that we may determine an empirical relation or calibration factor between them.

In this paper, we first determine an empirical voltage – transport relation for the Tsugaru Strait, for which direct observations of the transport are available. Then we proceed to the cases of the Izu Islands region and the Tokara Strait for which the direct observation of transport is not available. In these cases, we compare tidal signals of the voltage with the tidal currents obtained from a numerical tidal model. Discussion will be given of why the calibration factor thus determined differs considerably from region to region and why it varies with time.

2. Voltage calibration factor for the Tsugaru Strait

Tsugaru Strait separates Hokkaido from Honshu (Japanese Main Island) and connects the Sea of Japan with the Pacific. In the Tsugaru Strait, both the amplitude of tidal current and the ocean current (sub-tidal current) are greater than 1 m/s in the western ends of the strait. The motion-induced voltage across the Tsugaru Strait was measured during the period February 1994 – July 2000, with several times of breaks. The voltage was measured at intervals of about one second, and 10-minute averages were automatically transmitted once a day to the remote laboratory by using telephone. We also monitored time variation of the geomagnetism so that we may estimate the effect of geomagnetic disturbances on the voltage.

According to the theory of geostrophic flow, the sea surface is expected to incline along the cross-stream direction. Then the daily mean values of voltage have been compared with those of the sea level differences between Tappi (Honshu) and Yoshioka (Hokkaido). A linear relation between them, with the voltage of 100 mv being corresponding to the sea level difference of 20 cm, was obtained, though some exceptions were seen which were ascribed to abnormal sea levels due to occasional storm surges. It was has also been that the voltage is considerably contaminated by geomagnetic disturbances. However, if we are concerned with the sub-tidal current with time scales larger than a couple of days, we can smooth out the geomagnetic effects by simply applying the moving average technique.

Then, we made direct observations of the volume transport by repeating the cross section at the western end of the Tsugaru Strait by using Acoustic Doppler Current Profiler (ADCP). It required 60 – 70 minutes for us to complete a section, and time variation of the transport reflected that of the tidal current. Some of the transport observations were effected by the geomagnetic disturbances, and we applied a statistical method to reduce the geomagnetic effects. From comparison of the transports with the voltages, we found a linear relation between them, with the voltage of 1 v being corresponding to the volume transport of 12 x $10^6 m^3/s$.

3. Voltage calibration factor for the Izu Islands region and the Tokara Strait

Direct observations of the transport are available only for the sea of shallow water, because the acoustic method is applicable to the depth shallower than 400 m. Also, it is not practical to cover a wide cross-section with a number of mooring stations. For the Izu Islands region and the Tokara Strait, therefore, it is difficult to make direct observation of the transport.

For these regions, it is suggested to use the tidal part of the voltage measurements. In general, the tidal current is vertically uniform while the velocity of ocean current (sub-tidal current) decreases considerably with depth. The tidal current is also rather uniform in the cross-stream direction while the ocean current is more or less concentrated. If we integrate the tidal current with respect to the depth and width, the tidal current transport becomes very large. For this reason, amplitude of the tidal signal of the voltage turns out to be very large. It is therefore possible to obtain a reasonable calibration factor by comparing the tidal signal of the voltage with the integrated tidal current that is available from a numerical tidal model.

In the Izu Islands region, we setup an observation station at Miyake Island to monitor the voltage between Oshima and Miyake Island and between Miyake and Hachijo Islands. In general, the voltage between Miyake and Hachijo Islands becomes very large when the Kuroshio flows between the two islands, and becomes very small when the Kuroshio flows south of Hachijo Island. Fig. 1 shows tidal signals of the voltage (Miyake - Hachijo Islands) for the year 1999, which are obtained by subtracting 25-hour running averages from the original hourly values. It shows clear alternations of the neap and spring tides at intervals of two weeks. The total amplitude of the tidal signals is roughly as large as 0.6 v at the spring tide, which is comparable with the range of the low-frequency variation of the voltage (about 0.8 v).

Recently, on the other hand, Matsumoto et al. (2000) have developed very fine tidal models in which tide gauge data and satellite altimeter data are assimilated into a full hydrodynamical model. Their high-resolution (5‘x5’) model for the region around Japan (NAO.99Jb model) has demonstrated a very high performance in terms of rms misfit. Accordingly, we have reproduced harmonic constants (amplitude and phase) of the tidal current for eight major constituents (M2, S2, N2, K2, K1, O1, P1, Q1) from their model in order to calculate the barotropic tidal current. The eastward component of the tidal currents are integrated from the surface to the bottom along the meridian 139 54’ E (33 00’ – 34 12’ N) to obtain the tidal current transport. Obviously, the tidal transport changes its direction with time and no net transport is expected after all.

