Twofold expansion of Indo-Pacific warm pool warps MJO lifecycle

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Abstract

The Madden Julian Oscillation (MJO) is the most dominant mode of subseasonal variability in the tropics, characterized by an eastward moving disturbance of rain clouds. The MJO modulates the El Niño Southern Oscillation[1], tropical cyclones[2,3] and the monsoons[4-10]—and contributes to severe weather events over Asia, Australia, Africa, Europe and the Americas. MJO events travel a stretch of 12,000–20,000 kms over the tropical oceans, which has been warming during the twentieth and early-twenty first centuries in response to greenhouse gas forcing[11], and is projected to warm further. However, the impact of this warming on the MJO lifecycle is largely unknown. Here we show that rapid warming over the tropical oceans during 1981–2018 has warped the MJO lifecycle, with its residence time decreasing over the Indian Ocean by 3–4 days, and increasing over the Indo-Pacific Maritime Continent by 5–6 days. We find that these changes in the MJO lifecycle is associated with a twofold expansion of the Indo-Pacific warm pool, which has been expanding on an average by 2.3 $\times 10^5$ km^2 (the size of Washington State) per year during 1900–2018 and at an accelerated average rate of 4×10^5 km^2 (the size of California) per year during 1981–2018. The changes in the warm pool and the MJO are related to an increased rainfall over Southeast Asia, northern Australia, Southwest Africa and the Amazon, and drying over the west coast of United States and Ecuador.

Article

Each year, weather variability at subseasonal to seasonal timescales costs the global economy over $2 trillion, with $700 billion alone in the US (3.4% of US GDP in 2018)[12,13]. The Madden Julian Oscillation (MJO) contributes to more than 55% of this weather variability over the tropics[14]—and modulates the Asian[4,5], Australian[6] , African[7] and American monsoons[8-10], tropical cyclogenesis[2,3] and the El Niño Southern Oscillation (ENSO)[1]. The phase and strength of the MJO at a given location can enhance or suppress the tropical rainfall variability, modulating or triggering extreme weather events including hurricanes, droughts, flooding, heat waves and cold surges[15]. The MJO can also lead to dramatic impacts in mid-latitudes, and is a strong contributor to extreme events in the United States and Europe[16,17]. The intensity and propagation of the MJO is shown to influence the circulation pattern in the Arctic stratosphere and the polar vortex[18], emphasizing the far-reaching impact of MJO on the earth's climate system.

The MJO is an ocean-atmosphere coupled phenomenon, characterized by eastward moving disturbances of clouds, rainfall, winds, and pressure along the equator. It is the most dominant mode of the subseasonal variability in the tropics[19]. Using observations and model simulations, previous studies have attempted to understand the changes in the MJO in a warming climate[20]. They found a link between increasing carbon emission and changes in the intensity, frequency and propagation of the MJO over the last few decades of the twentieth century[20,21], though there is considerable uncertainty in the extent of the changes and the mechanisms involved. A statistical reconstruction of the MJO activity over 1905–2008 using tropical surface pressures shows a 13% increase per century in the MJO amplitude[22]. The reconstructed MJO activity agrees with the satellite-observed (since 1979) MJO variability on decadal timescales—but the trends disagree after 1997[23], which adds to the considerable uncertainty as to their magnitude. Studies also suggest an increasing trend in the MJO frequency after the mid-1970s[24,25], which has been linked to the long term warming in the tropical oceans[26]. Numerical model experiments under idealized global warming scenarios indicate that increasing the surface temperatures over the tropical oceans results in an organized MJO activity with a faster eastward propagation[21,27], though an understanding based on observations is pending.

