Les courants-jets sous-marins: enjeux climatiques et défis scientifiques

Prix André Prud'homme 2022

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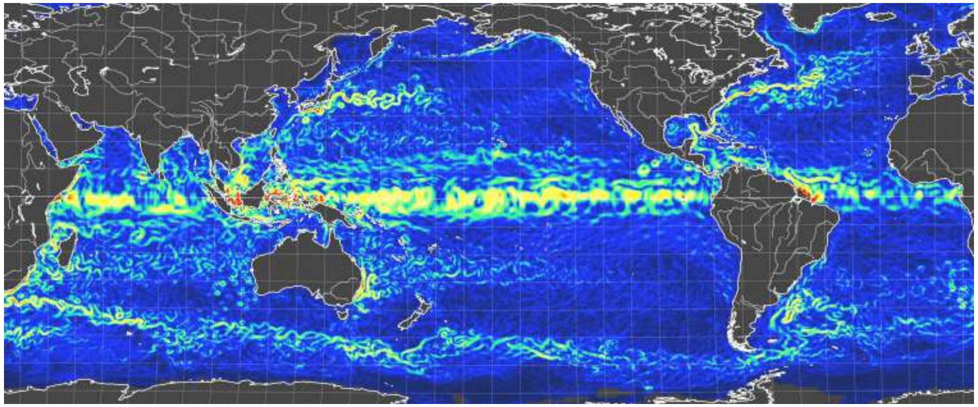
Introduction
Context

- Ocean currents play an important role in the climate system as they transport and heat and carbon at a global scale

- The understanding and predictions of ocean currents and their variability are therefore crucial to the development of climate models

- At the surface : ocean currents have been extensively observed thanks to satellite data and other in-situ data

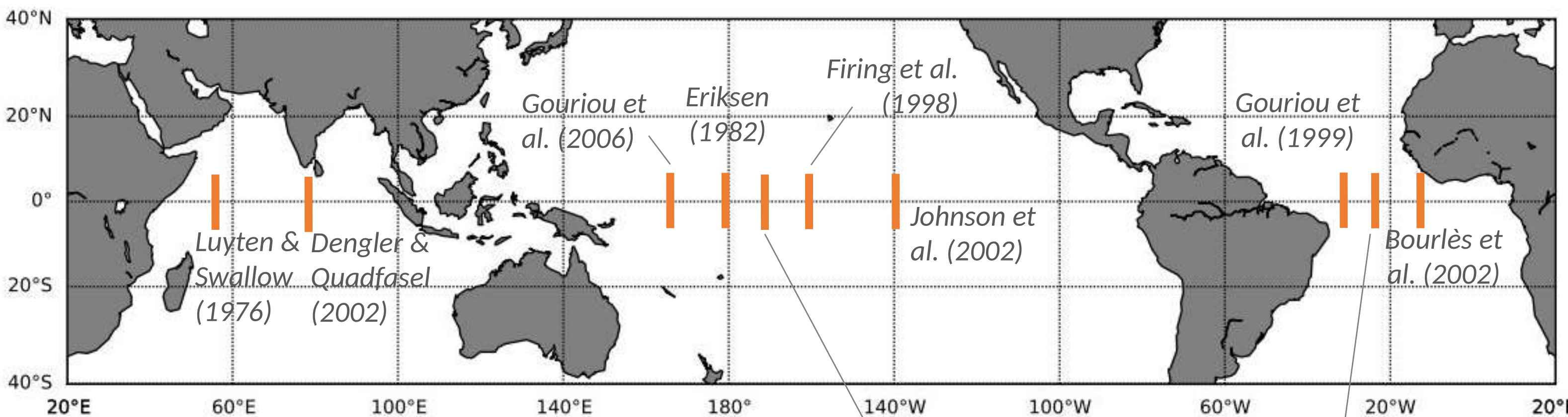


Surface currents for 20/01/2021 (OSCAR)

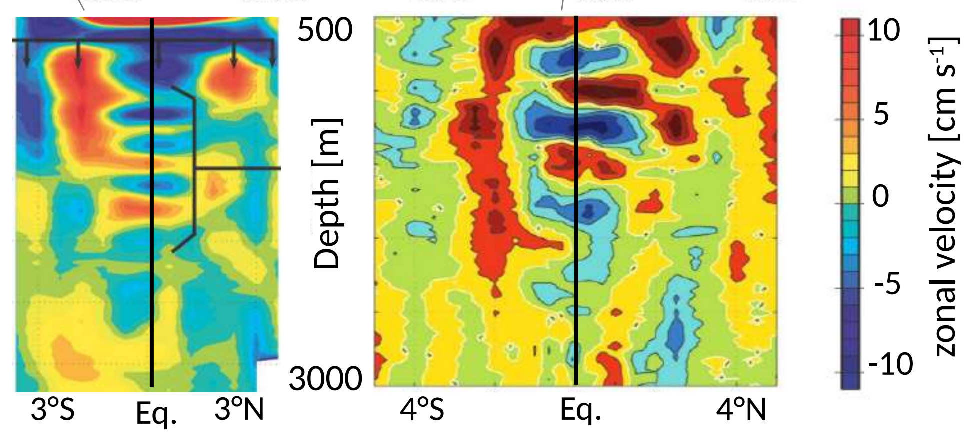
- At depth: only sparse observations, for long currents where considered very weak and the ocean almost at rest

Introduction
Observation of deep currents

First in-situ measurements from cruises or moorings



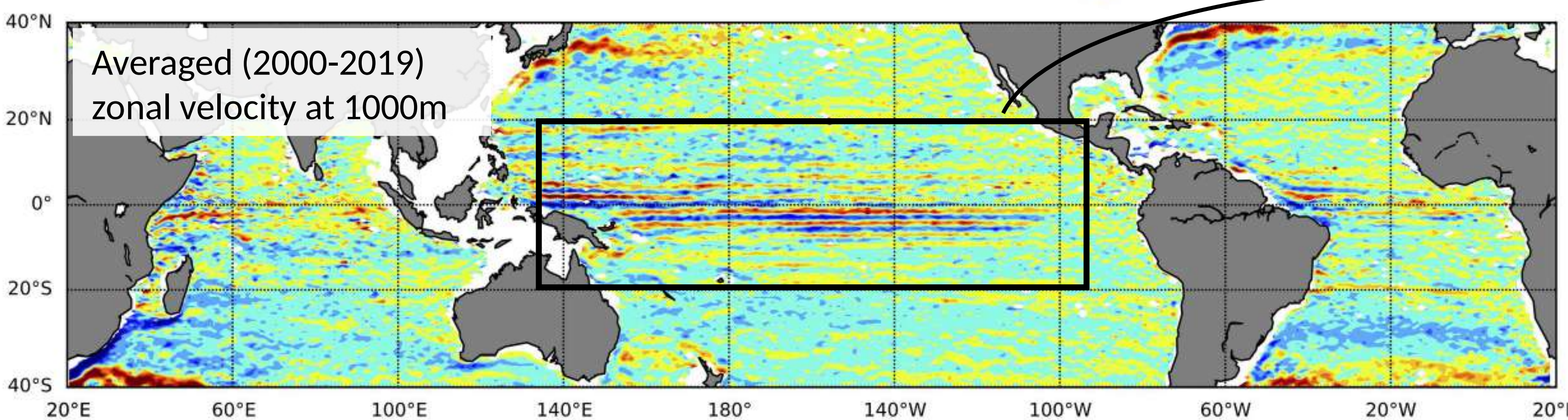
- Predominance of zonal currents
- Reversing direction with depth at the Equator
- Reversing direction with latitude off the Equator.

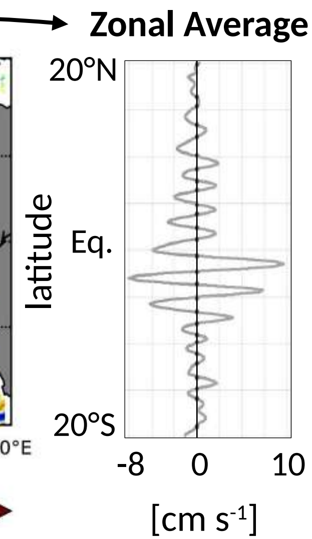


Firing et al. (1987) *Gouriou et al. (2001)*

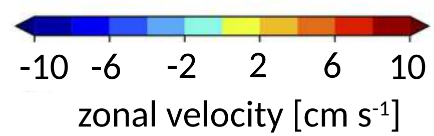
Introduction
Observation of deep currents

Global observation of the deep currents at 1000 m by Argo float drifts since 2000





Adapted from Ollitrault et al. (2006), Lebedev et al. (2007), Cravatte et al. (2012), Ollitrault et al. (2014)



Continuity of zonal currents at 100m: **deep zonal jets**

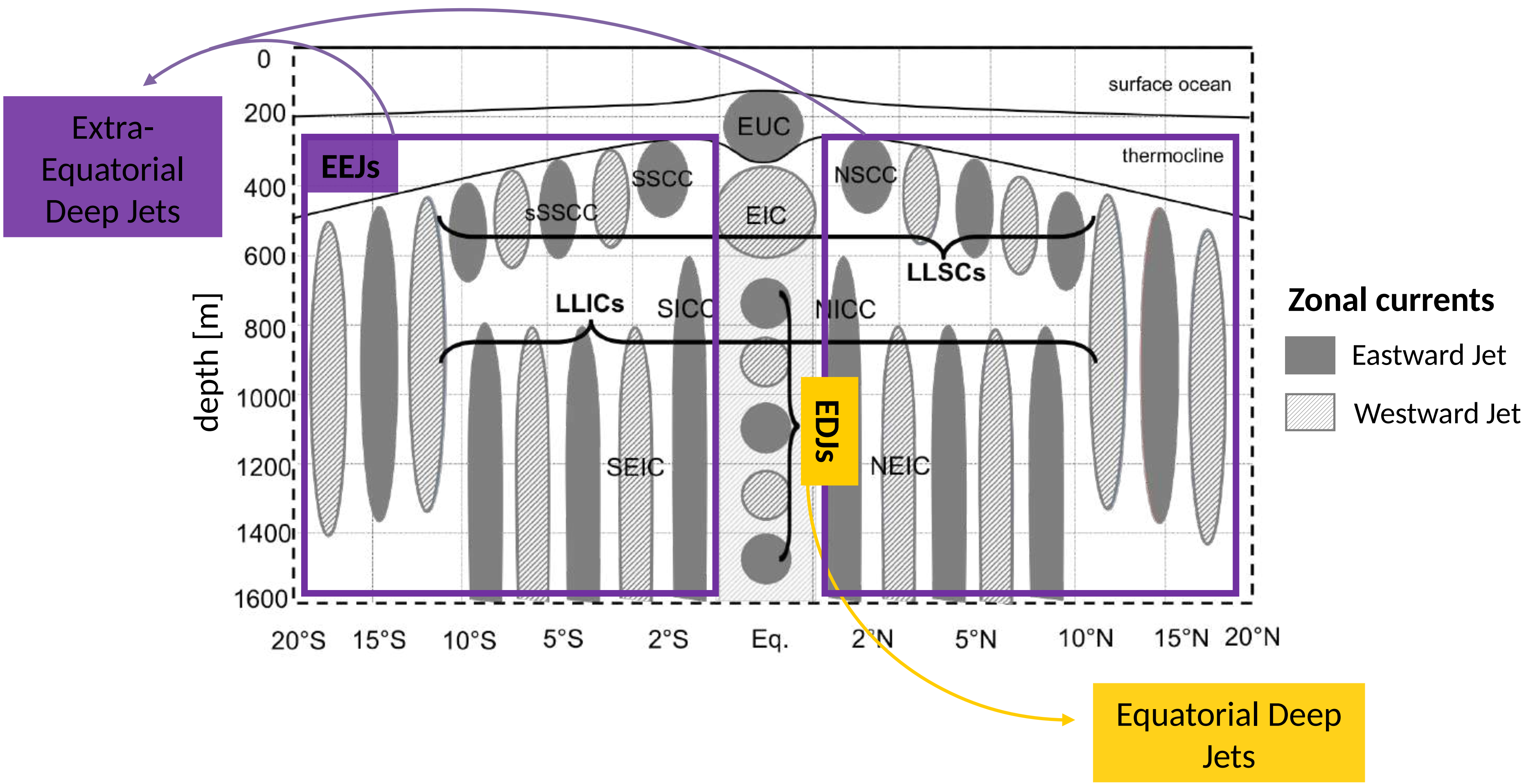
+ vertical structure investigated by

Cravatte et al. (2017)

