Cent. Eur. J. Geosci. • 1(3) • 2009 • 340-346
DOI: 10.2478/v10085-009-0020-9

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Central European Journal of **Geosciences**

Investigation of hydrogen sulphide eruptions along the Namibian coastline using different remote sensing systems

Research Article

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Received 18 March 2009; accepted 7 June 2009

Abstract: Hydrogen sulphide eruptions with their typical turquoise discolorations at the water surface are a unique phenomenon along the Namibian coastline. The remote sensing techniques of ocean colour sensors and microwave scatterometers were used for the investigation of such events.

The studies with ocean colour sensors showed that the turquoise discolorations near the Namibian coast were neither linked to dust deposition into the water column by desert storms nor to the reflection of bright material in shallow water areas. In addition, other coloured marine events like algae blooms and river outflows were differentiable from the hydrogen sulphide eruptions by their special optical properties. Quasi-true colour images and spectral identification methods were utilised to monitor and investigate the spatial and temporal distribution of sulphide events. In the past years, they were sometimes and locally limited discovered. Newest remote sensing observations including our own investigations have established that the occurrence of sulphide events is more frequent and longer lasting. The north-westerly direction of propagation and their velocity between 12 cm s^{-1} and 15 cm s^{-1} were derived from an event on 14 April 2004.

Lastly, the microwave scatterometer remote sensing was applied to investigate the relation of sulphide events to oceanographic conditions. The events from May 2004 were clearly related to strong coastal upwelling.

Keywords: remote sensing • hydrogen sulphide eruption • MODIS • MERIS • QuikSCAT

1. Introduction

From time to time milky to turquoise discolorations were observed in the nearshore and offshore coastal area off Namibia (Figure 1). Possible reasons for these discolorations in the surface water could be oxidised hydrogen sulphide, absorbing and scattering phytoplankton blooms, dust deposition by desert storms, reflection of bright bottom material as well as material from river outflows.

Observations of nearshore milky-turquoise discolorations made by the local inhabitants, coincident with a bad smell, corrosive effects and mortality of marine organisms indicate the existence of hydrogen sulphide in the water column and atmosphere [1, 2]. Measurements of uncommonly high concentrations of elemental sulphur in milky water bodies established the formation of colloidal sulphur by oxidation of hydrogen sulphide in the upper aerobic water body [1, 3]. The newest investigations have demonstrated that most of the nearshore discolorations are caused by

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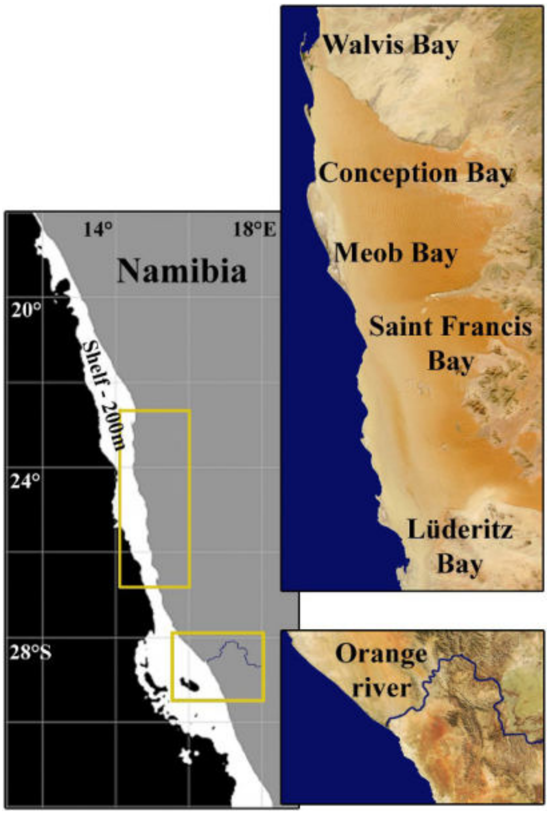

Figure 1. Map of studies area at the southwest African shelf off Namibia. The locations of some important bays and of the River Orange are given.

oxidised hydrogen sulphide which is produced in the shelf region in the sediment layer or in the water layer near the seafloor by sulphate reduction of anaerobic bacteria [2, 4].

