The Madden-Julian Oscillation

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with thanks to the WGNE MJO Task Force
especially
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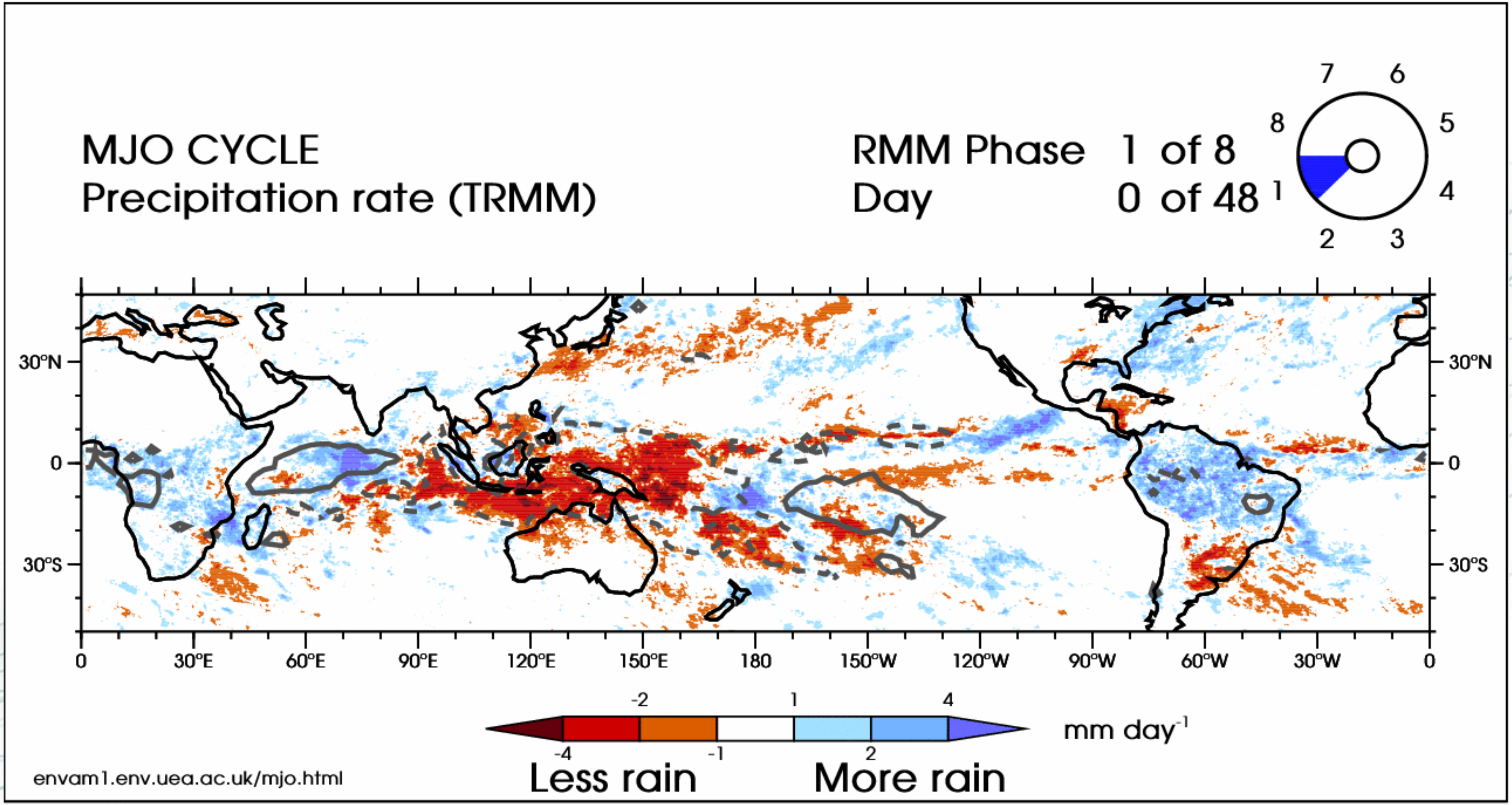

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Animation courtesy of Adrian Matthews http://envam1.env.uea.ac.uk/mjo.html

The Madden-Julian Oscillation

- Characteristics of the MJO
- Theories of the MJO
- MJO Forecast Skill
- MJO Teleconnections to the North Atlantic

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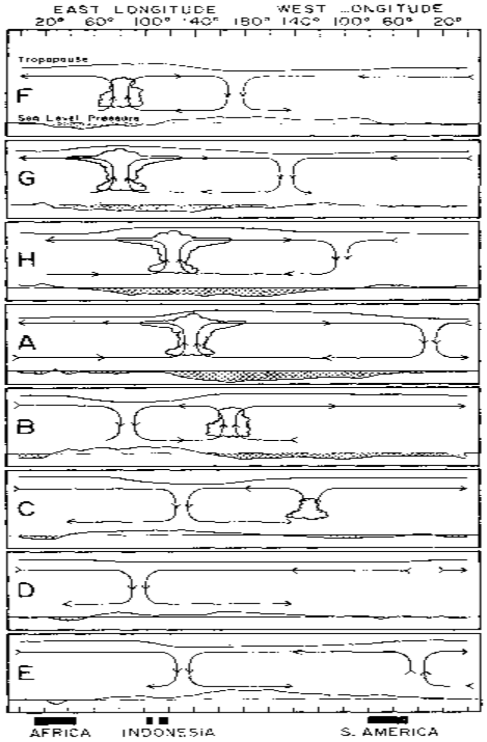
The Madden-Julian Oscillation

- The MJO is the dominant mode of sub-seasonal variability in the tropics
  - Eastward moving, planetary scale, tropical convection anomalies with a period of 30-60 days
  - Associated planetary scale baroclinic circulation in tropics
  - Strongest during boreal (extended) winter
- Significant global impacts on sub-seasonal timescales, e.g.
  - Linked to variability in major monsoon systems
  - Convective heating anomalies and associated divergent circulation acts as a Rossby wave source and provides teleconnections to extra-tropics (troposphere and stratosphere)
  - Modulates tropical cyclone activity
  - Westerly Wind Bursts important in development of El Niño events



MJO schematic from Madden and Julian (1972)

