Madden-Julian oscillation winds excite an intraseasonal see-saw of ocean mass that affects Earth’s polar motion

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Strong large-scale winds can relay their energy to the ocean bottom and elicit an almost immediate intraseasonal barotropic (depth independent) response in the ocean. The intense winds associated with the Madden-Julian Oscillation over the Maritime Continent generate significant intraseasonal basin-wide barotropic sea level variability in the tropical Indian Ocean. Here we show, using a numerical model and a network of in-situ bottom pressure recorders, that the concerted barotropic response of the Indian and the Pacific Ocean to these winds leads to an intraseasonal see-saw of oceanic mass in the Indo-Pacific basin. This global-scale mass shift is unexpectedly fast, as we show that the mass field of the entire Indo-Pacific basin is dynamically adjusted to Madden-Julian Oscillation in a few days. We find this large-scale ocean see-saw, induced by the Madden-Julian Oscillation, has a detectable influence on the Earth’s polar axis motion, in particular during the strong see-saw of early 2013.
The Madden–Julian oscillation (MJO) is the most energetic large-scale intraseasonal atmospheric disturbance.\(^1,2\) It originates in tropical Africa and travels eastward through the Indian and the Pacific basins as 16th and 2nd zonal wave-numbers of zonal wind, precipitation, and convection.\(^3\) Eventually, these disturbances die out over the Atlantic Ocean and the African Continent. These disturbances are largely confined in the tropical belt. Strong boreal winter MJO is associated with intense winds over the Maritime Continent, the tropical interface between the Indian and the Pacific Ocean, generating significant intraseasonal barotropic sea-level variability in the entire tropical Indian Ocean.\(^4\) It amounts to a basin-scale signal that reaches up to 4–6 cm in the tropical Indian Ocean, with the mass redistribution achieved through fast-propagating barotropic waves adjusting the tropical Indian Ocean in \(~2–3~\) days.\(^5\) Past studies on the impact of MJO on the global ocean barotropic variability have been rare.\(^6\) We report that during boreal winter MJO, the rise of oceanic mass in the tropical Indian Ocean is concurrent with a fall of oceanic mass in the Pacific Ocean, and vice versa at intraseasonal timescales. The periodic reversal of MJO winds, therefore, leads to an intraseasonal see-saw in the oceanic mass in the Indo–Pacific basin, with the fulcrum stationed over the Maritime Continent. Due to the extent of the Pacific Ocean—well beyond the tropics—this fast barotropic dynamics incites a far-reaching, quasi-global oceanic response to the MJO encompassing tens of thousands of kilometers within a few days. This challenges the earlier understanding of response only via slow-propagating baroclinic waves thereby adjusting the density field of the basins in \(~2–3~\) months.\(^7\)

The Earth’s rotation about its three axes is not constant, and presents fluctuations over a broad range of frequencies.\(^8\)–\(^13\) The rotation changes are classically separated into two parts: the changes in the angular velocity are described in terms of changes in the length-of-day, whereas the rotation of the solid Earth around its rotation axis corresponds to polar motion.\(^11\)–\(^13\) Most of those signals come from the exchange of angular momentum between the solid Earth and the fluid parts, namely the Earth’s core and its fluid envelope (atmosphere and ocean).\(^11,13,14\) For geometry reasons, the atmosphere impacts dominate that from the ocean for the length-of-day, except at tidal frequencies.\(^14\) The picture is more complex for polar motion, for which the relative domination of the ocean or atmosphere depends on the frequency band. In the intraseasonal band of interest for our study, the polar motion is mostly forced by the atmosphere.\(^4\) However, the contribution from the ocean is also significant.\(^8,15,16\) The impact from the ocean on polar motion mostly comes from the spatial distribution of the oceanic mass, though, for some particular phenomena, the mass transport gives rise to an observable change.\(^8,15,16\) The see-saw generation involves large-scale mass redistribution and currents across and within the Pacific and the Indian basins. The associated global-scale angular momentum, arising both from a large-scale circulation in the ocean and a global-scale mass redistribution, is expected to leave its signature in the Earth’s rotation about its polar axis and the polar motion.\(^8\)–\(^10,\)\(^13\) We demonstrate that the MJO-induced see-saw, being a large-scale process, does leave oceanic footprints on the polar motion. The excitations induced by the oceans, though generally minor, are at times up to about half the magnitude as those induced by the atmosphere.

