

Global Seasonal Microseism Intensity and Hemispheric Asymmetry

Jason N. Becker^{*1}, Richard C. Aster¹, Yakov Rapoport¹, Thomas A. Lee², Frederik J. Simons³, Adam T. Ringler⁴, and Robert E. Anthony⁴

Abstract

Earth's microseism wavefield dominates seismic background levels at periods between approximately 4 and 20 s, and reflects periodic and secular variations in ocean swell energy. Ocean wave energy couples to the seismic wavefield via distinct primary microseism and secondary microseism (PM and SM) source mechanisms, which are excited by basal swell tractions and seafloor pressure variations due to crossing seas, respectively. This study examines annual amplitude variations for the globally dominant PM (14–20 s) and SM (4–10 s) period bands. Annual harmonic variations are represented by four-term Fourier series fits to vertical-component seasonally smoothed acceleration time series from 73 stations in the Global Seismographic and GEOSCOPE networks with over 20 yr of recording and at least 75% data completeness. These annual periodic functions fit between 14%–95% (PM) and 22%–97% (SM) of signal variance. Station annual peak-to-peak variations range between 1.2–14.3 dB (PM) and 1.5–20.6 dB (SM). An asymmetry in microseism features exists between the Northern (NH) and Southern (SH) Hemispheres. High-latitude NH stations show highly correlated PM and SM annual amplitude variations. This character dominates the wider extratropical NH but diminishes at tropical latitudes, and widespread relative PM–SM decorrelation is observed in the SH. These hemispheric characteristics reflect systematic differences in both extratropical storm activity and ocean wave state. Greater annual variation and seasonal predictability in the NH reflect the influence of the large continental landmasses that enhance both storm intensity seasonality and SM-generating coastal wave reflection. Notable clusters of low PM–SM correlation stations are also observed in continental Antarctica due to seasonal sea ice influences, and in East Asia, reflecting unusual PM and SM source responses to South Asian monsoonal and tropical cyclone ocean wave influences.

Cite this article as Becker, J. N., R. C. Aster, Y. Rapoport, T. A. Lee, F. J. Simons, A. T. Ringler, and R. E. Anthony (2026). Global Seasonal Microseism Intensity and Hemispheric Asymmetry, *Seismol. Res. Lett.* **XX**, 1–24, doi: [10.1785/0220260057](https://doi.org/10.1785/0220260057).

Supplemental Material

Introduction

Earth's global continuous seismic wavefield between about 4 and 20 s is generated by ocean seafloor tractions from ocean gravity waves via two fundamental (primary and secondary) source processes (e.g., [Ardhuin et al., 2015](#)), and the period-dependent history of global wave activity is thus reflected in the long-period seismic record (e.g., [Bromirski et al., 1999](#); [Aster et al., 2008](#); [Stutzmann et al., 2009](#); [Aster et al., 2010](#); [Borzi et al., 2023](#); [Bromirski, 2023](#)).

The secondary microseism (SM) arises from nonlinearly excited basal seafloor pressure variations in regions of crossing seas, and excites seismic waves at half of the causative ocean wave periods ([Longuet-Higgins, 1950](#)). The surface-wave-dominated microseism spectrum typically peaks in the SM band between approximately 4 and 10 s (e.g., [Peterson, 1993](#)) and strongly controls the noise threshold for the detection of transient long-period seismic events in this period range (e.g., [Peterson, 1993](#); [Walter et al., 2012](#); [Ide, 2019](#); [Poli and Shapiro,](#)

[2022](#)). Although we restrict our analysis to periods longer than 4 s to cover the most globally consistent SM energy, the SM band extends appreciably to shorter periods approaching 1 s in some regions for regional storm sources (e.g., [Chen et al., 2011](#); [Borzi et al., 2023, 2025](#); [Lin et al., 2024](#)).

Vertical-component primary microseism (PM) acceleration is approximately 25–60 dB smaller than the vertical-component

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SM. It arises from direct basal gravity wave seafloor tractions in the shallowest approximately 11% of the global ocean, where depths are less than approximately 600 m (e.g., Gualtieri *et al.*, 2019). PM energy manifests as a spectral feature between approximately 14–20 s. Because the ocean swell energy spectrum falls off very rapidly at periods longer than about 14 s (e.g., Ardhuin *et al.*, 2025; Aster *et al.*, 2026), this PM period band and its associated source regions are observed without interference from SM sources. Conversely, the SM source spectrum typically far exceeds the PM spectrum at periods shorter than about 10 s. Examining the 14–20 s and 4–10 s bands thus effectively isolates PM and SM energy, respectively. When vertical-component data are analyzed, observations are dominated by Rayleigh waves and are unaffected by Love waves and by Rayleigh-wave propagation direction.

Large globally observed annual variations in microseism intensity have long been recognized by the seismological community (e.g., Omori, 1901; Gutenberg, 1947). This study is a focused analysis of annual temporal and geographical variations for PM- and SM-dominated period ranges of the microseism wavefield using globally distributed high-quality seismic stations with long operational histories. Complementary investigations and applications of the global microseism encompass secular variation (e.g., Grevenmeyer *et al.*, 2000; Aster *et al.*, 2010, 2023; Bromirski, 2023; Aster *et al.*, 2026), ocean wave–sea ice interaction (e.g., Tsai and McNamara, 2011; Pratt *et al.*, 2017; Anthony *et al.*, 2017; Chen *et al.*, 2025), ambient noise tomography using microseism surface and body waves (e.g., Shapiro and Campillo, 2004; Nakata *et al.*, 2019; Li *et al.*, 2020), wave state and source zone imaging (e.g., Gualtieri *et al.*, 2019; Igel *et al.*, 2021, 2023; Gao *et al.*, 2026), storm tracking and monitoring (e.g., Bromirski, 2001; Ebeling and Stein, 2011; Borzi *et al.*, 2023, 2024), and large-scale seismic network calibration (e.g., Ringler *et al.*, 2014; Gal *et al.*, 2019; Lee *et al.*, 2020).

We analyze long-term records of vertical-component ground motion from 73 globally distributed seismic stations (49 in the Northern Hemisphere and 24 in the Southern Hemisphere; Fig. 1, Table 1) in the Global Seismographic (Anderson *et al.*, 2015; Ringler *et al.*, 2022; Davis, 2024; FDSN IU/II/IC) and GEOSCOPE (Leroy *et al.*, 2023; FDSN G) networks operating between the late 1980s and October 2025. Stations were unbiasedly selected for having records exceeding 20 yr with greater than 75% data completeness by Aster *et al.* (2026). We focus here on the character and geographic distribution of PM (14–20 s) and SM (4–10 s) annual microseism amplitude variations across this multidecade interval.

Methodology

PSD data processing and culling

Data processing is described in Aster *et al.* (2023, 2026) and is briefly re-summarized here for convenience. Moving window

acceleration power spectral densities (PSDs) are calculated in 1-hr 50% overlapping moving windows as in Anthony *et al.* (2015). We examine continuous long-period high-gain vertical-component (LHZ) 1 sample per second seismic data recorded by the primary sensor at each station (location code 00), retrieved from the EarthScope Data Management Center. Microseism band square root integrated power is estimated in eight 2-s wide period bands between 4 and 20 s by integrating PSD estimates, applying the trapezoidal rule (e.g., Burden and Faires, 2011) to obtain a semihourly time series, $A(t)$, of band-limited amplitude in acceleration units (nm/s^2). 2-s PSD integral bands are summed to produce estimates for PM- (14–20 s) and SM- (4–10 s) dominated periods (Fig. 2).

Large earthquakes generate strong signals at microseism periods. Time windows containing potentially strong signals from earthquakes with magnitudes $M \geq 5.75$ are removed using the U.S. Geological Survey Comprehensive Catalog of Earthquake Events and Products (ComCat; U.S. Geological Survey, 2017). Specifically, data are removed for all stations beginning at the earthquake origin time for 3, 6, 12, 24, and 48 hr for magnitude ranges $5.75 \leq M < 7.0$, $7.0 \leq M < 7.5$, $7.5 \leq M < 8.0$, $8.0 \leq M < 9.0$, and $M \geq 9$, respectively. An additional window length-extending factor of $2 \times 10^4 \text{ km}/D$, in which D is epicentral distance in km, is applied for earthquakes greater than $M 7.5$. This window-extending factor ensures that microseism energy estimates are not strongly biased by regionally elevated microseism band earthquake energy from aftershocks. Nonphysical outlier PSDs are removed by comparing integrated signal power to that predicted by the period-dependent global new-high/low-noise models (NHNM/NLNM) of Peterson (1993), applying an acceptance corridor between five times that predicted by the (infrequently reached) NLNM and 25 times that predicted by the NHNM. To focus on annual variations in this study, daily median time series are further smoothed by a $T_0/6$ (≈ 60.9 -day) moving median filter, in which $T_0 = 365.24219$ days is the tropical year.

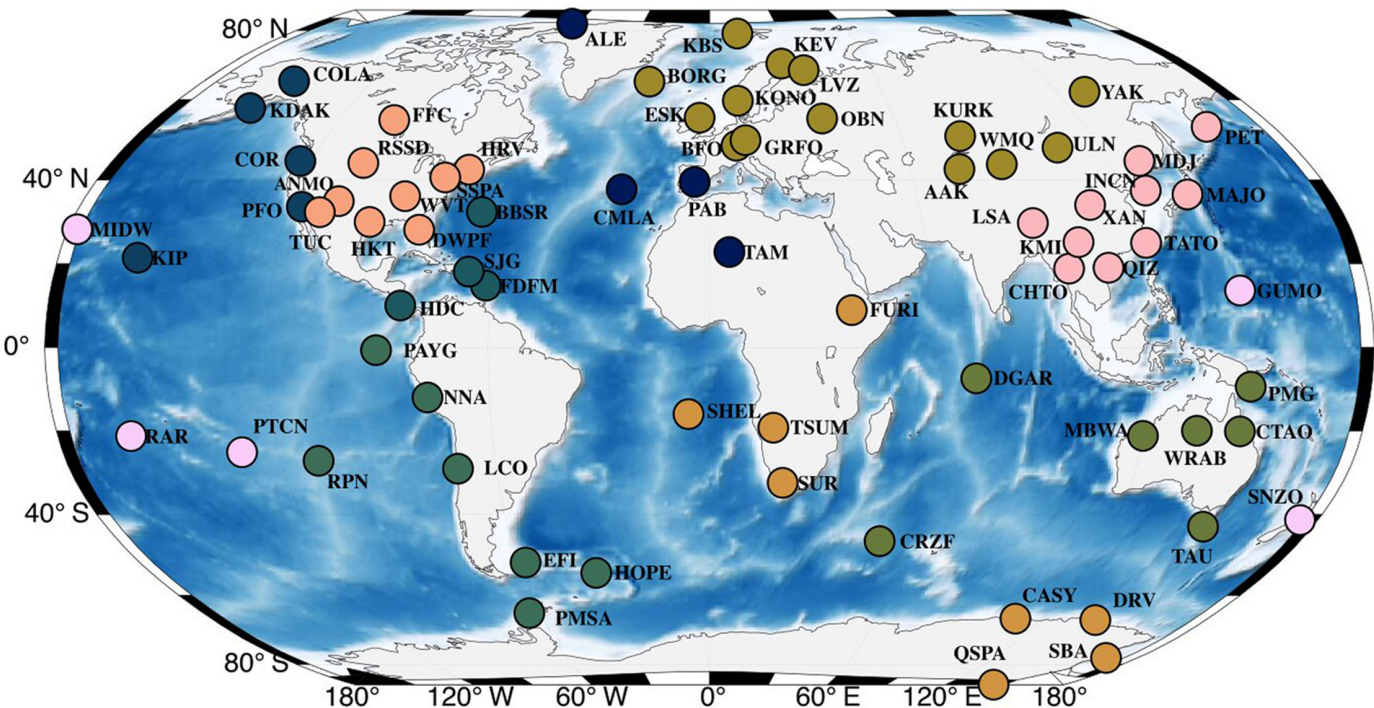
Annual harmonic and secular variations

We characterize annual harmonic variations about the mean for each station for microseism band time series $A(t)$ using a four-term Fourier series, with zero time referenced to 00:00:00 UTC on 1 January (to Gregorian calendar accuracy), which we designate the annual harmonic function,

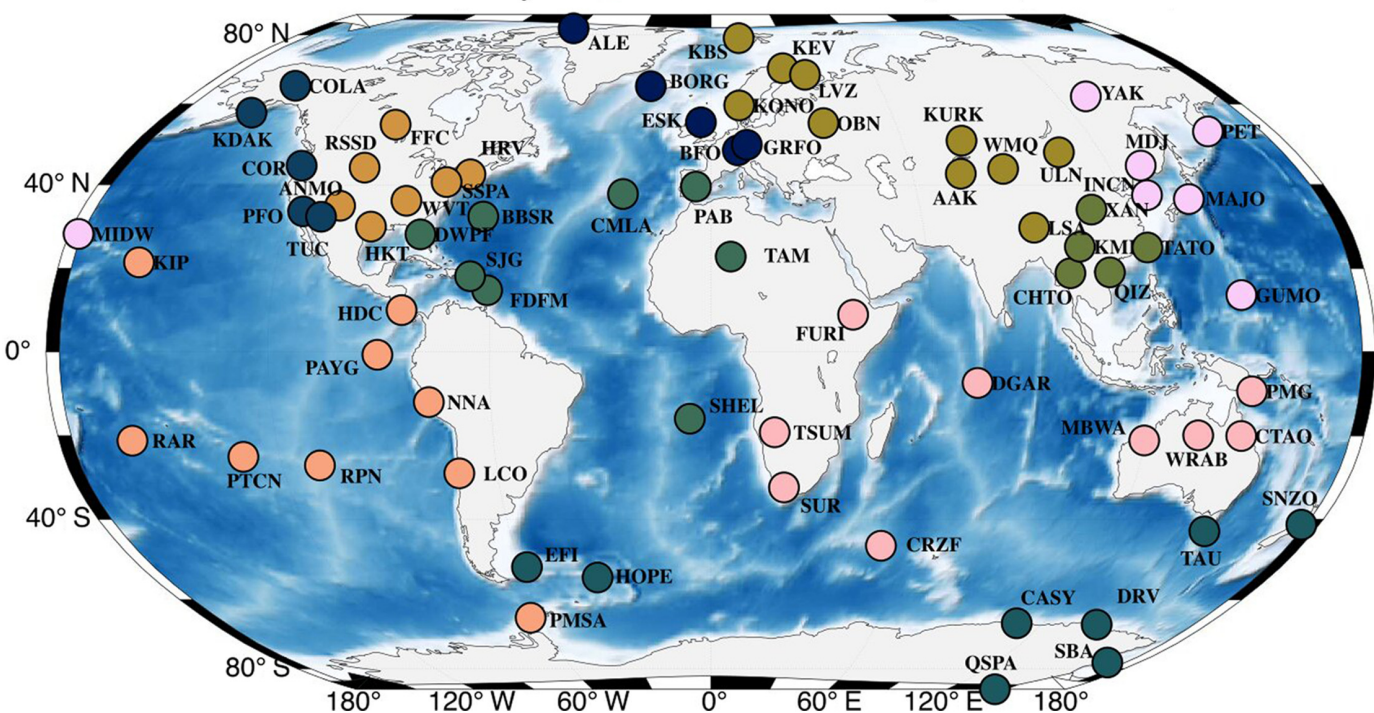
$$H(t) = \sum_{n=1}^4 c_n \cos(2\pi n t / T_0 - \theta_n), \quad (1)$$

in which t is time in days, and c_n and θ_n are values estimated in a least-squares sense. The degree to which annual variations $A(t)$ are characterized by their annual harmonic functions ($H(t)$, equation 1) is assessed by one minus the variance ratio between the residual (aperiodic) signal, $R(t) = A(t) - H(t)$, and $A(t)$

(a)



(b)



$$F = 1 - \frac{\text{Var}(R(t))}{\text{Var}(A(t))} = \frac{\text{Var}(H(t))}{\text{Var}(A(t))}, \quad (2)$$

in which the second equality arises because $H(t)$ is orthogonal to $R(t)$, and thus

$$\text{Var}(A(t)) = \text{Var}(H(t)) + \text{Var}(R(t)), \quad (3)$$

in which $\text{Var}(\cdot)$ denotes the variance.

