Intra-annual waves as a potential driver of the mean deep circulation in the tropical oceans

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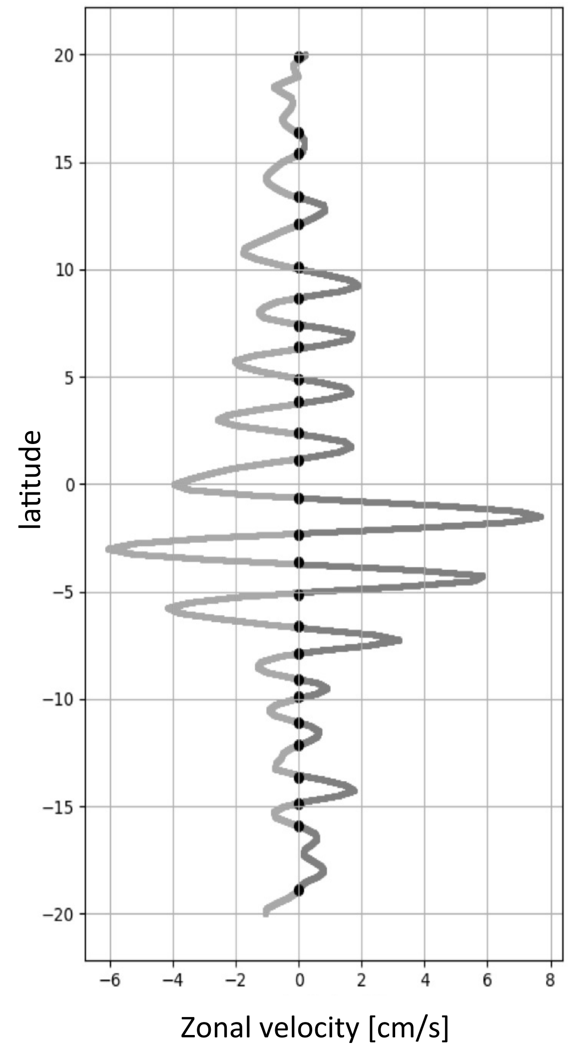
Chat session Monday, May 4th at 2 pm

Session OS1.9/AS2.13/CL2.18 – Tropical & Subtropical climate variability

Motivations

- The mean circulation in the tropcial oceans is organized into system of zonal jets.
- These jets are able to transport and mix water masses. They play a major role in the transport of oxygen and the ventilation of the deep ocean (Brandt, 2008, Delpech et al., 2020a).
- The underlying physical mechanisms generating this system of alternating zonal jets are still poorly understood (Ménesguen et al. 2019).
- One of major energy sources present at depth in the tropical ocean are planetary waves. Waves are particularly present at annual and intra-annual time scales (Delpech et al., 2020b).
- Waves can develop instabilities. The destabilization of some particular waves have been shown to be a potential mechanisms for the formation of jet-like structures (Gill 1974, Hua et al., 2008).

5 years average of zonal velocity at 1000 m from Argo drift



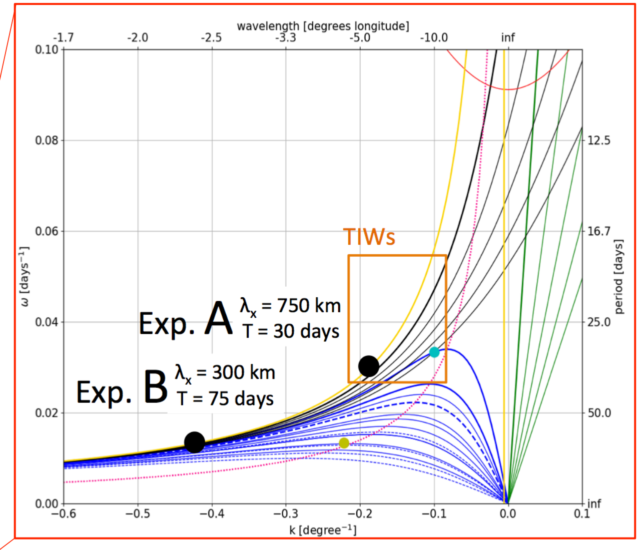
In this study:
what is the potential for intra-annual waves to create off-equatorial, meridionally-alternating jet-like structures ? Insights from idealized numerical simulations

Idealized numerical simulations in the **CROCO model** (primitive equation solver)

Assumptions:
o Equatorial beta-plane
o Constant stratification

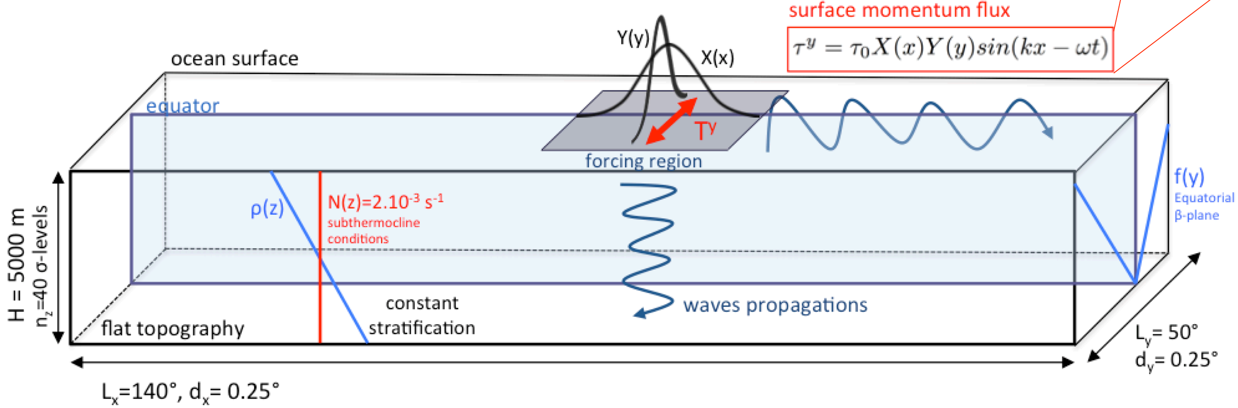
Boundary conditions :
o Surface : periodic momentum flux to act as a wave maker
o Bottom : linear bottom drag to damp wave reflections
o N-S boundary : sponge layers to damp coastal waves
o E-W boundary : rigid walls to represent idealized coasts

Forcing frequency and wavenumber



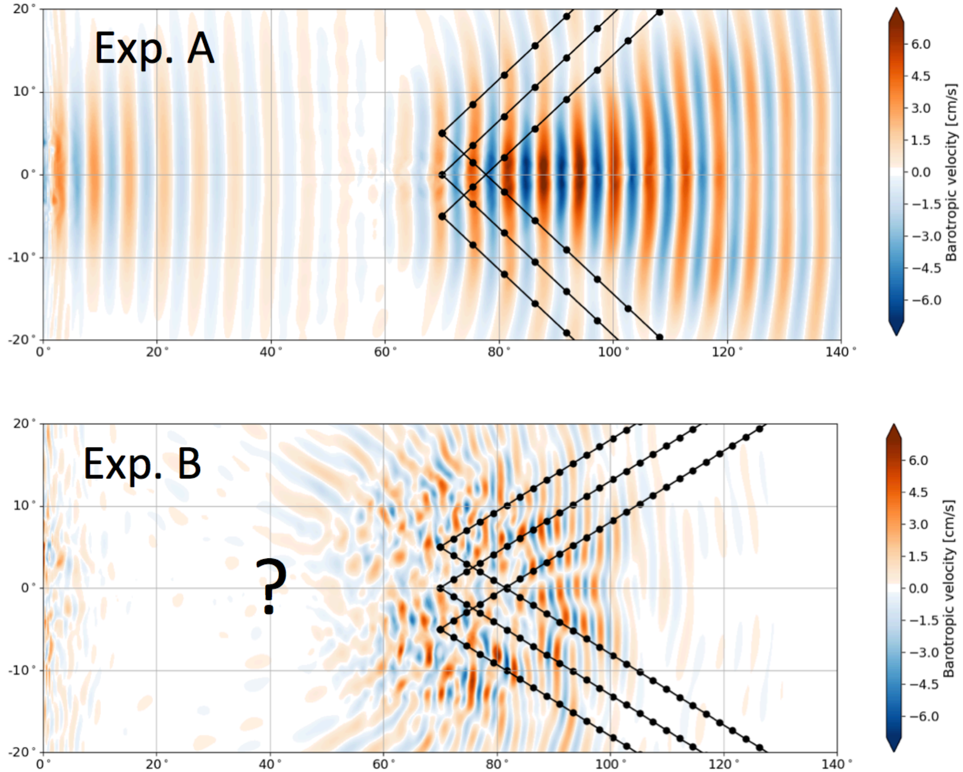
surface momentum flux

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



Characteristics and propagation of the forced waves in the simulation

Snapshot of barotropic meridional velocity afer 5 years of simulation



- In both simulations: propagation of the forced wave as barotropic Rossby wave along the theoretical ray path (black lines graduated with the wave period)
- In Simulation B, a different wave with a westward group velocity seems to develop
- Results from an instability ? Which one ?

