Local and Remote Forcing of the Ocean by the Madden-Julian Oscillation

Centre for Australian Weather and
Climate Research Seminar

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July 6, 2012

Introduction

- Historically, our ability to predict the weather has relied on items of **weather lore** such as the old saying

> Red sky at night, sailor's delight
> Red sky at morning, sailors take warning

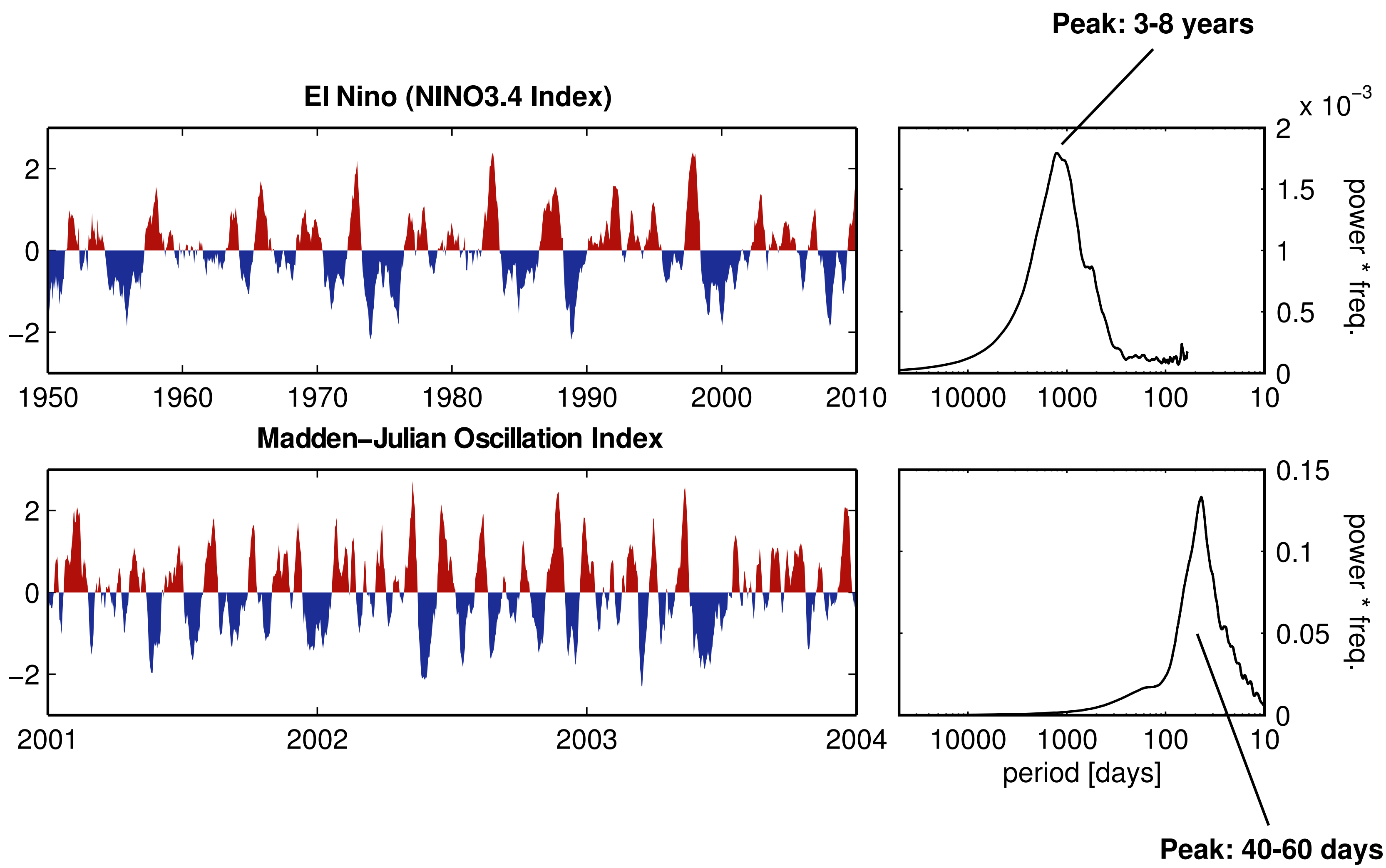
- Advances in **science and technology** over the last few centuries have improved our ability to predict **weather and climate**. For example, the identification of **modes of variability**.

- In addition, advances in our understanding of **dynamics**, as well as the development of **numerical models**, have also led to much better forecasts.

- In the course of my Ph.D. I approached problems in prediction of ocean variability by using **empirical methods**, similar although more sophisticated than above, as well as **dynamical theory** and **numerical models**.

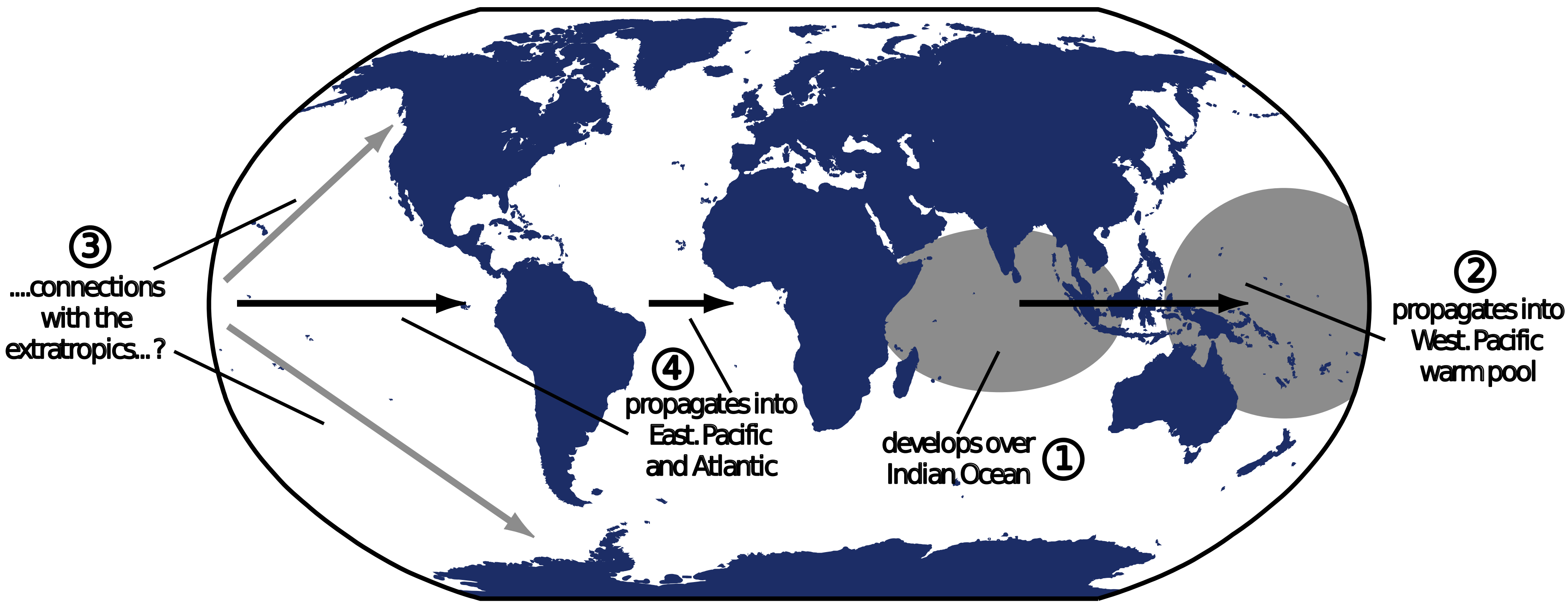
Modes of Variability

El Nino and the Madden-Julian Oscillation (MJO) are both **modes of variability** which operate on very different **time scales**



Madden-Julian Oscillation

- MJO is dominant mode of **atmospheric variability** in the tropics on intraseasonal time scales (30-90 days)
- **Eastward propagating** disturbance detectable in tropical deep convection, precipitation, surface pressure, and zonal wind:



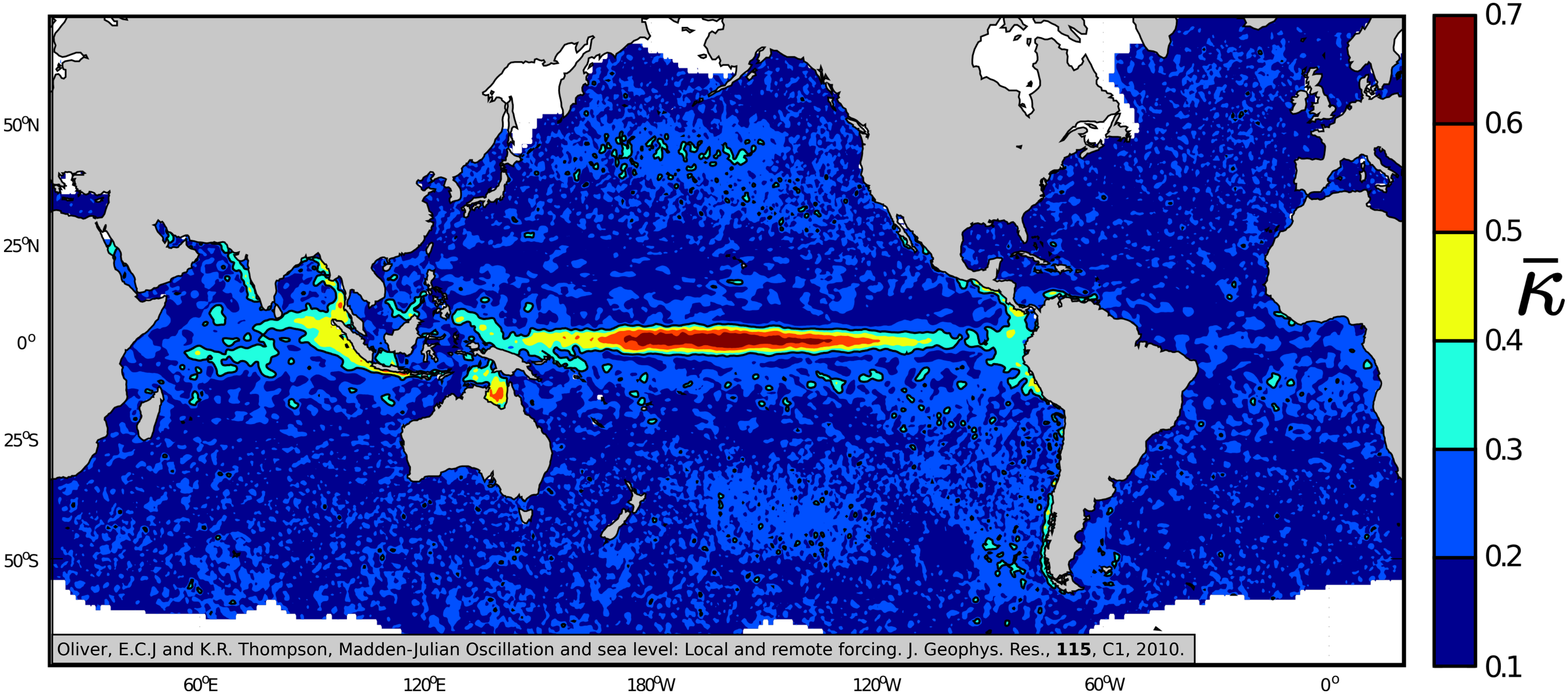
Main Questions

How does the MJO impact the ocean?

Is the MJO a potentially useful source of oceanic predictability?

The MJO and Global Sea Level

- The **statistical connections** between **the MJO and global sea level** have been mapped using a coherence-based metric



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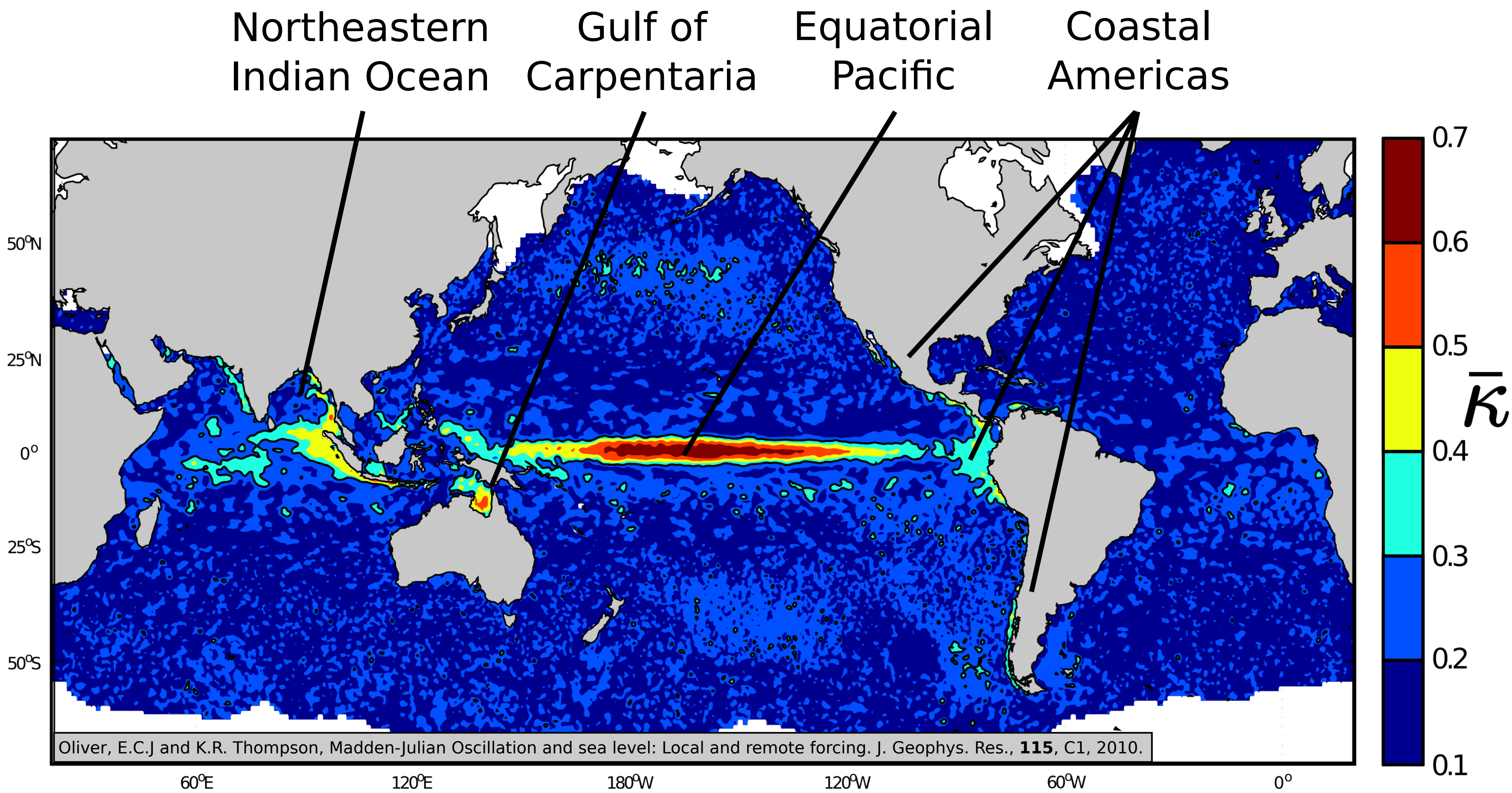
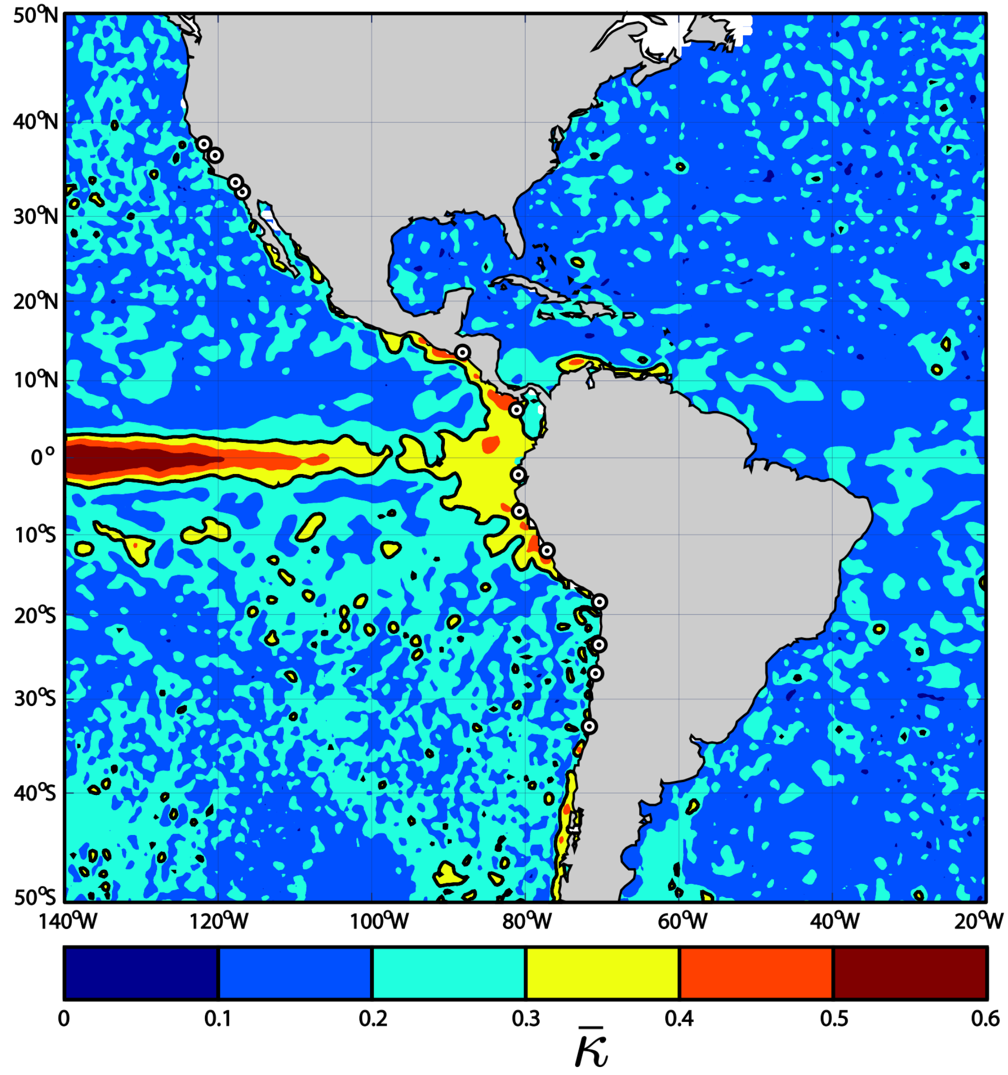