**Role of MJO.** The large-scale anomaly in equivalent water depth variability in the tropical Indian Ocean is driven by MJO winds over the Maritime Continent.\(^4\) To determine to which extent the MJO winds also drive the large-scale variability in the Pacific Ocean, a sensitivity model experiment (MC-EXP; see methods section) is run for the 2009–2019 period, with wind forcing restricted to the Maritime Continent (black box in Fig. 2b). The spatial correlation of anomaly in equivalent water depth over the Maritime Continent from MC-EXP during each December–April with all model grid points is plotted in Fig. 2b. The correlation pattern in the Indo–Pacific basin is, to a large extent, similar to the correlation pattern obtained from the control run (Fig. 2a). So, the intraseasonal see-saw in the Indo–Pacific basin persists even if the model is forced only by winds over the Maritime Continent. Note that the signature is not consistent with what is observed in the anomaly in equivalent water depth in
the Arctic and the North Pacific Ocean, most probably due to dominant local dynamics\textsuperscript{18,19}.

Whereas the MC-EXP largely captures the variance in the tropical Indian Ocean (with values >70\%\textsuperscript{4}) its impact is also significant over the Pacific Ocean (Fig. 2c). The winds over the Maritime Continent alone can generate as much as \(\sim 15\text{–}20\%\) of variance in the equivalent water depth over the tropical and the southern Pacific Ocean. The rest of the variability in the Pacific Ocean may be an outcome of local dynamics and/or remote effects that owe their origin outside the Maritime Continent. In
contrast, the Arctic and the Atlantic Ocean are mostly not influenced by the winds over the Maritime Continent. Nevertheless, it is remarkable that the wind forcing from such a small region (~4% of global ocean coverage) casts such a large-scale influence and excites ~15–20% of the intraseasonal oceanic mass fluctuations over a large part of the tropical Pacific.

During a positive cycle of the index, the MJO winds drive ~2 Sv of Pacific waters into the Indian Ocean through the Indonesian straits. An equivalent flux is subsequently flushed out into the Southern Ocean after ~1–2 days. The Southern Ocean conveys it eastward and subsequently injects ~2 Sv into the Pacific Ocean after another ~1 day, thereby closing this anticyclonic circulation around the Australian continent (Supplementary Fig. 4). This barotropic circulation is schematically illustrated in Fig. 2d. As expected, the circulation reverses its direction during the negative phase of the see-saw. This intraseasonal circulation occurs over and above a permanent anticyclonic barotropic negative phase of the see-saw. This barotropic circulation is schematically illustrated in Fig. 2d. As expected, the circulation reverses its direction during the negative phase of the see-saw. This intraseasonal circulation occurs over and above a permanent anticyclonic barotropic negative phase of the see-saw. This barotropic circulation is schematically illustrated in Fig. 2d.

Observational imprint of the see-saw. We investigated the imprint of the intraseasonal see-saw through the bottom pressure recorder network, although this network is very sparse. Figure 3a shows the evolution of intraseasonal equivalent water depth from two bottom pressure recorders, one located in the Maritime Continent (BPR-MC; red line) and another one in the central Pacific Ocean (BPR-PAC; blue line) during boreal winters of 2009–2019 (see methods section for data processing). BPR-PAC is often out-of-phase with BPR-MC, particularly in 2011–2012 and 2012–2013, when the MJO wind stress was strong over the Maritime Continent. The variability in the BPR-MC amounts to 4–6 cm peak-to-peak, that of the BPR-PAC is ~2–3 cm—half compared to the Indian Ocean. Anomaly in equivalent water depth at the BPR-MC was correlated with anomaly in equivalent water depth from all available bottom pressure recorders globally and all bottom pressure recorders whose significance (see methods section) exceeds 90% are plotted in Fig. 3b. Nineteen out of forty-five (~42%) bottom pressure recorders in the Pacific Ocean exhibit a significant correlation. All the Indian Ocean bottom pressure recorders synchronously oscillate, whereas all the bottom pressure recorders in the Pacific and in the Arctic Ocean are anticorrelated with the bottom pressure recorders in the Indian Ocean. The observed features are in line with the model results, and consistent with what is expected from the existence of a large-scale see-saw between the Indian and the Pacific basins.

