Decadal-scale variability of upper ocean heat content in the tropical Pacific

著者	Hasegawa Takuya, Hanawa Kimio
journal or publication title	Geophysical Research Letters
volume	30
number	6
page range	2171
year	2003
URL	http://hdl.handle.net/10097/51466

doi: 10.1029/2002GL016843

Decadal-scale variability of upper ocean heat content in the tropical Pacific

Takuya Hasegawa and Kimio Hanawa
Department of Geophysics, Graduate School of Science, Tohoku University, Sendai, Japan

Received 25 December 2002; accepted 7 February 2003; published 18 March 2003.

[1] Decadal-scale variability of upper ocean heat content (OHC) in the tropical Pacific is investigated and is compared with that of ENSO scale. The decadal-scale OHC anomaly with a period of about 13 years shows anticlockwise propagations in the tropical North Pacific like as that of ENSO scale. It is also shown that the entire equatorial OHC anomaly leads Niño-3 index anomaly by about a quarter (about 3 years) of the period of the decadal variability in the tropical Pacific. This time lag of a quarter of the period is consistent with the idea of the "recharge oscillator" model for ENSO dynamics. Further it is shown that the magnitude of leading OHC anomalies in the entire equatorial Pacific is linearly related to the subsequent magnitudes of Niño-3 and Niño-3.4 indices. This relationship is also similar with that of ENSO scale, but there are several different points between them. Particularly, in contrast with the ENSO scale, the amplitude is larger in central equatorial Pacific (Niño-3.4 region) than in the eastern region (Niño-3 region). *INDEX TERMS:* 4522 Oceanography: Physical: El Niño; 4572 Oceanography: Physical: Upper ocean processes; 9355 Information Related to Geographic Region: Pacific Ocean. **Citation:** Hasegawa, T., and K. Hanawa, Decadal-scale variability of upper ocean heat content in the tropical Pacific, *Geophys. Res. Lett.*, *30*(6), 1272, doi:10.1029/2002GL016843, 2003.

1. Introduction

[2] Numerous studies on decadal-scale climate variability in the Pacific have been done since the late 1980s initiated by the work of *Nitta and Yamada* [1989]. Spatial pattern of decadal-scale sea surface temperature (SST) anomaly field is similar to that accompanying with an El Niño/Southern Oscillation (ENSO) event [e.g., *Zhang et al.*, 1997]. Studies on interannual variabilities of upper ocean heat content (OHC) or warm water volume show the propagation of OHC anomaly related to the ENSO events, and the relationship between the entire equatorial OHC and the eastern equatorial SST anomalies [*Kessler*, 1990; *Zhang and Levitus*, 1996; *Meinen and McPhaden*, 2000, hereinafter referred to as MM00; *Hasegawa and Hanawa*, 2003, hereinafter referred to as HH03] strongly supports the idea of the "recharge oscillator" model for ENSO dynamics [*Jin*, 1997a, 1997b].

[3] Recently, ENSO-like propagation characteristics of decadal-scale OHC anomaly have been shown in the analyses for observational data [*Luo and Yamagata*, 2001] and numerical model experiments [e.g., *Knutson and Manabe*, 1998]. However, detailed description about the "ENSO-like" decadal-scale OHC anomalies in the tropical Pacific has not been made so far. The purpose of the present study is to describe behaviors of the decadal-scale variability of OHC anomaly in the tropical Pacific and to compare with that of ENSO scale, with special attention to the propagation characteristics and the relationship between the OHC and SST anomalies in the equatorial Pacific.

0094-8276/03/2002GL016843$05.00

2. Data

[4] OHC is calculated from the upper ocean temperature dataset made by an optimum interpolation method [*White*, 1995]. In this study, OHC is defined as vertically averaged temperature from the sea surface to the depth of 300 m. The analysis region is the Pacific basin (30°S to 60°N) on 2° (latitude)−5° (longitude) grid. We also use the Niño-3 and Niño-3.4 indices prepared by the National Centers for Environmental Center/Climate Prediction Center. The analysis period is 45 years from January 1955 to December 1999, and annual mean anomalies are used for all the data.