1) Triadic interactions : Theory

Quasi-Geostrophic non-linear eaquation

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

Fourier transform

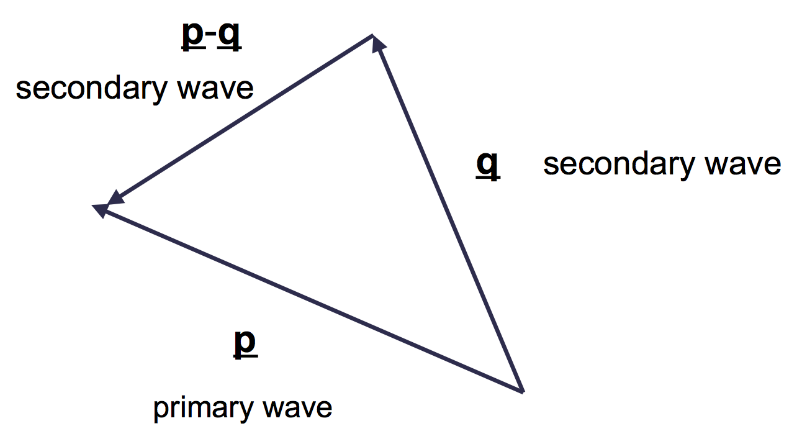
$$\frac{\partial}{\partial t}\psi_{\mathbf{k}} + i\omega_{\mathbf{k}} + \boxed{\frac{1}{2}\sum_{i,j|\mathbf{ki}+\mathbf{kj}=\mathbf{k}} T(\mathbf{k},\mathbf{k_i},\mathbf{k_j})\psi_{\mathbf{k}_i}\psi_{\mathbf{k}_j} = 0}$$

The non-linear term acts as a forcing term in the spectral domain.

3-mode truncation: limit the sum to one element and the interaction to one triad.

3 waves exchange energy between each other

When a primary wave is forced, it will flux energy into two secondary waves that are initially small perturbations



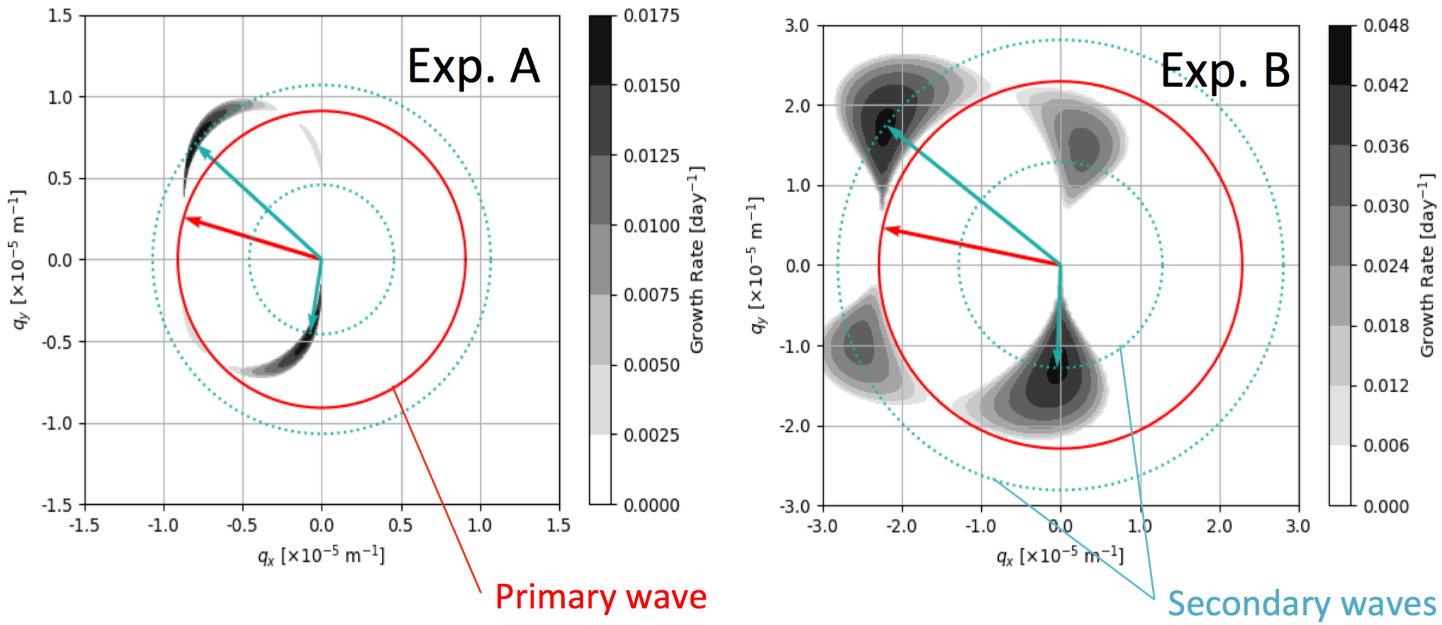
Triad relation

p = q + (p-q)

The growth rate of the two secondary waves can be computed theoretically in the 3-mode truncation (Connaugthon 2010).

2) Evidence for triadic instability of the barotropic mode in the simulations

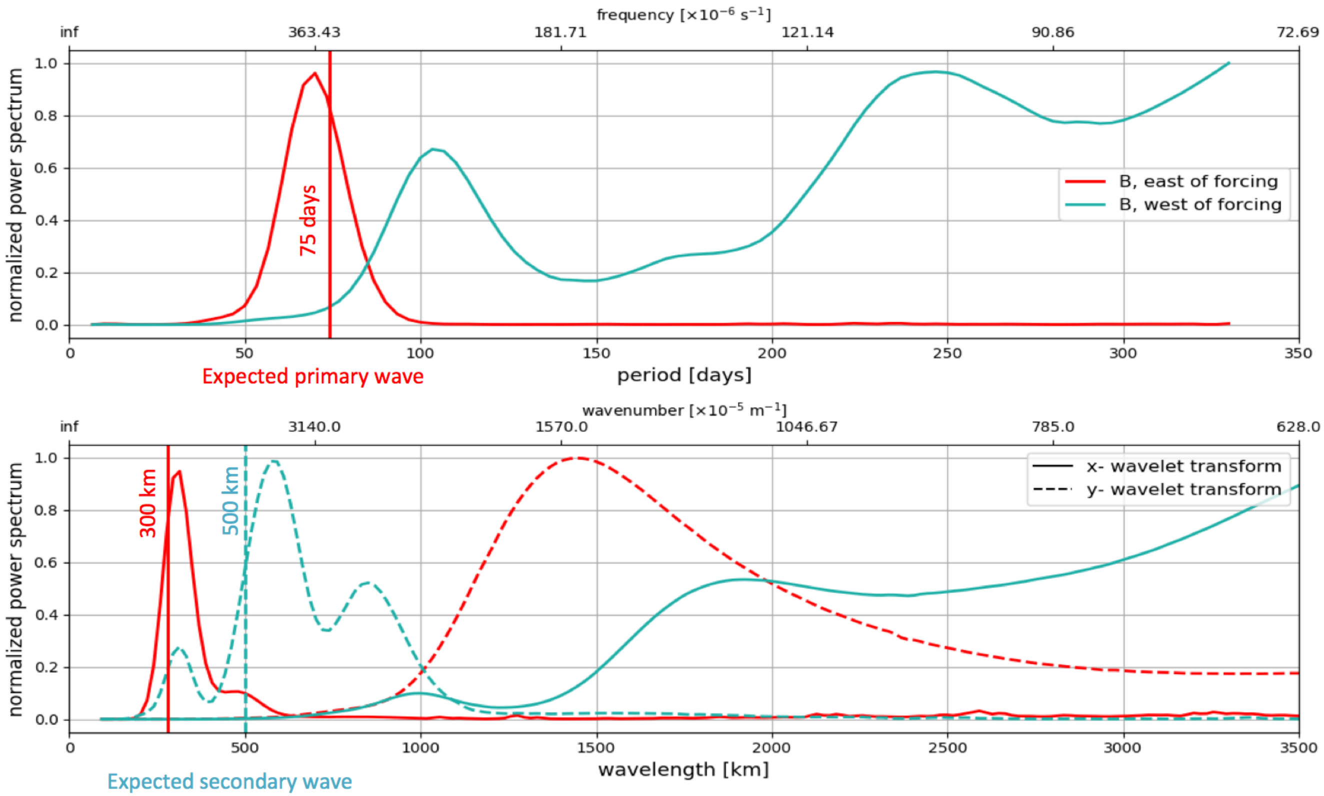
Growth rate for the instability in simulations A and B



- All primary waves are unstable to non- linear triadic interactions (Gill 1974, Connaugthon 2010)
- The emerging secondary waves are selected as the one with the maximum growth rate.
- **Instability emergence time**
  - simulation A: 190 days
  - simulation B: 90 days

