Discerning Subseasonal Pulses in the Indo-Pacific Throughflow and Gulf Stream Observations

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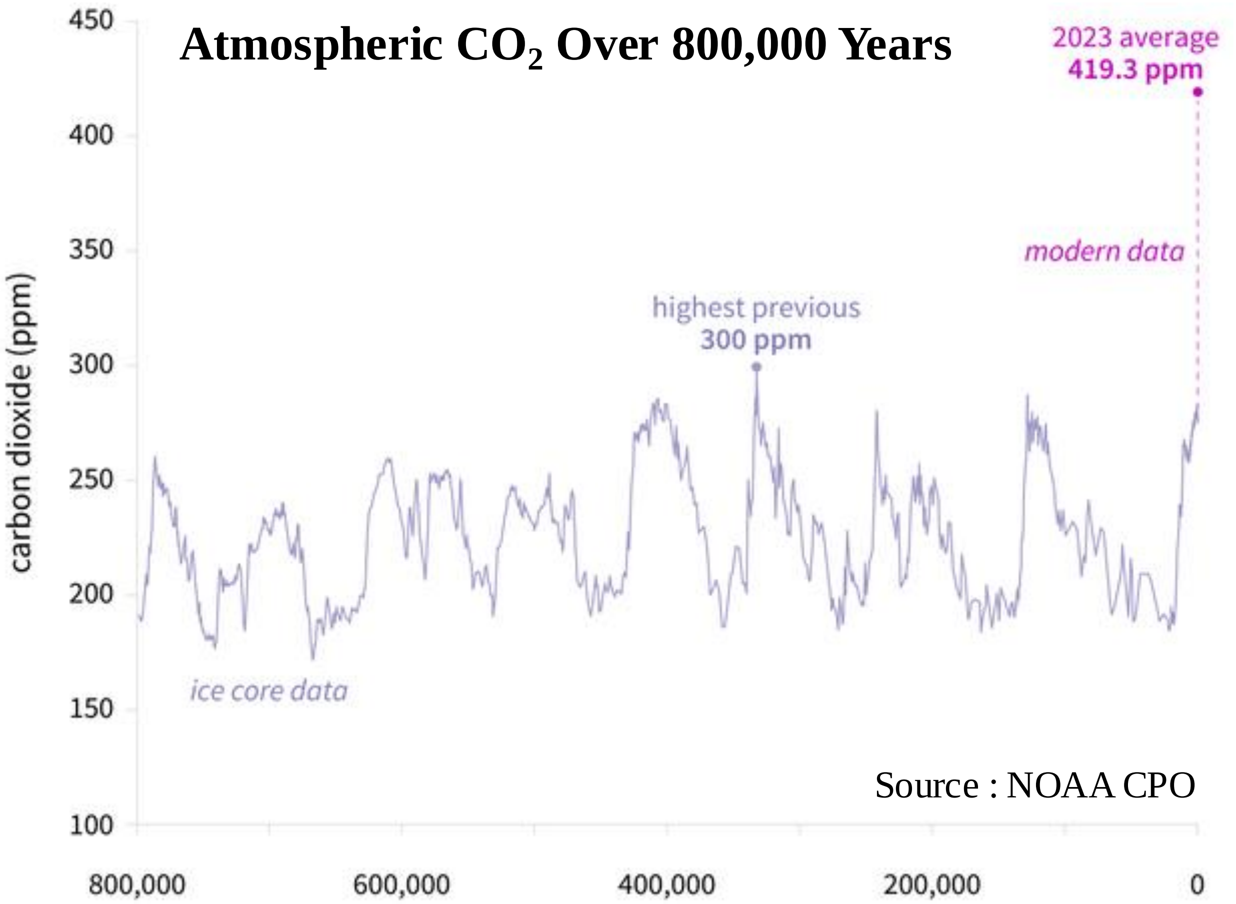
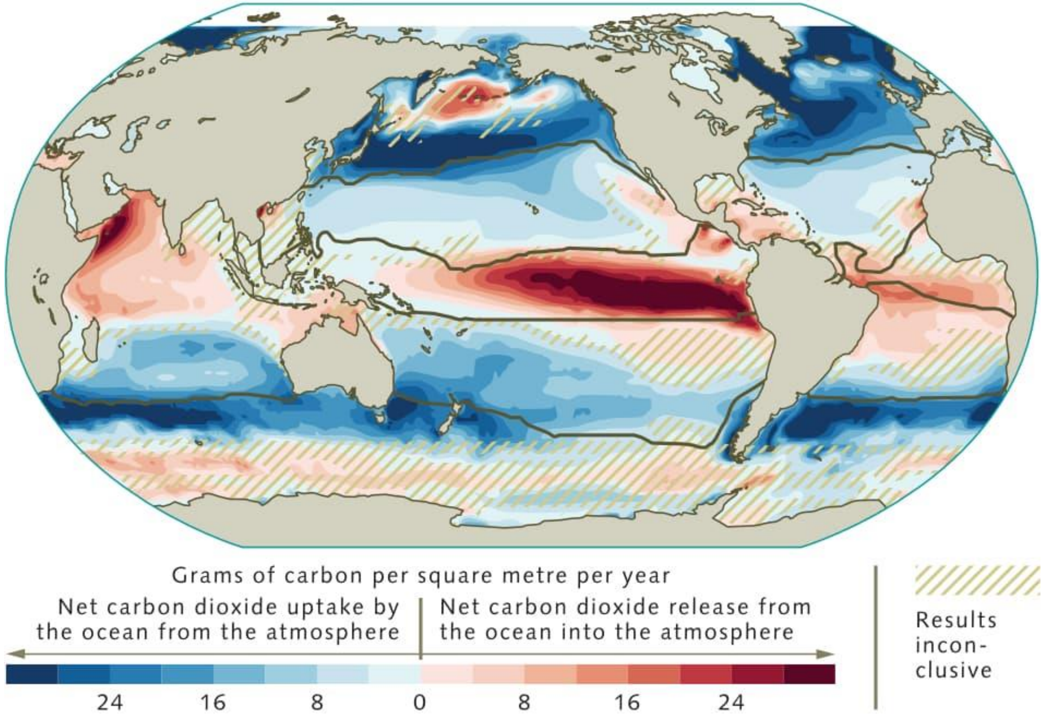
Background

Atmospheric CO_2 Over 800,000 Years



Source : NOAA CPO

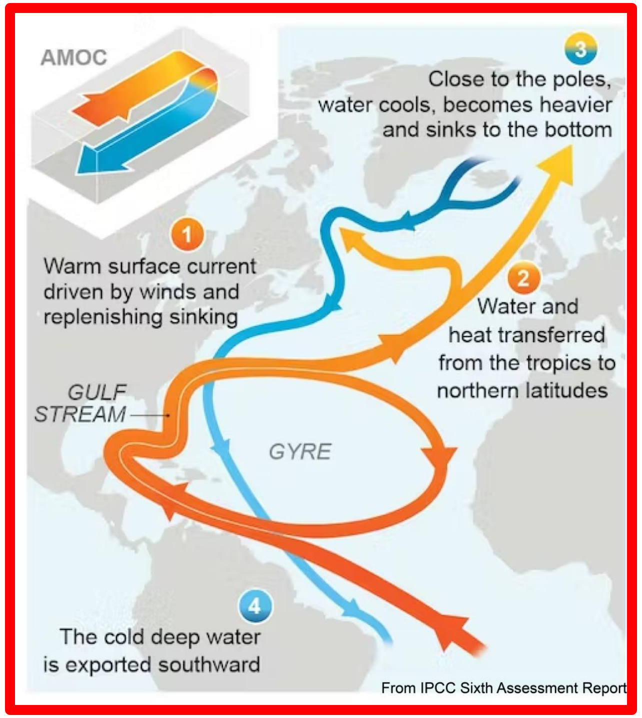
Net CO_2 flux between atmosphere and ocean

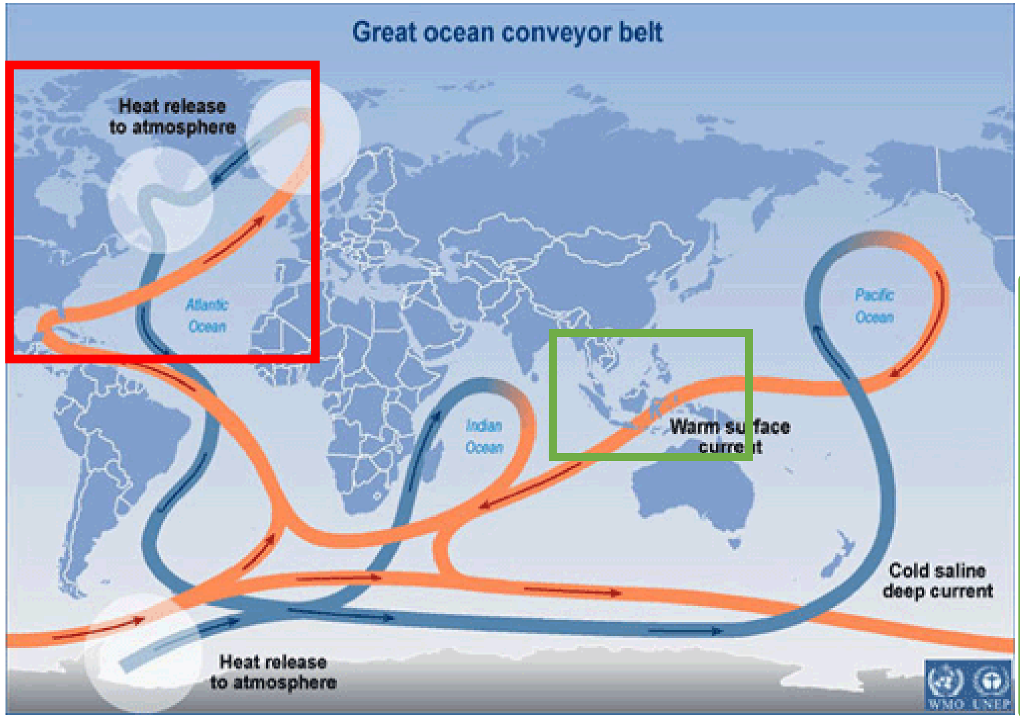


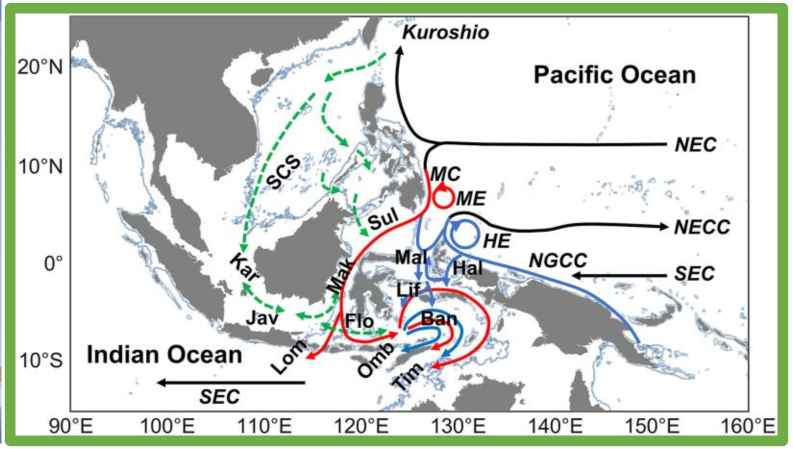
Source : IPCC 2021

- The atmospheric CO_2 concentration level has increased drastically since the industrial revolution. The current CO_2 level would have been way higher without the ocean.
- Ocean circulation and mixing transfer CO_2 from the surface to the deep.

Background







- Global thermohaline circulation distributes heat, freshwater, CO_2, nutrients etc.
- The Indo-Pacific/Indonesian throughflow [ITF] and Gulf Stream [GS] are two important components of the global circulation.
- The ITF is the only low-latitude inter-ocean exchange, while the GS is a major component of the Atlantic Meridional Overturning Circulation [AMOC].

Changes in the ITF and GS are important for weather & climate predictions!

Objective

Showcase applications of multi-faceted observations, including moored buoys, in discerning subseasonal processes in the Indo-Pacific [Indonesian] throughflow [ITF] and the Gulf Stream system.

Outline

1. Subseasonal variability in the ITF

   1.1. Properties and genesis of subseasonal eddies.

   1.2. MJO's imprints on the ITF

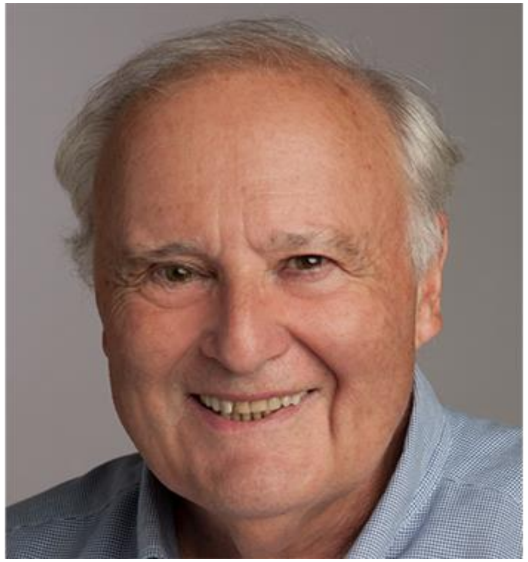
   1.2. Properties, genesis, and implications of subseasonal Kelvin waves.

2. Subseasonal variability in the GS

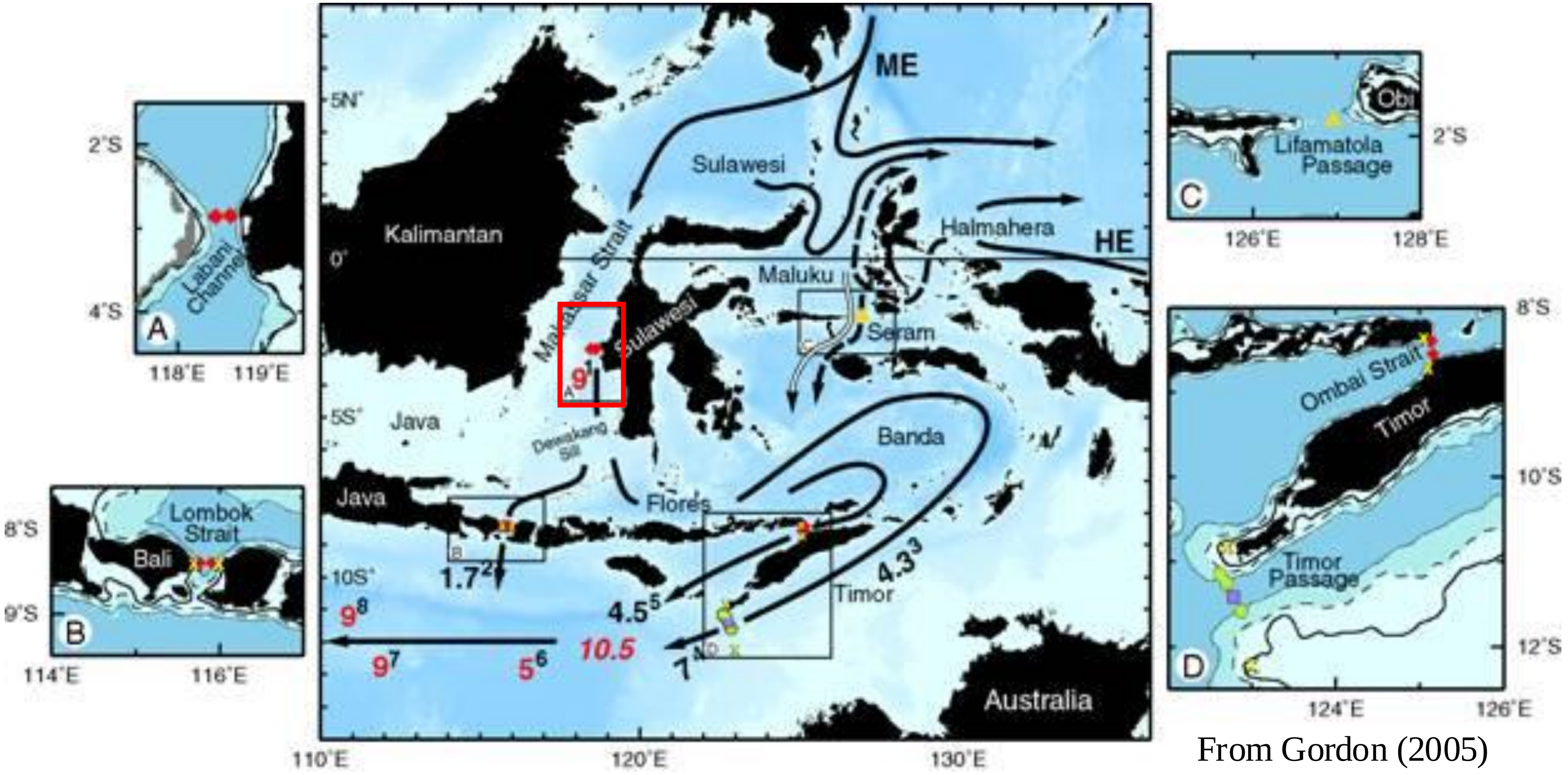
   2.1 Properties and genesis of continental shelf waves and coastal Kelvin waves

   2.2. Impact of subseasonal pulses on AMOC and nuisance flood along the U.S. East coast.

The Indo-Pacific [Indonesian] Throughflow



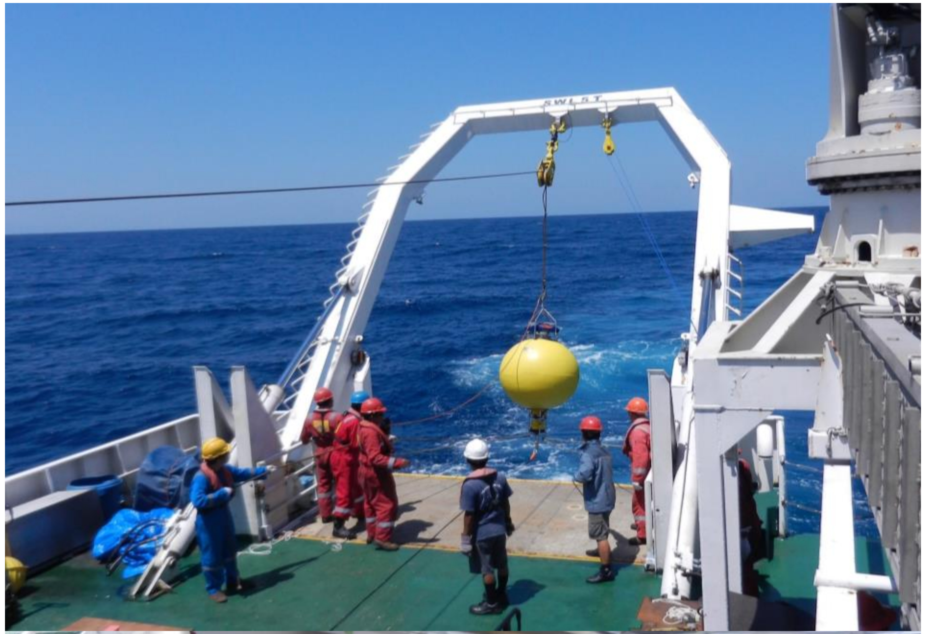
Dr. Arnold Gordon
Professor of Oceanography
[Emeritus]
Columbia University-USA



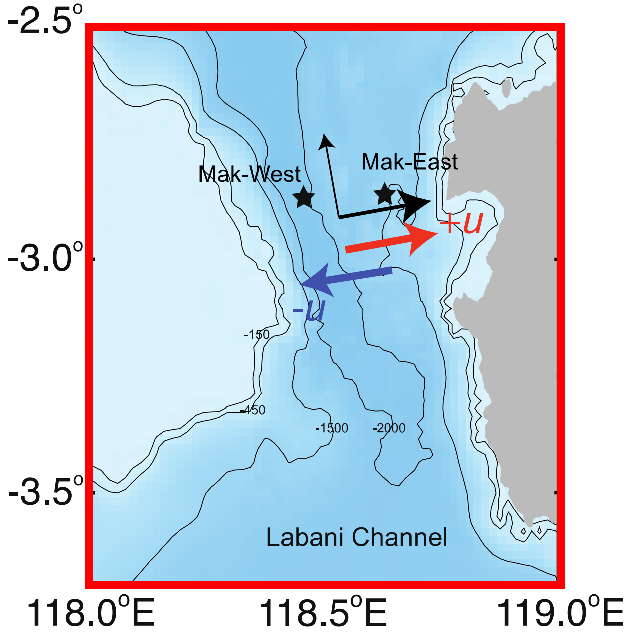
From Gordon (2005)

The ITF is the Pacific flow to the Indian Ocean, through multiple straits in the Indonesian seas, part of the global circulation important for regulating the regional weather and climate. The ITF main conduit is Makassar Strait.

