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Key Points:

- Intraslab earthquakes trigger tremor
- The triggering of intraslab earthquakes by tremor is not as significant
- Dynamic stress by small earthquakes increases tremor rate

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Triggering of tremor and inferred slow slip by small earthquakes at the Nankai subduction zone in southwest Japan

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Abstract The correlation of earthquakes with tremor and slow slip has not been clearly quantified. We investigate 12 year earthquake and tremor catalogs for southwest Japan and find that nearby small intraslab earthquakes are weakly correlated with tremor. In particular, the intraslab earthquakes with magnitudes ≥2.7 tend to be followed by tremor more often than expected at random by a factor of 2 to 6. The excess number of tremor before earthquakes is not as significant, although marginally more than expected. The underlying physical mechanism of the observed triggering of tremor and inferred slow slip by earthquakes is most likely to be the dynamic stress changes (several to several tens of kilopascals) rather than the much smaller static stress changes. The rate of triggering of tremor by earthquakes is similar to, although somewhat lower than, rates observed for similar amplitude stress changes due to the lower-frequency teleseismic surface waves and tidal stressing.

1. Introduction

Slow slip, occurring at the brittle-ductile transition zone with long duration of days to months, constitutes a third mode, in addition to stick slip (earthquakes) and continuous aseismic slip, of strain release at plate boundaries. Geodetically observed slow-slip events have been reported in various subduction zones [e.g., *Dragert et al.*, 2001; *Obara et al.*, 2004] as well as on the strike-slip San Andreas fault [*Linde et al.*, 1996]. Some slow-slip events are accompanied by emergent seismic signals of long duration known as tremor [*Obara*, 2002; *Rogers and Dragert*, 2003] and low-frequency earthquakes (LFEs) [*Obara*, 2002; *Katsumata and Kamaya*, 2003; *Shelly et al.*, 2006, 2007a, 2007b]. These slip phenomena are often called episodic tremor and slip (ETS). Both nonvolcanic tremor and slow slip have been observed in southwest Japan, where the Philippine plate subducts beneath the Eurasian plate. There have been a tremendous number of tremor (over 20,000 used in this study) and slow-slip events detected in this region. As has been reported in the Cascadia subduction zone [*Rogers and Dragert*, 2003], the tremor and slow slip in the Nankai subduction zone are found to be highly correlated in space and time [*Obara et al.*, 2004; *Obara and Hirose*, 2006].

The strong spatiotemporal coincidence of these slip phenomena suggests the same underlying physical mechanism, which is different from that of regular stick-slip earthquakes. The spatial and temporal correlation between regular earthquakes and slow slip (or tremor) is of great importance to understand the slip behavior at the fault plane. Also, study of the possible triggering of regular earthquakes from the neighboring tremor may help to mitigate the earthquake hazards by monitoring tremor activity and slow slip at the Nankai subduction zone as well as other places in the world.

Tectonic tremor, occurring near the brittle-ductile transition zone of the fault, is sensitive to stress changes from tidal loading [*Rubinstein et al.*, 2008; *Nakata et al.*, 2008; H. Houston, Response of tremor and slow slip to tidal stress: Constraints on fault friction and weakening, submitted to *Nature GeoScience*, 2014] and from dynamic shaking of propagating surface waves from distant large earthquakes [*Miyazawa and Mori*, 2006; *Rubinstein et al.*, 2007; *Chao et al.*, 2012, 2013]. On the other hand, slow slip has been observed to coincide with triggered seismicity, for instance, at Hawaii [*Segall et al.*, 2006], at New Zealand subduction zone [*Delahaye et al.*, 2009], and at Boso Peninsula, central Japan [*Hirose et al.*, 2014]. Spatiotemporal correlation of five small earthquakes around an ETS event has been reported at the Cascadia subduction zone [*Vidale et al.*, 2011]. These correlations suggest the potential for significant triggering between slow slip and earthquakes

[*Kato et al*., 2012] and thus the potential to forecast big earthquakes by monitoring slow slip and tremor activity. Studies of triggering between slow slip (or tremor) and earthquakes have been mostly based on an individual big earthquake or slow-slip event; the small data set limits the generality of the implications. Our direct comparison between tremor rate and local small earthquake seismicity from a large data set (about 20,000 events in each catalog) over a longer period (11.5 years) sheds more light on the as yet poorly resolved triggering relation between slow slip, as revealed by tremor, and regular earthquakes.

