The Madden–Julian Oscillation

Frédéric Vitart

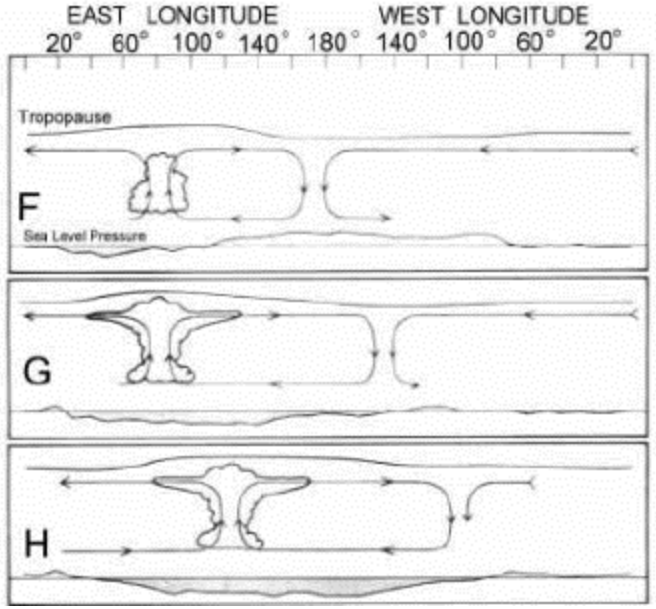
ECMWF

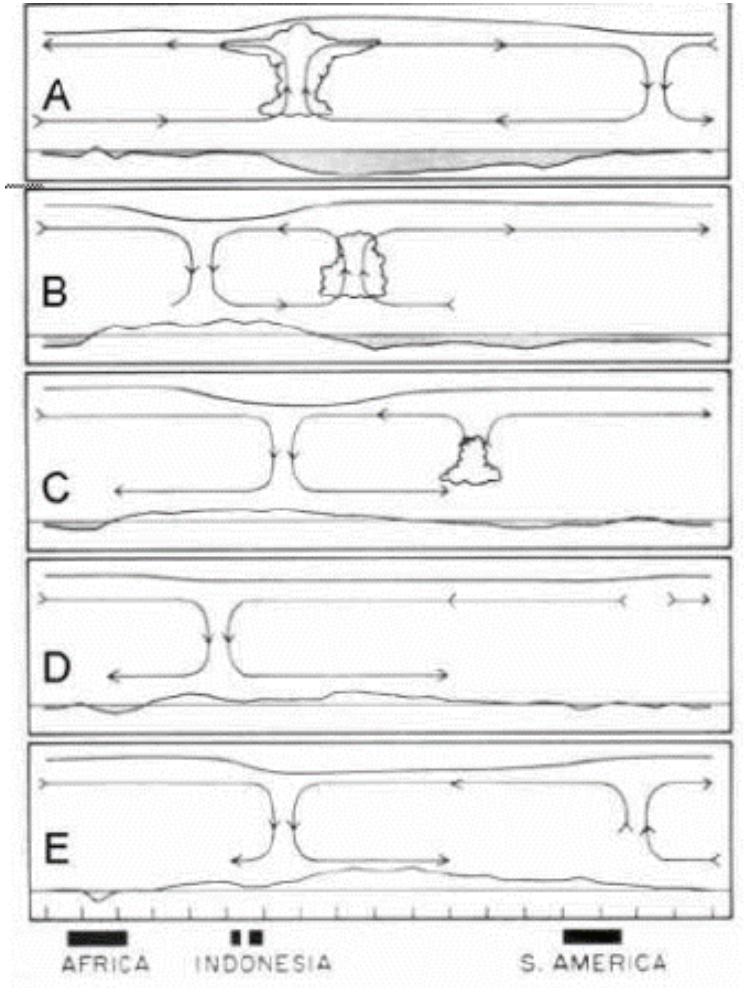


The Madden–Julian Oscillation (MJO)



Paul Julian
Roland Madden
AMS, 2013

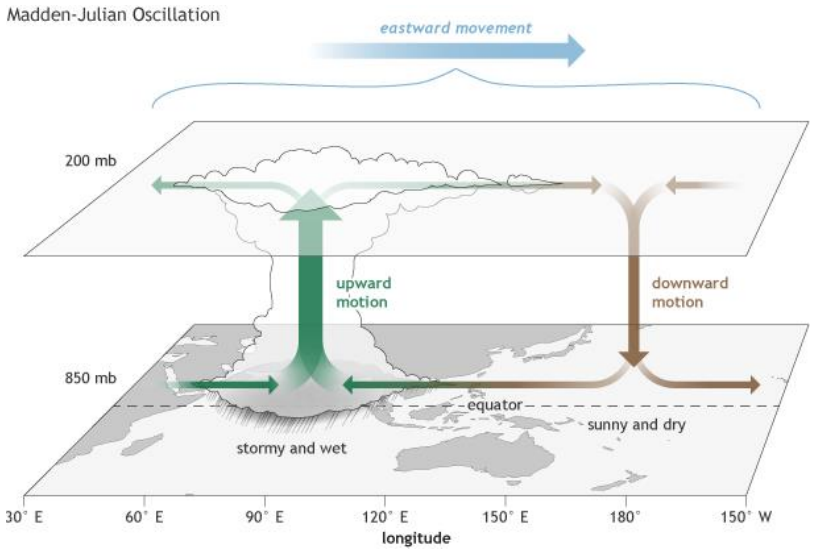




From Madden and Julian (1972)

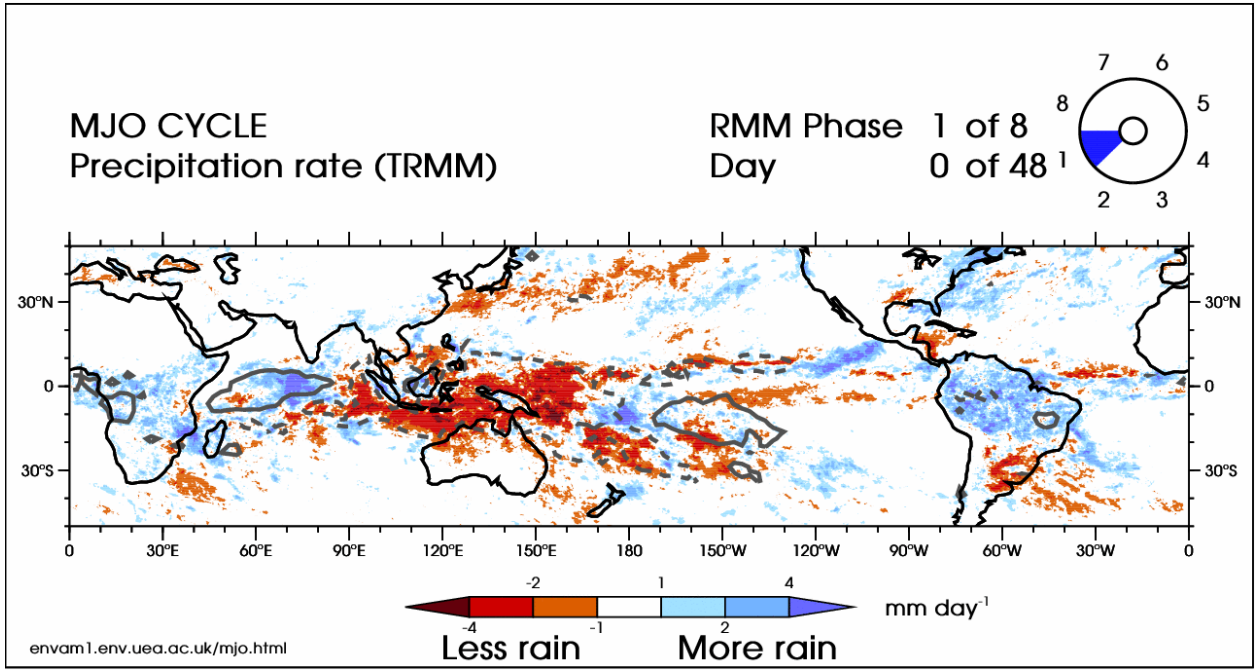
MJO structure and life cycle

MJO structure



Gottschalk et al., 2014

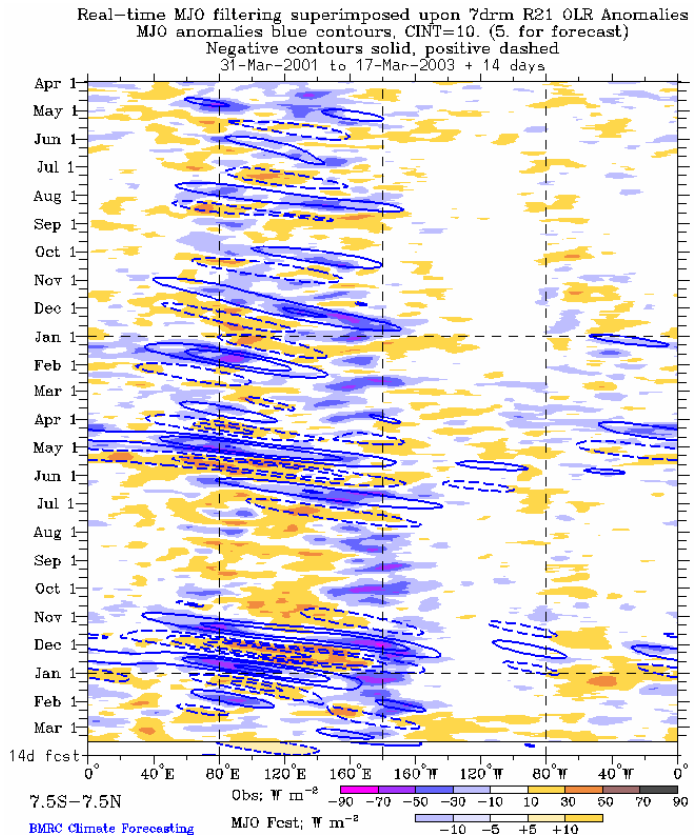
MJO life cycle



From http://envam1.env.uea.ac.uk/mjo.htm

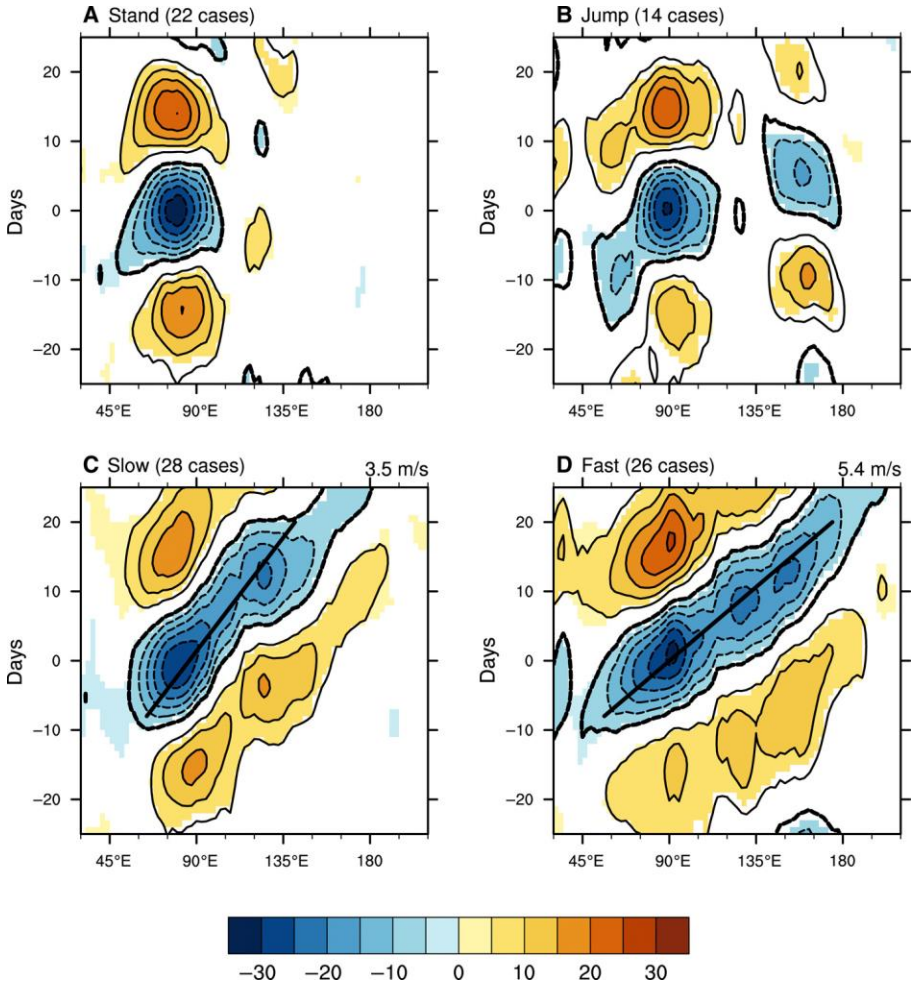
Diversity of Madden–Julian Oscillation events

OLR Hovmoeller 2001-2003



From http://www.bom.gov.au/bmrc/clf

4 types of MJO propagation



Wang et al. 2019

What is the MJO?

- The MJO is a 40–50-day oscillation.
- It is a near-global, quasi-periodic disturbance in surface pressure, tropospheric temperature and zonal winds. It moves eastward along the equatorial belt at 4–8 m/s, too slowly to be a Kelvin wave.
- The MJO is the dominant mode of tropical variability on timescales longer than a week and shorter than a season.
- Activity peaks during Northern Hemisphere winter and spring.