Figure 1. Seismic stations (Table 1) from the Global Seismographic (FDSN IU/IIC; [Anderson et al., 2015](#); [Ringler et al., 2022](#); [Davis, 2024](#)) and GEOSCOPE (FDSN G [Leroy et al., 2023](#)) networks. Station symbol colors show distinct (a) primary microseism PM and (b) secondary microseism (SM) time-series clusters ([Aster et al., 2026](#)) reflecting long-term aperiodic signal correlations. The color version of this figure is available only in the electronic edition.

TABLE 1

Station Names, Locations, International Federation of Digital Seismograph Networks (FDSN) Network Codes, Latitudes and Longitudes, and Creation Dates

Station	Location	FDSN Code	Latitude (°)	Longitude (°)	Elevation (m)	Creation Date (yyyy/mm/dd)
AAK	Ala Archa, Kyrgyzstan	II	42.6375	74.4942	1633.1	1990/10/12
ALE	Alert, Northwest Territories, Canada	II	82.5033	−62.3500	60	1990/02/20
ANMO	Albuquerque, New Mexico, United States	IU	34.9459	−106.4572	1850.0	1989/08/29
BBSR	Bermuda Biological Station for Research	IU	32.37120	−64.69620	50	2002/07/10
BFO	Black Forest Observatory, Schiltach, Germany	II	48.3301	8.3296	638.0	1996/05/29
BORG	Borgarfjordur, Asbjarnarstadir, Iceland	II	64.7474	−21.3268	110.0	1994/07/30/
CASY	Casey, Antarctica	IU	−66.2792	110.5354	10.0	1996/02/19
CHTO	Chiang Mai, Thailand	IU	18.8141	98.9443	420.0	1992/08/31
CMLA	Chã de Macela, Azores, Portugal	II	37.7665	−25.5225	429	1996/03/10
COLA	College Outpost, Alaska, United States	IU	64.873599	−147.8616	200.0	1996/06/14
COR	Corvallis, Oregon, United States	IU	44.5855	−123.3046	110.0	1989/10/26
CRZF	Port Alfred, Crozet Islands, France	G	−46.43	51.860000	140.0	1986/03/13
CTAO	Charters Towers, Australia	IU	−20.0882	146.2545	357.0	1991/06/17
DGAR	Diego Garcia	II	−7.41	72.45	1	2004/01/22
DRV	Dumont D'Urville, Antarctica	G	−66.66	140.01	40	1986/02/01
DWPF	Disney Wilderness Preserve, Florida, United States	IU	28.1103	−81.4327	30.0	1998/08/02
EFI	Mount Kent, East Falkland Island	II	−51.6753	−58.0637	110.0	1996/02/16
ESK	Eskdalemuir, Scotland, United Kingdom	II	55.3167	−3.205	242.0	1987/11/13
FDFM	Fort de France, West Indies, France	G	14.73	−61.14	467.0	1998/11/25
FFC	Flin Flon, Canada	II	54.725	−101.9783	338.0	1993/08/28
FURI	Mount Furi Ethiopia	IU	8.9030	38.6883	2545	1997/09/01
GRFO	Grafenberg, Germany	IU	49.6919	11.2217	4235	1994/01/26
GUMO	Guam, Mariana Islands	IU	13.5893	144.8684	170.0	1991/06/09
HDC	Heredia, Costa Rica	G	10.00	−84.11	1150	1997/03/08
HKT	Hockley, Texas, United States	IU	29.9618	−95.8384	−413.0	1995/07/11
HOPE	Hope Point, South Georgia Island	II	−52.28	−36.49	20	1996/12/10
HRV	Adam Dziewonski Observatory, Massachusetts, United States	IU	42.5064	−71.5583	200.0	2008/09/22
INCN	Inchon, Republic of Korea	IU	37.4776	126.6239	80.0	1995/07/20
KBS	Ny-Alesund, Spitzbergen, Norway	IU	78.9154	11.9385	90.0	1994/11/05
KDAK	Kodiak Island, Alaska, United States	II	57.7828	−152.5835	152.0	1997/06/09
KEV	Kevo, Finland	IU	69.7565	27.0035	100.0	1993/06/07
KIP	Kipapa, Hawaii, United States	IU	21.42	−158.0112	110.0	1988/08/15
KMI	Kunming, Yunnan Province, China	IC	25.1233	102.7400	1945	1996/04/26

Sensors are installed in observatory vaults or boreholes (Anderson *et al.*, 2015; Ringle *et al.*, 2022; Leroy *et al.*, 2023) with associated metadata maintained by the U.S. Geological Survey, the EarthScope Consortium Data Management Center, and the International Federation of Digital Seismograph Networks. All metadata are based on the first epoch analyzed.

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TABLE 1 (continued)

Station Names, Locations, International Federation of Digital Seismograph Networks (FDSN) Network Codes, Latitudes and Longitudes, and Creation Dates

Station	Location	FDSN Code	Latitude (°)	Longitude (°)	Elevation (m)	Creation Date (yyyy/mm/dd)
KONO	Kongsberg, Norway	IU	59.6491	9.5982	216.0	1991/06/20
KURK	Kurchatov, Kazakhstan	II	50.7154	78.6202	184.0	1995/03/26
LCO	Las Campanas Astronomical Observatory, Chile	IU	−29.011	−70.7005	2274.0	2014/08/04
LSA	Lhasa, Tibet Province, China	IC	29.70	91.15	3774	1995/08/03
LVZ	Lovozero, Russia	II	67.8979	34.6514	630.0	1992/12/01
MAJO	Matsushiro, Japan	IU	36.54567	138.20406	405.0	1990/08/18
MBWA	Marble Bar, Western Australia	IU	−21.159	119.73120	194	2001/08/25
MDJ	Mudanjiang, Heilongjiang Province, China	IC	44.617	129.5908	270.0	1996/11/09
MIDW	Midway Island, United States	IC	28.21570	−177.36970	19.0	1999/10/23
NNA	Nana, Peru	II	−11.9875	−76.8422	575.0	1988/06/22
OBN	Obninsk, Russia	II	55.1146	36.5674	160.0	1988/09/14
PAB	San Pablo, Spain	IU	39.5446	−4.3499	950.0	1992/10/20
PAYG	Puerto Ayora, Galapagos Islands	IU	−0.6742	−90.2861	270.0	1998/06/19
PET	Petropavlovsk, Russia	IU	53.0233	158.6499	110.0	1993/08/28
PFO	Pinon Flat, California, United States	II	33.6092	−116.4553	1280.0	1986/10/24
PMG	Port Moresby, New Guinea	IU	−9.4047	147.1597	90.0	1993/09/10
PMSA	Palmer Station, Antarctica	IU	−64.7744	−64.0489	40.0	1993/03/03
PTCN	Pitcairn Island, South Pacific	IU	−25.0713	−130.0953	220.0	1996/12/29
QIZ	Qeongzhong, Guangduong Province, China	IC	19.02928	109.84398	230.0	2001/02/18
QSPA	South Pole Remote Earth Science Observatory	IU	−89.92790	145.000	2860	2002/12/29
RAR	Rarotonga, Cook Islands	IU	−21.2125	−159.7733	28.0	1992/03/07
RPN	Rapa Nui (Easter Island), Chile	II	−27.1267	109.3344	110	1988/01/01
RSSD	Black Hills, South Dakota, United States	IU	44.1212	−104.0359	2090.0	1999/09/24
SBA	Scott Base, Antarctica	IU	−77.8492	166.7572	50.0	1998/10/28
SHEL	Horse Pasture, St. Helena Island	II	−15.9594	−5.7455	537.0	1995/06/19
SJG	San Juan, Puerto Rico	IU	18.1091	−66.15	420.0	1993/05/26
SNZO	South Karori, New Zealand	IU	−41.3087	174.7043	120.0	1992/04/07
SSPA	Standing Stone, Pennsylvania	IU	40.6358	−77.8876	270.0	1994/12/01
SUR	Sutherland, South Africa	II	−32.3797	20.8117	1770.0	1990/10/30
TATO	Taipei, Taiwan	IU	24.9735	121.4971	160.0	1992/09/26
TAM	Tamanrasset, Algeria	G	22.791	5.527	1377.0	1983/11/16
TAU	Hobart, Tasmania, Australia	II	−42.9099	147.3204	132.0	1994/01/17
TSUM	Tsumeb, Namibia	IU	−19.2022	17.5838	1260.0	1994/08/19

Sensors are installed in observatory vaults or boreholes (Anderson *et al.*, 2015; Ringer *et al.*, 2022; Leroy *et al.*, 2023) with associated metadata maintained by the U.S. Geological Survey, the EarthScope Consortium Data Management Center, and the International Federation of Digital Seismograph Networks. All metadata are based on the first epoch analyzed.

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TABLE 1 (continued)

Station Names, Locations, International Federation of Digital Seismograph Networks (FDSN) Network Codes, Latitudes and Longitudes, and Creation Dates

Station	Location	FDSN Code	Latitude (°)	Longitude (°)	Elevation (m)	Creation Date (yyyy/mm/dd)
TUC	Tucson, Arizona, United States	IU	32.3098	-110.7847	910.0	1992/06/13
ULN	Ulaanbaatar, Mongolia	IU	47.8651	107.0532	1610.0	1994/10/31
WMQ	Urumqi, Xinjiang, China	IC	43.8211	87.6950	903	1995/09/23
WRAB	Tennant Creek, NT, Australia	II	-19.9336	134.36	366.0	1994/03/27
WVT	Waverly, Tennessee, United States	IU	36.1297	-87.83	170	1997/04/06
XAN	Xi'an, China	IC	34.0313	108.92370	630	1992/12/02
YAK	Yakutsk, Russia	IU	62.031	129.6805	110.0	1993/08/31

Sensors are installed in observatory vaults or boreholes (Anderson *et al.*, 2015; Ringler *et al.*, 2022; Leroy *et al.*, 2023) with associated metadata maintained by the U.S. Geological Survey, the EarthScope Consortium Data Management Center, and the International Federation of Digital Seismograph Networks. All metadata are based on the first epoch analyzed.

Results

Median amplitudes

SM median acceleration amplitudes are typically around 30–40 dB (≈ 40 –100 times) larger than PM amplitudes (Fig. 2; Table S1, available in the supplemental material to this article; e.g., Peterson, 1993; McNamara and Buland, 2004). Widespread higher PM and SM amplitudes in the Southern Hemisphere reflect annually persistent high-energy ocean wave activity in the Southern Ocean that partially couples into the solid Earth (e.g., Reguero *et al.*, 2019; Aster *et al.*, 2026). Exceptionally large SM amplitudes occur at some ocean island sites in the central Pacific (KIP, RAR, PTCN, RPN, and MIDW) and north Atlantic regions (BORG and CMLA). Station overall mean-to-median amplitude ratios vary from approximately 0.97 to 1.26 in both the PM and SM bands, reflecting a tendency for amplitude time series to have relatively sharp maxima and broader minima (e.g., Fig. S1).

Annual harmonic function characterization

We fit equation (1) to earthquake- and outlier-culled PM and SM time series for the 73 stations of Figure 1 (20 or more annual cycles) to quantify periodic characteristics through 1 October 2025. Fourier coefficient amplitudes (c_n ; Fig. 3) show that annual harmonic variations in both the PM and SM bands are well characterized by four terms at all stations, with dominant annual and subannual ($n = 1$ and $n = 2$) terms.