Introduction
Observation of deep currents

Schematic representation of the deep jets

From *Ménesguen, Delpech et al. (2019)*, based on observations from *Cravatte et al. (2017)*

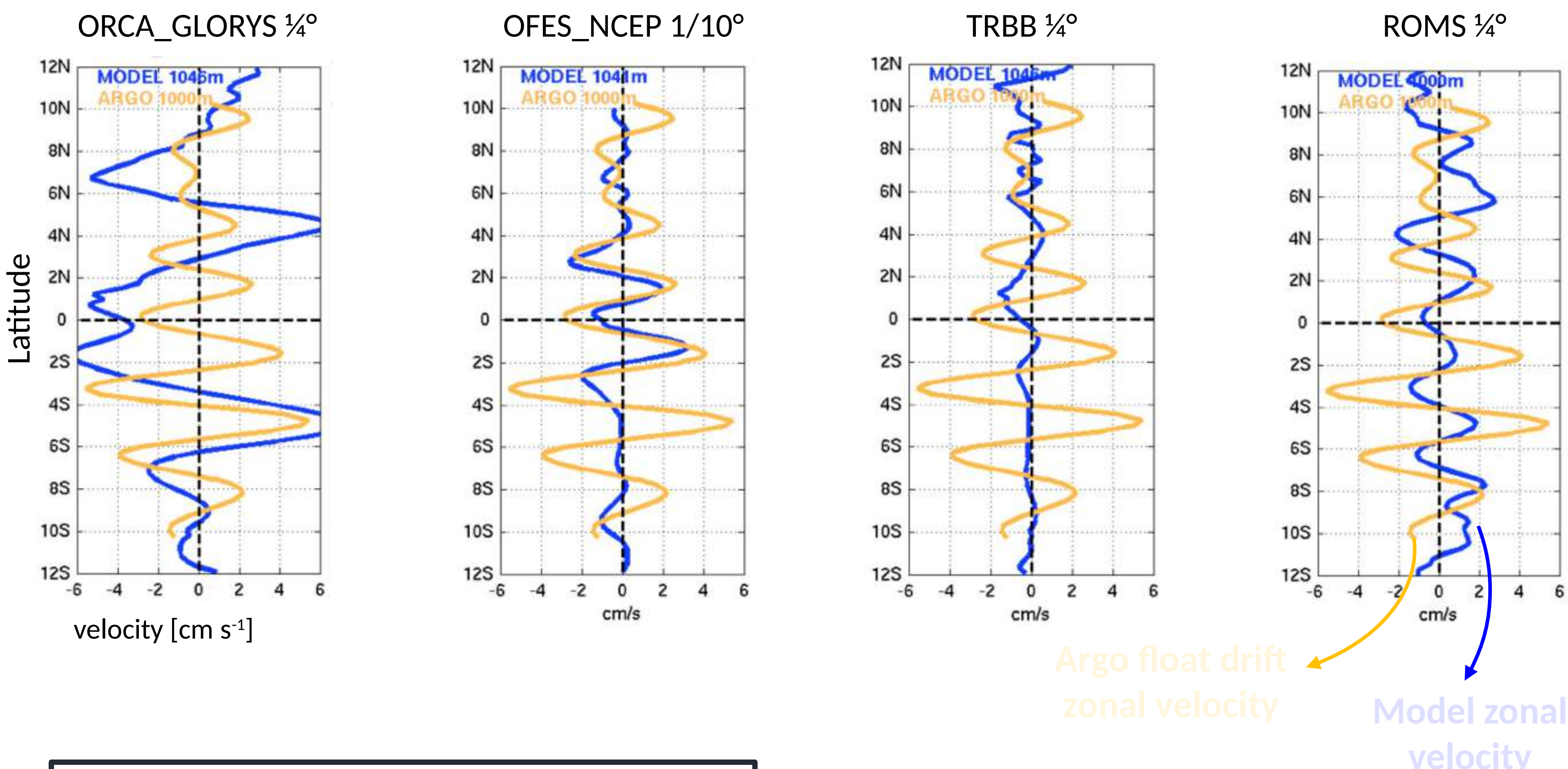


Introduction
Scientific questions

- How do low-latitude deep zonal jets contribute to the global ocean circulation?
- Do they play a role in the transport of water masses?
- What physical processes control their formation and maintenance?
- Are they well represented in climate models?

Introduction
Deep zonal jets in climate models

Comparison of models with observations: zonal average (165°E – 175°E) of zonal velocity at 1000 m

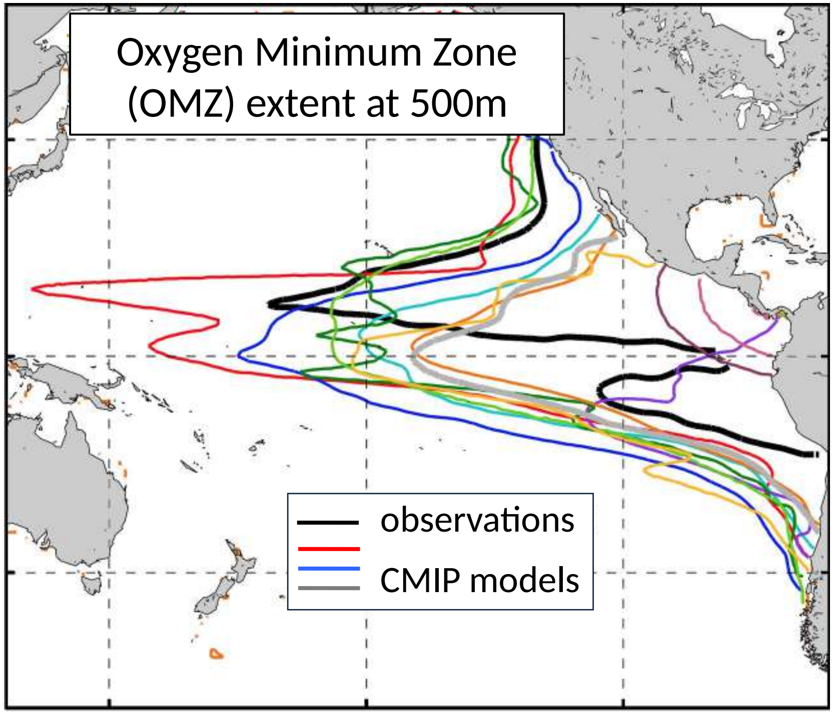


Deep jets are **misrepresented in all models**

Cravatte et al. (2014)

Introduction
Biogeochemical feedback of deep zonal jets

Systematic bias in the representation of the Oxygen Minimum Zones in climate models

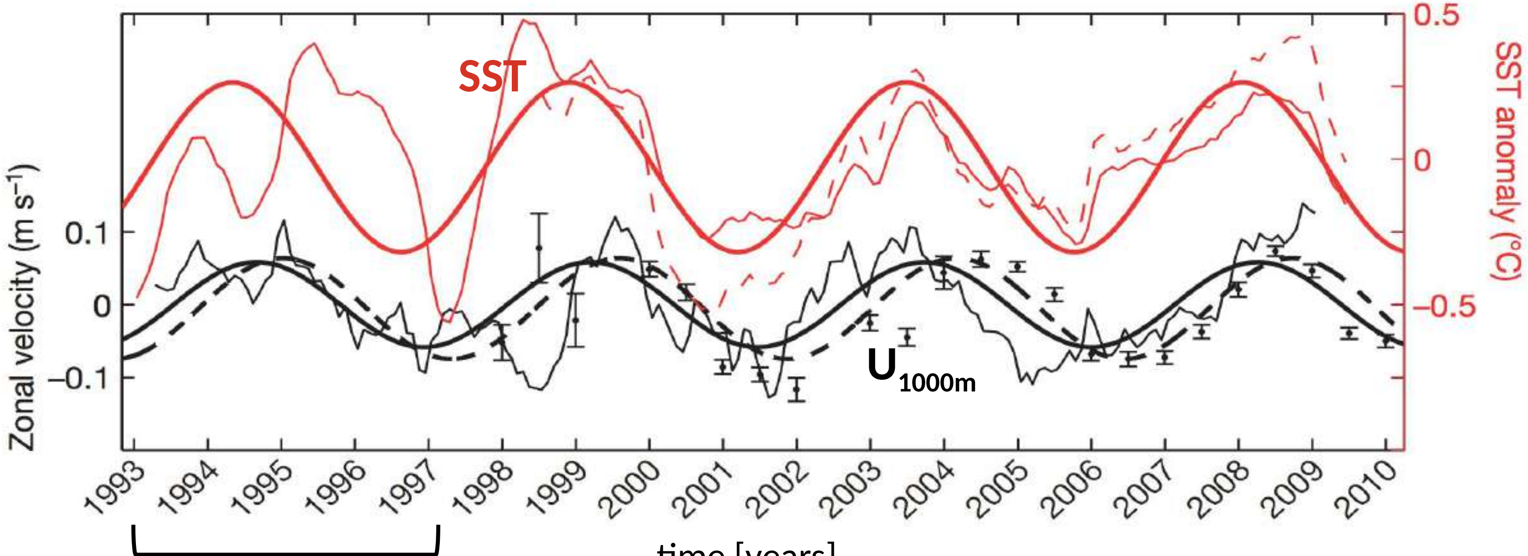


(Cabre et al., 2015)

Implications for **physical-biological coupling** and **carbon cycle estimation**

Introduction
Atmospheric feedback of deep zonal jets

Decadal Modulation of Sea Surface Temperature (SST) by Equatorial Deep Jets in the Atlantic Ocean.