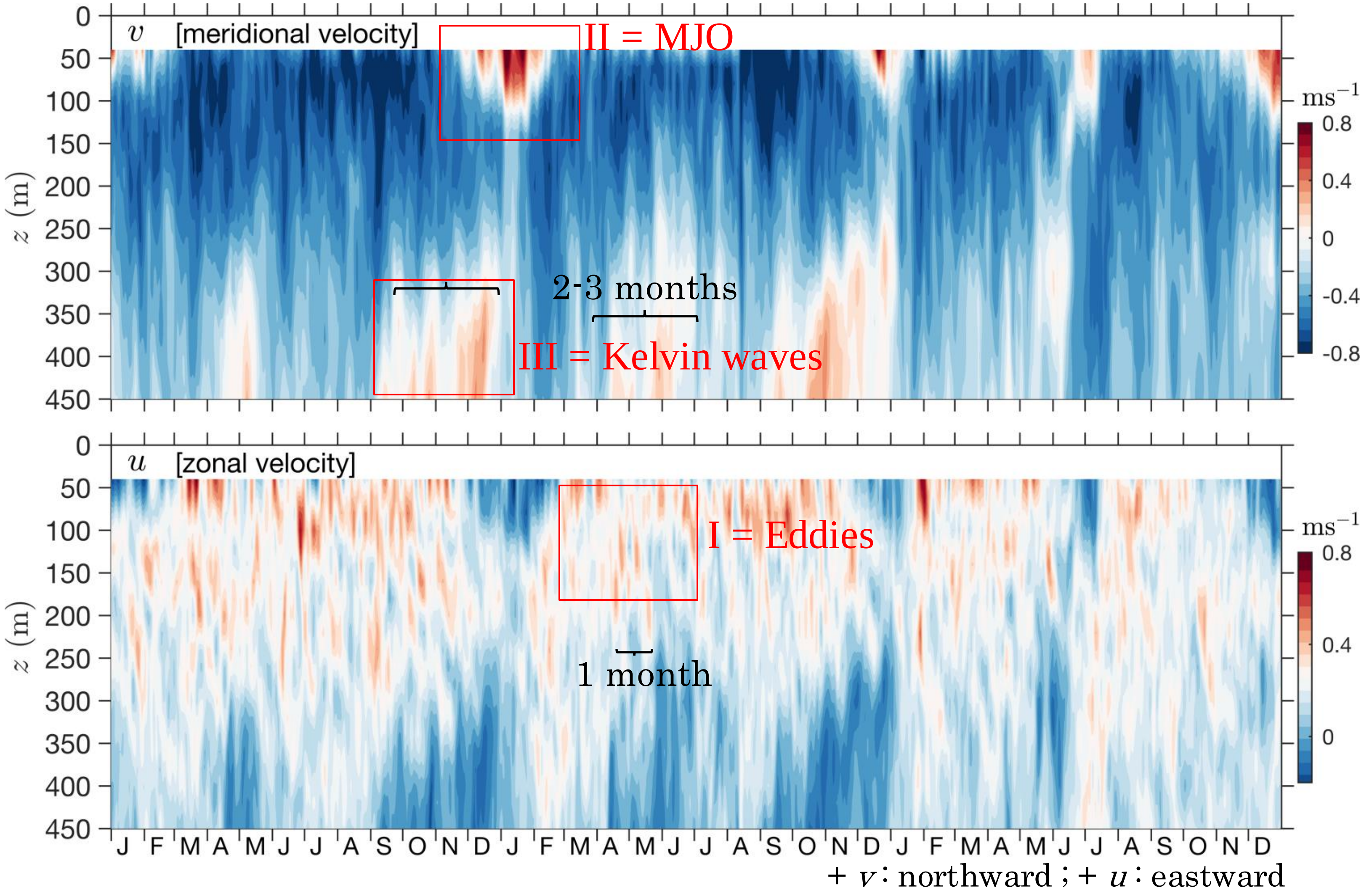
The ITF Observation



ITF Observation in Makassar Strait



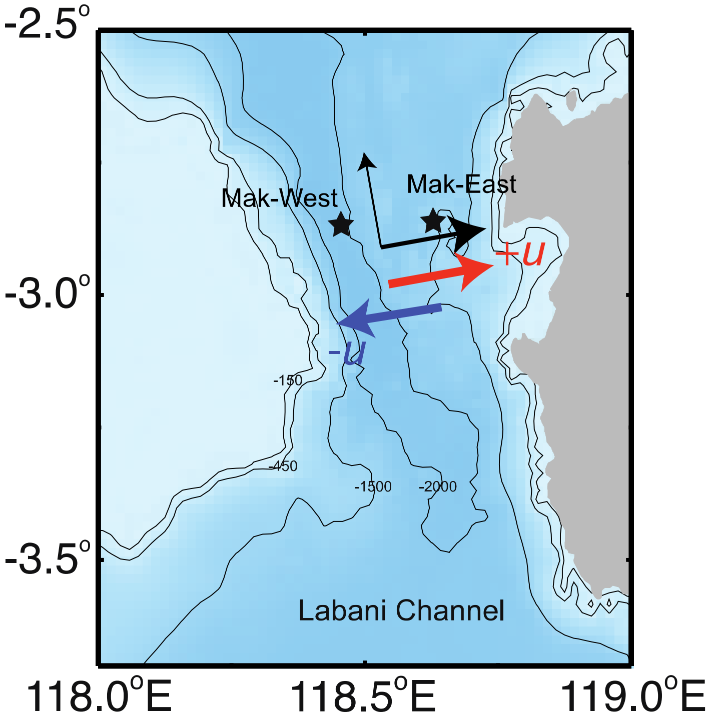
The temporal structures of the ITF in Makassar Strait are complex and rich in texture across timescales.

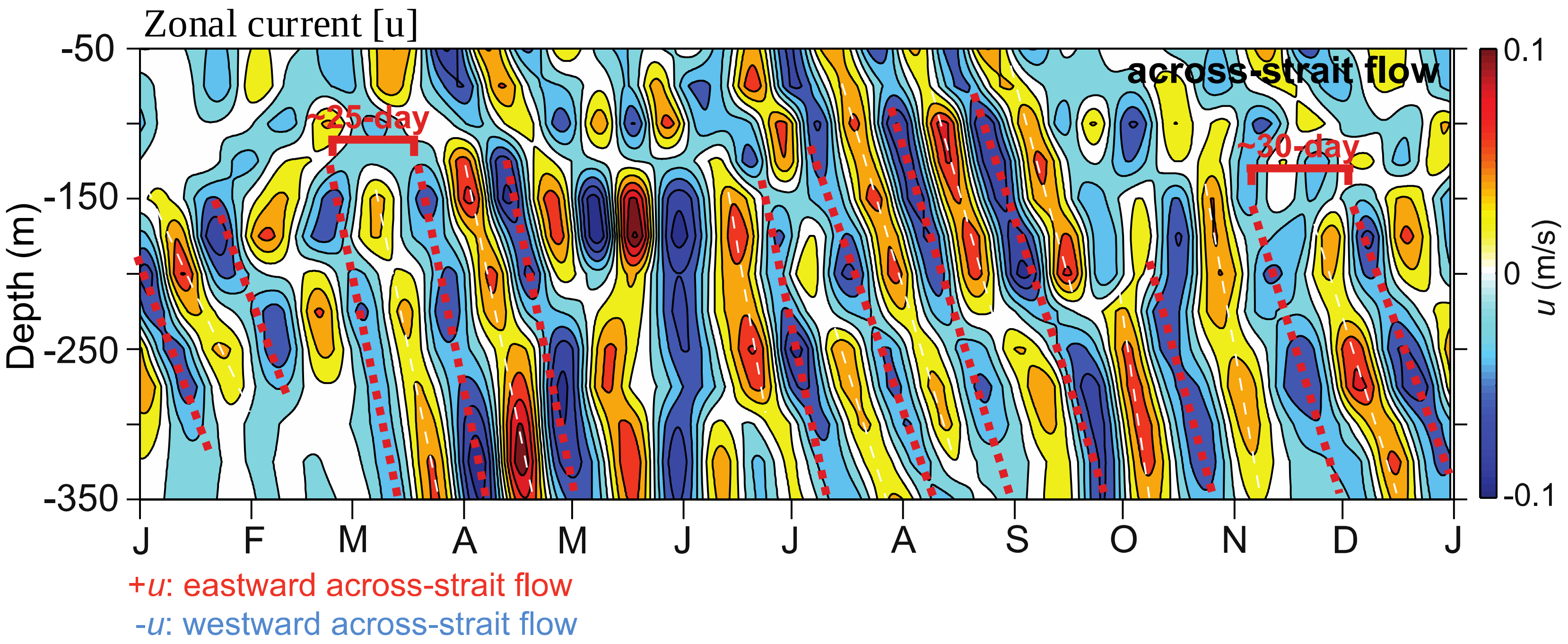


Dr. Gordon said “the seasonal and longer ITF variability, I got it. But the subseasonal part was elusive. Are you ready to take up the challenge?”

Subseasonal Eddies

Monthly variation in zonal velocities

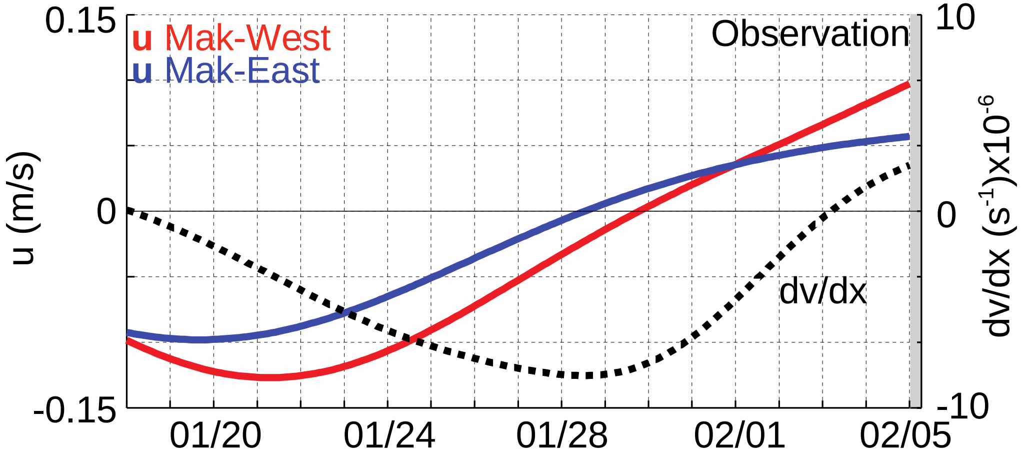


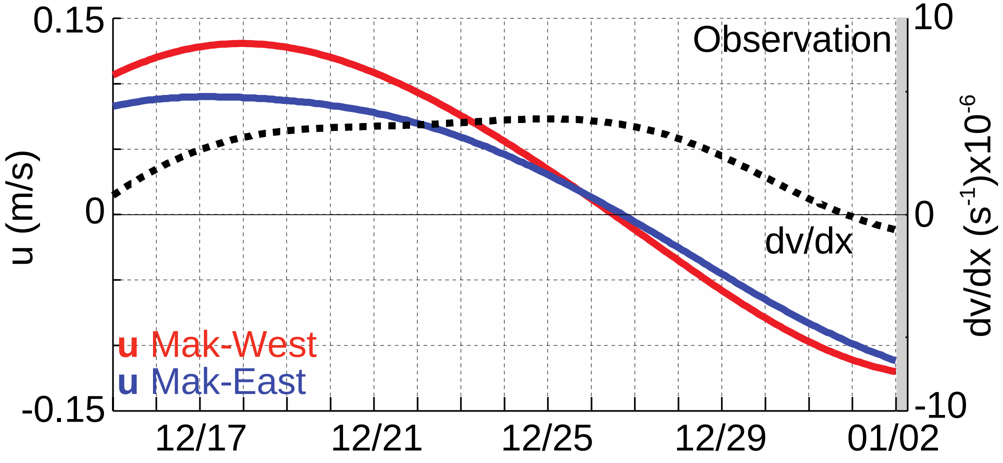


- Monthly oscillation characterizes *u* below 100 m.
- Downward phase propagation marks the monthly oscillation.

Subseasonal Eddies in Makassar Strait

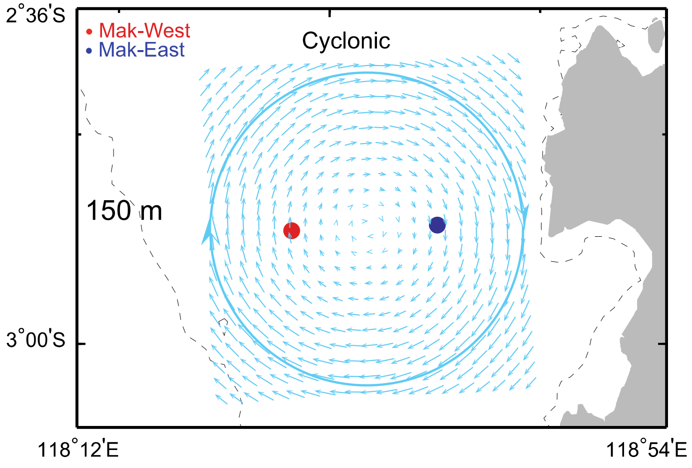
Zonal velocities versus zonal shear of meridional velocities

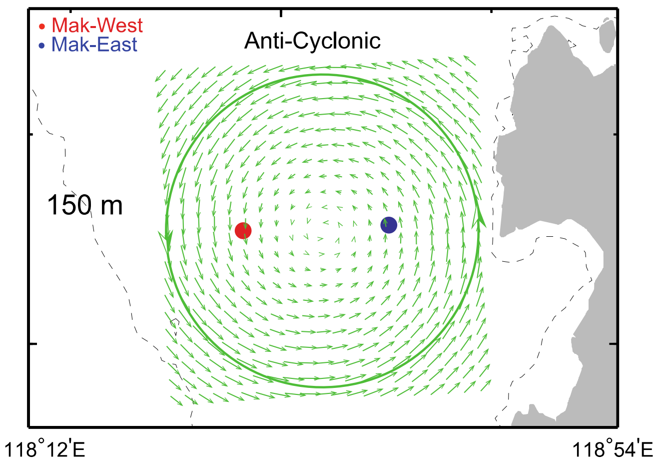




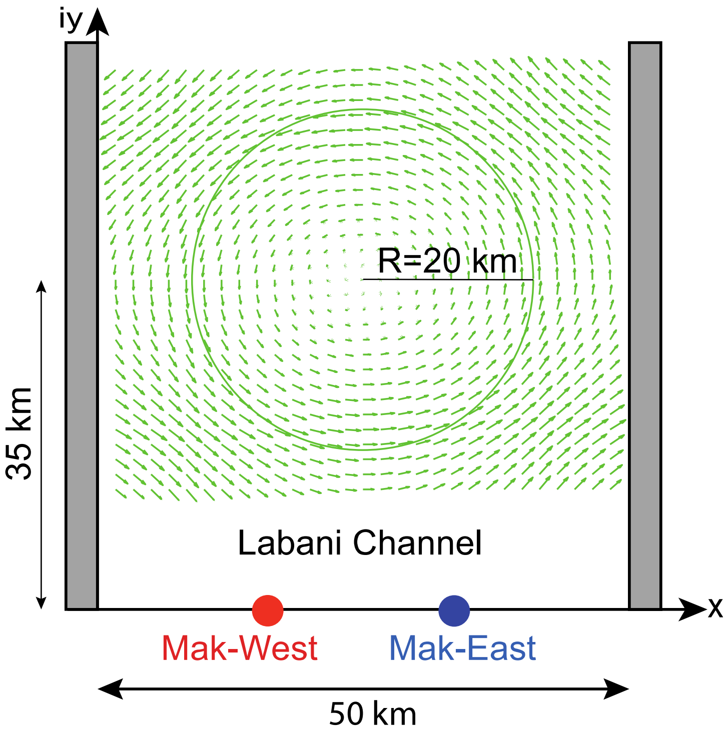
Westward [eastward] currents precede positive [negative] values of dv/dx

What force the monthly oscillation? Eddies.





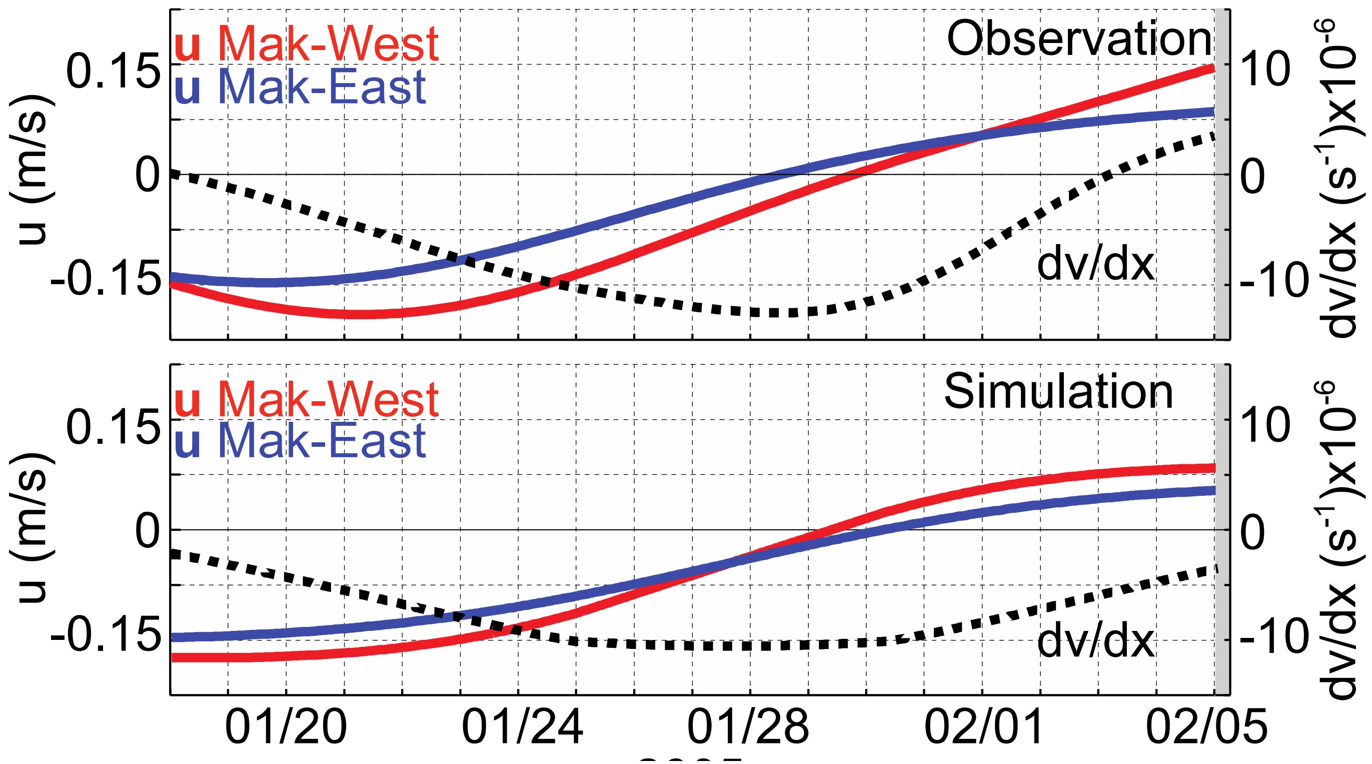
Subseasonal Eddies in Makassar Strait



$$x(t) = \begin{cases} \overline{V}(t - t_0)R^{-1}v_r - iR^{-1}v_r x; & |x| < R \\ \dfrac{v_r R}{\overline{V}(t - t_0)} - i\dfrac{v_r R}{x}; & |x| > R \end{cases}$$

