Scales and properties of cold filaments in the southern Benguela upwelling system

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Introduction

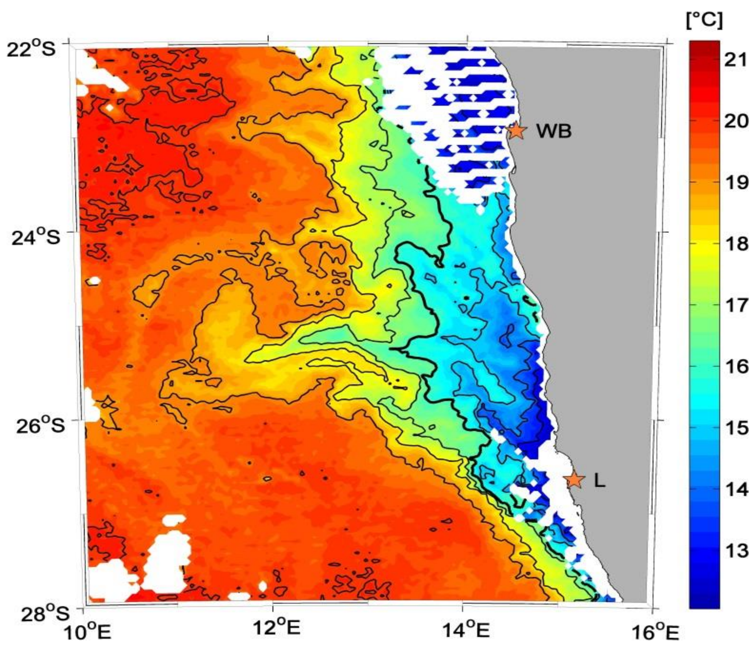


Fig.1: Sea surface temperature (SST) off Namibia from satellite data on 5th January 2012. The blue and green colours show clearly the cold upwelling area off Lüderitz as well as the in-homogeneous front at the western boundary of the upwelling system and a filament at approximately 25° S. White colour in this plot marks regions which are covered by clouds (no data).
WB: Walvis Bay; L: Lüderitz

Upwelling filaments as a feature of eastern boundary current systems are an important factor in the heat exchange between the coastal region and the open ocean. Figure 1 shows a typical filament arising at the front and propagating to the west at approximately 25° S. The combination of satellite and in-situ data allows a comprising analysis of the occurrence, scales and properties of cold upwelling filaments off Lüderitz.

We use satelltite data of sea surface temperature (SST) of MODIS[1]. The in-situ data sets were mainly collected during two cruises which were carried out on board of the research vessel METEOR in August 2013 and February 2014 in our study area. Measurements of the sea surface temperature and salinity as well as profiles of temperature, salinity and velocity were measured during these two cruises. Additionally SST measurements from three further cruises are available and contribute to this study. The different data sets are summerised in table 1.

Data and Methods

While the satellite data enables multiannual observations on regional scales, the in-situ data provides insight into the vertical structure of the filaments and allow to look at scales below the resolution of the satellite data.

The basic analysis is a frequency analysis (wavelet analysis) of the anomalies calculated from the temperature measurements.
For the satellite data we give a temperature anomaly regarding to a 3-year mean climatology, for the in-situ data regarding to the mean ambient temperature.

We define separate criteria regarding the minimal temperature anomaly and the meridional extent of a structure to distinguish between cold upwelling filaments and other cold structures.

Tab.1: Spatial and temporal distribution of the data sets used and the accuracy of the measurements. The given values for the in-situ instruments are mean values over the measuring periods.

Instrument	Spatial distribution	Temporal distribution	accuracy
AMSR-E/MODIS	9 km	24h for January 2006 – September 2011	0.25° C[2]
MODIS	4 km	24h for January 2011- July 2014	0.4° C[3]
Thermo-salinograph	50 m	10s for 23.9.2011 – 1.10.2011 31.7.2013 – 23.8.2013 19.9.2013 – 9.10.2013 18.12.2013 – 11.2.2014	Temperature: ± 0.04° C Salinity : ± 0.003psu
ADCP	1 km	3min for 31.7.2013 – 23.8.2013 23.2.2014 – 26.2.2014	2cm/s
UCTD	4 – 8km	1h 4.8.2013 – 7.8.2013 10.8.2013 – 17.8.2013 24.2.2014 – 26.2.2014	Temperature: ± 0.02° C Salinity: ±0.007psu Density: ± 0.009