Typically, the MJO events are initiated over the Indian Ocean and move eastward over the Maritime Continent to the Pacific (Extended Data Figure 1). Some of these events weaken or breakdown over the Maritime Continent or the central Pacific[28], but others propagate further to the east Pacific and occasionally continue into the Atlantic[29]. On average, MJO events travel a zonal distance of 12,000–20,000 kms (7,500–12,500 miles) over the generally warm tropical oceans. This entire stretch of the tropical ocean has been warming during the twentieth and early-twenty first centuries in response to greenhouse gas forcing[11], and is projected to warm further in the future. The rapid warming across the tropical basins is not uniform. In the equatorial belt, the largest warming during November–April when the MJO is active is observed over the Indo-Pacific warm pool (Figure 1). This warm pool is the largest region of permanently warm sea surface temperatures (SSTs > 28°C), covering an area greater than 2.7×10^7 km^2 (see the Methods section), over which there is vigorous deep convection. The tropical ocean warming has led to an expansion of this warm pool, particularly in the recent decades. Even though we have a preliminary understanding of the general changes in MJO amplitude and frequency in a warming climate, we do not know how the non-uniform ocean warming associated with the expanding warm pool may affect the MJO regionally.

In our study, we find a twofold expansion of the Indo-Pacific warm pool during 1981–2018, in comparison to 1900–1980, with the largest warming over the western Pacific. We show that this warm pool expansion has led to significant changes in the lifecycle of MJO events over the Indo-Pacific region. While the total period of the MJO does not show any detectable trends, its residence time (MJO phase duration) over the Indian Ocean has been reduced by 3–4 days while that over the Maritime Continent has increased by 5–6 days. Essentially, this means that MJO-related convective activity has grown shorter over the Indian Ocean while the convection over the Maritime Continent is being prolonged.

Results

Observed changes in MJO lifecycle

We select the MJO events which exhibit 1) strong coupling between tropical convection and largescale circulation, 2) prominent active eastward propagation and 3) an amplitude of the Real-time

Multivariate (RMM) MJO index[30] that is greater than one for November–April, 1981–2018 (see the Methods section). From its normal initiation in the Indian Ocean (RMM Phase 1), the MJO propagates into the Central Pacific and beyond (Phase 8) in about 30–60 days (Extended Data Figure 2). We compute the average number of days of the selected MJO in each RMM phase to describe the MJO phase duration over the tropical ocean basins. In the RMM index, interannual variations, including those associated with ENSO[30], have been removed. This makes it suitable for our investigation focusing on the changes in the MJO related to global warming.

Figure 2 shows the timeseries of the MJO phase duration and how it has changed over time. The average period of the MJO does not exhibit any detectable trends and broadly remains within the normal 30–60 days' timescale (Extended Data Figure 2). However, a closer inspection (Figure 2) shows significant changes in individual phases, which essentially are offset while averaging over the entire MJO domain. Over the Indian Ocean (RMM phases 1, 2 and 3), the MJO phase duration decreases by 3–4 days, from an average of 19 days (during 1981–1999) to 15.4 days (during 2000–2018) (Figure 2a, b). Over the Maritime Continent and the west Pacific (RMM phases 5, 6 and 7), the MJO phase duration increases by 5–6 days, from an average of 17.5 days to 23 days (Figure 2c, d). The observed trends are statistically significant at the 95% confidence level. The changes are consistent with those documented by previous studies which compared the MJO activity across different RMM phases, using observations and climate model experiments[31,32]. This means that during recent decades, convective cloud bands associated with the MJO linger over the Indian Ocean for a shorter period, while they persist longer over the Maritime Continent and the west Pacific.

The role of Indo-Pacific warming

SST variations mediate the exchange of heat across the air-sea interface. High SSTs over the tropics are usually accompanied by enhanced convective activity[33]. Being an ocean-atmosphere coupled convective phenomenon, MJO activity is hence highly dependent on tropical SSTs, with higher MJO activity typically occurring when SSTs are higher[26]. Previous studies have shown accelerated warming over the Indo-Pacific warm pool and its expansion[11,34], which can potentially impact the MJO characteristics. To examine the changes in the warm pool, we estimate the surface area covered by the climatological 28°C isotherm of SST, during November–April (Figure 1), in the tropical Indo-Pacific region within 40°E–140°W, 25°S-25°N. Here we show that tropical SST warming has led to an almost twofold expansion of the Indo-Pacific warm pool, from an area of 2.2×10^7 km^2 during 1900–1980, to an area of 4×10^7 km^2 during 1981–2018 (Figure 1a, b, d). The warm pool expansion is non-uniform, with the SST warming more pronounced over the west Pacific in contrast to the Indian Ocean (Figure 1c). The difference in the warm pool expansion trends between the 1900–1980 and 1981–2018 periods is statistically significant at the 95% confidence levels. The shift in warm pool SSTs during the 1977–1980 period co-occur with the shift in global mean SSTs at the same time (Figure 1d), followed by an accelerated surface warming as a response to anthropogenic emissions[35]. It is important to note that the shift in SSTs also coincides with the positive phase of the Pacific Decadal Oscillation (PDO). A comparison of the warm pool area using multiple SST datasets shows that the changes in warm pool area presented here are robust (Extended Data Figure 3a). A breakpoint analysis confirms that the shifts to higher warm pool values occurred during 1979–1980 (Extended Data Figure 3b, c).

