Climate and earthquake patterns linked through variations in Pacific Ocean sea-level.

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Abstract

The El Niño-Southern Oscillation (ENSO) produces large shifts in ocean and atmospheric conditions in the Pacific and Indian Ocean basins, including major changes in sea level in equatorial regions across the Pacific basin, including the Pacific Rim\textsuperscript{1-6,18}. The Pacific Ocean rim is also well known as a region prone to a high frequency of earthquakes\textsuperscript{16,17}, which has a profound influence on lives, economies, and ecosystems in the region. An ability to better estimate earthquake risk frequency would be of enormous value in preparedness and response planning\textsuperscript{16}. Here we show that ENSO-driven sea-level variability, measured in the equatorial, northern or overall Pacific Ocean is coherent with subsequent variability in earthquake frequency in the western Pacific Ocean Basin. While the statistical link is evident for M4.7 to M5.5 and $\geq$M6.5 earthquakes, it is strongest for M4.7 to M5.5 earthquakes. We hypothesize that the relationship is due to a systematic influence of the climate-ocean system on the lithospheric stress field and plate coupling along subduction zones. We suggest these results would underpin an ability to better assess earthquake frequency risk in and around the western Pacific several months in advance.

Full Text

ENSO is the ‘most dramatic, most energetic global climate system at interannual scales’\textsuperscript{5}, having a particularly major influence on ocean-atmosphere dynamics over much of the Pacific-Indian Ocean region\textsuperscript{1-3,5,6,17,18,24}. ENSO phases are also able to produce changes in length of day due to their influence on atmospheric angular momentum\textsuperscript{7,8}. It follows that global changes in mass distribution due to ENSO-related fluctuations may affect the stress levels within the solid earth, implying a possible link to earthquake activity\textsuperscript{9,10}. It was once suggested that ENSO could be driven by seismic activity\textsuperscript{11}. However, recently it has, instead, been tentatively implied that ENSO activity is more likely to lead variations in seismic activity in some regions of the equatorial Pacific\textsuperscript{12,13,37}. ENSO produces significant variations in sea level and atmospheric pressure, including the draining of warm water from the western Pacific Ocean following La Niña events\textsuperscript{2,3,4,6,14,18} (Fig. 1). Considering ENSO’s Pacific basin-wide impact – in terms of producing basin-wide sea-level anomalies and major precipitation variations – these observations provide the focus for further exploring ENSO climate/oceanographic relationships with Pacific-basin earthquake activity.

It is, of course, well known that earthquakes pose a significant seismic hazard and can produce substantial losses to infrastructure and lives across many regions of the Indo-Pacific Basins\textsuperscript{16,17}.

We know the Gutenberg-Richter power law distribution for energy released at earthquakes can be understood as a consequence of the earth crust being in a self-organized critical state\textsuperscript{22}. Further, the size of earthquakes is unpredictable since the evolution of an earthquake depends crucially on minor details of the crust\textsuperscript{22}. Yet, we know that seasonal climate/rainfall variability is chaotic\textsuperscript{5}; however, using knowledge of the phase-locked persistence of ENSO (approximately from June to May)\textsuperscript{2,3}.
as well as the precursors of ENSO in the months previous\(^3\), probabilistic seasonal climate forecasts are now routinely used in risk management planning within that chaotic system\(^25\). Seasonal climate forecasts, whether of ENSO itself \(^3,23\) or, more directly of ENSO's lagged impacts\(^2,25\), are being applied by users, globally, to assist in their risk management decisions. We suggest that, similarly, assessments of likely earthquake event hazard for the Pacific Rim regions, here analysed, may be considered in a probabilistic sense utilising antecedent knowledge of ENSO patterns or phases. This approach builds upon and utilises knowledge of antecedent ENSO phase variation as applied in seasonal climate forecasting\(^2,27\).