Velocitiy distribution and typical properties

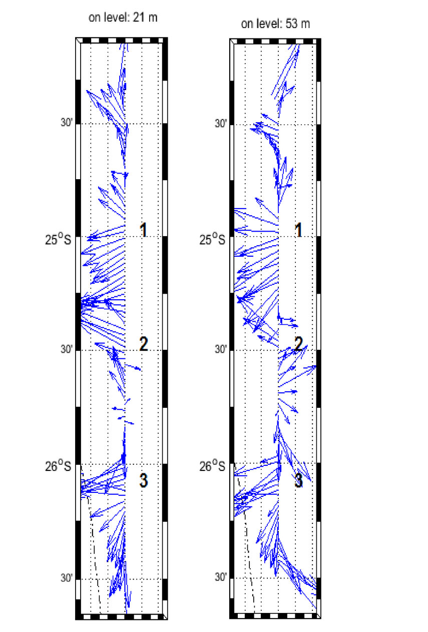


Fig. 7: Velocitiy vectors close to the surface (21m and 53m) from 75kHz ship ADCP

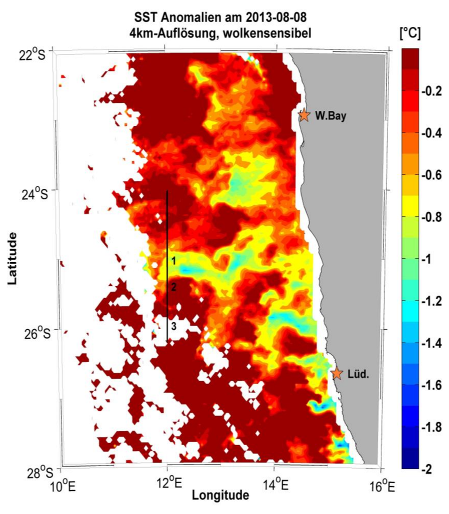


Fig. 8: SST anomaly from MODIS on the 8th August 2013

The region off Namibia is characterized by a northward surface current. Within filaments westward currents were observed and at the boundaries of the filaments eastward currents.
The maximal westward currents are established about 30m below surface.
The velocity gradient is stronger at the northern boundary of a filament than on the southern boundary.

Typical properties of filaments:
Temperature: 0.4° C – 1.6° C below ambient temperature
Velocity: 10cm/s – 30cm/s westward; at the boundaries 4cm/s eastward
Salinity: 0 – 0.103 below the ambient salinity

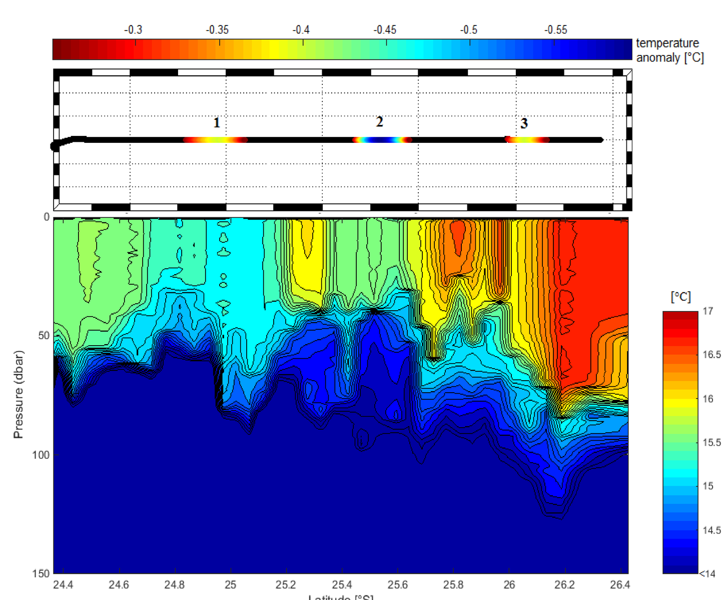


Fig. 9: Example for 3 cold anomalies observed at the 7th August 2013. The strucutres could be identified by a wavelet analysis both in SST and vertical temperature measurements.