Assumptions: simplified channel; southward advection velocity = 0.2 m/s; Azimuthal speed at the eddy edge, v_r = 0.15 m/s

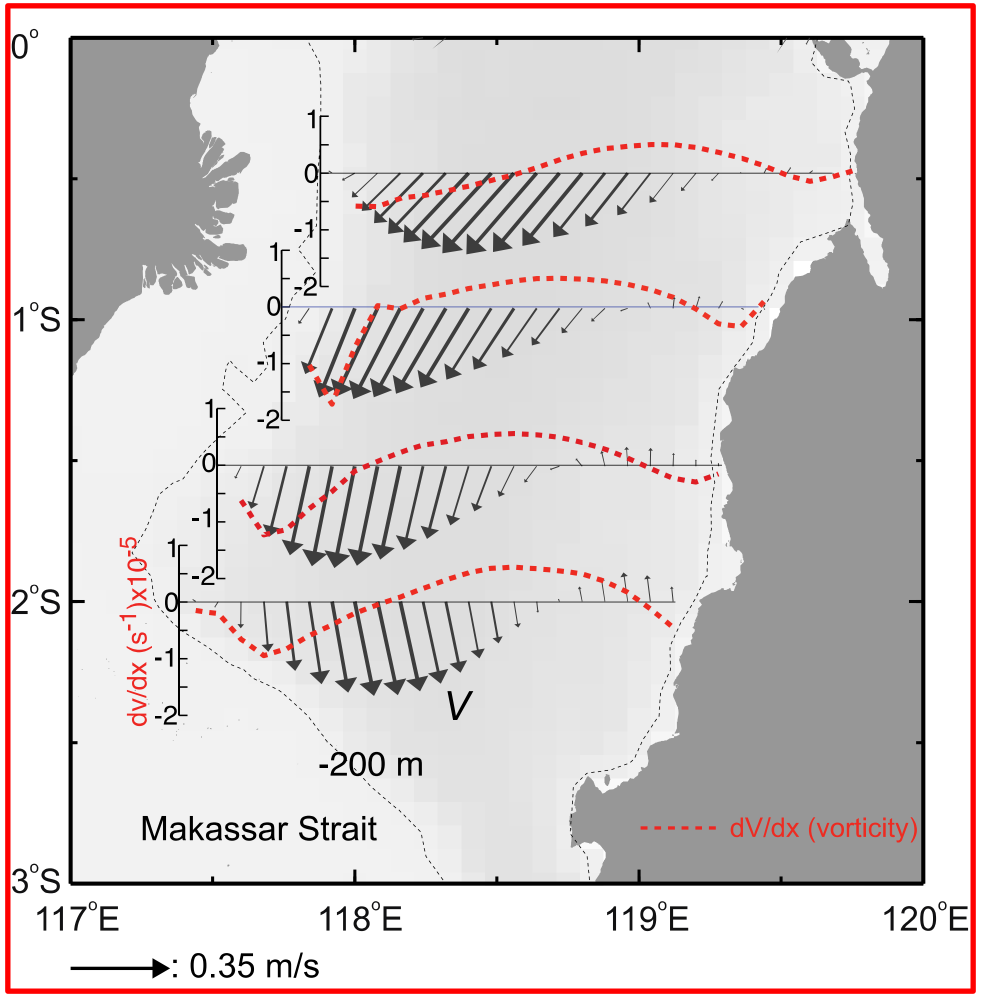
A Rankine vortex solution versus observation



Eddy currents for a Rankine vortex [Solid body rotation] reasonably replicate the observed monthly oscillation.

Subseasonal Eddies in Makassar Strait

Instability-generated eddies



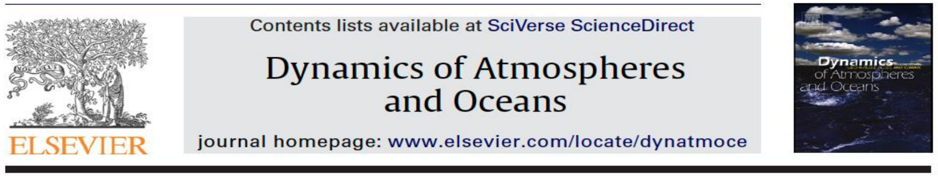
Two criteria for instability:

$$c_i \int \left(\frac{\partial^2 V}{\partial x^2} |f|^2 / |V - c|^2\right) dx = 0$$

or *v* needs to change sign across the Strait

$$\int \left(\frac{\partial^2 V}{\partial x^2} (V - V_I) |f|^2 / |V - c|^2\right) dx < 0$$

and the max vorticity is away from the boundary

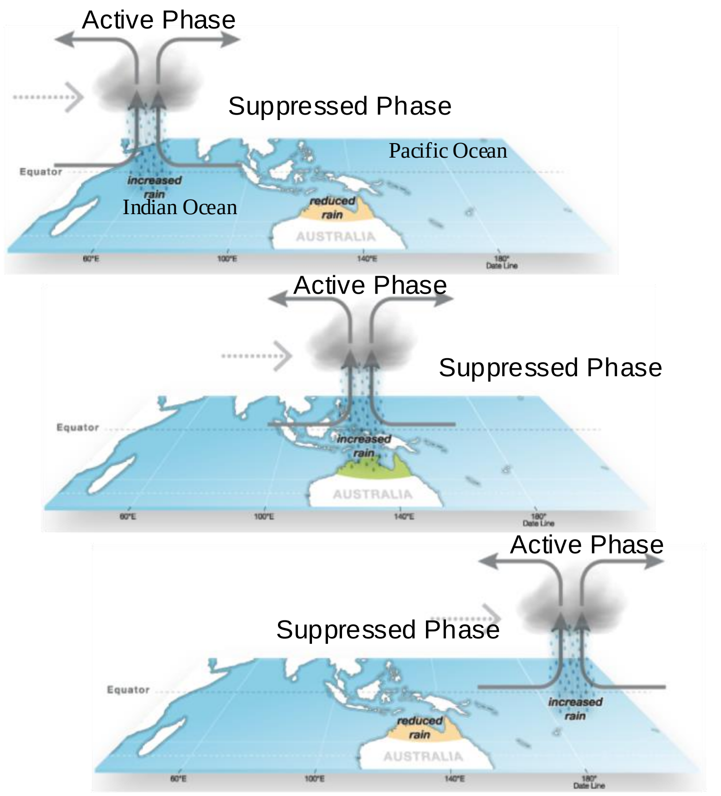


The Makassar Strait pycnocline variability at 20–40 days

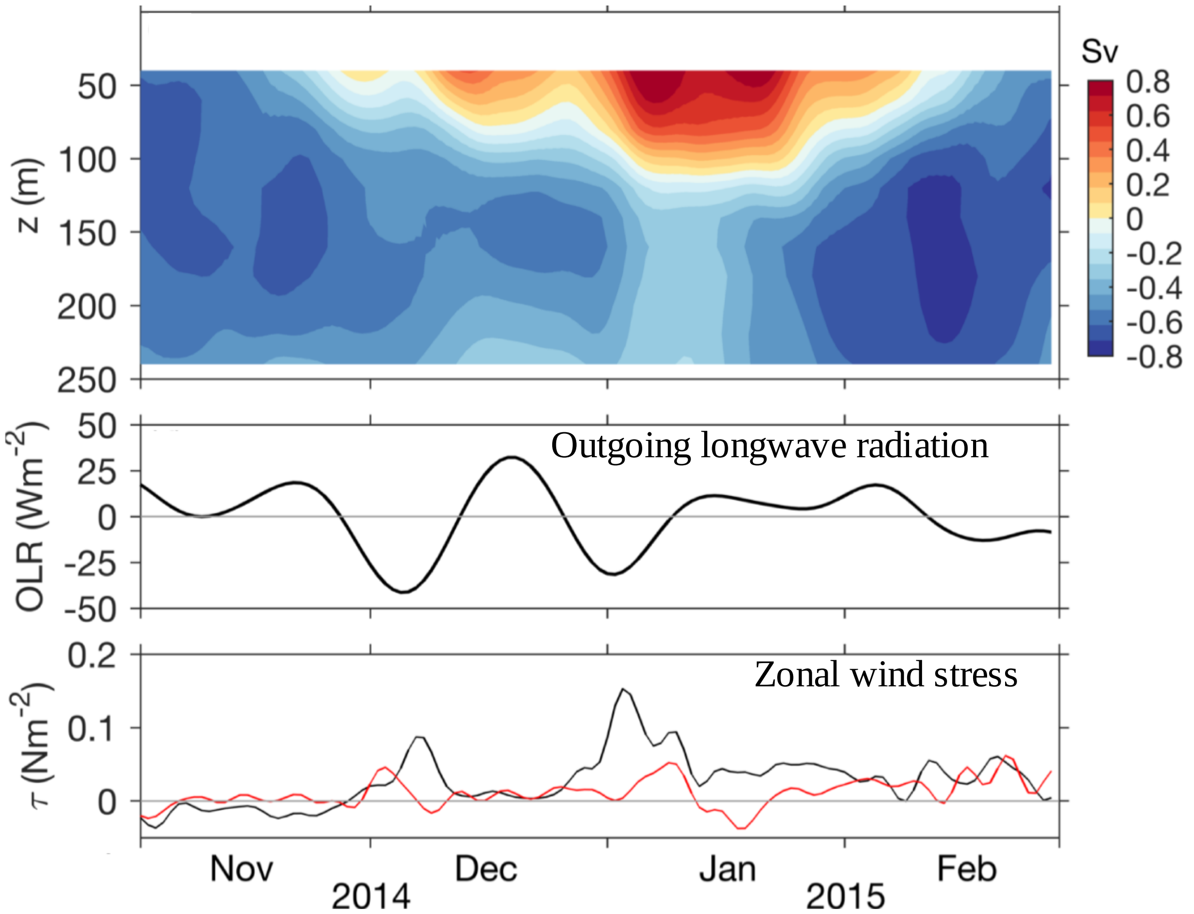
Kandaga Pujiana[a,d,*], Arnold L. Gordon[a], E. Joseph Metzger[b], Amy L. Ffield[c]

Genesis of the eddies? Instability of the background flow [ITF].

Madden-Julian Oscillation[MJO] ’s Signature in Makassar Strait



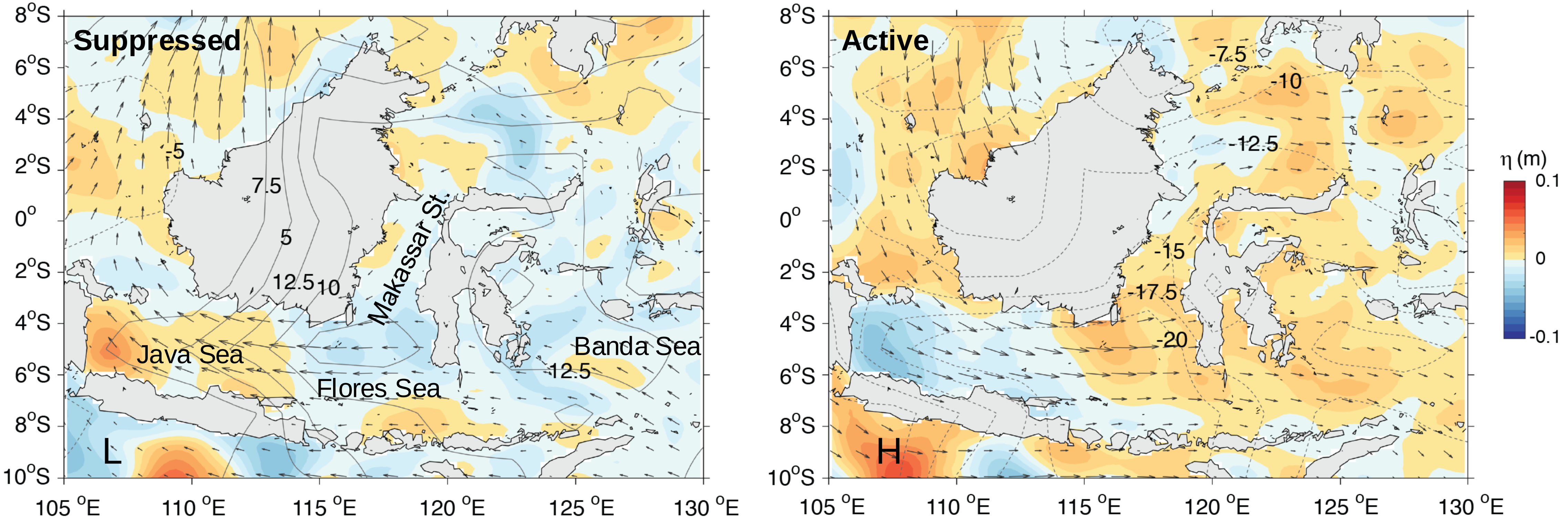
Source：Australian Bureau of Meteorology



The ITF transport reverses in the upper 100 m, coinciding with increased eastward zonal wind stress and reduced outgoing longwave radiation [OLR]

What causes energetic westerlies and suppressed OLR? The active phase of the MJO.

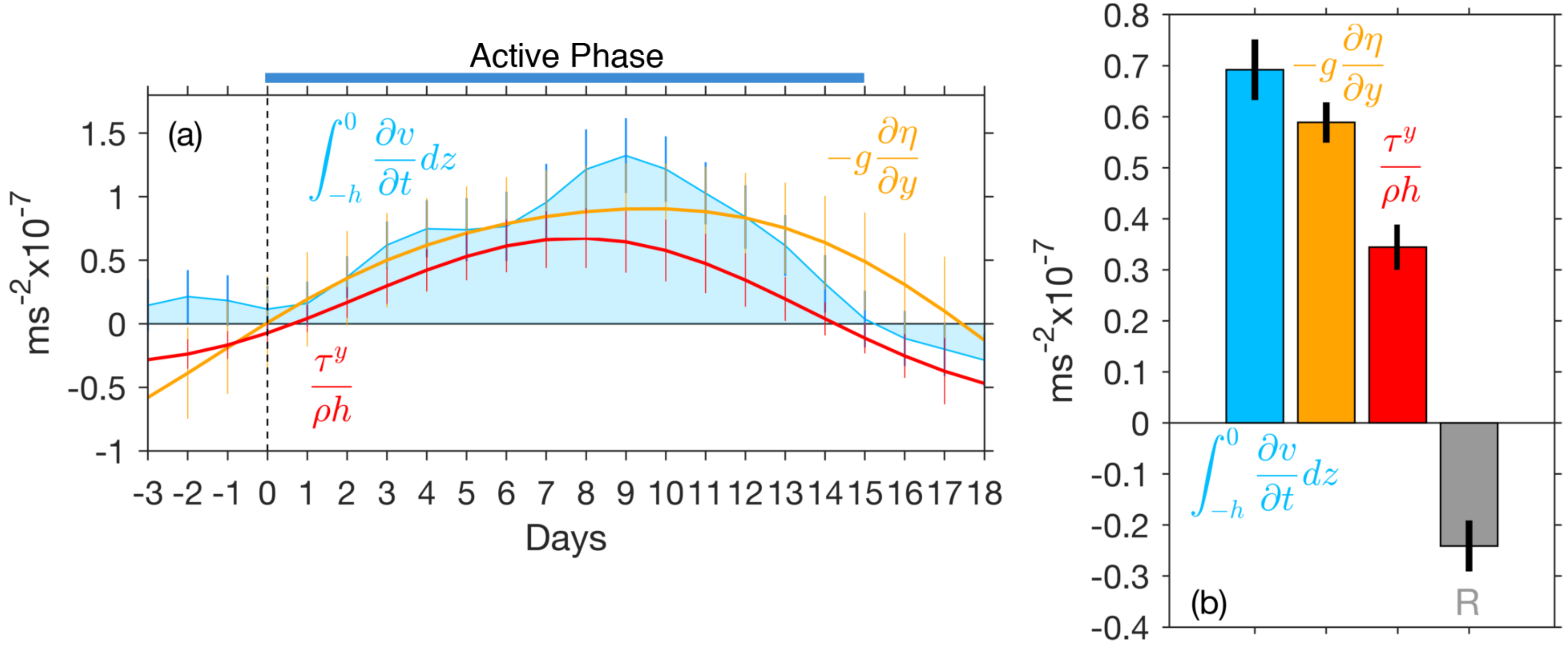
Madden-Julian Oscillation[MJO] 's Signature in Makassar Strait



During MJO active phase, westerlies are prevalent across Java, Flores and Banda Seas and sea level is higher than normal in the southern Makassar Strait

What processes account for ITF reversals during MJO?

Madden-Julian Oscillation[MJO] 's Signature in Makassar Strait



Northward pressure gradient offsets the vertical divergence of Reynold stresses to force the northward transport during the MJO.

JGR Oceans

RESEARCH ARTICLE

10.1029/2018JC014729

Special Section:
Recent Progresses in

The Madden-Julian Oscillation's Impact on the Makassar Strait Surface Layer Transport

Asmi M. Napitu[1,2], Kandaga Pujiana[3,4], and Arnold L. Gordon[1]

8710 JOURNAL OF CLIMATE VOLUME 28

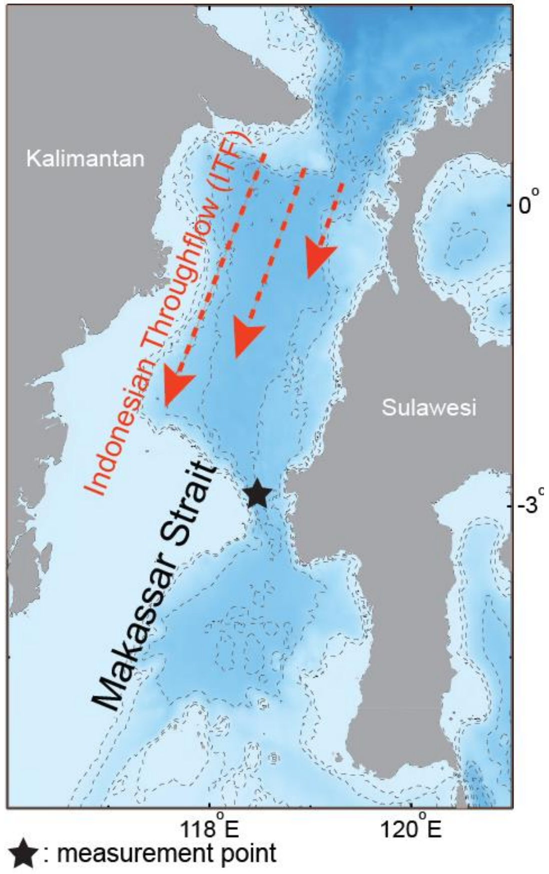
Intraseasonal Sea Surface Temperature Variability across the Indonesian Seas*