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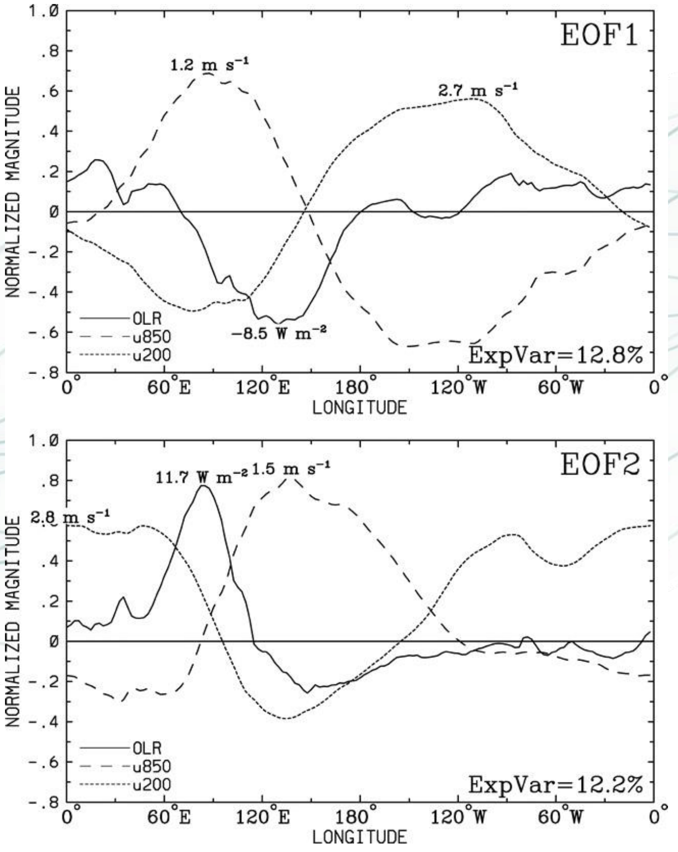
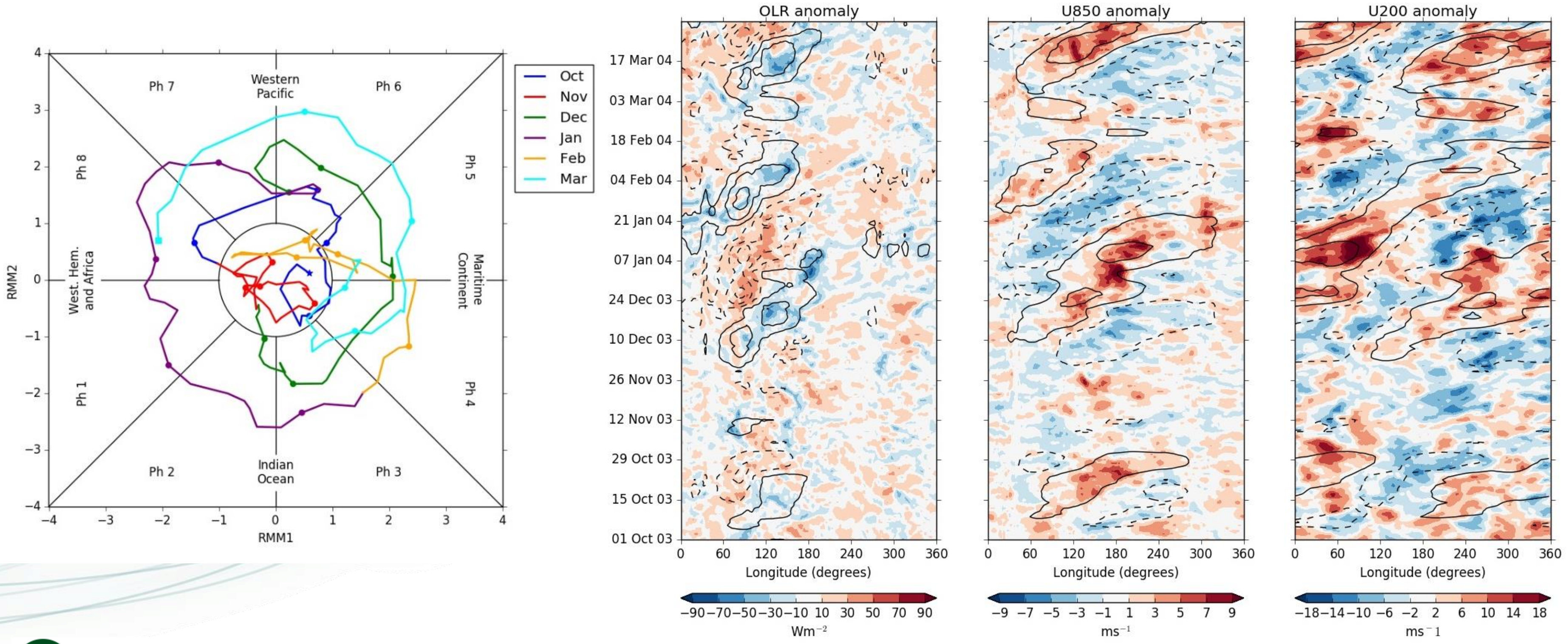
RMM index

- Characterising the MJO requires a method for isolating the MJO signal in observations.
- Wheeler and Hendon (2004) developed a Real-time Multivariate MJO (RMM) index which
    - doesn’t rely on filtering to identify the signal
    - exploits both the convective and dynamical signature of the MJO
    - can be used identify the MJO in real-time applications
    - Constructed by projection of 15N-15S averaged normalized U850, U200 and OLR anomalies onto the two leading EOFs
    - PCs (RMM1 & RMM2) can be projected into phase space
    - MJO anomalies can be reconstructed from EOFs