See-saw impact on polar motions. The geometry of the see-saw circulation (Fig. 2d) is near-optimal for generating a large signature in the polar motion excitation. The excitation of the polar motion is classically estimated using excitation functions—$\chi_1$ for rotation around an axis at the Greenwich meridian ($x$ axis) and $\chi_2$ for rotation around an axis that passes through the Indian Ocean at 90°E ($y$ axis) (see methods section). Considering the geometry of the currents shown in Fig. 2d, the see-saw motion mostly impacts the polar motion through $\chi_2$. Due to the Chandler wobble resonance that dominates the polar motion, it is not possible to directly compare our model-derived estimates with the polar motion observation. However, we can compute the excitation functions required to generate the observed polar motion during the strong see-saw of 2012–2013.

Detection of 2012–2013 event. The ocean is the only one of the contributors to intraseasonal polar motion excitation—the atmosphere and the hydrology being the other sources. An oceanic signal can only be separated from the climate noise if it is sensibly larger in the excitation than the nonoceanic contributions, or if we can correct the observed excitation with such precision that the residuals are notably smaller than the oceanic contribution. When dealing with intraseasonal excitation, the standard deviation, estimated over the last 10 years, is at the level of ~16 milliarcseconds (mas), to be compared with the 40 mas of the MJO-induced ocean signature, which makes it necessary to

![Fig. 3 See-saw in the bottom pressure recorders.](https://example.com/figure3.png)

**Fig. 3** See-saw in the bottom pressure recorders. **a** The plot of intraseasonal equivalent water depth at the BPR-MC (solid red; 117.94°E, 15.02°S, 5664 m) and the BPR-PAC (solid blue; 176.32°E, 9.517°S, 4921 m) during each December–April from 2009 to 2019. **b** Correlation (>90% significance; see methods section) of intraseasonal equivalent water depth from bottom pressure recorders across the globe with respect to the intraseasonal equivalent water depth at the BPR-MC (red box). All other bottom pressure recorders are marked as solid circles. The blue square box is used to mark BPR-PAC. The background color shades represent the bathymetry. The number of bottom pressure recorders analyzed in the Indian Ocean, Pacific Ocean, Atlantic Ocean, and the Arctic Ocean are 8, 45, 23, and 6, respectively.
subtract the nonoceanic signal. The raw observed excitation (shaded gray) during 2012–2013 is plotted in Fig. 4a, together with the residuals (solid black) when the nonoceanic signals are subtracted. The contributions from the atmosphere (solid green) and hydrology (solid red), estimated from the Earth System Model ESMGFZ, are also plotted to analyze the relative contributions of ocean, atmosphere, and hydrology. The most dominant contribution to the intraseasonal polar motion comes from the atmosphere as expected. We also observe a strong oceanic signal in early 2013. The oceanic contribution is of comparable order of magnitude as the atmosphere, whereas the contribution from hydrology is relatively negligible. The oceanic signal is primarily out of phase with the atmospheric signal and hence subdues the intraseasonal polar motion excitations caused by the atmosphere. The ocean, therefore, dampens the intraseasonal polar motion excitations caused by the atmosphere.

How much of this oceanic signal owes its origin to the MJO winds over the Maritime Continent during 2012–2013? During weak MJO years, the oceanic excitation of polar motion is not significantly influenced by the barotropic processes originating in the Maritime Continent. In contrast, during the 2012–2013 strong MJO event, the ocean angular momentum from the MC-EXP (cyan curve) captures ~70% of the variance of the oceanic signal from the control run. In addition, MC-EXP is in phase with the residual geodetic excitation function (black curve) and the oceanic excitation computed from the MC-EXP captures ~50% of the variance of the residual geodetic excitation. This is surprising because the MC-EXP captures ~15–20% of the variance of equivalent water depth in some regions of the Pacific Ocean, and 70% in the Indian Ocean from the control run. This is possible because the mass and motion terms of the ocean excitation estimated from the MC-EXP are similar in magnitude (Fig. 4b), which stands in stark contrast with earlier findings that suggested the mass term dominates the motion term by a factor of 5–10 over a broad range of frequencies, including the intraseasonal timescales. The ocean mass and ocean motion terms are synchronous and thereby constructively add up during 2012–2013 to yield a detectable signal up to about half the magnitude as its atmospheric counterpart. This synchronicity of mass and motion term is relatively weak or absent during other years—particularly during weak MJO years—leading to subdued oceanic excitations during see-saw events. Nevertheless, the agreement in amplitude and phase between the residual excitation and the ocean excitation demonstrates that the wind stress over the small region of the Maritime Continent is indeed able to cast a significant influence on the polar motion of the solid Earth during the boreal winter of 2012–2013.

