Physics at the equator: from the lab to the stars

Observations and mechanisms for the formation of deep equatorial and tropical circulation in the ocean

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Observations of the Deep Equatorial Circulation

Atlantic Ocean

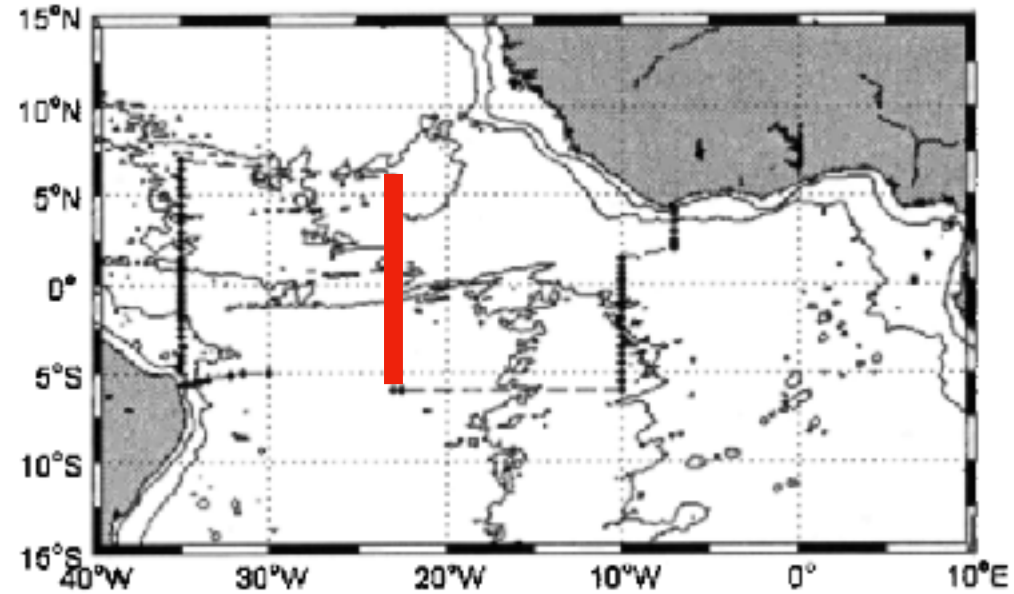
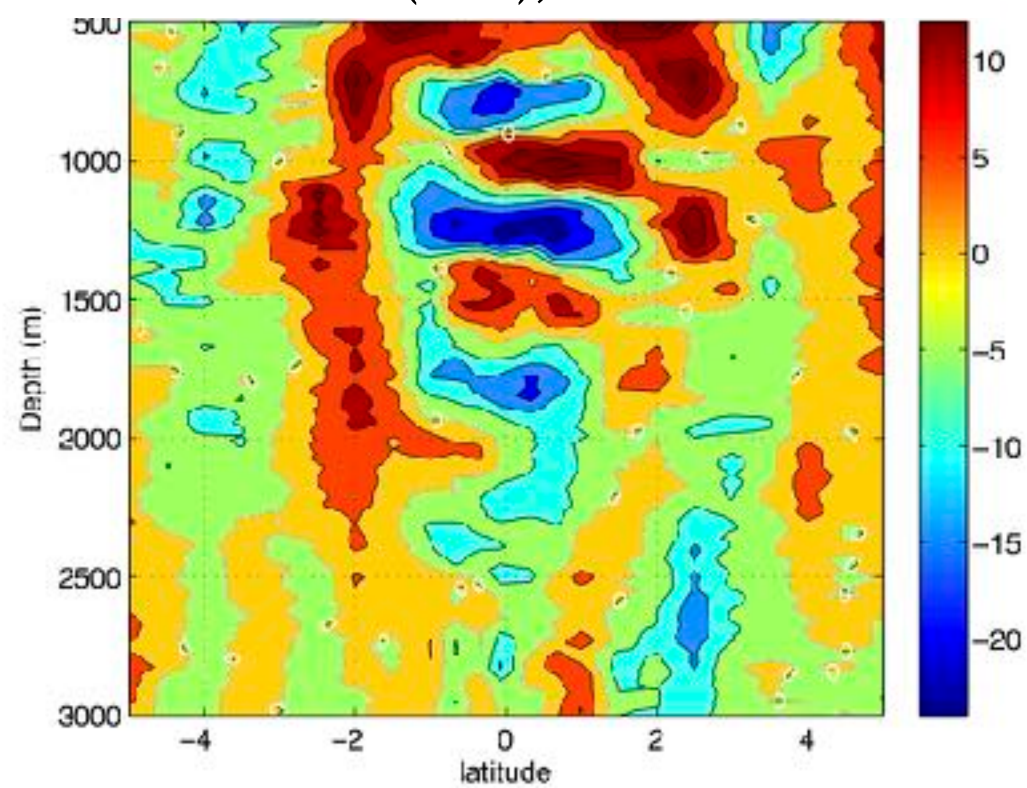


Figure 1. Track of the EQUALANT 99 cruise, July 13 to August 21, 1999.

Gouriou et al. 2001

U(m/s), 23°W



High and low vertical modes of U

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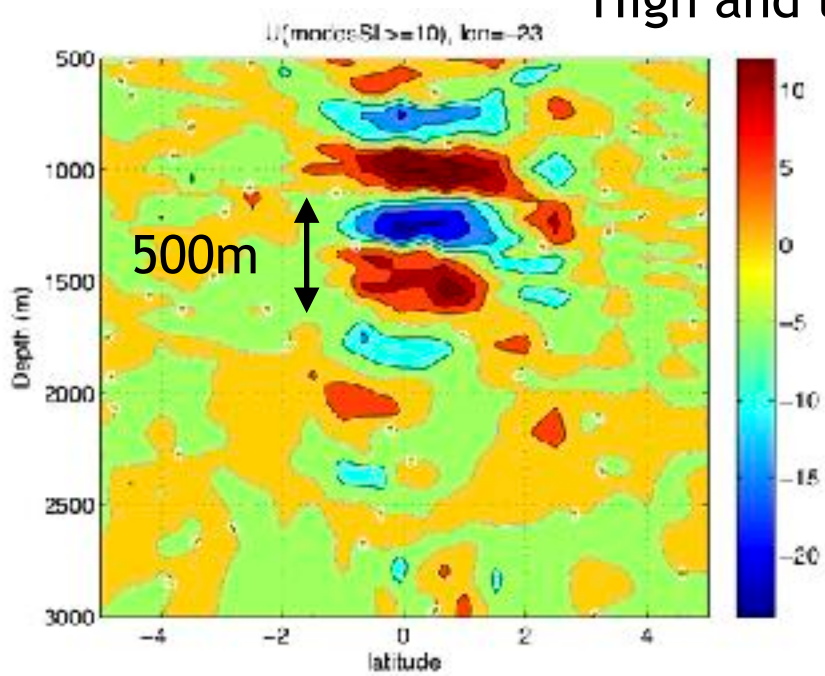

Equatorial Deep Jets (EDJ), V0~20cm/s, T=4.5yrs

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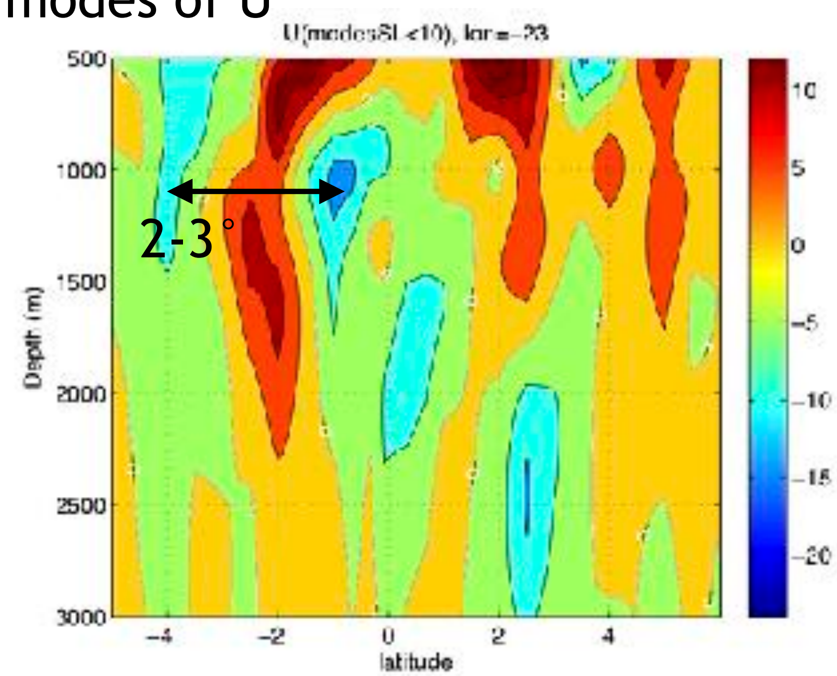
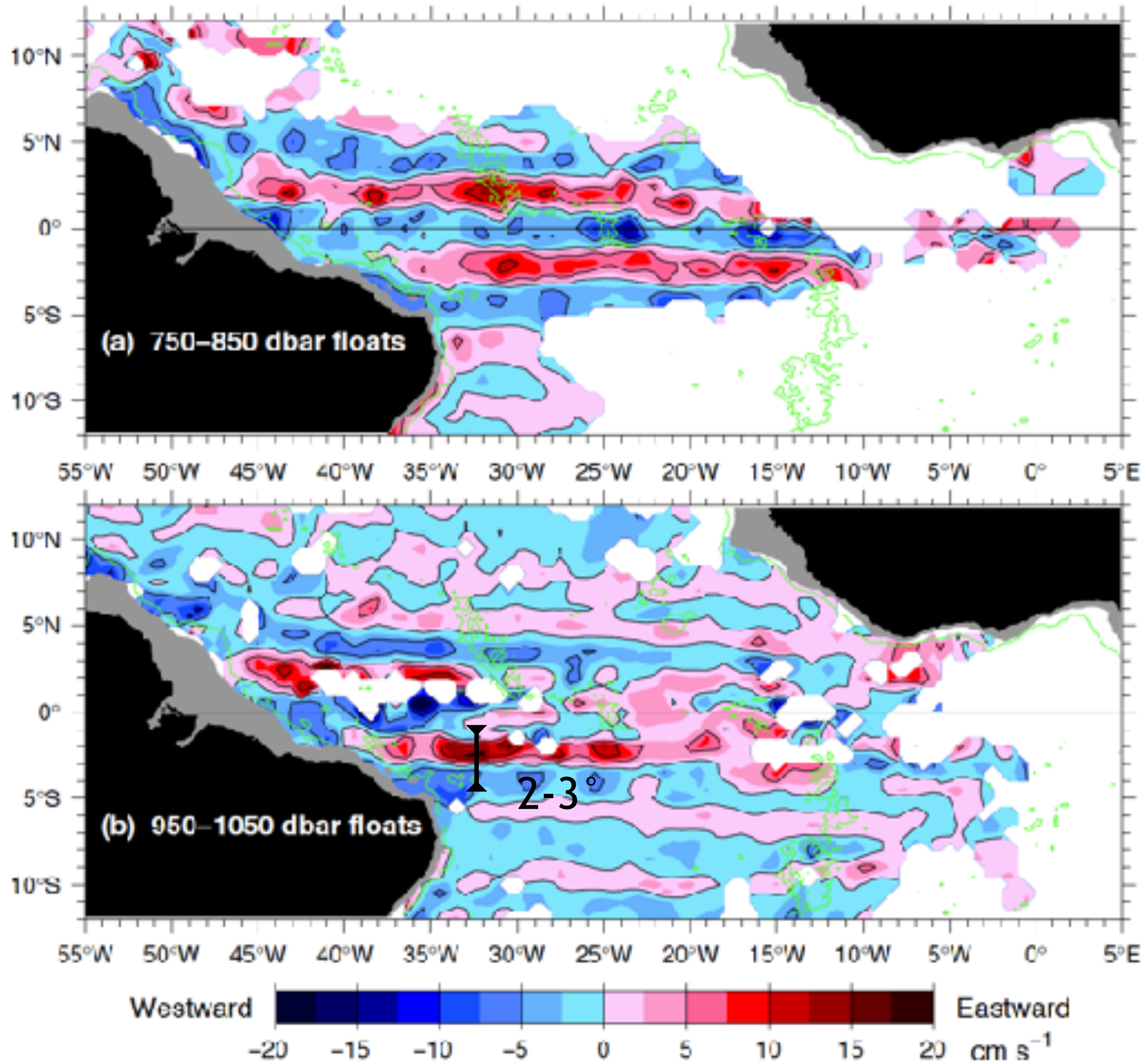


first Extra Equatorial Jets (EEJ)

Observations of the Deep Equatorial Circulation

Atlantic Ocean



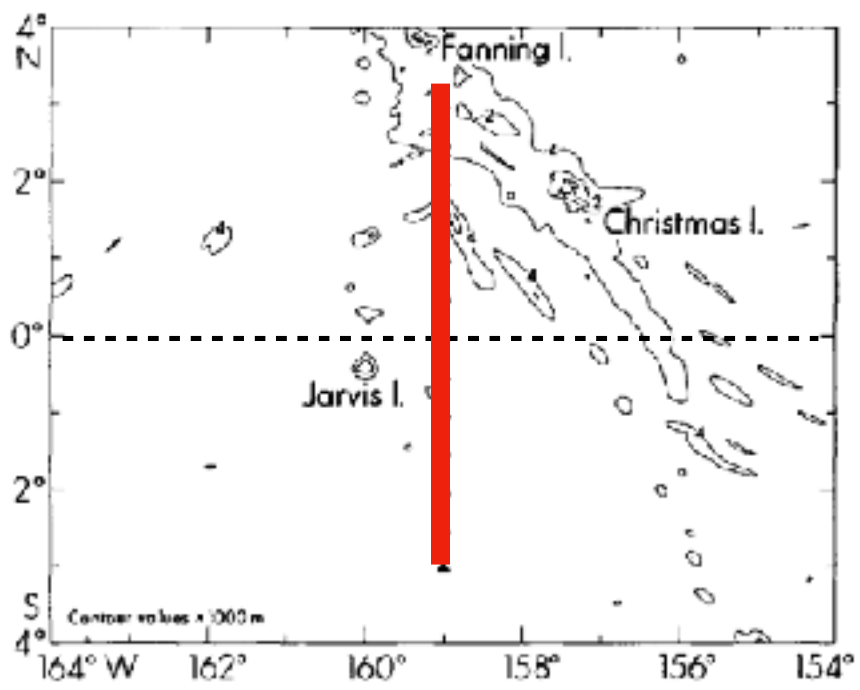
Lagrangian mean from ARGO floats of zonal velocity over a 6 yrs period

Ollitrault et al. 2006, Ollitrault et al. 2014

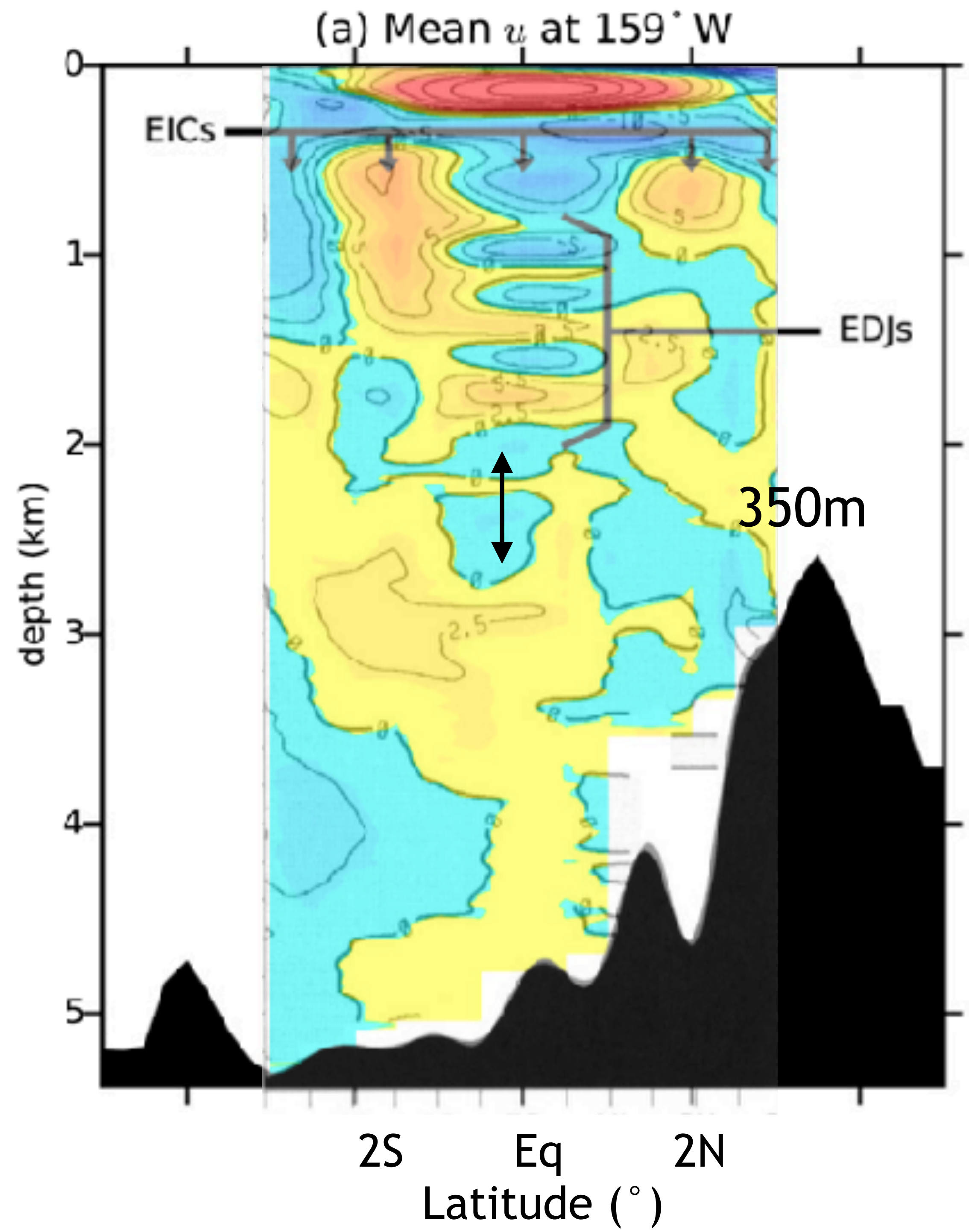
Extra Equatorial Jets (EEJ) over the full Atlantic basin,
V0~5 to 15 cm/s decreasing poleward