Different absorbing and scattering phytoplankton blooms were often observed in the coastal area off Namibia due to the transport of nutrients by upwelling processes [5–7]. Sometimes these blooms discoloured the water surface bluish-green to turquoise depending on their optical properties. Some of the blooms were similarly turquoise like the hydrogen sulphide events. Newer studies have demonstrated that the offshore plumes outside the immediate upwelling area are generated by coccolithophores increasing the backscattering due to the calcite coccoliths [5].

The objective of this paper is the investigation and evaluation of different reasons for the turquoise discolorations in the coastal area of Namibia. This paper will specifically consider the possibility of discolorations from events like dust storms and river outflows as well as bottom material in shallow water areas. Another focus of the paper is the study of the extent and development of some hydrogen sulphide events in relation to upwelling processes.

2. Methods

The studied area, with a meridional extent from 12°W to 18°W and a zonal extent from 18°S to 32°S (Figure 1), was selected in order to investigate the different discolorations of the coastal area, offshore Namibia.

The remote sensing with ocean colour sensors in combination with microwave scatterometers is a useful technique for the investigation of discoloured surface water areas and their possible connections to upwelling processes.

Quasi-true colour (RGB-red-green-blue) MODIS (Moderate Resolution Imaging Spectroradiometer) images available at MODIS Rapid Response System (rapidfire.sci.gsfc.nasa.gov) were analysed and used for the comparison of different discoloured events. The RGB-images use MODIS Bands 1, 4, and 3 (670 nm, 565 nm, 479 nm) corresponding to the red, green, and blue range of the light spectrum. This combination of wavelengths is similar to what the human eye would see. In the RGB-images features like land surfaces, ocean waters and atmospheric properties are natural-looking.

An identification method based on the high spectral resolution of MERIS (Medium Resolution Imaging Spectrometer) sensor and on different optical properties of discoloured areas was applied to detect the hydrogen sulphide events [4]. This method uses a multispectral classification algorithm by selection of different threshold values. All details are given in [4], but for instance, the absence of chlorophyll-a reflectance minima in the sulphide spectra was used to eliminate MERIS - pixels of productive water bodies (Figure 2). The property of a smaller slope in the red wavelength range of river outflows was taken to eliminate the corresponding pixels in MERIS - scenes. The results of the classification algorithm are images showing the identified pixels of sulphur plumes by masks. The identification is difficult for areas with low concentrations of elemental sulphur in the upper water layer because of the seamless transition of optical properties to surrounded yet un-influenced water bodies. The error depends on the size of detected areas and was estimated in the order of 5% at 1000 km^2 and 20% at 100 km^2.

The wind speed and the wind direction of the microwave scatterometer SeaWinds (QuikSCAT) available from the Remote Sensing System, Santa Rosa (http://www.remss.com) in a resolution of 0.25 degrees were taken for the calculation of the pseudo-windstress. The root-mean-squared differences of the wind speed and direction between QuikSCAT dataset and in-situ data are 1.0-1.7 m s^{-1} and 14 - 23 degrees, respectively [8–10]. The

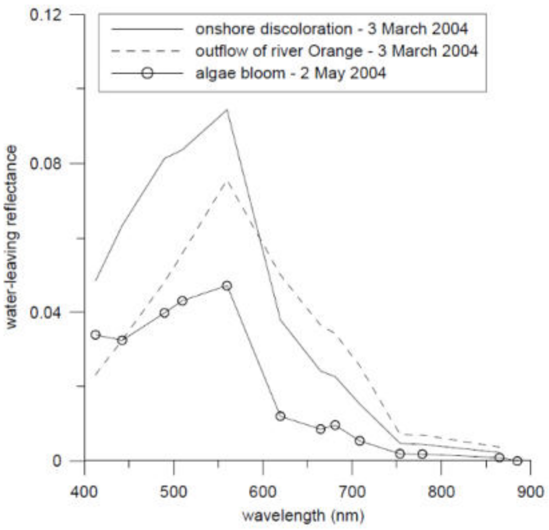

Figure 2. Examples of mean water-leaving reflectance of MERIS sensor for events like the nearshore turquoise discoloration of sulphur plumes, outflows of the River Orange and absorbing algae blooms.

