Coastal upwelling limitation by onshore geostrophic flow in the Gulf of Guinea around the Niger River plume

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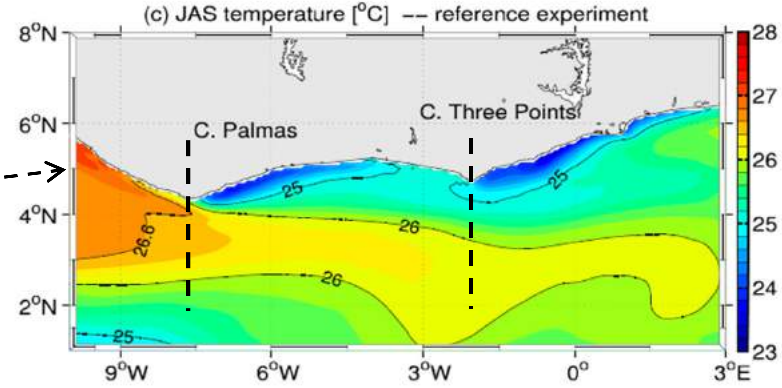
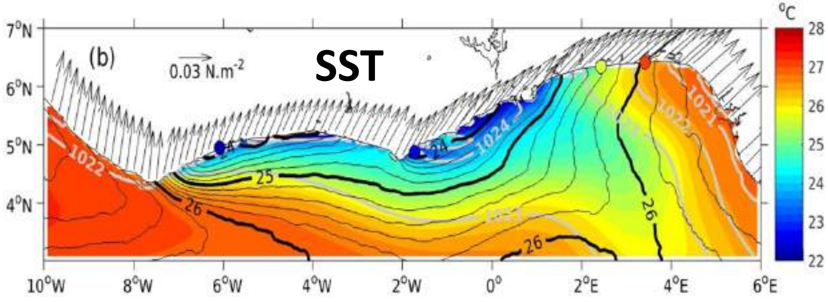
Regional context

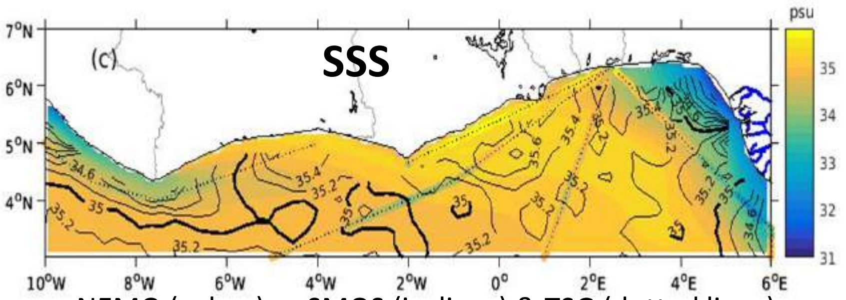


- Summer upwelling off Côte d'Ivoire/Ghana driven by detachment of the eastward Guinea Current from the coast east of Cape Palmas and local wind east of Cape Three Points (*Djakouré et al., 2014, 2017*)
- Possible compensation by geostrophic downwelling (*Marchesiello & Estrade, 2010*) due to Niger river plume in the east?

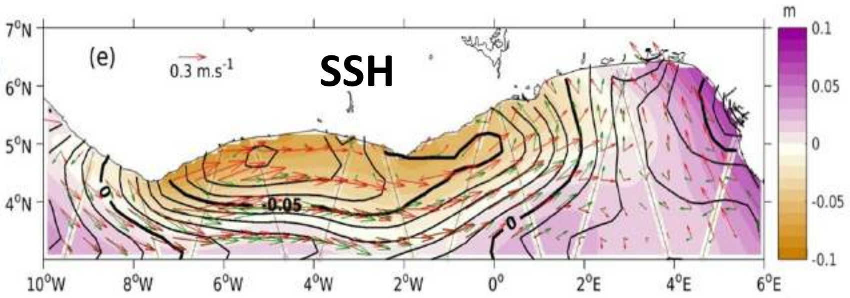
Upwelling surface signature



NEMO (colors) *vs* MUR (isolines) & PROPAO (dots)