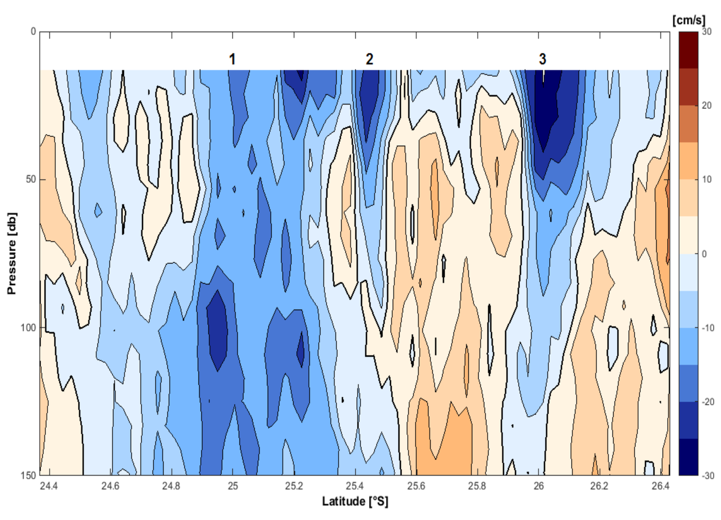


Fig. 10: Vertical distribution of the east-west component of the velocitiy along the track measured by a 75kHz ADCP.

Scales of cold upwelling filaments

53% of all filaments were observed between 25° S and 27° S. The distribution of the filament occurrence shows two maxima one at 27° S and one at 25.5° S. The maximum at 27° S (26° S in winter) corresponds to the Lüderitz upwelling cell, the most active cell in the Benguela upwelling system. The second maximum describes an other weaker upwelling cell further north.

- Meridional extent: 12km – 80km; whereby 45% of all filaments have meridional extent between 30km and 40km.The analysis of the in-situ SST shows that smaller filaments to scales of 5km exist.
- Longitudinal extent: 90km – 470km; whereby 58% of all filaments have a longitudinal extent larger than 300km.
- Vertical extent: 70m – 180m, whereby 72% of all filaments show a vertical extent between 80m and 140m.The vertical extent increases with increasing distance to the coast.

The observed scales are in good agreement to results of previous studies, which were mainly based on observations of single filaments.

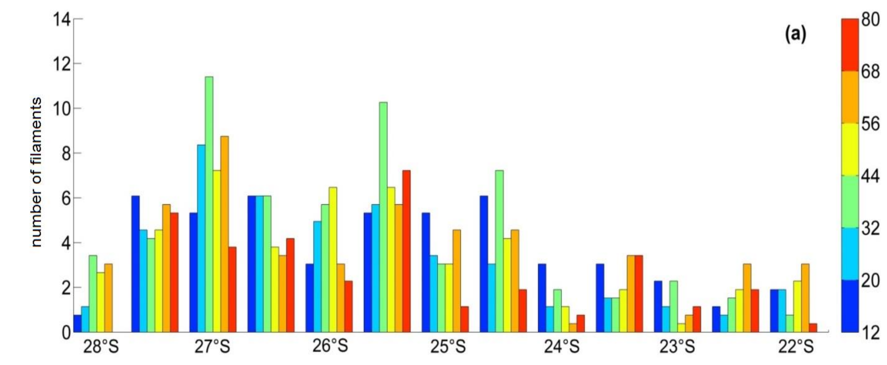


Fig4: Histogram of the meridional distribution of filaments at 13° E exemplary for January. The color gives the meridional extent of the filaments (km).

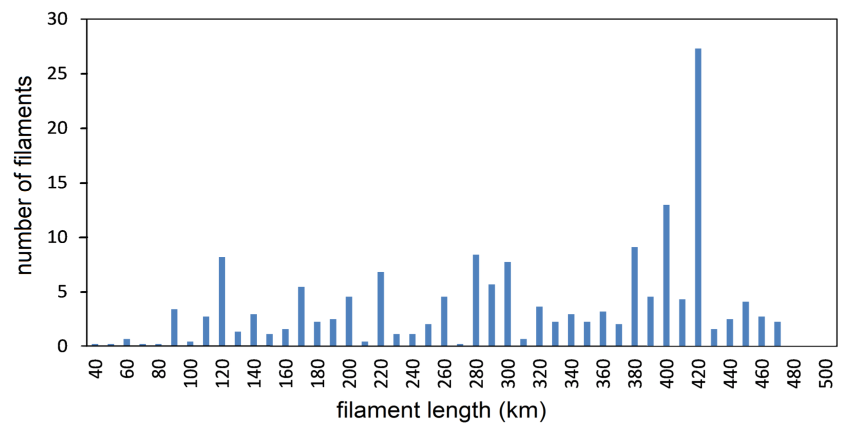


Fig. 5: Histogram of the longitudinal extent of the filaments.