**Summary.** The MJO winds, acting over ~4% of the Earth’s surface, induce a global-scale ocean mass redistribution, which in turn significantly influences the Earth rotation. This entire phenomenon is schematically illustrated in Fig. 5. The strong boreal winter MJO winds over the Maritime Continent elicit an intraseasonal large-scale barotropic response from the Indian and the Pacific Ocean whose extent is not only limited to the tropics but...
also reaches the extratropics within a span of days compared to earlier estimates of months deduced from slow-moving baroclinic excitations. The winds induce a barotropic circulation around the Australian continent and its periodic reversal at intraseasonal timescales is manifested as a see-saw in the oceanic mass within the Indo–Paciﬁc basin. The large-scale oceanic mass redistribution in the Indo–Paciﬁc basin, accompanied by large-scale to-and-fro transports in the two basins associated with this see-saw, beneﬁts from a favorable geometry to excite polar motions. The strong 2013 MJO allowed us to detect the signature of a mode of variability on the polar motion due to oceanic mass and currents are computed from our model using the algorithm adapted from ref. 4. The polar motion excitation functions χ1 and χ2 describe the effective changes in the angular momentum components about two equatorial axes are conventionally taken to point toward the Greenwich (x axis) and 900° meridians (y axis), respectively. These two excitation functions, χ1 and χ2, can be expressed as the sum of a mass term and a momentum term (Eq. (2)).

where

\[ \Delta T = T_{a} - T_{c} \]

\( \theta, \chi \) represent the longitude and the latitude. The factor of 1.44 accounts for the yielding of the solid Earth to imposed surface loads, and the factor of 1.61 accounts for reality in the absence of wind stresses. The wind, radiative forcing, and ocean heat transport are considered as supplementary mass and therefore modiﬁed the volume. A biharmonic-like dissipation term. A total variance diminishing ﬁlter50. The state-of-the-art ocean/sea-ice general circulation model (OGCM)—Nucleus for European Modeling of the Ocean (NEMO—version 3.6 stable)16 is used in this study. The ocean component of NEMO is based on version 9.1 of the OPA primitive equation z-level model with hydrostatic and Boussinesq approximations30,31. This OGCM is coupled to the Louvain-la-Neuve (LIM3) sea ice model32. All simulations in this study are performed using the NEMO-based high-resolution model conﬁguration (ORCA12) developed under the Copernicus Marine Environment Monitoring Service (CMEMS) framework33.

The NEMO-ORCA12 is a global ocean conﬁguration with an orthogonal, curvilinear, tripod Arakawa C-type grid with a nominal resolution of 1/12°34. In the tri-polar ORCA12 grid, the horizontal resolution gets ﬁner with increasing latitude, i.e., 9 km at the equator, 7 km at mid-latitudes, and 2 km near the poles35. Our model set-up consists of 75 vertical levels and a partial cell representation of bottom topography36,37. The resolution of this vertical discretization decreases from 1 m at the surface to 200 m in the deep ocean. The NEMO-ORCA12 conﬁguration uses a nonlinear free surface with a split-explicit formulation to compute barotropic and baroclinic modes38 and a z* coordinate approach39. In the z* formulation, the variation of the column thickness due to sea surface undulations is not concentrated in the surface level, as in the z-coordinate formulation, but is equally distributed over the full water column. Any freshwater ﬂux is considered as a supplementary mass and therefore modiﬁes the volume. A baroclinic time step of 360 s and a barotropic time step of 12 s are used. The momentum advection scheme is a 3rd order Upstream-Based Scheme40 that contains a biharmonic-like dissipation term. A total variance diminishing advection scheme is used for the tracers41,42, and the mixing scheme is k-ε turbulence closure scheme43.