As the ENSO-linking mechanism explaining the variation in earthquake numbers is potentially absolute sea-level variation\(^13,14\), we examined several regions and sub-regions of earthquake activity around the Pacific Basin in relation to ENSO variation. This study focussed on the utilisation of detrended sea-level data sets that contained sufficient time series for statistical analyses\(^14,15\). All sea-level data sets, providing data from 1992-2019, were detrended to account for sea-level rise issues associated with climate change as well as removing seasonal influences. Altimetry data were provided by the NOAA Laboratory for Satellite Altimetry. We further confirmed the relationships between the ONI, as an indicator of and link to the ENSO system, with sea-level anomalies in the four broad key Pacific Ocean regions where SLA data were utilised. We found strong correlations between the ONI and the SLA data sets used in this analysis (for example, regarding the overall Pacific Ocean SLA in Fig 2). The time series and correlations for all Pacific Ocean regions utilised are provided in Supplementary Figure 1.

ENSO proxy data sets that may be indirectly associated with sea-level height variation associated with ENSO (eg the Southern Oscillation Index (SOI); Oceanic Niño Index (ONI)) were investigated for any relationship/correlation with earthquakes. We found occasional association/correlation between a three-month warming trend in the ONI (as occurs in El Niño development) and, also, in three-month average values of the SOI with earthquake variability in the Central America and the Nazca Plate, eastern Pacific Rim regions. However, these correlations were not found in other Pacific region (results not shown here) and were not consistent across depths or months.

Sea level anomaly (SLA) data were derived from Topex-Poseidon satellite data and, in order to also produce associated cumulative probability distributions, further (arbitrarily) partitioned into positive anomalies/phases (>\(+0.5\) standard deviation (SD)), neutral values (between \(+0.5\)SD and \(-0.5\)SD), and negative anomalies/phases (<\(-0.5\)SD). This was done in a similar manner to that applied in use of ENSO indices in seasonal climate forecasting\(^2,27\). The levels of partitioning (eg \(+0.5\)SD) can be reduced or increased. When doing so, we found that if levels of partitioning are varied, little or no change occurs in the results obtained in terms of resultant probability distributions of earthquakes associated with each SLA pattern or phase.

We find that detrended sea-level height anomaly values, using overall Pacific, northern Pacific, equatorial Pacific Tropics Ocean data, are significantly and moderately to strongly (negatively) correlated with subsequent earthquake activity for the aggregated western Pacific Rim region. We also find similar
results for many Pacific sub-regions. For all sea-level data sets analysed, the stronger the respective negative Pacific SLA anomalies the higher the number of ensuing shallow earthquake events subsequently occurring in the western Pacific Rim region. Conversely, the larger the positive SLA measured in these Pacific regions the fewer the number of ensuing earthquake events. This result is especially the case for earthquakes occurring during rolling six-month periods commencing in December, January, February, March, or April and continuing through to the end of October. There is also evidence of similar correlations for periods commencing August in some regions (eg Polynesia). We find the strongest (Spearman-Rank) correlations, together with associated shifts in cumulative probability distributions of earthquakes, in the analysis of earthquakes ≥M4.7*

We reason that if the variation in the weight of the water is causing changes in the local stress field which affect the earthquake occurrence rates, we expect to see a stronger effect for shallow events compared to deeper events. This is because the strength of the rock reduces the vertical stress change with depth. Consequently, we find moderate to strong negative correlations between SLA and shallow earthquakes, defined as 0-60km (Supplementary Tables 1,4,5,6). We noted similar but generally weaker correlations between SLA and intermediate depth earthquakes (defined as 60-120km depth or more generally, ≥60km^33) when analysing equatorial ‘Pacific Tropics’ SLA or NPBSLA sea-level data with subsequent earthquakes. However, although statistically significant for smaller earthquakes, we did not find consistent results for higher magnitude intermediate depth earthquakes nor major shifts in median numbers of earthquakes associated either with negative or positive SLA at those focal depths.