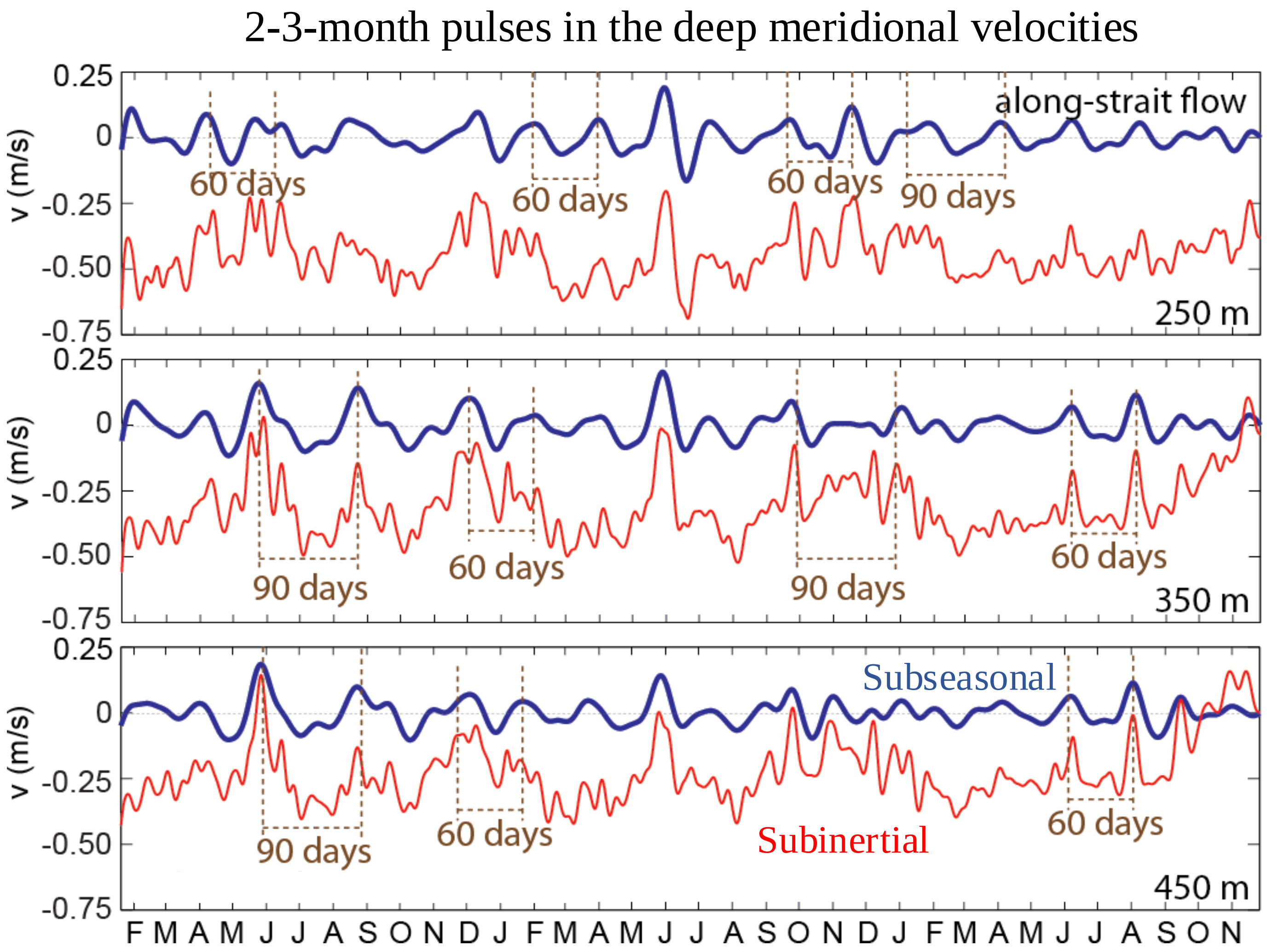
ASMI M. NAPITU[+] AND ARNOLD L. GORDON

Lamont-Doherty Earth Observatory, Columbia University, Palisades, New York

KANDAGA PUJIANA[#]

Subseasonal Kelvin Waves in Makassar Strait

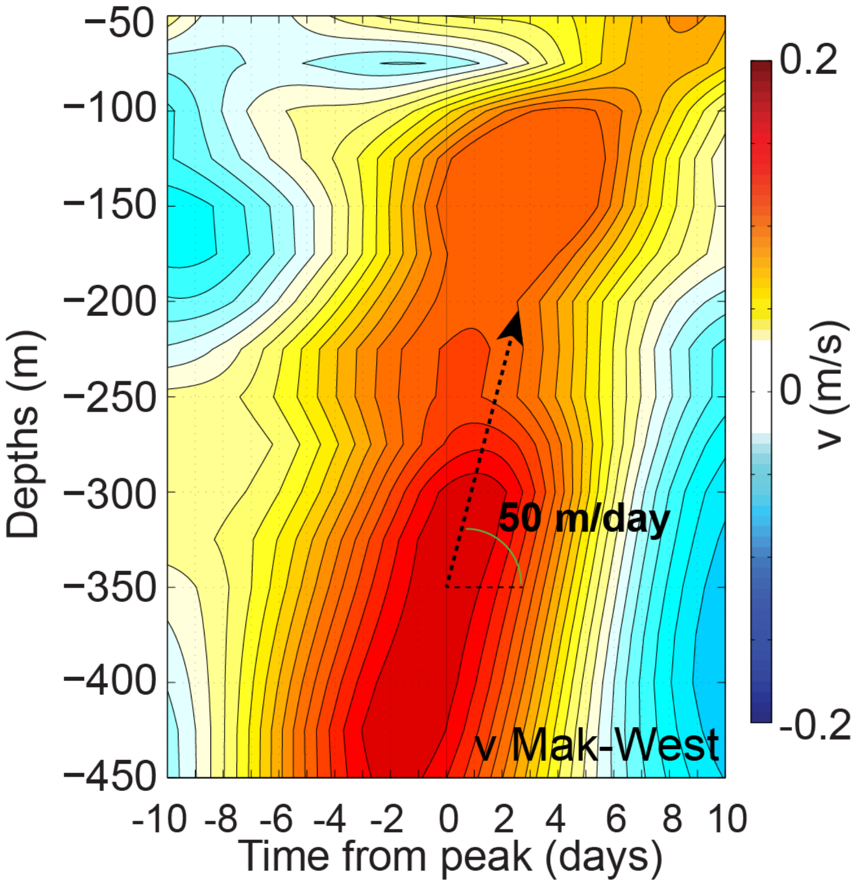


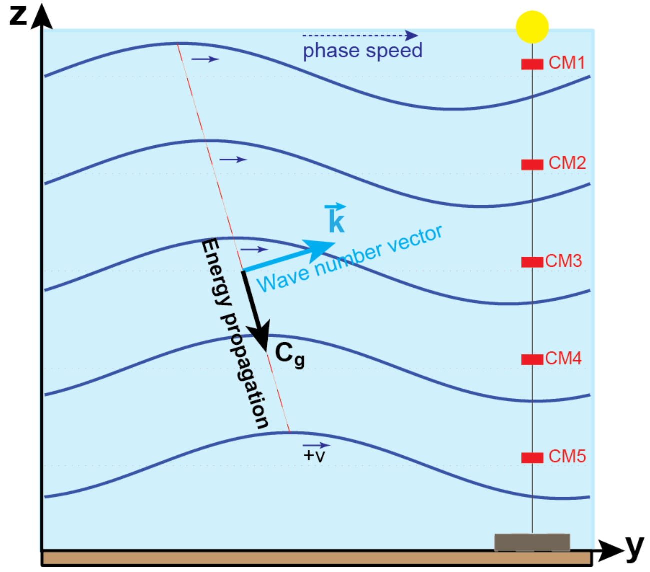


2-3-month oscillations mark *v* deeper than 150 m in Makassar Strait

Subseasonal Kelvin Waves in Makassar Strait

A composite of v due to the ITF reversals





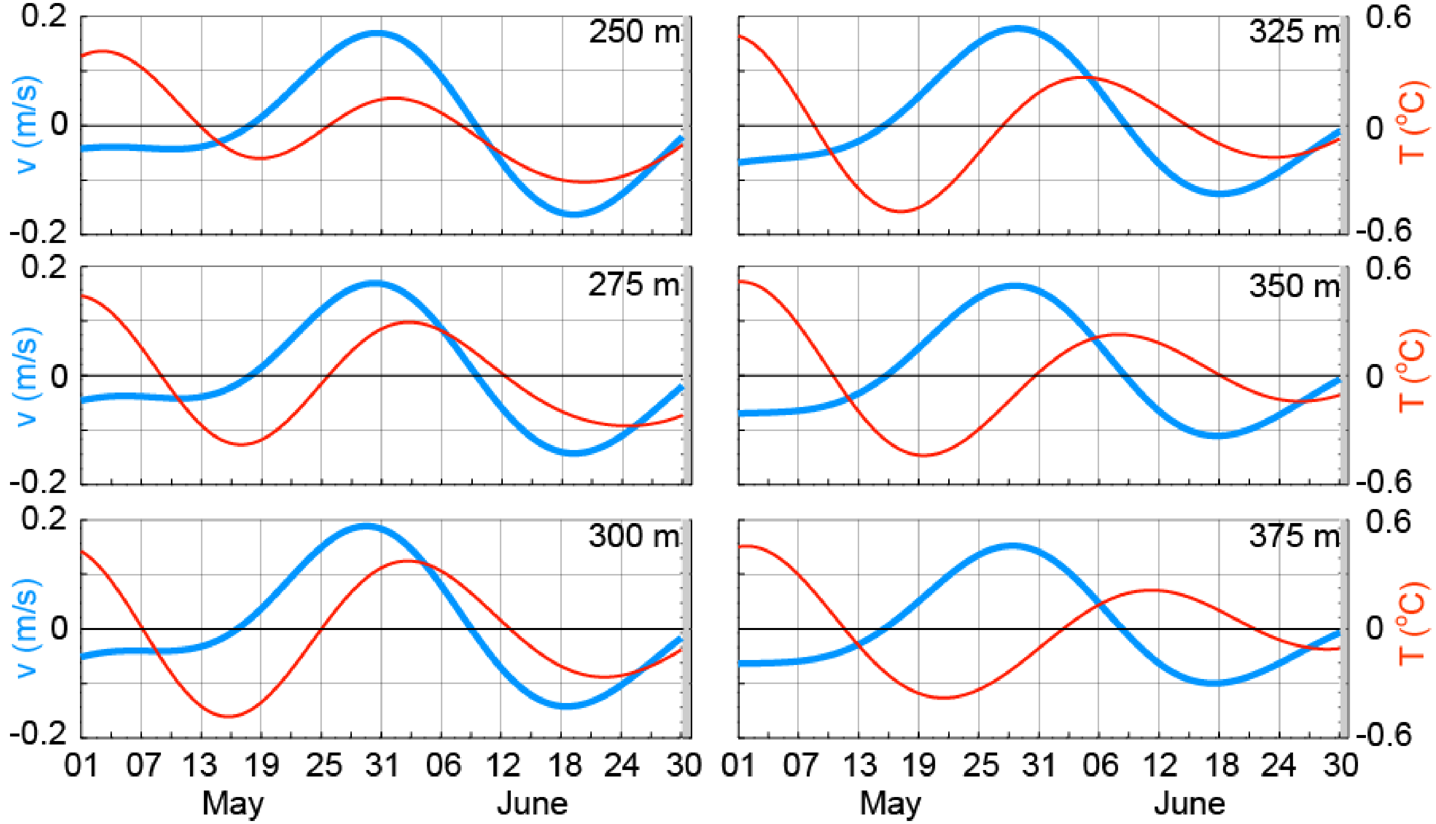
The slope is a function of wave frequency (ω), phase speed (c), and buoyancy frequency (N):

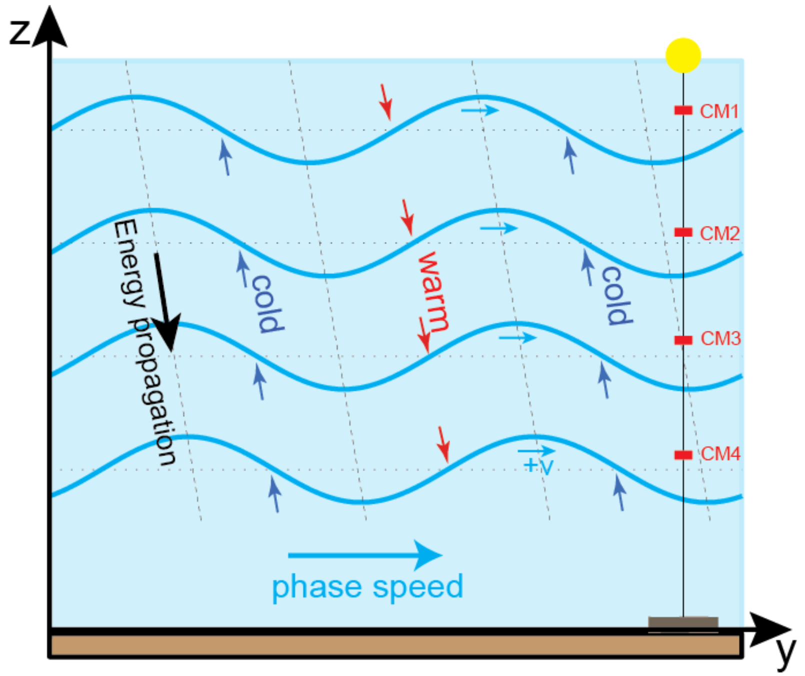
$$\frac{dz}{dt} = \frac{w.c}{N}$$

- 2-3-month oscillations mark v deeper than 150 m in Makassar Strait.
- Upward phase tilt is observed (+v occurs at deeper depth first)

Subseasonal Kelvin Waves in Makassar Strait

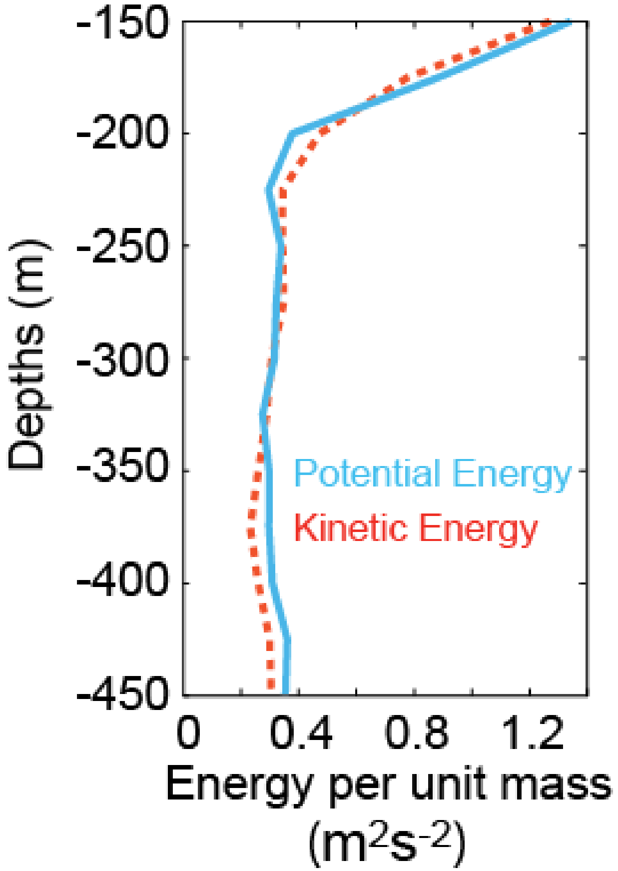
ITF reversals versus subsurface temperature [T]





v leads temperature (*T*) by ¼ cycle : maximum (+v) occurs ¼ cycle ahead of warmest *T*

Subseasonal Kelvin Waves in Makassar Strait



Potential Energy : $PE = \frac{1}{2} r g \overline{h^2}$

$$h(z,t) = \frac{T(z,t)}{\frac{\partial \overline{T}}{\partial z}} \text{ x } \frac{N}{N_o}$$

Kinetic Energy : $KE = \frac{1}{2} r \overline{v^2}$

- PE and KE vertical structures have similar magnitudes, indicative of equipartition between the two.
- The energy of a Kelvin wave is partitioned equally between the kinetic and potential forms, like in the oscillation of a pendulum.

Subseasonal Kelvin Waves in Makassar Strait

Journal of Marine Research, 67, 757–777, 2009

Intraseasonal variability in the Makassar Strait thermocline

by Kandaga Pujiana[1,2], Arnold L. Gordon[1], Janet Sprintall[3] and R. Dwi Susanto[1]

JOURNAL OF GEOPHYSICAL RESEARCH: OCEANS, VOL. 118, 2023–2034, doi:10.1002/jgrc.20069, 2013

Intraseasonal Kelvin wave in Makassar Strait

K. Pujiana,[1,3] A. L. Gordon,[1] and J. Sprintall[2]

JGR Oceans

RESEARCH ARTICLE
10.1029/2019JC015839

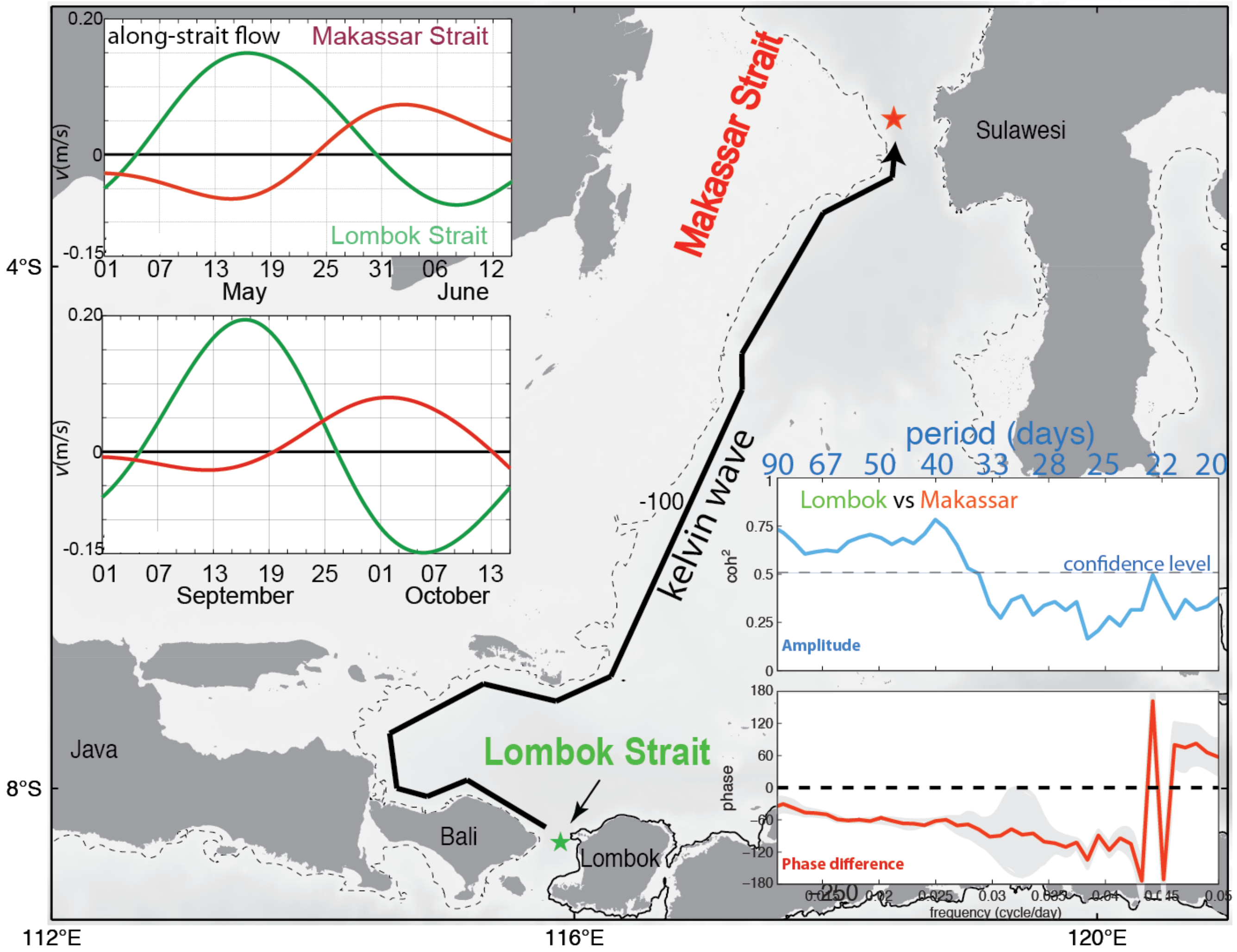
Special Section:
Years of the Maritime Continent

Intraseasonal Kelvin Waves in the Equatorial Indian Ocean and Their Propagation into the Indonesian Seas

Kandaga Pujiana[1,2] and Michael J. McPhaden[1]

Kelvin waves force subseasonal variability in Makassar Strait.
Are the waves locally generated?

