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THE DIFFERENCES IN STATION MOVEMENTS OBSERVED BY VLBI FROM THE NUVEL-1 MODEL CLOSE TO AND AWAY FROM PLATE BOUNDARY

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ABSTRACT

I compare observed station movements against predictions by the NUVEL-1 model. I divided stations into two areas, those near plate boundary and those away from it to examine the effects of deformation near plate boundary. I obtained the following three results; (1) movements at stations away from plate boundary agree well with the NUVEL-1 model; (2) bias of—4 mm/year is found in easterly movements of stations on or around the Pacific plate; (3) all movements of of stations near plate boundary are different from those predicted by the NUVEL-1 model, and differences in distribution are a few times greater than the observational error. I therefore consider that the plate boundary is deformed by the effects of plate motion, producing a buffer zone for plate motion.

Keywords: VLBI, plate motion, inner-plate deformation, NUVEL-1 model

1. Introduction

Stations move due to two reasons. One is global movement caused by plate motion, and the other is local movement caused by deformation of the inner plate. Movements of stations near plate boundaries were precisely observed using the VLBI (Very Long Baseline Interferometer) and SLR (Satellite Laser Ranging). For example, the Kashima station is considered to be on the North American plate, but it moves about 1 cm/year toward the northwest direction against the North American plate(1). Also movements of stations in Alaska on the North American plate near the plate boundary deflect toward the north because of the pressure of the Pacific plate. The relationship between station movements predicted by the no-net-rotating NUVEL-1 model and those obtained by VLBI have been presented(2). I compare the difference in observed station movements from the NUVEL-1 model close to and away from plate boundary separately, due to the deformation near plate boundary. Furthermore, I describe the relationship of differences based on distance from plate boundary.

2. Data and Analysis

Observed movements of 66 stations have been compared with movements predicted by the NUVEL-1 model. The data used to determine station movements are the results of analysis (Solution

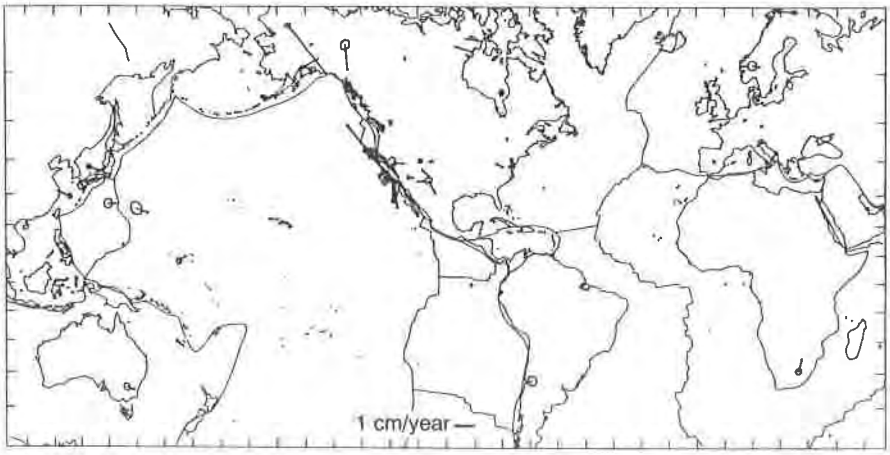

Fig. 1 Differences in observed station movements for all 66 stations from the NUVEL-1 model

GLB907, "GSFC93")[3] of GSFC (Goddard Space Flight Center) using VLBI data. The model of plate motion used to predict station movements is the no-net-rotation NUVEL-1 model[4]. During data analysis, the station positions of Westford, and the direction of the baseline vector from Westford to Richmond are determined based on the no-net-rotation NUVEL-1 model. Vertical movement at Kauai (Hawaii) is constrained to zero.

