Analysis of freshwater plumes thermohaline variations from intra-seasonal to seasonal scales in the Gulf of Guinea

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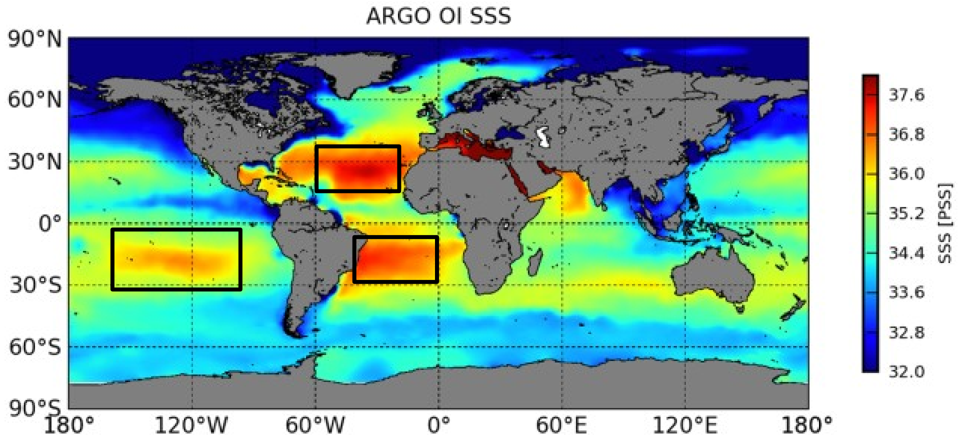
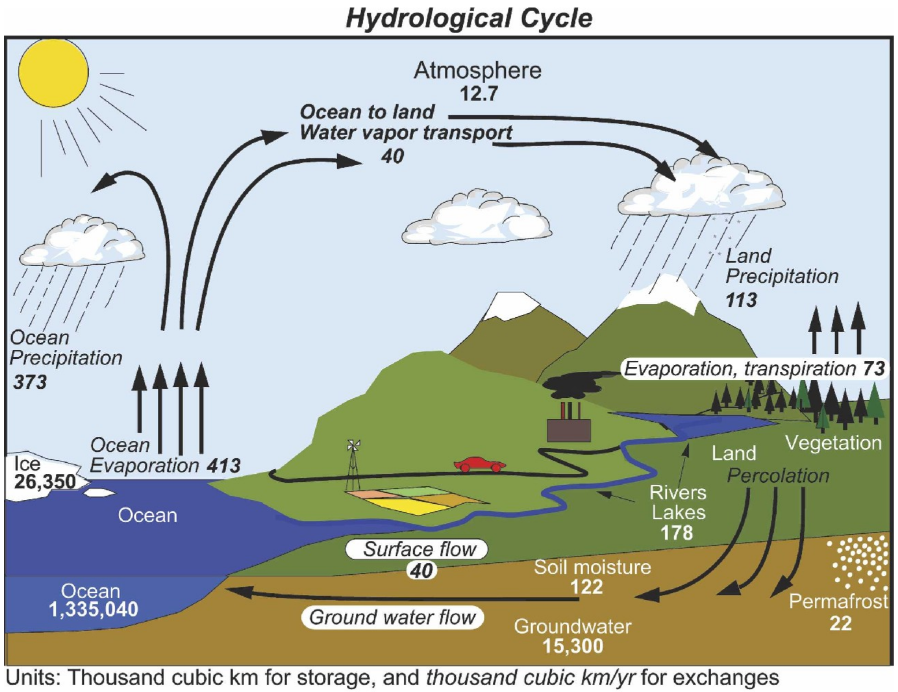


(Boutin et al., 2013)

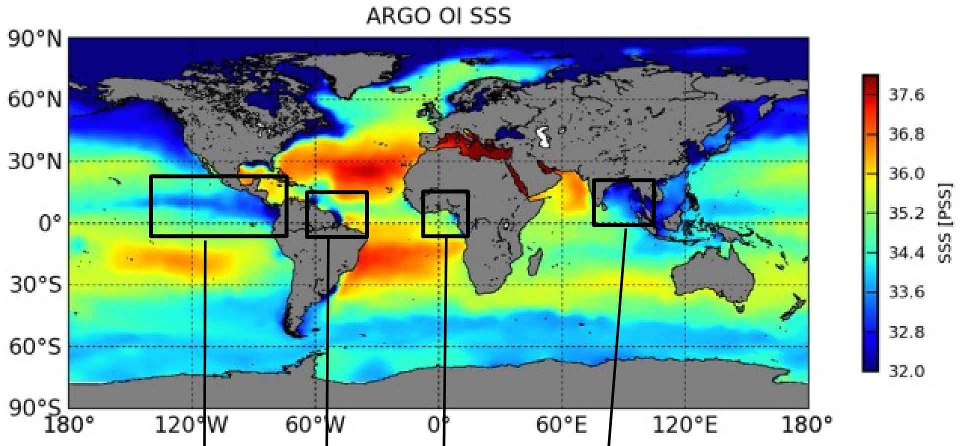


Units: Thousand cubic km for storage, and *thousand cubic km/yr* for exchanges

(Trenberth et al., 2007)

Ocean Evaporation induces:

- High SSS water masses



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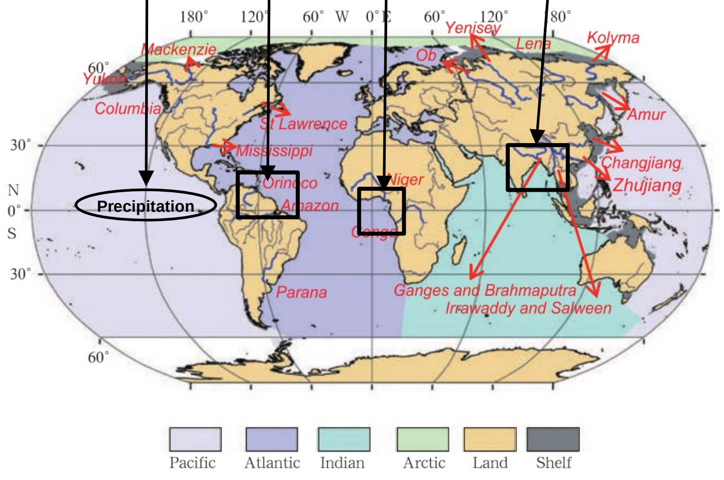

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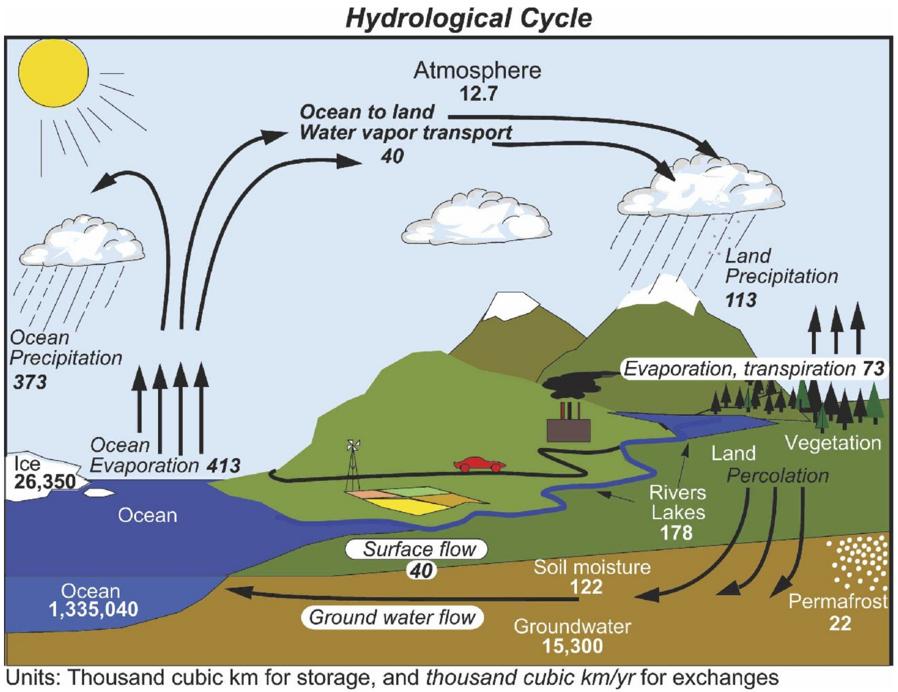
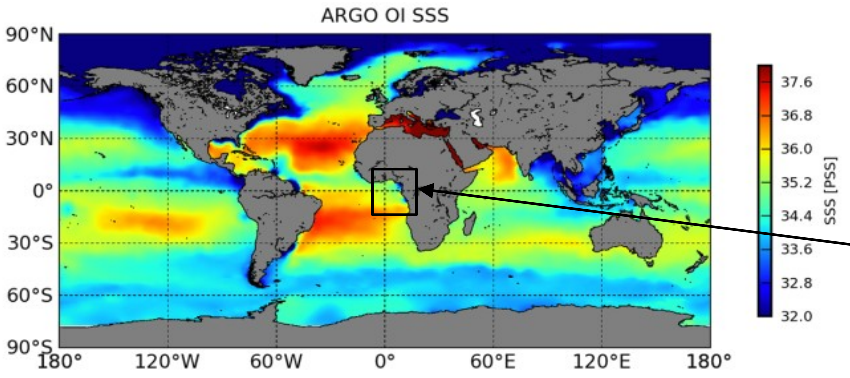


Ocean freshwater plumes

Low SSS water masses induced by:

- Precipitation
- Rivers runoff



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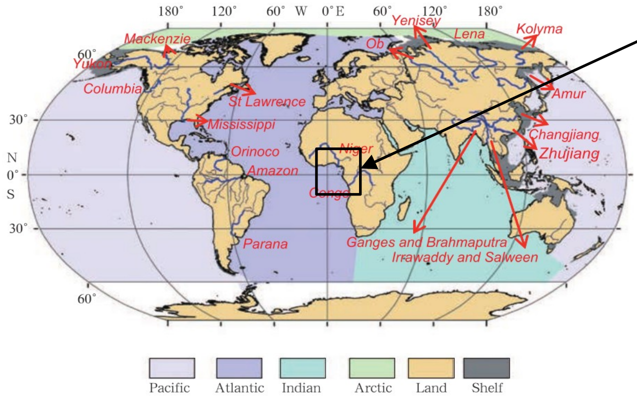

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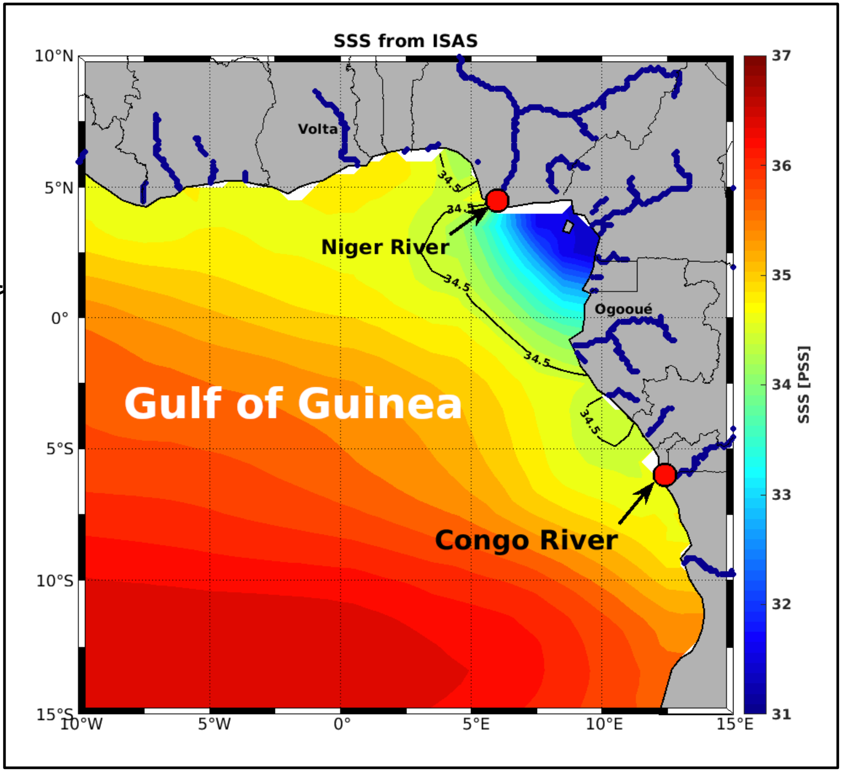
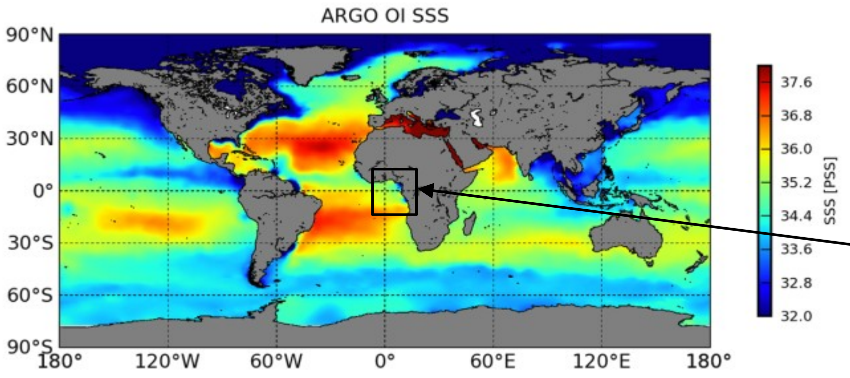
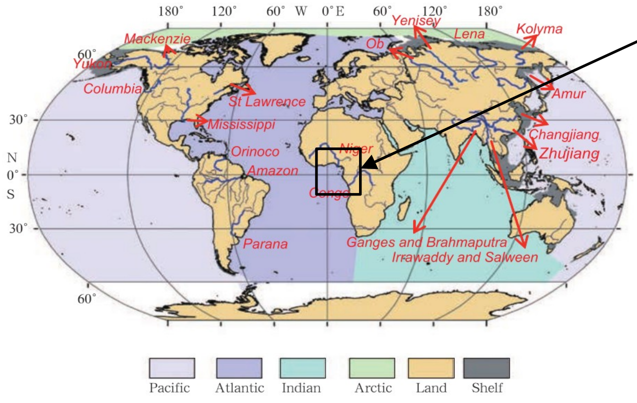


- Strong land-sea exchanges through ~ 13 rivers runoff (Mahé, 1991):
  - Congo River : 40,000 m³/s
  - Niger River : 6,000 m³/s



(Boutin et al., 2013)



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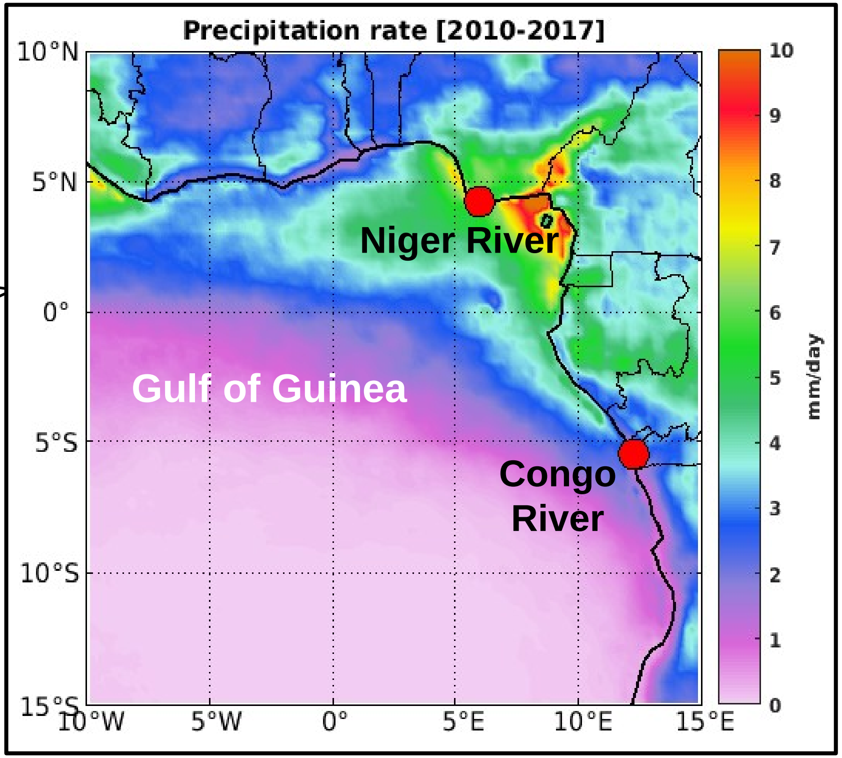
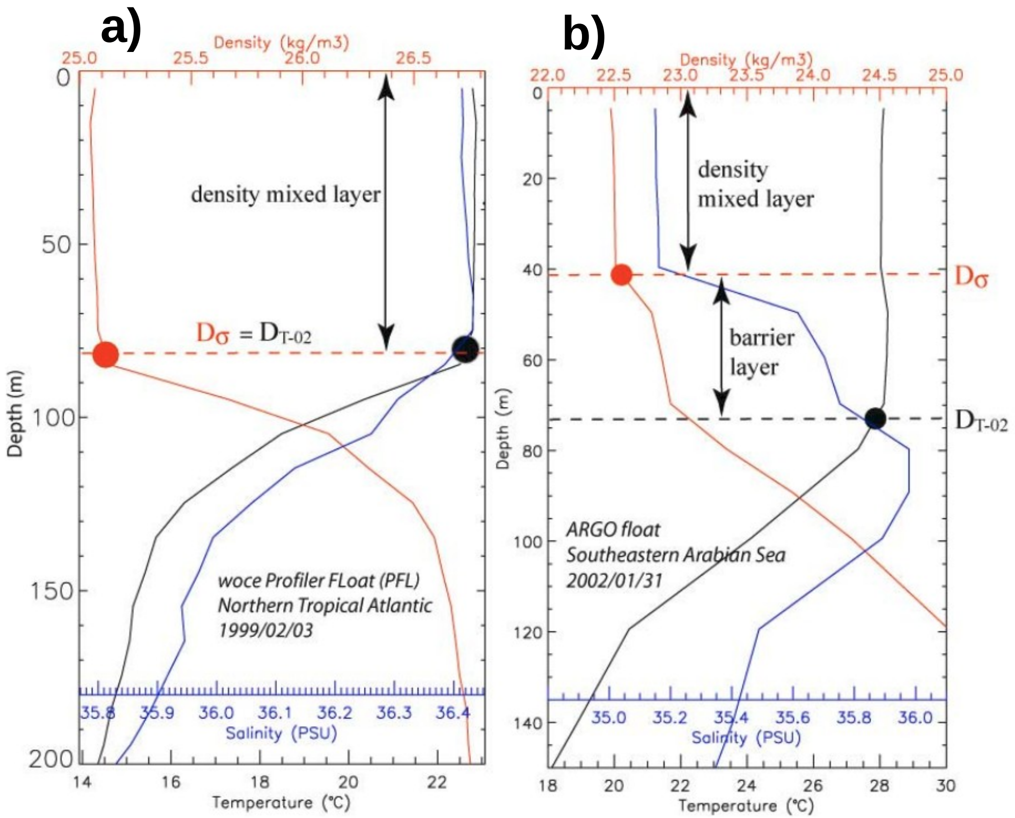