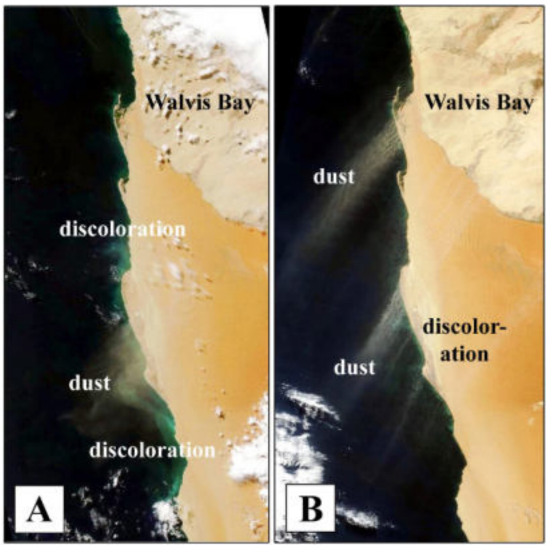

Figure 3. RGB-MODIS images of desert storms on 31 March and 5 May 2004.

mean vector pseudo-windstress (τ_{vp}) was calculated by an approximation to estimate the offshore Ekman transport and to identify upwelling events at the Namibian coastal area [11, 12]. The pseudo-windstress which depends on "w", the scalar QuikSCAT wind speed and "θ", the angular difference between the QuikSCAT wind direction and the orientation of the Namibian coast is given by

τ_{vp} = (w cos $\theta)^2$ if cos $\theta > 0$ (offshore Ekman transport, coastal upwelling)

and

τ_{vp} = - (w cos $\theta)^2$ if cos $\theta < 0$ (onshore Ekman transport, coastal downwelling).

The coastline angles were determined in intervals of 0.25 degrees latitude by fitting a line to the trend of the coast. Only the positive pseudo-windstress leading to offshore Ekman transport is used in the following investigations.

3. Results and discussion

In Figures 3A and 3B two examples of desert storms are given, on the basis of quasi-true colour RGB-images of the MODIS sensor. It is clearly seen that the nearshore discolorations were registered also in regions where no dust reached the ocean surface (see Figure 3A). The desert dust was blowing to the offshore area in Figure 3B but the discolorations were only observed in the nearshore regions.

The sea bottom can influence the water colour at the sea surface depending on the optical properties of the water, the bottom material and the water depth [13–16]. Satellite images of ocean colour sensors show definite structures and specific colours at the sea surface due to features in the sea bottom topography, if a water body of relatively high transparency covers a high reflective sea bottom. The independence of bottom topography and discolorations at the Namibian coast is demonstrated in Figures 4A and 4B. The bottom structures are different from the patterns of discolorations because only a low reflective diatomaceous mud belt is found at the Namibian shelf [2] and the transparency of the high biological productive water is low [5]. Furthermore, the discolorations developed in a completely different manner than the patterns of ocean-bottom topography. Their spatial and temporal changes were much faster in contrast to the potential weaker sea bottom changes.