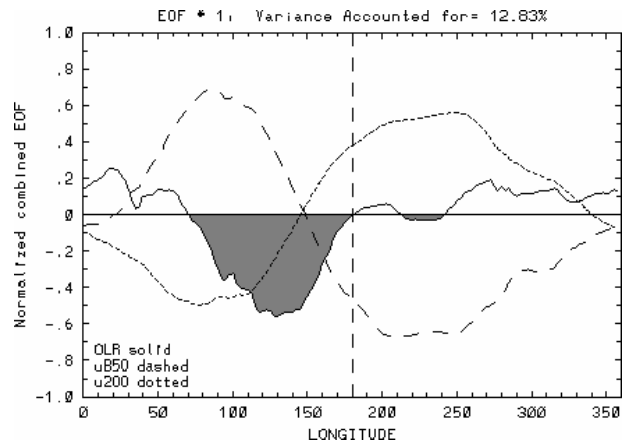
Theories for MJO onset

- Local recharge/discharge processes (e.g. Hendon 1988, Blade and Hartmann 1993, Hu and Randall 1994)
- Upstream effects of circumnavigating waves (e.g. Knutson et al. 1986, Knutson and Weickmann 1987, Lau and Peng 1987)
- Stochastic forcing (Wilson and Mak 1984, Neelin and Yu 1994, Yu and Neelin 1994)
- Extratropical influences (e.g. Lau and Peng 1987, Hsu et al. 1990, Lin et al. 2007, Ray et al. 2010, Wedi and Smolarkiewicz 2010)

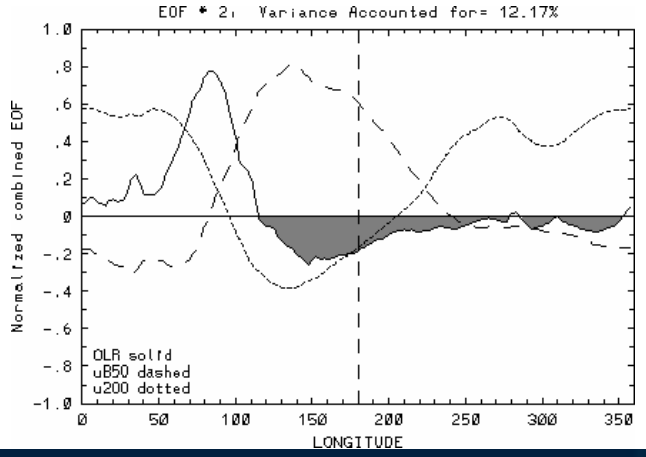
Diagnosing the MJO

The real-time multivariate MJO (RMM) index

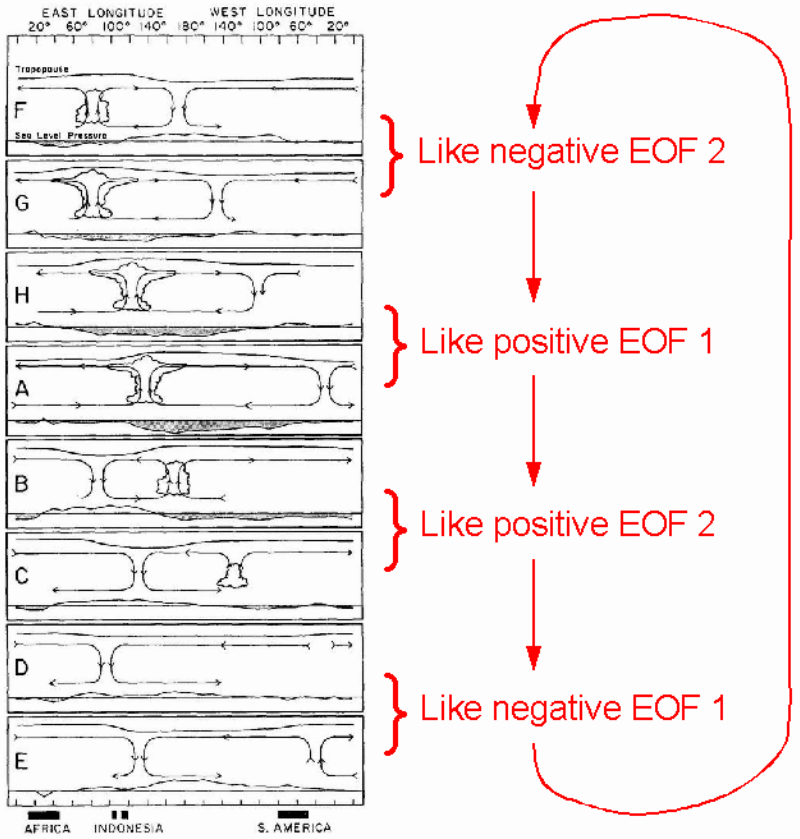
Combined EOF1



Combined EOF2



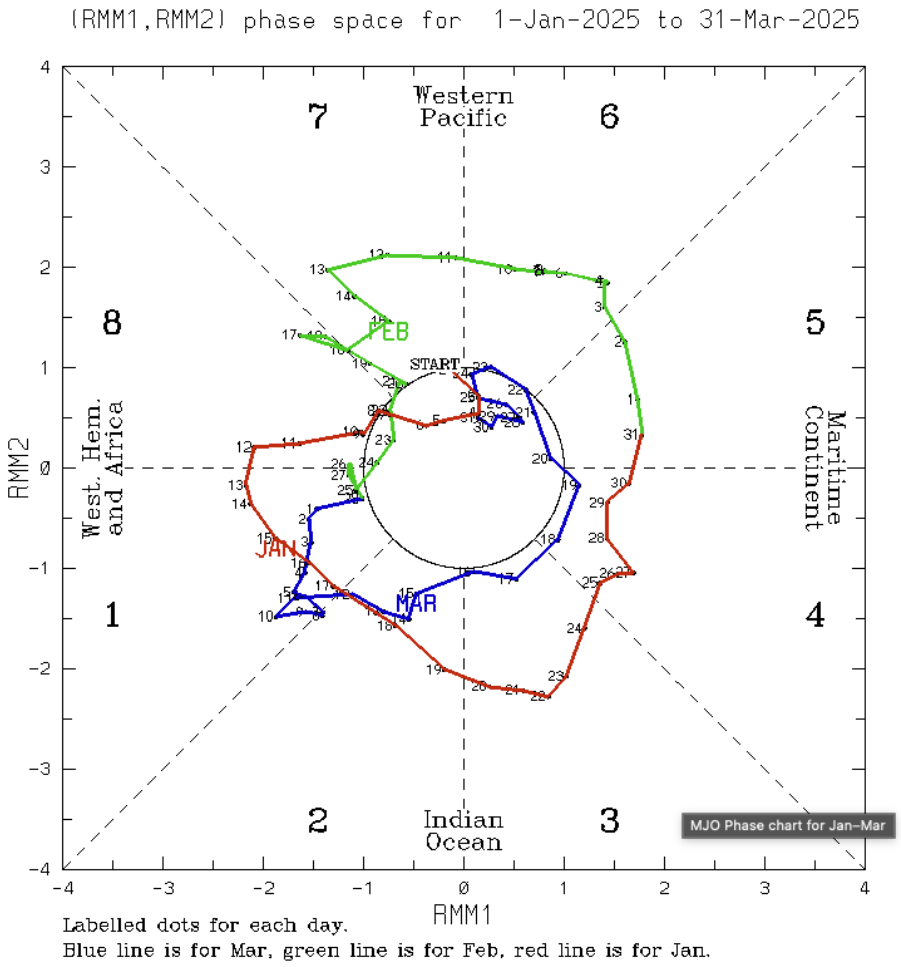
Madden and Julian's (1972) schematic



From Wheeler and Hendon, 2004

- Daily OLR/U200/U850 from NCEP re-analysis 1979-2001
- Averaged over latitudinal band 15N-15S
- 2.5-degree resolution (144 longitudinal points)
- Remove ENSO signal and slow variability (interannual to trends)
- Compute combined EOF patterns

MJO in RMM phase space



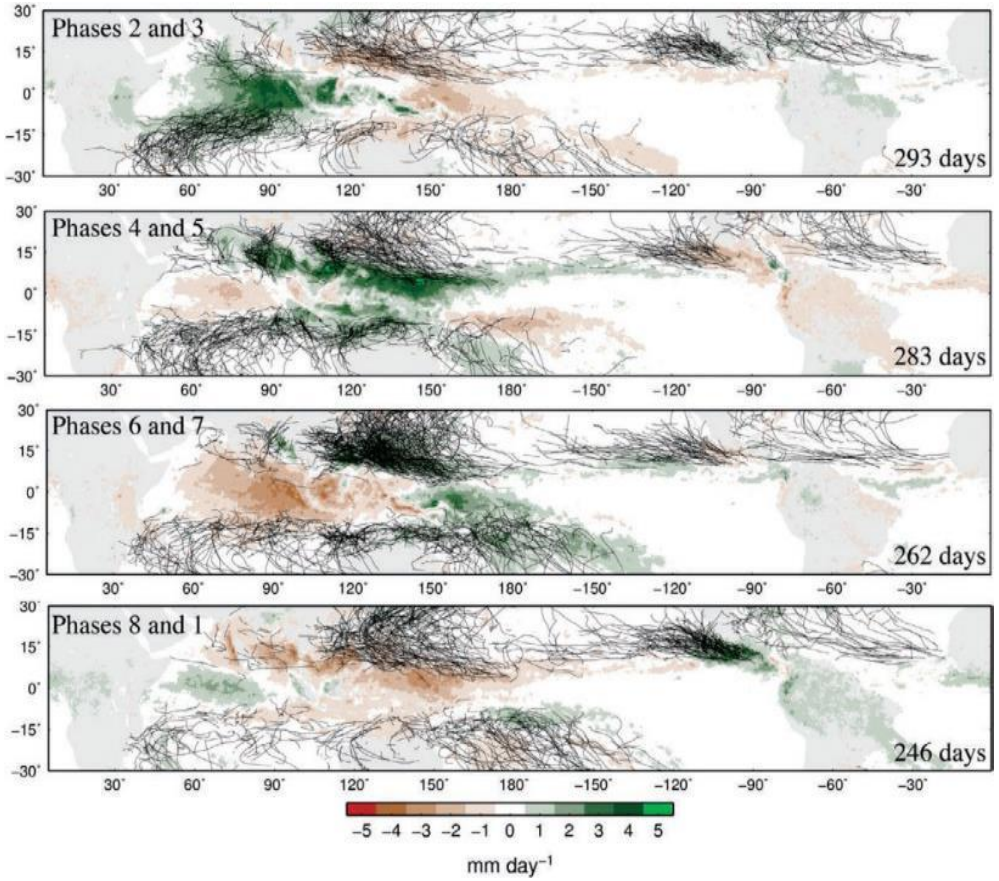
(C) Copyright Commonwealth of Australia Bureau of Meteorology

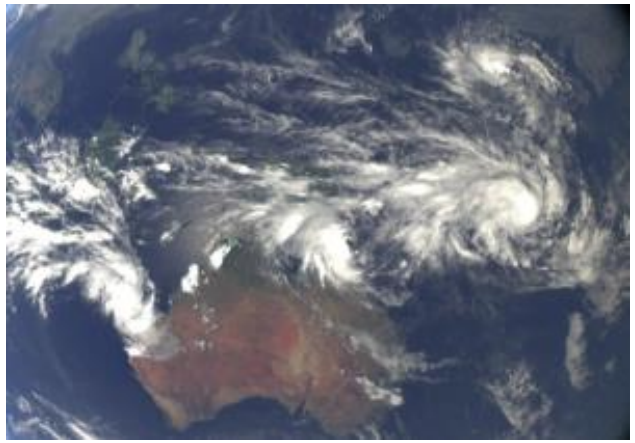
MJO phase diagram

Why do we care about the MJO?

- Indian and Australian summer monsoons (Yasunari 1979, Hendon and Liebman 1990)
- ENSO: westerly wind bursts produce equatorially trapped Kelvin waves that affect the onset and development of El Niño (Kessler and McPhaden 1995)
- Tropical storms (Maloney et al. 2000, Mo 2000)
- Northern Hemisphere weather

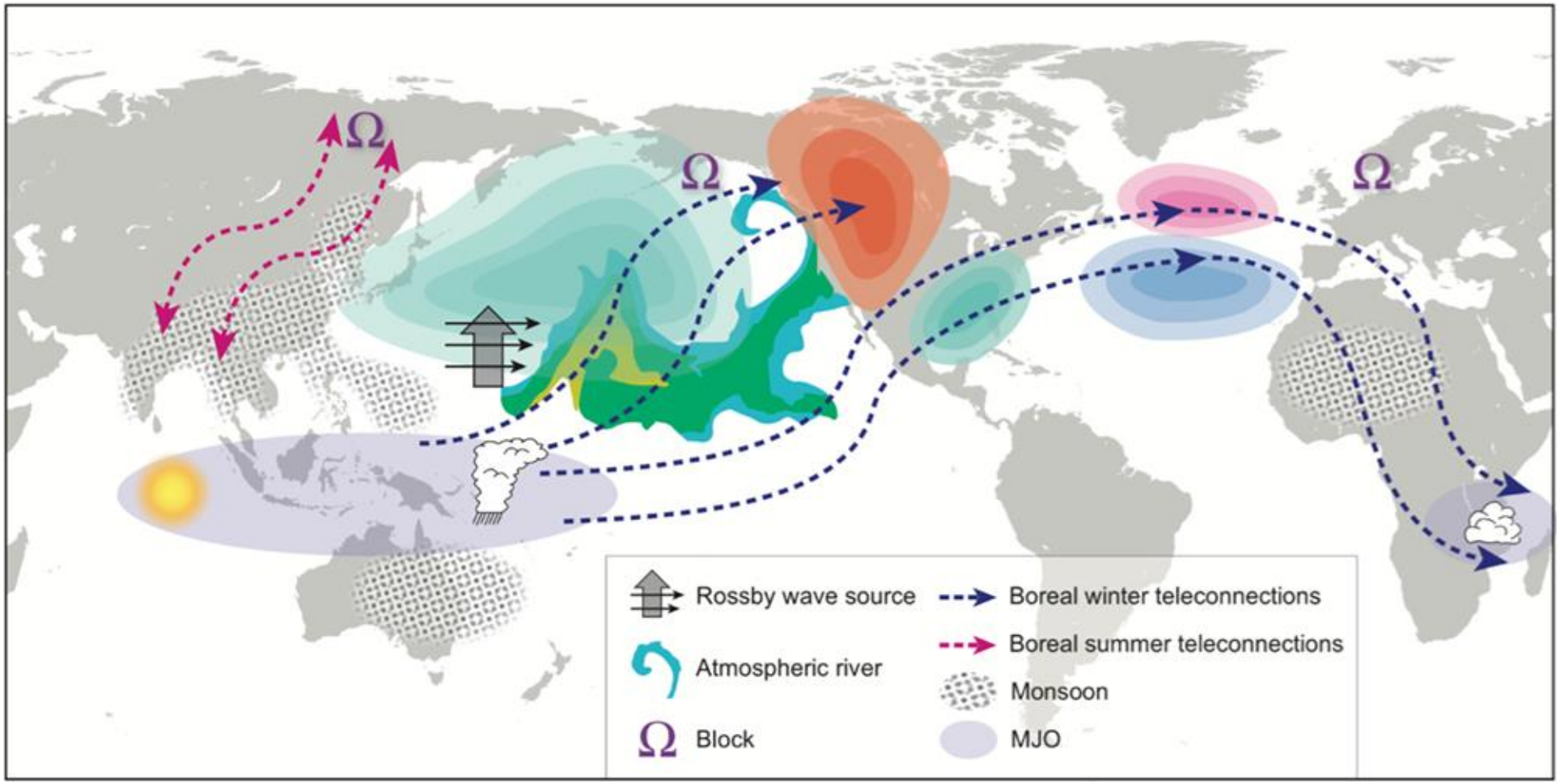
Impact of the MJO on tropical cyclone activity