The changes in the MJO phase duration (Phases 5, 6 and 7) appears to be significantly correlated (Figure 3, Extended Data Figure 4) to the changes in SST collocated over the west Pacific warm pool, where the warming trends and the background mean SSTs are the largest. The fact that the correlation is significant even after the trends are removed suggests that the mechanisms working on the interannual and longer time scales are similar. SST warming is also large in the Indian Ocean, though it is interesting that these SST trends do not show any significant correlation with the MJO phase duration (Phases 5, 6 and 7). This might mean that the observed changes in the MJO phase duration is driven by SST changes in the west Pacific. In fact, an investigation of the atmospheric circulation shows enhanced convective activity and a strengthening of low-level westerlies over the west Pacific (120°E–160°E) associated with the trends in the MJO phase duration (Figure 3b). The enhanced convective activity over the west Pacific is compensated by subsidence over the central and west Indian Ocean (40°E–70°E). Pohl and Matthews[25] hypothesize that on interannual timescales when the west Pacific is warmer than normal, the latent heat release over the moist convective region decreases the effective static stability of the atmosphere and slows down the MJO over the warm pool. The long-term changes in the MJO phase duration and associated ocean-atmospheric interactions discerned here are consistent with the physical mechanisms observed for the MJO phase duration on interannual timescales[25,36].

MJO variability and propagation are largely linked to the moist static energy in the atmospheric column[36-38]. We inspected the specific humidity and temperature profiles independently, for a detailed examination of the factors driving the observed trends in the MJO phase duration (Figure 3c). While the MJO trends (Phases 5, 6 and 7) exhibit a positive correlation with the tropospheric temperatures over the warm pool from 90°E–170°E, the specific humidity anomalies show a significantly negative correlation over the Indian Ocean and positive correlation over the west Pacific. This indicates that while the warm SST trends in the west Pacific prolongs the local convective activity, it also drives dry air subsidence over the Indian Ocean, shortening the residence time of MJO over that region. Hence, though the entire Indo-Pacific SSTs are warming, it appears that the MJO response is more sensitive to the west Pacific SSTs—possibly because the SST trends and background mean values are relatively larger over this region during November–April. Meanwhile, the low-level winds associated with the observed changes in phase duration are westerly over the Indian Ocean (Figure 3b), converging into the west Pacific. This indicates that the prolonged residence time of MJO over the Maritime Continent may be supported by moisture supply from both local (west Pacific) and remote (Indian Ocean) sources. Extended Data Figure 5 shows a significant increase in tropospheric moisture (900–400 hPa levels) over the Maritime Continent-west Pacific warm pool region and a reduction in the moisture over the Indian Ocean. This is consistent with the previous studies[39] which suggest that the moisture gradient in the lower troposphere over the Indo-Pacific warm pool assist the eastward propagation of MJO.