The outflow of the River Orange transports a high amount of sediment along the south-west African coast. This suspended material could be responsible for a part of the observed discolorations in the area around this river. There are many algae blooms in the area of investigation because of the upwelling of nutrient-rich water masses [5–7]. The algae blooms (diatom, coccolithophorid, red tides and others) discolour the water depending on the algae species and could also generate the turquoise discolorations. The spectral characteristics of the River Orange and of absorbing algae blooms were studied on the basis of MERIS (Medium Resolution Imaging Spectrometer) Level-2 data to check these possibilities [4]. Examples of mean water-leaving reflectance of a sulphur

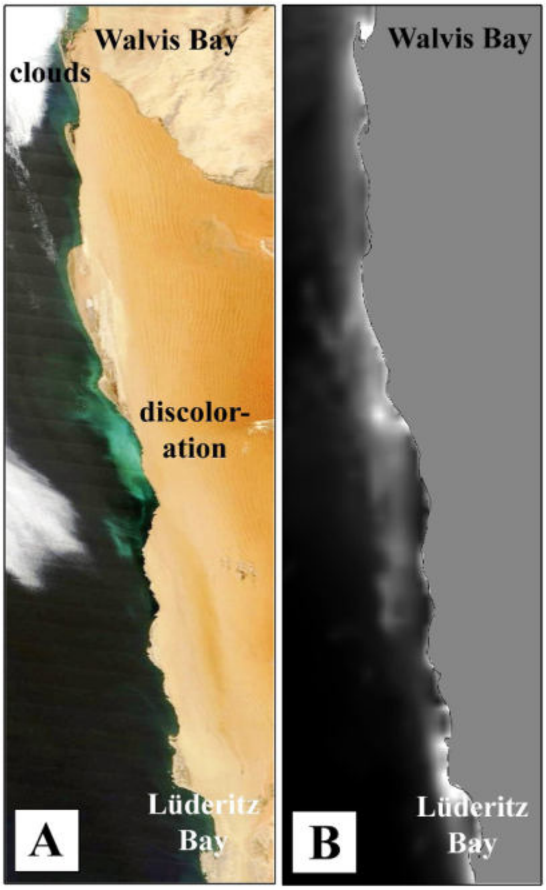

Figure 4. RGB-MODIS image of the sulphur plumes of 5 March 2004 and bottom topography are shown. The gray scaled pixels of Figure 4B are sea bottom structures up to 40 m.

plume, outflow of the River Orange and of an algal bloom are given in Figure 2. The comparison of the optical properties of the different events clearly shows the special optical behaviour of nearshore discolorations formed by sulphur plumes. Uncommonly high water-leaving reflectances were found for the corresponding curve in the blue to green wavelength range with maximum always at 559.6 nm.

There are similarities between the water-leaving reflectance curves of river outflows and sulphur plumes. Both types of curves have nearly no chlorophyll-a reflectance minima at 442.4 nm and 664.6 nm and the highest reflectance values at 559.6 nm. The reflectance slope of the Orange River in the red wavelength range is smaller due to the different kind of suspended matter in this river outflow.

Only the spectra of absorbing algae blooms have minima at 442.4 nm and 664.6 nm coming from chlorophyll-a absorption maxima (see Figure 2). The maxima of sulphur plumes are always at 559.6 nm and much higher in contrast to the algae blooms. Therefore, river outflows and absorbing algae blooms are not the reasons for the nearshore turquoise discolorations because of their different optical properties and their different geographical locations as well as their different patterns and spatial extents.

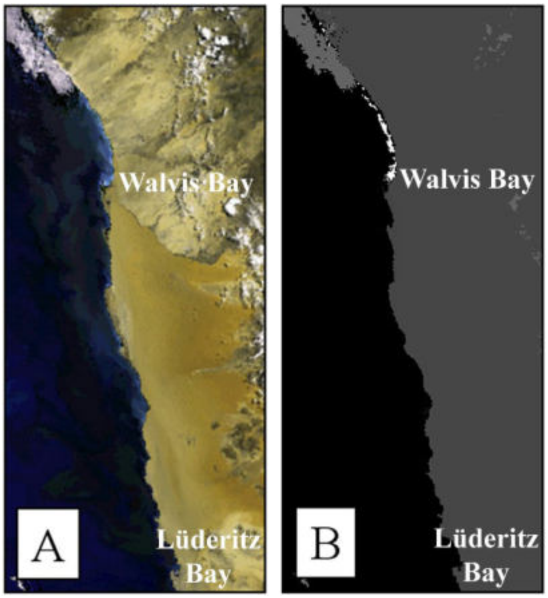

Figure 5. Result of classification algorithm of a MERIS scene from 19 March 2004. The white pixels of Figure 5B are the identified sulphide pixels. Dark-grey areas are land pixels, light-grey areas are cloud pixels and black areas are water pixels. The RGB-MODIS image in Figure 5A is given for comparison.

