The Madden-Julian Oscillation

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Second Split Workshop in Atmospheric Physics and Oceanography (SWAP) 2010

Outline

- **Observed features**

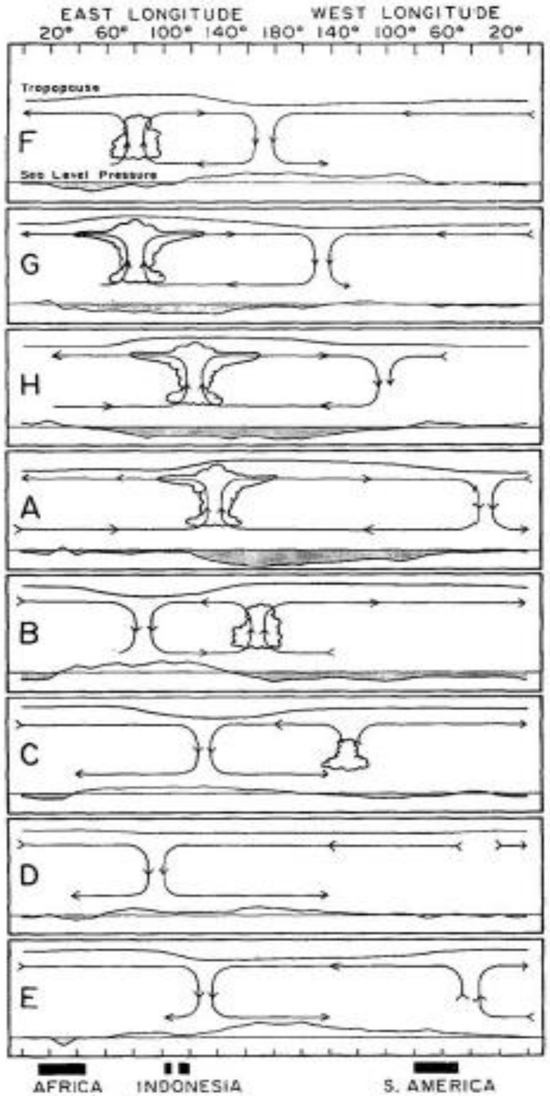
  Intraseasonal period, planetary zonal scale, eastward propagation, convection-wind coupling, large-scale vertical structure, multiscale structure, geographical preference, seasonal cycle, interannual variability

- **Mechanisms**
  - Atmospheric response to independent forcing
  - Atmospheric intstability, other factors

- **Uni- and multivariate index for the MJO:**
  - Matthews 2008
  - Wheeler and Hendon 2004

- **Summary**

Observed features – An introduction



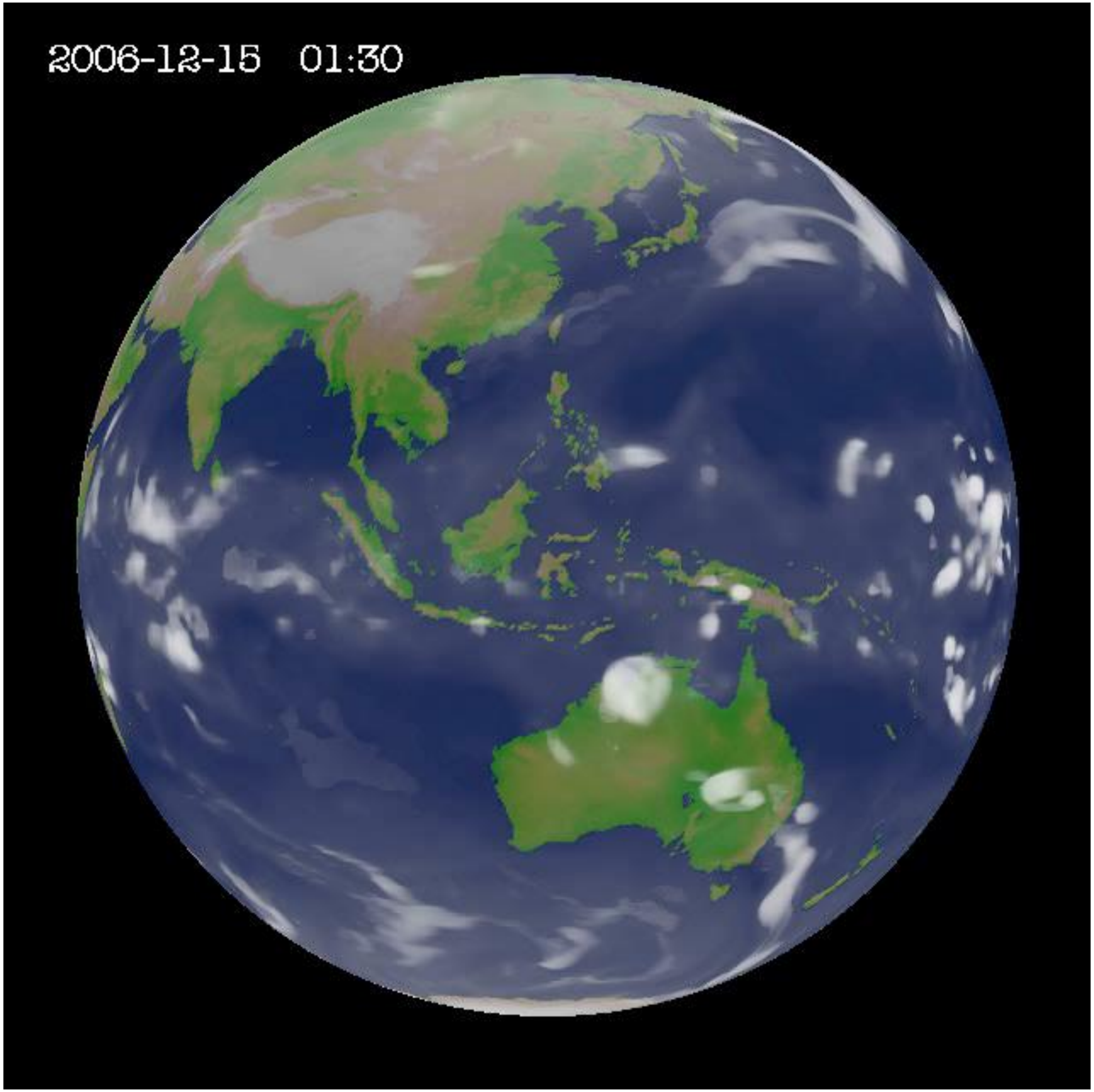
Longitude-height schematic diagram along the equator. From Madden and Julian 1972.