3. Results

[5] First, we investigate the spatial distribution of OHC anomaly variations in the Pacific by a spectral analysis using a wavelet analysis [*Torrence and Compo*, 1998]. When we use other methods such as FFT (Fast Fourier Transform) or MEM (Maximum Entropy Method) instead of the wavelet analysis, the same results are obtained (not shown here). Figure 1 shows that the spatial patterns of power of variations for ENSO scale (about 4 years, Figure 1a), decadal scale (about 12 years, Figure 1b) and interdecadal scale (about 20 years, Figure 1c) are different from each other. In the tropical Pacific, although the power of ENSO scale is large in the entire equatorial region, that of decadal scale is low in the eastern equatorial Pacific and large in the western and central equatorial Pacific. Further, the pattern of decadal scale (Figure 1b) resembles to that of periods from 10 to 18 years (not shown here). At the interdecadal scale, signals in the entire equatorial Pacific are small, while relatively large signals can be seen in the South Pacific and mid to high latitudes of the North Pacific. Recently, *Yasunaka and Hanawa* [2003] have shown that signals of the "regime shift" [*Nitta and Yamada*, 1989] can be seen in the Niño-3.4 index rather than Niño-3 index. That is, the central equatorial region might play an important role in the decadal-scale climate change in the tropical Pacific. Based on the above analysis, we adopt the band-passing filter having the window from 10 to 18 years in period, using the wavelet analysis on

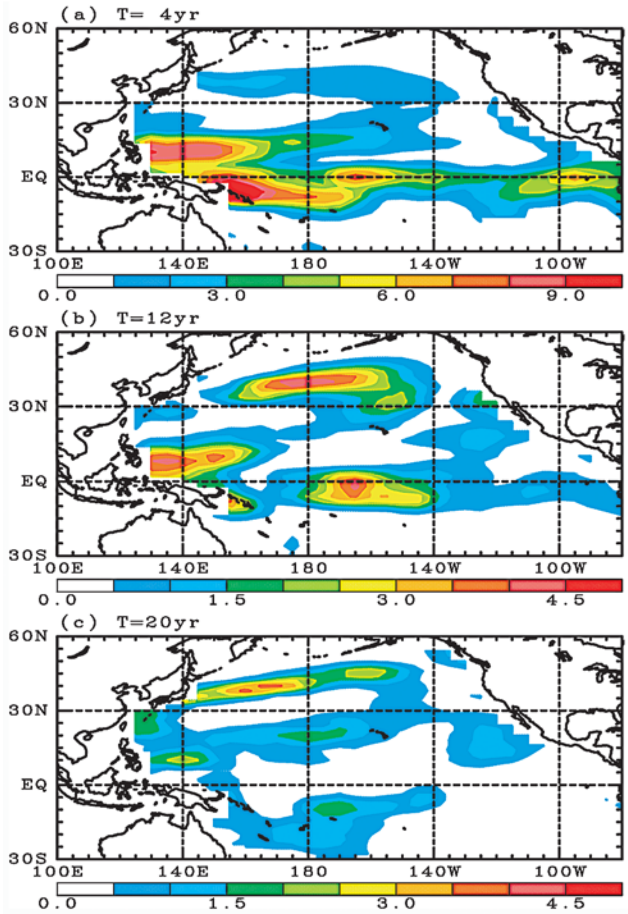

Figure 1. Spatial distributions of power of variations at the periods of about (a) 4 years, (b) 12 years, and (c) 20 years. Units in 0.01°C^2.

OHC anomaly fields, in order to investigate the decadal-scale OHC variability solely.

[6] Figure 2 shows a half cycle of spatial patterns of the first complex empirical orthogonal function (EOF) mode of the decadal scale. This mode can account for about 50% of total variance. Anticlockwise propagation of OHC anomalies can be clearly seen in the tropical North Pacific: an eastward propagation along the equator and a westward propagation along the latitudinal belt centered on 16°N. One cycle is about 13 years. This anticlockwise propagation resembles to that of ENSO-related OHC anomalies [e.g., *Kessler*, 1990; *Zhang and Levitus*, 1996; HH03]. The eastward propagation along the equator is also consistent with the result of *Luo and Yamagata* [2001]. This anticlockwise propagation also appears in the result of numerical model experiment [*Knutson and Manabe*, 1998], although the latitudinal band where decadal-scale OHC anomaly propagates westward is a little bit higher in this study than that of their model result.