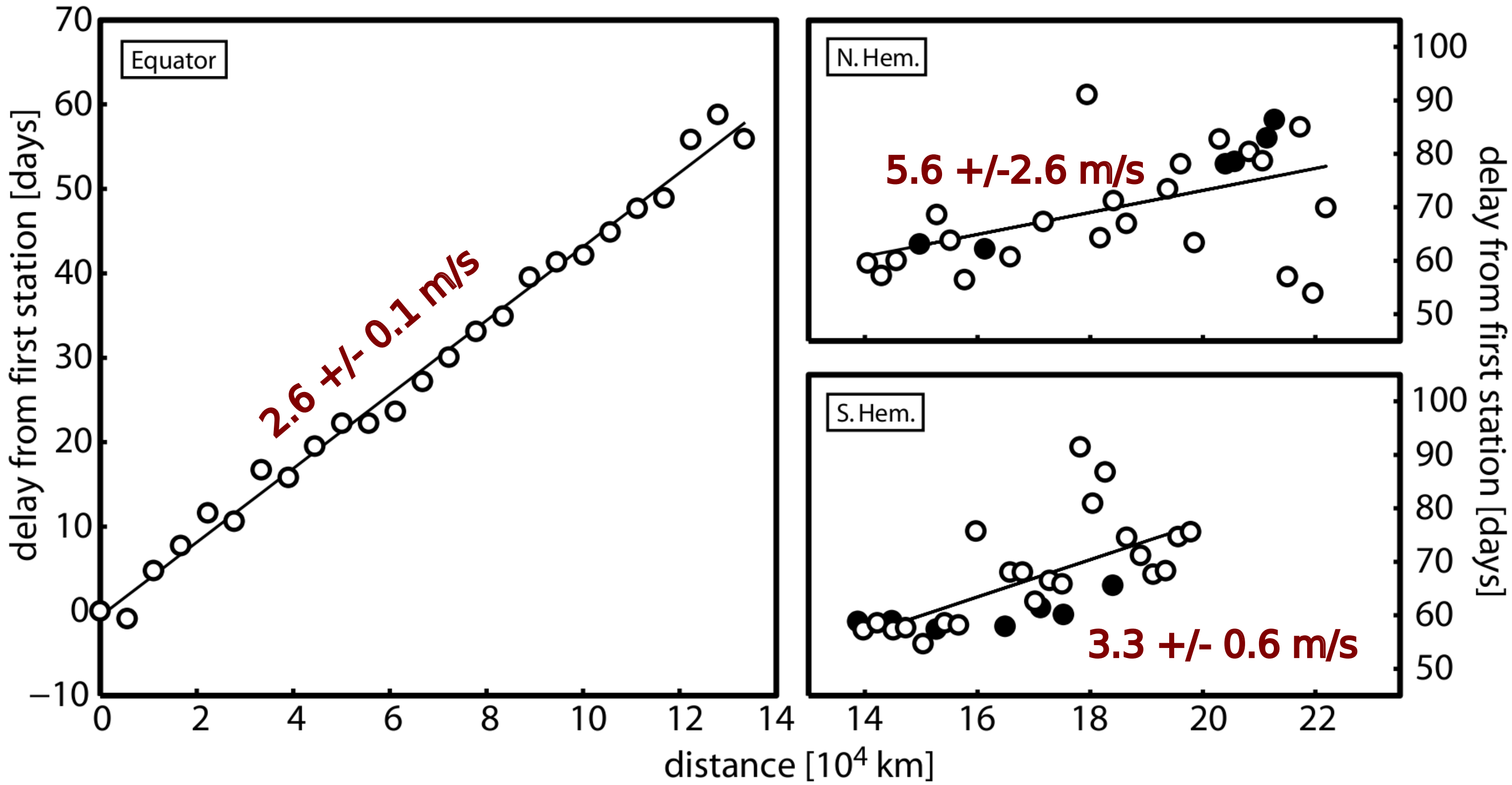
Eq. Pacific and Coastal Americas

- Geography: long unbroken coastline may channel information from the tropics to the extratropics
- Data used in regional analysis:
  - Altimeter: 25 points along the equator (155E-85W) and 44 along the coastline
  - Tide gauge: 13 stations along coastline (see dots in figure)



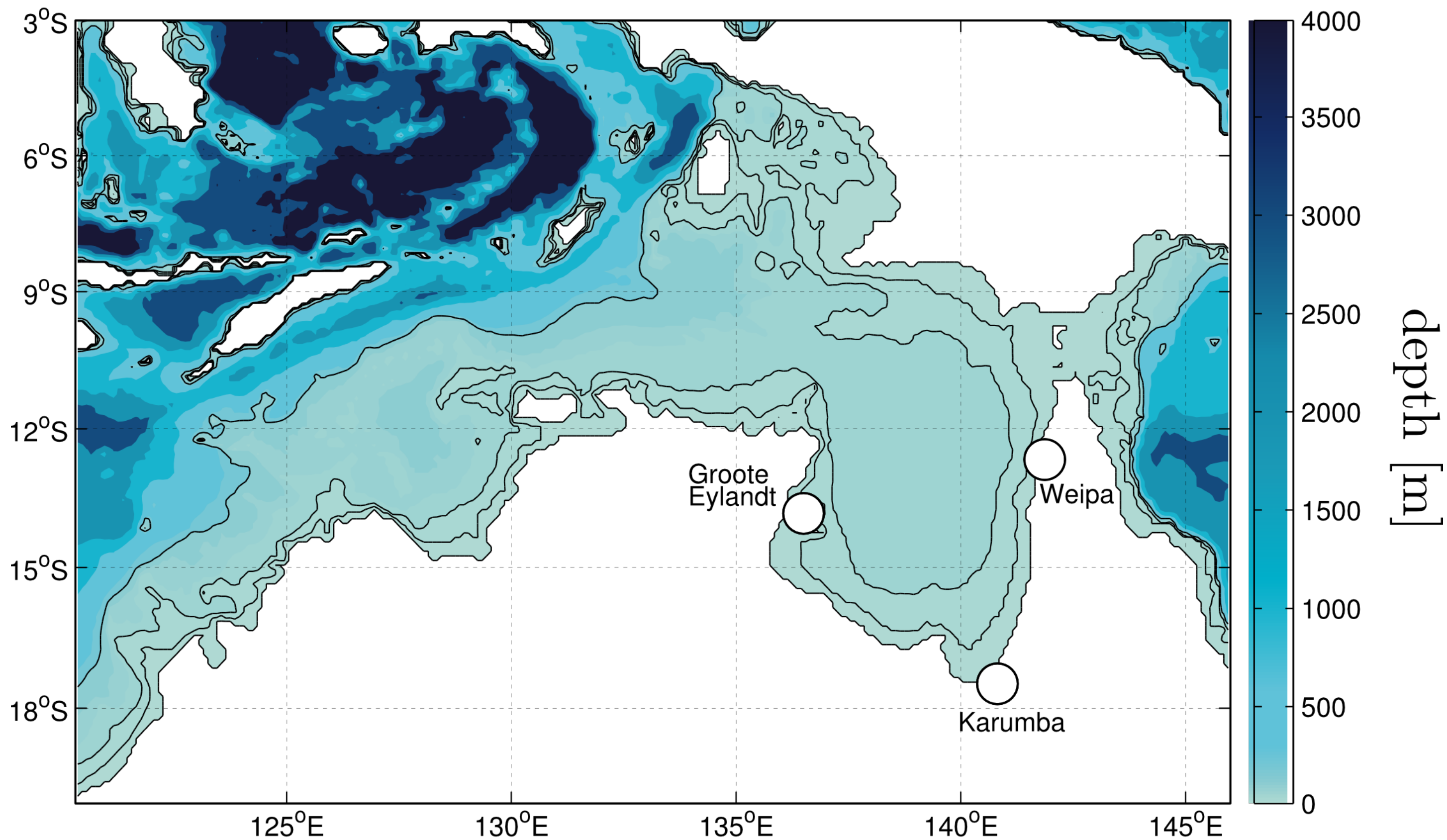
Equatorial and Coastal Waveguide

- Dominant mode of variability at a period of 75 days: wave propagation along **equatorial and coastal waveguides**



This region has since been studied in more detail, e.g., X. Zhang, Y. Lu, and K.R. Thompson. Sea level variations in the tropical Pacific Ocean and the Madden-Julian Oscillation. J. Phys. Ocean., **39**, 8, 2009 and X. Zhang, Y. Lu, K.R. Thompson, and J. Jiang. Tropical Pacific Ocean and the Madden-Julian Oscillation: Role of wind and buoyancy forcing, J. Geophys. Res., **115**, C5, 2010.

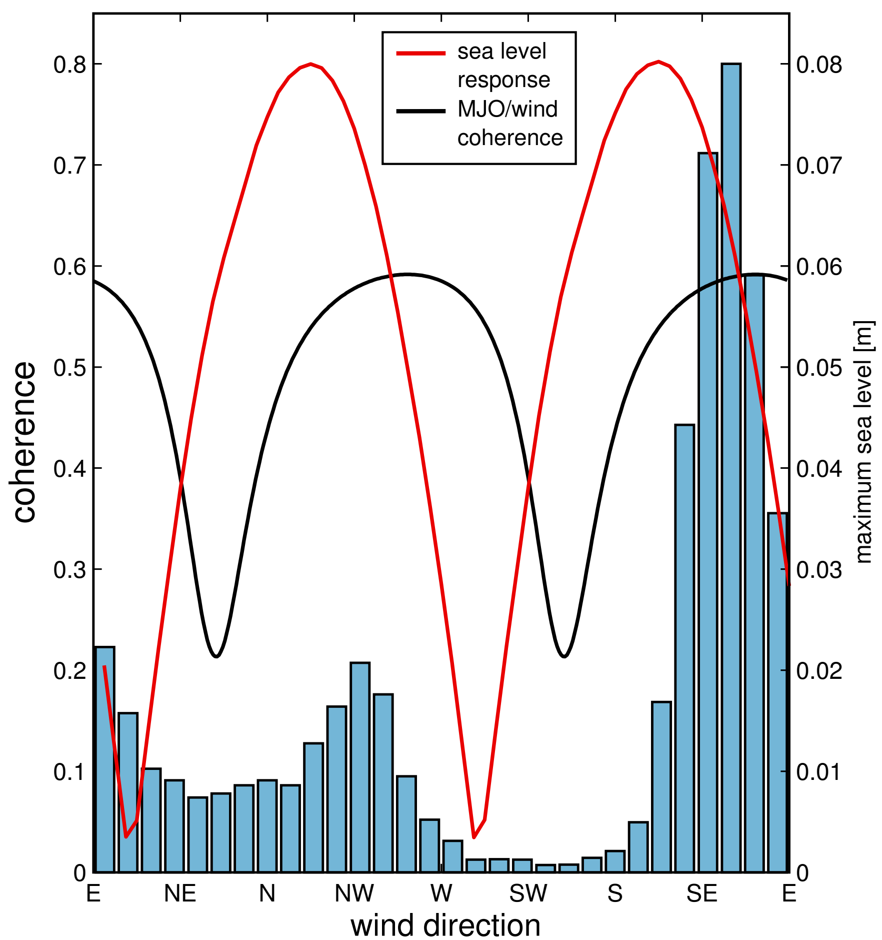
The Gulf of Carpentaria



- The Gulf of Carpentaria is a **shallow sea** north of Australia
- Shallow regions amplify the direct **sea level set-up** response due to surface wind stress

Numerical Model

- Model: **Princeton Ocean Model (POM)**, non-linear, two-dimensional barotropic general circulation model
- Ten-minute spatial resolution, forced by NCEP/NCAR winds (6 hourly)

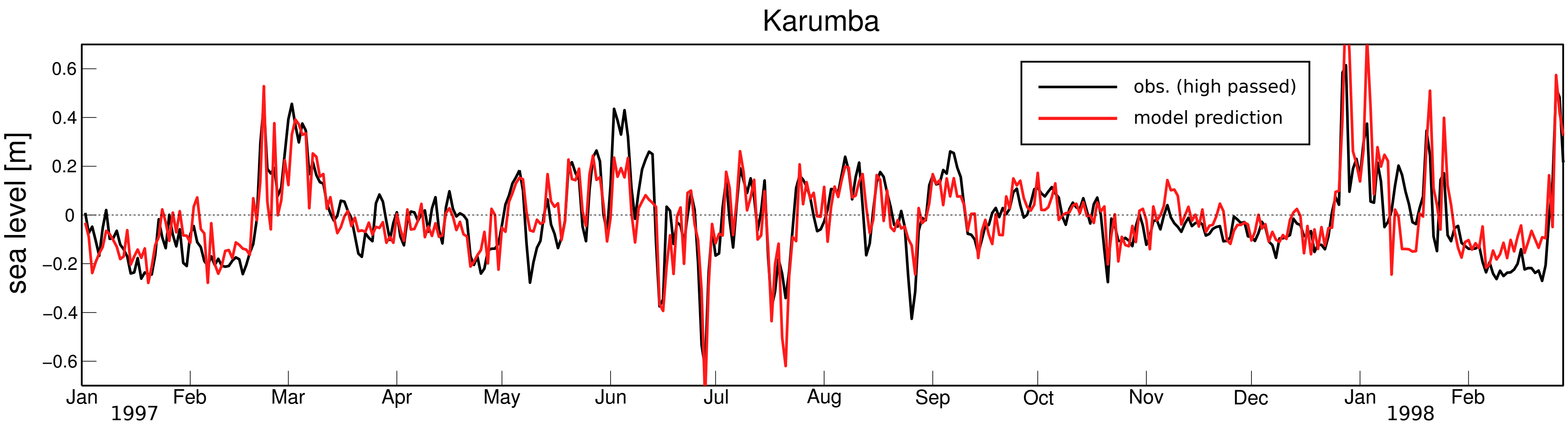


- Wind over the Gulf is **predominantly northwesterly** or **southeasterly** (histogram bars)
- Sea level in the Gulf responds **preferentially** to SSE and NNW winds (— red line)
- The **coherence** between the MJO and surface wind is highest for ESE and WNW winds during **Boreal Winter** (— black line)

These factors combine to make **sea level** in the Gulf particularly **responsive to the MJO**

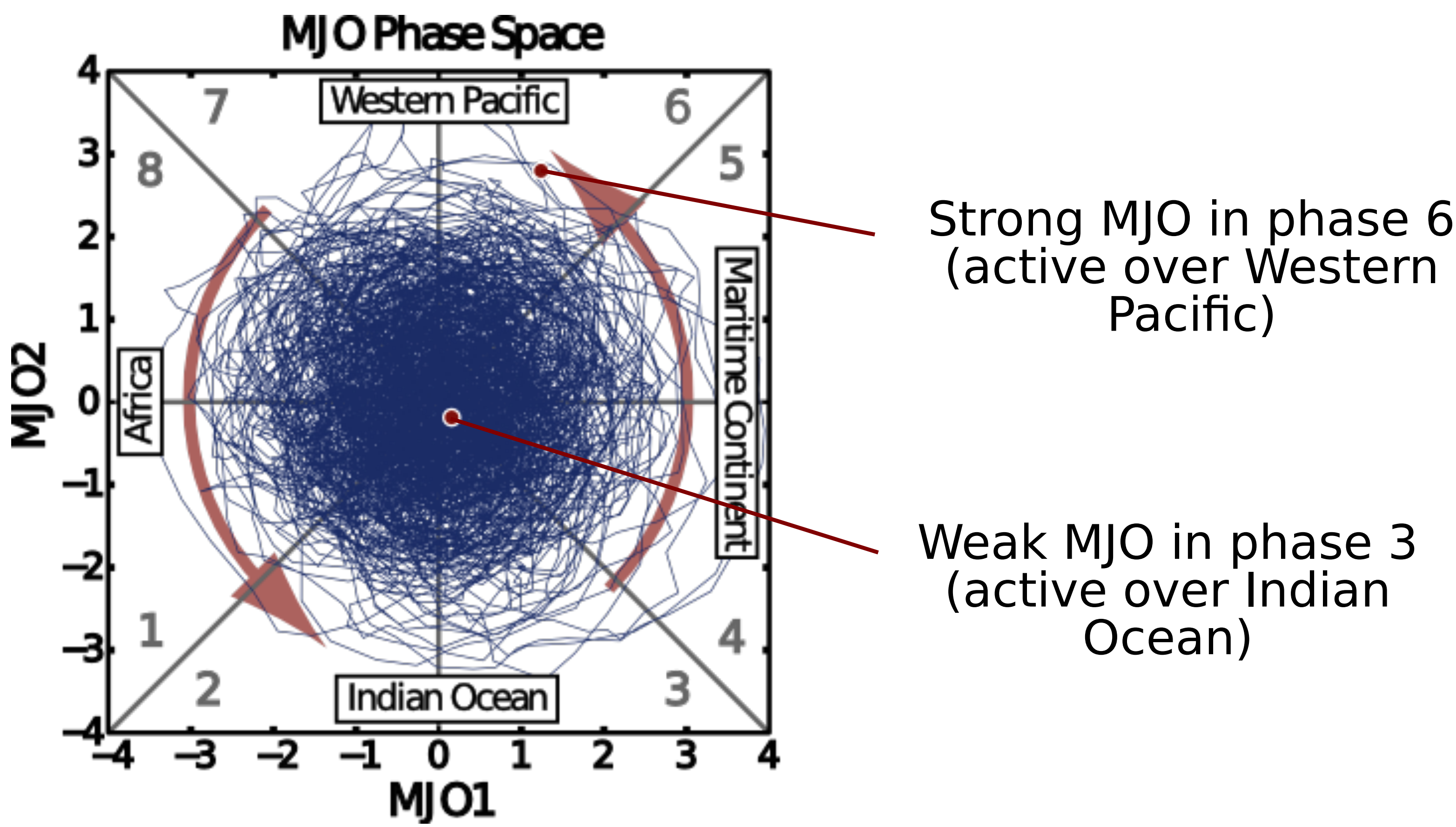
Numerical Model

- Model: **Princeton Ocean Model (POM)**, non-linear, two-dimensional barotropic general circulation model
- Ten-minute spatial resolution, forced by NCEP/NCAR winds (6 hourly)
- Modeled sea level **matches well** with tide gauge records: coherence is high (0.80-0.95) on **intraseasonal frequencies** (20-100 days)



The MJO Index

- Daily bivariate MJO index (MJO1 and MJO2) first two PCs of EOF analysis.
- Indices in quadrature so they form an “MJO phase space”:



Wheeler, M. C. and Hendon, H. H. ``An All-season Real-time Multivariate MJO Index’’. Monthly Weather Review, 2004