We found the strongest correlation values by sub-region and time periods with SLA for earthquakes at all depths in the magnitude range M ≥4.7-M 5.5. Fewer numbers of periods of significant moderate correlations were found for magnitude ranges M≥5.5-M 6.5. However, we found moderate/strong correlations for those shallow earthquakes M ≥6.5 with preceding negative SLA (Supplementary Table 2). We find for large earthquakes (eg M≥6.0; M≥6.5) there are moderate/strong negative correlations between PBSLA, NPBSLA and ‘Pacific Tropics’ SLA for key sub-regions where sufficient data exist for analysis (eg. the Japan Region or for the aggregated western Pacific Rim) (Supplementary Table 3). We find this result to be particularly the case for shallower earthquakes at 0-30km or 0-20km focal depth.

*Magnitudes ≥4.7 were selected as the base level magnitudes to provide both sufficient sample sizes in earthquake numbers for statistical analyses and also to account for potential issues associated with completeness of the respective catalogues if lower values applied^33.

We found shifts in the cumulative probability distributions of earthquakes at 0-60km focal depth associated with negative and positive ‘Pacific Tropics’ patterns, produced here as boxplots, to be highly statistically significant (p<.01) (Fig. 3a). We found shifts in cumulative probability distributions for most sub-regions to also be statistically significant, whether associated with antecedent ‘Pacific Tropics’, NPBSLA, or PBSLA data. These shifts in cumulative distributions – and associated correlation values -
may persist throughout the year in some sub-regions (eg. Eastern Margins of the Australian Plate, Polynesia regions). For the aggregated region of the western Pacific Rim, we found moderate/strong statistical correlations for both zero lag detrended sea-level height anomaly data and with up to 8 months lead times – although with strongest correlation values at four to five-month lead times (Fig.4).

Other rolling time periods of earthquake activity (eg. over 3 months, 9 months) can similarly be selected for this type of analysis. We chose the six-month ‘validity period’ as the default period based upon on similar application of statistical approaches in seasonal climate forecasting\textsuperscript{2,27}. However, we found far less strong correlation results for the aggregated eastern Pacific Rim region and associated sub-regions, although with weak negative correlations for the boreal fall period (Supplementary Tables 1(d);7).

We reason the capability to provide these long-lead correlations between PBSLA, NPBSLA, and ‘Pacific Tropics’ SLA, with number of western Pacific Rim earthquakes is due to the known persistence of ENSO events once an ENSO event starts to develop, usually in the June to October period of any given year\textsuperscript{3}. We note the known ‘sloshing’ of water from the western to eastern extremities of the equatorial Pacific following the build-up of water in the western equatorial Pacific during La Niña events. The relaxation of the south-east trade winds during the late boreal spring leads to the extensive drainage of water from the western equatorial Pacific\textsuperscript{18,19}. This pattern also means that while there has been increase in water in the western Pacific (of the order of 20cm or more during La Niña and falling by similar amounts in the eastern Pacific)\textsuperscript{18} the total sea-level in the entire Pacific also drops by some millimetres\textsuperscript{19} (also refer Fig. 1).

We find the spatial distribution of intermediate earthquake risk following detrended negative or positive sea-level height anomalies to be reasonably uniform throughout the north, north-west, and south-west Pacific regions. We find these relationships particularly strong for the 0-60km focal depth and/or when aggregated over all levels (Fig. 6,7). We found few statistically significant relationships between any of the (detrended) SLA data or patterns and the number of earthquakes for the combined Oregon, Cascadia, or California region. However, when including the Mexico and Central America, Central South America, and the Nazca Plate Regions, we found limited periods of correlation/shifts in probability distributions in those regions associated with the various SLA data sets (ref. also Fig 6,7) (Supplementary Table 7). We further found particularly consistent spatial relationships and across all SLA data sets (Pacific Tropics, NPBSLA, and PBSLA) between positive SLA and the low probability of obtaining long-term median number of earthquakes (Fig 7).