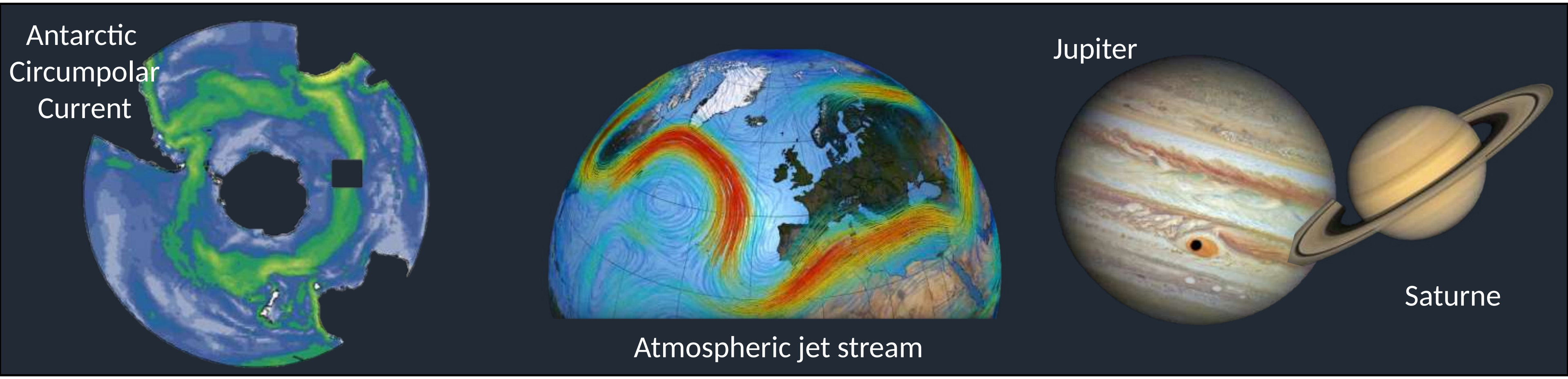
(Brandt et al., 2011)

Implications for **ocean-atmosphe coupling** and **prediction of rainfalls** in equatorial regions

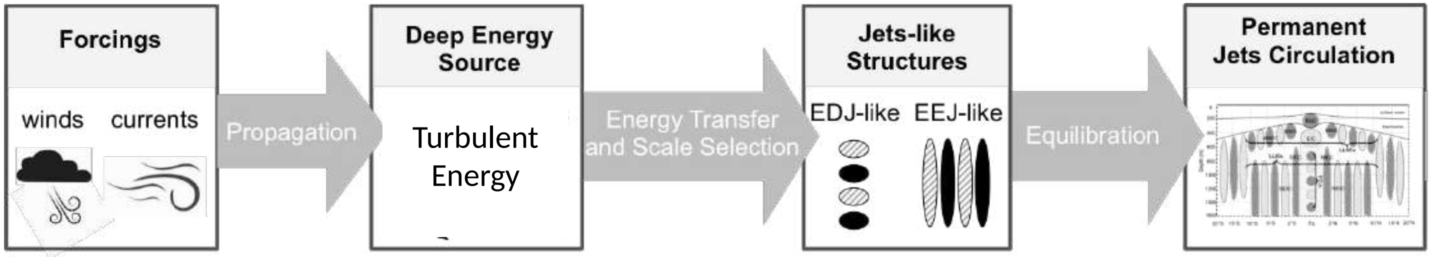
Introduction
Theories for zonal jet formation

A mystery…

… in oceanic physics **… in atmospheric physics** **… in astrophysics**

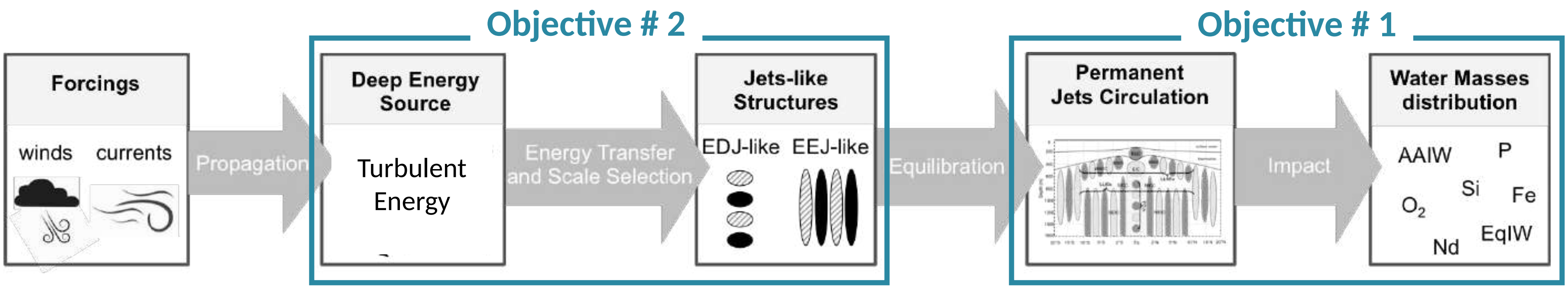


Introduction
Theories for zonal jet formation



Introduction
Thesis Objectives

Objective 1 Assess the impact of the deep jets at on the transport and transformation of water masses



Objective 2 Understand the energy sources and energy pathways for the formation of the deep jets

Outline

1. Introduction

2. Impact of deep jets on water masses

   [Delpech et al. (2020a). Observed tracer fields structuration by deep zonal jets in the tropical Pacific. *Journal of Physical Oceanography*.]

3. Energy Sources in the deep ocean at low-latitudes

   [Delpech et al. (2020b). Deep Eddy Kinetic Energy in the tropical Pacific from Lagrangian floats. *Journal of Geophyscial Research: Oceans*.]

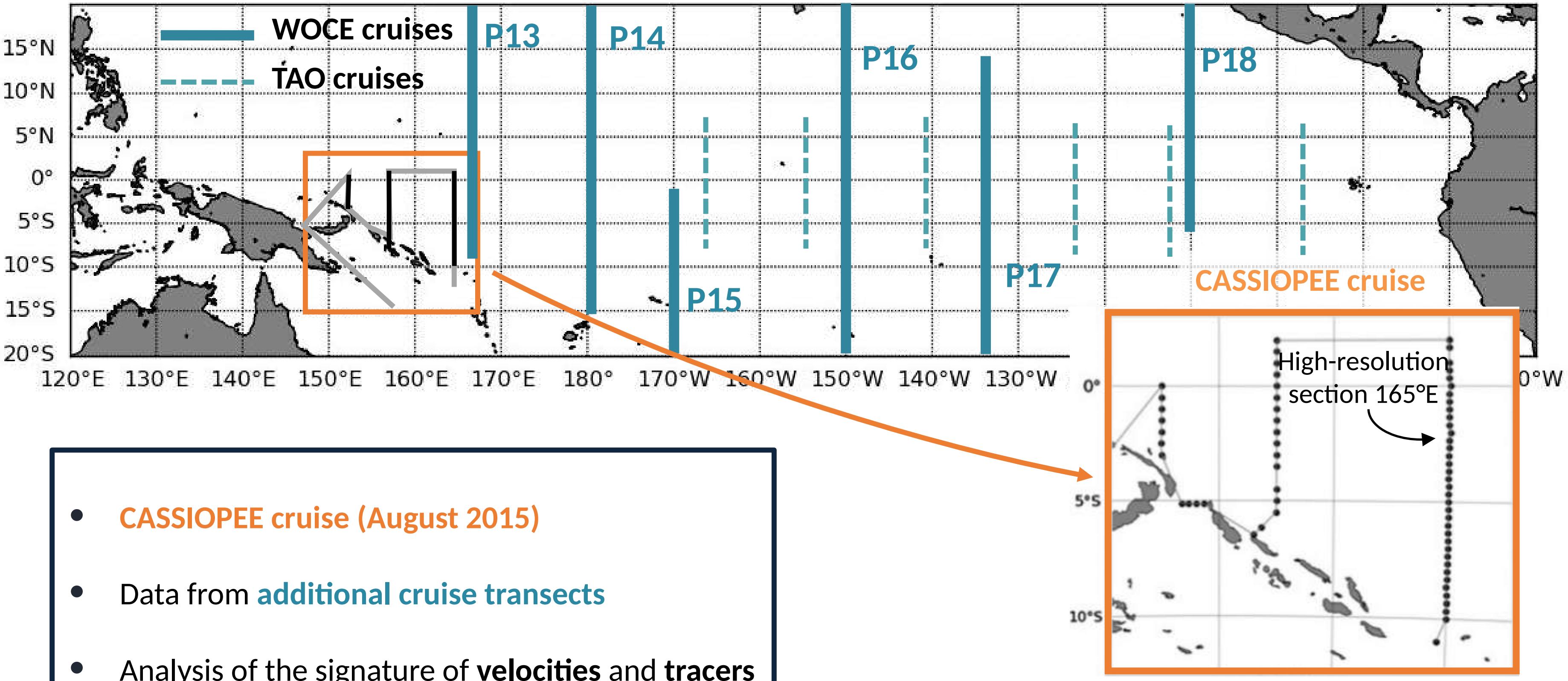
4. Mechanisms for the formation of the deep jets

   [Delpech et al. (2020c). Intra-annual waves destabilization as a potential driver of the deep low-latitude zonal jets: Barotropic Dynamics. *Journal of Physical Oceanography*.]

5. Conclusions and Perspectives

2. Impact of deep jets on water masses
Method

Cruise transects used to characterize the deep jets and their water masses

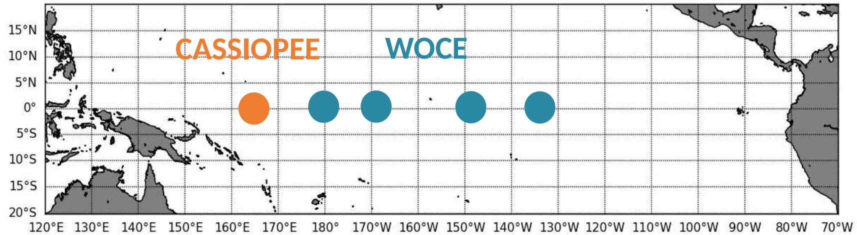


- **CASSIOPEE cruise (August 2015)**
- Data from **additional cruise transects**
- Analysis of the signature of **velocities** and **tracers of water masses**: O_2 (oxygen), **S** (salinity) and **PV** (potential vorticity)

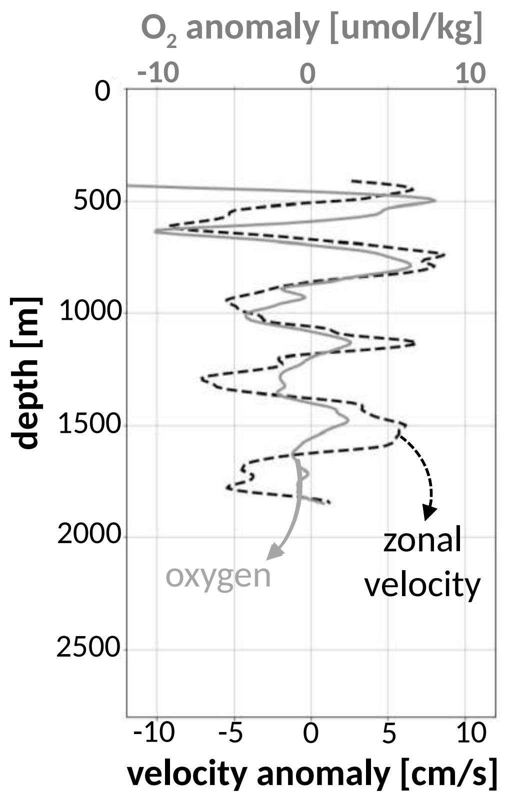
2. Impact of deep jets on water masses
Tracers signature in Equatorial Deep Jets