Observations of the Deep Equatorial Circulation

Pacific Ocean

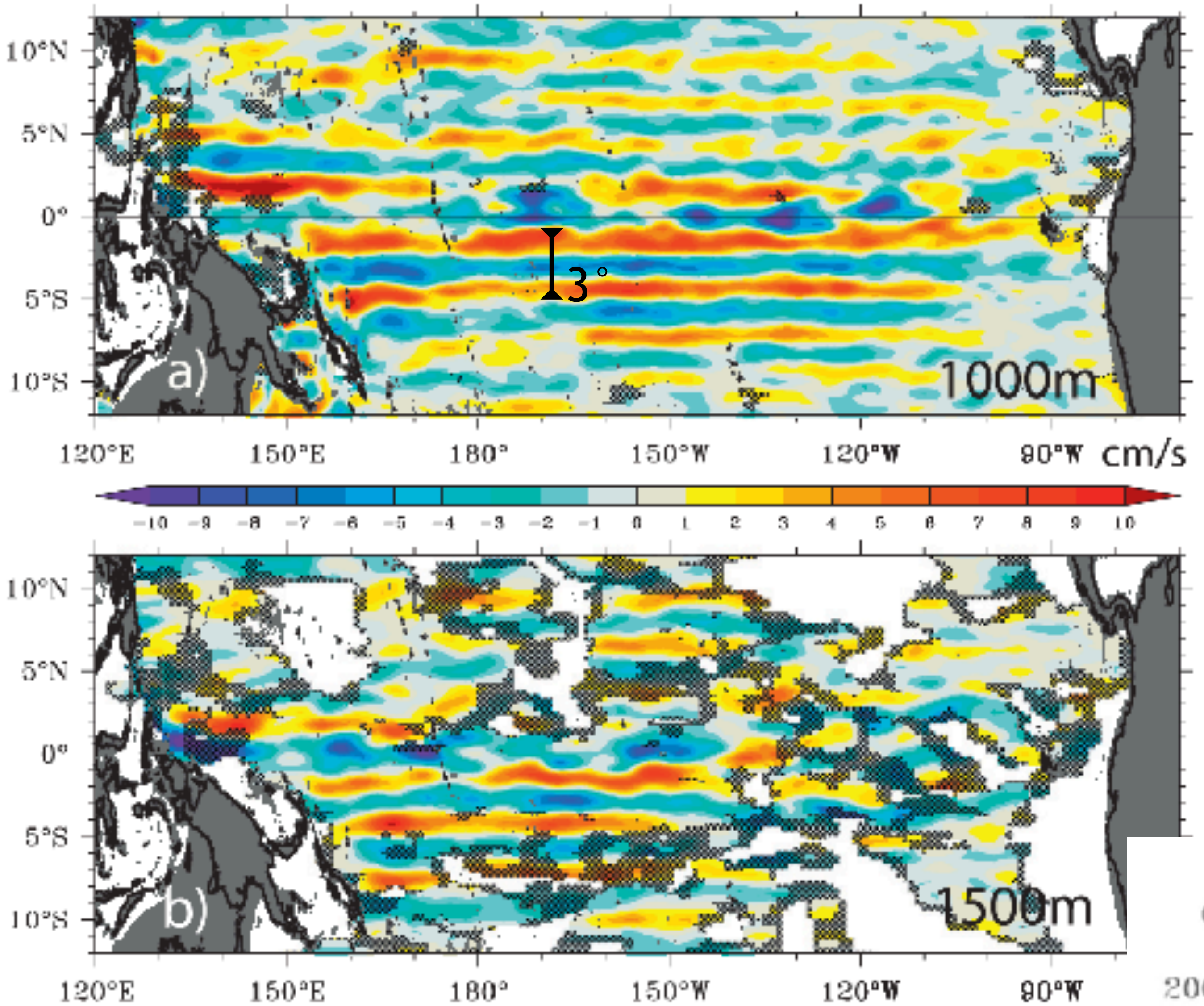


Firing 1987, Ascani et al. 2015



Equatorial Deep Jets (EDJ),
V0~10cm/s, T=12-30yrs

Observations of the Deep Equatorial Circulation

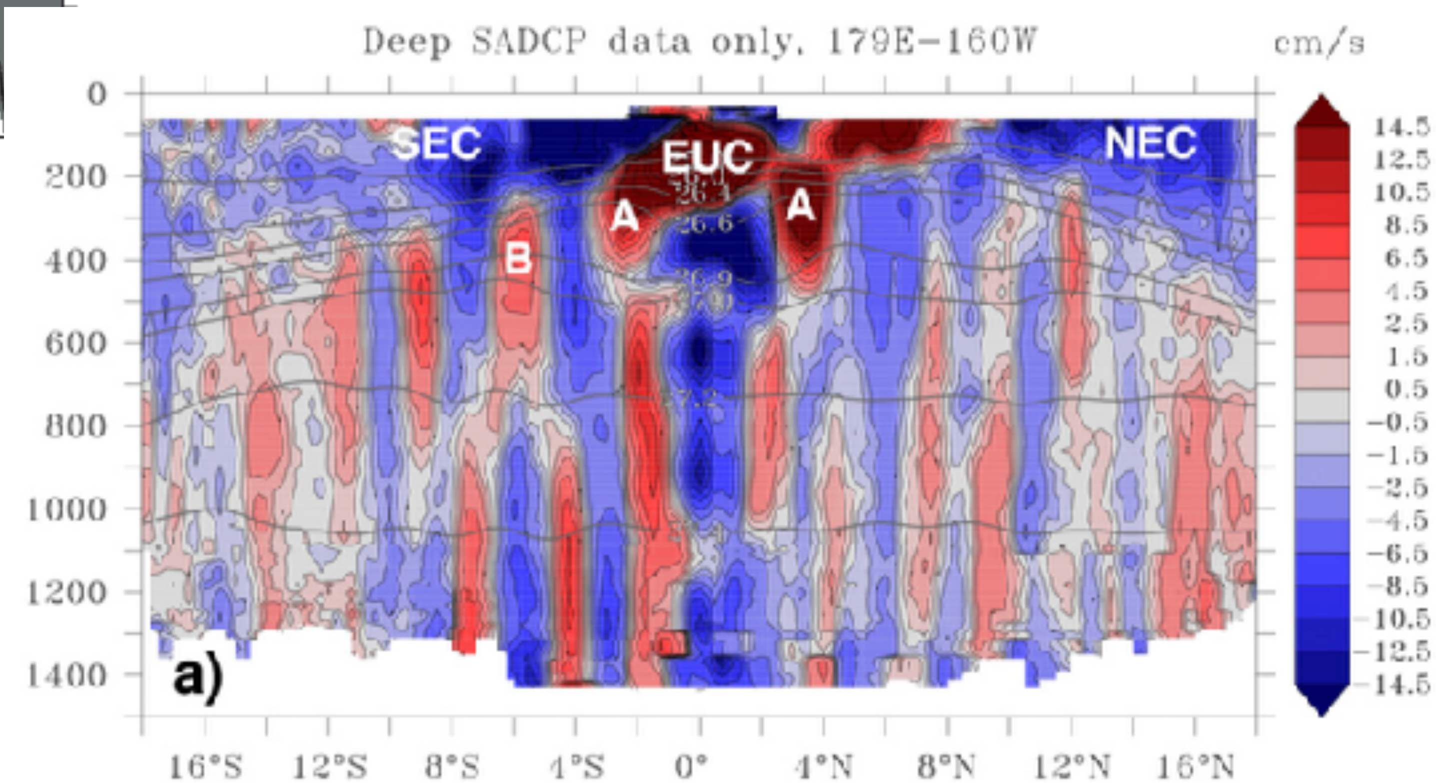


Pacific Ocean

Lagrangian mean from ARGO floats of zonal velocity over a 10 yrs period

Cravatte et al. 2012, Ollitrault et al. 2014

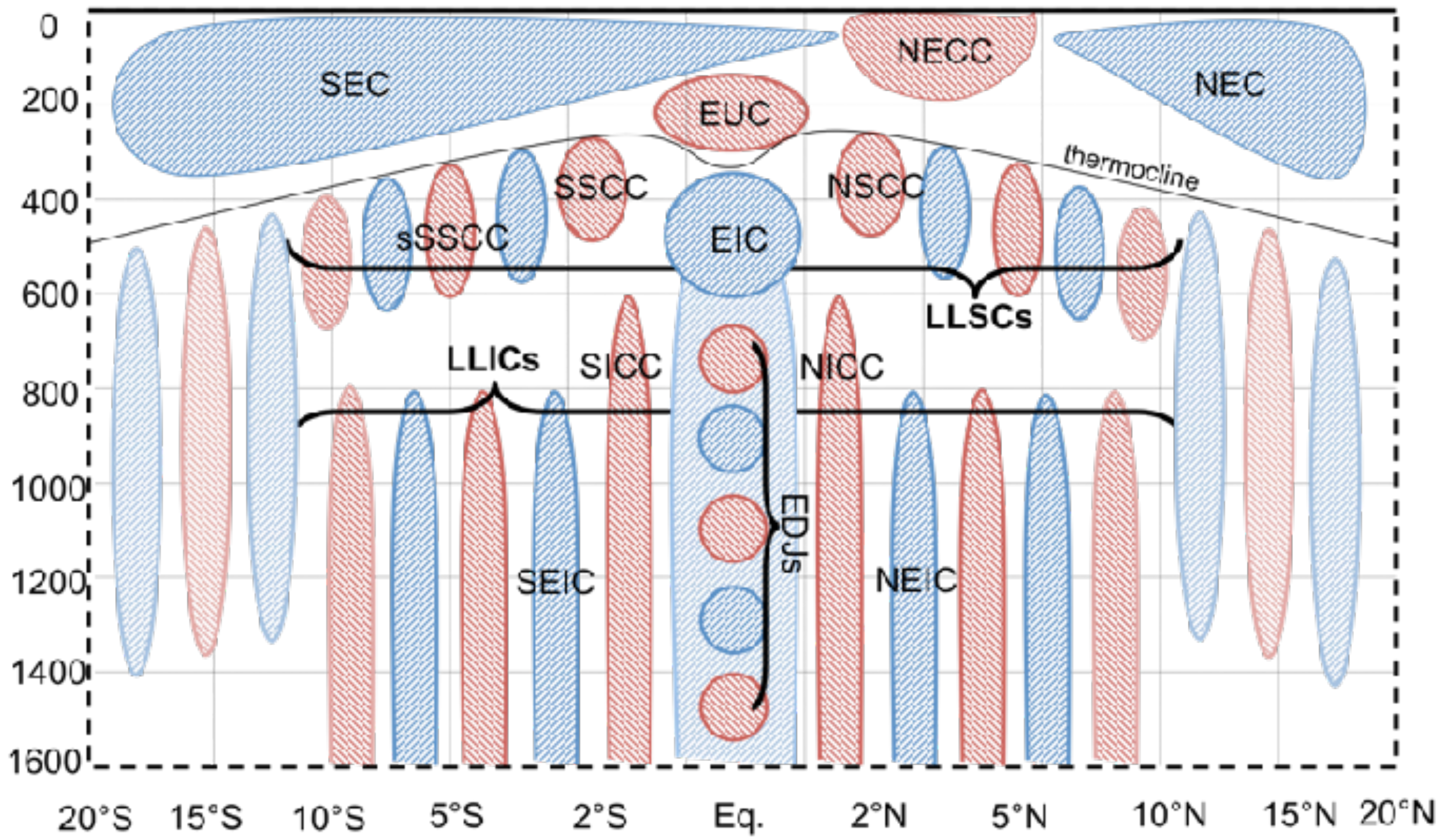
zonal velocity averaged over 16 yrs



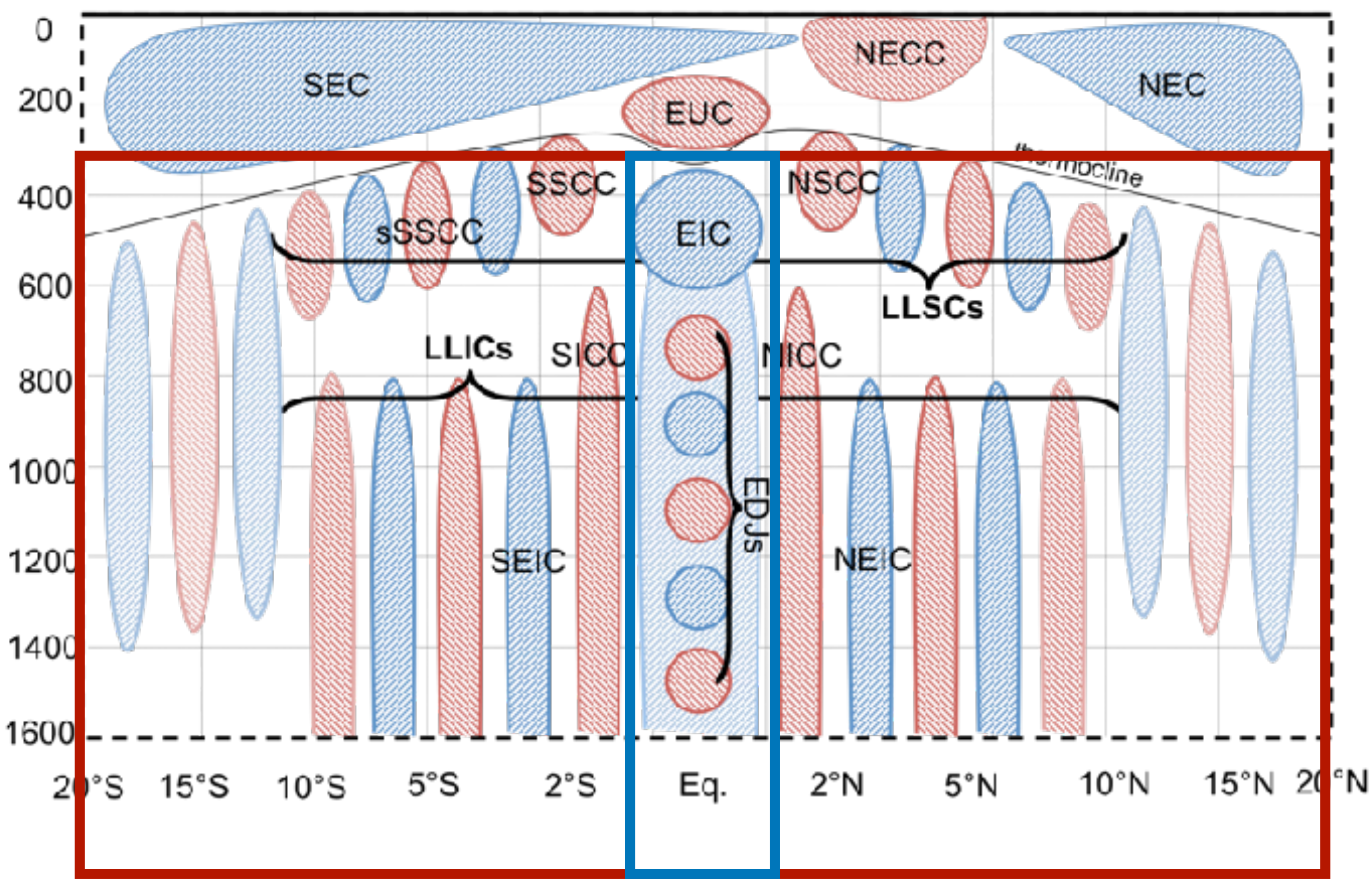
Cravatte et al. 2017

Extra Equatorial Jets (EEJ)
over the full Pacific basin,
V0~5 to 10 cm/s
decreasing poleward and eastward

Schematic view of the Deep Equatorial Circulation



Schematic view of the Deep Equatorial Circulation

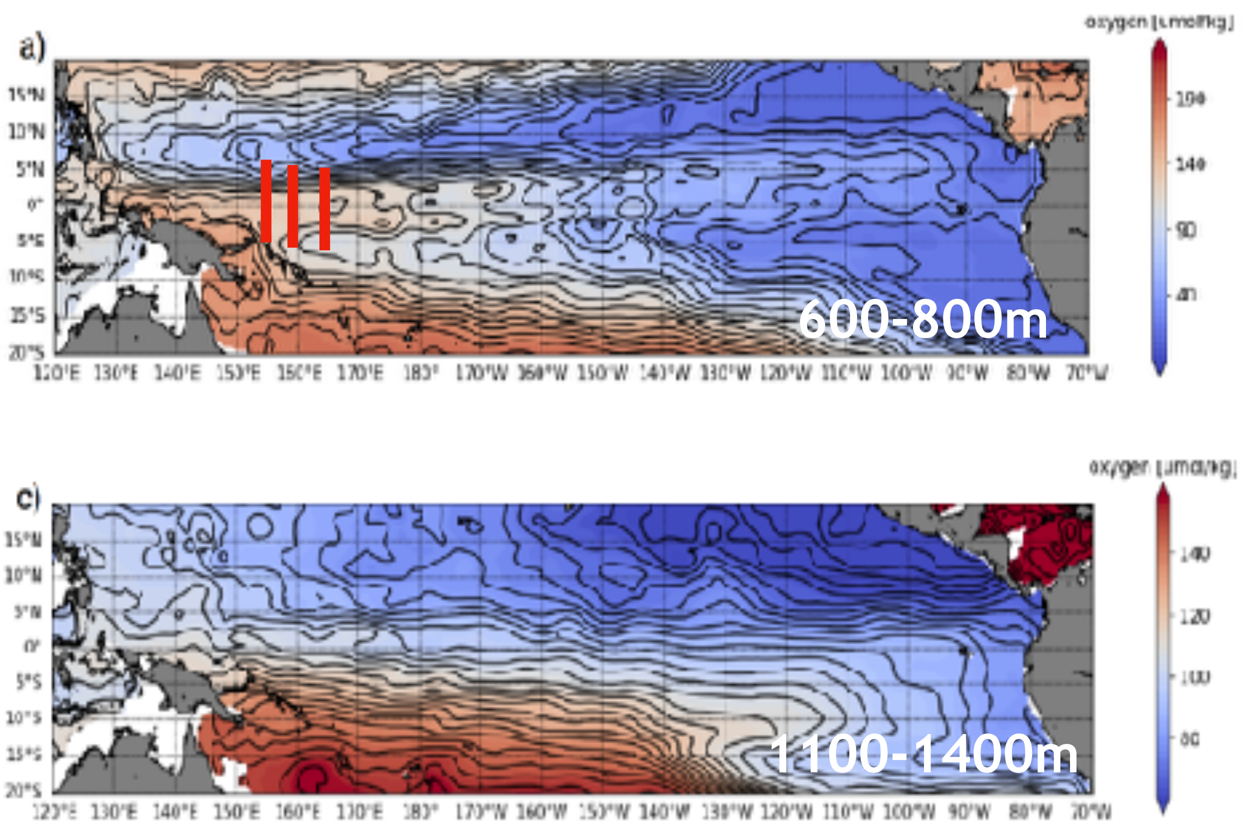


EDJ:
high baroclinic zonal jets

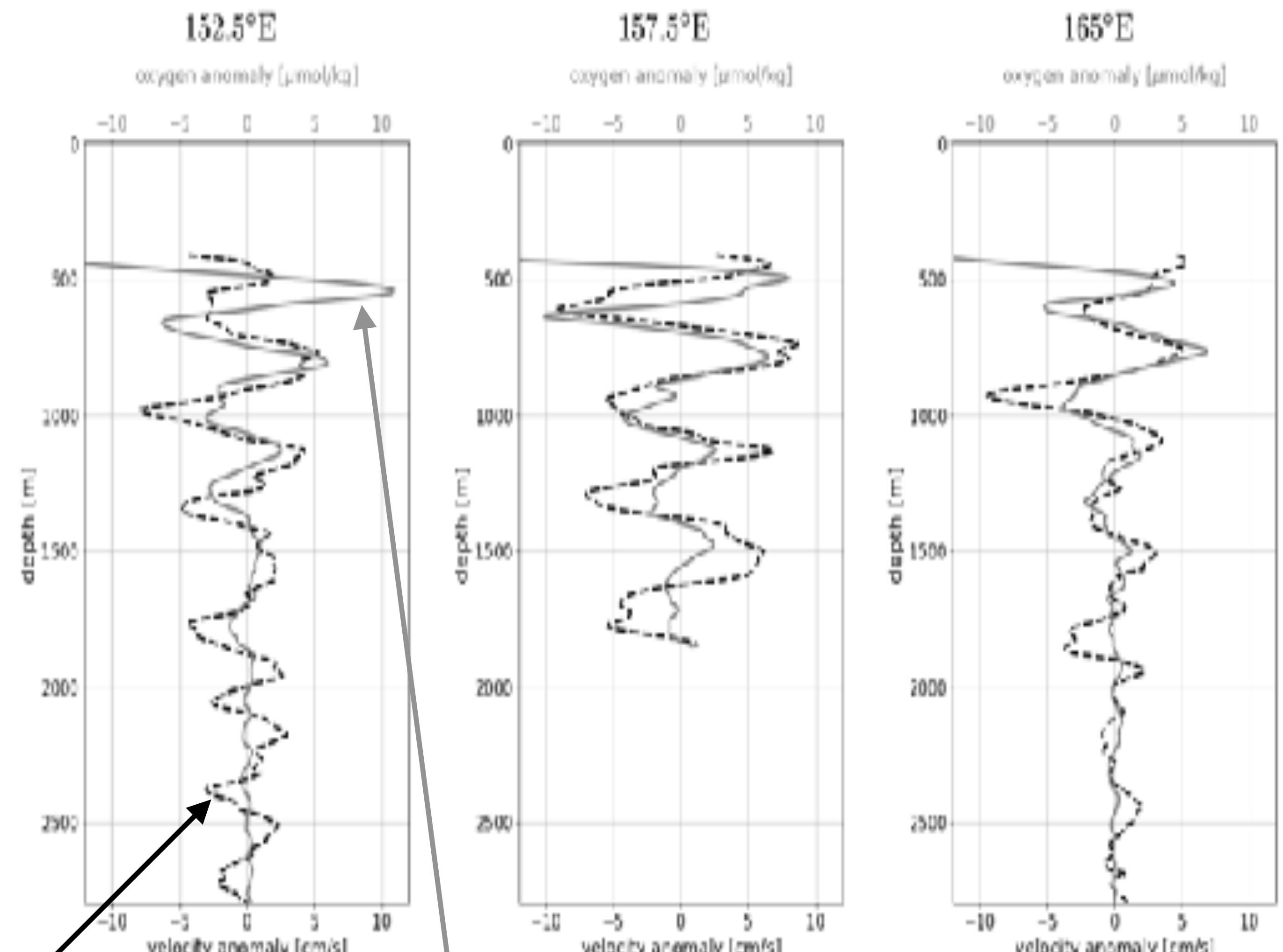
EEJ:
low baroclinic zonal jets

Impact of the Deep Equatorial Circulation on tracer transport

Pacific Ocean



Delpech et al. 2019



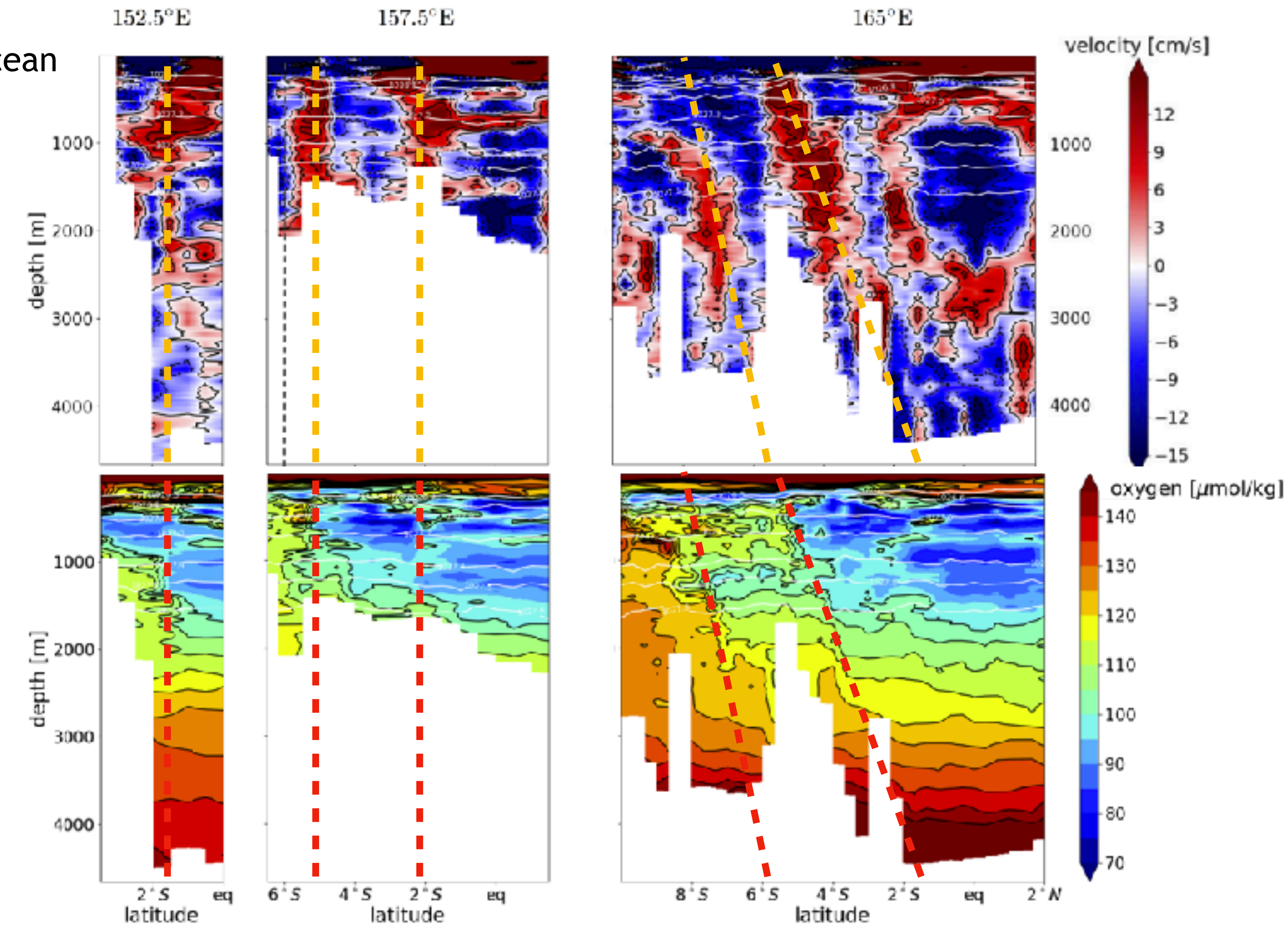
velocity anomaly

oxygene anomaly

At the equator, the western maximum of oxygen is advected by eastward EDJ.

