Impact of intra-seasonal coastal Kelvin waves on SST in the eastern boundary upwelling systems of the Tropical Atlantic : a composite analysis of boreal winter

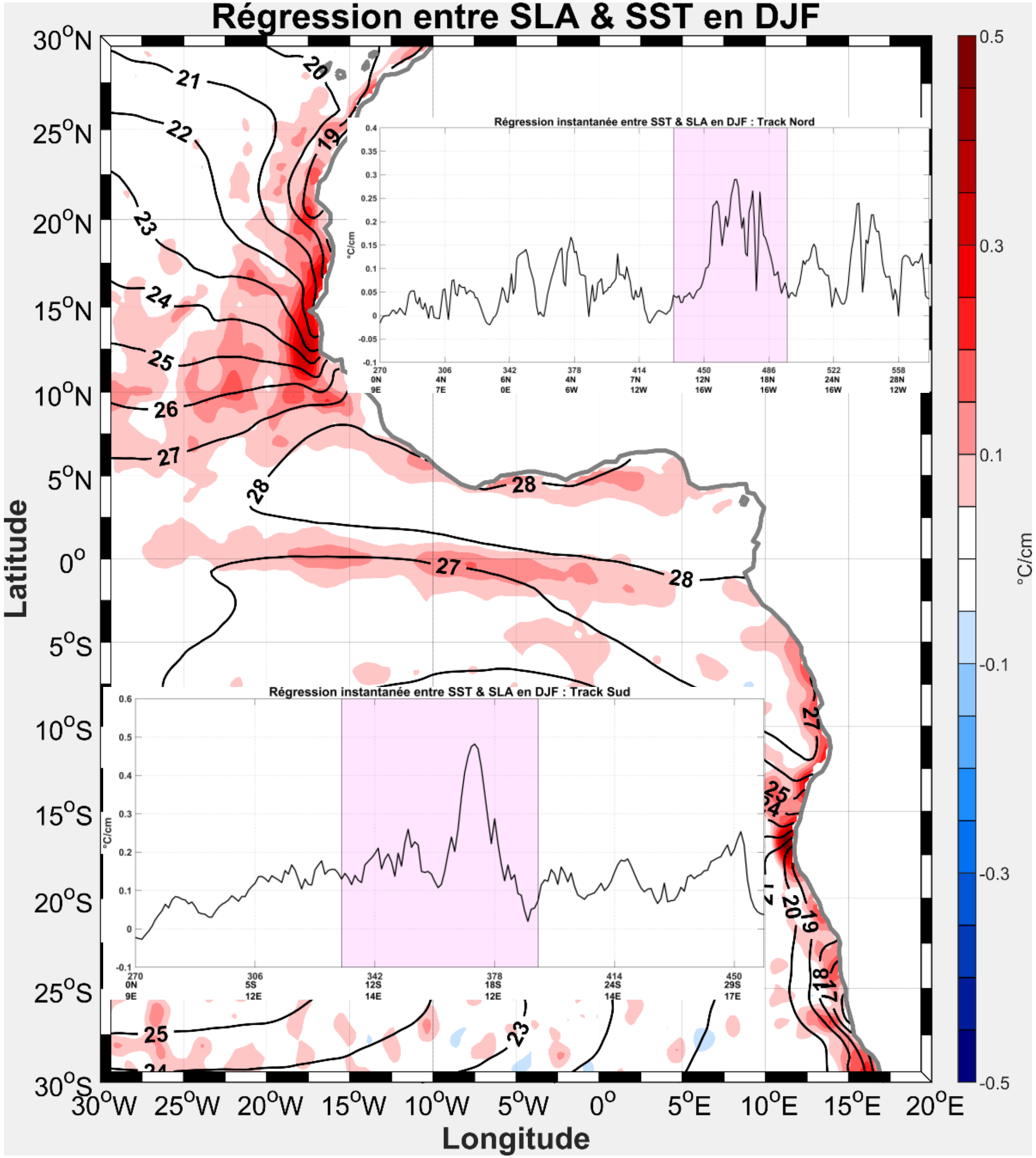
B. Sané[1,2], A. Lazar[2], M. Wade[3]

