UPWELLING FILAMENTS AND THEIR ROLE IN CROSS-FRONTAL WATER EXCHANGE

A.G. Kostianoy[1], D.M. Soloviev[2]

(1) P.P. Shirshov Institute of Oceanology, Russian Academy of Sciences, 36, Nakhimovsky Pr., Moscow, 117997 Russia
E-mail: kostianoy@online.ru
(2) Marine Hydrophysical Institute, National Academy of Sciences of Ukraine, Sevastopol, Ukraine

ABSTRACT: Satellite data (thermal and color imagery) show that offshore flowing filaments off the west coasts of North America, North and South Africa can influence significantly the cross-frontal mixing in the coastal upwelling zones. To evaluate this role, we investigated structure, dynamics and behavior of surface filaments in the Canary and Benguela upwelling regions on the base of daily satellite IR and VIS imagery (AVHRR NOAA, MODIS-Aqua). It was found that seasonal variability of the filaments location depends on intra-annual shift of general upwelling intensity along the coast. The main statistical characteristics of filaments - length, width, temperature anomaly and estimates of velocity were obtained. Estimates of cross-frontal water exchange due to filamentation based on the statistical data show that these coherent structures play a major role in the water and particle exchange between coastal zone and the open ocean in both upwelling regions.

KEY WORDS: Upwelling, Filaments, Satellite imagery, AVHRR-NOAA, MODIS-Aqua.

1. INTRODUCTION

One of the important problems in the oceanography of the wind-driven upwelling regions of the Ocean is the investigation of water exchange processes in the coastal zone. Satellite data (thermal and colour imagery) have changed our view on these processes after the discovery of cold, chlorophyll-rich, narrow (< 50 km wide) offshore flowing filaments off the west coasts of North America, North and South Africa, and Portugal (Van Foreest et al., 1984; Davis, 1985; Flament et al., 1985; Ginzburg, Fedorov, 1985; Huyer, Kosro, 1987; Kosro, 1987; Lutjeharms, Stockton, 1987; Nykjaer et al., 1988; Rienecker, Mooers, 1989; Hood et al., 1990; Paduan, Niiler, 1990; Shillington et al., 1990; Fedorov, Ginzburg, 1991; Kostianoy, 1991; Van Camp et al., 1991; Lutjeharms et al., 1991; Shillington et al., 1992; Swenson et al., 1992; Fiuza, Sousa, 1992; Gabric et al., 1993; Kostianoy, Boubnov, 1995; Kostianoy, Zatsepin, 1996).

It has been pointed out that these features represent an effective mechanism of seaward transport (1-2 Sv) of nutrients and plankton biomass from the coastal zone, and that this transport contributes significantly to production offshore (Lutjeharms, Stockton, 1987; Lutjeharms et al., 1991). Besides that, it was found that suspended matter, formed on the shelf, propagates offshore not only along the sea surface and the bottom, but also at intermediate depths. It it is still unclear to what extent these filaments contribute to the water exchange and to suspended matter lateral transit between the coastal zone and the ocean. Moreover, 3D structure and a real length of upwelling filaments are unknown.