Impact of the Deep Equatorial Circulation on tracer transport

Pacific Ocean

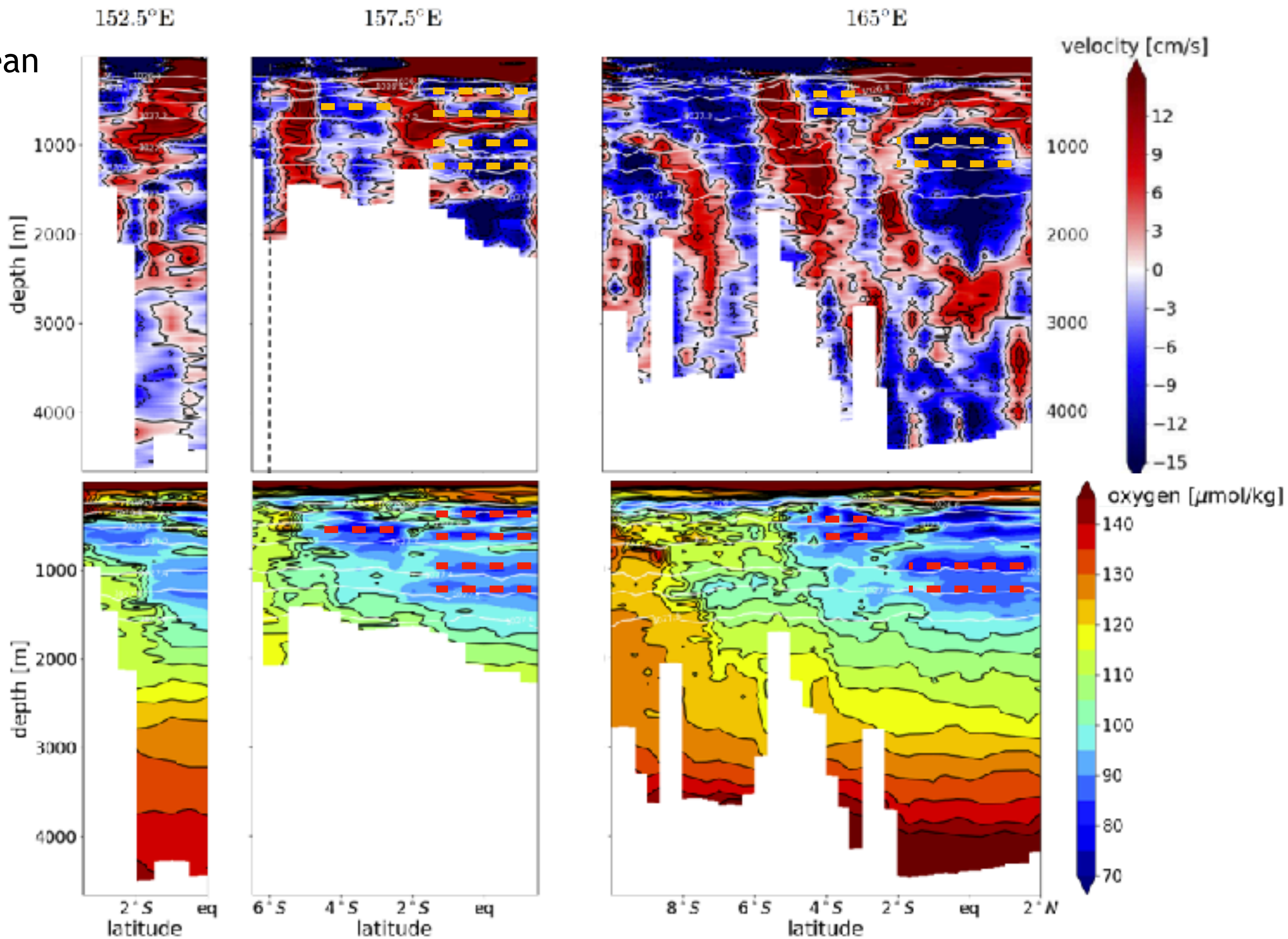


Delpech et al. 2019

Eastward jets act as tracer barriers,

Impact of the Deep Equatorial Circulation on tracer transport

Pacific Ocean

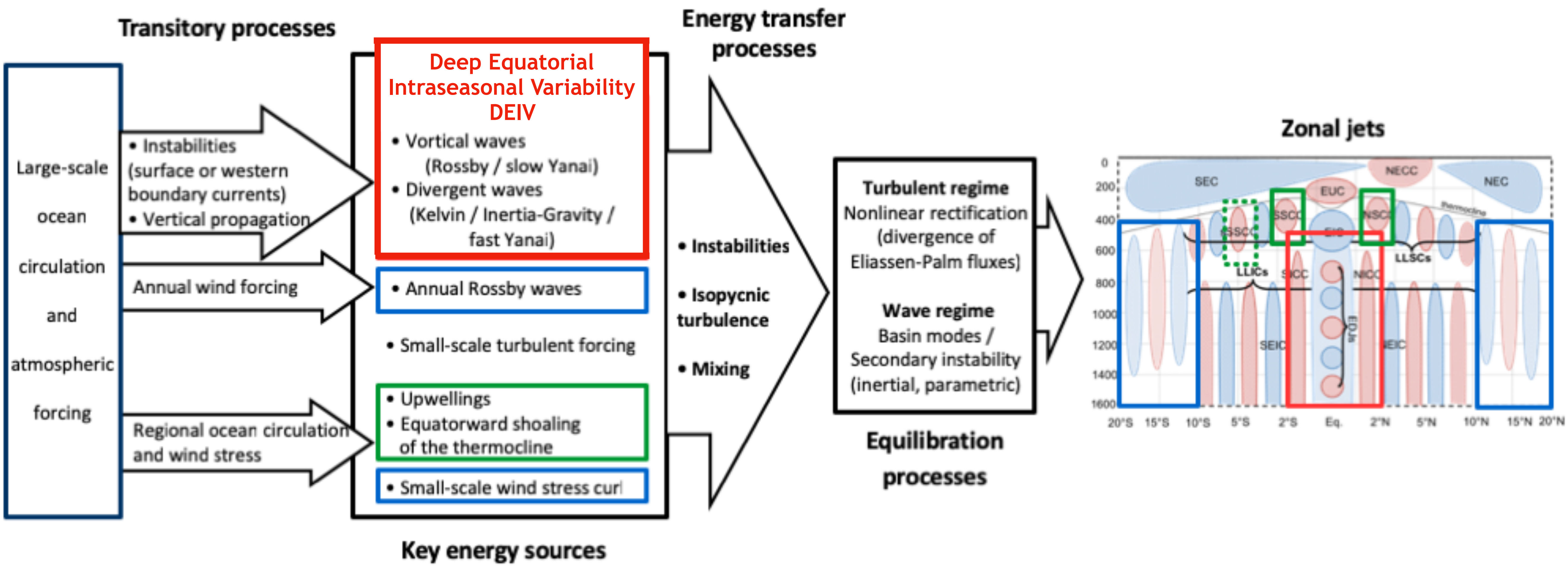


Delpech et al. 2019

while westward jets are co-localized with tracer plateaus.

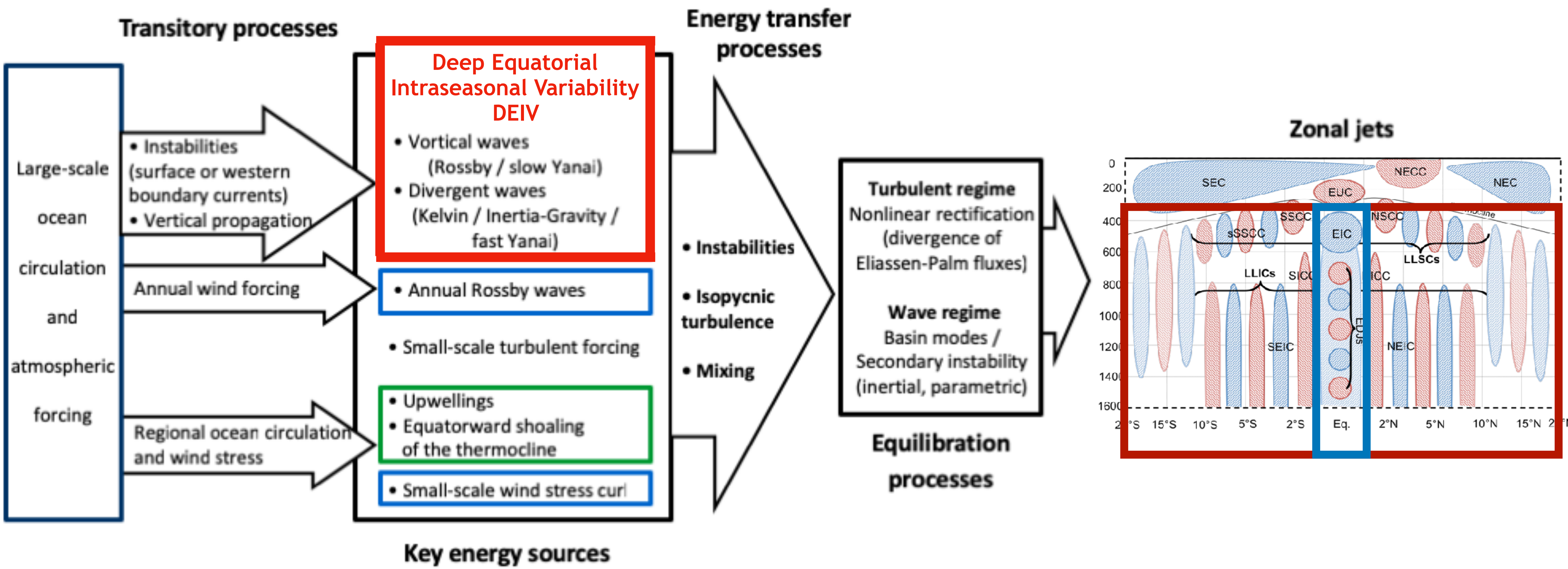
Large scale meridional tracer gradients highlight an isopycnal mixing inside westward jets.

Formation and equilibration of the DEC and DTC: cascades of mechanisms



Ménesguen et al. 2019

Formation and equilibration of the DEC and DTC: cascades of mechanisms

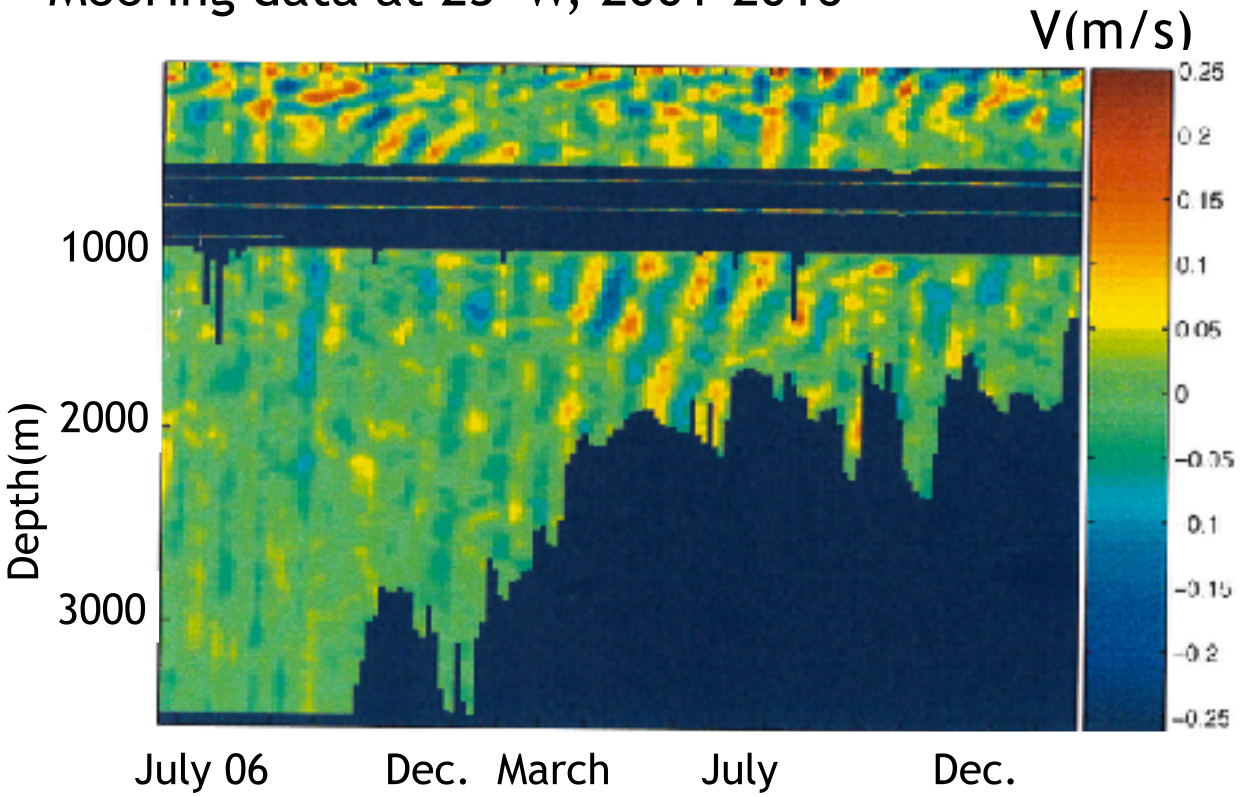


Ménesguen et al. 2019

Is there a single cascade of mechanisms able to explain the global formation and equilibration of equatorial and tropical zonal jets?

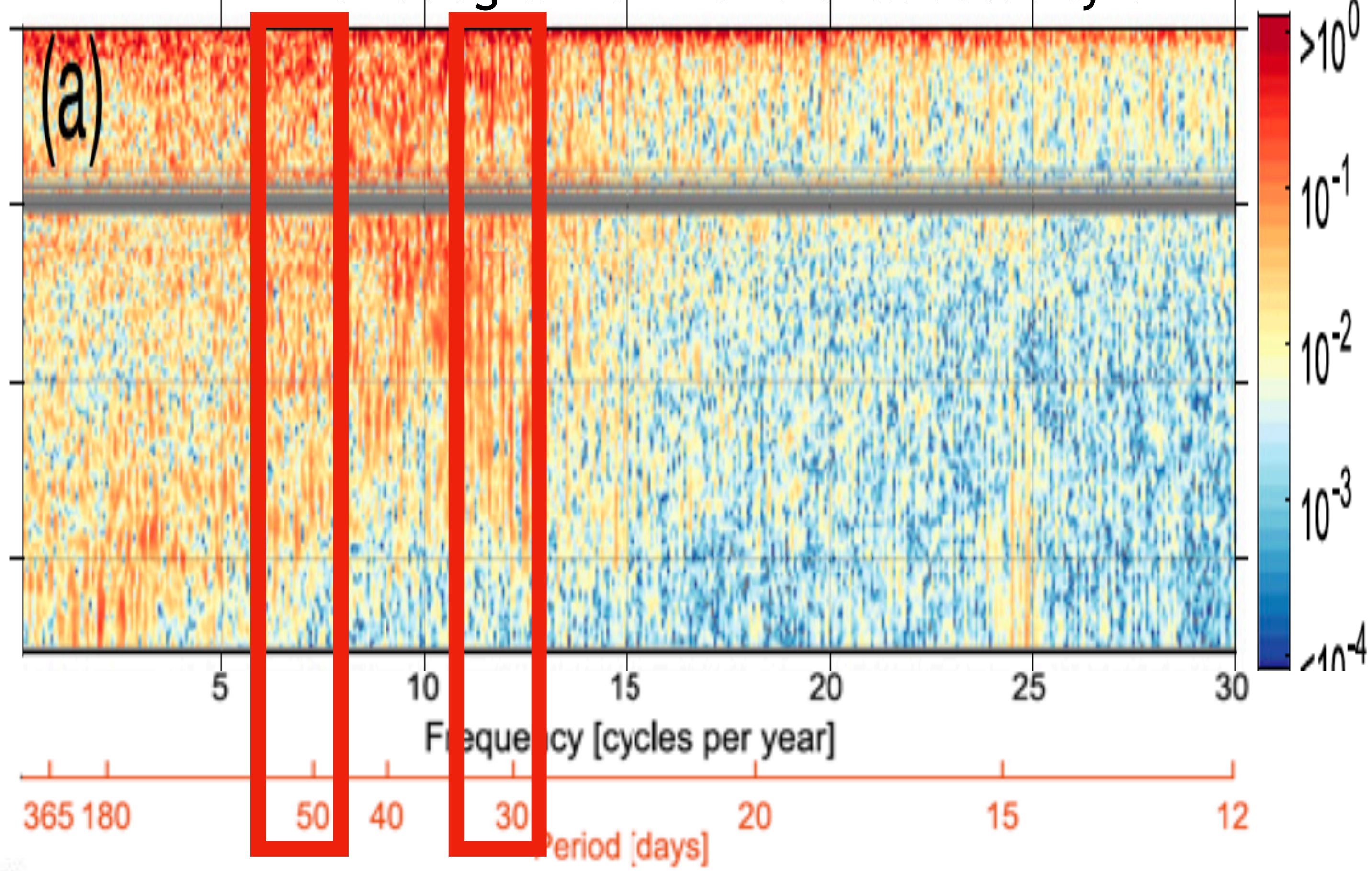
Deep Equatorial Intraseasonal Variability (DEIV) in the Atlantic