A comparison of the MJO phase duration over the Maritime Continent and west Pacific warm pool area (120°E–160°E, 25°S–25°N, highlighted region in Figure 3, Phases 5, 6 and 7) demonstrates a considerable correlation (r=0.42, τ=0.3) statistically significant at the 95% confidence level (Figure 3d). The MJO phase duration over the Indian Ocean (Phase 1, 2 and 3) also shows a significant negative correlation with the west Pacific (r=-0.33), suggesting that the MJO changes over the Indian Ocean is also largely driven by SST warming over the west Pacific. A correlation with the trends removed from both the time series still shows statistical significance at the 90% confidence level, and it can be argued that the results of this analysis strongly hold, even if the large values of the correlation coefficient are due to the existence of a real trend. Meanwhile, the mean surface temperatures over the west Pacific also exhibit an interannual variability and long-term change similar to that of the warm pool expansion (Figure 3d, r=0.97, τ=0.86). The results presented here establish a clear role of warm pool expansion and increasing SSTs in shortening the residence time of MJO over the Indian Ocean by 3–4 days and prolonging it over the Maritime Continent by 5–6 days. Such a large change in the MJO phase duration may have direct implications on the global weather and climate which is tightly linked to these MJO phases.

Impacts on global climate

To assess the potential impacts of the observed changes in the MJO phase duration on global climate, we performed a correlation analysis with the rainfall anomalies at each location across the globe, after removing the trends and ENSO-related variability. Figure 4a shows significantly large correlation between observed changes in the MJO phase duration and rainfall variability over the tropical and mid-latitude regions. The changes in the MJO phase duration over the Indo-Pacific are associated with enhanced rainfall over the Maritime Continent-west Pacific region, the Amazon basin in South America, southwest Africa and northern Australia (color shades in Figure 4a indicates correlation coefficients significant at the 95% confidence level). Meanwhile, the changes in MJO phase duration indicates a strong link with reduced rainfall over central and east Pacific, east Africa, Ganges basin in India, Yangtze basin in China and the east and west coasts of United States of America.

Interestingly, a trend analysis of rainfall for November–April shows consistent changes over some of these regions (Figure 4c). An increase in mean rainfall is observed over most of the Maritime Continent including southeast Asia (Indonesia, Philippines and Papua New Guinea), northern Australia, west Pacific, Amazon basin and southwest Africa. A decline in rainfall is observed over the central Pacific, Ecuador and along the west coast of United States (California). A slight decrease in rainfall is observed over the Yangtze basin in China and east coast of United States (Florida), consistent with changes in the MJO phase duration. The observed impacts are consistent with the MJO impacts on interannual timescales reported by previous studies[15], which means that similar processes are operating at interannual and lower frequency timescales (Extended Data Figure 6). We confirm this with a composite analysis of the MJO events with longer phase duration for phase 5, 6 and 7 (standard deviation greater than one) which show similar results as in the correlation analysis and the trends (Figure 4b).

The recent California droughts (2013–2014, during which the MJO was in phases 5, 6 and 7 for 25–28 days), southeast Asia floods (in 2011, during which the MJO was in phases 5, 6 and 7 for

30 days) and east Africa droughts (2011) occurred during those years when the MJO phase duration was longer over the Maritime Continent and the west Pacific (Figure 2c). Extreme flooding events in Brazil, such as the 2011 Rio de Janeiro floods, have been linked to a strong MJO interacting with the South Atlantic Convergence Zone[10]. It cannot be ruled out that the same mean state change (namely warm pool expansion) can affect both the MJO and the regional rainfall changes presented here. In addition, large scale changes in the circulation due to Indo-Pacific warming[40] and the phase of the PDO could also interact with the MJO to influence the regional rainfall changes observed here. Regardless of their inter-relationship, we can certainly say that the Indo-Pacific warm pool expansion is not only changing the MJO but also these regional precipitation anomalies, either synergistically through the MJO or through independent pathways. Though we have not investigated the dynamics behind these events individually, we cannot overemphasize the need to closely monitor the changes in the Indo-Pacific warm pool for triggering or intensifying severe weather events in the future. Maintaining and enhancing existing ocean observational arrays over the Indian and Pacific basins and extending it to the straits in the southeast Asian maritime region is hence a high priority[41,42]. Climate model projections suggest further warming of the warm pool region, which may intensify the observed changes in MJO lifecycle in the future. However, state-of-the-art climate models fail to accurately simulate the observed distribution of SST changes over the Indo-Pacific even in the present climate, and hence may need further improvement (for example, via the subseasonal to seasonal prediction project[42,43]) in order to meet the challenges presented by a warming world.