- Madden-Julian Oscillation: dominant component of the intraseasonal (30-90 days) variability in the tropical atmosphere. It consists of a large-scale coupled pattern in atmospheric circulation and deep convection, with coherent signals in many other variables, all propagating eastwards slowly (5 m/s). [Zhang 2005]

- first documented by Madden and Julian (1971/72)

- influences variability of rainfall over parts of the tropics and extratropics [e.g. Lawrence and Webster 2002, Bond and Vecchi 2003], and modulates the genesis of tropical cyclones in the Pacific Ocean. [e.g. Higgins and Shi 2001] => MJO affects global medium and extended range weather forecasts. [e.g. Jones and Schemm 2000]

- Interaction with the ocean => influence on the evolution of El Nino-Southern Oscillation (ENSO). [Zhang 2005]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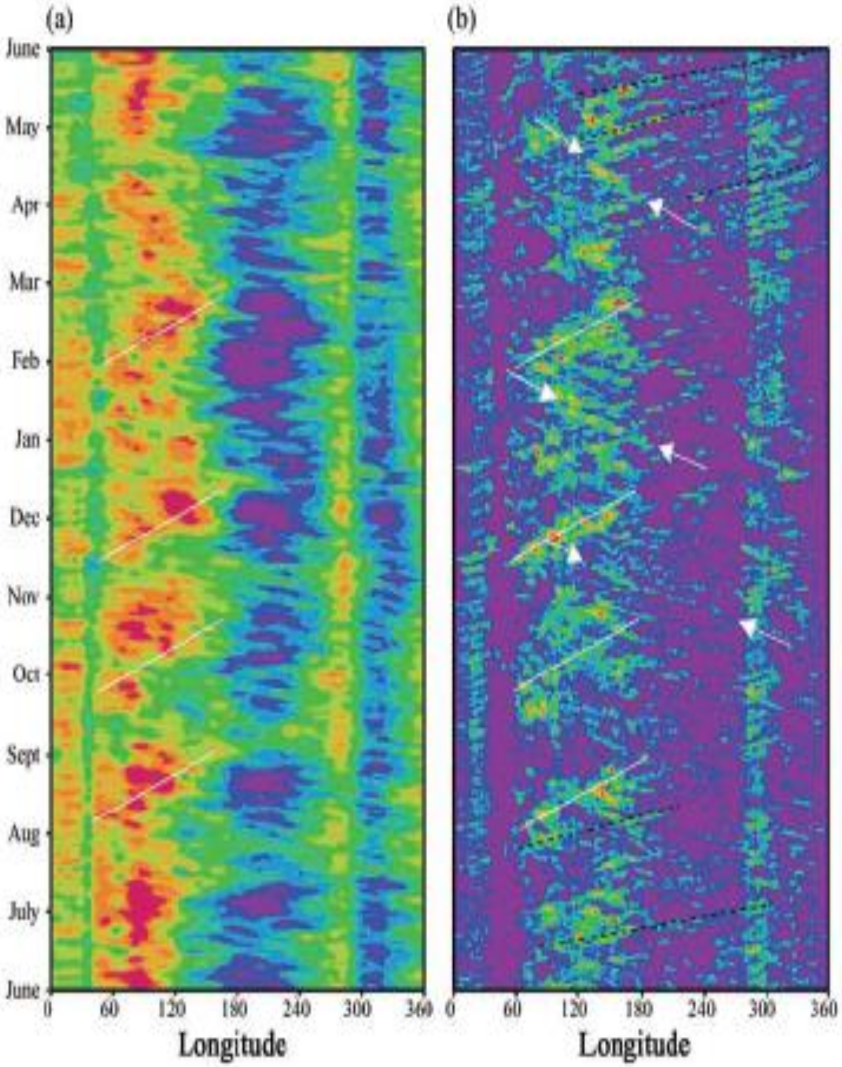
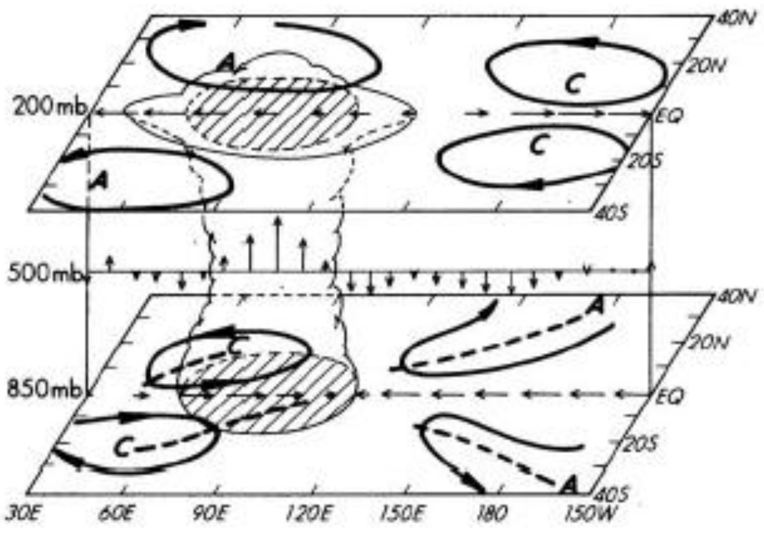
Observed features: Planetary zonal scale and eastward propagation