Figure 1 shows the difference in station movements obtained by the NUVEL-1 model. I compared all observed station movements with the NUVEL-1 model, and the distribution of their differences is indicated by the modified histogram in the paper[2]. I found that the differences in easterly movements between observed data and prediction by the model had a systematic tendency. I also found that differences in northerly or vertical movements between observed data and predictions by the model were distributed statistically, that is, they produced a Gaussian distribution. The dispersion of distribution was about 6 mm/year for easterly movements, 8 mm/year for northerly movements and 19 mm/year for vertical movements.

The station movements close to plate boundary are considered to be different to those away from plate boundary. I divided stations into two areas, those near plate boundary and those further than 300 km from plate boundary. There are 31 stations available near plate boundary, and there are 35 stations available away from plate boundary.

Error in each item of data should be considered when calculating distribution. The probability function $p_i(x)$ for each data item at difference x of observed movement from the NUVEL-1 model is indicated by the following Gaussian distribution.

$$p_i(x) = \exp\left(-\left(x - d_i\right)^2/\sigma_i^2\right)/\left(\sigma_i\sqrt{\pi}\right)$$
$$\int_{-\infty}^{\infty} p_i(x)dx = 1 \qquad \text{(1)}$$

where d_i is the difference in observed movement from movement predicted by the NUVEL-1 model, and σ_i is the observed error for data i. The probability function for all data $P(x)$ at difference x is described as the summation of each probability function;

$$P(x) = \sum_{i=1}^{n} \exp\left(-(x - d_i)^2/\sigma_i^2\right)/\left(\sigma_i\sqrt{\pi}\ \cdot\right)/n$$

$$\int_{-\infty}^{\infty} P(x)dx = 1 \qquad \cdots\cdots (2)$$

where n is the number of data. Probability (percentage of occupation) in the range from x to $x + \Delta x$ is described as $P(x)\Delta x$. That is the number of data in the range from x to $x + \Delta x$ is $P(x)\Delta x \cdot n$ when the number of data is n. In this paper, I use this probability function to indicate the distribution of differences in observed station movements from those predicted by the NUVEL-1 model.

3. Differences in Observed Data and Model

3.1 All stations

I first compared data for all 66 stations. Figures 2–4 show the probability functions for easterly movements, northerly movements and vertical movements, respectively. The dotted line shows the Gaussian distribution with weighted mean value and dispersion for all data. The weight for each data to obtain weighted mean and dispersion is 1/(error)2. This Gaussian distribution fits the observed distribution when all data has statistical random distribution. However, when some systematic scattering occurs, this Gaussian distribution does not fit as well.

The easterly movements is negative, and the mean value of the differences is –3.3 ± 0.77 mm/year, that is, movement toward the west is greater. Dispersion is 6 mm/year. Distribution is different from Gaussian distribution. For northerly movements, the main peak is near 0 mm/year and secondary peaks near 8 mm/year are found. The whole distribution has no clear systematic tendency and it is similar to Gaussian distribution since statistical distribution becomes Gaussian when data is distributed randomly. The mean value is 1.7 ± 0.9 mm/year, and dispersion is 7 mm/year. Vertical movements are also similar to Gaussian distribution. The mean value is 0.5 ± 2.2 mm/year and dispersion is 18 mm/year. These results have already been presented(2).

3.2 Stations away from plate boundary

Distribution of differences in observed station movements from the model are described in the same way for stations near plate boundary and movements of stations away from plate boundary. Stations nearer than 300 km are assumed to be near plate boundary, and stations further than 300 km are assumed to be away from plate boundary. This value of 300 km is discussed in section 4.2. Figures 5–7 show the probability function of differences for easterly movements, northerly movements, and vertical movements of stations away from plate boundary. For easterly movements, there are two peaks. One is near 0 mm/year which means that observed movements agree with the NUVEL-1 model, and the other peak is close to –4 mm/year. There are 11 stations around the Pacific plate where differences are close to –4 mm/year. These are DSS45 and Hobart (Australia), ELY and FD-VLBA and FLAGSTAF and LA-VLBA (Nevada), Pietown (Arizona), Kauai and Haleakal (Hawaii), Kwajalein (Marshall Islands), and Marcus (Japan). They are fixed stations, and differences

