Polar Meteorol. Glaciol., **18**, 19–29, 2004

Long-term and seasonal changes of the mean sea level at Syowa Station, Antarctica, from 1981 to 2000

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(Received January 30, 2004; Accepted July 6, 2004)

Abstract: Sea level has been observed since 1966 at Syowa Station, a Japanese Antarctic station located on East Ongul Island (39.6°E, 69.0°S). An almost continuous record has been obtained from 1981 to 2000 and analyzed to investigate long-term and seasonal changes of mean sea level. After correction of year-to-year variation of the datum, it is found that the annual mean sea level has been falling at a rate of 1.2 cm/year. This rate is bigger than previous estimations calculated from shorter records of sea level without appropriate datum adjustment, and also bigger than that expected from geological evidence. Based on discussion of the reasons for the trend, it is suggested that glacial rebound can not be excluded as the cause. The present analysis based on a long record for about 20 years also provides the amplitude (2.7 cm) and phase of the nodal tide with the period of 18.6 years. Characteristics of the seasonal change for the first half of the record (1981–1989) are different from those for the second half (1990–2000), associated with replacement of the observing system in 1990. Comparing with seasonal changes at other Antarctic stations and considering the results of previous studies, it is concluded that the seasonal change observed in the second half is more reliable, and that it reaches its maximum in April and minimum in October with an estimated annual tidal range of about 14 cm.

key words: Antarctic, sea level, tide, long-term trend, seasonal change

1. Introduction

The Japanese Antarctic Research Expedition (JARE) initiated tidal observations in 1966 at Syowa Station, a Japanese Antarctic research station located on the coast of East Ongul Island (39.6°E, 69.0°S). Although it is difficult to maintain long-term tidal observations in such a hostile environmental condition, an almost continuous sea level record has been obtained since the late 1970s (Michida, 1988).

Although there are some tidal stations in Antarctica, most of them provide short records except for the low latitude area of the Antarctic Peninsula, for example, a Ukrainian base, Vernadski Base (previously named Faraday Base of the UK) that has a long sea level record for more than 30 years since the 1960s (Peterson, 1988). Apart from the Antarctic Peninsula, however, there are few stations maintaining long-term record. Syowa Station is a unique station where sea level has been observed for longer than 30 years within the Antarctic zone.

Odamaki *et al*. (1991) analyzed the sea level data of Syowa Station from 1981 to 1987, and showed a trend in the annual mean sea level with a falling rate of about 1 cm/year. It has been suggested that the sea level fall is caused by a continuous rise of the crust around Syowa Station. As the rising rate of the crust estimated from geological features is about 0.4 cm/year (Kaminuma, 1986), other unknown causes of the sea level fall remain.

One of the important factors in discussing the long-term trend of sea level is the influence of the nodal tide, of which the period is 18.6 years and has a significant amplitude, particularly in high latitude, based on equilibrium tidal theory. A continuous sea level record at Syowa Station has been obtained from 1981 to 2000, and in this paper, this 20-year record is analyzed to investigate the long-term trend of mean sea level with reduced influence of the nodal tide.

With regard to seasonal changes, Nagata *et al*. (1993) analyzed the sea level record at Syowa Station from 1979 to 1989, calculated ten-year averages of monthly mean sea levels, and concluded that the annual range of monthly mean sea level was 26 cm. They also noted that sea level reached a maximum in early winter and falled to a minimum in mid-summer, and that the annual cycle was asymmetric. A couple of studies have attempted to explain the causes of the seasonal changes. Michida *et al*. (1996) examined the local effect of seasonal density changes upon the pressure gauge and estimated it at 2–3 cm. Ohshima *et al*. (1996) investigated the effects of the seasonal change of coastal current off Syowa Station and concluded that 7 cm could be explained by the baroclinic component and the rest might be due to the barotropic component caused by a barotropic coastal current. There seem to be still some unknown factors in the seasonal sea level range of 26 cm reported by Nagata *et al*. (1993).

After their analysis, the tide gauge with a strain gauge was replaced in 1990 with a new pressure sensor using a quartz oscillator that would be more accurate and stable. Annual profiles of the monthly mean sea level are different in the first and second halves of the 20-year record, associated with the change of the observing system (Odamaki *et al*., 1999). In this paper, we analyze the sea level record from 1981 to 2000 to investigate the seasonal change of sea level at Syowa Station. In the 1990's, other tide stations located on the coast of Antarctica started to provide sea level data. We compare the seasonal variations among these stations including Syowa, and discuss possible mechanisms for them.