‘Bootstrapping’ techniques\textsuperscript{20} (combined with tests of statistical significance) provided further confidence intervals associated with the derived partitioned earthquake probability distributions, especially for the sub-regions analysed. From this we found that over the annual period, the Sumatra sub-region has particularly strong shifts in the distributions of earthquakes for the January to June period, associated with preceding ‘Pacific Tropics’ SLA (Fig. 8a). We found the Polynesia sub-region as having the strongest and significant shifts in earthquake probability distributions for the August to January period and associated with antecedent NPBSLA values or patterns (Fig.8b). Similarly, we also noted the Japan
Region as one with strongest and significant shifts for intermediate depth earthquakes (≥60km) for the April to September period associated with preceding PBSLA data (Fig. 8c).

The earthquake triggering reported in this study is mainly observed along subduction zones where shallow angle thrust faulting is dominant. For example, there are no strong correlations for the strike-slip faulting offshore of the western US. Earthquake triggering for shallow angle thrust faulting at subduction zones during times of low sea levels may be qualitatively explained by the Coulomb failure criterion. Lower sea levels would produce less water weight, reducing the vertical normal force and thus promote thrust faulting. Consistent with this idea, a correlation of earthquakes and low ocean tide was found for events in the northeast Pacific\(^{30}\). The same explanation (with opposite geometry) is given for tidal triggering of earthquakes at spreading ridges during high tide\(^{31}\). High tides produce additional water weight and increase the vertical normal stress which promotes normal faulting earthquakes (normal faults have the opposite slip direction from thrust faults). The surprising aspect of this study is the small change of normal stress that appears to cause earthquake triggering. The observed sea level anomalies of 10-20 centimetres represent stress changes that are in the same range as the tidal changes (~2 kPa) that trigger earthquakes at the spreading ridges\(^{32}\). The large dataset used in this study may enable resolution of the very small stress effect.

Our evidence suggests a mechanistic relationship between subsequent earthquake occurrence and apparent mass variation in the Pacific Basin associated with ENSO. This is here interpreted as a variable thickness of liquid water to sea-level height and related to the nature of ENSO progression in the Pacific Ocean basin. Additionally, our work demonstrates the wider extent of impact of ENSO events beyond (near-global) rainfall variability. The nature of ENSO, which produces major changes in sea level, demonstrates that ENSO then causes major fluctuations in key elements of the whole Earth's system - in the geosphere, biosphere, cryosphere, hydrosphere, and atmosphere.

We suggest utilisation of each of the detrended SLA data sets utilised may assist in assessing potential western Pacific Rim earthquake risk, particularly following ENSO-related negative or positive SLA patterns. We suggest our results provide the potential further development of a regionalised, operational earthquake-risk analysis system for some regions comprising the Pacific Basin Rim. Aspects associated with change in water mass, utilising other measurements additional to sea-level variability could also be further explored. Given recent climate-change research\(^{26}\), it also remains an open question as to whether the risk of more frequent earthquakes is likely under future climate change conditions and any subsequent changes in ENSO, especially La Niña events.

**Methods**

**Sea-level height anomalies.**

We utilised values of the Pacific Basin sea-level height anomalies (PBSLA), North Pacific Basin sea-level height anomalies (NPBSLA), and equatorial Pacific (‘Pacific Tropics’) sea-level height anomalies,
averaged over a three-month period, as potential predictors or precursors of earthquakes occurring at 10km depths ranging from 0km to 120km in aggregated western and eastern regions of the Pacific Rim as well as for sub-regions (e.g. Philippine Plate). (Assuming normal distributions) we also used threshold SLA values, arbitrarily partitioned into thirds, as $\geq +0.5$ Standard Deviation (SD), $+/0.5$ to $-0.5$S.D., $\leq -0.5$S.D., averaged over three-month periods (e.g., January-March, February to April) to partition earthquake event numbers (‘predictands’), by focal depth thresholds in depth levels from 0km to $>120$km, in 10km depth steps. This approach was carried out for each starting six-month period through the year. This approach was also applied to stratified earthquake focal depth levels from 0km to 20km; 0km to 60km, and from 60km to 120km. These focal depth levels can be extended to deeper values as may be required. The partitioning of SLA values can also be changed but with little change to the ensuring results, although having produced larger sample sizes if reduced.