In this study, we investigate the relation between the earthquake seismicity and the activity of tremor at Nankai subduction zone in Japan by looking into the spatial temporal correlation between small intraslab earthquakes and tremor in this region. The shallow earthquakes in the overlying upper crust are 20 km or farther away from the tremor, and the stress loading from these events would be minor. So we focus our work on the nearby intraslab earthquakes that would be more likely to trigger or to be triggered by tremor. We find that there is higher probability that tremors follow bigger earthquakes. The excess probability for earthquakes following tremor is not as significant, although there are marginally more than background. The triggering stress for the observed triggered tremor is most likely to be dynamic shaking of propagating wave rather than static stress associated with the earthquakes.

2. Data and Method

We examine two data catalogs. One is the tremor catalog [*Obara et al*., 2010] with time resolution of 1 h. The other is the earthquake catalog from the Japan Meteorological Agency (JMA). The JMA catalog clearly separates the earthquakes and LFEs [*Katsumata and Kamaya*, 2003], and we only use the intraslab earthquakes below the plate interface which is 7 km above the oceanic Moho estimated by *Shiomi et al*. [2006]. To investigate the correlation between the tremor and intraslab earthquakes in this region, we use data from January 2001 to June 2012.

The hourly tremor catalog [*Obara et al*., 2010] that we use is constructed with the assumption of depth fixed at the plate interface, which is assumed to be 5 km above the oceanic Moho depth estimated by *Shiomi et al*. [2006]. In this study we use this original tremor catalog but assume 7 km oceanic crust thickness. This shifts the tremor 2 km shallower, which causes little horizontal shift in the tremor location, due to the insensitivity of travel time to depth in event location. Examining crustal thicknesses of 5 km and 6 km, in addition to 7 km, we determined that crustal thickness does not significantly influence our results.

We restrict our catalog to only include those intraslab earthquakes within 20 km horizontal distance of any tremor, so these are the events analyzed below. Given the weak effect that we find, events at greater distances are not expected to show correlations and are not in this initial reconnaissance. The earthquakes investigated in this study have magnitude $M_j = 0.7$ or greater (JMA magnitude, which is approximately equal to moment magnitude for $M_j < 4.5$ [*Katsumata*, 1996]), which is the estimated completeness magnitude (Figure S1 in the supporting information). We take JMA earthquake magnitude as equal to moment magnitude when evaluating stress level later in the paper. We decluster the earthquake catalog following *Reasenberg* [1985] so that we can minimize the degradation of the final correlation result by aftershocks and earthquake swarms. The final intraslab earthquake catalog that we used in this correlation study contains 19,955 events (Table S1 in the supporting information), with 4.2% of the original events removed by declustering.

To evaluate the degree of triggering between earthquakes and tremor, we first find how many earthquakes and tremor are spatially and temporally close to each other. For each earthquake (T_e and X_e), we search the tremor catalog and keep all those tremors (T_t and X_t) that satisfy the following conditions:

$$D_{\min} < |X_t - X_e| \leq D_{\max}, \quad T_{\min} < T_t - T_e < T_{\max} \tag{1}$$

$$D_{\min} < |X_e - X_t| \leq D_{\max}, T_{\min} < T_e - T_t < T_{\max} \tag{2}$$

in which T_e is the occurrence time of earthquake *e* and T_t is the time of hourly episode of tremor *t*; $\boldsymbol{X}_e$ and $\boldsymbol{X}_t$ are the three-dimensional locations of earthquake *e* and tremor *t*, $D_{\min}$ and $D_{\max}$ specify the proximity bins in space, and $T_{\min}$ and $T_{\max}$ specify the proximity bins in time. The distance bins we used are 0–8, 8–1, 11–14, 14–17, and 17–20 km, and the time bins are 0–6, 6–12, 12–24, and 24–48 h. The criteria (equations (1) and (2)) above are for the evaluation of earthquake-triggering tremor and triggered by tremor, respectively.