2. Tidal observation system and data

The sea level record has been measured with a pressure sensor installed at the bottom in shallow water in Nishi-no-ura, northwest of East Ongul Island, from 1981 to 2000. During the first half of the observation period (1981–1989), the variation of water pressure due to sea level changes was measured together with the atmospheric pressure with a strain gauge, and the total pressure was recorded. In the second half (1990–2000), air pressure was subtracted from the total pressure measured with a quartz oscillator pressure sensor, and the pressure equivalent to that of the water column was recorded. The tide gauge has been fixed on the sea floor at about 15 m depth with anchors and sand bags. The data were transmitted through an electric cable covered with a protecting tube to the tide observation hut and recorded in the Earth Science Laboratory. For the first half, the data were recorded only in analogue form. For the second half, in addition to analogue data, raw data digitally sampled 5 times per second are averaged over one minute and recorded in digital form on a solid memory every 10 min (Odamaki *et al*., 1991; Tateoka *et al*., 2002).

The accuracy of the tide record depends on that of tide gauge itself, oceanic density condition, and perhaps atmospheric condition, too. Though it is not easy to estimate error sources, there have been calibration data comparing tide gauge record and visual observation using a tide pole once a year. In 1987, for example, both types of tide gauge were working parallel, and a calibrating observation was carried out for 25 hours during the summer mission of JARE-28. The standard deviations of the difference between the tide pole readings twice an hour and the values of tide gauge record on the regression line were about 5 cm and 1 cm for the old and new tide gauges, respectively. They gave us an error estimation of the observation. The reference level in this case was expected to be determined with an error of less than ±1.5 cm within the 95% confidence limit.

The JARE Data Reports series reports the relative sea level height every one hour referred to the zero level of the tide gauge, which has been determined every year for datum correction. The reported sea level record has jumps due to the variation of reference level. For example, there was an intentional change of the reference level between 1992 and 1993, which was larger than 1.0 m. Before analyzing the sea level data from 1981 to 2000 consecutively, the zero level of each year was corrected to be at a uniform height referred to Benchmark 1040. Corrections for the atmospheric pressure were applied to the second half of the sea level record. In the time series of daily mean sea levels for the second half after barometric correction, variations of higher frequency due to the variation of atmospheric pressure are remarkably reduced in

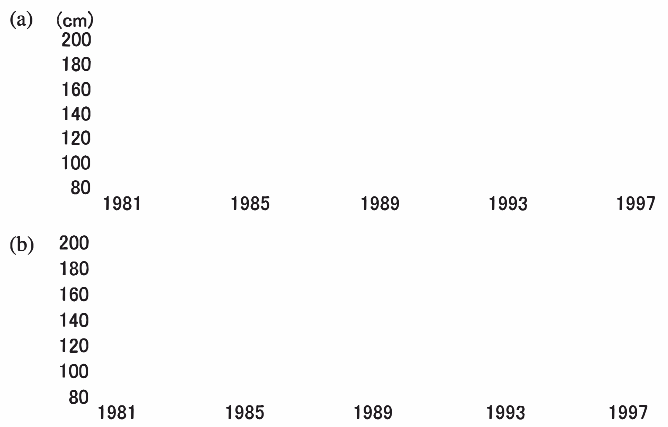

Fig. 1. Daily mean sea level at Syowa Station with datum correction from 1981 to 2000. Correction for atmospheric pressure has been applied for the period from 1990; (a) before the correction (b) after correction.

comparison with those before correction, and annual cycles can clearly be seen (Fig. 1).

To compare the sea level at Syowa Station to those at other stations, mean sea level data of other Antarctic stations including Vernadsky Base, Mawson Base, and Davis Base, and those of Stockholm, were downloaded from the data base service system operated by the Permanent Service for Mean Sea Level (PSMSL; http: //www.nbi.ac.uk/psmsl/).

