The MJO: properties, mechanism & importance for midlatitude dynamics

Sébastien Fromang *(CEA Saclay, France)*
and
Gwendal Rivière *(LMD, Paris, France)*

Physics at the equator: from the lab to the stars
Lyon – 16-18 Oct 2019

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Outline

1. Introduction

The MJO

The observed teleconnections

The MJO-NAO lagged correlation

2. MJO ⇔ NAO

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Idealized simulations

3. Physical interpretation

Streamfunction budget

Tropospheric vs. Stratospheric pathways

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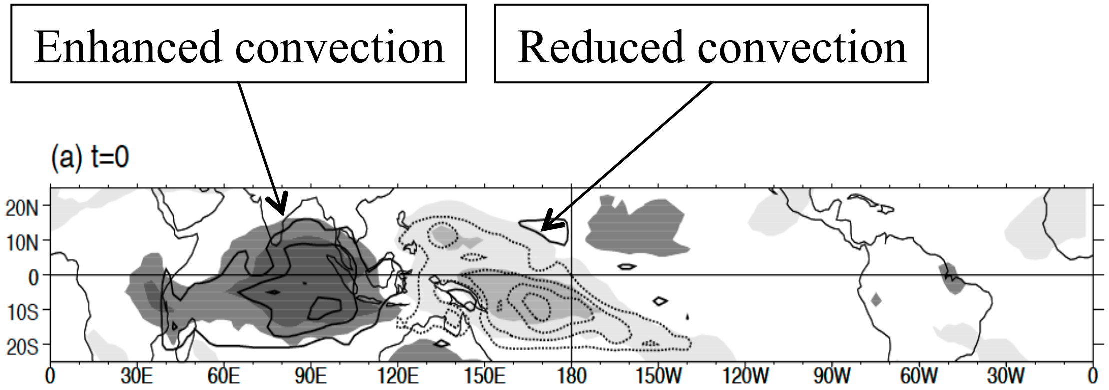
The Madden Julian Oscillation (MJO)

(Madden & Julian 1971, 1972)

Dominant mode of intraseasonal variability in the tropics



Outward Longwave Radiation (OLR) – from Matthew et al. (2004)

Main properties

- Coupled enhanced/suppressed convection dipole propagating eastward (v_{prop}~5 m/s)
- Typical period ~ 40-50 days
- Appear in Indian Ocean – weakens in eastern Pacific
- Eight phases typically distinguished

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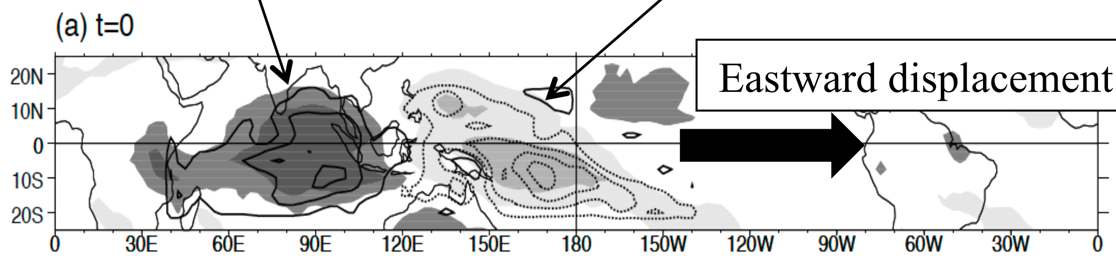
Enhanced convection

Reduced convection



Eastward displacement

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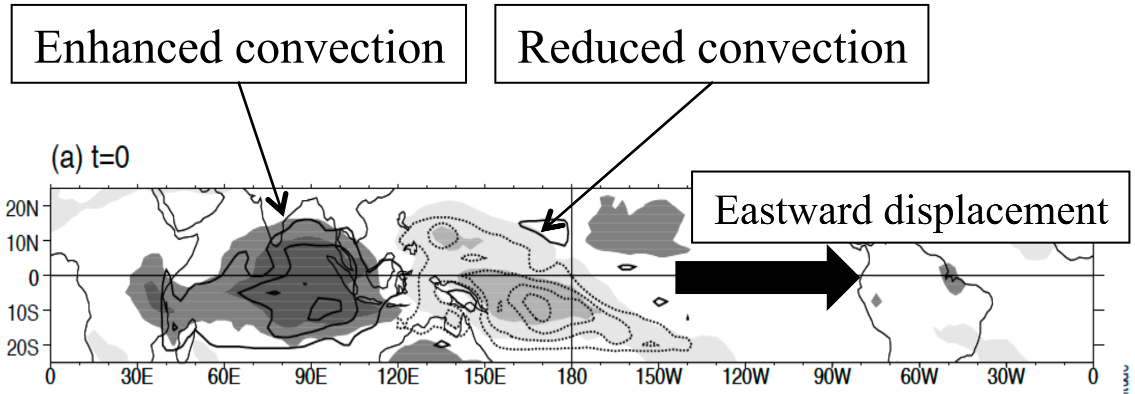

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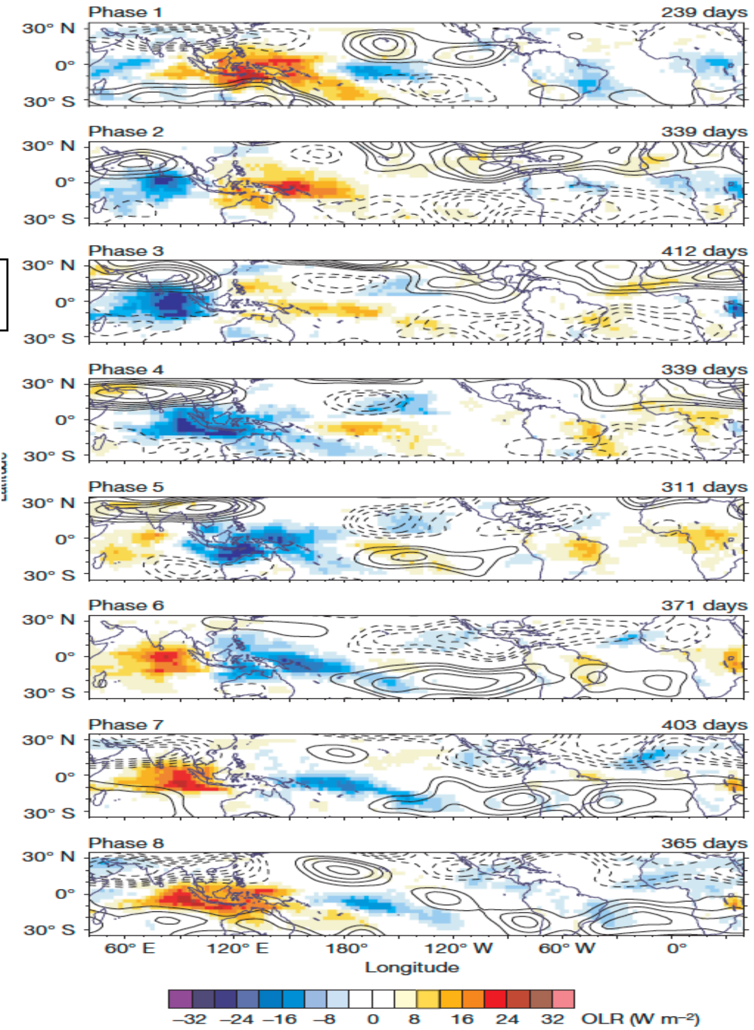

Cassou (2008)

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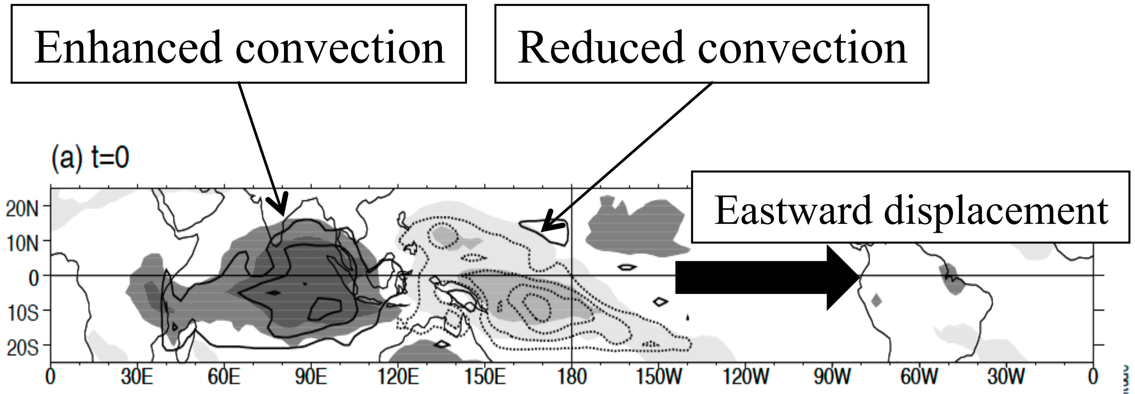

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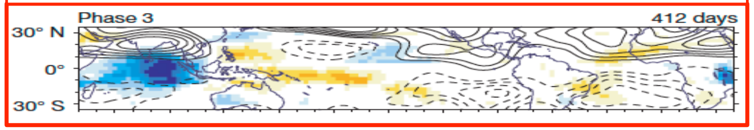
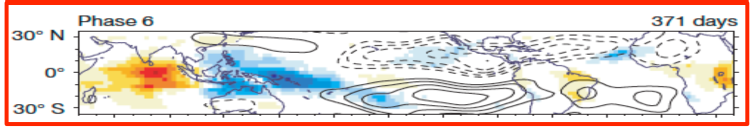
Phase 3
Enhanced convection in Indian ocean
Reduced convection in Pacific



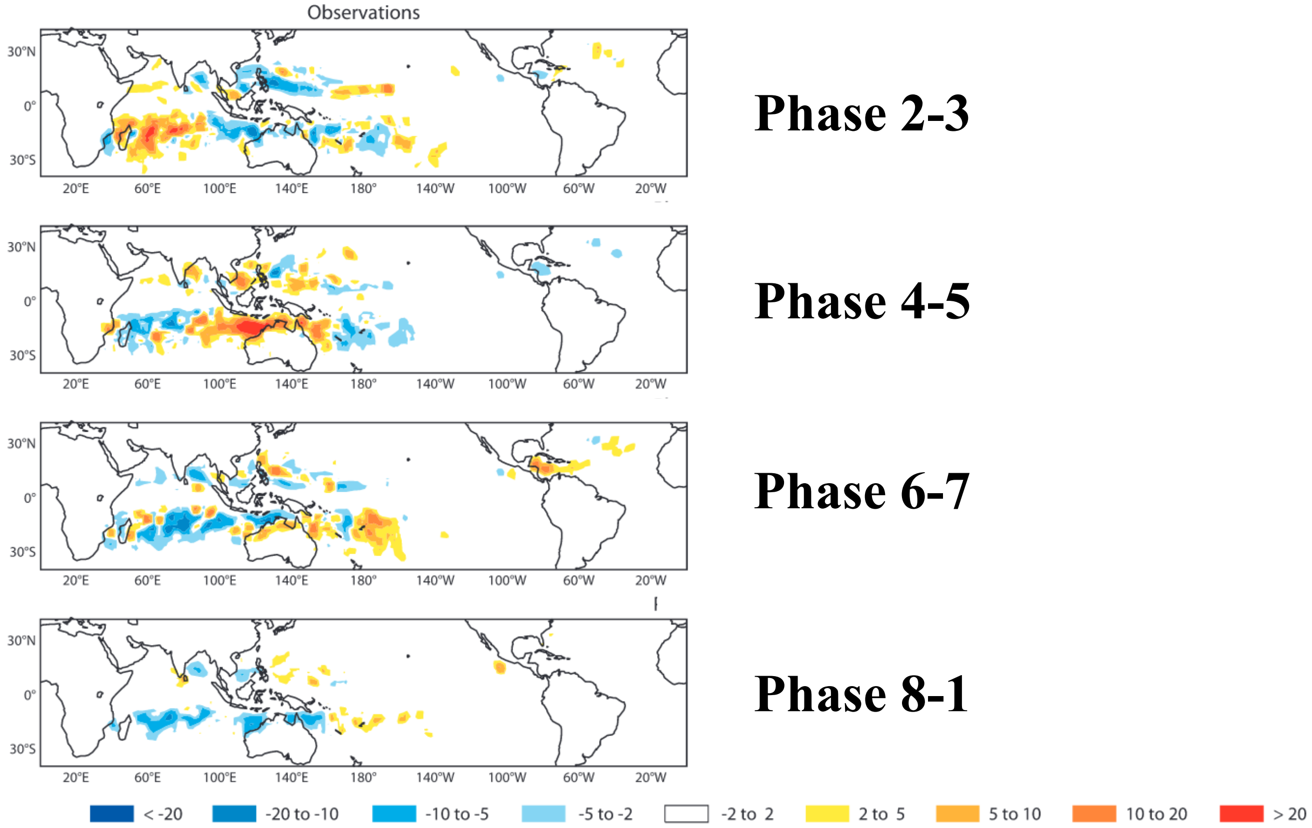
Phase 6
Enhanced convection in Pacific
Reduced convection in Indian ocean



Cassou (2008)

The MJO influences multiple aspects of the Earth atmospheric circulation

In the tropics



Phase 2-3

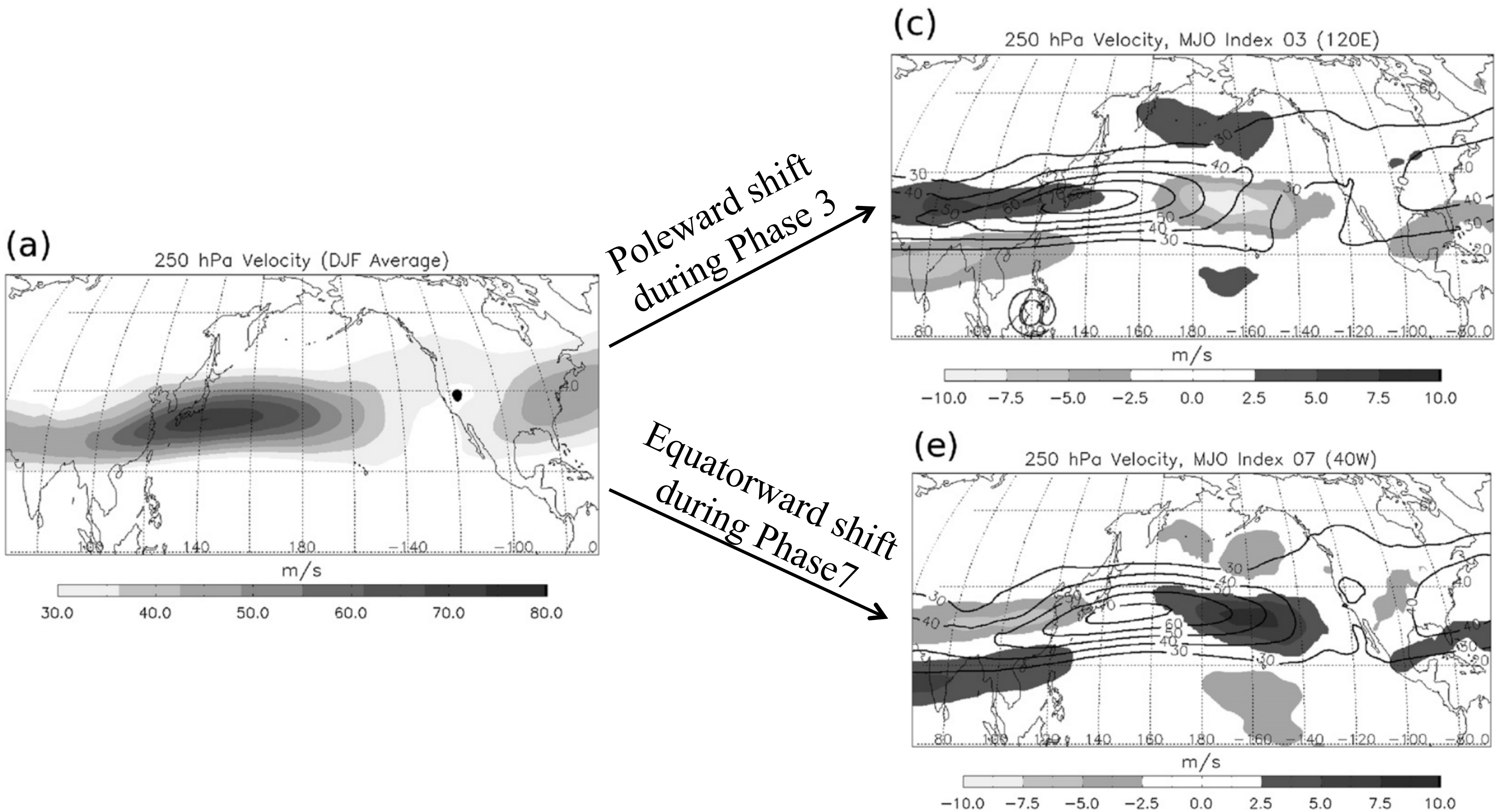
Phase 4-5

Phase 6-7

Phase 8-1

Cyclone frequencies modulated in phase with MJO phases (*Vitart 2009*)

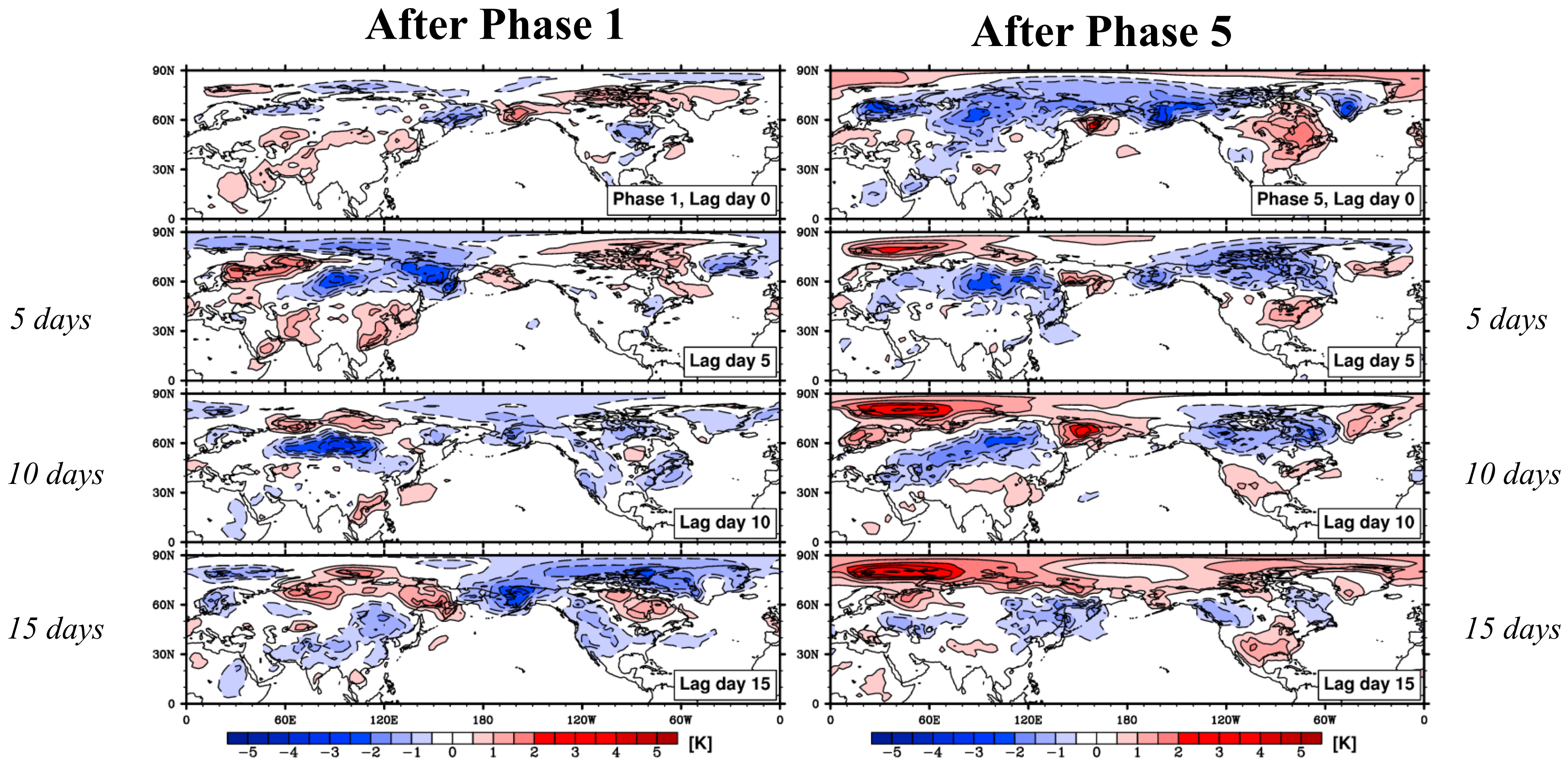
In the Pacific region



Northern Pacific jet shifts in latitude modulated by the MJO

(Moore et al. 2010)

In the Arctic regions



Arctic surface air temperature modulated by MJO phases

⇒ Possible links with the Arctic Amplification?