Fourier term phases θ_n (Fig. 4) strongly reflect the well-known bihemispheric tendency for high microseism driven by large-scale wave activity arising from extratropical cyclonic storm activity during the hemispheric winter (e.g., Aster *et al.*, 2008; Colosi *et al.*, 2021; Shabtian *et al.*, 2023). This leads to many Northern Hemisphere stations having annual maximum amplitudes close to 1 January ($\theta = 0$) and many Southern Hemisphere stations having annual maximum amplitudes close to 1 July ($\theta = 180$). However, tropical and Southern Hemisphere stations show

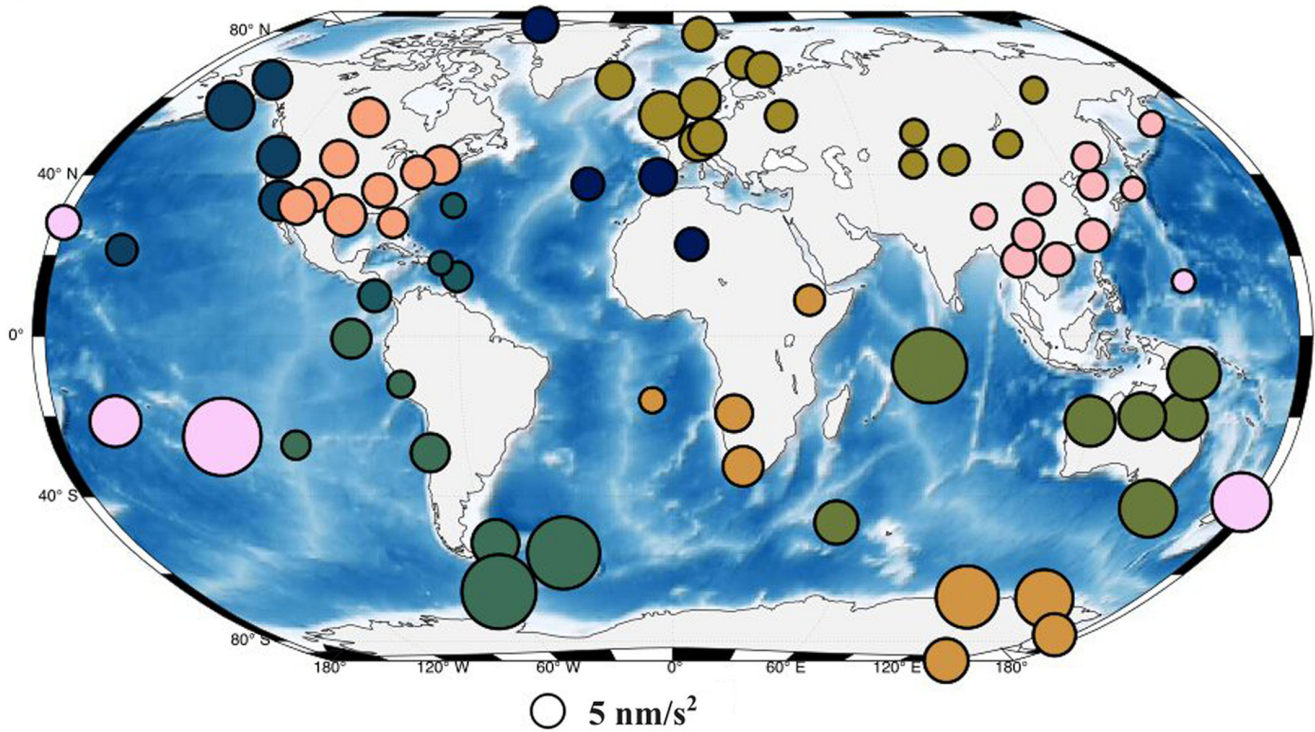
greater complexity in their coefficient phases. Continental Antarctic stations (QSPA [South Pole], SBA [Scott Base], DRV [Dumont d'Urville], CASY [Casey Station], and PMSA [Palmer Station]) show an annual ($n = 1$) phase near $\theta = 90^\circ$, which has been previously shown to be due to the effects of the seasonal sea ice on ocean swell and microseism generation. This alters the annual phase (θ_1) of PM and SM microseism generation (e.g., Grob *et al.*, 2011; Anthony *et al.*, 2015; Anthony *et al.*, 2017; Pratt *et al.*, 2017; Cannata *et al.*, 2019). A corresponding $n = 1$ phase anomaly is not observed at the highest latitude Northern Hemisphere stations. The $n = 1$ annual phase difference between PM and SM periodic fit functions is near zero for most stations, with interesting exceptions at tropical to mid-latitudes in East Asia (e.g., CHTO [Chiang Mai, Thailand], QIZ [Qiongzong, China], KMI [Kunming, China], and LSA [Lhasa, China]) and the Southern Hemisphere (e.g., PTCN, RAR, TSUM, and NNA), and for the equatorial station PAYG. The geographic variability of annual harmonic functions characterized by their first two coefficients is shown in map view (Fig. 5), which highlights relative uniformity over much of the Northern Hemisphere, relative heterogeneity in the Southern Hemisphere, and unusual Antarctic and East Asian station behavior.

The degree to which station amplitude variations are periodic is assessed by calculating the variance reduction fit (equation 2) of the annual harmonic functions (Fig. 6). Fits range from 0.14 (PMSA) to 0.95 (RSSD; Black Hills, South Dakota) for the PM, and from 0.23 (PMSA) to 0.97 (RSSD) for the SM (surprisingly, these PM and SM fit extremes occur for the same station pair).

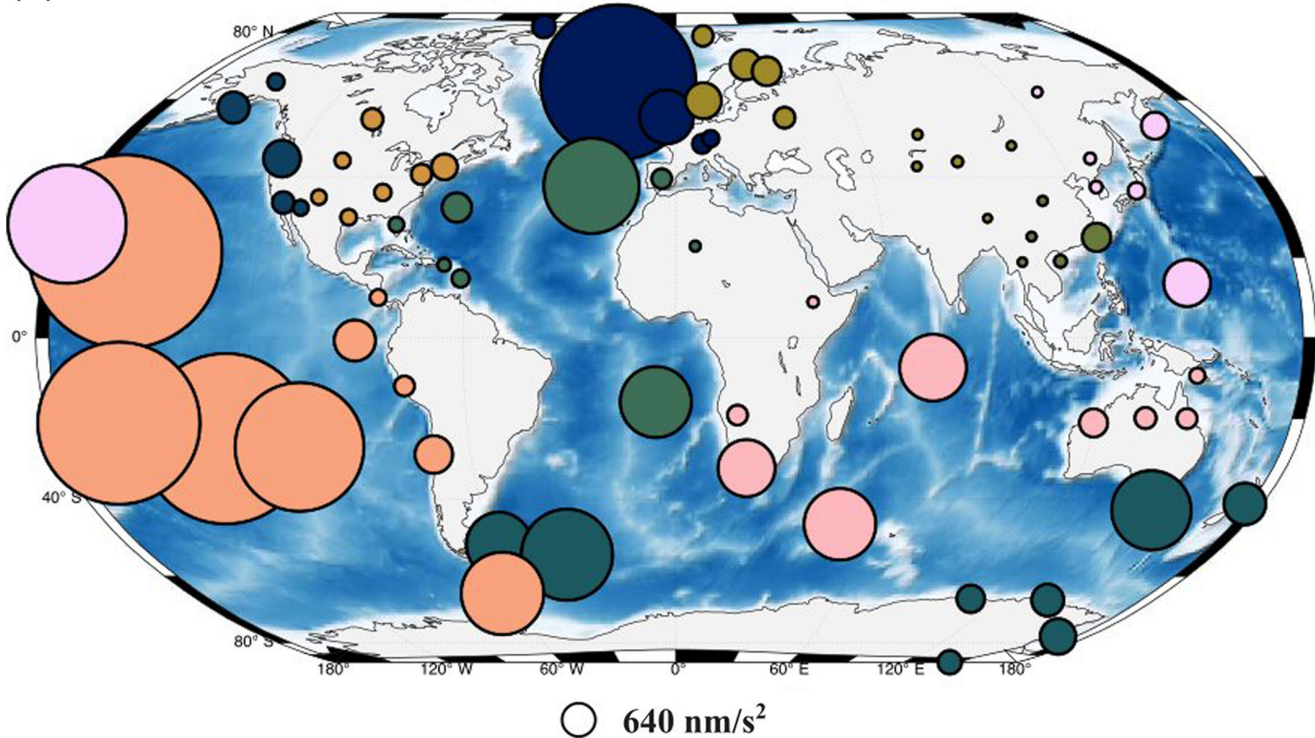
Annually periodic primary and secondary variations

PM and SM fits, F , are displayed in Figure 6, and in map form in Figure 7. As noted in examining the annual harmonic function

(a)

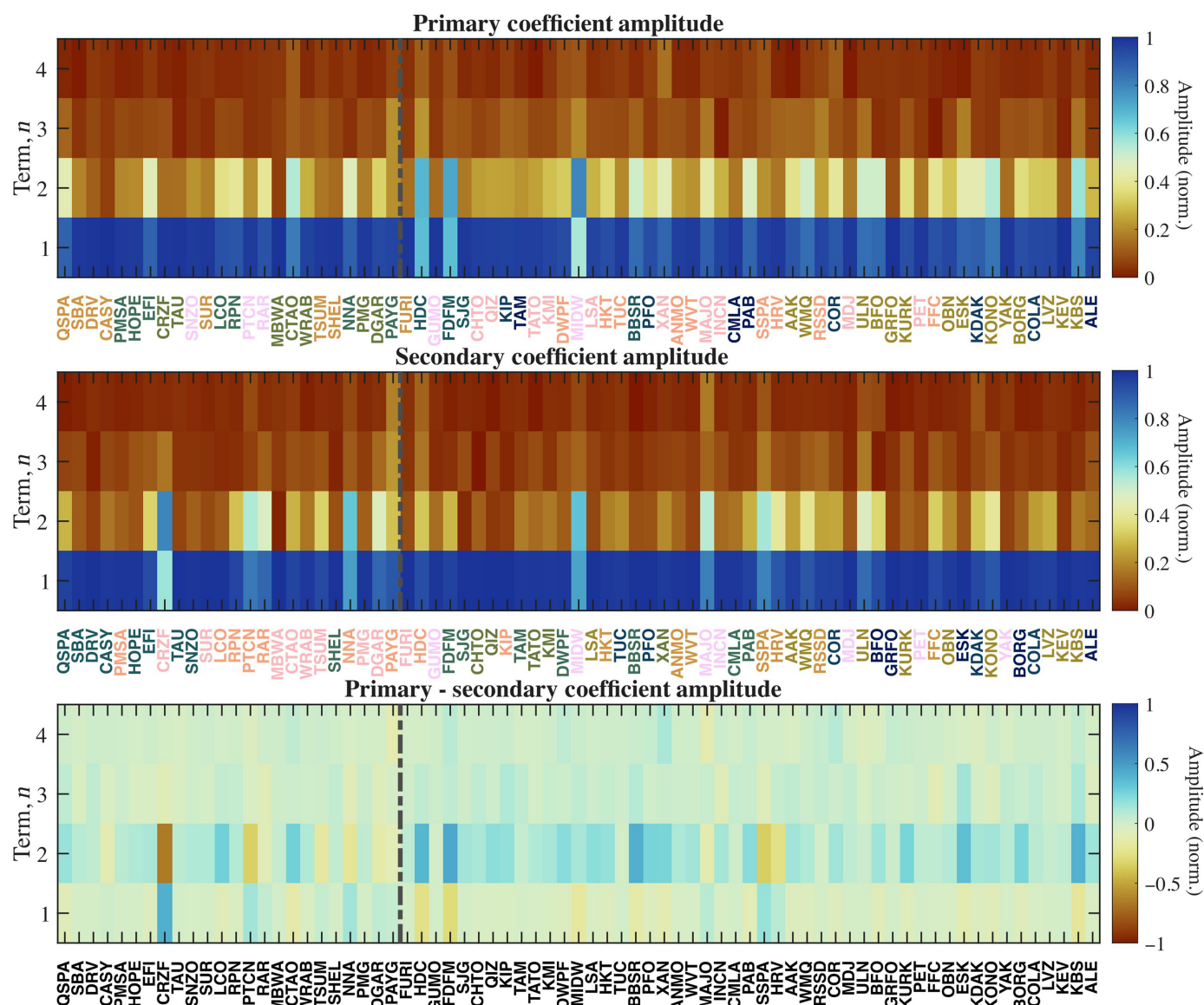
Primary (14–20 s)

(b)

Secondary (4–10 s)

Fourier coefficients (Figs. 3 and 4), a systematic difference is observed between the Northern and Southern Hemispheres, with generally high values of F (smaller relative residual) at most higher latitude Northern Hemisphere stations and lower values of F , reflecting larger aperiodic signal energy, at lower Northern

Figure 2. Map view of median microseism band amplitudes for the (a) PM and (b) SM. Station colors mirror the PM and SM cluster colors of Figure 1. The color version of this figure is available only in the electronic edition.

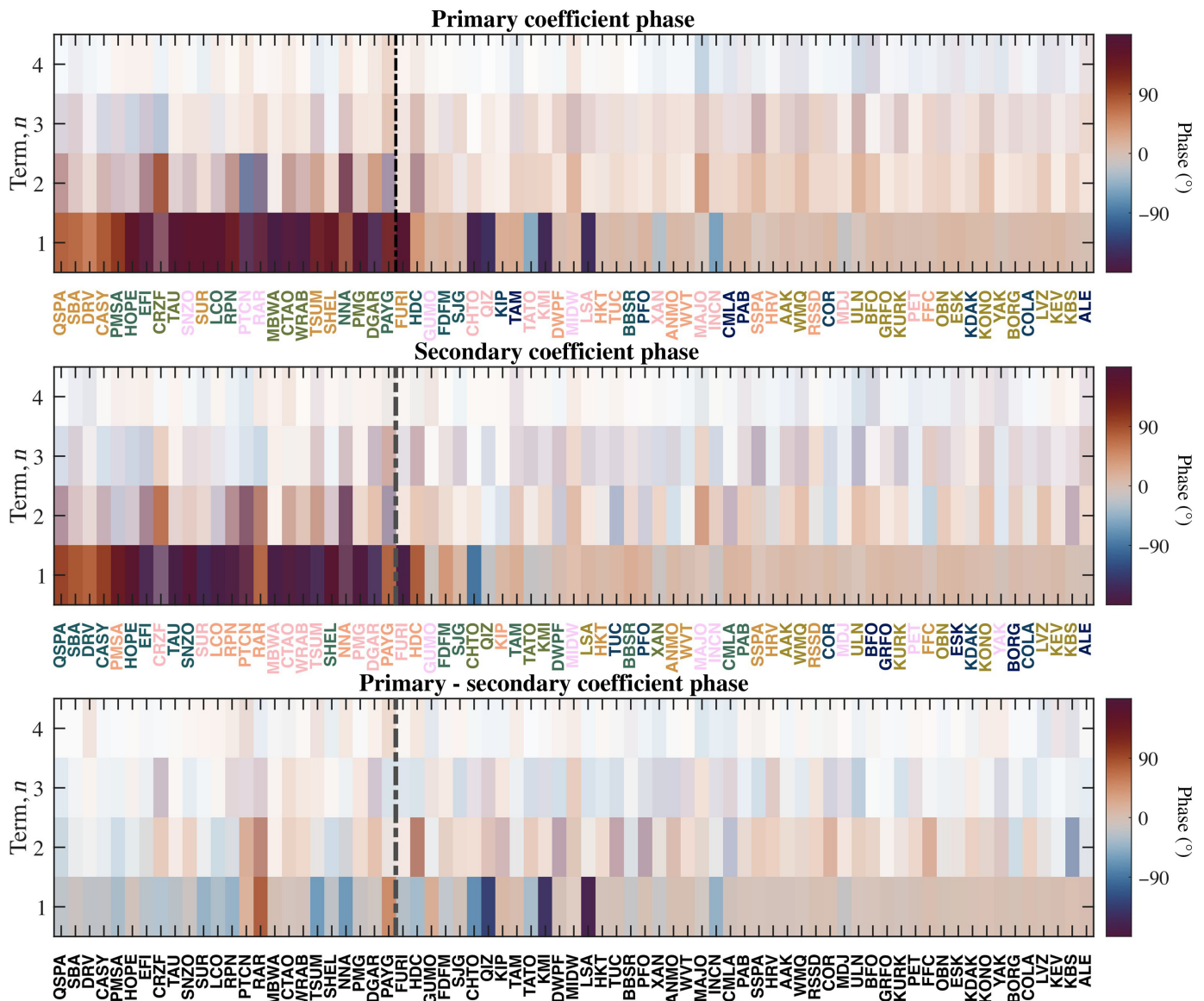


Hemisphere latitudes and in the Southern Hemisphere. Off-continent Antarctic and sub-Antarctic stations (EFI, HOPE, and PMSA) have notably low values of F , whereas on-continent Antarctic stations have higher degrees of fit driven by annual sea ice forcing (which also imposes unusual Fourier coefficient phases at these sites; Fig. 4). The general aperiodic and periodic signal ranges are displayed with respect to latitude in Figure 8 and Table S1, showing systematically smaller annual amplitude variations in the Southern Hemisphere and larger annual variations (of up to 20.6 dB for the SM at KONO; Kongsberg, Norway; Fig. S4) for Northern Hemisphere Atlantic region stations. Higher latitude annual summer minima at comparable latitudes are widely lower at the Northern Hemisphere stations, consistent with greater seasonality and quieter summer wave conditions in Northern Hemisphere oceans compared with the less seasonal and more intense extratropical storminess of the Southern Ocean (e.g., Morales-Márquez *et al.*, 2020; Shaw *et al.*, 2022; Gao *et al.*, 2026).