[1]Laboratoire de Physique de l'Atmosphère et de l'Océan Siméon Fongang (LPAO-SF/ESP/UCAD, Dakar, Sénégal)

[2]Laboratoire d'Océanographie et du Climat : Expérimentations et Approches Numériques(LOCEAN/SU, Paris, France)

[3]Laboratoire des Sciences de l'Atmosphère et des Océans: Matériaux-Énergies-Dispositifs (LSAO-MED/UGB, Saint-Louis, Sénégal)

Spatial map of regression between SLA & SST in DJF along the Northern and Southern track



To study the link between sea level (SLA) and sea surface temperature (SST), we plotted the regression map between SLA and SST in the upwellings in December-January-February (in color), and the regression curves along the northern and south wave track.

- **In the northern:**

\- a strong link between SLA and SST in coastal upwelling systems with coefficients that vary between 0.01 to 0.3 °C/cm

- **In the southern:**

\- a strong link between SLA and SST in coastal upwelling systems with coefficients that vary between 0.05 to 0.5 °C/cm

Figure 1: *December-January-February regression map of SLA on SST for the period 1993-2018 along the Kelvin wave paths in the equatorial Atlantic and the northern and Southern West African coasts.*

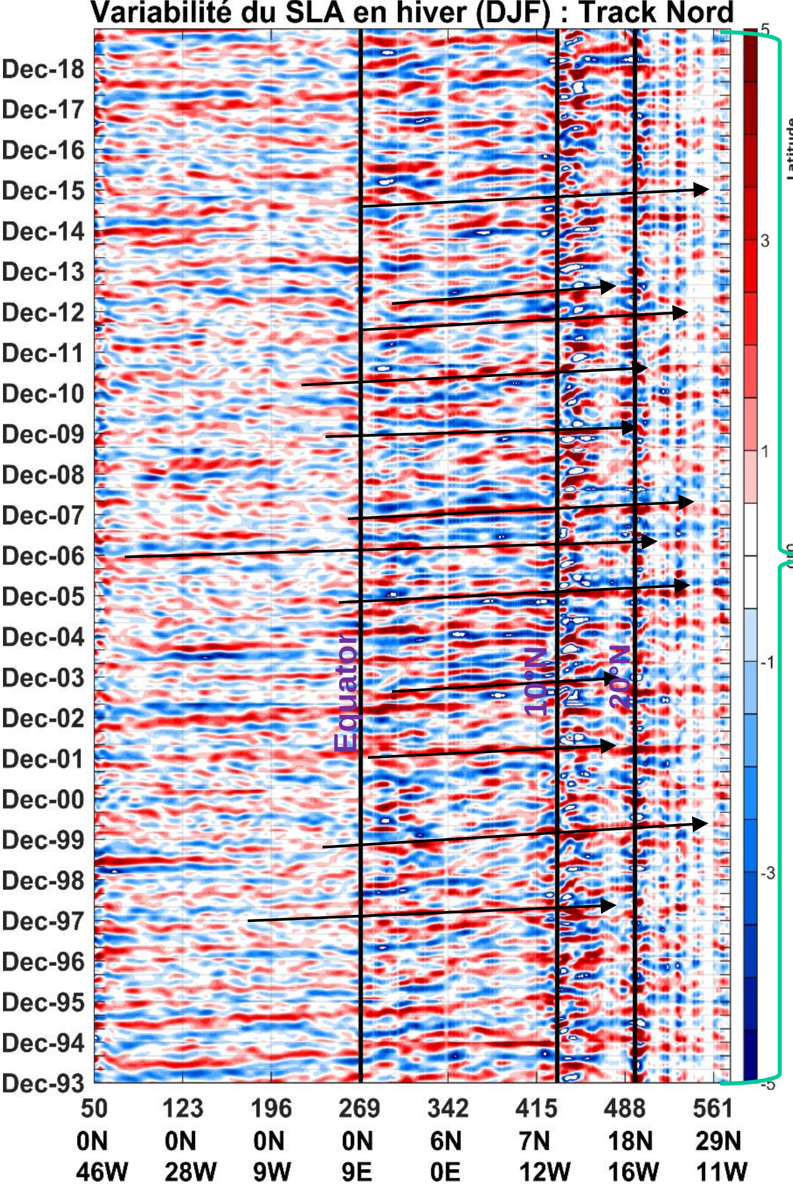
Figure 1 shows the spatial regression map between the sea-level anomaly (SLA) and the sea surface temperature anomaly (SST) in color as the wave passes through the upwelling systems in DJF along the northern and southern track, the variation of the SST in black-circle DJF and at the same time the values of these regression coefficients are black-contoured. The link between intra-seasonal and curved coastal Kelvin waves, the regression coefficients between SLA and SST as they pass through West African coastal upwelling systems. Indeed, we chose to make the regression in December-January-February since the upwelling period takes place at that time along the northern and southern coasts of West Africa.