Mooring data at 23°W, 2001-2016

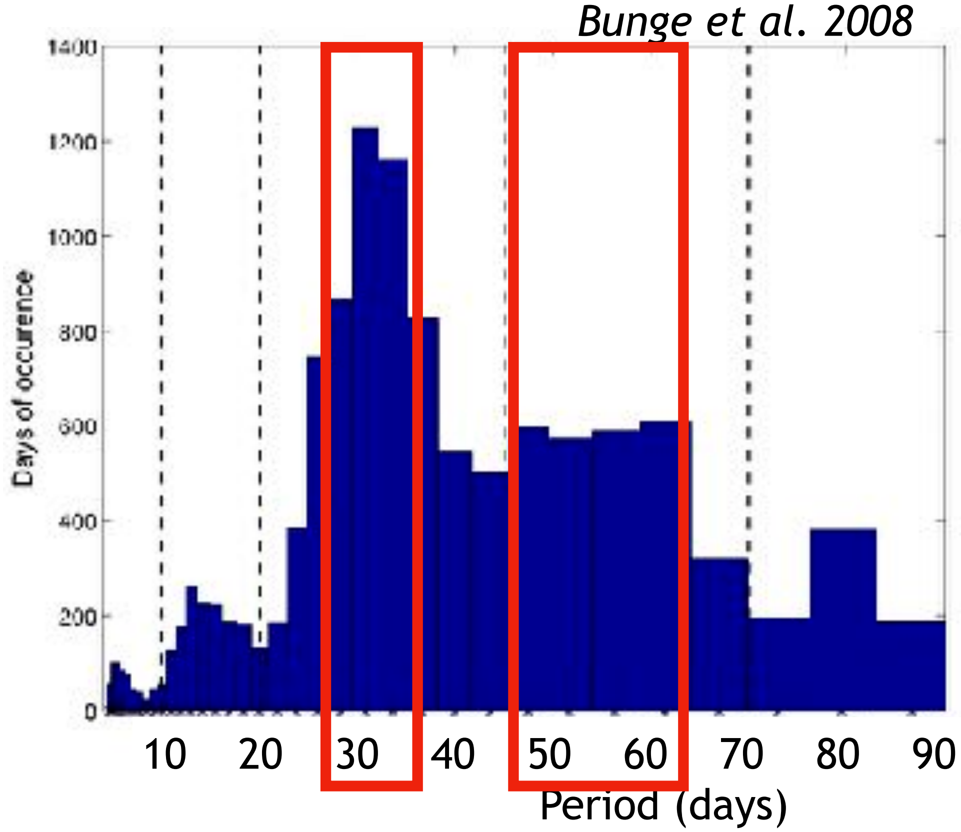


Tuchen et al. 2018

Periodogram of meridional velocity V

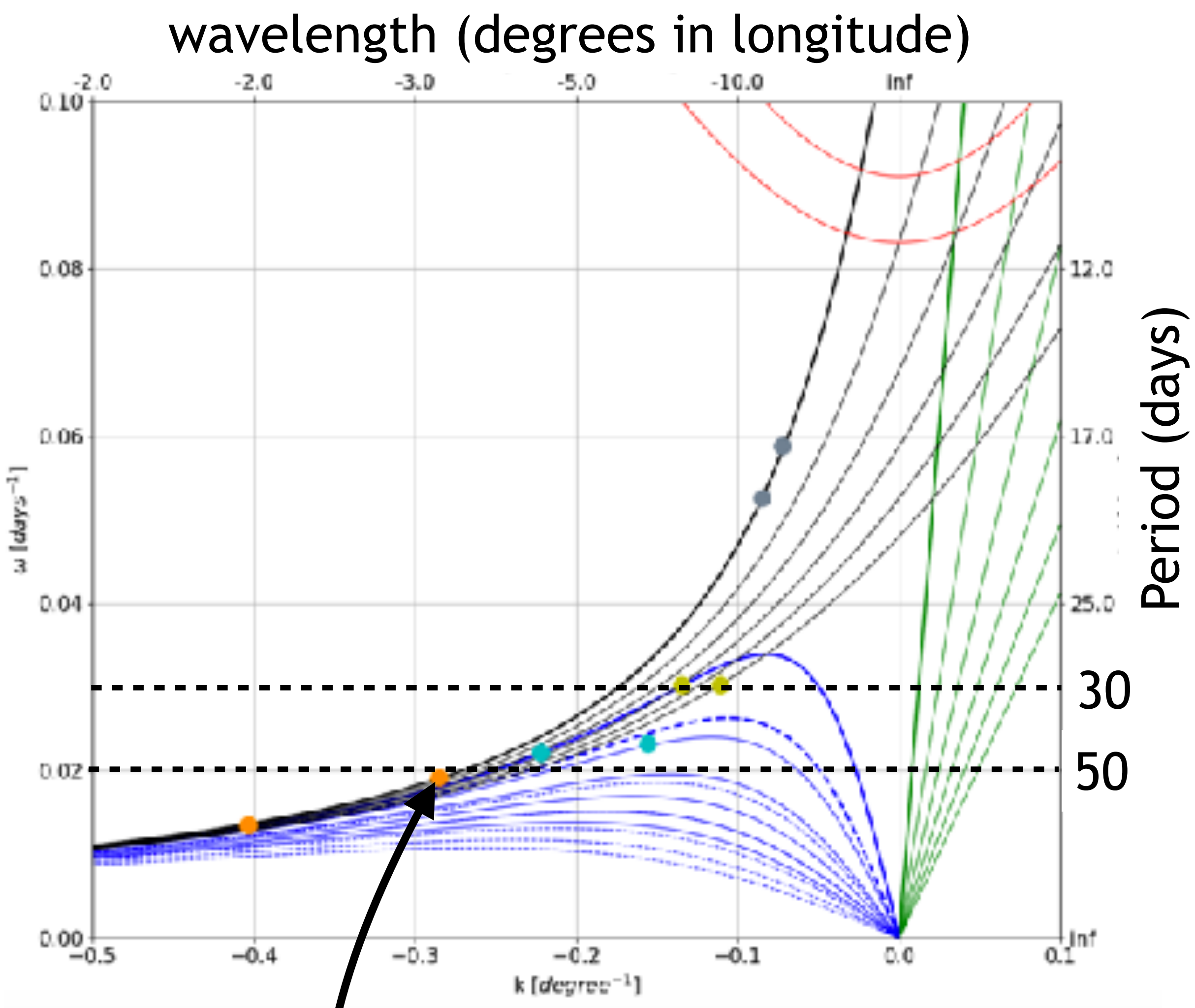


Bunge et al. 2008

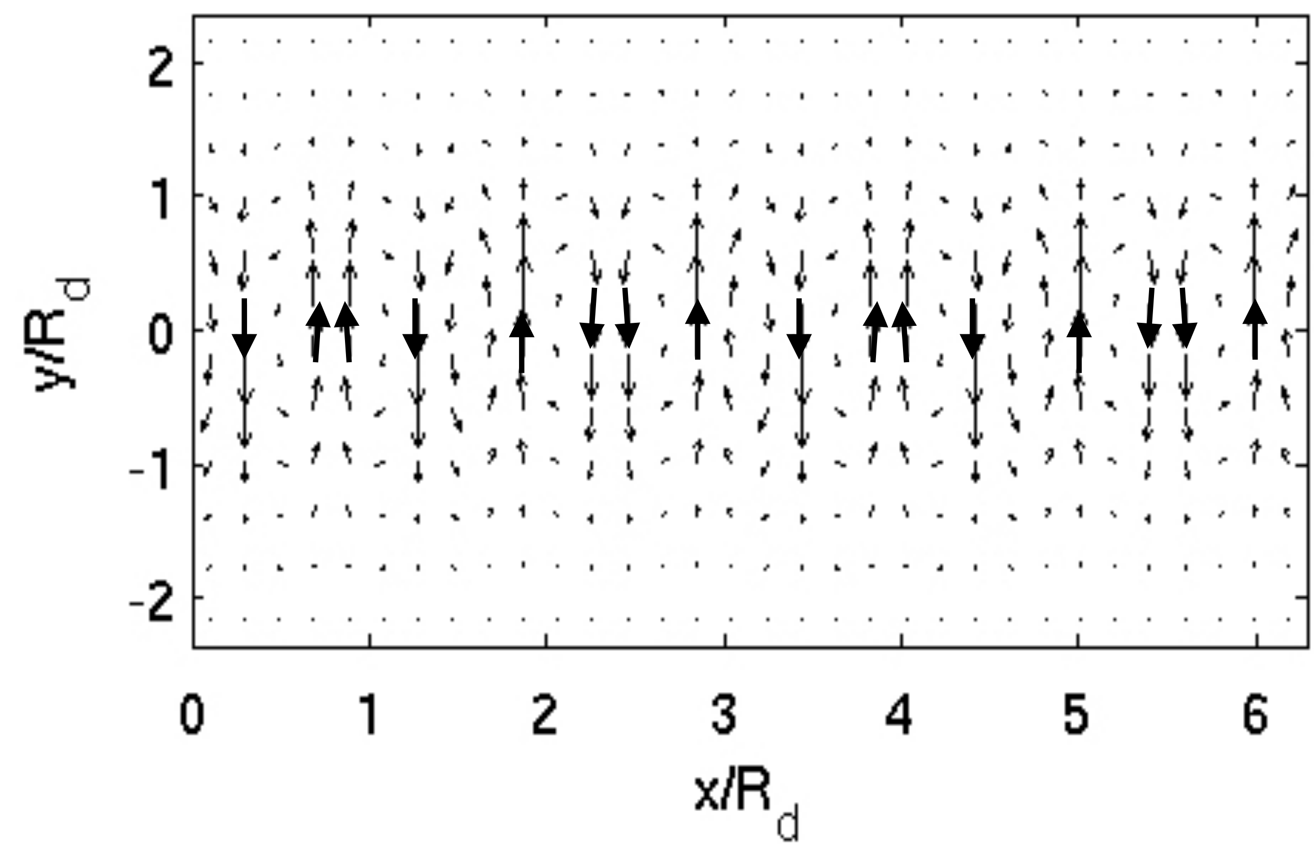


In the meridional velocity variability, there is a predominance of T=30 days, and T=50-60 days, over depth.

Deep Equatorial Intraseasonal Variability (DEIV) in the Atlantic

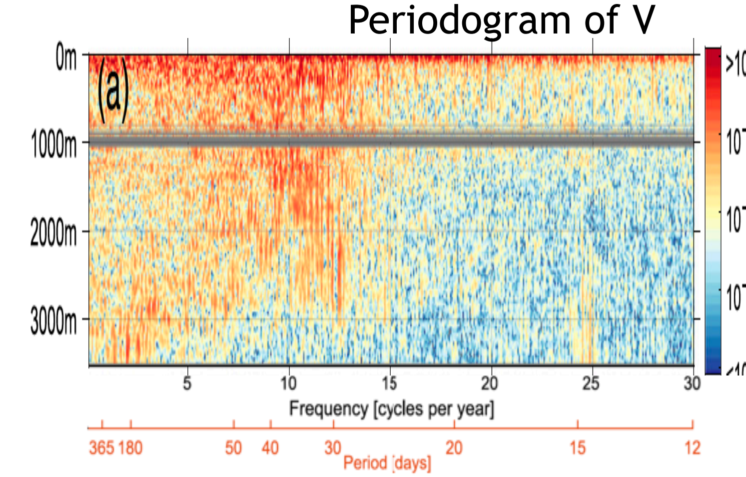


short Yanai waves velocity field

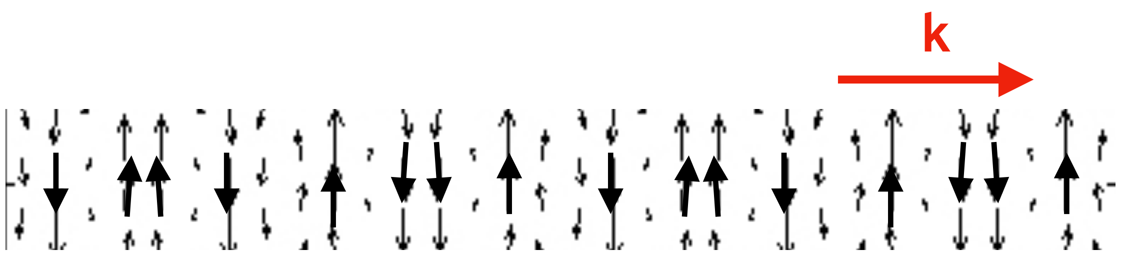


signature of short Yanai waves
at depth at the equator

Periodogram of V

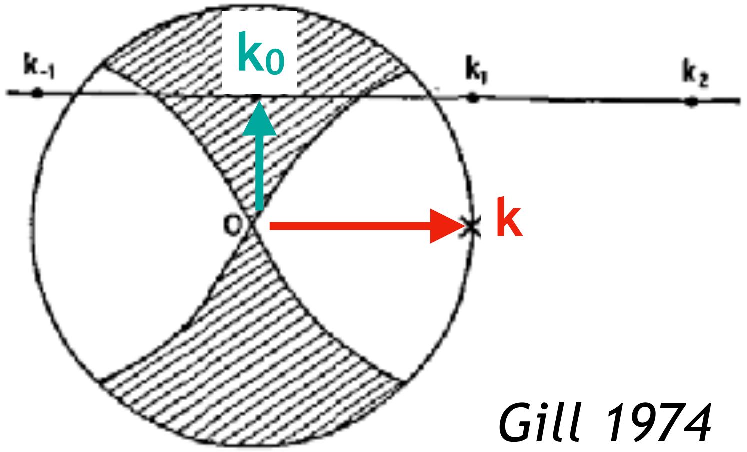


A quick jump to midlatitudes: barotropic short wave instability



Primary wave:
spatially periodic shear:
V = V0 sin(kx), k<<1

periodically: **barotropic shear instability** (*Lorenz 1972, Gill 1974*)



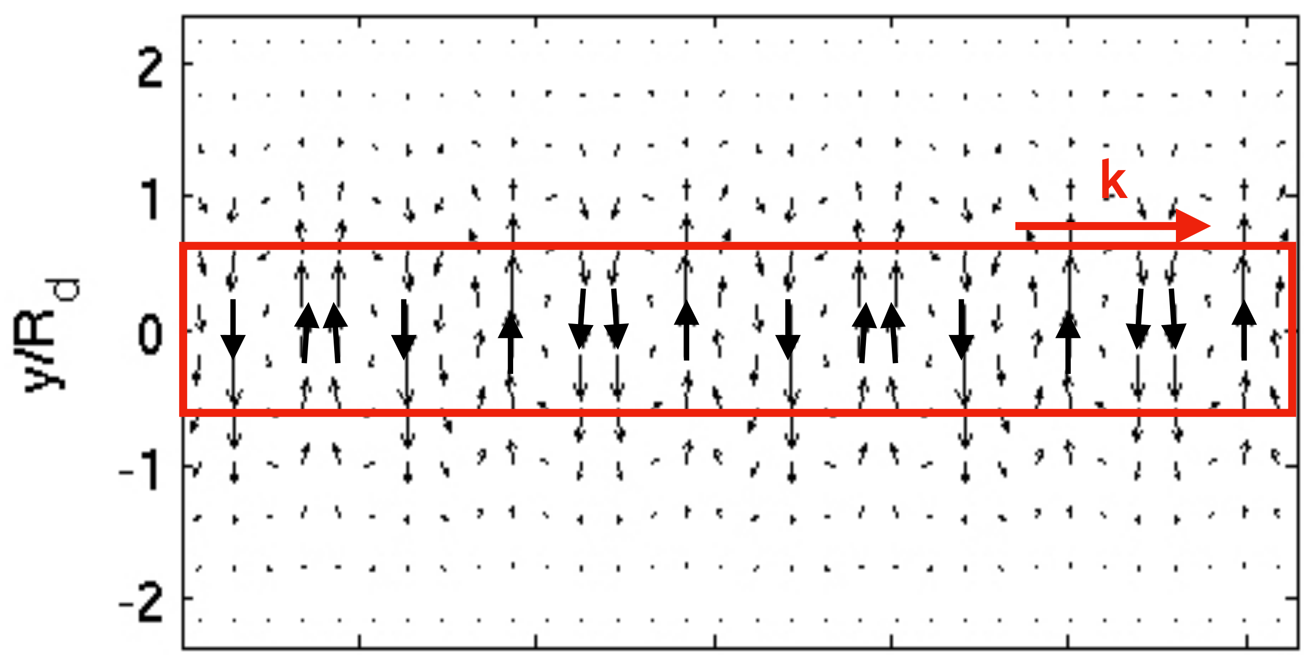
Gill 1974

Possible values (shaded area) of k_0 for unstable disturbances to a large amplitude wave with short wavenumber k

faster growing mode :
a **wave orthogonal** to primary wave,
with $|k_0| \sim |k|$

if primary wave has meridional velocity->
formation of zonal jets

What about the equatorial region?



Primary wave: short Yanai wave ($k,0,k_z^Y$)

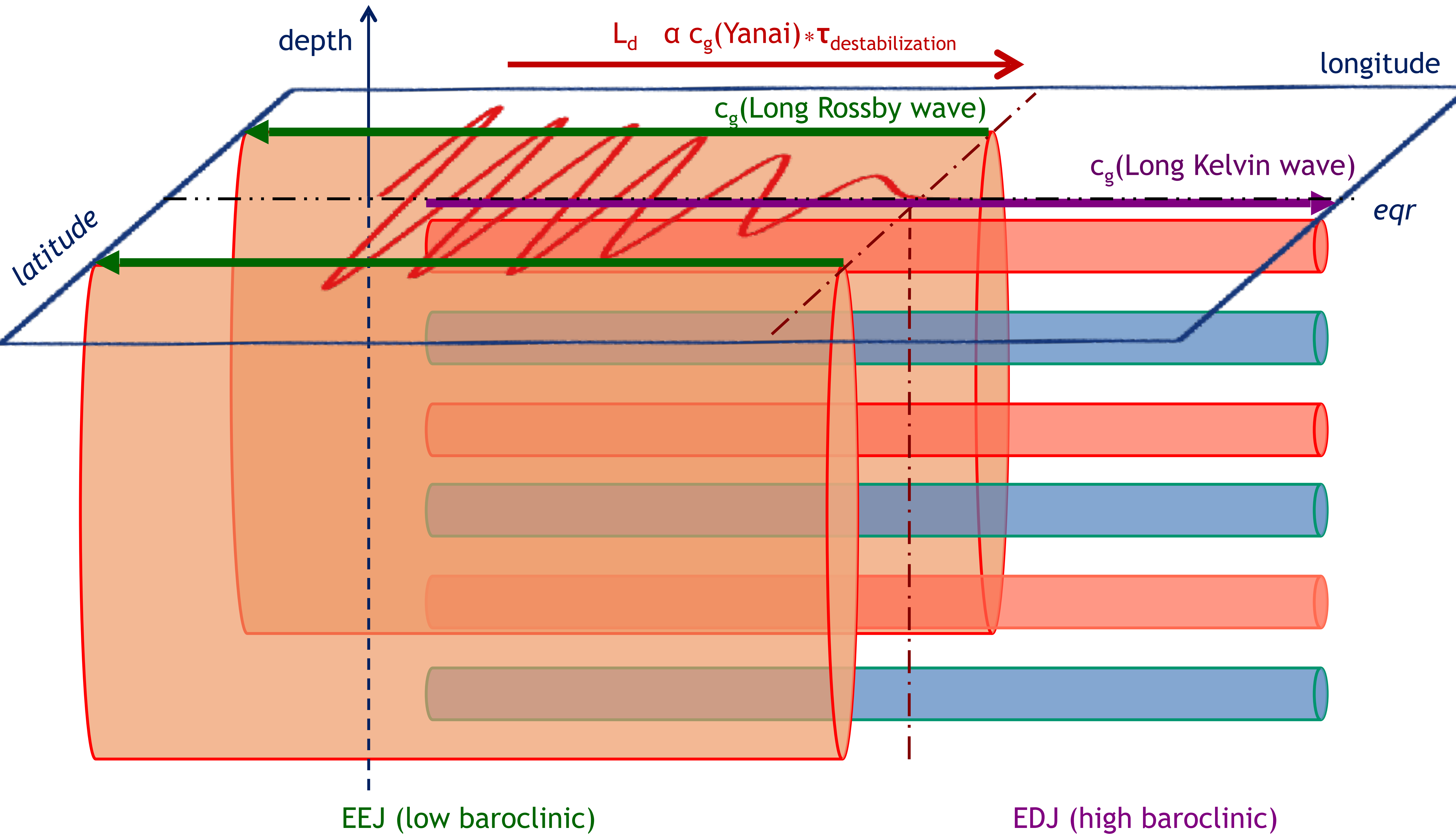
~ spatially periodic shear in the equatorial region:
$V = V0 \sin(kx)$, $k \ll 1$

periodically: **barotropic shear instability** (*Hua et al. 2007*)

faster growing mode :
a wave **orthogonal** to primary wave,
with $|\mathbf{k_0}| \sim |\mathbf{k}|$

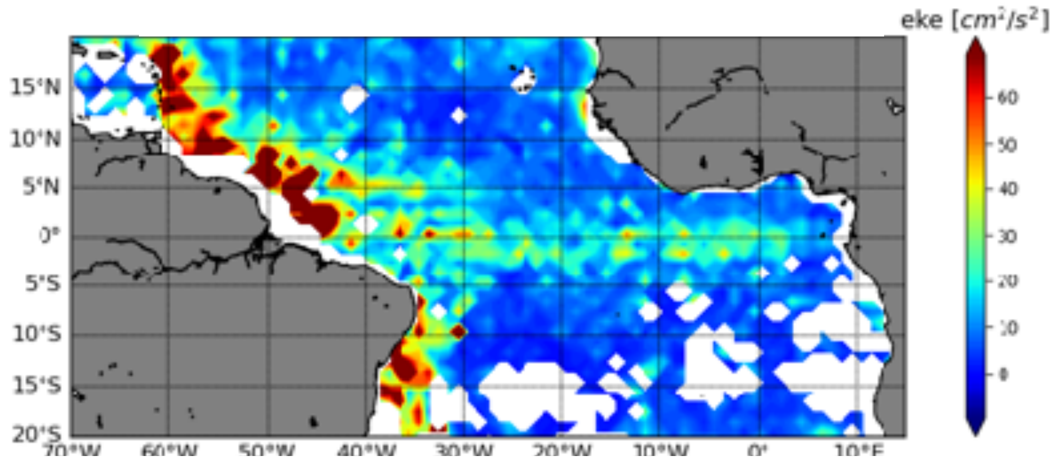
At the equator, two ways to make it:
- long Kelvin waves, low meridional mode, high baroclinic modes ($k_x \sim 0$, -1, $k_z \propto k^2$)
- long Rossby waves, high meridional modes, low baroclinic modes ($k_x \sim 0$, $k_x \sim k$, $k_z \sim 0$)