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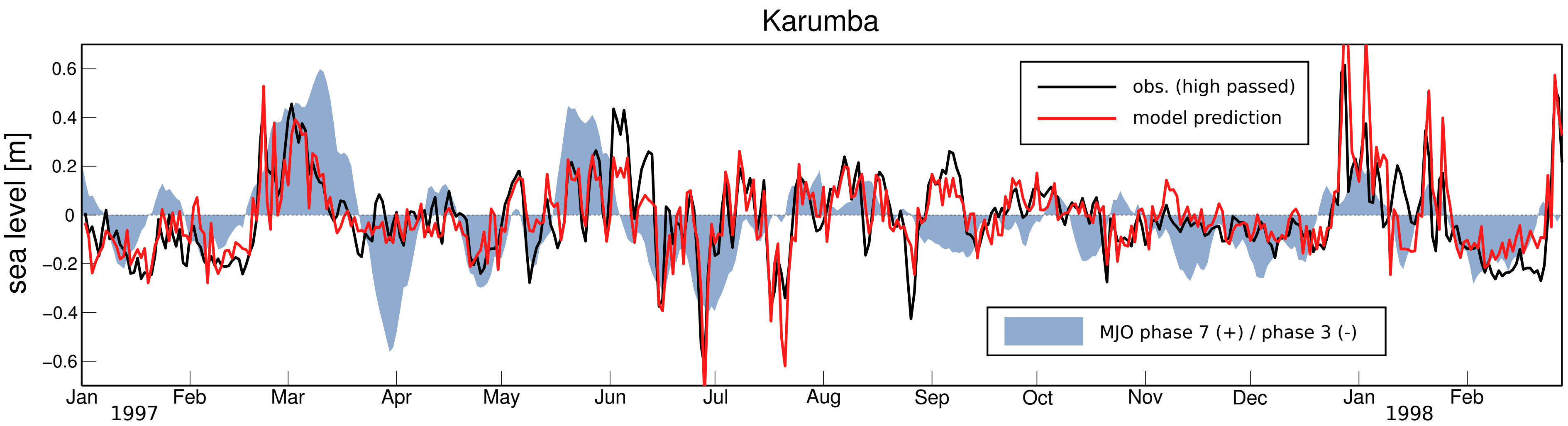


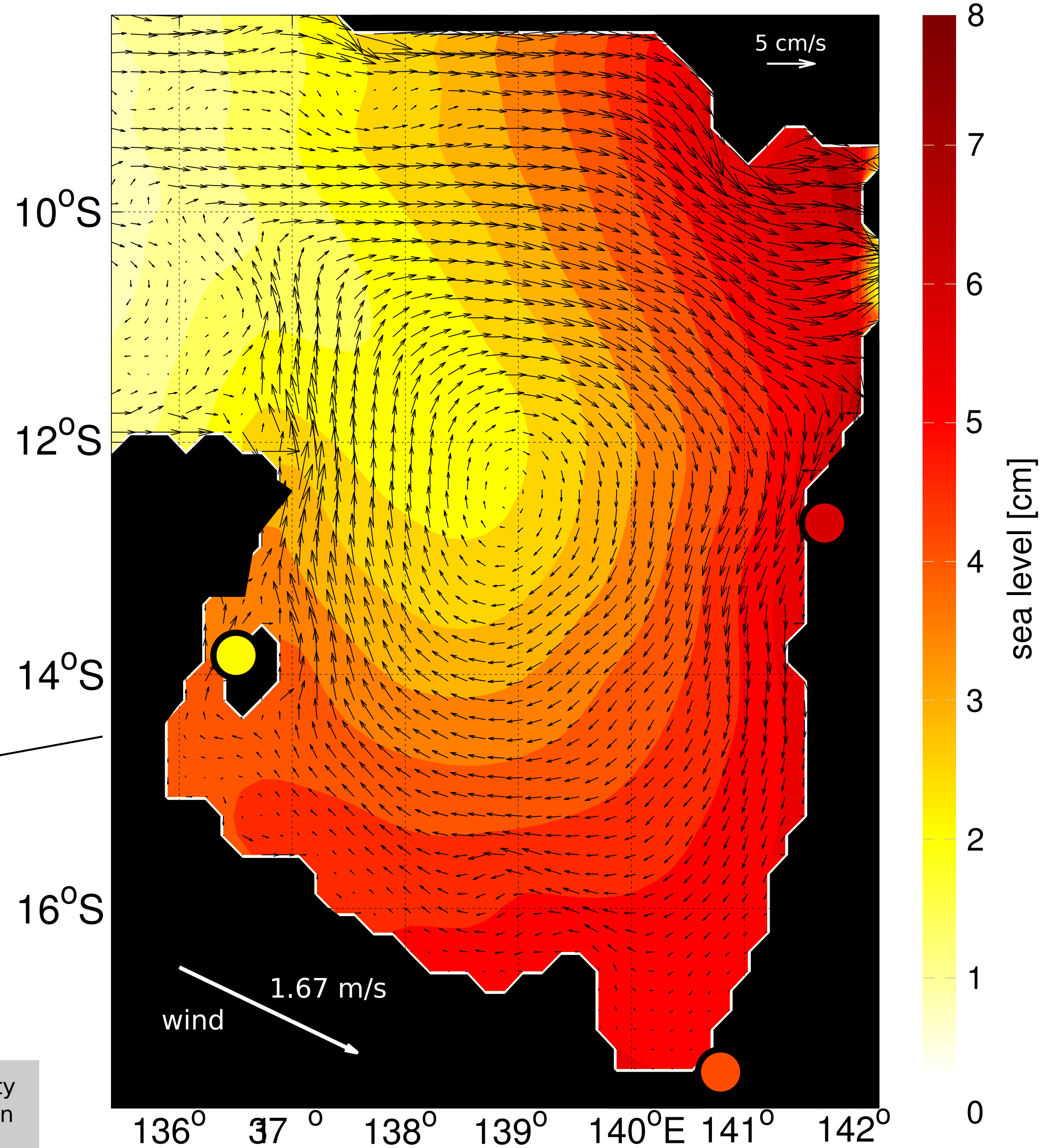
- The MJO index (projected on to phase 7/3) shows **remarkable correlation** with intraseasonal sea level in the Gulf of Carpentaria.
- Implications for **predictability**: the MJO index can be used as an indicator for **set-up** or **set-down** favourable conditions.

Canonical Response to the MJO

- **Composites** of observed wind, modeled sea level and circulation with the MJO:

canonical response of the Gulf to the MJO

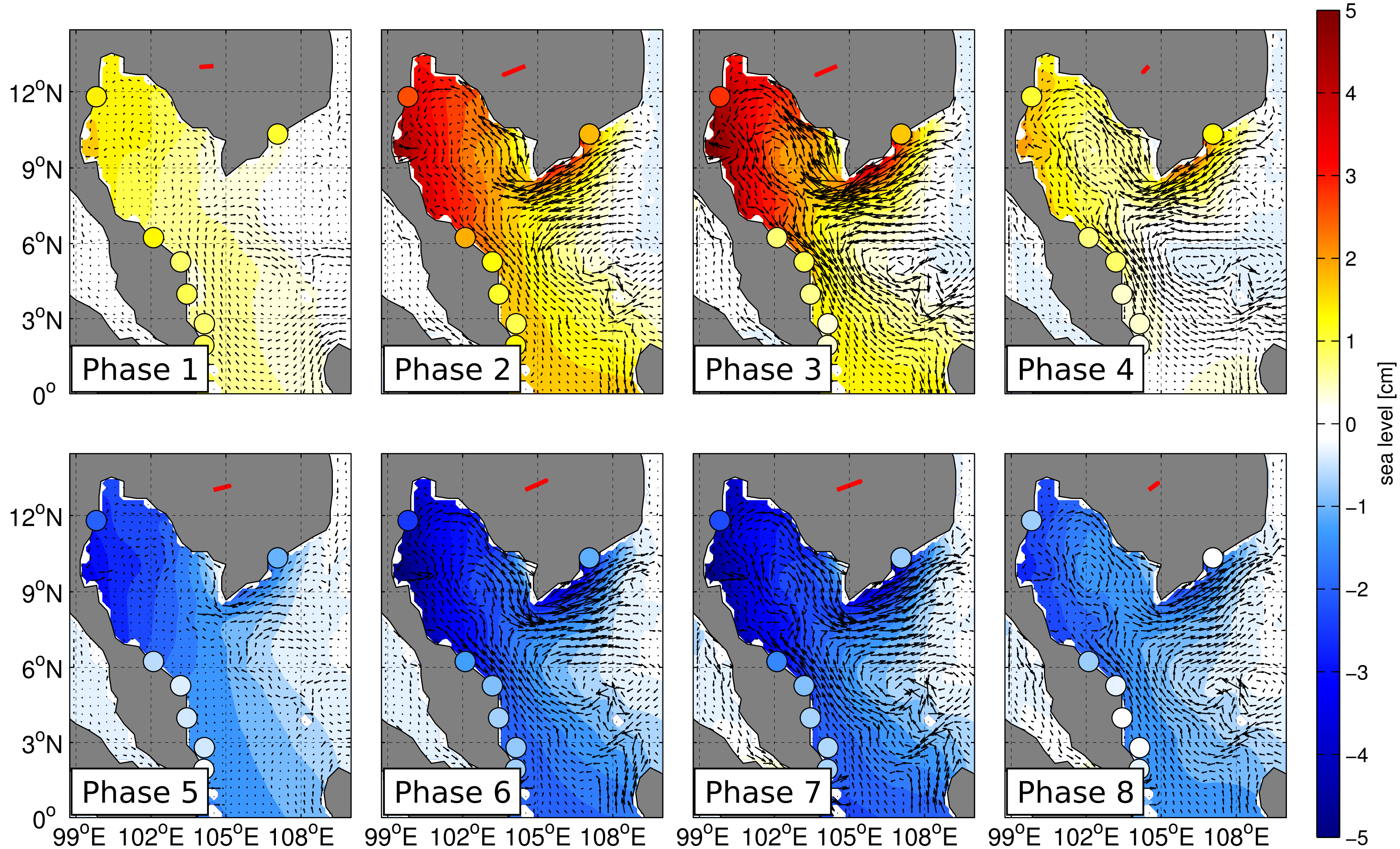
Phase 7
(MJO active over W. Pac)



Oliver, E.C.J. and K.R. Thompson, Sea level and circulation variability of the Gulf of Carpentaria: Influence of the Madden-Julian Oscillation and the adjacent deep ocean. J. Geophys. Res., **116**, C2, 2011

The Gulf of Thailand

Currently, I am examining a similar effect in the **Gulf of Thailand**, although in this case the distinction between the MJO and the **Boreal Summer Intraseasonal Oscillation** is important.

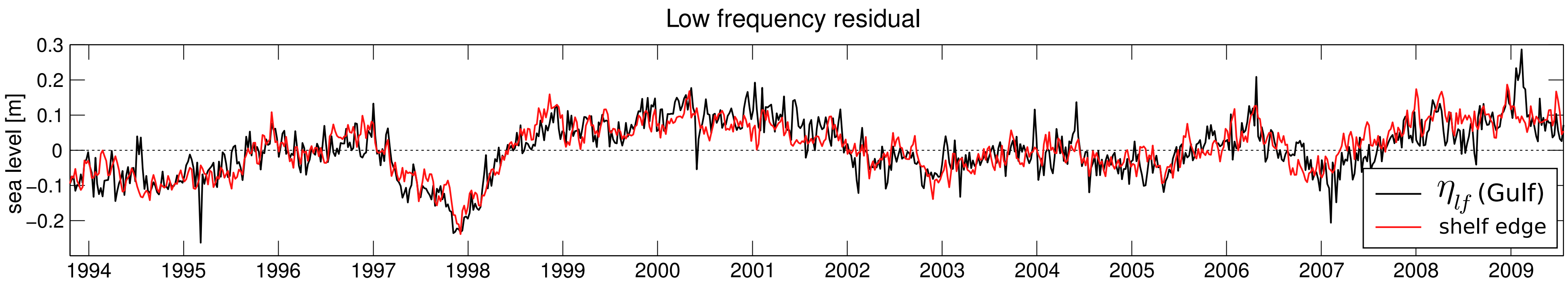


Low Frequency Residual

- Model prediction represents **wind-driven** component of sea level
- Tide gauges can be **de-winded** by subtracting the model prediction

$$\underbrace{\eta_{\text{tot}}}_{\text{tide gauge}} = \underbrace{\eta_{\text{hf}}}_{\text{model}} + \underbrace{\eta_{\text{lf}}}_{\text{low freq. residual}}$$

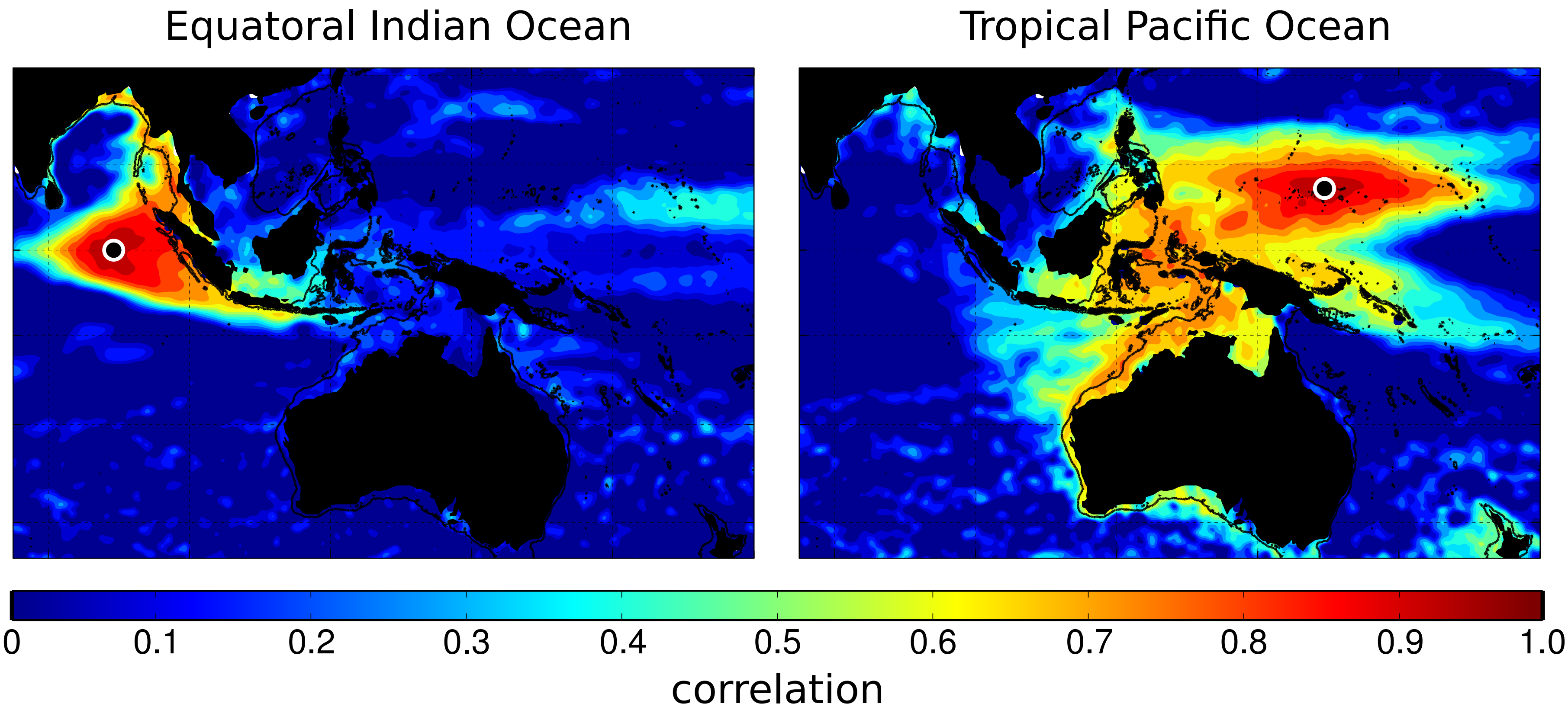
- **Low frequency residual** at each location is correlated with sea level at shelf edge



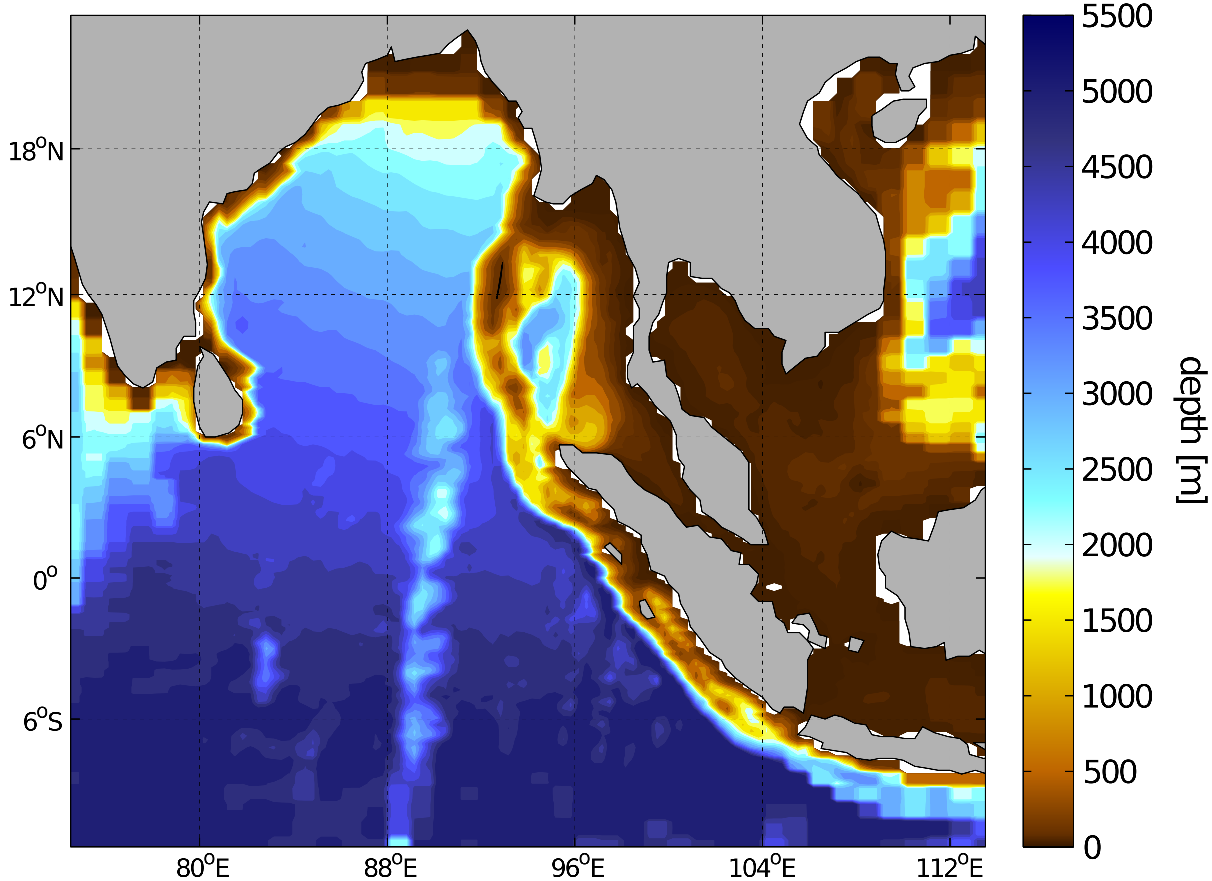
- **Where** does this variability come from? Does the **Indian** or **Pacific** dominate?