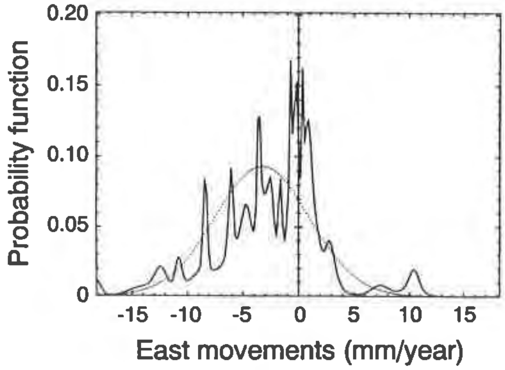

Fig. 2 Differences in observed easterly movements for all 66 stations from the NUVEL-1 model. Abscissa is the difference in easterly movement (mm/year), and ordinate is the probability function.

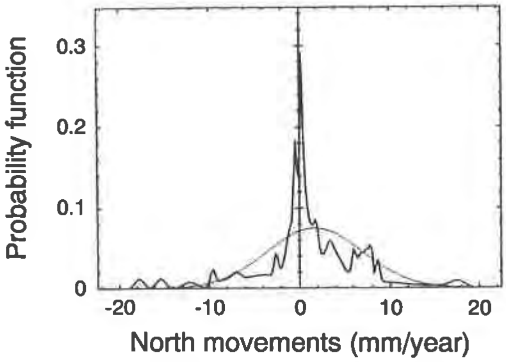

Fig. 3 Differences in observed northerly movements for all 66 stations from the NUVEL-1 model. Abscissa is the difference in northly movement (mm/year) and ordinate is the probability function.

are three times greater than the error except for the FD-VLBA station. Movements of the other 24 stations agreed very well with the NUVEL-1 model, and Fig. 8 shows the differences in easterly movements.

Mean value of the differences in the 35 stations is -1.3 ± 0.6 mm/year, and dispersion is 3.7 mm/year. The large systematic tendency which is found in easterly movements of all the stations, disappears when the stations are away from plate boundary. Furthermore, when we only use 24 stations, the mean value of differences is 0.2 ± 0.7 mm/year and dispersion is 3.6 mm/year.

In northerly movements of 35 stations, distribution is similar to Gaussian distribution. The mean value of differences is 0.7 ± 4 mm/year and dispersion is 2.6 mm/year.

In the vertical movements of 32 stations (3 stations are fixed for vertical movements), distribution is very similar to the Gaussian. Mean value is 2.1 ± 1.8 mm/year and dispersion is 10 mm/year. Dispersion is three times greater than those in horizontal movements. The reason for the

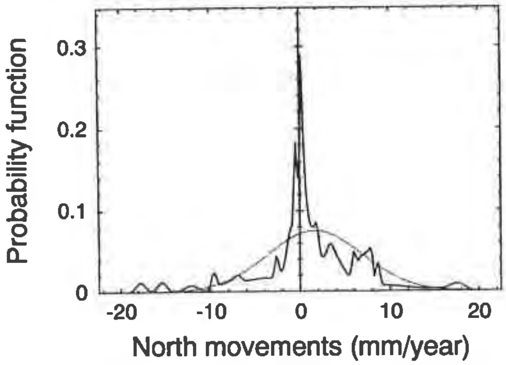

Fig. 4 Differences in observed vertical movements for all 61 stations from the NUVEL-1 model. Abscissa is the difference in vertical movement (mm/year) and ordinate is the probability function.