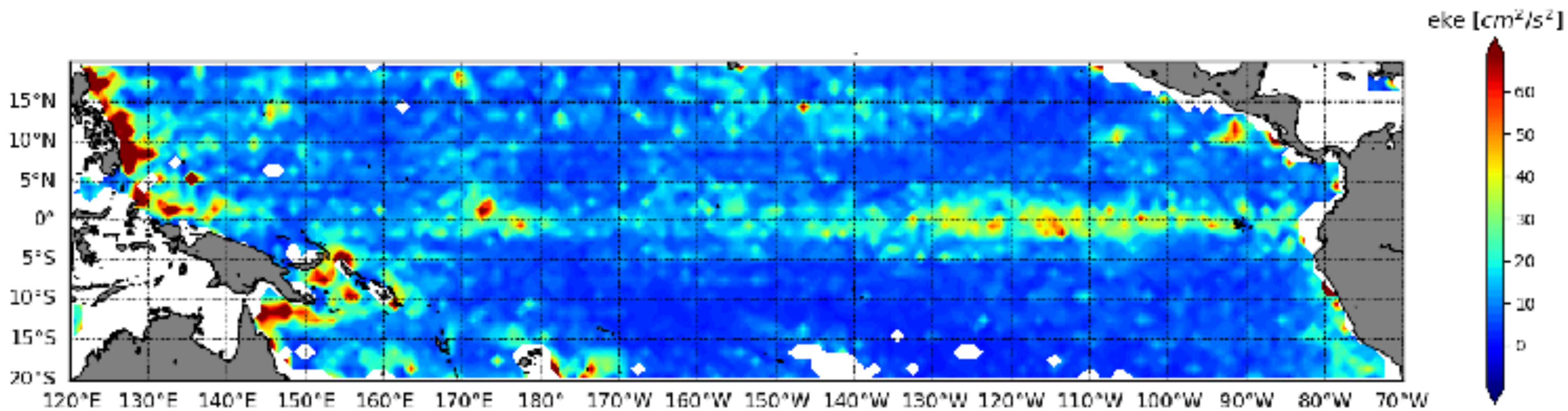
Schematic summary of zonal jets formation by barotropic instability



Deep Equatorial Intraseasonal Variability (DEIV) in the ocean

Mean EKE from the meridional velocity component,
from ARGO floats at ~1000m depth





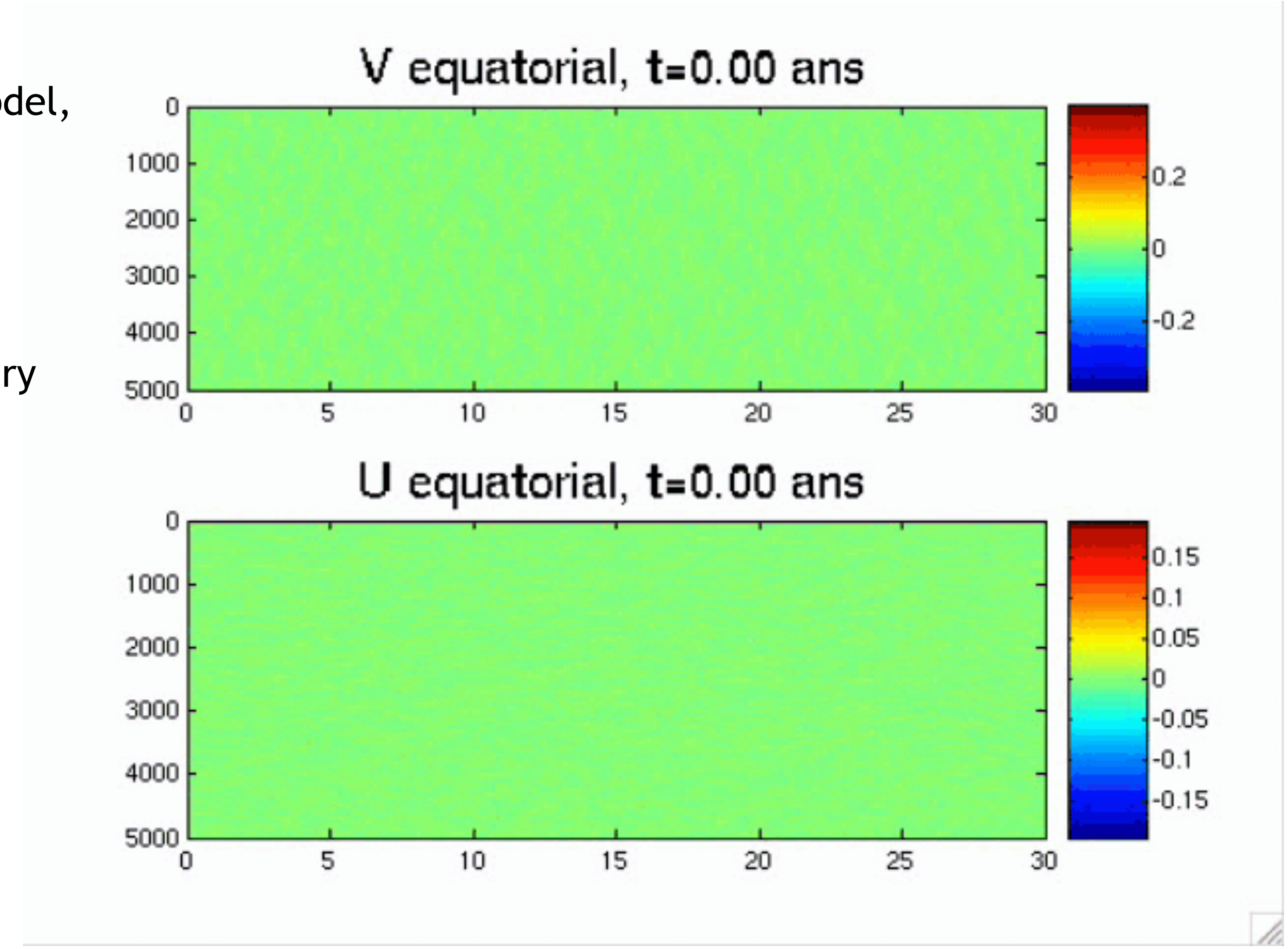
deep v-variability is strong :

- in the western boundary, specifically for the Atlantic,
- and in the middle of the basin, specifically for the Pacific

Numerical simulations with an oscillating source inside the western boundary layer, with a low vertical mode and a fixed period

ROMS: Primitive Equations model,
idealized basin geometry,
constant stratification,
equatorial beta-plane

T_forcing = 40 days,
for V in the western boundary



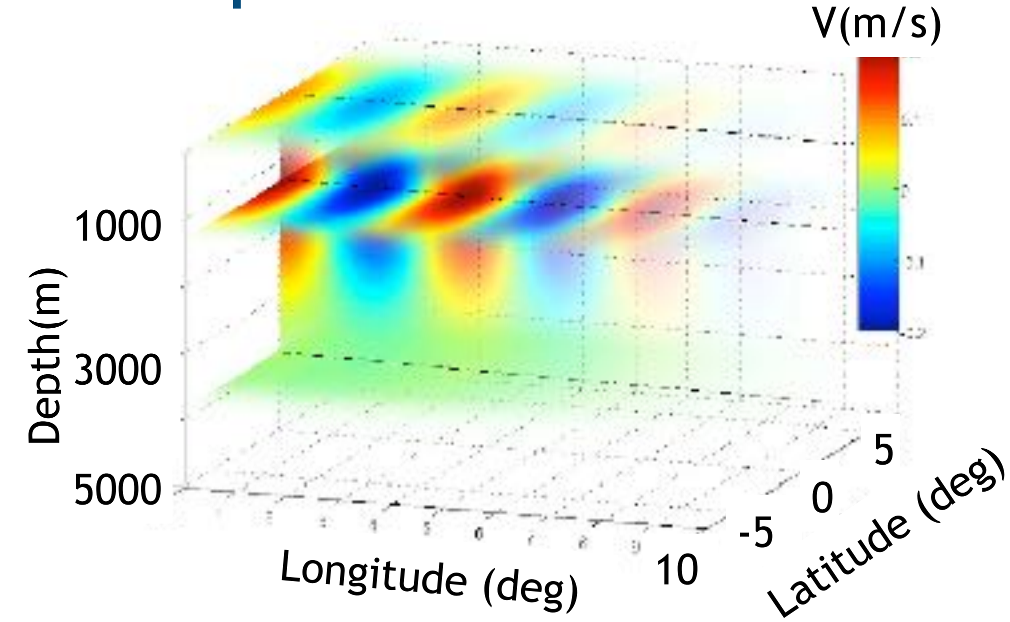
d'Orgeville et al. 2006, Hua et al. 2007

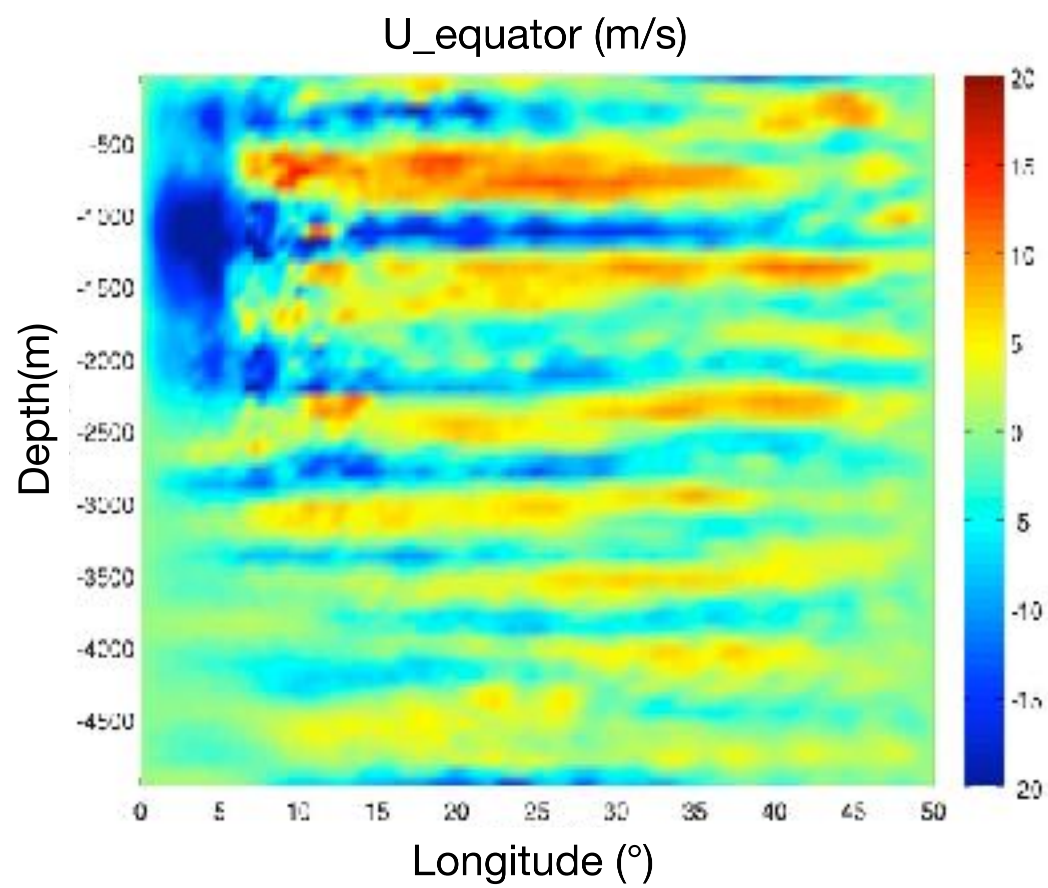
The destabilization of short Yanai wave produces zonal jets with high vertical mode (similar to EDJ)

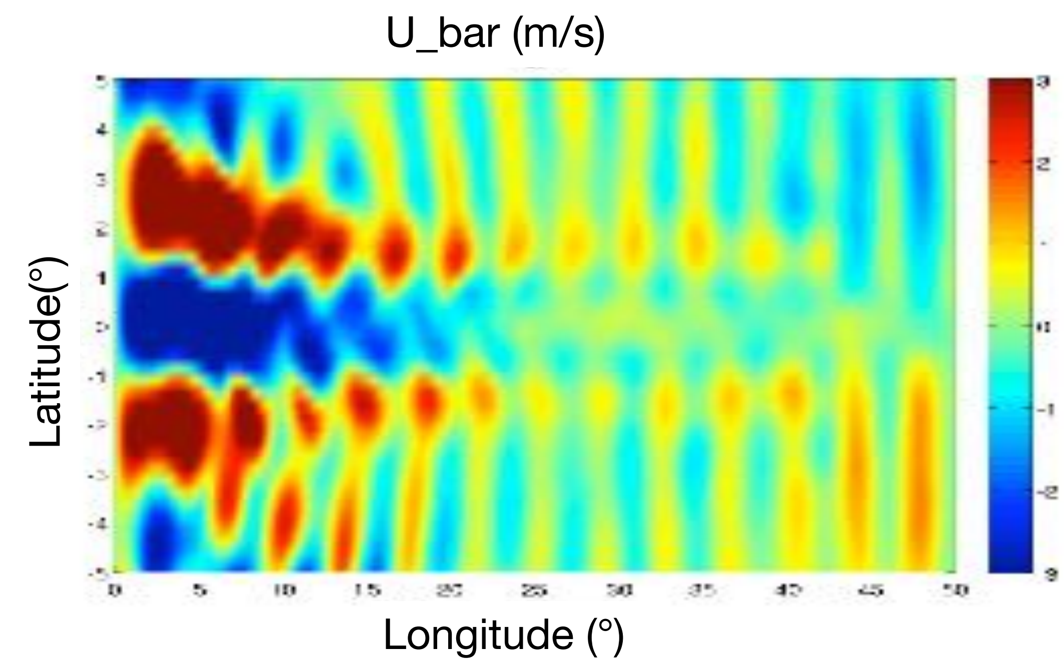
Numerical simulations with an oscillating source inside the western boundary layer, with a 0-3000m confinement and a fixed period

ROMS: Primitive Equations model,
idealized basin geometry,
constant stratification,
equatorial beta-plane

T_forcing = 50 days,
for V in the 'upper' western equatorial rail







Ménesguen et al. 2009a

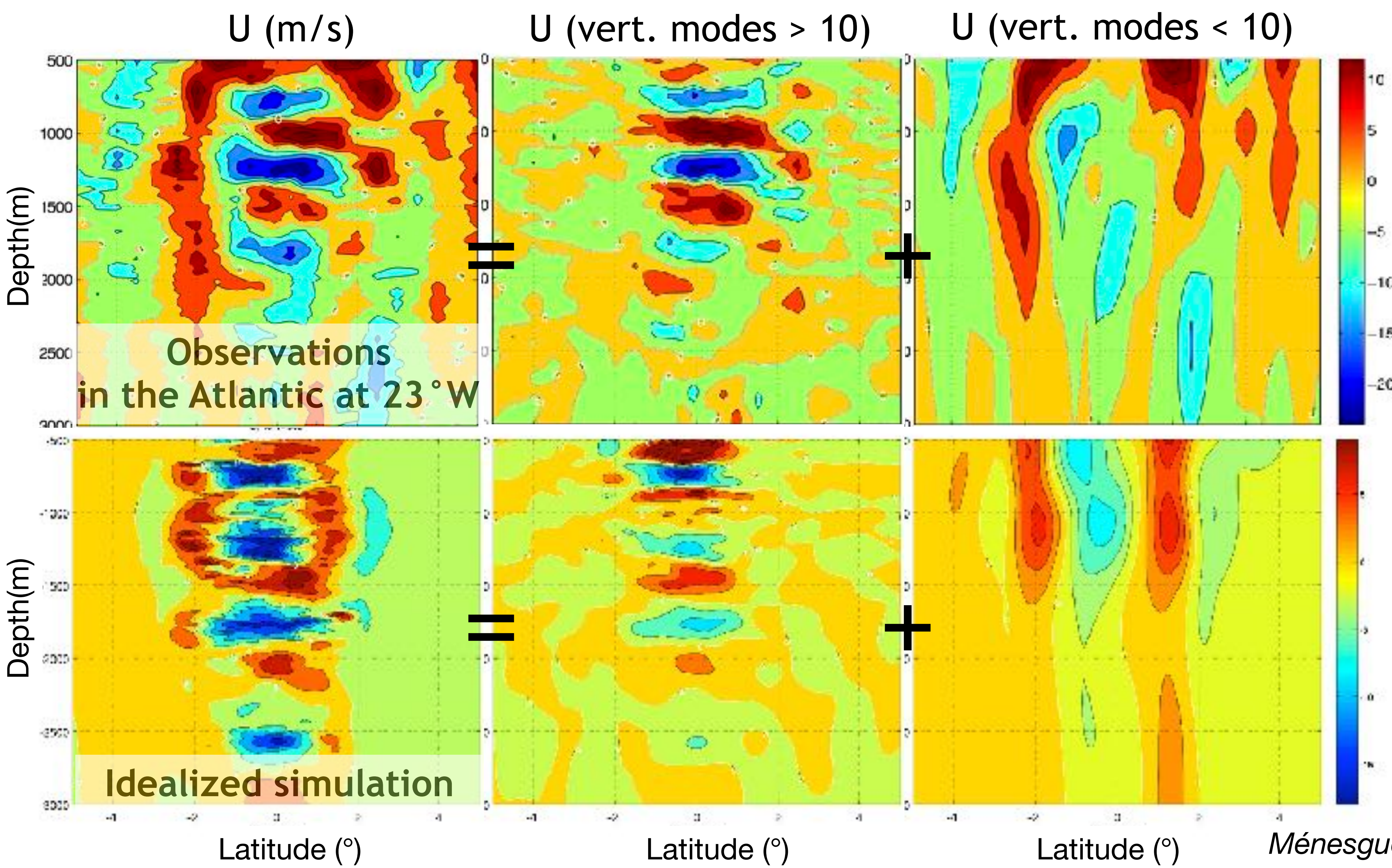
EDJ are developed in the whole domain, intensified in the 0-3000 m depth range.
The zonal velocity barotropic signature (first EEJ) is significant in the western part of the basin.

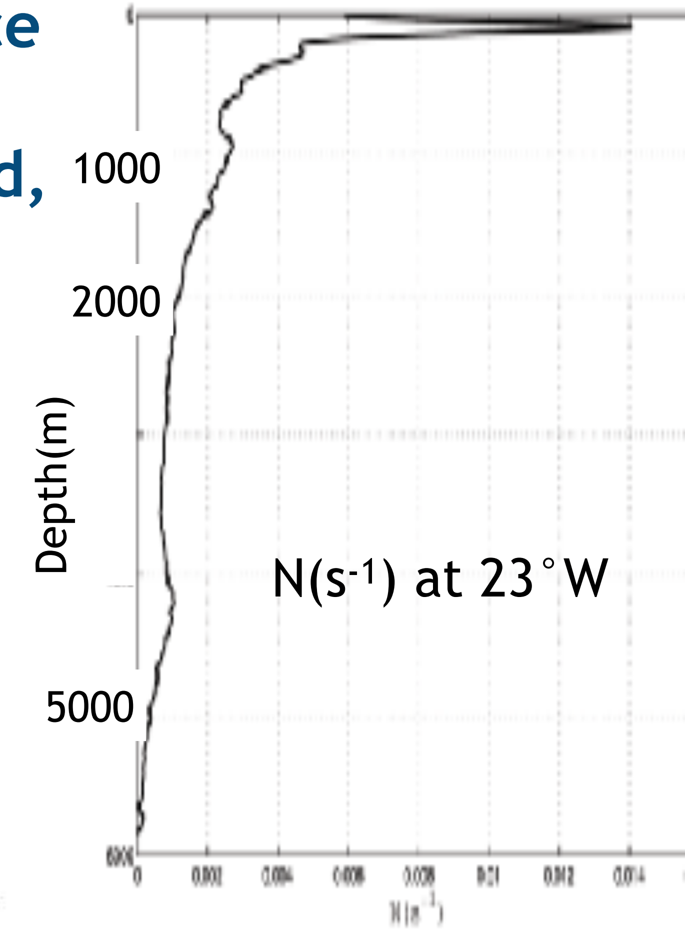
Are simulated jets robust to more realistic configurations?

- depth varying stratification
- multi-frequency forcing
- deep western boundary forcing
  vs surface forcing and vertically propagating wave
- coastline / topography
- realistic simulations?

Can we extend this mechanism to higher latitudes?

