**Long-Term Upwelling Activity along the Moroccan Atlantic Coast**

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**Abstract**

*The long term activity of the upwelling along the Moroccan Atlantic coast between Cape Blanc (21°N) and Cape Spartel (36°N) is investigated in this work using a monthly Ekman Upwelling Index over the period 1967-2019 (53 years). Three stations that are representative of the upwelling’s activity along the Moroccan Atlantic coast from North to South were selected in this study for analysis: ST5 (31°N-10.5°W) between Cape Sim and Cape Ghir, ST7 (29°N-10.5° W) between Cape Ghir and Cape Draa and ST12 (24.5°N-15.5°W) North Dakhla between Cape Boujdor and Cape Barbas. The results show a seasonal variability in the northern area between Cape Juby – Cape Spartel and a permanent activity mostly all the year in the southern area between Cape Juby - Cape Blanc. Strongest activities of upwelling were observed during summer seasons in the northern area, in particular over the period 1998-2003, and its activity slightly exceeded the average over the periods 1972-1977, 1980-1984, 2004-2008. The weakest upwelling activities in this region were observed in the fall-winter seasons, particularly during the periods 1967-1970, 1995-1998 and 2000-2005. In the southern area, the upwelling variations showed strong upwelling activity in summer over the periods 1967-1980 and 2009-2019, with annual and interannual variability between these two periods. This activity was slightly above average in summer over the 1981-2007 period, except for the years 1982-1983, 1988-1989, 1995-1997 and 2004-2007 where a relative downward trend was observed. Lower upwelling activities were observed in this area over the 2003-2010 period in fall /winter seasons.*

