UCRL-JC-149401

Propagation and the Vertical Structure of the Madden-Julian Oscillation

Kenneth R. Sperber[1] and Julia M. Slingo[2]

[1]Program for Climate Model Diagnosis and Intercomparison, Lawrence Livermore National Laboratory, P.O. Box 808, L-103, Livermore, CA 94550 USA (sperber1@llnl.gov)
[2]Centre for Global Atmospheric Modelling, Dept. of Meteorology, University of Reading, P. O. Box 243, Reading RG6 6BB, England

1. Introduction

The Madden-Julian Oscillation (MJO) is a dominant mode of tropical variability (Madden and Julian 1971, 1972). It is manifested on timescales of ~30-70 days through large-scale circulation anomalies which occur in conjunction with eastward propagating convective anomalies over the eastern hemisphere. The baroclinic nature of the MJO has been elucidated (e.g, Madden and Julian 1971, Knutson and Weickmann 1987). However, studies have typically been limited to examination of one upper-tropospheric and one lower-tropospheric level, and the interrelationships as a function of altitude have not been explored in detail. Furthermore, little attention has been devoted to the conditions occurring during the onset of MJO convection in the western Indian Ocean. The purpose of this paper is to examine in detail the vertical structure of the MJO during the boreal winter and to provide a comprehensive picture of the MJO within the dynamically consistent framework of the NCEP/NCAR Reanalysis. This study differs from previous work by focussing only on those winters where the MJO was notably active as a well-defined eastward propagating mode. This work will provide a more comprehensive suite of diagnostics for understanding the limited ability of general circulation models to simulate the MJO (e.g., Slingo et al. 1996, Sperber et al. 1997). A more through analysis is given by Sperber and Slingo (2003).

2. The Data

Daily NCEP/NCAR reanalysis (Kalnay et al. 1996), AVHRR OLR (Liebmann and Smith 1996) and pentad CMAP (Xie and Arkin 1997) are analyzed. In this study, all data have been bandpass filtered with a 20-100 day Lanczos filter, and the analysis is for the months November-March.

3. Propagation of the MJO

Using the 10^{o}N-10^{o}S 200hPa zonal mean zonal wind MJO index described in Slingo et al. (1996, 1999; not shown) we have identified seven years of strong MJO variability (1984/85, 1985/86, 1987/88, 1989/90, 1991/92, 1994/95, and 1996/97). For these years an EOF analysis of bandpass filtered AVHRR OLR has been performed to isolate the convective signature of the MJO (Figs. 1a-b). The EOF’s are in quadrature and indicate convective anomalies of ~10-25Wm^{-2}. On average PC-2 leads PC-1 with a maximum positive correlation of 0.83 at 12 days, indicating coherent eastward propagation.

Figures 1c-d are linear regressions of PC-1 with bandpass filtered AVHRR OLR and 200hPa wind, and CMAP rainfall and 850hPa wind at zero time lag. Data are plotted where the regression is significant at the 5% level or better, assuming each pentad is in-