Numerical simulations with an oscillating source inside the western boundary layer, with a 0-3000m confinement and a fixed period, with a depth-varying stratification





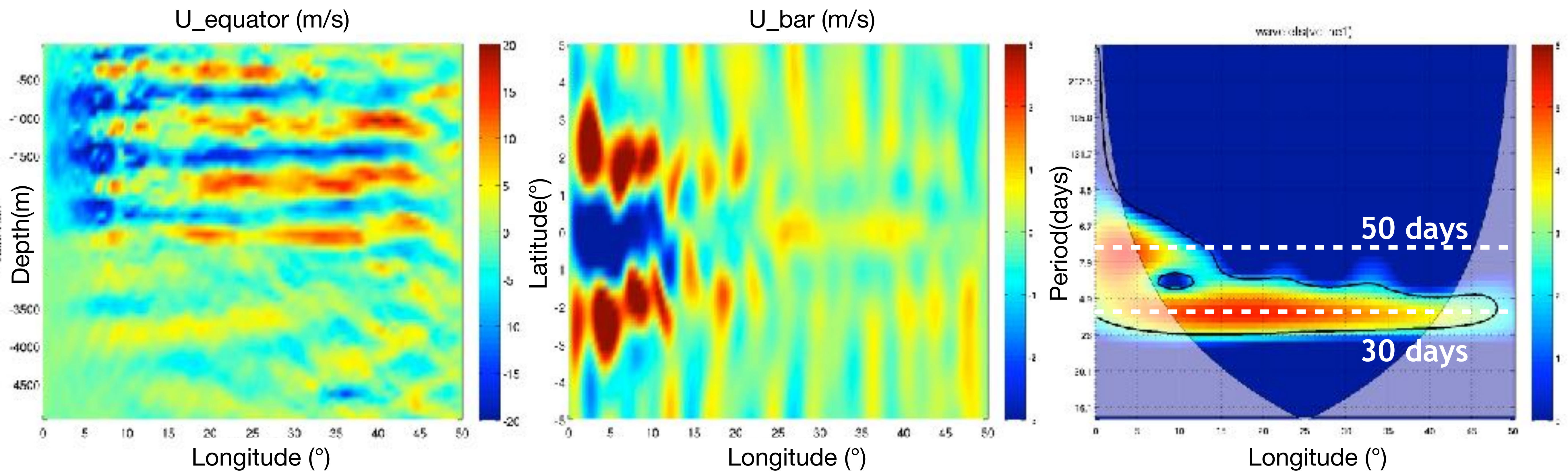
ROMS: Primitive Equations model,
idealized basin geometry,
constant stratification,
equatorial beta-plane

T_forcing = 50 days,
for V in the 'upper' western equatorial rail

Ménesguen et al. 2009a

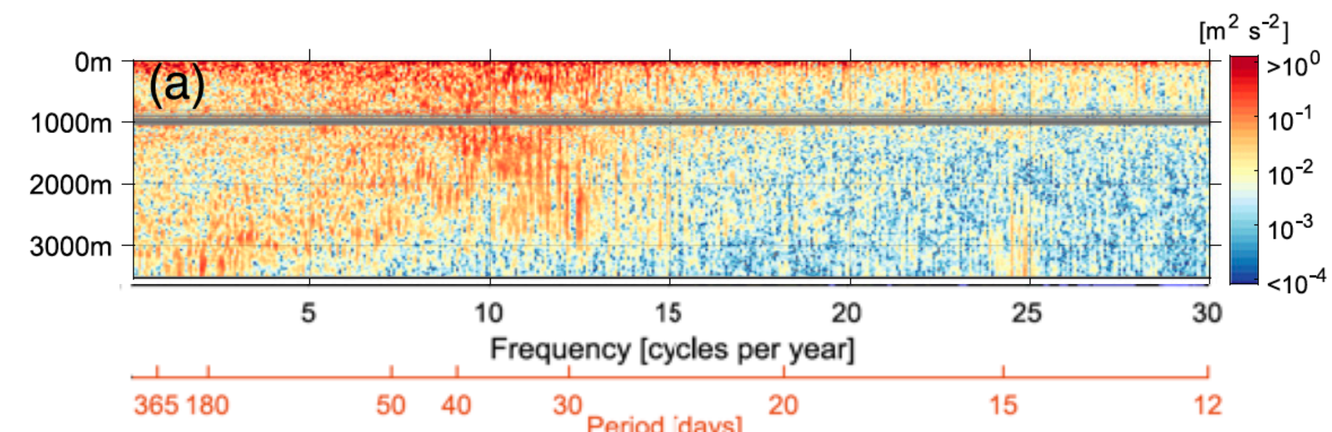
EDJ and first EEJ are correctly-reproduced.

Numerical simulations with an oscillating source inside the western boundary layer, with a 0-3000m confinement and 2 fixed periods



Ménesguen et al. 2009a

T_forcing = 50 & 30 days



Tuchen et al. 2018

The 50 days-wave is destabilized between 0° and 15° of longitude, it creates EDJ, propagating eastward, and EEJ, propagating westward from the destabilization area.

The 30 days-wave does not destabilized and remains strong over the basin -> in Atlantic mooring data, 30-40 days periods remains strong over depth, while longer periods are present but less strong

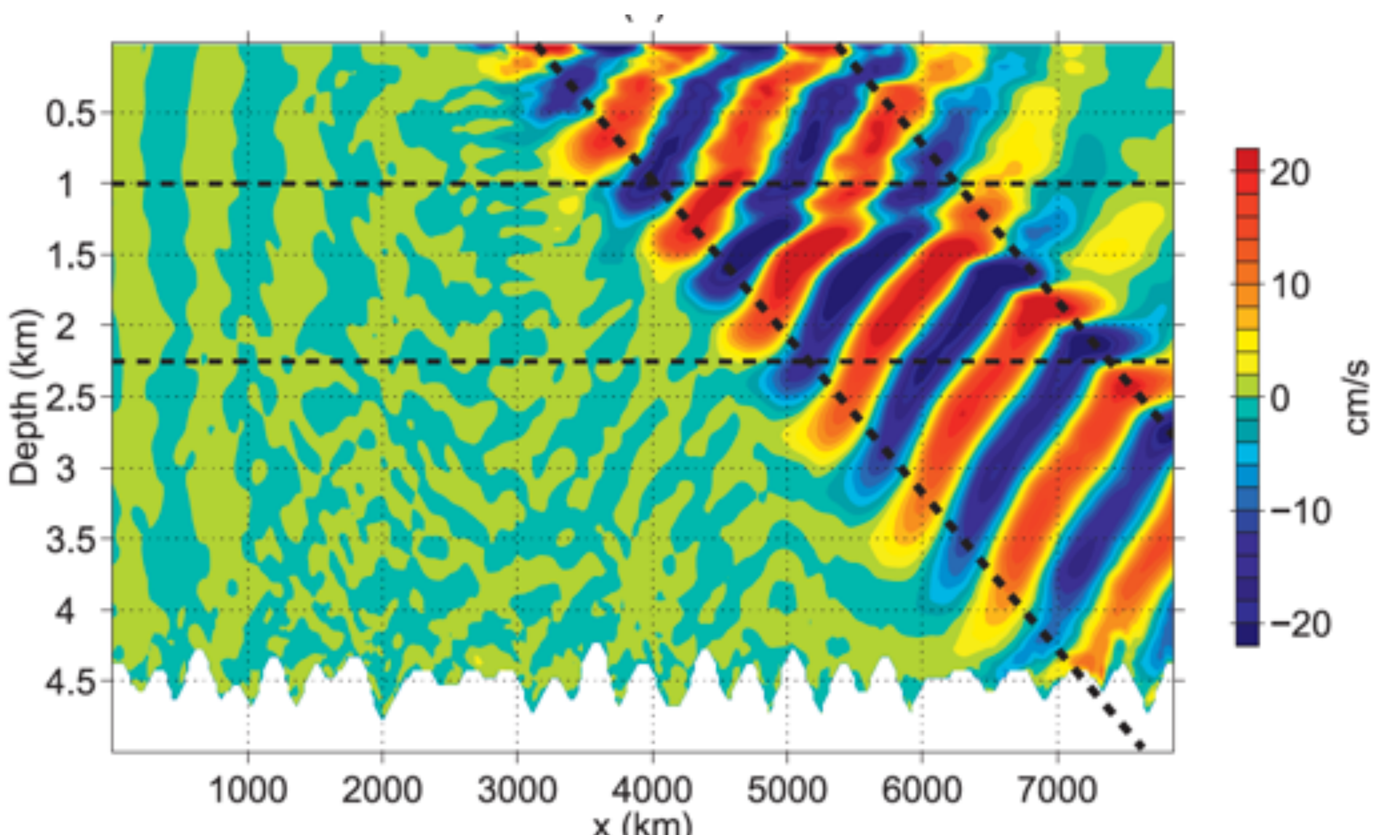
Numerical simulations with an oscillating source at surface, with a fixed period

POP: Primitive Equations model

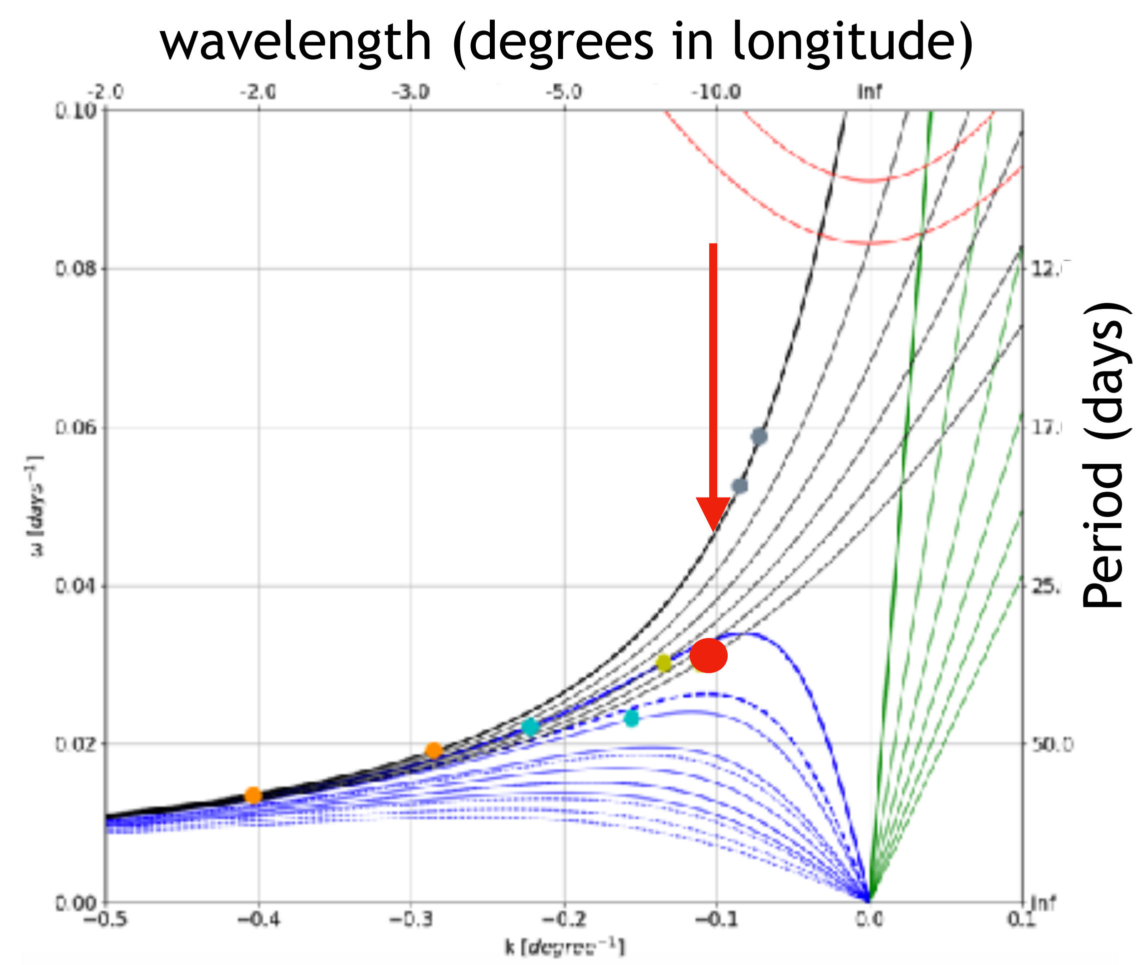
Idealized basin: lat = +/- 20°, lon = 0-72°
equatorial beta-plane
dx = 1/4°, 100 levels
$N = 2e\text{-}3\ s^{-1}$

forcing $\tau^y = \tau_0 X(x) Y(y) \sin(kx-\omega t)$
$T = 2\pi/\omega = 33$ days
$L = 2\pi/k_{Yanai}$

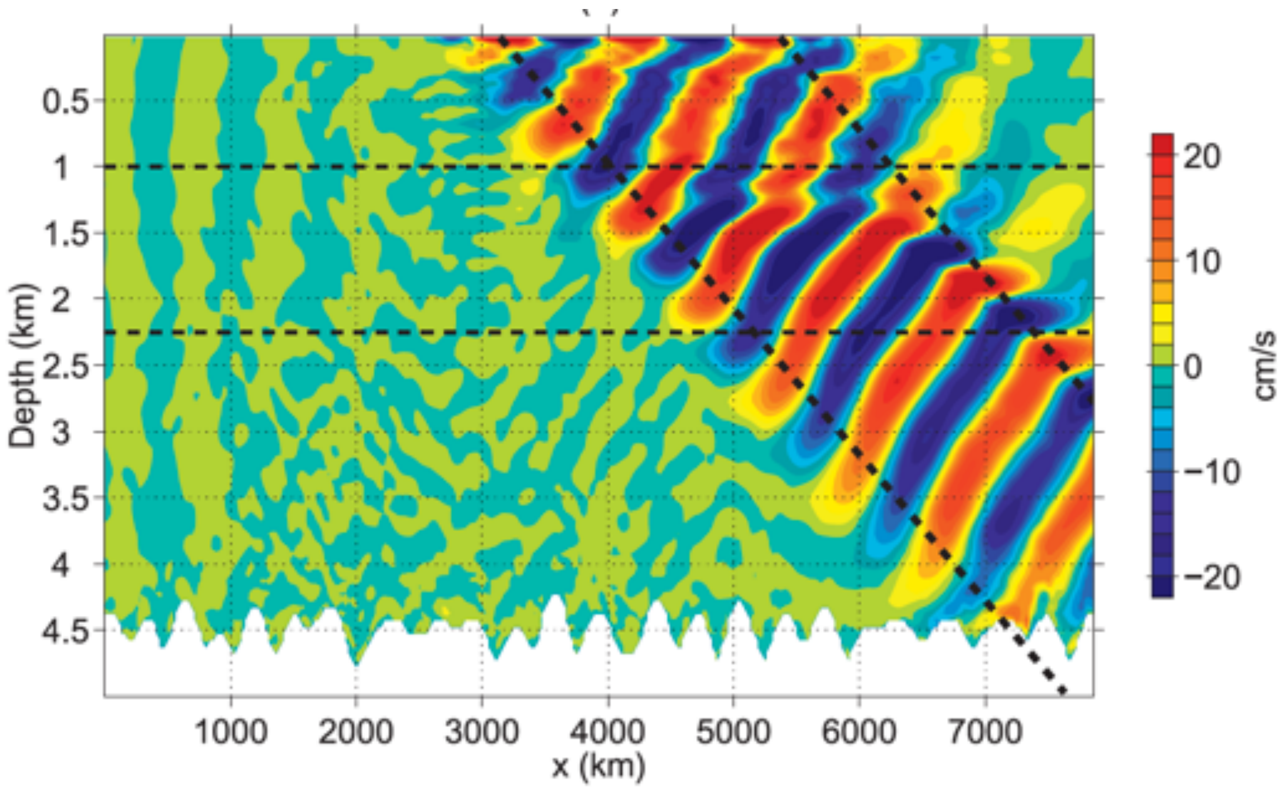
viscosity



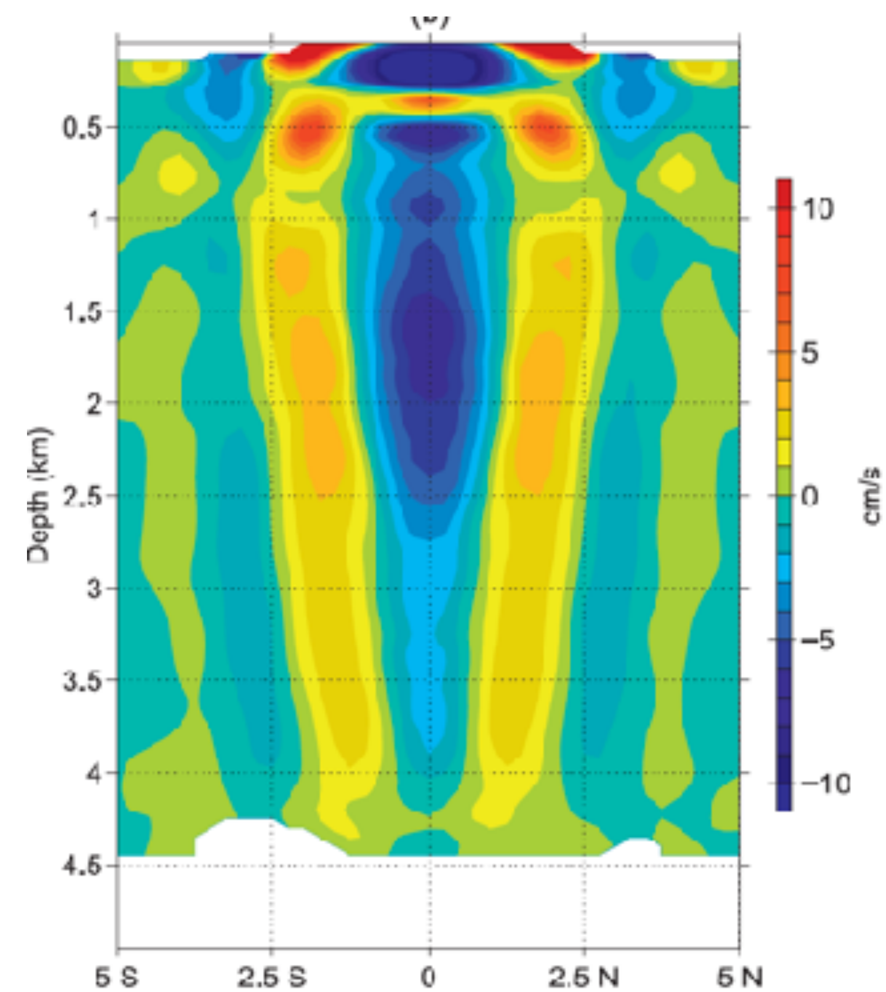
Ascani et al. 2010



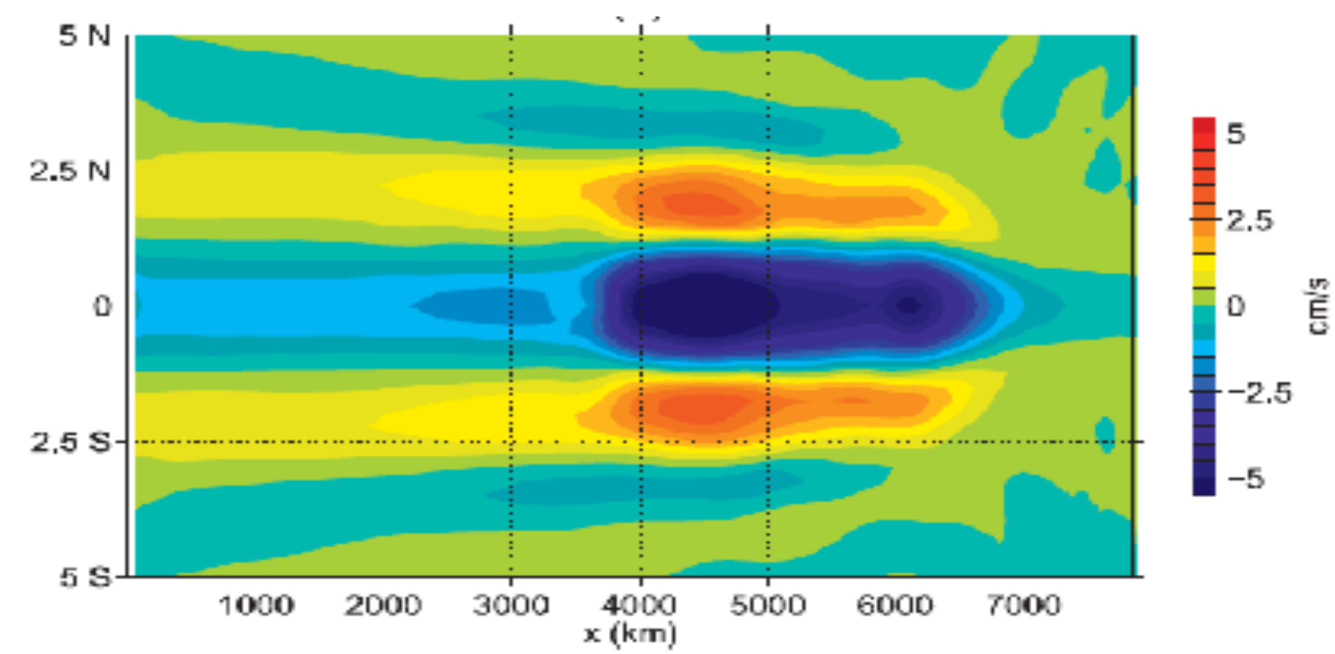
Numerical simulations with an oscillating source at surface, with a fixed period