**Key words**: Morocco, Atlantic Coast, Ekman Upwelling Index, Seasonal & Long Term Activity.

1. Introduction

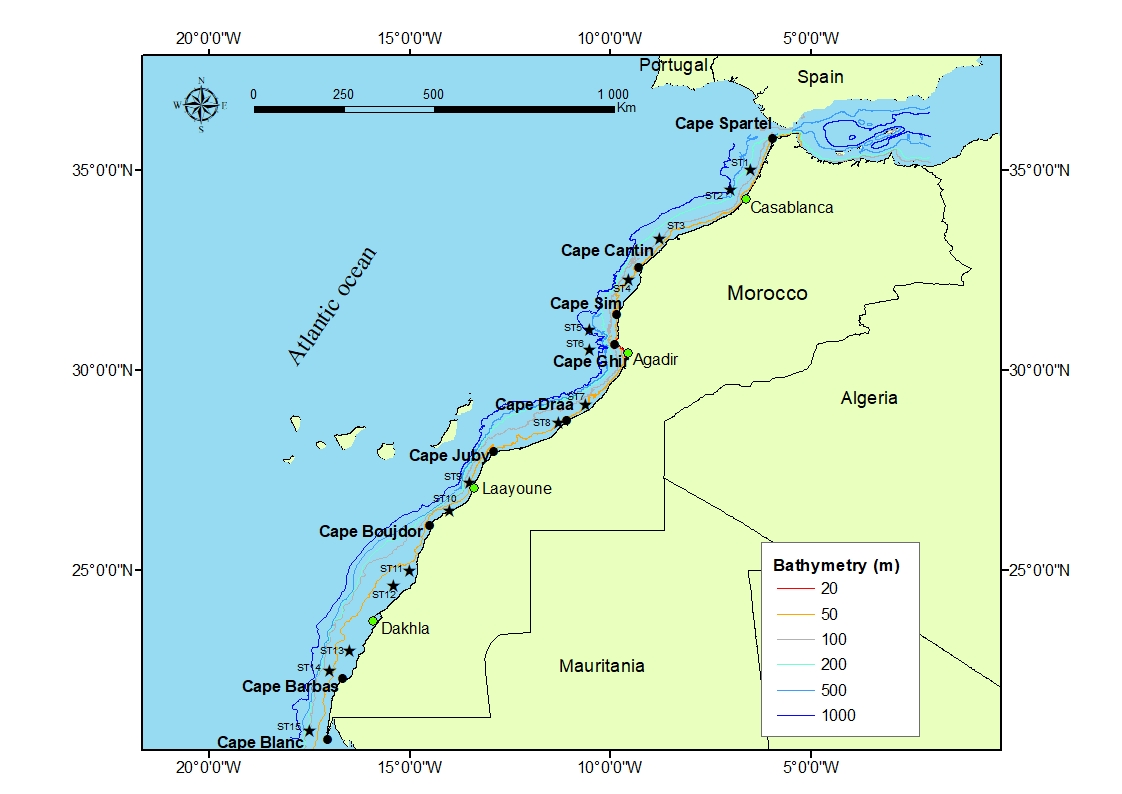
The upwelling is an upward motion of sea water sea water from intermediate depths (typically 50–200 m) toward the ocean surface. It is an oceanographic phenomenon resulting from the friction of the wind on the ocean surface. Upwelled water masses are colder and richer in nutrients than the surface waters they replace. Upwellings therefore correspond to areas of very productive marine ecosystems and high fish resources (SYLLA DIOP et al. 2019). There are four major coastal upwelling systems (called « EBUSs» for Eastern Boundary Upwelling Systems) in the global ocean, that are the Canary, Benguela, Humboldt and California systems. These areas cover less than 1% of the global ocean surface, but they contribute to about 8% of the global marine primary production (CARR & KEARNS 2003; GOMEZ-LETONA et al. 2017) and more than 20% of the global fish catches (PAULY & CHRISTENSEN 1995). The Canary Upwelling Ecosystem is a typical Eastern Boundary Upwelling System whose coastal dynamics are directly linked to the atmospheric wind forcing and highly influenced by stratification, shelf/slope topographic shapes, and coastline irregularities (ESTRADE et al. 2008; MARCHESIELLO & ESTRADE 2010; ROY 1989, 1998; DEMARCQ & FAURE 2000). The wind regime driven by the seasonal migration of the intertropical convergence zone and of the Azores high-pressure cell (WOOSTER et al. 1976; MASON et al. 2011) is responsible for quasi-permanent Ekman pumping and coastal upwelling along the southern Canary upwelling system during winter and spring (NDOYE et al. 2017). The northwest African upwelling area is a part of the Canary upwelling ecosystem. Like other major upwelling areas in the world, the vigorous equatorward trade winds play a dominant role in determining the strength and duration of upwelling events. The subsurface waters ascending to the surface under the influence of the winds have physical and chemical properties that are distinct from the usual surface waters. The upwelled waters are, for instance, colder and richer in nutrients than the surface waters (NYKJAER & VAN CAMP 1994). Coastal upwelling is an upwelling of deep water on the continental shelf that compensates for the drift of surface waters out to sea (Ekman's drift), under the combined actions of a favorable wind and the rotation of the Earth. It characterizes a large part of the eastern borders of the oceans in tropical and subtropical latitudes where the regularity of the trade winds gives the phenomenon of upwelling variability in space and time and a permanent or seasonal character (WOOSTER et al. 1976). According to JACOX et al. (2018), wind-driven coastal upwelling is a key driver of physical, biogeochemical, and ecological variability near the land-sea interface, particularly in EBUS, which are characterized by seasonal equatorward wind forcing. Nutrient-rich water, supplied to the sunlit surface layer by wind-driven upwelling, stimulates the growth of phytoplankton that ultimately fuel diverse and productive marine ecosystems. In addition to this bottom-up forcing through the base of the food web, upwelling can influence higher trophic levels directly through exposure to physical and chemical signatures of the deeper ocean (e.g., lower temperature, oxygen concentration, and pH) (JACOX et al. 2018). Impacts of upwelling variability can be felt on timescales ranging from single events(days) to decades and longer, and they propagate to commercial and recreational activities that derive considerable socioeconomic benefits from EBUS (BOGRAD et al. 2016). The Moroccan Atlantic coast (Fig. 1) which is the subject of this study is under the influence in its northern area to very active seasonal upwelling in summer between Cape Juby and Cape Spartel and almost permanent in its southern area between Cape Juby and Cape Blanc, very active in spring/summer and autumn (ATILLAH et al. 2005; BESSA et al. 2017, 2020; BENAZZOUZ et al. 2013, 2014, 2015; EL AOUNI et al., 2019 a and b, 2020; HILMI et al. 2020; LARISSI et al. 2013; MAKAOUI et al. 2005, 2012; ORBI et al. 1998; TAMIM et al. 2018). The cold waters, coming up along the Moroccan Atlantic coast are generally rich in nutrients (MAKAOUI et al. 2005, 2012; ORBI et al. 1998) are essential for maintaining the organic production (ABDELOUAHAB et al 2020; BERRAHO et al. 2005; IKRAM et al. 2017).

2. Material and methods

2.1. Study area and objective of the work

We focused in this paper on three stations for analysis that are representative of the upwelling’s activity along the Moroccan Atlantic coast from north to south (Fig. 1): ST5 (31°N-10.5°W) between Cape Sim and Cape Ghir, ST7 (29°N-10.5° W) between Cape Ghir and Cape Draa and ST12 (24.5°N-15.5°W) north Dakhla between Cape Boujdour and Cape Barbas. The seasonal, annual to interannual variability of the upwelling’s activity over the period 1967-2019 at these three selected stations are presented and discussed in the next sections.