If we compare the tidal current transport with the tidal signals of the voltage (Fig. 1), then we can see that both coincide very well in terms of tidal phase such as ebb and flood, and neap and spring tides (figure not presented). This suggests that we can indeed obtain the calibration factor by comparing the two envelopes. We have thus found that the voltage of 1 v corresponds to the volume transport of 60 x $10^6 m^3/s$. Note that this value is about 5 times as large as the calibration factor for the Tsugaru Strait.

The same method has been applied to the Tokara Strait, through which the Kuroshio flows from the East China Sea to the Pacific. The tidal current transport has been obtained by integrating the eastward component of the barotropic tidal current vertically and horizontally along the meridian 130 18’ E (28 24’ – 30 18’ N). We have compared the envelope of the voltage tidal signals (Yaku - Amami Islands) with that of the tidal transport, and have found that the voltage of 1 v corresponds to the tidal transport of about 25 x $10^6$$m^3$/s. Note that this value is about two times as large as the calibration factor for the Tsugaru Strait.

4. Discussion

Now that the calibration factor has been determined, the voltage observations may give us information on the variation of the transport of the Kuroshio. However, the cable from Miyake to Hachijo Islands does not necessarily cover the entire stream of the Kuroshio. In other words, the Kuroshio sometimes flows north of the Hachijo Island and sometimes south. Thus, variation of the voltage represents north-south migration of the Kuroshio axis rather than the variation of the Kuroshio transport. Accordingly, the maximum value of the voltage corresponds to the case in which the Kuroshio flows between the Miyake and Hachijo Islands, and the minimum to the case in which the Kuroshio flows south of the Hachijo Island. Therefore, the value of the maximum minus minimum voltage may represents the actual volume transport of the Kuroshio. Since the difference is about 0.8 v, we may conclude that the mean transport of the Kuroshio is about 48 x $10^6$$m^3$/s. This value is very consistent with former estimations from the hydrographic observations by assuming the motionless layer of 1,000m.

For the Tokara Strait, on the other hand, the cable from Yaku to Amami-Oshima Islands covers the entire stream of the Kuroshio. The variation of the voltage, therefore, may represent the variation of the Kuroshio transport. In other words, we can only estimate the range of variation of the transport, not the value of transport itself. It has been found that the range of variation of the Kuroshio transport is about 5 x $10^6$$m^3$/s in the Tokara Strait.

One of the most important findings of this study is the fact that the voltage calibration factor differs considerably from region to region. The calibration factor has been shown to be 12 x $10^6$$m^3$/s/v for the Tsugaru Strait, 60 x $10^6$$m^3$/s/v for the Izu Islands region, and 25 x $10^6$$m^3$/s/v for the Tokara Strait. Note that the calibration factor for the Tsushima Strait is about 12 x $10^6$$m^3$/s (Lyu and Kim, 2001). It is rather surprising that we have this large difference of the calibration factor, and we present some explanation below.

According to the theory of Longuet-Higgins et al. (1954), the voltage calibration factor k may be given by k = Ho (1+ Hs Cs/Ho Co)/Fz when the current is uniform in the horizontal space. Here, Fz represents the vertical component of the geomagnetism (almost constant value), Ho the water depth, Hs the penetration depth of the motion-induced electric current under the seabed, Co the resistivity of the sea water, and Cs the resistivity of the seabed. Since the tidal current is generally uniform in the horizontal space, the above theory may apply to our cases. Unknown factors in the above formulation are Hs and Cs.

We first assume that 1 >> (HsCs/HoCo), then the calibration factor reduces to simply k = (Ho/Fz). This follows that calibration factor only depends on the water depth. However, this expression fails to explain the actual difference of the calibration factor among the four regions. We next consider another extreme case of 1 << (HsCs/HoCo). In this case, k = (HsCs) / (FzCo). Since Hs and Cs may be constant values, the calibration factor may be inversely proportional to the resistivity of the seawater, which becomes the minimum in summer and the maximum in winter. In fact, the calibration factors for the three regions show a clear seasonal fluctuation with the maximum in summer and the minimum in winter, as suggested in Fig. 1. We may therefore conclude that the latter condition (1 << HsCs/HoCo) is the actual case.

We next assume, by following Longuet-Higgins et al. (1954), that Hs is nearly equal to the width of the strait, and substitute typical values for the water depth and width of the strait. We may then expect that the value for Cs of the Izu Islands region is almost as large as that of the Tsugaru Strait, and Cs for the Tokara Strait 5 times and Cs for the Tsushima Strait 10 times. Here ,Cs for the Tsugaru Strait must be less than a few ohm-cm owing to the constraint of 1 << (HsCs/HoCo).