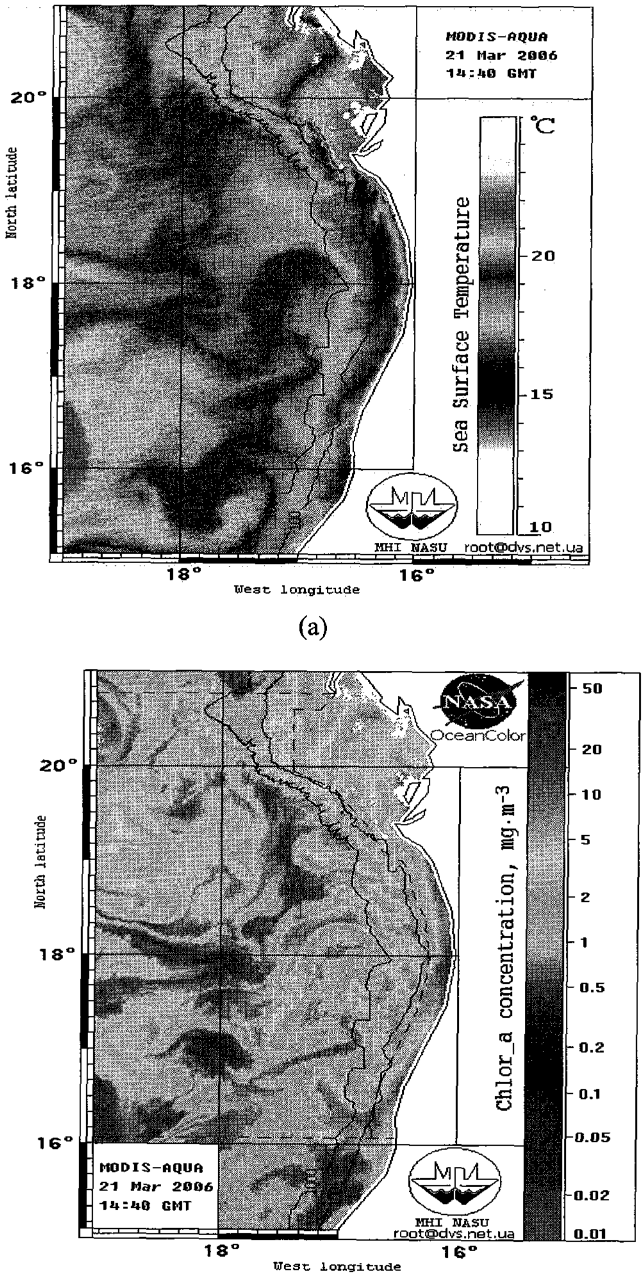
This paper focuses on the filaments of northwest and southwest African upwelling regions, and evaluates their role in the cross-frontal water exchange.

2. NW AFRICAN UPWELLING REGION

The main characteristics and seasonal variability of the system of filaments in the upwelling zone between 15° and 26°N were determined from a series of more than 1200 IR AVHRR NOAA images of this region, acquired in 1984-1987, and 2006. The most important result of the analysis was the detection not only of the system of cold filaments flowing offshore (Fig.1-2), but cold filaments moving alongshore and warm filaments moving to the coast.

The analysis of the geographic distribution of cold filaments revealed the following peculiarities:
(l) High concentration of filaments in the region between 26° and 16°N.
(2) Filaments normally propagate from the upwelling front, perpendicularly or at a small angle towards the open ocean (Fig.1-2).
(3) Northward/southward of 21°N filaments are often oriented to the northwest/southwest, i.e. opposite to the direction of the main current.
(4) In the southern (Fig.1) and northern (Fig.2) areas, filaments reach 18-19°W, and 19-19°30'W in the central area (21°N).
(5) Near the Banc d'Arguin, cold filaments are sometimes formed, that from 20°N propagate along the 100-200 m isobath to the southeast.

The analysis of seasonal variability of the system of cold filaments showed that 30% of filaments were observed in May-June and 58% in November-December (Kostianoy, 1991). It is well known that between 15°N and 20°N the upwelling is most intense in winter and spring, then