2) Evidence for triadic instability of the barotropic mode in the simulations

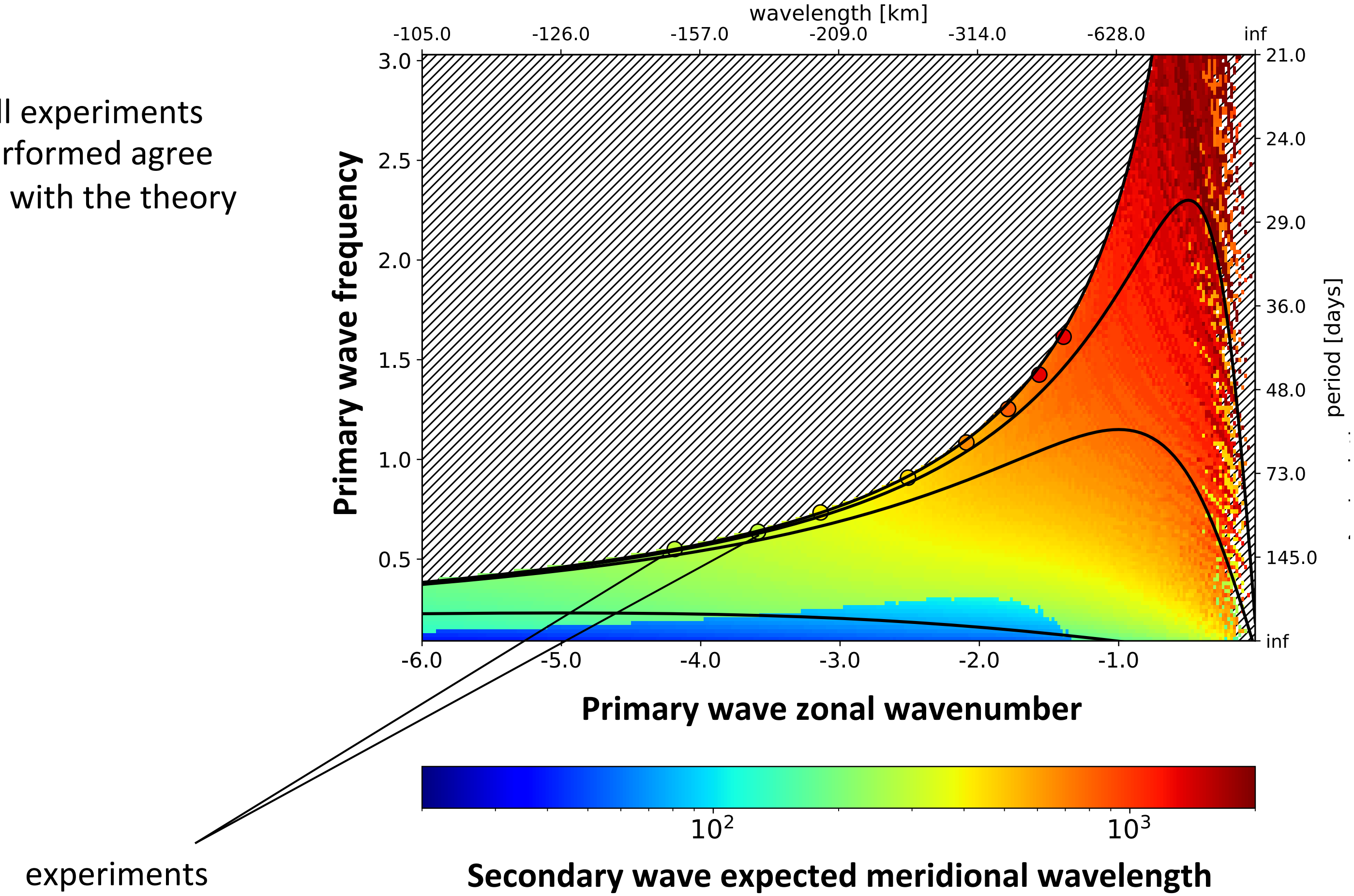
Simulation B spectral analysis from wavelet transform



- A secondary wave develops in simulation B. It has the characteristics of the most unstable mode predicted by the 3-mode truncation non-linear theory.
- It has a short y-wavelength, a long x-wavelength and a long period. This coincides with jet-like structures.
- No secondary waves are observed in simulation A (not shown).

2) Evidence for triadic instability in the simulations

All experiments performed agree well with the theory



1) Sensitivity of jet-like scales to the spectral characteristics of the primary wave

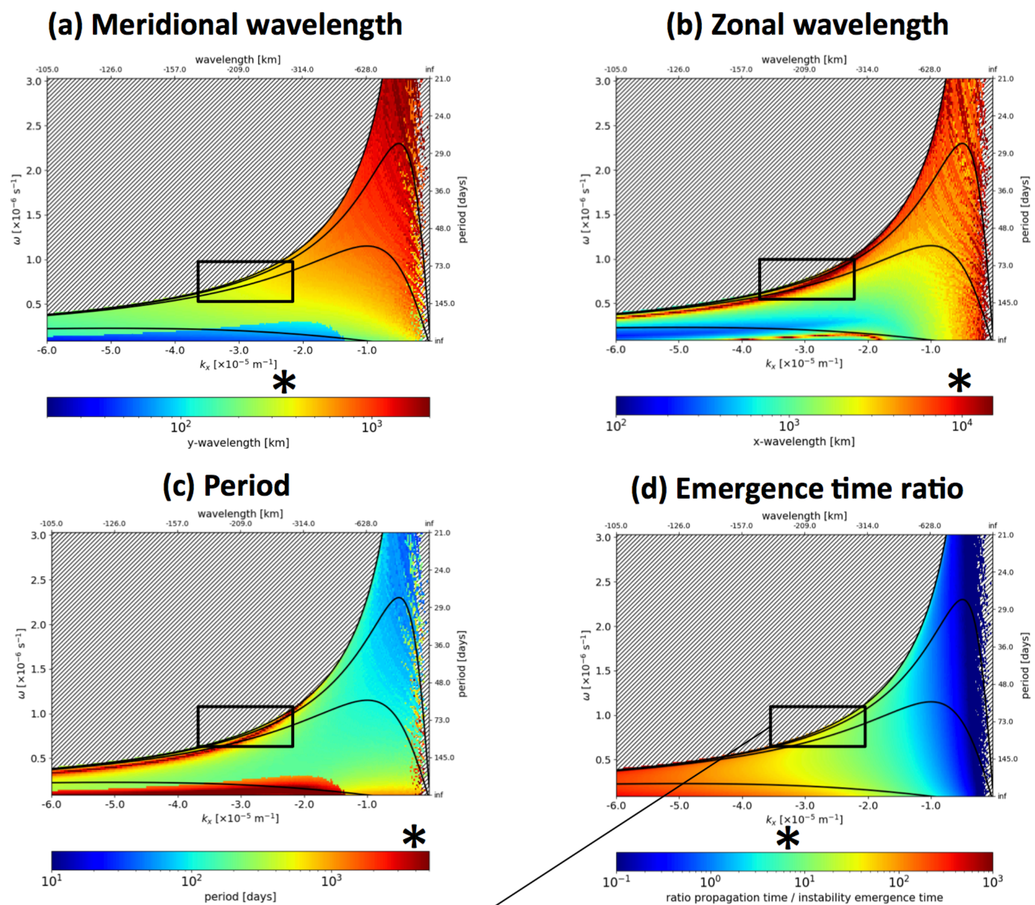
Does all the wave have the same potential to form realistic jet-like structures ?

Realistic jet characteristics:

- Long period (> 1000 days)
- Long zonal wavelength (> 10000 km)
- Meridional scale ~ 300 – 500 km

Optimal spectral region are waves with:

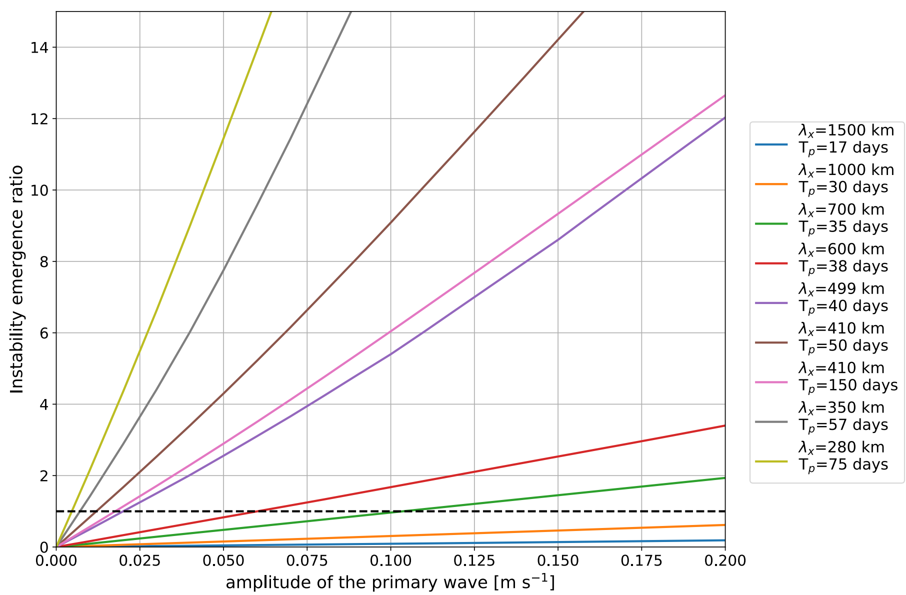
- ~70-day period
- ~ 250-350 km wavelength



Short waves are found to be the ones that trigger the instability with the most realistic characteristics of jet structures (noted by *).

