The Mariana dam's disaster: quantifying turbidity changes and behavior of the River Doce plume in Brazil.

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Abstract. On November 5th 2015, the Fundao's dam collapsed in Mariana, Minas Gerais state, releasing approximately 55 million/m³ of tailings to the coast and marine conservation units. The dam's sediment plume carried by the River Doce could alter local physical conditions and our study focuses on the changes in turbidity. We made use of a specific method, MODIS-Aqua images and meteorological data to assess and quantify turbidity before and after the disaster. Our results show that the plume dispersion and turbidity are very sensitive to precipitation rates and the predominating winds. Before the disaster, close to the river mouth, turbidity values can sometimes reach around 900 FNU, whereas after the disaster this variable reached values beyond the 1,000 FNU, suggesting the influence of the tailings' dam. We also generated a map that shows the percentage change in turbidity after the incident, based on maximum value of turbidity per pixel observed before. We observed an increase of more than 600% in turbidity during different periods. Our data suggest that turbidity was indeed altered at further regions, reaching both conservation units of Costa das Algas and Santa Cruz. The tailings' plume showed a strong influence on turbidity until late January of 2016, weakening from February on.

Keywords: remote sensing, image processing, river discharge, physical processes, environmental hazard, tailings transport.

1. Introduction

On November 5th 2015, the Fundao's dam collapsed in Mariana, Minas Gerais state, constituting the largest environmental disaster in Brazil (Minas Gerais, 2016). The dam was retaining approximately 55 million/m³ of tailings (Minas Gerais, 2016), and according to the Brazilian Institute of Environment (IBAMA) one month after the disaster nearly 34 million/m³ of tailings had been released into the environment, whereas the rest was still being conveyed towards the Atlantic Ocean (IBAMA, 2015).

The mudflow ran through 663.2 km of hydric bodies including the River Doce, one of the largest rivers in the country, until it finally achieved the Atlantic Ocean, on November 21st (IBAMA, 2015). Not only has it caused socioeconomic impacts and affected the fauna, ichthyofauna and compromised the water quality, but it has also impacted conservation units such as the Costa das Algas (CA) and Santa Cruz (SC) regions, contesting the Brazilian New Forestall Code (IBAMA, 2015).

The dam's sediment plume was able to alter the physical conditions at the coast as it brought a great volume of particles at once. Among all physical-chemical variables in the marine environment, turbidity is the most important when it comes to light attenuation through the water column. It is defined as an optical parameter of water transparence (Constantin et al., 2016) comprising in any particulate material that alters light absorption and dispersion in the water. Therefore, it is intimately related with plankton production and dispersion of suspended particulate matter (SPM) (Chen et al., 2007).

Turbidity show great spatial-temporal variability in coastal and estuarine waters, since it can be influenced by sediment resuspension processes, river discharges, meteorological conditions and human interventions (Chen et al., 2007; Constantin et al., 2016). The continental contribution is one of the main mechanisms on the transport of SPM predominantly inorganic that eventually achieves the coast. Generally, this process follows a seasonal pattern (Doxaran et al., 2009) and carries sediment to both estuarine and coastal areas, almost always forming a plume. When it finally reaches the platform, the plume conveys nutrients and SPM, which alters water transparency, stratification (Hickey et al., 2015) and consequently its turbidity. For this reason, river plumes are also responsible for fertilizing the platform, following a pattern of dispersion that depends entirely on the environment dynamics.

In that case, the use of remote sensing brings an advantage on the analysis of physical-chemical and biological parameters of the ocean. A good example is the MODIS sensor, which has been broadly used to map turbidity and SPM in coastal waters (Chen et al., 2007; Doxaran et al., 2009).

Hence, the aim of this study is to quantify and to compare the turbidity pattern of the River Doce plume before and after the Fundao dam's collapse. We assess satellite and meteorological data and then describe the plume dynamics over the last 4 years.