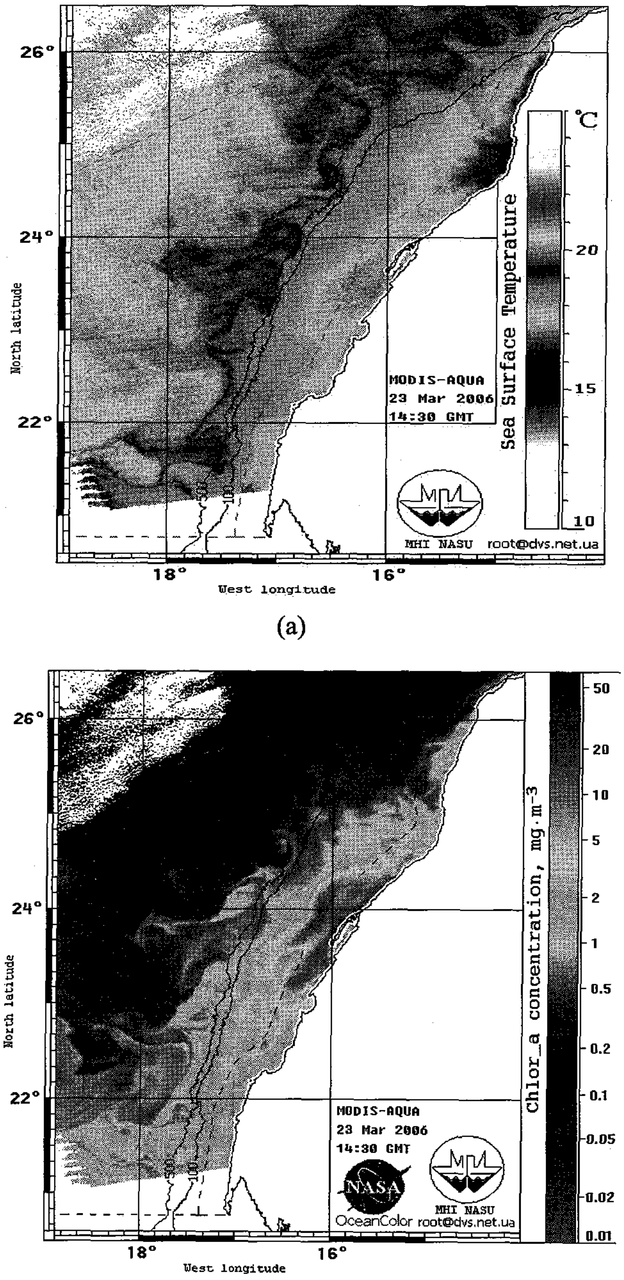


(a)

(b)

Figure 1. Upwelling filaments along the northwest coast of Africa (15-21°N) on 21 March 2006: (a) SST, (b) Chl a (MODIS-Aqua).

it gradually moves northward and becomes most intense between 20° and 33°N in spring and summer. In autumn, winds drop and the intensity of the upwelling decreases. Thus, we may assume that the frequency of occurrence of upwelling filaments during the year corresponds to the seasonal variability of the upwelling itself. This is confirmed by observations of filaments near Cape Gir (30°05'N), where in seven out of nine cases, filaments were recorded in May-June and no instances in winter months (Nykjaer et al., 1988) and by observations of filaments only in summer near the coast of Portugal (Fiuza and Sousa, 1992).



(a)

(b)

Figure 2. Upwelling filaments along the northwest coast of Africa (21-26°N) on 23 March 2006: (a) SST, (b) Chl a (MODIS-Aqua).

The analysis of main characteristics of cold filaments gave the following results. The maximum length of a filament at the sea surface ***L*** varies from 50 to 250 km (130 km in average), typical width ***d*** ranges from 10 to 75 km (30 km) and temperature difference ***ΔT*** between filaments and the surrounding water ranges between -0.8° and -2.4°C (-1.4°C). In 12% of cases ***L*** was more than 200 km. We note that the mean value and the lower limit of ***L*** variation is underestimated, because in 40% of cases there was only one image of a filament from which it was not possible to determine whether it had reached its maximum length or was continuing to develop.

Maximum velocity of filament propagation was in the range of 35-218 cm/s (average value of 91 cm/s). The lower limit (35 cm/s) is underestimated also because of a lack of daily sets of data that could cover the total lifetime of a filament (3-11 days). Kostianoy (1991) described the dynamics of filaments in the stages of development and relaxation, the pecularities of their behaviour, and the interaction between filaments in detail.