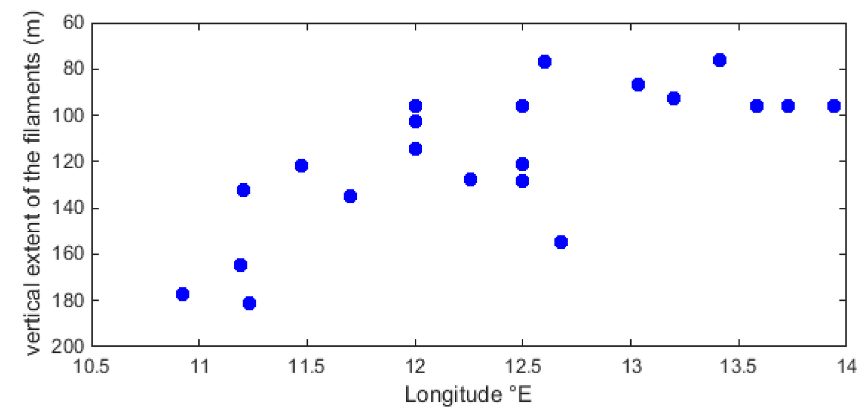


Fig.6: Vertical extent of 21 observed filaments at the longitudinal position of observation

Seasonality in the occurrence of cold filaments

52% of all filaments were found during the main upwelling season (October-February). The minimum in the filament occurrence is observed in September prior to the onset of the upwelling favourable winds.

The filaments persist between 2 and 28 days, whereby 83% of all filaments have a lifetime between 2 and 12 days.

The meridional extension of the filaments is between 30km and 40km during the upwelling season in summer. They have a larger extension (>50km) during winter as reduced upwelling enables possibly a stronger baroclinic stability at the upwelling front which possibly causes less but more extended filaments.

During summer most filaments were observed between 25.5° S and 27° S. This maximum in the filament occurrence is shifted northward during winter (25° S and 26° S).