Low Frequency Residual

- **Correlation maps** suggest where energy propagates
- Partial correlations can be used to remove the effects one basin from the other . . . energy from the **Pacific Ocean dominates** in the Gulf



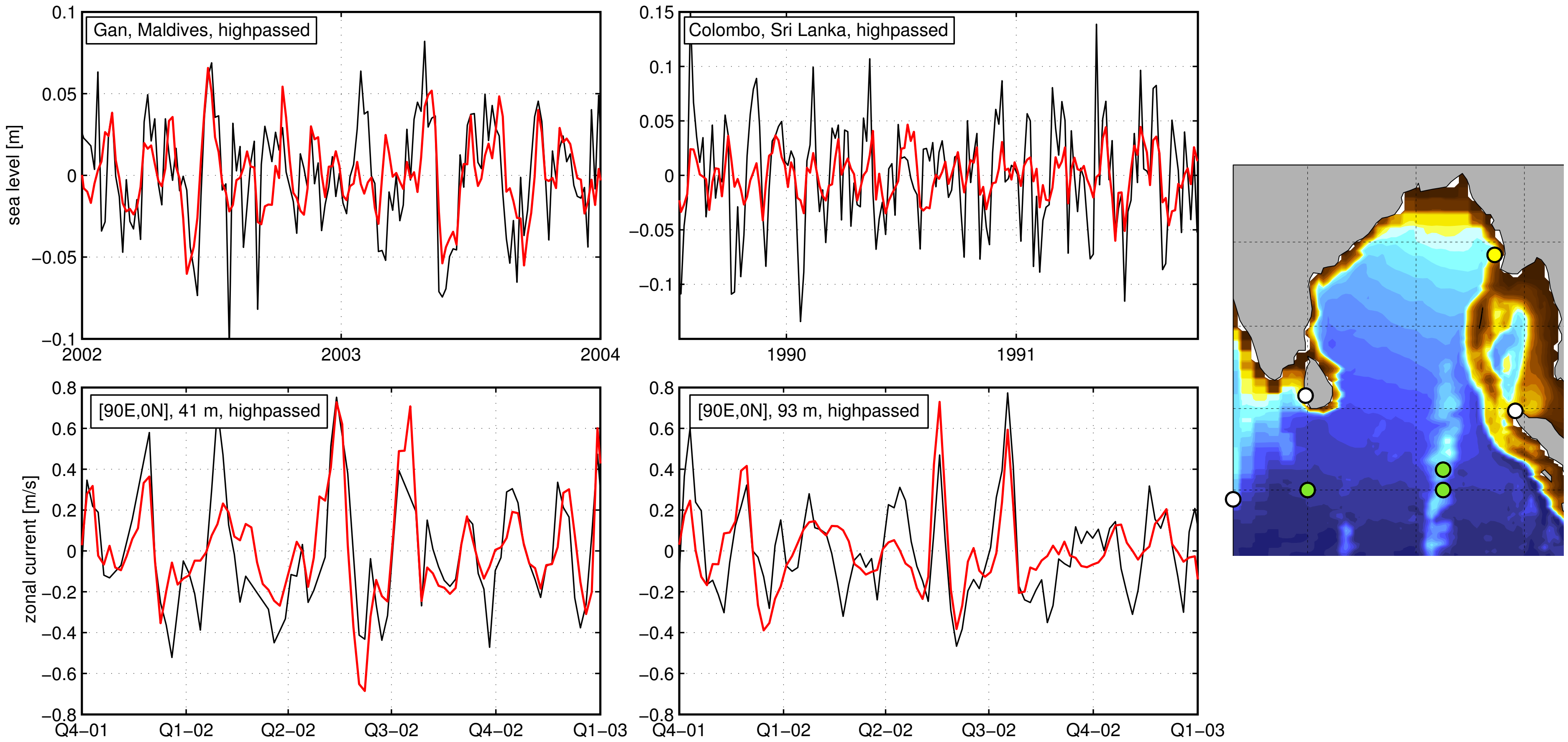
Northeastern Indian Ocean



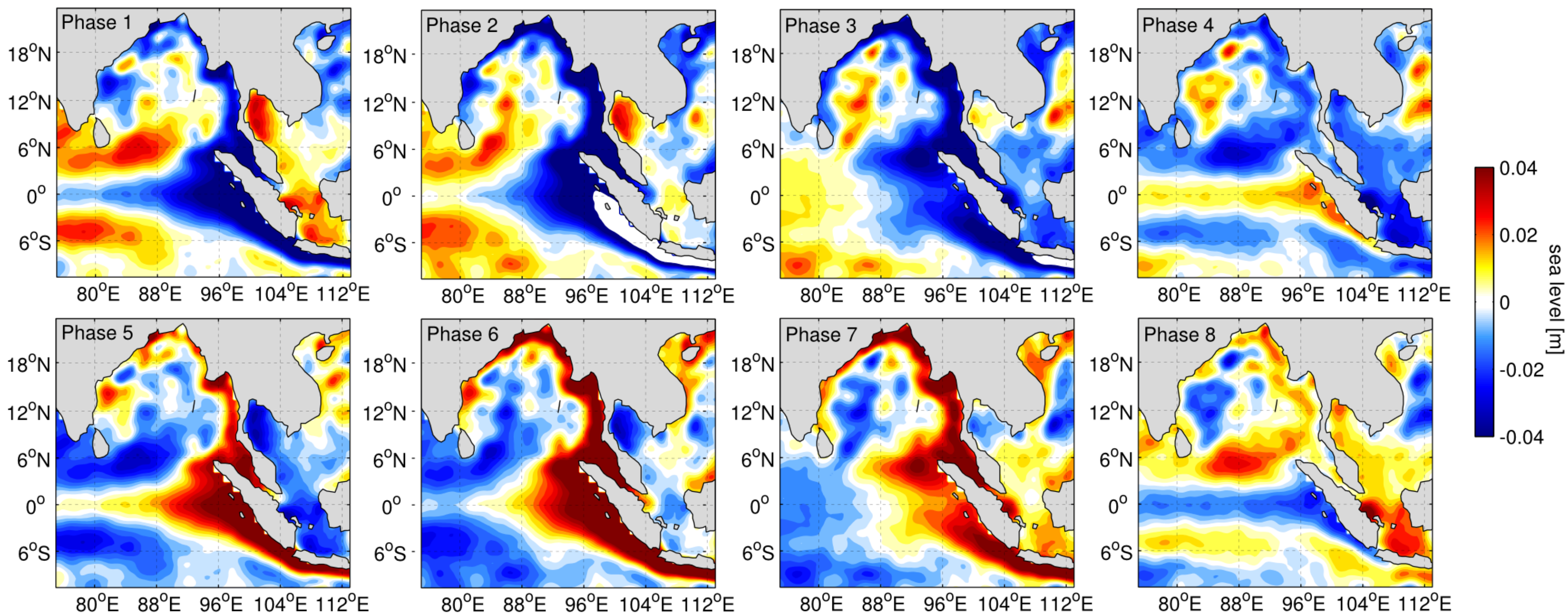
- Northeastern Indian Ocean is a region straddling the Equator and comprises both **deep ocean** and **shallow coastal regions**.
- **Surface wind** over this region is strongly related to the MJO

Numerical Model

- Model: **NEMO**, ~1 degree resolution global model with 3x higher resolution sub-model in the northeastern Indian Ocean.
- Model results match well with **tide gauges** and **ADCP profiles**

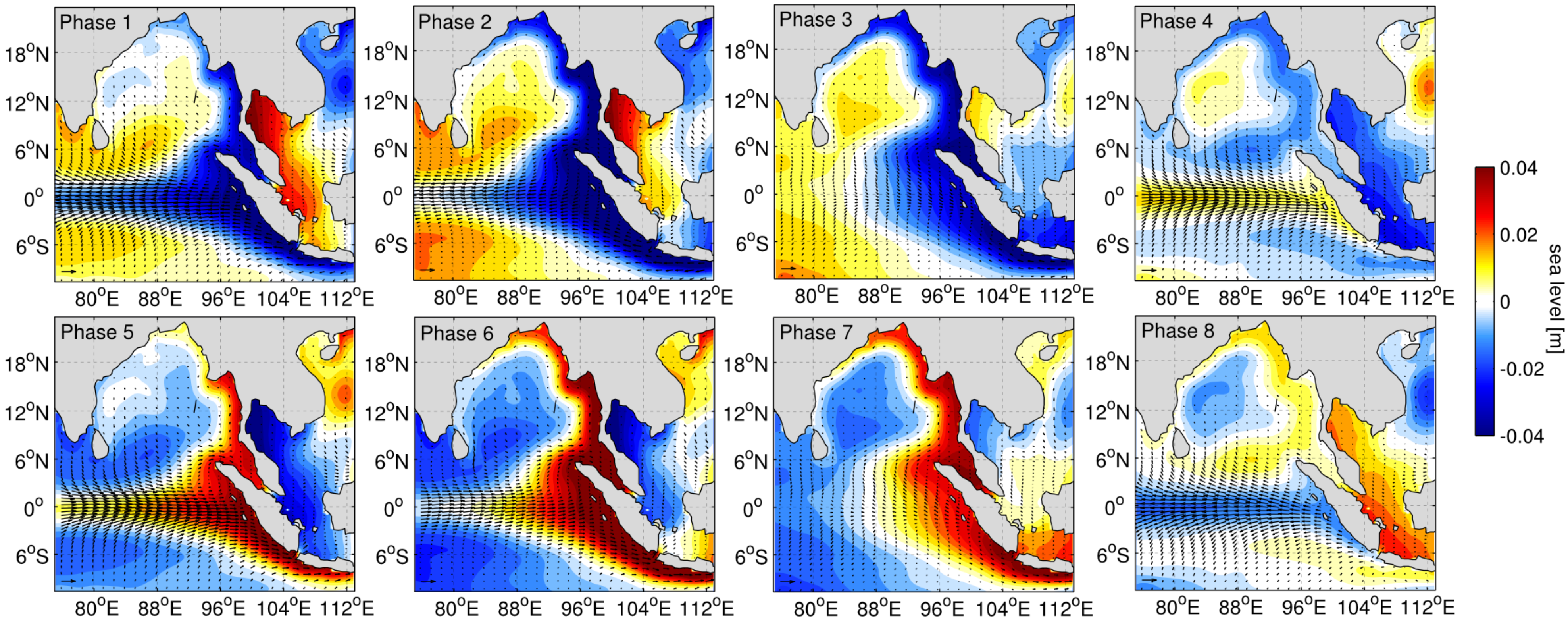


Observed Sea Level-MJO Relationship



- Sea level in the northeastern Indian Ocean has a strong relationship to the MJO and exhibits:
  1. Waves propagating **eastward** along the Equator
  2. **Reflected** waves, propagating **westward** off the Equator
  3. **Coastally** trapped waves, propagating **poleward**

Predicted Sea Level-MJO Relationship



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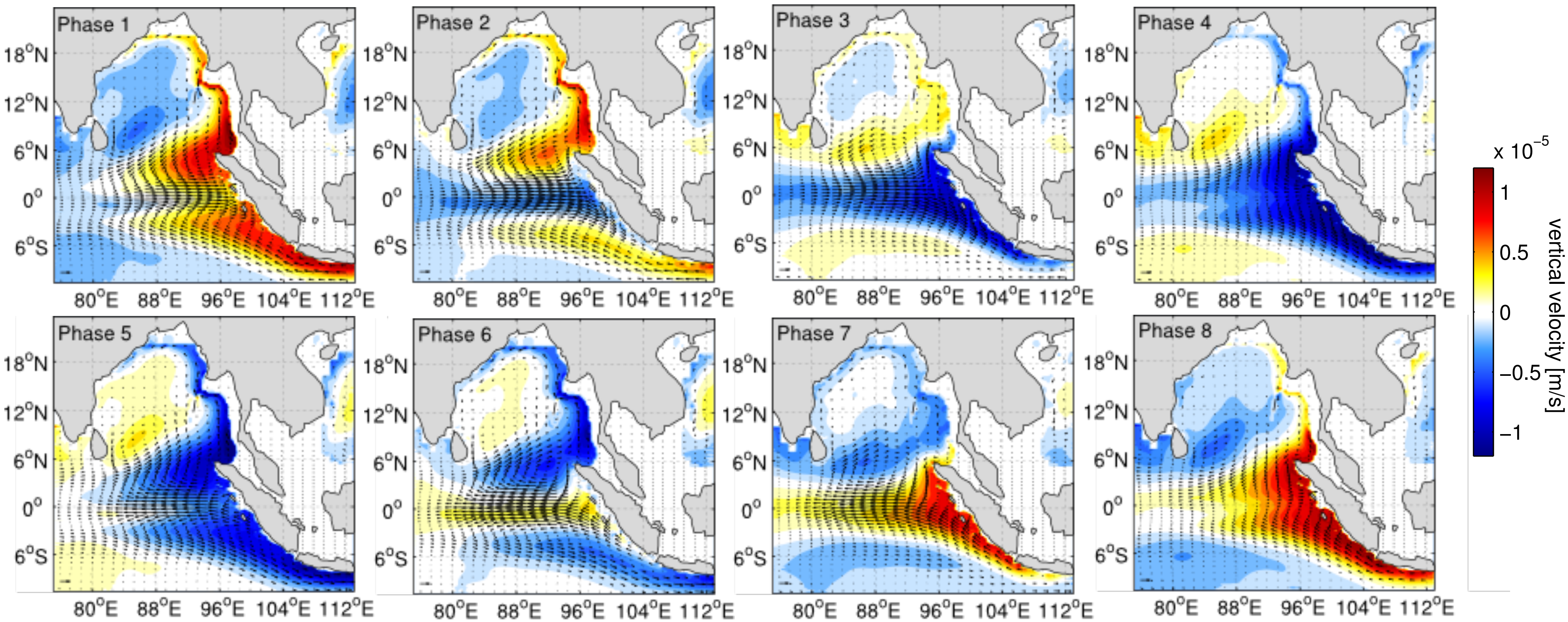
Predicted MJO Relationship at Depth



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  2. **Reflected** waves, propagating **westward** off the Equator
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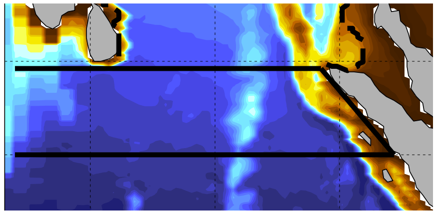
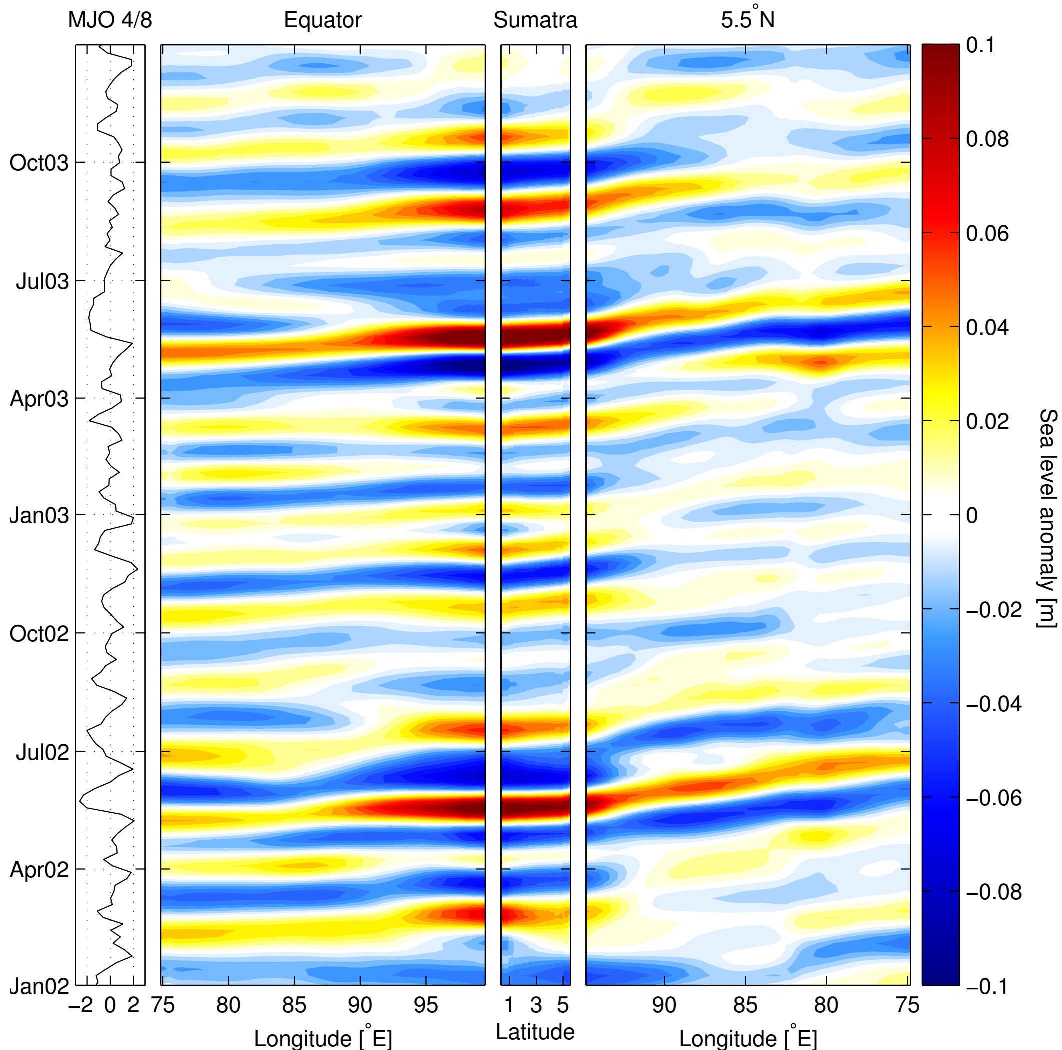
Equatorial Waveguide

- Continuous wave propagation East along equator, north along coastal Sumatra and west along 5.5N





estimated wavespeeds:

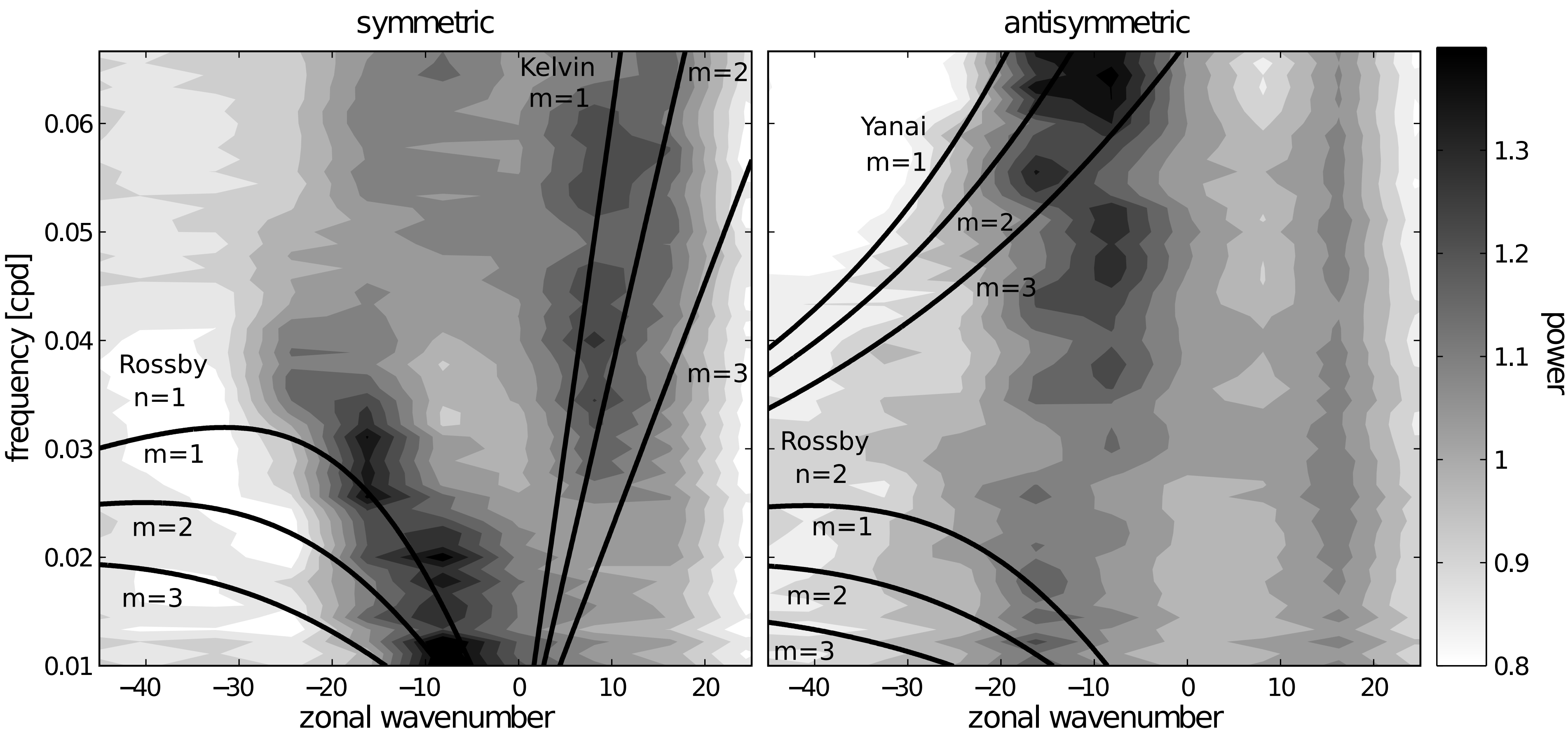
2.17 +/- 0.37 m/s along equator

2.14 +/- 0.22 m/s along Sumatra

1.15 +/- 0.44 along 5.5N

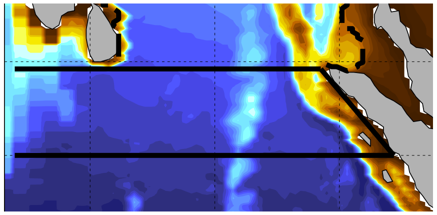
Frequency-Wavenumber Diagram

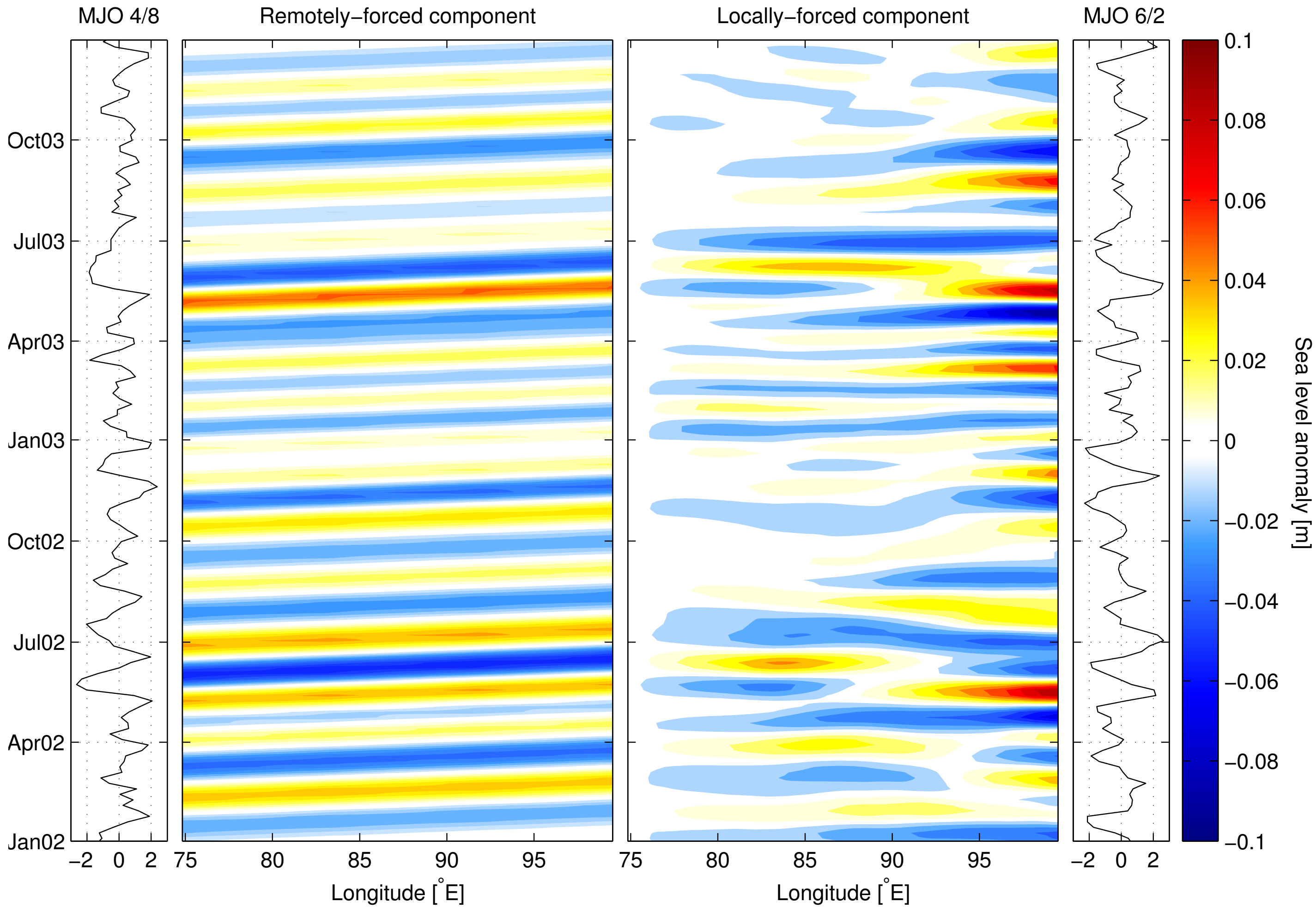
- Frequency-wavenumber spectra (following Wheeler and Kiladis, 1999) for ssh/u/v/w down to 2000 m, between 6.5S and 6.5N
- Energy consistent with 1st baroclinic mode Kelvin wave and Rossby wave (first meridional mode)



Local versus Remote Forcing

- Remotely-forced component was estimated by propagating sea level from 75E eastward at 2.17 m/s

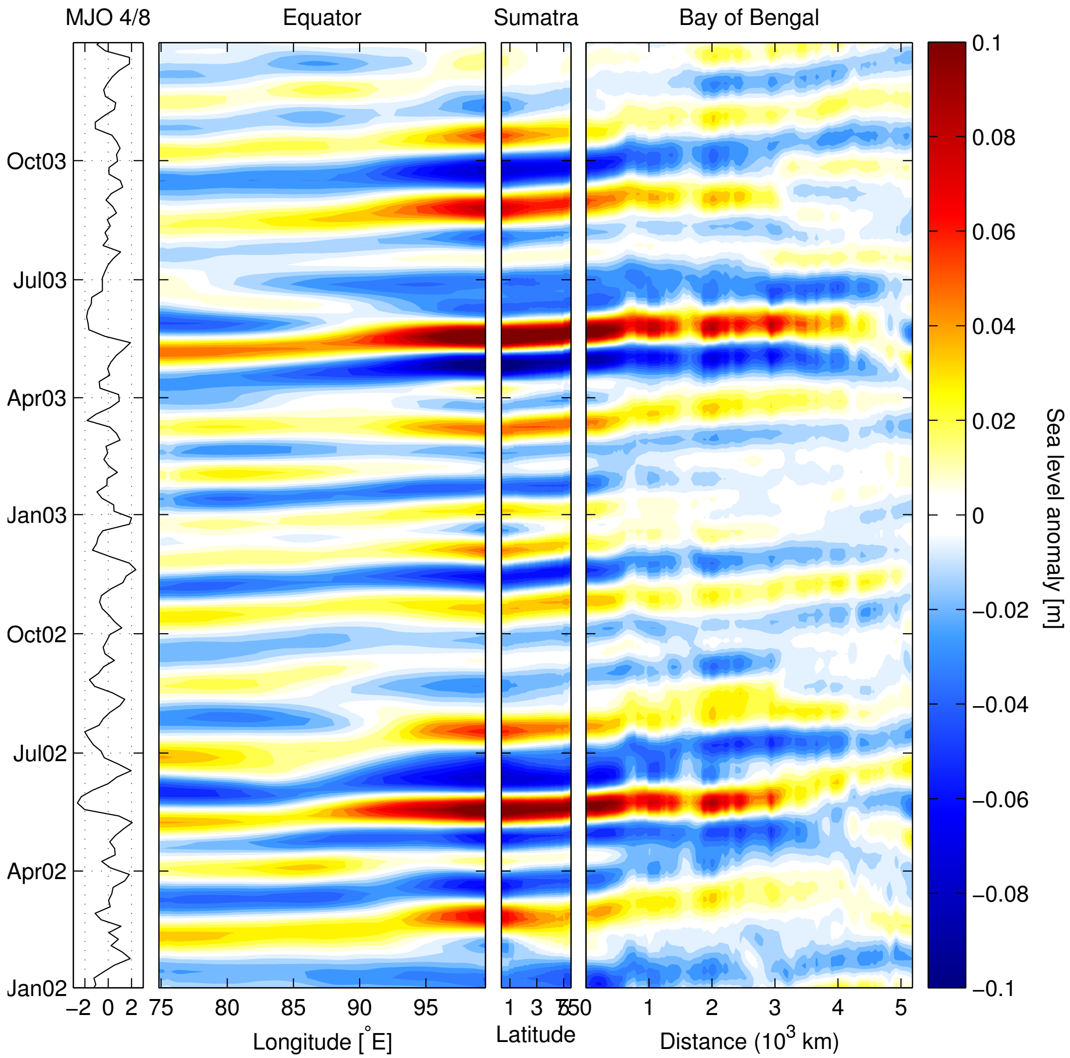


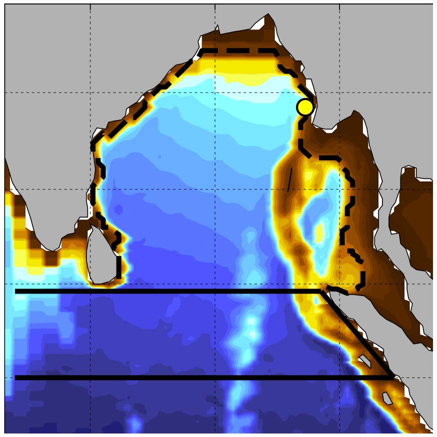


waves appear to be forced by a **combination** of local and remote MJO-related wind forcing

Coastal Waveguide

- Continuous wave propagation East along equator, north along coastal Sumatra and west along 5.5N





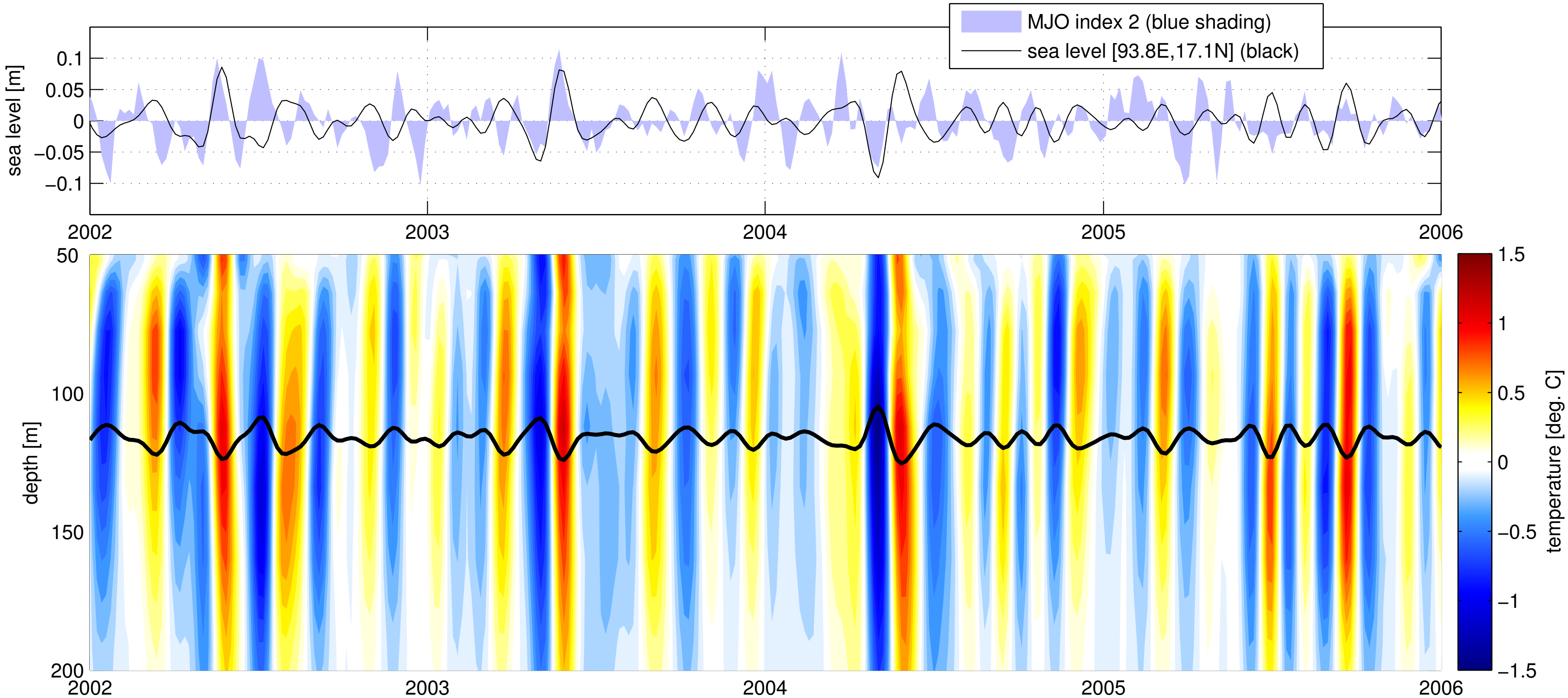
estimated wavespeeds:

2.17 +/- 0.37 m/s along equator

2.14 +/- 0.22 m/s along Sumatra

2.66 +/- 0.69 m/s around the Bay of Bengal

Predictability of Near-shore signal



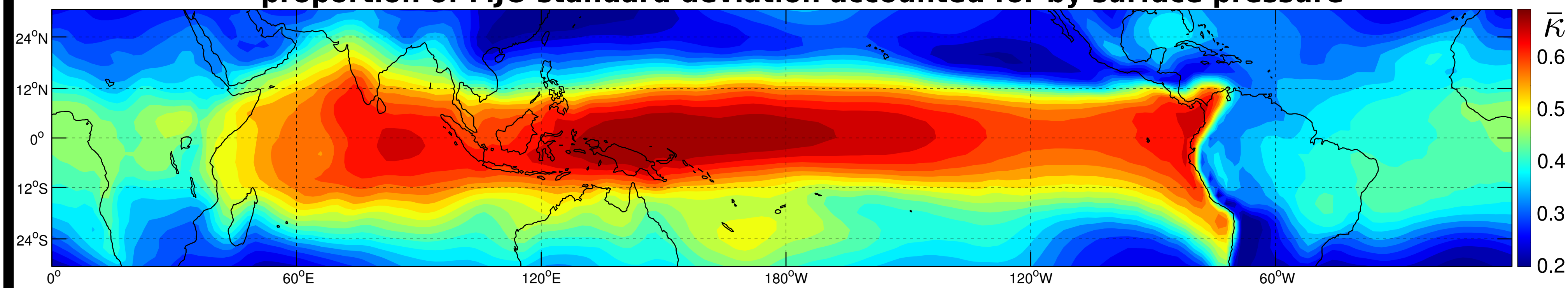
Sea level at [93.8E,17.1N] **well-correlated with the MJO** index. This MJO-related variability is also present at depth in **temperature** and the **isopycnal depth** (1025 g/kg) . . . **MJO lends predictability** to the system.

Oliver, E.C.J., K.R. Thompson and Y. Lu, The northeastern Indian Ocean: Response to local and remote forcing related to the Madden-Julian Oscillation. Submitted to J. Geophys. Res.

A 100-year Reconstruction of the MJO

- The **MJO has a strong signature in surface pressure** and daily measurements of surface pressure are available for 100+ years.

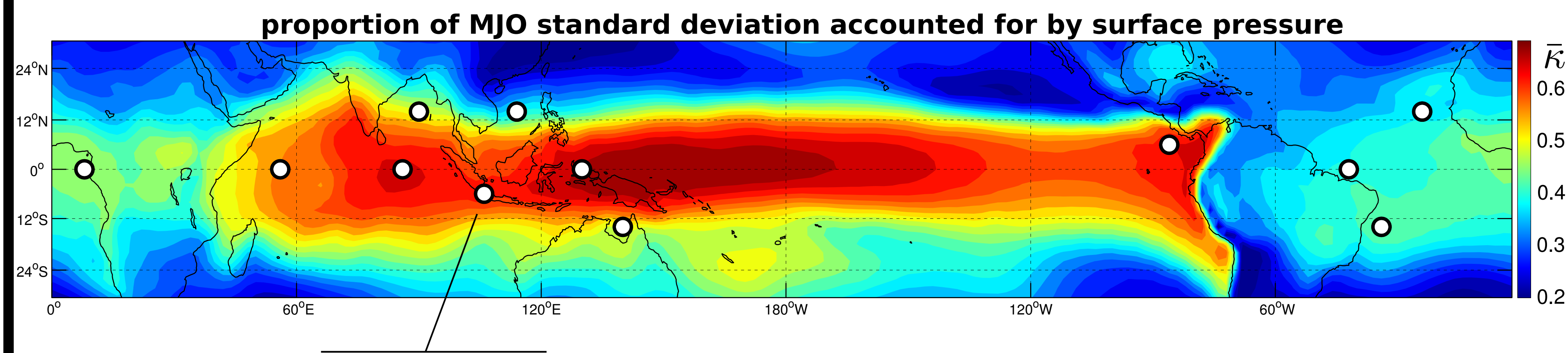
proportion of MJO standard deviation accounted for by surface pressure



- The Wheeler and Hendon MJO index has been reconstructed from **1905 to 2008** based on a **multivariate linear regression** of surface pressure.
- Use time series of pressure at a number of locations ... but **the number of locations must be limited** so that we don't overfit the model!