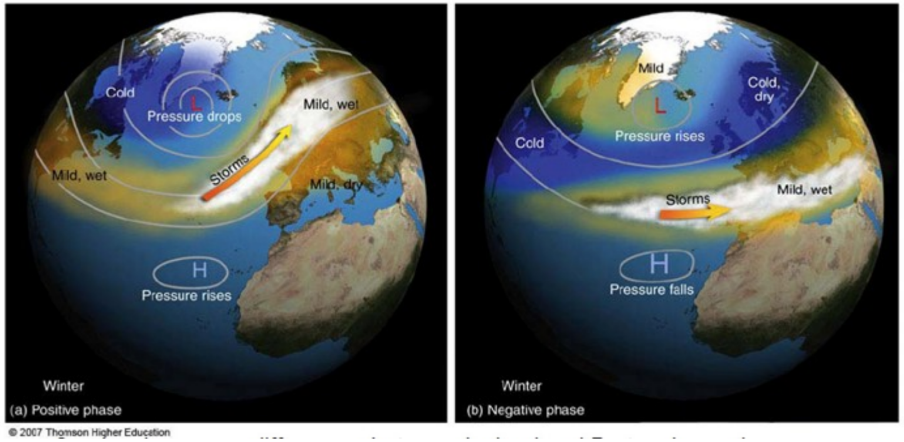
(Yoo et al. 2011)

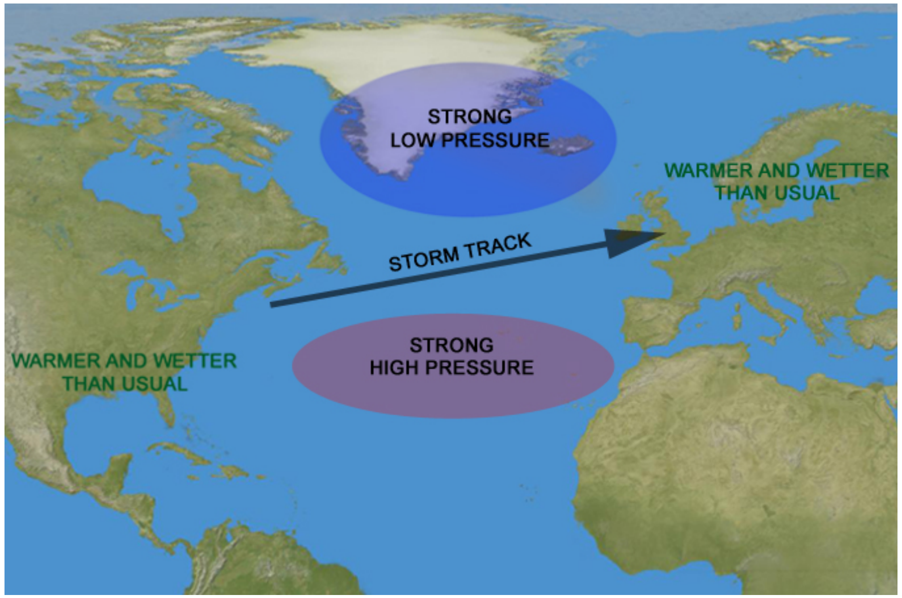
The MJO also influences the NAO...

The North Atlantic Oscillation (NAO)

Main properties

- Northward/southward displacement of the atlantic eddy-driven jet
- Subseasonal timescales
- Strongly affect European weather
- NAO+ => jet displaced northward
- NAO- => jet displaced southward





Pressure perturbations during NAO+

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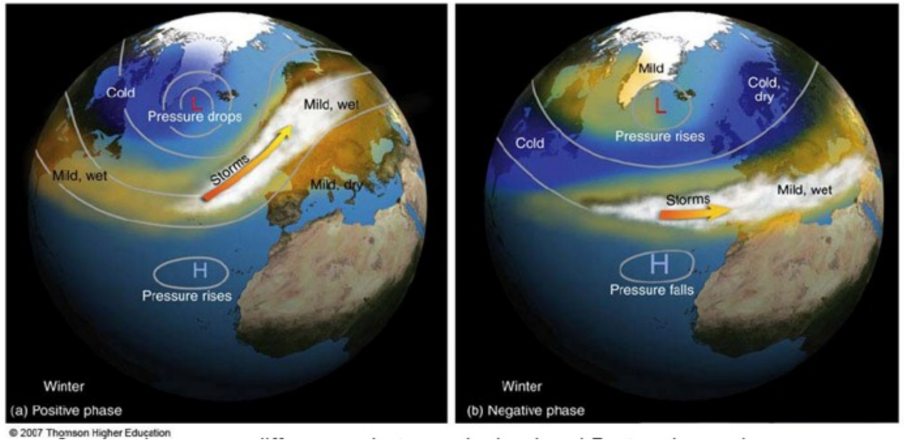
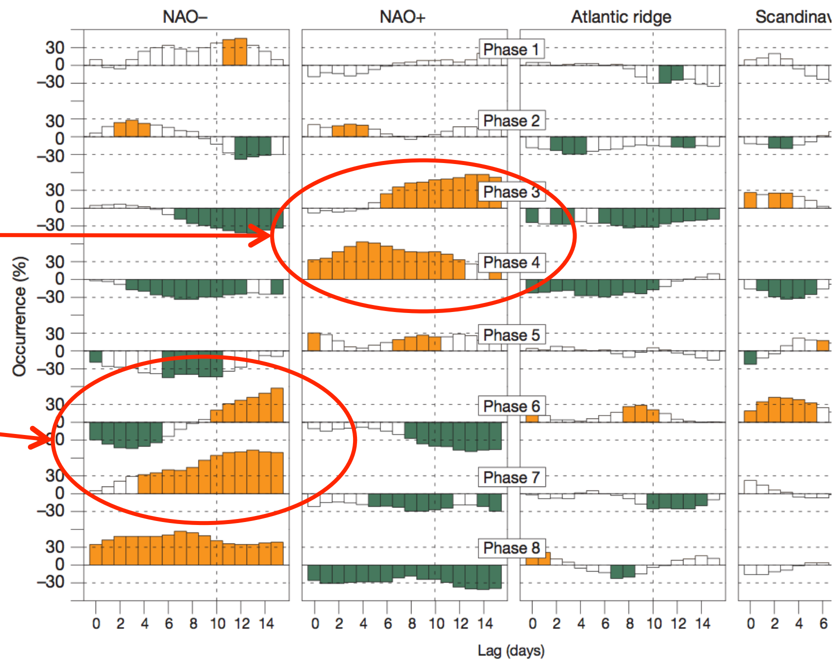


The MJO-NAO observed teleconnexion

Excess of NAO+ occurrence ~10 days after MJO Phase 3

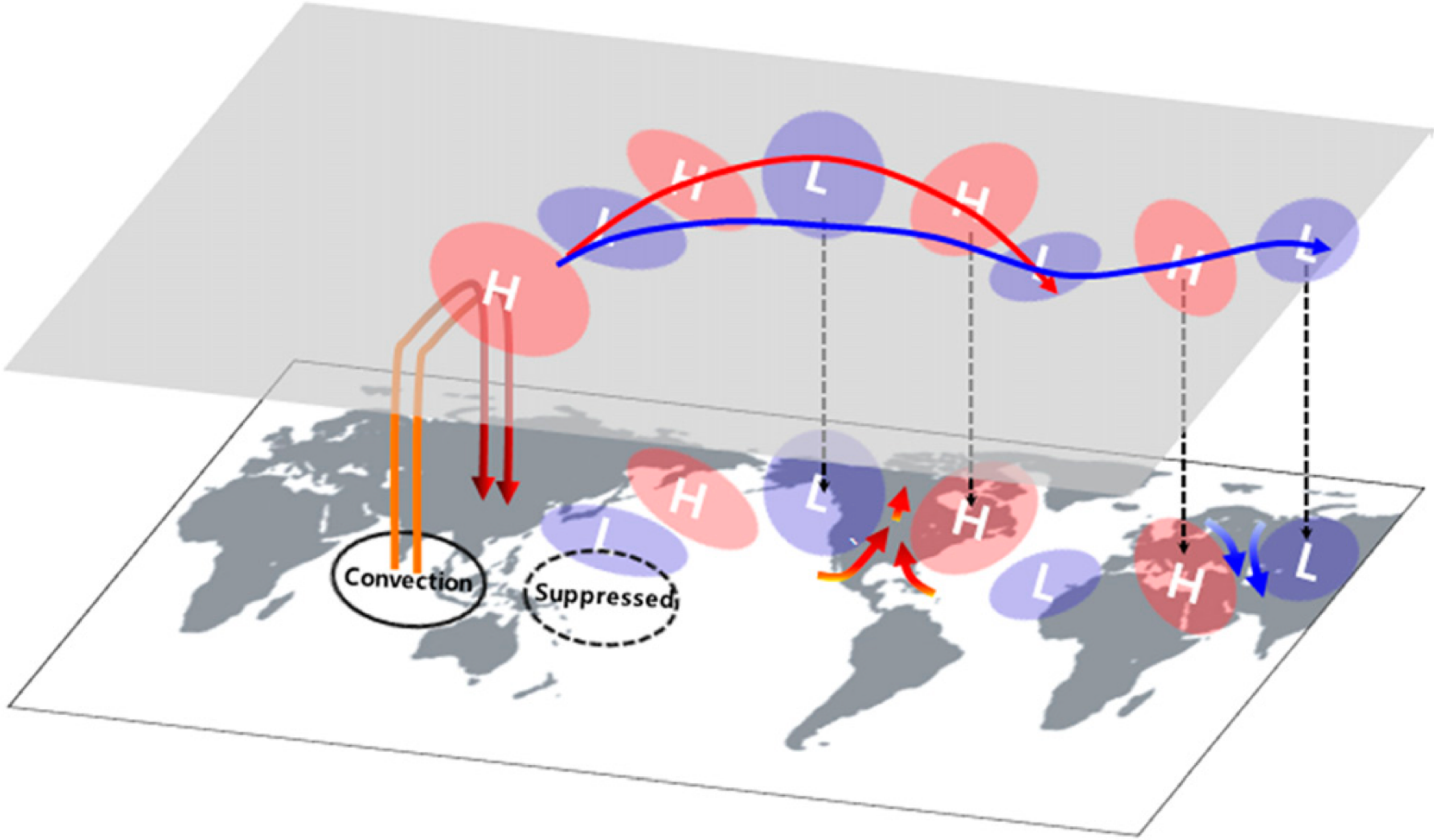
Excess of NAO- occurrence ~10 days after MJO Phase 6



Confirmed by e.g. Lin et al (2009), Henderson et al. (2016)

Cassou (2008)

MJO ⇔ Extratropical teleconnections



Seo & Son (2016)

The MJO excites a quasi-stationary Rossby wave that propagates to the midlatitudes – timescale 10-15 days

Hoskins & Karoly (1981), Hoskins & Ambrizzi (1993), Jin & Hoskins (1995)

What is the dynamical mechanism linking the MJO to the NAO?

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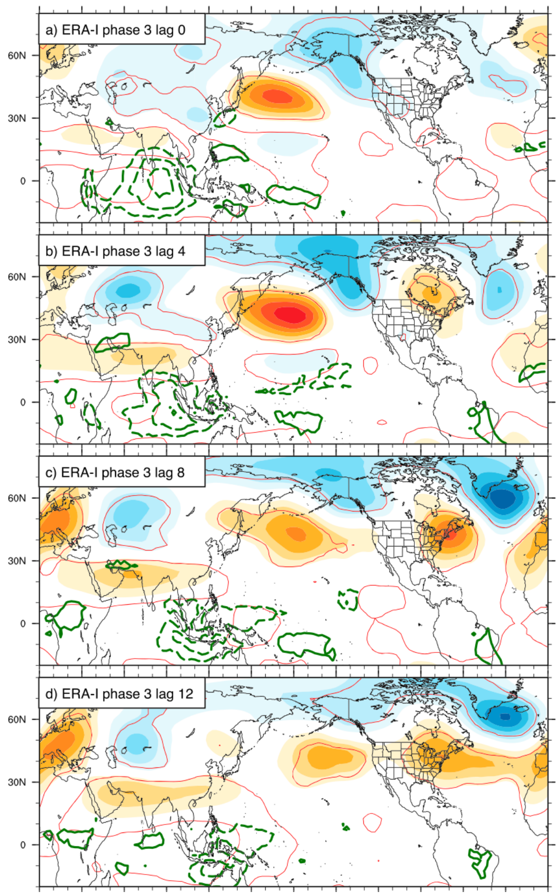
Streamfunction anomalies following Phase 3

Reanalysis data



Zheng et al. (2019) – similar to Lin & Brunet (2018)

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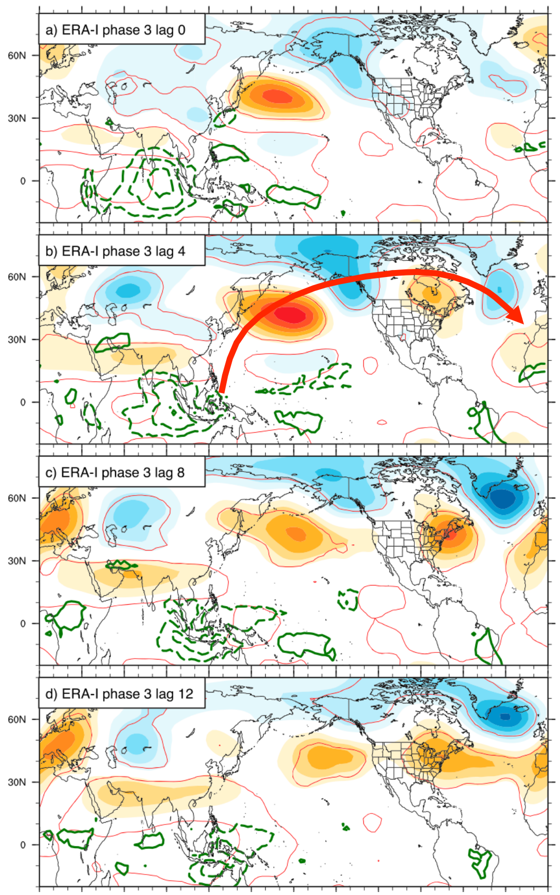

Stationary Rossby wave

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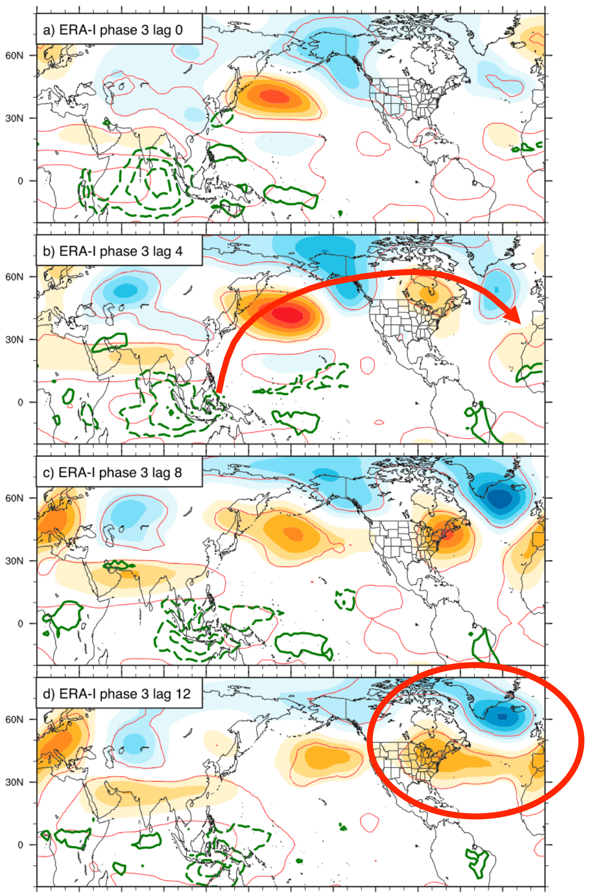

Stationary Rossby wave

Positive NAO after 12 days

Zheng et al. (2019) – similar to Lin & Brunet (2018)

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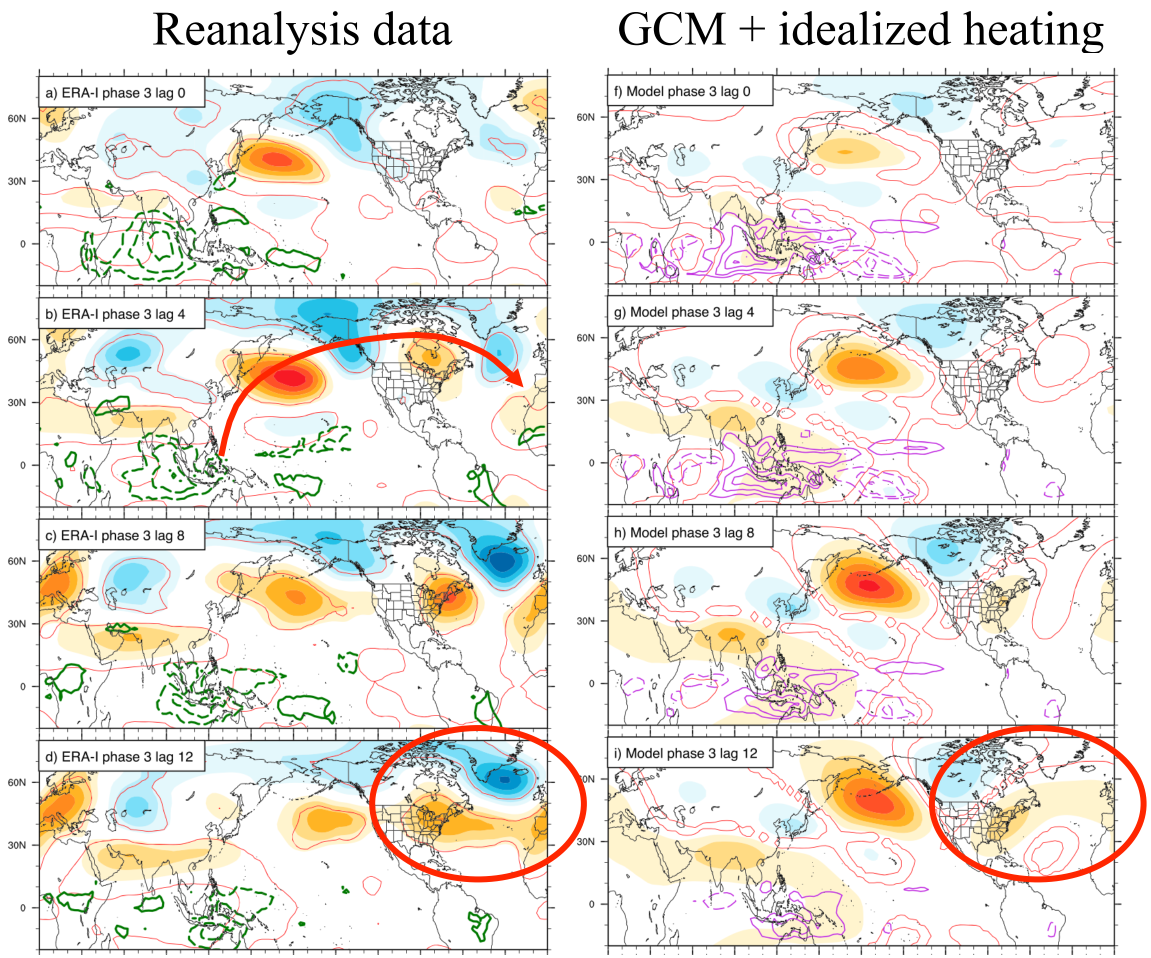
Streamfunction anomalies following Phase 3



