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Title: MJO Structure Associated with the Higher-Order CEOF Modes
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Abstract:
The real-time multivariate Madden-Julian oscillation (RMM; MJO) index has been widely employed to monitor the amplitude, phase, and time evolution of MJO events, as the index is formulated from the leading two combined-EOF (CEOF) modes of daily anomalous OLR and 850-hPa and 200-hPa zonal winds, and the modes describe the MJO dynamics well.

These two CEOF modes, however, are known to dominate in power spectra at zonal wavenumber one and may underestimate the power and structure at wavenumbers 2-5 where many MJO events are also prominent. This study approximated a baseline for MJO by applying band-pass filters to daily anomalies on 30-100
day periods and at 1-5 eastward propagating waves, as slightly different bands led to the same conclusions. Following the procedures to develop the RMM index, the daily anomalous data were derived and subjected to the CEOF analysis with all modes archived for diagnosis. Different numbers of the leading modes were compared in explained variance, standard deviation, and wavenumber power spectra to describe the overall MJO magnitude and structure, and on the Hovmöller diagrams to represent the evolution of three distinct MJO events.

Results show that the two leading CEOF modes explain only a small portion of the power spectra at wavenumbers 2-5.
This spectral leakage notably reduces the MJO amplitude, particularly of the OLR in the western Pacific. The CEOF modes 3-10 can
withhold power sufficiently such that the anomalies reconstructed by the first 10 modes contribute most of the baseline variance; their structures agree well with the baseline by constituting nearly the same proportion in the region from the central Indian Ocean to the dateline
and by providing more complete evolutions of the three MJO events on the Hovmöller diagrams. Meanwhile, these modes introduce a notable amount of power for the equatorial Rossby and Kelvin waves that are partially embedded in the evolution of MJO. The first 50 of the total 432 CEOF modes retain all variance of the baseline MJO, while those higher than 10 contain less information and more noise and can be discarded. Furthermore, this study indicated that the longitudinal standard deviation (STD) of the reconstructed anomalies detects the MJO phases and magnitudes in the western Pacific with more physical meaning and in better agreement with the Hovmöller diagrams than the RMM-like amplitude. The results provide an integral figure of the MJO structure from the CEOF analysis and a more robust RMM framework for monitoring the MJO's evolution in real time and for validating its numerical forecast and simulations.

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