2) Sensitivity of jet-like scales to the amplitude of the primary wave

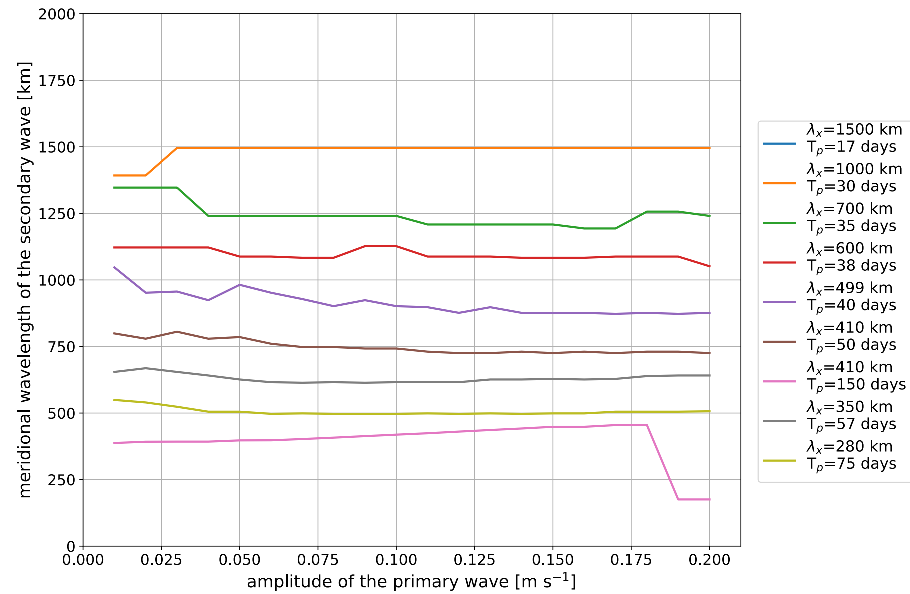
Instability emergence as a function of the amplitude



Instability emergence ratio, R, is defined as the ratio between the time needed for the primary to reach the boundaries of the domain and the time it takes for the instability to develop.

If R > 1, we expect to see the instability in the simulations
If R < 1, we don't .

Meridional scale as a function of the amplitude



- The amplitude of the primary wave play a role in the emergence of the instability. Waves become unstable above a given amplitude threshold.

- The amplitude does not play a role in the scale selection of the secondary wave (jet-like structure).

Conclusions

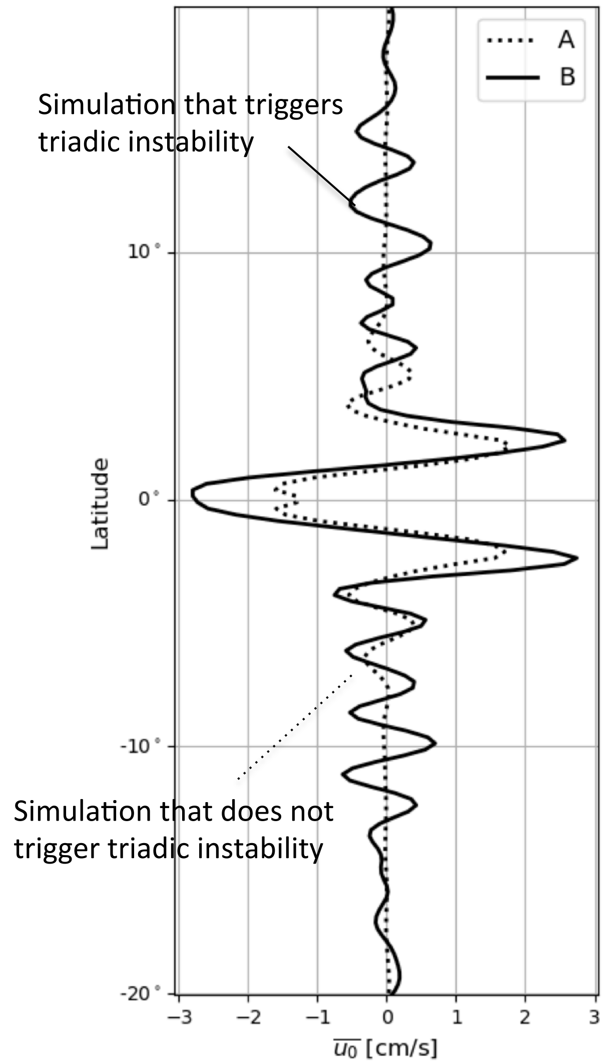
- Deep intra-annual waves, which are ubiquitously present at depth in the ocean are prone to non-linear interaction and instability
- The growth rate and the characteristics of the instability are a function of the primary wavenumber and frequency. In particular cases, the secondary waves have jet-like structures
- We investigated the potential for intra-annual waves to destabilize into jet-like structures using idealized numerical simulations
- We determine that the optimal primary wave characteristics range to reproduce realistic jet-like is reached for waves with period ~70 days and wavelengths ~300 km.
- We evidence that the energy transfer mechanisms is well approximated using a truncated non-linear triadic interaction theory.

Perspectives

Are the ~70 days and ~300 km waves observed in the ocean ?

See next presentation : “Deep Eddy Kinetic energy in the tropical Pacific from Lagrangian floats”.

5 years average of zonal velocity at 1000 m in the simulations



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Deep Eddy Kinetic Energy in the tropical Pacific from Lagrangian floats

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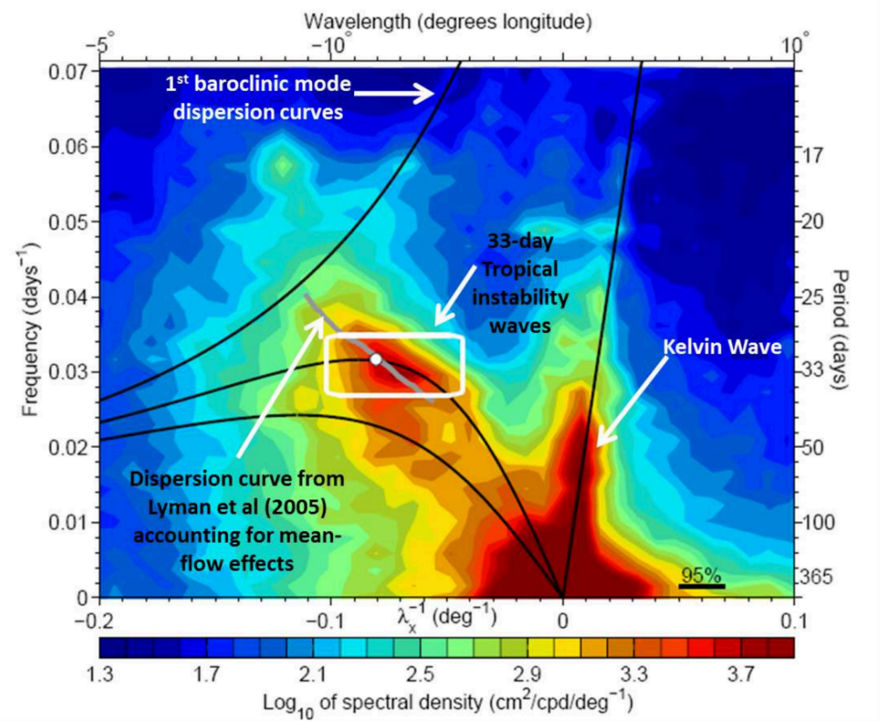
Oral presentation Tuesday, May 5th at 2.30 pm

Session OS1.9/AS2.13/CL2.18 – Tropical & Subtropical climate variability
Zoom link : https://zoom.us/j/2768323256pwd=eXdCSWZXeFY2N1htcTIyYWxKallEQT09

Motivations

- Satellite observations have revealed a large spectrum of waves at the ocean surface in the equatorial regions.
- At depth however, the scale dependence of the velocity variability is poorly known. In particular in the intra-annual (20-90 days) frequency band.
- Most of the observations rely on sparse moorings measurements
- Intra-annual variability and in particular intra-annual waves are potentially playing an important role in energizing the mean circulation at depth (Greatbatch et al., 2018 Ménesguen et al., 2019.)



Spectral energy content from satellite derived sea level anomaly (Lindstrom et al., 2014)

In this study, Delpech et al. (2020), *Journal of Geophysical Research : Ocean*., in revision : Characterize deep EKE at basin scale in the equatorial Pacific from Argo floats, with a focus on the intra-annual periods.