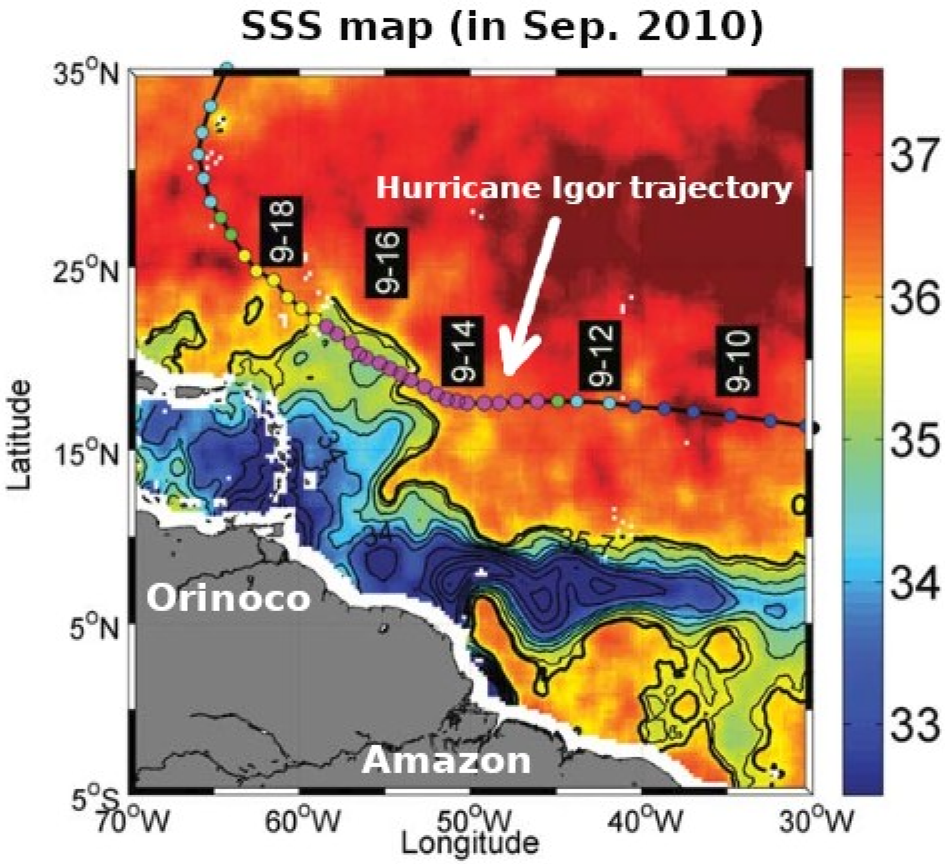
- Heavy precipitation due to the Inter-Tropical Convergence Zone with seasonal variation in latitude



(Mignot et al., 2009)

Ocean stratification

- Influence the upper ocean density stratification
  - Induce strong salinity stratification
  - Limit the mixed layer (Dossa et al., 2019)
  - Induce salt Barrier Layer structure (Mignot et al 2009)
  - Weaken the vertical heat exchanges (Katsura et al.,2015)



(Reul et al., 2014b)

Rivers plumes

- Modulate the heat storage and influence the air-sea interaction

  (eg. Grodsky et al., 2012 & Reul et al., 2014b)

  ➔ Amazon and Orinoco Rivers plumes salt-driven stratification enhance oceanic heat content in the North-West Atlantic Hurricane zones

- Sources of nutrient rich supply for the near coastal marine biological life

  (eg. Fournier et al. 2015)

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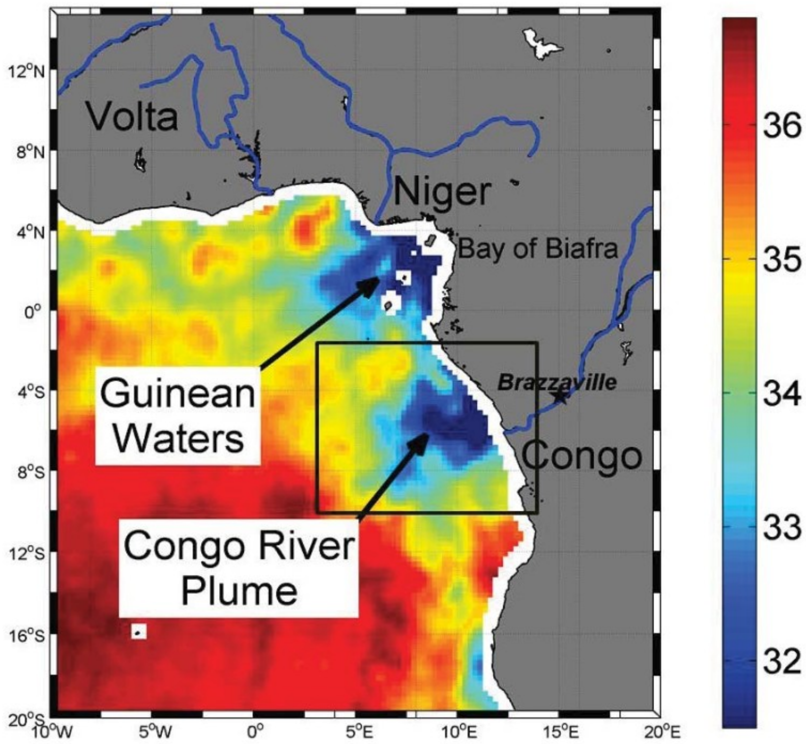


(Reul et al., 2014a)

- Variability of freshwater plumes remains poorly documented from observation.

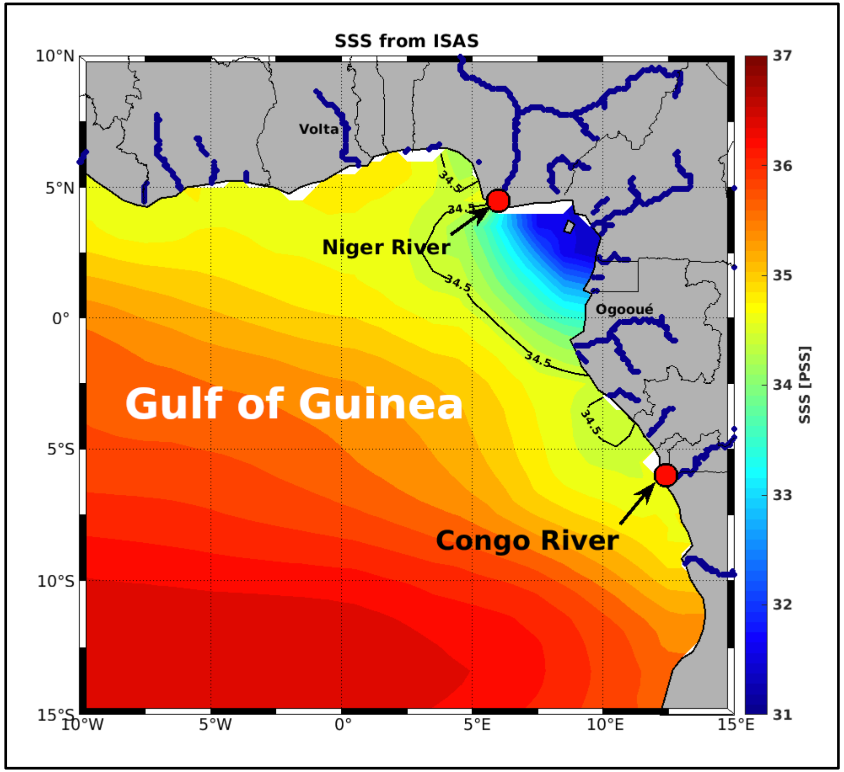
  (eg. Hopkins, et al., 2013; Reul et al., 2014a)

- What is the 3D thermohaline structure - the stratification within the freshwater plumes?

- Only few specific studies have been carried out on small scales
  - Horizontal: 10-100km
  - Vertical: 0-100m
  - Intra-seasonal to seasonal

(eg. Da-Allada et al., 2013; Berger et al., 2014; Hopkins et al., 2014)

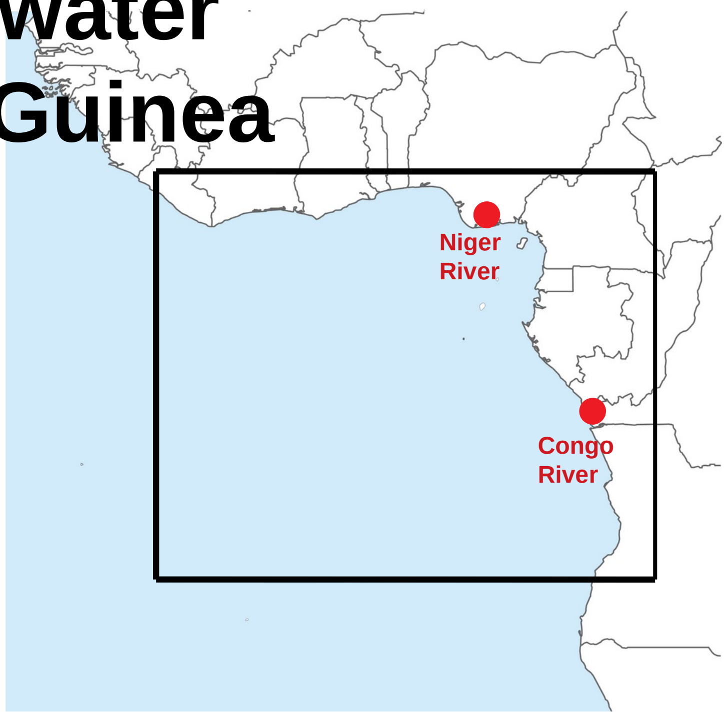
Document the variability of the 3D thermohaline structure of the freshwater plumes in the Gulf of Guinea at intra-seasonal to seasonal mesoscale



1. What is the seasonal spatial variability of freshwater plumes in the Gulf of Guinea basin?
2. What are the main physical processes that control their spatio-temporal variations?
3. What are the thermohaline stratification in the south-eastern Gulf of Guinea?
4. What are the 3D pathways of water masses interactions off Congo at intra-seasonal scale?

Part 1

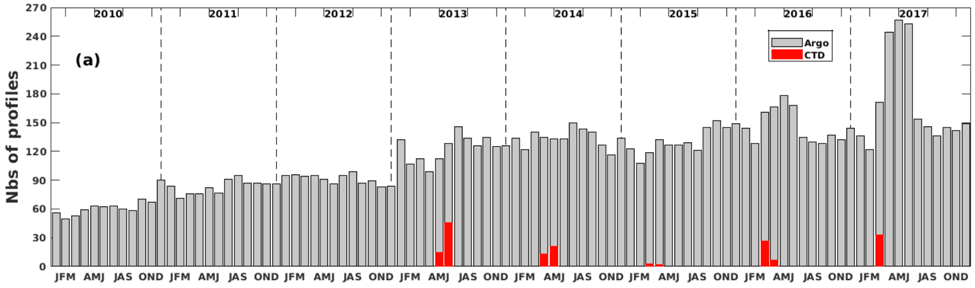
Seasonal variability of freshwater plumes in the eastern Gulf of Guinea



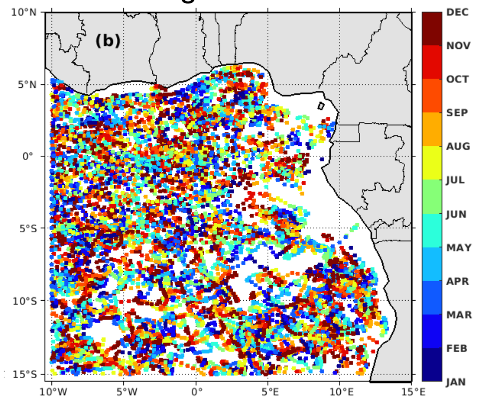
- To characterize and to identify the dominant physical processes controlling the freshwater plumes variability of Niger and Congo Rivers runoff areas

- In situ data and products available in the Gulf of Guinea (2010-2017).

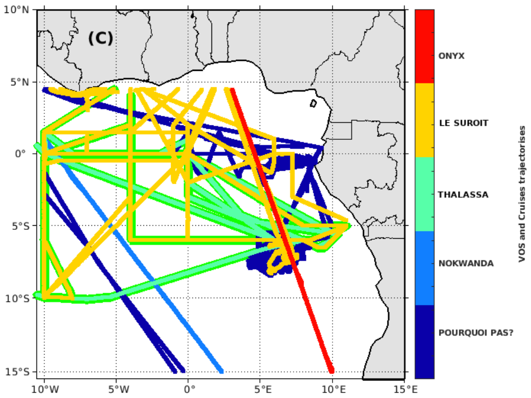
Nbs of profiles: Argo & CTD (2010-2017)



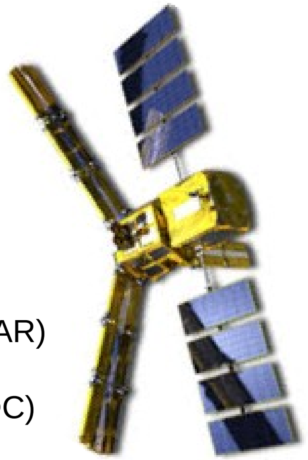
Argo & CTD



TSGs transects

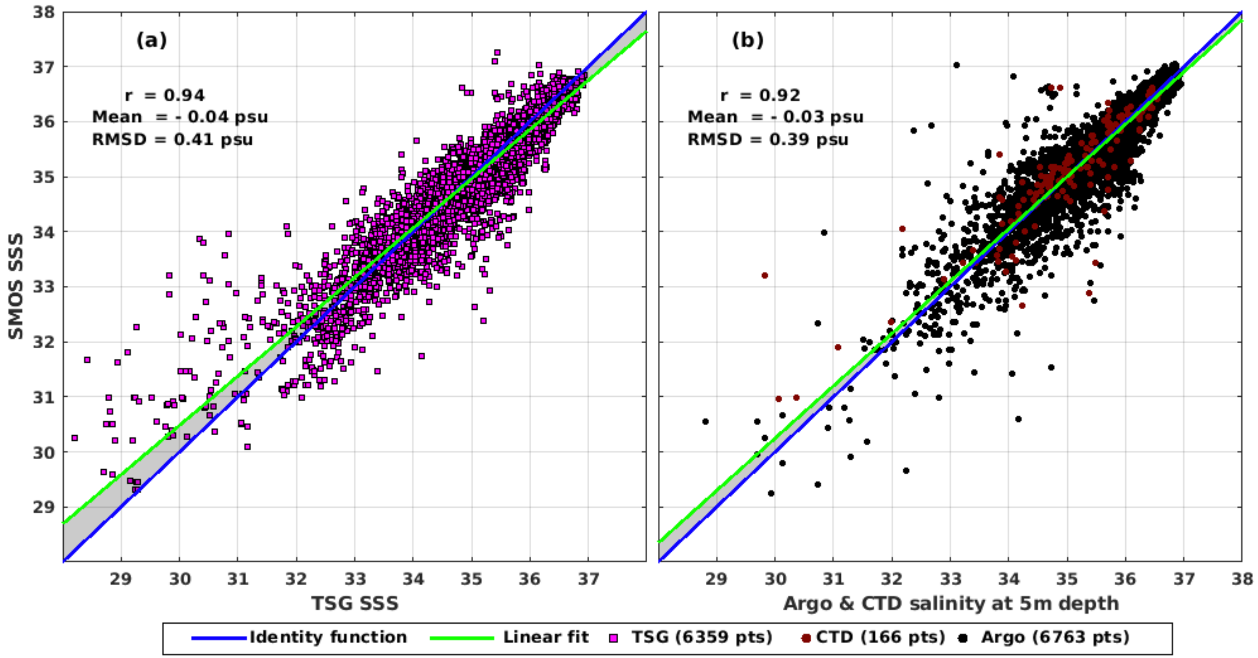


- **SSS SMOS** : 1/4° grid (*Boutin et al*. 2018)
- **GEKCO** (1/4°) **& OSCAR** (1/3°)
- **ANDRO, ADCP** and, **Drifter** current
- **Précipitation** (TRMM): 1/4°
- **Evaporation** (Oaflux) : 1°
- **River Runoff** (SO-HYBAM and NCAR)
- **Argo profiles** (Coriolis, AOML, BODC)
- **CTD** profiles (**PIRATA** FR cruises)
- **TSG SSS** (SNO-SSS & SEANOE)



- SMOS SSS validation from In Situ Measurements: Argo, CTD and TSGs in the Gulf of Guinea (2010-2017)