Zhang 2013

Impact of the MJO on the northern extratropics

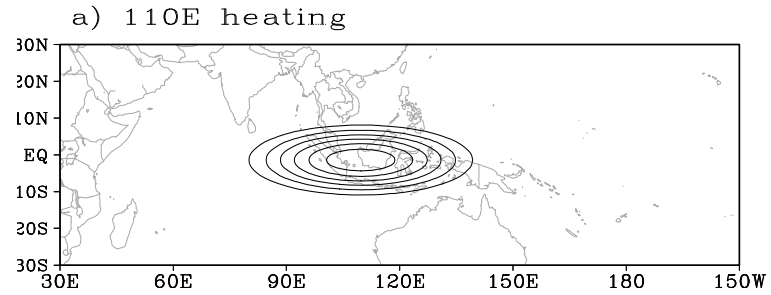


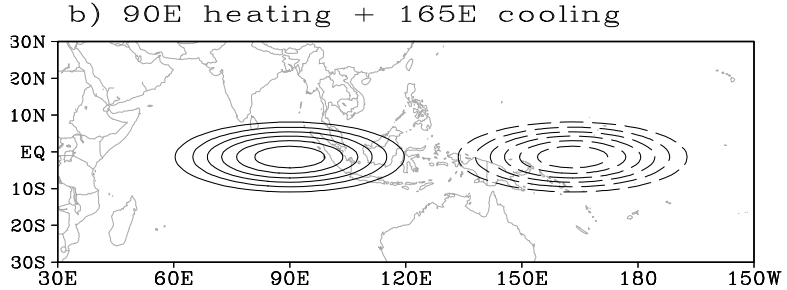
Stan et al., 2017

Impact of the MJO on the northern extratropics

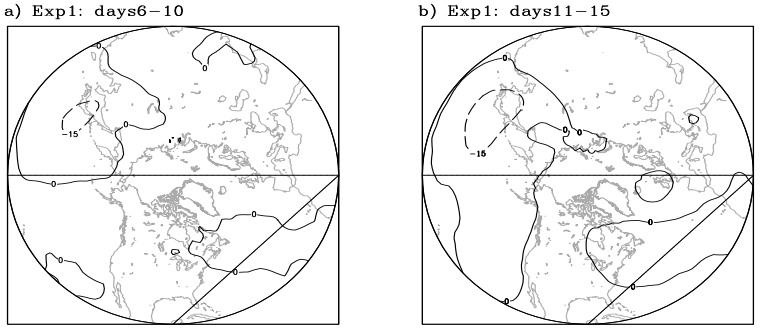
- *Simmons et al JAS 1983*
- *Ferranti et al. JAS 1990*
- *Ting and Sardeshmukh JAS 1993*
- *Lin et al, MWR 2010*

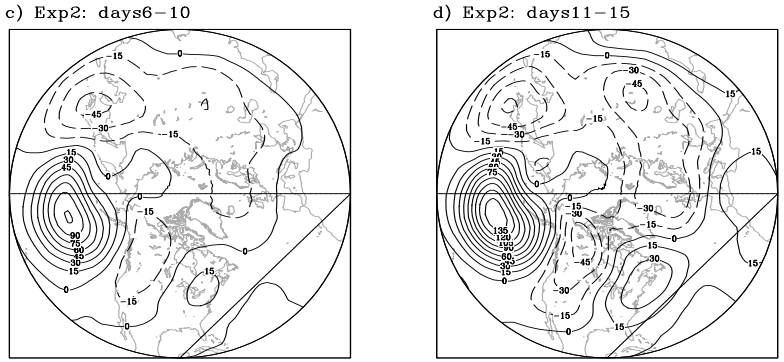
Forcing





500 hPa geopotential response





Lin et al., MWR 2010

Impact of the MJO on Euro-Atlantic weather regimes

MJO Phase 1

MJO Phase 2

MJO Phase 3

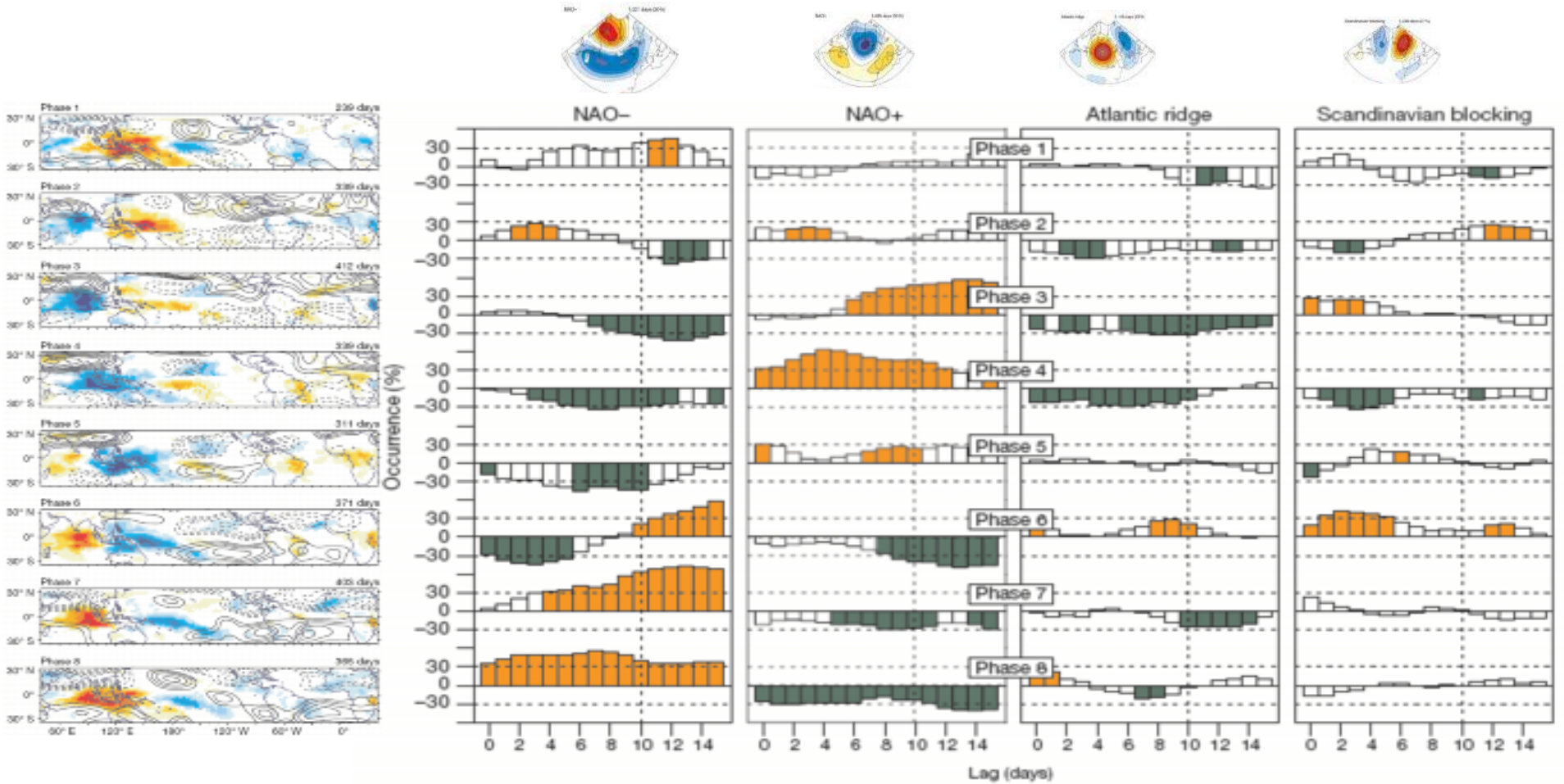
MJO Phase 4

MJO Phase 5

MJO Phase 6

MJO Phase 7

MJO Phase 8

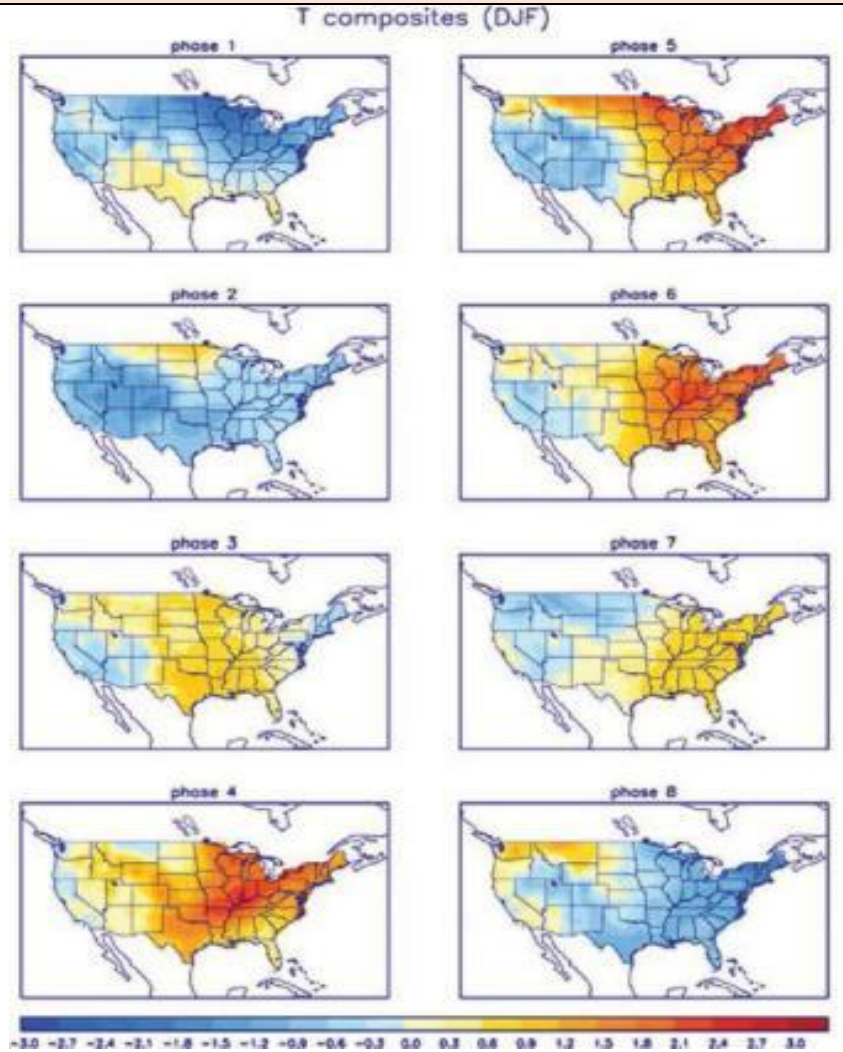


Cassou C,2008: Intraseasonal interaction between the Madden-Julian Oscillation and the North Atlantic Oscillation. *Nature*, **455**, 523-527.

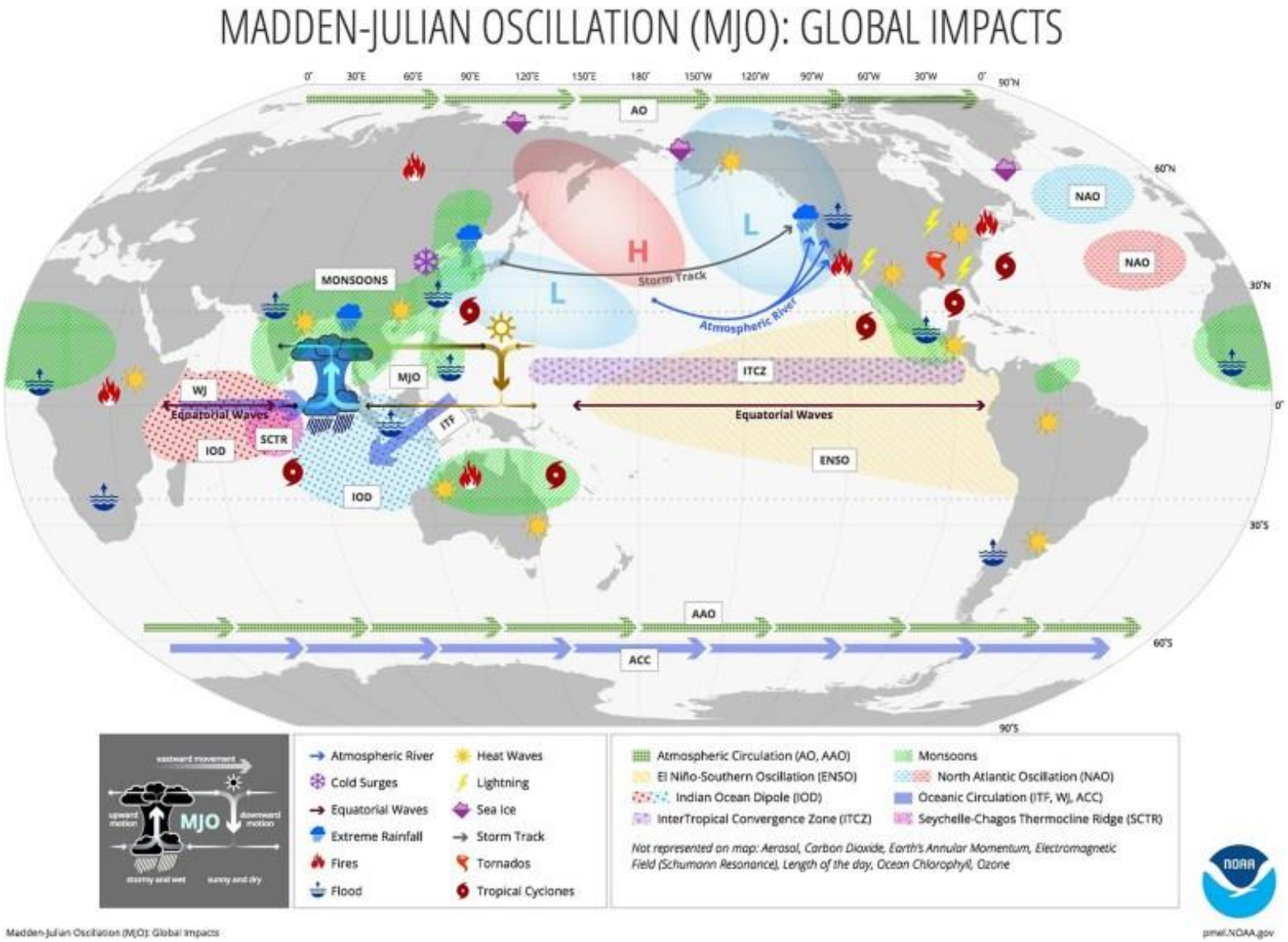
NAO+ (NAO−) becomes more likely after active MJO over the Indian Ocean (western Pacific)

Impact of the MJO on the northern Extratropics

MJO influences on wintertime (December–February) surface air temperature over the United States



Impact of the MJO on extreme events



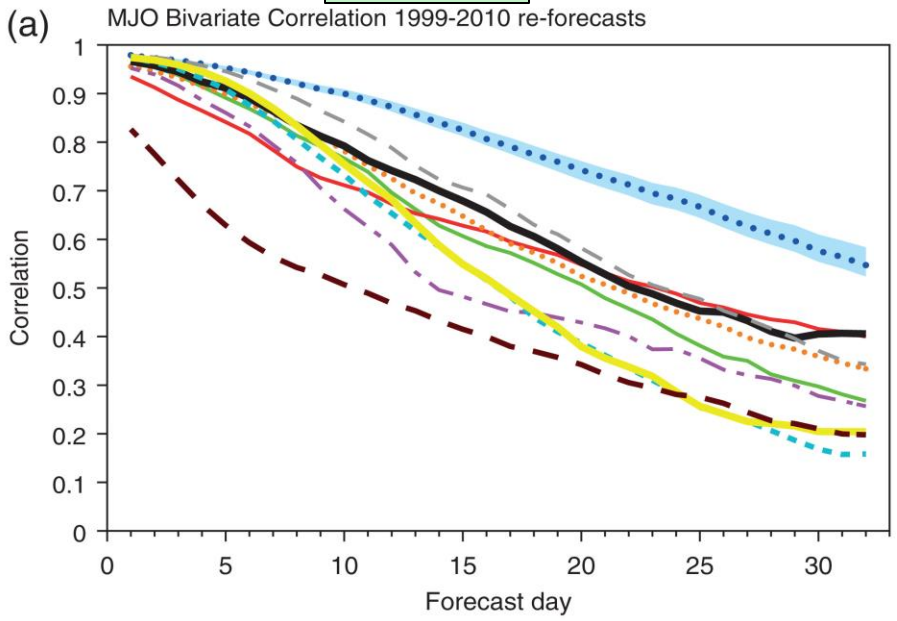
Madden-Julian Oscillation (MJO): Global Impacts