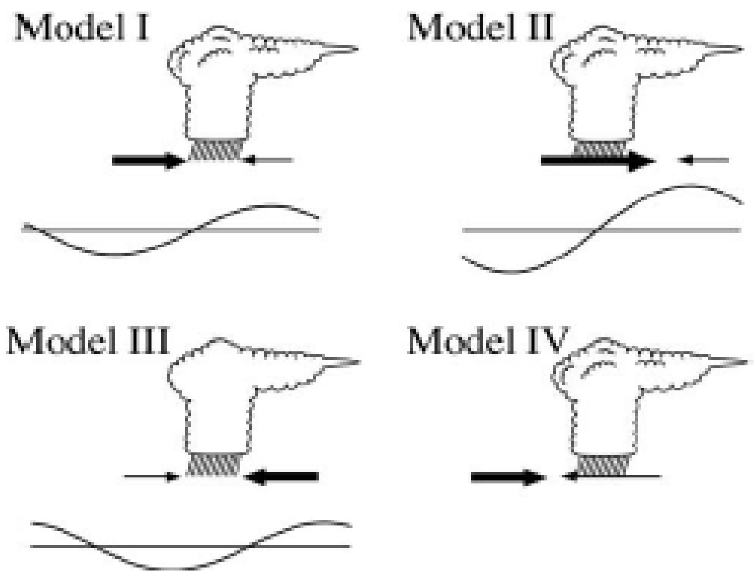
Longitude-time plots of daily zonal wind at 850 hPa (a) and precipitation (b) for June 2000-June 2001. From Zhang 2005.

- Planetary scale: 12.000-20.000 km
  - less for convection component than that of the circulation (atmospheric response to localized heating). [Salby et al. 1994]
- average eastward propagation speed: 5 m/s. (convectively coupled Kelvin waves: 15-17 m/s) [e.g. Knutson et al. 1986, Wheeler and Kiladis 1999]
- convective signals: vanishes (normally!) in eastern Pacific [e.g. Matthews 2000]
- signal in wind and surface pressure propagte farther east as free (uncoupled with convection) waves at 30-35m/s. [e.g. Matthews 2000]

Observed features: Convection-Wind Coupling



Schematic depiction of the large-scale wind structure of the MJO. From Zhang 2005.



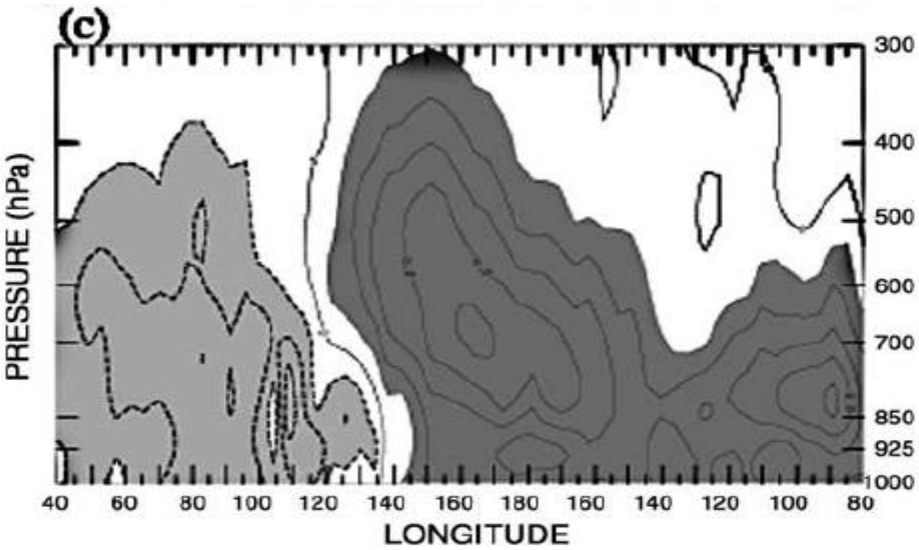
Schematic diagrams of four MJO models describing the phase relationship between ist convective center and surface zonal wind speeds. From Zhang 2005.

- Both equatorial Kelvin and Rossby waves are dynamically essential to the MJO. [Zhang 2005]

- relative phase between the large-scale surface zonal wind and convective center varies during the life cycle of the MJO (Model 1 and 2). [e.g. Hendon and Salby 1994]

- Model 3 and 4 predicted by theory and some numerical models never observed.

Observed features: Large-scale vertical structure



Longitude-height composite of the MJO along the equator. Specific humidity (10^{-1} g kg^{-1}). From Zhang 2005.

- Water vapor, temperature, divergence and diabatic heating show large-scale patterns coherent with wind and deep convection of the MJO. [e.g. Lin et al. 2004]

- Westward tilt and zonal asymmetry:
  - east of the convective center: low-level convergence, ascending motions positive anomalies in humidity, providing favorable conditions for the development of new convective systems => consideration in MJO theories and hypotheses. [e.g. Kiladis et al. 2005]

Observed features: Geographical preference, seasonal cycle and interannual variability

- **MJO signal in convection is normally (!) confined to Indian Ocean and western Pacific, where the sea surface is warm („warm pool“)**
  - zonal displacement of the MJO in concert with ENSO
  - MJO signal in eastern Pacific north of the *equatorial cold tongue* and adjacent to the Central American coast during boreal Summer. [Maloney and Kiehl 2002]
  - convective component of the MJO over Maritime Continent is generally much weaker

- **Seasonal cycle both in strength and latitudinal locations** [e.g. Zhang and Dong 2004]
  - Primary peak season: austral Summer/Autumn (strongest signal south of Equator); related to Australian Summer monsoon.
  - Second peak season: boreal Summer; related to Asian monsoon.