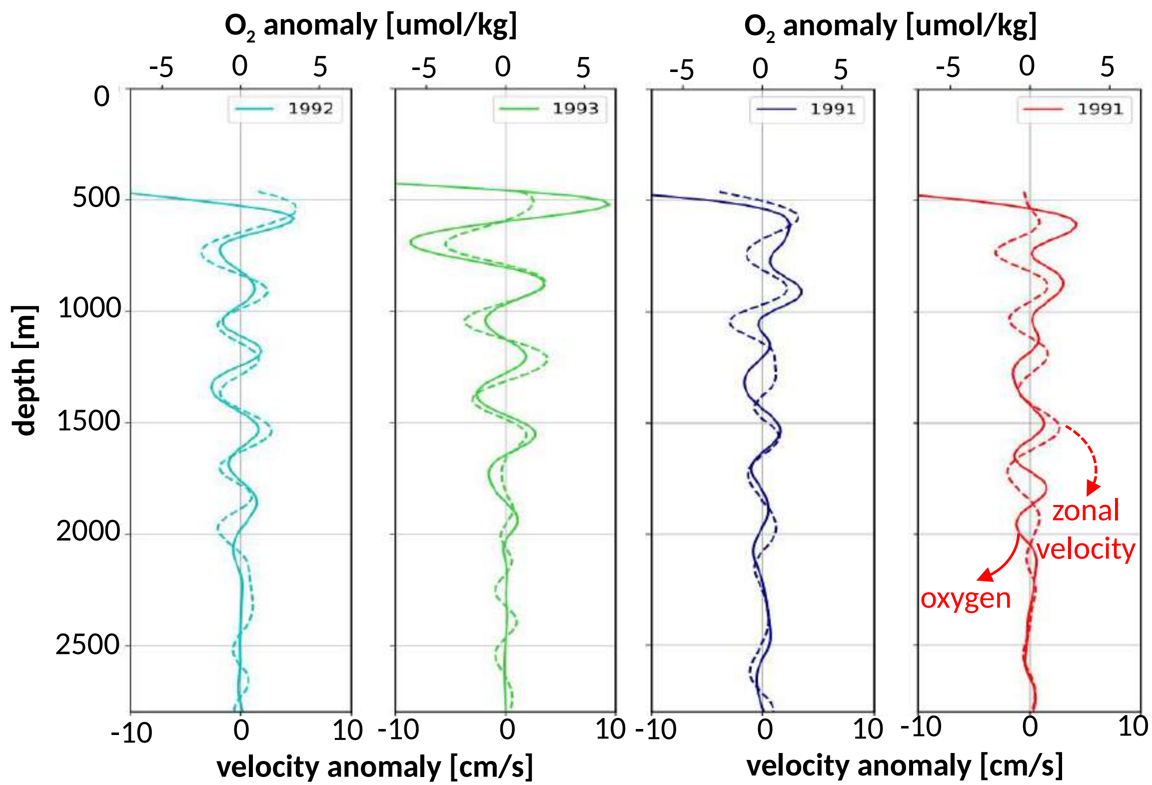
- O_2 maxima in eastward jets
- O_2 minima in westward jets

↳ **Equatorial deep jets transport oxygen towards the Eastern Pacific OMZ**



Equatorial Profiles of zonal velocity and oxygen

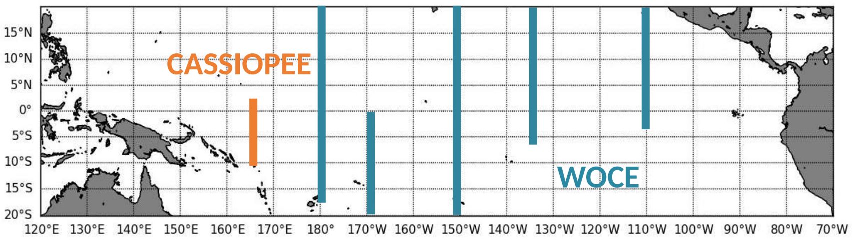




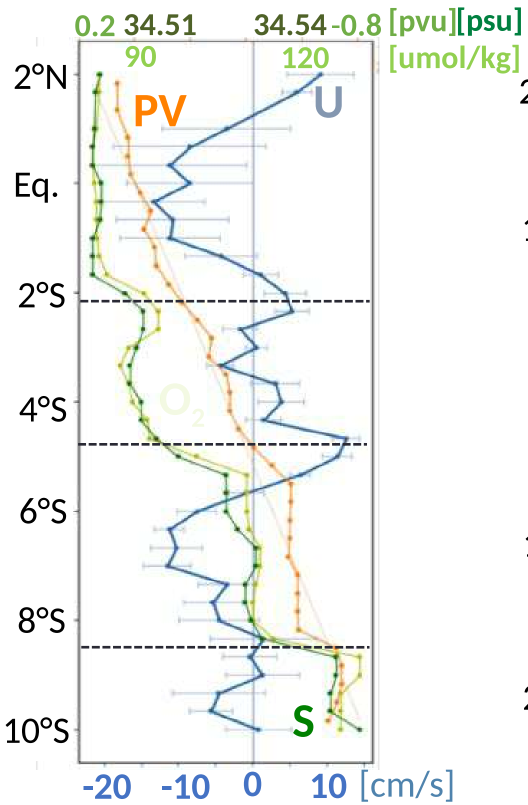
2. Impact of deep jets on water masses
Tracers signature in Extra-Equatorial Deep Jets

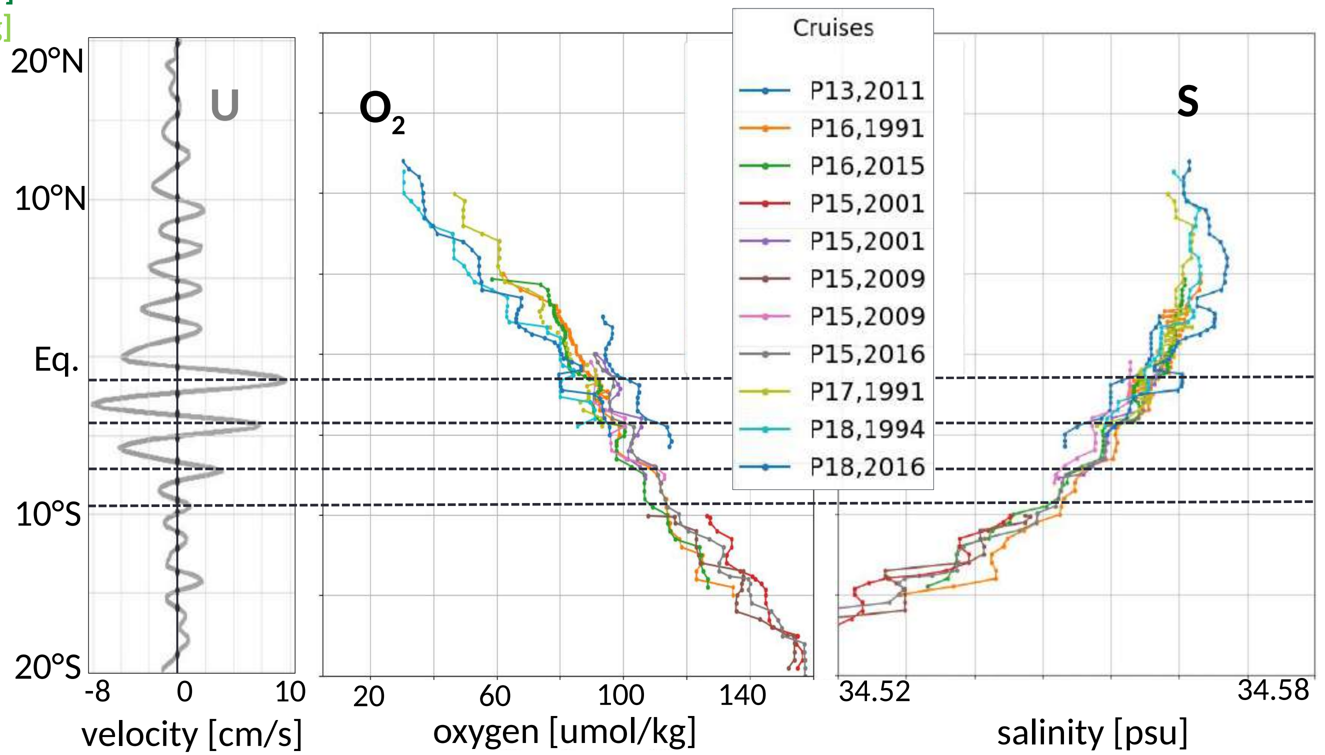
- Sharp gradient (fronts) in eastward jets
- Smooth gradient in westward jets = presence of mixing

↳ **Extra-Equatorial Deep Jets contribute to the mixing of water masses**



vertical average of zonal velocity and tracers

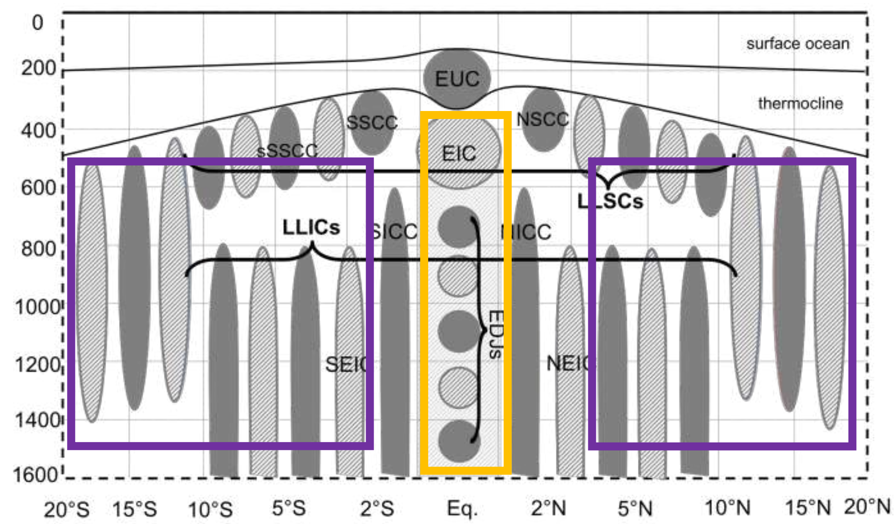




2. Impact of deep jets on water masses
Summary

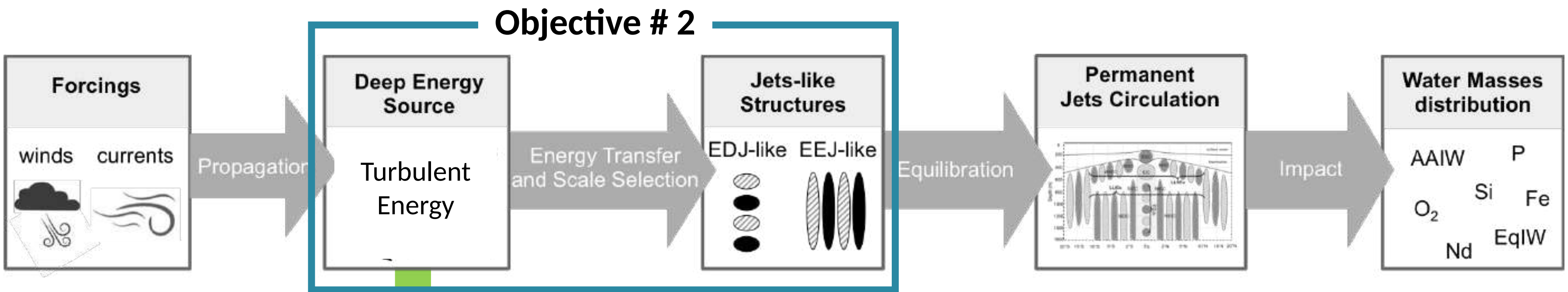
The deep jets contribute to:

- **The ventilation (= oxygen advection)** of the eastern Pacific OMZ
- **The erosion of water masses (= transformation by mixing)** advected equatorward from both hemispheres



Confirm the hypothesis of *Cabre et al. 2015* that the misrepresentation of the deep jets in climate model could explain the systematic bias in the OMZ extent

Outline



2 Understand the energy sources and energy pathways for the formation of the deep jets

- What is the spatial distribution of turbulent energy at depth ?
- What are the spectral characteristics of this energy ?

Outline

1. Introduction

2. Impact of deep jets on water masses

   [Delpech et al. (2020a). Observed tracer fields structuration by deep zonal jets in the tropical Pacific. *Journal of Physical Oceanography*.]

3. Energy Sources in the deep low-latitude ocean

   [Delpech et al. (2020b). Deep Eddy Kinetic Energy in the tropical Pacific from Lagrangian floats. *Journal of Geophyscial Research: Oceans*.]

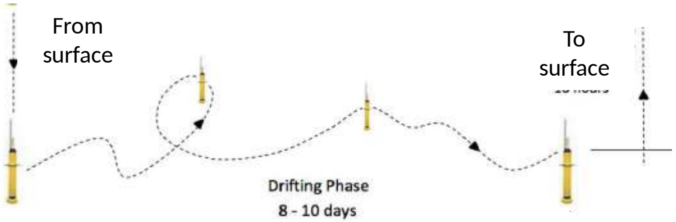
4. Mechanisms for the formation of the deep zonal jets at low latitude

   [Delpech et al. (2020c). Intra-annual waves destabilization as a potential driver of the deep low-latitude zonal jets: Barotropic Dynamics. *Journal of Physical Oceanography*.]