MJO prediction

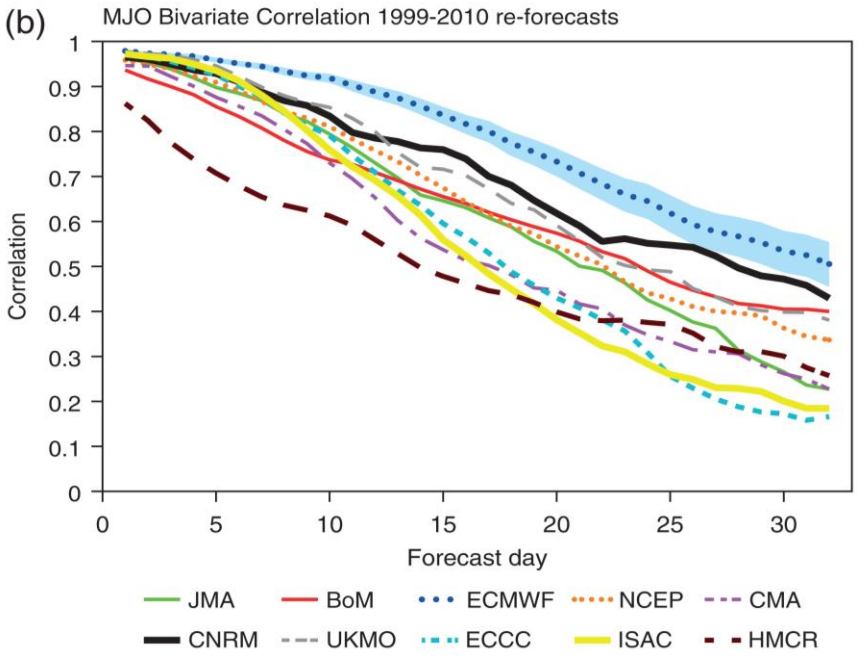
MJO forecast skill scores

Bivariate correlation of forecast ensemble-mean RMM1 and RMM2 with ERA5 RMM1 and RMM2, as a function of lead time

All year



Boreal Winter

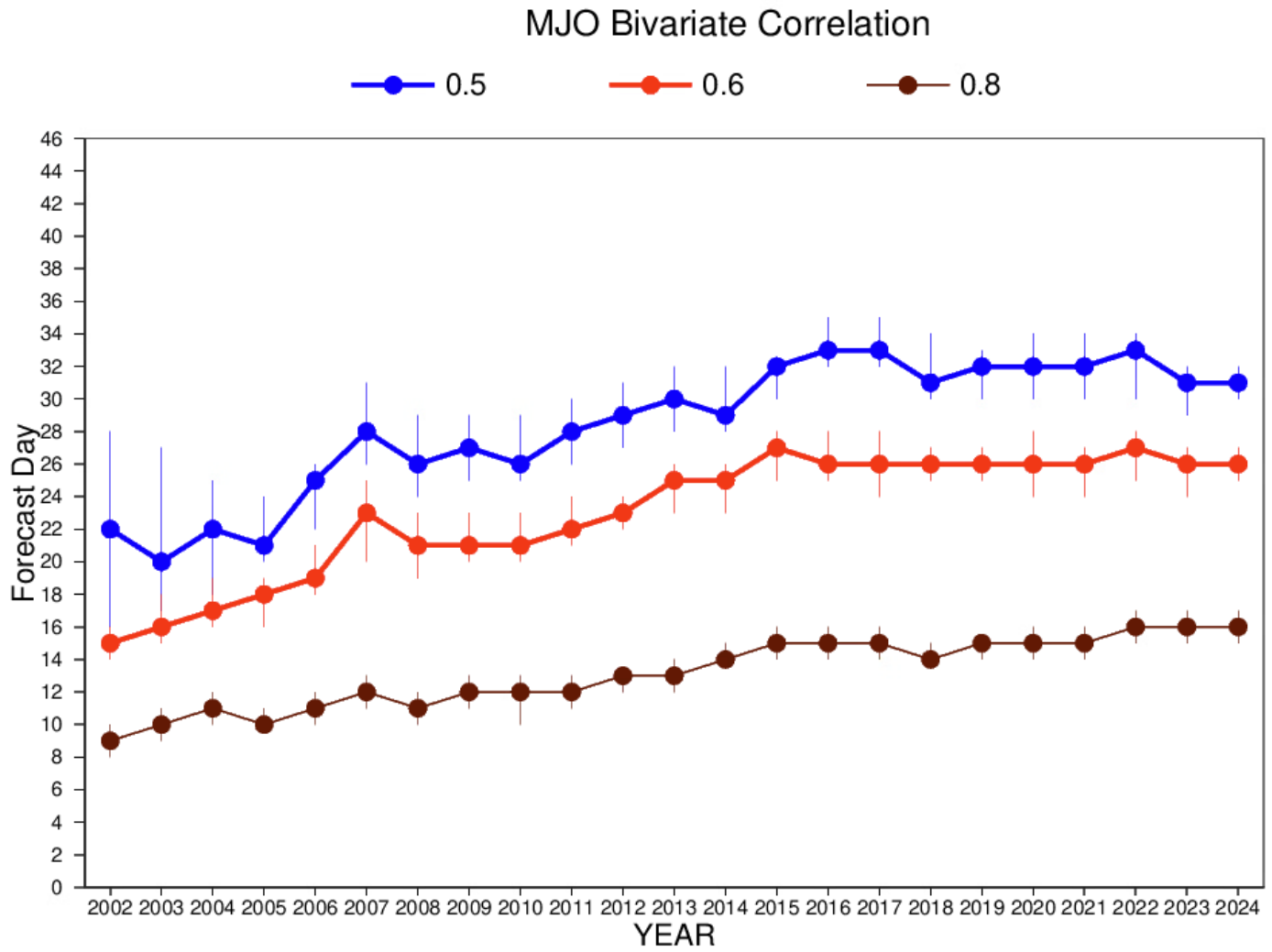


MJO forecast skill horizon up to 4 weeks

Vitart, 2017

$$\mathrm{COR}(\tau) = \frac{\sum_{t=1}^{N}\left[RMM1(t)\cdot rmm1(t,\tau) + RMM2(t)\cdot rmm2(t,\tau)\right]}{\sqrt{\sum_{t=1}^{N}\left[rmm1(t,\tau)^2 + rmm2(t,\tau)^2\right]}\sqrt{\sum_{t=1}^{N}\left[RMM1(t)^2 + RMM2(t)^2\right]}}$$

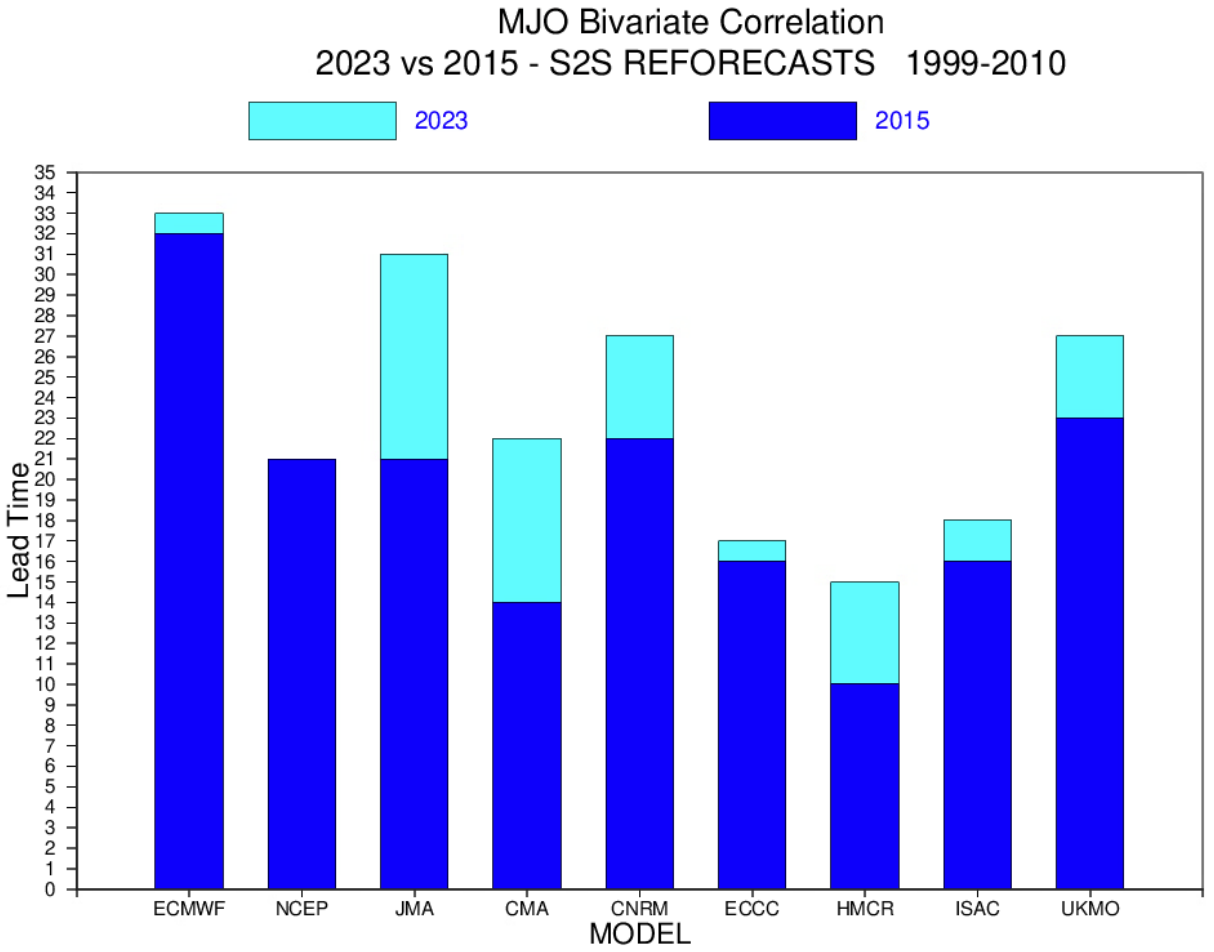
MJO forecast skill is improving



Lead time at which MJO bivariate correlation falls to 0.5, 0.6 and 0.8

MJO forecast skill is improving

Lead time at which MJO bivariate correlation falls to 0.5 for S2S models operational in 2015 and 2023

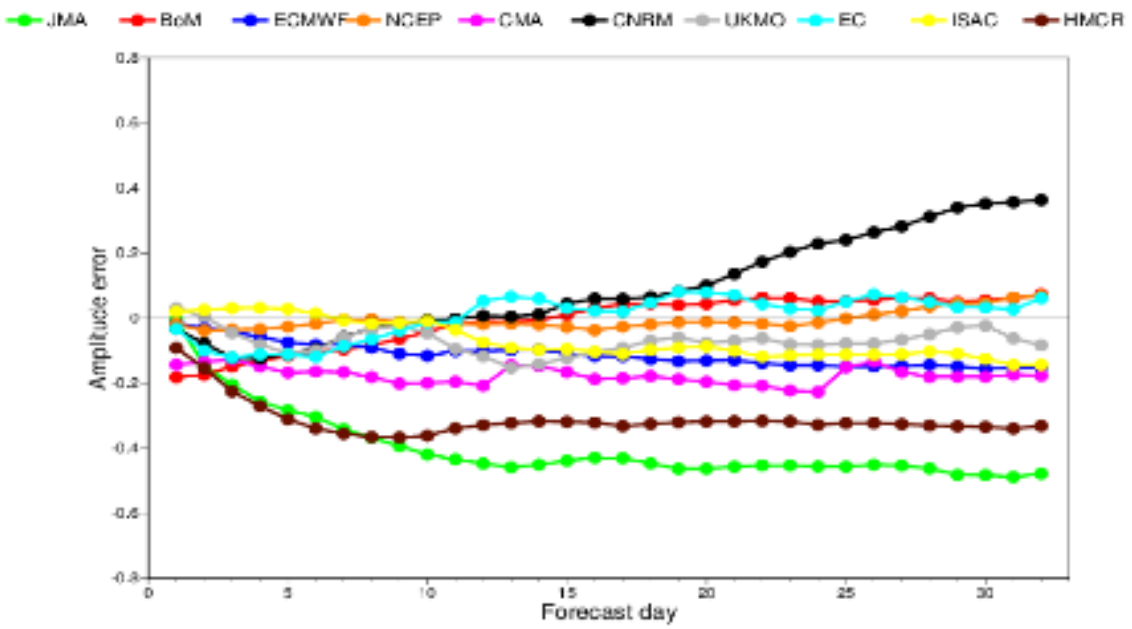


Vitart et al. 2024

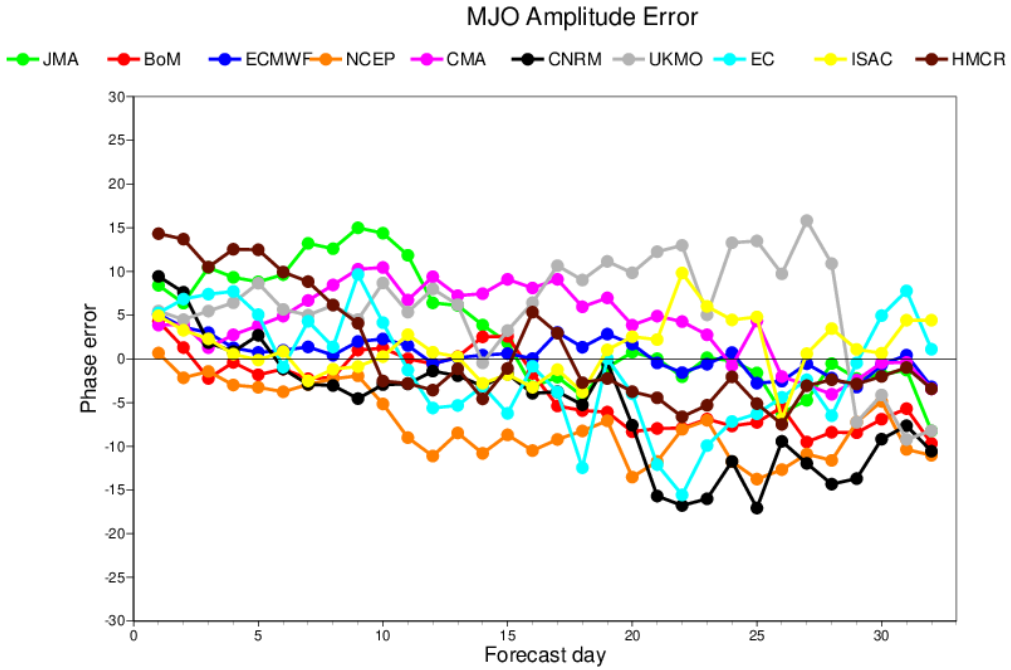
MJO prediction skill in the S2S database has increased since 2015