Scatter-plot between SMOS SSS and In Situ salinity data

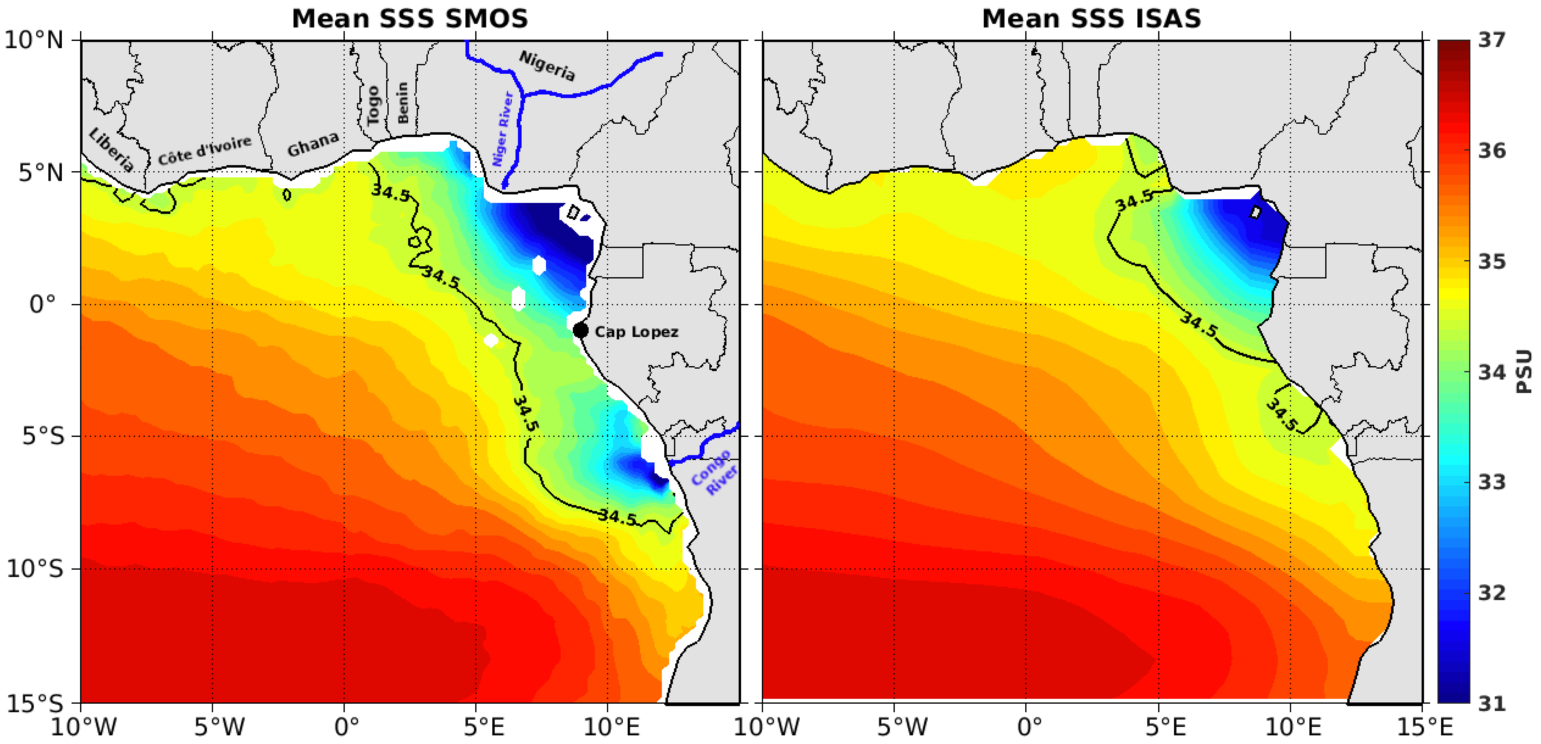


Mean(ΔSSS) = **- 0.04** *pss* STD = **0.40** *psu*

RMSD = 0.40 *psu* r = 0.94

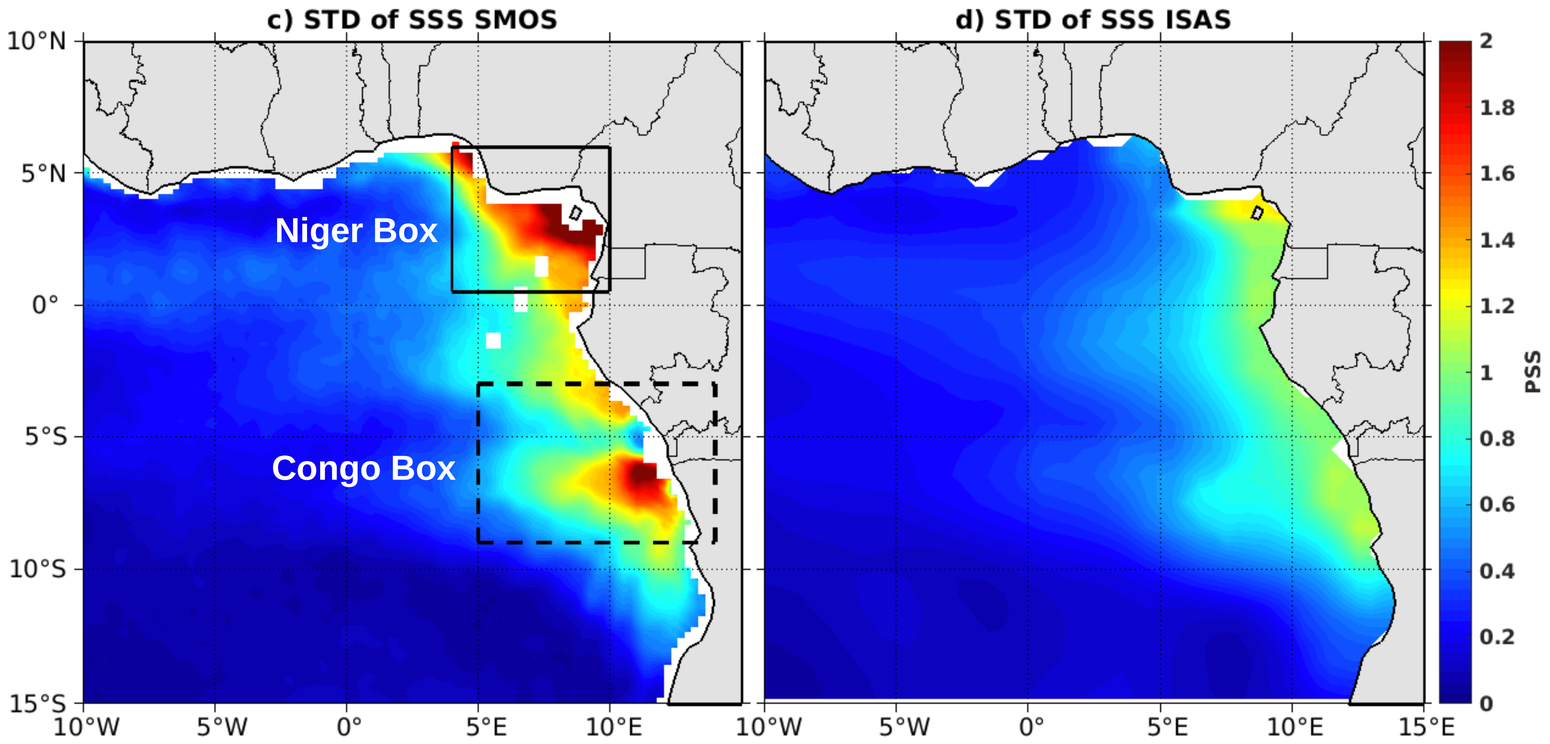
→ SMOS SSS data are well validated and reliable to study the freshwater plumes in the Gulf of Guinea

- Freshwater plumes in the eastern Gulf of Guinea as observed from SMOS (2010-2017)



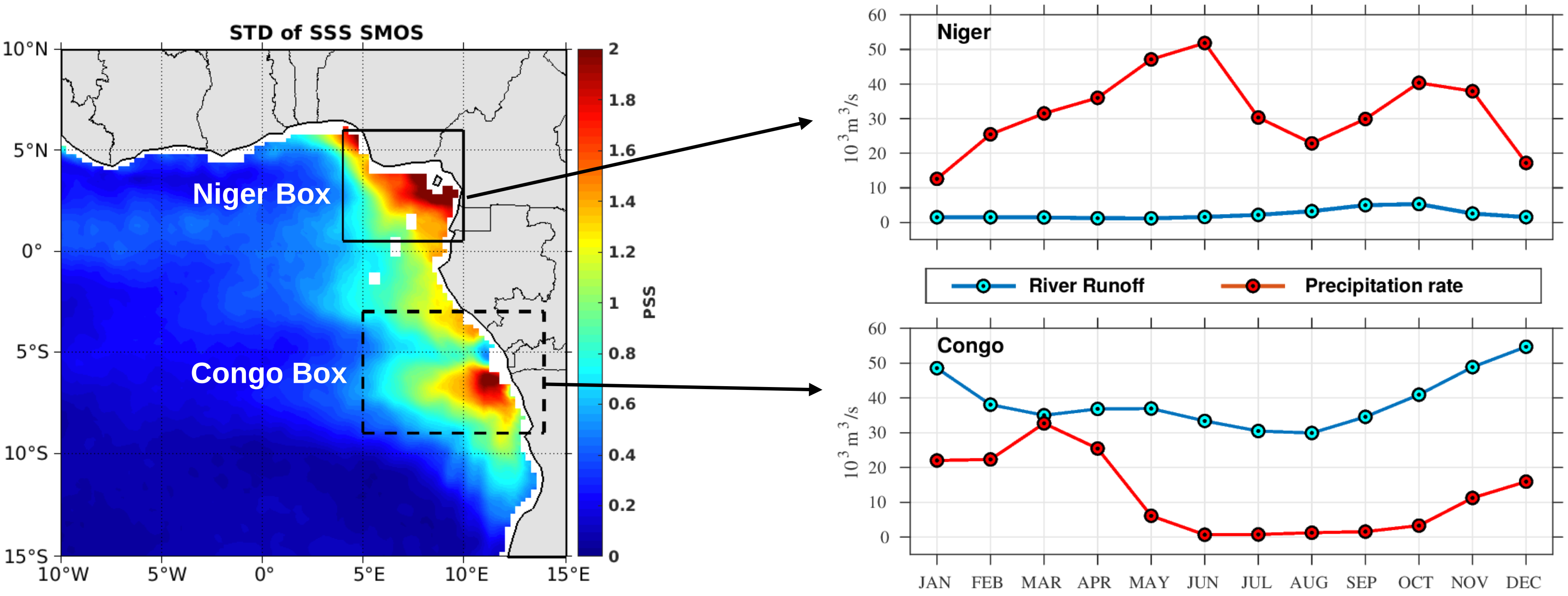
- Freshwater plumes in the eastern Gulf of Guinea is well observed from SMOS SSS.
- The far field of freshwater plumes is delimited by 34.5 pss isohaline contour

- Freshwater plumes in the eastern Gulf of Guinea as observed from SMOS (2010-2017)



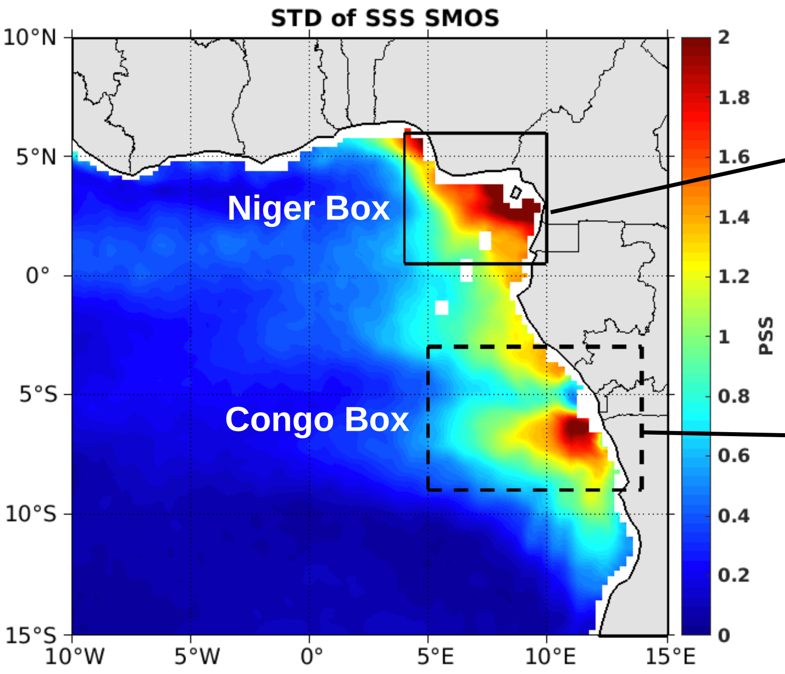
→ Strong seasonal variability of SSS is well observed by SMOS in the eastern Gulf of Guinea

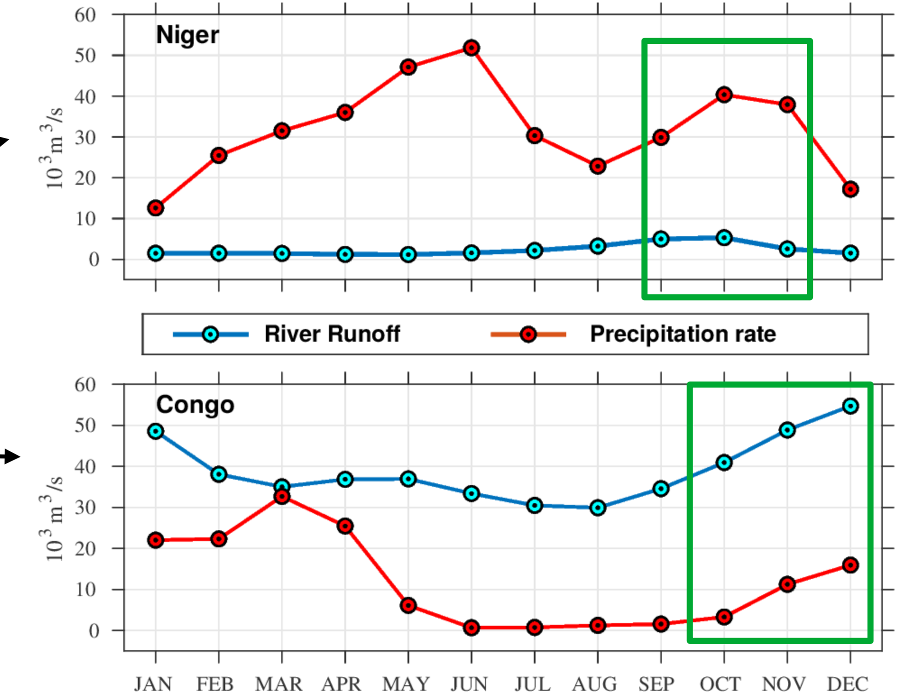
- Seasonal Cycle of Precipitation and rivers runoff over the freshwater plumes zones (2010-2017)



→ River runoff largely dominant the precipitation overs Congo freshwater plume area and inversely for the Niger freshwater plume area.

- Seasonal Cycle of Precipitation and rivers runoff over the freshwater plumes zones (2010-2017)

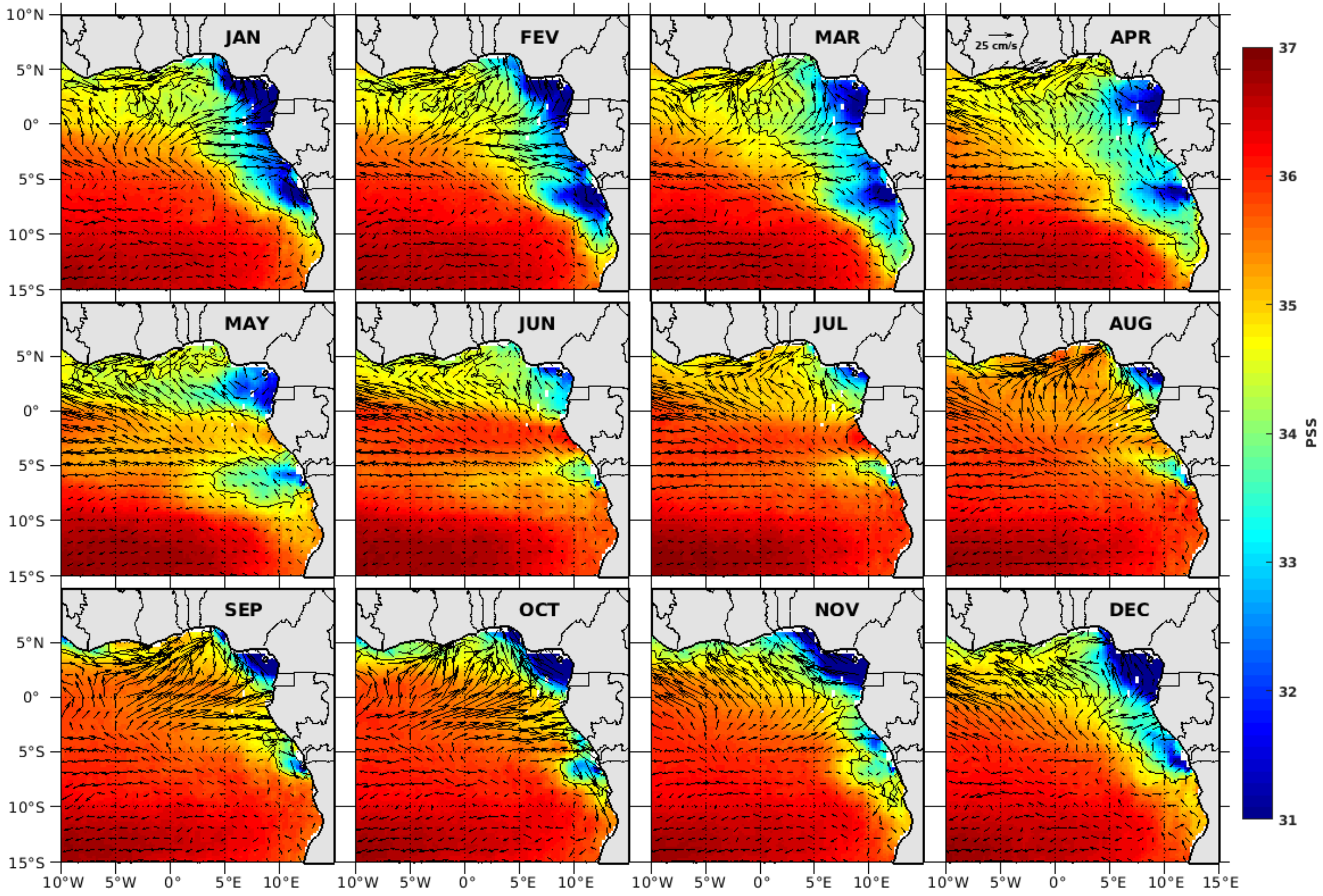


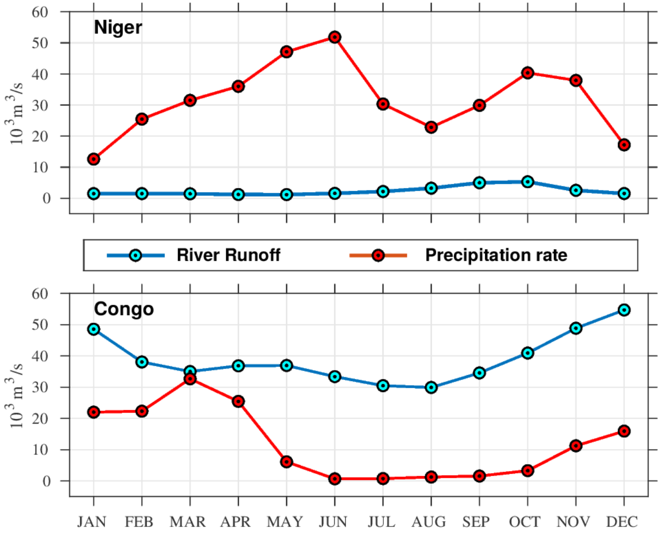


→ Period of intense rivers runoff & precipitation

- Niger freshwater plume area : Sep. to Nov.
- Congo freshwater plume area : Oct. to Dec.