[7] It is interesting to note that relatively weak negative anomalies are seen along about 15°S, when the negative anomalies propagate toward the western Pacific along about 15°N (Figures 2b, 2c and 2d). This suggests that the OHC anomalies also propagate westward along about 15°S. However the lack of data in the South Pacific particularly in the eastern part (east of about 130°W) does not allow us to say that this symmetric westward propagation pattern surely exists.

[8] Figure 3 shows the time series of decadal scale OHC anomalies on a closed circuit around the tropical North Pacific. This circuit is the same as that set in HH03. The anticlockwise propagations can be clearly seen and the time needed to close one cycle is about 10 years or more. Large signals are found in the tropical western Pacific near the western boundary and the central equatorial Pacific (dark red and blue colored areas in Figure 3). These features are consistent with the results of Figures 1 and 2. Large positive (negative) values appear in the central equator (i.e., the Niño-3.4 region) in 1980, 1992 (in 1985, 1998) and along the western boundary in 1987, 1999 (in 1982, 1993). The time series in the 1950s and 1960s does not show well-organized feature of propagation, and the amplitude is smaller (not shown here), as suggested by the later discussion (Figure 4a). This might be related to the '1976/1977

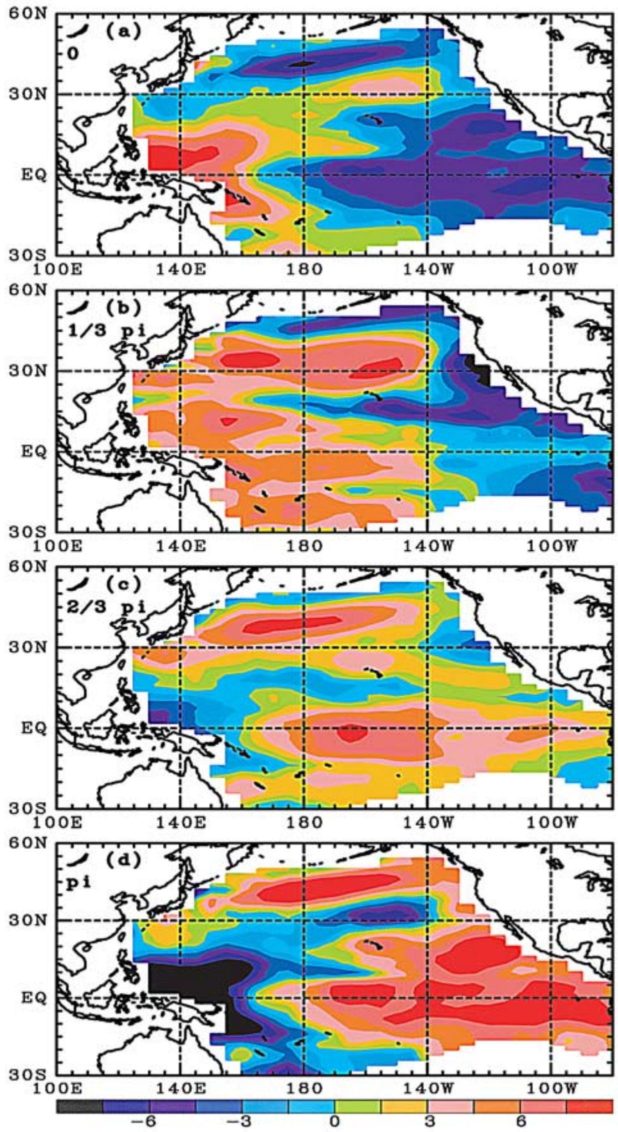

Figure 2. Reconstructed decadal-scale OHC anomaly field from the first complex EOF mode at the phases of (a) 0, (b) 1/3π, (c) 2/3π, and (d) π. Units in 0.01°C.

regime shift' [*Nitta and Yamada*, 1989; *Yasunaka and Hanawa*, 2003].