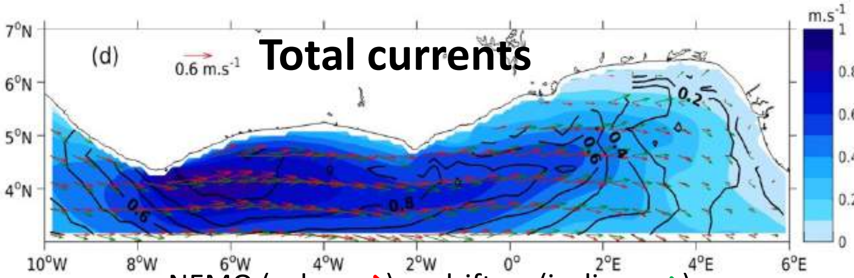
NEMO (colors) *vs* SMOS (isolines) & TSG (dotted lines)



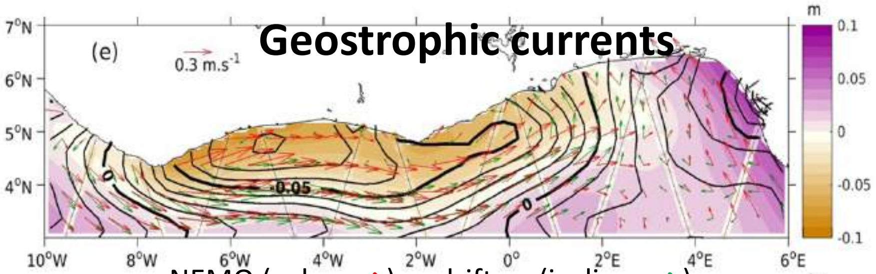
NEMO (colors) *vs* CMEMS (isolines)

- Wind-driven upwelling ➔ cool & salty tongue that extends southeastward
- Niger freshwater plume to the east
- 10 cm eastward increase of sea level at the coast

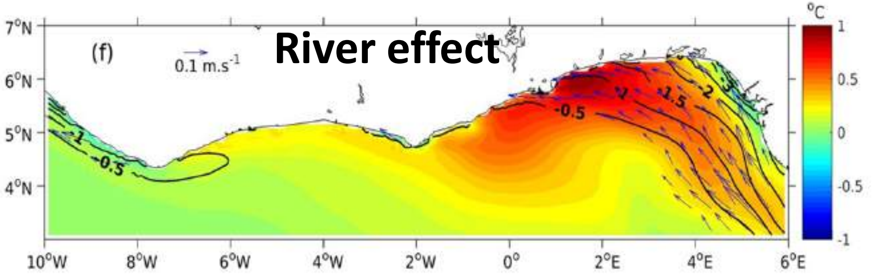
Surface currents



NEMO (colors, →) *vs* drifters (isolines, →)