Errors in MJO prediction

MJO amplitude error vs ERA-Interim



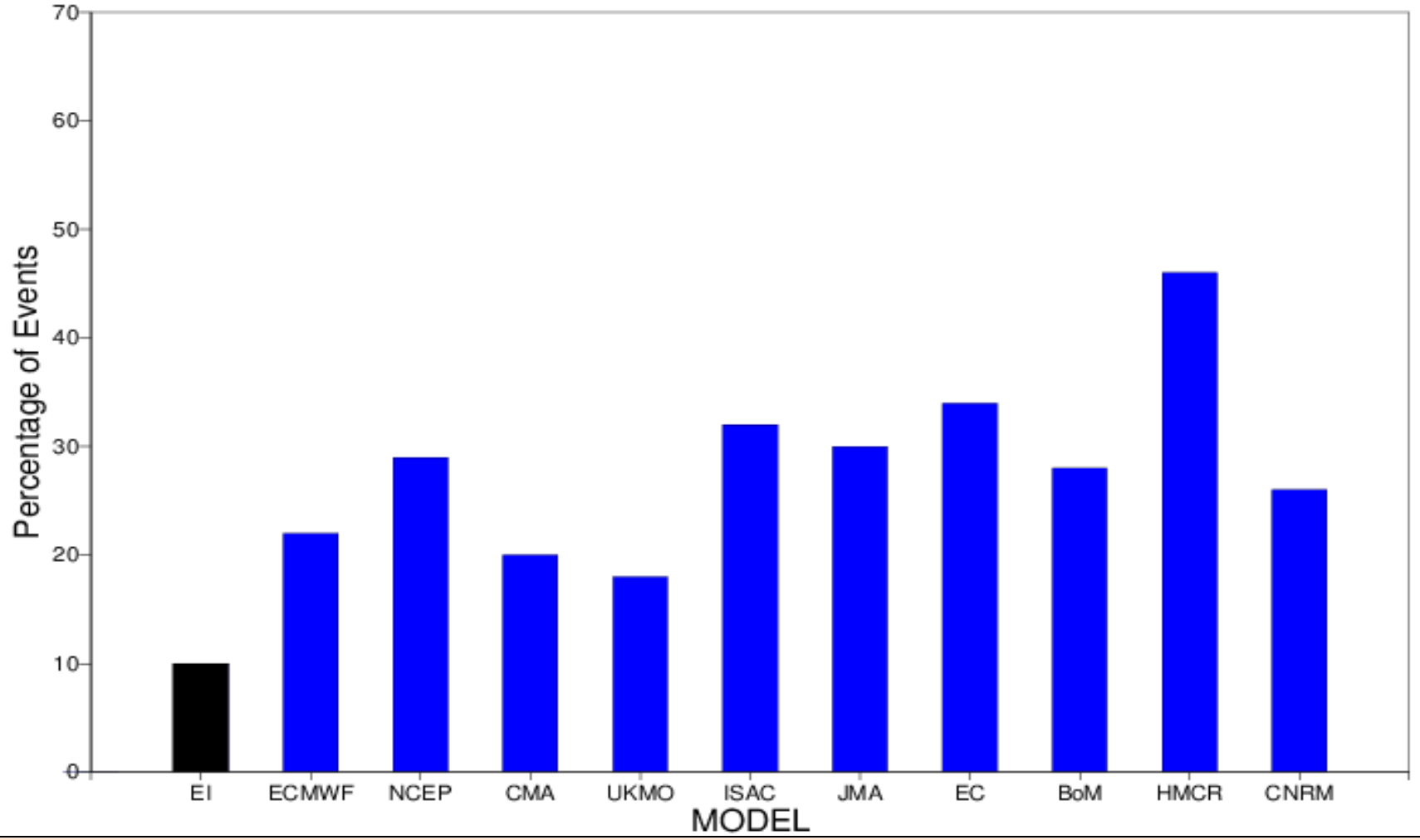
MJO phase error vs ERA-Interim



Vitart 2017

- MJO is generally too weak in S2S models
- MJO propagation slows down with lead time

The Maritime Continent barrier

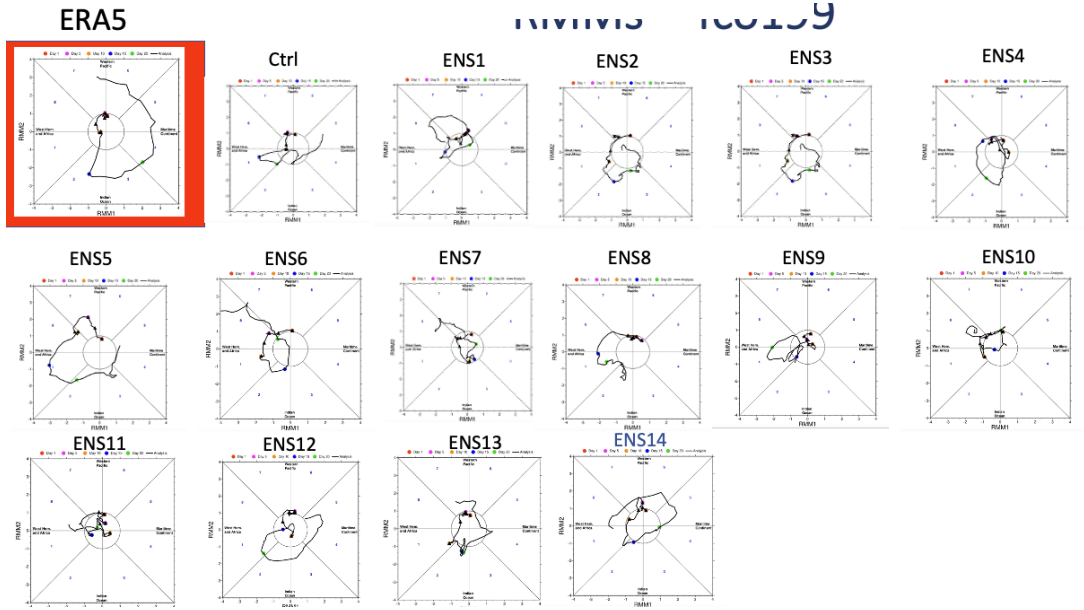


Vitart 2017

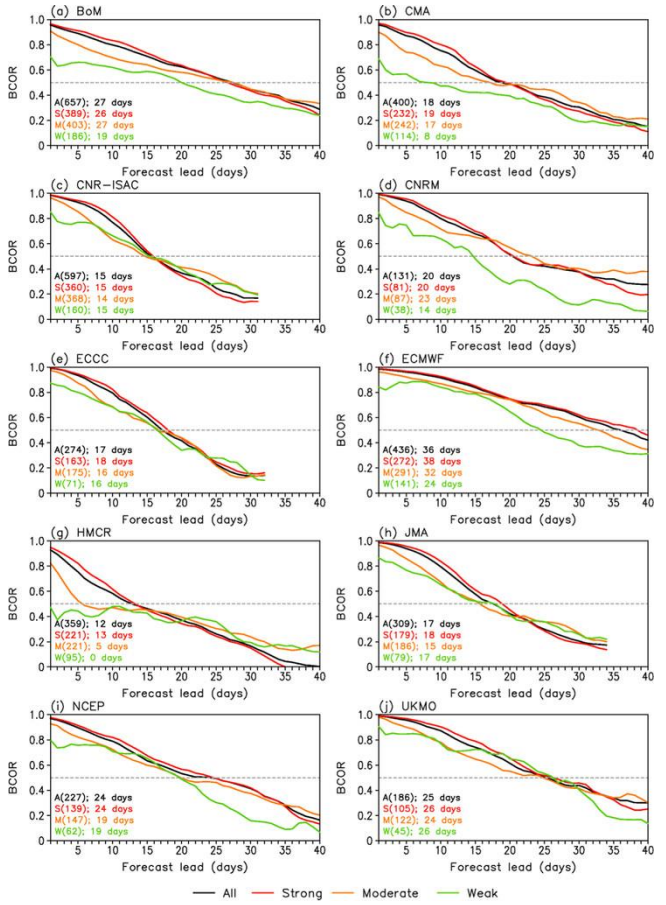
More MJO events dissipate over the Maritime Continent in S2S models than in reanalysis

MJO onset prediction is particularly challenging

April 2019 MJO event
forecasts starting 10 days before onset

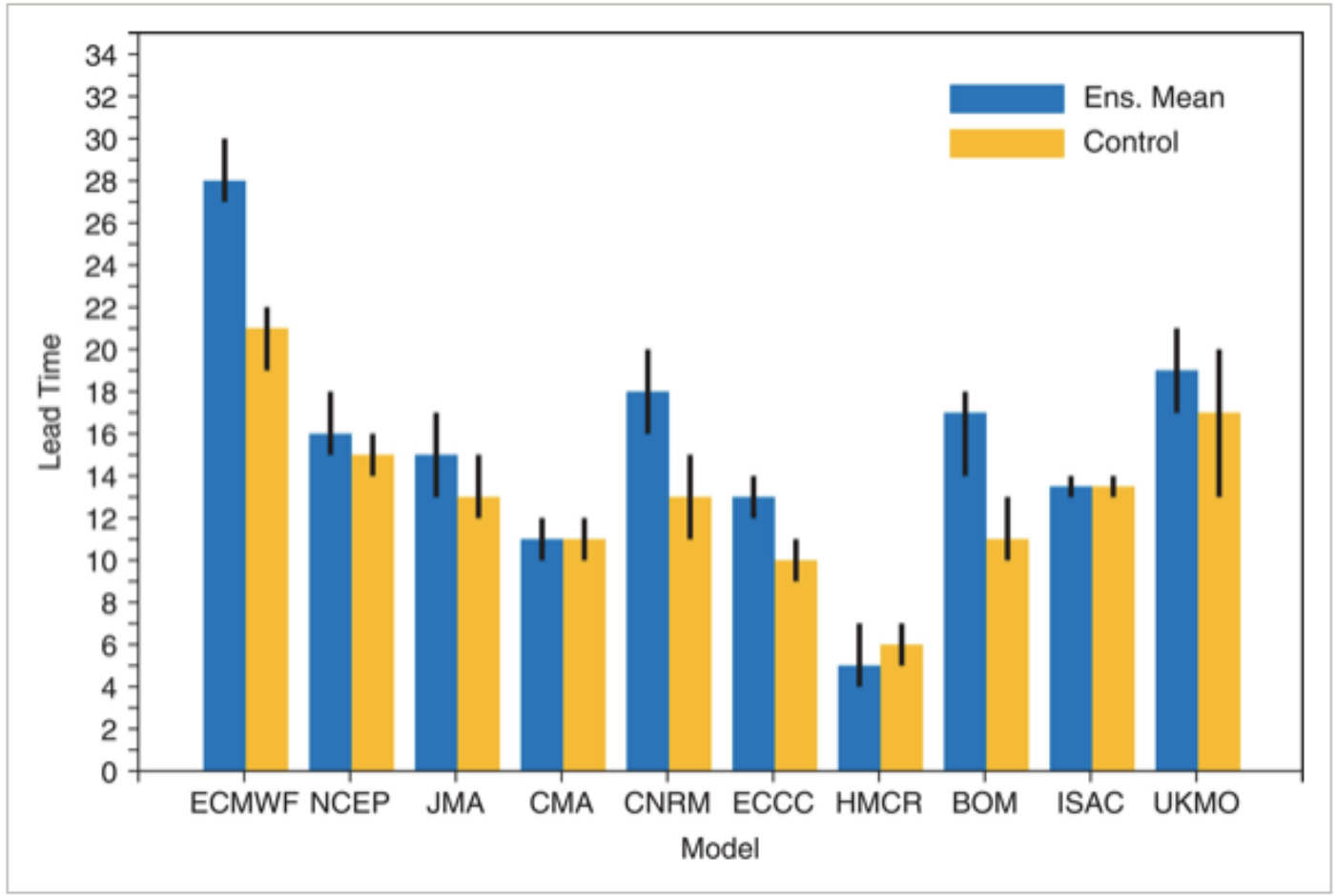


MJO forecast skill by initial MJO intensity



Lim et al., 2018

MJO ensemble prediction



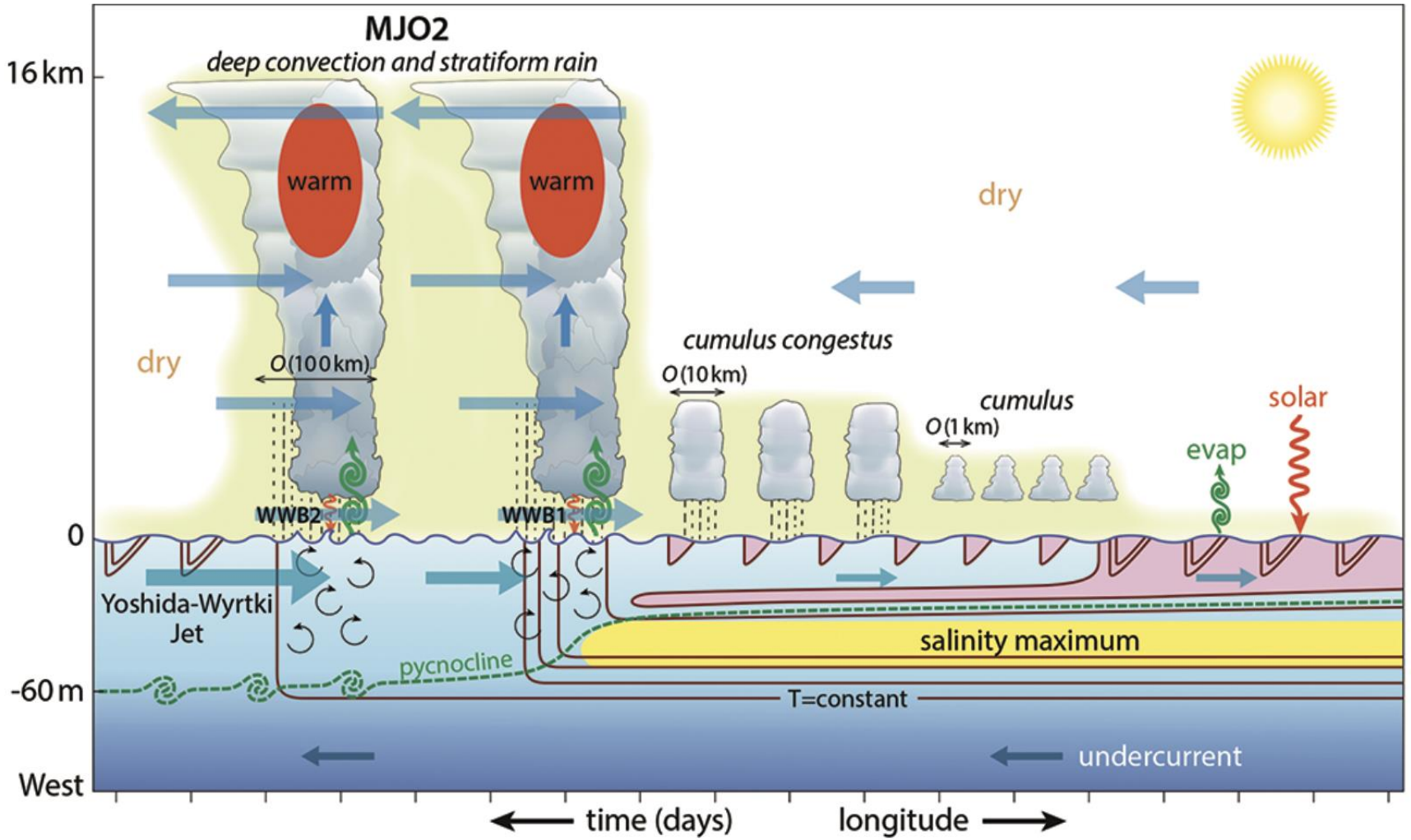
Vitart 2017

Ensemble forecasts of the MJO are more skilful than individual members

Simulation of the MJO

- Horizontal resolution: not important
- Vertical resolution: positive impact
- Air–sea coupling: positive impact, but not crucial
- Convection scheme: crucial

