Could decadal variations in the ocean accelerate plate subduction in the Japan Trench before the 2011 M9 Tohoku earthquake?

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Recent seismological observations have revealed that tides within diurnal bands can trigger non-volcanic tremors occurring on the down-dip extension of the megathrust faults in Cascadia and Nankai. Tidal stresses can be related with the Coulomb Failure Stress (dCFS) associated with fault slip on the plate interface. Previous studies indicate that numbers of tremors tend to increase exponentially with dCFS, implying that plate subduction speed in the transition zone fluctuates in accordance with tides. It was also found that tidal responses of tremors change during the occurrence of a slow slip event (SSE).

Compared with short-term tidal responses, relatively few researches have been conducted for periods longer than a day. Ide and Tanaka (2014) explained annual and 18.6-year variations in tremors and seismicity of shallower earthquakes in the Nankai region with tidal responses. Pollitz et al. (2013) applied a hydrological surface loading model to interpret the periodicity of tremors in Cascadia. Tanaka et al. (2015) showed that subduction speed and seismicity in the Tokai area correlated with the Kuroshio Current.

Mavrommatis et al. (2014) found from GNSS data during 1996—2011 that subduction speed gradually accelerated at depths below the coseismic rupture zone of the 2011 M-9 Tohoku earthquake. Nucleation is a possible interpretation of its cause. However, a rapid acceleration just before the earthquake, which has been predicted by ordinary earthquake-cycle simulations, was not observed. Another interpretation is that a long-term SSE occurred. However, no SSE has been reported so far which keeps accelerating as long as 15 years.

In this study, based on Tanaka et al. (2015), we investigate frictional properties required, if a slip response of the transition zone to long-term variations in the ocean could reproduce the above acceleration. We construct a slip model consisting of two elements, representing the acceleration area and a portion below it. The acceleration area is expressed by a spring slider with velocity-weakening friction having a small value of b-a (>0). Rate-and-state law is employed for this area. The lower portion is phenomenologically described and assumed to have an extremely low effective normal stress, by which slip speed fluctuates by tidal and non-tidal stress changes according to a form of V=V_0 exp (dCFS/A) as in the tremor zones. This portion gives traction to the acceleration area.

The result indicates that, in order that the predicted slip agrees with the observed acceleration, the coefficient A is one order of magnitude smaller than that for tidal responses of tremors. When effective normal stress is equal to 1 MPa or lower, the effect of the non-tidal variation in the ocean with a period longer than 10 years becomes dominant in the slip history, which successfully reproduces the observed acceleration. Moreover, the inferred slip history exhibits smaller-magnitude SSEs with reccurence periods of 2-3 years. This feature is consistent with that obtained from an analysis of repeating earthquakes in the Japan Trench (Uchida et al. 2016) When effective normal stress is larger, the effects of the external stresses are almost negligible and SSEs with larger magnitudes and longer intervals occur as in the Bungo Channel.

Meteorological studies indicate that sea level variations in Tohoku have periods of 10-20 years. If plate subduction speed is subject to long-term ocean loads, slip acceleration should occur also in the past. Actually, the predicted slip velocity during 1990-1995 by the model is faster than in 1996-2000, when M-8 class earthquakes occurred in NE Japan. We will investigate if such a correspondence can be seen between past earthquake/crustal deformation data and long-term variations in the ocean.

Keywords: Slow earthquakes, earthquake triggering , slow slip, crustal deformation, tides, ocean bottom pressure