Figure 3. Annual stationary primary and secondary four-term Fourier coefficient ($n = 1, 2, 3, 4$) amplitudes c_n (equation 1), normalized (norm.) by the coefficient amplitude sum, with stations sorted by latitude. Station colors reflect the PM and SM clusters of Figure 1. The phase is plotted in degrees ($^{\circ}$). The dashed line separates stations in the Southern and Northern Hemispheres. Note the dominance of annual and semiannual terms ($n = 1$ and $n = 2$). The lower panel shows the amplitude difference between primary and secondary normalized c_n or, equivalently, the coefficient amplitudes of the corresponding difference time series. The color version of this figure is available only in the electronic edition.

Annual covariation of primary and secondary amplitudes

The covariation of PM and SM amplitudes as characterized by their annual harmonic functions can be examined using the daily sampled time series and generalized Lissajous curves of



$H_{SM}(t)$ versus $H_{PM}(t)$ (equation 1). Figure 9 shows these plots for all 73 stations, sorted by latitude. Figure 10 and Table 2 display SM to PM correlations for daily sampled time series and their corresponding annual harmonic functions.

Discussion

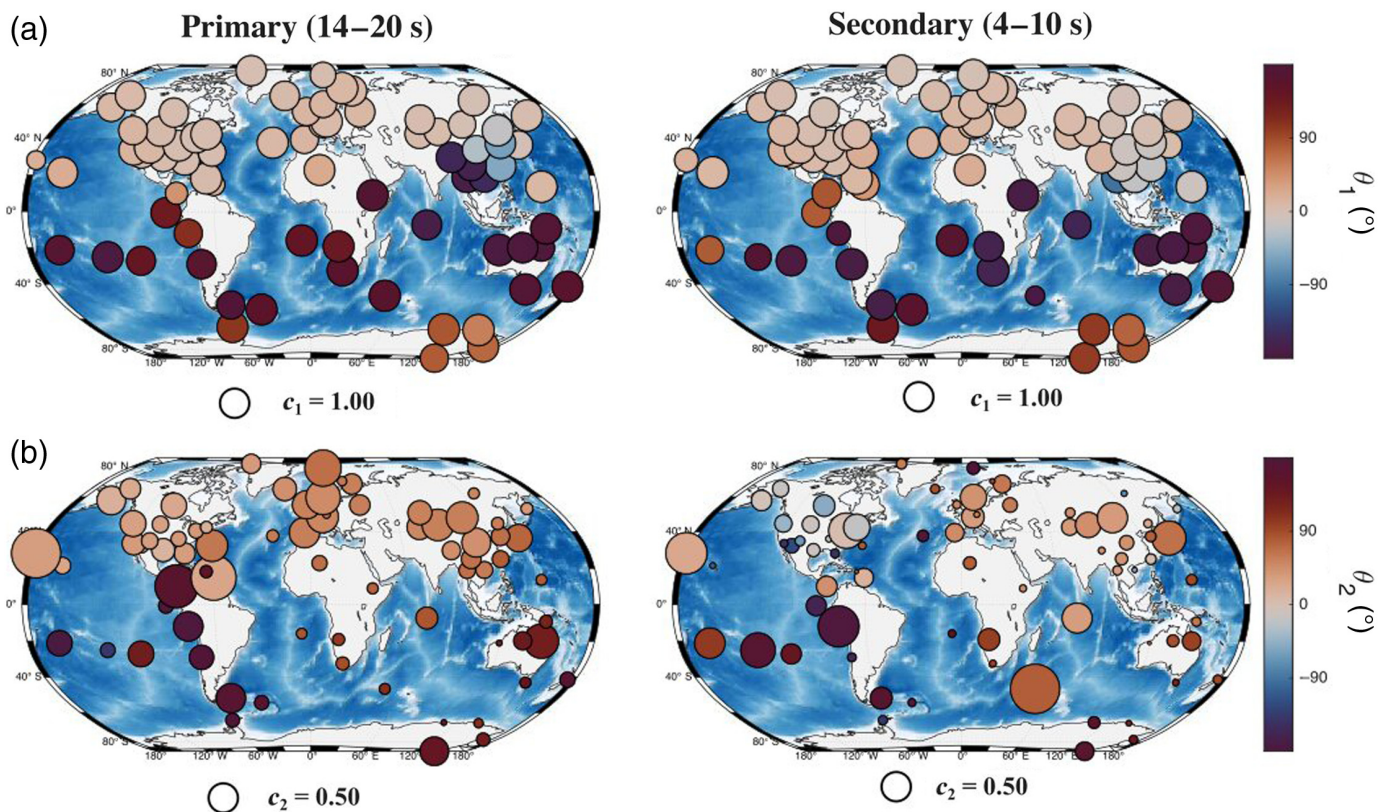
PM–SM amplitude covariation

Figure 9 shows SM versus PM daily amplitude time series with $T_0/6$ median smoothing with associated generalized H_{SM} versus H_{PM} Lissajous curves. We explore annual (PM and SM) covariation in terms of correlations between station time series C , correlations between corresponding annual harmonic functions C_H , and in the orbital motion of $H_{SM}(t)$ versus $H_{PM}(t)$ Lissajous curves in the (PM and SM) plane (Fig. 10, Table 2).

The majority of stations (e.g., ANMO; Figs. S1, S2, and S5) exhibit significant positively correlated (e.g., C and $C_H > 0.5$) SM and PM amplitudes (Figs. 9 and 10, Fig. S3), with 48 stations (66%) having $C_H > 0.9$ (Fig. 10, Table 2). Many highly SM to

Figure 4. Annual stationary primary and secondary four-term Fourier coefficient phases (equation 1) corresponding to Figure 3, with phase θ_n indicated by the circular color scheme indicated by the bars on the right. Station colors reflect the PM and SM clusters of Figure 1. The phase is plotted in degrees ($^\circ$). The transparency of each cell is inversely proportional to the corresponding normalized coefficient amplitudes (Fig. 3). Note the (uneven) hemispheric shift in coefficient phase from near 1 July ($\theta = 180^\circ$) to near 1 January ($\theta = 0^\circ$) for the dominant, fundamental ($n = 1$) term between the Southern and Northern Hemispheres, respectively. The unique $n = 1$ term annual phase values of $\theta \approx 90^\circ$ for Antarctic sites result from the annually varying swell and microseism source attenuation effects of sea ice. The lower panel shows the phase difference or, equivalently, the coefficient phase of the difference signal. The color version of this figure is available only in the electronic edition.

PM correlated stations commonly show relatively broad minima during hemispheric summer and relatively sharp maxima during hemispheric winter (e.g., Figs. S1, S3, and S4). This is consistent



with episodic winter amplitude peaks due to extratropical storms versus longer-duration low-wave state energy in summer. Amplitude peaking leading to sharp maxima may be further enhanced by SM source process nonlinearity (e.g., [Ardhuin et al., 2015](#); [Aster et al., 2026](#)). For continental Antarctic stations, PM-SM amplitude correlation is also enhanced by seasonal sea ice attenuation of both PM and SM sources, as discussed further subsequently.

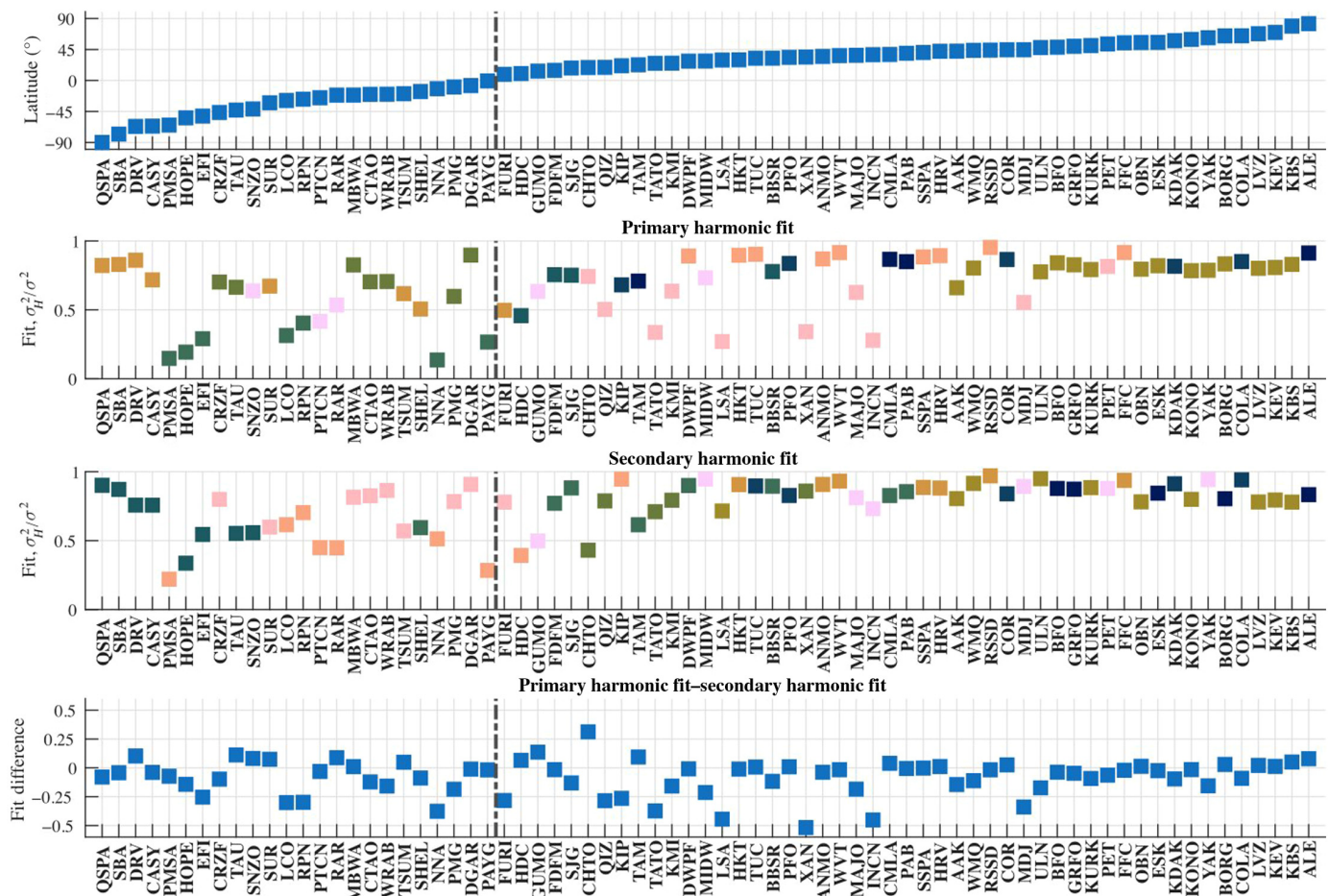
Northern-Southern hemisphere asymmetry

PM-SM correlation and annual covariation show broad differences between the Northern and Southern Hemispheres (Figs. 9 and 10). Stations with highly correlated SM and PM amplitudes, and thus more linear aspects in Figure 9, are widely observed for stations at temperate and arctic latitudes in the Northern Hemisphere, with this behavior being particularly prominent and geographically correlated for sites in (relatively densely instrumented) North America and Europe. This behavior has been associated with continental stations where crossing seas created by incoming swell and associated coastal reflections (the class II SM source condition described by [Ardhuin et al. \(2011\)](#) enhance temporally correlated SM and PM source excitation ([Aster et al., 2026](#)). Across the Southern Hemisphere, highly correlated annual SM versus PM covariation, comparable to that widely observed in the Northern Hemisphere, occurs at just three stations in Northern Australia (MBWA, CTAO, and WRAB) and at one regionally nearby site in Papua New Guinea (PMG).

Figure 5. Fourier coefficient amplitudes, shown as symbol size (Fig. 3; symbol size) for (a) $n = 1$ and (b) $n = 2$, and corresponding Fourier term phases (Fig. 4; symbol color). Note that the size of the markers in the plots for the $n = 2$ Fourier coefficients are scaled up by a factor of two for better visibility. The color version of this figure is available only in the electronic edition.

Northern Hemisphere extratropical storm activity exhibits greater proportional annual variation compared with the Southern Hemisphere. This enhanced seasonality is driven by the presence of extensive Northern Hemisphere landmasses, which amplify winter jet stream excursions and lateral temperature gradients. These atmospheric dynamics are conducive to the formation of extreme extratropical storms (e.g., [Shaw et al., 2022](#)). Resulting wave state variations lead to more systematic annual microseism amplitude periodicity, as reflected in high PM and SM annual harmonic function fits (Figs. 6 and 7). In addition, extensive Northern Hemisphere coastlines enhance the occurrence of class II crossing sea states, which contribute to higher PM-SM amplitude correlations (Fig. 10). Greater seasonal variation and quieter summers in the Northern Hemisphere have also been shown to be present in the global seismic hum band between periods of approximately 50 and 150 s ([Deen et al., 2018](#)).

Sites in the more ocean-dominated Southern Hemisphere show broadly lower values of C and C_H (Fig. 10, Table 2). This behavior may generally, and nonexclusively, reflect relevant PM and SM source sensitivity to annual systematic



variation in: (1) swell propagation direction; (2) hemispherical storm seasonality and swell energy; and (3) wave period. Isolated Southern Hemisphere ocean islands such as RAR (Rarotonga), CRZF (Crozet Islands), and PTCN (Pitcairn) (Fig. 9) that display low PM–SM correlations and quasi-circular Lissajous curves are likely most strongly affected by local effects. Local seasonal wave direction and wave period influences on PM and SM band amplitude are likely to be stronger for the SM, as indicated by much shorter correlated period-dependent signal great-circle correlation paths (Aster *et al.*, 2026). Interestingly, both RAR and PTCN in the remote southern Pacific show similar (clockwise) Lissajous curve orbital senses and PM–SM seasonality variations despite being separated by approximately 3000 km. In contrast to isolated Southern Hemisphere island stations, PM–SM annual covariation at KIP (Kipapa, Hawaii), BBSR (Bermuda), and CMLA (Azores) is well correlated, demonstrating the driving influence of strong annually periodic storm intensity variation at isolated islands in tropical and higher latitudes in the Northern Hemisphere (Fig. 9).