A 100-year Reconstruction of the MJO

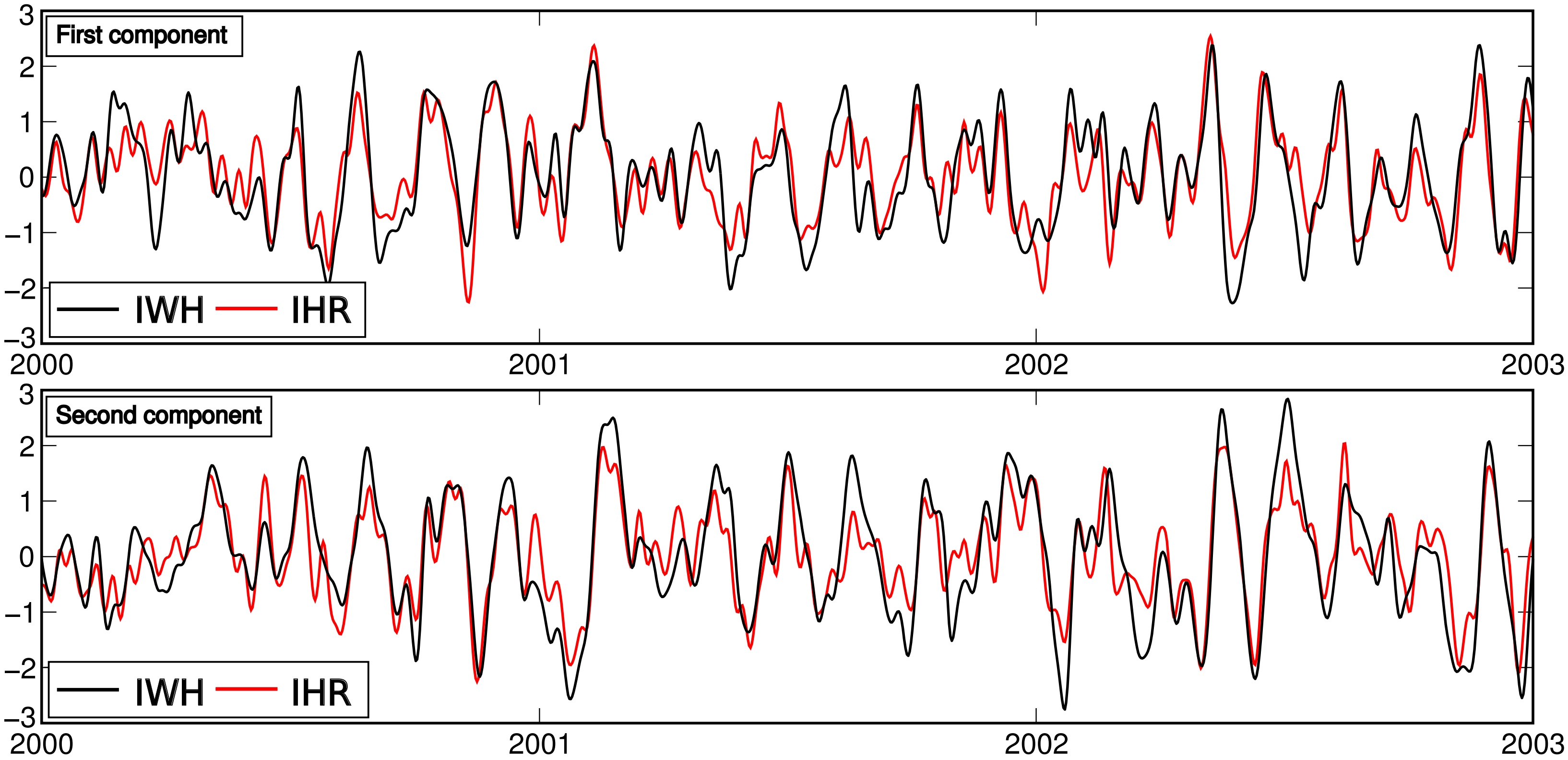
- Locations were chosen by considering
  1. The quality of the reanalysis pressures
  2. The strength of connection to the MJO
  3. Spatial decorrelation lengthscales



- Chose **12 locations**. Took pressure time series at these locations and filtered out seasonal, interannual, and high frequency variability.
- These time series of pressure, along with Hilbert transforms, were **regressed** onto the MJO index and then **hindcast over the 1905 to 2008** period to give a reconstruction of the MJO.

The Reconstructed Index

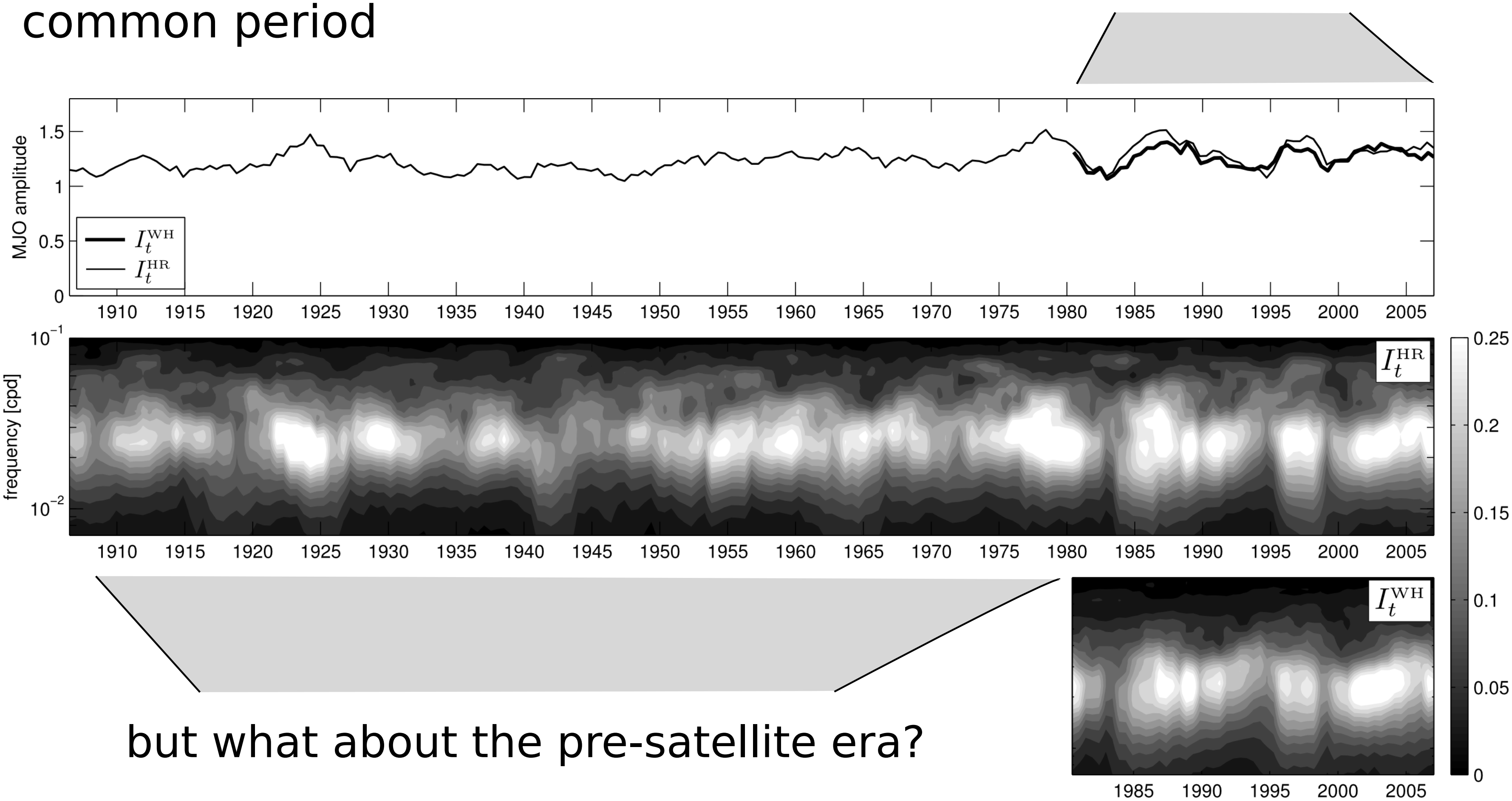
- The reconstructed index (IHR) explains 67% of the variance of the Wheeler and Hendon index (IWH). Corresponds to a correlation of ~0.82.



- Extensive validation of the reconstructed index over the pre-1979 period has been performed using **cloud**, **wind**, **precip**, and **sea level** data.

The Reconstructed Index

- 3-year running variance and power spectra match over the common period



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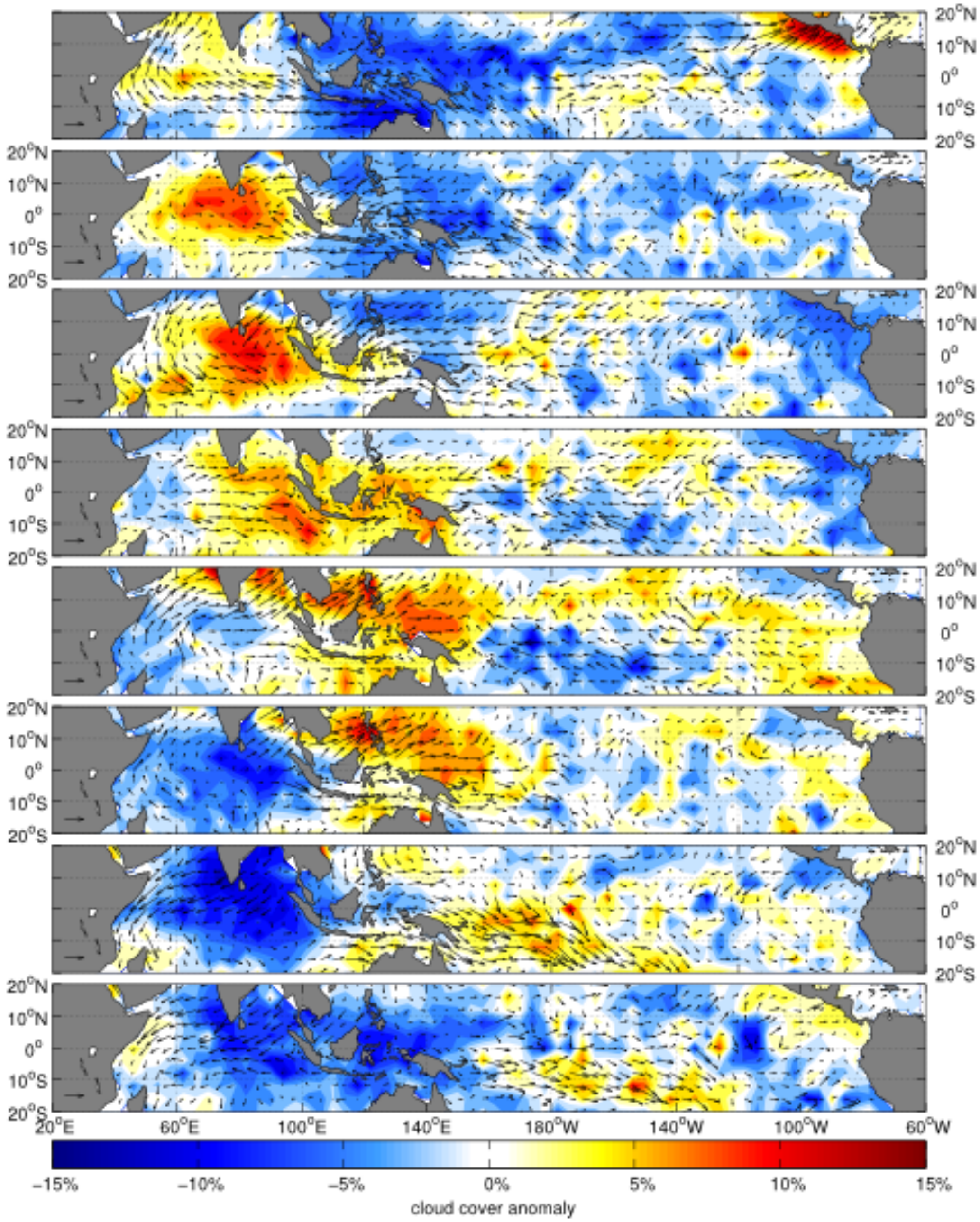
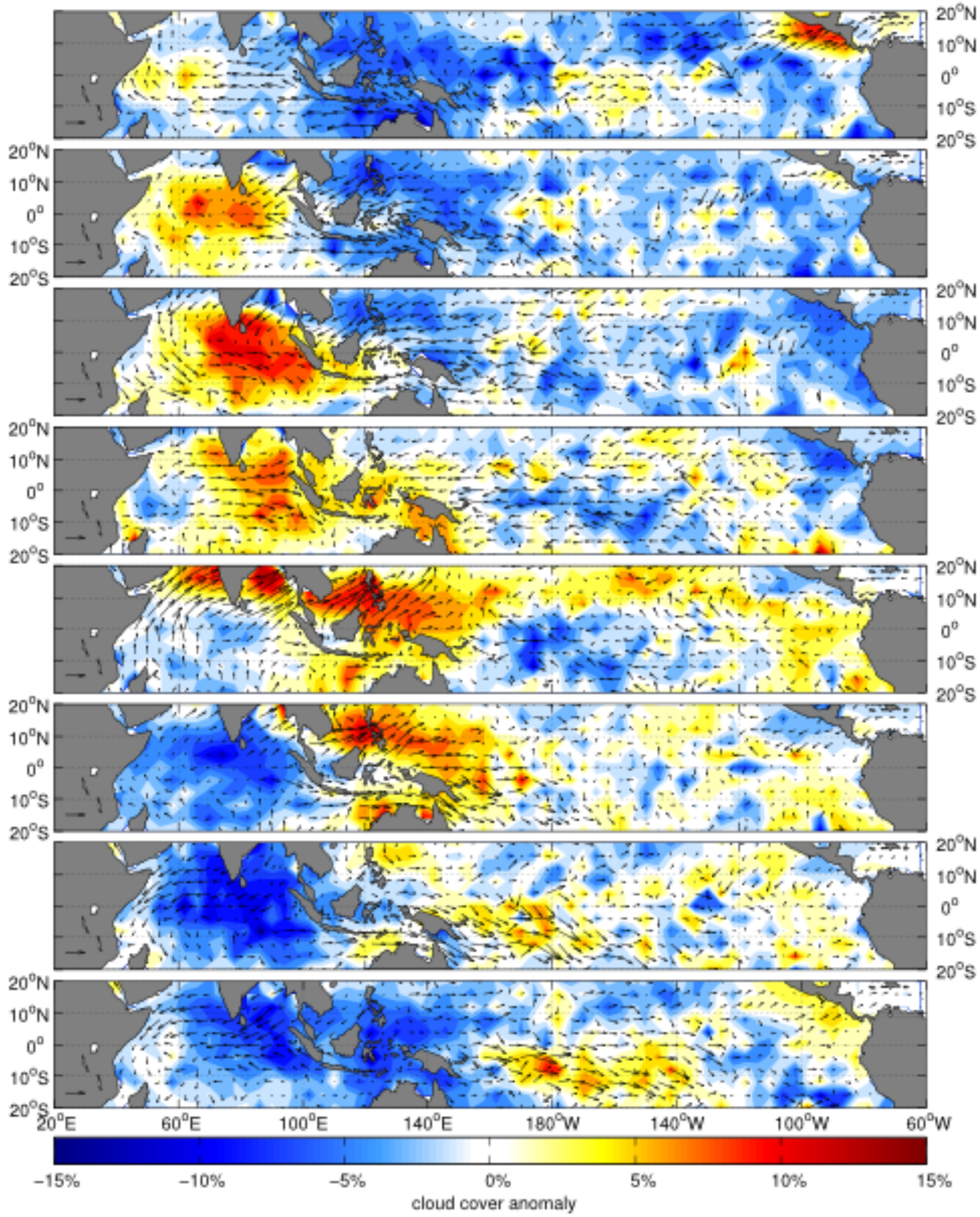
Cloud Cover and Surface Wind



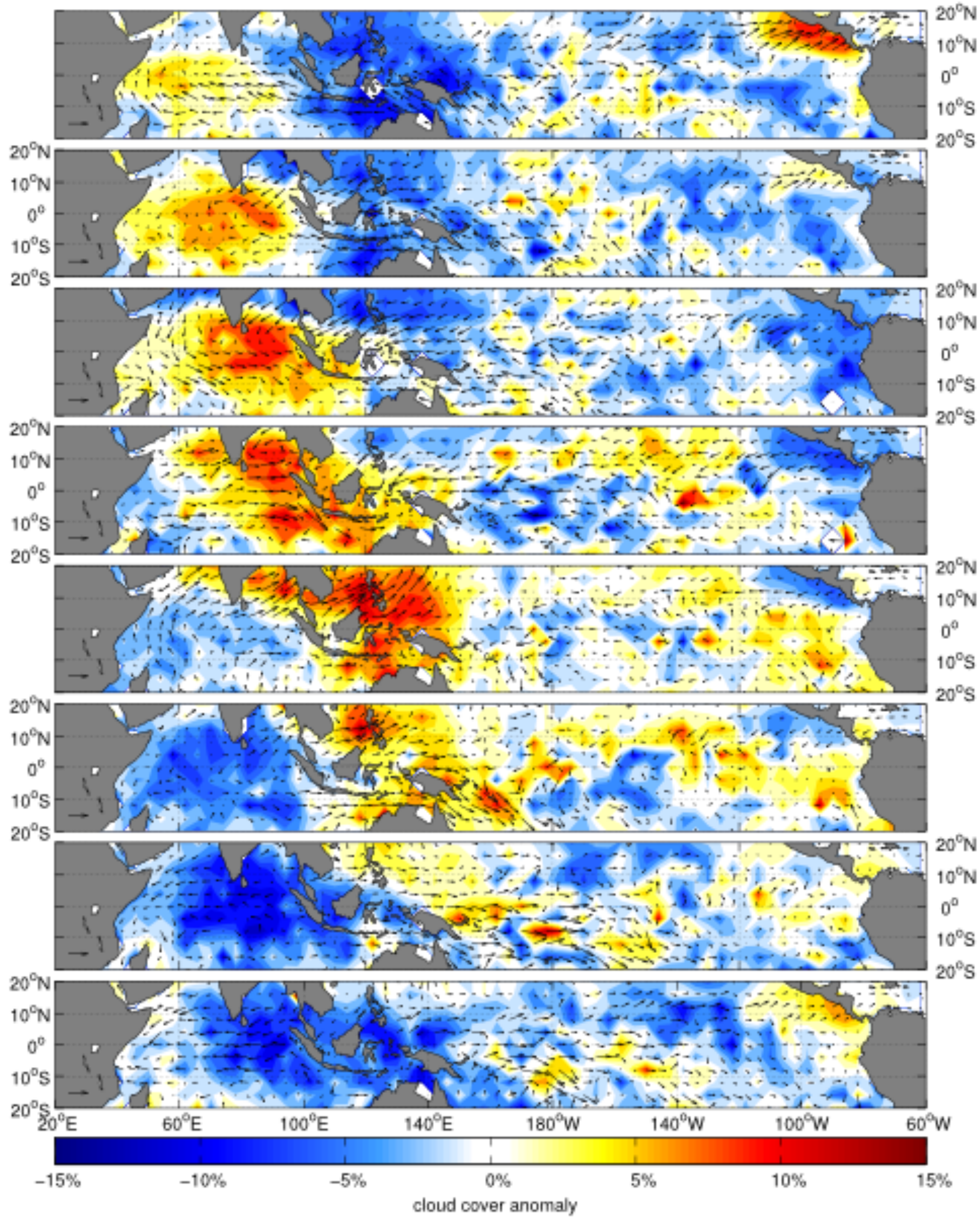
Composites of cloud cover and surface wind with IHW