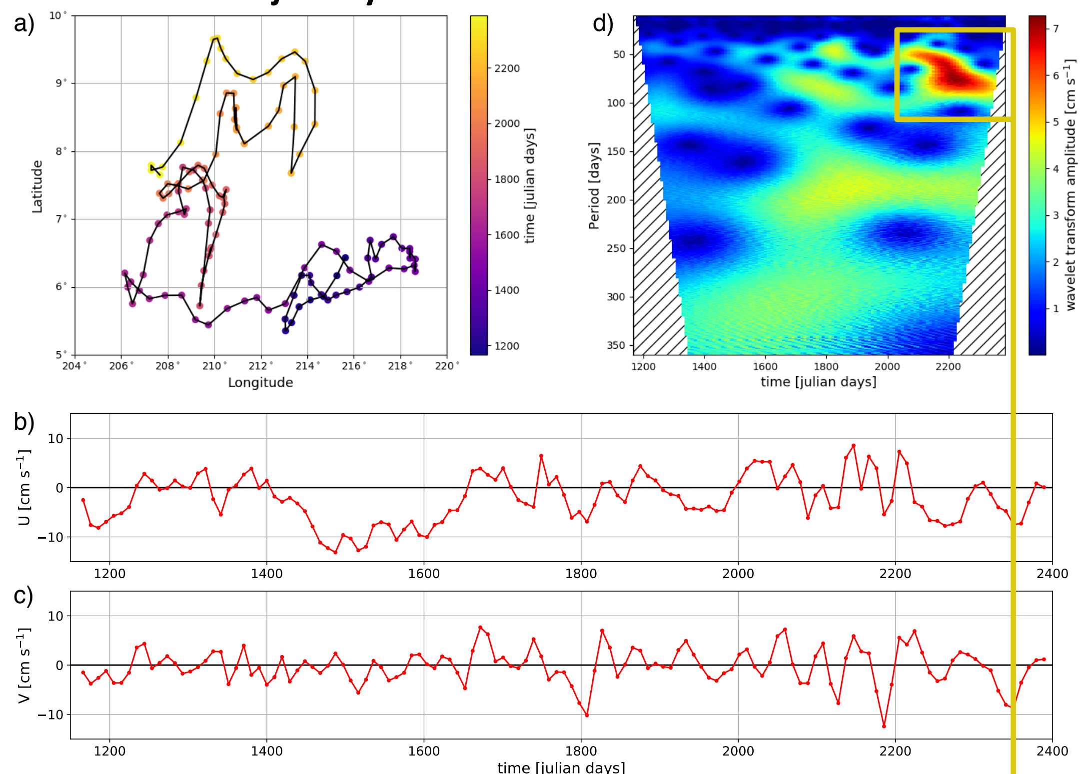
1) Argo database in the Pacific

- More than 250 000 Argo cycle in the tropical Pacific (TP) since the beginning of the program
- Each cycle gives an estimate of the 10-days average deep velocity
- About 15 000 deep velocity measurements every year in the TP.

2) Dominant period of variability

- Extraction of the period with maximum amplitude in the wavelet transform of velocity time series
- Construction of ampltiude-weighted histograms in box regions.

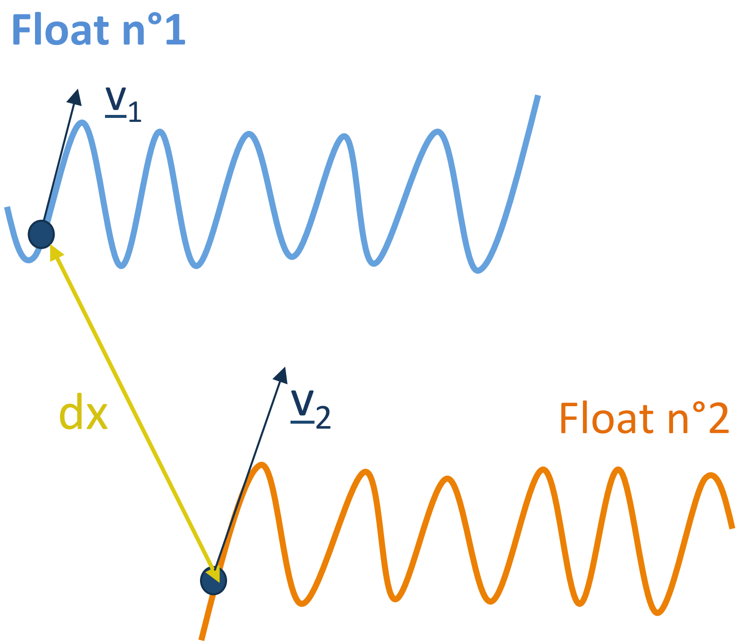
Float trajectory **wavelet transform of V time series**



Float U and V velocity time series

Extraction of period of maximum amplitude

2) Statistical Scale Functions (SSF) : definition



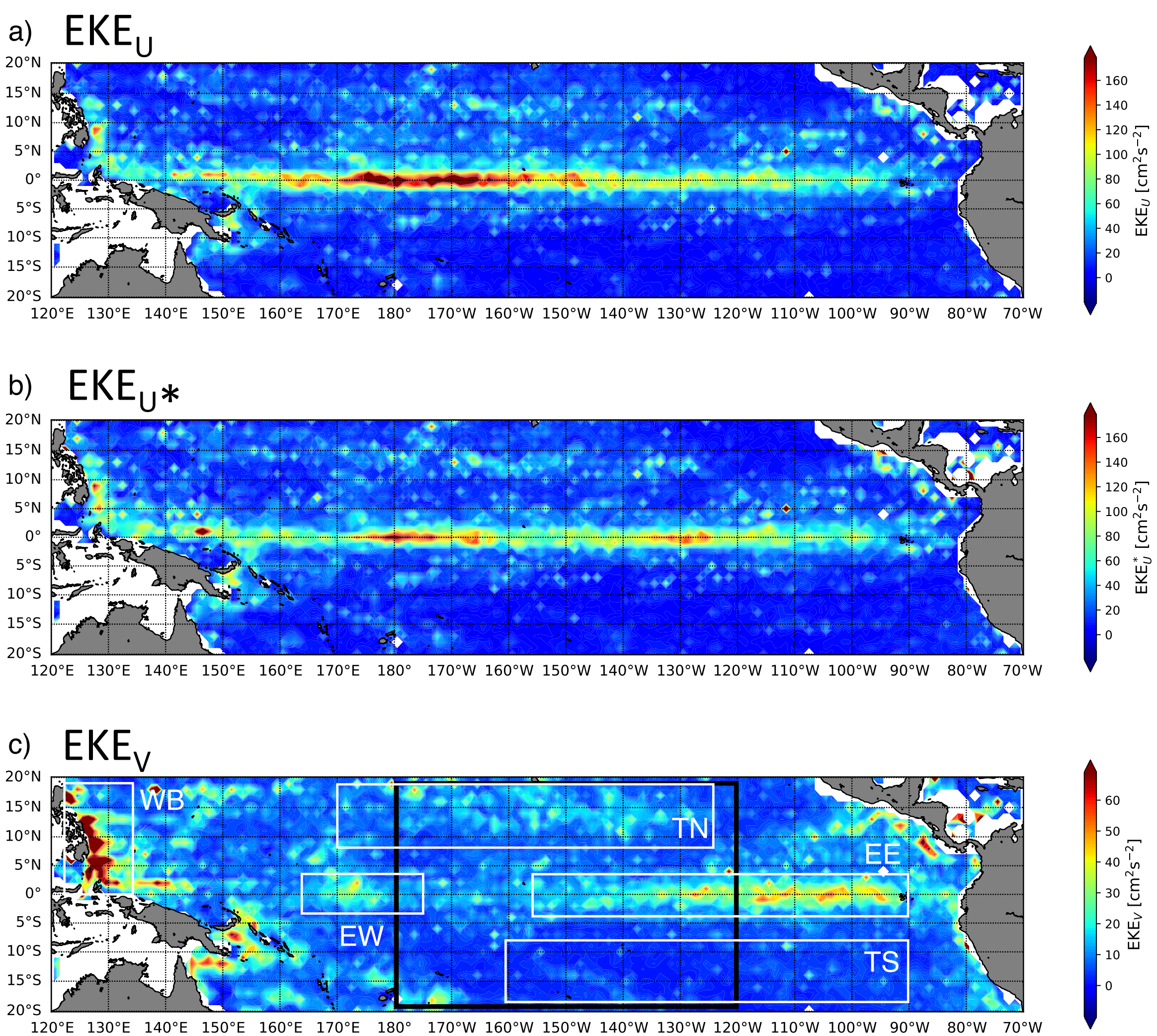
$$\underbrace{\boxed{D_q(dx,dt)}}_{\text{Scale-dependent statistics}} = \frac{1}{n_{ij}} \sum_{\{i,j\} \left| \substack{x_j - x_i = dx \\ t_j - t_i = dt} \right.} \underbrace{\boxed{\delta q(x_i,t_i,x_j,t_j)^2}}_{\text{Increment}}$$