The objective of this work is to assess the long-term upwelling activity of the Moroccan Atlantic coast over the period 1967-2019 (53 years), based on a monthly Ekman Upwelling Index commonly called “Bakun Upwelling Index” (BAKUN 1973, 19975; EKMAN, 1905; SCHWING et al. 1996) at 15 stations (ST1 - ST15) along the Moroccan Atlantic coast (Fig. 1 and Table 1).



**Fig. 1:** Location of the “Ekman Upwelling Stations” (★) along the Moroccan Atlantic coast. Their geographical coordinates are included in Table 1.

**Table 1**: Ekman Upwelling Stations (ST1 to ST15) and their geographical coordinates along the Moroccan Atlantic coast. The bolded stations in \* (ST5, ST7 and ST12) are selected for analysis in this work.

|  |  |  |
| --- | --- | --- |
| Ekman upwelling stations | Latitude (°North) | Longitude (°West) |
| ST1 | 35 N | -6.5 W |
| ST2 | 34.5 N | -7 W |
| ST3 | 33 N | -8.5 W |
| ST4 | 32.5 N | -9 W |
| **ST5\*** | **31 N** | **-10 .5 W** |
| ST6 | 30.5 N | -10.5 W |
| **ST7\*** | **29 N** | **-10.5 W** |
| ST8 | 28.5 N | -11 W |
| ST9 | 27 N | -13 W |
| ST10 | 26.5 N | -14 W |
| ST11 | 25 N | -15 W |
| **ST12\*** | **24.5 N** | **-15 W** |
| ST13 | 23 N | -16.5 W |
| ST14 | 22.5 N | -17 W |
| ST15 | 21 N | -17.5 W |

2.2. Ekman Upwelling Index

Given the importance of coastal upwelling as a driver of dynamics in EBUs, the usefulness of quantifying its variability in space and time has been recognized for several decades [13]. However, the spatial-temporal variability of vertical oceanic intensities and their weak signal compared to horizontal speeds do not allow direct monitoring of upwelling. To meet the needs of historical and continuous estimates of the intensity of coastal upwelling. BAKUN (1973, 1975) and SCHWING et al. (1996) developed the coastal upwelling index, based on the theory of EKMAN (1905), on coastal upwelling for estimates the Ekman Transport as an indicator of coastal upwelling. This coastal upwelling index is estimated from the following equations, assuming homogeneity across the water column, uniform wind and steady state conditions (BAKUN 1973, 1975; SCHWING et al. 1996):

(1)



(2)



where:

-  is the unit vector directed vertically upward;



- is the wind stress vector (N.m-2);



- is the air density (kg.m-3);



-  is an empirical drag coefficient: a Cd of 0.0013 is used to calculate upwelling from the six-hourly surface pressure fields; the Cd is increased to 0.0026 when the monthly-mean pressure data is used [36].



- is the estimated wind vector near the sea surface with magnitude (m.s-1).



-  is the Ekman transports; According to [36], Ekman transports are resolved into components parallel and normal to the local coastline orientation. The magnitude of the offshore component is considered to be an index of the amount of water upwelled from the base of the Ekman layer. Positive values are, in general, the result of equatorward wind stress. Negative values imply downwelling, the onshore advection of surface waters accompanied by a downward displacement of water. The sign of the offshore component of the Ekman transport, Mx = ꞇy/f, where x is normal and y parallel to the local coastline orientation, is then reversed to reflect that negative (offshore) Ekman transport leads to positive (“upwelling”) vertical transport, and positive (onshore) Ekman transport leads to negative (“downwelling”) vertical transport (SCHWING et al. 1996). The upwelling indices are expressed in units of cubic meters per second per 100 meters of coastline (m3.s-1.100m-1), which is equivalent to metric tons/s/100 m coastline. These values are an index of large-scale coastal upwelling, a mean value representative of mass transport averaged spatially over approximately 200 nautical miles. Small-scale upwelling and downwelling events unresolved by the upwelling indices time and space scales may occur during the averaging period for a particular location (SCHWING et al. 1996). The monthly Ekman Upwelling Index data, used in this work, come from the NOAA (National Oceanic and Atmospheric Administration - Fisheries) (www.pfeg.nooa.gov) and cover the period 1967-2019.