Example Season 2003-2004



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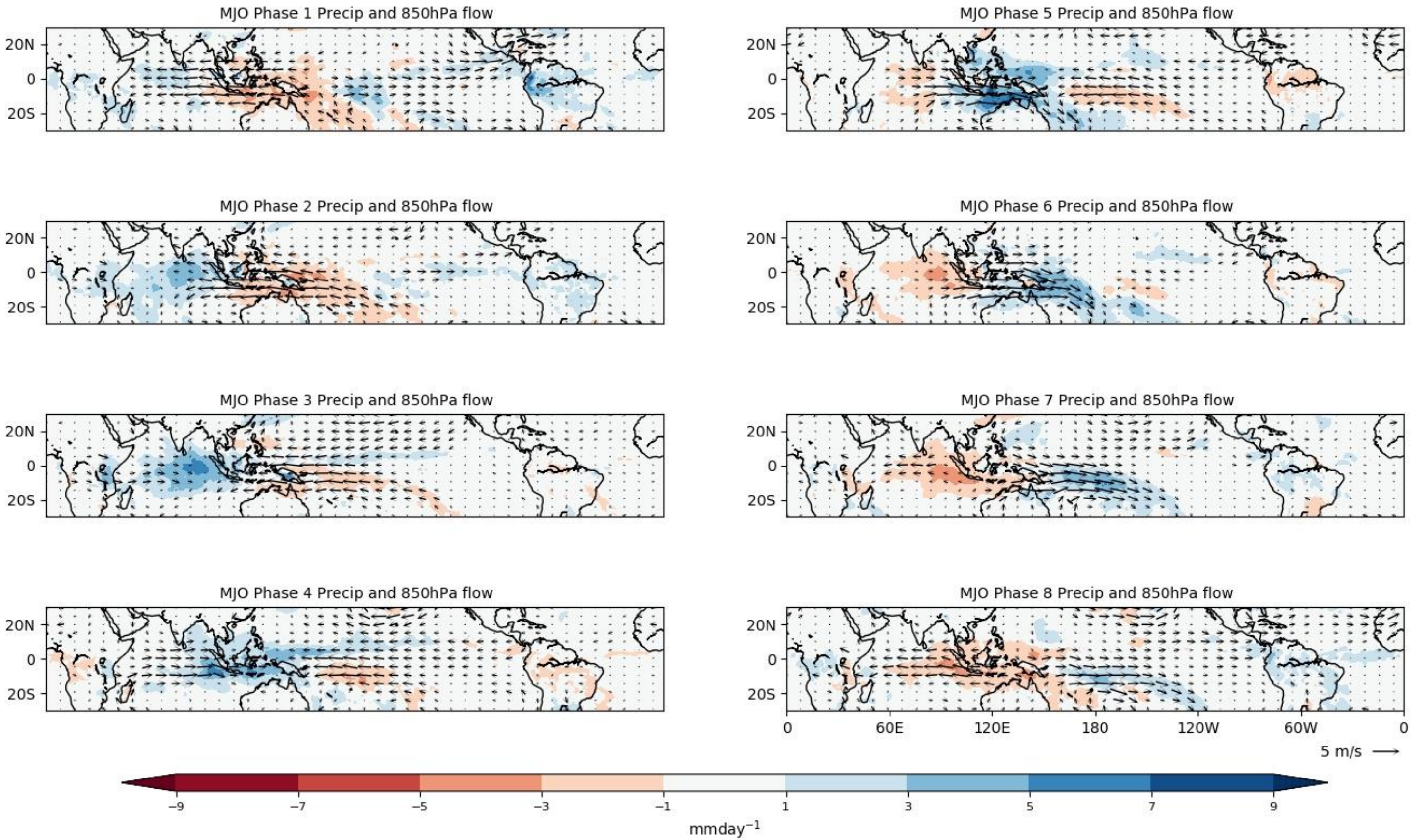
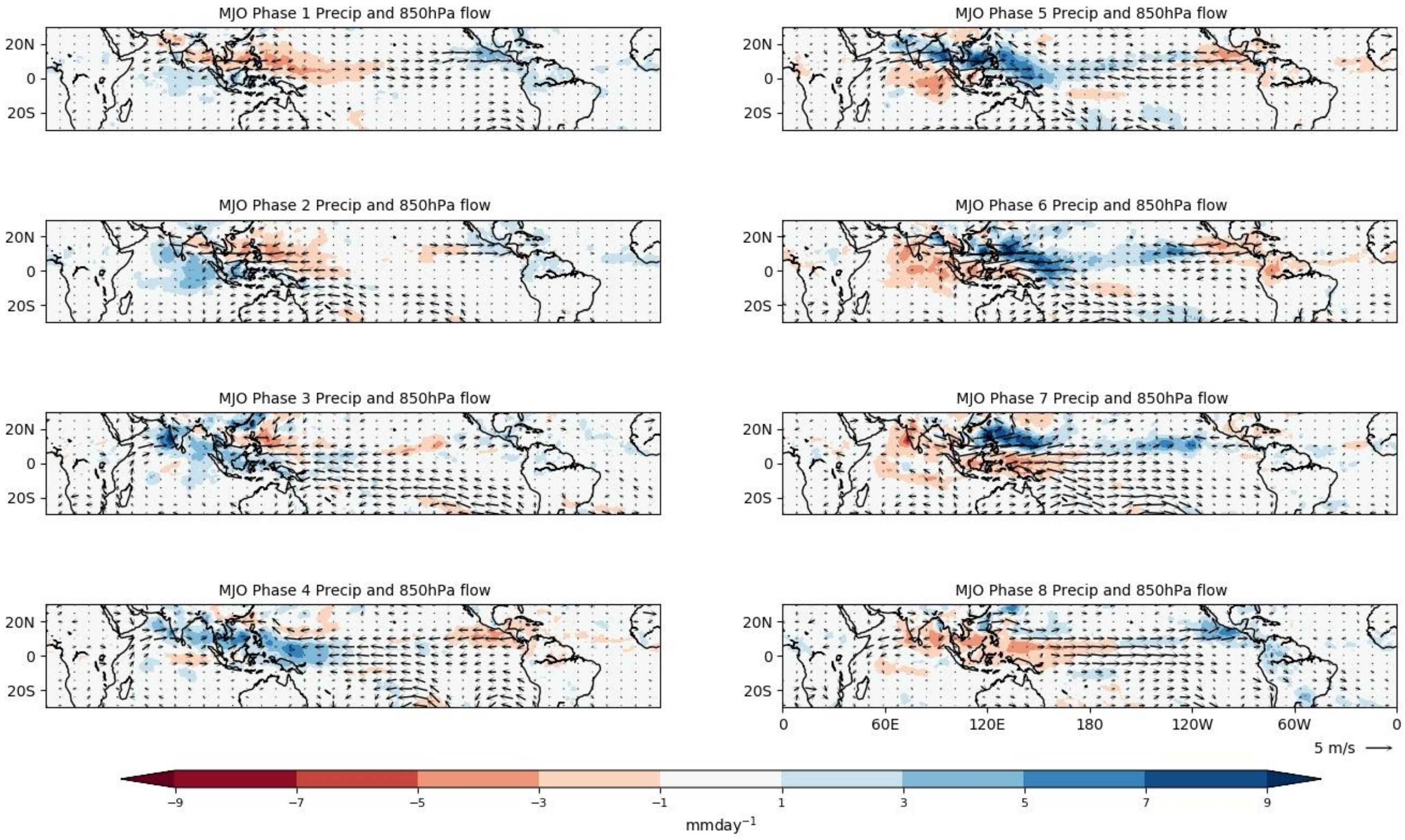
MJO Composite - Boreal Winter (Nov-Apr)

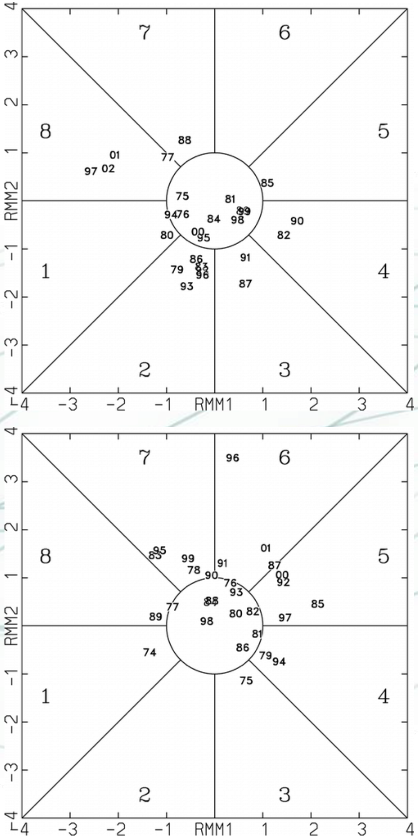


MJO Composite - Boreal Summer (June-Sep)



MJO Modulation of Tropical Weather

- Links to onset of major monsoons
  - Monsoon onset occurs most frequently in Phases 8-3 over India
  - Phases 4-7 over N Australia



RMM phase for date of onset of Indian Summer monsoon (top) and Australian Monsoon (bottom). Reproduced from Wheeler and Hendon (2004)

MJO Modulation of Tropical Weather

- Links to onset of major monsoons
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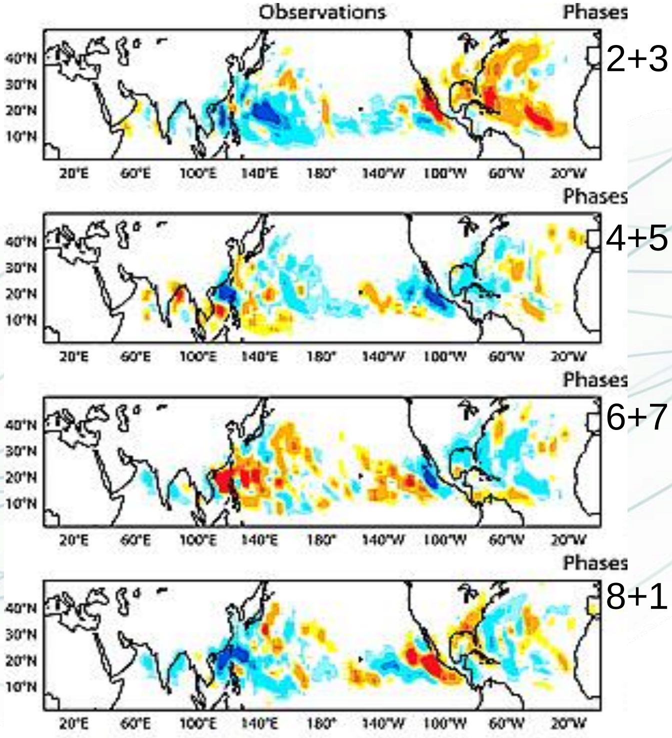
- Links to tropical cyclone activity
  - Modulation of TC density by up to ~50% by MJO