[9] Next, the relationships between the entire equatorial OHC anomaly averaged in 4°N–4°S, 140°E–80°W (hereafter *Teq*) and SSTs in the central and eastern equatorial Pacific are explored. Figure 4a shows that *Teq* leads the Niño-3 and Niño-3.4 indices. The lag correlation coefficient between the Niño-3 index and *Teq* has the maximum value of 0.93, when *Teq* leads the Niño-3 index by 3 years. This time lag of 3 years corresponds to about a quarter of the period of anticlockwise propagation of the OHC anomaly shown in Figures 2 and 3. On the other hand, *Teq* leads the Niño-3.4 index by 2 years with correlation coefficient of 0.93. The time difference of one year between the Niño-3 and Niño-3.4 indices can be interpreted as the time needed for OHC anomaly to propagate between the two regions along the equator. These time lags can be reconfirmed in the trajectory plot of Figures 4b and 4c. As seen in Figure 4b, the trajectory of *Teq* and Niño-3 index is almost circular, which means that the time lag of 3 years between *Teq* and Niño-3 index corresponds to about a quarter of the period. On the other hand, the trajectory of *Teq* and Niño-3.4 index is an elliptical shape as seen in Figure 4c, which means that the time lag between *Teq* and Niño-3.4 index is shorter than that between *Teq* and Niño-3 index as mentioned above. These features are clearly seen after 1977 (the points on which symbol '+' is attached) and amplitudes are also larger after 1977 (Figure 4a). This might be related to the '1976/1977 regime shift' [*Nitta and Yamada*, 1989; *Yasunaka and Hanawa*, 2003].

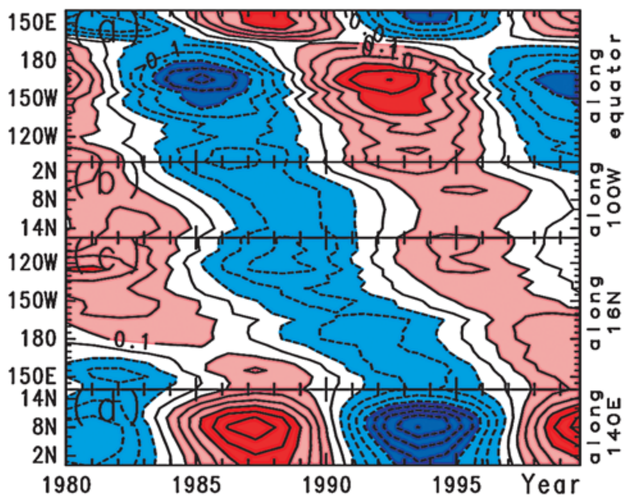

Figure 3. Time series of decadal-scale OHC anomalies on the rectangular path (circuit) around the northern tropical Pacific from 1980 to 1999. (a) Along the equator from the western boundary (140°E) to the eastern boundary (100°W). (b) Along the eastern boundary from the equator to 16°N. (c) Along the 16°N line from the eastern boundary to the western boundary. (d) Along the western boundary from 16°N to the equator. Units in °C. Counter interval is 0.05°C and negative values are represented by the broken lines. The values from 0.1°C to 0.2°C (from −0.2°C to −0.1°C) are represented by light red (blue) color, and values greater than 0.2°C (less than −0.2°C) are represented by dark red (blue) color.