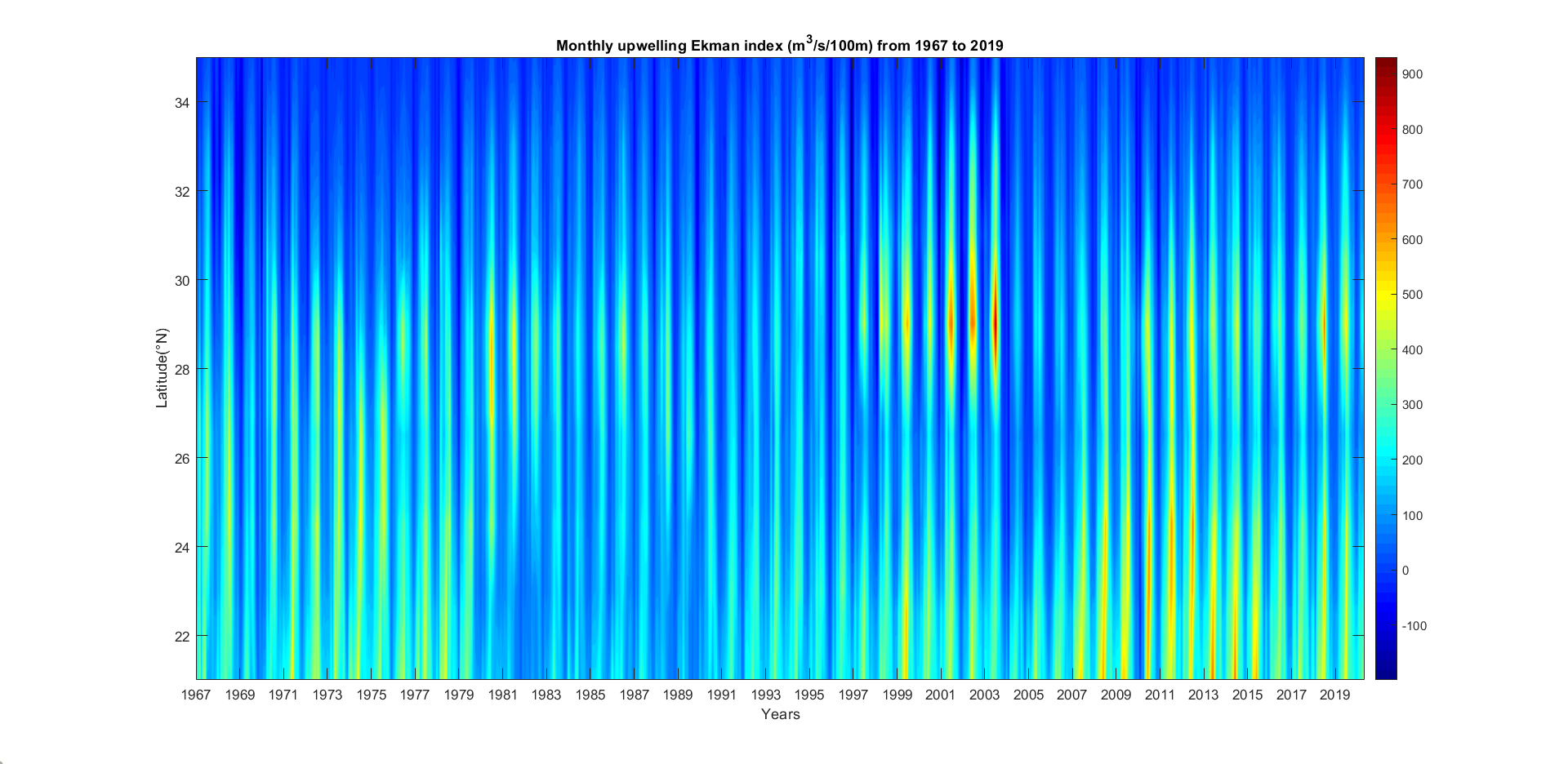
2.3. Wavelet analysis

According to GRINSTED et al. (2004), geophysical time series are often generated by complex systems of which we know little. Predictable behavior in such systems, such as trends and periodicities, is therefore of great interest. Most traditional mathematical methods that examine periodicities in the frequency domain, such as Fourier analysis, have implicitly assumed that the underlying processes are stationary in time. However, wavelet transforms expand time series into time frequency space and can therefore find localized intermittent periodicities. There are two classes of wavelet transforms: the Continuous Wavelet Transform (CWT) and its discrete counterpart (DWT). The DWT is a compact representation of the data and is particularly useful for noise reduction and data compression whereas the CWT is better for feature extraction purposes (GRINSTED et al. 2004). As we are interested in extracting low s/n ratio signals in time series, we focus in this work only on CWT, where CWT is a common tool for analyzing localized intermittent oscillations in a time series. More details about CWT are described in GRINSTED et al. (2004).