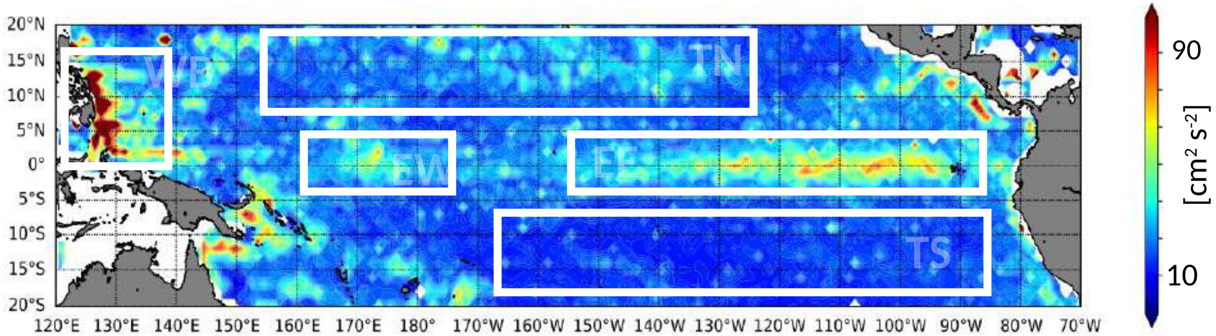
5. Conclusions and Perspectives

3. Deep Energy Sources
Method

Computation of Turbulent (Eddy) Kinetic Energy (EKE) from Argo float deep velocity estimates



Mean EKE at 1000 m (1999-2019)



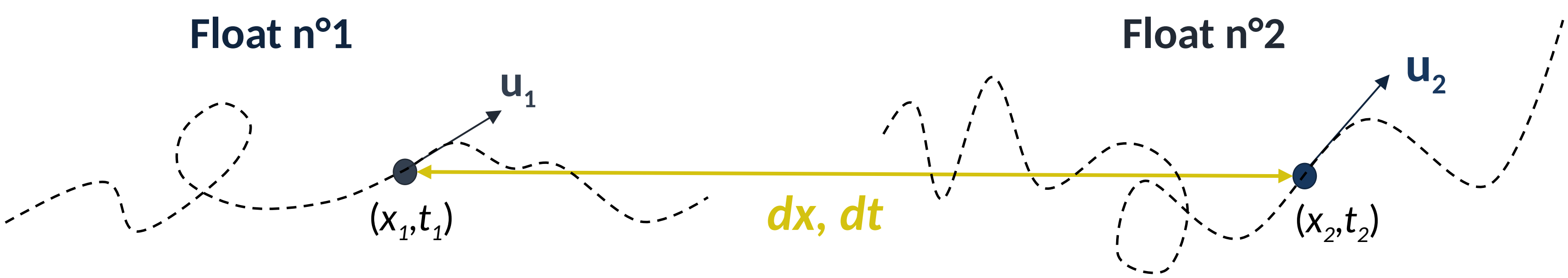
Objective

Characterize the spectral scales of the EKE in each region

Irregular data set.
Not suitable for Fourier transform

3. Deep Energy Sources Method

Statistical Scale Function (SSF)



Definition

number of measurements that satisfy the time and scale separation conditions

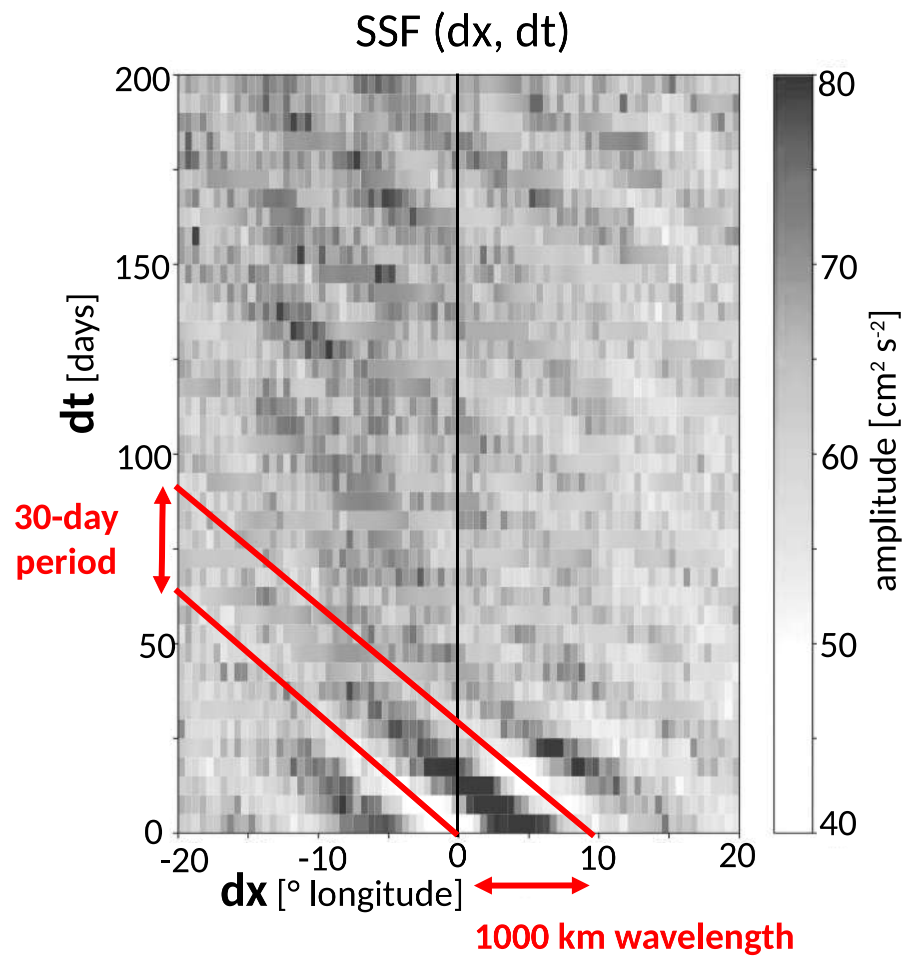
$$\mathrm{SSF}_{\mathbf{u}}(dx, dt) = \frac{1}{n_{ij}} \sum_{\{i,j\} \,\middle|\, \substack{x_j - x_i = dx \\ t_j - t_i = dt}} (\mathbf{u_j} - \mathbf{u_i})^2$$

Scale-dependent statistics

Velocity increment

3. Deep Energy Sources

Example in the Eastern Equatorial Pacific

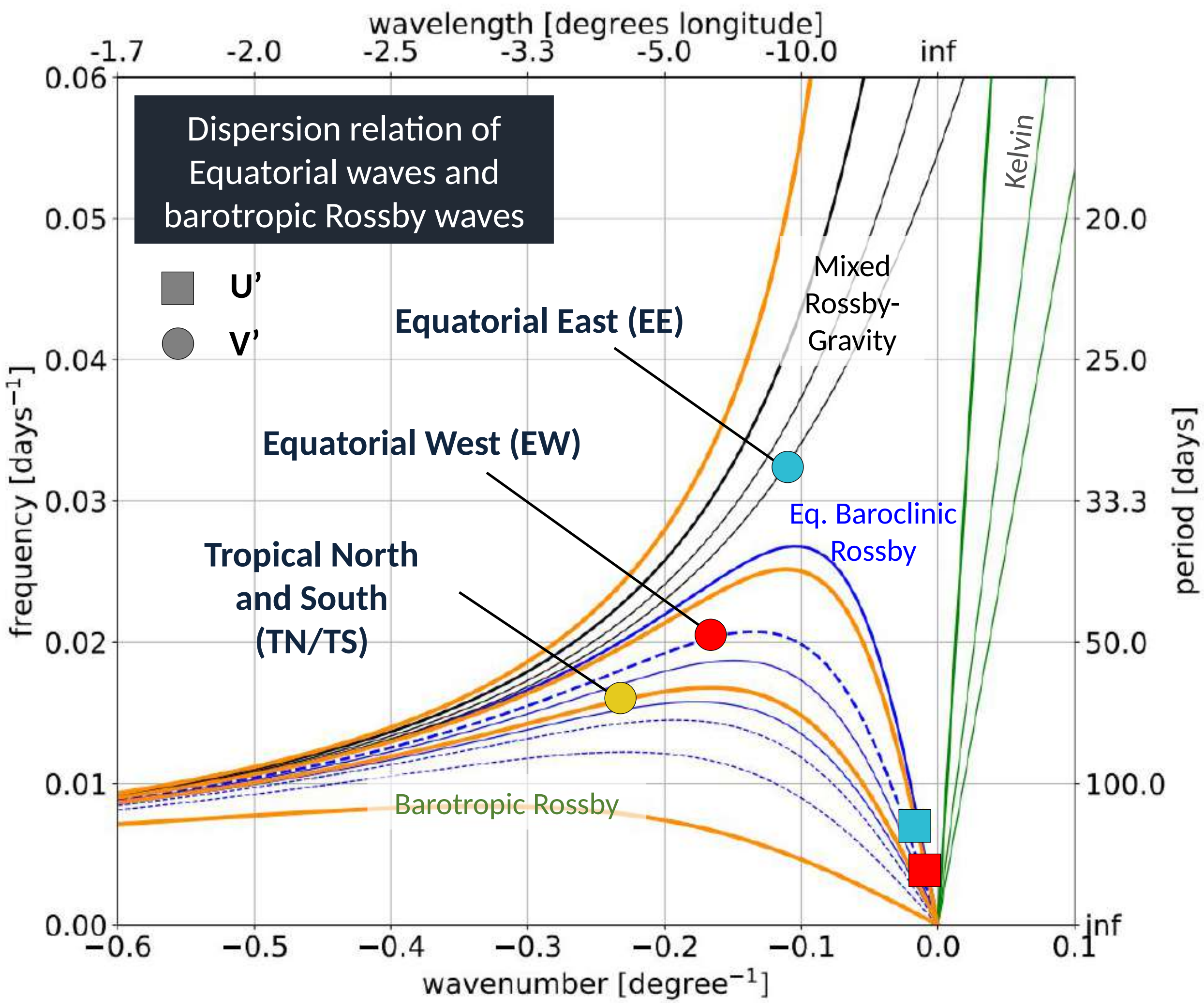


Dominant variability:

Wave with characteristics

1000-km wavelength
30-day period

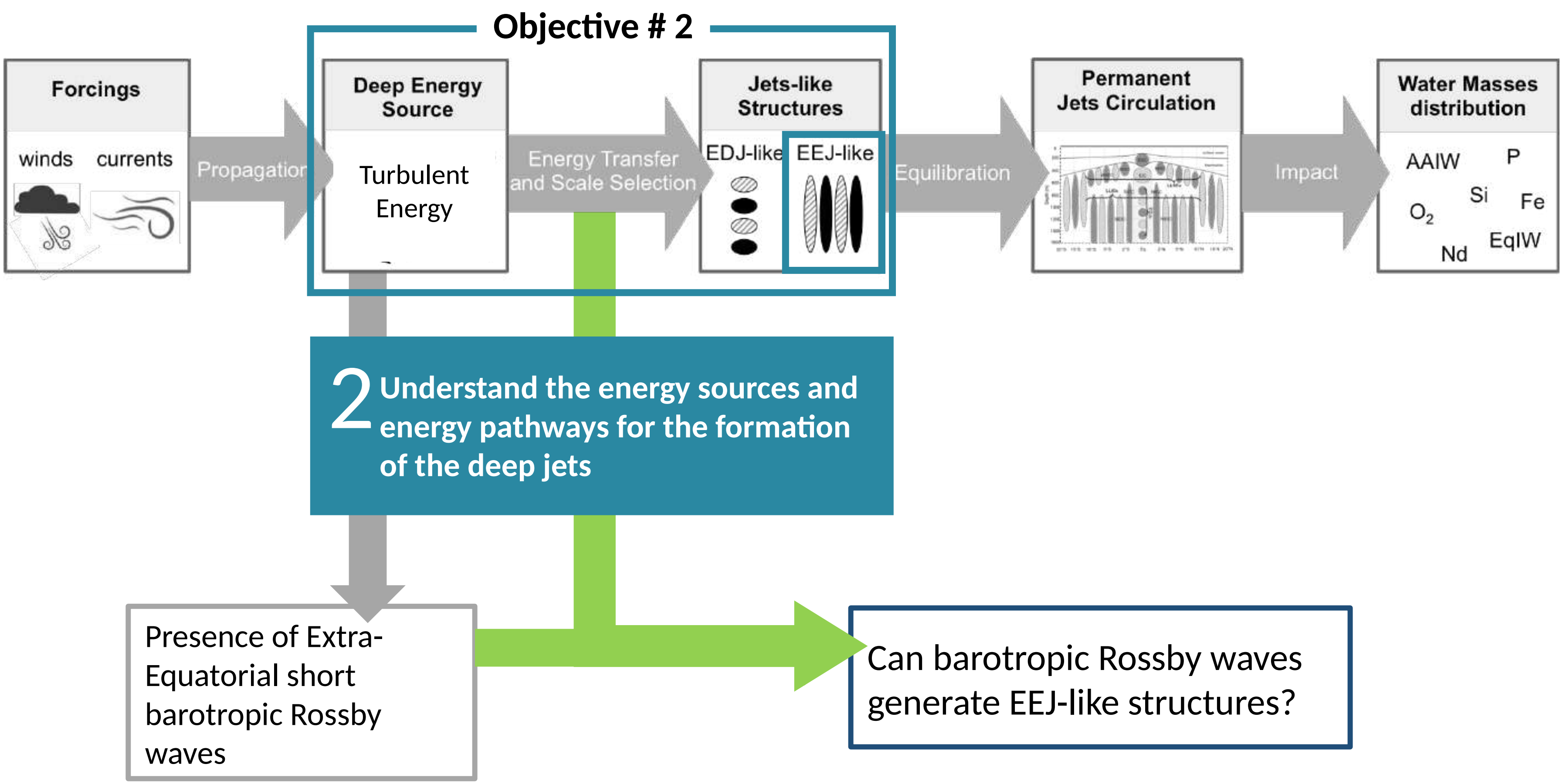
3. Deep Energy Sources
Summary



The deep turbulent energy is characterized by:

- A presence of planetary waves
- Annual and semi-annual Rossby waves for U' along the equator
- Intra-annual waves for V'

Outline


Objective # 2
Forcings
winds
currents
Propagation
Deep Energy Source
Turbulent Energy
Energy Transfer and Scale Selection
Jets-like Structures
EDJ-like
EEJ-like
Equilibration
Permanent Jets Circulation
Impact
Water Masses distribution
AAIW
P
Si
Fe
O_2
Nd
EqIW
2 Understand the energy sources and energy pathways for the formation of the deep jets
Presence of Extra-Equatorial short barotropic Rossby waves
Can barotropic Rossby waves generate EEJ-like structures?

Outline

1. Introduction

2. Transport and Mixing of water masses by deep zonal jets

   [Delpech et al. (2020a). Observed tracer fields structuration by deep zonal jets in the tropical Pacific. *Journal of Physical Oceanography*.]

3. Energy Sources in the deep low-latitude ocean

   [Delpech et al. (2020b). Deep Eddy Kinetic Energy in the tropical Pacific from Lagrangian floats. *Journal of Geophyscial Research: Oceans*.]

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5. Conclusions and Perspectives

4. Deep zonal jets formation mechanisms
Method

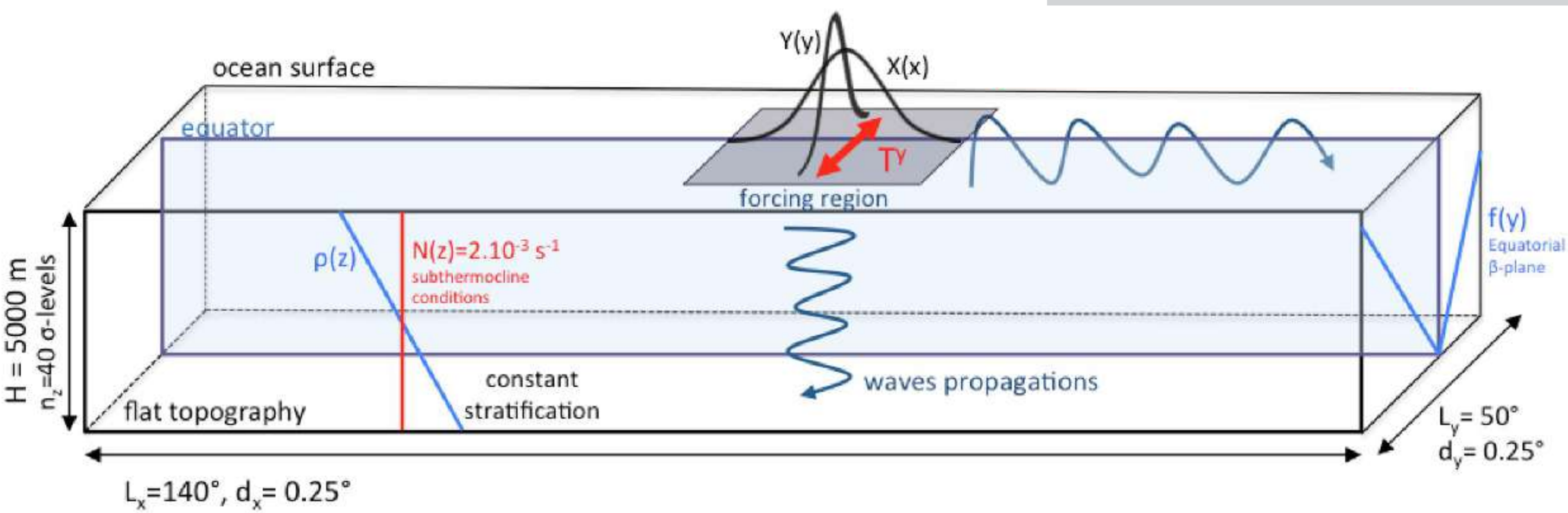
Idealized numerical simulations to investigate the instability of planetary waves

CROCO model (primitive equations solver)

Forcing: oscillatory surface stress (wavemaker)

$$\tau^y = \tau_0 X(x) Y(y) sin(kx - \omega t)$$

k,*ω*: wavenumber and frequency



Physics: **2d – configuration** only barotropic Rossby waves are generated from the forcing

4. Deep zonal jets formation mechanisms
Experiments

Sensitivity of simulations forced with different waves

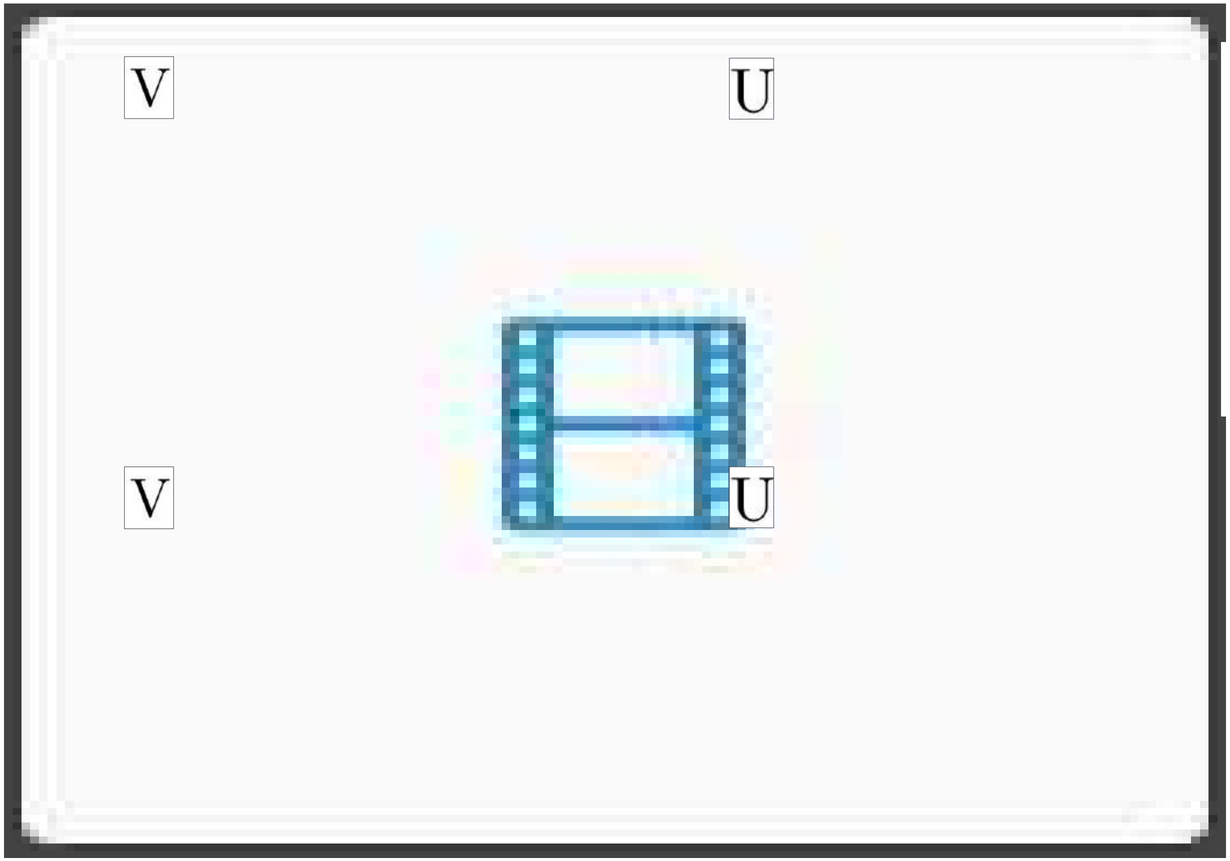
Delpech et al. (2020c)

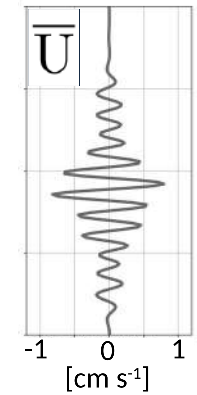
Example 1:

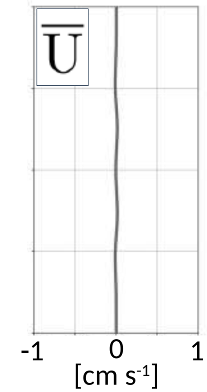
Primary Wave
T=75 days, λ_x=250 km
A=7 cm s^{-1}

Example 2:

Primary Wave
T=40 days, λ_x=500 km
A=7 cm s^{-1}







In some simulations, an instability occurs and produces EEJ-like structures

Can we describe this instability analytically ?