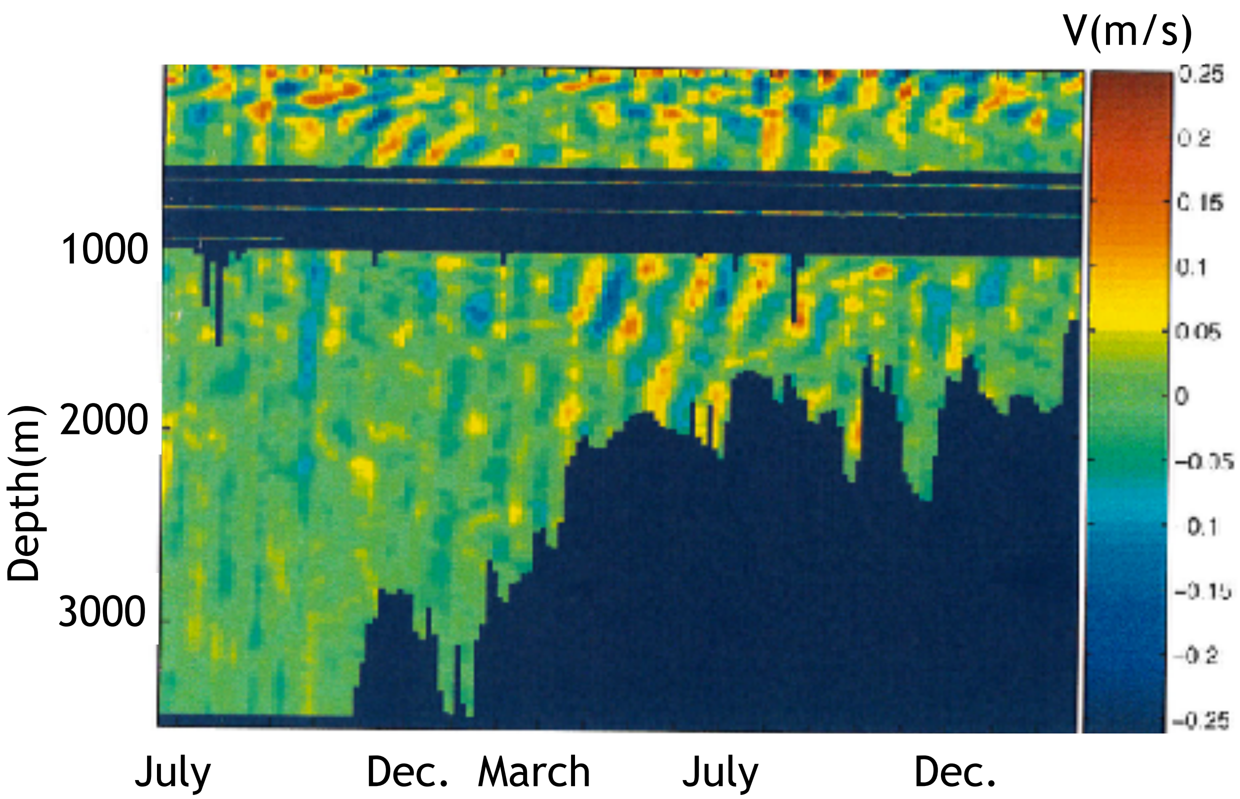
Ascani et al. 2010



A Yanai beam vertically propagating is forced,
EEJ are produced,
while EDJ are not visible



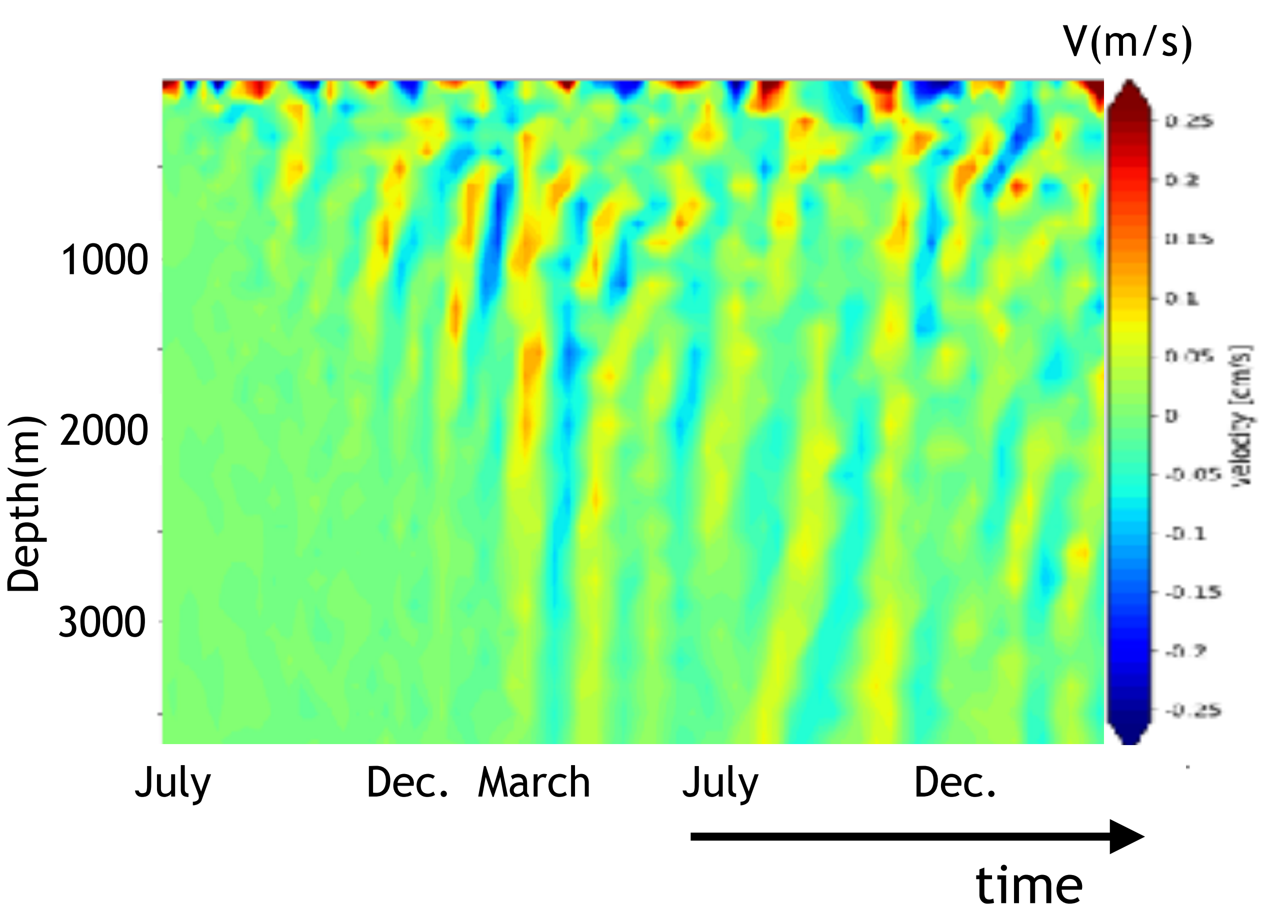
Numerical simulations with an oscillating source at surface, with fixed period

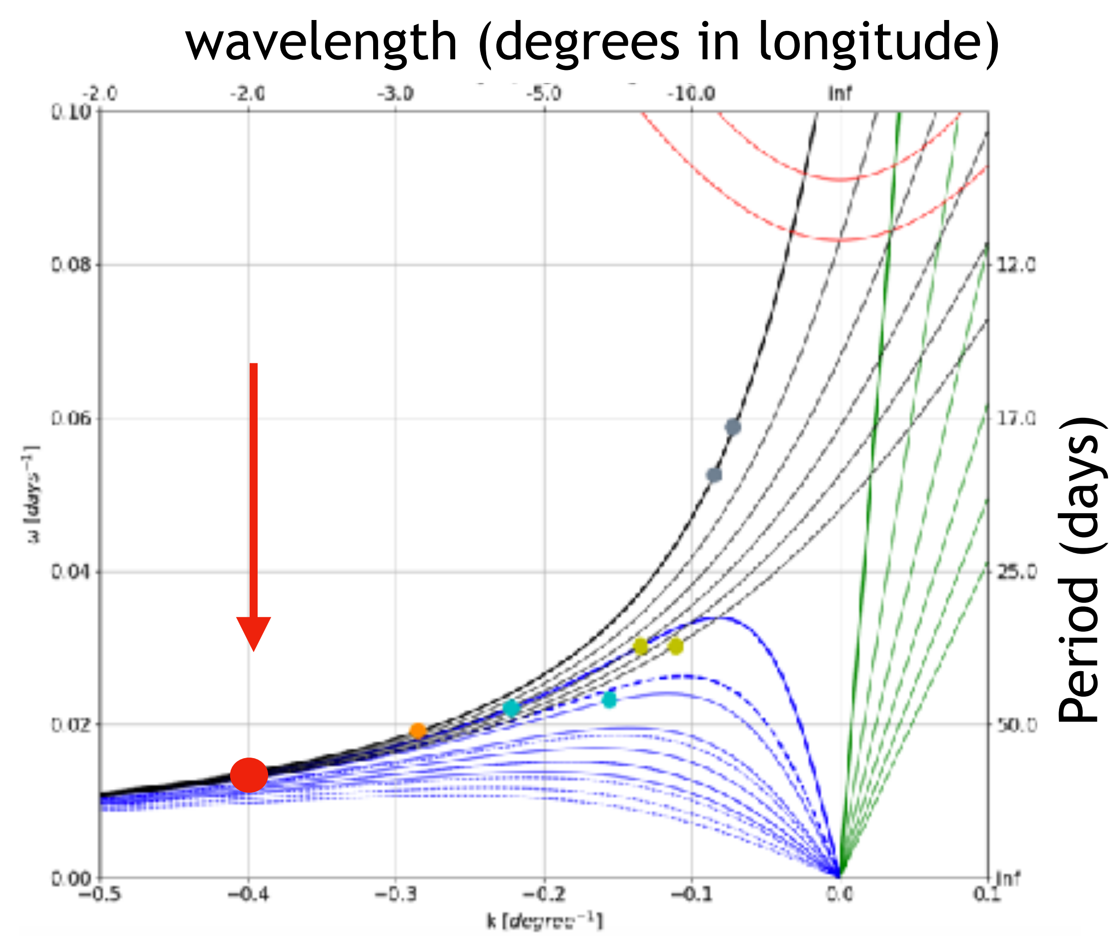


CROCO: Primitive Equations model

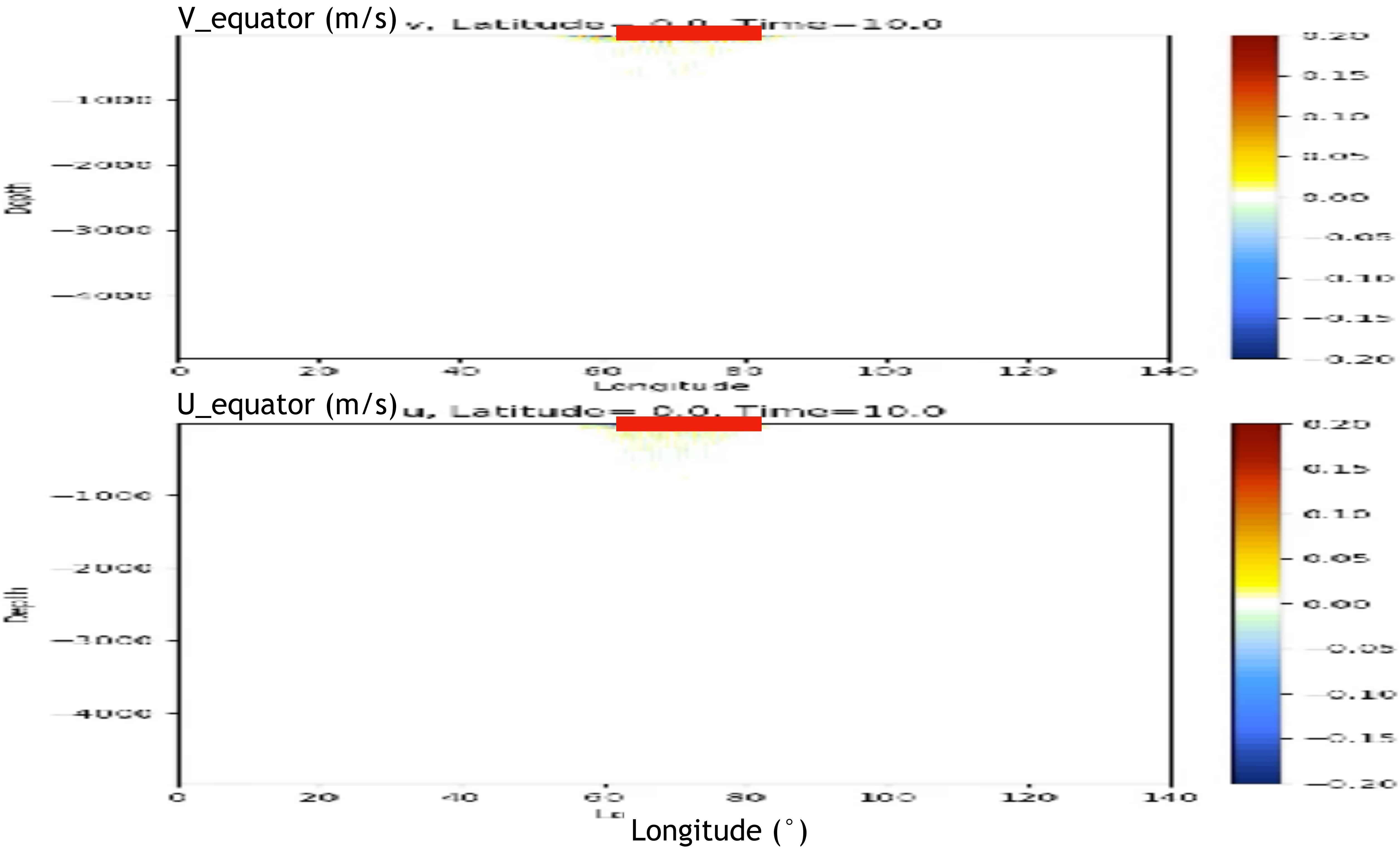
Idealized basin: lat = +/- 20°, lon = 0-140°
equatorial beta-plane
dx = 1/8°, 80 levels
N = 2e-3 s^{-1}

forcing $\tau^y = \tau_0 X(x) Y(y) \sin(kx-\omega t)$
$T = 2\pi/\omega$ = 74 days
$L = 2\pi/k_{Yanai}$





Numerical simulations with an oscillating source at surface, with fixed period

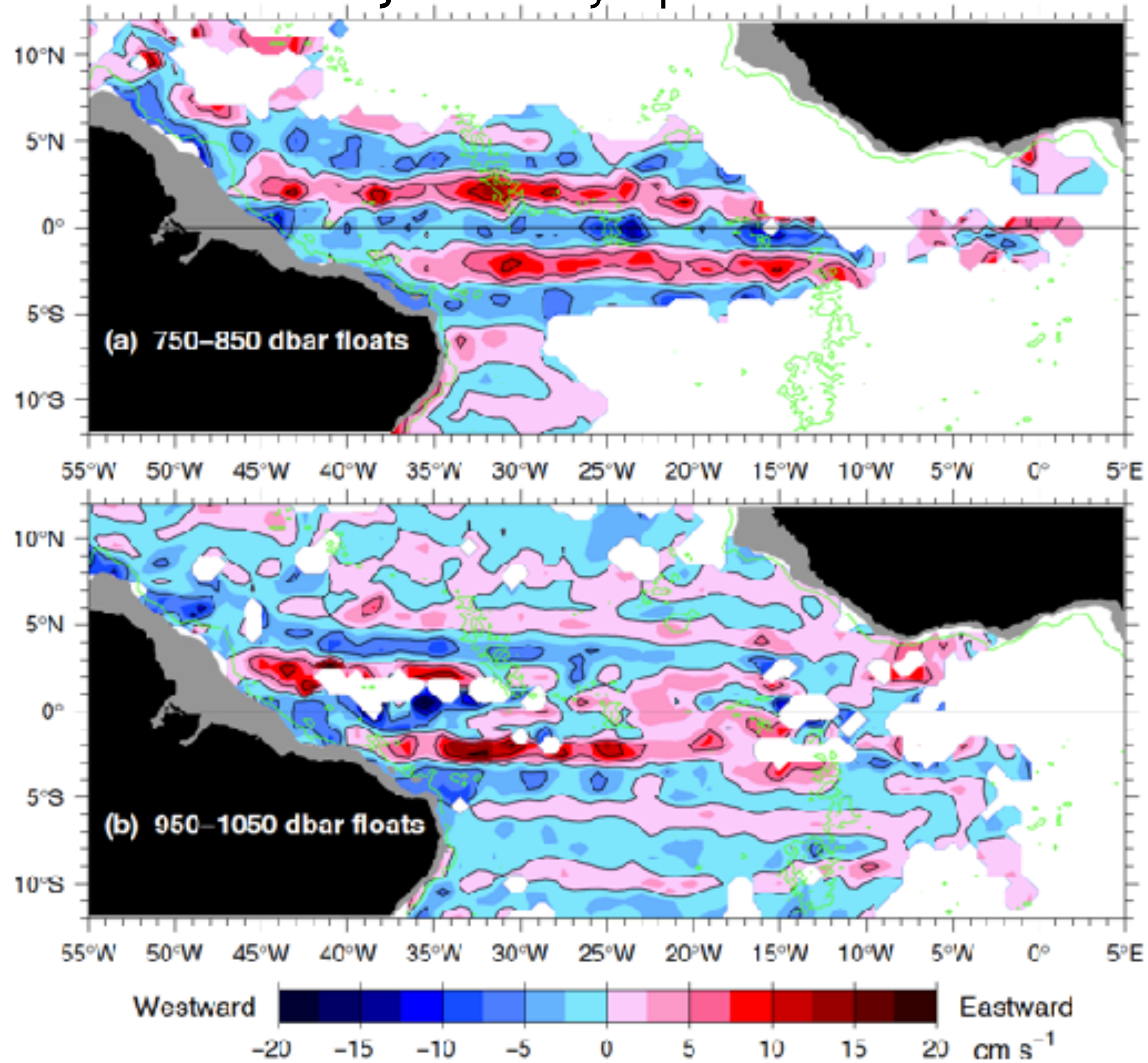


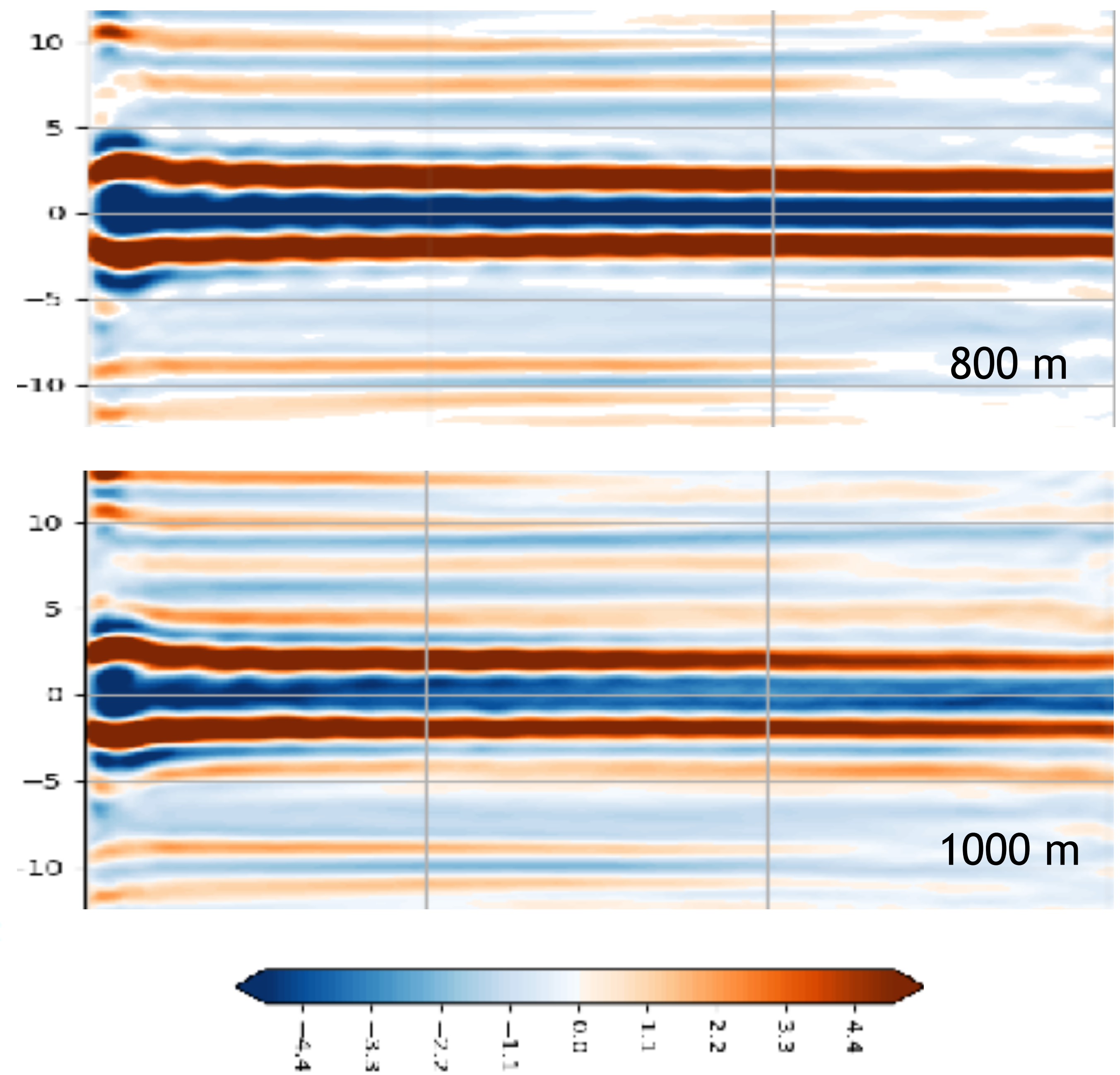
The destabilization of short Yanai wave produces zonal jets with high vertical mode (similar to EDJ)