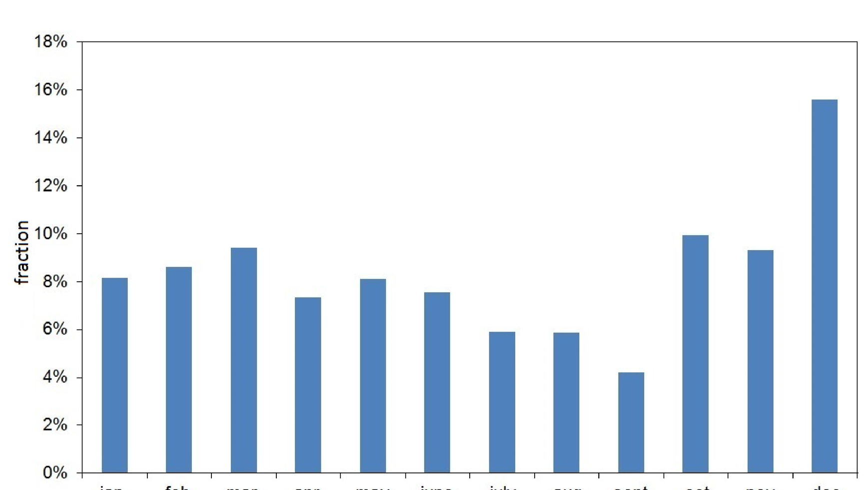
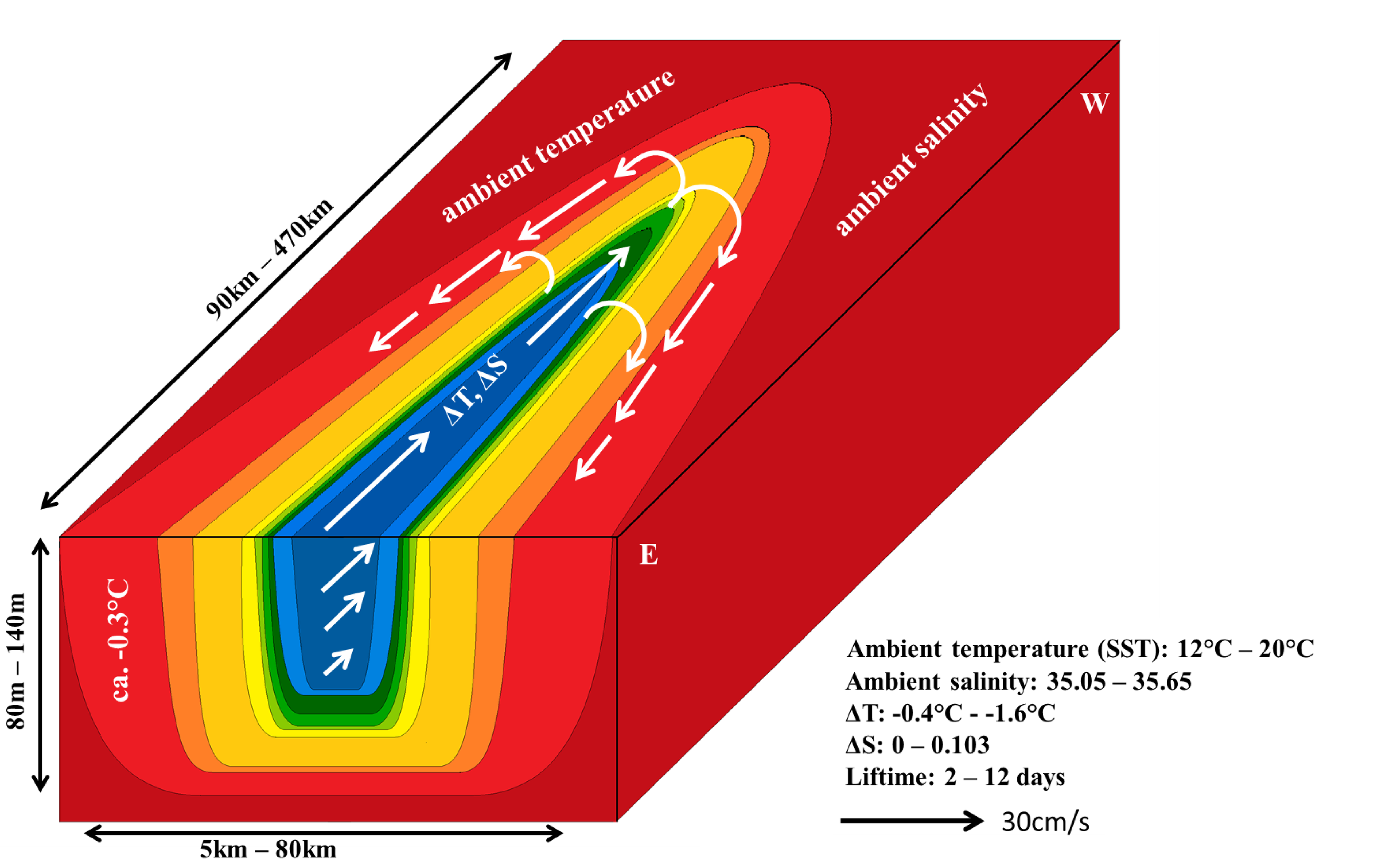


Fig.2: Mean monthly distribution of the filament occurrence between 22° S and 28° S.

Fig.3: Fraction of all filaments from MODIS SST as a function of the meridional exten of the filaments

Summary: Scheme of a filament and its typical properties



Scheme of filament with typical scales and properties. The direction of the current is given by the white arrows; the length of the arrows shows the velocity of the current. The colors represent the temperature distribution. The values ΔT and ΔS are the temperature anomaly resp. salinity anomaly to the mean ambient temperature resp. salinity.

References:
1 Satellite data obtained from http://podaac-ftp.jpl.nasa.gov/ , provided by the Integrated Climate Data Center (ICDC,http://icdc.zmaw.de) University of Hamburg, Hamburg, Germany for the period January 2006 to July 2014
2 Gentemann, C.L., T. Meissner and F.J. Wentz, 2010, Accuracy of Satellite Sea Surface Temperatures at 7 and 11 GHz, IEEE Transactions on Geoscience and Remote Sensing, Vol. 48, doi:0.1109/TGRS.2009.2030322
3 Walton, C.C., W.G. Pichel and J.F. Sapper, 1998, The development and operational application of non-linear algorithms for the measurement of sea surfaces temperatures with the NOAA polar-obiting environmental satellites, J. Geophys. Res., 103 C12, DOI: 10.1029/98JC02370

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