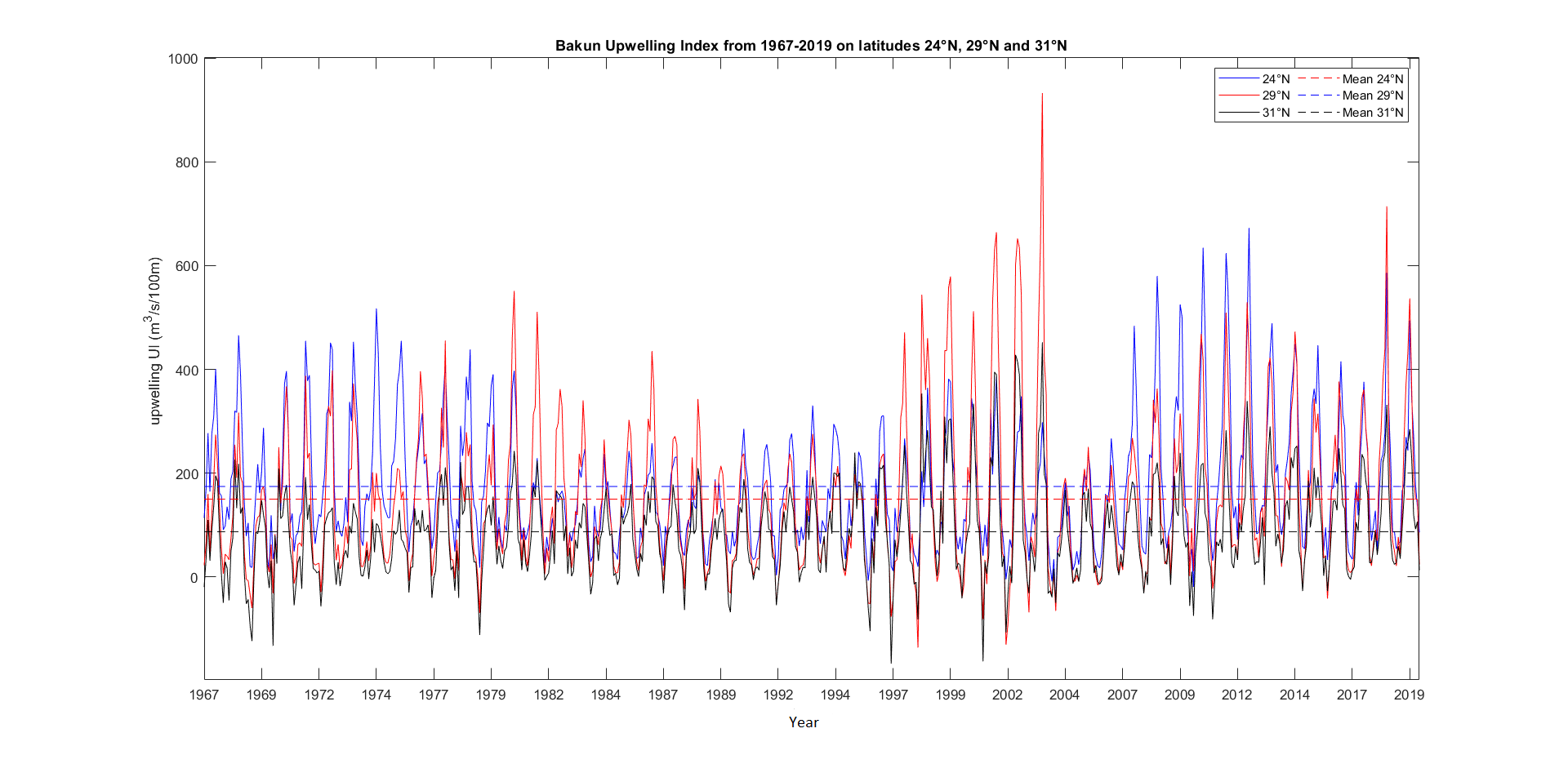
3. Results and discussion

3.1. Ekman Upwelling Index

Based on this methodology and to meet the objectives of this work, figure 2 presents a Hövmuller plot of the coastal upwelling index computed for the 15 stations stated above, over the period 1967-2019 (53 years) (Fig. 1 and Table 1). Their latitudes are represented on Y axis and their period on X axis (Fig. 2). The monthly Ekman Upwelling index varies from -200 m3.s-1.100 m-1 to around 950 m3.s-1.100 m-1. The upwelling maximum (“upwelling favorable”) is centered at around 28°N-29°N and during all the year south of 28°N (Fig. 2). Minima occur north of latitude (34°N) in the winter with negative (“downwelling favorable”). These results are in agreement with others studies about the upwelling seasonality along the Moroccan Atlantic coast (ATILLAH et al. 2005; BESSA et al. 2017, 2020; BENAZZOUZ et al. 2013, 2014, 2015; EL AOUNI et al. 2019 a and b, 2020; HILMI et al. 2020; LARISSI et al. 2013; MAKAOUI et al. 2005, 2012; ORBI et al. 1998; TAMIM et al. 2018). Between Cape Juby (28°N) and Larache (34°N), the upwelling’s activity is seasonal and very active in summer and, between Cap Juby (28°N) and Cap Blanc (21°N), the upwelling’s activity is around all the year and very strong in summer seasons Based on these criterias, we focuses our analysis in this work on three stations: ST5 (31°N-10.5°W) between Cape Sim and Cape Ghir and ST7 (29°N-10.5° W) between Cape Ghir and Cape Draa in summer and at ST12 (24.5°N-15.5°W) North Dakhla, between Cape Boujdor and Cape Barbas (Fig. 3).