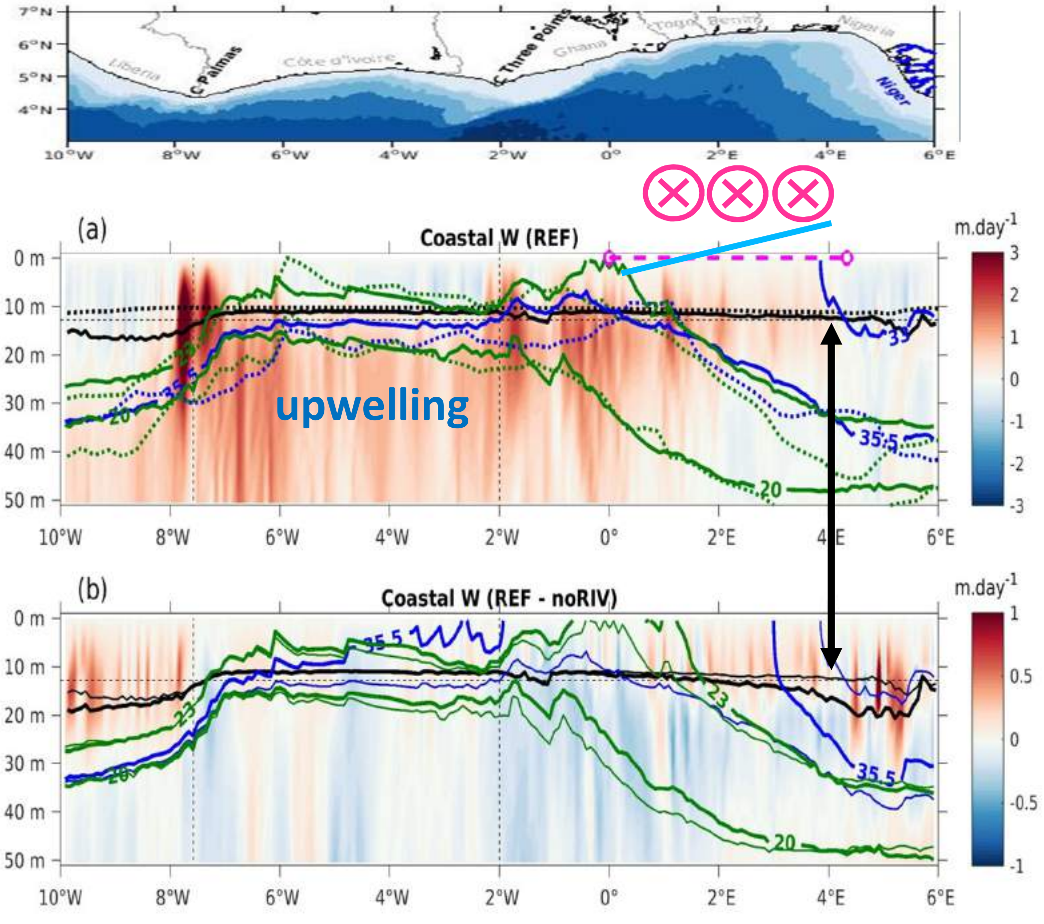
NEMO (colors, →) *vs* drifters (isolines, →)



NEMO: REF-noRIV diff in SST (colors), SSS (isolines), U/Vgeo (→)

- Eastward flow dominated by the Guinea Current, largely geostrophic
- Geostrophic currents toward the coast between 0°E and 4°E
- Niger River plume contributes to onshore geostrophic currents and warms the upwelling tongue by ~1°C

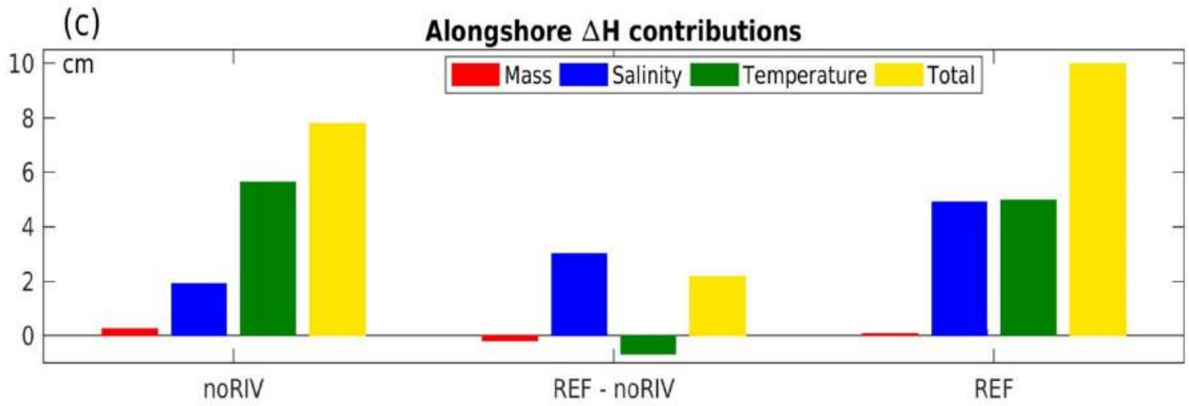
Upwelling vertical along-shore dynamics

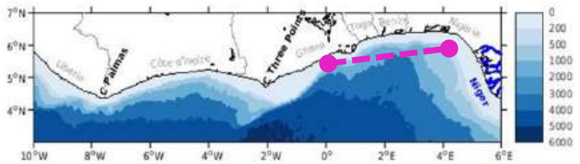


NEMO W (colors), iso-T (—) iso-S (—), MLD w/wo river (▬ /—)