Finally, it is noted that the calibration factor k for Oshima – Miyake Islands (where volcanic and seismic activities are observed) shows a gradual increase in these three years. We do not know whether this implies that the resistivity of the seawater is decreasing or that the resistivity of the seabed is increasing there.

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References

Longuet-Higgins, M., M. Stern, and H. Stommel, 1954: Pap. Phys. Ocean. Meteor.,13, 1-37.

Matsumoto, K., T. Takanezawa, and M. Ooe, 2000: J. Oceanography, 56, 567-581.

Lyu, S.-J., and K. Kim, 2001: Extended Abstract, OHP/ION Joint Sympojium, 236 – 240.

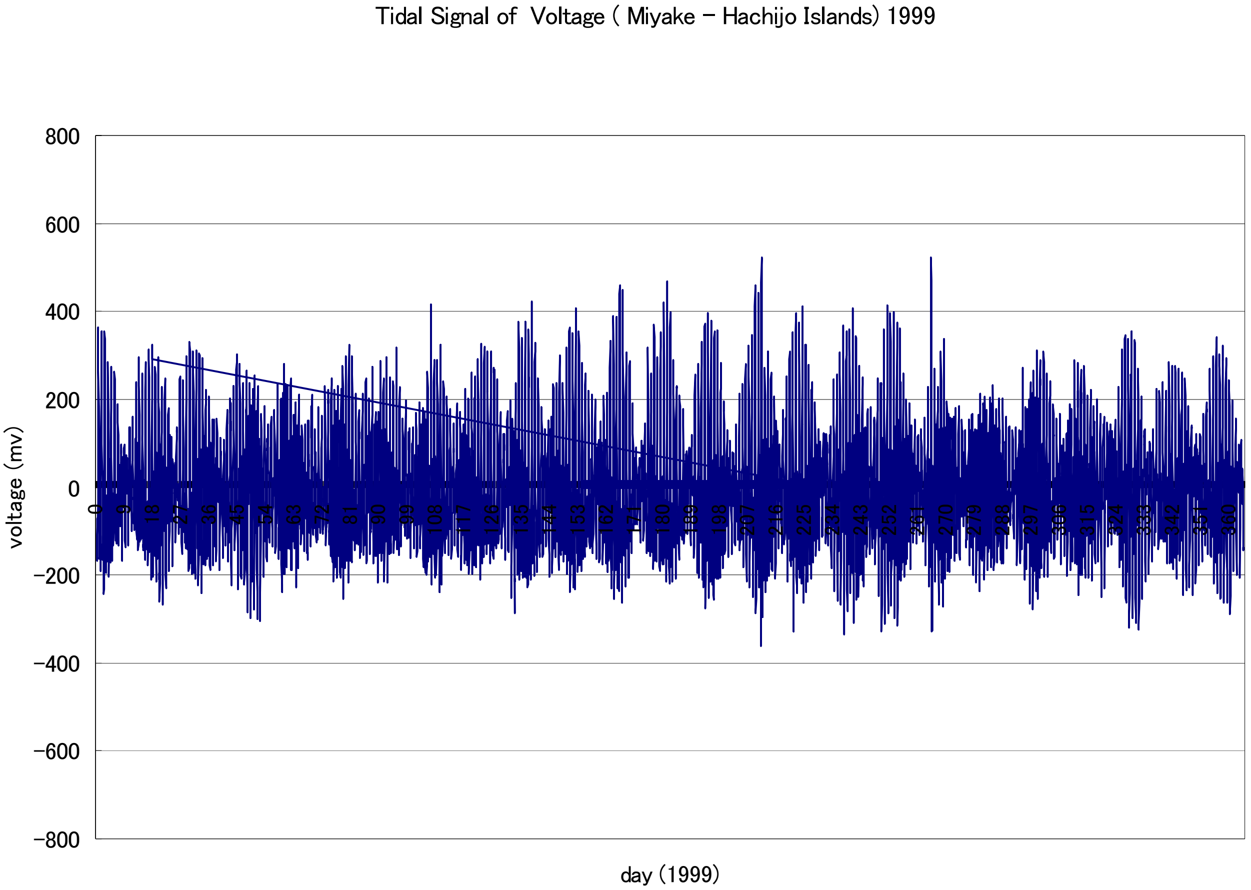

Fig. 1 Time series of high-pass filtered voltage between Miyake and Hachijo Islands for the year 1999.