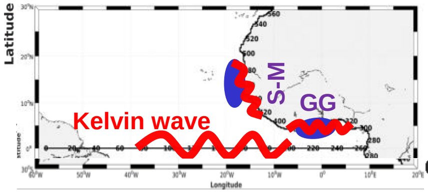
The amplitude ranges from -0.01 to 0.3 °C/cm along the northern track and the maximums of regression are found in regions of strong upwelling (Atlantic cold-tongue regions, Côte d'Ivoire and Senegal). These maximums range from 0.05 to 0.3 °C/cm in the Gulf of Guinea and in the upwelling regions of Senegal. Positive values in regressions suggest that a negative (positive) SLA anomaly is associated with a negative (positive) SST anomaly. We expect the regressions to be found in the regions where the average meridian gradients of SST at lag0 in DJF strongest along the equatorial Atlantic and the Northern and Southern West African coast (unrepresented).

However, along the southern track, regression coefficients range from -0.01 to 0.5 °C/cm along the southern track, and regression maximas are found in regions of strong upwelling (Atlantic Cold Language Regions, Angola and Benguela). These maxima vary between 0.05 to 0.5 °C/cm in the upwelling regions of Angola and Benguela. Positive values in regressions suggest that a negative (positive) SLA anomaly is associated with a negative (positive) SST anomaly.

It is noted that the regression coefficients are stronger in the southern than in the north, which could indicate that there is less impact of the wave on SST in the Senegal-Mauritanian upwelling system than in other upwelling systems during the DJF season. The same calculations applied to other seasons show a decrease in regression in Senegal and Angola (not shown).

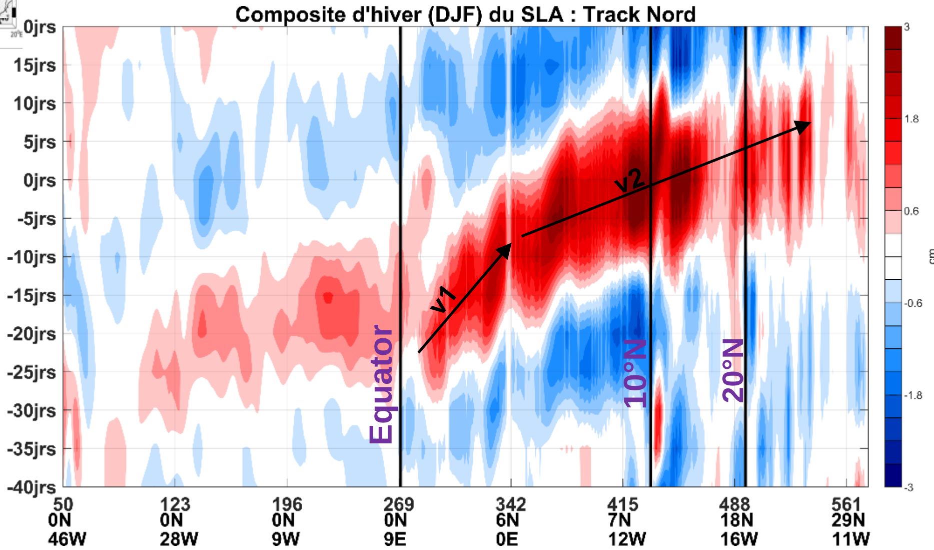
Method for the identification of intra-seasonal Kelvin waves in DJF along the northern track