Monthly mean sea level height anomalies were constructed from NOAA Satellite Altimetry data that were then detrended and normalised with the seasonal signal removed.

**Tests of Statistical Significance.**

We tested for statistical significance levels in the relationships between detrended PBSLA, NPBSLA, and ‘Pacific Tropics’ at seasonal timescales and regional seismicity using established methods in statistical seasonal climate forecasting\textsuperscript{2,25,27}. We partitioned the history of events according to the antecedent or concurrent patterns of detrended Pacific Basin SLA and NPBSLA. We derived both Spearman Rank Correlation Coefficient values and levels of statistical significance associated with the shifts in probability distributions. We applied non-parametric statistical tests to provide the levels of statistical significance in the shifts in the conditional probability distributions of integrated regional earthquake numbers that we detected. We utilised the Kolmogorov-Smirnov testing procedures following previous work in seasonal climate forecasting\textsuperscript{2,25,34} but acknowledge issues of attribution associated with over reliance on the use of such statistical significance procedures\textsuperscript{28,29}. We provide complete results including ‘p-values’.

Use of ‘bootstrapping’ techniques, which apply random sampling with replacement\textsuperscript{20}, further provided confidence intervals around the derived partitioned probability distributions. Use of ‘bootstrapping’ together with non-parametric statistical testing provided enhanced confidence in the direction and strength of the results obtained from the (currently available) relatively small sample sizes.

**Conditional probability distributions of earthquake numbers.**

Conditional probability is a measure of the probability of an event occurring, given that another event (by assumption, presumption, assertion or evidence) has already occurred\textsuperscript{2,36}. A core method in this paper is based on the use of conditional probability analysis in which the probability distribution of earthquake numbers is conditional on the patterns of detrended sea-level height anomalies. This approach is
similarly applied in statistical seasonal climate forecasting\textsuperscript{2,25,27} to obtain probability distributions of climate variables and has been adapted to application in this paper.

**Correlation analysis.**

Spearman-Rank Correlation analysis coefficients were used in the calculation of the correlations between three-monthly averaged detrended mean PBSLA, ‘Pacific Tropics’, and NPBSLA and the cumulative number of earthquakes. These analyses were conducted for rolling six-month periods in each given geographical region. Correlation coefficients have been expressed as \( r \) values which measure the linear correlation between two sets of data\textsuperscript{34,36}. The \( r \) values have been calculated between either: the three-monthly averaged detrended mean Pacific Basin sea level anomalies (PBSLA), the three-monthly averaged detrended North Pacific basin sea level anomalies (NPBSLA), and the equatorial ‘Pacific Tropics’ sea level anomalies and the ensuring six-monthly cumulative number of earthquakes. The six-month cumulative number of earthquakes can be varied arbitrarily to assess required risk values. This means, for example, that detrended three-month SLA patterns for January-March, are correlated with the total number of earthquakes for the ensuing six-month period, April-September. Similar calculations are continued through the year on a rolling monthly basis. For the number of earthquakes, we analysed six-monthly moving window averages as the general default period of analysis in order to obtain sufficiently large enough sample sizes. However, shorter, or longer event periods frequently provided similar results and statistical outcomes, although additional results may vary in \( r \) values and statistical significance according to region.

**Non-parametric tests.**

We utilised the Kolmogorov-Smirnov testing procedures\textsuperscript{2,27} to test the statistical significance represented as a \( p \) value that pertains to the shifts in the conditional probability distributions of regional earthquake values but again acknowledge issues of attribution associated with over reliance on the use of such statistical significance procedures\textsuperscript{28,29}. We provide complete results including ‘\( p \)-values’.