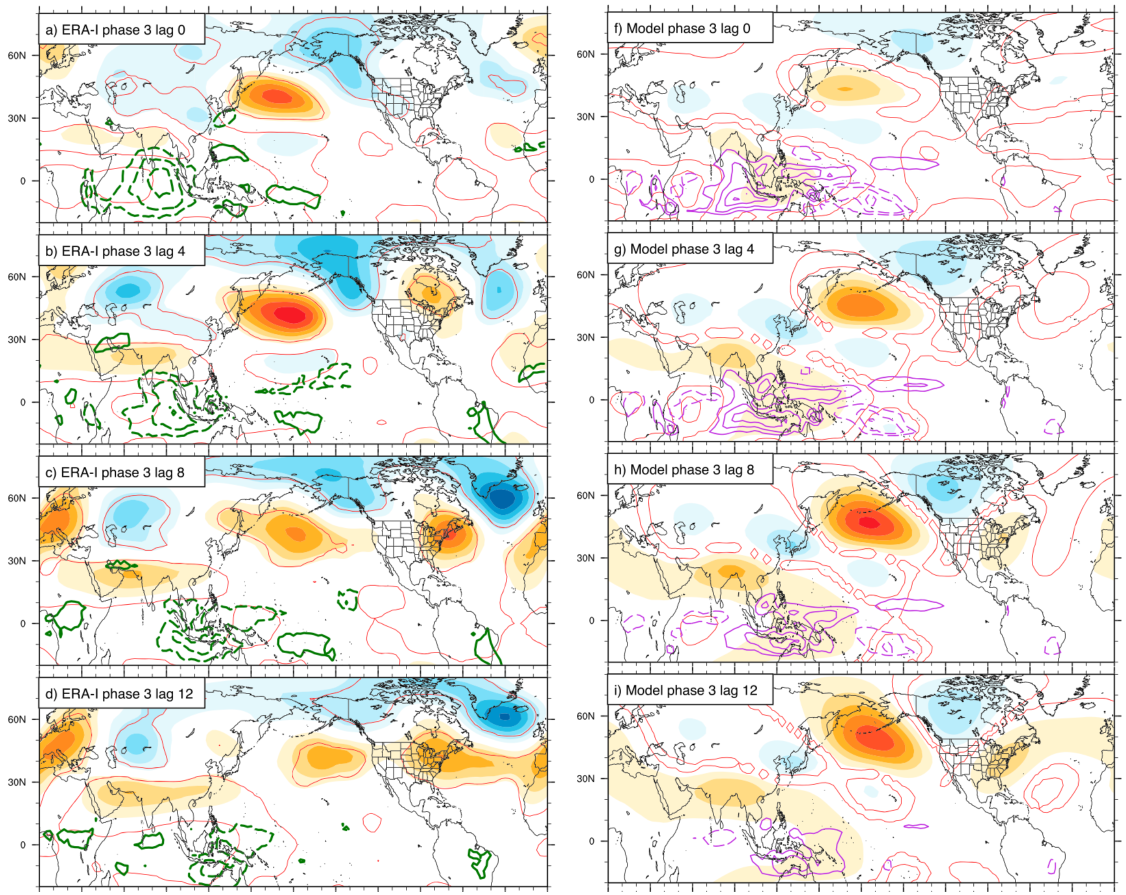
Little/no projection on the NAO in the simulations

Zheng et al. (2019) – similar to Lin & Brunet (2018)

What is the dynamical mechanism linking the MJO to the NAO?

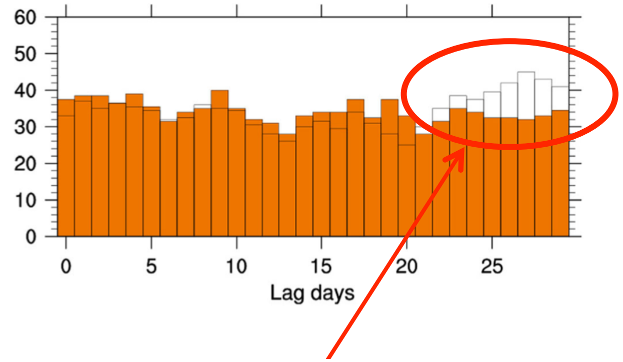
Streamfunction anomalies following Phase 3

Reanalysis data | GCM + idealized heating



Zheng et al. (2019) – similar to Lin & Brunet (2018)

Shao et al. (2018)



Increased NAO+ occurrences following Phase 3

Influence of synoptic eddies speculated, but not much analysis…

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Streamfunction anomalies following Phase 3

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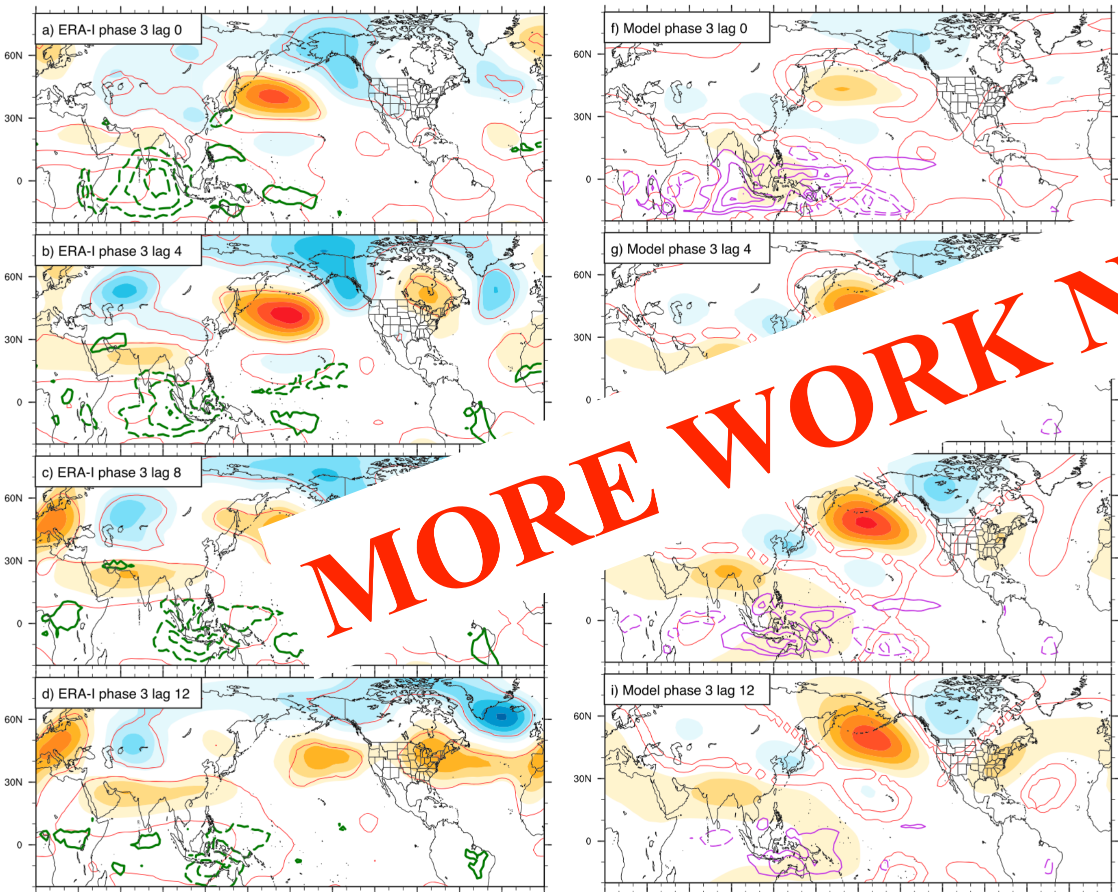

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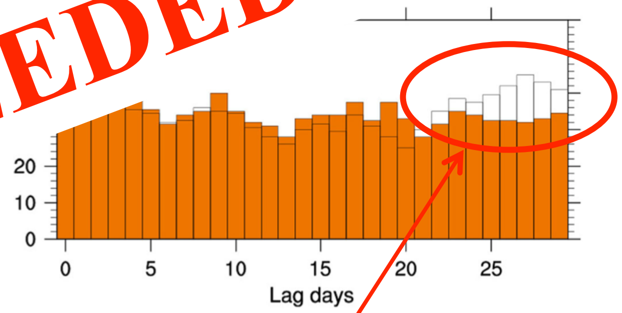
MORE WORK NEEDED!

2018)



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A three levels QG code on the sphere

Marshall & Molteni (1993)

One single equation that describes Potential Vorticity (PV) evolution on the sphere

$$\underbrace{\frac{\partial q_i}{\partial t}}_{\text{PV tendency}} = -\underbrace{J(\psi_i, q_i)}_{\text{Advection}} - \underbrace{D_i(\psi_1, \psi_2, \psi_3)}_{\text{Dissipation}} + \underbrace{S_i}_{\text{Forcing}}$$

Streamfunction: ψ - Potential vorticity: q

Numerical method

- Pseudo-spectral spatial scheme (*T42 discretization)*
- 3 levels: 200, 500 & 800 mbars
- « Realistic » orography and surface drag

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How to choose the forcing term S_i?

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Such that the mean flow is close to observations

⇒ Inverse problem: S_i evaluated using a Newton-Krylov algorithm

⇒ Atmospheric flow is time variable

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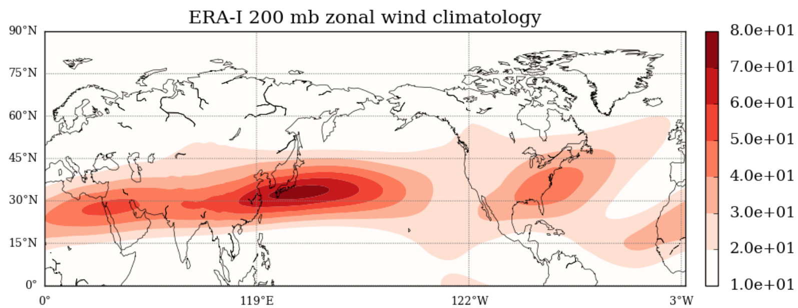
$$\mathbf{S_i = S_i^{clim}}$$

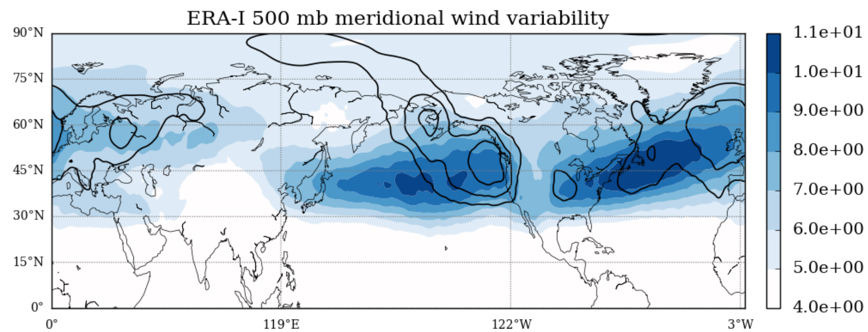
Model climatology & variability

Control simulation:

- 300,000 days (perpetual winter – about 800 years)

Observations





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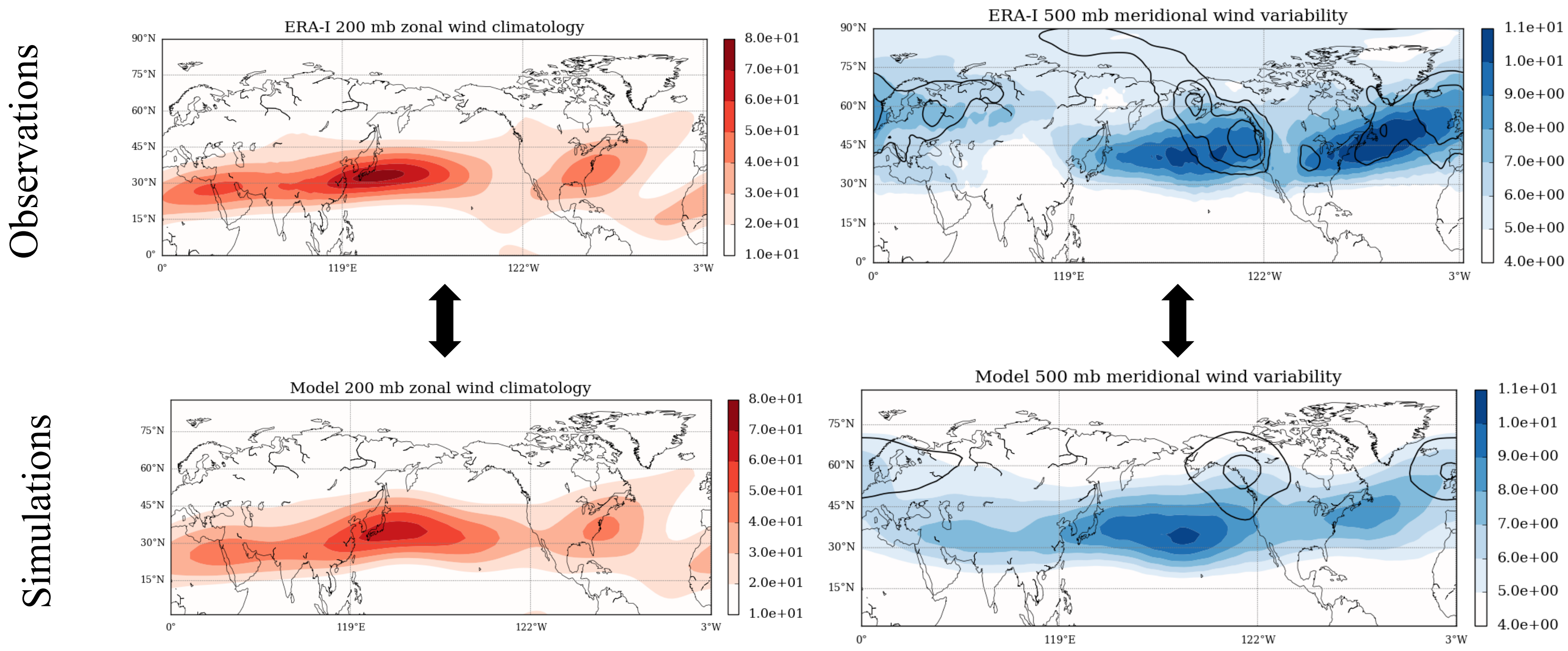

Good agreement between model & observations given the model simplicity

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⇒ Atmospheric flow is time variable

$$S_i = S_i^{clim}$$

$$S_i = J(\psi_i^{REF}, q_i^{REF}) + D_i(\psi_1^{REF}, \psi_2^{REF}, \psi_3^{REF})$$

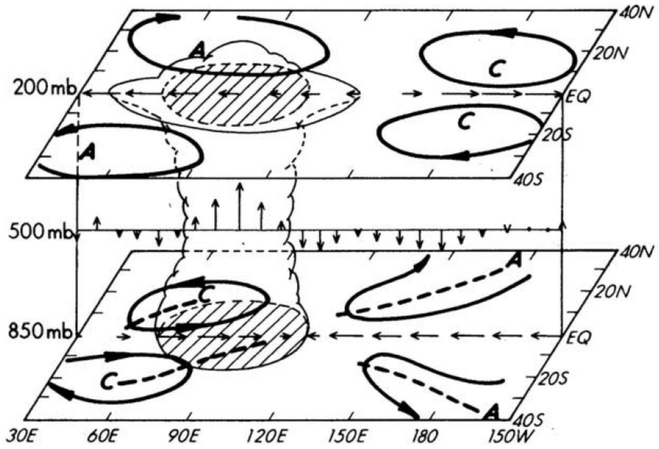
⇒ Reference flow independent of time

⇒ Only perturbations w.r.t to ψ_i^{REF} evolve with time

$$S_i = S_i^{stat}$$

A simplified MJO forcing

Enhanced convection creates:
⇒ Upper level anticyclone to the west
⇒ Upper level cyclone to the east



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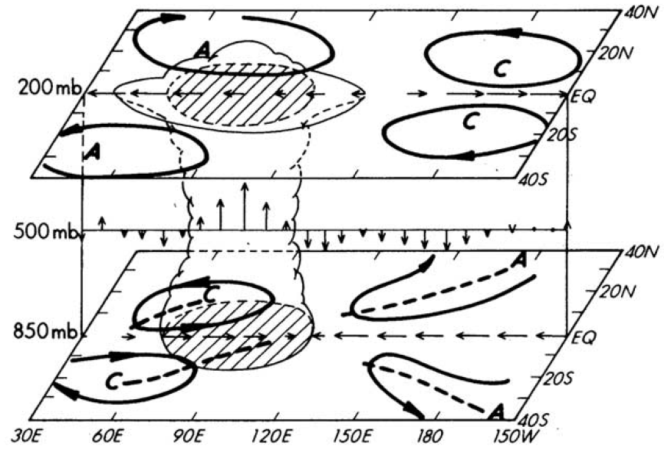
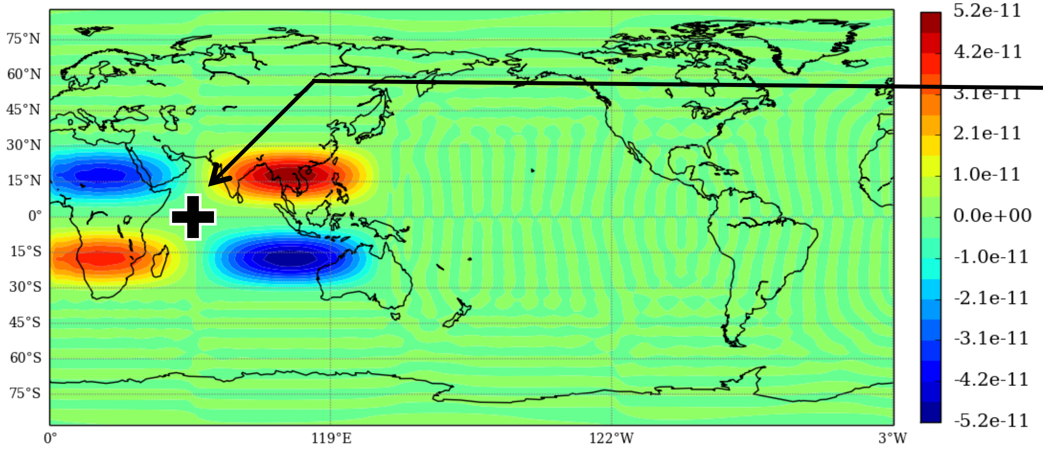


From Zhang (2005)