$$\boxed{\delta q(x_i,t_i,x_j,t_j) = q(x_j,t_j) - q(x_i,t_i)}$$

where q is a quantity, here we use U or V

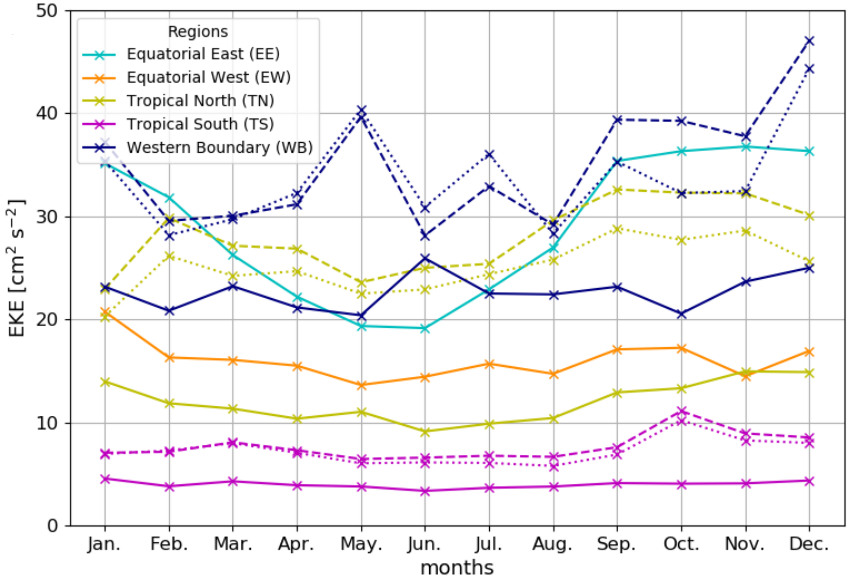
- Measure of the covariance between pairs of floats
- If D_{qq} << 1 : measurements vary in phase, dx and dt are close to the wavelength and period
- If D_{qq} >> 1 : measurements vary in phase opposition, dx and dt are close to the half-wavelength and half-period.

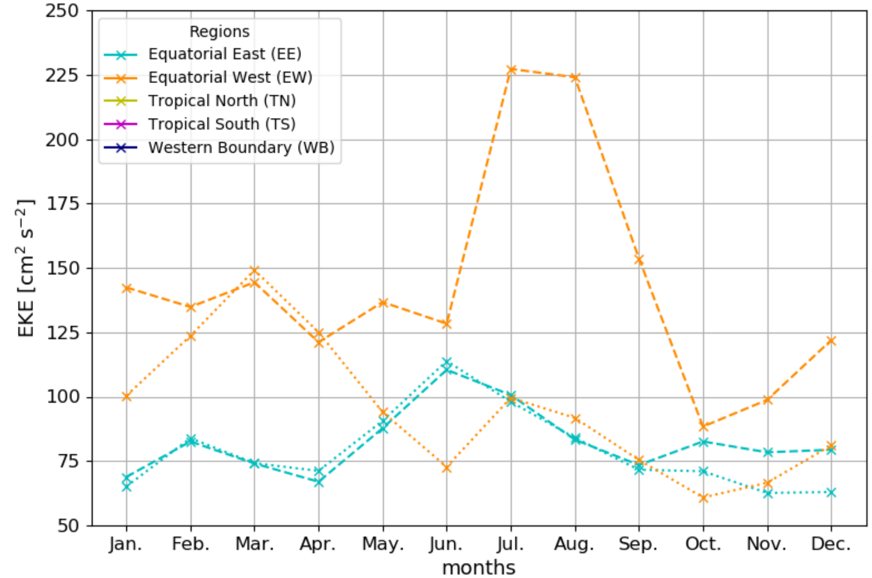
1) Spatial distribution of the 1000 m EKE



- Maximum of EKE_U along the equator in the western part
- Probable link with the mean annual cycle of the equatorial currents
- Filtering out annual variability (EKE_{U*}) redues the equatorial maximum
- Maxima of EKE_V along the western boundary, along the equator with two distinct maxima in the west and in the east, and above 7°N.

2) Annual distribution of the 1000 m EKE





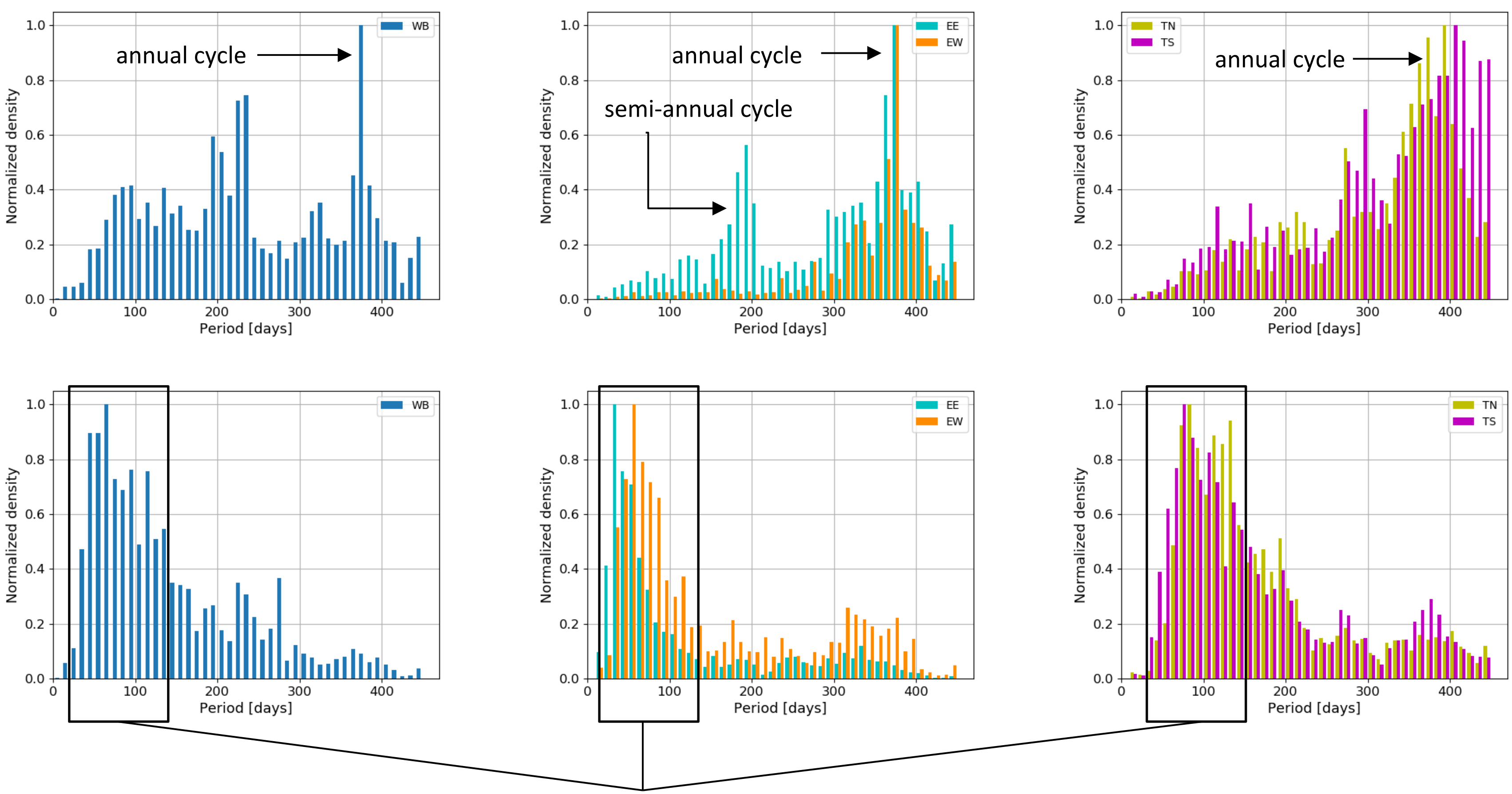
- Strong annual cycle of EKE_V in the eastern equatorial Pacific (EE) with an EKE intensification from September to January.
- Weak annual cycle of EKE_U and EKE_V in the north tropical Pacific (TN) with an EKE intensification from September to January.
- Intensification of EKE_U in the western equatorial Pacific (WE) in July, August and September.