$$\frac{1}{12}\sum_{i=1}^{12} SLA(lag+j,:) =$$

We identify 12 number of waves in DJF over the period 1993-2018



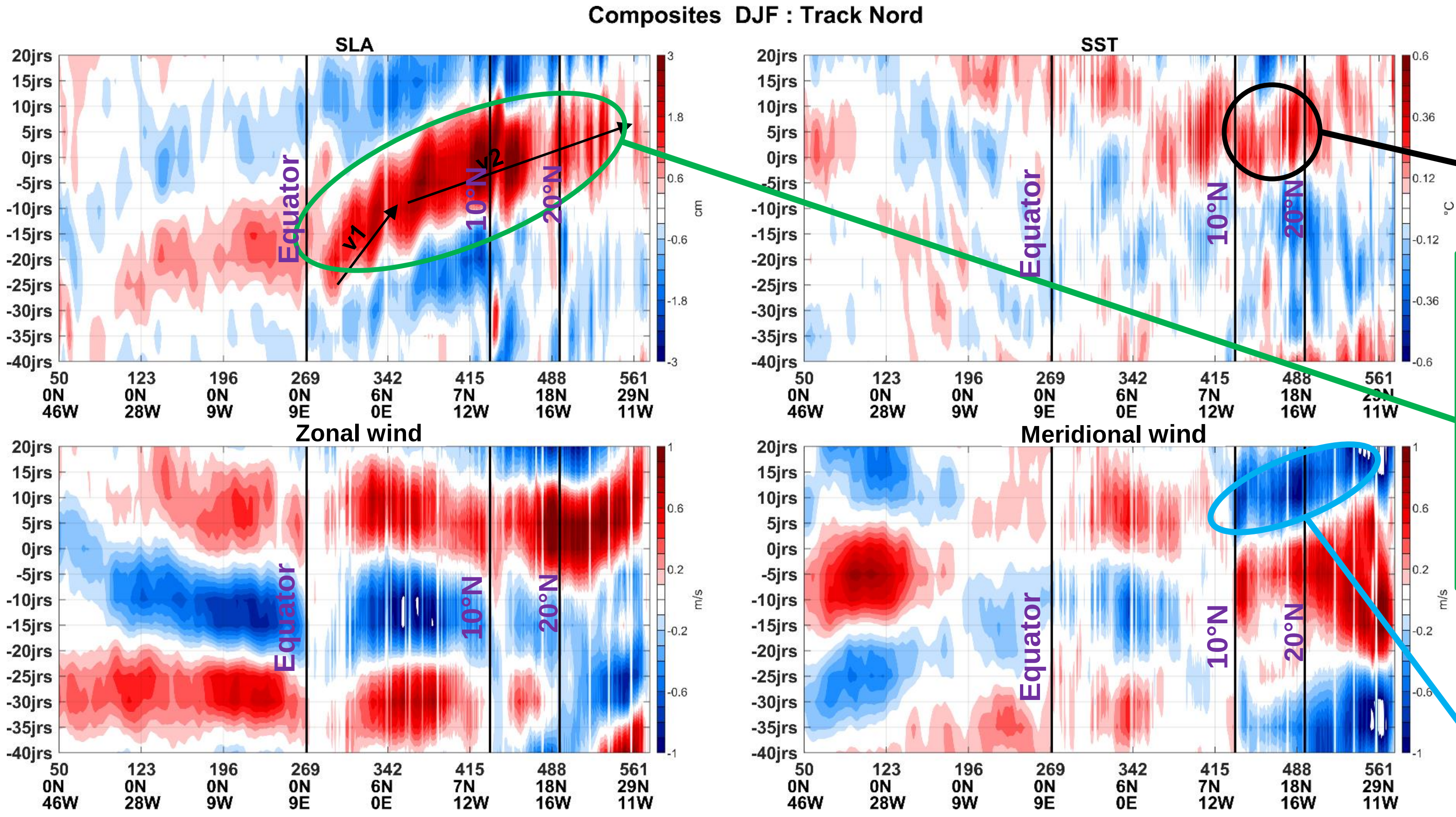
The propagation speeds of the downwelling wave:
v1=0.7 m/s and v2=2.8 m/s

Figure 2: *Hovmûllers diagrams of the intra-seasonal variability of SLA (cm) for the DJF season on the left and the average SLA composite in DJF for the period 1993-2018 on the right along the northern track. The first black line on the two panels represents the separation between the equator of the coast. The second black line represents 10 °N. The third line represents 20 °N. The black arrows materialize the wave's propagation speeds.*