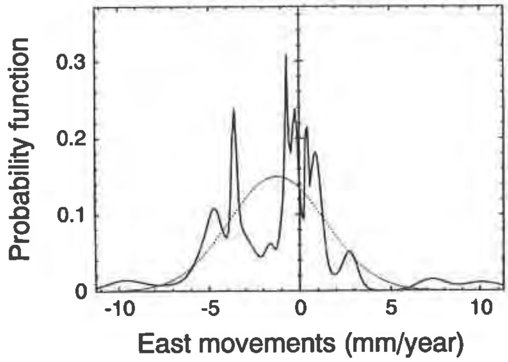

Fig. 5 Differences in observed easterly movements for 35 stations away from plate boundary from the NUVEL-1 model. Abscissa is the difference in easterly movement (mm/year), and ordinate is the probability function.

large dispersion is the large observational error in vertical component. In VLBI, the error in the vertical component is three or four times worse than the error in the horizontal component.

3.3 Stations near plate boundary

Observed station movements near plate boundary are compared with predictions by the NUVEL-1 model. Figures 9–11 show the probability function of the differences. There are 31 stations available. The easterly movements have a clear negative bias and distribution is similar to the Gaussian. The systematic tendency of all stations is caused by this bias of easterly movements for stations near plate boundary. The mean values of differences is –5.6 ± 1.3 mm/year and dispersion is 7.2 mm/year. The bias is significant.

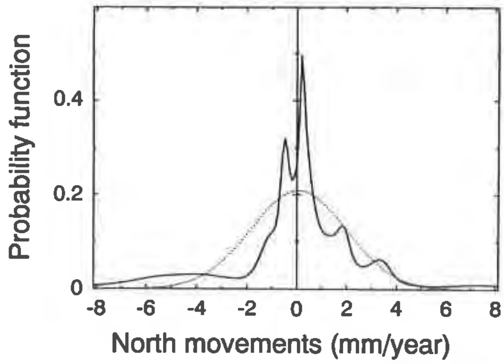

Fig. 6 Differences in observed northerly movements for 35 stations away from plate boundary from the NUVEL-1 model. Abscissa is the difference in northly movement (mm/year), and ordinate is the probability function.

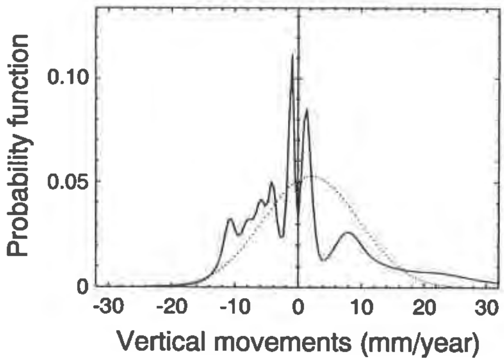

Fig. 7 Differences in observed vertical movements for 32 stations away from plate boundary from the NUVEL-1 model. Abscissa is the difference in vertical movement (mm/year), and ordinate is the probability function.

For northerly movements, there is a remarkable peak of nearly 8 mm/year. The mean value of differences is 3.4 ± 1.9 mm/year and dispersion is 10.2 mm/year. There is no clear bias.

The distribution of vertical movements is similar to Gaussian distribution. The mean values of differences in 29 stations is −1.3 ± 4.3 mm/year and dispersion is 22.7 mm/year.

4. Discussion

4.1 Agreement between current and long term plate motion

The NUVEL-1 model represents average plate motion over the last few million years taking into consideration ocean magnetic anomalies, slip-direction of inter-plate earthquakes and the stress of

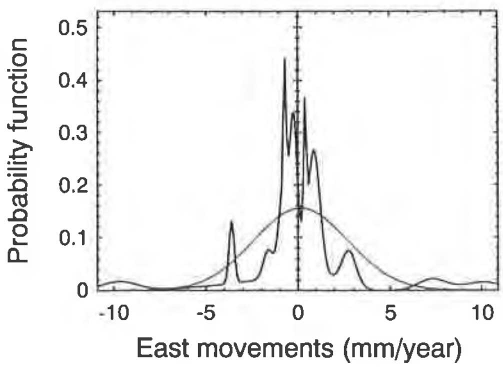

Fig. 8 Differences in observed easterly movements for 24 stations away from plate boundary from the NUVEL-1 model not including 8 stations with differences near −4 mm/year. Abscissa is the difference in easterly movement (mm/year), and ordinate is the probability function.