Indian Ocean and East Asia Region stations

Stations in the broad Indian Ocean region display unique SM-to-PM relationships (Figs. 11 and 12; Zhou *et al.*, 2024; Arya *et al.*, 2025). For example, at CHTO, two annual SM maxima

Figure 6. Variance-based harmonic fits (equation 2) of four-term Fourier annual stationary models to primary and secondary amplitude time series, sorted by station latitude (top subfigure). The dashed line separates stations in the Southern and Northern Hemispheres. The lower panel shows the PM minus SM fit difference, showing that the SM variations are generally more annually periodic than PM variation. Station symbol colors reflect the PM and SM station clusters of Figure 1. The color version of this figure is available only in the electronic edition.

occur near 1 July and 1 January, but the annual PM signal shows a single maximum near 1 July. This twice-yearly SM peak behavior at stations such as LSA, CHTO, and KMI, seen in Figure 11, is much less apparent in the PM and is a unique feature of wave activity and microseism generation in the Indian Ocean region. This also occurs at the Central Indian Ocean island station DGAR (Diego Garcia) accompanied by a prominent peak in the Southern Hemisphere winter. This likely reflects both summer and winter monsoonal wave generation (e.g., Colosi *et al.*, 2021) superimposed on contributions from long-distance propagating Southern Hemisphere winter swell, particularly for the PM (Remya *et al.*, 2016; Aster *et al.*, 2026).

KMI (Kunming, China) shows annual (PM and SM) amplitude variation with some similarity to CHTO, but the 1 July maximum is much lower amplitude than the 1 January

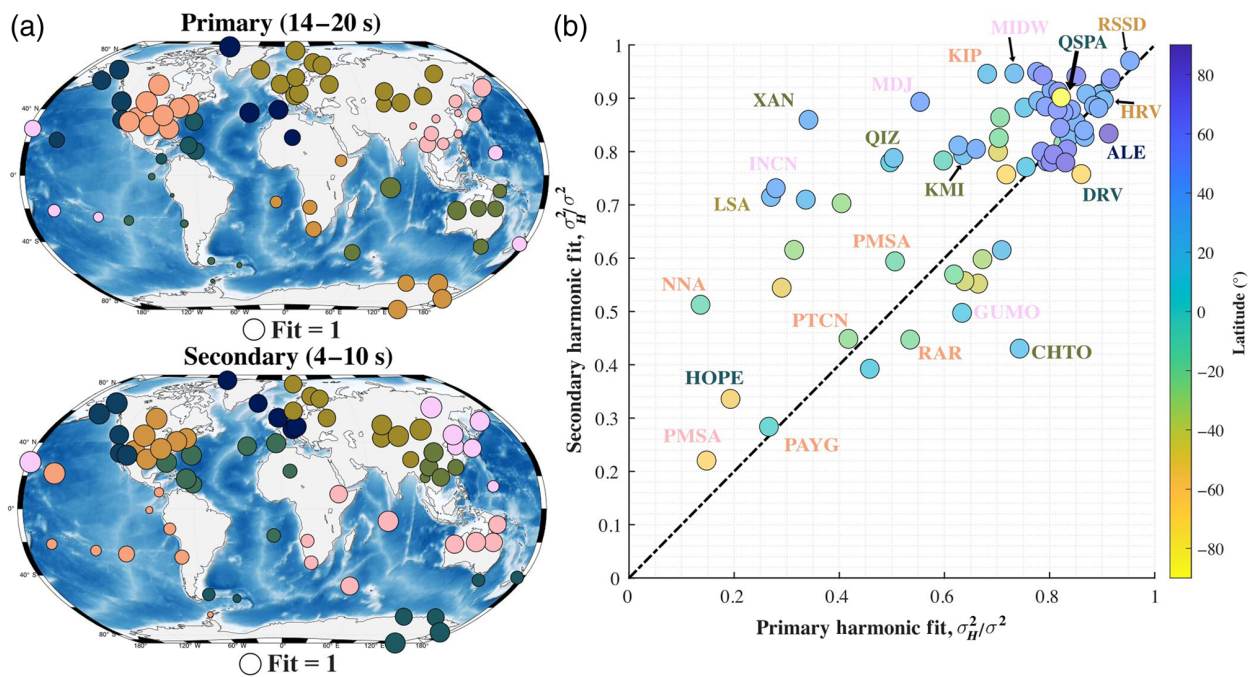


Figure 7. (a) Maps of PM and SM harmonic variance-based fits (equation 2; Fig. 6) shown proportional to symbol diameter. The symbol colors mirror the distinct PM and SM clusters of Figure 1. (b) SM versus PM variance-based fit (Pearson correlation coefficient 0.71; e.g., Weisstein, 2026). The symbol color indicates

station latitude, and selected station name colors reflect the SM clusters of Figure 1. The phase is plotted in degrees (°). The color version of this figure is available only in the electronic edition.

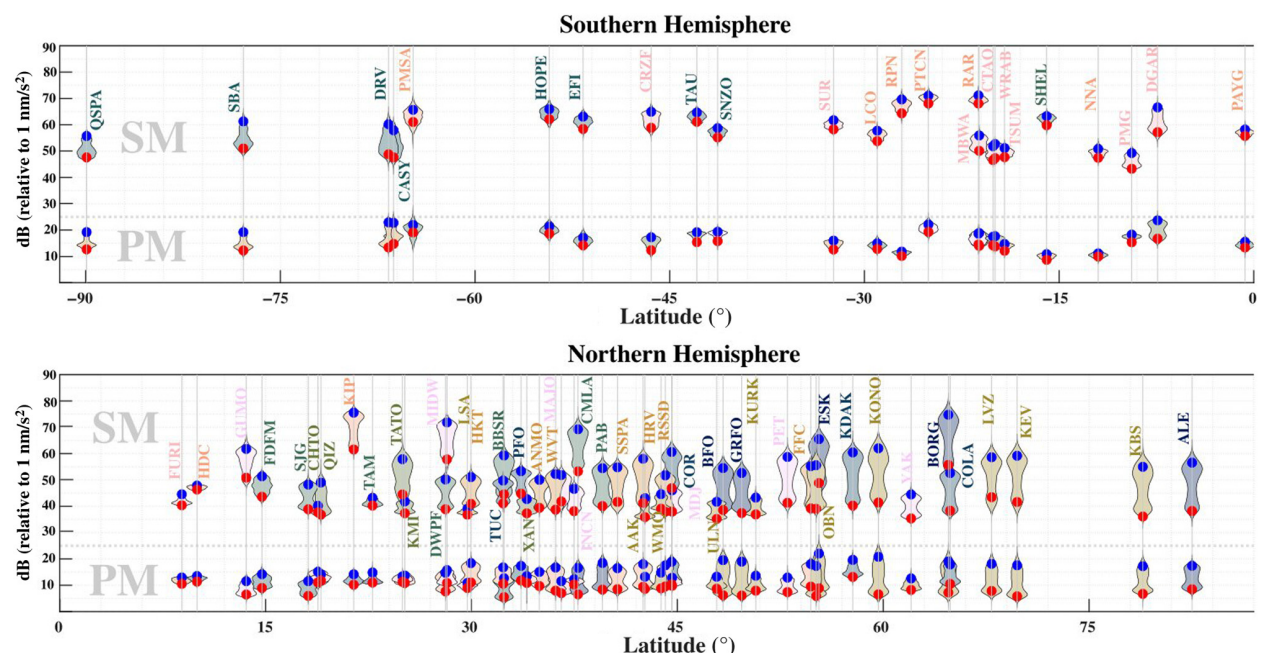
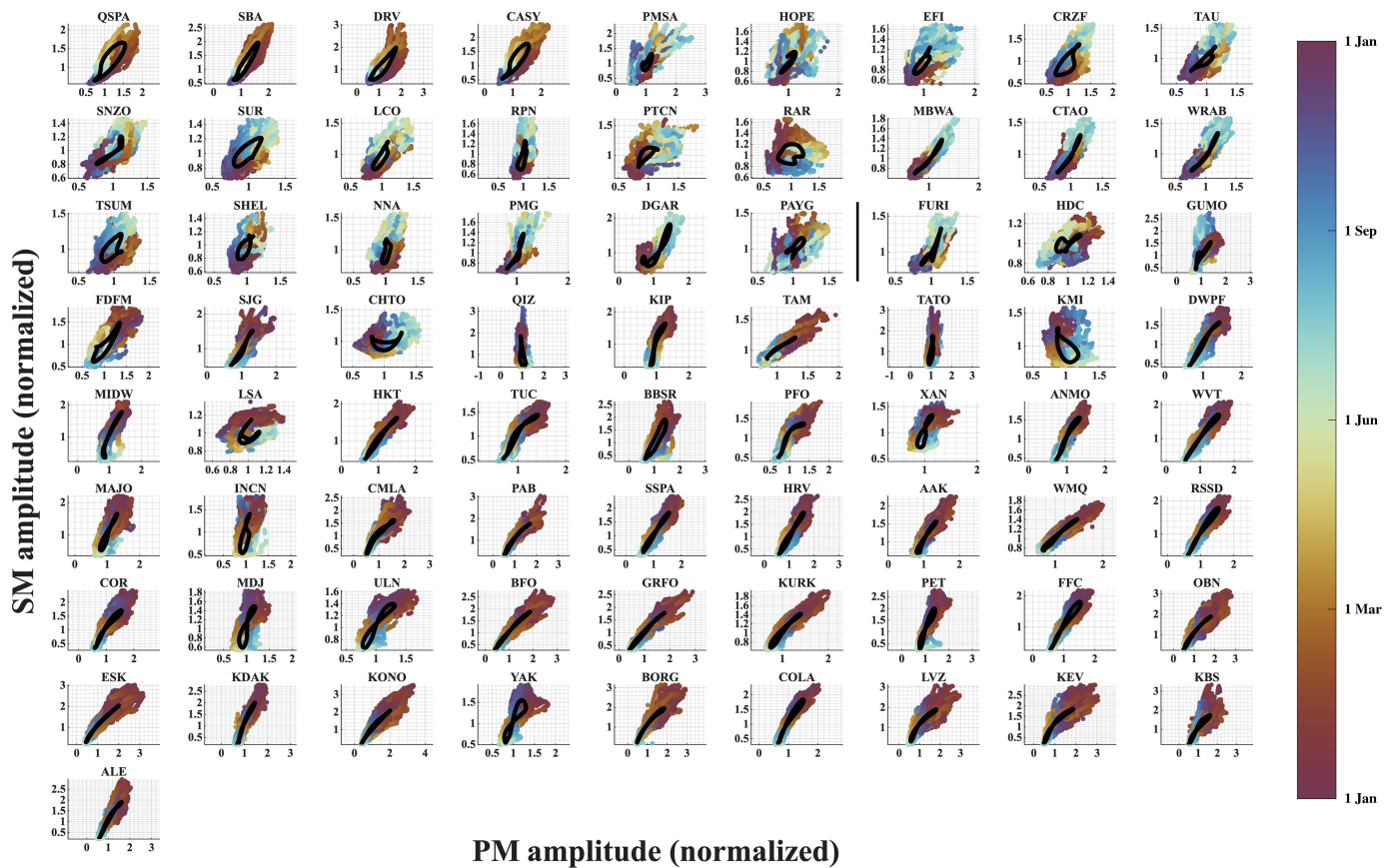


Figure 8. Total and annual harmonic variation for all stations. Total variation of $T_0/6$ -day smoothed data are shown as violin plot densities (Hintze and Nelson, 1998), and blue and red dots indicate annual harmonic function maxima and minima. Stations are plotted with respect to latitude (in degrees (°)) for the SM (4–10 s) and PM (14–20 s) bands in dB relative to 1 nm/s².

Station name and SM density colors reflect the reference SM clusters of Figure 1. Minimum (red) and maximum (blue) values of each station's harmonic PM and SM signals, and station median values, are in Table S1. Note generally greater annual ranges and lower summer minima for the Northern Hemisphere. The color version of this figure is available only in the electronic edition.



maximum, and its SM and PM amplitudes are negatively correlated ($C_H = -0.733$ and $C = -0.438$; Figs. 10 and 11, Table 2), a distinction shared only with QIZ ($C_H = -0.585$ and $C = -0.280$). LSA (Tibet, China) also displays both SM peaks, hemispheric winter peaks, and two PM peaks (Fig. 11), with the larger of the two near 1 January indicative of long-range sensitivity to Northern Hemisphere winter swell.

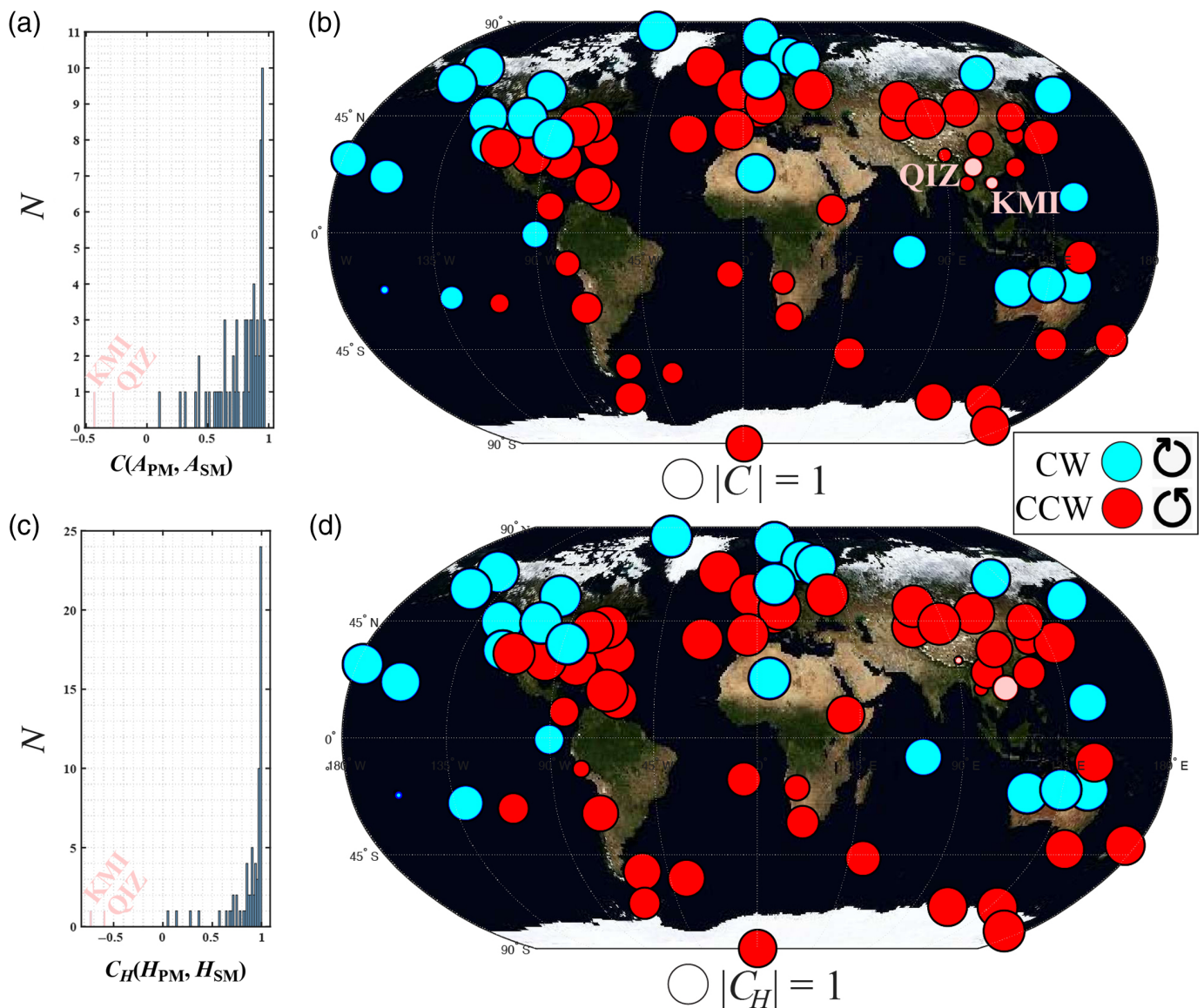
QIZ and TATO (Taipei, Taiwan) display unique features in that their time series and their annual harmonic variations follow a tight path, but the generalized Lissajous curve (PM and SM) plane is nearly vertical, reflecting low amplitude and nearly uncorrelated PM annual variability (Figs. 9, 10, and 12). This behavior is reflected as far north as the Korean Peninsula at INCN (Inchon, Republic of Korea). Repeating and very high-amplitude SM extrema at QIZ (Fig. 12) occur during strong tropical cyclonic storms (including tropical storms Lekima, October 2007, and Haitang, September 2011; and typhoons Lingling, November 2001; Molave, October 2020; and Neneng, October 2022). These local tropical cyclonic storms generate extreme seismic amplitudes in the SM band without corresponding peaks in the PM band. This suggests unusual factors attributable to bathymetry and wave direction in the South China Sea during such events that strongly excite crossing seas in SM source zones without generating corresponding strong PM tractions at depths less than approximately 600 m. High-SM amplitudes have also been noted in