3. Seasonal changes of mean sea level

The time series of monthly mean sea level is shown in Fig. 2. A clear annual cycle and a continuous falling trend can be seen as reported in previous studies (Odamaki *et al.*, 1991; Tateoka *et al.*, 2002). The falling rate is estimated at about 1.4 cm/year; this is larger than previous estimations by Odamaki *et al.* (1991). With regard to the averaged annual cycle for 20 years from 1981 to 2000, monthly mean sea level has a

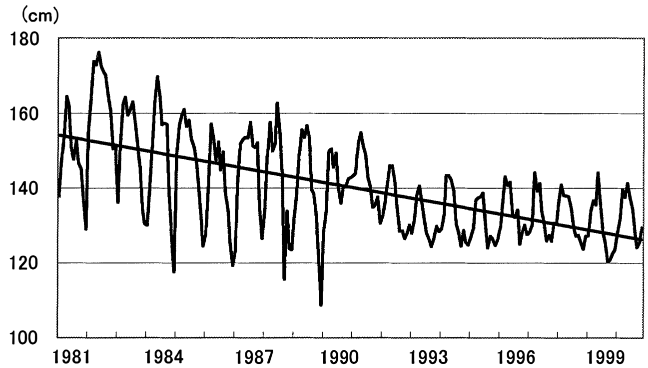

Fig. 2. Monthly mean sea level with a linear regression line.

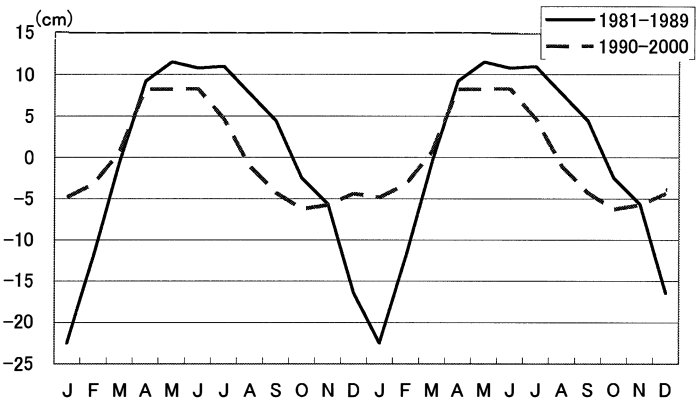

Fig. 3. Seasonal changes of averaged monthly mean sea level for the first half (1981–1989, solid line) and the second half (1990–2000, dashed line). Curves of annual cycle are shown twice so that the shapes can easily be recognized.

maximum in May and minimum in January, and the range of seasonal change is about 22 cm.

However, the characteristics of the variability seem to have changed after 1990 when the observing system was changed. We compare the seasonal change in the first half (1981–1989) and in the second half (1990–2000). Figure 3 shows seasonal changes averaged for the first and second halves. In the first half, sea level reaches a maximum in May and falls to a minimum in January, and the seasonal tidal range between the maximum and the minimum is about 34 cm. The shape of the annual cycle is asymmetric: the winter peak is flat and the summer trough is sharp. On the other hand, in the second half, a maximum appears in April and a minimum in October. The range is about 14 cm and the annual cycle is more symmetric compared with the shape in the first half. After 1990, averaged seasonal change is clearly different from the

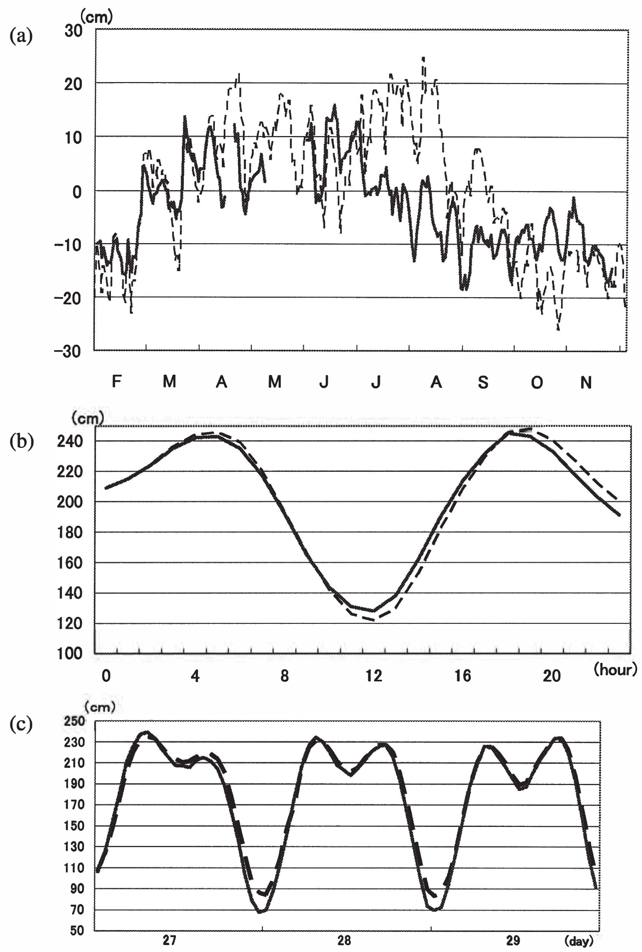

Fig. 4. Comparison of the sea level record with the old gauge (dashed line) to that with new gauge (solid line), (a) daily mean values from February to November in 1988, (b) hourly values on March 1, 1988, (c) hourly values for July 27–29, 1988.

result of Nagata *et al*. (1993).