The model requires the following ﬂuxes—wind, radiative ﬂuxes, air temperature, and rainfall, and speciﬁc humidity. There is no atmospheric pressure gradient forcing in the model as the effect of atmospheric pressure on open ocean bottom pressure is negligible at timescales longer than ~3 days46. Snow and river runoff ﬂuxes are imposed at the land boundaries47. ETOP0118 and GEBCO_0849 have been combined to derive ORCA12 bathymetry30. The minimum depth in the model is set to 12 m. Regions shallower than 12 m are deepened to the minimum depth. The above conﬁguration is the same across the control run and the two sensitivity experiments. Ocean bottom pressure (in Pa) is computed within the model. We obtain intraseasonal equivalent water depth from the model-derived ocean bottom pressure by scaling it with density and applying a Lanzcos ﬁlter50.

Control run. The global NEMO is run for the period 2009–2019 starting from an initial condition obtained from a 30-year spin-up of the model using ERA-Interim ECMWF reanalysis48. Subsequently, the model is forced with six-hourly National Centre for Medium Range Weather Forecasting (NCMRWF) ﬂuxes extracted from January 2009 and is run till August 2019. Sea surface temperature (SST) and sea surface salinity (SSS) are weakly restored to the monthly climatological values derived from World Ocean Atlas 2013 (WOA13)35,36. The restoration timescale is 2 months.

Sensitivity experiment: MC-EXP. To understand the importance of MJO winds over the Maritime Continent in establishing the see-saw in the Indo–Paciﬁc oceanic mass, a sensitivity experiment (MC-EXP) is carried out by restricting the wind forcing to the boxed region (90°–140°E, 32°S–2°N, black box) in Fig. 2b and zero elsewhere. All other ﬂuxes are prescribed across the globe. The wind mask is created using a hyperbolic tangent function. To avoid numerical instabilities, the winds at the edges of the box are smoothly decayed to zero over a length scale of 300 km.

The 6-hourly NCMRWF52 forcing is used for the wind while the rest of the ﬂuxes are climatological and taken from CORE-II climatology ﬂuxes55. The simulation is performed for the period 2009–2019 starting from the same initial condition as the control run. In this experiment, SST and SSS are restored strongly from ORCA12 climatology every 12 h to the climatological values derived from World Ocean Atlas 2013 (WOA13)33,34. This is done to keep the baroclinic structure of the ocean close to reality in the absence of wind ﬂuxes outside the Maritime Continent.

Bottom pressure recorder data processing. The bottom pressure recorder measures ocean bottom pressure in pascals per square inch absolute (PSIA). This information is disseminated as equivalent water depth after applying a constant 670.0 mm of water/PSIA conversion factor. The bottom pressure recorders have a time resolution of 15 min when operating in the normal mode. However, we chose hourly data by subsampling only the zeroth frequency of every hour from the normal mode data. The hourly data are subjected to TASK200056 software to remove tidal frequencies. For this study, a total of 82 bottom pressure recorders were processed. All the bottom pressure recorders were processed using the method described in ref. 4 and a continuous de-tided daily time series was constructed. Intraseasonal equivalent water depth was estimated from the daily time series using the Lanzcos ﬁlter50.

Estimation of degree of freedom for a band-passed time series. The formula for estimating the degree of freedom (DOF) for a band-passed time series57 is

\[ \text{DOF} = 2N \left( \frac{\Delta T}{T_{1}} \right)^{1/2} \left( \frac{\Delta T}{T_{2}} \right) - 2. \]

where \( \Delta T \) is the sample interval, \( T_{1} \) and \( T_{2} \) are the cutoff periods in the band-pass ﬁltering (\( T_{1} < T_{2} \)) and \( N \) is the sample size. In this study for intraseasonal (30–80 days) band-pass ﬁlter, \( \Delta T \) is taken as 1 day, \( T_{1} \) and \( T_{2} \) are 30 and 80 days, respectively, and \( N \) is 1501 (10 years of daily data during December–April). Based on this estimate, we estimated that the DOF for the winter months (December–April) of 2009–2019 is 60. Corresponding to this DOF, the correlation values greater than 0.21 and less than −0.21 are 90% signiﬁcant in accordance with the Pearson correlation table.