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Author contributions

M.K.R. conceived the study, performed the analysis and prepared the manuscript. P.D. performed the MJO detection and initial analysis. T.S. provided additional MJO tracking algorithm for verification. All coauthors contributed to the interpretation of the results and drafting of the manuscript for publication.

Author information

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Figure legends

Figure 1. A twofold expansion of the warm pool.

Indo-Pacific warm pool with its characteristic permanently warm SSTs of temperatures greater than 28°C for the period (**a**) 1900–1980 and (**b**) 1981–2018. The observed warm pool expansion is almost twofold, from an area of 2.2×10^7 km^2 during 1900–1980, to an area of 4×10^7 km^2 during 1981–2018. The warm pool area is estimated as the surface area covered by climatological 28°C isotherm of SST, during November–April, in the tropical Indo-Pacific region within 40°E–140°W, 25°S-25°N. (**c**) The observed trend in SST (°C per 38 years) during 1981-2018, for November–April. (**d**) Time series of the warm pool area during 1900–

2018. Theil–Sen trend estimates are overlaid on the time series for the entire period (solid blue line, Sen slope of 2.25×10^5 km^2 per year) and for 1981–2018 (dashed blue line, Sen slope of 4.14×10^5 km^2 per year). The positive trend in warm pool area is significant at the 95% confidence level, according to the Mann–Kendall test. The grey shade overlaid on the time series represents ± two standard deviations of the warm pool area, based on monthly SST values. Yellow line represents global mean SSTs (°C) averaged for November–April. Warm pool SST values and area are based on HadISST dataset.

Figure 2. Changes in MJO lifecycle.

Time series (black line) and distribution of average yearly phase duration (in days) of MJO events during 1981–2018 over (**a**, **b**) the Indian Ocean (RMM phases 1, 2 and 3) and (**c**, **d**) the Maritime-west Pacific region (RMM phases 5, 6 and 7). Grey shading in (a, c) is ± two standard deviations of the MJO phase duration over a ten-year moving window. Pink lines overlaid on the time series represent the 20-year running trend of MJO phase duration (in days per year). Mann–Kendall test for the time series indicate that the trends are significant at the 95% confidence level. The phase duration distribution compares the probability density function of MJO phase duration during the earlier period (1981–1999) and later period (2000–2018), where $\mu 1$ and $\mu 2$ represents the mean number of days. $\mu 2$-$\mu 1$ indicates the change in MJO phase duration, with a decrease of 3–4 days over the Indian Ocean and increase of 5–6 days over the Maritime-west Pacific region. A Mann–Whitney test on the difference in the phase duration distributions in ***b***, ***d*** shows that the difference is statistically robust ($P < 0.05$), implying that the null hypothesis can be rejected.

Figure 3. Correlation between MJO phase duration and ocean-atmosphere conditions.

Correlation between MJO phase duration (phases 5, 6 and 7) with (**a**) SST anomalies, (**b**) winds and vertical velocity and (**c**) air temperature (colors) and specific humidity (contours) at each grid point over the Indo-Pacific basin for November–April, during 1981–2018 (n=38). The correlation analysis is performed after removing the trend and the ENSO variability from the time series. Color shading denotes correlation coefficients, with the significance at the 95% confidence levels noted below the color scale on top of ***a***. Vector arrow lengths are proportional to correlation coefficient according to the scale on top of ***b***. Thick contours in ***c*** denotes correlation coefficients significant at the 95% confidence level. The region within the solid black lines highlight the west Pacific warm pool region (120°E–160°E) where the ocean-atmospheric changes related to the MJO phase duration are the largest, and consistent across the various parameters. The longitude-pressure plots are averaged over 10°S–10°N. (**d**) Time series of MJO phase duration (phases 5, 6 and 7) and the surface area (km^2) enclosed by the 28°C isotherm of SST over the west Pacific (120°E–160°E, 25°S–25°N), during November–April, 1981–2018. Kendall rank correlation test (two tailed) for the two variables provided a tau coefficient of 0.3. The Kendall (τ) and Pearson (r) correlation coefficients shown are significant at the 95% confidence level (significant at the 90% confidence level after removing the trends, n=38). Yellow line overlaid on the time series represent the yearly mean SST over the west Pacific. Kendall rank correlation test for the west Pacific warm pool area and SST provided a tau coefficient of 0.86, significant at 95% confidence level.