To consider the reasons for the difference of averaged seasonal change between the first and second halves, we examine the difference of output between the two types of tide gauges. For the years 1987, 1988 and 1989, the official data reports adopted the sea level data measured with the old gauge, but the new type of tide gauge was also working. Within that period, we use the sea level data in 1988 when both tide gauges worked well to investigate the difference between the old and new observing systems.

Figure 4 shows daily mean sea levels in 1988 and hourly mean sea levels in March and July, 1988. A clear difference of daily mean sea level measured with the old and new tide gauges can be seen from July to September (Fig. 4a). The sea level measured with the new gauge is falling from July, but that with the old one doesn't fall in July and begins to fall from August. This characteristic will cause a difference of amplitude and shape in averaged seasonal change. Figure 4b shows a comparison between two gauges for a day in March, rising phase of seasonal sea level. The difference of hourly sea levels between the old and new gauges seems to be getting bigger as time passes. Figure 4c shows a similar comparison as Fig. 4b, except for 3 days in July, falling phase of seasonal change. Sea level measured with the old gauge does not seem to fall easily than that of new gauge. Accumulation of these differences in hourly mean sea level may lead to a difference of averaged seasonal change between the old and new tide gauges.

Although such differences are observed in monthly means and in the tide record on a given day or for a couple of days, annual mean values with these two tide gauges are almost the same, at least for the year 1988: 147.4 cm by the old gauge and 148.2 cm by the new one.

4. Long-term changes of mean sea level

Monthly mean sea level in Fig. 3 shows a long-term trend. It shows almost a continuous fall, as reported in the previous study (Odamaki *et al*., 1991). The regression in Fig. 3 is calculated for the whole period and is expressed as the following formula,

$$y(\text{cm}) = -1.4(\text{cm/year}) \times t + 155(\text{cm}), \tag{1}$$

where y means monthly mean sea level and t the year originating in 1981 ($t=0$ for 1981).

As mentioned before, in the discussion of the long term sea level change, we have to take into account the influence of the nodal tide, an astronomical tidal component having a period of 18.6 years. We assume that the long term change of the sea level shown in Fig. 3 consists of a simple summation of a linear trend (Y) and a sinusoidal function for the nodal tide (T). Then we apply the least square method to it with four unknown values: a regression coefficient and a constant for the linear trend, and amplitude and phase for the nodal tide. The estimated linear trend and the nodal tide are,

$$\text{Y}(\text{cm}) = -1.2(\text{cm/year})t + 152(\text{cm}), \tag{2}$$

$$\text{T}(\text{cm}) = 2.7(\text{cm})\cos(2\pi t/18.6 - 0.75), \tag{3}$$

where t again means year so that $t=0$ means the year 1981, and the unit of sea level is in cm.

With regard to the linear trend, the falling rate of mean sea level is estimated at 1.2 cm/year. The rate is larger than that of the previous estimate of 1 cm/year given by Odamaki *et al*. (1991). It is also larger than other geological estimates of less than 0.5 cm (James and Ivins, 1998; Kaminuma, 1986) based on the assumption of glacial rebound of the Antarctic crust after the last glacier period.

The estimated nodal tide has an amplitude of 2.7 cm. The phase predicts that it should have had a peak in 1984. The estimated nodal tide component provides an interannual trend at −0.6 cm/year for the falling phase.

5. Discussion

As pointed out in Section 3, one possible reason for the difference between the old and new tide gauges may be the difference of response to pressure variations. The new tide gauge with quartz oscillator responds to the variation of water pressure more quickly than the old one. Accumulation of such lagged responses may cause the difference in hourly mean sea level between the old and new tide gauges. It is not easy to determine which tide gauges are reliable, but there is one suggestive analysis by Aoki *et al*. (2002). They observed the vertical motion of fast ice due to tidal sea level changes using a GPS receiver set on the fast ice in 1998 and observed almost the same seasonal change as that observed by the new tide gauge. The seasonal tide range estimated with GPS is about 13 cm. This result may support the accuracy of the new tide gauge. The annual tide range observed with the new tide gauge, 14 cm, is consistent with the previous study (Aoki *et al*., 2002). Based on this result, the new gauge can be considered to be more reliable at least for seasonal changes.