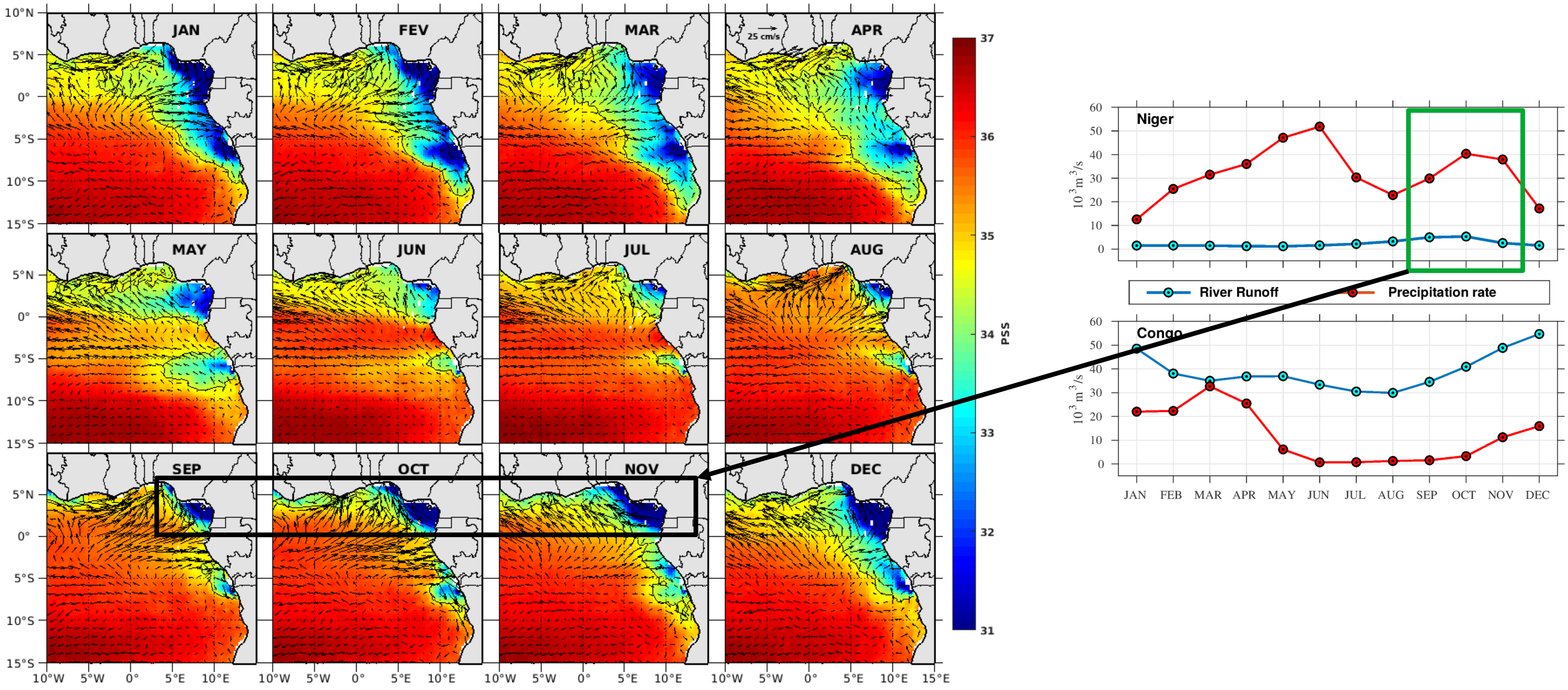
- Seasonal variability of freshwater plumes in the eastern Gulf of Guinea as inferred from SMOS





Surface currents from GEKCO (Sudre et al., 2013)

- Seasonal variability of freshwater plumes in the eastern Gulf of Guinea as inferred from SMOS



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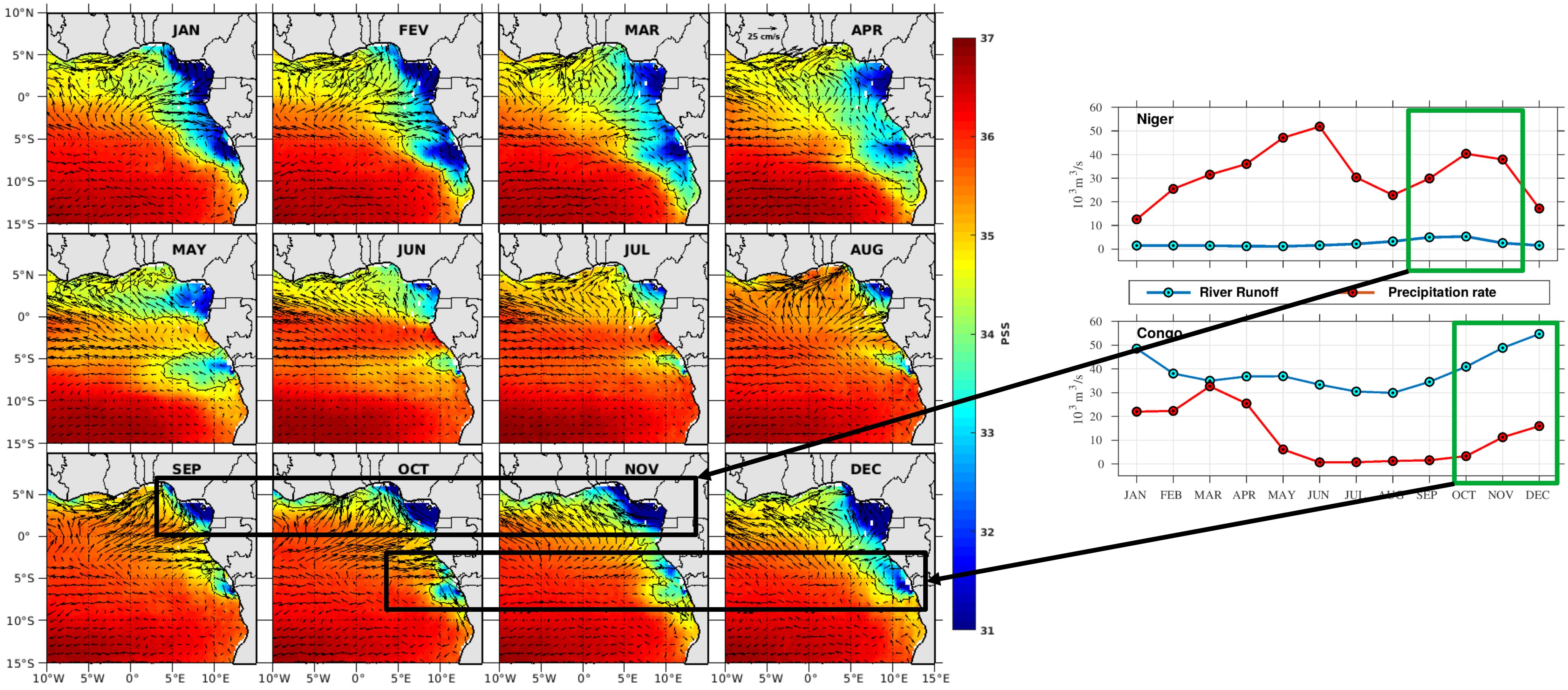

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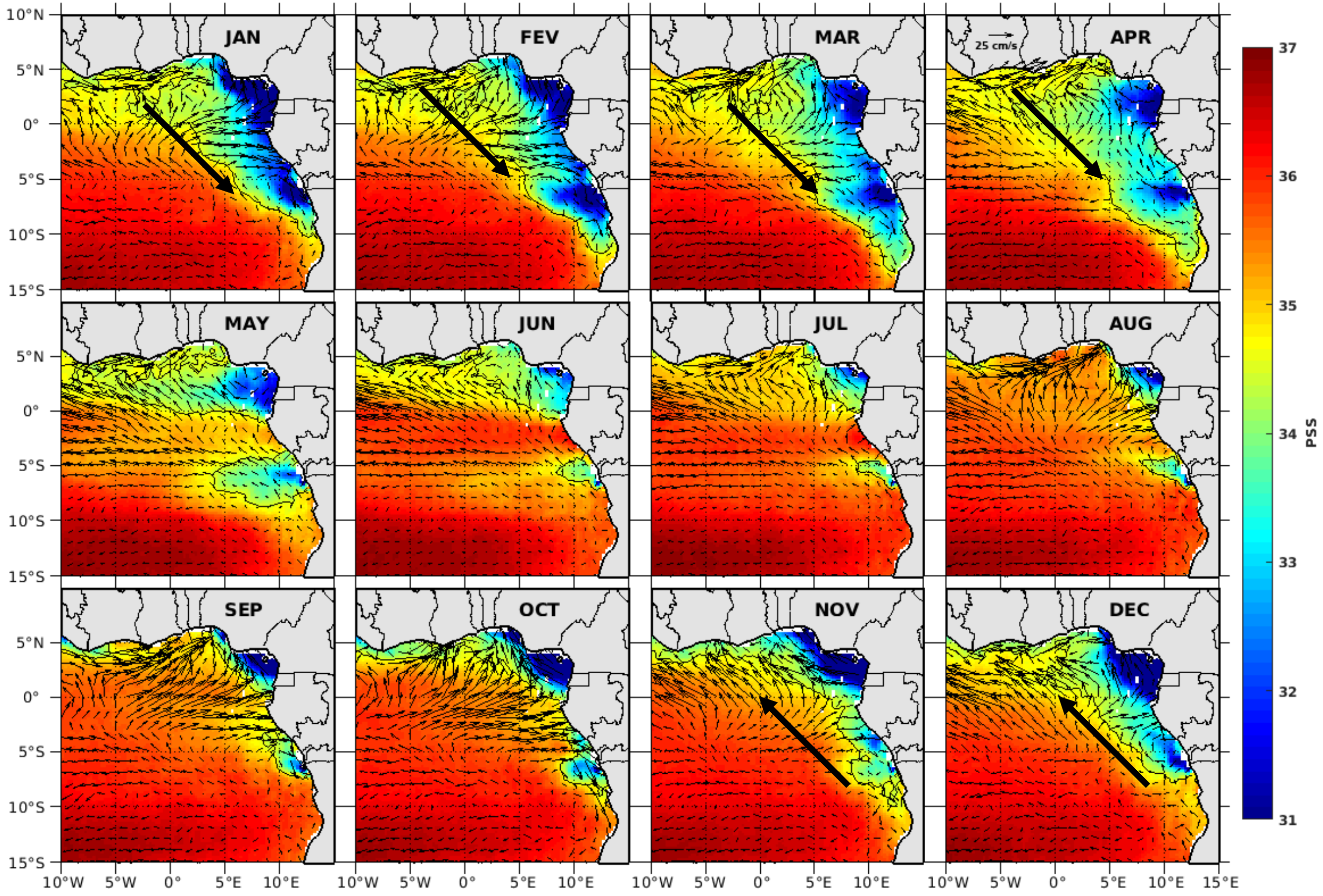

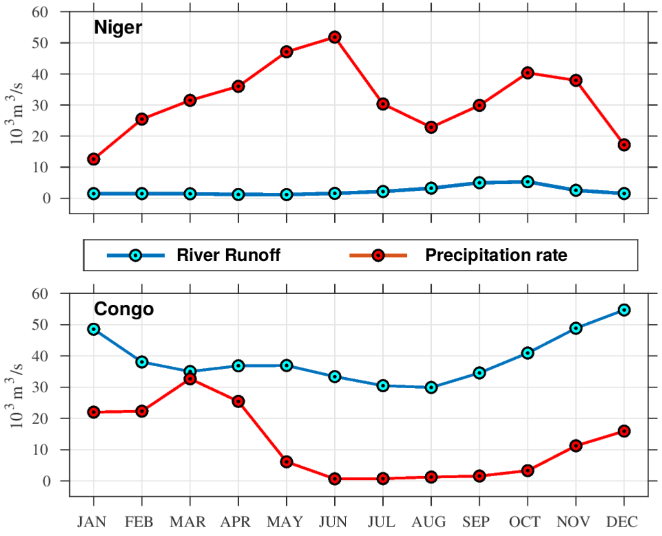

Surface currents from GEKCO (Sudre et al., 2013)

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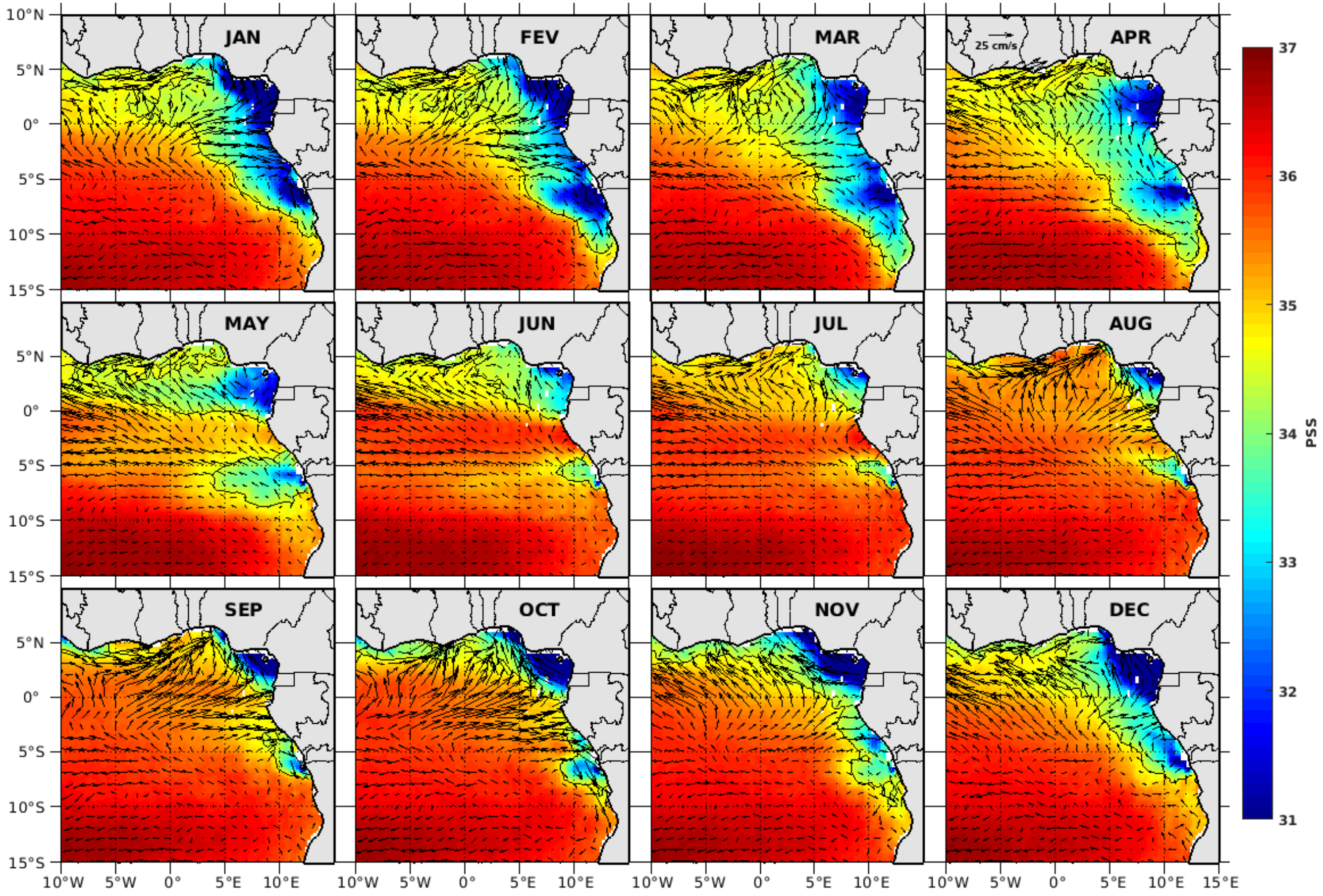
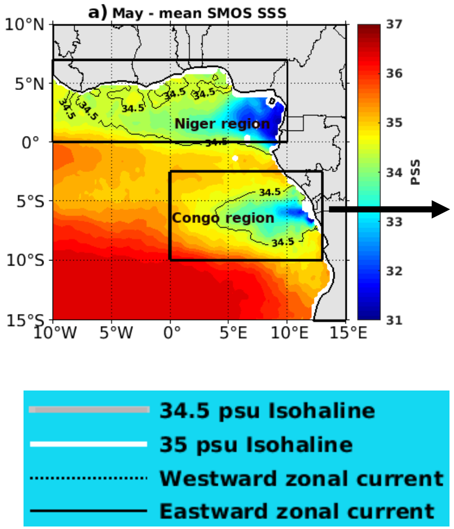