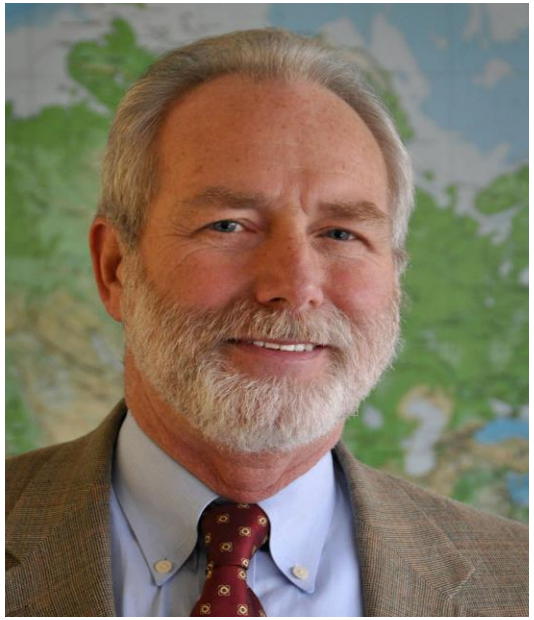
Origin of Kelvin Waves in Makassar Strait



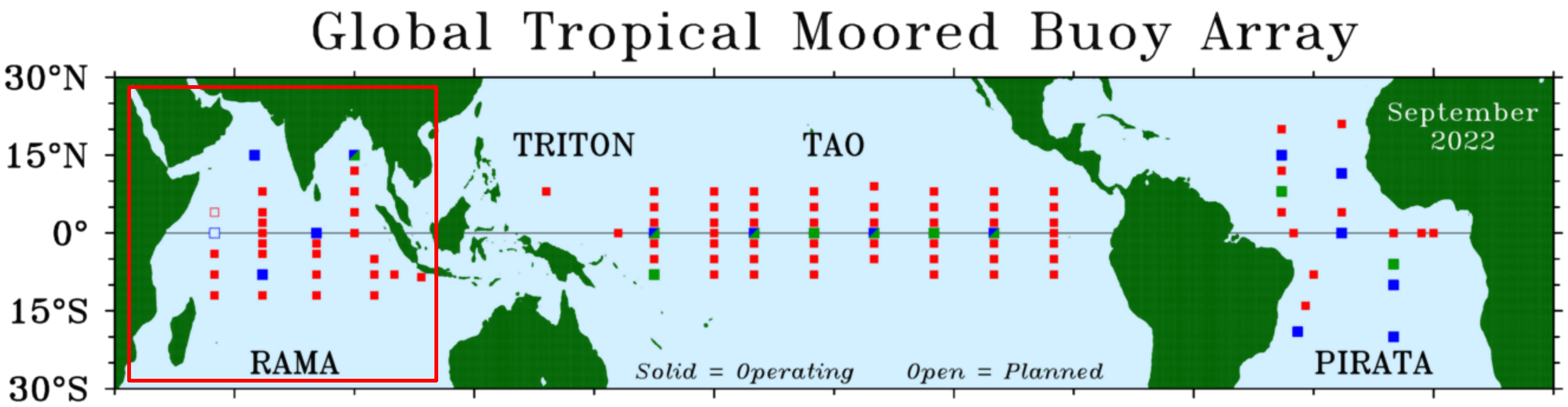
- Subseasonal ITF reversals are not locally wind driven.
- Subseasonal variations in *v* in Lombok and Makassar Straits are coherent on subseasonal timescales.
- The coherence indicates propagation from Lombok to Makassar Strait.

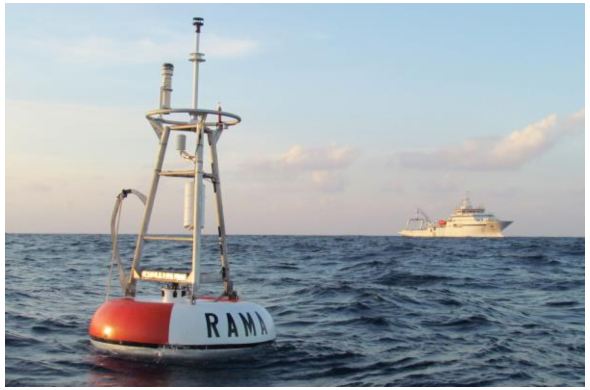
Subseasonal Kelvin waves in Makassar Strait are remotely forced. Where?

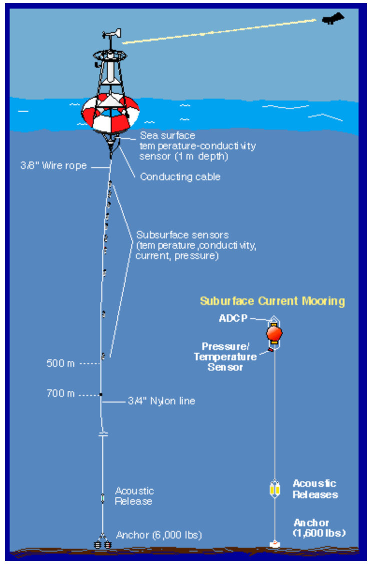
Global Tropical Moored Buoy Array



Dr. Michael McPhaden
Senior Scientist
Director of GTMBA-NOAA/PMEL

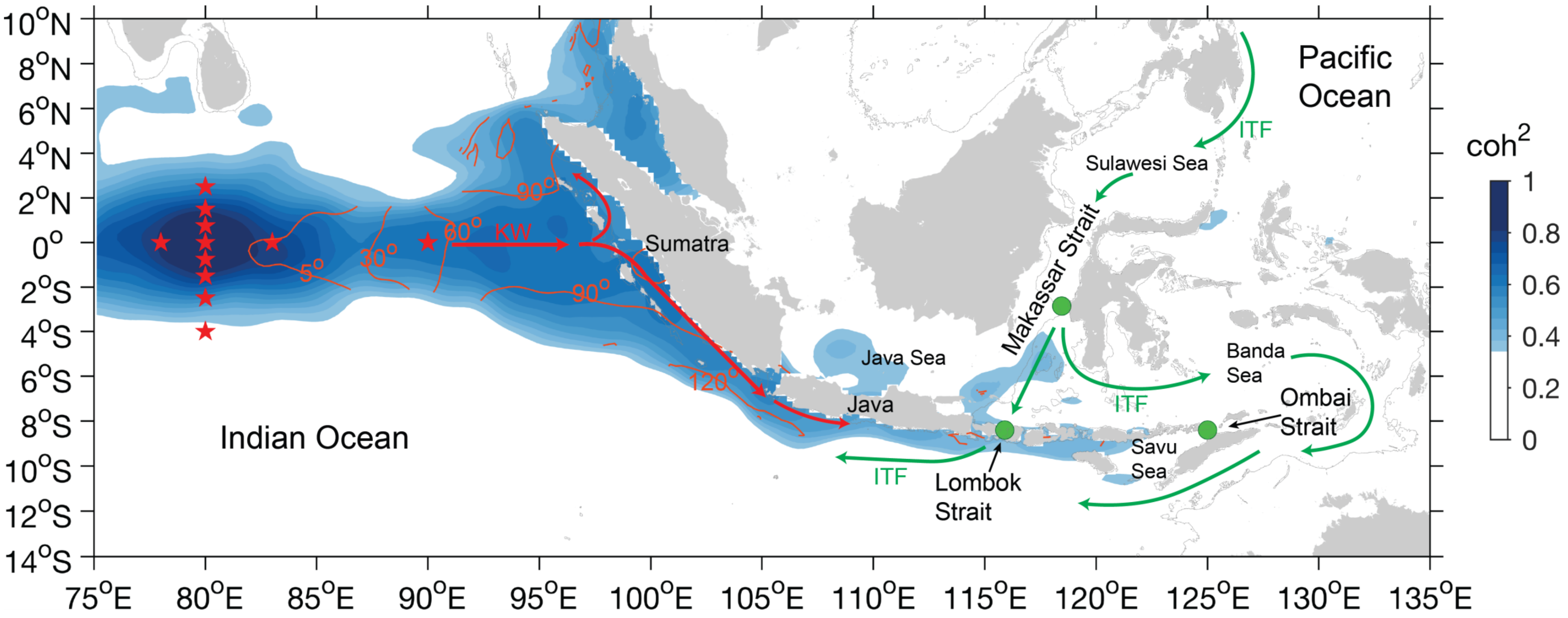






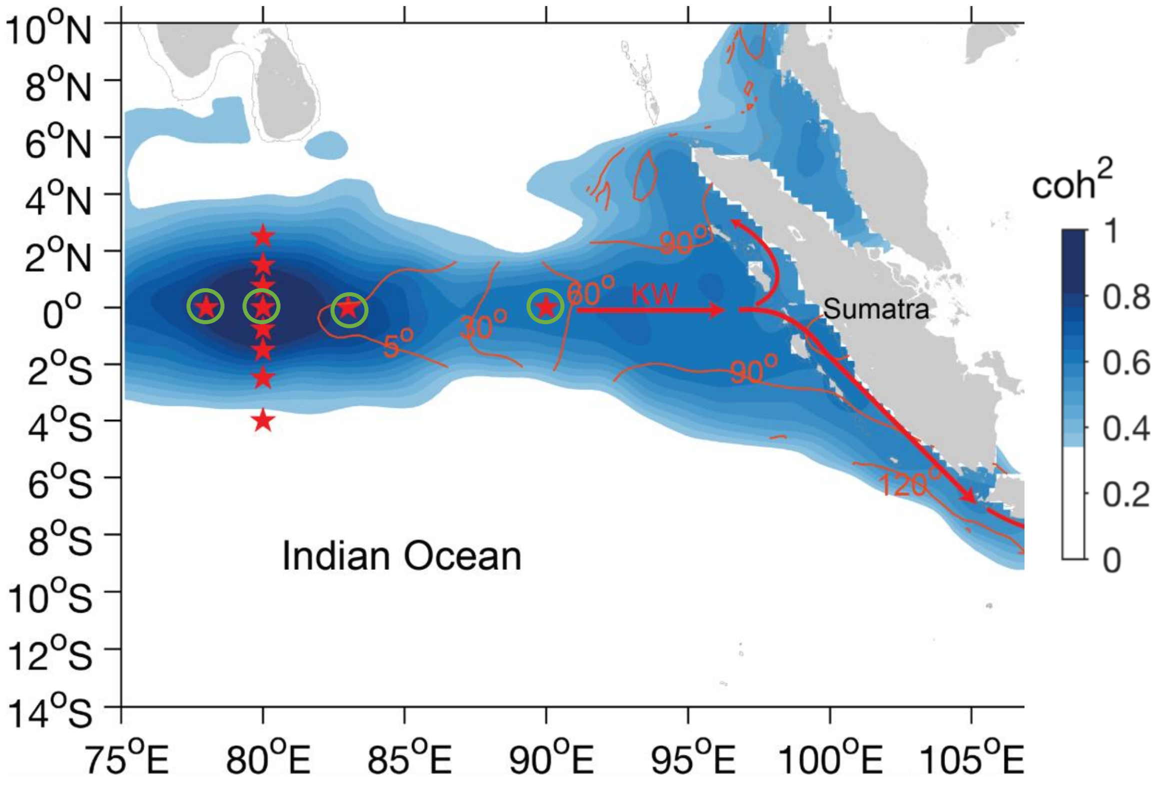
The RAMA buoy array provides ocean current, temperature and salinity data in the upper ocean and near surface atmospheric parameters, critical for our understanding of ocean-atmosphere processes and interactions.

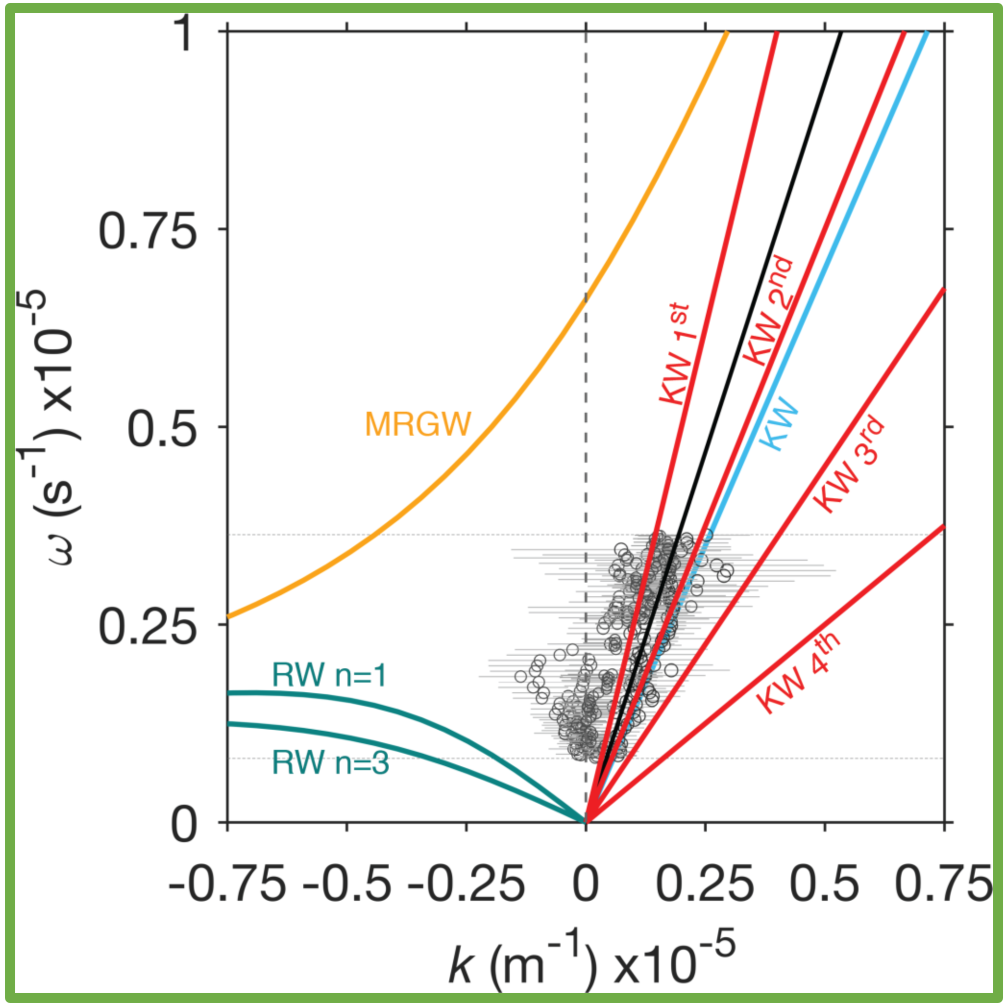
Propagation of Indian Ocean Kelvin Waves to Indonesian Seas



Subseasonal sea level anomalies in the equatorial Indian Ocean and southern coasts of the Indonesian archipelago are coherent, exemplifying propagation into the internal Indonesian seas.

Propagation of Indian Ocean Kelvin Waves to Indonesian Seas

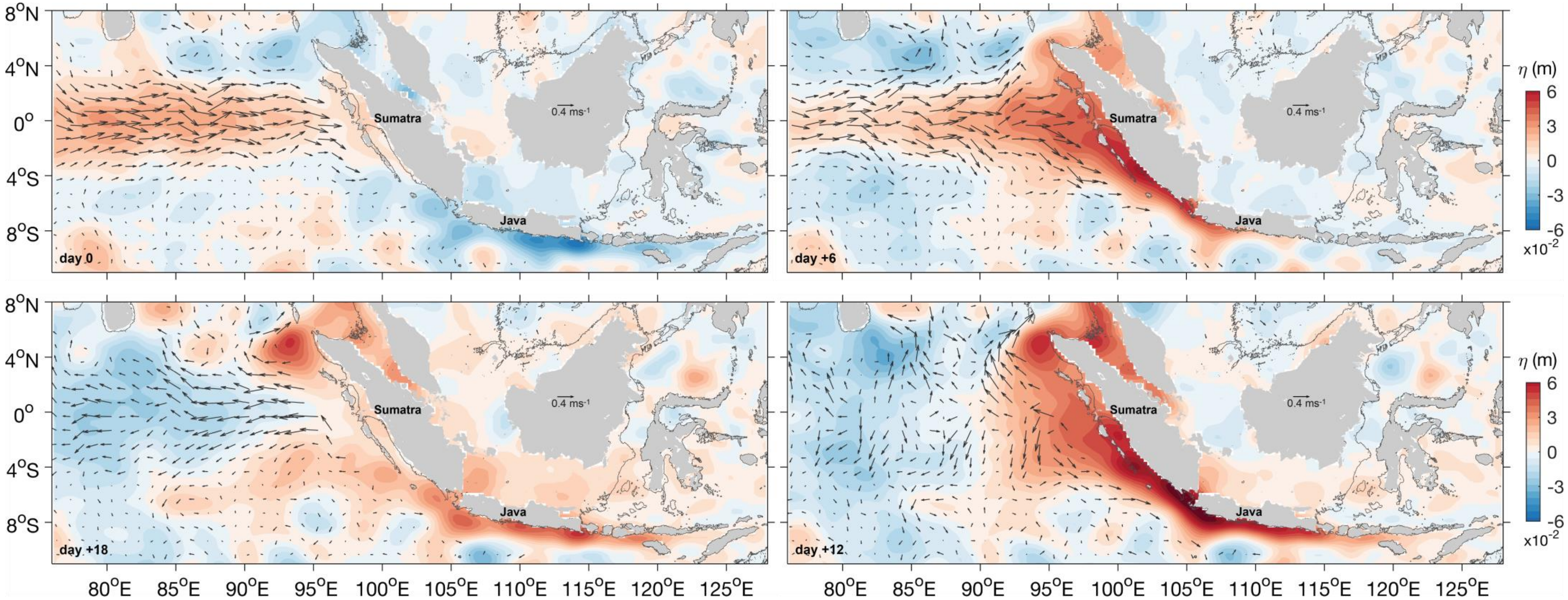




- Analysis of zonal currents at different equatorial moorings yields the frequency - wavenumber relationship ($\omega - k$).
- Observed $\omega - k$ clusters around the theoretical dispersion curves for Kelvin waves.