Tropical storm density anomalies as a function of MJO phases in observations for the period August to October. Yellow and red colours indicate an increase of tropical cyclone activity. Reproduced from Vitart (2009)

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MJO Modulation of Tropical Weather

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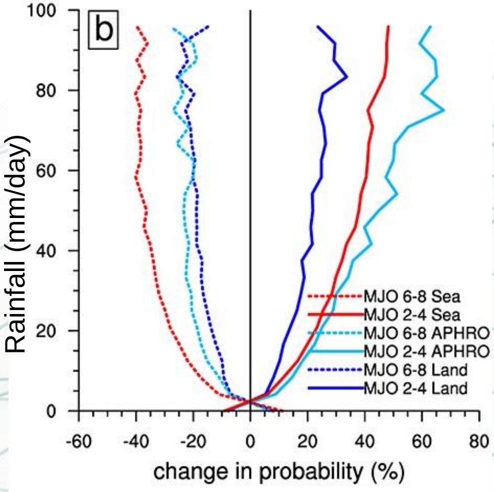
- Links to tropical cyclone activity
  - Modulation of TC density by up to ~50% by MJO
- Modulation of mean and extreme precipitation
  - e.g. 20-50% increase in probability of rainfall exceeding 40mm/day in active phases of the MJO over SE Asia



Percentage change of probabilities of rainfall for different MJO states with respect to the PDF of all days for All land points between 90°–125°E and 10°S–10°N.
Reproduced from Xavier et al. (2014)

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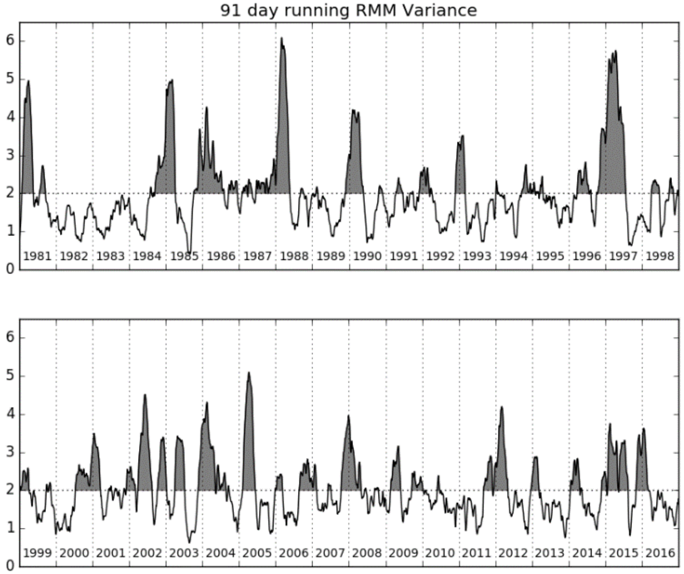
Interannual Variability of the MJO



Running 91-day RMM variance (RMM_1^2+ RMM_2^2) showing the interannual modulation of MJO activity, after Wheeler & Hendon (2004)

- Considerable Interannual Variability in MJO activity
- No evidence of strength of MJO activity being related to ENSO overall
- Some evidence that MJO activity is enhanced in Central Pacific El Niños and reduced in Eastern Pacific El Niños (e.g. Feng et al, 2015; but note small sample size)
- MJO events do remain convectively active further into central Pacific during El Niño years (and conversely in La Niña years)
- Recent evidence the MJO activity is enhanced during Easterly phases of the Quasi-Biennial Oscillation (e.g. Yoo & Son, 2016), possibly due to QBO related changes in upper tropospheric stability (e.g. Hendon & Abhik, 2018)

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MJO Initiation

- Once underway the MJO can make several circuits of the globe
- However Matthews (2008) showed that about 40% of MJO events are “primary” i.e. not preceded by another MJO
- Indian Ocean slightly preferred for initiation of Primary MJO over other locations
- Several studies on MJO initiation with differing findings
    - A number of studies (e.g. Hsu et al,1990) found evidence of extra-tropical wave propagation into the tropics being important for MJO inititation
    - Matthews et al. (2008) found no such evidence of wave propagation for primary events in the Indian Ocean but that some but not all were preceded by an area of supressed convection which develops in situ
    - Straub (2013) found no supressed signal over the Indian Ocean but that although there was no convective signal the circulation was similar to that for successive events
- However there are significant differences in dates and locations of initiation depending on the choice of index and this makes diagnosing MJO precursors from observations difficult

MJO Theories

- Since it’s discovery there have been a number of theories and mechanisms for MJO propagation (see Wang, 2012 for a review) but there is still no clear consensus.
- Two key components for a theory of the MJO
  - A model for **the large-scale dynamical response** to the anomalous heating, primarily the latent heat release in **convection** but also **radiation** and **surface fluxes**
  - A model for how the anomalous heating evolves in response to the anomalous circulation
- **The dynamical model**
  - Theories for the large-scale dynamical structure of the MJO are commonly based on a linearized set of equations of motion for tropical dynamics with simplified vertical structure, with or without a representation of the boundary layer
  - Some elements of this dynamical model are critical for how the convection evolves (e.g. the frictional convergence mechanism of Wang and Rui, 1990a depends on the inclusion of a boundary layer)

Major differences between most theories is how the heating evolves in response to the anomalous circulation

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MJO Theories

Moisture Convergence Induced Heating

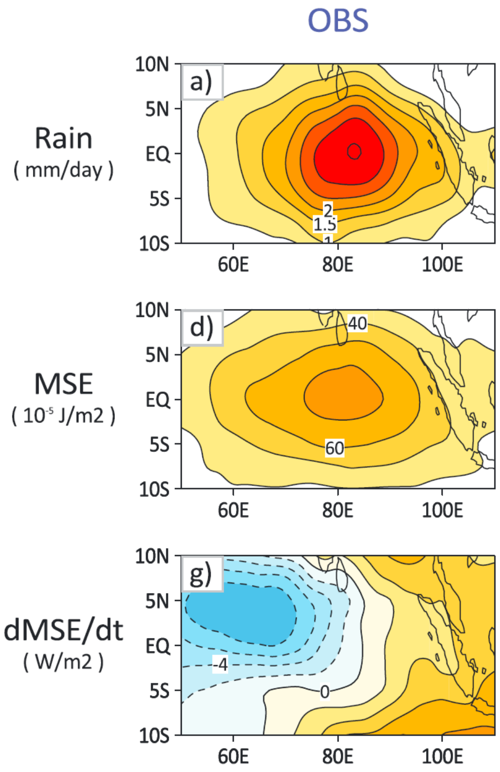
- Heating is related directly to the moisture convergence (e.g. Wang and Rui, 1990)
    - Moisture convergence is linked to the dynamical convergence through a specified moisture field
    - Precipitation is proportional to the moisture convergence via a precipitation efficiency but moisture field does not evolve with flow
    - Wang & Rui (1990) highlight the importance of the boundary layer moisture convergence