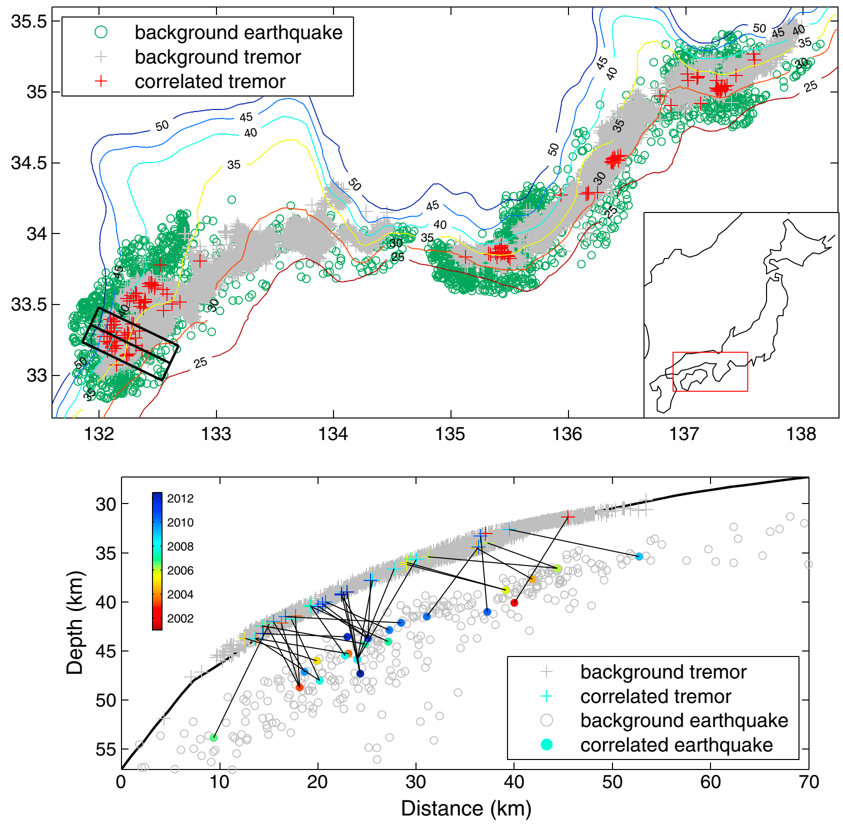

Figure 1. Tremor and intraslab earthquakes at Nankai subduction zone from January 2001 to June 2012. (a) Background intraslab earthquakes (green circles) with $M \geq 2.5$ are plotted. Correlated earthquakes and tremor (red pluses) are those within 14 km and 12 h. The colored contours indicate the plate interface depth in kilometers. The black box indicates the cross-section position. (b) The cross section shows the correlation between tremor at the plate interface and the slab earthquakes ($M \geq 1.8$) below. Tremor and earthquakes of the same color and connected by a black line occurred close together in time.

We perform this evaluation process again using the same tremor catalog (T_t and $\boldsymbol{X}_t$) but a temporally randomized earthquake catalog (T_e^* and $\boldsymbol{X}_e$), where T_e^* has a uniformly random distribution between the beginning and the end of the investigated time interval. We apply this algorithm 500 times and estimate the expectation and standard deviation of correlations for each spatial and temporal proximity. Tests with 1000 times did not appreciably change the results. Using the observed distribution of earthquakes in assessing correlation is necessary because earthquakes are far from uniformly distributed across the subduction zone.

Comparing the number of earthquakes that correlated with some tremor and the expected number of correlated earthquakes from a randomized catalog gives insight into the frequency of triggering between earthquakes and tremor. We use the ratio between observed correlated earthquake number and that expected at random to quantify the degree of triggering between tremor and earthquakes.