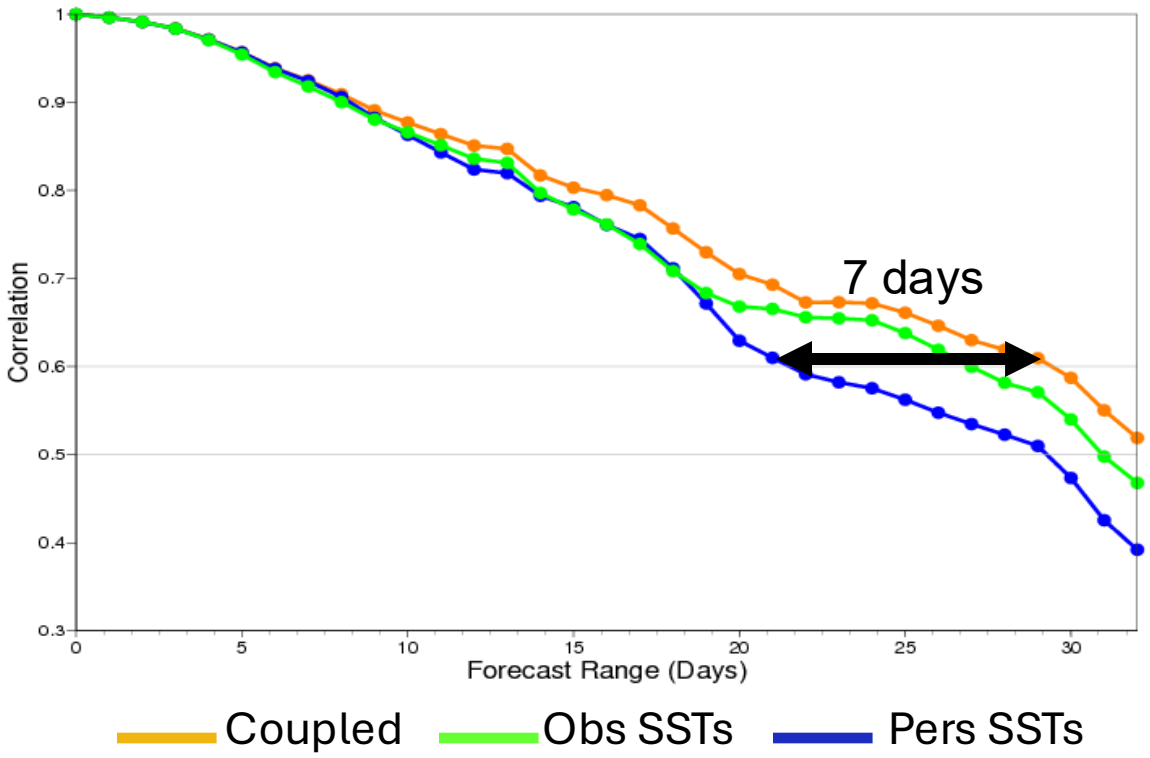
Air-sea interaction



Moum et al., 2014

Impact of ocean-atmosphere coupling on MJO skill

MJO Bivariate Correlation
80 cases, starting on 1st Feb/May/Aug/Nov 1989-2008



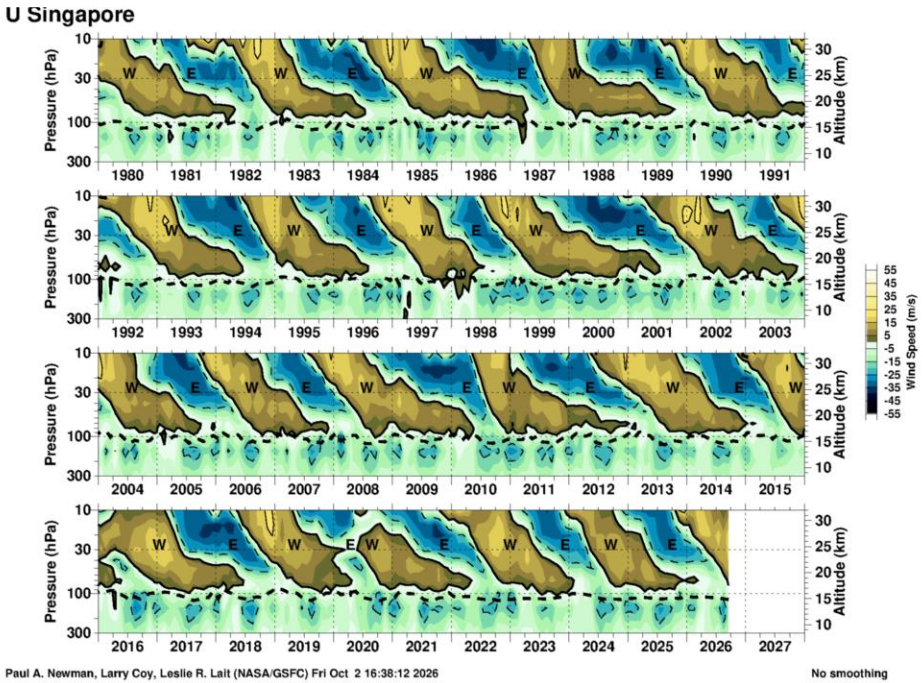
The uncoupled model has skill in predicting MJO evolution.

- Ocean–atmosphere coupling significantly extends the MJO forecast skill horizon.
- The coupled model outperforms an atmospheric model forced by observed SSTs.

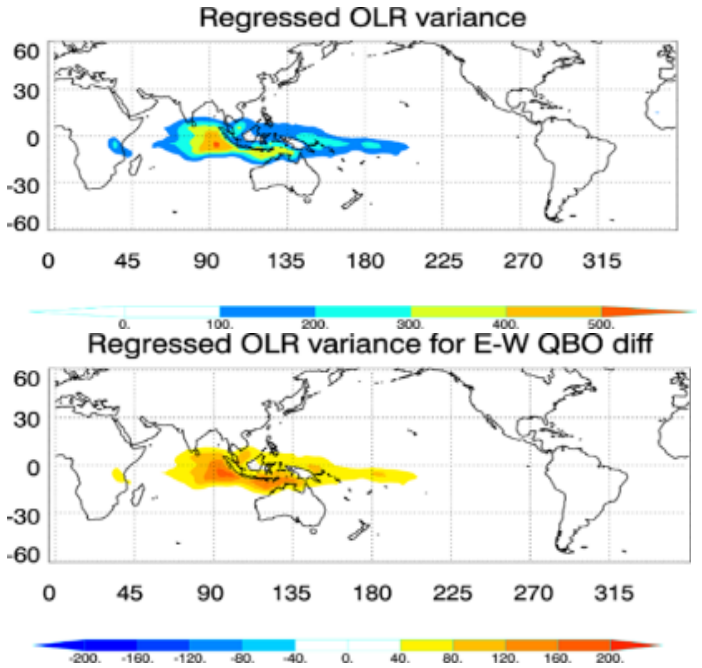
Impact of the QBO on the MJO

The quasi-biennial oscillation (QBO)

Singapore sonde monthly mean zonal wind, 1980–present



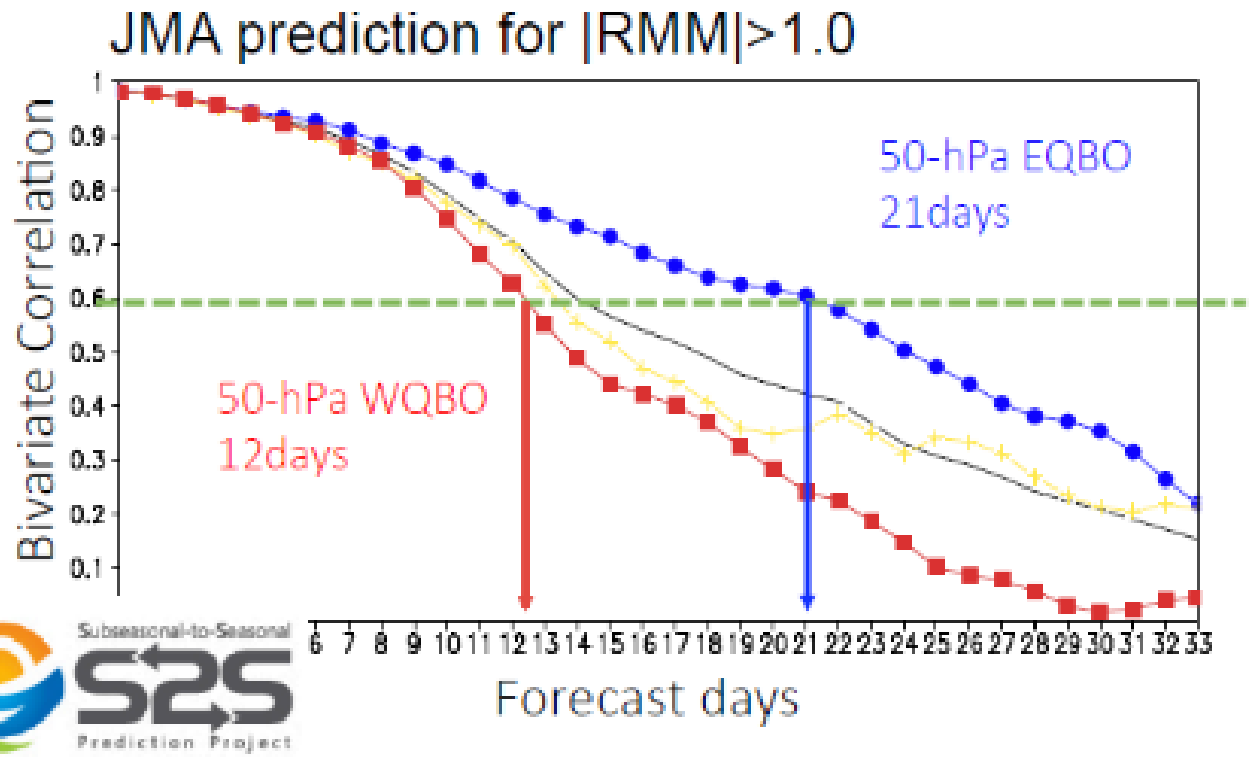
MJO OLR variance (DJF), reconstructed from RMM



Yoo and Son 2016

Two proposed mechanisms for impacts on tropical convection
1) Tropopause stability: a lower, more stable tropopause in the westerly phase may reduce convection and make the heating profile less top-heavy (Nie and Sobel 2015).
2) Vertical wind shear: weaker tropopause shear over the equatorial Indian Ocean and western Pacific in the easterly phase may favour stronger convection.

Impact of the QBO on the MJO



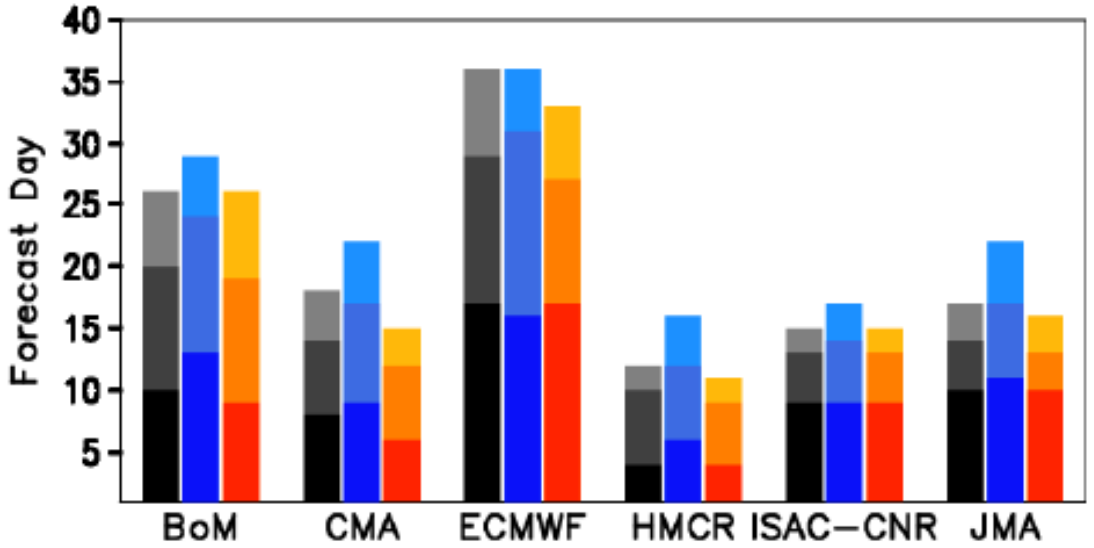
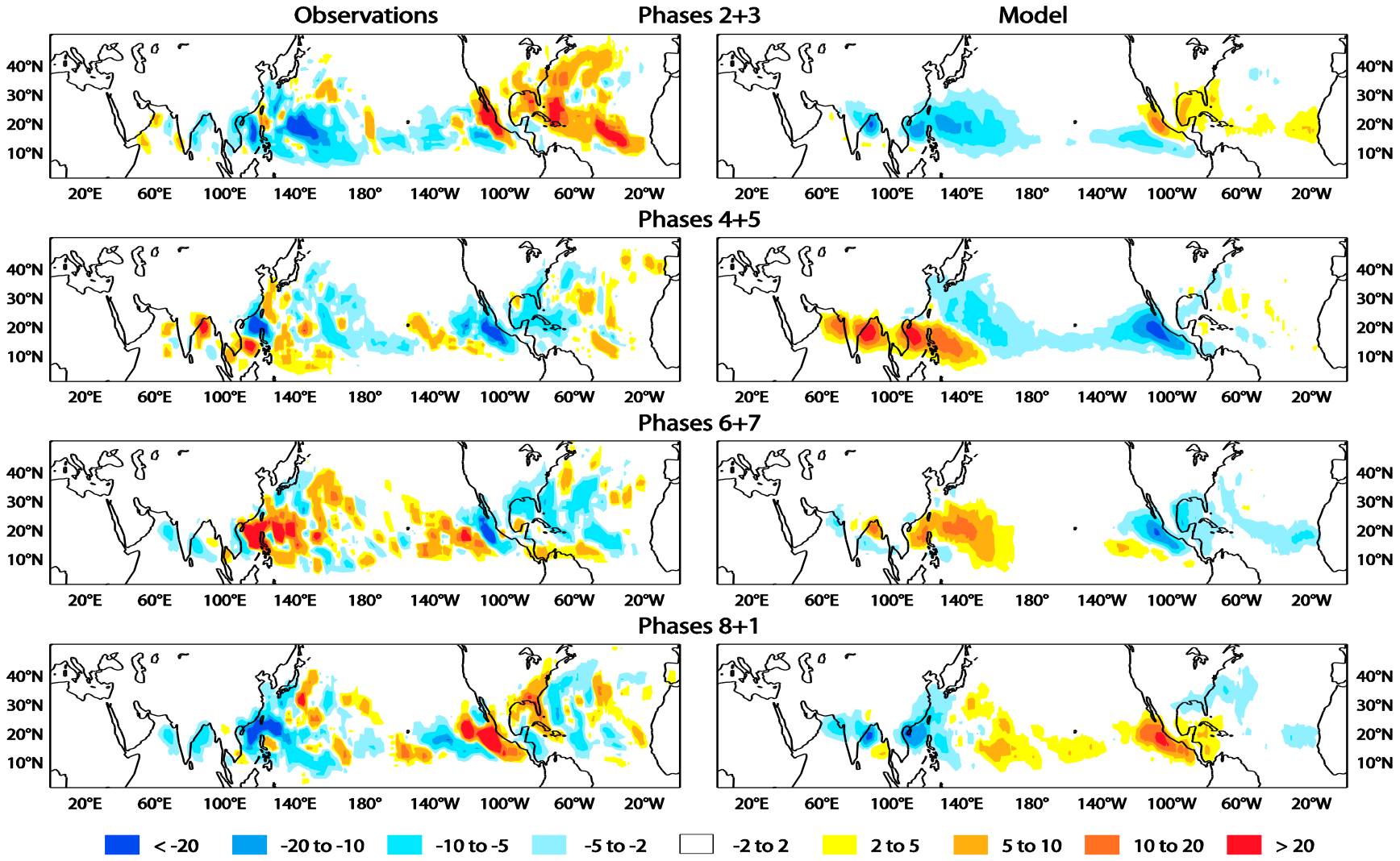


Figure 4. MJO prediction skill for six models. Light, medium, and Dark bars indicate respectively day when the MJO bivariate correlation reaches 0.5, 0.6, and 0.8

S2S models show higher forecast skill during easterly than westerly QBO phases

Sub-seasonal prediction of MJO impacts

Impact on tropical cyclone density

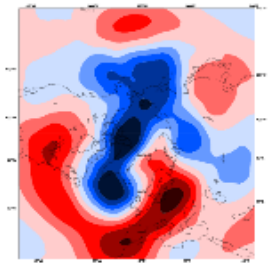


- ECMWF sub-seasonal forecasts reproduce MJO modulation of tropical cyclone activity.
- They underestimate the impact over the North Atlantic and eastern Pacific.