**Fig. 2**: Hövmuller plot of the monthly Ekman Upwelling Index at the 15 stations along the Moroccan Atlantic coast from 1967-2019. The 15 stations refer to Fig. 1 and Table1.



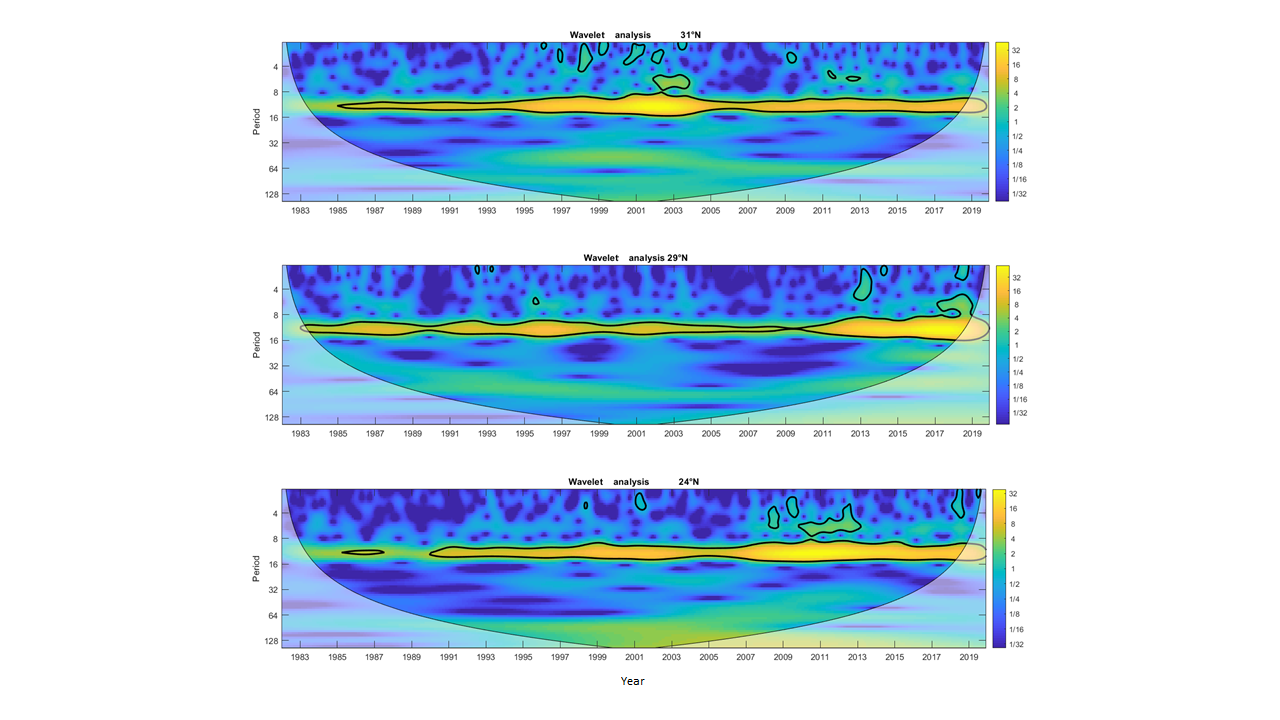
**Fig. 3**: Ekman Upwelling Index (EUI) at the 3 selected stations over the period 1967-2019: ST5 (white color), ST7 (red color), and ST12 (blue color). The mean value (EUI), calculated over this period, is represented by dashed lines at each station.