Figure 9. SM (4–10 s) versus PM (14–20 s) vertical-component median-normalized daily median acceleration amplitudes sorted by station latitude from south to north, as in Figures 6 and 8. Daily samples are colored by day of year (color bar at right). The black curves are annual median-normalized $H_{SM}(t)$ versus $H_{PM}(t)$ (equation 1) Lissajous figures characterizing PM and SM annual harmonic function covariation. The black line in the third row (between PAYG and FURI) divides stations between the Southern and Northern Hemispheres. Corresponding point density plots are shown in Figure S6. The color version of this figure is available only in the electronic edition.

the South China Sea region due to the southwest Summer Monsoon winds (Zhou *et al.*, 2024) irrespective of tropical cyclones. GUMO (Guam, Mariana Islands) in the western Pacific approximately 4500 km east of QIZ shows characteristics (Fig. 12) dominated by winter and summer Southern Hemisphere extratropical storm cycles that are well reflected in both the SM and PM bands, but it additionally displays repeated high amplitudes during late summer–fall tropical cyclone season.

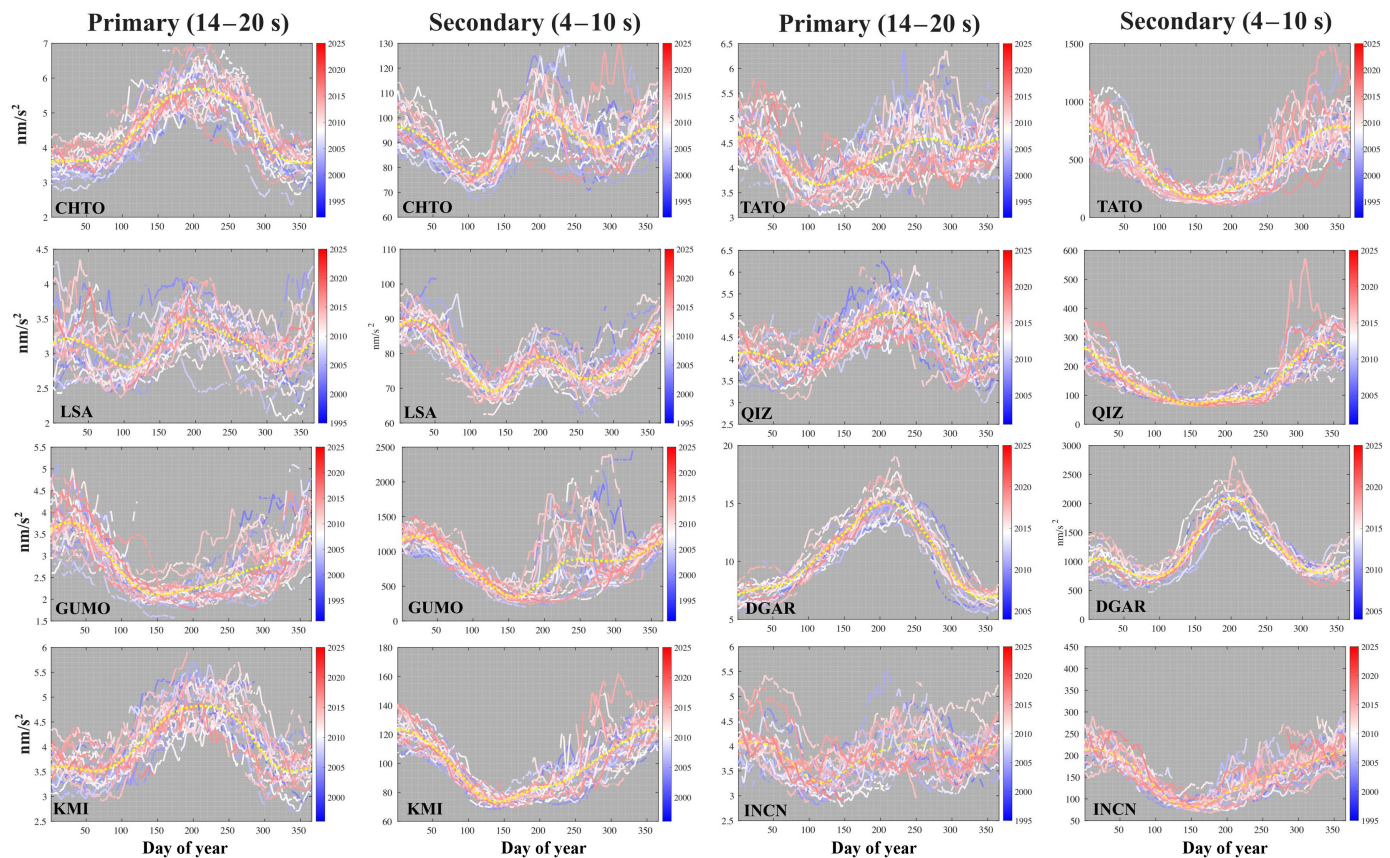
Antarctic stations

Antarctic sea ice typically peaks in September and reaches a minimum in late February, and it has undergone dramatic fluctuations during this study period, including a record



maximum February extent in 2014 and record minimum extent in 2023 (e.g., [Raphael et al., 2025](#)). As previously noted, sea ice most strongly influences the annual character of microseism amplitudes at continental Antarctic stations QSPA, CASY, DRV, and SBA (e.g., [Anthony et al., 2015, 2017](#); [Pratt et al., 2017](#); [Cannata et al., 2019](#)). The greatest influence of sea ice on microseism amplitudes is observed in the annual ($n = 1$) phase shift (Fig. 4) in both the SM and PM bands. Smaller phase shifts due to seasonal sea ice are observed at sub-Antarctic stations PMSA ([Anthony et al., 2017](#)) and HOPE (South Georgia). Comparable sea-ice-induced microseism annual phase shift and amplitude variation does not occur at the highest latitude Northern Hemisphere Stations (e.g., KBS [Kings Bay, Norway] and ALE [Alert, Canada]) at periods between 4 and 20 s, but it becomes evident at shorter periods ([Tsai and McNamara, 2011](#); [John and West, 2025](#); [Chen et al., 2025](#)). For Antarctic continental stations, there is also a relative phase lag between SM and PM annual

Figure 10. (a) Histogram of all-data PM-SM time-series correlations, $C = \text{cor}(A_{\text{PM}}(t), A_{\text{SM}}(t))$, with the negatively correlated East Asian stations KMI and QIZ noted in light red. (b) All-data correlations in map view corresponding to histogram (c), and showing annual orbital sense; CW and CCW: clockwise and counterclockwise; see legend and Table 2. (c) Histogram of PM-SM annual harmonic function (equation 2) correlations, $C_H = \text{cor}(H_{\text{PM}}(t), H_{\text{SM}}(t))$. (d) Annual harmonic function correlations in map view corresponding to histogram (c). CW and CCW metrics are determined from generalized Lissajous curves (black curves in Fig. 9) using the MATLAB *ispolycw* function. Station Lissajous curve circular indices CI, a measure of the circularity of SM versus PM annual harmonic amplitude for each station, are given in Table 2, where CI value of 1 corresponds to a circular orbit and a value of zero indicates zero enclosed area for the Lissajous curve (CI values vary between 0.000 (ESK) and 0.550 (RAR)). The color version of this figure is available only in the electronic edition.



amplitudes, with PM amplitude reductions occurring earlier in the annual cycle of sea ice growth than SM reductions. This behavior is consistent with sea ice growth first attenuating near-coastal PM source zones and later attenuating further off-coast SM source zones. This produces strongly counter-clockwise characteristic amplitude orbits in the (PM and SM) plane (Figs. 9 and 13).

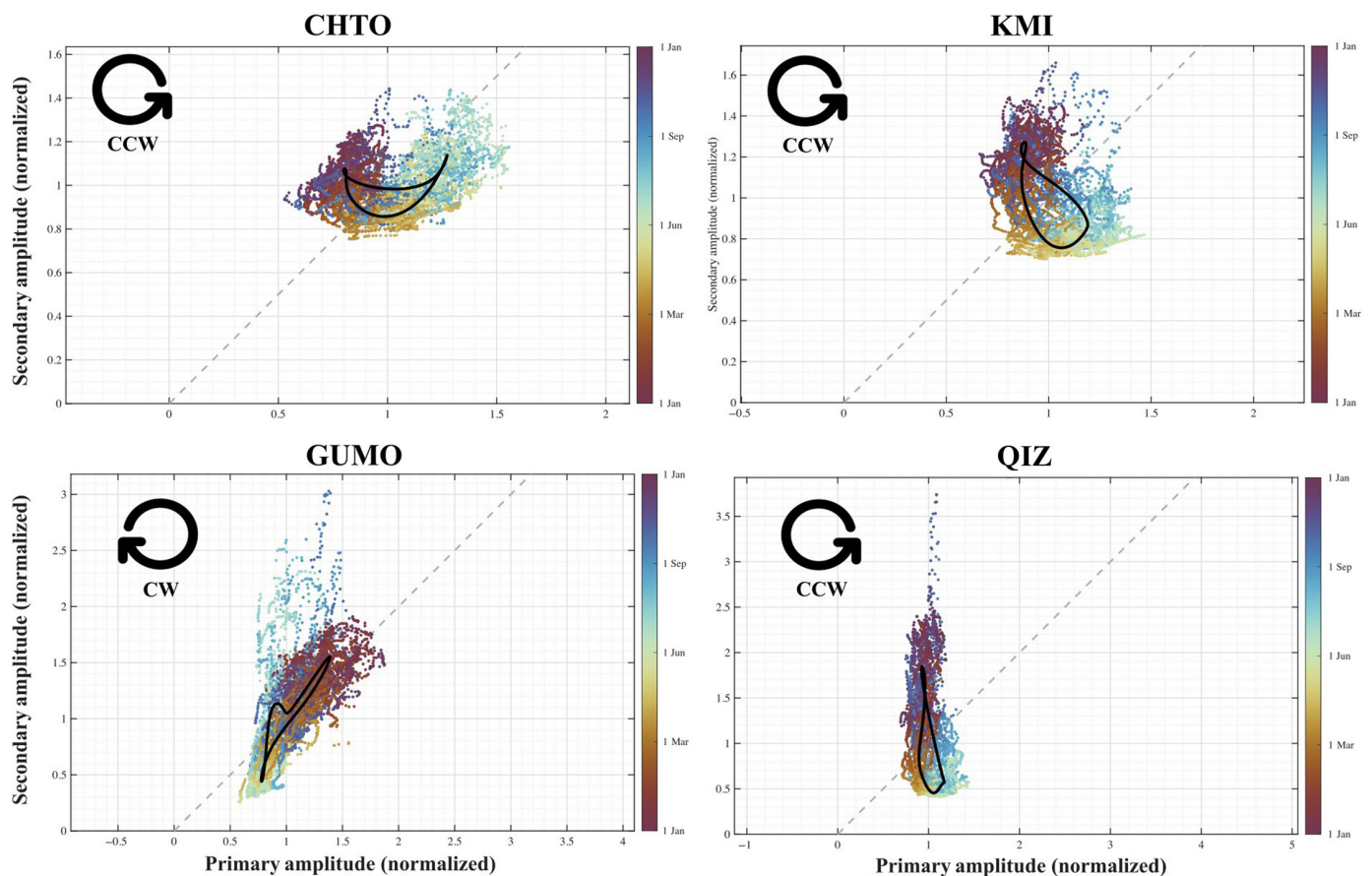
Primary–secondary annual harmonic function relative phase

The globally observed orbital direction of Lissajous curve-determined annual variations in the (PM and SM) plane, reflecting the relative phase of characteristic SM and PM annual harmonic functions, is asymmetric, with net clockwise orbits observed at just 27 of 73 stations (Fig. 10, Table 2). Figure 10 shows that orbital sense variation is hemisphere-correlated, with net clockwise orbits limited to the Northern Hemisphere, northern Australia, and to some Pacific and Indian Ocean islands. This systematic difference reflects spatially correlated regional variations in the annual excitation pattern of relevant PM and SM source regions and requires further investigation. One hypothesis for the southerly bias of counterclockwise annual variation is a widespread influence of Southern Hemisphere winter PM generation through long-range swell and Rayleigh-wave teleconnection (Aster *et al.*, 2023, 2026) sufficient to cause a leading PM signal during quiet summer wave periods in the Northern Hemisphere.

Figure 11. PM and SM amplitudes displayed as in the left side panels of Figure S2 for East Asian, Western Pacific, and South Asian Monsoonal- and/or tropical cyclone-influenced stations CHTO, LSA, GUMO, KMI, TATO, QIZ, and DGAR. Annual harmonic functions are represented by a yellow dotted line. The color version of this figure is available only in the electronic edition.