Following Polo et al., 2008; the figure 2 shows the intra-seasonal variability of SLA for the 1993-2018 DJF season (left panel) and the average DJF SLA composite (right panel) along the northern track. Indeed, to identify the propagations of intra-seasonal Kelvin waves along the Equatorial Atlantic and along the West African Northern coasts over the period 1993-2018 during the DJF season, we have drawn hovmûller diagrams of the intra-seasonal variability of sea-level anomaly (SLA) along the equatorial Atlantic and the northern track over the whole period 1993-2018. Although propagations are difficult to identify unequivocally because basin-wide interannual sea level anomalies (França et al., 2003; Handoh and Bigg., 2000; Illig et al., 2019; Imbol et al., 2018), many signals similar to propagation appear strikingly from the equator to the African coast along the Gulf of Guinea and along the northern and southern African coasts. The hovmûllers diagrams for the filtered signal show downwelling and upwelling wave propagations observed year round for all years for the period 1993-2018 with a period of about 2 months. The continuity of the equatorial Kelvin wave is east and the coastal propagation is sometimes broken due to the shape of the coast.

These figures show us that we have equatorial and coastal Kelvin wave propagations of downwelling (November and mid-January) and upwelling (October and mid-February) along the northern and southern track. Indeed, the average composite was built by averaging all the downwelling waves of the DJF season.

Hovmûller of the downwelling wave composite in DJF (DJF)



Maximum SST anomaly of ~0.3°C @lag 0d&5d

- Propagation of the average wave from -25 days in the GG and along the Senegal-Mauritanian coast
- A wave with two propagation speeds:

- In the GG: v1=0.72 m/s

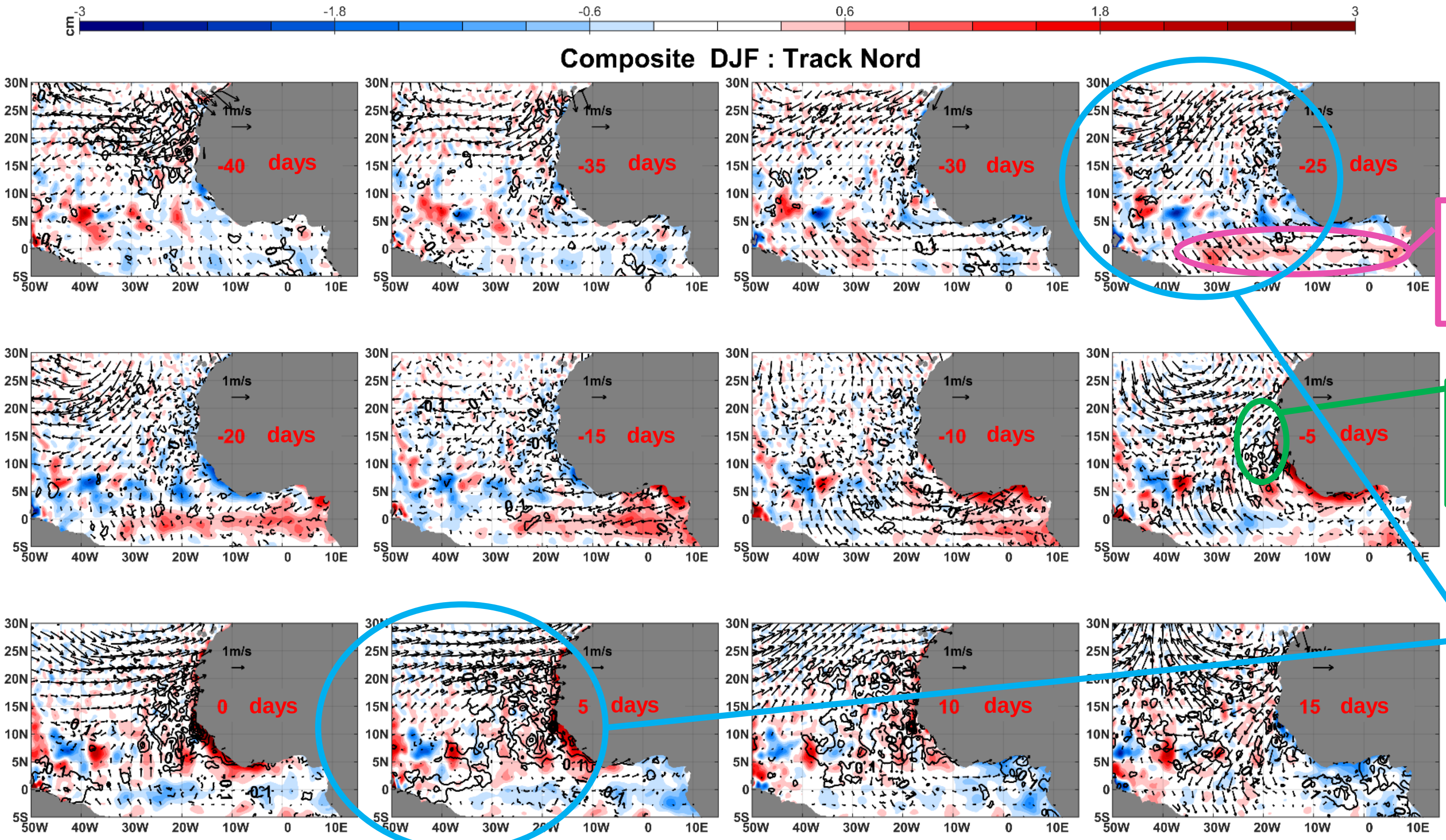
-Along the Senegal-Mauritanian coast: v2=2.83 m/s