« Phase 3 » forcing

200 mbar forcing – initial time



Increased convection in Indian Ocean

Forcing @800 mbar reversed in sign

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Enhanced convection creates:
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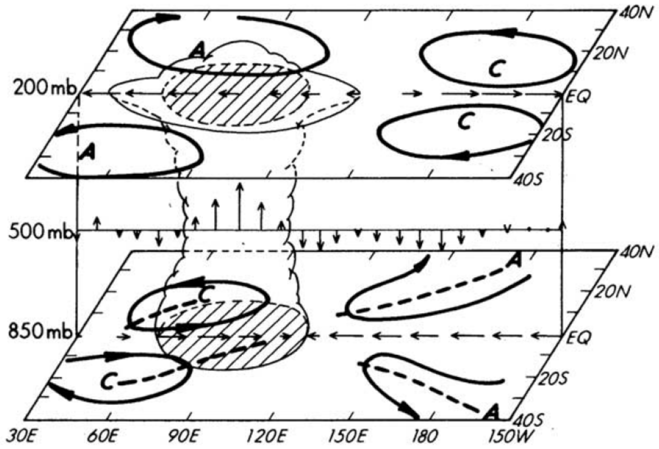

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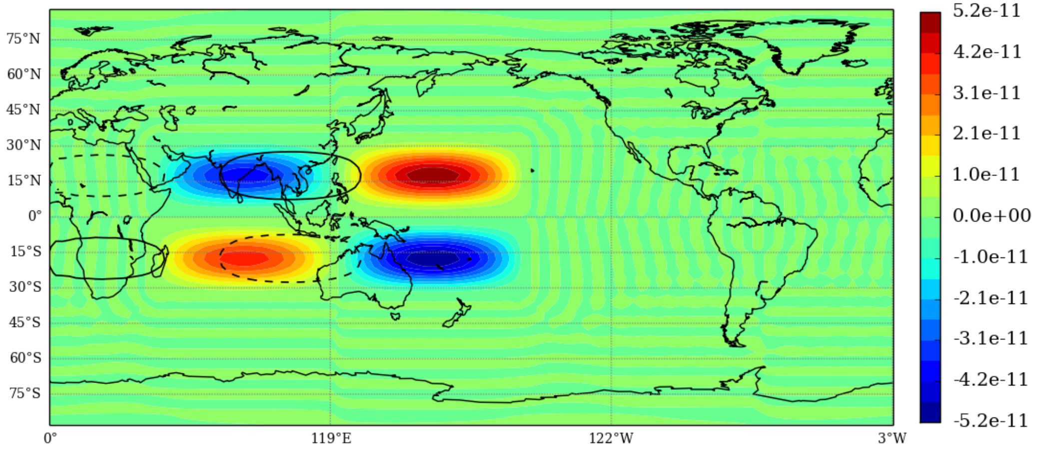
« Phase 3 » forcing

200 mbar forcing – 15 days



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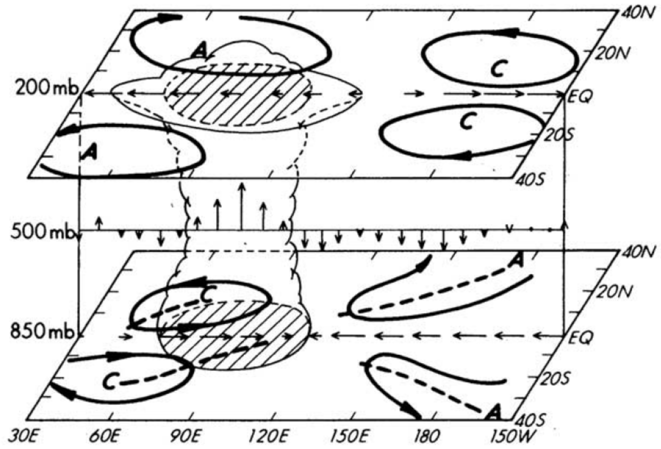
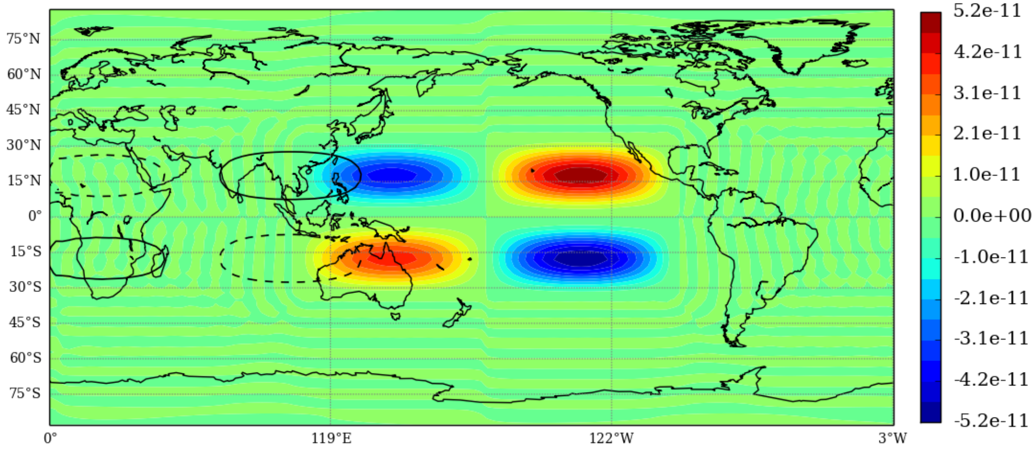


From Zhang (2005)

« Phase 3 » forcing

200 mbar forcing – 30 days



Forcing @800 mbar reversed in sign

Numerical experiments

« Time-varying reference flow experiment »

$$S_i = S_i^{clim} + S_i^{MJO}$$

⇒ Two series of **10,000 short runs** of 30 days (restarted every 30 days):

- 1 series with MJO forcing
- 1 series w/o MJO forcing

« Stationary reference flow experiment »

$$S_i = S_i^{stat} + S_i^{MJO}$$

⇒ Two runs of 30 days:

- 1 run with MJO forcing
- 1 run w/o MJO forcing

⇒ Composite analyse of anomalies (streamfunction, wind velocities) as a function of time

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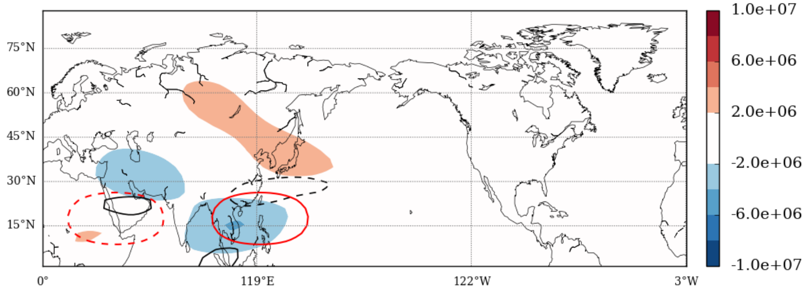
« MJO Phase 3 » forcing

The case of a stationary background flow

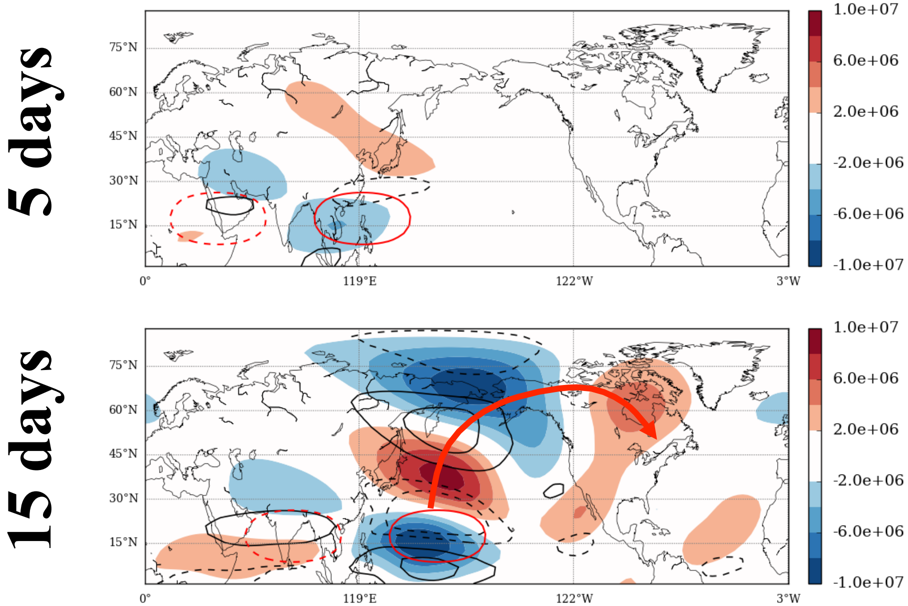
5 days



200mb streamfunction perturbation, $q0_{MJO}=4\times10^{-11}\ s^{-2}$*, wind perturbation ~ a few m/s*

« MJO Phase 3 » forcing

The case of a stationary background flow



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- **Stationnary wave train similar to published GCM results** *(ex: Seo & Son 2012)*

« MJO Phase 3 » forcing

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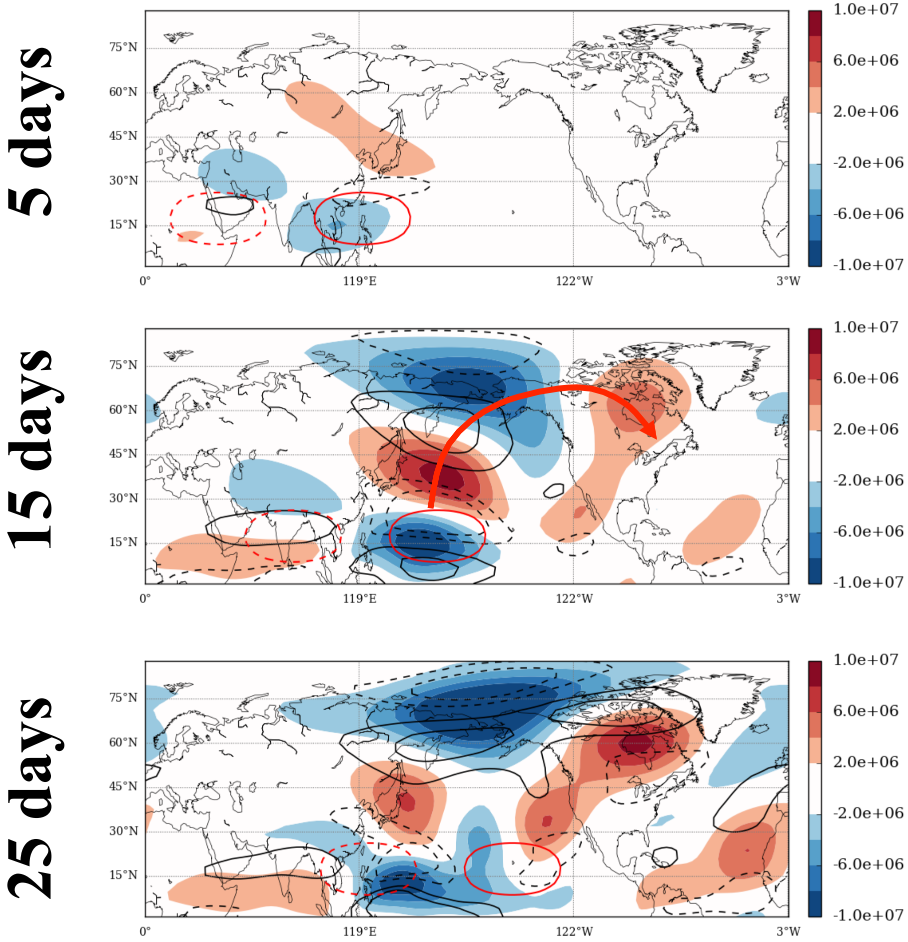


200mb streamfunction perturbation, $q0_{MJO}=4\times10^{-11}\ s^{-2}$, wind perturbation ~ a few m/s

- **Stationnary wave train similar to published GCM results** *(ex: Seo & Son 2012)*
- **But pattern in North Atlantic does not project on the NAO+: $PC1_{t=25d}=0.04$**

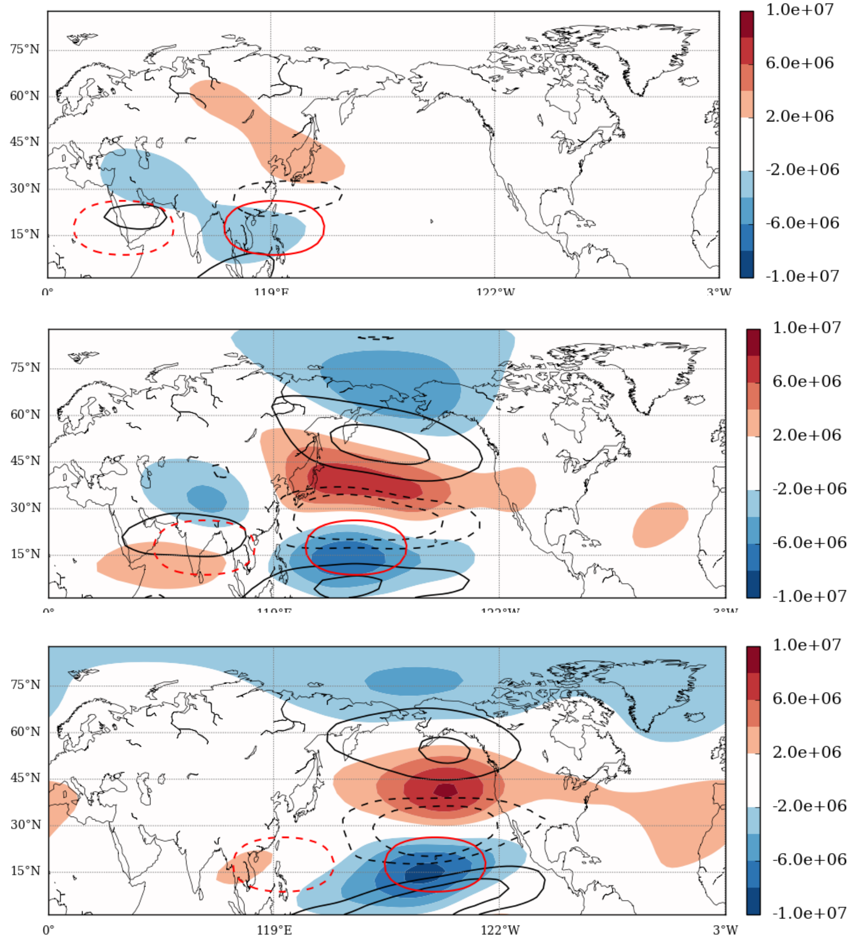
« MJO Phase 3 » forcing

The case of a varying background flow

5 days

15 days

25 days



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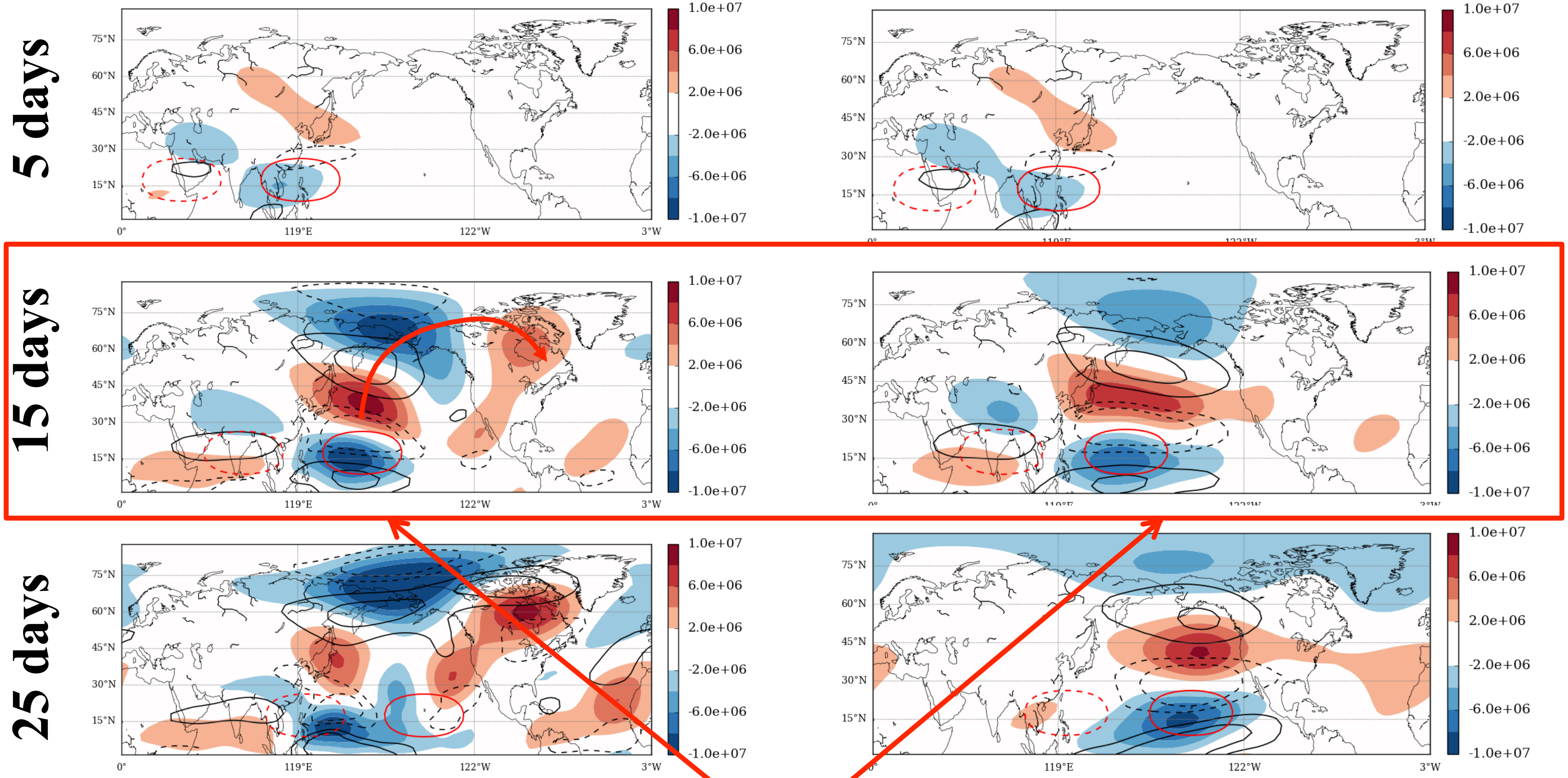
The case of a stationary background flow	The case of a varying background flow