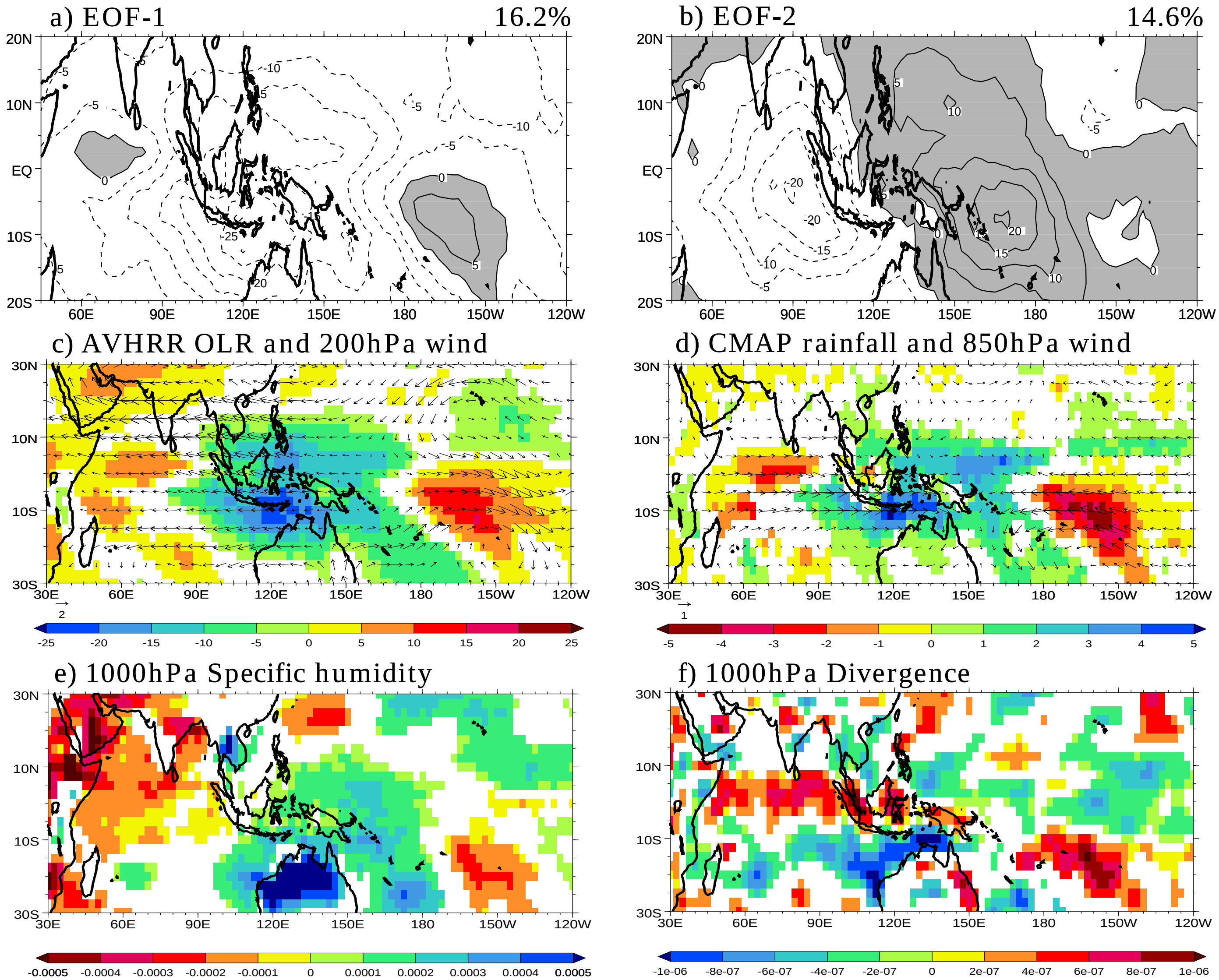

Figure 1. (a-b) EOF's 1 and 2 of 20-100 day bandpass filtered AVHRR OLR for November-March of strong MJO years. The EOF's have been scaled by a one standard deviation perturbation of the respective PC's to give units of Wm-2. Negative values correspond to enhanced convection. Lag 0 linear regressions of PC-1 against 20-100 day filtered (c) AVHRR OLR (Wm-2) and 200hPa wind (ms^{-1}), (d) CMAP rainfall (mm day^{-1}) and 850hPa wind (ms^{-1}), (e) 1000hPa specific humidity (kg kg^{-1}), and (f) 1000hPa divergence (s^{-1}). The regression is for a one standard deviation perturbation of PC-1.

dependent. The close correspondence between the OLR and rainfall is apparent, as is the baroclinic structure of the winds.

Of importance to the mechanism of eastward propagation of the MJO are the regressions against 1000hPa specific humidity and divergence (Figs. 1e-f). Consistent with the low-level moisture convergence paradigm (e.g., Hendon and Salby 1994, Jones and Weare 1996) near the equator the largest moisture increase occurs to the east of the convective center, with low-level convergence (negative divergence) leading. Enhanced latent heat flux occurs at and to the west of the convection where the low-level westerly anomalies dominate (not shown), as in Woolnough et al (2000). The vertical structure, given in Fig. 2, clearly shows enhanced convergence, moisture, and upward motion to the east of the area of precipitation. This preconditioning of the lower troposphere to the east of the convection is favorable for the development of convection. That moistening in the lower-troposphere leads that in the upper-troposphere is consistent with the analysis of TOVS specific humidity by Myers and Waliser (2003). To the west of the center of convection, subsidence,