We think that the old gauge can be used on a longer time scale, by applying datum checks regularly once a year. On a shorter time scale, we need to be careful of the response characteristics of the gauge as discussed in the previous section. If we would have carried out calibrations and datum checks on shorter intervals (every day, every month, or shorter than annual time scale), the accumulation of errors due to hysteresis could be adjusted over a shorter interval, and the data set could be used in the discussion of seasonal or shorter time scales. Unfortunately, we could carry out such observations only once a year. In addition to the hysteresis in the response of the old gauge, there is a possibility that the regression coefficient estimated through calibration once a year in summer may not be applicable in other seasons, particularly in winter. The new gauge, with almost no hysteresis in its response, can be used on even a shorter time scale, applying datum corrections once a year.

The long term trend was estimated in the previous section by analyzing the continued record of the first and second halves, because the difference in annual averages with the old and the new gauges was less than 1 cm for the year 1988 when overlapping observations with two types of gauges were available. In order to examine the reliability of the present estimation for the falling rate, two falling rates are estimated independently for the first and the second halves: 2.0 cm/year for the first half, and 0.9 cm/year for the second half. The rate for the second half is closer to previous estimates, and still bigger than that expected from geological estimates of the rise in land height. This estimate does not take the nodal tide into account. The nodal tide is in the falling phase in the first half and in the rising phase in the second half, according to the calculation for the whole period from 1981 to 2000. The falling rate for the whole period is estimated at 1.2 cm/year in the present study, taking into account the influence of the nodal tide. After correction for the contribution of the nodal tide, the falling rates for the first and second halves are calculated at 1.4 cm/year and 1.0 cm/year, respectively. The falling rate for the whole period, which is not much different from those with either the old or the new tide gauges, should give us a reliable value.

This falling rate of 1.2 cm/year is larger than the estimate for the period from 1981–1987 by Odamaki *et al*. (1991). This may be partly due to the effect of the nodal tide, which was not considered in their study. They did not apply a datum correction in their analysis of the long-term trend, assuming that the interannual change of the zero point (the reference level) was small. But in reality, it was not negligible in the estimation.

The present estimation of the falling rate is still larger than that of less than 0.5 cm/year expected from geological analysis of the rate of land rise. There are some possible reasons for this that we discuss here. If unknown observational errors cause a falling trend in the mean height of winter peaks relative to the level of the previous and successive summer troughs, the estimated falling rate should contain a spurious factor. However, such a trend is not found in the seasonal range of the monthly mean sea levels. As another candidate to explain such a rapid fall, we can consider inter-decadal changes in oceanographic condition, which affect the sea level trend at Syowa Station. With regard to circumpolar scale variability, for example, we have examined the Drake Passage Oscillation Index (DPOI) presented by Naganobu *et al*. (1999), which is proposed to be a good index for the strength of westerlies in the Drake Passage, and have not found a clear trend in it over the last two decades. However, as we cannot discard the possibility based only on the above discussion, further investigation is required to study the relationship between long-term variability of oceanographic conditions and the falling trend in sea level, not only on the scale of the whole Southern Ocean but also local scale dynamics.

In terms of glacial rebound as the cause of the sea level fall, the falling trend on a very long time scale of hundreds to thousands of years is expected to be less than 0.5 cm/year based on geological evidence around Syowa Station. The falling trend in the sea level record at Stockholm, Sweden, which is in a similar situation as Syowa Station from the viewpoint of the field of glacial rebound, is estimated at 0.4 cm/year for the whole period from 1889 to 2001, while it is 0.9 cm/year for 20 years from 1921–1940. This means that more than twice as large a falling rate is possible on a shorter time scale such as twenty years, as in the present study.

We suggest in conclusion on the long-term trend that the falling rate (1.2 cm/year) for the last two decades given in this study presents the best estimation by applying datum adjustment, correction for atmospheric pressure, and extraction of the nodal tide component, although there are remaining problems on the causes of relative sea level change which have partly been discussed above.