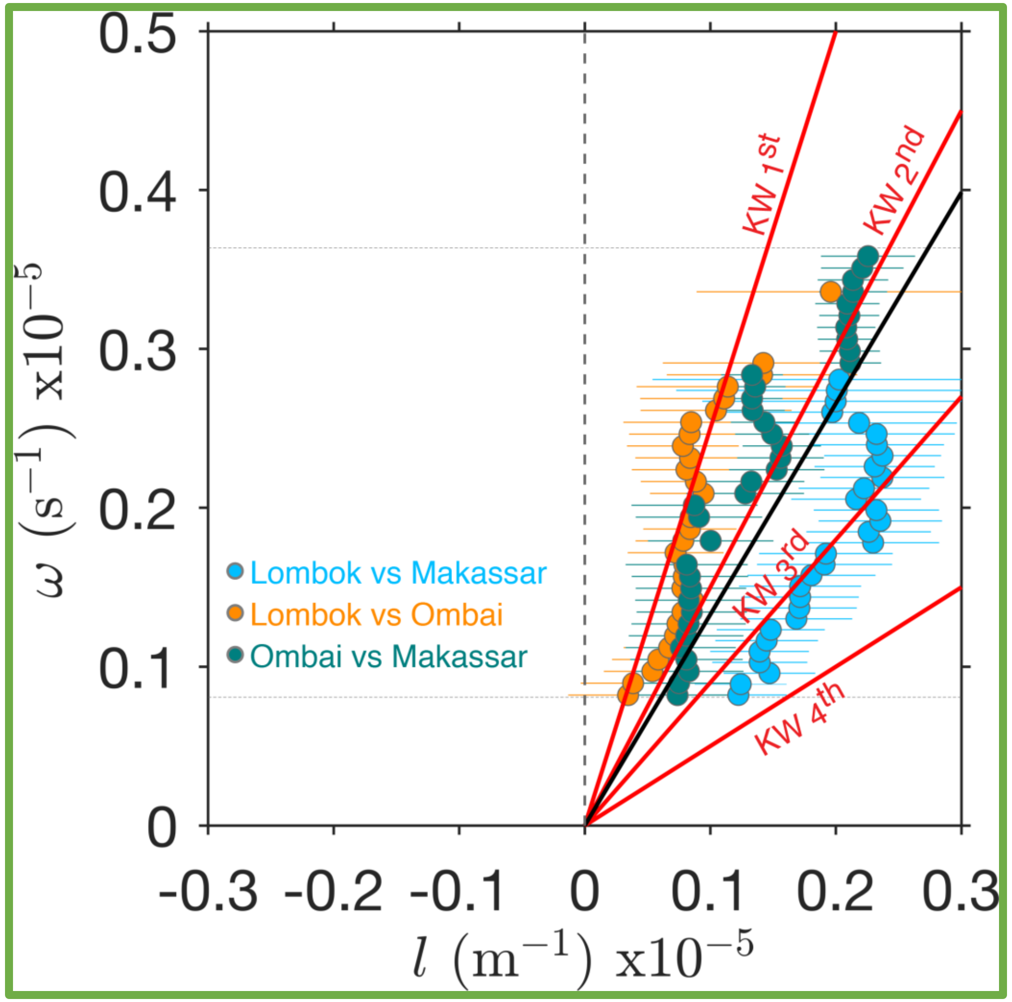
Propagation of Indian Ocean Kelvin Waves to Indonesian Seas

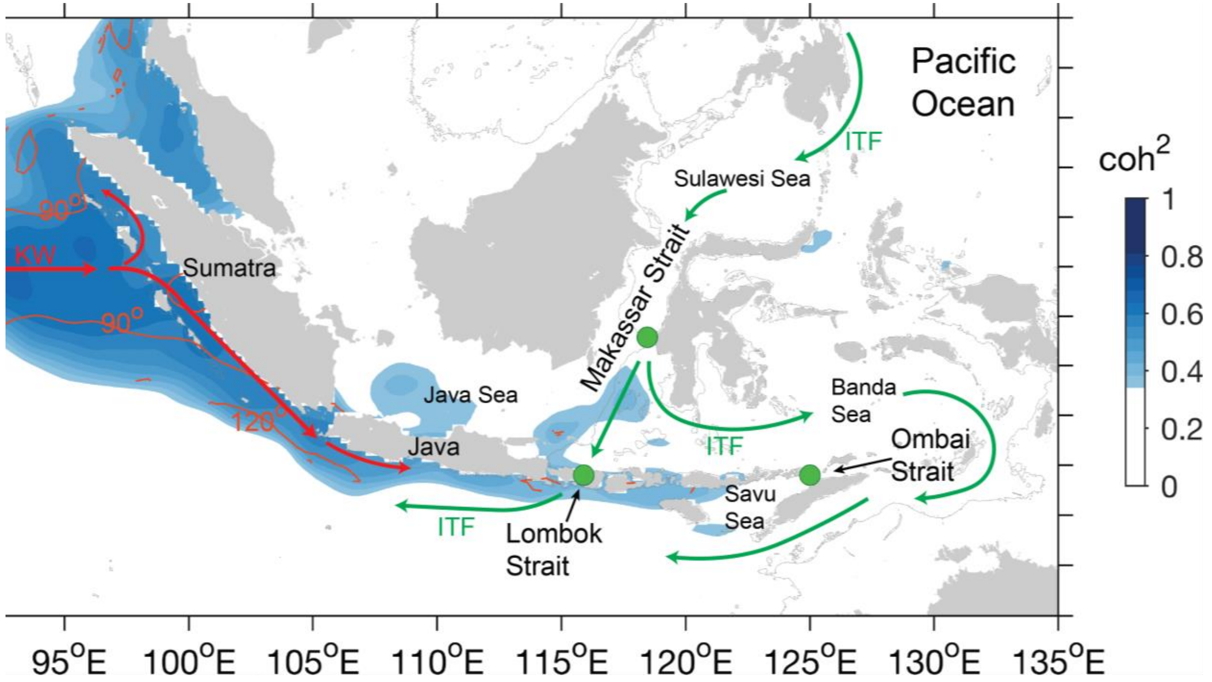
A sequence of downwelling equatorial Kelvin waves propagating into the Indonesia Seas



- Kelvin waves propagate eastward along the equator and then poleward once they encounter the coast of Sumatra.
- The waves propagate along the southern coast of Sumatra and Java as coastally trapped Kelvin waves.
- Reflected Rossby waves are observed at 5 °N and 5 °S off Sumatra.

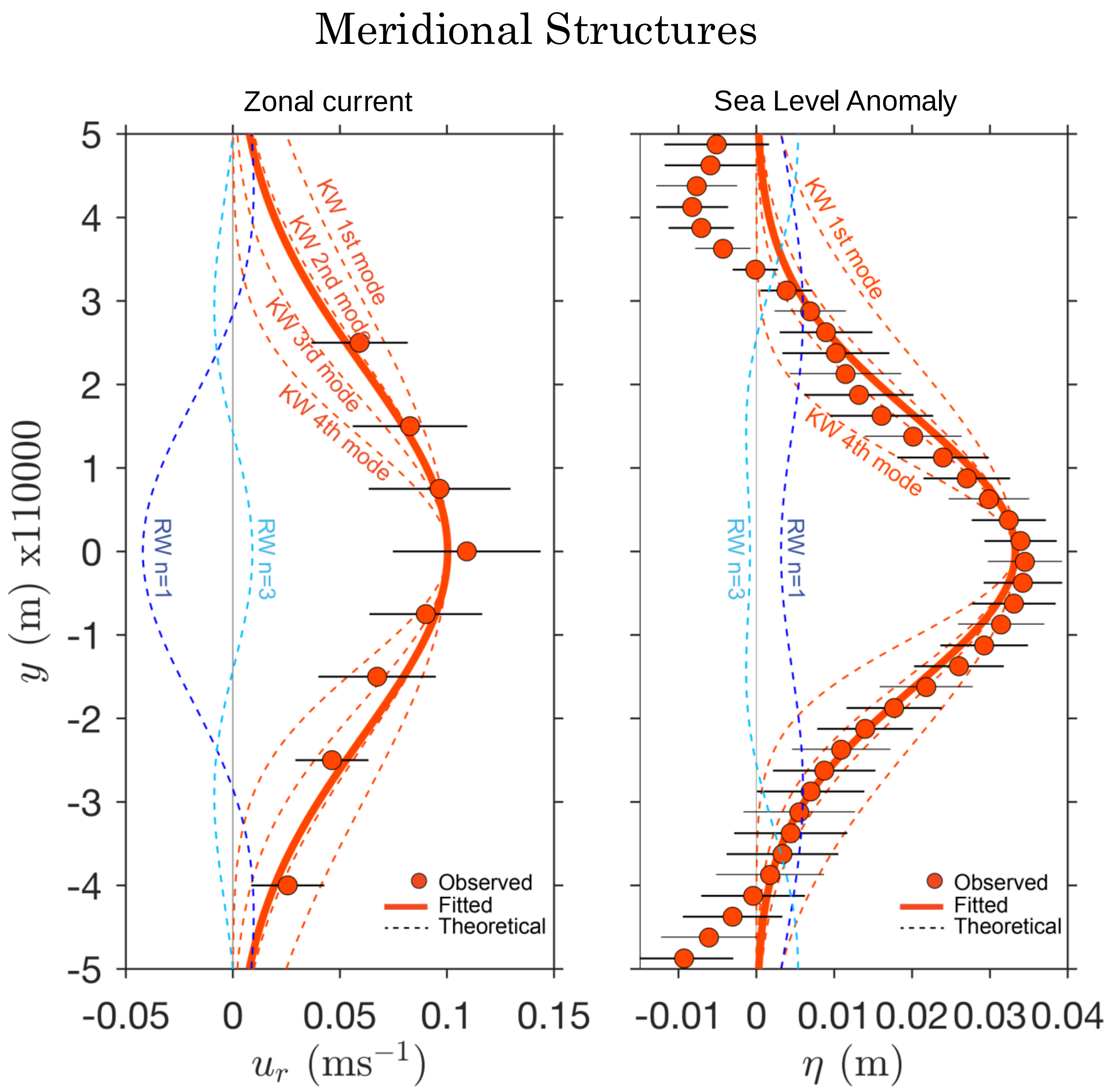
Indian Ocean Kelvin Waves





Observed $\omega - l$, from the ITF moorings, clusters around the theoretical dispersion curves for Kelvin waves. The waves propagate slower from Lombok Strait to Makassar Strait than from Lombok Strait to Ombai Strait.

Indian Ocean equatorial Kelvin Waves



- The observed meridional structures of moored u and satellite-derived η decay away from the equator, with a scale of ~ 250 km.
- The theoretical Kelvin wave solution best replicates the observed meridional structures.
- The separation constant c approximates the phase speed of the 2^{nd} baroclinic Kelvin wave mode.
- Low-frequency Rossby waves appear less influential.

Impacts of Indian Ocean Kelvin Waves

Kelvin waves affect the evolution of extreme negative Indian Ocean Dipole events and modulate the ITF transports

JGR Oceans

RESEARCH ARTICLE

10.1029/2018JC014574

Special Section:
Recent Progresses in

Unprecedented Response of Indonesian Throughflow to Anomalous Indo-Pacific Climatic Forcing in 2016

Kandaga Pujiana[1,2], Michael J. McPhaden[1], Arnold L. Gordon[3], and Asmi M. Napitu[3,4]

Ocean Sci., 18, 193–212, 2022

Interannual variability of sea level in the southern Indian Ocean: local vs. remote forcing mechanisms

Marion Kersalé[1,2], Denis L. Volkov[1,2], Kandaga Pujiana[1,2], and Hong Zhang[3]

Kelvin waves play a role in dictating the diversity of Java-Sumatra Nino/Nina events

4292 JOURNAL OF CLIMATE VOLUME 35

Java–Sumatra Niño/Niña and Its Impact on Regional Rainfall Variability

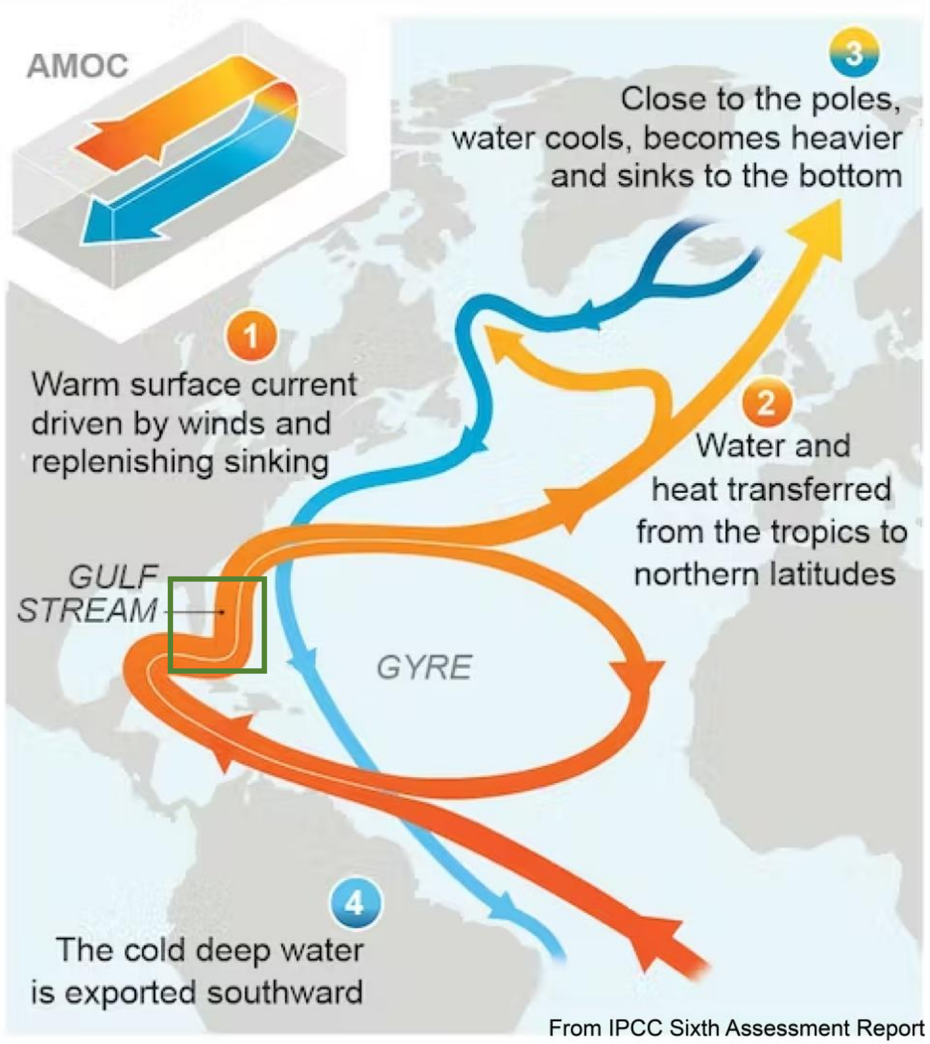
SANG-KI LEE,[a] HOSMAY LOPEZ,[a] GREGORY R. FOLTZ,[a] EUN-PA LIM,[b] DONGMIN KIM,[c,a] SARAH M. LARSON,[d] KANDAGA PUJIANA,[c,a] DENIS L. VOLKOV,[c,a] SOUMI CHAKRAVORTY,[c,a] AND FABIAN A. GOMEZ[e,a]

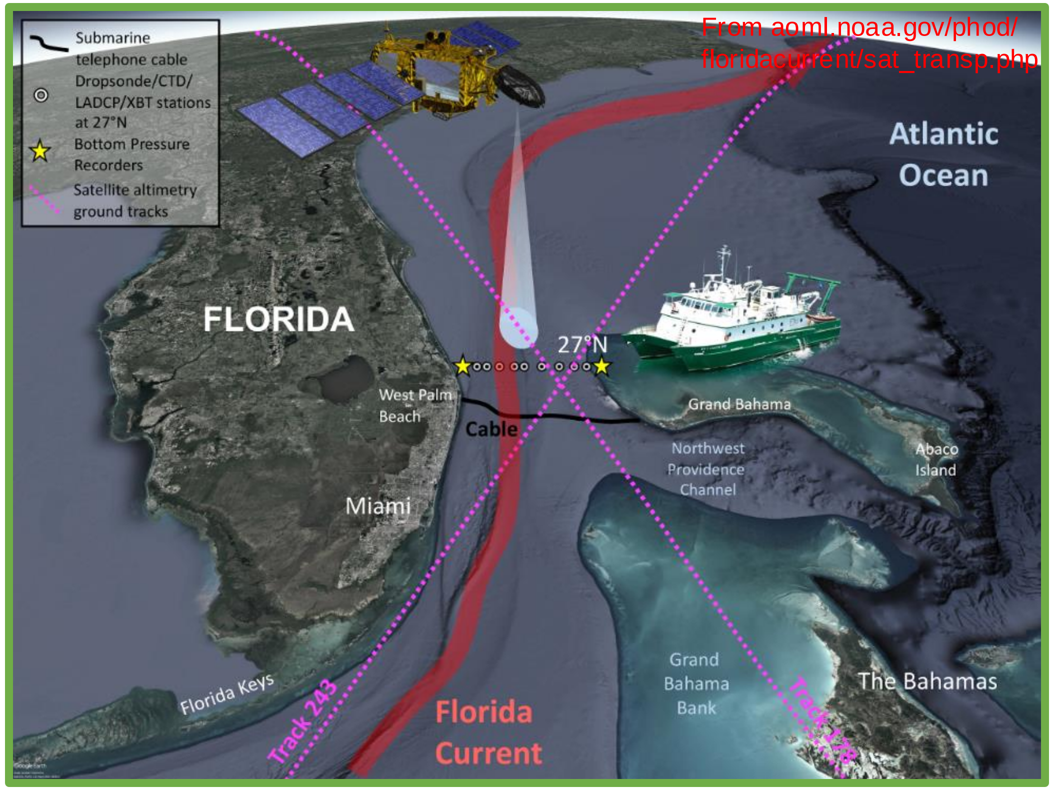
Summary

- Subseasonal variability is ubiquitous in the ITF velocities.
- The MJO and eddies account for the subseasonal ITF variability in the upper 250 m, while Kelvin waves are dominant at deeper depths.
- The eddies are instability-generated, and the MJO and Kelvin waves originate from the Indian Ocean.
- The ITF's response to the MJO is due to a balance between along-strait pressure gradient and the vertical divergence of Reynold stresses (i.e. ocean mixing is important).

Gulf Stream

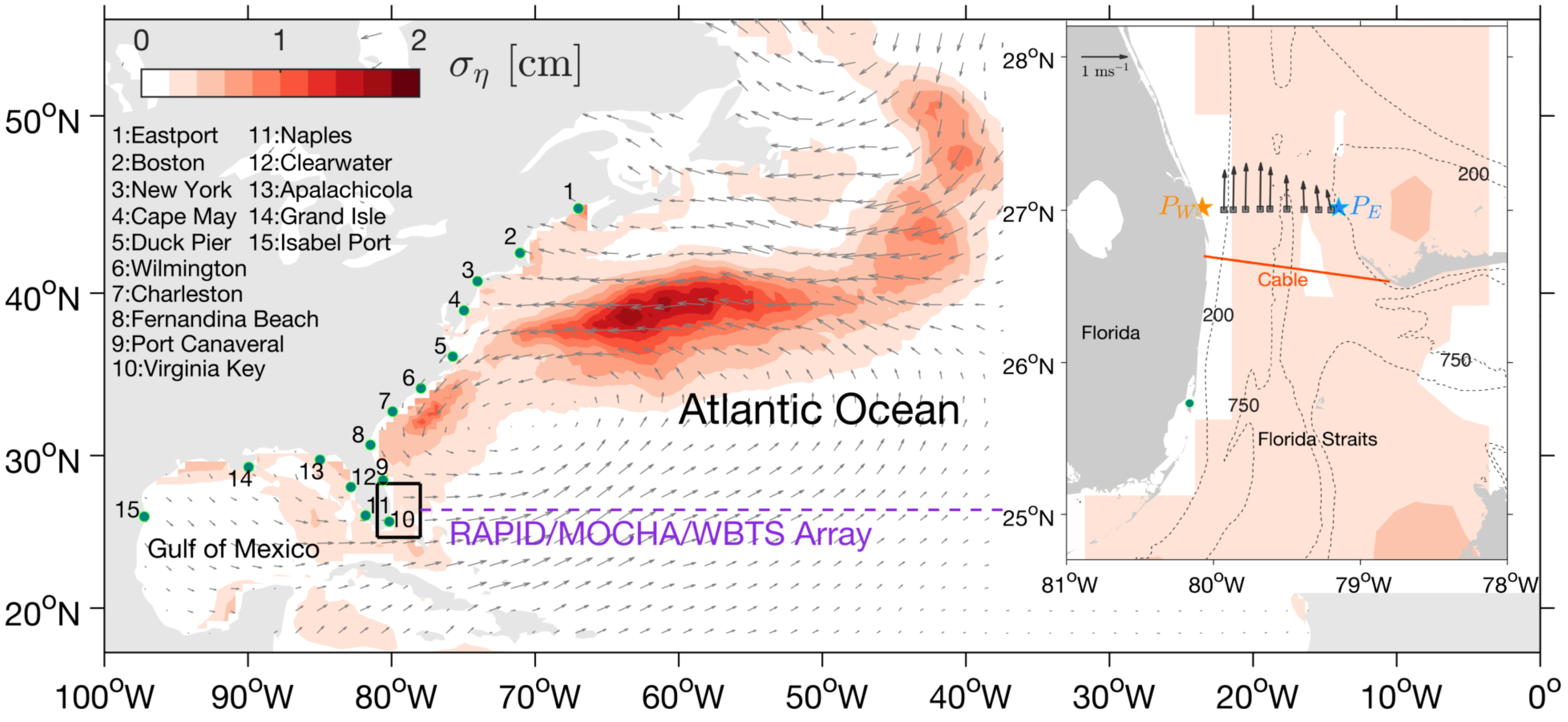
Why Gulf Stream matters?