3. Results and Discussion

Intraslab earthquakes occurred up to about 20 km below the plate interface, with a peak distribution around the oceanic Moho (Figure 1b and Figure S2 in the supporting information) [see also *Shelly et al*., 2006]. To reiterate, since these intraslab earthquakes and tremor are sometimes very near to each other, we are searching for the component of seismicity in response to the slow slip or tremor activity and tremor response to earthquake activity. The small but significant correlations between the tremor and intraslab earthquakes that we find here show that there is triggering between the two.

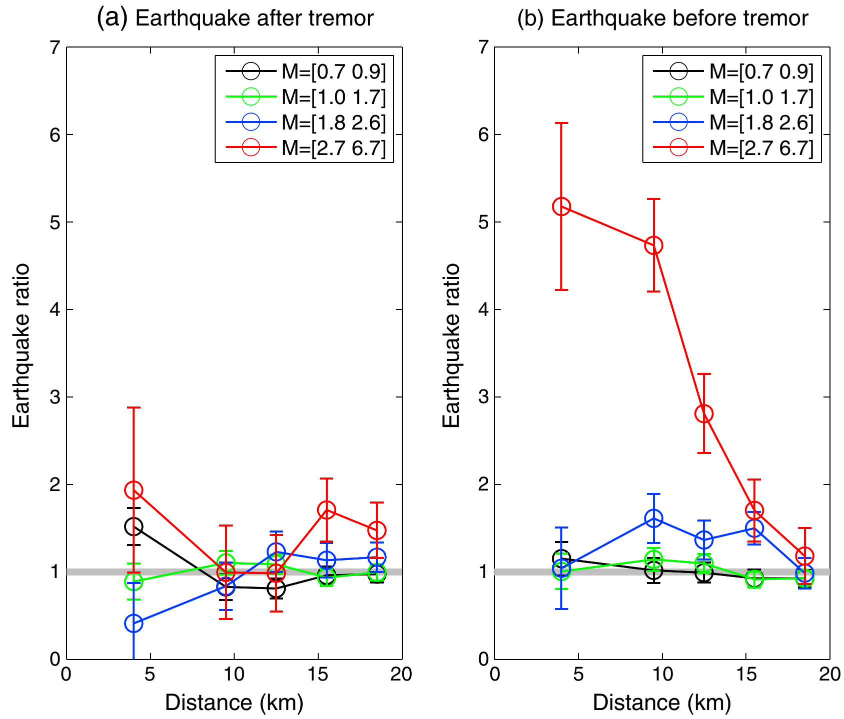

Figure 2. Earthquake ratio (correlated earthquakes in real catalog divided by correlated earthquakes in randomized catalog) versus distance. The distance bins are 0–8, 8–11, 11–14, 14–17, and 17–20 km. The time delay limit considered is 12 h. (a) Earthquake ratio for earthquake after tremor. (b) Earthquake ratio for earthquake before tremor. The thick horizontal grey bar represents the level in the randomized catalog. The error bars are calculated by σ/*N*, where *N* is the average number of correlated earthquakes from randomized catalogs and σ is its standard deviation. See Tables S2 and S3 in the supporting information for correlated event numbers and average magnitude in each magnitude and distance bin. See Figures S4–S6 in the supporting information for the results with other time interval.

For a range of distance and time delay parameters, we find that the ratio is distinctly higher than one, especially for those earthquakes with magnitude bigger than 2 (Figures 2b and 3b). There are about 2 to 6 times more intraslab earthquakes with nearby tremor shortly after them than expected from randomized catalogs. This means that earthquakes have triggered some tremor. We find higher ratios for earthquakes in higher magnitude ranges, showing that, as expected, bigger earthquakes are more likely to trigger tremor (Figures 2b and 3b and Figure S11 in the supporting information). The biggest magnitude of a correlated earthquake is 4.7. Within each magnitude bin, there is a systematically decreasing ratio with increased distance (Figure 2b), which is physically expected from the lower stress loading of the more distant earthquakes (see Figure S3 in the supporting information). Quantitative stress estimates based on distance and magnitude ranges are given and discussed later in the paper (Figure 4). Similarly, with increased delay time, we find that the ratio starts high at short times, then with time, decreases down to one, the expected value when there is little triggering. This suggests that the triggering mechanism has a time scale less than about 24 h (Figure 3b).