4. Deep zonal jets formation mechanisms
Theory

Non-Linear Triad Interactions (NLTI)

Theory developed to describe wave instability in plasma by *Connaughton et al. 2010*, applied to barotropic Rossby waves in the ocean

Barotropic Quasi-Geostrophic equation

$$\frac{\partial}{\partial t}(\nabla^2\psi) + \beta\frac{\partial\psi}{\partial x} + J(\psi, \nabla^2\psi) = 0$$

Resolution for:

$$\psi_0 e^{i(\mathbf{k}\cdot\mathbf{x}-\omega_\mathbf{k}t)} + \sum_\mathbf{k} \psi_{0\mathbf{k}}(t)e^{i(\mathbf{k}\cdot\mathbf{x})}$$

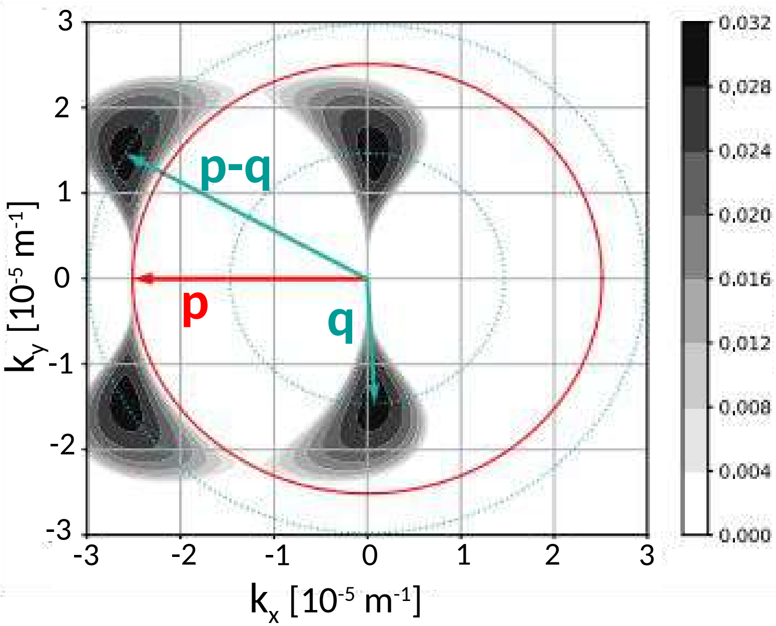
primary wave p

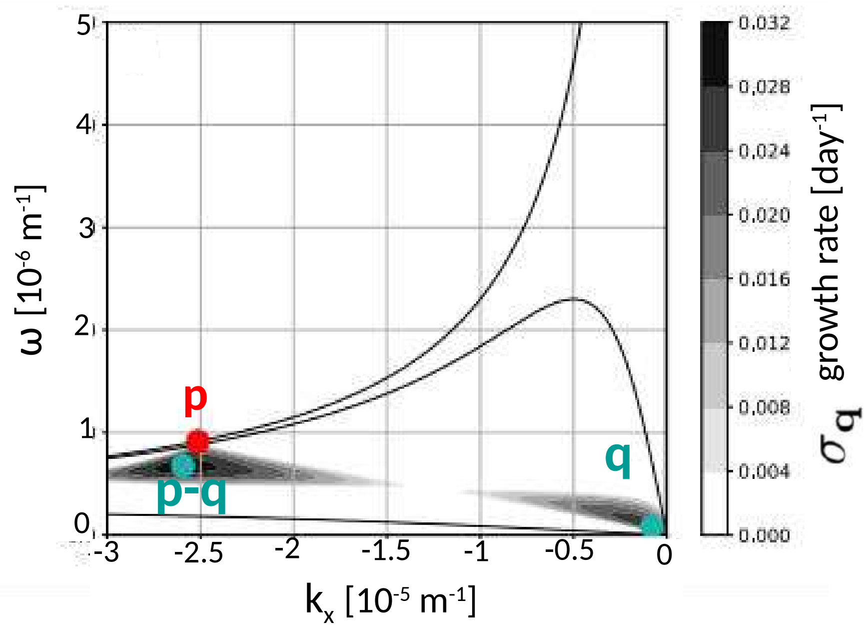
secondary waves *initial small perturbations*

- Two secondary waves will grow
- Their wavenumbers **q** and **p_= p-q** form a triad with the primary wave number such that **q** + **(p-q)** = **p**
- Their growth rate $\sigma_\mathbf{q}$ is the same and can be computed analytically

4. Deep zonal jets formation mechanisms
Theory

Application Example : **Primary Wave** T=75 days, λ_x=250 km





Two **secondary waves** = $\sigma_{\mathbf{q}}^{\max}$:

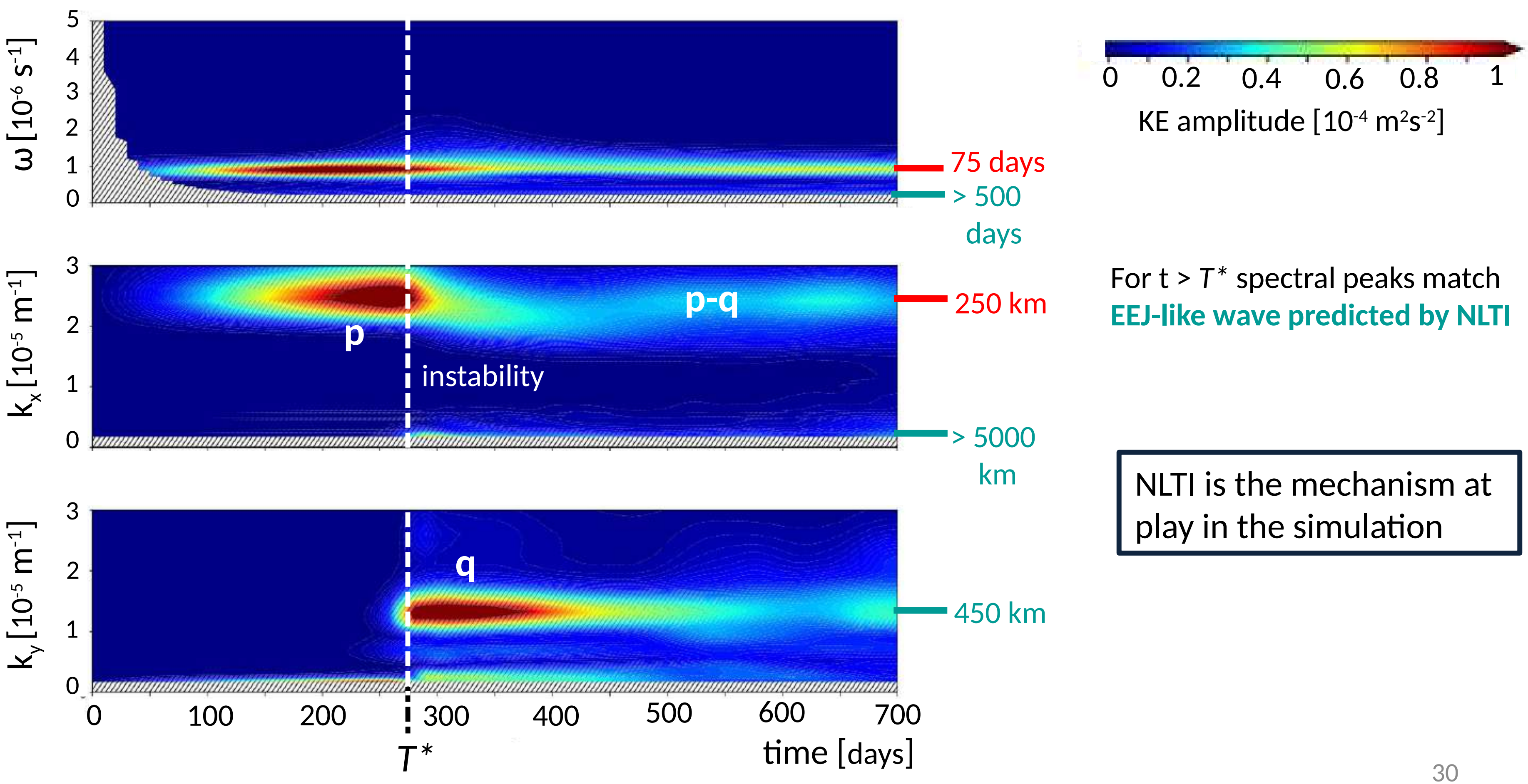
EEJ-like wave

	λ_x	λ_y	T
Primary wave	250 km	> 5000 km	75 days
Secondary wave (q)	> 5000 km	450 km	> 500 days
Secondary wave (p-q)	≈ 250 km	450 km	110 days