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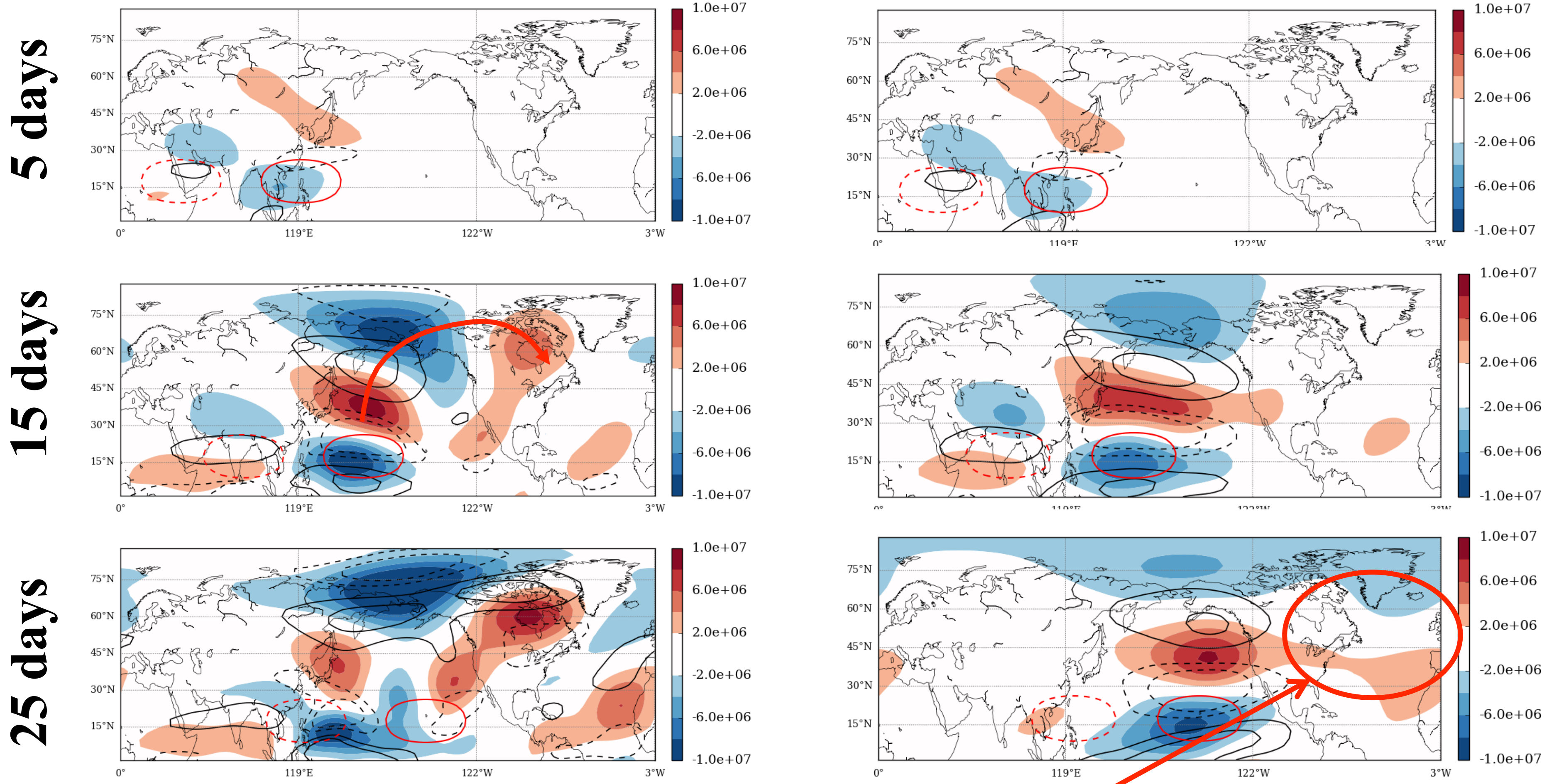
- **Stationary Rossby wave path different in the two sets of experiments**

« MJO Phase 3 » forcing

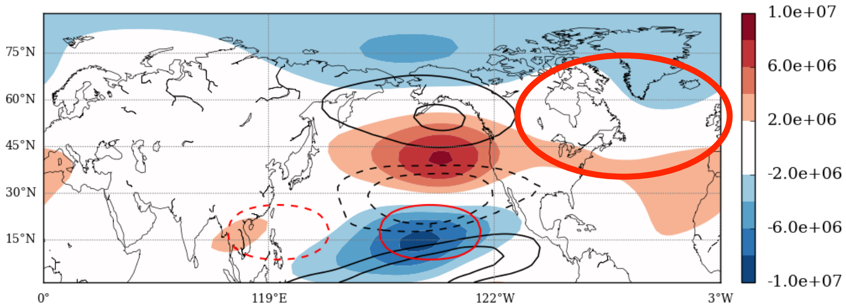
The case of a stationary background flow	The case of a varying background flow



200mb streamfunction perturbation, $q0_{MJO}=4\times10^{-11}\ s^{-2}$, wind perturbation ~ a few m/s

- **Stationary Rossby wave path different in the two sets of experiments**
- **Signature of NAO+ after 20/25 days…**

Consequence for the NAO

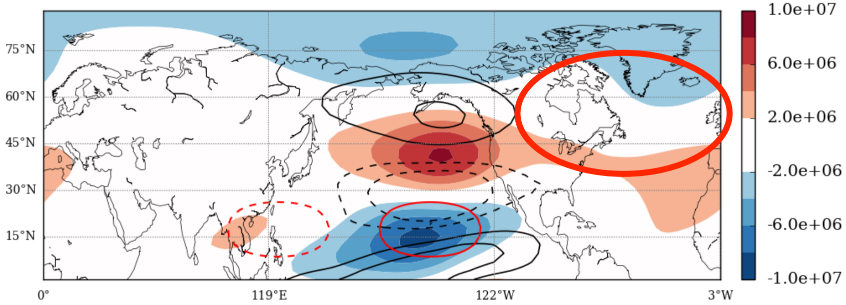


Weak signature of the NAO+ after ~20-25 days in the composite map

$PC1_{t=25d}=0.23$

(x5 compared to stat case)

Consequence for the NAO

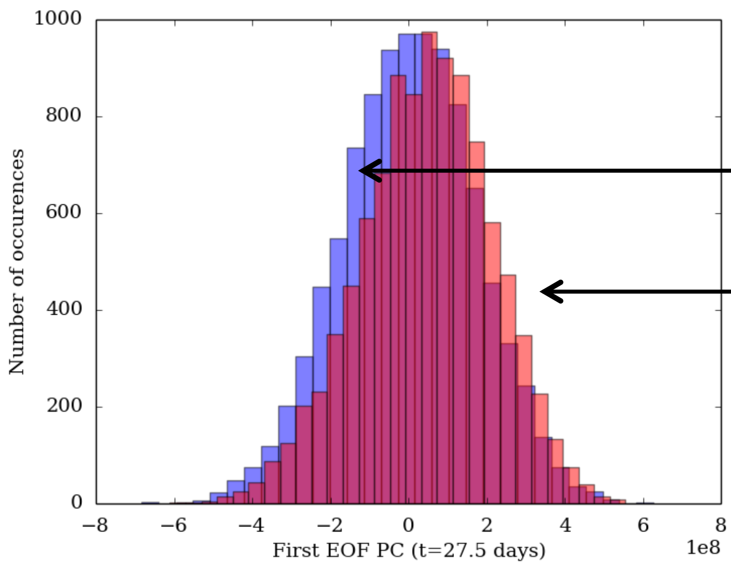


Weak signature of the NAO+ after ~20-25 days in the composite map

$PC1_{t=25d}$=0.23

(x5 compared to stat case)

Probability Distribution Function of the first EOF Principal Components at t=25 days



w/o MJO forcing

with MJO forcing

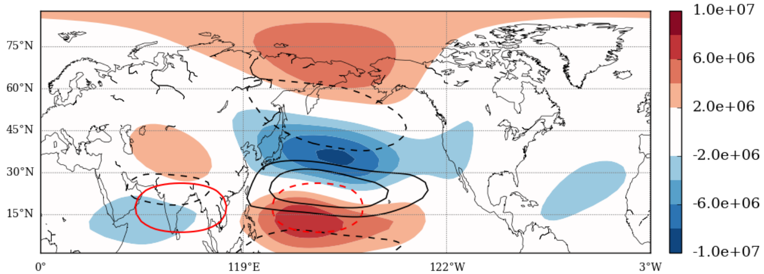
Result comparable to Cassou (2008): 30% excess NAO+ days (i.e $PC_{EOF1} > \sigma_{EOF1}$)

MJO « Phase 6 » forcing

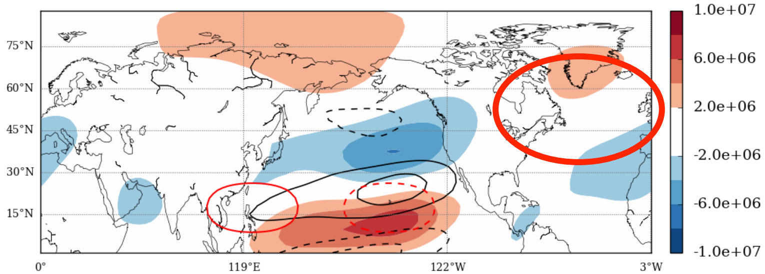
Recipe: take opposite sign of the forcing – redo 10,000 short runs

MJO « Phase 6 » forcing

Recipe: take opposite sign of the forcing – redo 10,000 short runs



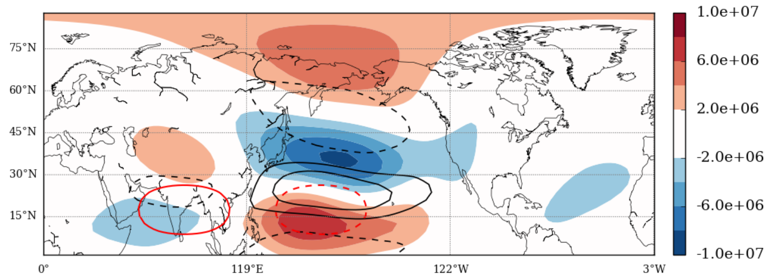
⇒ Wave train of opposite sign after 15 days



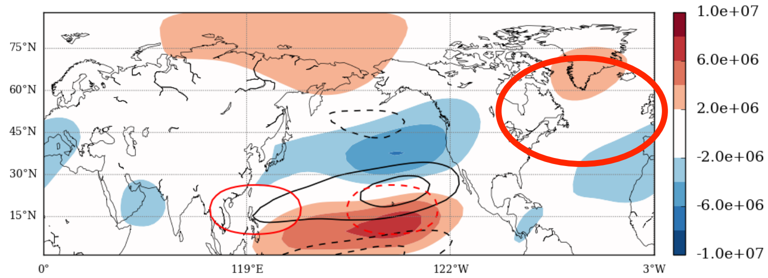
⇒ Signature of NAO- after 25 days

MJO « Phase 6 » forcing

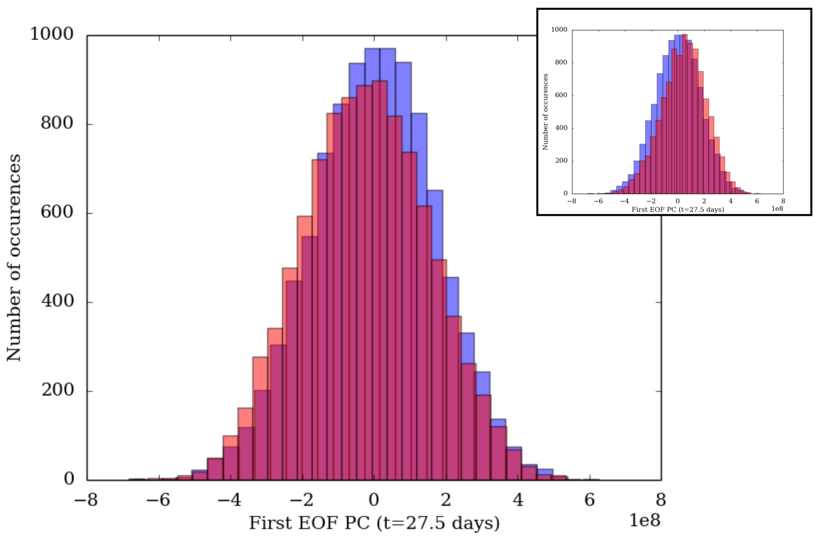
Recipe: take opposite sign of the forcing – redo 10,000 short runs



⇒ Wave train of opposite sign after 15 days



⇒ Signature of NAO- after 25 days



~ 27% excess NAO- days at t=25d (comparable to « phase 3 » results)

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2. MJO ⇔ NAO

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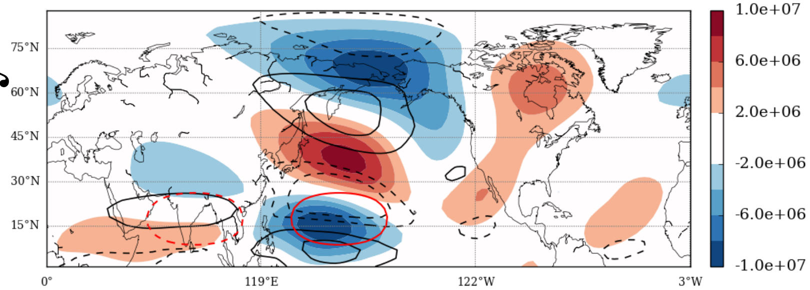
Tropospheric vs. Stratospheric pathways

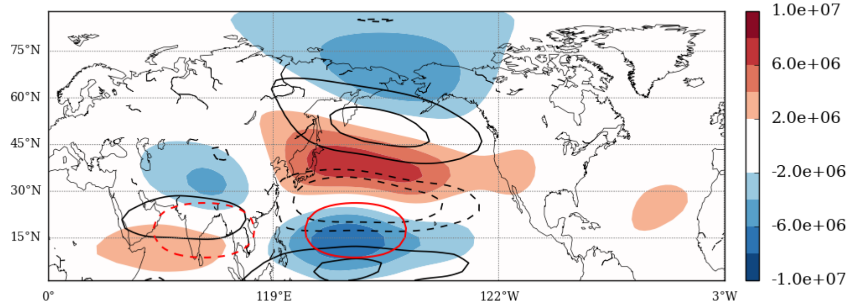
4. Conclusions

Flow response in the north Pacific basin

The case of a stationary background flow	The case of a varying background flow

15 days





Why is the flow response zonally elongated when background flow is time varying?

Streamfunction budget analysis

1. $$\psi_i(t)=\psi_i^{REF}+\psi_i^{LF}(t)+\psi_i^{HF}(t)$$

Time-averaged
(or climatology)

Low frequency (>8 days)
component

High frequency (<8 days)
Component
(synoptic activity)

Streamfunction budget analysis

1. $\psi_i(t)=\psi_i^{REF}+\psi_i^{LF}(t)+\psi_i^{HF}(t)$

Time-averaged (or climatology) → ψ_i^{REF}

Low frequency (>8 days) component → $\psi_i^{LF}(t)$

High frequency (<8 days) Component (synoptic activity) → $\psi_i^{HF}(t)$

2. Inject the terms into evolution equation for PV

$\psi_i(t)=\psi_i^{REF}+\psi_i^{LF}(t)+\psi_i^{HF}(t)$ $\quad$ $\psi_i(t)=\psi_i^{REF}+\psi_i^{LF}(t)+\psi_i^{HF}(t)$

$$\frac{\partial q_i}{\partial t} = -J(\psi_i, q_i) - D_i(\psi_1, \psi_2, \psi_3) + S_i$$

Streamfunction budget analysis

1. $$\psi_i(t)=\psi_i^{REF}+\psi_i^{LF}(t)+\psi_i^{HF}(t)$$

- ψ_i^{REF}: Time-averaged (or climatology)
- $\psi_i^{LF}(t)$: Low frequency (>8 days) component
- $\psi_i^{HF}(t)$: High frequency (<8 days) Component (synoptic activity)

2. Inject the terms into evolution equation for PV

3. Compute ensemble average & anomalies

Streamfunction budget analysis

1.

$$\psi_i(t)=\psi_i^{REF}+\psi_i^{LF}(t)+\psi_i^{HF}(t)$$

Time-averaged (or climatology)

Low frequency (>8 days) component

High frequency (<8 days) Component (synoptic activity)

2. Inject the terms into evolution equation for PV

3. Compute ensemble average & anomalies

$$\langle d\psi(t)/dt \rangle = \underbrace{\delta\psi_{LIN}(t) + \delta F}\, + \delta\psi_{LF\text{-}LF}(t) + \delta\psi_{HF\text{-}HF}(t) + R$$

Streamfunction time derivative

Linear processes & Forcing (describe low freq. wave propagation)

Nonlinear low-frequency processes

Nonlinear high-frequency processes

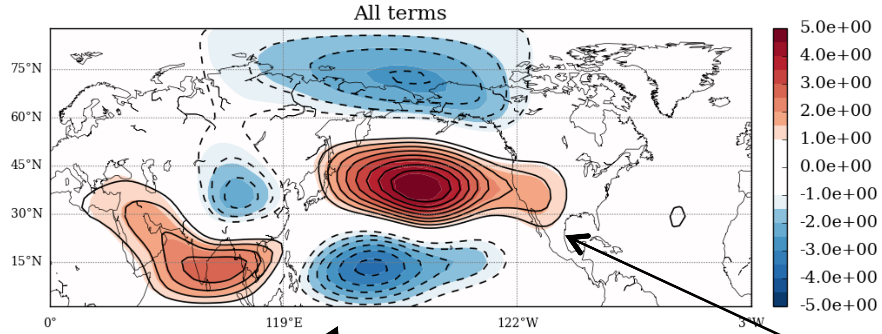
Streamfunction budget in Pacific (5 -> 15 days)

Time-varying reference flow case

$$\langle d\psi(t)/dt \rangle = \delta\psi_{LIN}(t) + \delta F + \delta\psi_{LF\text{-}LF}(t) + \delta\psi_{HF\text{-}HF}(t) + R$$

Streamfunction budget in Pacific (5 -> 15 days)

Time-varying reference flow case



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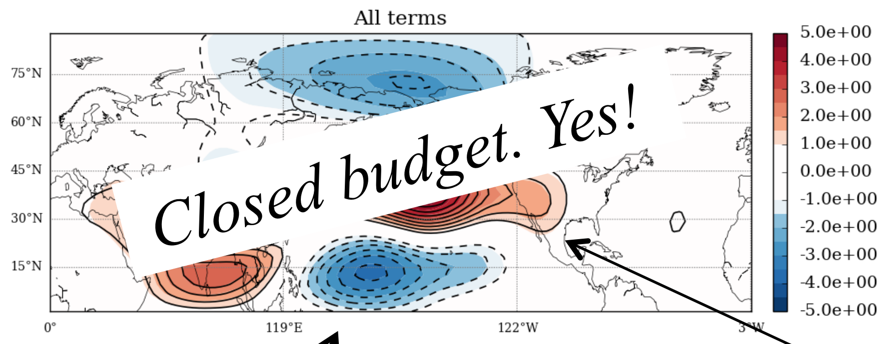

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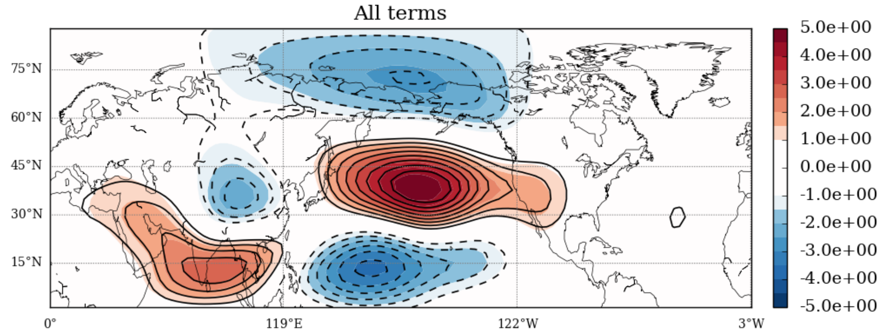