- **Interannual variability**: During warm event of ENSO, as eastern edge of the warm pool extend eastward, so does the MJO activity. [e.g. Hendon et al. 1999]

Mechanisms – 1) Atmospheric response to independent forcing

- What are the mechanisms that distinguish the MJO from the convectively coupled Kelvin waves? What processes must take place to supply energy against dissipation selectively to the intraseasonal, planetary-scale, and slowly eastward propagating disturbances known as the MJO? [Zhang 2005]

- **2 major schools of thought:**
  - 1) MJO as an atmospheric response to independent forcing (coupling between convection and circulation are secondary by-products)
  - 2) MJO creates its own energy source through atmospheric instability (coupling between convection and circulation is center of that instability)

- **1) Atmospheric response to independent forcing**
- a) Tropical intraseasonal stationary forcing

- b) tropical stochastic forcing

- c) lateral forcing

Mechanisms – 2) Atmospheric Instability and 3) Other factors

2) Atmospheric Instability

- Moisture Congergence: equatorial Kelvin wave becomes unstable when its convective heating interacts with its low-level convergence in „mobile wave-CISK" [Lau and Peng 1987] or „Kelvin wave-CISK" theories [Chang and Lim 1988]

- Surface evaporation: critique:
  - direct dependence of convective heating on moisture convergence are unphysical. [Emanuel et al. 1994, Raymond 1994]
  - surface evaporation interacting with the surface wind component of planetary-scale, intraseasonal Kelvon mode has been considered the source of instability for the MJO in the theory of WISHE: Wind-induced surface heat exchange [Emanuel 1987, Yano and Emanuel 1991]

- **3) Other factors:**
  - Radiation
  - Water vapour: discharge-recharge hypothesis
  - Sea surface temperature
  - Scale interaction
  - Heating profile

An index for the MJO – Forecast skill

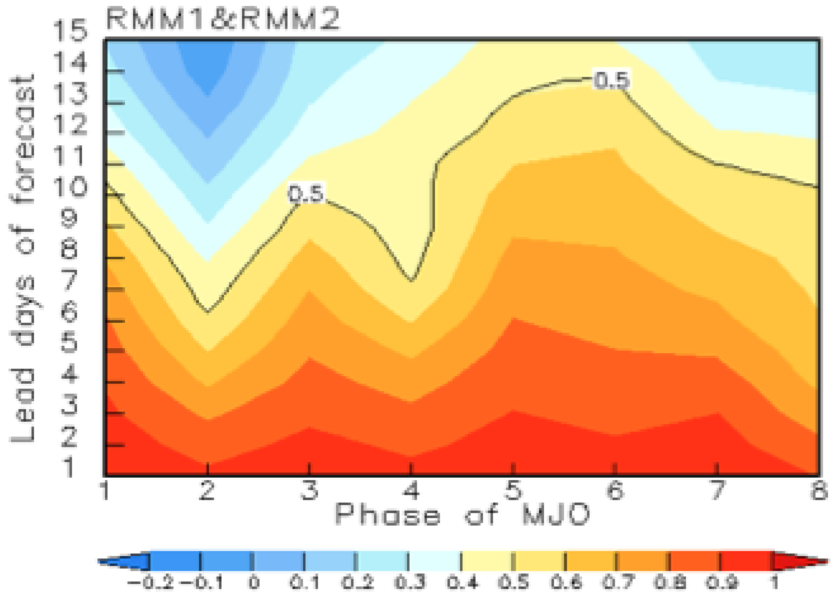
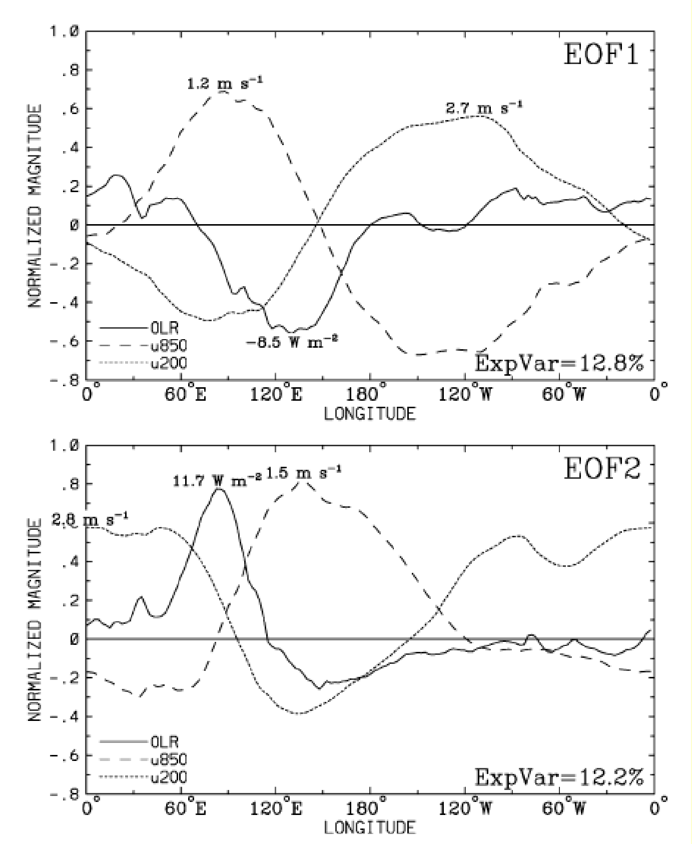


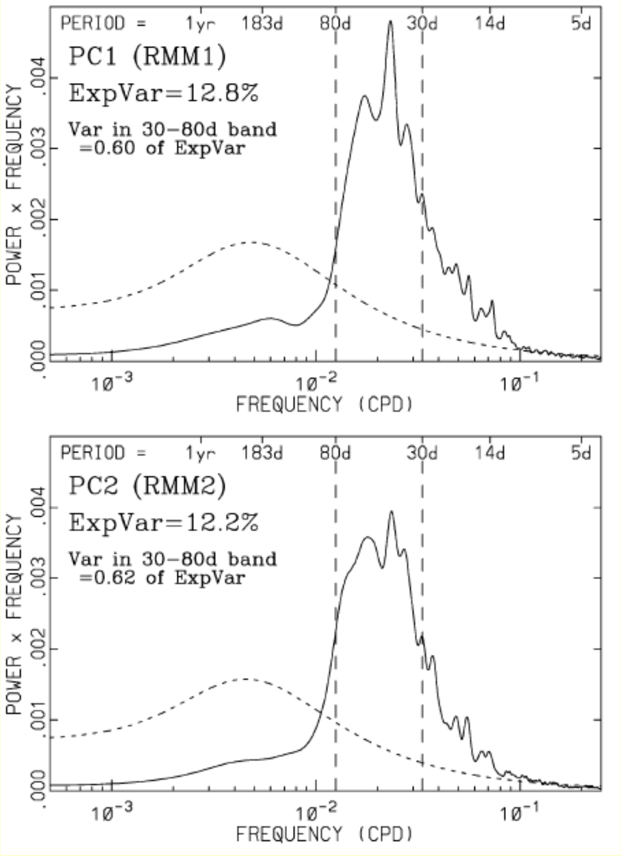
Figure 2 Correlation between observed Wheeler and Hendon (2004) MJO index and predicted by the NCEP Global Forecast System (GFS). Courtesy of Jon Gottschalck and Qin Zhang)