Moisture Mode

- Convection is related to the moisture (or moist static energy) variations (e.g. Adames and Kim 2016)
    - Precipitation is related to a measure of column humidity
    - Precipitation removes moisture but it is recharged by the **large-scale circulation** and **surface fluxes**
    - Jiang et al. (2017) find that advection of background moisture by the anomalous circulation is an important component of positive moisture tendency to the east of convection
    - Sobel et al. (2014) find that the cloud radiative heating is has an important role in maintaining the MSE anomalies; can be interpreted as the radiative warming by the clouds driving ascent and moistening the column

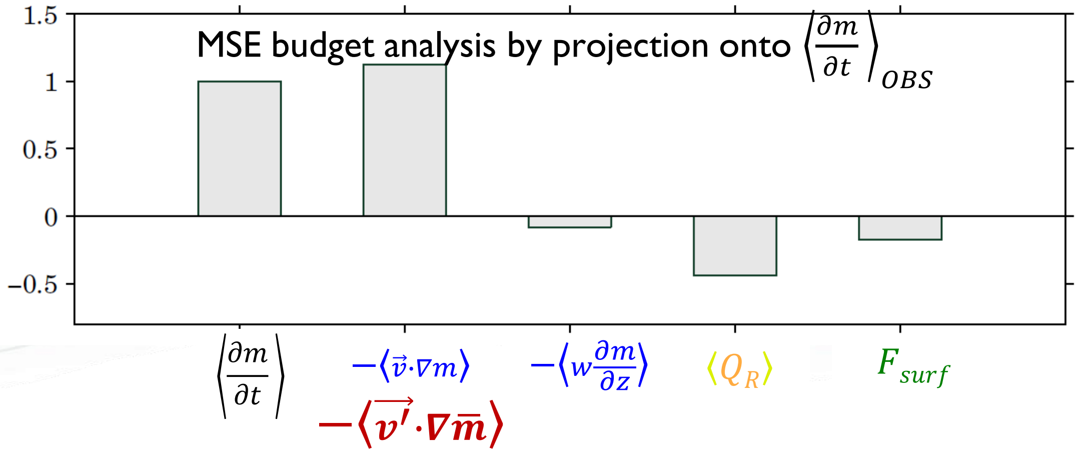
Moisture Mode theory for the MJO

MJO maintenance and propagation related to process which govern the Moist Static Energy Budget



$$\left\langle \frac{\partial m}{\partial t} \right\rangle = -\langle \vec{v} \cdot \nabla m \rangle - \left\langle w \frac{\partial m}{\partial z} \right\rangle + LE + SH + \langle LW \rangle + \langle SW \rangle$$

Circulation (GMS) Surface Fluxes Radiation



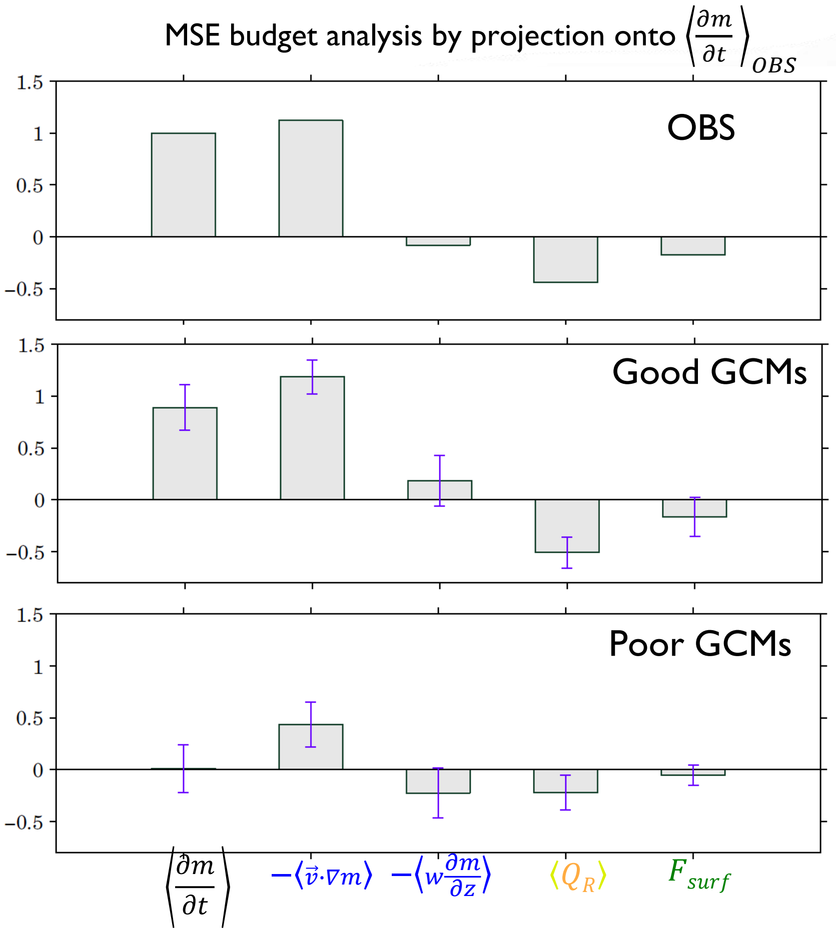
Moistening to east of MJO dominated by advection of mean state moisture by MJO winds

Jiang (JGR-Atmos, 2017)

Moisture Mode and relationship to model performance

Analysis of models submitted to MJO-TF/YoTC/GASS
Vertical Structures and Diabatic Process of the MJO Global Model Evaluation Project

- Model MJO simulation highly correlated with ability to reproduce moistening pattern
- Errors in *dm/dt* due to large errors in moisture advection term
    - Linked to errors in both circulation and basic state moisture
- Simulation skill also strongly correlated with mean moisture pattern in maritime continent region (Gonzalez and Jiang 2017)
- May be linked to errors in sub-seasonal prediction systems (Kim, H. et al. 2019)



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Challenges in interpreting sensitivity to Physics changes

- Sensitivity to background state presents challenges in interpreting the sensitivity of MJO to changes in physics (particularly the representation of convection) or coupling
- Are changes in MJO simulation
  - Due directly to the way in which the convection interacts with the MJO (in moisture mode theory we might think of this as the relationship between the mse anomaly and the precipitation) **or** changes in the anomalous circulation leading to changes in the moisture convergence

  or
  - Due to changes in the basic state moisture gradient leading to changes in the moisture convergence
    - *<u>large</u> changes in the basic state due to coupling can be mitigated by comparing coupled model to atmosphere only model with same SST*
- all complicated by the possibility of
  - feedbacks between the MJO and the mean state
  - differences in interannual variability (e.g. IOD or ENSO) between simulations *(e.g. Klingaman & DeMott, in review)* either by chance or because the MJO has changed; …..