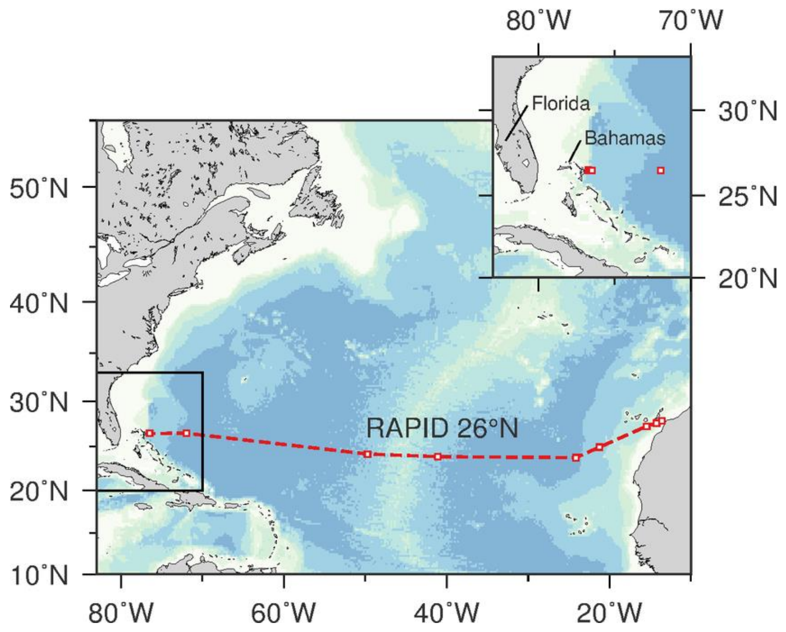
- The Gulf Stream is part of the subtropical gyre and AMOC.
- The Florida Current composes the Gulf Stream in the Florida Straits.

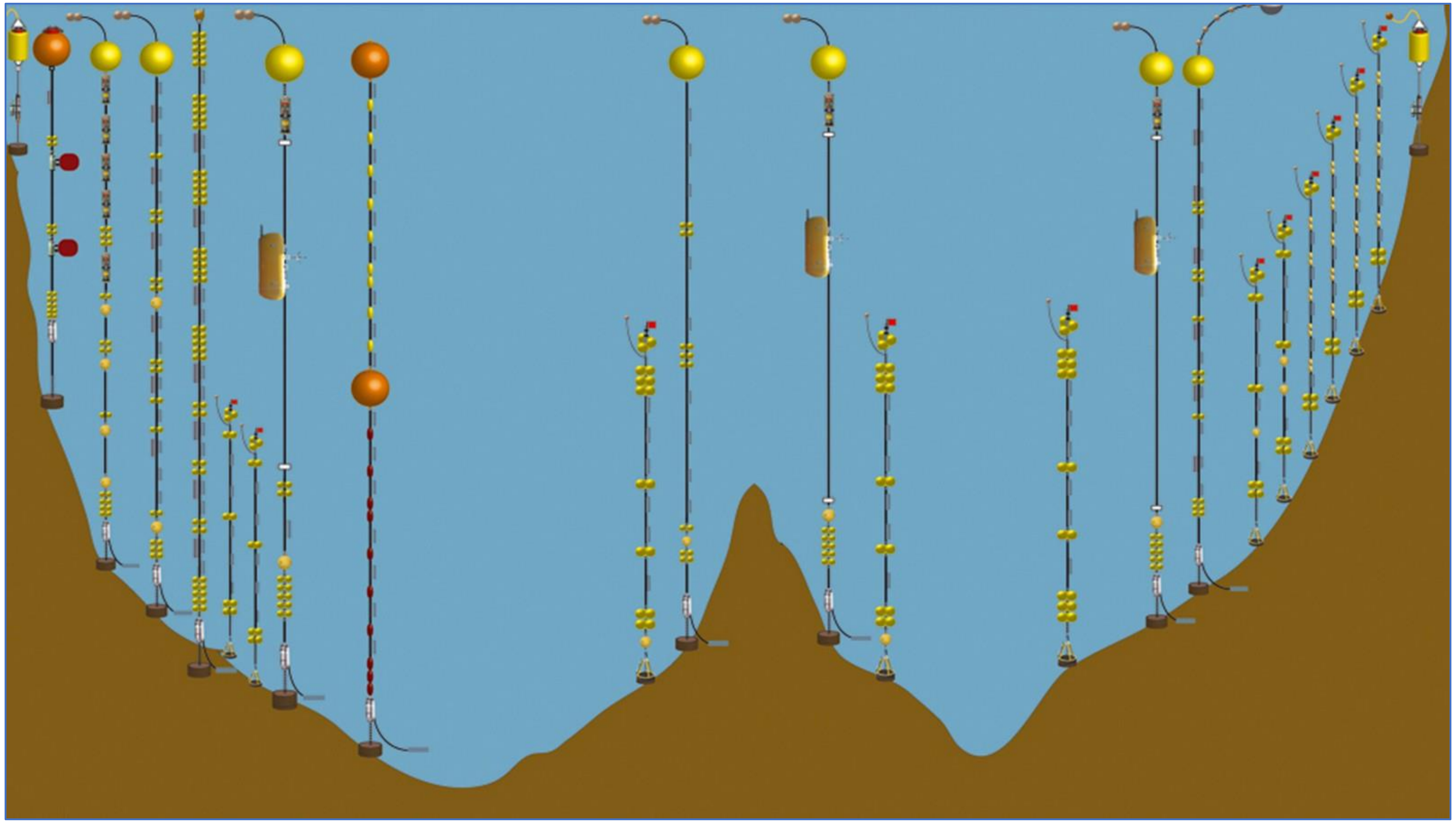
Gulf Stream Observation



- Daily averages of Florida Current [FC] transport from cable voltages & bottom pressure [P_W and P_E] in the Florida Straits, tide gauge sea level anomaly along the U.S. East and Gulf Coast.
- XBT and CTD casts in the vicinity of the cable site in the Florida Straits.
- Daily transports of the MOC components from the RAPID/MOCHA/WBTS array.
- Daily satellite sea surface height and wind stress.

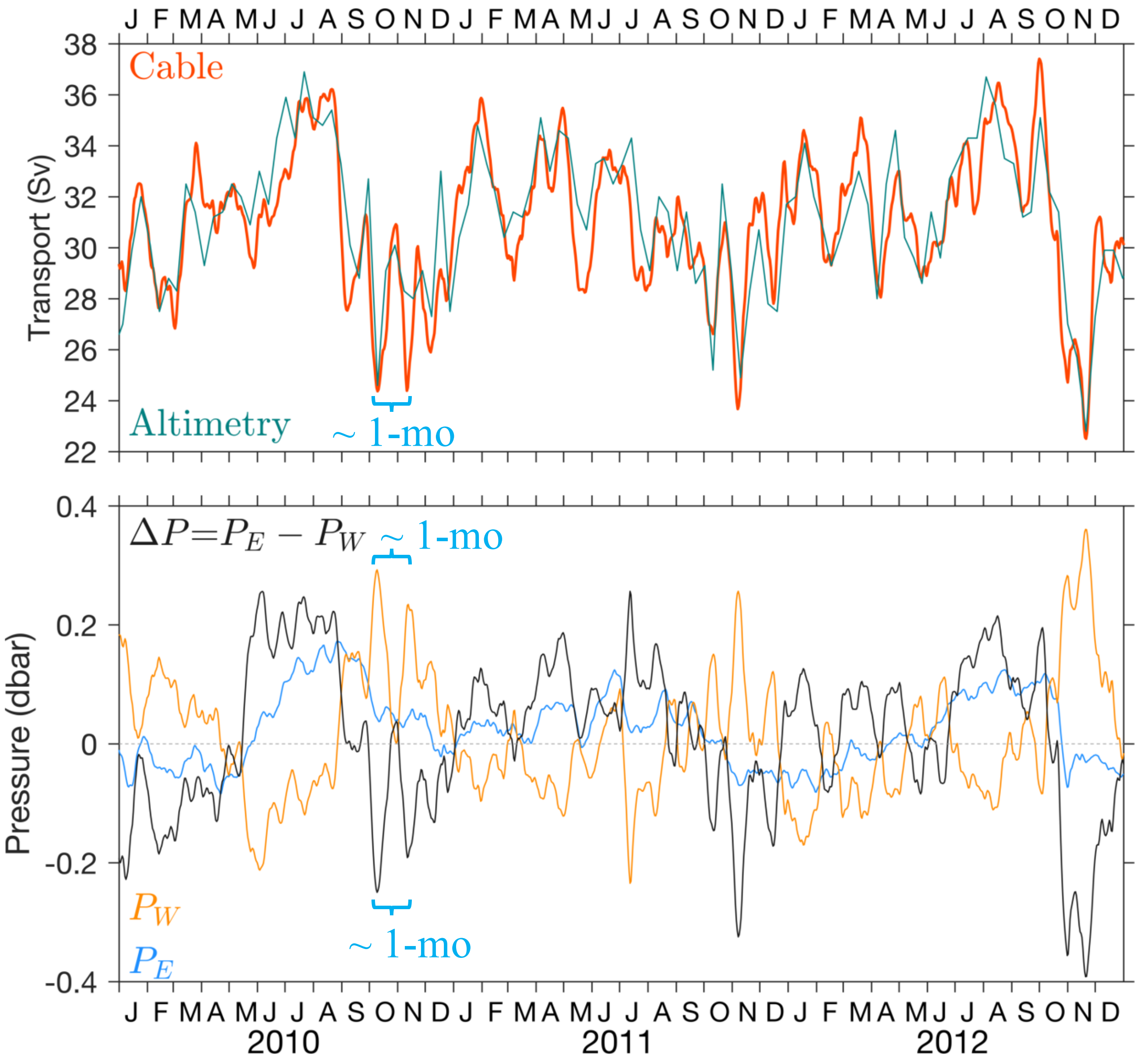
AMOC Observation

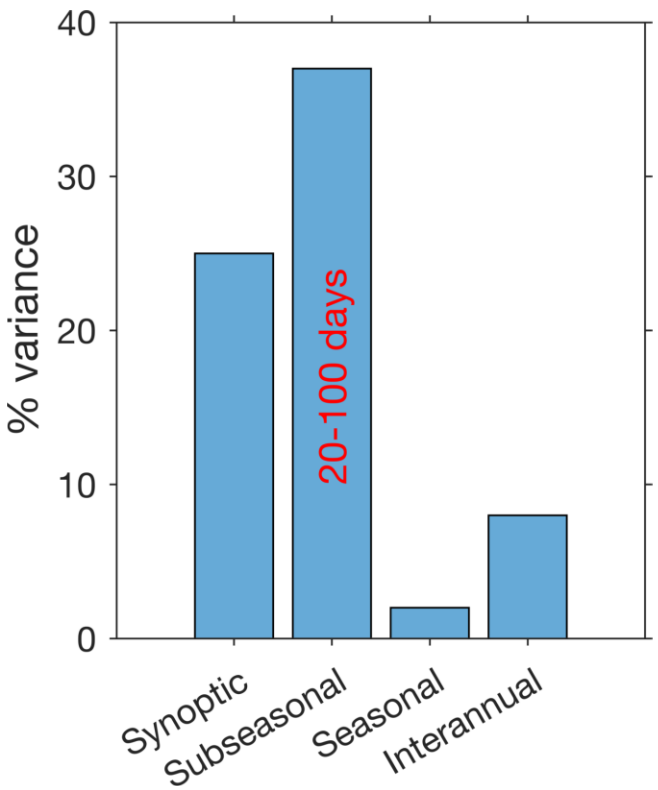




RAPID MOCHA subsurface mooring arrays

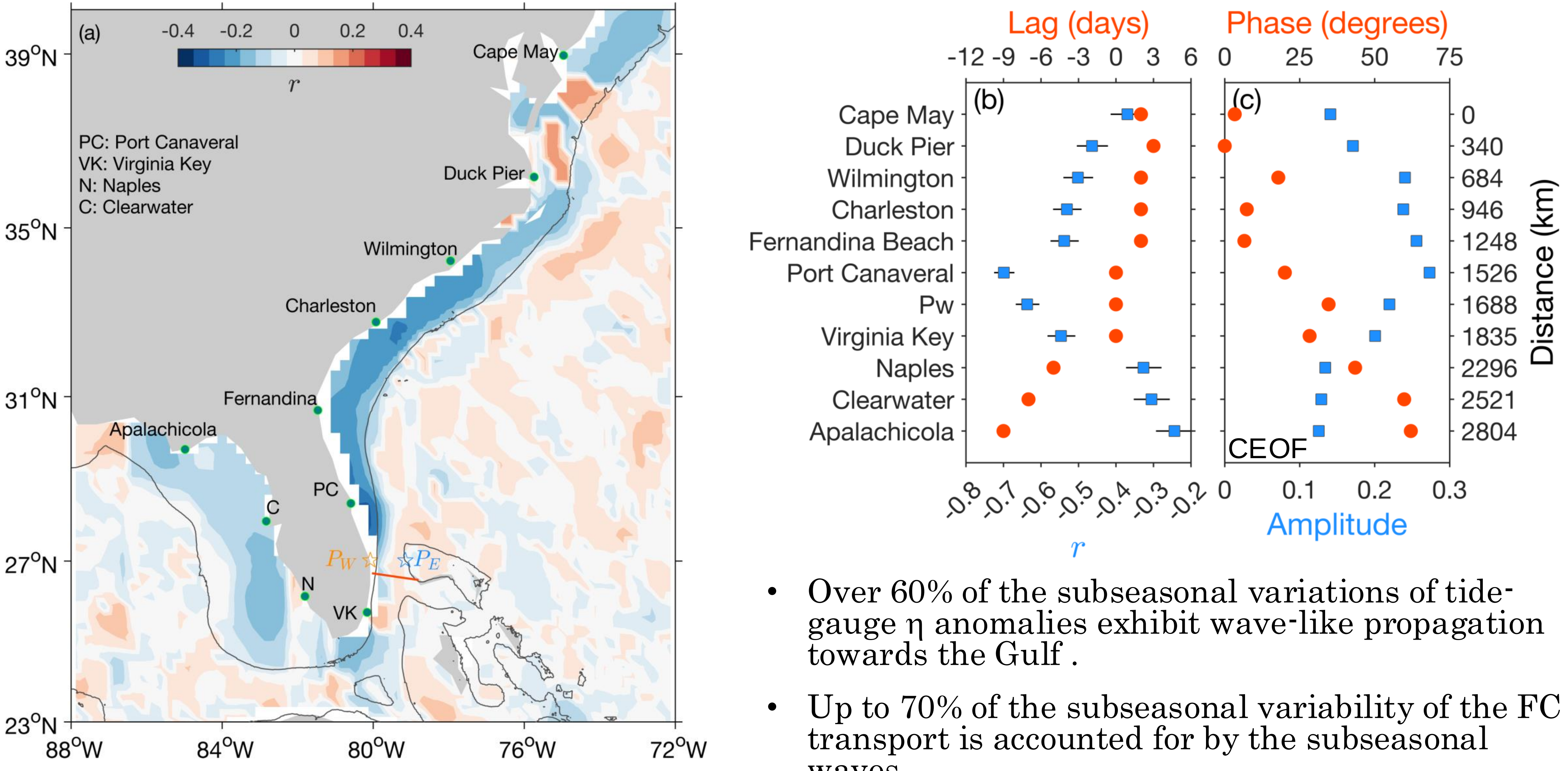
Subseasonal variability in the Gulf Stream





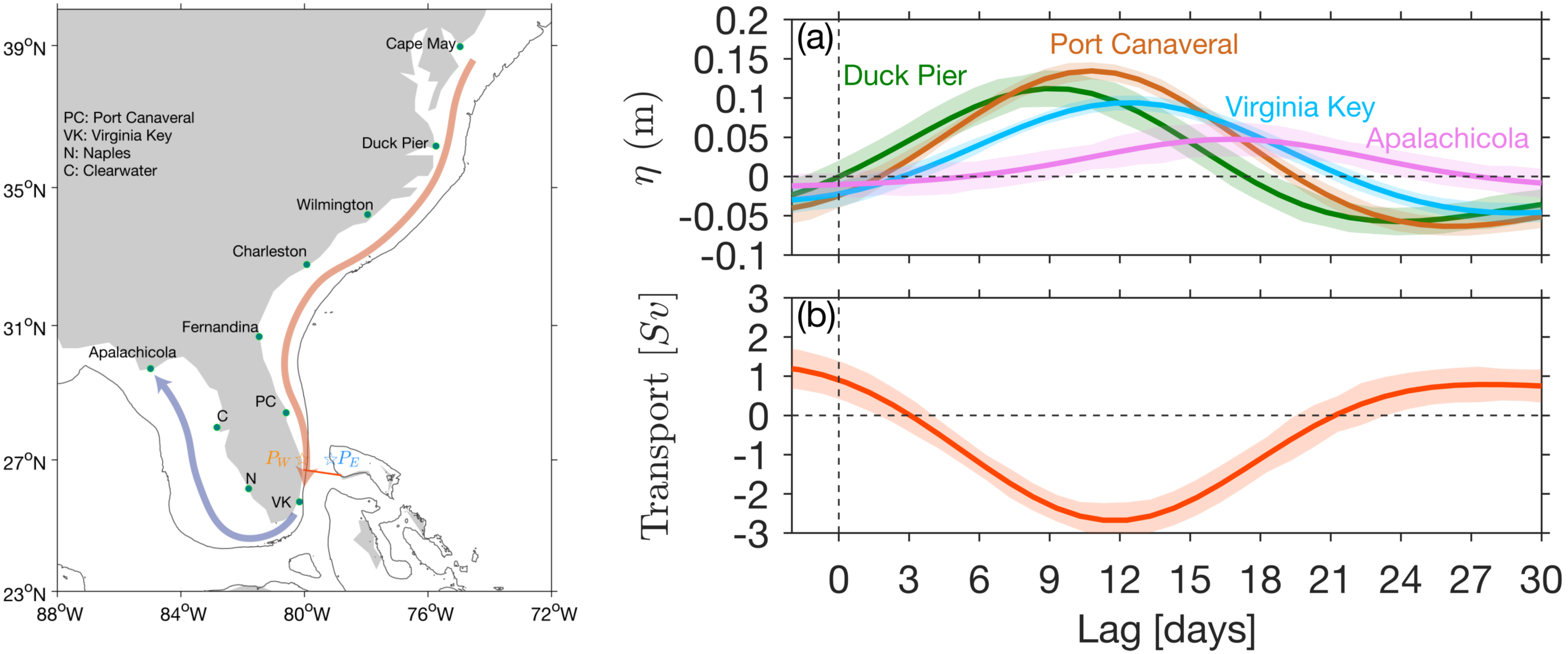
- Subseasonal variability is ubiquitous in the FC transport & bottom pressure records.
- Monthly variation marks the variability.

Subseasonal variability along the U.S. East & Gulf Coast



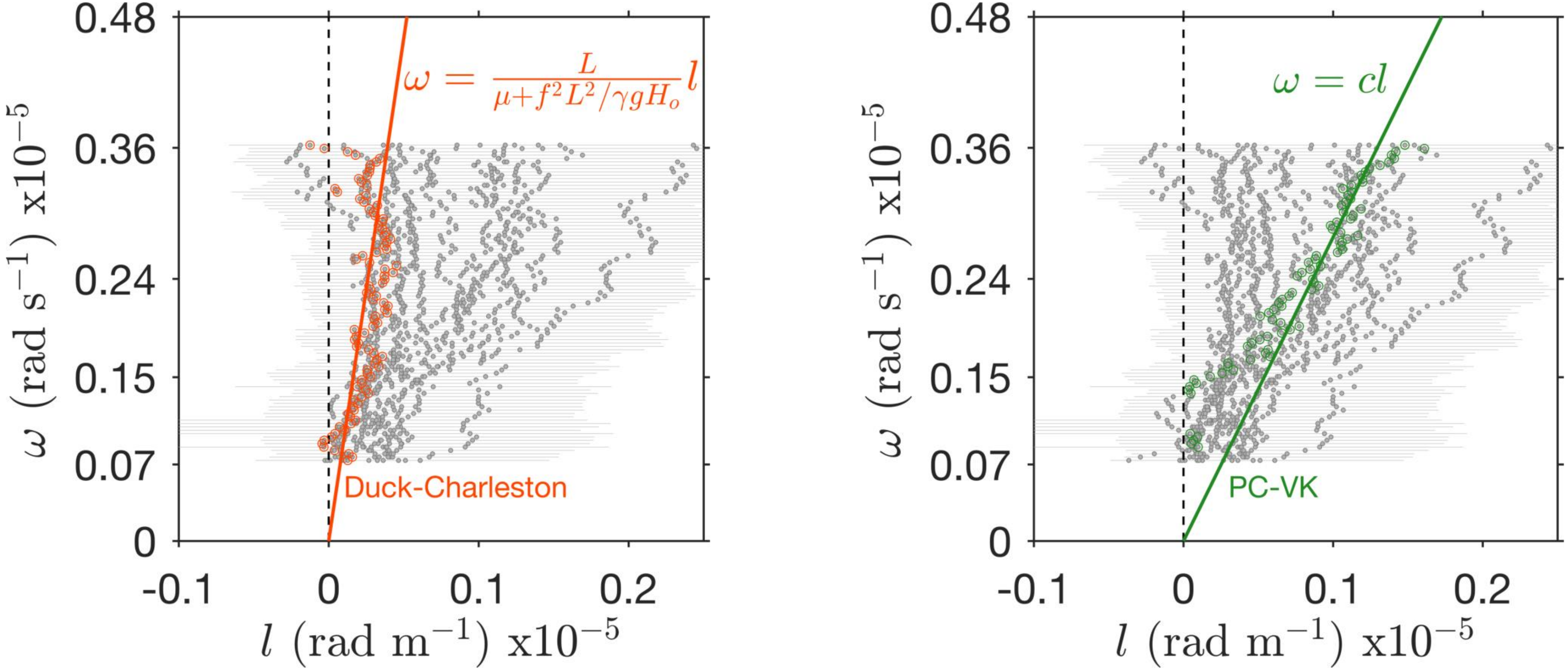
- Over 60% of the subseasonal variations of tide-gauge η anomalies exhibit wave-like propagation towards the Gulf .
- Up to 70% of the subseasonal variability of the FC transport is accounted for by the subseasonal waves.