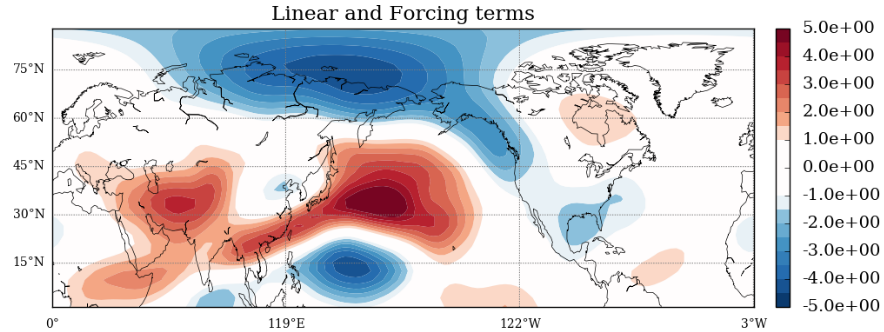

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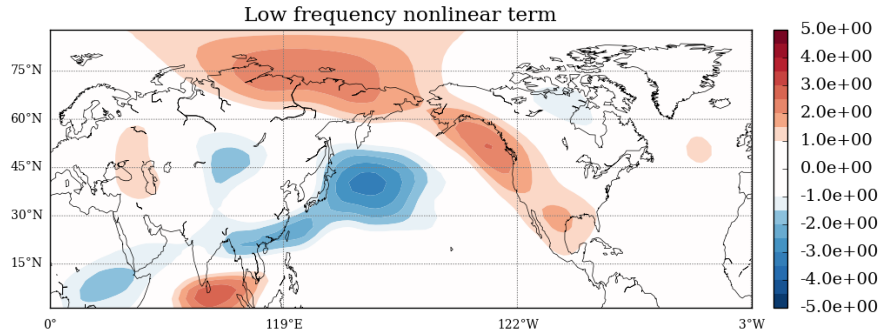
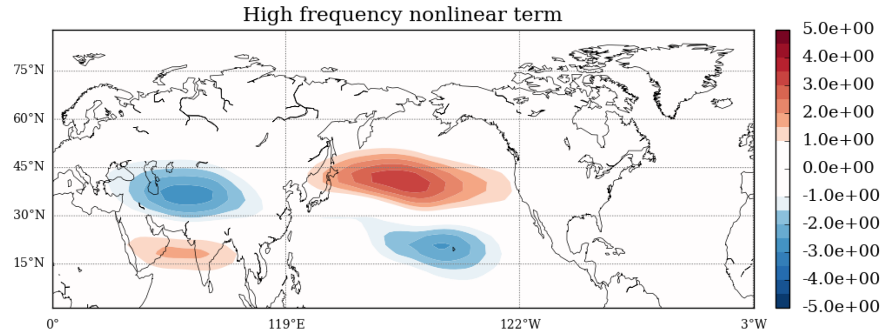
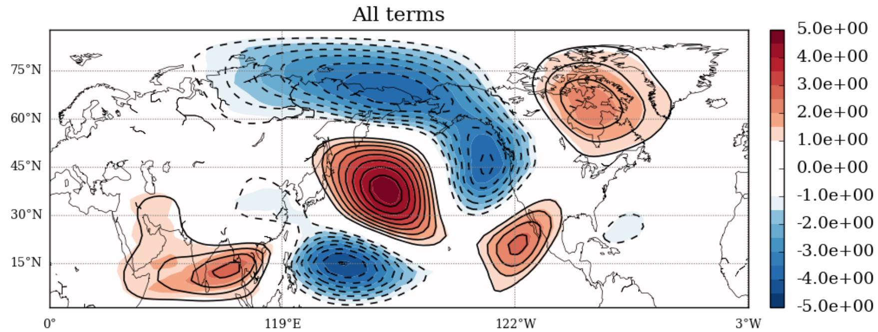
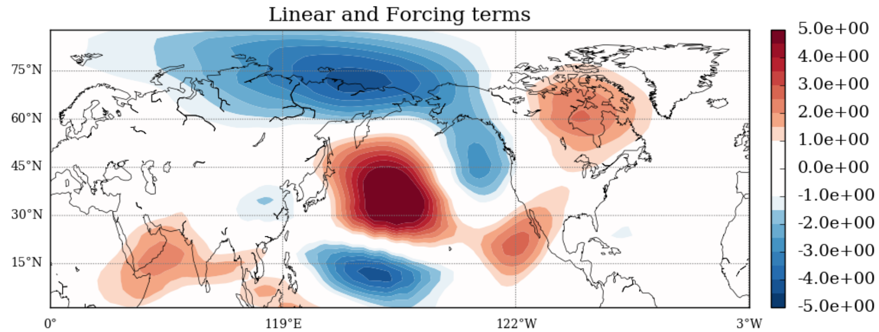




Streamfunction budget in Pacific (5 -> 15 days)

Stationary reference flow case





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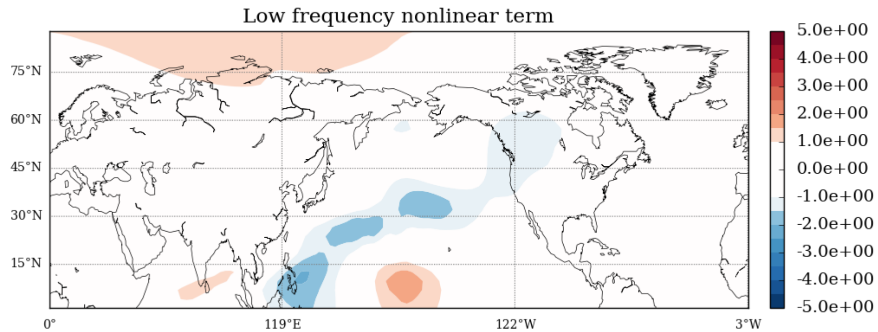
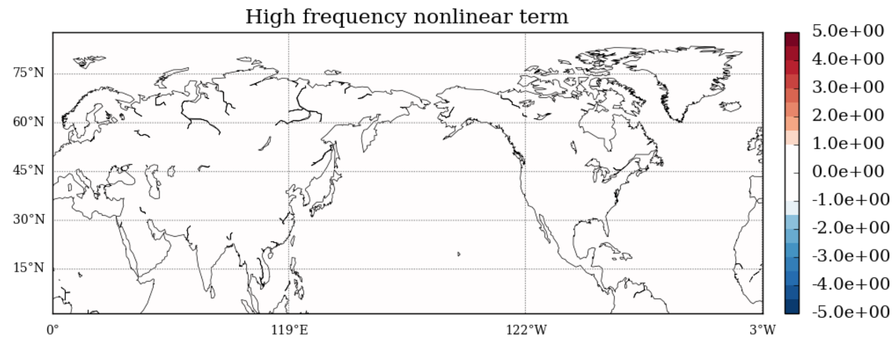
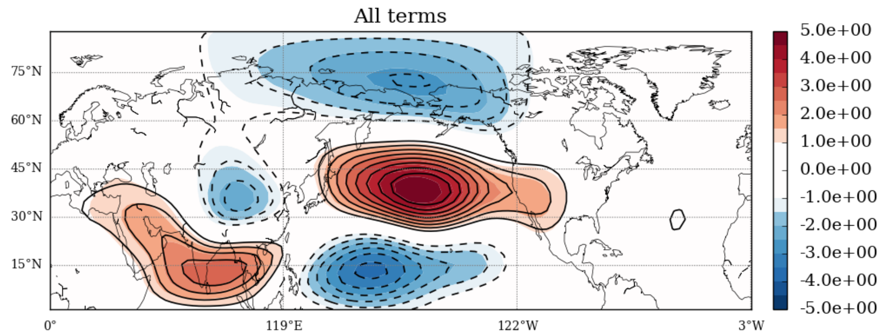
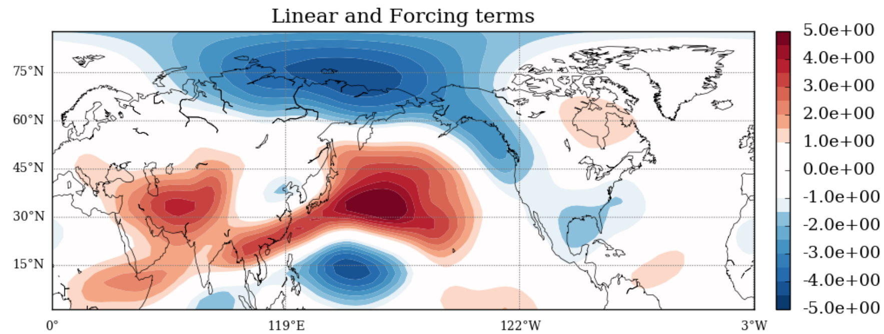




Streamfunction budget in Pacific (5 -> 15 days)

Time-varying reference flow case





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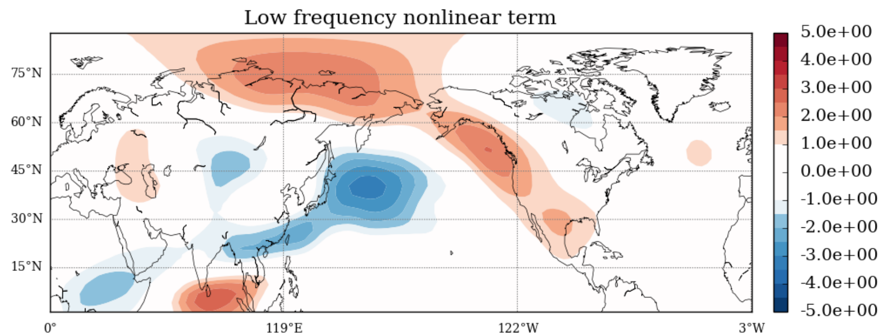
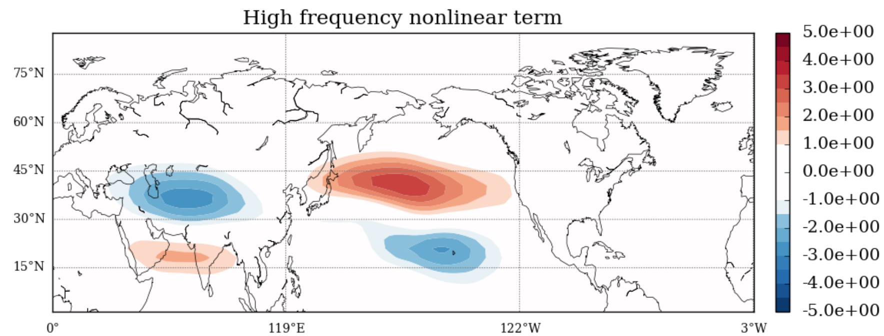
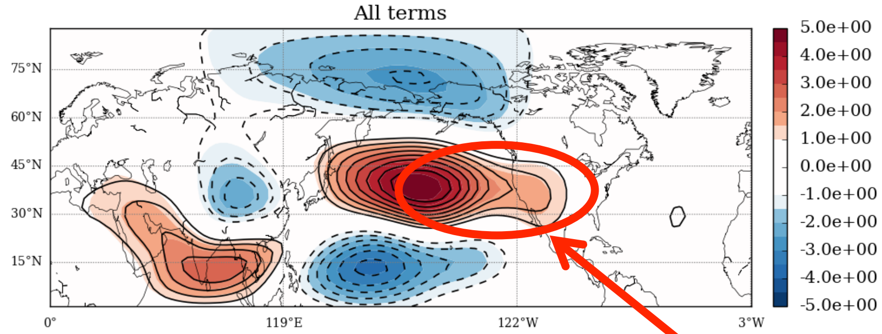
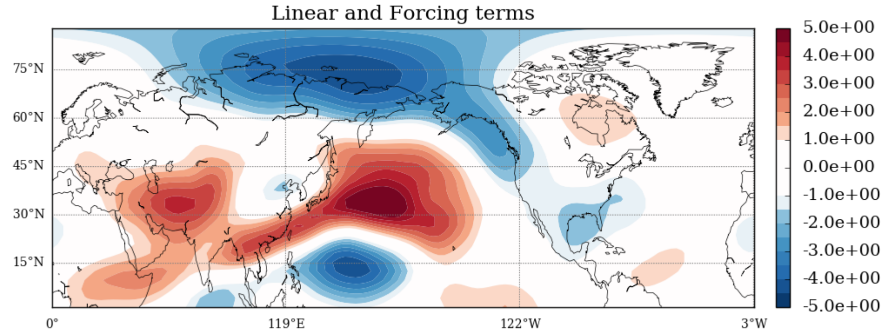




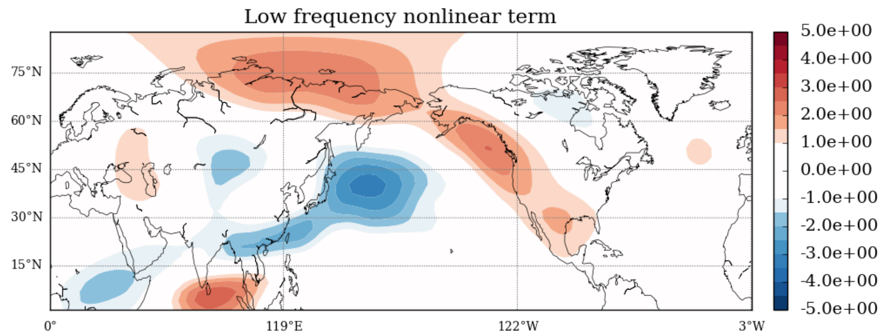
Streamfunction budget in Pacific (5 -> 15 days)

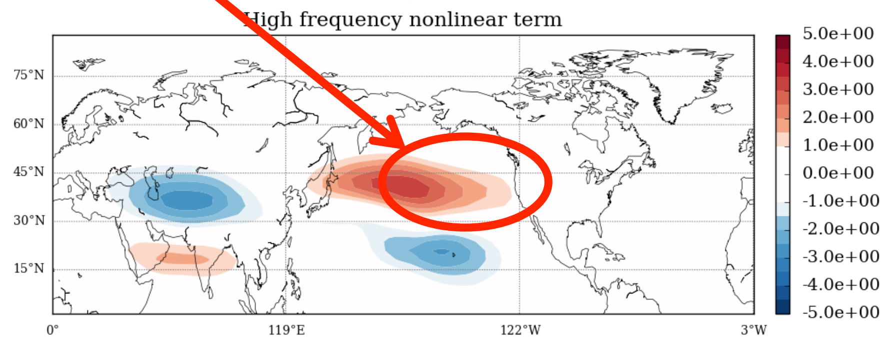
Time-varying reference flow case



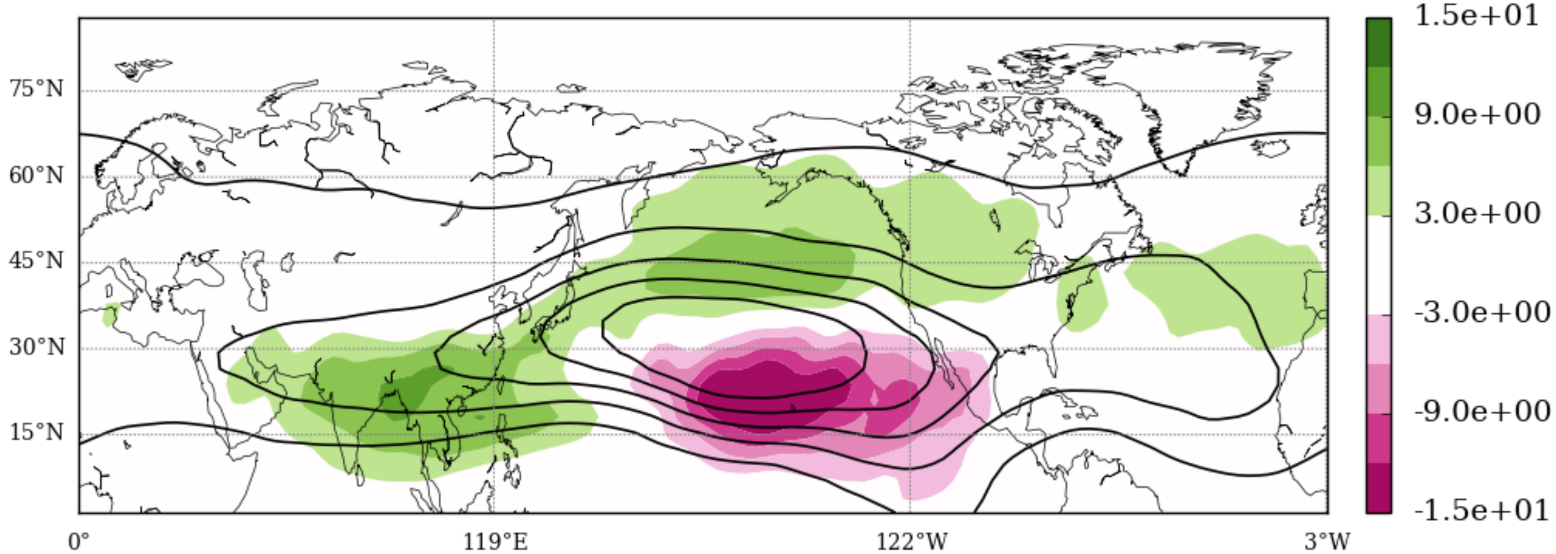


$$\langle d\psi(t)/dt \rangle = \delta\psi_{LIN}(t) + \delta F + \delta\psi_{LF\text{-}LF}(t) + \delta\psi_{HF\text{-}HF}(t) + R$$





Effect on the Pacific storm-track @ 15 days



Contours: high frequency eddy Kinetic Energy (climatology)
Shadings: Anomalies & 15 days

Poleward shift of the stormtrack 5-10 days after Phase 3
(in agreement with e.g. Moore et al. 2010)

Flow response in Pacific basin

1/ « Normal » Rossby wave response in Western Pacific

2/ Modification of the Pacific synoptic activity in Eastern Pacific (poleward shift of the stormtrack)

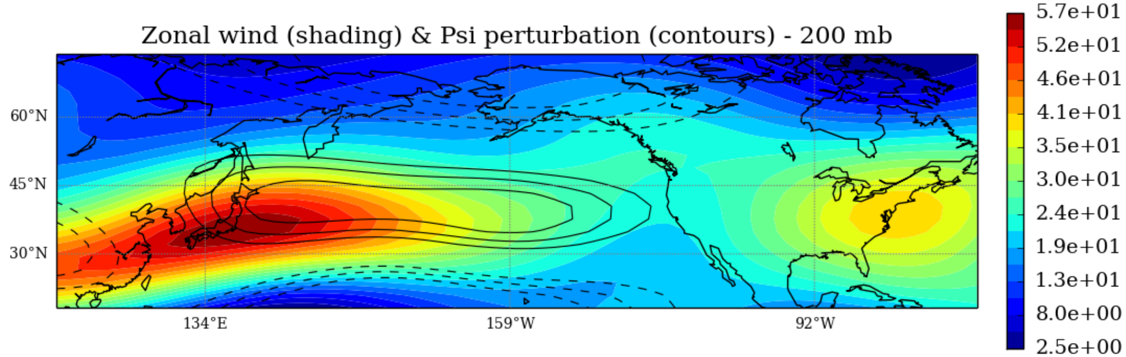
⇒ Flow response zonally elongated

⇒ Pacific jet displaced poleward

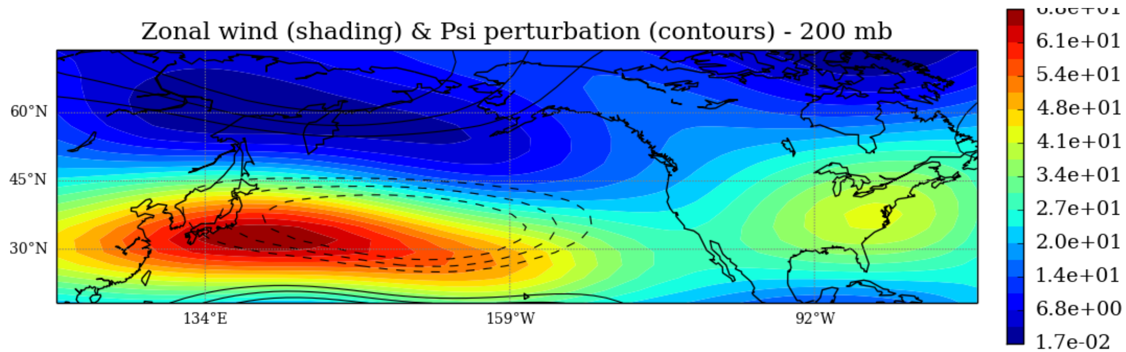
Effect on Atlantic synoptic eddies

⇒ Pacific jet displaced in latitudes

« Phase 3 » Case



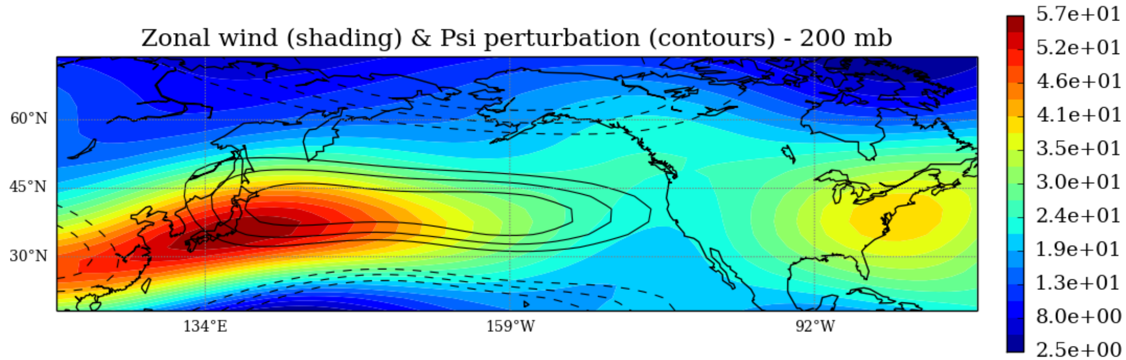
« Phase 6 » case



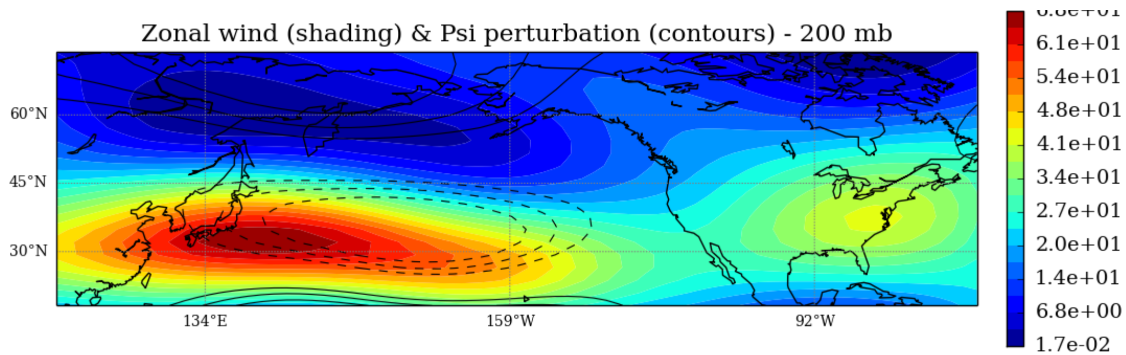
Effect on Atlantic synoptic eddies

⇒ Pacific jet displaced in latitudes

« Phase 3 » Case



« Phase 6 » case

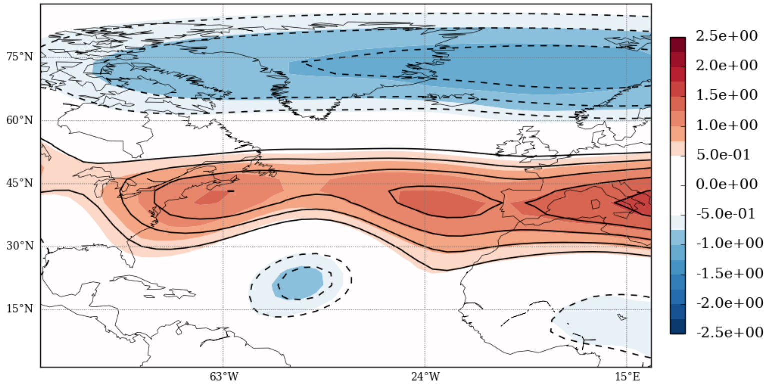


⇒ Pacific synoptic eddies deflected when going to the Atlantic
(Drouard et al. 2013, Rivière & Drouard 2015, Tan et al. 2017)