- Upwelling strongest east of capes, weak east of 1°E
- Relatively small river-induced vertical velocities
- MLD reduced by river plume

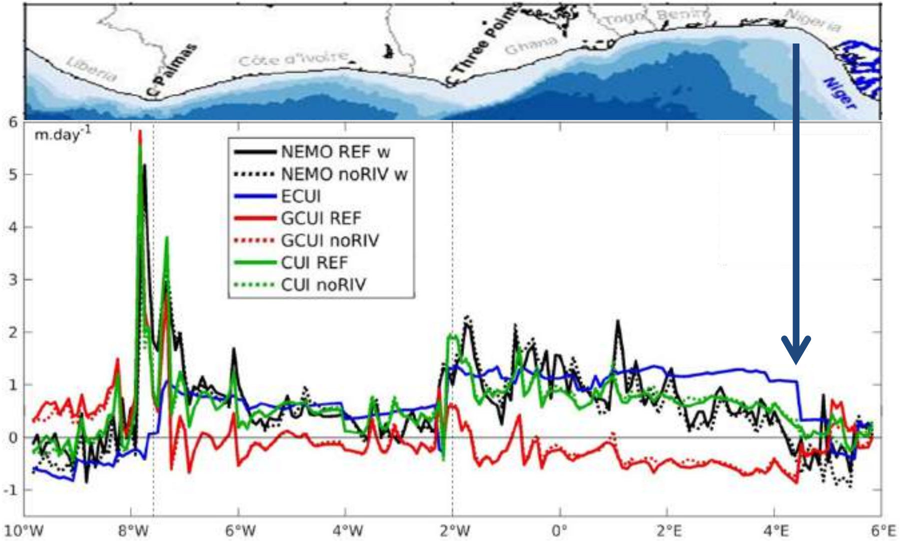
Steric contributions to coastal sea level slope





- Decomposition of 0°E-4°E sea level slope into thermosteric and halosteric components
- Slope equally driven by temperature and salinity coastal variations
- River: 60% of halosteric component but only 20% of total slope
- 40% of halosteric and all thermosteric component due to upwelling itself

Upwelling dynamical indices



Ekman Coastal Upwelling Index :

$$ECUI = \frac{\tau_{alongshore}}{\rho_o f L_u}$$

L_u : upwelling width (12 km)

Geostrophic Coastal Upwelling Index :

$$GCUI = -\frac{u_G D}{2L_U}$$

u_G : cross-shore

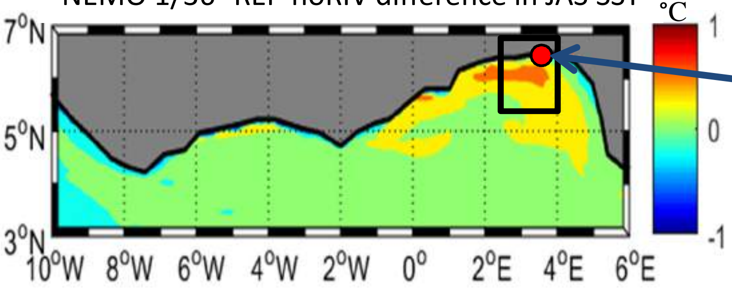
D : mixed layer depth (12 m)

CUI=ECUI+GCUI

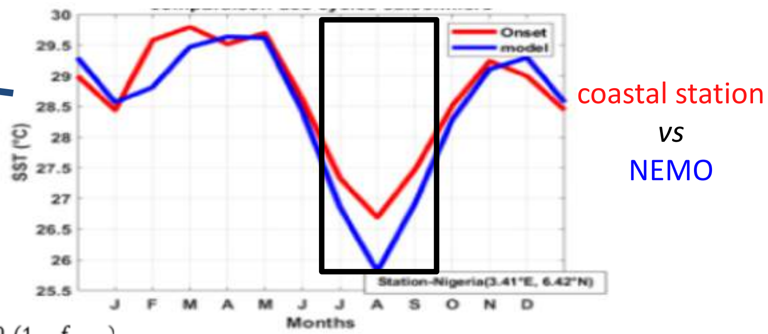
- Good agreement between CUI and NEMO vertical velocity (*r=0,72*)
- ECUI gets stronger east of 2°W
- From 1°E to 5°E, geostrophy compensates Ekman transport by 30-50%
- **Very small river effect on GCUI**
- Sharp decrease of ECUI with coastline direction change