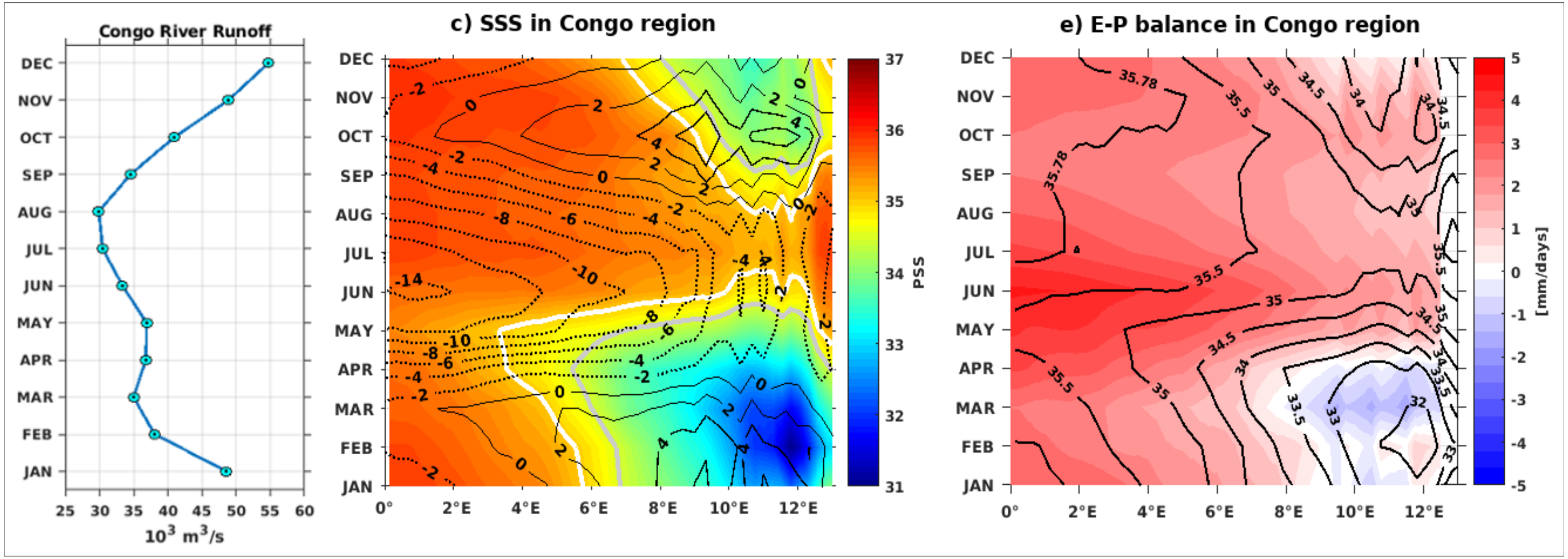
Surface currents from GEKCO (Sudre et al., 2013)

- May to Aug.:
  - Salinization episode
  - Minimal extension
- EUC outcropping
- Shear : EUC & SEC

(Kolodziejcyk et al., 2014
Da-Allada et al., 2017)

- Seasonal variability of freshwater plumes in the eastern Gulf of Guinea as inferred from SMOS

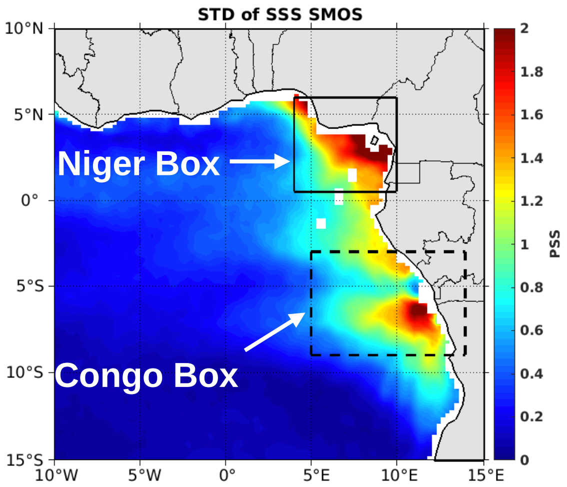




- Period of low SSS : September – mid-April.
  - High runoff & weak rainfall rate dominate surface evaporation
  - Westward spreading of low SSS not correlated with zonal currents
- Period of high SSS : May – early September.
  - Intensification of Eastward zonal currents
  - High evaporation processes

- Identify the dominant physical processes controlling the variability of Niger and Congo Rivers freshwater plumes
  Following *Moisan et al., 1998* and *Köhler et al., 2018* method, applied to Mixed Layer salinity :

$$\underbrace{\frac{\partial \bar{S}}{\partial t}}_{\text{Total trend}} = -\underbrace{\bar{u}\cdot\nabla\bar{S}}_{ZADV\ \text{(Zonal advection)}} - \underbrace{\bar{v}\cdot\nabla\bar{S}}_{MADV\ \text{(Meridional advection)}} + \underbrace{\frac{E-P-R}{h}SSS}_{SFFLUX\ \text{(Freshwater flux)}} - \underbrace{\frac{1}{h}W_e.(\bar{S}-S_{-h})}_{ENT\ \text{(Entrainment)}} + \underbrace{\overline{k_H\nabla_H^2 S}}_{HDIFF\ \text{(Horizontal diffusion)}} + R_e$$

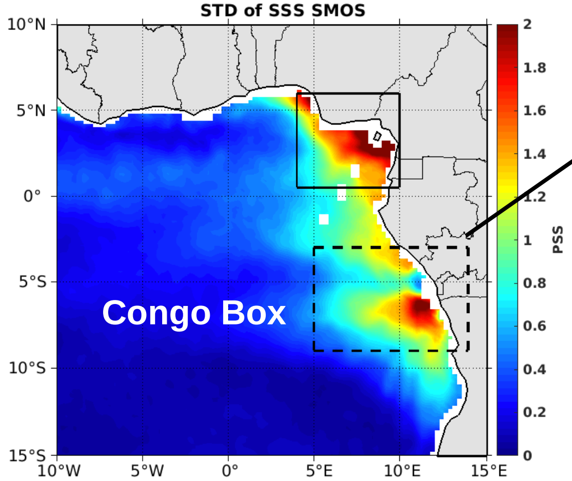


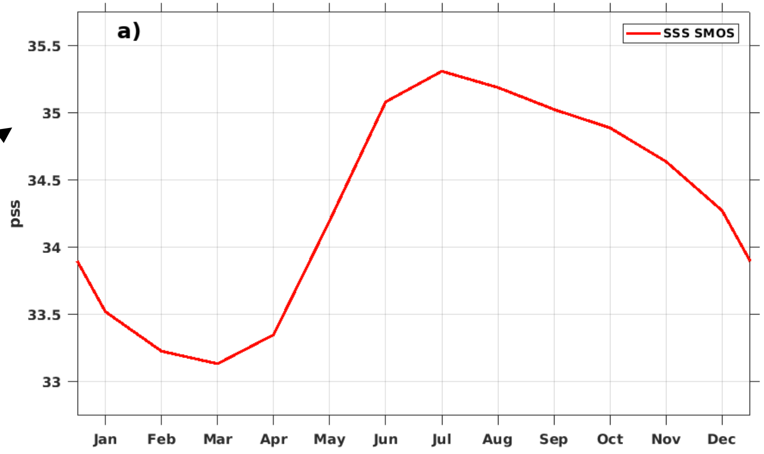
$$\underbrace{R_e = -\underbrace{\frac{1}{h}\left(k_z\frac{\partial S}{\partial z}\right)_{z=-h}}_{\text{VDIFF}} - \underbrace{\frac{1}{h}\nabla\cdot h\overline{\left(\hat{V}\hat{S}\right)}}_{\text{Vertical shear}} - \underbrace{\overline{\nabla\cdot V'S'}}_{\text{EHADV}} + \underbrace{\frac{1}{h}\left(w'S'\right)_{z=-h}}_{\text{EVADV}}}_{\text{Residues}}$$

h* = *MLD estimated with the approach of Boyer Montegut et al. (2004)

(**0.03 kg.m^{-3}** criterion, depth$_{ref}$ = **10**m)

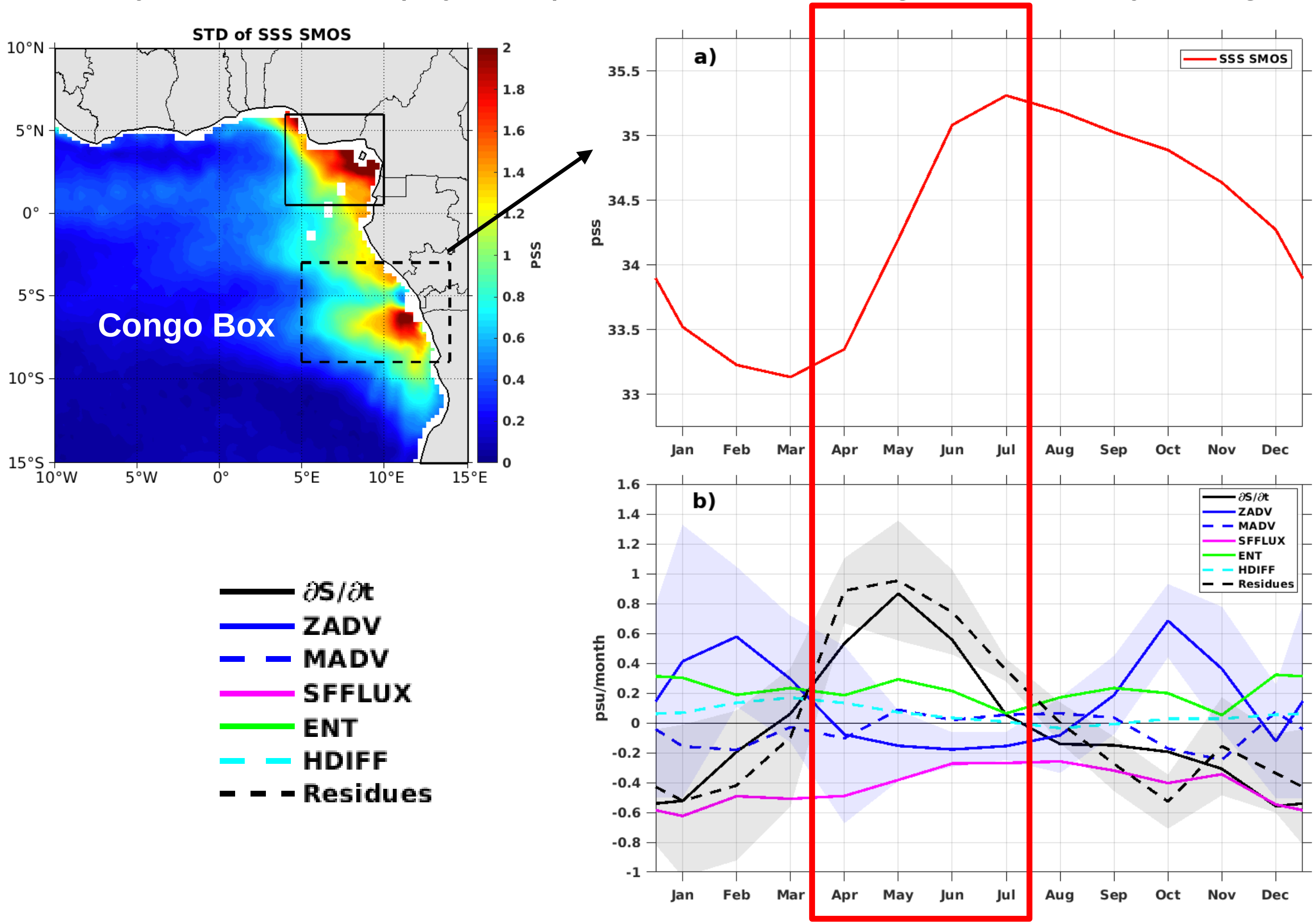
- Identify the dominant physical processes controlling the variability of Niger and Congo Rivers freshwater plumes





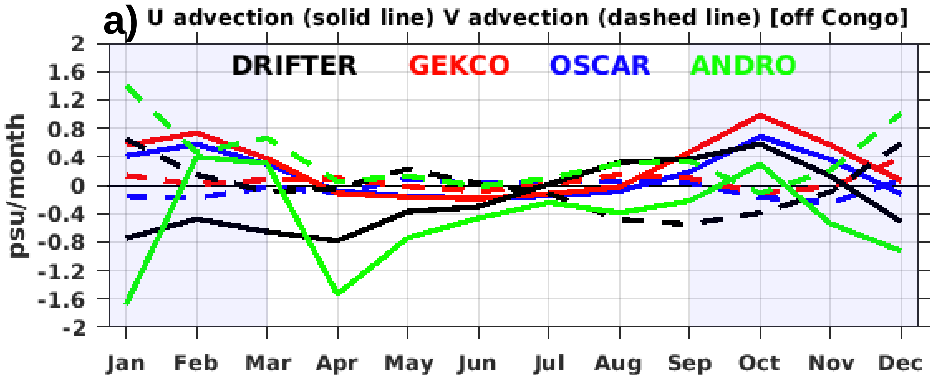
→ Seasonal cycle of SSS of ~2pss as amplitude within the Congo freshwater plume

- Identify the dominant physical processes controlling the variability of Niger and Congo Rivers freshwater plumes



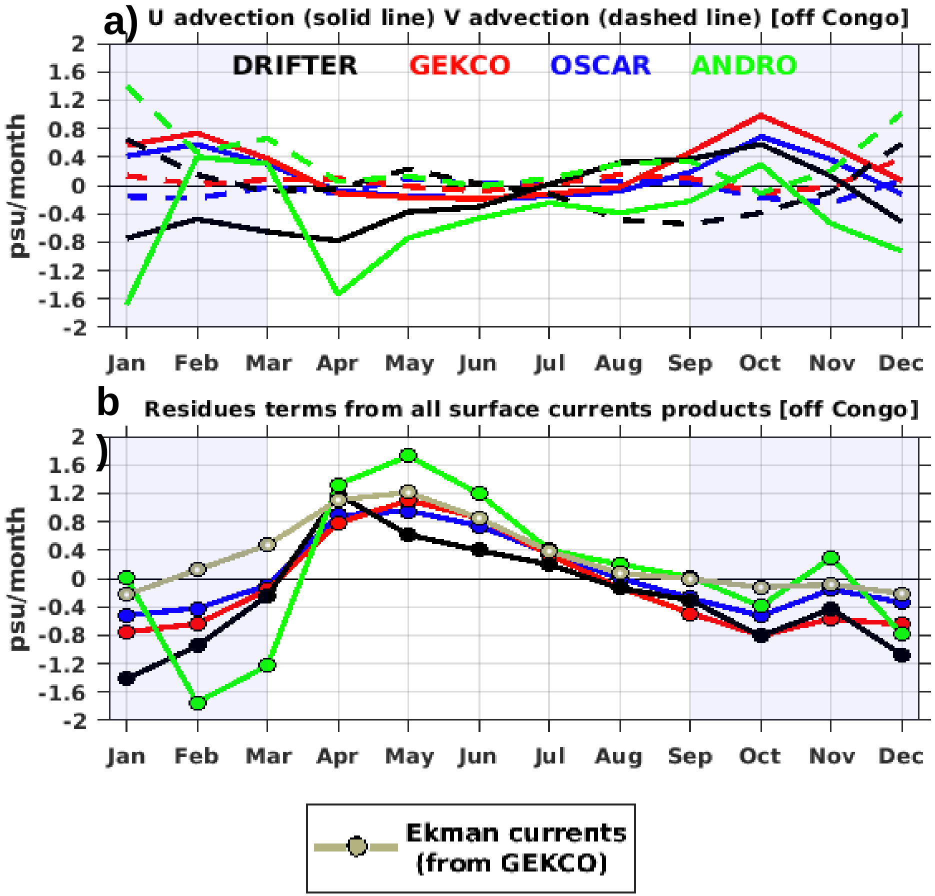
- Always negative SFFLUX
- : $Period\ of\ \partial S/\partial t < 0$
  - → mid-August to March
  - → Zonal advection
  - → Vertical processes (Residues)
- : $Period\ of\ \partial S/\partial t > 0$
  - → March to July
  - → Vertical processes (Residues)

- Sensitivity to the surface Currents Products in the freshwater plumes zones in the Gulf of Guinea



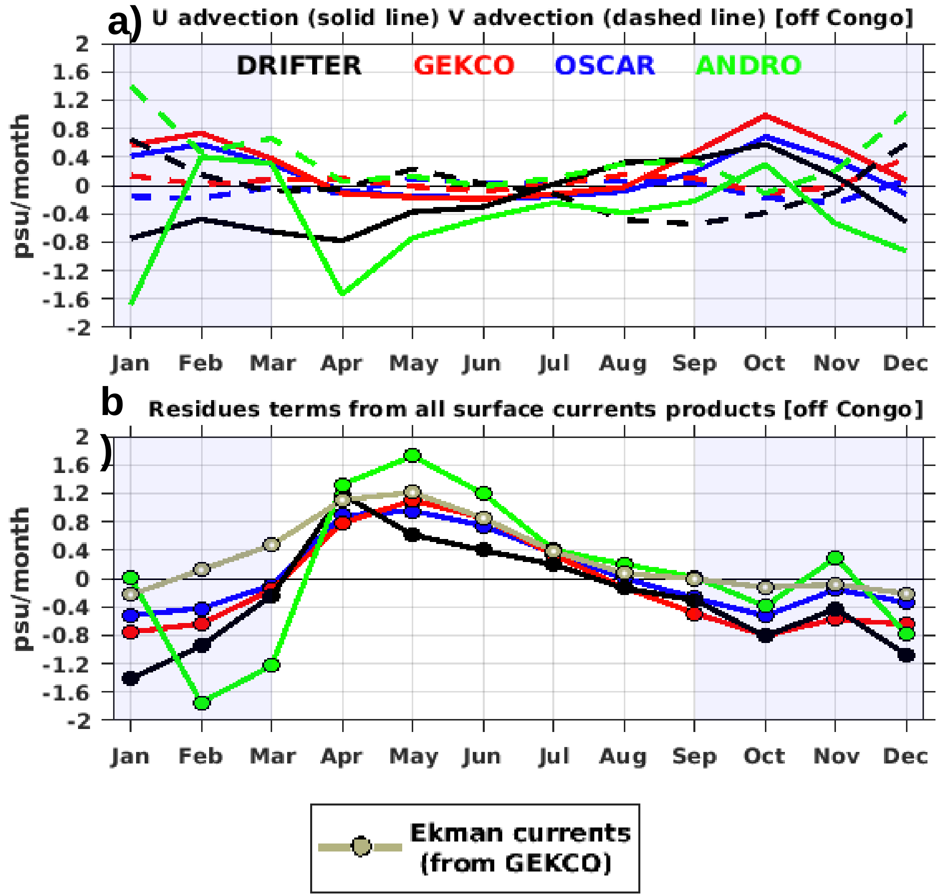
→ Amplitude and sign differences over the period of high freshwater input
- GEKCO & OSCAR (altimetry) are similar
- ANDRO & DRIFTER (in situ) are not similar