Whether the tremor (or more likely the slow slip driving it) triggers seismicity is also interesting and important for mitigation of earthquake hazard. In southwest Japan, the tremor occurred at the plate interface with depth variation from 30 km to 45 km (Figure 1), and it has not been very clear about how close tremor is from the rupture zone of the shallow megathrust. The potential for the updip megathrust triggering by deep tremor has not been well understood yet. Intraslab earthquakes just beneath the plate interface at the tremor zone could be triggered by nearby tremor and slow slip, and these intraslab events, in turn, might as well contribute to the stress loading for the potential updip megathrust.

We find that the triggering of earthquakes by tremor is not as significant as the triggering of tremor by earthquakes (Figures 2a and 3a). The ratio of apparently correlated events between the real catalog and randomized catalogs also shows a decreasing pattern with the delayed time, albeit much weaker. Although

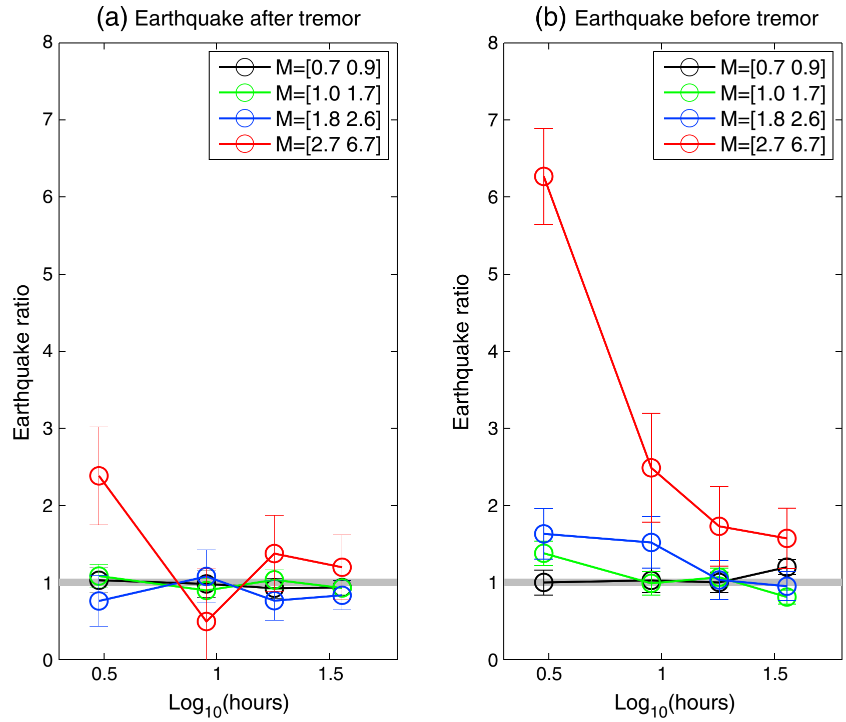

Figure 3. Earthquake ratio (same definition as in Figure 2) versus with time delay between earthquake and tremor. The time bins are 0–6, 6–12, 12–24, and 24–48 h, respectively. The distance range is within 11 km. (a) Earthquake ratio for earthquake after tremor. (b) Earthquake ratio for earthquake before tremor. The thick horizontal grey bar represents the level in the randomized catalog. The error bars are defined as in Figure 2. See Figures S7–S10 in the supporting information for the results with other distance range.