Cause of river-induced warming

NEMO 1/36° REF-noRIV difference in JAS SST



SST seasonal cycle

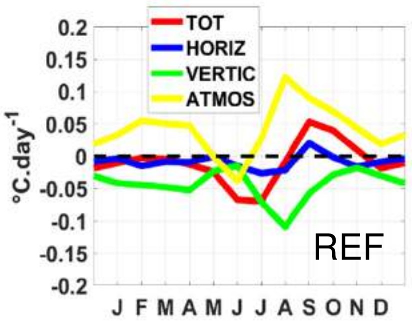


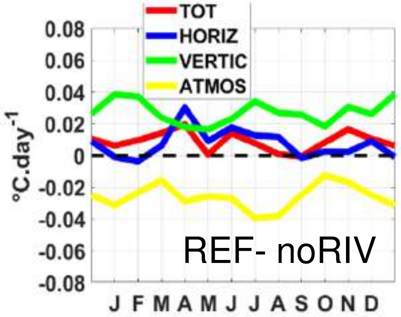
$$\underbrace{\frac{\partial\langle T\rangle}{\partial t}}_{TOT} = \underbrace{\underbrace{-\langle u\partial_x T\rangle}_{XAD} - \underbrace{\langle v\partial_y T\rangle}_{YAD} + \underbrace{\langle D_l(T)\rangle}_{LDF}}_{HORIZ} \underbrace{\underbrace{-\langle w\partial_z T\rangle}_{ZAD} - \underbrace{\frac{1}{h}(k_z\partial_z T)_{z=-h}}_{ZDF} - \underbrace{\frac{1}{h}\frac{\partial h}{\partial t}(\langle T\rangle - T_{z=-h})}_{RES}}_{VERTIC} + \underbrace{\frac{Q^* + Q_s(1-f_{z=-h})}{\rho_0 C_p h}}_{ATMOS}$$

HORIZ: advection + diffusion

VERTIC: advection + diffusion + entrainment

ATMOS: heat fluxes

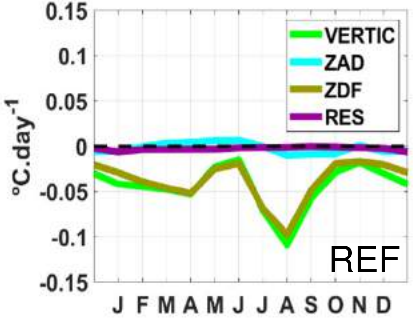


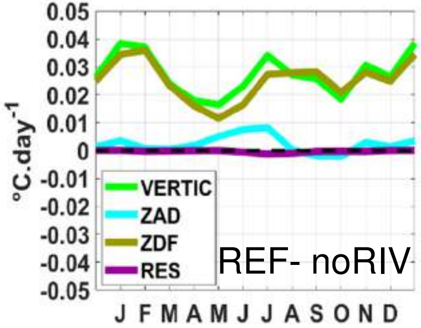


- Mixed-layer heat budget in river-induced warming box
- Summer cooling mostly due to oceanic vertical processes
- River-induced warming due to vertical and horizontal processes