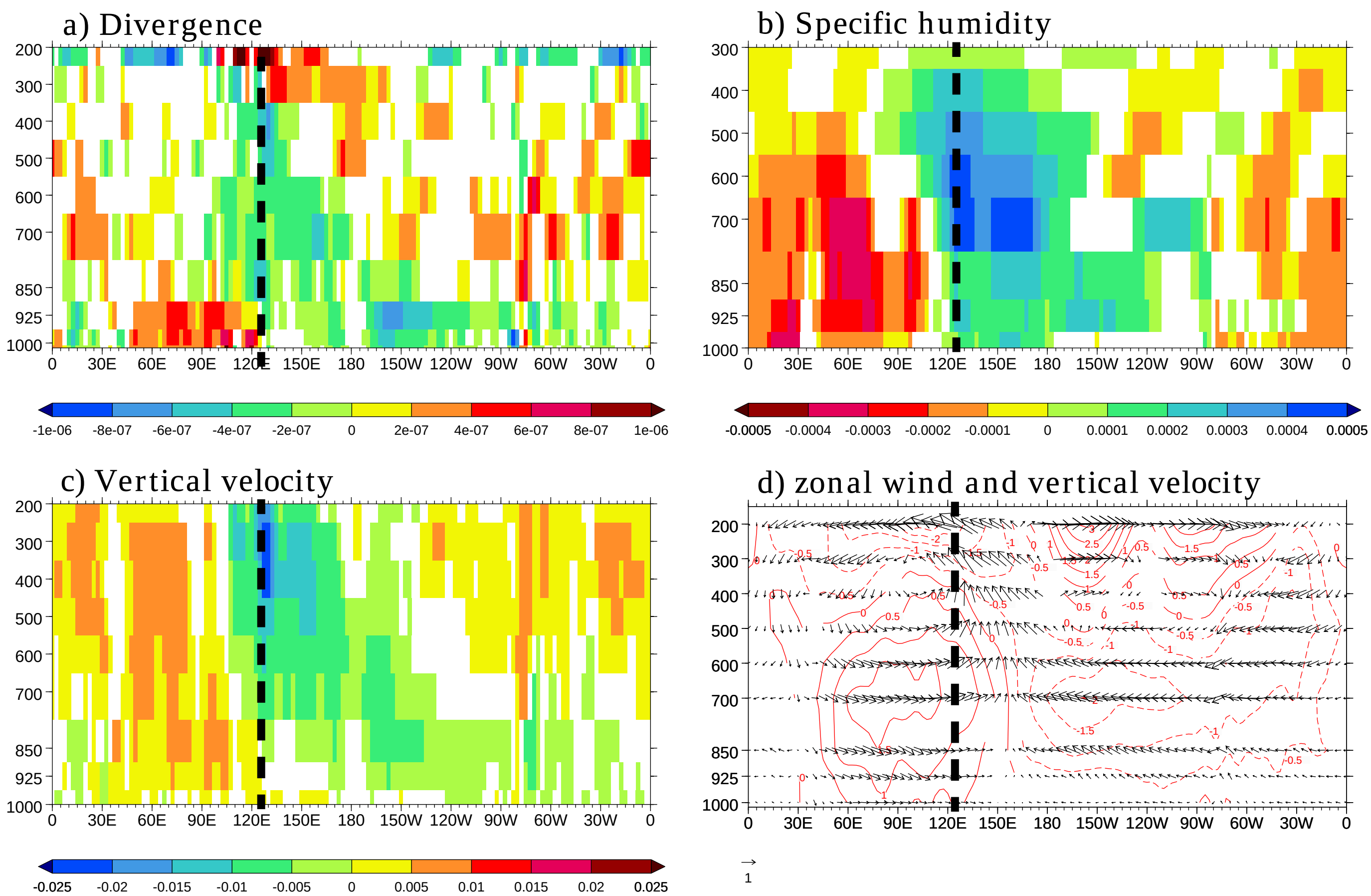

Figure 2. Lag 0 regressions of PC-1 against 5^oN-5^oS filtered a) divergence (s^{-1}), b) specific humidity (kg kg^{-1}), (c) vertical velocity (Pa s^{-1}), (d) zonal wind (m s^{-1}) and vertical velocity (-100x Pa s^{-1}). Isolines of the zonal wind are plotted for 0.5 ms^{-1} increments. The vertical dashed line corresponds the location of the center of the anomalous convection (Fig. 1c-d). The regression is for a one standard deviation perturbation of PC-1.

drying, and low-level divergence dominate; conditions that favor the demise of convection. As seen in Fig. 2d, near 700-600hPa there is a broad region of convergence, enhanced moisture, and strong zonal wind anomalies, particularly east of the center of convection, that indicates an important role of the free-troposphere in the development of MJO convection. This is confirms the modelling study of Woolnough et al. (2001).