Multivariate index for the MJO

Wheeler, M.C. and Hendon H.H., 2004: An All-Season **R**eal-Time **M**ultivariate **M**JO Index: Development of an Index for Monitoring and Prediction.

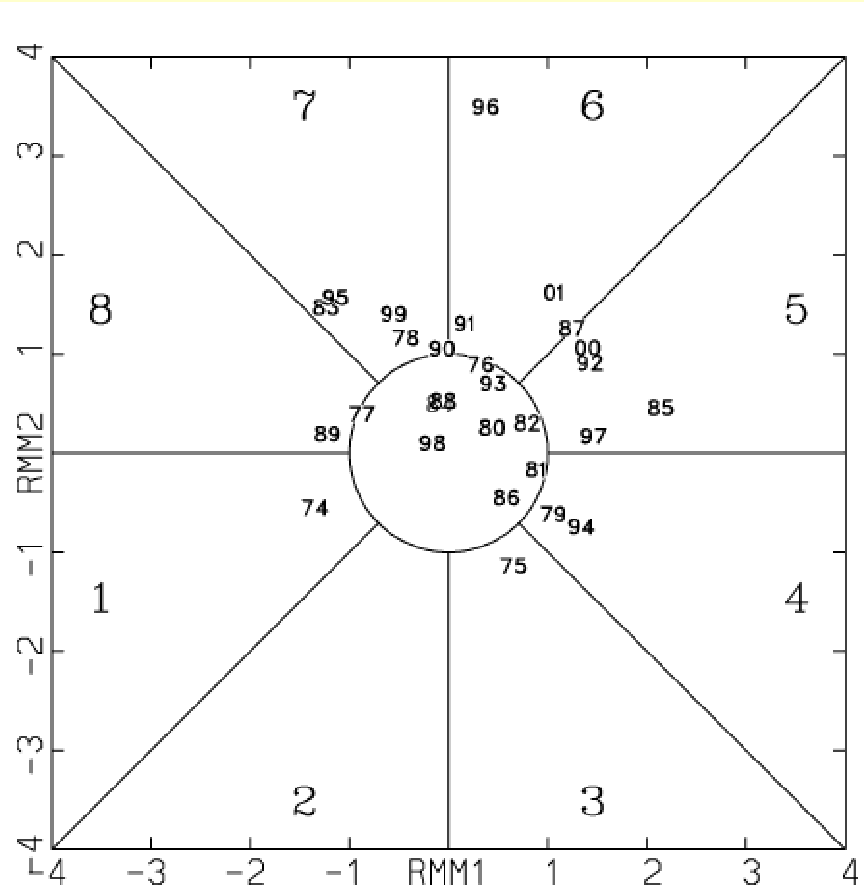
$$f(t,\lambda,\varphi) = \sum_{k=1}^{N} f_k(t)\, H_k(\lambda,\varphi)$$



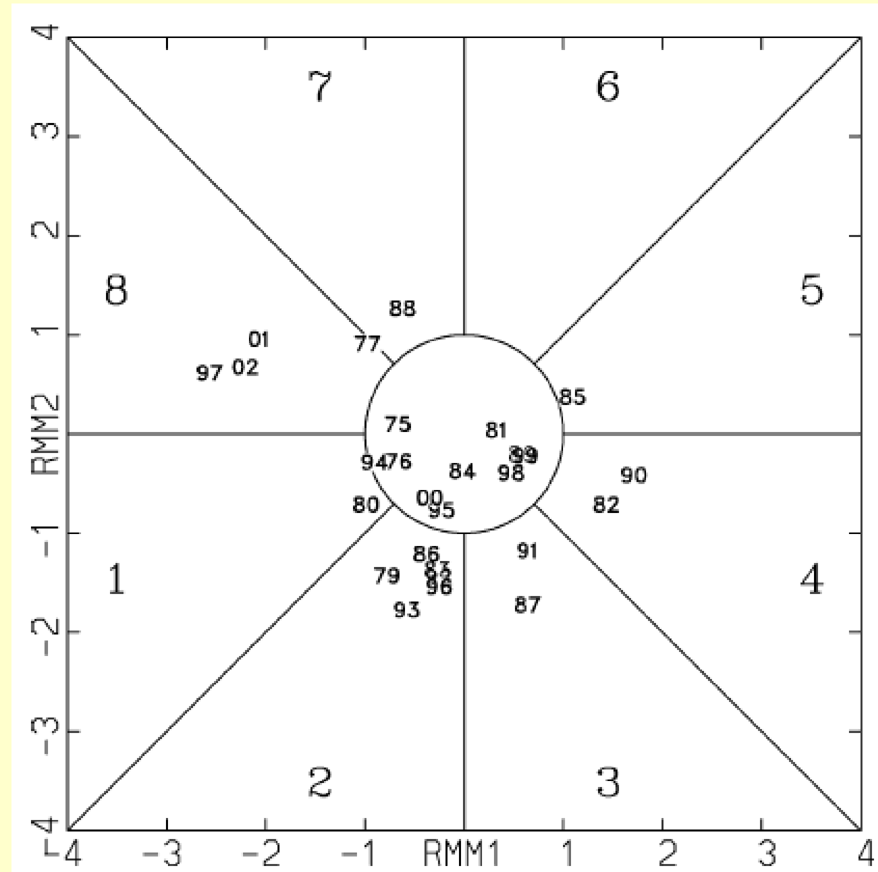


Multivariate index for the MJO – applications to synoptic weather

Australian monsoon onset



Asian monset onset



(RMM1, RMM2) phase points for the days on which the monsoon was defined to onset at Darwin , Australia (left) and at Kerala, India (right). From Wheeler and Hendon 2004.