1) Dominant Periods of Variability at 1000 m

Western Boundary | Equator | Off Equator

U’

V’

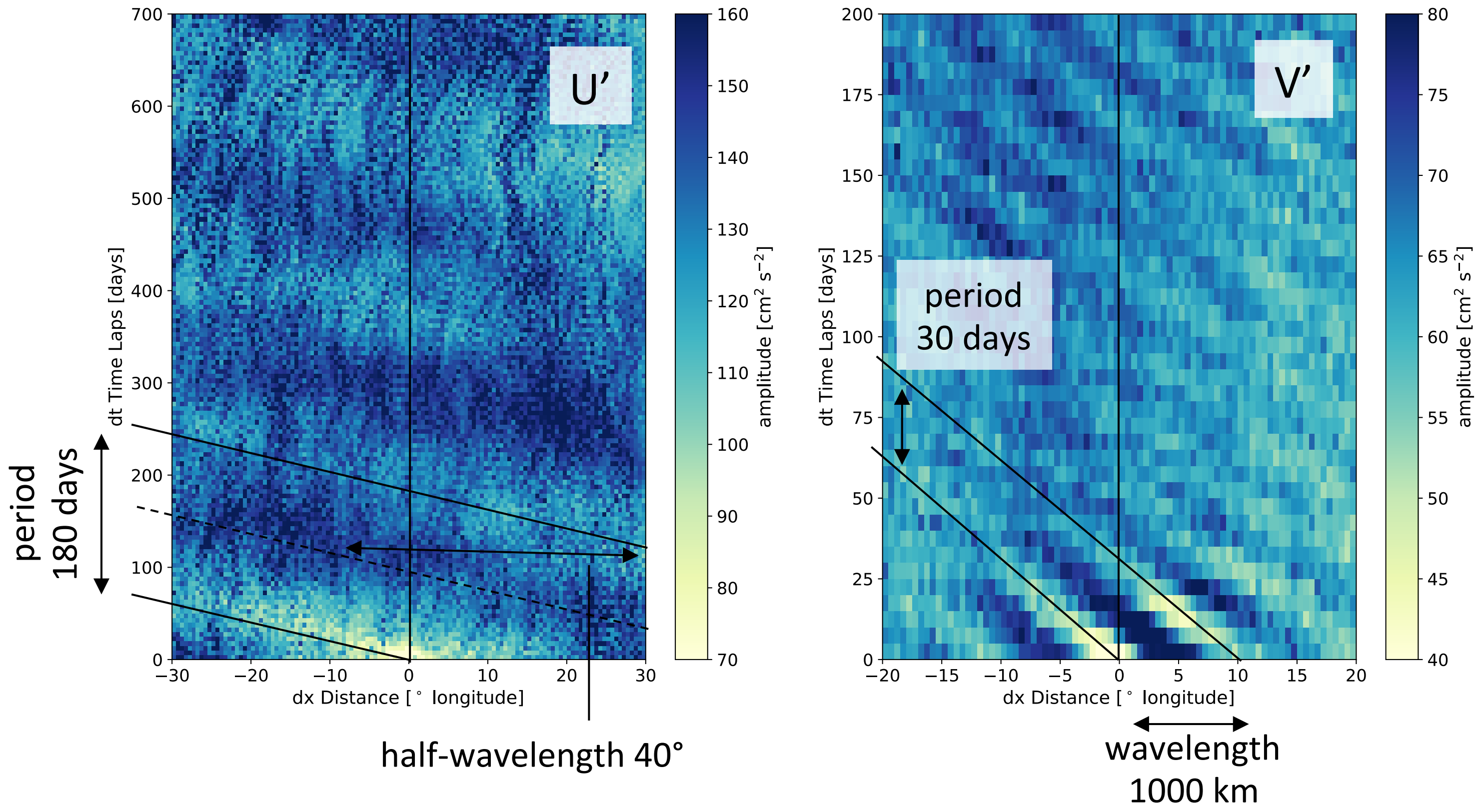


Intra-annual periods dominate the variability of the meridional velocity

2) Spatio-temporal scale analysis

Region: Eastern Equatorial Pacific (EE)

Statistical Scale Functions (SSF)



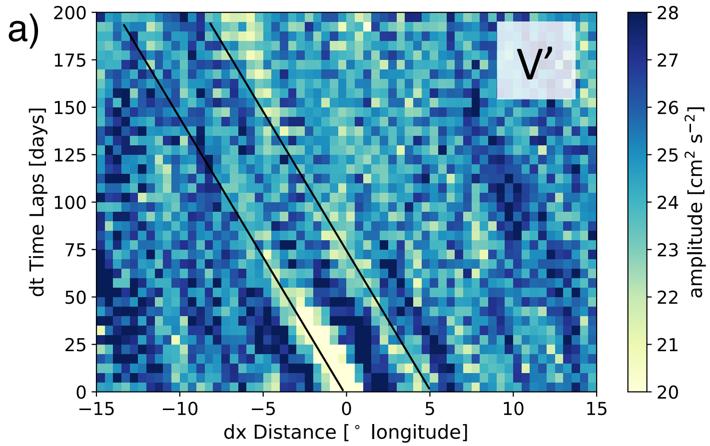
Semi-annual long wave

TIW-like variability

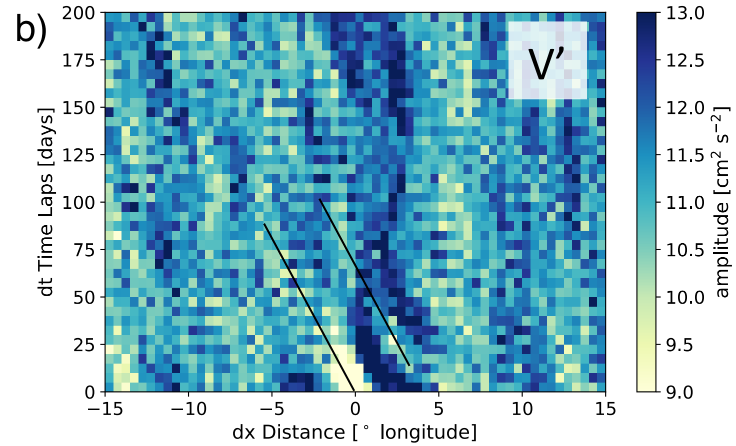
2) Spatio-temporal scale analysis

Statistical Scale Functions (SSF)

Region: Tropical North (TN)



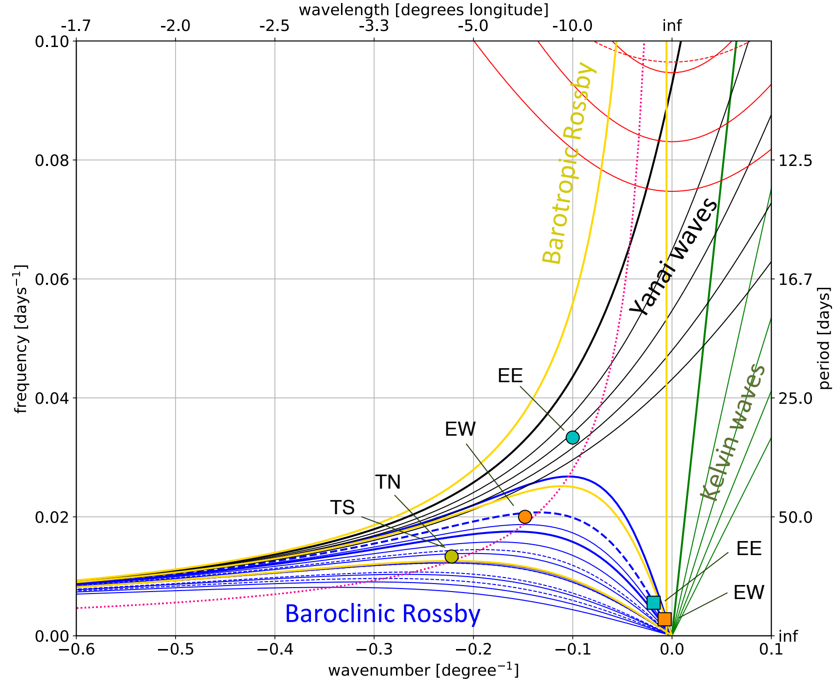
Region: Tropical South (TS)



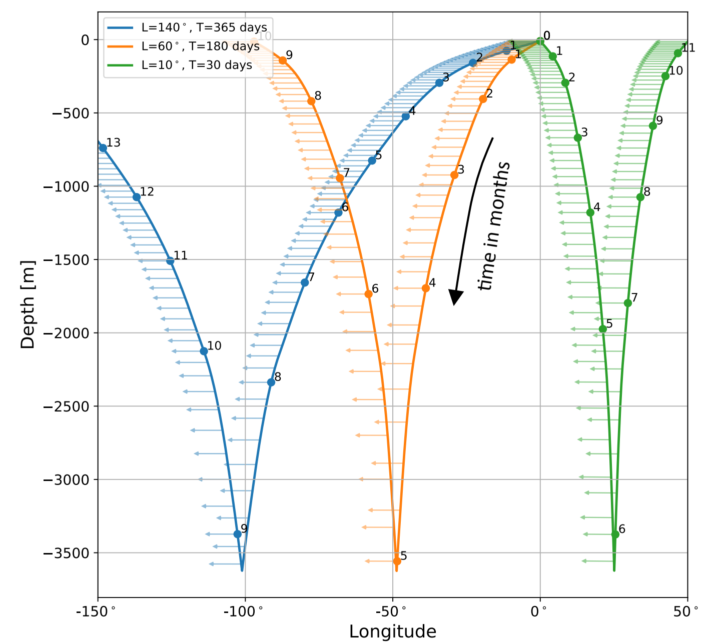
The dominant variability off the equator is at 70-day period and 450 km wavelength