3. SW AFRICAN UPWELLING REGION

Main characteristics and seasonal variability of the system of filaments in the SW African upwelling zone between 15° and 32°S were determined from a limited series of more than 100 IR images of the region acquired in 1986, 1988 and 2004 (Fig.3). The analysis of spatial distribution of cold filaments revealed the following peculiarities:

(1) High concentration of filaments in the region 18°-19°, 22°-23°30', 26°-27°30'S.

(2) Filaments propagate perpendicularly or at a small angle from the upwelling front towards the open ocean.

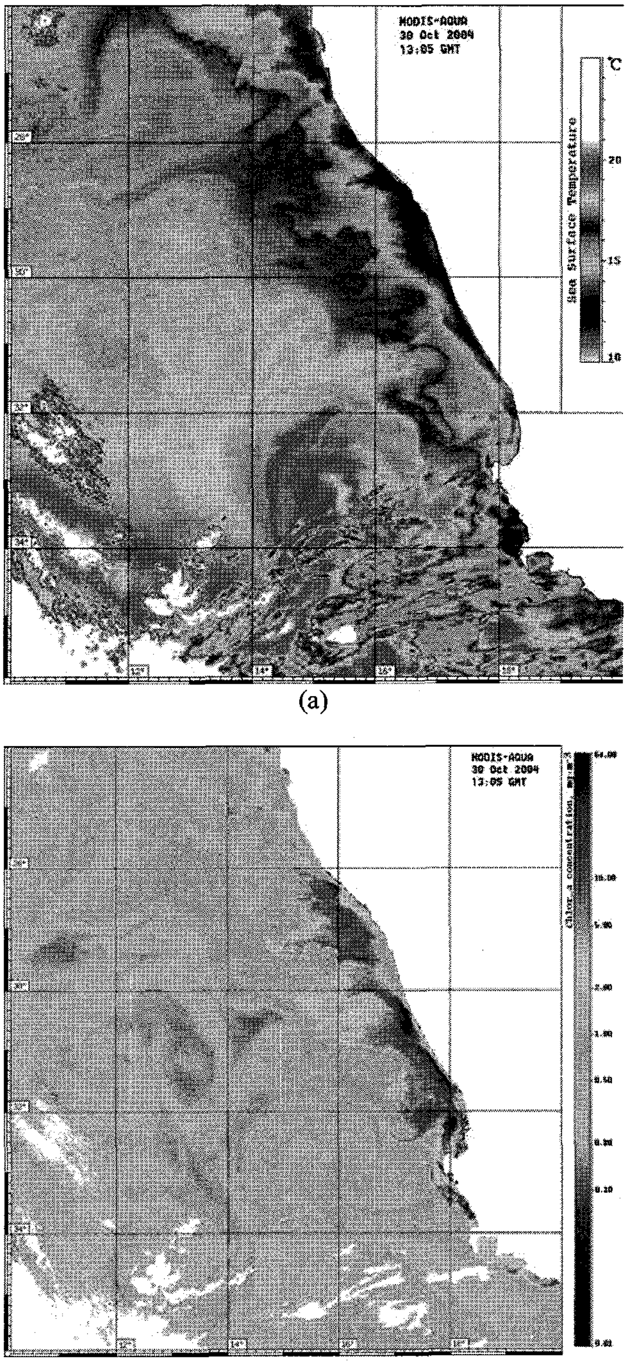
(3) At 22°-23°30'S filaments reach 8°30'E, at 26°-27°30'S they reach 10°E, thus the upwelled waters are carried out from the coast at a distance of 500-600 km.