Univariate index for the MJO

- Matthews (2008) took advantage of the sporadic nature of the MJO and classified each observed MJ event as either **primary**, with no immediately preceding MJ event, or **successive**, which does immediately follow a preceding event. (Matthews, A.J., 2008: Primary and successive events in the Madden-Julian Oscillation)

- **Aim:** 1) to identify (or reject) precursor signals or triggers of the MJO
  2) to investigate the starting location

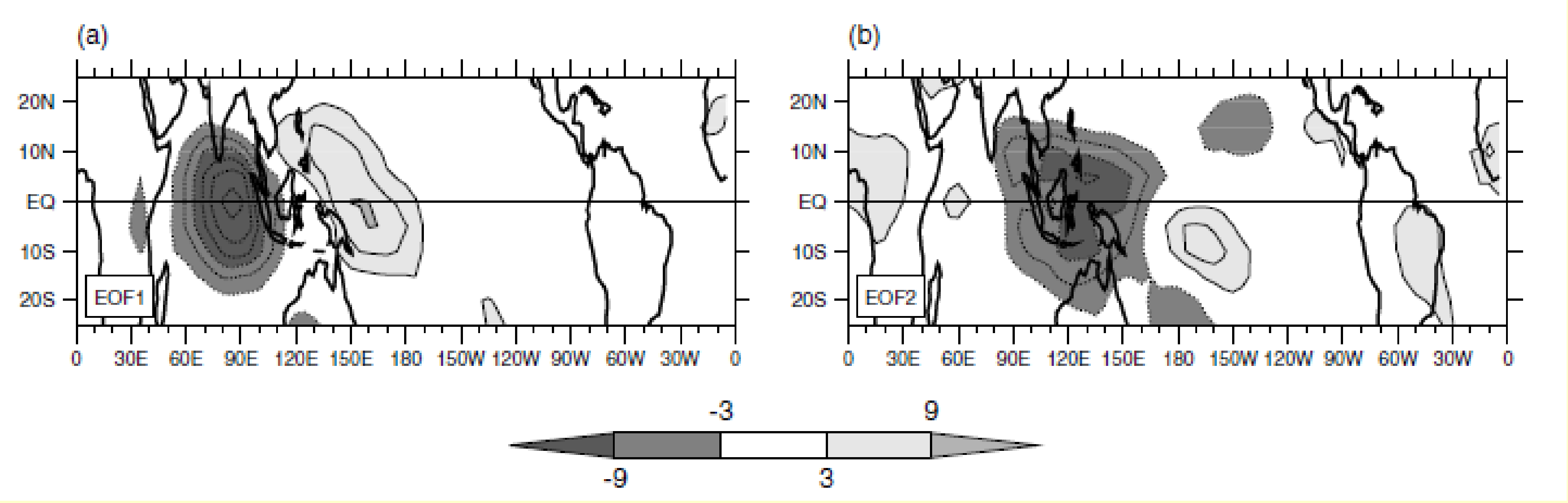
- **Definition of an univariate index**
  - Data:
    - Outgoing longwave radiation (OLR) from 1. 6. 1974 – 31. 12. 2005 from the daily mean, gridded, interpolated dataset from Liebmann and Smith
    - to isolate the intraseasonal signal: Anomaly fields (OLR) passed through a 20-200day band-pass Lanczos filter
  - conventional empirical orthogonal function (EOF) analysis on the OLR anomalies in the tropical region (25°S - 25°N).

Univariate index for the MJO

Empirical orthogonal functions (EOFs)

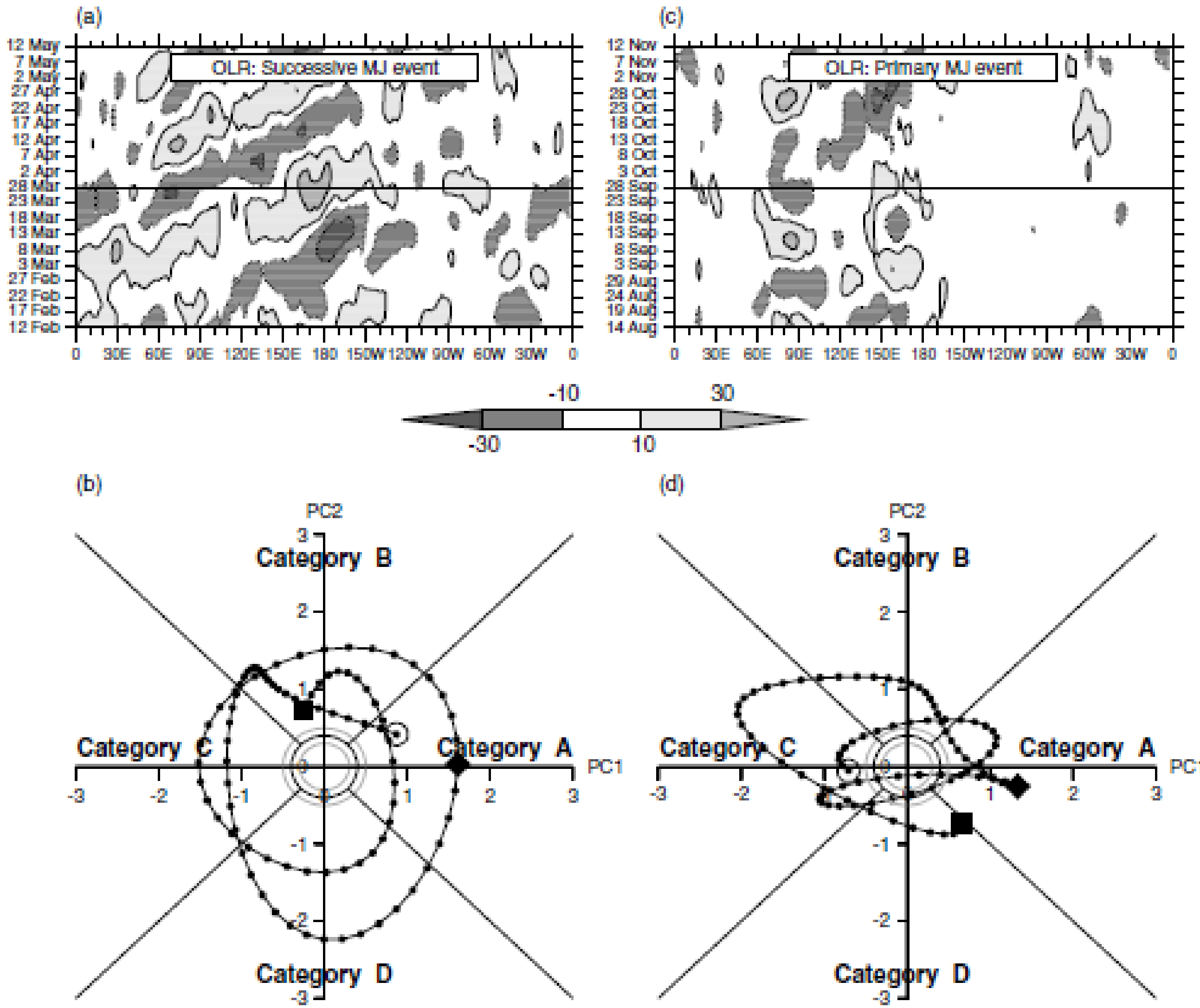
$$f(t,\lambda,\varphi) = \sum^{N}_{k=1} f_k(t) H_k(\lambda,\varphi)$$