4. The Onset of Convection in the Western Indian Ocean

Lag correlations indicate that next active phase of MJO convection begins in the western Indian Ocean on day +10 (Fig. 3a). At this time the convection from the previous active phase of the MJO is present in the western/central Pacific and SPCZ. Figure 3b indicates that the bulk of the troposphere from the Pacific to the Atlantic is moister than normal. This is associated with a dry Kelvin wave pulse, readily seen in the sea-level pressure, that impinges on the Andes mountains before propagating across the Atlantic and impacting the East African highlands (not shown; Matthews 2000). Over the central/eastern Indian Ocean the suppressed phase of the MJO dominates, being manifested as below-normal rainfall and higher than normal sea-level pressure (not shown). Low pressure occurs to the west, associated with the Kelvin wave pulse, and is consistent with near surface easterly anomalies over the western/central Indian Ocean. Such a pulse is also seen in the 1000hPa divergence suggesting a potential role for circumnavigating signals in the re-establishment of MJO convection (not shown). The onset rainfall, located near 55^oE, 2.5^oN, is in-

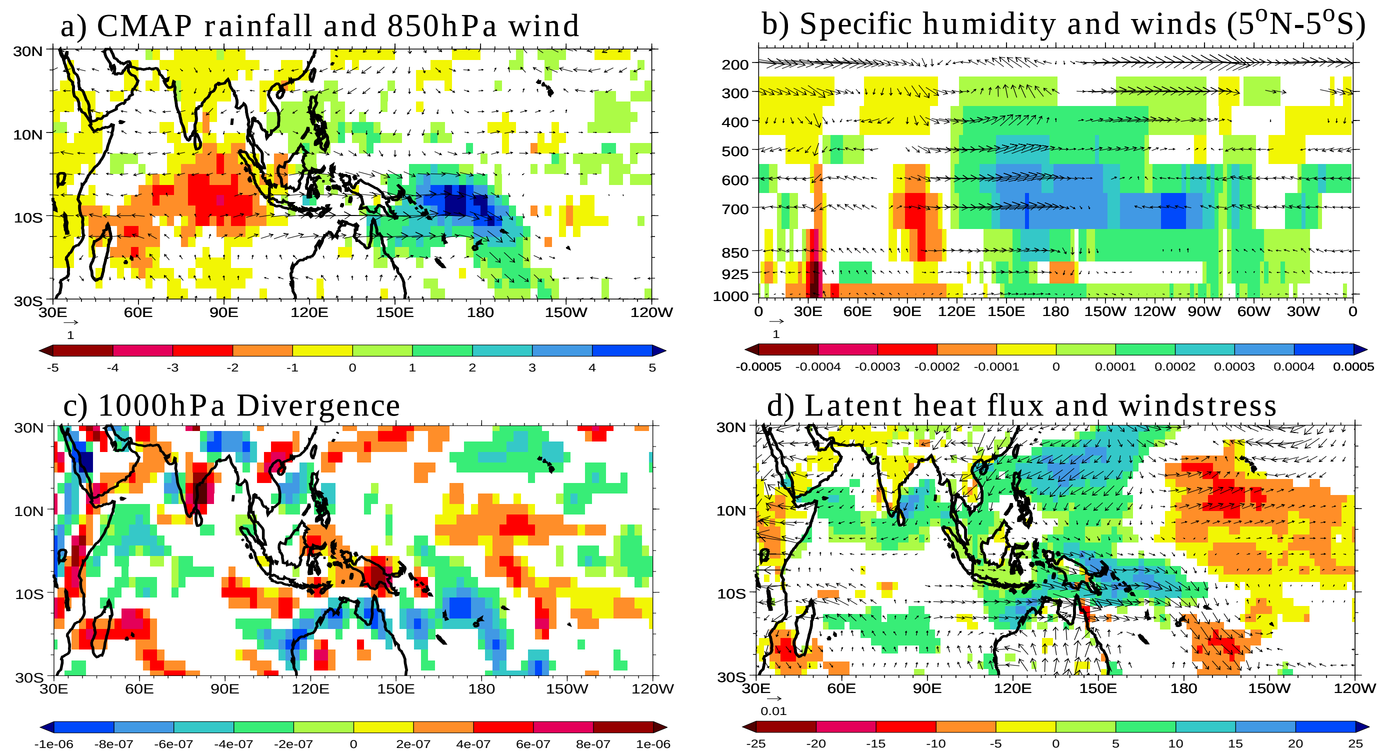

Figure 3. Day +10 linear regressions of PC-1 against (a) CMAP rainfall (mm day^{-1}) and 850hPa wind (ms^{-1}), (b) specific humidity (kg kg^{-1}), and zonal wind (m s^{-1}) and vertical velocity (-100x Pa s-^{1}), (c) 1000hPa divergence (s^{-1}), and (d) latent heat flux and surface windstress. The regression is for a one standard deviation perturbation of PC-1.