Estimation of ocean excitation functions from the model. Changes in the polar motion due to oceanic mass and currents are computed from our model using the algorithm adapted from ref. 4. The polar motion excitation functions \( \chi_{1} \) and \( \chi_{2} \) describe the effective changes in the angular momentum components about two equatorial axes are conventionally taken to point toward the Greenwich (x axis) and 90°E meridians (y axis), respectively. These two excitation functions, \( \chi_{1} \) and \( \chi_{2} \), can be expressed as the sum of a mass term and a momentum term (Eq. (2)).

From the model, the changes in the excitation function due to the oceanic mass distribution (Eq. (3)) were computed by integrating the density (ρ) over the ocean volume (V). Similarly, changes due to the currents (Eq. (4)) were computed by integrating density (ρ) multiplied by the zonal (u) and meridional (v) currents over the ocean volume. The partial cell representation of bottom topography in the model was accounted for during the vertical integration along with the depth of the ocean. In Eqs. (3) and (4), \( R \) (6371 km) and \( \Omega \) (7.2921 × 10−5 s−1) are the Earth’s mean radius and angular velocity, respectively, \( A \) (7.316 × 1017 kg m2) and \( C \) (7.041 × 1026 kg m5 s−2) are the earth’s polar and equatorial free surface with a zonal and polar latitudes, respectively, and \( \lambda \) and \( \theta \) represent the longitude and the latitude. The factor of 1.44 accounts for the yielding of the solid Earth to imposed surface loads, and the factor of 1.61 includes the effect of core decoupling. Intraseasonal \( \chi_{1} \) and \( \chi_{2} \) were obtained from the daily \( \chi_{1} \) and \( \chi_{2} \) using Lanzcos ﬁlter50.

Data availability

Bottom pressure recorder data were downloaded from NDBC (http://www.ndbc.noaa.gov/index.shtml), INCOOS/NIOT (http://www.incos.gov.in), ROSAME (http://www.legos.obs-mip.fr/observations/rosame), SAMOC (http://www.aoml.noaa.gov/phod/SAMOC_inter-national), ABPR (http://psc.apl.washington.edu/northpole/Data.html), and BGEF (https://www.whoi.edu/page.do?pid=66559). Bottom pressure recorder data located at 37.283°W, 32.2548°N have been obtained in the framework of EMSO-Azores
observatory and the intra seasonal filtered data can be accessed from the link https://data.mendeley.com/datasets/29h94hnj6k/1. National Center for Medium Range Weather Forecasting (NCMRF) fluxes can be obtained on request directed to vprasad@ncmrwf.gov.in. Real-time Multivariate MJO index (RMME) is available at http://www.bom.gov.au/bmrc/cifor/clifsta/mattv/maproom/MRM/. The Earth System Modelling Group of GeoForschungszentrum Potsdam (ESM(G)FZ) data is available from https://esgf-data.meteoFri.de/esgf-depository. International Earth Rotation and Reference Systems Service (IERS) polar motion excitations are downloaded from https://hpiers.obspm.fr/eop-eo/acss/extractive.html. International Nusantar Stratification And Transport (INSTANT) data are available from http://www.marine.csiro.au/~cow074/index.htm.

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Author contributions
A.P., F.D., B.R., and S.S.C.S. conceived the idea. M.A. carried out the NEMO runs aided by B.R., R.B.B., and F.D. P.V.S. had carried out similar model experiments, supported by M.A. and B.R., using coarser MOM5.0 in her project dissertation with A.P. B.R. processed the bottom pressure recorder data. A.P., F.D., B.R., M.A., and R.B.B. analyzed the results. A.P., F.D., and O.d.V. wrote the manuscript and others corrected it. V.B. provided bottom pressure data located at 37.283°W, 32.2548°N. All authors contributed to the material of the paper through multiple discussions.

Competing interests
The authors declare no competing interests.

Additional information

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