The identification method of [4] was used to monitor the sulphide events and to study their location and extent as well as the temporal and spatial development. One example of this classification method is given in Figures 5A and 5B for a MERIS scene from 19 March 2004. The turquoise discolorations caused by colloidal sulphur are clearly seen in Figure 5A in the near of the Walvis Bay (cf. Figure 1). The classification tool delivers the areas of sulphur discolorations which can be found as a white mask in Figure 5B.

The detected sulphide events of MERIS scenes from May 2004 are given in Table 1. The spatial and zonal extent of sulphur patches is shown. Unfortunately, there are data gaps in the table because the ocean colour sensors can not determine the water colour below clouds and sometimes the MERIS swaths do not match the studied area. Wide activities of sulphur plumes were observed in May 2004 (cf. Table 1). An area of 406 km^2 was affected in the middle of May and the zonal extent reached 10 km. The sulphide

Table 1. Table of identified sulphide events of May 2004.

date	day	area in km×km	zonal extension in km
02.05.2004	123	98	5
03.05.2004	124	227	7
05.05.2004	126	26	3
12.05.2004	133	406	10
16.05.2004	137	50	5
22.05.2004	143	57	7
28.05.2004	149	2	1
31.05.2004	152	25	4

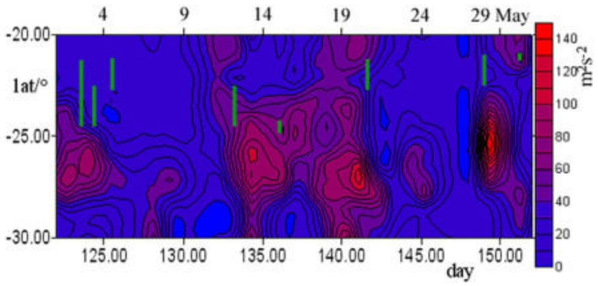

Figure 6. Positive pseudo-windstress at the Namibian coast in May 2004 derived from QuikSCAT data. The locations of the identified sulphur plumes are given by green bars.

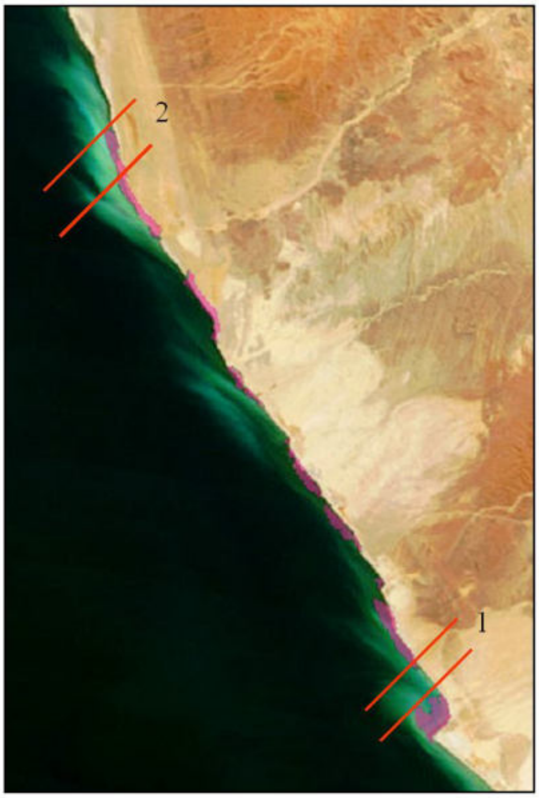

Figure 7. The pattern difference (red lines) of two MODIS scenes from 16 (features in magenta) and 17 April 2004 (features in turquoise) is given.

events show no uniform ongoing development from smaller to larger events or vice versa (Table 1). For instance, the sulphide area mainly decreased from 3 May to 5 May, and increased up to 12 May, and decreased after this again up to the 28 May. All registered sulphide events of the first half of year 2004 were observed nearshore in a very small band near the coast [4].