phase with the anomalous 1000hPa convergence (Fig. 3c), and the latent heat flux is greatest at and to the east of the enhanced convection (Fig. 3d) in the presence of surface easterly anomalies (Fig. 3b). Thus, the onset conditions are distinctly different from the low-level moisture convergence paradigm which only becomes manifest once the convection has matured over the Indian Ocean.

5. Caveats

A caveat of this work is that many of the variables analyzed have been termed Class B or C by Kalnay et al. (1996), in which the user is warned to be especially cautious. Validation of the surface fluxes indicates that the net shortwave is the most problematic, though overall the phasing of the surface fluxes is well captured relative to buoy data and other independent estimates. The amplitude of intraseasonal net surface heat flux and surface windstress is well captured (Shinoda et al. 1999). Even so, the regressions herein, over a large number of events, underestimates the anomalies present during individual events, though where comparison is possible, the lead/lag relationships compared to previous work remain intact (e.g., Woolnough et al. 2000). This suggests that the analysis presented here is at least schematically correct.

Acknowledgments. This work was performed under the auspices of the U.S. Department of Energy at the University of California Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48. K. R. Sperber gratefully acknowledges the support of the Centre for Global Atmospheric Modelling and Dept. of Meteorology at the University of Reading, England, at which a portion of this work was completed.

References

Hendon, H. H., and M. L. Salby, 1994: J. Atmos. Sci., 51, 2225-2237.
Jones, C., and B. C. Weare, 1996: J. Clim., 9, 3086-3140.
Kalnay, E, M. Kanamitsu, R. Kistler, W. Collins, D. Deaven, L. Gandin, M. Iredell, S. Saha, G. White, J. Woollen, Y. Zhu, M. Chelliah, W. Ebisuzaki, W. Higgins, J. Janowiak, K.-C. Mo, C. Ropelewski, J. Wang, A. Leetmaa, R. Reynolds, R. Jenne, and D. Joseph, 1996: BAMS, 77, 437-471.
Knutson, T. R., and K. M. Weickmann, 1985: Mon. Wea. Rev., 115, 1407-1436.
Liebmann, B., and C. A. Smith, 1996: Bull. Amer. Meteorol. Soc., 77, 1275-1277.
Madden, R. A. and P. R. Julian, 1971: JAS, 28, 702-708.
Madden, R. A. and P. R. Julian, 1972: JAS, 29, 1109-1123.
Matthews, A. J., 2000: Quart. J. Roy. Meteorol. Soc., 126, 2637-2651.
Myers, D. S., and D. E. Waliser, 2003: J. Clim. (in press)
Shinoda, T., H. H. Hendon, and J. Glick, 1999: Mon. Wea. Rev. 127, 678-693.
Slingo, J. M., K. R. Sperber, J. S. Boyle, J.-P. Ceron, M. Dix, B. Dugas, W. Ebisuzaki, J. Fyfe, D. Gregory, J.-F. Gueremy, J. Hack, A. Harzallah, P. Inness, A. Kitoh, W. K.-M. Lau, B. McAvaney, R. Madden, A. Matthews, T. N. Palmer, C.-K. Park, D. Randall, and N. Renno, 1996: Clim. Dyn., 12, 325-357.
Slingo, J. M., D. P. Rowell, K. R. Sperber, and F. Nortley, 1999: QJRMS, 125, 583-609.
Sperber, K. R., and J. M. Slingo, 2003: Mon. Wea. Rev. (submitted)
Sperber, K. R., J. M. Slingo, P. M. Inness, and W. K.-M. Lau, 1997: Clim. Dynam., 13: 769-795.
Woolnough, S. J., J. M. Slingo, and B. J. Hoskins, 2000: J. Clim., 13, 2086-2104.
Woolnough, S. J., J. M. Slingo, and B. J. Hoskins, 2001: Quart. J. Roy. Meteorol. Soc., 127, 887-907.
Xie, P., and P. Arkin, 1997: Bull. Amer. Meteorol. Soc., 78, 2539-2558.