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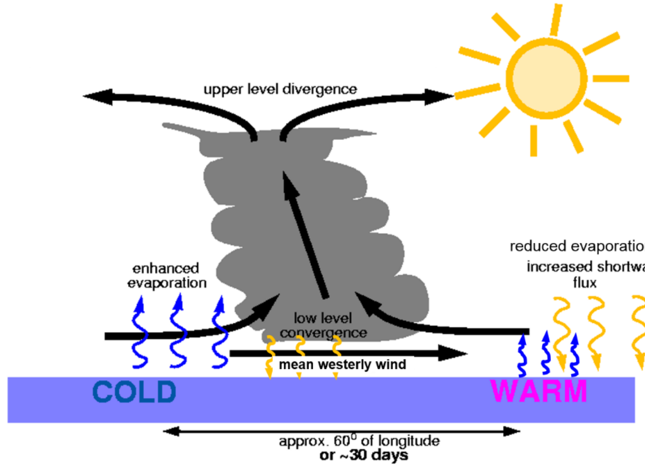
Air-sea interaction in the MJO

- Observations show modulation of SST by MJO
  - Reduced latent heat fluxes (due to reduced wind stress) and increased solar radiation warm ocean to east of active convection
    - Additional role of shoaling of mixed layer and increased diurnal cycle of SST
  - Enhanced latent heat fluxes (due to enhanced wind stress) and reduced solar radiation cool ocean under and to west of convection
  - Increased SST to east of convection “promotes” eastward propagation

- Mechanisms for MJO driving SST are clear
- Mechanisms for SST feedback on atmosphere are less clear
  - Increased SST slightly elevates the LH fluxes to east of convection? (e.g. DeMott et al. 2016)
  - SST induced boundary layer convergence leads to additional moisture convergence? (e.g. Hsu and Li, 2012)



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The role of changes in the basic state in the sensitivity to air-sea interaction

- Analysis of MSE budget from re-analysis suggests that the direct ‘linear’ effect of intraseasonal SST variability in the MJO is around a 10% contribution to the MSE tendency (DeMott et al. 2016), partially offsetting the wind-driven LH anomalies.
- DeMott et al. (in review) analyse the MSE budget of a 4 model (coupled vs uncoupled) comparison with interannually varying monthly mean SSTs from CGCM prescribed to its AGCM
- Dominant change in MJO MSE budget is a increased contribution to the moistening from the horizontal (meridional) advection term – *note this includes the ‘non-linear’ effects of changing the MJO*
- Coupled models show increased meridional moisture gradient which favours propagation

- Moisture changes arise from rectification of

Change in moistening profile (Q2) for a given rain rate with SST

X

change in frequency of rain rates with SST

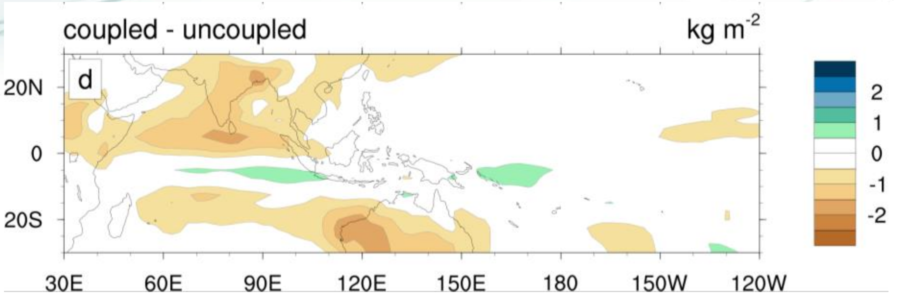
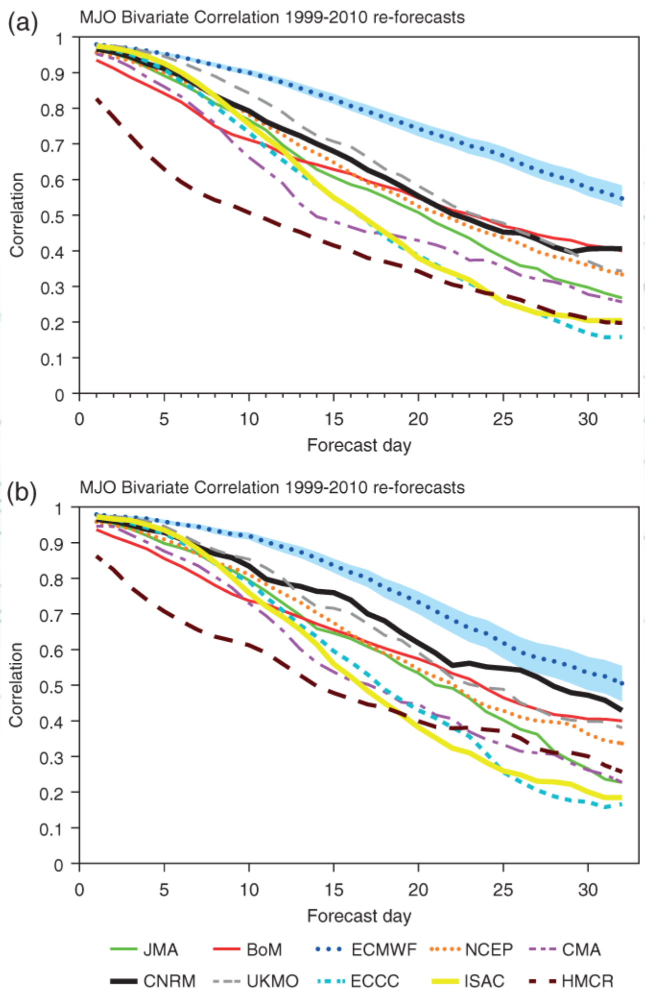


Figure courtesy of Charlotte DeMott

MJO forecast Skill

- Over recent years their have been significant improvements in MJO prediction skill
- Correlation > 0.6 for ~5-28 days depending on model for ensemble mean
- Range reduces to 6-21 days for individual members
- Generally higher skill during boreal winter than other seasons
- Skill improved for forecasts with active MJO in initial conditions (e.g. Rashid et al., 2011)



Evolution of the RMM bivariate correlation as a function of lead time for the ensemble mean for ten models from the S2S database. for (a) all seasons and (b) extended winters (December to March). The shaded area represents the 95% level of confidence. Reproduced from Vitart (2017)

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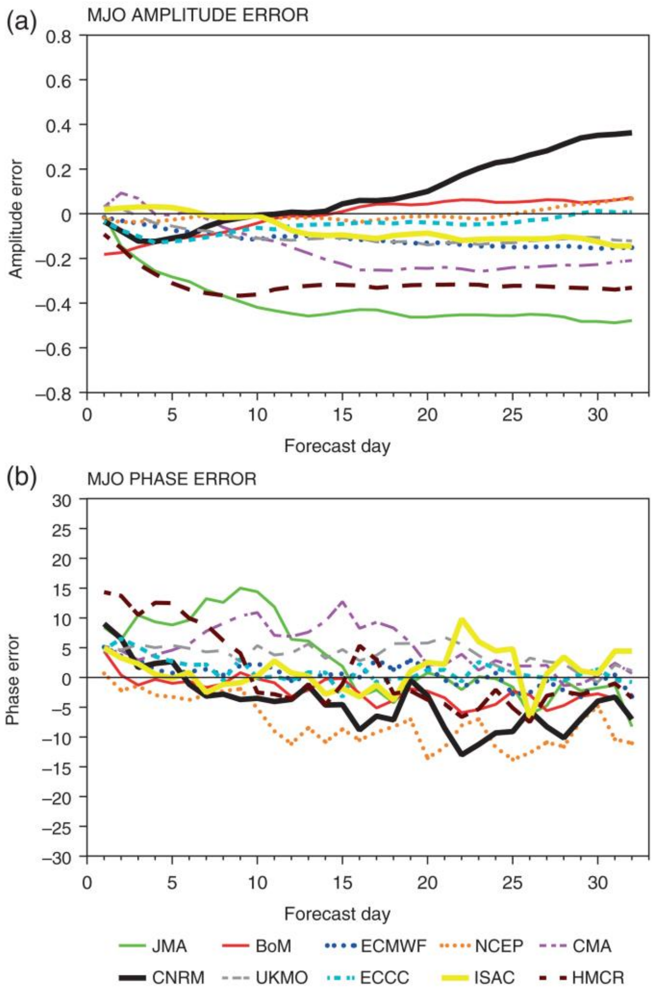
MJO forecast Skill