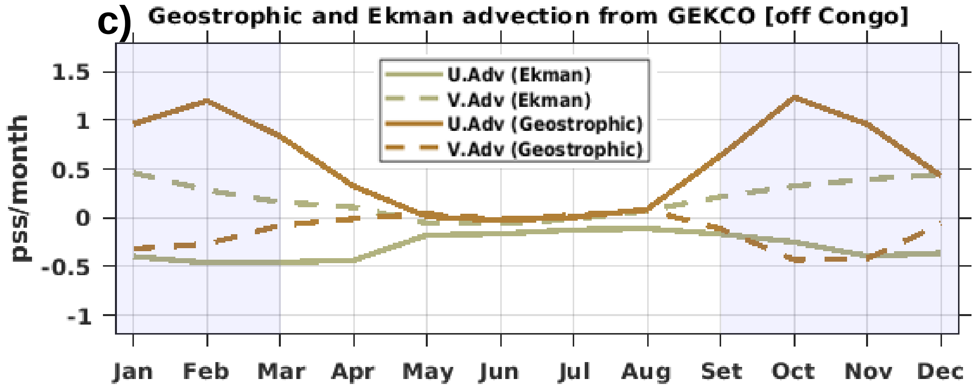
- Sensitivity to the surface Currents Products in the freshwater plumes zones in the Gulf of Guinea



- Negative contributions of Residues reduce with surface Ekman current (from GEKCO)
- Highlights the important role the wind-driven surface Ekman current in the freshwater plume advection

- Sensitivity to the surface Currents Products in the freshwater plumes zones in the Gulf of Guinea



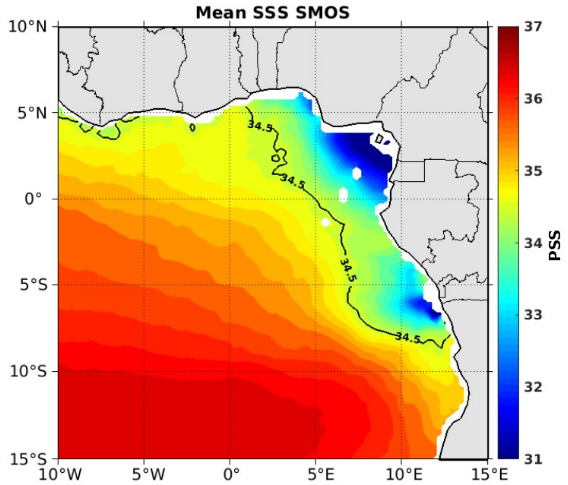


- Dominance of geostrophic component in GEKCO current product.
- The dynamics of freshwater plumes might not be resolved in the currents product in this region

Part 1

- To summarize:

  - SSS SMOS mission enabled to study the seasonal variability of freshwater plumes in the Gulf of Guinea
    - Freshwater plumes dynamics follow two spreading regimes:
      - Northwestward and Southwestward
      - Maximal extension by April & Minimal extension by August.
  - Seasonal variability is controlled by the interplay between :
    - Advection and vertical processes (Residual terms)
  - Horizontal low SSS advection is dominated by Ekman wind-driven currents.
  - Surface currents in the freshwater plumes may not be well estimated.



- Published in

JGR Oceans

RESEARCH ARTICLE
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Seasonal Variability of Freshwater Plumes in the Eastern Gulf of Guinea as Inferred From Satellite Measurements

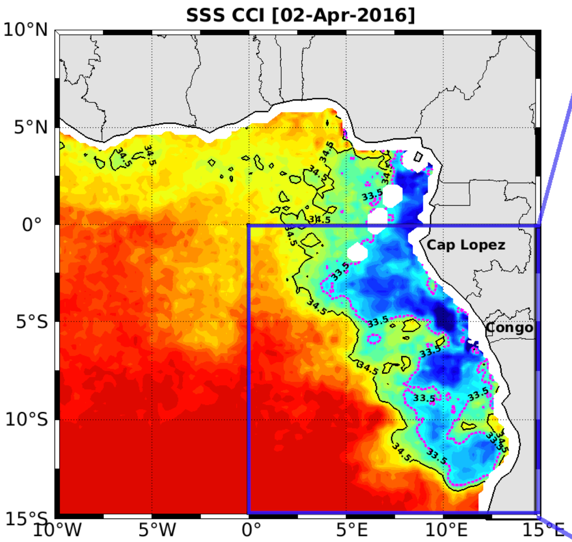
O. J. Houndegnonto[1], N. Kolodziejczyk[1], C. Maes[1], B. Bourlès[2], C. Y. Da-Allada[3,4,5], and N. Reul[1]

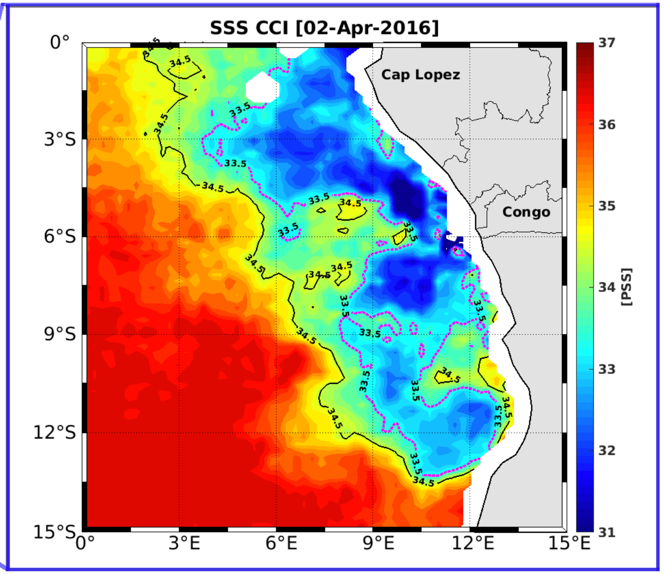
Key Points:

- The Gulf of Guinea's freshwater plumes spreading is characterized

Part 2

Characterization of thermohaline stratification in the Congo River plume





How do the dynamics of the Congo River plume control the thermohaline stratification of surface layers in the south-eastern Gulf of Guinea?

↓

1- Characterization of vertical thermocline stratification off Congo

2- Identify the mechanisms controlling the thermohaline stratification formation

- Quantification of thermohaline stratification parameters

  - Brunt-Väisälä frequency :

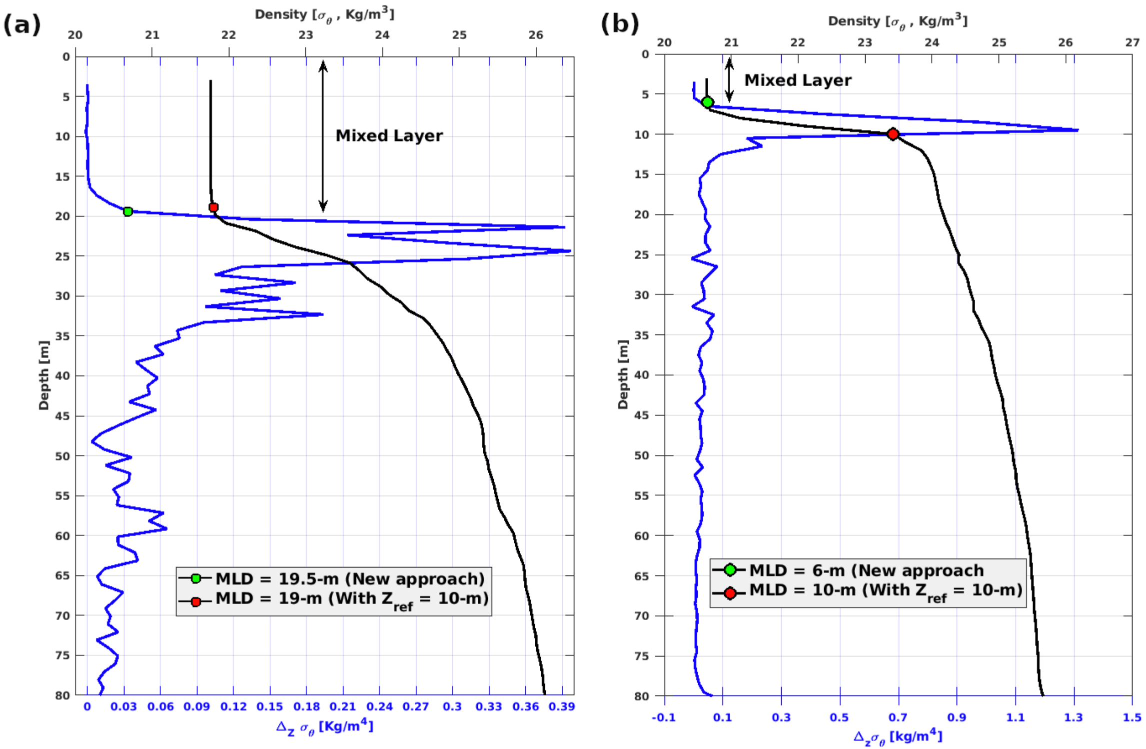
$$N^2 = N_T^2 + N_S^2$$

  - **MLD** correspond to the depth over which:

$$\frac{\Delta \sigma_\theta}{\Delta z} \leq 0.03\, kg/m^4 \;\Longrightarrow\; N^2 \leq 3.10^{-4} S^{-2}$$

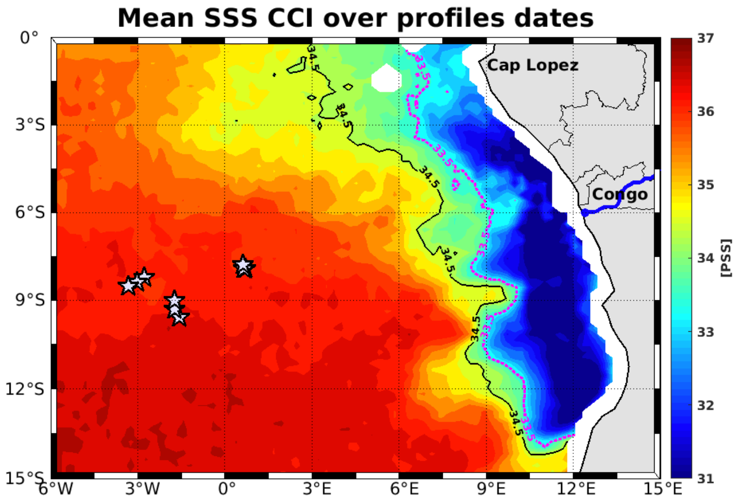
  - **ILD** correspond to the depth over which:

$$N_T^2 \leq 3.10^{-4} S^{-2}$$

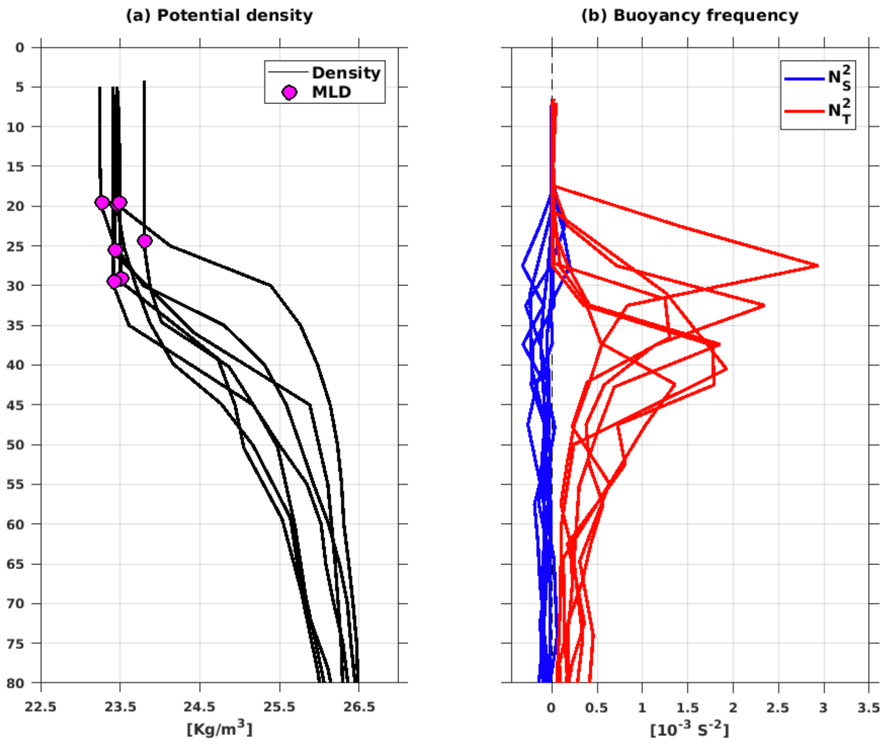


→ Exploring Argo and CTD PIRATA FR profiles through the Congo Rivers plume zone

- Thermohaline stratification out of the zone influenced by the far field of the Congo River plume



☆ Argo profiles localisations (March 2016)

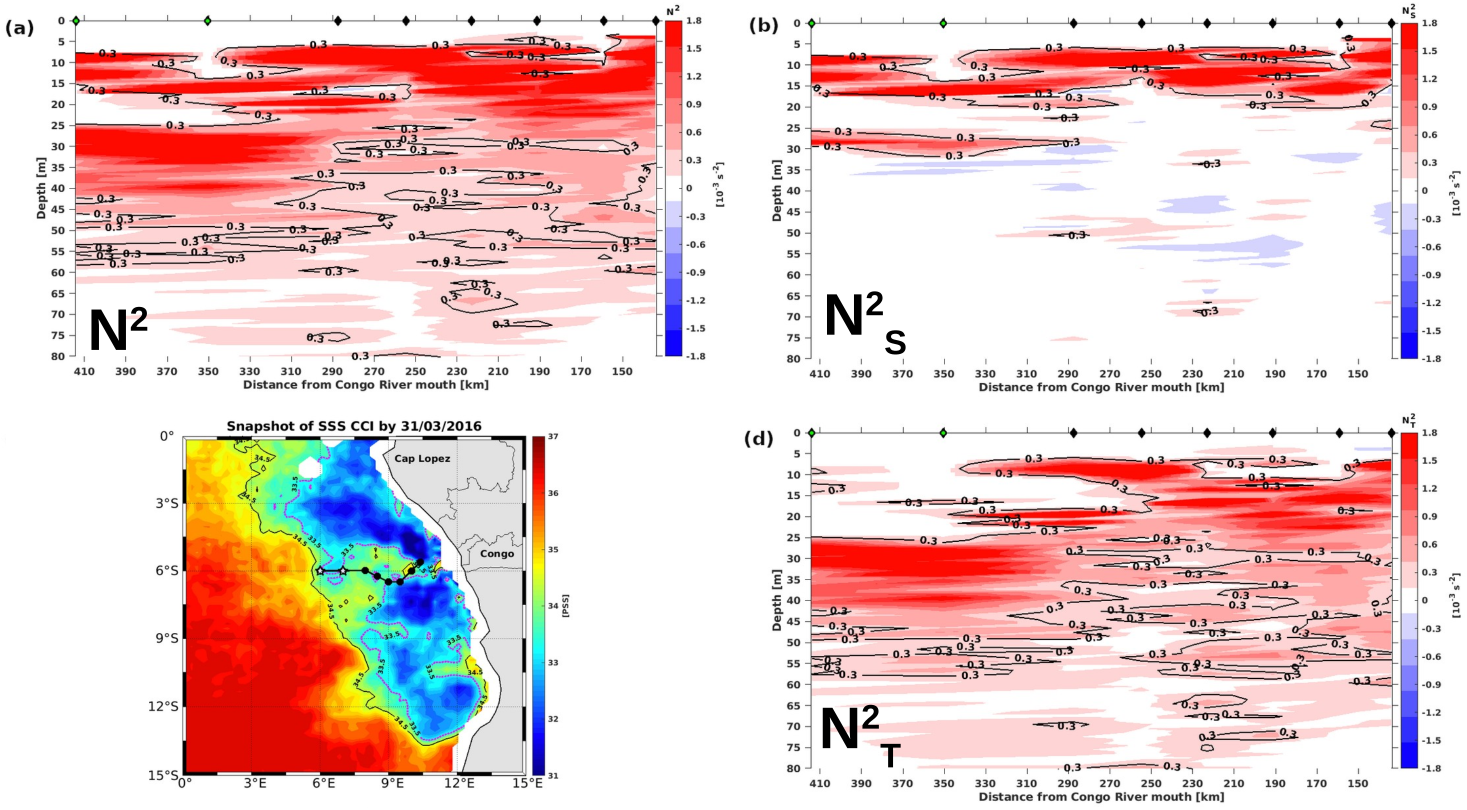


Out of the Congo River plume SSS> 34.5 pss

✓ Deep Mixed layer: 20-30m

✓ Density stratification is controlled by temperature gradient

- Thermohaline stratification across the far field of the Congo River freshwater plume



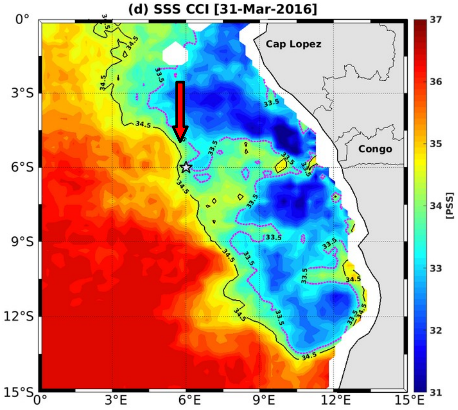
- ~0-25m: upper stepped density stratification is:

↓

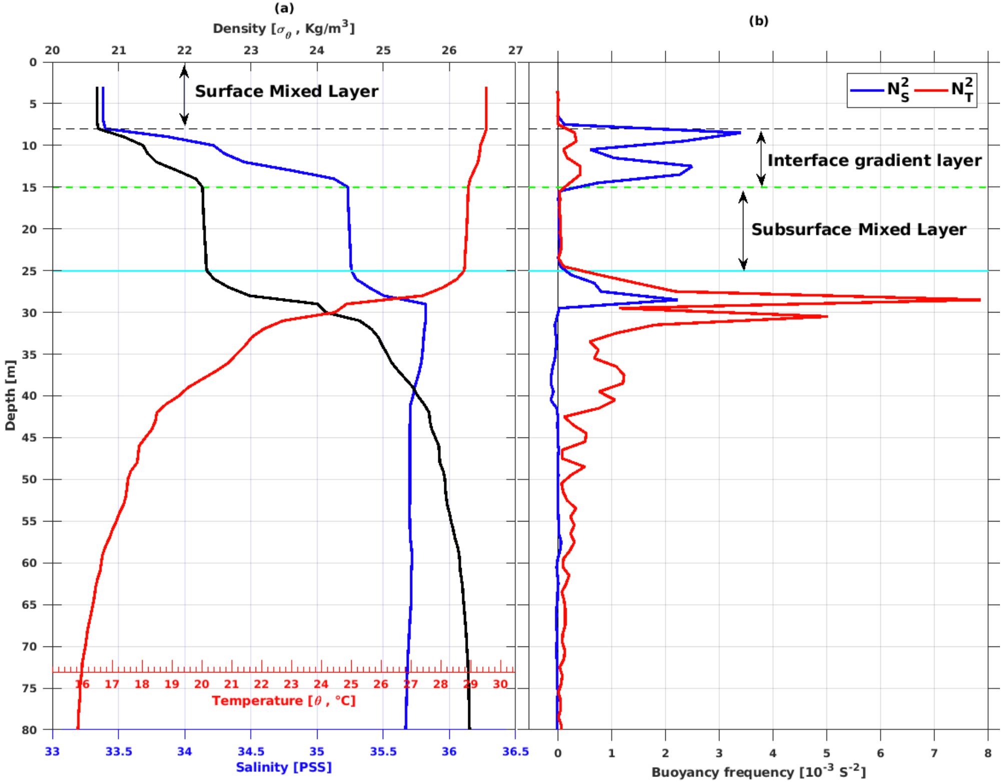
Dictated by the salinity vertical gradient

- CTD profiles from PIRATA FR 26 (2016) off Congo

- Thermohaline stratification within the SSS front: transition zone between freshwater & the open sea water mass



☆ **Profile localisation**



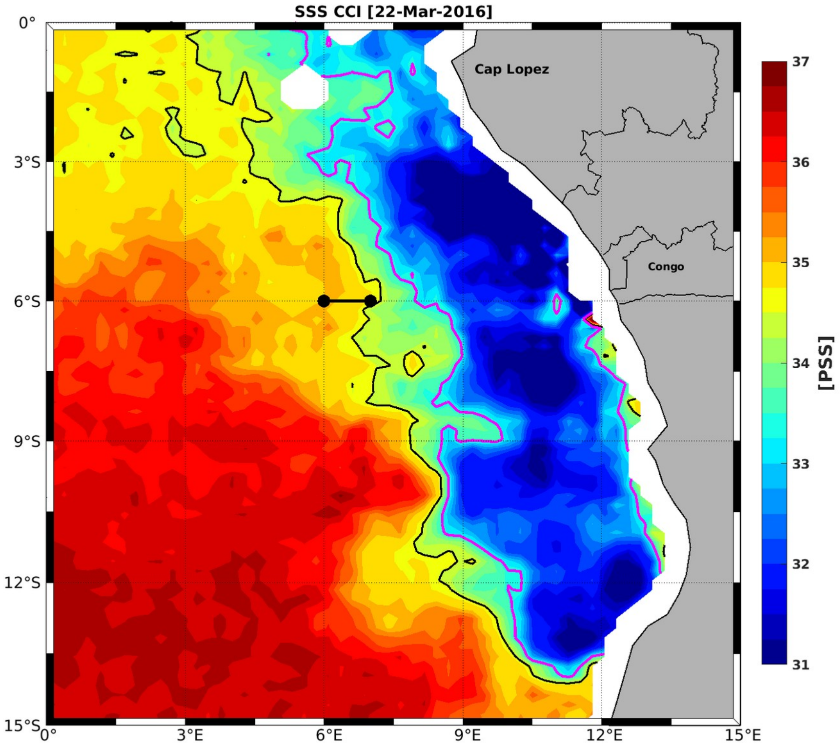
} ~7-m thick ←

ΔS = 2pss
$\Delta\theta$ = -0.6°C
$\Delta\sigma_\theta$ = 1.6 kg/m³

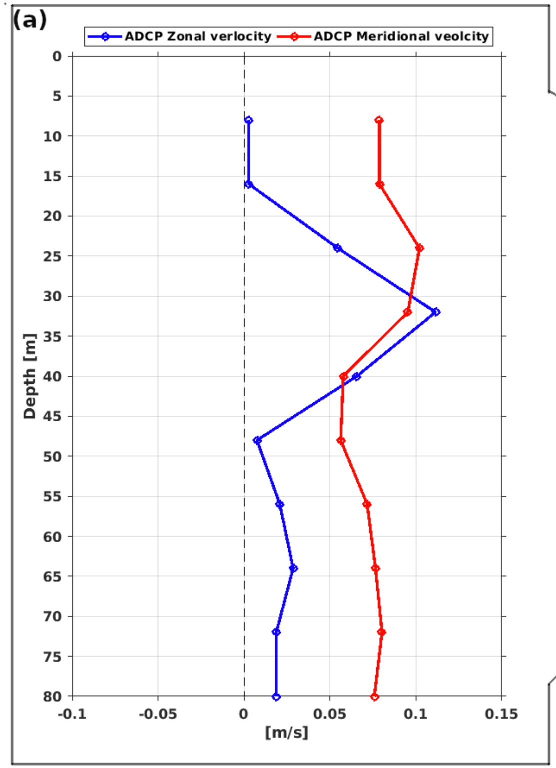
✓ ~0-25m: Double mixed layer structure with density gradient interface like «Thermohaline staircase»

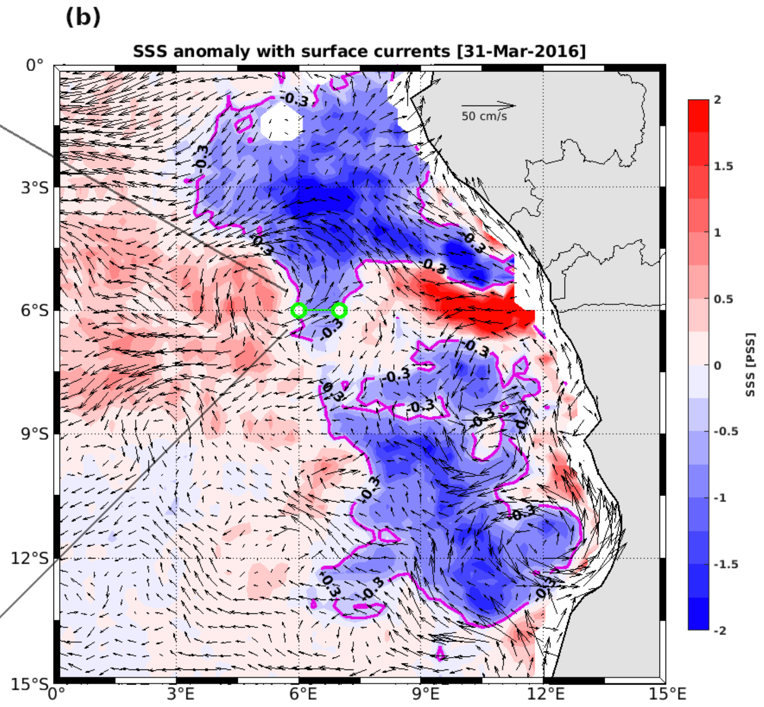
- Case study: Intra-seasonal variations of SSS around the observed stepped density profiles

- Southwestward advection of freshwater plume
- Westward displacement of SSS front
- Southwestward SSS anomalies of **-0.3** pss



- Case study: Surface dynamics contribution: horizontal and vertical fields of total currents

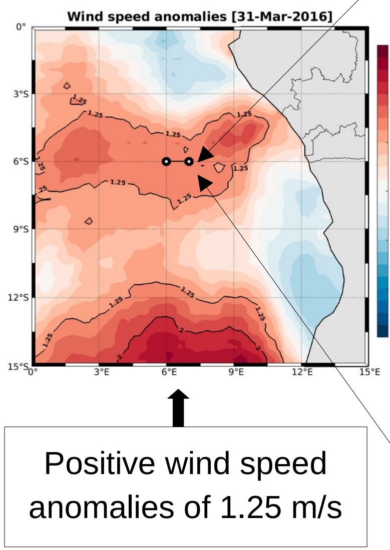


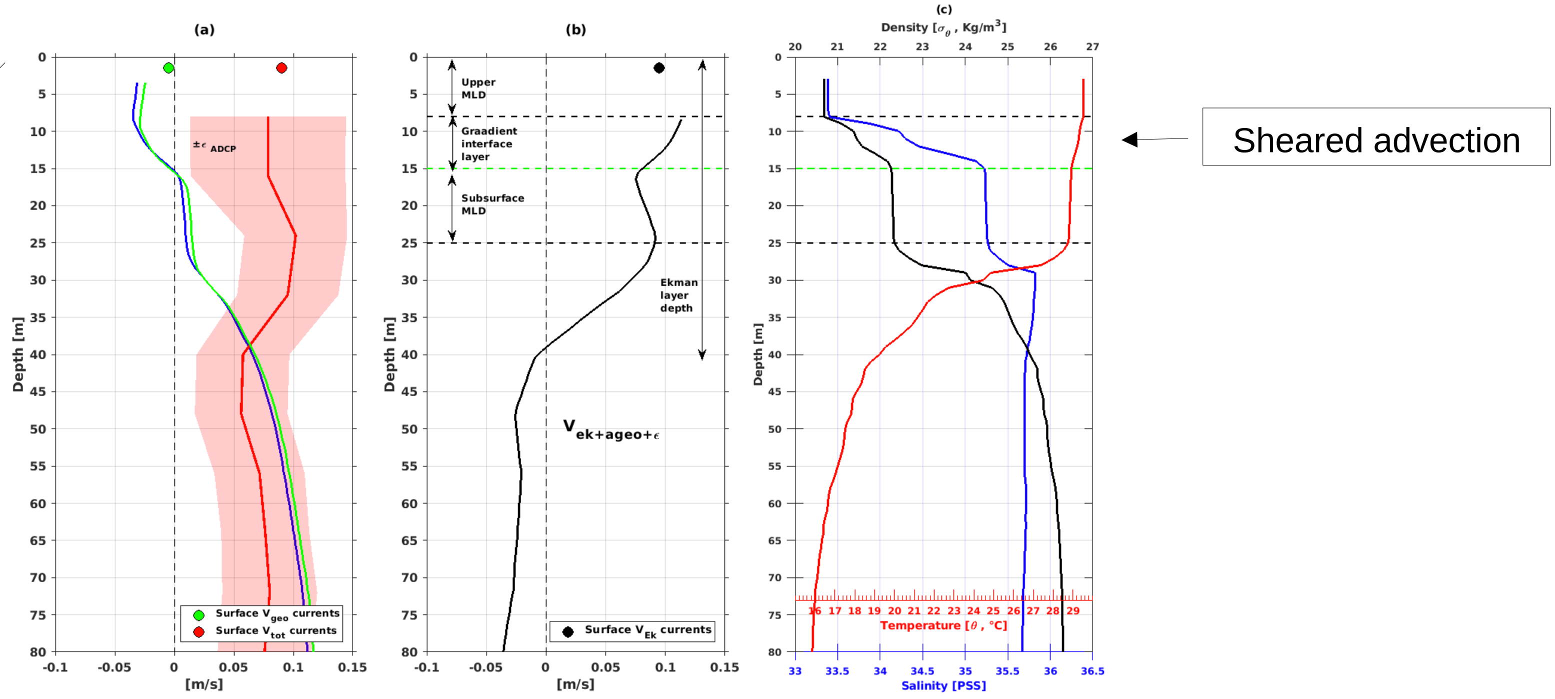


➔ Surface currents from GLORYS Mercator

- ✓ ~0-15m : Northward currents
- ✓ ~15-35m: Intensified North-eastward currents
- ✓ Shear between surface and subsurface layers

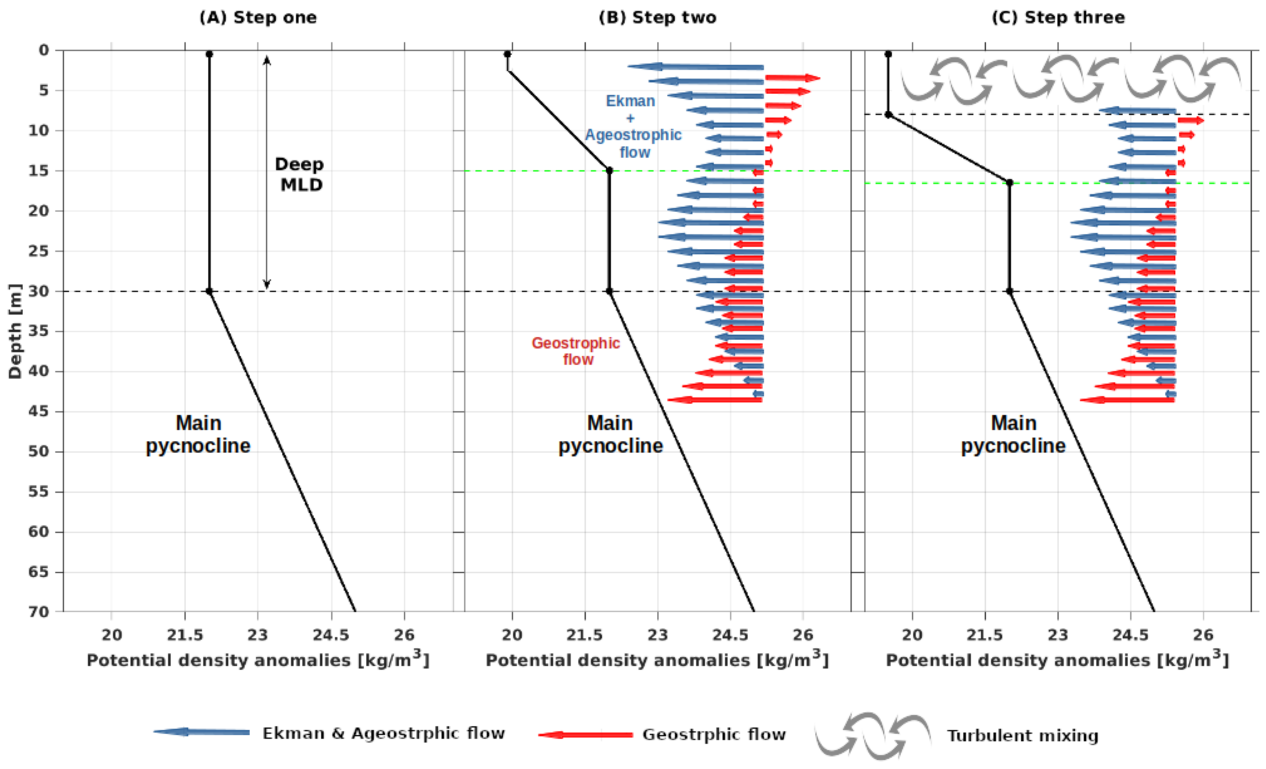
- Case study: Vertical profiles of meridional currents : geostrophic and wind-driven Ekman currents





➔ Staircases density structures are associated with sheared ageostrophic currents within the surface layers

- Case study: Mechanism of formation of the stepped thermohaline stratification



1. Deep mixed layer
2. Interface density gradient associated with sheared ageostrophic currents
3. Upper turbulent mixing due to positive wind speed anomalies

Part 2

- To summarize:

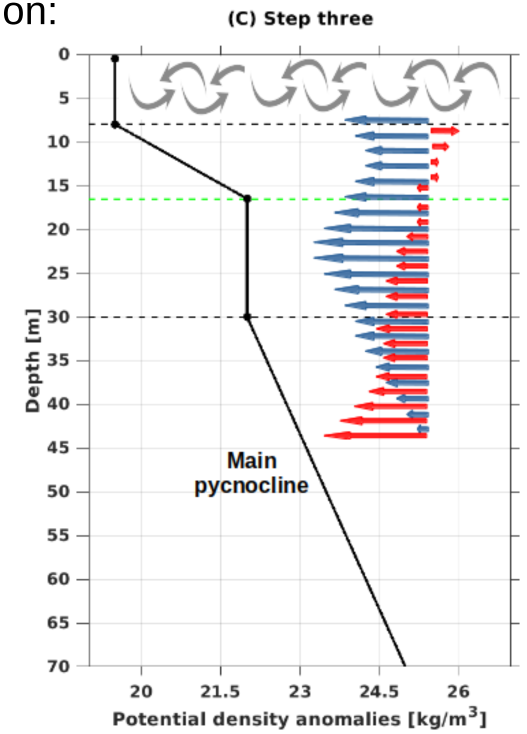
The Congo River plume westward dynamics influence the thermohaline stratification:

✓ Strong pycnocline over ~0-20-m due to salinity stratification

✓ Steeped density stratification like « Thermohaline staircase »

are suggested to formed by sheared advection:

- Sheared ageostrophic currents within the surface layers
- Dominated by the wind-driven Ekman component



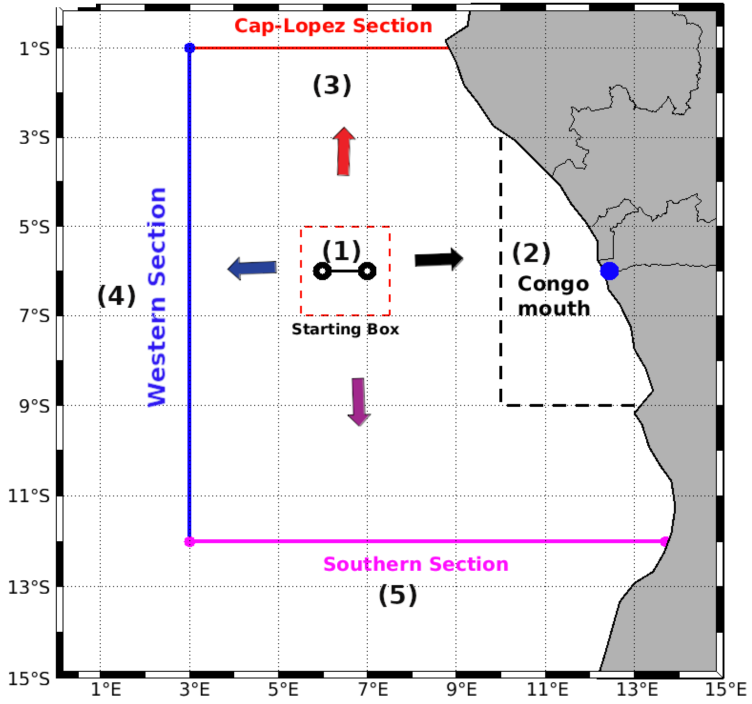
Part 3

Study of origin and fate of the Congo water masses

- What are the 3D pathways of water mass off the Congo at intra-seasonal scale?