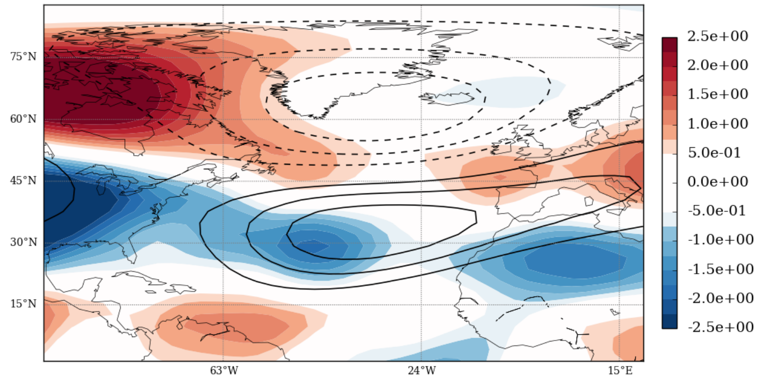
⇒ Positive phase of the NAO is favored due to (anticyclonic) eddy wave breaking

Budget over the Atlantic (15 -> 25 days)

All terms

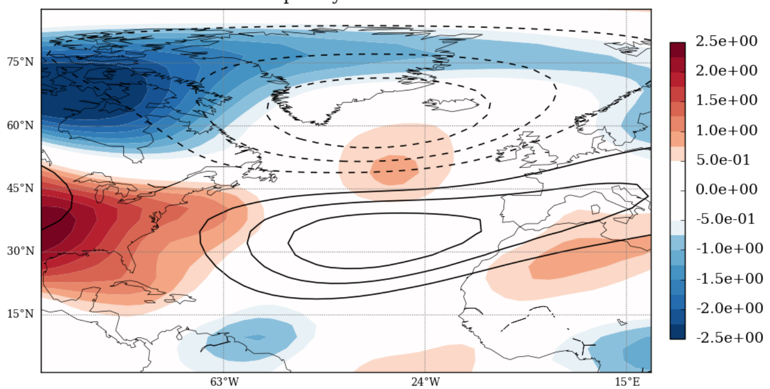


Linear and Forcing terms

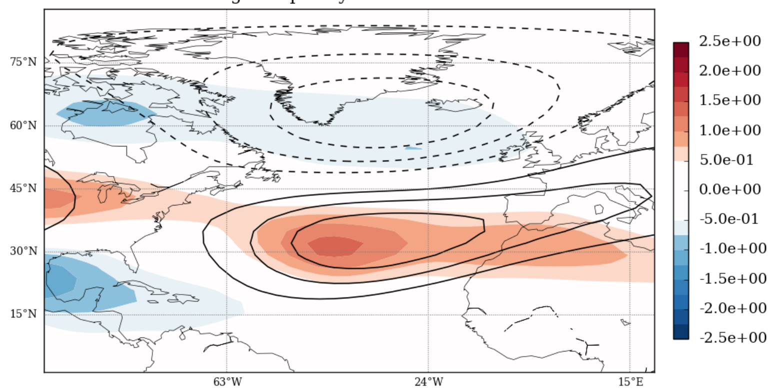


$$\langle d\psi(t)/dt\rangle = \overbrace{\delta\psi_{LIN}(t) + \delta F} + \delta\psi_{LF-LF}(t) + \delta\psi_{HF-HF}(t) + R$$

Low frequency nonlinear term

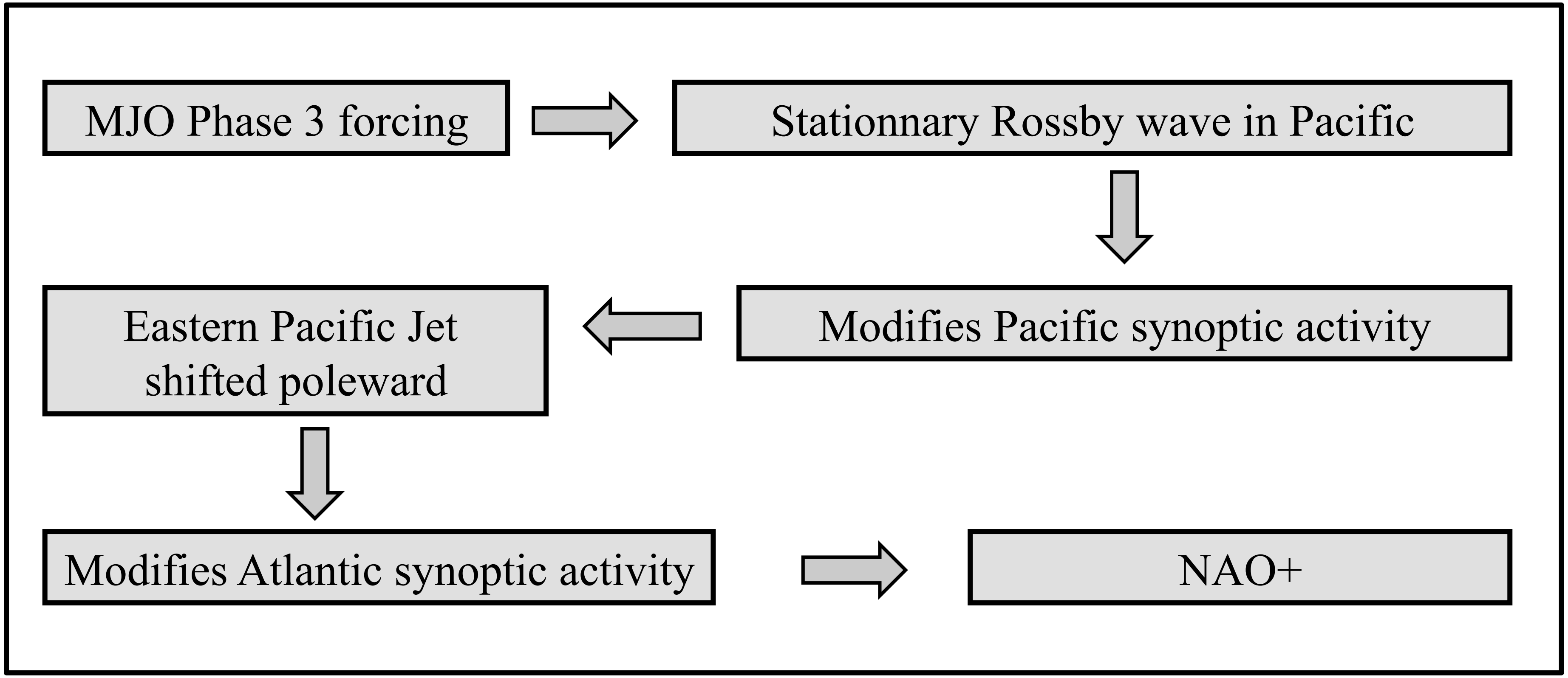


High frequency nonlinear term



⇒ Atlantic projection on NAO+ dominated by nonlinear high frequency correlations

Mechanism



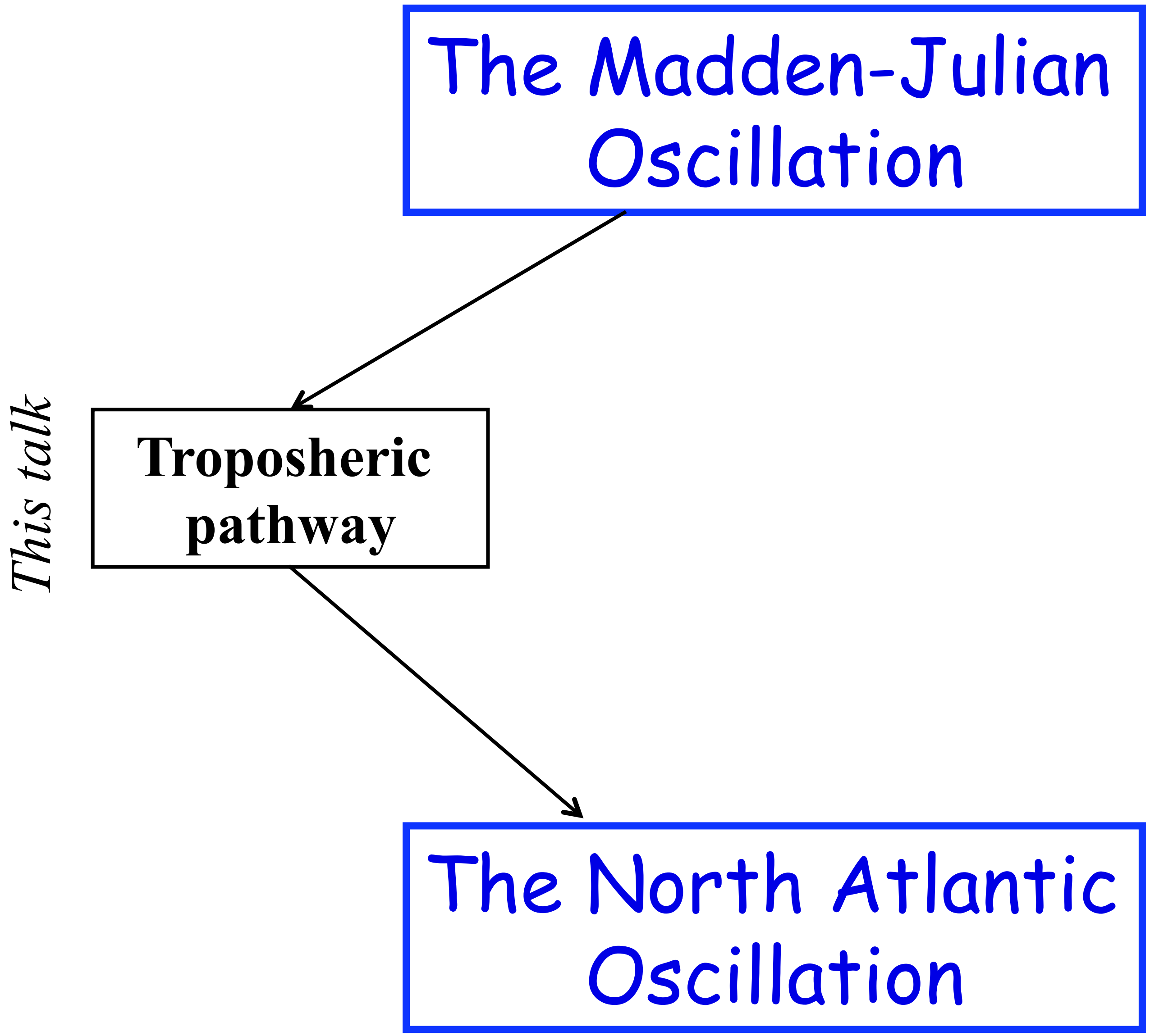
MJO Phase 3 forcing
Stationnary Rossby wave in Pacific
Modifies Pacific synoptic activity
Eastern Pacific Jet shifted poleward
Modifies Atlantic synoptic activity
NAO+

Limitations

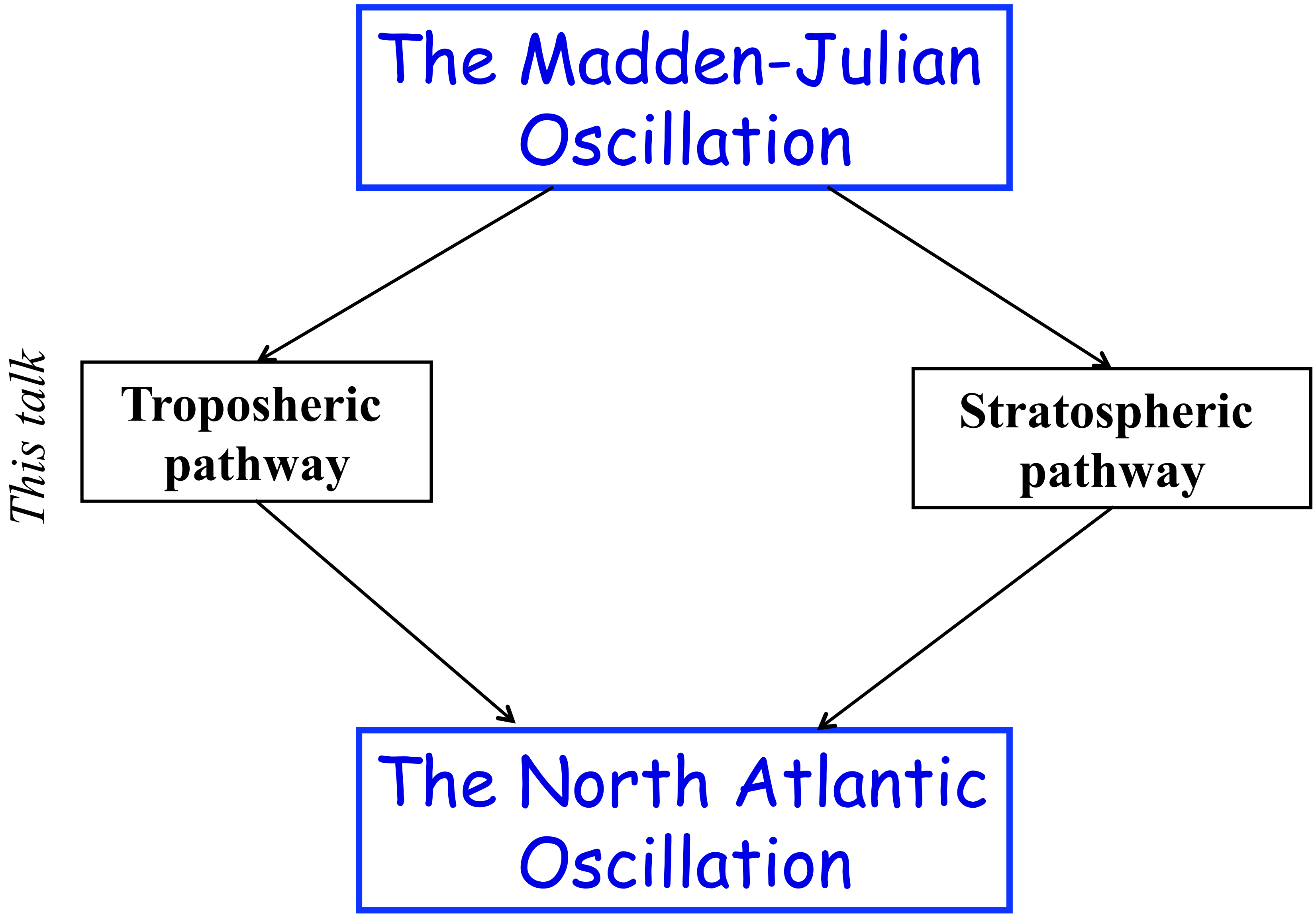
- **Limited realism** (difficult to compare with obs)
  (ex: orography)

- **Equatorial dynamics not properly captured within the QG approximation**
  Spurious artefacts in the forcing
  (ex: small residual forcing in the Atlantic)

- **Stratospheric dynamics absent**



See e.g. Barnes et al. (2019)



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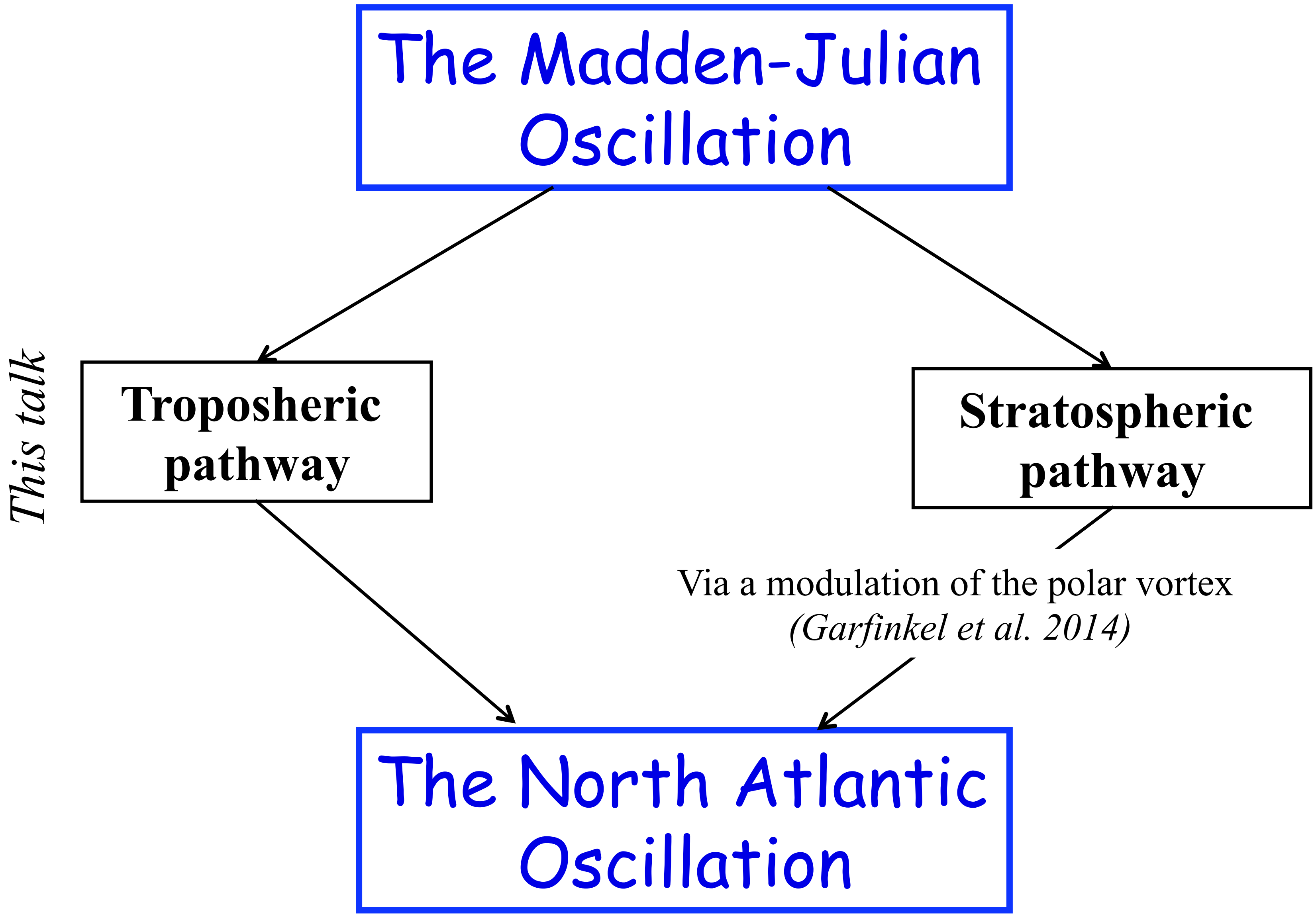