Secular trends

Although the focus of this study is on stationary annually periodic variations, we note that complementary work has estimated linear secular amplitude trends by fitting ℓ_1 -norm minimizing linear functions to the residual time series $R(t) = A(t) - H(t)$ (e.g., Fig. S1d). Secular trends for stations in this study (see: Aster *et al.*, 2023, 2026) are positive at 3σ significance in both bands at a majority of stations, with global average rates of PM and SM vertical-component acceleration intensification of 0.17%/yr and 0.11%/yr (0.015 and 0.0095 dB/yr), respectively. Microseism secular changes over the multidecade history of these seismic stations are much smaller than the annual harmonic amplitude variations that are the focus of this study. Secular changes correspond to an intensification of approximately 10% (0.85 dB) at faster changing sites such as ANMO (Albuquerque, New Mexico) (Figs. S1 and S2; PM band secular rate of 0.33%/yr $\pm$ 0.02%/yr and SM band secular rate of 0.22%/yr $\pm$ 0.03%/yr) over the past approximately 30 yr. An interesting associated question for



future investigation is whether there may be resolvable secular trends reflected in the best-fit annual harmonic function coefficients or other periodic metrics across multiyear intervals.

Conclusions

We examine the global annual periodicity of the ocean wave-generated primary (PM; 14–20 s) and secondary (SM; 4–10 s) microseism bands across 20 or more annual cycles. We examine data from 73 stations (Table 1) in the Global Seismographic and GEOSCOPE networks located from -90° S to 82.5° N (49 in the Northern Hemisphere and 24 in the Southern Hemisphere) using seasonally smoothed (60.9 d) vertical-component acceleration amplitudes. The annually (tropical year) periodic component of amplitude variation is characterized by four Fourier terms.

Annual harmonic functions fit between 14% and 95% (NNA–RSSD) and 22% and 97% (PMSA–RSSD) of total signal variance in the PM and SM bands, respectively (Table 3). Very low harmonic fits for NNA (Nana, Peru) and PMSA (Palmer Station, Antarctica) in both microseism bands indicate that these two stations experience the greatest degree of annually aperiodic wave activity. Annual harmonic function PM and SM dynamic ranges are between 1.2 and 14.2 dB (NNA–KONO) and 1.4 and 20.6 dB (HDC–KONO), indicating that KONO experiences the greatest characteristic annual variation in both microseism bands.

Figure 12. Median-normalized SM versus PM daily acceleration amplitudes and annual harmonic functions (black) for East Asian/Western Pacific stations CHTO, KMI, GUMO, and QIZ. The arrows depict the sense of annual data and harmonic function net rotation (either CCW or CW) in the (PM and SM) plane (Fig. 10, Table 2). The color version of this figure is available only in the electronic edition.

The fundamental Fourier term phase of annual harmonic functions is strongly aligned near 1 January at sites north of 35° N reflecting the early winter maximum of Northern Hemisphere extratropical storm activity. Southern Hemisphere extratropical storminess is more annually sustained, and its corresponding approximately 1 July annual storm peak is less consistent. Southern Hemisphere seasonal influences first become evident at higher northern tropical latitudes, particularly in the (14–20 s) PM band. This greater geographic reach of Southern Hemisphere PM source influences is consistent with more extensive microseism teleconnections arising from both long-period swell propagation in the more ocean-dominated Southern Hemisphere, and from longer-period and higher quality factor (Q) Rayleigh-wave propagation from distal PM source regions.

Unique annual periodicity is observed for Antarctic continental stations due to sea ice influences. Stations in East Asia indicate unusual microseism source characteristics in the South China Sea region that can produce very large SM

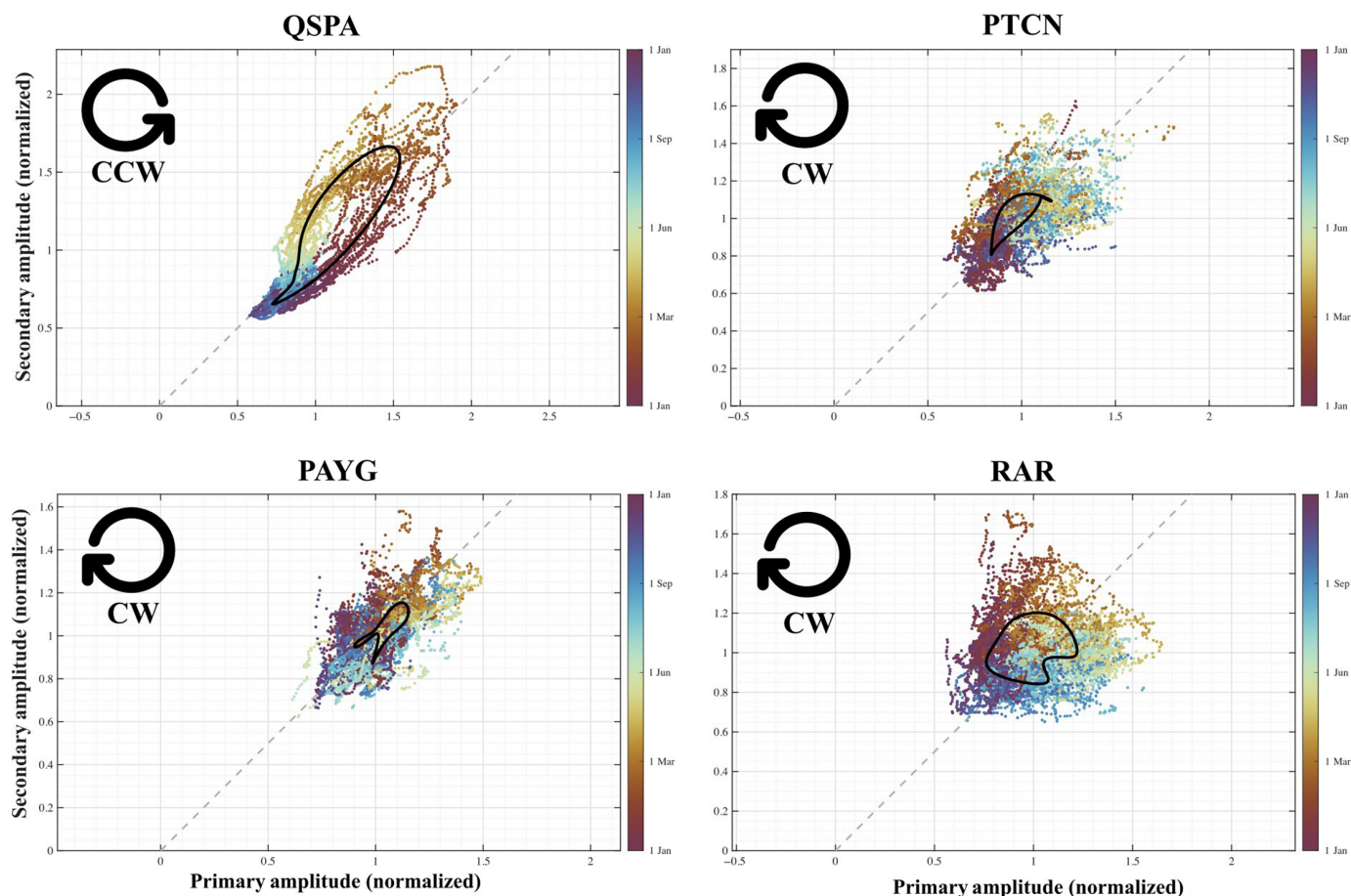


Figure 13. Median-normalized (PM and SM) daily acceleration amplitudes and annual harmonic functions (black) for East Asian/Western Pacific stations, the Antarctic station QSPA, and the Pacific island stations PTCN, PAYG, and RAR. The arrows depict

the sense of annual data and harmonic function net rotation (CCW or CW) in the (PM and SM) plane (Fig. 10, Table 2). The color version of this figure is available only in the electronic edition.

TABLE 2

SM to PM Annual Harmonic Function (equation 1) Correlations C_H , and Full Time-Series Correlations C (Fig. 10) Sorted by Descending C_H , Net Annual Periodic Function Generalized Lissajous Curve Orbital Sense, Net Counterclockwise (–; 27 Stations) or Clockwise (+; 46 Stations) of (PM and SM) Generalized Lissajous Curves (Fig. 9), Lissajous Circularity Index (CI, 0 = Collinear, 1 = Circular), and Range of PM and SM Annual Harmonic Functions (r_H) and Full Daily Time Series (r) in dB (Fig. 8)

Station	C_H	C	Orbital Sense	CI	$r_{H_{PM}}$ (dB)	$r_{H_{SM}}$ (dB)	r_{PM} (dB)	r_{SM} (dB)
GRFO	0.996	0.965	–	0.019	12.89	15.23	18.19	18.96
BFO	0.996	0.961	–	0.002	13.32	15.94	17.63	21.32
WVT	0.995	0.961	+	0.015	8.77	13.50	11.92	16.70
SSPA	0.994	0.955	–	0.010	7.96	13.15	13.33	20.01
ESK	0.993	0.954	–	0.000	13.18	16.68	18.89	26.52
HKT	0.993	0.954	–	0.025	7.37	10.14	11.48	13.82

Net orbital sense is determined using the MATLAB *ispolycw* function. PM, primary microseism; and SM, secondary microseism.
(Continued next page.)

TABLE 2 (continued)

SM to PM Annual Harmonic Function (equation 1) Correlations C_H , and Full Time-Series Correlations C (Fig. 10) Sorted by Descending C_H , Net Annual Periodic Function Generalized Lissajous Curve Orbital Sense, Net Counterclockwise (-; 27 Stations) or Clockwise (+; 46 Stations) of (PM and SM) Generalized Lissajous Curves (Fig. 9), Lissajous Circularity Index (CI, 0 = Collinear, 1 = Circular), and Range of PM and SM Annual Harmonic Functions (r_H) and Full Daily Time Series (r) in dB (Fig. 8)

Station	C_H	C	Orbital Sense	CI	$r_{H_{PM}}$ (dB)	$r_{H_{SM}}$ (dB)	r_{PM} (dB)	r_{SM} (dB)
DWPF	0.993	0.924	-	0.025	7.07	11.29	10.35	14.06
KONO	0.992	0.942	+	0.019	14.26	20.59	20.42	29.92
WMQ	0.992	0.942	-	0.016	5.98	5.49	10.09	8.15
HRV	0.992	0.944	-	0.014	8.59	16.75	12.97	22.67
OBN	0.991	0.930	-	0.011	11.38	16.53	16.76	23.48
RSSD	0.991	0.954	+	0.025	7.99	13.82	11.36	16.25
ALE	0.990	0.932	+	0.015	8.91	18.35	12.53	25.11
TAM	0.990	0.908	+	0.003	3.84	2.94	8.95	7.08
SJG	0.990	0.863	-	0.035	5.59	9.36	10.84	14.09
MBWA	0.988	0.933	+	0.015	4.89	5.85	8.37	9.83
KDAK	0.988	0.936	+	0.011	6.49	20.19	10.91	24.73
PAB	0.988	0.949	-	0.011	10.12	14.38	15.17	21.53
BORG	0.987	0.929	-	0.016	11.81	19.02	18.11	30.18
ANMO	0.987	0.932	+	0.010	5.37	10.63	8.64	14.24
COLA	0.986	0.954	+	0.033	7.38	14.25	11.74	18.41
KURK	0.985	0.938	-	0.032	5.68	6.37	10.11	10.05
FFC	0.985	0.955	+	0.041	8.55	16.07	11.70	19.09
CTAO	0.983	0.865	+	0.001	3.28	5.28	6.78	8.80
COR	0.982	0.930	+	0.025	8.53	13.77	13.23	20.12
WRAB	0.980	0.855	+	0.006	3.90	5.36	7.81	8.89
KBS	0.978	0.866	+	0.028	10.52	18.88	16.56	25.60
AAK	0.976	0.894	-	0.010	4.62	7.21	9.48	13.17
LVZ	0.976	0.877	+	0.005	10.29	15.17	17.33	25.80
CMLA	0.974	0.906	-	0.043	10.05	15.99	14.21	23.30
KEV	0.974	0.881	+	0.006	11.77	17.55	17.37	26.26
MAJO	0.972	0.814	-	0.037	4.56	10.05	9.51	17.06
TUC	0.971	0.921	-	0.019	6.19	8.65	9.03	11.46
PET	0.965	0.895	+	0.008	5.51	17.41	10.34	22.57
SBA	0.964	0.900	-	0.070	6.98	10.29	11.69	16.02
MIDW	0.961	0.826	+	0.014	4.89	14.04	8.09	19.57
ULN	0.960	0.875	-	0.010	4.59	6.51	7.80	8.72
BBSR	0.943	0.820	-	0.102	7.17	14.72	12.14	20.90
PFO	0.941	0.883	+	0.002	5.57	8.49	9.95	14.15

Net orbital sense is determined using the MATLAB *ispolycw* function. PM, primary microseism; and SM, secondary microseism.

(Continued next page.)

TABLE 2 (continued)

SM to PM Annual Harmonic Function (equation 1) Correlations C_H , and Full Time-Series Correlations C (Fig. 10) Sorted by Descending C_H , Net Annual Periodic Function Generalized Lissajous Curve Orbital Sense, Net Counterclockwise (–; 27 Stations) or Clockwise (+; 46 Stations) of (PM and SM) Generalized Lissajous Curves (Fig. 9), Lissajous Circularity Index (CI, 0 = Collinear, 1 = Circular), and Range of PM and SM Annual Harmonic Functions (r_H) and Full Daily Time Series (r) in dB (Fig. 8)

Station	C_H	C	Orbital Sense	CI	$r_{H_{PM}}$ (dB)	$r_{H_{SM}}$ (dB)	r_{PM} (dB)	r_{SM} (dB)
KIP	0.938	0.811	+	0.052	3.96	13.99	7.57	17.81
DRV	0.933	0.839	–	0.097	9.55	11.41	13.54	19.74
SNZO	0.922	0.738	–	0.038	3.54	3.54	8.50	8.02
YAK	0.918	0.820	+	0.036	4.37	9.11	8.74	12.58
TAU	0.910	0.735	–	0.081	3.75	3.53	8.50	8.50
CASY	0.910	0.848	–	0.126	8.02	10.31	14.86	17.60
GUMO	0.910	0.708	+	0.064	5.06	10.91	10.21	21.46
PMG	0.909	0.752	–	0.003	2.93	5.97	8.99	10.74
FDFM	0.908	0.794	–	0.115	5.22	7.76	9.98	11.91
QSPA	0.891	0.847	–	0.138	6.55	8.12	10.36	11.80
DGAR	0.888	0.805	+	0.010	6.96	9.43	10.80	15.45
FURI	0.878	0.681	–	0.013	2.41	4.16	5.93	7.16
EFI	0.872	0.590	–	0.129	2.85	4.69	8.60	11.07
HOPE	0.859	0.478	–	0.084	2.63	3.78	10.24	10.64
MDJ	0.854	0.656	–	0.054	3.05	8.11	6.95	11.22
XAN	0.847	0.588	–	0.071	2.57	5.42	12.76	8.21
PTCN	0.844	0.551	+	0.170	2.81	2.93	9.78	8.35
LCO	0.839	0.715	–	0.159	2.16	3.95	6.76	8.56
CRZF	0.810	0.723	–	0.216	4.93	6.09	9.55	12.34
SHEL	0.784	0.615	–	0.183	2.14	3.46	5.56	8.61
SUR	0.752	0.638	–	0.302	3.38	3.44	6.65	7.59
TATO	0.743	0.429	–	0.062	2.07	13.38	6.34	22.93
PMSA	0.721	0.730	–	0.219	2.80	4.64	15.80	18.24
PAYG	0.707	0.638	+	0.175	2.13	2.43	7.73	8.05
RPN	0.704	0.427	–	0.152	1.67	5.28	4.29	11.06
HDC	0.680	0.633	–	0.210	2.13	1.49	5.62	4.60
INCN	0.649	0.395	–	0.097	1.94	8.46	5.90	12.76
TSUM	0.573	0.512	–	0.283	2.60	3.44	6.60	8.00
NNA	0.360	0.569	–	0.174	1.19	3.39	5.30	8.96
CHTO	0.280	0.316	–	0.144	4.05	2.46	9.36	5.61
LSA	0.144	0.274	–	0.135	1.91	2.26	6.52	4.34
RAR	0.051	0.097	+	0.550	4.10	3.10	9.34	8.38
QIZ	–0.585	–0.280	–	0.062	2.36	12.17	6.37	19.10
KMI	–0.733	–0.438	–	0.287	2.77	4.52	6.84	7.43

Net orbital sense is determined using the MATLAB *ispolycw* function. PM, primary microseism; and SM, secondary microseism.