Cloud Cover and Surface Wind



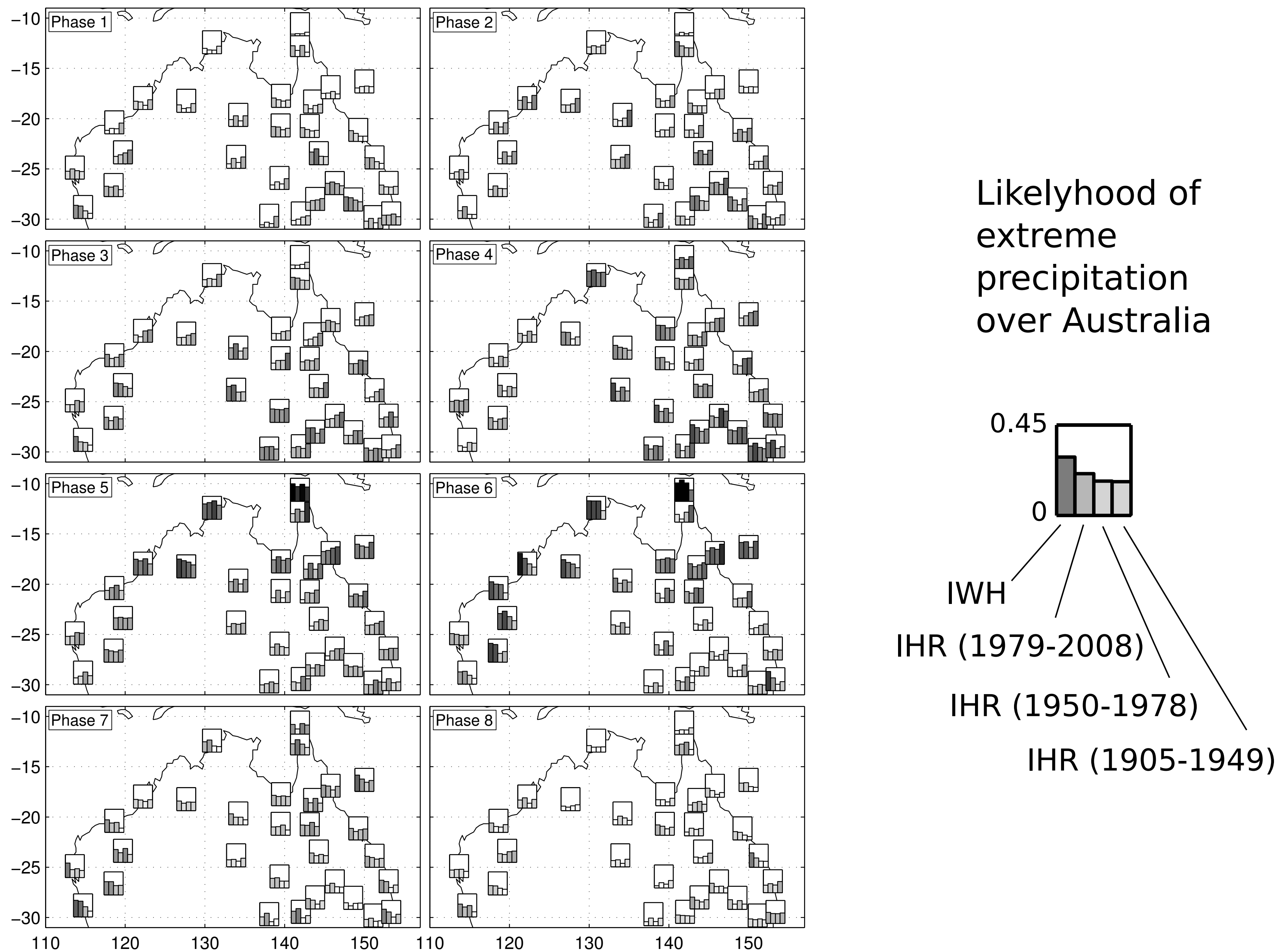
Composites of cloud cover and surface wind with IHR (1979-2008)

Cloud Cover and Surface Wind

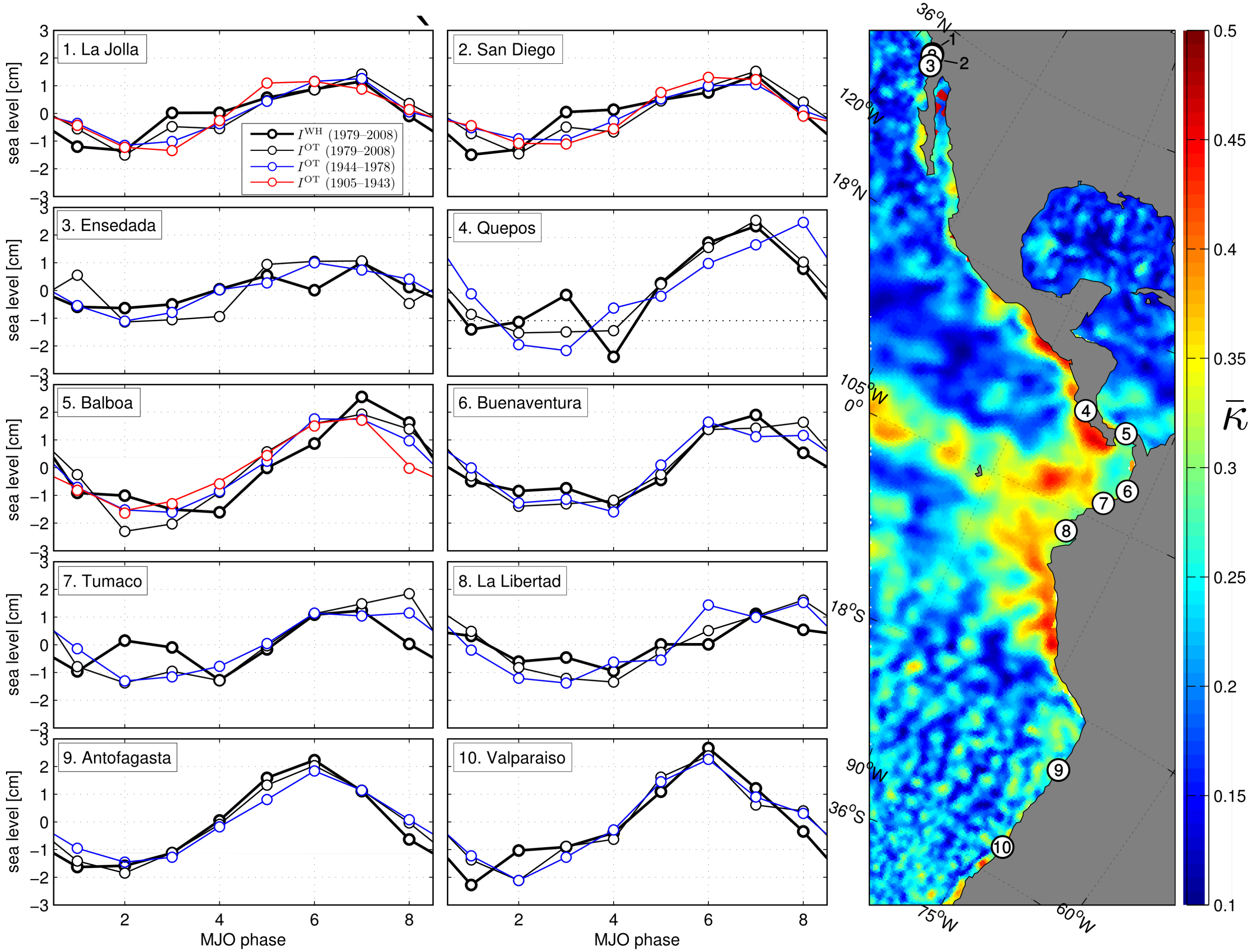


Composites of cloud cover and surface wind with IHR (1952-1978)

Australian Precipitation

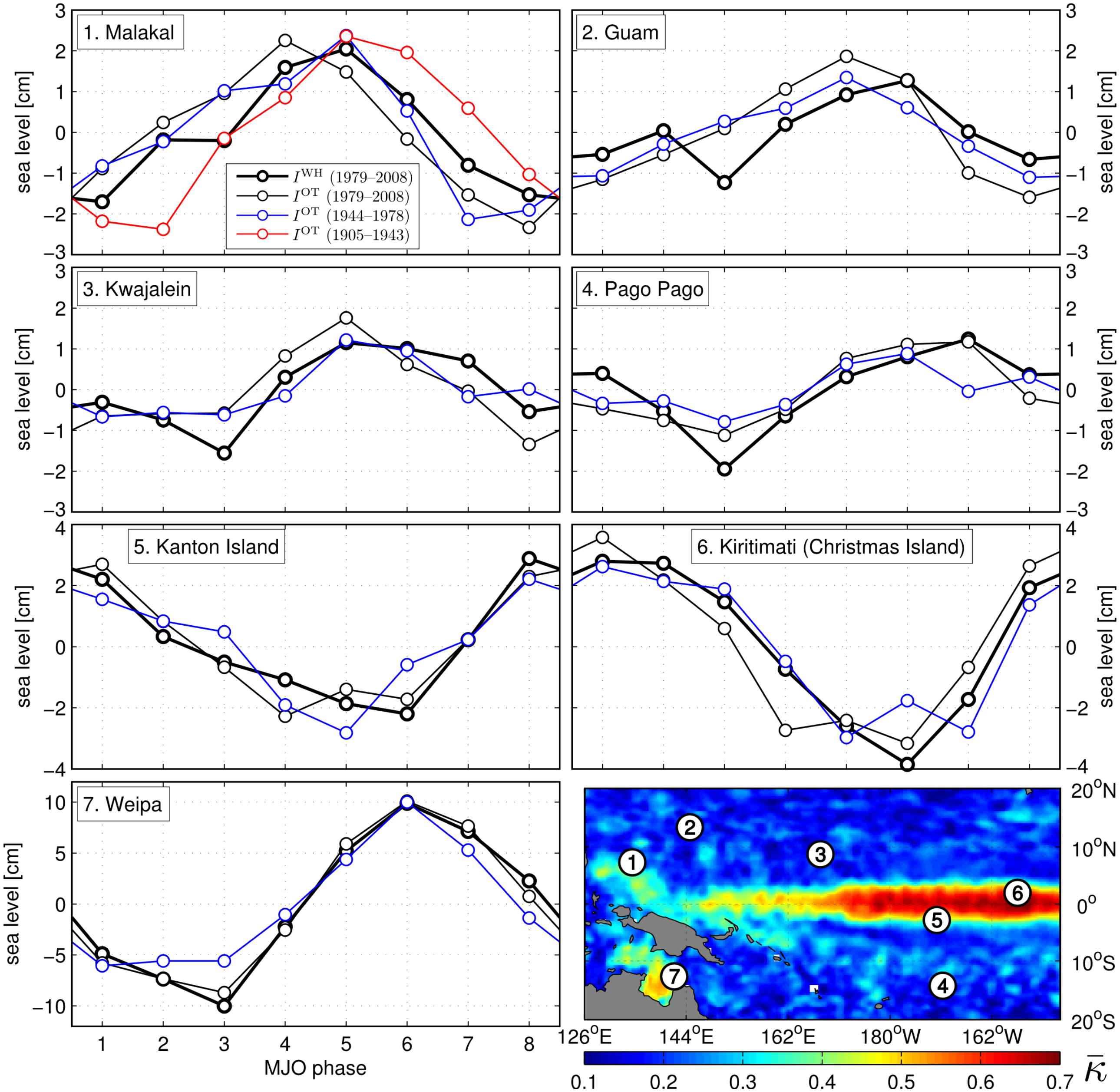


Sea Level (E. Pac.)



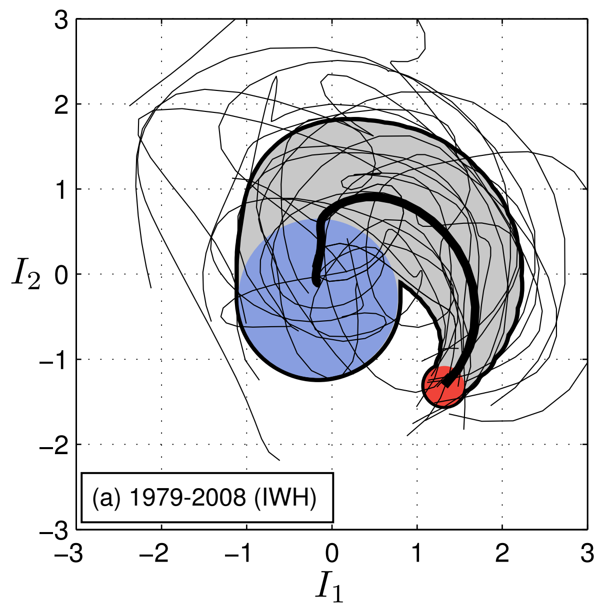
Composites of Sea Level with MJO

Sea Level (W. Pac.)



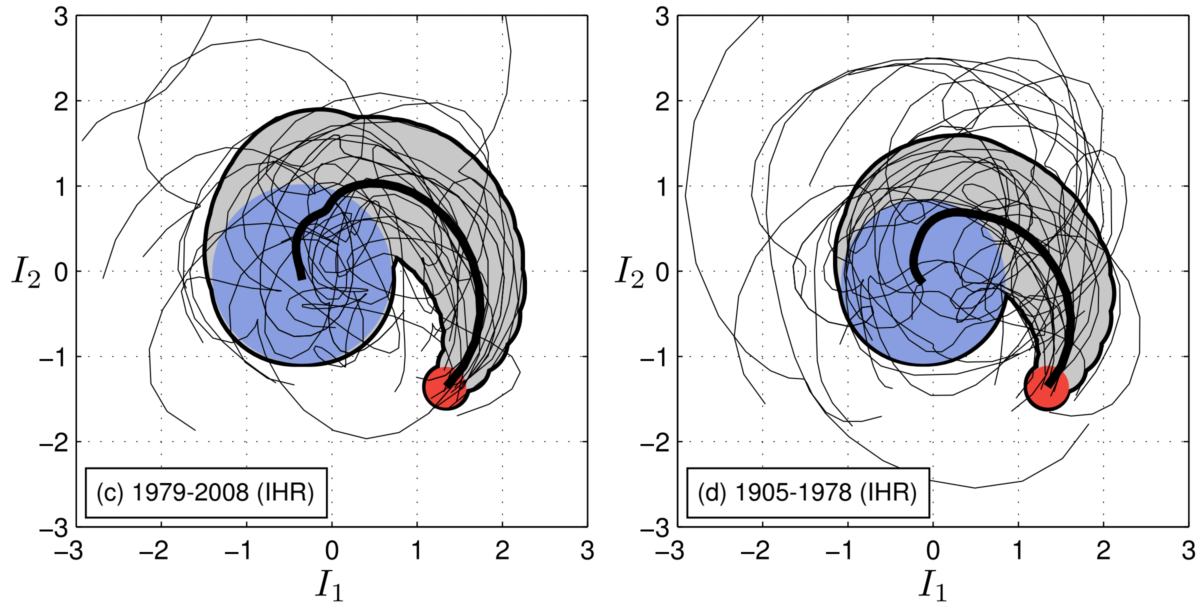
Composites of Sea Level with MJO

Predictability of the MJO

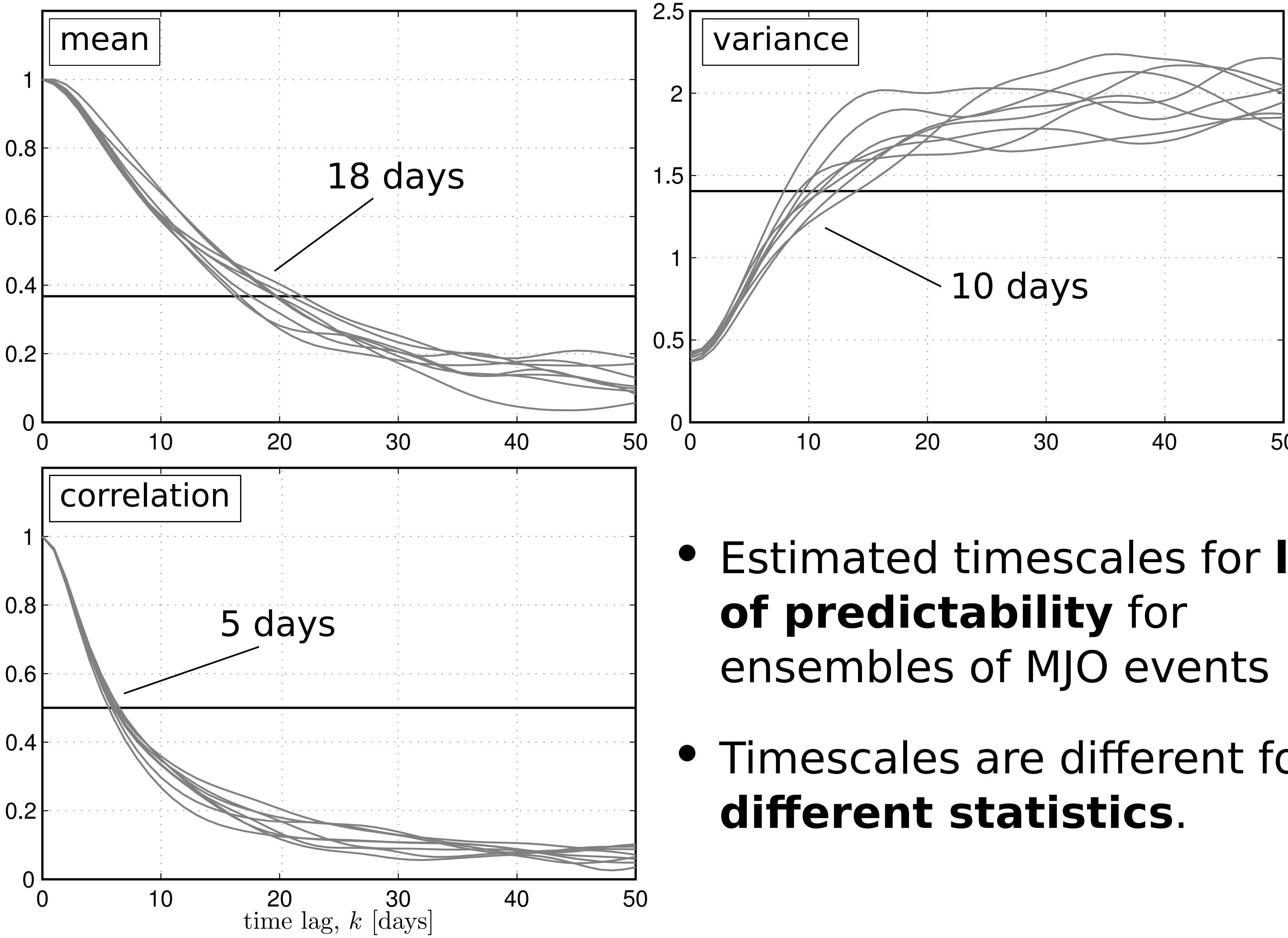


Ensembles of MJO events which pass through the same point show systematic behaviour.