- A number of models underestimate MJO amplitude (~10% typically, but up to 50%)
- Mixed signal for phase errors, with tendency for positive phase errors (1-2days) at short lead and negative phase errors (too slow propagation) at long lead times
- No consistent signal for dependence of amplitude or phase errors on initial MJO phase of amplitude
- S2S models overestimate by a factor of 2 - 4 the number of MJO events which are active in the Indian Ocean at initial time and reach phase 6-7 (even as a weak MJO within 30 days



Evolution of the MJO (a) amplitude error and (b) phase error relative to ERA-Interim as a function of lead time. In (a), a positive (negative) value indicates a too strong (weak) MJO. In (b), a positive (negative) value indicates a too fast (slow) MJO propagation. Reproduced from Vitart (2017)

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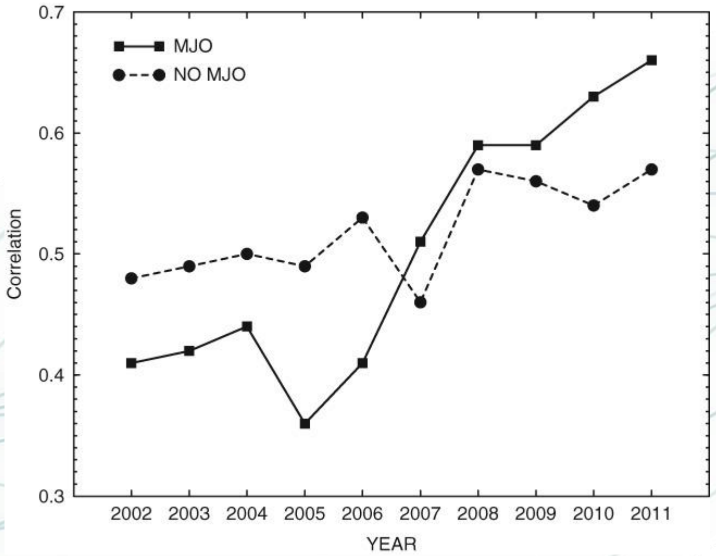
MJO teleconnections to the North Atlantic

- Rossby Waves generated by MJO heating provide a teleconnection to the North Atlantic sector (e.g. Cassou 2008)
  - NAO+ (index or regime) favoured 5-15 days following MJO phase 3
  - NAO- (index or regime) favoured 5-15 days following MJO phase 7
- Important source of predictive skill for the North Atlantic
- Significant improvements in NAO skill scores at ECMWF
  - Dominated by improvements in skill for active MJO initial conditions
  - Large improvements correspond to improvements in MJO amplitude



Evolution of the ensemble mean NAO (index) skill scores for leadtime 19–25 days in the EMCWF monthly forecasting system: for all the cases when there is an MJO in the initial conditions (solid) and when there is no MJO in the initial conditions (dashed). Reproduced from Vitart (2014)

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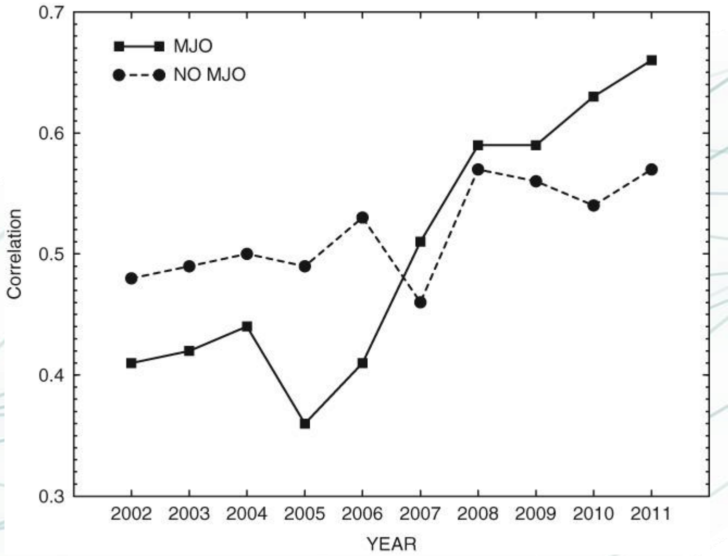

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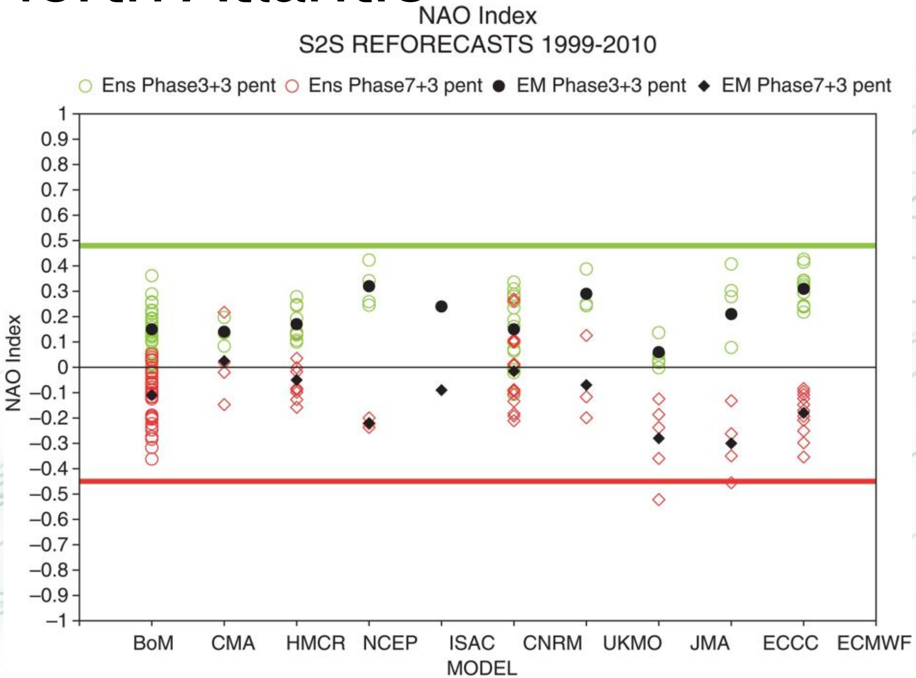
MJO teleconnections to the North Atlantic

- Analysis of MJO teleconnection in S2S models (Vitart 2017)
- S2S Models significantly underestimate the strength of the teleconnection
  - Strength of MJO?
  - Strength of RWS?
  - RW propagation errors?
  - Wave breaking errors?
  - ...
- Considerable spread in mean teleconnection for individual ensemble members
- Within ensemble member 20-50% more intra-event variance than for ERA-I



NAO index of the MJO teleconnections 11-15 days after a strong MJO (in Phase 3 and Phase 7 for the S2S models. Green and red solid lines show the values of the NAO index of ERA-Interim for Phase 3 and Phase 7. The black circles (diamonds) show the mean NAO index obtained over all the ensemble members The open circles (diamonds) show the NAO index obtained for each ensemble member Reproduced from Vitart (2017)