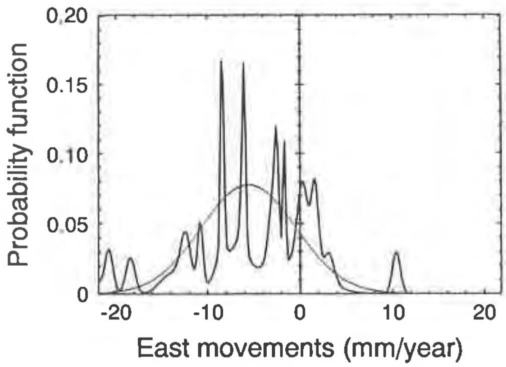

Fig. 9 Differences in observed easterly movements for 31 stations near plate boundary from NUVEL-1 model. Abscissa is the difference in easterly movement (mm/year), and ordinate is the probability function.

transform faults[4][5]. It is very important when considering plate dynamics to study the driving force of plate motion to measure current plate motion. However, before direct measurements of plate motion by techniques such as VLBI, SLR and GPS (Global Positioning System), current plate motion was not well known. It was considered long time ago that the motion zigzagged or that changed as a results of huge earthquakes. The measurements of VLBI revealed that current parameters of plate motion, such as Euler poles and velocities of plates, almost agree with the NUVEL-1 model averaged over a few million years. This suggests that the driving force behind plate motion is probably almost constant over a period of a few million years, and speed is not affected by earthquakes. Recently, however, a difference of a few percent in observed plate motion from the NUVEL-1 model has been observed. Differences are important because they suggest some disagreement between current plate motion and average plate motion over the last few million years. If that is the case, we must consider the driving force of the plate as changeable.

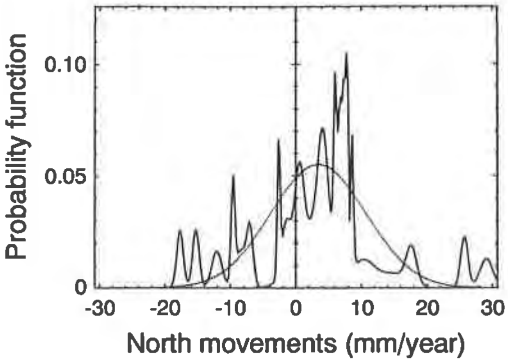

Fig. 10 Differences in observed northerly movements for 31 stations near plate boundary from NUVEL-1 model. Abscissa is the difference in northly movement (mm/year), and ordinate is the probability function.

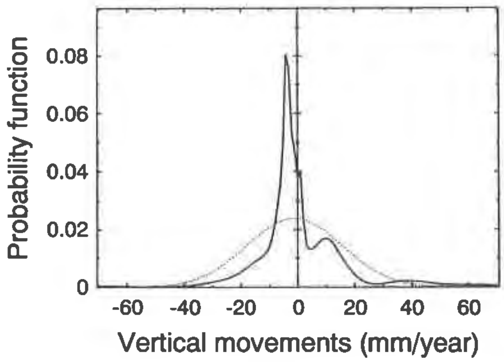

Fig. 11 Differences in observed vertical movements for 29 stations near plate boundary from NUVEL-1 model. Abscissa is the difference in vertical movement (mm/year), and ordinate is the probability function.