- Understand the large scale water mass structure off Congo
- Identify water mass particules trajectories
- Origin of particles and associated thermohaline changes

- Lagrangian experiments



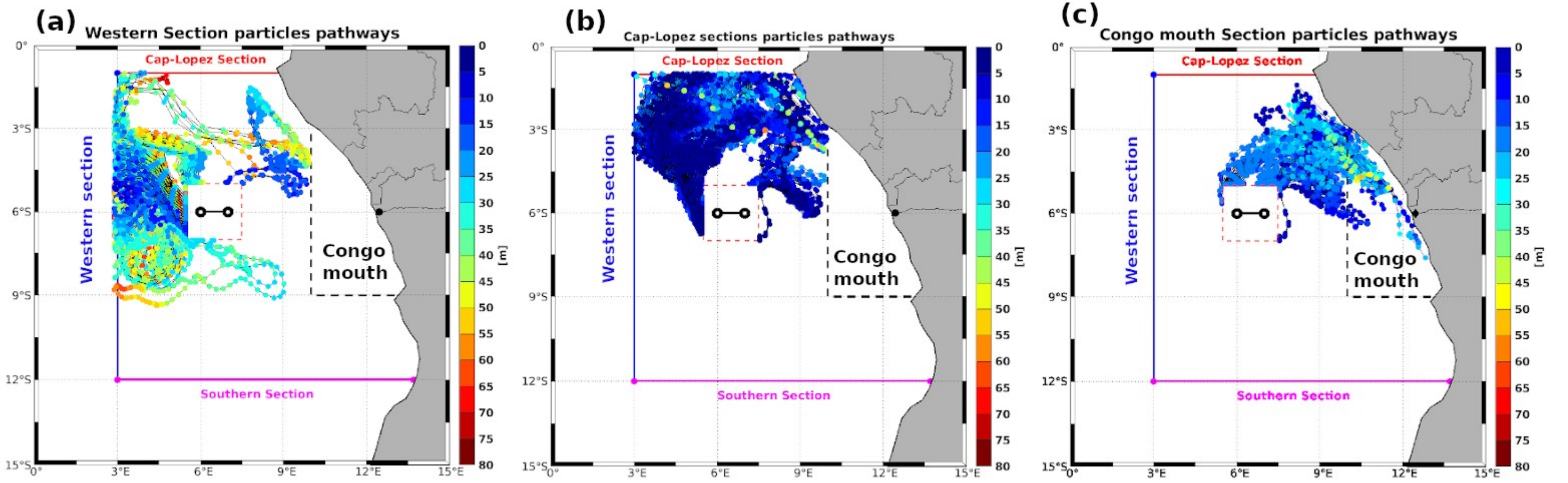
- **Starting box** (1) :
  - Horizontal dimensions :
    - ~ 220x220 km² (5-7°S & 5.5-7.5°E)
  - Vertical dimension :
    - 20 first vertical levels : ~ 0-66 m
- **Interception sections :**
  - Congo mouth (2)
  - Cap-Lopez section (3)
  - Western section (4)
  - Southern section (5)

  all 50 vertical levels: ~ 0-5700m

- **ARIANE** : Lagrangian software
- **GLORYS** reanalysis data :
  - Ocean 3D : U, V, W
  - 3D temperature and salinity
  - 1/12°x1/12° lon.lat resolution
  - 50 vertical level
  - Daily time step

- **Backward** experiment: from « **Starting box** » to **Interception sections**
  - Particle initialization : 31st March 1st April 2016
  - Backward toward the interception sections
  - End of the experiment : 01/09/2015
  - 7 months (214 days)

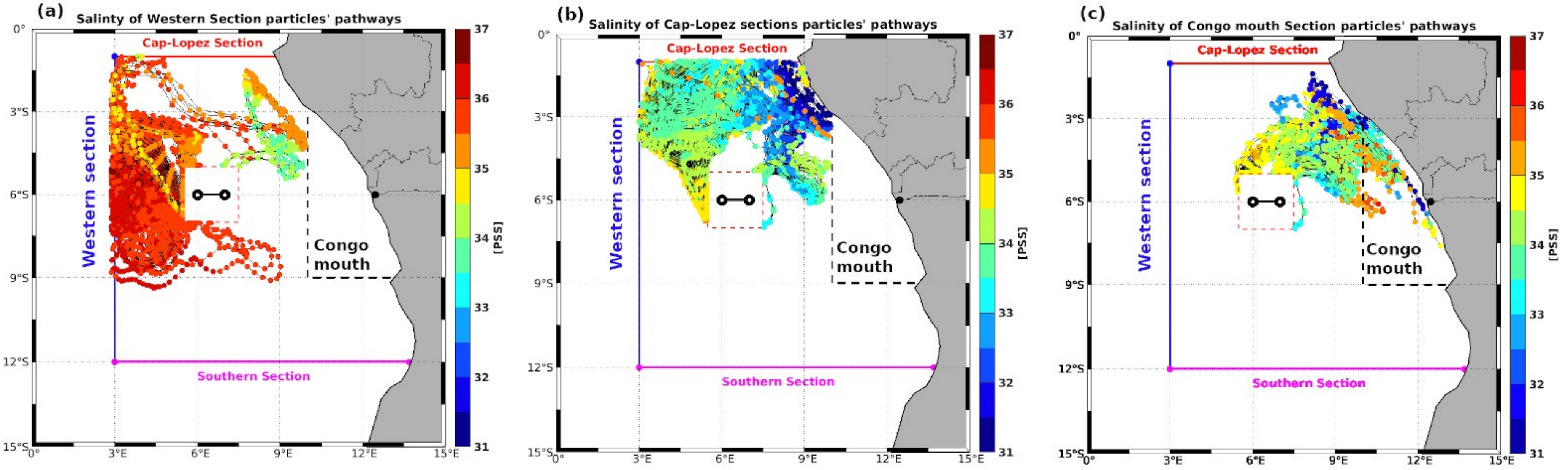
- Water particles trajectories from « Starting box » to each interception section



- Subsurface water particles (~10-65m)
- Complex trajectories

- Surface water mass particles (~0-20m)
- Cap-Lopez section: North-westward path
- Congo mouth: South-westward path

- Salinity changes of water particles over path from « Starting box » to each interception section



- More salty water particles (>35 pss)
- Less Salinity changes over path
- Cold water particles (25°-27°C)

- Less salty water particles from influence zones of freshwater
- Salinity increase (31-34.5 pss) over path
- Hot water particles (>27°C)

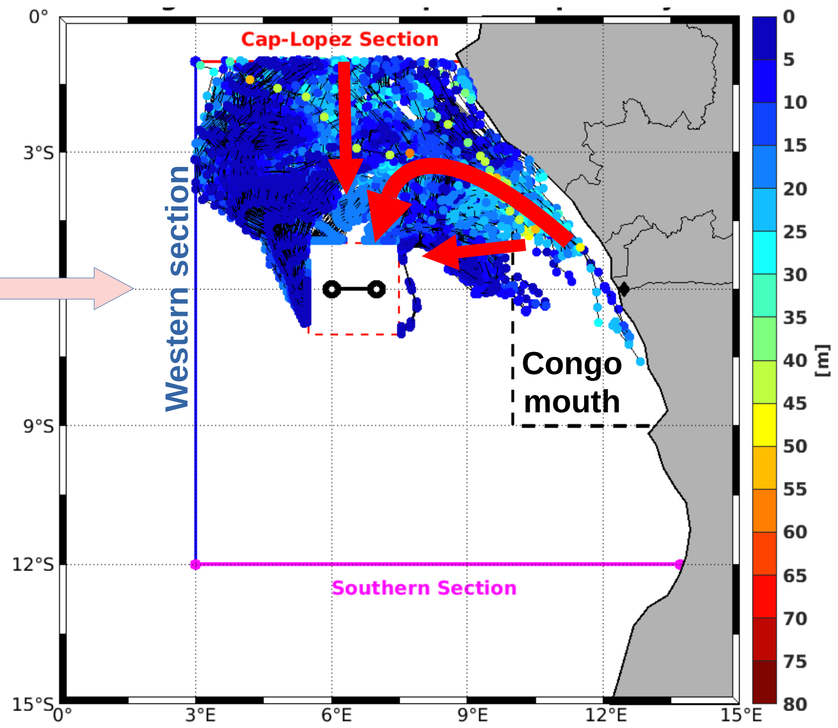
Part 3

- To summarize:

✓ Subsurface water mass: (10-65m)

- Denser, Cold & Salty

✓ Density changes are due to temperature variations

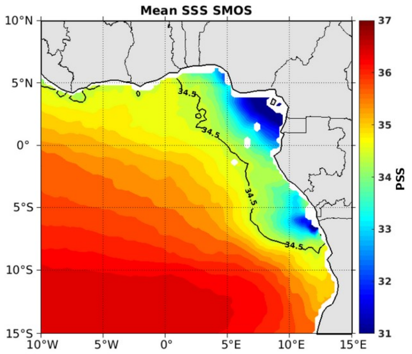


✓ Surface water mass: (0-20m)

- Less dense, Hot & less Salty

✓ Density changes are due to salinity variations

- The Gulf of Guinea's freshwater plumes spreading is characterized by two regimes:
  - Northwestward (Sep–Jan) and Southwestward (Jan–Apr)
  - Maximal extension by April & Minimal extension by August



- Freshwater seasonal variability:
  - Precipitation, river runoff, and horizontal advection are major drivers
  - Horizontal SSS advection is dominated by Ekman wind-driven currents
  - Vertical processes (Residues) and salinization episode contribute to freshwater dissipation

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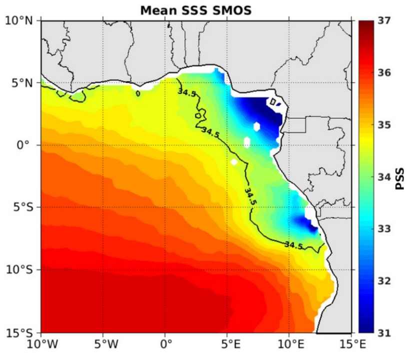

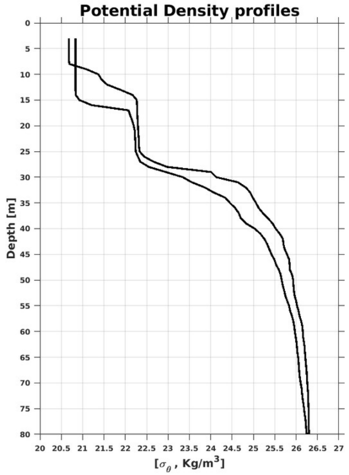

- The Congo River strongly influences the thermohaline stratification (~0-20m) off Congo:
  - Shallow pycnocline due to salinity vertical gradient
  - Steeped density stratification like « Thermohaline staircases »
    - Suggested to be formed by sheared advection of:
      - Ageostrophic currents within the surface layers off the Congo River plume
      - Dominated by the wind-driven Ekman currents

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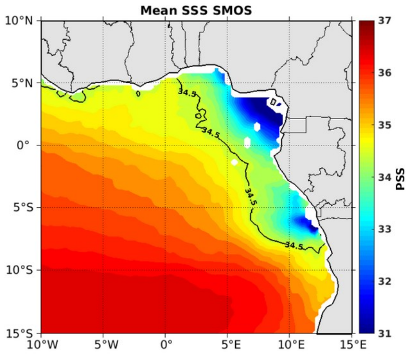

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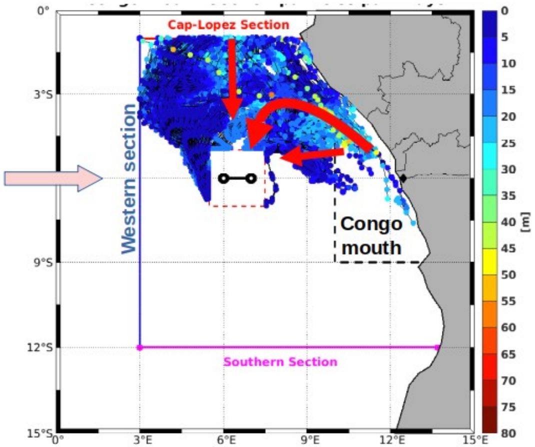


- Lagrangian approach:
  - Highlighted the origin and pathways structuring of water masses involved in the strong salinity stratification off Congo.
  - Strong salinity stratification result from Interaction between water masses from open sea and Cap-Lopez and Congo River freshwater

1. Study the seasonal variability of :
   - Surface thin layers structures
   - Thermohaline staircases structures
   - Linkage with the SST in the Gulf of Guinea.

→ Argo profiles (2000 - 2021)

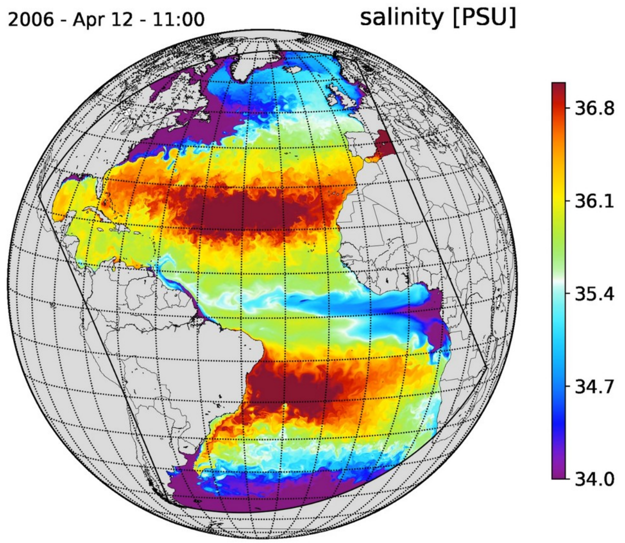
ADCP & CTD PIRATA/EGEE (2005-2020)

2. How does the mixed-layer salinity balance can be resolved with a high-resolution model like CROCO?
   - 3km.3km.hour – 100 levels (10 years)

✓ Impact of freshwater plumes on the SST?

✓ Impact of freshwater plume on surface currents?

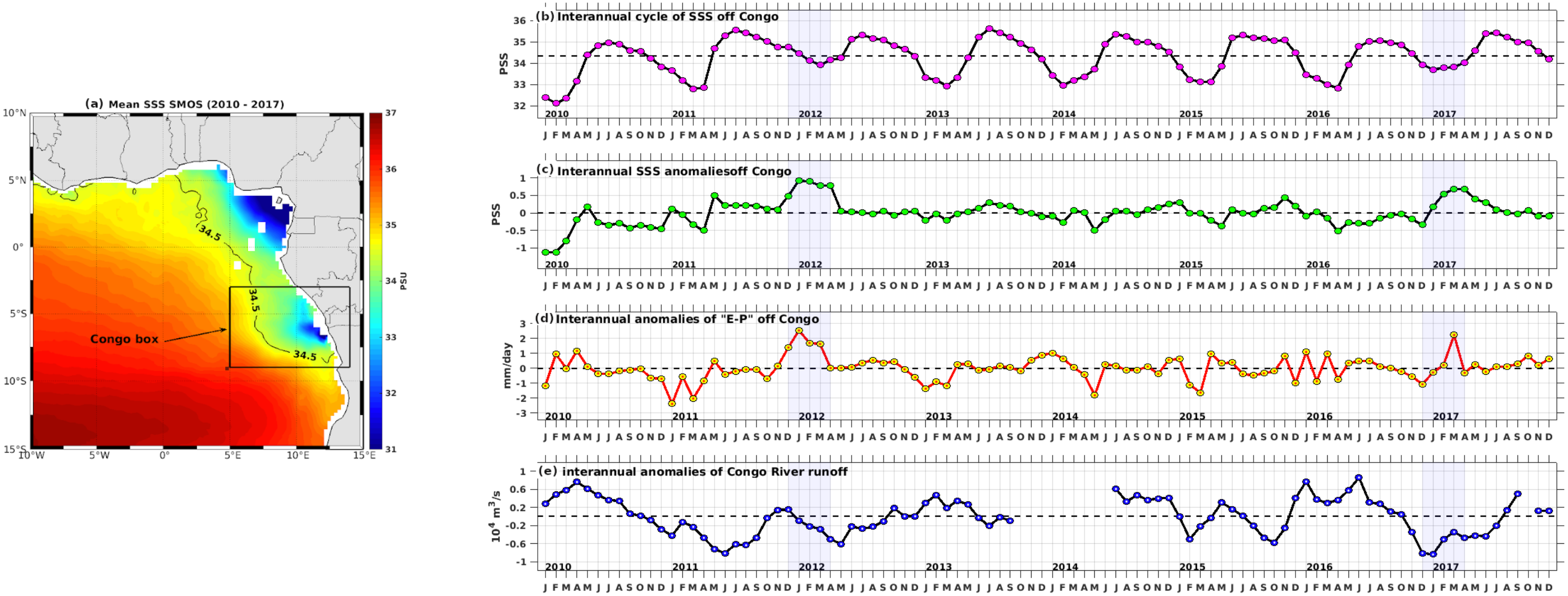
→



GIGATL, from Jonathan Gula, LOPS

3. Study the inter-annual variability of SSS off Congo :

- What can we learn from 10 years SMOS SSS observation within the Congo freshwater plume?



- 2012 & 2017 : salinization events during freshwater plume period

Thank you