In February, filaments were observed southward of 24°S and were absent to the north. During April-June 2/3 of filaments were located northward of 24°S and only 1/3 of them - to the south. The observed tendency is confirmed by the monthly number of filaments southward of 24°S for 1984 (Lutjeharms, Stockton, 1987). This variation corresponds to the principle scheme of the seasonal general upwelling propagation along the coast of SW Africa. Thus, seasonal variability of the filaments' location in the NW and SW African upwelling regions is identical, because high atmospheric pressures over the North and South Atlantic Ocean move to the north and back to the south synchronously during a year (Kostianoy, Boubnov, 1995).

Analysis of filaments characteristics showed that ***L*** varied from 80 to 370 km (177 km), ***d*** - from 10 to 80 km (40 km), ΔT - from -0.8° to -2.4°C (- 1.3°C). In 23% of cases ***L*** > 200 km. Filaments propagate with a velocity of 1-2 m/s, that is similar to the estimates made by Van Foreest et al. (1984). We note that such high velocities (up to 1.3 m/s) were measured by drifters in a cold filament off Point Arena, California (Swenson et al., 1992).

4. CONCLUSIONS

Water exchange due to filamentation for both upwelling regions along the coasts of northwest and southwest Africa was calculated on the base of methodology proposed by Zatsepin and Kostianoy (1992). The results obtained by Kostianoy and Zatsepin (1996) show that filamentation plays a significant role in upwelled water balance. Gabric et al. (1993) indicated that mean monthly offshore cross-shelf Ekman transport in the Mauritanian upwelling zone (21-24°N) equals to 1000-2000 kg/m•s. From the other side, our estimates of the mean cross-frontal water transport, produced by filaments in the NW African upwelling region gives 500-1000 kg/m•s. It means that approximately a half of water mass upwelled by Ekman pumping process in the coastal zone is transported by filaments to the open ocean. The water exchange due to filamentation may be an order higher than pointed above (averaged for the time and area of observation) for certain seasons and geographic places.



(a)

(b)

Figure 3. Upwelling filaments along the southwest coast of Africa (21-26°N) on 30 October 2004: (a) SST, (b) Chl a (MODIS-Aqua).

The obtained estimates mean very important paradoxical statement: coastal upwellings and related systems of filaments represent a single hydrodynamic feature because hypothetic absence of upwelling filaments inevitably could lead to two times wider upwelling zones than observed now or an increase of currents related to the upwelling fronts or to both effects simultaneously.

ACKNOWLEDGEMENTS

This study was supported by the Russian Academy of Sciences Project "Influence of hydrophysical and meteorological conditions on the bioproductivity of coastal upwellings". We would like to thank NOAA and NASA Goddard Space Flight Center for the production and distribution of MODIS (Terra and Aqua) data.

REFERENCES

Davis, R.E., 1985. Drifter observations of coastal surface currents during CODE: The method and descriptive view. *J. Geophys. Res.*, 90, pp. 4741-4755.

Fedorov, K.N. and Ginzburg, A.I., 1991. *The Near-surface Layer of the Ocean.* VSP, Utrecht.

Fiuza, A.F.G. and Sousa, F.M., 1992. Mesoscale variability in the Portuguese coastal ocean studied with satellite imagery. *Ann. Geophys.*, 10(suppl. 2), pp. 208.

Flament, P.J., Armi, L. and Washburn, L., 1985. The evolving structure of an upwelling filament. *J. Geophys. Res.*, 90, pp.11,765-11,778.

Gabric, A.J., Garcia, L., Van Camp, L., Nykjaer, L., Eifler, W. and Schrimpf, W., 1993. Offshore export of shelf production in the Cape Blanc (Mauritania) giant filament as derived from Coastal Zone Color Scanner imagery. *J. Geophys. Res.*, 98(C3), pp. 4697-4712.

Ginzburg, A.I. and Fedorov, K.N., 1985. Systems of transverse jets in coastal upwellings. *Sov. J. Remote Sens. (Issled. Zemli Kosmosa),* 5, pp. 3-10 (in Russian).