this trend could indicate triggering of earthquakes by tremor events, the correlated earthquake number is within the standard deviation of the expectation derived in the randomized searches. That is to say that the resultant ratio, in spite of being larger than one, is not a compelling indicator of tremor triggering earthquakes. This result is not unexpected, given that the stress changes associated with tremor at the plate interface may well be too small to trigger intraslab earthquakes. The ratio higher than one might be from the contributions of a few earthquakes within a period of extensive slow slip, as was shown for Cascadia subduction zone by *Vidale et al*. [2011], which claims an elevated rate of tiny intraslab earthquakes in response to an ETS event. Previous studies have also found increased seismicity rate accompanying slow-slip event at Hawaii [*Segall et al*., 2006], New Zealand [*Delahaye et al*., 2009], and Boso Peninsula, central Japan [*Hirose et al*., 2014], probably due to stress loading from the slow slip. Similarly, we think that the triggering of intraslab earthquakes by tremor at Nankai subduction zone, although very weak, is likely due to the stress changes associated with slow-slip events.

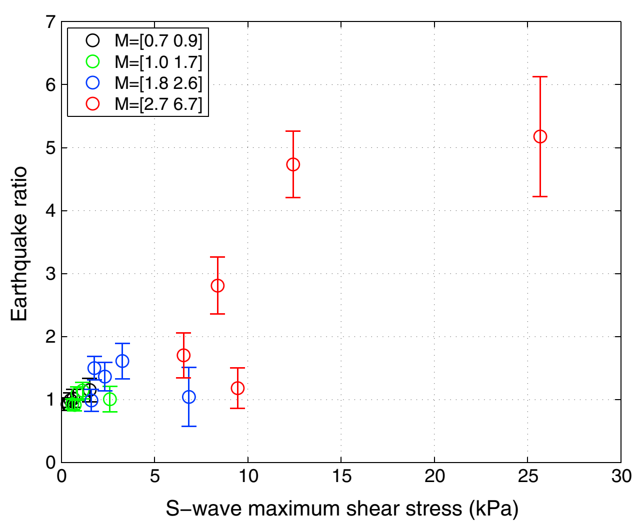

Figure 4. Earthquake ratio (defined as in Figure 2) variation with maximum shear stress calculated for *S* wave from the earthquakes. For the stress calculation, the distances are binned as in Figure 2, and the magnitude is averaged among the correlated earthquakes in each bin.

The different triggering potential between earthquakes and tremor is probably because both the dynamic and static stress changes associated with earthquakes are larger than those associated with tremor. Moreover, tremor is thought to occur at the plate interface with low effective stress and thus is very sensitive to driving stresses. Stress change due to tidal loading, with magnitude of a few kilopascals or less, is enough to modulate tremor activity [*Shelly et al*., 2007a, 2007b; *Rubinstein et al*., 2008; H. Houston, submitted manuscript, 2014] and slow slip [*Hawthorne and Rubin*, 2010] by a factor of 2 to 3. Previous studies have also observed many tremor events amplified or triggered by dynamic shaking from distant large earthquakes [*Rubinstein et al*., 2007; *Peng et al*., 2008; *Chao et al*., 2012, 2013], with amplitudes of a few tens of kilopasclas. Thus, stress of amplitude around 1 kPa seems necessary in order to measurably trigger tremor.

Possible tremor triggering mechanisms include static Coulomb stress change and dynamic stress changes caused by shaking that result from the earthquake seismic wave passage. These two mechanisms might both contribute to the observed correlations. To understand the triggering mechanism of tremor at Nankai subduction zone, we evaluated both the static stress and dynamic stress associated with earthquakes at the tremor location. First, we calculate the static stress tensor at the location of tremor resulting from a double-couple point source using a code based on *Okada* [1992]. The maximum static shear stress generated at the tremor location was on the order of several to tens of pascals, which is too small to trigger tremor, as it is far smaller than the tidal stresses that only moderately influence tremor [*Nakata et al*., 2008]. We conclude that the triggering of tremor by static stress change of the intraslab earthquakes, at least for the data set that we studied, is negligible.