Figure 4. Changes in global rainfall in response to the changes in MJO phase duration.

(**a**) Correlation between the MJO (phases 5, 6 and) phase duration with rainfall anomalies for November–April, during 1981–2018. (**b**) Composite difference between years when MJO phase duration (phases 5, 6 and 7) is long and short (above and below 1 standard deviation). (**c**) Observed trend in rainfall (mm day^{-1} per 38 years) during the same period. The correlation and composite analyses are performed after removing the trend and the ENSO variability from the time series. Color shading denotes correlation coefficients and trends significant at the 95%

confidence level. The circled regions indicate large continental areas where the trends in rainfall are consistent with the correlation and composite analyses. Red circles indicate increasing rainfall and blue circles indicate decreasing rainfall associated with the observed changes in MJO phase duration. Rainfall values are based on GPCP dataset.

Methods

MJO data and identification of events

The Real-time Multivariate MJO (RMM) index of Wheeler and Hendon[30], provided by the Australian Bureau of Meteorology, is used as a preliminary reference for identifying MJO events during 1981–2018. The RMM index[30] relies on an Empirical Orthogonal Function (EOF) analysis which combines equatorially averaged (15°S–15°N) lower (850 hPa) and upper (200 hPa) tropospheric zonal winds with outgoing longwave radiation (OLR, proxy indicator for convective activity). While the RMM index efficiently captures the dominant role of zonal winds during mature phases of strong MJO events, it can be inconsistent in representing the convective conditions associated with it[44-46]. As a result of this absence of interplay between circulation and convection, capturing the MJO events with its convective implications has been a conundrum—as the index occasionally captures non-existent events, while some events appear to occur early or late, or are even missing[28,44-47].

Hence, we identified MJO events by following a set of steps which consider the RMM index but clearly captures the MJO characteristics of eastward propagation and convective activity. We focus on the boreal autumn–winter–spring seasons (November–April) during which the MJO exhibits a prominent eastward propagation, and is sensitive to SST variations in the Indian and Pacific Ocean[48]. In order to factor in the convective activity, we used the daily OLR from the National Oceanic and Atmospheric Administration (NOAA) at 2.5° × 2.5° horizontal resolution, which has been conventionally used for detecting the MJO related convective activity. We also verified the detected events using the high resolution (1° × 1°) daily OLR Climate Data Record[49] (HIRS OLR), which is better suited for identifying the tropical variability at subseasonal timescales[50]. The MJO phase duration is strongly linked to the strength of MJO convection and its coupling with the largescale circulation[51]. Hence the current method makes sure to capture the MJO events which exhibit strong coupling between tropical convection and largescale circulation.

The OLR on subseasonal timescales also represents other types of equatorial propagating modes of convection, such as the westward moving equatorial Rossby waves, eastward moving Kelvin waves and mixed Rossby-gravity waves. The MJO component is hence filtered from the OLR data by including eastward zonal wavenumbers 1–5 and a period of 30–96 days, while the Kelvin wave component is separated by identifying eastward wavenumbers 1–14 and a period of 2–30 days, and equatorial Rossby waves by their westward zonal wavenumbers 1–10 and periods of 10–50 days[52,53]. We select eastward propagating convective MJO events in the filtered OLR anomalies, which are initiated in the Indian Ocean (Phases 1, 2 or 3)[28], proceed to the Pacific (Phases 6, 7 or 8) and propagate through at least six of the RMM phases with an average RMM amplitude greater than one (~1.5 standard deviation). We consider the initiation date as when the RMM index indicates MJO entry into the Indian Ocean from the west and starts to propagate eastward. We find 88 such MJO events over the 38 years, during November–April. The selected events are comparable to the MJO events detected by the tracking method used by Suematsu et al.[36], which is based solely on the RMM index at a threshold amplitude of 0.8, but with a relatively wide window for the band-pass filter (20–120 days).