H_k `s = EOFs, $f_k(t)$ = principal components (PC's)



EOF1 (a) and EOF2 (b) of 20-200 day filtered tropical OLR anomalies. They account for 7.8% and 6.7% of the 20-200 day filtered tropical OLR variance. *From Matthews 2008.*

Univariate index for the MJO – An example



Hovmöller diagram of 20-200-day filtered meridionally averagedOLR anomalies for 12. Feb. 1992-12.May 1992 (a and b). (PC1,PC2) phase-space diagram (c and d). From Matthews 2008.

Univariate index for the MJO – Starting location

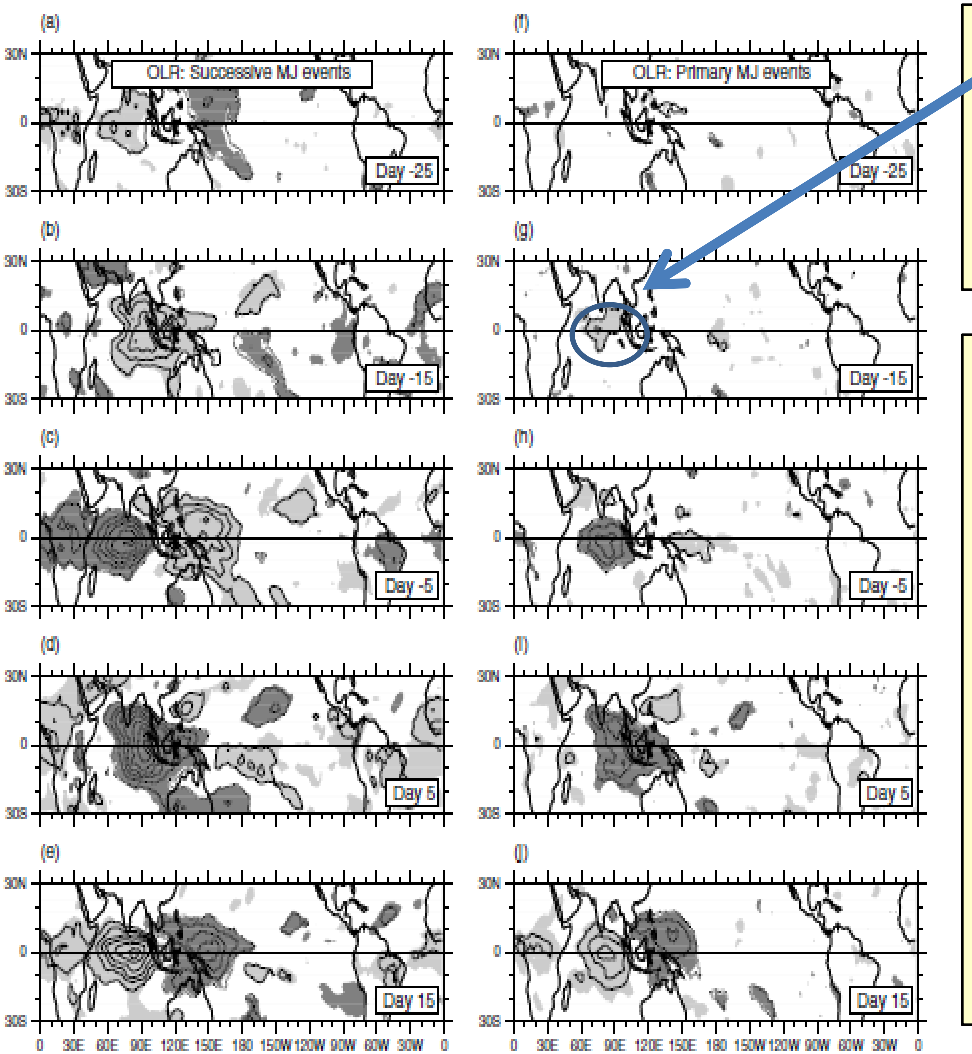
Table II. Number of instances of MJ events.