Hood, R.R., Abbot, M.R., Huyer, A. and Kosro, P.M., 1990. Surface patterns in temperature, flow, phytoplankton biomass and species composition in the coastal transition zone off Northern California. *J. Geophys. Res.*, 95(C10), pp. 18,081-18,094.

Huyer, A. and Kosro, P.M., 1987. Mesoscale surveys over the shelf and slope in the upwelling region near Point Arena, California. *J. Geophys. Res.*, 92, pp. 1655-1681.

Kosro, P.M., 1987. Structure of the coastal current field off Northern California during the Coastal Ocean Dynamics Experiment. *J. Geophys. Res.*, 92(C2), pp. 1637-1654.

Kostianoy, A.G., 1991. System of filaments in the Canary upwelling region. *Sov. J. Remote Sens. (Issled. Zemli Kosmosa),* 5, pp. 78-86 (in Russian).

Kostianoy, A.G. and Boubnov, G.G., 1995. Investigation of the Benguela upwelling filaments on the base of satellite data. *Sov. J. Remote Sens. (Issled. Zemli Kosmosa),* 4, pp. 67-75 (in Russian).

Kostianoy, A.G. and Zatsepin, A.G., 1996. The West African upwelling filaments and cross-frontal water exchange conditioned by them. *J. Mar. Syst.,* 7, pp.349-359.

Lutjeharms, J.R.E., Shillington, F.A. and Duncombe, Rae CM., 1991. Observations of extreme upwelling filaments in the Southeast Atlantic Ocean. *Science,* 253(5021), pp. 774-776.

Lutjeharms, J.R.E. and Stockton, P.L., 1987. Kinematics of the upwelling front off southern Africa. *S. Afr. J. Mar. Sci.,* 5, pp. 35-49.

Nykjaer, L., Van Camp, L. and Schlittenhardt, P., 1988. The structure and variability of a filament in the Northwest African upwelling area as observed from AVHRR and CZCS images. Proc. IGARSS'88 Symp., Edinburgh, pp. 1097-1100.

Paduan, J.D. and Niiler, P.P., 1990. A lagrangian description of motion in Northern California Coastal transition filaments. *J. Geophys. Res,* 95(C10), pp. 18,095-18,109.

Rienecker, M.M. and Mooers, N.K., 1989. Mesoscale eddies, jets and fronts off Point Arena, California, July 1986. *J. Geophys. Res.,* 94, pp. 12,555-12,569.

Shillington, F.A., Peterson, W.T., Hutchings, L., Probyn, T.A., Waldron, H.N. and Agenbag, J.J., 1990. A cool upwelling filament off Namibia, southwest Africa: preliminary meassurements of physical and biological features. *Deep-Sea Res.,* 37(11), pp. 1753-1772.

Shillington, F.A., Hutchings, L., Probyn, T.A., Waldron, H.N. and Peterson, W.T., 1992. Filaments and the Benguela frontal zone: offshore advection or recirculating loops? *S.Afr. J. Mar. Sci.,* 12, pp. 207-218.

Swenson, M.S., Niiler, P.P., Brink, K.H. and Abbott, M.R., 1992. Drifter observations of a cold filament off Point Arena, California, in July 1988. *J. Geophys. Res.,* 97(C3), pp. 3593-3610.

Van Camp, L., Nykjaer, L., Mittelstaedt, E. and Schlittenhardt, P., 1991. Upwelling and boundary circulation off Northwest Africa as depicted by infrared and visible satellite observations. *Prog. Oceanogr.,* 26, pp. 357-402.

Van Foreest, D., Shillington, F.A. and Legeckis, R., 1984. Large scale, stationary, frontal features in the Benguela Current system. *Cont. Shelf Res.,* 3, pp. 465-474.

Zatsepin, A.G. and Kostianoy, A.G., 1992. On the intensity of cross-frontal water exchange in the ocean. *Dokl. USSR Acad. Sci.,* 323(5), pp. 949-952 (in Russian).