Then, we calculated the dynamic stress tensor at the time of the *S* wave from a double-couple point source in a whole space. A whole space is an adequate assumption here because the distances between earthquakes and tremor and the wavelengths of the transient *S* waves are small relative to the depth. The strain tensor was calculated from the spatial gradient of the far-field *S* wave displacement vector and is dominated by a term with the time derivative of the source pulse and 1/r fall off with distance. Thus, the duration of the transient *S* wave affects the amplitude of the strain. Triangular source time functions were estimated from the *Madariaga* [1976] model with stress drop of 3 MPa [*Shearer*, 2009]. The duration ranges from 0.005 to 0.1 s for the earthquake magnitude range studied here. The stress tensor was determined from the strain tensor using Hooke's law, assuming a Poisson solid with density of 3200 kg/m^3 and shear wave velocity of 4400 m/s, which equates to a rigidity of 6.2×10^{10} Pa.

We focus on shear, rather than Coulomb stress, for simplicity and because friction on the plate interface appears to be low (e.g., H. Houston, submitted manuscript, 2014). Maximum shear stresses from the dynamic *S* wave stress tensor are half the difference between the maximum and minimum principal stresses. The dynamic shear stresses are 2 to 3 orders of magnitude higher than the static stresses at the distances and magnitudes of the triggering quakes. Rather than guess focal mechanisms and trust precise relative locations, we simply plot the amplitude averaged across the focal sphere [*Boore and Boatwright*, 1984]. Figure S3 in the supporting information shows shear stresses versus distance for earthquakes of different magnitudes. Shear stresses of a few to tens of kilopascals are generated for the largest average magnitude value as shown by red circles in Figure 4. These are on the order of the minimum tremor triggering stresses from surface waves of large distant earthquakes (e.g., 2–3 kPa by *Rubinstein et al*. [2009] and *Peng et al*. [2009], 7–8 kPa by *Chao et al*. [2012], and 10 kPa by *Chao et al*. [2013]) and an order of magnitude greater than the tidal stresses that trigger tremor and slow slip on the Cascadia and Japan subduction zones [e.g., *Rubinstein et al*., 2008; *Nakata et al*., 2008; *Hawthorne and Rubin*, 2010; H. Houston, submitted manuscript, 2014]. Figure 4 shows that the triggering ratio depends systematically on the applied shear stress for the distance and magnitude ranges studied here. Large shear stresses, due to either very close distance or large earthquake moment release or both, are a plausible cause of the tremor triggered at the plate interface.

Tremor triggering by regional earthquakes has been studied in central California [*Guilhem et al*., 2010], where four regional earthquakes with magnitudes 6.6, 6.9, 7.2, and 7.2 were observed to trigger tremor. The inferred threshold of triggering stress by these regional events is 1 kPa, the same magnitude as for teleseismic events. Our results suggest that even a very brief stress increase can increase tremor rate by 2 to 7 times over background rates. The stress levels that trigger tremor are the same magnitude or only slightly higher than those for other much more prolonged stressing processes that trigger tremor, surface waves of distant large earthquakes and Earth and ocean tides. The durations of stressing for the points in Figure 4 also vary by more than an order of magnitude, but given the similarity of triggering thresholds between these tiny events and tidal stresses lasting hours, duration does not affect thresholds as strongly as amplitude. From Figure 4, we estimate the stress magnitude for tremor rate increasing due to the nearby intraslab earthquakes to be ~10 kPa. The stress range we evaluated here with notable tremor rate increase is also comparable with the static stress level that accounts for increased tremor rate [*Nadeau and Guilhem*, 2009]. Thus, it seems that a change of over several kilopascals of either static or dynamic stress might increase the tremor rate by a measurable level, suggesting a very weak fault for tremor genesis.

4. Conclusions

By investigating decadelong catalogs of earthquakes and tremor at Nankai subduction zone in Japan, we find that small intraslab earthquakes trigger tremor with the effectiveness of such triggering dependent on magnitude. The triggering of earthquakes by tremor is not as significant. This difference in triggering between tremor and earthquakes is probably due to the different stress change magnitudes associated with the two categories of events. The dynamic shear stress of incoming *S* waves from the nearby earthquakes is several or several tens of kilopascals and is observed to increase the tremor rate by a factor of 2 to 6, comparable to triggering observed from much longer-period surface waves and tides of similar stress amplitude.

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