**Data**

We used earthquake catalogue data obtained from U.S. Geological Survey [USGS] (earthquake archive http://earthquake.usgs.gov/earthquakes/search/), recognising that at comparatively low Magnitude 4 the catalogue maybe incomplete in some places\textsuperscript{21}. On the other hand, in some sub-regions there may be low numbers of cases (earthquake events) at higher Magnitude levels. In order to provide a balance between completeness and number of cases, we utilised earthquake magnitude values of \( \geq M4.7 \) as the standard ‘default’ value. This approach was made so as to provide data series as complete as possible while also providing large enough sample sizes for detailed statistical analyses. These assessments also utilised frequency-magnitude calculations to determine a minimum magnitude for use in the statistical analysis (output available but not shown here). In all the statistically significant results obtained, the frequency-magnitude plots were non-overlapping. Aftershocks were removed from the catalogue using
typical space-time windows\textsuperscript{32}. Much larger space-time windows of (over 1000 kilometres and 10 years) were used to remove aftershocks of the 2004 Sumatra (Mw9.0) and 2011 Tohoku-oki earthquakes (Mw9.1).

We note that often the depth of a shallow event without depth ‘phasing’ is poorly constrained within a catalogue such as we applied here. In those cases, the depth is set to a predetermined depth, which may vary regionally and between various catalogues. Typical values for predetermined depths are 5 km or 10 km, which, as we noted, often resulted in ‘horizontal streaks’ at these depths in vertical cross sections which can make thorough statistical analysis problematic at these very shallow depths\textsuperscript{36}. Interestingly, we found these issues of horizontal streaking with smaller earthquakes at these shallow depths but not with analysis of large earthquakes such as $M \geq 6.0$ or $M \geq 6.5$.

**Declarations**

**Online content**

Any methods, additional references, Nature Research reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41586-021-03884-7.”

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**Author's contributions.** R.S. identified the original concepts and drafted the paper. J.M. provided detailed input on likely mechanisms and overall construct. Y.E. provided critical input on the statistical and mathematical analyses. D.M. provided critical input into aspects regarding the underlying geophysical mechanisms. T.M. provided the extensive computer modelling and software engineering design for the analysis. C.P. provided data quality analysis and data investigation.

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**References**


**Figures**
Figure 1

Global sea surface (sea-level) height anomaly in centimetres during the La Niña of 2010/11. Note the negative anomalies across most of the central and northern Pacific Basin associated with this La Niña. Courtesy NOAA/PMEL.
Figure 2

Time series of correlation values between ONI as an ENSO indicator with a Pacific Ocean SLA, example given for the Pacific Basin SLA (PBSLA). $r=0.67$ ($p<.0001$) (in this example strongest correlation occurs at 6-month lag). (La Niña is defined as periods with ONI values of $<-0.5$; El Niño with ONI of $>+0.5$). La Niña events are identified when negative ONI occurs, with strong La Niña’s such as in 1999/00 and 2010/11 (source: NOAA Center for Weather and Climate Prediction).
Figure 3

a. Boxplots depicting median values, 25 percentile and 75 percentile values, and whiskers denoting the extremes of number of earthquakes $\geq$ M4.7, 0-60km focal depth, in the aggregate western Pacific Rim region associated with antecedent (5-month lead) negative and positive ‘Pacific Tropics’ SLA patterns. Values shown in this example are for total number of earthquakes for the February to July period. Median value following negative SLA=729 (min. 539; max. 1339), median value following positive SLA=523 (min. 385; max. 611). Shift in probability distribution $p<.003$.

b. Boxplots depicting median values, 25 percentile and 75 percentile values, and whiskers denoting the extremes of number of earthquakes $\geq$ M4.7, for all focal depth levels >0km combined, in the aggregate western Pacific Rim region associated with antecedent (5-month lead) negative and positive ‘Pacific Tropics’ SLA patterns. Values shown in this example are for total number of earthquakes for the February to July period. Median value following negative SLA=955 (min 676; max 1671), median value following positive SLA=715 (min 552; max 798). Shift in probability distribution $p<.01$.