To clarify whether the seasonal change of sea level at Syowa Station is common along the Antarctic coast or not, a comparison is made with the seasonal sea level change observed at other tide stations. Sea level data are available at Mawson and Davis on the East Antarctic coast, and Vernadsky base on the Antarctic Peninsula from 1993 to 1997, although these data show water column height without barometric corrections. We compare the sea level data at these stations with the sea level record at Syowa Station

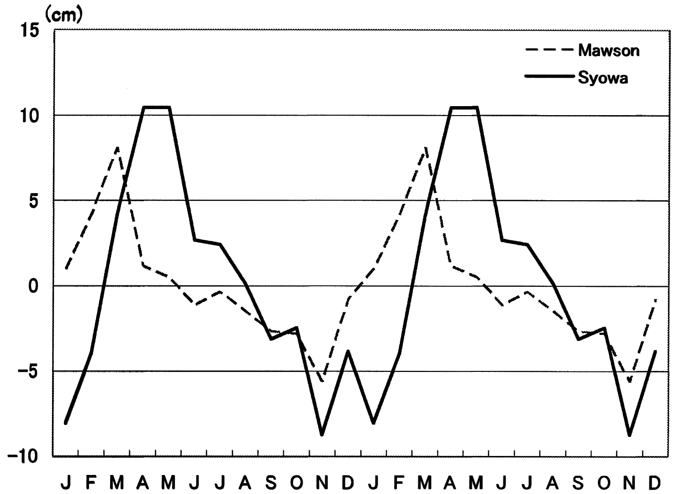

Fig. 5. *Monthly mean sea levels averaged for years from 1993–1997 at Syowa Station (solid line) and Mawson Base (dashed line). Curves of annual cycle are shown twice so that the shapes can easily be recognized.*

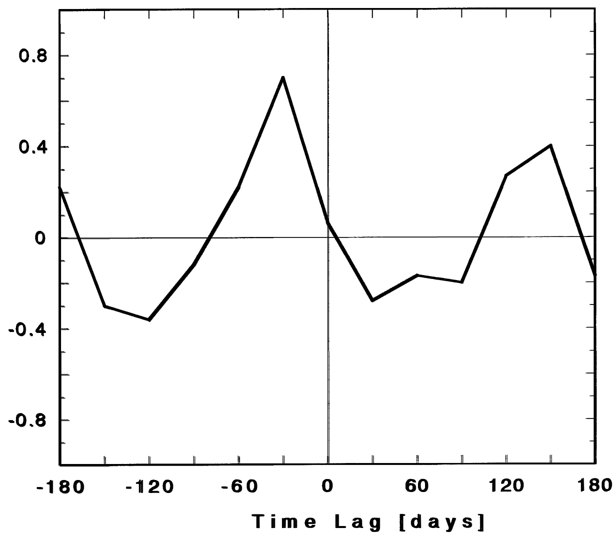

Fig. 6. *Lag correlation of monthly mean sea levels between Syowa Station and Mawson Base. Negative time lag means that the variation at Mawson Base precedes Syowa Station.*

without correction for atmospheric pressure. In the seasonal change of sea level averaged for 1993–1997 at these stations, the monthly mean sea levels reach a maximum in late summer and fall to minimum in spring, and annual tide ranges are 10–14 cm. The annual cycles seen in averaged monthly mean sea levels for these stations are basically similar to that for Syowa Station, and some time lag is observed.

Figure 5 shows monthly mean sea level from 1993 to 1997 at Syowa Station and Mawson Station (67.5°S, 62.1°E), and Fig. 6 shows lag coherences of monthly mean sea level between these two stations. The shape of monthly mean sea level at Mawson is similar to that at Syowa. But, that peak is shifted ahead of Syowa by one month (Fig. 5). The coherence of sea levels at the two stations, Syowa and Mawson, is fairly high ($R=0.7$). The time lag between them is about 1 month (Fig. 6).

One possible factor in this time lag is the difference in wind variation. The wind velocity in Mawson reaches a maximum in March, but in Syowa a maximum appears in April (Inoue, 1988). The time lag of the wind is also 1 month, and the seasonal variation of wind velocity is similar between Syowa and Mawson. The change of wind velocity may cause a change of barotoropic coastal current related to sea level variation. Though this can be a key factor for seasonal change of sea level as pointed out in previous studies, more quantitative analysis of the relation between sea level and wind is required.

Acknowledgments

Meteorological data at Syowa Station used for barometric correction in the present study were provided by Japan Meteorological Agency. All the efforts of the JARE members who maintain the tide gauge at Syowa Station are acknowledged with authors' sincere appreciations. We sincerely thank Dr. Shuki Ushio for his help in obtaining meteorological data used in this study and for constructive discussion. Finally we deeply appreciate the Editors and two anonymous reviewers, whose comments and suggestion with their careful and critical reading substantially improved the manuscript.

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