4. Deep zonal jets formation mechanisms
Validation of the Theory

Simulation Example 1 : Primary Wave T=75 days, λ_x=250 km

Time evolution of KE spectral characteristics in the numerical simulation

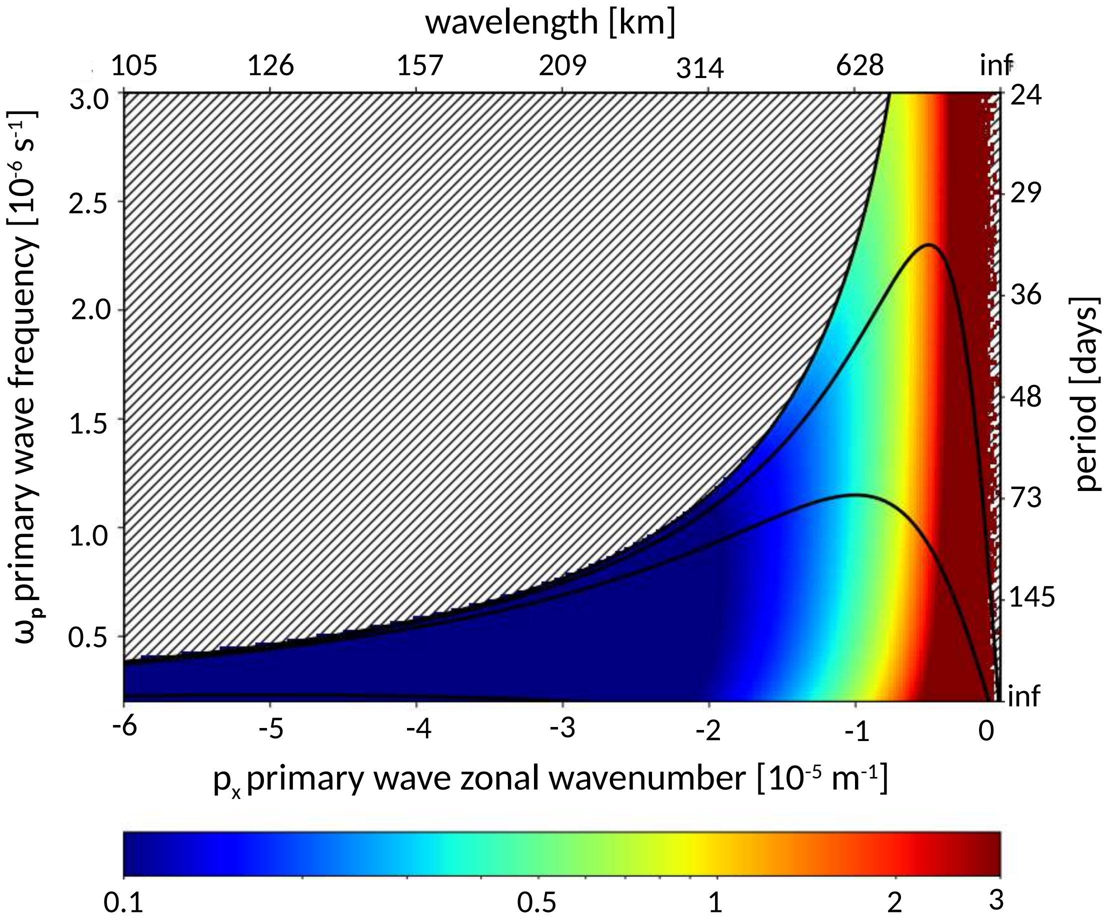


For t > T^* spectral peaks match **EEJ-like wave predicted by NLTI**

NLTI is the mechanism at play in the simulation

4. Deep zonal jets formation mechanisms
Can all primary wave generate EEJ-like structures ?

Sensitivity to the amplitude of the primary wave



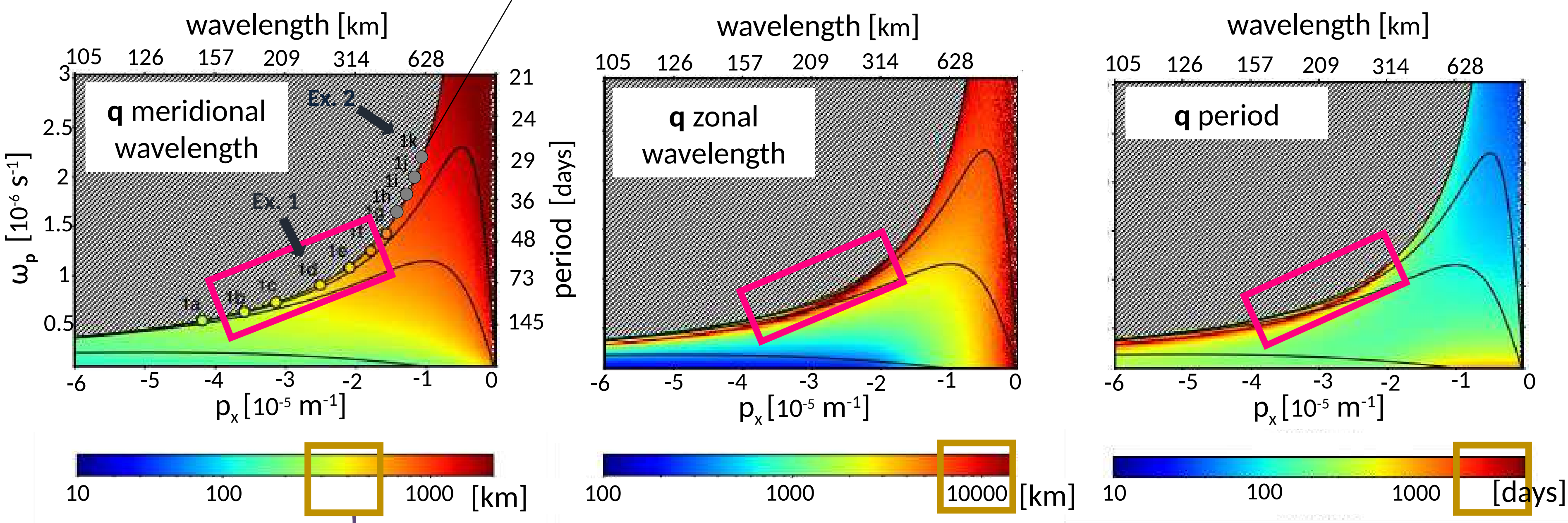
$A_\mathbf{p}$ primary wave minimal amplitude to meet instability criterion [m s^{-1}]

For realistic amplitudes, only short (< 600 km) barotropic Rossby waves are unstable

4. Deep zonal jets formation mechanisms
Can all primary wave generate EEJ-like structures ?

Sensitivity of the secondary wave characteristics

Numerical simulations



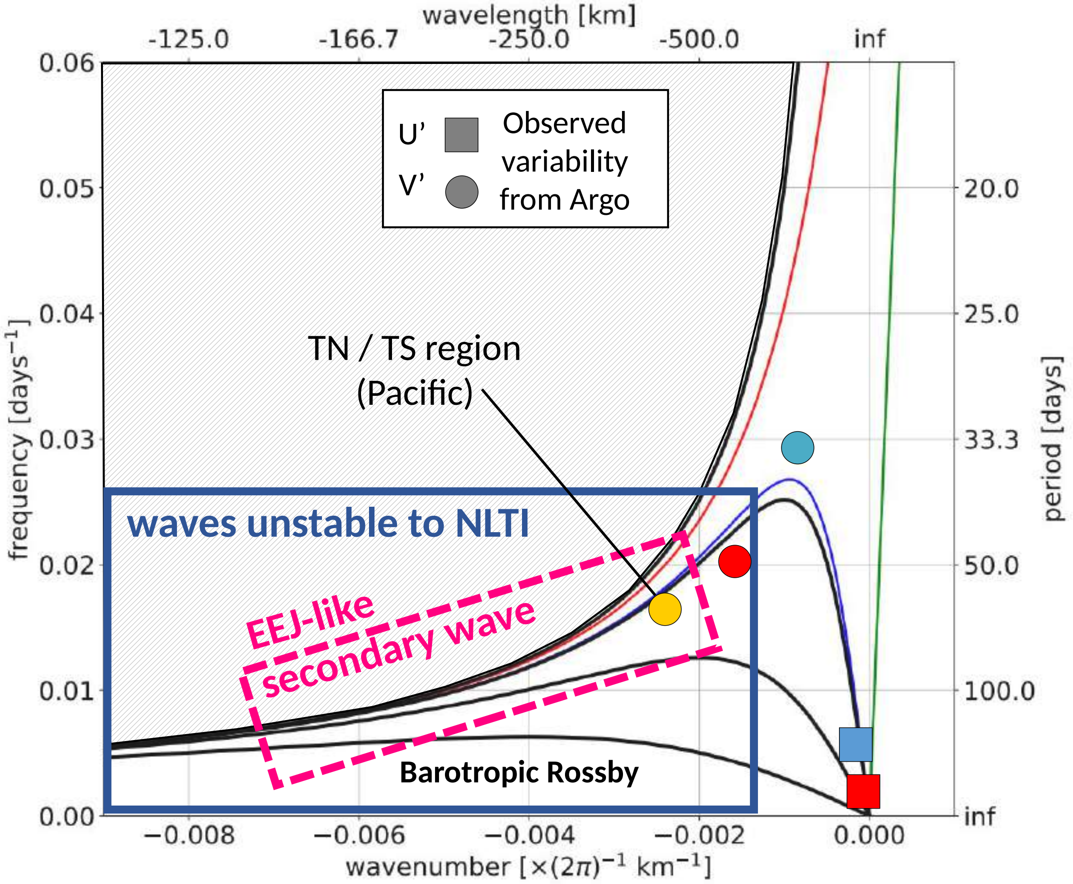
Observed EEJ characteristics

Only short (150-500 km) intra-annual (50-130 days) primary waves can destabilize in EEJ-like secondary waves

4. Deep zonal jets formation mechanisms
Summary

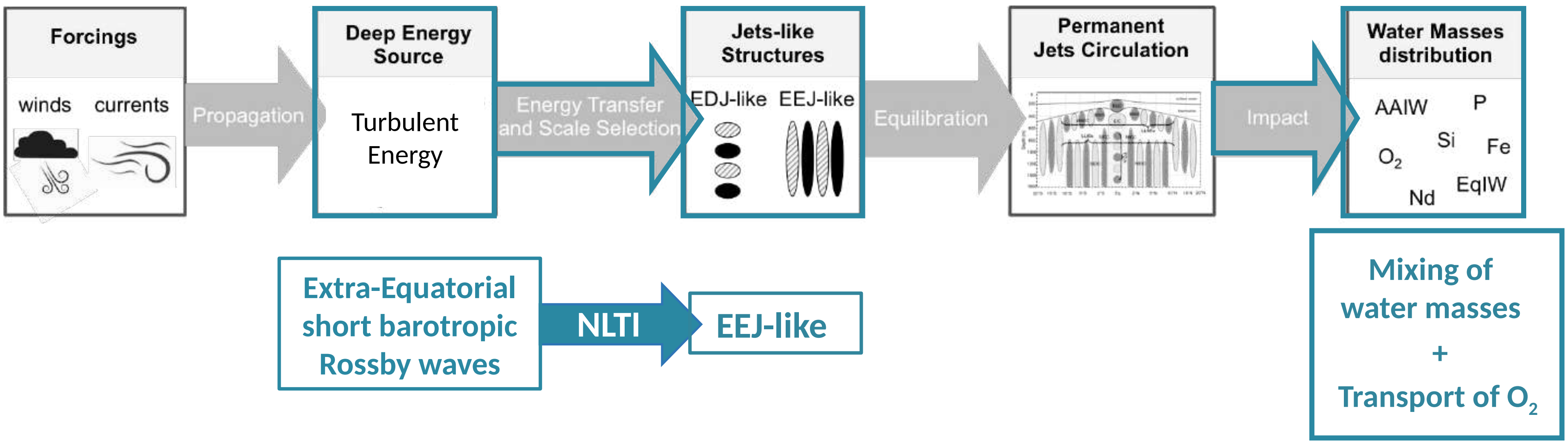
- Non-Linear Triad Interactions (NLTI) can explain the formation of Extra-Equatorial Jet (EEJ)-like structures
- **Short barotropic Rossby Waves** are unstable to NLTI
- **Short intra-annual barotropic Rossby Waves** destabilize into EEJ-like structures with realistic scales

Observed short intra-annual Rossby Waves can create EEJ at low-latitudes



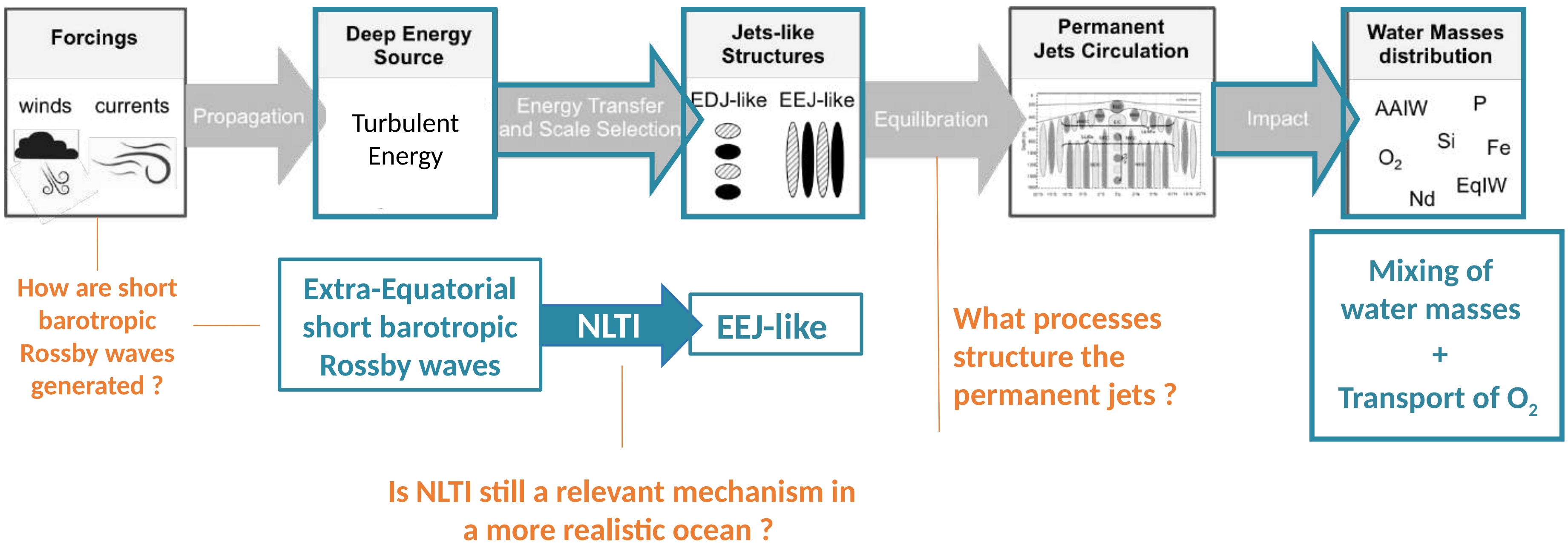
Conclusions & Perspectives

In this PhD



Conclusions & Perspectives

In this PhD | Perspectives



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