Constructive wind anomaly (the meridional component decrease amplifies the downwelling wave)

Figure 3: *Composite of downwelling in the north for the months of DJF the time steps are 5 days and the 0 day corresponds to the arrival of the wave at the level of the Senegalo-Mauritanian upwelling system (10 °N). Top left: composite of the SLA anomaly (cm). Bottom left: composite of the zonal wind anomaly (m/s). Top right: composite of the SST anomaly (°C). Bottom right: Composite of meridional wind anomaly (m/s).*

The composite method consists in identifying each signal, isolating them and then averaging them in order to obtain an average event. We selected the events arriving up to the northern and southern upwelling fronts. We do not distinguish the waves according to their zone of birth and departure of propagation. After having located the events over the whole period and selected their time to arrive in the upwelling zones, we average the SLA, SST and wind values over these time steps. We also average over the 8 (-40 days) previous time steps and over the next 3 (+15 days) over the whole route. In our case, a composite is defined as the average of the selected downwelling waves arriving in the 10-20°N zones where we have SST gradient maxima along the northern coast. The figure 3 shows the intra-seasonal Kelvin wave composites for the months of DJF of the SLA anomaly, the SST anomaly, the Zonal and Meridional Wind along the northern track. At this period, we are in the situation where the ITCZ is in its southern most position. During this season we are interested in the Senegal-Mauritanian (S-M) front 10-20°N.The DJF mean downwelling wave seems to be generated off the Gulf of Guinea (GG) by a zonal gale from the West (West to East) in this area creating an Ekman transport towards the southern and inducing a warming of the ocean surface in the GG. The DJF wave propagates initially at a propagation speed of 0.7 m/s along the coast of the Gulf of Guinea corresponding to a sea level rise of 2 cm thus inducing a warming of 0.1°C, then on the Northern African coast at a speed of 2.8 m/s (Polo et al., 2008) for an amplitude of 3 cm accompanied by a warming of 0.4°C. This change in slope may be the result of a change in stratification or by local wind forcing changing the speed of propagation. The Senegalese Mauritanian front is affected by a positive temperature anomaly of about 0.2°C appearing 5 days after the passage of the wave through the upwelling system. The wave is accompanied by a positive meridional wind anomaly which contributes to the attenuation of the upwelling effect. There is also a temperature impact in the GG of around 0.4°C which could be explained by the negative zonal wind anomaly at -5 days. The maximum impact on the temperature of the S-M front is located northern of the buoy (northern position of the front) and is of the order of 0.2°C with a propagation of the positive meridional wind anomaly along the path, impacting the front zone (constructive anomaly). The maximum temperature impact is at the level of the strongest temperature gradients following the seasonal migration of the front. However, the downwelling wave is accompanied by a constructive zonal wind anomaly in the GG and a meridional wind anomaly in the S-M upwelling system.