TABLE 3

Station Names, Coordinates (Sorted by Latitude), Annual Harmonic Fits F (Equation 2), and Annual ($n = 1$) Normalized Coefficient Amplitude and Phase (c and θ)

Station	Latitude (°)	Longitude (°)	F_{PM}	F_{SM}	c_{1PM}	c_{1SM}	θ_{1PM} (°)	θ_{1SM} (°)
QSPA	-89.9289	144.4382	0.8220	0.9015	0.8493	41.3435	77.9121	99.5693
SBA	-77.8492	166.7572	0.8295	0.8717	2.3475	301.0598	70.7915	83.2629
DRV	-66.6649	140.0021	0.8604	0.7577	1.2231	110.7914	56.0325	75.7457
CASY	-66.2792	110.5354	0.7178	0.7572	1.2236	361.5699	81.9436	101.2328
PMSA	-64.7744	-64.0489	0.1476	0.2203	3.6773	225.9251	102.9520	136.5743
HOPE	-54.2836	-36.4879	0.1931	0.3360	3.3704	2462.9203	155.4827	161.8787
EFI	-51.6753	-58.0637	0.2905	0.5446	3.5647	244.7677	172.3775	-162.9596
CRZF	-46.4300	51.8610	0.7020	0.7996	1.1505	9.9657	157.7274	-169.8936
TAU	-42.9099	147.3204	0.6641	0.5522	2.3300	1190.6843	167.0527	-169.1981
SNZO	-41.3087	174.7043	0.6383	0.5569	2.2592	174.8121	159.8437	170.3702
SUR	-32.3797	20.8117	0.6724	0.5981	2.7314	429.0479	159.0604	-157.7067
LCO	-29.0110	-70.7005	0.3140	0.6154	1.4826	454.5975	160.8469	-169.4301
RPN	-27.1267	-109.3344	0.4043	0.7030	1.0376	80.0364	140.2612	-174.8533
PTCN	-25.0713	-130.0953	0.4174	0.4486	4.0549	633.1740	-170.4161	169.3550
RAR	-21.2125	-159.7733	0.5348	0.4473	4.4835	333.2788	164.9164	80.3433
MBWA	-21.1590	119.7313	0.8260	0.8153	1.4669	120.0434	-169.7626	-168.4407
CTAO	-20.0882	146.2545	0.7036	0.8255	0.9185	273.0790	176.0033	-178.7863
WRAB	-19.9336	134.3600	0.7060	0.8639	4.9023	806.6112	-175.2786	-169.8036
TSUM	-19.2022	17.5838	0.6182	0.5694	1.1302	96.1570	137.6325	-159.9779
SHEL	-15.9594	-5.7455	0.5060	0.5941	2.4303	239.7083	144.2553	164.6039
NNA	-11.9875	-76.8422	0.1360	0.5126	0.4421	27.0877	107.2914	179.0946
PMG	-9.4047	147.1597	0.5979	0.7833	3.4209	180.2838	167.6176	-178.4157
DGAR	-7.4121	72.4525	0.8975	0.9083	0.7717	360.1466	-163.5098	-154.9213
PAYG	-0.6742	-90.2861	0.2662	0.2837	0.4402	19.1617	129.9197	79.1201
FURI	8.8952	38.6798	0.4967	0.7798	2.3596	124.5653	166.6708	-167.8497
HDC	10.0021	-84.1114	0.4580	0.3924	1.2253	316.2220	42.1912	84.1913
GUMO	13.5893	144.8684	0.6335	0.4974	2.4297	328.6673	10.5156	-9.7391
FDFM	14.7350	-61.1463	0.7553	0.7710	0.3496	60.9201	16.3702	39.7666
SJG	18.1091	-66.1500	0.7518	0.8824	2.5584	265.2491	5.9207	10.9285
CHTO	18.8141	98.9443	0.7428	0.4304	2.4090	469.8474	-160.4977	-89.9569
QIZ	19.0291	109.8445	0.5032	0.7881	2.7939	414.6673	-146.8664	-17.1197
KIP	21.4200	-158.0112	0.6813	0.9459	0.8380	2327.4952	20.9108	11.0647
TAM	22.7915	5.5284	0.7090	0.6151	0.7167	23.8937	23.2942	20.0941
TATO	24.9735	121.4971	0.3363	0.7098	4.3623	571.0413	-49.8469	-16.1544
KMI	25.1483	102.7475	0.6356	0.7934	1.1403	39.9577	-155.8768	-12.3300

Data are plotted in Figures 2–7. The dashed line separates stations in the Southern and Northern Hemispheres.
(Continued next page.)

TABLE 3 (continued)

Station Names, Coordinates (Sorted by Latitude), Annual Harmonic Fits F (Equation 2), and Annual ($n = 1$) Normalized Coefficient Amplitude and Phase (c and θ)

Station	Latitude (°)	Longitude (°)	F_{PM}	F_{SM}	c_{1PM}	c_{1SM}	θ_{1PM} (°)	θ_{1SM} (°)
DWPF	28.1103	-81.4327	0.8911	0.9000	0.5791	129.3220	2.8721	5.5240
MIDW	28.2156	-177.3698	0.7328	0.9465	0.2854	8.5838	18.8066	16.2388
LSA	29.7031	91.1270	0.2700	0.7149	2.8373	372.6155	-149.7403	12.4598
HKT	29.9618	-95.8384	0.8962	0.9068	0.7089	130.8993	3.5311	7.3601
TUC	32.3098	-110.7847	0.9034	0.8964	1.8770	149.7288	9.4805	11.8937
BBSR	32.3713	-64.6963	0.7781	0.8949	0.5390	61.3241	2.4075	20.4642
PFO	33.6092	-116.4553	0.8371	0.8278	1.2287	1496.1780	13.5132	12.9236
XAN	34.0311	108.9232	0.3415	0.8595	0.1829	53.9578	-26.6198	-9.8602
ANMO	34.9459	-106.4572	0.8698	0.9078	2.6678	262.7956	10.2726	9.3118
WVT	36.1297	-87.8300	0.9158	0.9320	2.8554	219.0512	4.3628	2.7659
MAJO	36.5457	138.2041	0.6266	0.8113	0.5367	76.9583	-3.1862	5.3136
INCN	37.4776	126.6239	0.2793	0.7313	1.0501	369.3369	-56.5769	-11.7132
CMLA	37.7637	-25.5243	0.8668	0.8275	1.6404	147.7745	9.7761	14.0976
PAB	39.5446	-4.3499	0.8500	0.8553	1.0100	66.9035	11.9370	13.2661
SSPA	40.6358	-77.8876	0.8842	0.8862	1.6210	322.8200	1.2285	3.4644
HRV	42.5064	-71.5583	0.8932	0.8817	1.8439	501.8560	3.0346	7.2054
AAK	42.6375	74.4942	0.6603	0.8050	0.5785	104.5473	6.2608	10.5717
WMQ	43.8138	87.7049	0.8037	0.9152	2.1044	168.9590	5.4902	8.5081
RSSD	44.1212	-104.0359	0.9530	0.9700	1.4547	486.2377	6.8341	4.1252
COR	44.5855	-123.3046	0.8655	0.8398	0.2981	649.4155	11.5917	9.4663
MDJ	44.6170	129.5908	0.5536	0.8933	2.1877	150.8493	-16.3589	0.3986
ULN	47.8651	107.0532	0.7761	0.9493	2.2463	361.7478	-1.8424	0.1339
BFO	48.3301	8.3296	0.8411	0.8786	0.3381	237.2465	10.3896	10.8632
GRFO	49.6909	11.2203	0.8268	0.8737	0.8832	87.9115	7.7173	10.1935
KURK	50.7154	78.6202	0.7926	0.8846	1.5181	131.1109	3.7558	8.2153
PET	53.0233	158.6499	0.8152	0.8785	2.0378	219.7386	3.7884	6.1356
FFC	54.7250	-101.9783	0.9163	0.9370	0.9199	183.7628	4.3487	-0.3170
OBN	55.1146	36.5674	0.7951	0.7816	1.0048	20.5809	10.7480	11.0925
ESK	55.3167	-3.2050	0.8201	0.8444	0.4563	311.0009	12.0713	11.2006
KDAK	57.7828	-152.5835	0.8164	0.9125	1.4961	265.3115	8.6747	7.2633
KONO	59.6491	9.5982	0.7846	0.7998	0.6700	51.3946	11.8961	8.2943
YAK	62.0310	129.6805	0.7872	0.9430	1.6557	98.3084	-0.9866	-3.5089
BORG	64.7474	-21.3268	0.8336	0.8042	0.8673	32.9396	6.0262	6.0780
COLA	64.8736	-147.8616	0.8507	0.9413	1.3299	40.4817	7.7819	3.6054
LVZ	67.8979	34.6514	0.8016	0.7806	1.2758	93.4979	8.9889	6.6964

Data are plotted in Figures 2–7. The dashed line separates stations in the Southern and Northern Hemispheres.
(Continued next page.)

TABLE 3 (continued)
Station Names, Coordinates (Sorted by Latitude), Annual Harmonic Fits F (Equation 2), and Annual ($n = 1$) Normalized Coefficient Amplitude and Phase (c and θ)

Station	Latitude (°)	Longitude (°)	F_{PM}	F_{SM}	c_{1PM}	c_{1SM}	θ_{1PM} (°)	θ_{1SM} (°)
KEV	69.7565	27.0035	0.8074	0.7948	2.1737	160.1071	10.5287	8.1798
KBS	78.9154	11.9385	0.8301	0.7796	0.4716	30.3576	4.1439	−0.5635
ALE	82.5033	−62.3500	0.9126	0.8337	0.8160	52.6770	1.6104	−2.3035

Data are plotted in Figures 2–7. The dashed line separates stations in the Southern and Northern Hemispheres.

amplitudes with small contemporaneous PM amplitudes. Stations in the Indian Ocean region exhibit unique annual variations in SM and/or PM amplitudes reflecting superimposed influences of bi-yearly monsoonal winds and waves, seasonal tropical cyclones, and long-distance Southern Hemisphere swell.

These observations highlight a systematic hemispheric asymmetry in Earth’s annually varying ocean wave-excited background seismic wavefield. Temperate and Arctic Northern Hemisphere stations are quieter in summer, have high-PM–SM amplitude correlations (commonly greater than 0.9), and have consistently higher annual harmonic function data fits (typically greater than 90%). PM–SM correlation and annual harmonic functional fits diminish and show greater geographic variability south of the Northern Hemisphere tropics and across the Southern Hemisphere. This hemispheric difference is attributed to lesser extratropical storm seasonality and more extensive swell propagation in the less land-dominated Southern Hemisphere, contrasted with greater storm seasonality and more extensive SM-generating coastal swell reflection from large land masses in the Northern Hemisphere.

This study presents a global assessment of annually periodic PM and SM band seismic intensity amplitude. The methodology described here can be further applied at finer geographic and spectral resolution to improve understanding of annual variability and PM–SM covariation across the microseism spectrum. Improved PM and SM source modeling integrating oceanographic, atmospheric, and other observational and modeling efforts can further advance understanding of wave state variations and their influences on seismic signals. Such efforts can also facilitate period-dependent global models of seismic background amplitude variability and predictability to statistically characterize seasonally dependent variations in long-period band transient signal detection capabilities.

Data and Resources

Data examined and used in this work are freely available from the EarthScope Data Management Center from the Global Seismographic (FDSN IU/II/IC; doi: 10.7914/SN/IU and doi: 10.7914/SN/II; doi: 10.7914/SN/IC; Ringler *et al.*, 2022; Davis, 2024; Anderson *et al.*, 2015) and GEOSCOPE (FDSN G; doi: 10.18715/GEOSCOPE.G; Leroy *et al.*, 2023) networks. Data processing, analysis, and plotting were performed using MATLAB version R2025b and the ObsPy Python package (Beyreuther *et al.*, 2010). Colorblind friendly color maps were

used from the Crameri MATLAB package (Crameri, 2019). Figures 1, 2, 5, and 7 were made using the M_Map mapping package available online at <https://www.eoas.ubc.ca/~rich/map.html>. Scripts used for reproducing figures are available at <https://code.usgs.gov/asl/papers/ringler>. Both websites were last accessed in June 2026. The supplemental material for this article includes six figures and one table.

Declaration of Competing Interests

The authors acknowledge that there are no conflicts of interest recorded.

Acknowledgments

This work was supported by National Science Foundation (NSF) awards 2422648 (R. C. A. and J. N. B.) and 2422649 (F. J. S.). R. C. A. received support during 2024–2025 through the Princeton University Harry H. Hess Distinguished Visiting Faculty and the California Institute of Technology Moore Distinguished Scholars programs. The facilities of the EarthScope Consortium were used to access seismic waveforms, related metadata, and/or derived products through the U.S. National Science Foundation Seismological Facility for the Advancement of Geoscience (SAGE) Award under Cooperative Agreement EAR-1724509. The Global Seismographic Network is a cooperative scientific facility operated jointly by the National Science Foundation (NSF) and the U.S. Geological Survey. The NSF component is part of the NSF SAGE Facility, operated by the EarthScope Consortium under Cooperative Agreement EAR-1724509. The authors thank Patrick Bastien and Brian Shiro for helpful reviews of this work.

Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U. S. Government.

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Manuscript received 29 January 2026

Published online 20 August 2026