The strongest events occurred in the Meob- and Saint Francis Bay. Moderate and weak events were found along the majority of the Namibian coast but mainly in the biggest bays like Walvis-, Conception-, Meob- and Saint Francis Bay (see Figures 3-6).

The wind and upwelling situations were studied on the basis of data from the microwave sensor QuikSCAT to investigate their relation to oceanographic conditions. The positive pseudo-windstress leading to offshore Ekman transport is given in Figure 6 for May 2004. The highest windstress values were observed nearly between 23°S and 28°S on 3, 13, 21 and 28 May. The meridional locations of the windstress patterns fluctuated but were closedly related to the Lüderitz upwelling cell, e.g. [17]. The temporal comparison of the identified sulphide events of Table 1 with the observed patterns in Figure 6 shows that both kinds of events seem to be correlated. The development of sulphur plumes from the beginning to the end of May 2004 is connected to the offshore Ekman transport. The area of sulphide events is expanded if the upwelling of water masses is enhanced due to the stronger windstress. These upwelled water masses contain hydrogen sulphide and discolour the water surface if hydrogen sulphide is oxidised to colloidal sulphur in the upper oxygenated water layers [1–4, 18].

In Figure 7 the difference in patterns of two MODIS scenes from 16 (features in magenta) and 17 April 2004 (features in turquoise) is given. The distance of the discoloured areas of the two dates was measured at two positions (red lines in Figure 7). The velocity of expansion was derived with the obtained distance and the time difference of the two used MODIS scenes. The events propagate in north-westerly direction due to the wind driven Ekman transport. Velocities between 12 cm s^{-1} and 15 cm s^{-1} were found which corresponds to mean speeds of the Benguela current between 11 cm s^{-1} and 23 cm s^{-1} [17–19].

4. Conclusions

The discoloured areas due to oxidised hydrogen sulphide along the Namibian coast can be identified, monitored and studied by different remote sensing earth observation systems. It was possible to use ocean colour sensors for registration because the sulphide events showed special optical properties. They were optically differentiable from river outflows, algae blooms and typical optical water types along the Namibian coast. It was found that they are not related to the dust deposition by desert storms and not to bottom material in shallow water areas. The main results can be summarised as follows:

- Registration of hydrogen sulphide eruption in a narrow band at the Namibian coast
- Monitoring of an increased number of hydrogen sulphide events in May 2004
- Observation of a maximal spatial area of 406 km^2 and a maximal zonal extension of 10 km
- Nearshore sulphur plumes of May 2004 were related to strong upwelling events
- Propagation in north-westerly direction with velocities like Benguela current

The relation of hydrogen sulphide eruption to strong upwelling events is only a first rough result. Their dependence on special oceanographic and meteorological conditions has to be studied in the future in detail on the basis of different in-situ and remote sensing datasets as well as an extended database of hydrogen sulphide events.

Acknowledgements

The paper is embedded in the European Space Agency accepted Announcement of Opportunities 535 as well as 2362. This research was based on MERIS and MODIS data provided by ESA (European Space Agency) and NASA (National Aeronautics and Space Administration). MERIS data are available from MERCI system (merci-srv.eo.esa.int). MODIS images courtesy of MODIS Rapid Response Project (rapidfire.sci.gsfc.nasa.gov). The investigations were supported by the Leibniz Institute for Baltic Sea Research. The study was funded by the German Federal Ministry of Education and Research in the frame of the NAMIBGAS project. I also thank anonymous reviewers for helpful comments.

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