Spatial map of the DJF composite in function of lag time



- At the equator, there are winds that are blowing southern ward creating a warming at this level

- winds favorable for downwelling along the coasts (positive SST anomalies)

Basin scale winds anomalies @-25d & +5d : Northern Trade acceleration (deceleration) associated to Southern Trade deceleration (acceleration)

Figure 4: *Spatial map of the composite of Sea Level Anomaly (SLA in color, in cm), Sea Surface Temperature (SST in contour, in °C) and Wind (U and V arrows, in m/s) along the northern track. The downwelling composite wave is in red.*

In order to visualize the spatial propagation of our DJF SLA composite, the spatial structure of the wind and SST composite observed over the entire Northern Tropical Atlantic (TA) basin as shown in Figure 4. The projection was made for different shifts (delay of the SLA domain from -40 days to +15 days) using 10°N as a reference to show the temporal evolution over the whole TA as the wave propagates. The projection shows a very clear spatial structure for the beginning of the equatorial Kelvin wave from downwelling (upwelling) at the western equator at -30 days, reaching the African coast at -25 days. Finally, the coastal trapped Kelvin wave propagates to ~24° latitude at +10 days after the arrival of the wave in the study area (10-20°N). However, we note that for a downwelling wave, the winds are destructive along the coasts (positive SST anomalies) and at the equator, southward winds generate a damping of the southern Trade winds that generate the downwelling wave. On the other hand, for an upwelling wave, the downwelling favorable winds reinforce the downwelling coastal wave (lag - 25 and 20) and at the equator, there are southern ward directed winds creating warming at this location. In conclusion we can say that the intensification of the winds differs from one season to another and is reflected in the upwellings (downwellings) by an intensification or not depending on the season. In summer, these anomalies are due to the SST, whereas in the other seasons we believe that they are due to wind forcing (remote + local forcing) and wave forcing. In the northern, there is an impact on the temperature in the upwelling zone of about 0.13°C per cm (warming for the downwelling wave and cooling for the upwelling wave). These waves are each season accompanied by a constructive wind anomaly to the northern, which reduces the upwelling because the effect of the slowing down of the wind anomaly will warm the surface water. This wind anomaly appears to be a large-scale signal at the equator.

Conclusion

This presentation focused on intra-seasonal Kelvin waves and their impact on SST in coastal upwelling areas of the Tropical Atlantic by performing a boreal winter composite analysis. This study is done with satellite observation data for SLA, OISST NOAA, Zonal and Meridional Wind from the ERA5 reanalysis for the period 1993-2018. To study the intra-seasonal coastal Kelvin waves, we filtered data such as sea surface level, sea surface temperature and finally the Zonal and Meridional Wind over the bandwidth in the period 20-90 days. This processing, frequently used along the equator, illuminates here the propagation of Kelvin wave signals towards the poles along the North West African coast.

In addition, the regression map allowed us to quantify the link between SLA and SST during the winter season at the passage of the wave in coastal upwelling systems and along the north coast. In fact, we note a very strong link between SST and SLA in the upwelling areas with regression coefficients between 0.05 and 0.3°C/cm.

However, in the analysis of seasonal composites, our study shows that we can simplify the intra-seasonal activity to an average signal by averaging all waves from all years arriving in upwelling systems with constructive wind anomalies and an impact of the order of 0.13°C/cm. The SST follows the forcings (waves and wind) with a delay of 5 days, physically it responds to them with an intensity of 0.4°C for an average wave of 3 cm. These waves seem to be generated by a zonal wind anomaly (positive for a downwelling wave and negative for an upwelling wave) persisting for 5 days. During the propagation of the wave we notice differences in propagation speeds between 0.7 and 2.8 m/s depending on the season. The winter wave seems to come from the Gulf of Guinea and a clear signal consistent with the SLA anomaly propagating up to 24°N is observed.