River-induced vertical processes

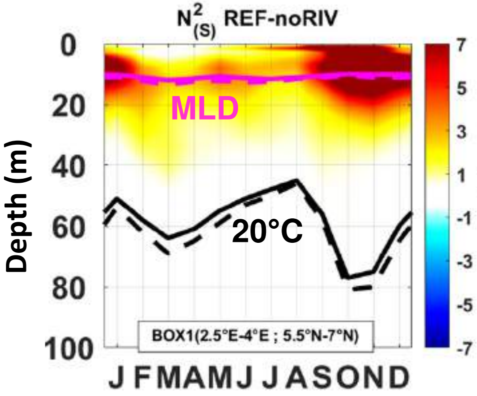
Decomposition of vertical processes



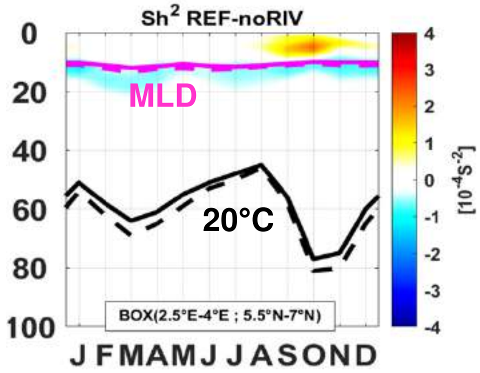


River-induced changes in:

Salt stratification



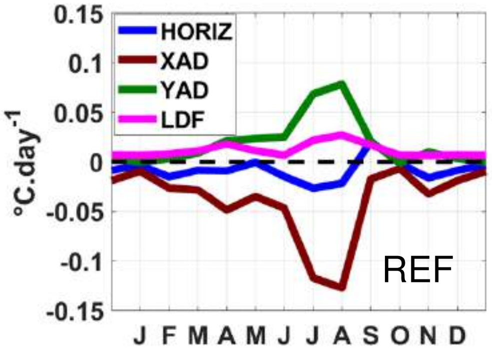
Current vertical shear stress

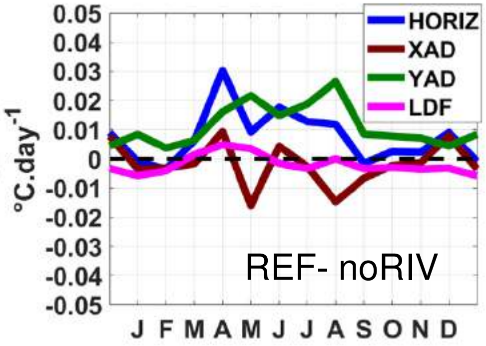


- Vertical processes largely controlled by vertical diffusion (mixing)
- River reduces cooling associated with vertical diffusion, due to:
    - Increase in haline stratification in the upper 20 m
    - Decrease in the vertical shear stress of horizontal currents under the mixed layer

River-induced horizontal processes

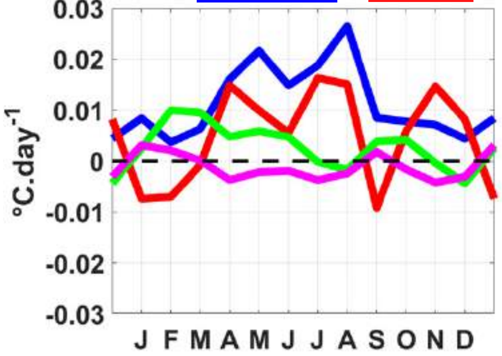
Decomposition of horizontal processes





Decomposition of meridional advection

YAD = $\Delta\left(V.\frac{\partial T}{\partial y}\right) = \Delta V.\frac{\partial T}{\partial y} + V.\Delta\left(\frac{\partial T}{\partial y}\right) + \Delta V.\Delta\frac{\partial T}{\partial y}$



r(/) = 0.61

r(/) = -0.10

- Horizontal processes: zonal advective cooling partially compensated by meridional advective warming

- River increases warming due to meridional advection, by strenghtening of meridional currents

Conclusion & perspectives

- Coastal upwelling in the eastern part of northern Gulf of Guinea (Togo/Benin/Nigeria coasts) weakened by up to 50% due to geostrophic compensation
- Niger plume contribution to upwelling small due to a compensation of the enhanced onshore geostrophic flow by reduced MLD (almost no effect on near-surface transport)
- Geostrophic compensation associated with eastern upwelling front (negative retroaction), triggered by sharp change in coastline orientation that decreases Ekman transport
- Warming effect (+1°C) of river plume in upwelling region mostly due to reduction of vertical mixing by haline stratification
- Other influence of river on upwelling regions (Congo region)?

Alory et al., 2021, Frontiers in Marine Science