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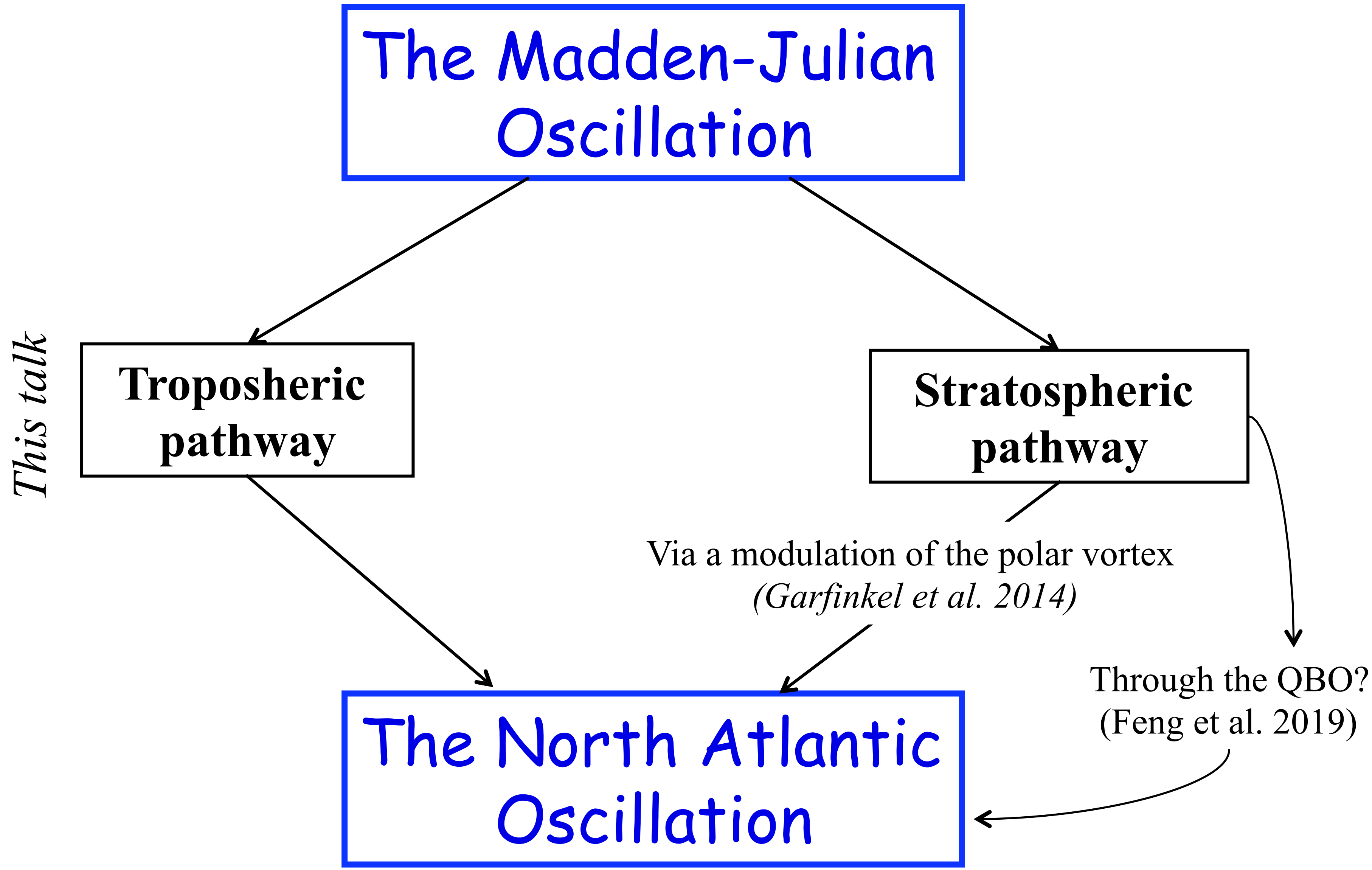
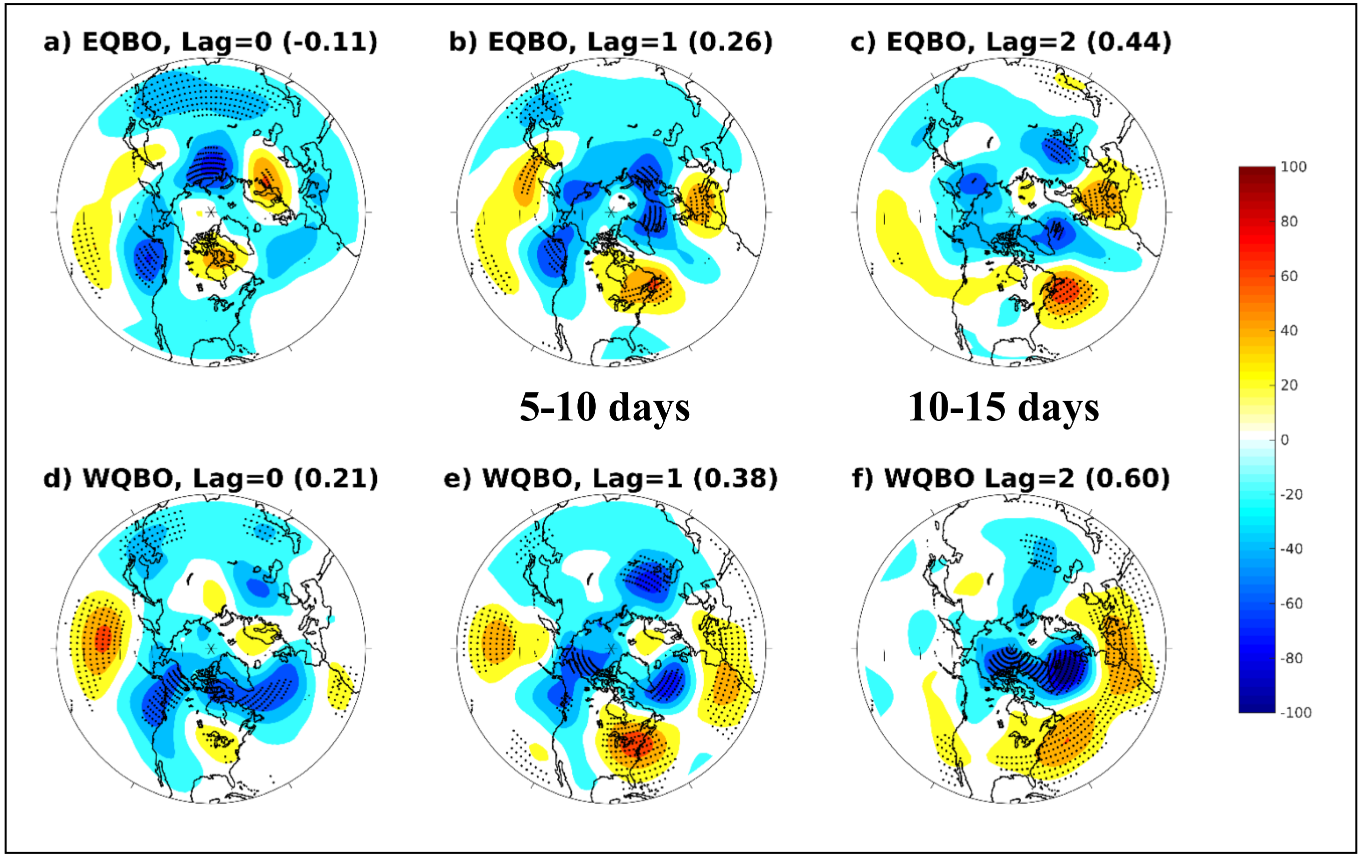


See e.g. Barnes et al. (2019)

MJO => QBO => NAO?

Feng & Lin (2019)

500 mb streamfunction anomalies following MJO Phase 3



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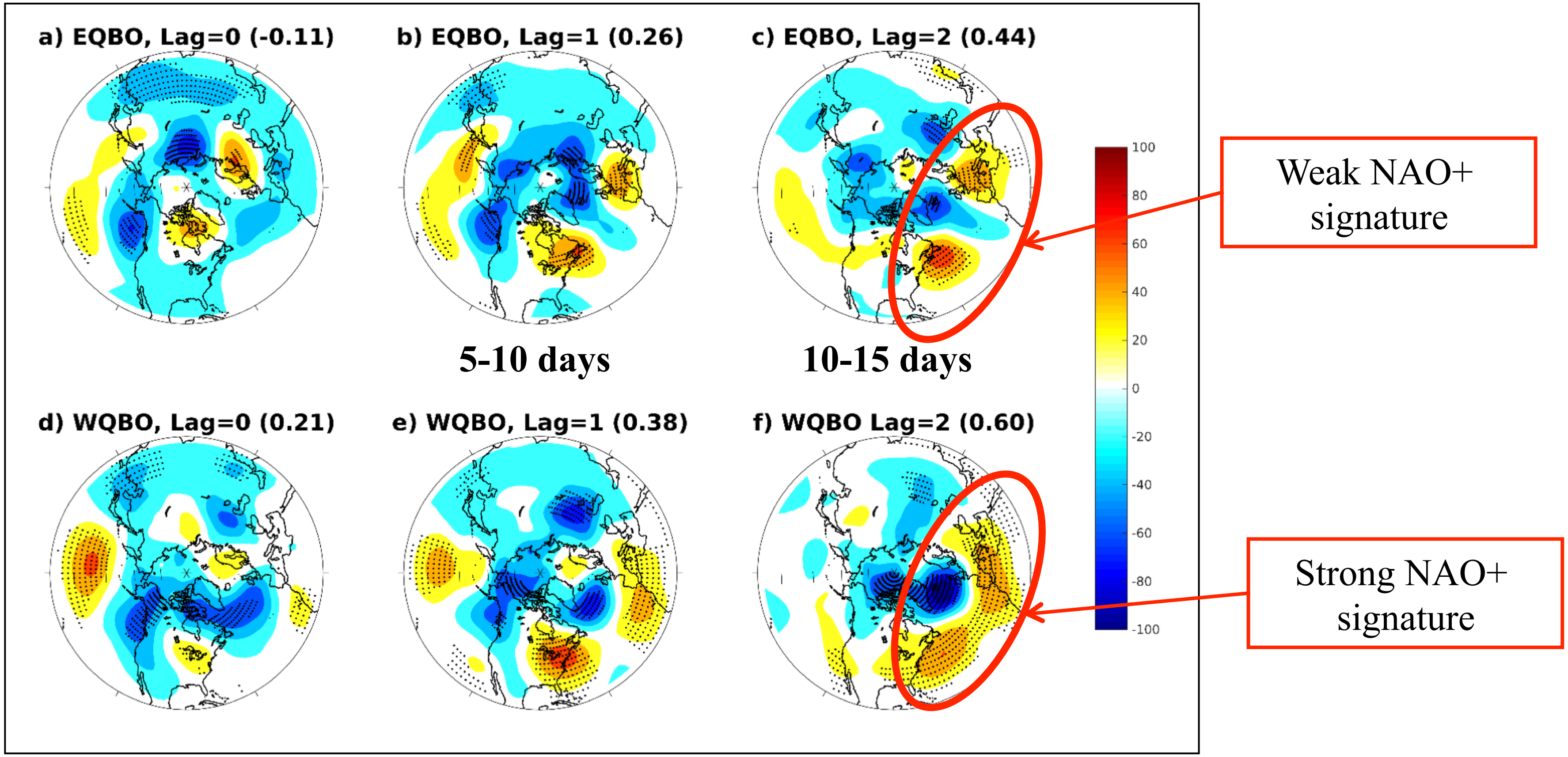
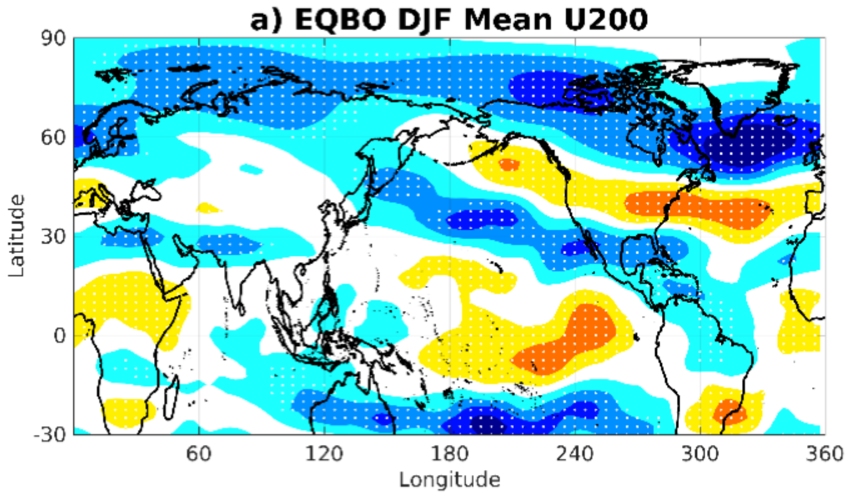


- **Stronger NAO** following the MJO during **Westerly QBO** years
- **Weaker NAO** following the MJO during **Easterly QBO** years

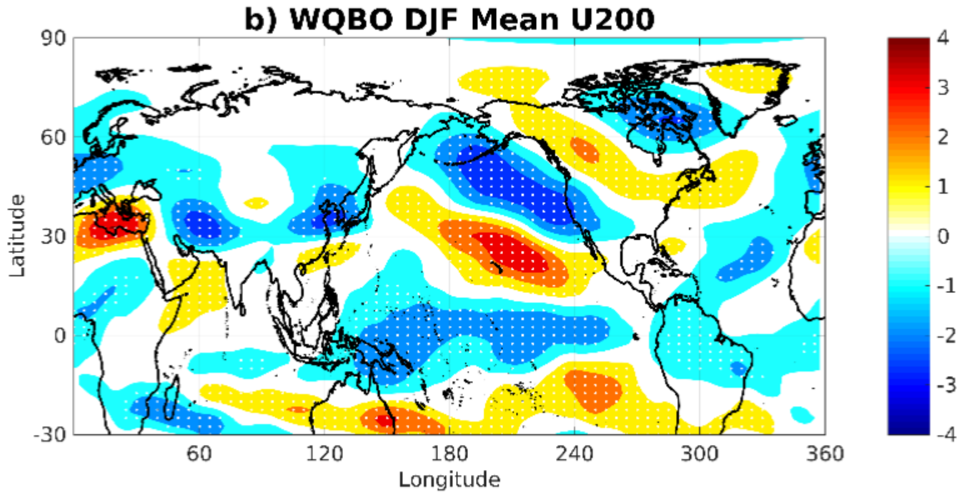
MJO => QBO => NAO: mechanism?

200 mb zonal wind anomalies

Easterly QBO



Westerly QBO



MJO => QBO => NAO: mechanism?

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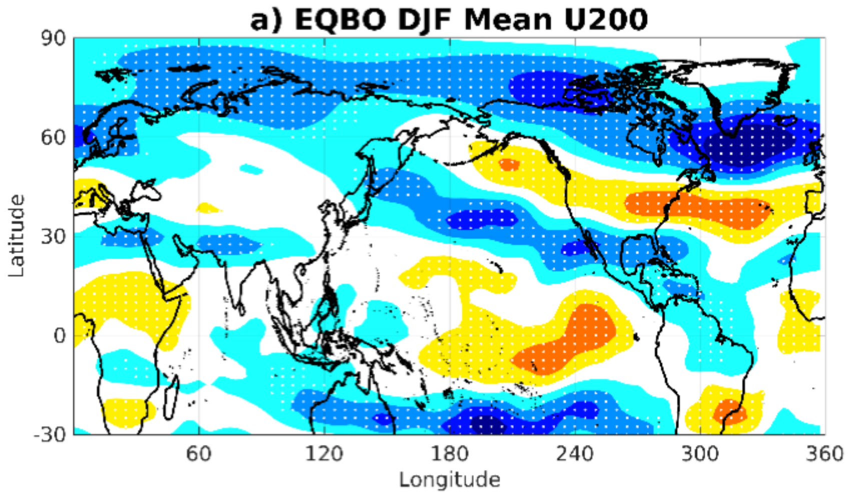
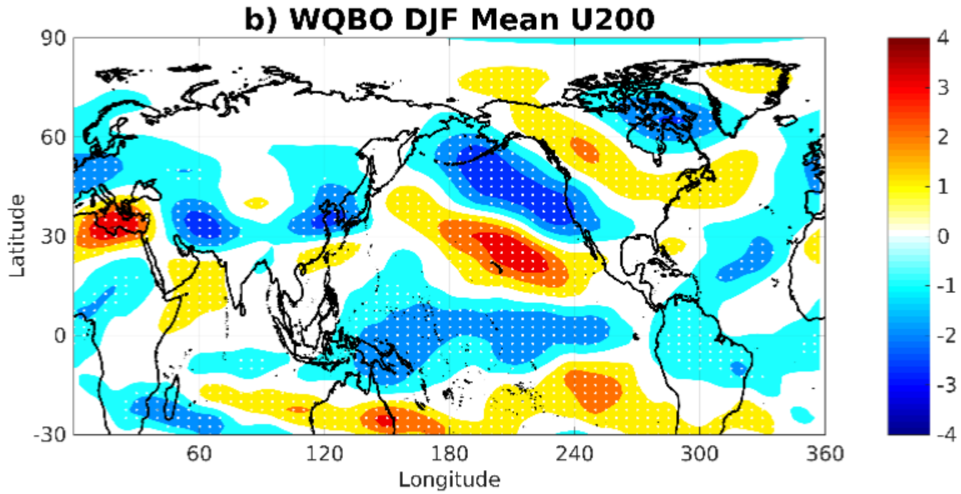


Westerly QBO



Pacific jet further North
⇒ Farther away from MJO
⇒ Weaker Rossby wave excitation
(Lin & Brunet 2018)

Pacific jet further South
⇒ Closer to MJO
⇒ Stronger Rossby wave excitation
(Lin & Brunet 2018)

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⇒ Physical mechanism suggested by the numerical experiments

Interplay between stationary Rossby wave & nonlinear eddy interactions

⇒ Relative importance of tropospheric vs. stratospheric pathways (e.g. QBO, Polar vortex) to be quantified…

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⇒ Relative importance of tropospheric vs. Stratospheric effect (e.g. QBO, Polar vortex) to be quantified…

Thank you for your attention!

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