Numerical simulations with an oscillating source at surface, with fixed period

Lagrangian mean from ARGO floats of **zonal velocity** over a 6 yrs period

Eulerian mean from the model of **zonal velocity** over a 4 yrs period

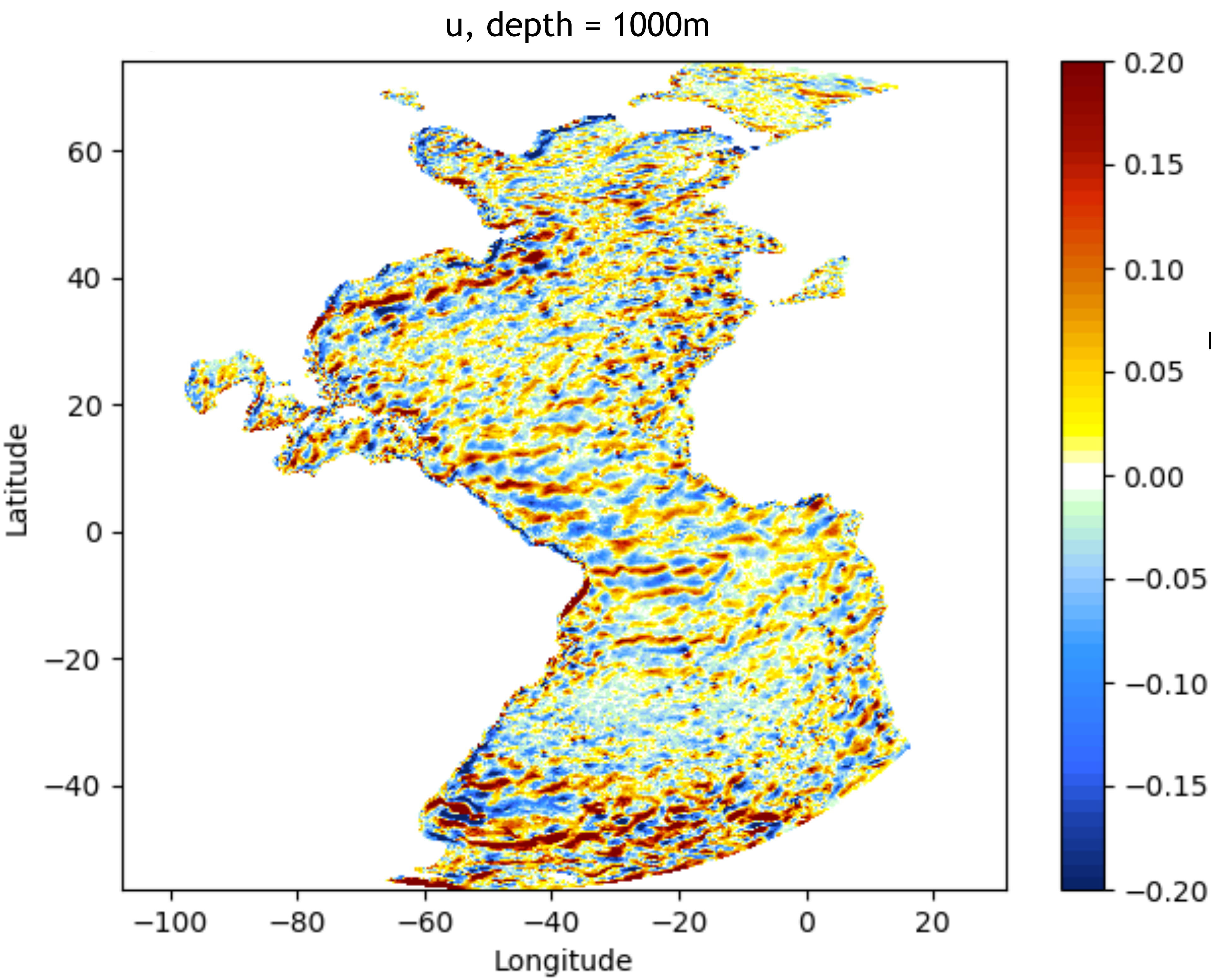




Ollitrault et al. 2006

EEJ are well represented.

Realistic simulations of the Atlantic basin



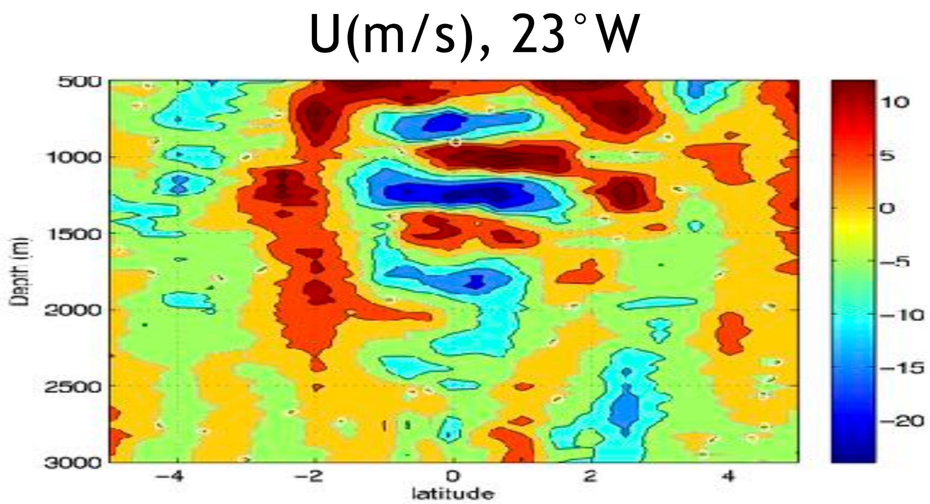
MEGATL - *J. Gula*

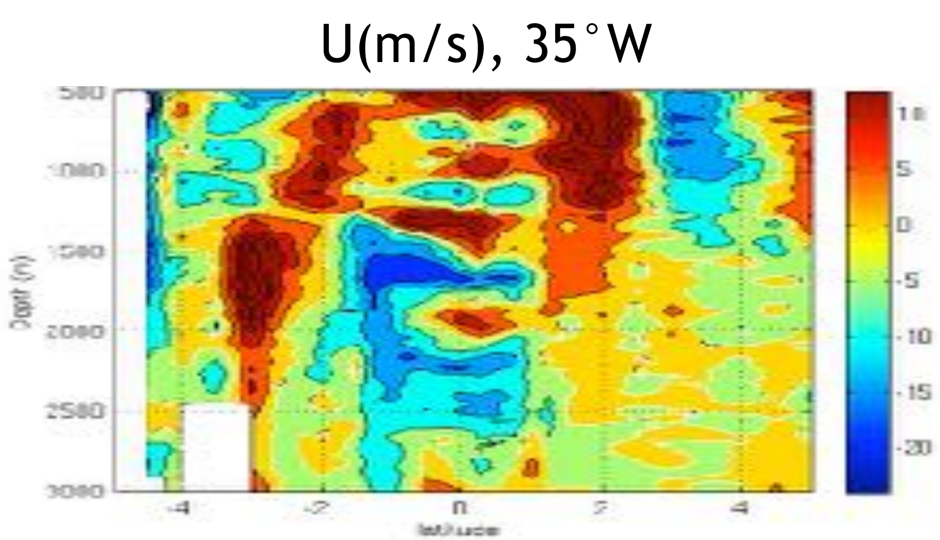
CROCO: Primitive Equations

MEGATL6: dx=6km, 50 levels
MEGATL3: dx=3km, 100 levels
realistic wind forcing (1h or 6h)

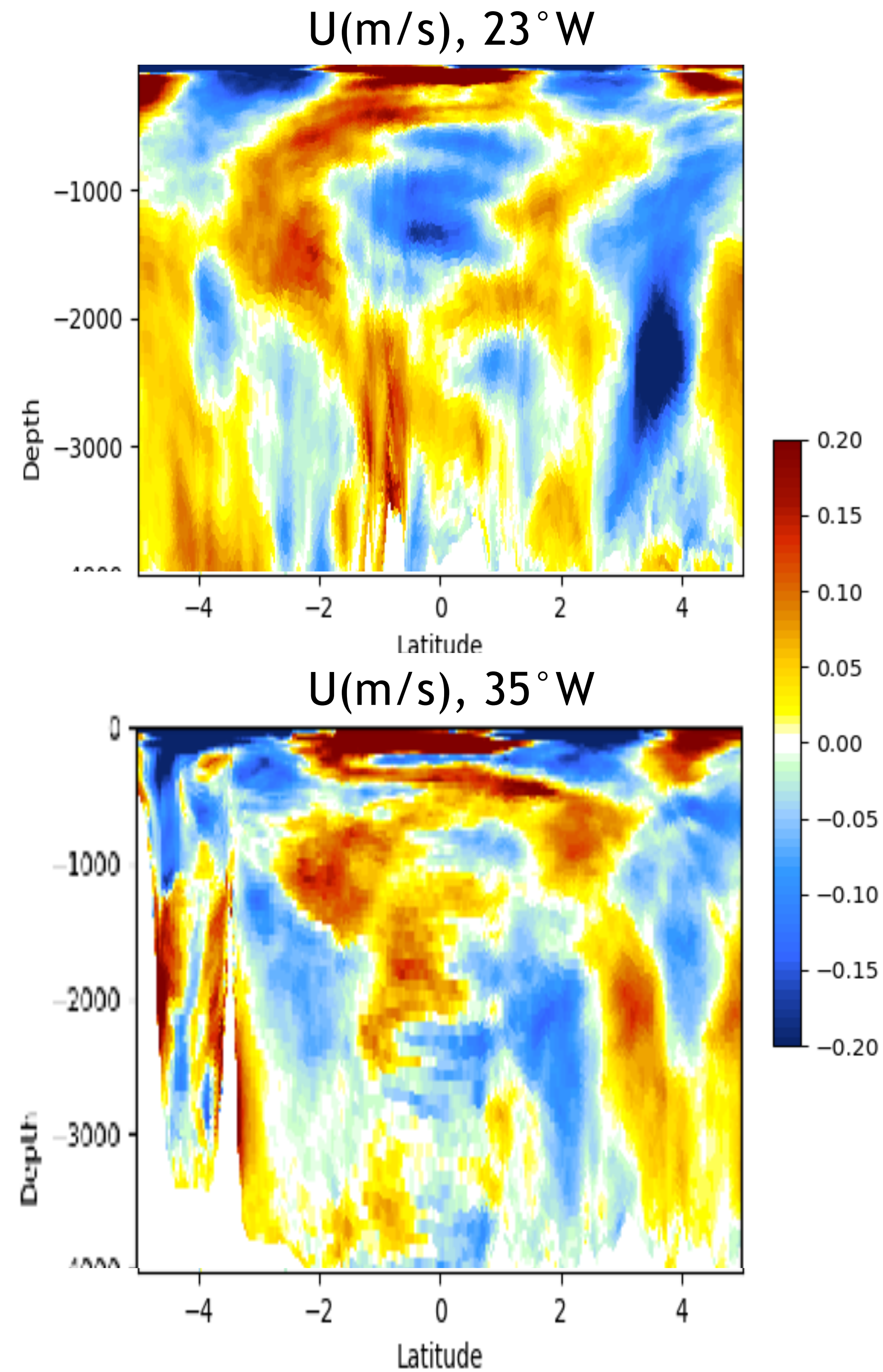
Realistic simulations of the Atlantic basin

observations





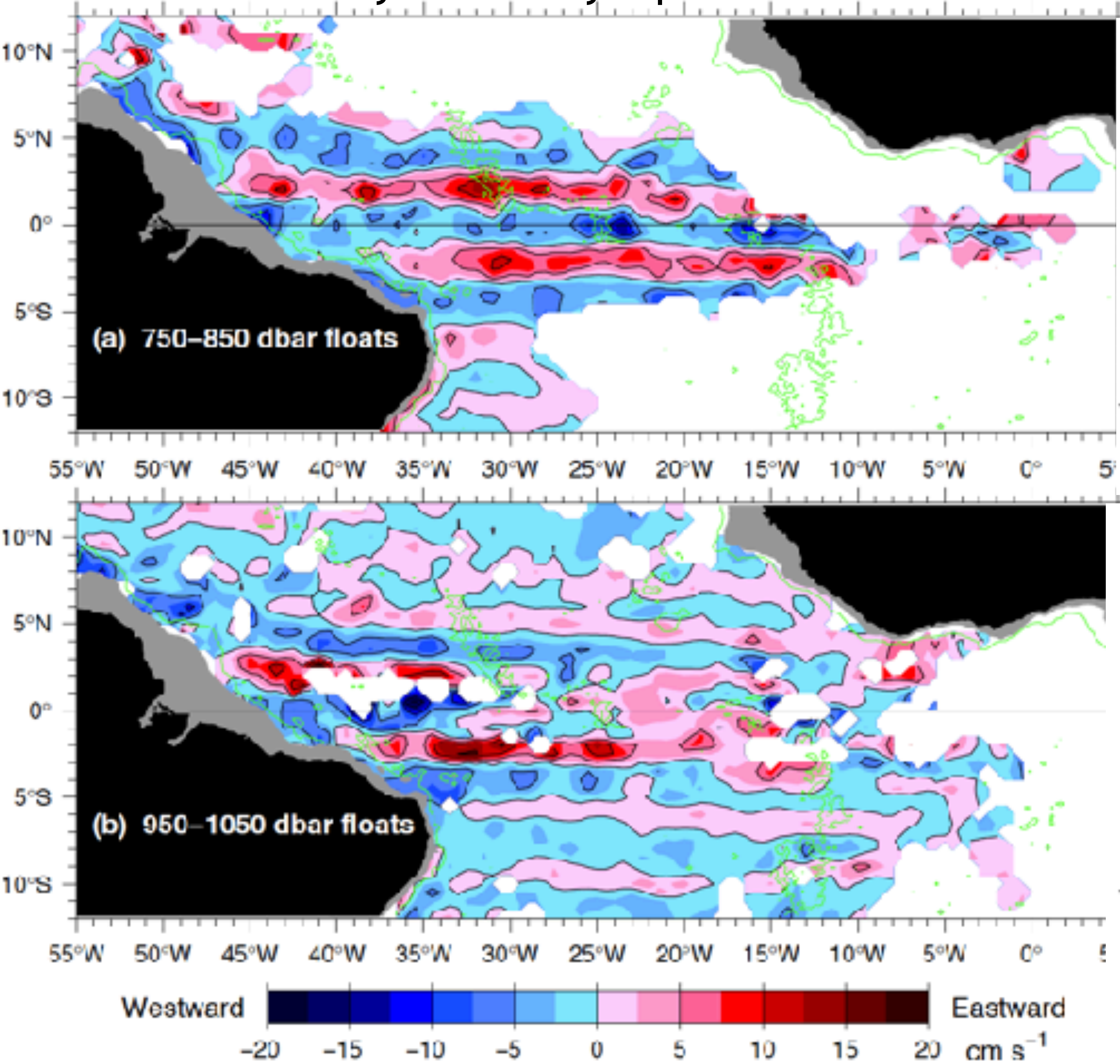
MEGATL



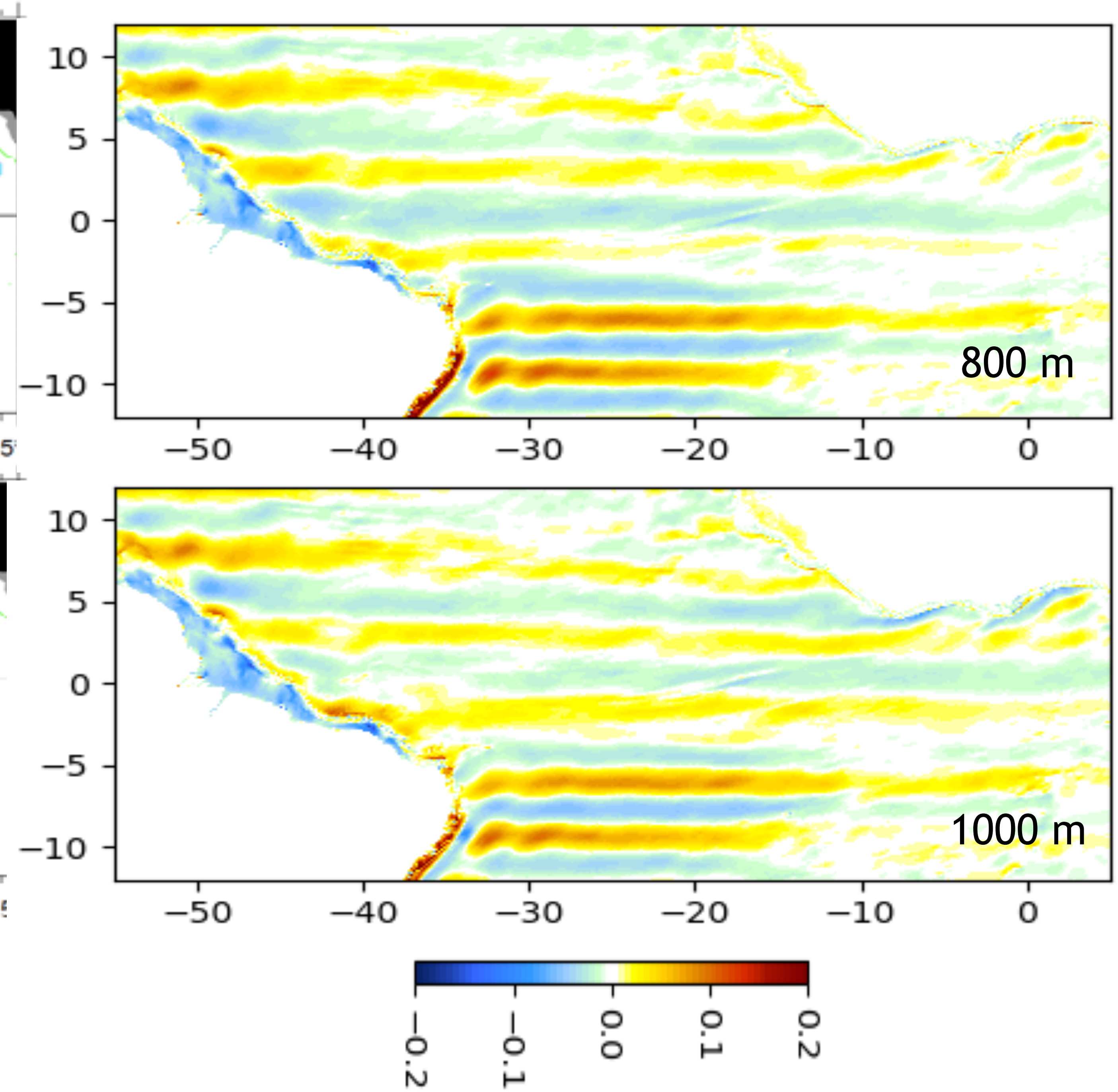
EDJ seems to be reproduced, analysis in progress…

Realistic simulations of the Atlantic basin

Lagrangian mean from ARGO floats of zonal velocity over a 6 yrs period



Eulerian mean from the model of **zonal velocity** over a 4 yrs period



EEJ are well represented, even at tropical latitudes.

Conclusions

- The destabilization of a short equatorial wave produces zonal jets at the equator and in its vicinity
- EDJ and first EEJ were well-reproduced in idealized simulations
- We begin to have results forming EEJ until +-20° off the equator in idealized configuration and realistic simulations.

Perspectives (Audrey Delpech's PhD)

- How propagate meridional velocity variability at depth?
  (characterization of the modeled short primary wave)
- What are the characteristics of the modelized zonal jets?
  (meridional extension, meridional wavenumber, …)
- Is there a link (as we expect) between DEIV and zonal jets characteristics?

Thank you!