In this paper, movements of stations away from plate boundary agree well with the NUVEL-1 model. Systematic discrepancy is less than 1 mm/year, and dispersion is about 3 mm/year for horizontal movements. Current plate motions agree with average plate motion over the last few million years, and appear to be constant and smooth. If movements of stations near plate boundary are considered in an analysis of the plate motion, certain discrepancies are found; for example, the systematic tendency of the easterly movements. I consider that current plate motion should only be obtained by using station movement away from plate boundary when observed plate motion is compared with average long term plate motion. This is because plate boundaries may be subject to local deformation.

A second peak in easterly movements is found for stations away from plate boundary. Only the easterly movement of 11 stations around or on the Pacific plate differ from the NUVEL-1 model by about –4 mm/year. Four of the stations on the Pacific plate (Kauai, Haleakal, Kwajalein and Marcus), have the systematic discrepancy. This seems to indicate that Pacific plate motion predicted by the NUVEL-1 model needs slight revision.

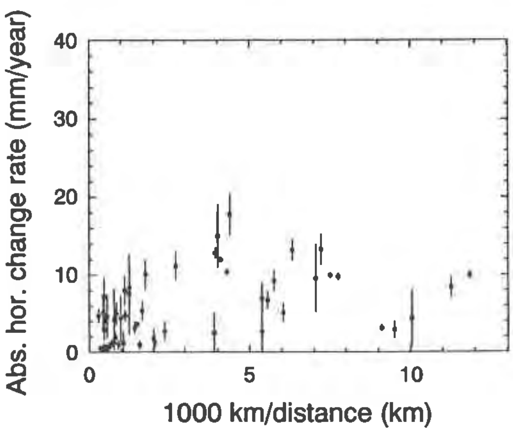

Fig. 12 Correlation of absolute value of difference in observed horizontal movement from NUVEL-1 model at a distance from plate boundary. Abscissa is the value 1000 km/(distance from plate boundary (km)) and the ordinate is the absolute value of difference. Stations closer than 50 km are not included.

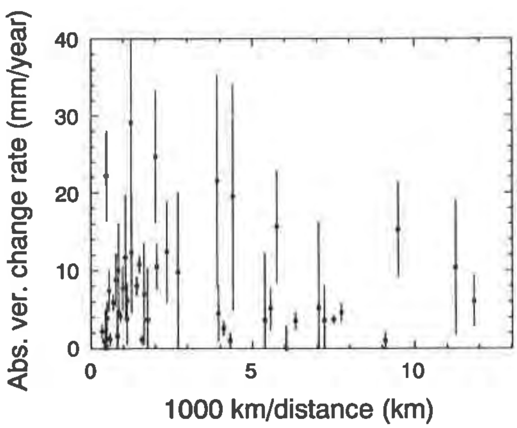

Fig. 13 Correlation of absolute value of difference in observed vertical movement from NUVEL-1 model at a distance from plate boundary. Abscissa is the value 1000 km/(distance from plate boundary (km)) and the ordinate is the absolute value of difference. Stations closer than 50 km are not included.

4.2 Deformation of plate boundary

The plate boundary is considered to produce deformation, and movements of stations near plate boundary may be complex. Regarding movements of stations near plate boundary, I have come to two conclusions.

The first concerns discrepancy with the NUVEL-1 model. In easterly movements, a bias of −6 mm/year appears. The many stations near plate boundary in the available data are located on the west coast of America and in Alaska, that is, they are located around the Pacific plate. This bias agrees with differences in observed easterly movements from those predicted by the NUVEL-1 model for stations on the Pacific plate away from the plate boundary, as described in section 4.1. Therefore, only stations with an easterly movement on or around the Pacific plate have a bias of about −4 mm/year against the NUVEL-1 model.