3) Summary and link with planetary waves propagation

a) Dispersion relation diagram of Equatorial waves



b) Vertical energy raypaths of Equatorial waves

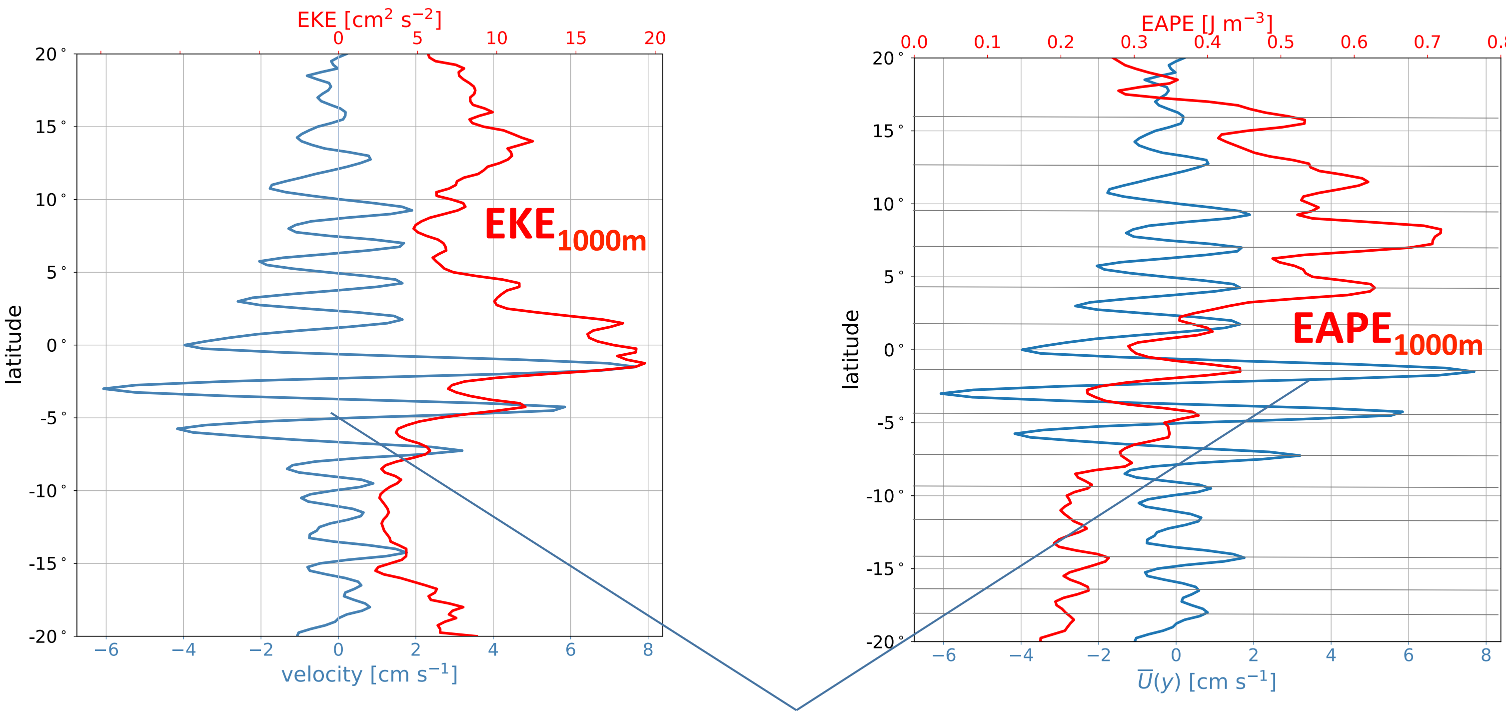


- TIW-like variability of V' in the eastern equatorial (EE circle) is compatible with baroclinic Yanai waves
- Variability of equatorial U' (EE and EW squares) are compatible with meridional mode 2, baroclinic mode 1 Rossby waves
- Off equatorial variability (TN and TS) is compatible with barotropic waves.

- Raytracing can explain why semi-annual variability is captured in the eastern part of the bassin, while annual variability can reach the western part.
- Annual intensification at depth of the TIW-like signal between Sep. and Jan. compatible with the 3-month phase lag of surface intensification reported in the litterature.

1) Strengthening of EKE and EAPE at the jet scale

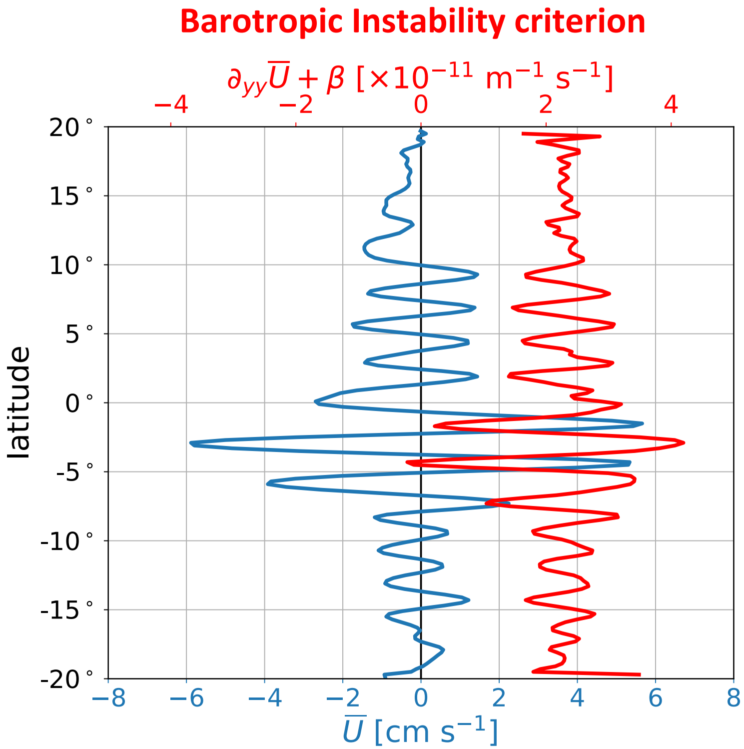
Time- Longitude average of U, EKE and EAPE

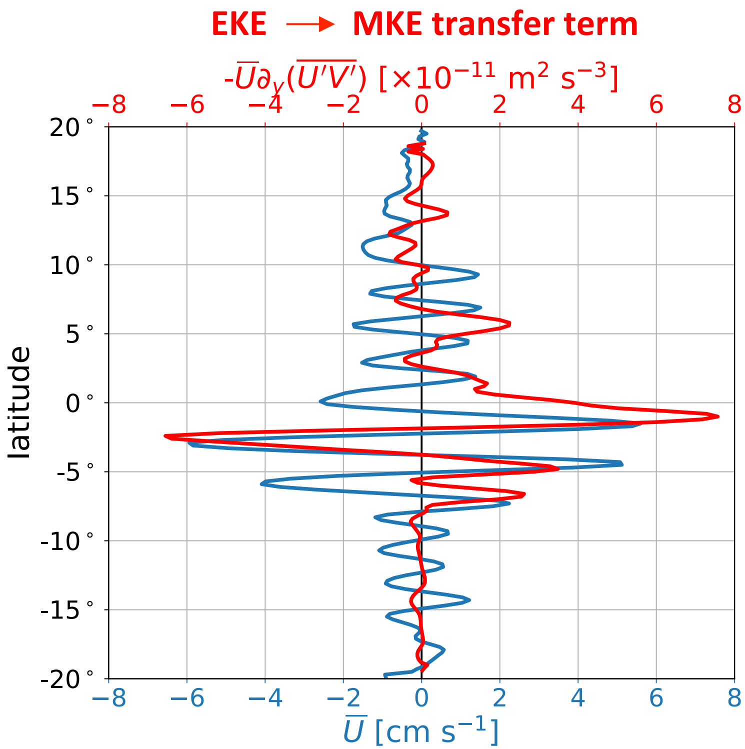


mean jet-structured circulation at 1000 m

- EKE and EAPE are intensified within eastward jets.
- Compatible with jet sharpening theory that predicts a local deformation of waves propagating on zonal jets background and have for consequence an intensification of the mean flow (Dritschel 2011, Greatbatch 2018).

2) EKE generation and transfer to MKE





- The EKE is not locally generated through barotropic instability of the background mean flow.
- It can be remotly generated and propagated through waves

- For most of the near equatorial jets, an energy transfer from EKE to MKE is evidenced.
- This support jet sharpening theories
- Exception: near 3°S where barotropic instability can play a role in transferring energy from MKE to EKE.

- EKE at 1000 m depth is investigated in the tropical Pacific Ocean using Argo floats

- Original Statistical methods allow for a characterization of the scale dependence of this EKE

- Variability associated with the zonal component of the velocity (U) is found along the equator with annual and semi-annual period. It corresponds to waves with large zonal wavelength (> 40°) and it is compatible with long Rossby waves.

- Variability associated with the meridional component of the velocity (V) is found in the eastern equatorial Pacific at 30-day period and ~1000 km wavelength. It is compatible with the signature of surface Tropical Instability Waves (TIWs). The intensification of the deep signal between September and January has a 3 month phase lag with the annual intensification of surface TIWs (Willet 2006). It matches the phase lag expected for downward propagating Yanai waves.

- Variability associated with V is also found off the equator at 70-day period and ~450 km wavelength and could be compatible with barotropic Rossby waves. **These waves in particular could play an important role in the formation of the mean jet-structured circulation.**

- EKE signal is also intensified at the jet scale and an energy transfer from the EKE to the MKE is evidenced. This result is compatible with jet sharpening theory (Dritschel 2011, Greatbatch 2018)

References

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