Warm pool SST and climate data analysis

HadISST1 SST data for the period 1900–2018, obtained from the Met Office Hadley Centre is used to estimate the changes in the Indo-Pacific warm pool and its role on the MJO phase duration. The warm pool area is estimated as the surface area covered by the climatological 28°C isotherm of SST, during November–April (Figure 1), in the tropical Indo-Pacific region within 40°E–140°W, 25°S-25°N. To examine the state and response of atmospheric circulation to the changing SSTs and MJO, we used air temperature, winds and specific humidity values for the tropospheric column from NCEP reanalysis for the period 1981–2018 at a 2.5° × 2.5° grid resolution. The global changes in rainfall are estimated using the NOAA GPCP Precipitation dataset which combines observations and satellite precipitation data on a 2.5° × 2.5° global grid. Note that for computational purposes, the data for November–April is considered together as belonging to the initial year (e.g., MJO activity during November 1981–April 1982 is considered together as representing the year 1981).

A breakpoint analysis[54] is conducted to identify significant shifts in the mean of the Indo-Pacific warm pool time series (Extended Data Figure 3b). The analysis employs a Bai–Perron test[55] to determine the optimal number of breaks using Bayesian information criterion[56] and the residual sum of squares, given the minimum segment size of the time series (30-year segments used here). The location of these breakpoints can be attributed to the timing of non-linear changes in the observed warm pool area over time. The analysis was performed using the 'strucchange' package in the R Statistical Software[54].

The lifecycle of the MJO and the tropical ocean-atmosphere conditions are also dependent on the state of ENSO. We use a frequency bandpass filter (2–6 years) to remove the interannual frequency band associated with ENSO-related variations, though removing all of the ENSO related variability is difficult since it can influence variability at both higher and lower frequency. The correlation analysis and trends in Figure 3 and Figure 5 are estimated using these filtered anomalies. The least-square linear regression and Theil–Sen slope methods are used to estimate the observed trends. The Theil–Sen approach is considered more robust than the least-squares method due to its relative insensitivity to extreme values and better performance even for normally distributed data[57].

The statistical significance of the trends, correlations, and the difference of slopes[58] (Extended Data Figure 3c) is examined using standard two-tailed Student's t-tests. The significance of the trends in the time series plots are further assessed with a Mann–Kendall test with block bootstrap to validate the significance when a time series shows auto-correlation[59]. Statistical significance exceeding the 95% confidence level is selected a priori as the level at which the null hypothesis can be rejected. The correlation analysis is also tested using Kendall rank correlation that is non-parametric and therefore makes no assumptions about the distribution and at the same time determine the direction and significance of the relation between the two variables[59]. The correlated variables are said to be concordant if their ranks vary together (+1) and discordant if they vary differently (-1). In order to compare the differences in the distribution of the MJO phase durations in Figure 2, we have used the Mann-Whitney test[60] to test the null hypothesis that there is no difference between two means (Supplementary Figure 7). The Mann-Whitney test is a non-parametric test useful for relatively short time series—and also takes into account the fact that MJO variability is not normally distributed about the mean state.

Data availability

The MJO RMM index used in the study for the period 1981–2018 is available from the Australian Bureau of Meteorology (http://www.bom.gov.au/climate/mjo/). The monthly values of air temperature, specific humidity and winds, and the daily OLR and GPCP monthly precipitation can be obtained from the NOAA website (https://www.esrl.noaa.gov/psd/data/gridded/). HadISST data is available for download at the Met Office Hadley Centre website (https://www.metoffice.gov.uk/hadobs/hadisst/). The high resolution daily OLR data can be acquired from the University of Maryland OLR CDR portal (http://olr.umd.edu/).

Code availability

The MJO events identified in this study, and the code for estimating the individual MJO phase duration and the Indo-Pacific warm pool area, are available at https://github.com/RoxyKoll/warmpool-mjo. The code for filtering the MJO component from the OLR data is available from Carl Schreck at GitLab (https://k3.cicsnc.org/carl/carl-ncl-tools/blob/master/filter/filter_waves.ncl).