Summary table of intra-seasonal Kelvin wave characteristics

Saisons	Track (Nord/Sud)	SLA	SST	Vitesses	Anomalie de vent
DJF	Nord Sénégal Nord GG	+4 cm +2 cm	+0.3°C +0.1°C	2,83 m/s 0,72 m/s	Anomalie positive (S-M négative) GG (constructif)
	Sud A-B Sud équatorial	+3,5 cm +0,5 cm	+0.4°C +0,2 °C	1,83 m/s 0,71 m/s	Anomalie négative (constructive)
MAM	Nord Sénégal Nord GG	+4 cm +1,5 cm	+0.3 °C +0.2°C	1,7 m/s 1,03 m/s	Anomalie positive (S-M négative (GG)(constructif)
	Sud	+3 cm	+0.4 °C	2,73 m/s	Anomalie négative (constructive)
JJA	Nord Sénégal	+5 cm	+0.3 °C	1.03 m/s	Anomalie positive (S-M) négative (GG) (constructif)
	Sud A-B Sud équatorial	+2.5cm 1 cm	+0.5°C 0,1 °C	1,96 m/s 0,53 m/s	Anomalie Négative (constructif)
SON	Nord Sénégal Nord GG	+4 cm +1.5 cm	+0.3 °C +0.1 °C	1,74 m/s 0,92 m/s	Anomalie positive (S-M) négative (GG) (constructif)
	Sud	+2,5 cm	+0.3 °C	0,93 m/s	Anomalie négative (constructif)

Table 1: Summary table of the characteristics of the Kelvin waves in the different seasons

Bibliography :

Diakhaté, M., de Coëtlogon, G., Lazar, A., Wade, M., Gaye, A.T., 2016. Intraseasonal variability of tropical Atlantic sea-surface temperature: air-sea interaction over upwelling fronts: Intraseasonal Variability of Tropical Atlantic Sea Surface Temperature. Q.J.R. Meteorol. Soc. 142, 372–386. https://doi.org/10.1002/qj.2657

Faye, S., Lazar, A., Sow, B.A., Gaye, A.T., 2015. A model study of the seasonality of sea surface temperature and circulation in the Atlantic North-eastern Tropical Upwelling System. Front. Phys. 3. https://doi.org/10.3389/fphy.2015.00076

Illig, S., 2004. Interannual long equatorial waves in the tropical Atlantic from a high-resolution ocean general circulation model experiment in 1981–2000. J. Geophys. Res. 109, C02022. https://doi.org/10.1029/2003JC001771

Illig, S., Bachèlery, M.-L., 2019. Propagation of Subseasonal Equatorially-Forced Coastal Trapped Waves down to the Benguela Upwelling System. Sci Rep 9, 5306. https://doi.org/10.1038/s41598-019-41847-1

Illig, S., Cadier, E., Bachèlery, M., Kersalé, M., 2018. Subseasonal Coastal-Trapped Wave Propagations in the Southeastern Pacific and Atlantic Oceans: 1. A New Approach to Estimate Wave Amplitude. J. Geophys. Res. Oceans 123, 3915–3941. https://doi.org/10.1029/2017JC013539

Imbol Koungue, R.A., Illig, S., Rouault, M., 2017a. Role of interannual Kelvin wave propagations in the equatorial Atlantic on the Angola Benguela Current system: EQUATORIAL KELVIN WAVES AND BENGUELA NINOS. J. Geophys. Res. Oceans 122, 4685–4703. https://doi.org/10.1002/2016JC012463

Imbol Koungue, R.A., Illig, S., Rouault, M., 2017b. Role of interannual Kelvin wave propagations in the equatorial Atlantic on the Angola Benguela Current system: EQUATORIAL KELVIN WAVES AND BENGUELA NINOS. J. Geophys. Res. Oceans 122, 4685–4703. https://doi.org/10.1002/2016JC012463

Polo, I., Lazar, A., Rodriguez-Fonseca, B., Arnault, S., 2008. Oceanic Kelvin waves and tropical Atlantic intraseasonal variability: 1. Kelvin wave characterization. J. Geophys. Res. 113, C07009. https://doi.org/10.1029/2007JC004495

Wade M, Lazar A, Peter AC. 2015. 'Thermal impact of oceanic Kelvin waves along the west African coast'. *PIRATA-PREFACE-CLIVAR Tropical Atlantic Variably Confrence*, 24–27 August 2015, Cape Town, South Africa