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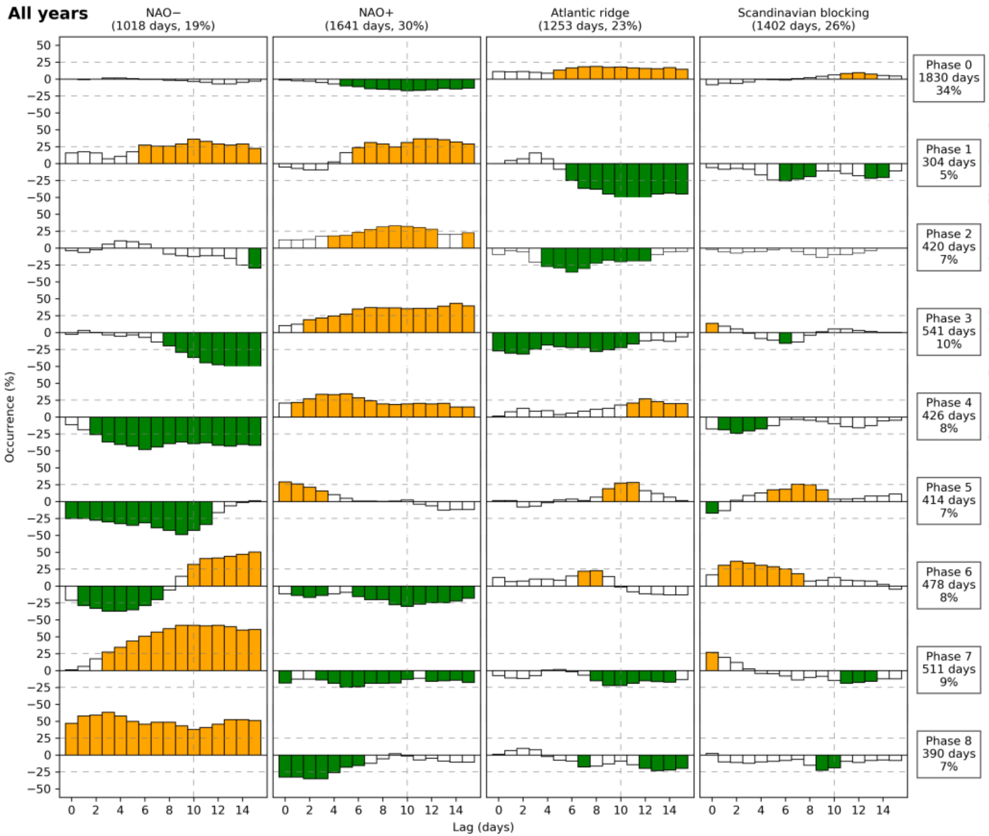
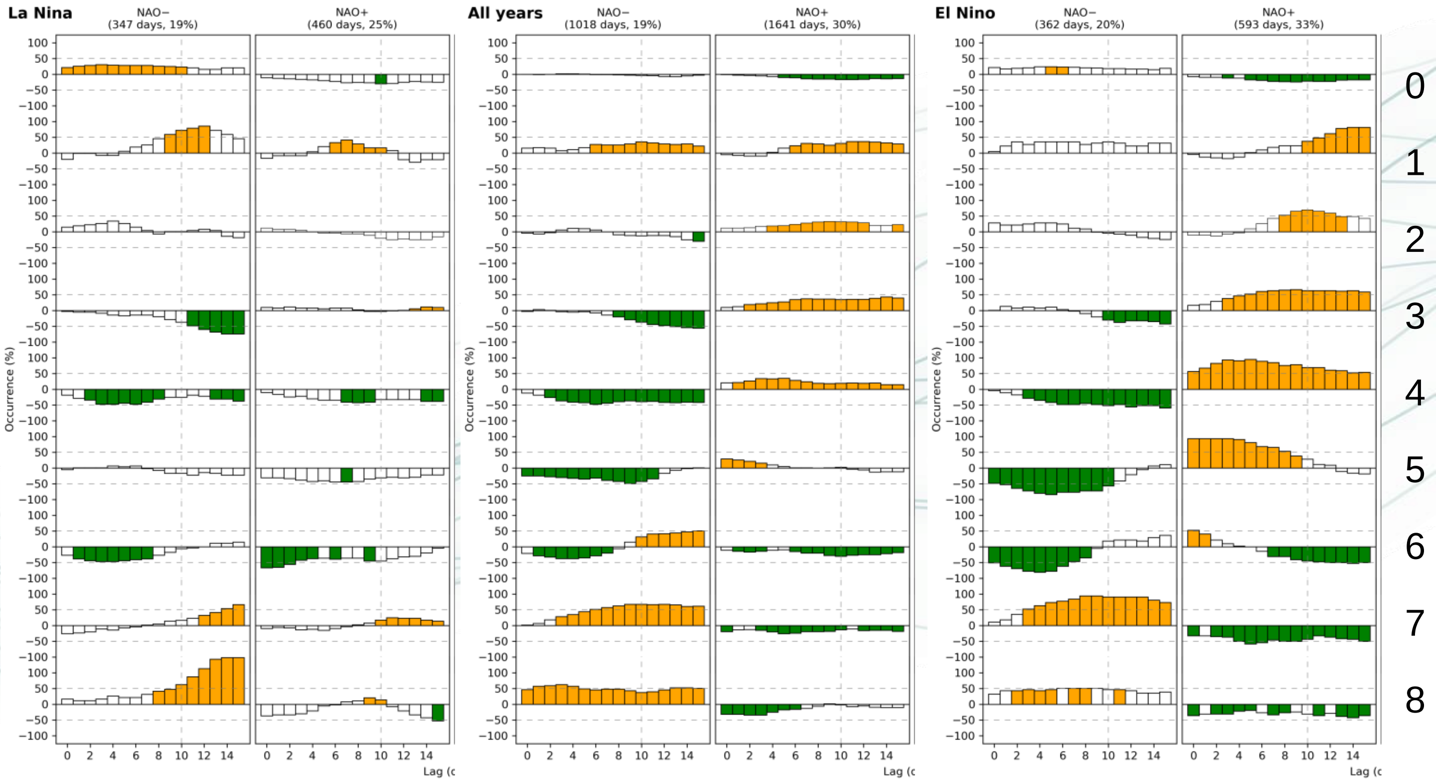
Dependence of MJO-NAO teleconnections on ENSO

- Analysis of NAO regime 1-15 days following MJO phases (after Cassou 2008, updated by Lee et al., in review)
- Increased occurrence of NAO+ regime after MJO phases 2-4
- Increased occurrence of NAO- regime after MJO phases 6-8
- Note each phase isn't independent because of cyclic nature of MJO
- Redo analysis but separate by El Niño / La Niña (Lee et al, in review)



Dependence of MJO-NAO teleconnections on ENSO

- Increased occurrence of NAO+ following MJO P3 in El Niño
- Reduced occurrence in La Niña
- Stronger but delayed teleconnection to NAO- in La Niña
- Changes in teleconnection may rectify onto mean state



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The Madden-Julian Oscillation

- The MJO is the dominant mode of sub-seasonal variability in the tropics
- Significant tropics-wide and global impacts on sub-seasonal timescales
- Significant levels of skill for MJO prediction out to days 15 (and beyond)
- Predictive skill for weather from the predictability of the MJO depends on both
    - Skill at prediction MJO evolution
    - Model's ability to capture the MJO impact
        - often well captured in the tropics (esp if directly related to precipitation)
        - Extra-tropical teleconnections less well captured
- MJO teleconnections are sensitive to slowly varying modes of the climate system
- MJO theory and modelling studies suggest an important role of the basic state moisture field in the maintenance and propagation of the MJO and its simulation

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MJO Forecast Skill

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