The **ensemble statistics** can be examined...



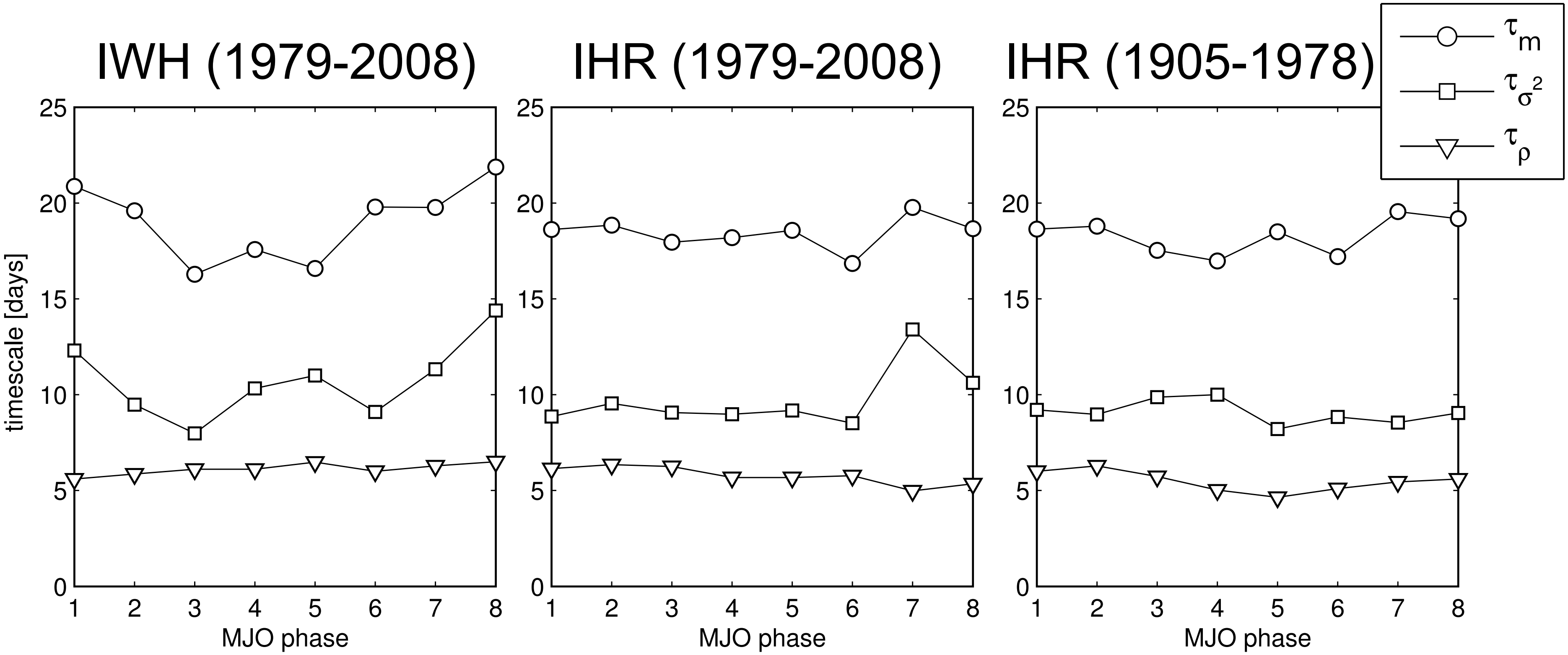
Predictability Timescales



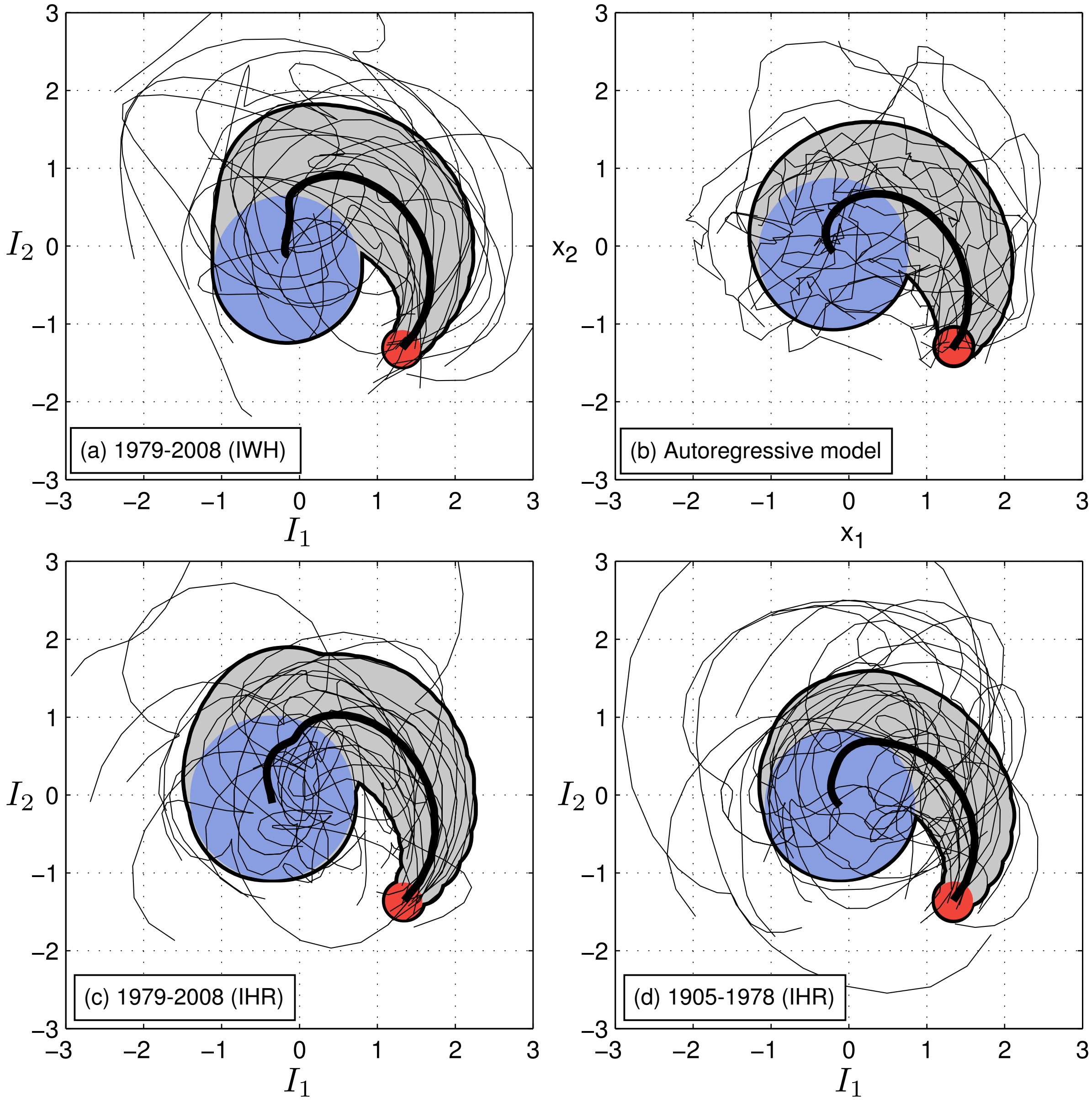
- Estimated timescales for **loss of predictability** for ensembles of MJO events
- Timescales are different for the **different statistics**.

Predictability Timescales

- Estimated timescales for **loss of predictability** for ensembles of MJO events initialized in different phases
- Timescales are different for the **different statistics**. Also, there is some dependence on phase, not reproduced by the reconstruction.



Predictability of the MJO



- Ensembles of MJO events which pass through the same point show behaviour reminiscient of a damped harmonic oscillator.

- Model as a stochastically forced, damped, harmonic oscillator using an autoregressive process:

$$\boldsymbol{x}_t = \boldsymbol{A}\boldsymbol{x}_{t-1} + \boldsymbol{\epsilon}_t$$

with three parameters:

1. rotation period P
2. damping timescale τ_1
3. autoregressive forcing timescale τ_2

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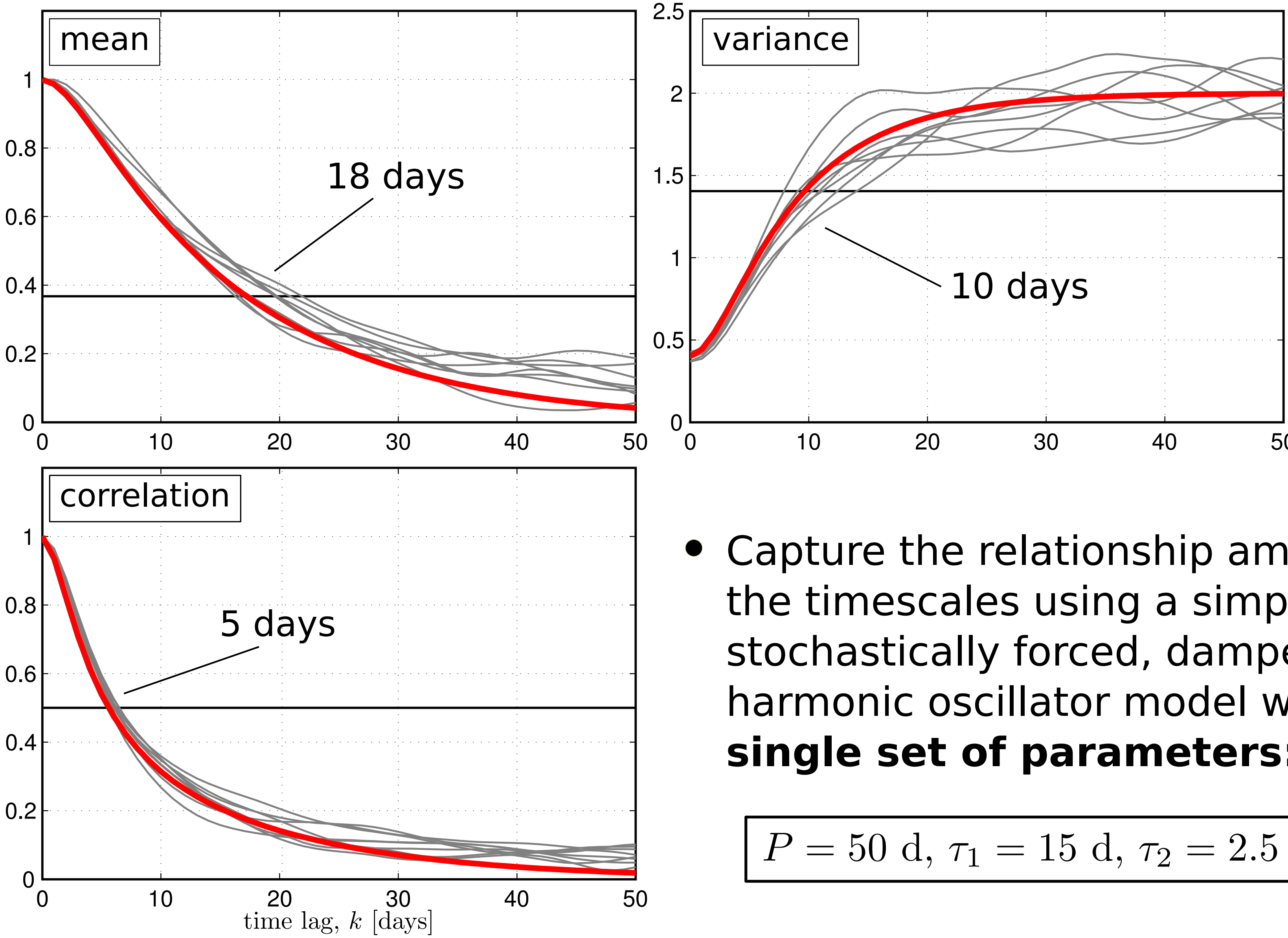
Predictability Timescales

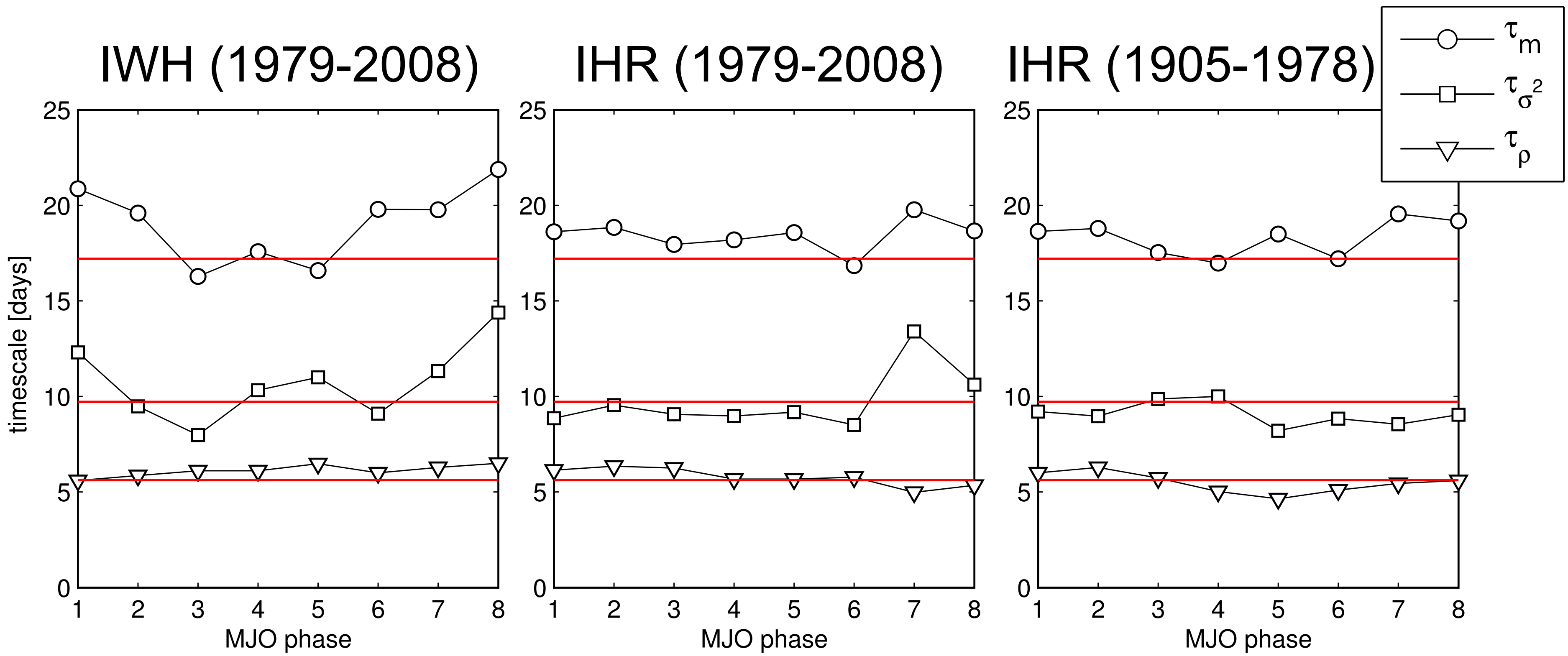


- Capture the relationship amongst the timescales using a simple stochastically forced, damped harmonic oscillator model with **a single set of parameters:**

$$P = 50 \text{ d}, \ \tau_1 = 15 \text{ d}, \ \tau_2 = 2.5 \text{ d}$$

Predictability Timescales

- Estimated timescales for **loss of predictability** for ensembles of MJO events initialized in different phases
- Timescales are different for the **different statistics**. Also, there is some dependence on phase, not reproduced by the reconstruction.
- Capture the relationship amongst the timescales using a simple stochastically forced, damped harmonic oscillator model with $P = 50\ \mathrm{d},\ \tau_1 = 15\ \mathrm{d},\ \tau_2 = 2.5\ \mathrm{d}$



Summary

- The connections between the Madden-Julian Oscillation and global sea level are **mapped for the first time**.
- **Three regions** with significant relationships are identified:
    1. The Equatorial Pacific and west coast of the Americas
    2. The Gulf of Carpentaria
    3. The northeastern Indian Ocean
- In each of these regions the spatial and temporal relationship with the MJO are explained using **dynamics, statistical tools, and numerical**
- The connections are shown to be either **remote** (eq. Pac / Americas), **local** (Gulf of Carpentaria) or a **mix of local and remote** (NE Indian Ocean)
- The MJO index was **reconstructed** from 1905 to 2008 using measurements of **tropical surface pressure**.
- Predictability time scales of the MJO, as described by **three measures**, give a rich and complex view of **MJO predictability**. This behaviour can be modeled as a simple **damped harmonic oscillator**.

Acknowledgements

I would like to thank the following people:

My PhD supervisor: Keith Thompson

Ian Folkins, Youyu Lu, Barry Ruddick, Hal Ritchie, Adam Monahan

Clark Richards, Faez Bakalian, Simon Higginson, Jennifer Mecking, Jean-Pierre Auclair, Trajce Alcinov, Xiaoming Zhai, Xu Zhang, Yang Zhou, Yimin Liu, Vasily Korabel, Cecilia Carrea

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Canadian Foundation for Climate and Atmospheric Sciences (CFCAS)
Fondation canadienne pour les sciences du climat et de l'atmosphère (FCSCA)

The Regions

- Coherence between the **MJO and sea level** in each of the three regions peaks with a period of ~**75 days**