Impact of the MJO on the northern extratropics

Composite 500 hPa geopotential height anomaly, 3 pentads after MJO phase 3

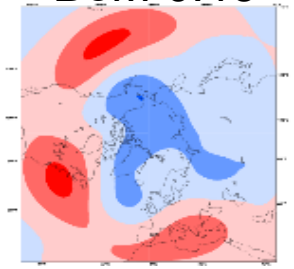
EI 0.48



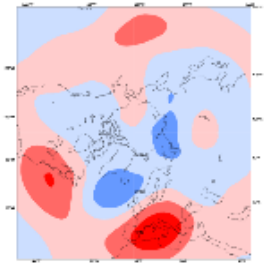
NAO Index: mean=0, std=1.02



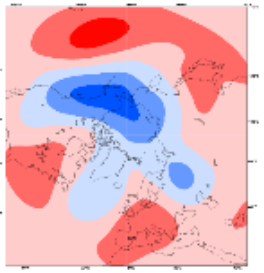
BoM 0.15



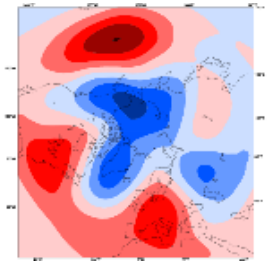
CMA 0.14



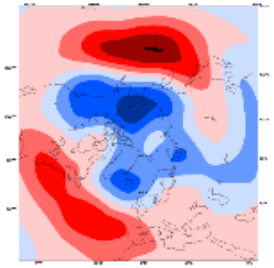
HMCR 0.13



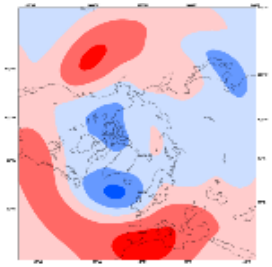
NCEP 0.32



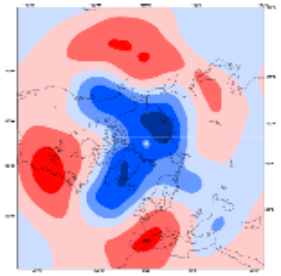
ISAC 0.25



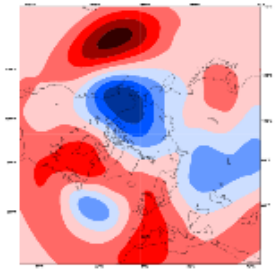
CNRM 0.15



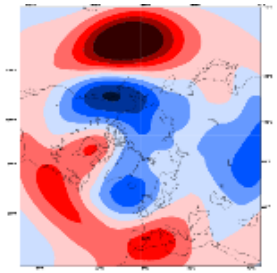
UKMO 0.28



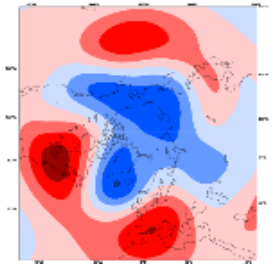
JMA 0.22



ECCC 0.21



ECMWF 0.31

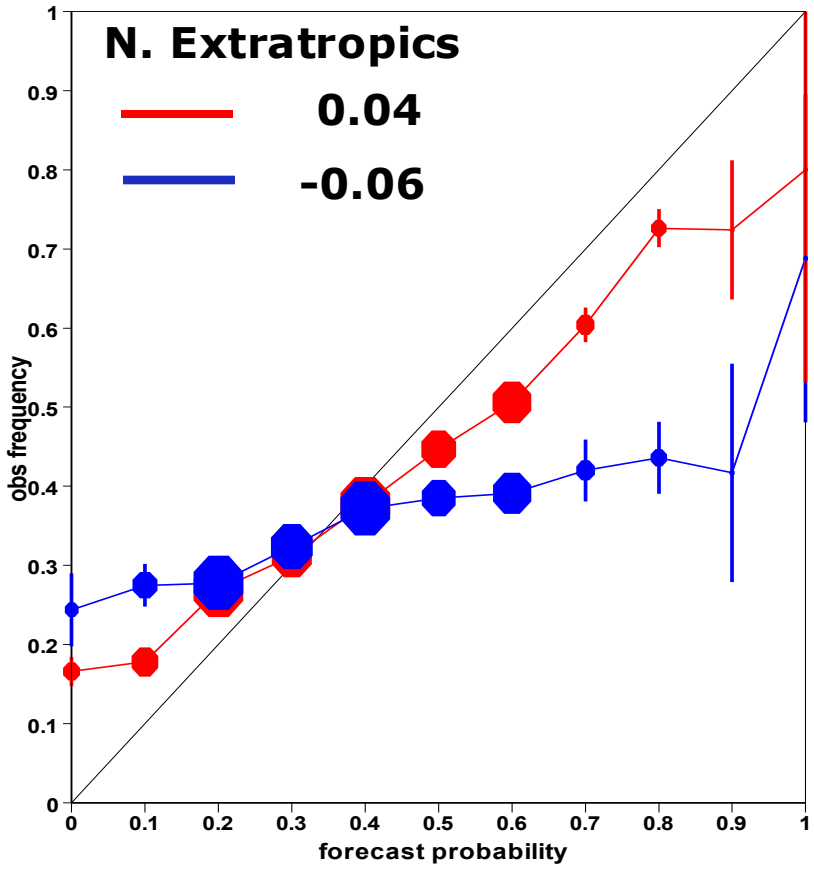


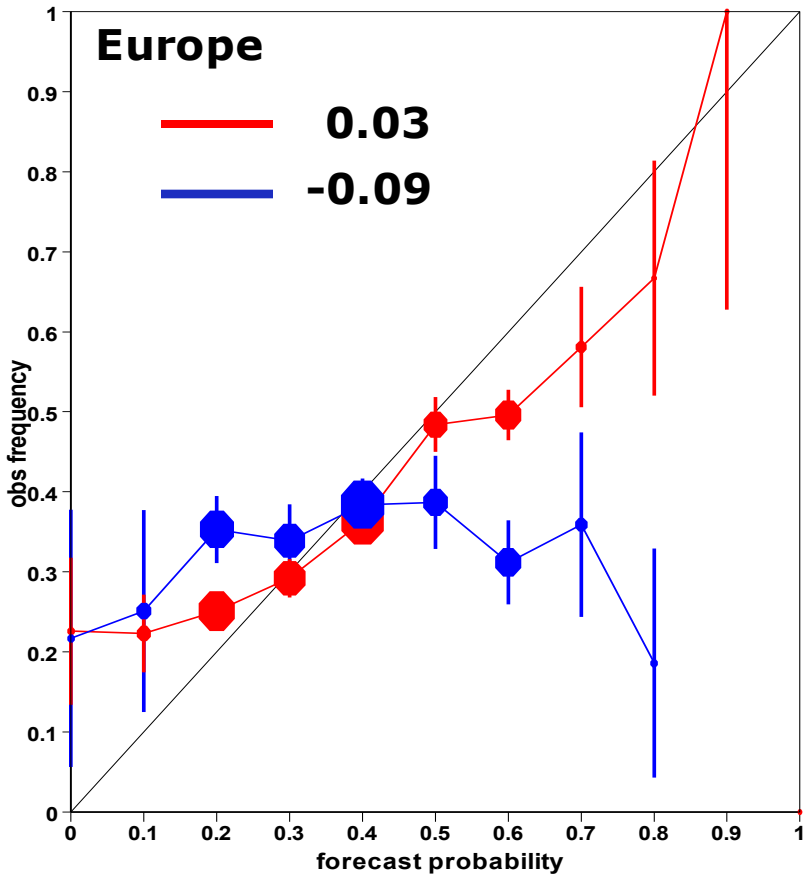
All models represent the MJO teleconnection patterns well.

- All models predict a positive NAO 3 pentads after MJO phase 3.
- All models severely underestimate teleconnection amplitude.

Impact of the MJO on the NAO

Reliability Diagram – NDJFMA 1989-2008
Probability of 2-m temperature in the upper tercile
Day 19-25



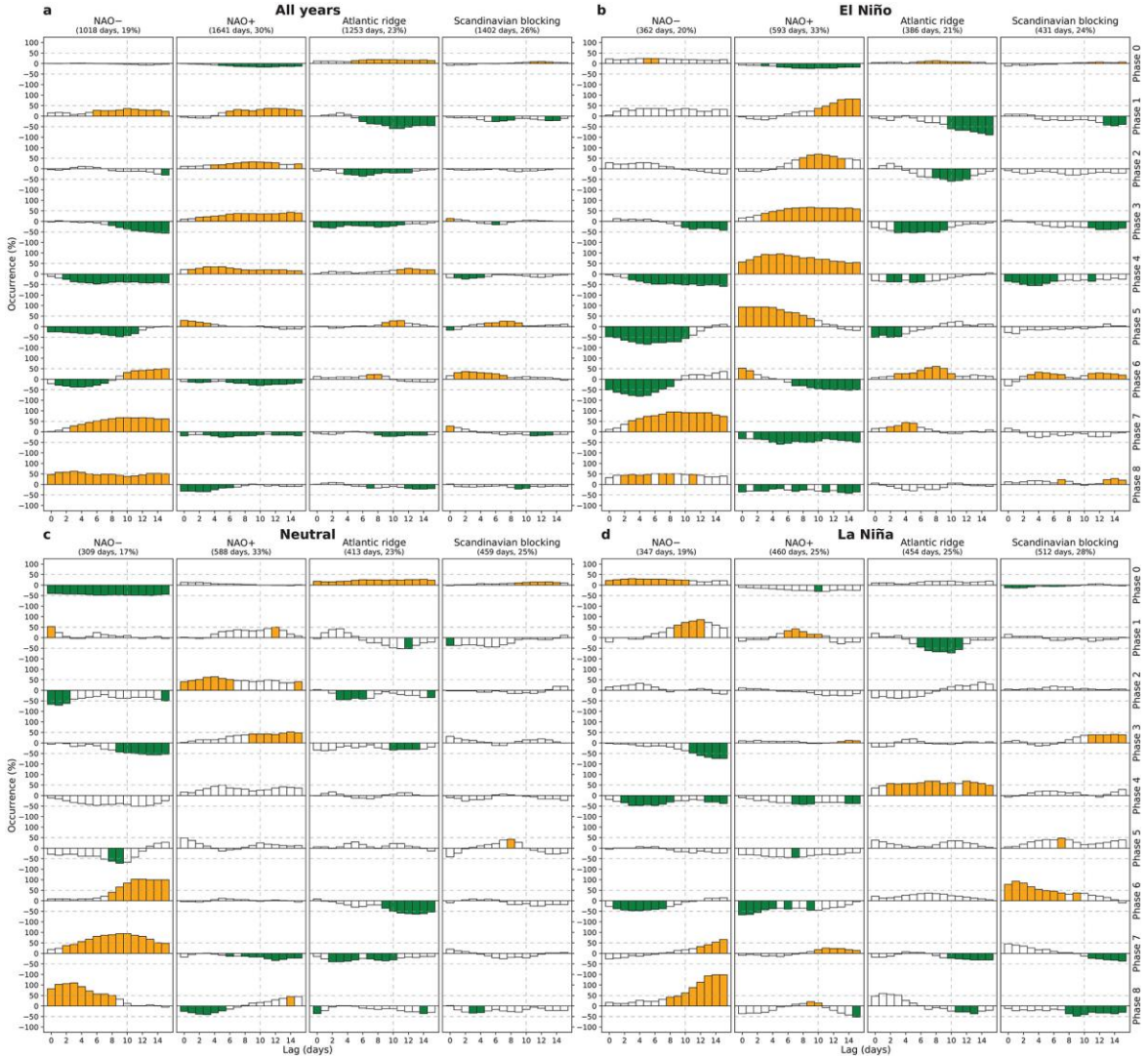


Week 4 forecasts are more reliable over the northern extratropics and Europe when initial conditions contain a strong MJO (amplitude > 1 standard deviation).