Start location MJ event	Indian Ocean ABCD	Indonesia BCDA	Western Pacific CDAB	Africa DABC	Total
Primary	NABCD 26	NBCDA 12	NCDAB 13	NDABC 12	63
Successive	DABCD 82	ABCDA 89	BCDAB 81	CDABC 82	≥89
Initial westward	BABCD 8	CBCDA 11	DCDAB 4	ADABC 9	32
Initial opposite	CABCD 0	DBCDA 0	ACDAB 0	BDABC 0	0
Total	116	112	98	103	

From Matthews 2008

- approx. 30% of MJ events are primary events.
- periodic view of MJO accounts only for about the half of the events, and the discrete view accounts for the other half.
- Most frequent starting location of primary events are in the Indian Ocean, but over half of them start elsewhere.

Univariate index for the MJO – Precursor signals
Convective anomalies and thermodynamical forcing



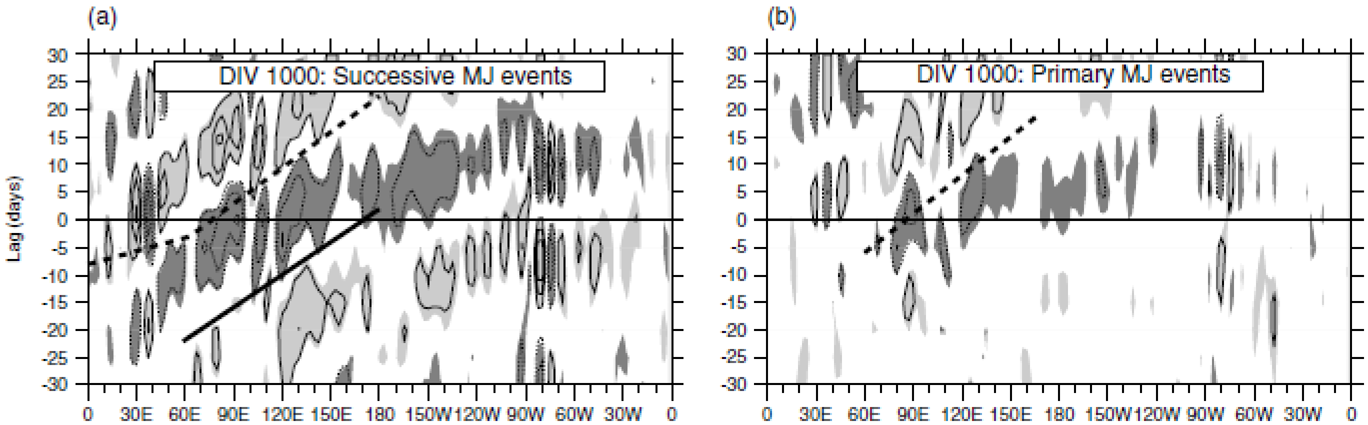
Composite maps of OLR anomalies for successive events (left) and primary events (right). From Matthews 2008.

- Primary events: on day -15, positive OLR anomalies over equatorial Indian Ocean, indicating **suppressed convection** there.

- The stationary suppressed convection anomaly is associated with a negative mid-tropospheric temperature (due to reduced latent heat release) which destabilizes the atmosphere to convection => MJ event.

- Ultimate cause of the precursor suppressed convection is unknown and needs further investigation.

Univariate index for the MJO – Precursor signals
Boundary-layer convergence and moisture



Hovmöller diagrams of 20-200-day filtered 1000 hPa divergence anomalies (averaged over 10°S-10°N) for successive (a) and primary (b) events. From Matthews 2008.

- Similarly forcing by the ocean (SST anomalies), and by synoptic wave activity (kinetic energy anomalies) were investigated. No such precursor signals preceding primary events.

- Theories that rely on these features, such as those of frictional moisture convergence, pre-moistening, air-sea interaction, **do not appear to be fundamental to the spontaneous generation of the MJO**. However, they are certainly not excluded from a role in the subsequent reinforcement and propagation of the MJO.

Comparison: Univariate vs. Multivariate Index

Univariate Index

Start Loc.	Indian Oc.		Indonesia		Western Pac.		Africa		Total
MJ event	ABCD		BCDA		CDAB		DABC		
Primary	NABCD	26	NBCDA	12	NCDAB	13	NDABC	12	63
Successive	DABCD	82	ABCDA	89	BCDAB	81	CDABC	82	>=89
Initial westw.	BABCD	8	CBCDA	11	DCDAB	4	ADABC	9	32
Initial oppos.	CABCD	0	DBCDA	0	ACDAB	0	BDABC	0	0
Total		116		112		98		103	

Multivariate Index

Start Loc.	Indian Oc.		Indonesia		Western Pac.		Africa		Total
MJ event	ABCD		BCDA		CDAB		DABC		
Primary	NABCD	19	NBCDA	10	NCDAB	9	NDABC	14	52
Successive	DABCD	69	ABCDA	65	BCDAB	59	CDABC	68	>=69
Initial westw.	BABCD	15	CBCDA	8	DCDAB	17	ADABC	15	55
Initial oppos.	CABCD	0	DBCDA	0	ACDAB	0	BDABC	0	0
Total		103		83		85		97	

Summary

- MJO: dominant component of the intraseasonal (30-90 days) variability in the tropical atmosphere with a coupled pattern in atmospheric circulation and deep convection and coherent signals in many other variables, all propagating eastwards (5 m/s) from the Indian Ocean to the eastern Pacific.

- It has a strong seasonal cycle and shows interannual variablity.

- 2 major schools of thought in theories explaing the MJO: atmospheric response to independent forcing and atmospheric instability.

- Wheeler and Hendon (2004) describe a multivariate index (RMM1/RMM2), which can be used to monitor and predict MJ events.

Summary

- Matthews (2008) classified primary and successive events and by doing this, a suppressed convective anomaly could be identified as a precursor signal to the generation of a (primary) MJ event. Premoistening of the atmosphere, air-sea interaction, and forcing by equatorward-propagating transients, do not appear to be fundamental to the spontaneous generation of the MJO => **consequences for theories!**

- Periodic view of MJO accounts only for about the half of the events, and the discrete discrete view accounts for the other half.

- Most frequent starting location of primary events are in the Indian Ocean, but over half of them start elsewhere.