3.2. Annual/Interannual upwelling’s variability

Figure 3 shows the annual and interannual changes of the upwelling’s activity over the period 1967-2019 (53 years) at the three selected stations mentionned above. The average of the Ekman Upwelling Index (EUI), estimated over this study period, is also represented in this figure. The average index is around 87.2 (± 88.2) m3.s-1.100 m-1 for ST5 and 174 .2 (± 118.6) m3.s- 1.100 m-1 for ST12 for example. This mode of representation is allowed to provide additional indication on the years where the upwelling’s activity is “above” the average activity or “below” its average (Fig. 3). Following these criterias, we observed i) a similar trend for the three selected stations which follow a general trend during summer seasons where the maximum peaks activities are observed and ii) an annual/decadal and interannual upwelling’s variability over the period 1967-2019. On the basis of these results (figure 3), a strongest activity is shown for station 12 (ST12) located in the southern part of the Atlantic coast than the other stations (ST5 and ST7) located in the northern part of this coast. Station 12 presents a strong upwelling’s activity in summer (maximum Ekman Index) over the periods 1967-1980 and 2009-2019, with annual variable fluctuations between these two periods, for example, for the years 1969, 1976 for the first period and between 2013 and 2017 for the secund period (Fig. 3). Over the period 1981-2007, the upwelling’s activity during the summer seasons is slightly above the “average”, except for the years 1982-1983, 1988-1989, 1995-1997 and 2004-2007 where a relative downward trend is observed. At this station, the strongest "minima" are observed over the period 2003-2010 in the autumn/ winter seasons (Fig. 3). Concerning ST5, the strongest upwelling activities are observed in the summer seasons as shown in figure 3a. They slightly exceed the average over the periods 1972-1977, 1980-1984, 2004-2008 and a very strong activity was observed in summer between 1998-2003 (figure 3). The strongest "minima" were observed in the fall / winter seasons, reporting low activity in these seasons over the periods 1967-1970 and 1995-1998 and 2000-2005 (Fig. 3). The annual upwelling variability between the two stations is explained by the strong seasonal dynamic of the upwelling’s activity along the Moroccan Atlantic coast where the north Atlantic area of Morocco is subject to climatic and oceanographic characteristics which are different from the southern part. Based on wavelet analysis (GRINSTED et al. 2004), the figure 4 shows the Continuous Wavelet Transform (CWT) at the three selected stations (ST5, ST7 and ST12). A strong signal (in yellow color) shows a strong signal between 6 and 12 months which reveals a strong seasonal and annual periodicity of the upwelling’s activity along the Moroccan Atlantic coast (Fig. 4).

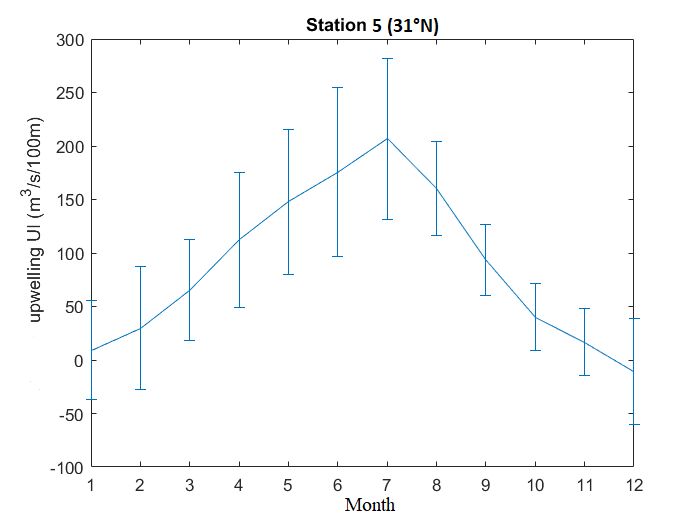
3.2. Seasonal upwelling ‘s variability

Figure 5 shows the monthly/seasonal Ekman Upwelling Index at stations 5 and 12 for example, averaged over the period 1967-2019. At station 5 (Fig. 5a), the index shows some negative values which represents a "downwelling" or absence of upwelling’s activity in December (-10.7 m3.s-1.100m-1). Upwelling’s activity is relatively weak in winter and begins to increase gradually in spring to reach its maximum activity during summer seasons. It begins gradually to decrease in the fall seasons. The maximum peak of upwelling’s activity is observed in July (207 m3.s-1.100m-1) (Fig. 5a). Figure 5b shows this index at ST12, averaged over the period 1967-2019. Similarly to figure 5a, this monthly index shows positive values observed throughout all the year, indicating a permanent upwelling ‘s activity throughout the year (Fig. 5b). This activity begins to increase gradually in winter (between 57 and 135 m3.s-1.100m-1), reaches its maximum peak in summer during July (359 m3.s-1.100m-1). It gradually decreases in autumn (between 70 and 200 m3.s-1.100m-1) (Fig. 5b).