MJO in IC

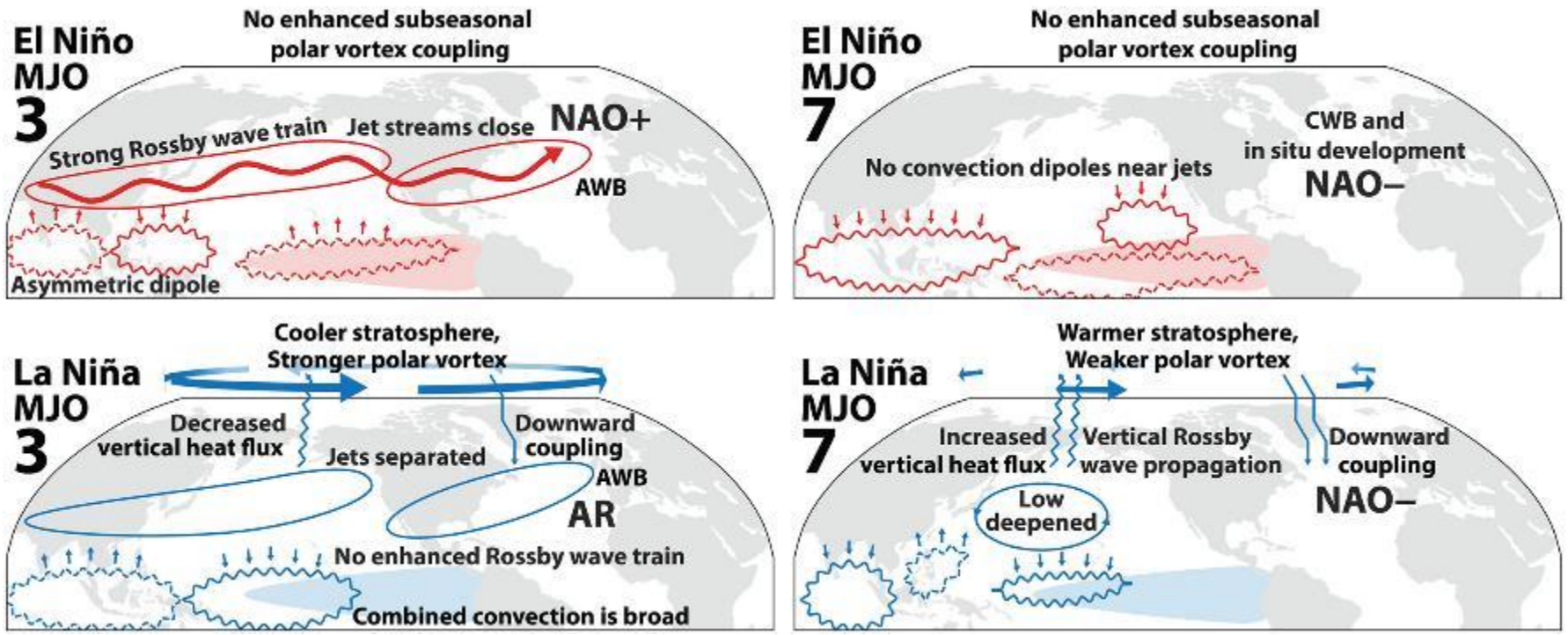
NO MJO in IC

ENSO modulation of MJO teleconnections



Lee et al., 2019

ENSO modulation of MJO teleconnections



Lee et al., 2019

ENSO modulation of MJO teleconnections

Forecasts underestimate the ENSO modulation of MJO-regime interactions

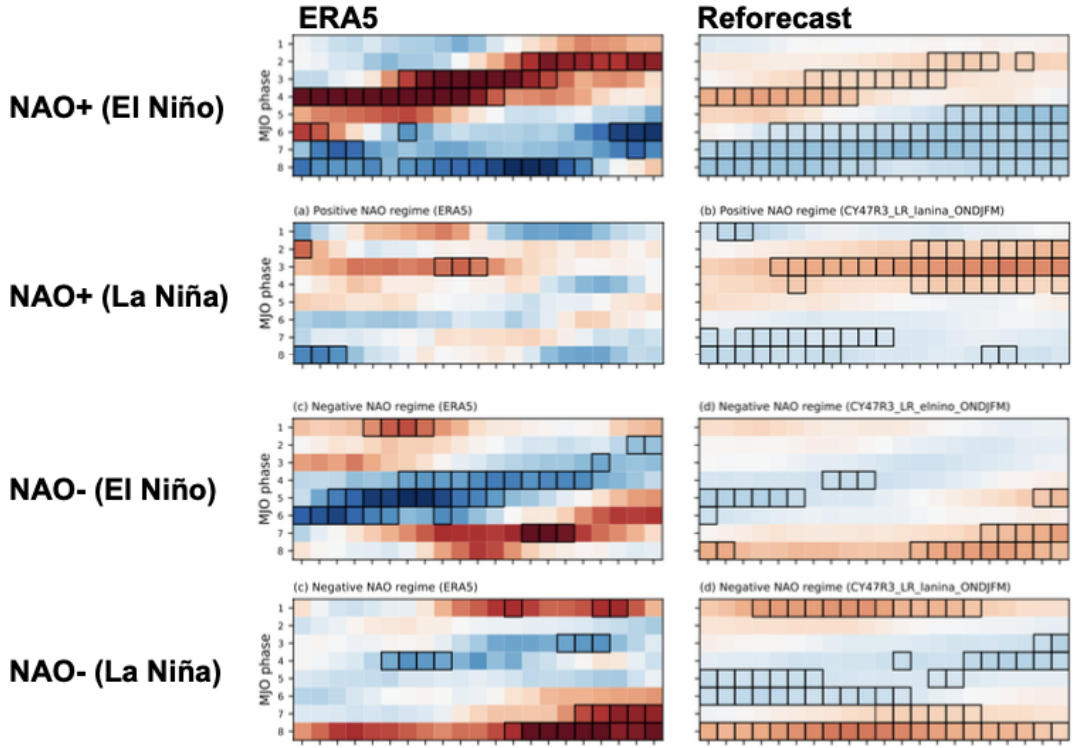
Lee et al. (2019) demonstrated that MJO-regime teleconnections depend on the ENSO background state.

1. Tropospheric teleconnection associated with increased NAO+ frequency following MJO phase 3/4 is stronger during El Niño years but suppressed during La Nina.

2. NAO- events following MJO phase 7/8 occurs later in the MJO phase cycle during La Niña years due to an enhanced stratospheric teleconnection pathway mediated by variations in the strength of the polar vortex.

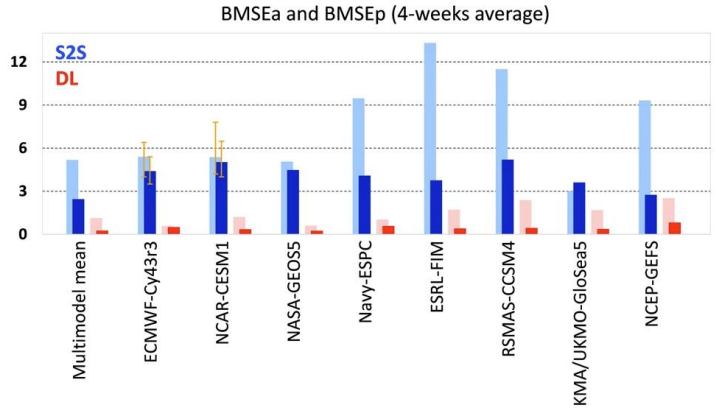
3. Reforecasts do not reproduce this modulation.

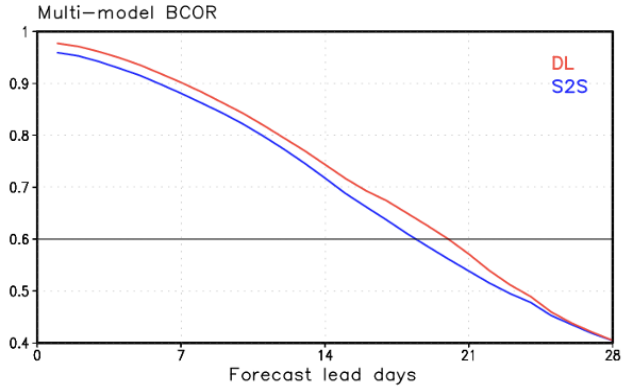
Regime frequency conditioned on ENSO and the phase of the MJO at different lags (1980-2020)



AI/ML for MJO prediction

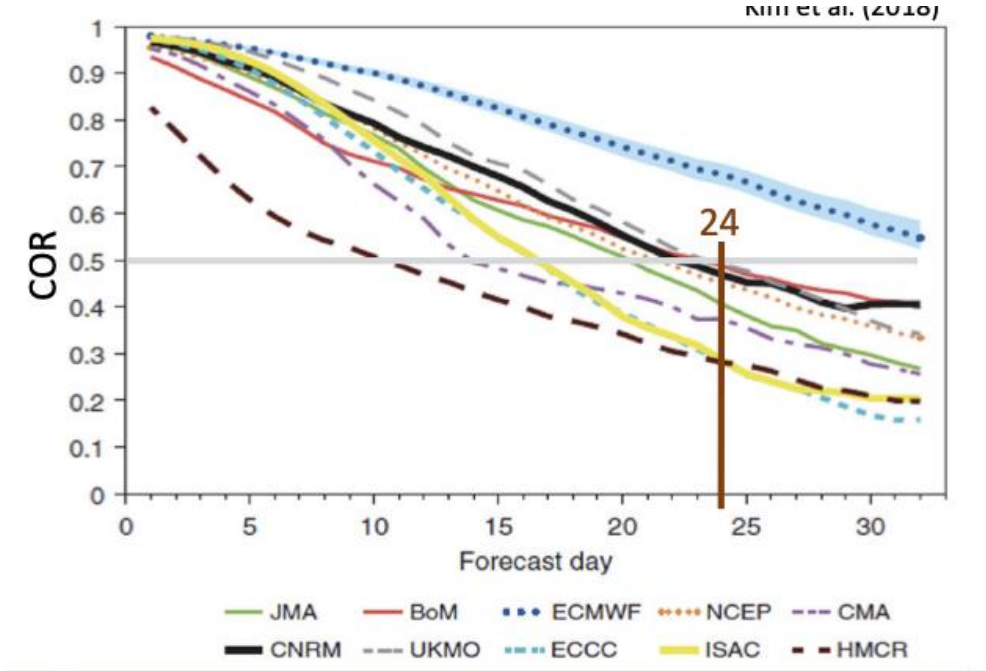
1. Deep learning to correct model outputs
(Kim et al., 2021, Nature Communications)





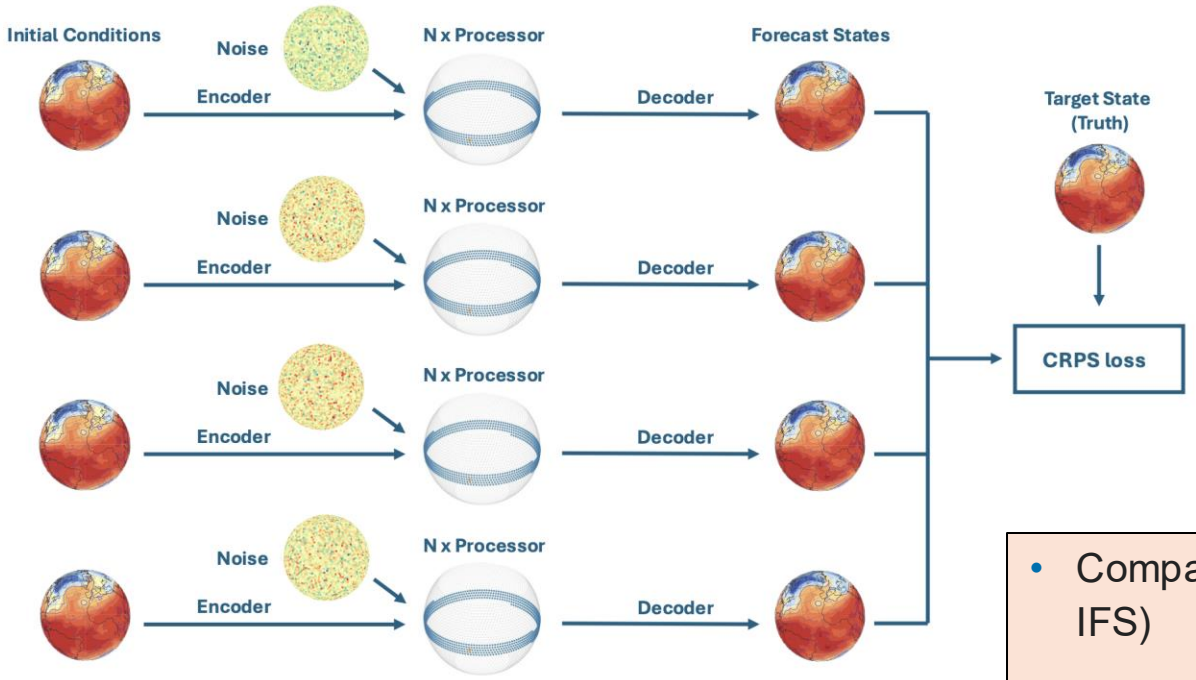
2. AI/ML methods to replace GCMs
(Silini et al., 2021)

Two artificial neural networks (ANNs) predict the MJO

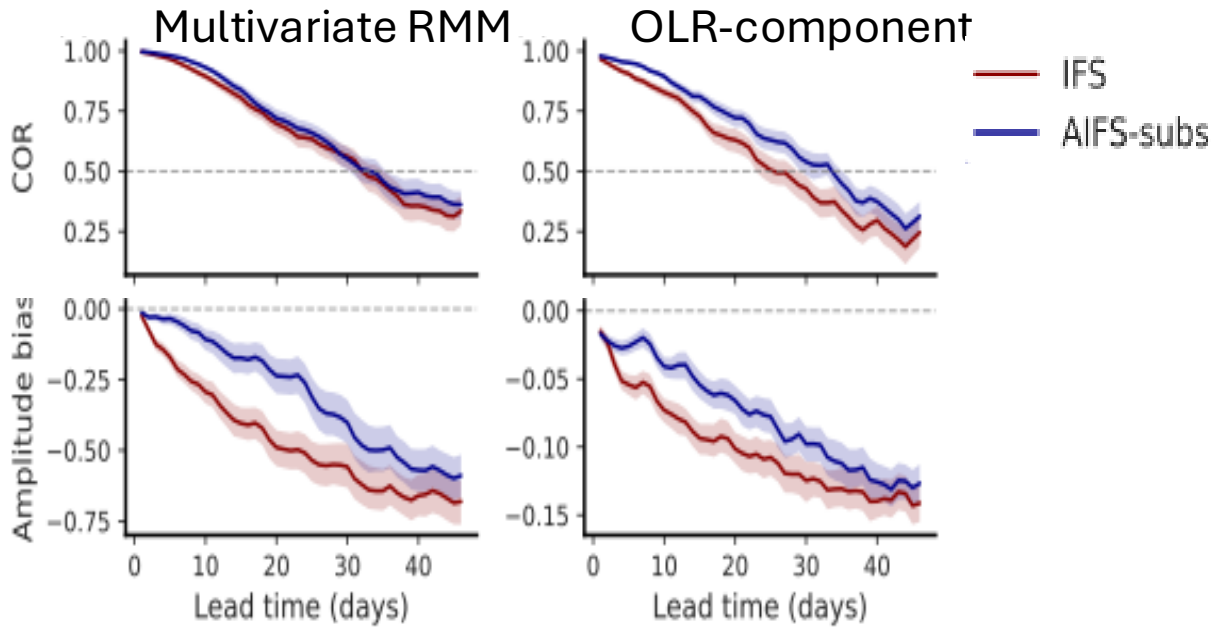


AIFS-SUBS for sub-seasonal prediction

- GraphTransformer encoder–processor–decoder
- 24-hour time step
- Almost-fair CRPS loss function



Verification:
- 2007-2011
- 5 initializations per month



- Comparable RMM skill and higher OLR prediction skill (eight days beyond IFS)
- Lower RMM amplitude bias than IFS

Future perspectives

- Coupled data assimilation may improve MJO initialization.
- Kilometre-scale resolution may improve MJO prediction by reducing errors associated with convective parameterization.
- Machine learning may reduce model errors in the representation of the MJO and produce more skilful forecasts.

Conclusions

- The MJO is the main source of tropical variability between a week and a season.
- Its global impacts, including over Europe, make it a main source of sub-seasonal predictability.
- MJO prediction has improved significantly over the past decade. Operational systems show predictive skill up to week 4.
- SST coupling is important, although not crucial.
- ENSO and the QBO modulate MJO activity.
- S2S models still struggle to represent MJO teleconnections adequately.
- Higher resolution and machine learning may improve sub-seasonal prediction of the MJO and its impacts.

Thank you



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