c. Sumatra sub-region ($p<.001$) and

d. Philippine Plate sub-region ($p<.01$).

e. Japan sub-region ($p<.10$) and

f. Australia Plate sub-region ($p<.03$)

g. Eastern Margins of the Australia Plate ($p<.02$) and

h. Polynesia ($p<.03$)
Figure 4

p-values and associated r-values for respective lead times (months) associated with (a) PBSLA, (b) ‘Pacific Tropics’ SLA, and (c) NPBSLA (the lower the p-value the higher the statistical significance and strength of the negative correlation). (We note that stronger correlation values also exist for a number of sub-regions).

Figure 5

Figure 6(a) probability of exceeding the historical median number of earthquakes (all levels >0km, ≥M4.7) for those years associated with antecedent (detrended) negative PBSLA phase. Example provided for the February to July period with a five-month lead-time.

Figure 6(b) probability of exceeding the historical median number of earthquakes (all levels >0km, ≥M4.7) for those years associated with antecedent (detrended) negative NPBSLA phase. Example provided for the February to July period with a five-month lead-time.

Figure 6(c) probability of exceeding the historical median number of earthquakes (all levels >0km, ≥M4.7) for those years associated with antecedent (detrended) negative ‘Pacific Tropics’ SLA phase. Example provided for the February to July period with a five-month lead-time.
Figure 6

Figure 7(a) probability of exceeding median number of earthquakes (all levels >0km, ≥M4.7) for those years associated with antecedent (detrended) positive PBSLA phase. Example provided for the February to July period with a five-month lead-time.

Figure 7(b) probability of exceeding median number of earthquakes (all levels >0km, ≥M4.7) for those years associated with antecedent (detrended) positive NPBSLA phase. Example provided for the February to July period with a five-month lead-time.

Figure 7(c) probability of exceeding median number of earthquakes (all levels >0km, ≥M4.7) for those years associated with antecedent (detrended) positive ‘Pacific Tropics’ SLA phase. Example provided for the February to July period with a five-month lead-time. (Results for Central South America and Central America included for reference).

Figure 7

Figure 8(a) Probability of exceedance of receiving any given number of shallow earthquakes for the Sumatra region for the January to June period and associated with preceding detrended Tropical Pacific SLA with a 5-month lag (KS: p<.000). Assessment of confidence intervals (bootstrapping analysis) applied. Example for Magnitude ≥M4.7 and 0-60km focal depth. (In this, by way of example, the probability of exceeding the long-term median of 48 earthquakes during this period is zero per cent following a positive Tropics SLA pattern but 71 per cent following a negative Tropics SLA pattern).
Figure 8(b) Probability of exceedance of receiving any given number of shallow earthquakes for the Polynesia region for the August to January period and associated with preceding detrended NPBSLA with a 5-month lag. (KS: p<.000). Assessment of confidence intervals (bootstrapping analysis) applied. Example for Magnitude $\geq M4.7$ and aggregated over all focal depths. (In this, by way of example, the probability of exceeding 700 earthquakes $\geq M4.7$ is zero per cent following a positive NPBSLA pattern but 90 per cent following a negative NPBSLA SLA pattern).

Figure 8(c) Probability of exceedance of receiving any given number of intermediate depth earthquakes for the Japan region for the April to September period and associated with preceding detrended PBSLA with a 5-month lag (KS: p<.000). Assessment of confidence intervals (bootstrapping analysis) applied. Example for Magnitude $\geq M4.7$ and $\geq 60km$ focal depths. (In this, by way of example, the probability of exceeding 35 earthquakes $\geq M4.7$ is zero per cent following a positive PBSLA pattern but 100 per cent following a negative PBSLA SLA pattern).

**Supplementary Files**

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