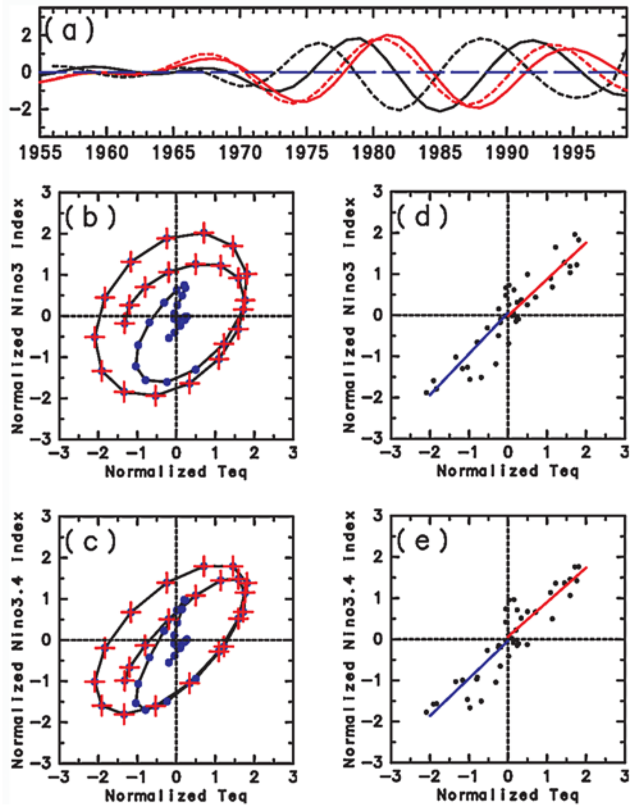

Figure 4. (a) Time series of decadal-scale anomalies of *Teq* (black solid line), temporal changing rate (time derivative) of *Teq* (black dotted line), Niño 3 index (red solid line), and Nñio-3.4 index (red dotted line). (b) Trajectory plot of decadal components of *Teq* and Niño-3 index. The symbol '+' is attached on the points whose period is from 1977 to 1999. (c) Same as (b) but *Teq* and Niño-3.4 index. (d) Scatter plots of decadal components of *Teq* and Niño-3 index when *Teq* leads Niño-3 index by 3 years. Solid lines represent the least square fitting for positive (red line) and negative (blue line) values of *Teq*. (e) Same as (d) but *Teq* and Niño-3.4 index when *Teq* leads Niño-3.4 index by 2 years. Values are normalized with the standard deviation.

[10] According to the "recharge oscillator" model for ENSO dynamics [*Jin*, 1997a, 1997b], it is expected that the temporal changing rate of *Teq* takes a positive value when the Niño-3 index takes a negative value. This relationship also can be seen in the decadal scale (Figure 4a). Further it is expected in the recharge oscillator model that the zonal wind stress over the entire equatorial Pacific has a positive correlation (in phase) with the Niño-3 index and a negative correlation (out of phase) with the temporal changing rate (time derivative) of *Teq*. Although we do not show any figures regarding wind stress field, it is confirmed that all these relationships hold in the decadal scale as in the ENSO scale.

[11] Scatter diagram between *Teq* and Niño-3 index at the decadal scale is shown in Figure 4d. It is clearly seen that there is a linear relationship between leading *Teq* and subsequent (3 years later) Niño-3 index. Larger amplitude of leading *Teq* causes larger value of the subsequent Niño-3

index. The same result is obtained when the Niño-3.4 index is used instead of the Niño-3 index, but *Teq* leads the Niño-3.4 index by 2 years (Figure 4e). Although this relationship between the OHC and Niño-3 index anomalies is similar with that at the ENSO scale [MM00; HH03], a difference exists between the two time scales. That is, in the ENSO scale, the relationship is stronger in the warm phase than the cold phase, but such a strong asymmetry cannot be seen in the decadal scale.

[12] The linear relationship shown by Figures 4d and 4e can be seen when OHC anomalies in the western Pacific (4°N–4°S 140°E–160°E: *Tw*) are used instead of *Teq* (not shown here). The leading time is longer when *Tw* is used instead of *Teq* (6 years for Niño-3.4 index and 7 years for Niño-3 index), and the lag correlation coefficients become smaller when *Tw* is used ($R = 0.78$ for both the Niño-3 and Niño-3.4 indices). Thus *Teq* has a better skill of prediction of subsequent SSTs in the central and eastern equatorial Pacific than *Tw*. This finding is also consistent with that at the ENSO scale [MM00; HH03].

4. Concluding Remarks

[13] The anticlockwise propagation (Figures 2 and 3) and the relationship between *Teq* and Niño-3 and Niño-3.4 indices (Figure 4) observed in the decadal-scale variability of OHC anomalies are almost the same as the ENSO-scale variability [HH03]. The time lag of 3 years, a quarter of the period, between *Teq* and Niño-3 index suggests that a mechanism like the ‘‘recharge oscillator’’ model might operate in the tropical Pacific even at the decadal scale. In addition to these similarities between ENSO and decadal-scale variabilities, our results also show that there is a different point between the decadal and ENSO scales, as mentioned in the previous section. That is, in the decadal scale, the Niño-3.4 region shows a larger signal than the Niño-3 region (Figures 1, 2, and 3). This finding is also supported by the result of *Yasunaka and Hanawa* [2003] based on the analysis for SST. Therefore, it is inferred that the central equatorial Pacific, i.e., the Niño-3.4 region is an important region for decadal-scale climate change. The reason why the decadal-scale signal is stronger in the Niño-3.4 region is unclear at present.