Extended data legends

Extended Data Figure 1. Typical lifecycle of MJO.

Composite anomalies of 30–100-day OLR (W m^{-2}) during November–April, for the period 1981–2018, showing the RMM Phases 1–8. Typically, the MJO events are initiated over the Indian Ocean and move eastward over the Maritime Continent to the Pacific (a–h). The region within the solid black lines highlight the west Pacific warm pool region (120°E–160°E) where ocean-atmospheric changes related to the MJO lifespan are the largest. OLR values are based on the NOAA interpolated OLR dataset.

Extended Data Figure 2. Annual average period of MJO events.

Time series of yearly average period of MJO events during November–April, 1981–2016 (Phases 1–8). The grey shade overlaid on the time series represents ±two standard deviations of the MJO phase duration over a ten-year moving window.

Extended Data Figure 3. Warm pool area in multiple datasets and breakpoint analysis.

(**a**) Time series of the warm pool area during November–April, 1900–2018, based on HadISST, ERSST_v3b and COBE_SST2 datasets. Theil–Sen trend estimates computed based on HadISST (as in Figure 1 of the main text) are overlaid on the time series for the entire period (solid blue line) and for 1981–2018 (dashed blue line). (**b**) Breakpoint analysis identifying the significant shifts in the mean of the Indo-Pacific warm pool time series, using

HadISST. The breakpoint analysis shows two shifts in the time series, the first during 1945/46 and the second during 1979/80. Though the rate of change in warm pool area during 1900–1945 and 1946–1979 are different, the average warm pool area remains almost the same during both the periods. The breakpoint analysis confirms that the shifts to higher warm pool values occurred in the annual series during 1979–1980. (**c**) Table showing the trend in warm pool area using a range of breakpoints, from 1976/77 to 1982/83. The rate of warming does not change substantially with different breakpoints. At the same time, the difference between the trends are significant for all breakpoints considered. The significance of the difference between the slopes is estimated based on a t-test[58].

Extended Data Figure 4. Correlation between MJO phase duration and ocean-atmosphere conditions, without removing the trends.

Correlation between yearly average of MJO phase distribution (phases 5, 6 and 7) with (**a**) SST anomalies, (**b**) winds and vertical velocity and (**c**) air temperature (colors) and specific humidity (contours) over the Indo-Pacific basin for November–April, during 1981–2018 (n=38). The correlation analyses are performed after removing the ENSO variability from the time series, but without removing the trends.

Extended Data Figure 5. Trend in specific humidity anomalies.

Trend in specific humidity anomalies (g kg^{-1} 38 $years^{-1}$) for November–April, during 1981–2018. The trends indicate an increase (red colors) in tropospheric moisture over the warm pool region and a reduction (blue colors) in tropospheric moisture over the Indian Ocean (900-400 hPa levels).

Extended Data Figure 6. Relationship between MJO phase duration and global rainfall, without removing the trends.

Correlation between the MJO phase duration (phases 5, 6 and 7) with rainfall anomalies for

November–April, during 1981–2018. The correlation analysis is performed after removing the ENSO variability from the time series, but without removing the trends. Rainfall values are based on GPCP dataset.

Extended Data Figure 7. Mann–Whitney test, for testing the significance of the differences in MJO phase duration.

The difference in the mean of MJO phase duration distributions are tested for different starting points. The P values are computed for different groups (1981–1999, 1982–1999 to 1990–1999) as the first sample and 2000–2018 as the second sample. (**a**) According to Mann–Whitney test, the difference in MJO phase duration (1,2,3) is statistically robust ($P < 0.05$, where we can reject the null hypothesis) for most part of the varying first sample (1981-1999 to 1990-1999, except 1987-1999 where $P = 0.07$). (**b**) For the MJO phase duration (5,6,7) the difference in mean is always statistically robust (where we can reject the null hypothesis) for the varying first sample (1981-1999 to 1990-1999, where P always < 0.05).