The second concerns the widely distributed differences. The dispersions in the difference in observed station movements from the NUVEL-1 model are about 2 mm/year for stations away from plate boundary, and they are similar to error in observed movements. However, for movements of stations near plate boundary, the scattering ranges of differences are remarkably wider than error in observed movements. This suggests that the plate boundary has large and varied deformation. Differences in horizontal movements are distributed between ±20 mm/year and dispersion is about 10 mm/year. On the other hand, the differences in vertical movements are distributed between ±50 mm/year and dispersion is about 20 mm/year. The distribution of vertical movements is two or three times the distribution of horizontal movements. This relationship is similar to the relationship between observed vertical and horizontal errors. However, the distribution is greater than ten times the error, and the values are considered to be significant. These values may indicate deformation characteristics of the plate boundary. Furthermore, the plate boundary acts as a buffer zone for plate motion and the values represent the degree of buffering effect. The wide distribution of vertical movements near the plate boundary may indicate that upward deformation is greater than horizontal deformation.

Finally, I would like to consider a consistent explanation for the two results; i.e. that movements of stations away from the plate boundary agree well with the NUVEL-1 model, while various differences exist in movements near the plate boundary. In my opinion, the plate boundary produces the buffer zone like an accordion, and all movements of stations near the plate boundary are affected in the direction of plate motion due to inner-plate deformation by the pressure of plate motion.

To examine inner-plate deformation, the relationship between deformation near plate boundary and the distance from the plate boundary are plotted in Figs. 12–13. The abscissa is 1000 km/(distance from plate boundary (km)) and the ordinate is the absolute value of the difference in station movement from the NUVEL-1 model for the horizontal and vertical movements, respectively. When the value of the 1000 km/distance (km) is less than 3, that is the distance from plate boundary is further than 300 km, the distribution of differences is small. This behavior means that deformation due to plate motion is small at distances greater 300 km. This is the reason that we have adopted a distance of 300 km in selecting stations remote and proximate to plate boundary.

5. Conclusion

I investigated the differences in observed station movements from predictions by the NUVEL-1 model. I presented the distribution of these differences for stations near and away from plate boundary. The movements of stations away from the plate boundary agree well with the NUVEL-1 model. Current plate motion have been the same as average plate motion over the last few million years, and is unlikely to change this rate. However, the movement of stations on and around the Pacific plate have a bias of about −4 mm/year. Therefore correction of Pacific Plate motion data might be necessary.

Movements of stations near plate boundary are widely scattered. The plate boundary is deformed, producing a buffer zone of plate motion. When considering correction of Pacific plate motion of about −4 mm/year, mean values of differences in observed movements from the NUVEL-1 model show no clear bias. Average deformation in this region may agree with predictions by the NUVEL-1 model. Deformation of the plate boundary is in a range of ±20 mm/year and typical deformation is about 10 mm/year in terms of horizontal movement. Regarding vertical movement, deformation is in a range of ±50 mm/year, and typical deformation is about 20 mm/year. These values place constraints on the model of deformation and the degree of deformation near plate boundary.

I presented the results of plate motion and deformation near plate boundary. I suggested that station movements should be divided into two areas; movement of stations away from plate boundary and movement of the stations near plate boundary. The NUVEL-1 model should be compared against the current plate motion that has been obtained by using only station movement away from plate boundary since station movement near plate boundary is affected by local deformation. According to the data used in this analysis (GSFC analysis data), many stations near plate boundary are located near California and Alaska. Therefore, it is possible that my results might be influenced by movement in this area. General characteristics are determined by increasing worldwide data near plate boundaries. Recently, many GPS stations have been located near plate boundaries, and data should reveal the mechanism for deformation near plate boundaries, characteristics of the buffer zone, and the relationship between the buffer zone and plate motion occurring away from plate boundary.

I divided the stations into two areas of proximity based on a distance of 300 km from plate boundary. Though the available data was limited for our analysis, we analyzed deformation near plate boundary based on the distance from plate boundary.

Furthermore, deformation near plate boundary may correlate with plate motion. The difference in observed station movement from the model should be described for the direction of plate motion and its transverse direction. We will investigate deformation using this method in the future.

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