Subseasonal mode along the U.S. East & Gulf Coast



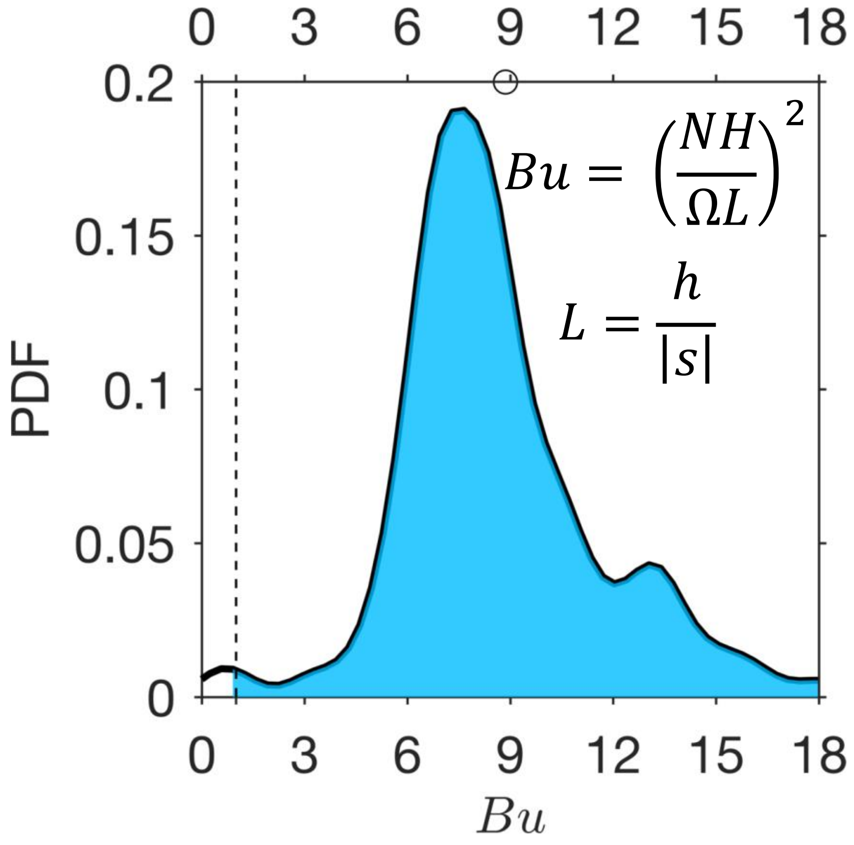
- The wave amplitude at Port Canaveral could be up to 15 cm while it is only 5 cm at Apalachicola.
- The wave crests could reduce the transport by up to 3 Sv.

Properties of subseasonal coastal-trapped waves

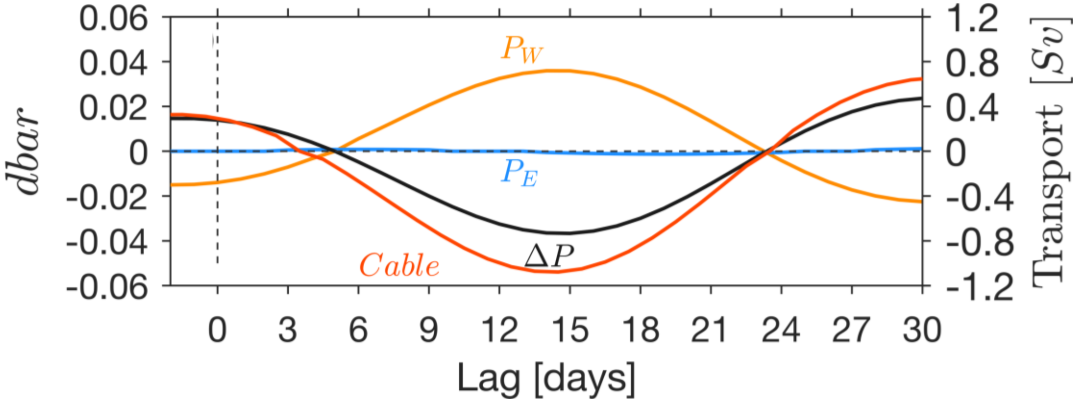


- The observed dispersion diagram indicates propagation into the Gulf Coast [$l > 0$]
- Subseasonal coastal-trapped waves behave as Kelvin waves in the Florida Straits and continental shelf waves along the rest of the waveguide.

Properties of subseasonal coastal-trapped waves

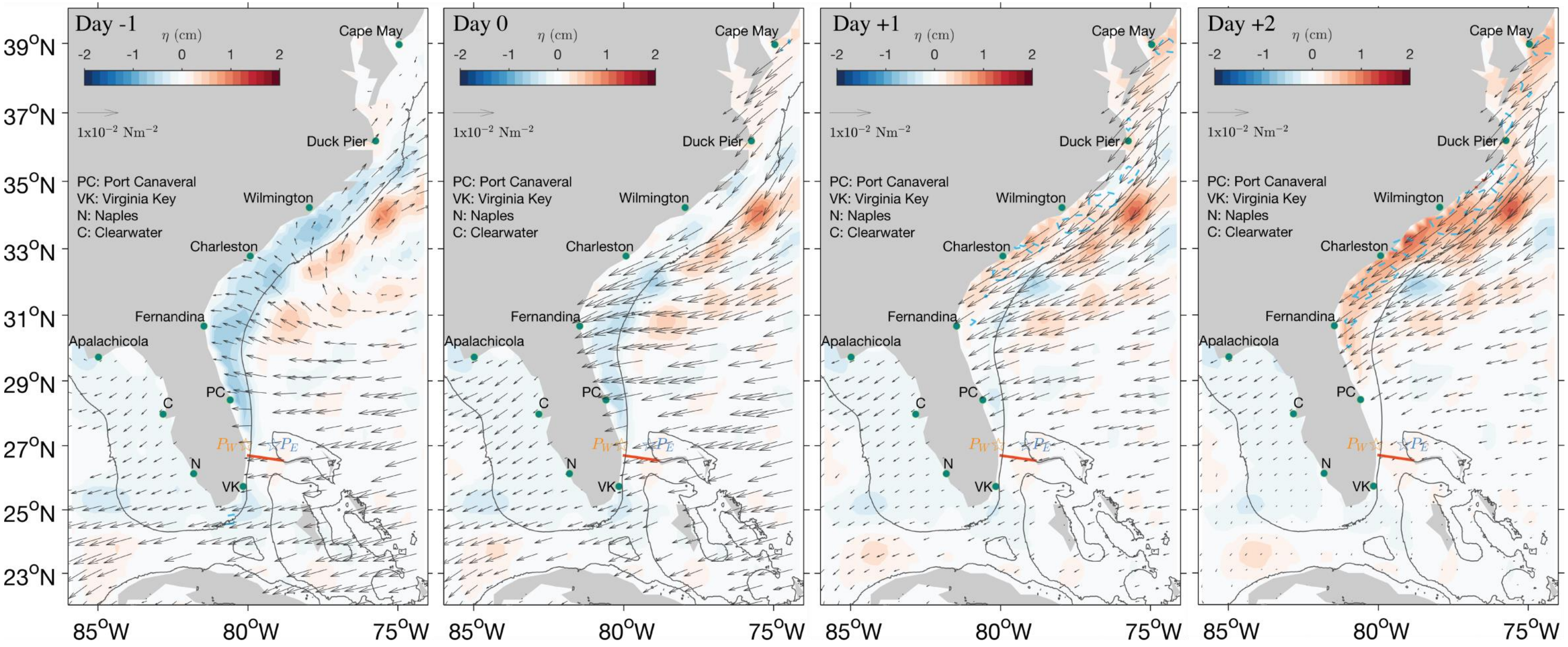


- In the Florida Straits, a vertical sidewall approximation is justified.
- The Rossby deformation radius exceeds the cross-shelf/slope length scale of the topography.



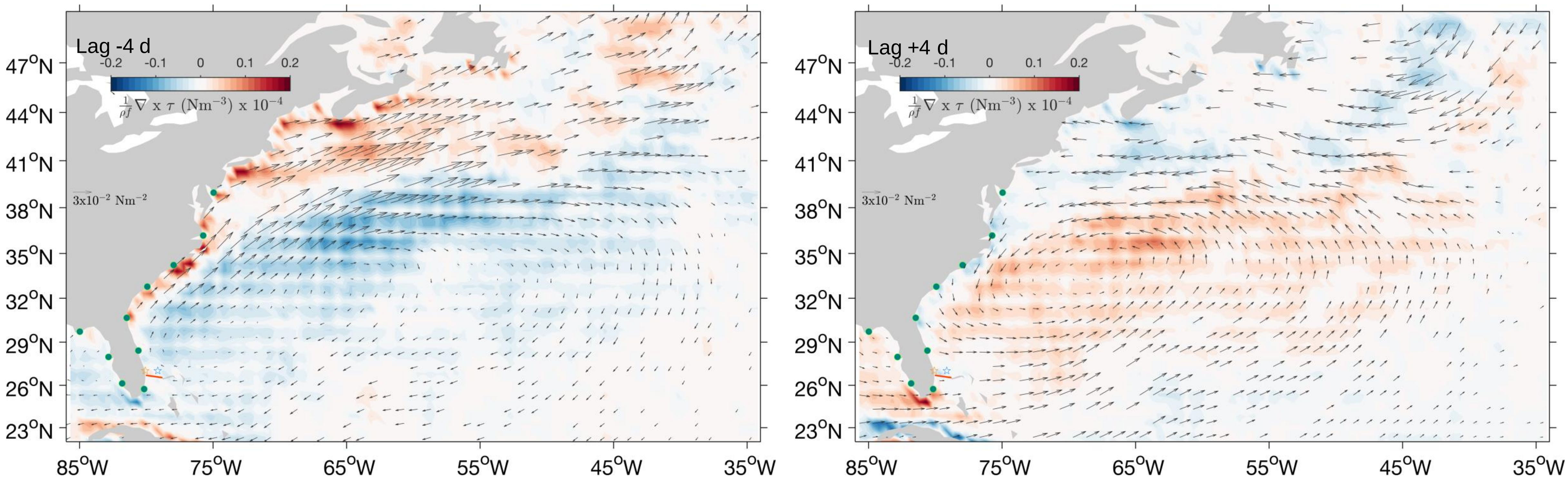
- The cross-stream pressure structure decaying eastward might reflect Kelvin wave modal structure with a decay scale of about 27 km.

Genesis of the subseasonal mode



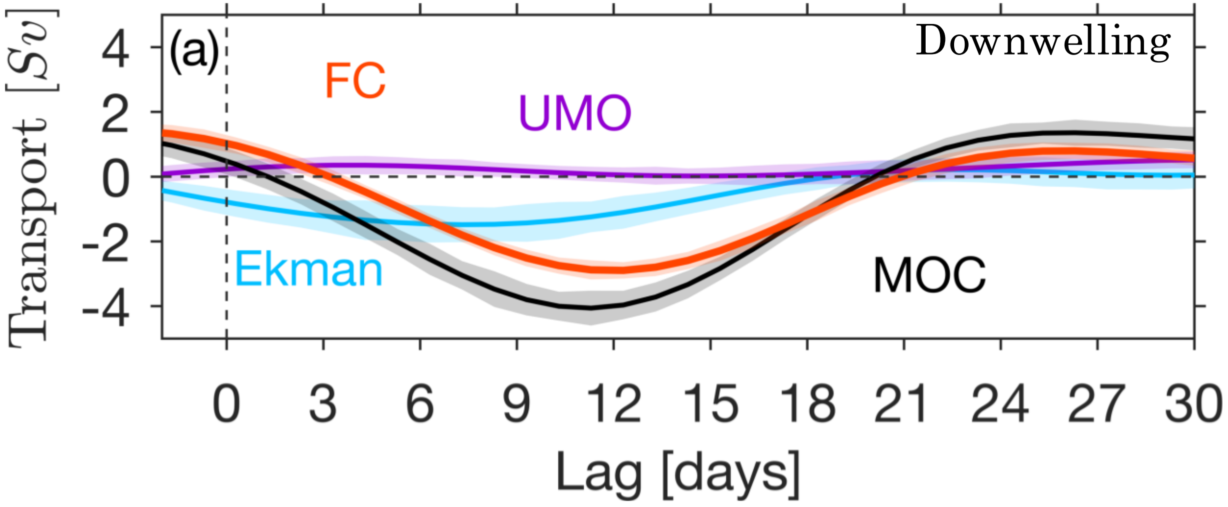
- The subseasonal waves are a transient response to a change in the subseasonal alongshore winds.
- The emergence of (Ekman-convergence favorable) northeasterly winds precede the onset of the subseasonal downwelling mode.

Changes in the subtropical anticyclone



- The along-shore winds are part of anomalous cyclonic/anticyclonic wind fields in the subtropics.
- Subtropical anticyclonic transitions into cyclonic, leading to the formation of subseasonal downwelling trapped waves, and vice versa.

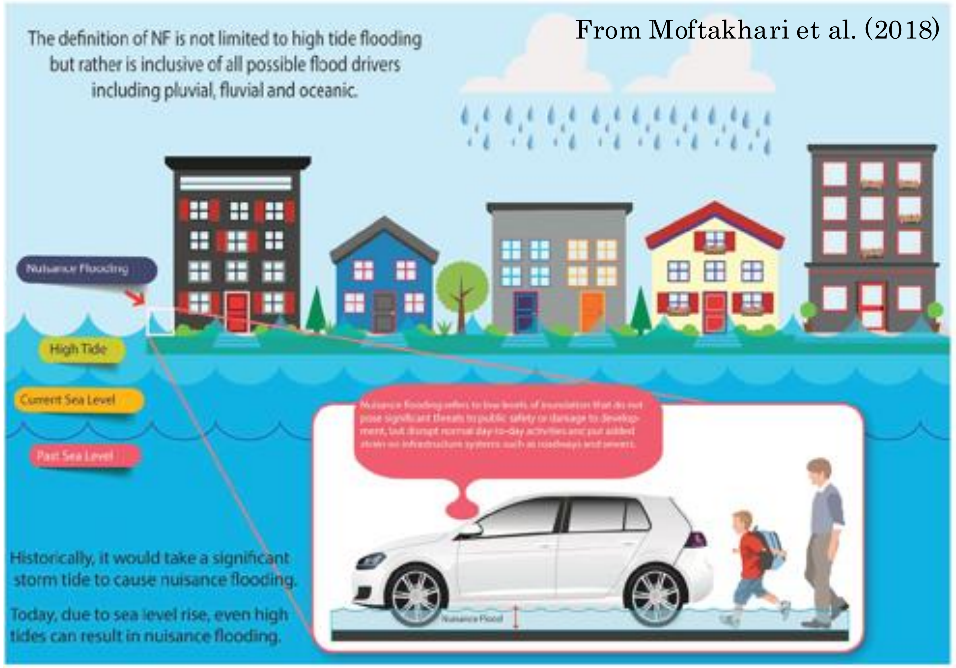
Impact of the subseasonal mode on the MOC



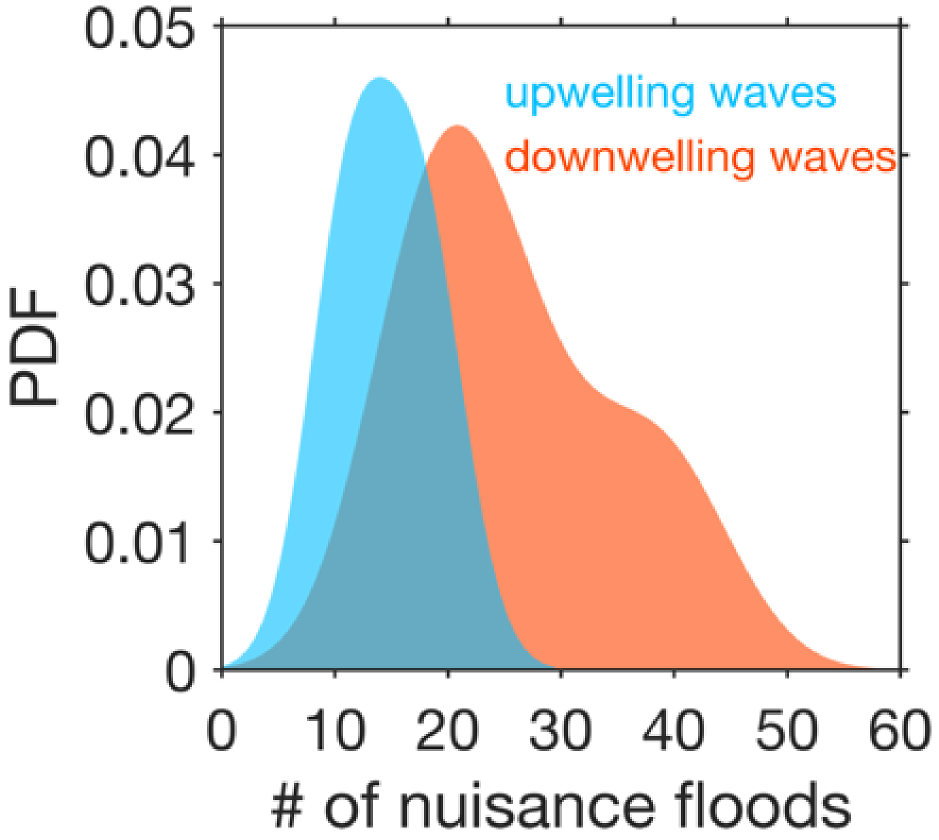
UMO : Upper Mid Ocean
FC: Florida Current
MOC : Meridional Overturning Circulation

- Notable MOC changes are observed, up to 4 Sv, concurrent with the subseasonal downwelling mode.
- The Ekman transport at 26°N attenuates by ~1.5 Sv in response to weaker subtropical anticyclone, partly compensating reduced FC transport during the subseasonal mode.

Impact of the subseasonal mode on nuisance floods



A nuisance flood event at a specific location occurs when the observed sea level exceeds the location's Mean Higher High Water [MHHW] tidal datum elevation by a nuisance flood threshold.



The number of nuisance floods is substantially larger during downwelling subseasonal waves than during upwelling ones as the former favorable to further increase the observed coastal sea level.

Summary

- Coastal-trapped waves are the main source of the subseasonal variability in the FC transport, accounting for up to 70% of the variability.
- The subseasonal waves behave as Kelvin waves in the Florida Straits, affecting the FC transport by up to 3 Sv and as shelf waves along the rest of the waveguide.
- The waves are along-shore wind forced, with the winds part of subseasonal changes to the subtropical anticyclone.
- The concurrent subseasonal changes of the MOC are up to 4 Sv.
- The waves modulate the recurrence of coastal flooding.

JGR Oceans

Research Article

Genesis of the Gulf Stream Subseasonal Variability in the Florida Straits

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