[14] This study indicates the accumulation of heat content anomaly in the equatorial Pacific by wave processes, which may be related to circulation changes, as shown by the previous studies based on the numerical model experiments [*Jin et al.*, 2001; *Nonaka et al.*, 2002] and on the observation [*McPhaden and Zhang*, 2002]. The westward propagations appear in the latitudinal band centered on 16°N, while in other latitudes do not show westward propagations (Figures 2 and 3). At present, the reason is not unclear, but numerical model experiments suggest that anticyclonic wind stress anomaly over the subtropical gyre can generate baroclinic oceanic Rossby waves there at decadal time scale [*Jin et al.*, 2001]. The interaction between tropics and extra-tropics in both North and South Pacific as well as the interaction between ocean and atmosphere should be investigated to understand the cause of the difference between ENSO and decadal scale, because a relationship between the tropics and extra-tropics might be more important in the decadal scale [e.g., *Gu and Philander*, 1997; *Jin et al.*, 2001; *McPhaden and Zhang*, 2002; *Nonaka et al.*, 2002].

[15] **Acknowledgments.** The authors wish to express their sincere thanks to members of Physical Oceanography Group at Tohoku University for their useful discussion.

References

Gu, D., and S. G. H. Philander, Interdecadal climate fluctuations that depend on exchanges between the tropics and extratropics, *Science*, *275*, 805–807, 1997.

Hasegawa, T., and K. Hanawa, Heat content variability related to ENSO events in the Pacific, *J. Phys. Oceanogr*, *33*, 407–421, 2003.

Jin, F.-F., An equatorial ocean recharge paradigm for ENSO, part I: Conceptual model, *J. Atmos. Sci.*, *54*, 811–829, 1997a.

Jin, F.-F., An equatorial ocean recharge paradigm for ENSO, part II: A stripped-down coupled model, *J. Atmos. Sci.*, *54*, 830–847, 1997b.

Jin, F.-F., M. Kimoto, and X. Wang, A model of decadal ocean-atmosphere interaction in the North Pacific basin, *Geophys. Res. Lett.*, *28*, 1531–1534, 2001.

Kessler, W. S., Observations of long Rossby waves in the northern tropical Pacific, *J. Geophys. Res.*, *95*, 5183–5217, 1990.

Knutson, T. R., and S. Manabe, Model assessment of decadal variability and trends in the tropical Pacific ocean, *J. Clim.*, *11*, 2273–2296, 1998.

Luo, J. J., and T. Yamagata, Long-term El Niño-Southern Oscillation (ENSO)-like variation with special emphasis on the South Pacific, *J. Geophys. Res.*, *106*, 22,211–22,227, 2001.

McPhaden, M. J., and D. Zhang, Slowdown of the meridional overturning circulation in the upper Pacific Ocean, *Nature*, *415*, 603–608, 2002.

Meinen, C. S., and M. J. McPhaden, Observations of warm water volume changes in the equatorial Pacific and their relationship to El Niño and La Niña, *J. Clim.*, *13*, 3551–3559, 2000.

Nitta, T., and S. Yamada, Recent warming of tropical sea surface temperature and its relationship to the Northern Hemisphere circulation, *J. Meteorol. Soc. Jpn.*, *67*, 375–383, 1989.

Nonaka, M., S.-P. Xie, and J. P. McCreary, Decadal variations in the subtropical cells and equatorial pacific SST, *Geopys. Res. Lett.*, *29*(7), 1116, doi:10.1029/2001GL013717, 2002.

Torrence, C., and G. P. Compo, A practical guide to wavelet analysis, *Bull. Am. Meteorol. Soc.*, *79*, 61–78, 1998.

White, W. B., Design of a global observing system for gyre-scale upper ocean temperature variability, *Prog. Oceanogr.*, *36*, 169–217, 1995.

Yasunaka, S., and K. Hanawa, Regime shifts in the Northern Hemisphere SST field: Revisited in relation to tropical variations, *J. Meteorol. Soc. Jpn.*, in press, 2003.

Zhang, R.-H., and S. Levitus, Structure and evolution of interannual variability of the tropical Pacific upper ocean temperature, *J. Geophys. Res.*, *101*, 20,501–20,524, 1996.

Zhang, T. Y., J. M. Wallace, and D. S. Battisti, ENSO-like interdecadal variability: 1900–93, *J. Clim.*, *10*, 1004–1020, 1997.

K. Hanawa and T. Hasegawa, Department of Geophysics, Graduate School of Science, Tohoku University, Aoba-ku, Sendai 980-8578, Japan. (hanawa@pol.geophys.tohoku.ac.jp; hasegawa@pol.geophys.tohoku.ac.jp)