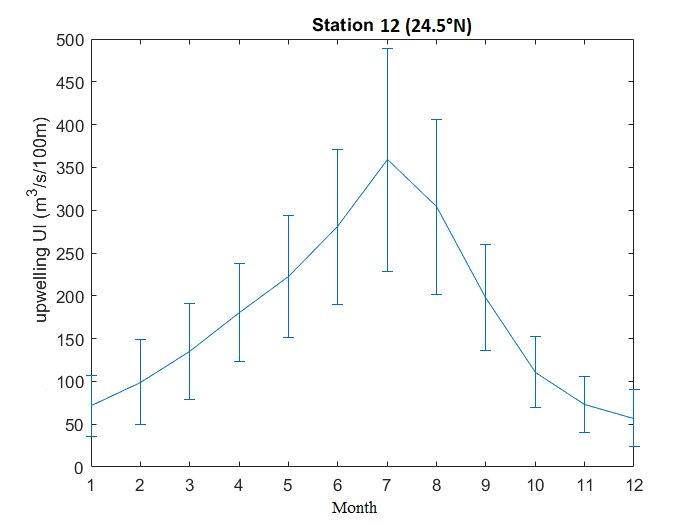


**Fig. 4**: Continuous Wavelet Transform (CWT) of Ekman Upwelling Index at stations 5, 7 and 12. The thick black contour designates the 5% significance level against red noise and the cone of influence (COI) where edge effects might distort the picture is shown as a lighter shade.

**a)**



**b)**



**Fig. 5**. Monthly variability of Ekman Upwelling Index with its standard deviation (m3/s/100m) under the period 1967-2019 for **a**) ST5 (31°N-10,5°W) and **b**) ST12 (24,5°N-15,5°W) along the Moroccan Atlantic coast.

Although this study is focused on a long time series of an upwelling index and despite the availability of data from several national and / or international platforms, several studies also focus on data resolution as well as data observation periods [38]. In a context of climate change where the trend of the upwelling ‘s activity in upwelling areas (EBUS) is strongly discussed toward « high » or « low » trend (BARTON et al. 2013; BAKUN 1990; BAKUN et al. 1995), actual work research is oriented towards IPCC climate model projections (RCP 2.0 to RCP 8.5). It is currently the subject of a wide debate among the scientific community and of advanced research (CROPPER et al. 2014; HOEGH-GULDBERG et al. 2014 a and b; MCGREGOR et al. 2007; NARAYAN et al., 2010; WANG et al. 2015) and many other studies on the upwelling areas of the CCLME (GOMEZ-GEISTERA et al. 2008; GOMEZ-LETONA et al. 2017; RUBEN et al. 2021; SANTOS et al. 2012; SOUZA et al. 2017 a and b) and other EBUEs around the world. Given the importance of upwelling activity on the wealth and productivity of the marine environment, this work complements previous studies in the region, most of which are based on the development of a coastal upwelling index, based on the sea surface temperature (or “SST”) obtained from satellite observations.

4. Conclusion

In addition to the previous studies established in the Canary current area (CCLME), the long term activity of the upwelling was investigated along the Moroccan Atlantic coast between Cape Blanc (21°N) and Cape Spartel (36°N) under the period 1967-2019 (53 years), using a monthly Ekman Upwelling Index. Three stations are selected here in this work for analysis: ST5 (31°N-10.5°W) between Cape Sim and Cape Ghir, ST7 (29°N-10.5° W) between Cape Ghir and Cape Draa and ST12 (24.5°N-15.5°W) North Dakhla between Cape Boujdor and Cape Barbas. These three stations are representative of the upwelling’s activities along the Moroccan Atlantic coast. Therefore, the results show a seasonal variability in the northern area between Cape Juby – Cape Spartel and a permanent activity mostly all the year in the southern area between Cape Juby - Cape Blanc. A strongest activities of upwelling were observed during summer seasons in the northern area, in particular over the period 1998-2003 and its activity slightly exceeded the average over the periods 1972-1977, 1980-1984, 2004-2008. On the other hand, the e weakest upwelling activities in this region were observed in the fall-winter seasons, particularly during the periods 1967-1970, 1995-1998 and 2000-2005. In the southern area, the upwelling activity showed strong upwelling activity in summer over the periods 1967-1980 and 2009-2019, with annual and interannual variability between these two periods. This activity was slightly above average in summer over the 1981-2007 period, except for the years 1982-1983, 1988-1989, 1995-1997 and 2004-2007 where a relative downward trend was observed. Lower upwelling activities were observed in this area over the 2003-2010 period in fall /winter seasons. especially over the 1967-1970 periods, 1995-1998 and 2000-2005. Given the high variability of the upwelling activity in space and time with strong impacts on the productivity of the marine environment and on fisheries, monitoring of upwelling activity by different platforms is required. Further progress are needed to better understand the periods of low / high upwelling activities and the interactions between the climate and the marine environment.

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