2. Metodology

2.1. Study Area

The area assessed is located on the River Doce's mouth, at the Espirito Santo state (19º39'31.83''S/39º48'50.05''W), adjacent to the city of Linhares, Espirito Santo state (Figure 1). The region presents a warm and humid weather, with the rainy season happening between late winter and summer - October to March - (Bruno, 2004) and the dry season between fall and winter – April to September (Felix, 2014).

The annual wind pattern is predominantly derived from the east-northeast (E/NE) quadrant and is associated with the trade winds, whereas southeastern winds (SE) prevail in association with eventual cold fronts, inverting the longitudinal current from south to north (Bruno, 2004). Therefore, the winds will influence wave movements, being the SE/E wave trains the most energetic ones (Felix, 2014), which will further affect the mixture process at the region.

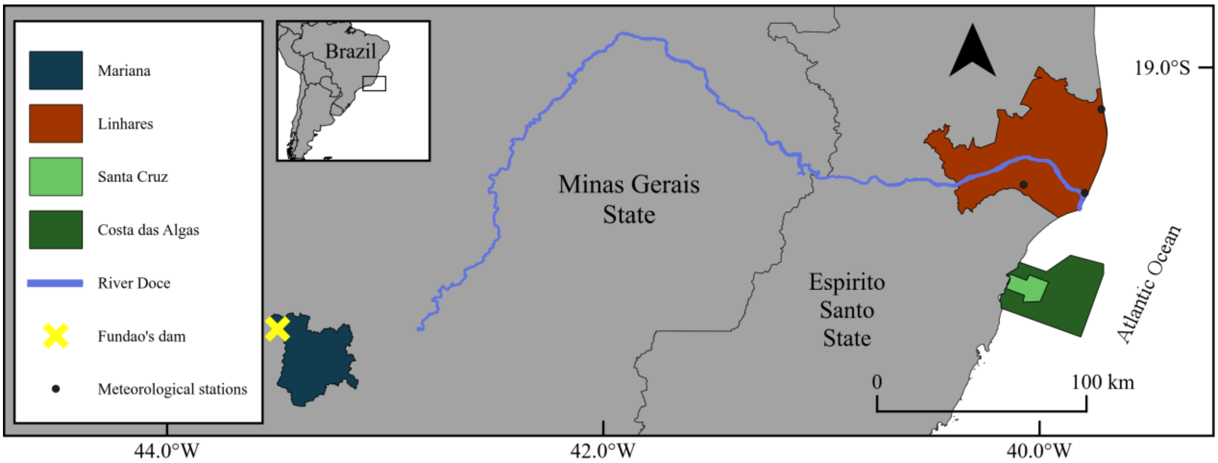

Figure 1. Study area with the Fundao's dam location adjacent to the city of Mariana, the conservation units of CA and SC, the River Doce's course and the meteorological stations.

2.2 Data Acquisition and Processing

We used MODIS-Aqua data from October 2012 to August 2016 to process images daily available of bands 1 (645 nm) and 2 (859 nm) with spatial resolution of 250 m. The data were obtained from the MYD09GQ V005 package, which provides remote sensing reflectance (Rrs) data as if they were taken at sea level, including atmospheric corrections. Moreover, the reflectance data corrupted or with cloud interference could be removed by using the layers *QC_250m_1* and *state_1km_1*, available in the packages MYD09GQ V005 and MYD09GA

V005, respectively. Both packages were acquired from the Level-1 and Atmosphere Archive & Distribution System (LAADS) Distributed Active Archive Center (DAAC), located in the Goddard Space Flight Center in Greenbelt, Maryland (https://ladsweb.nascom.nasa.gov/).

The turbidity (T) assessment was possible by using the generic algorithm described by Nechad et al. (2009) following the method proposed by Dogliotti et al. (2015), which obtains the parameter in FNU (formazin nephelometric unit). The method utilizes bands 1 and 2 of the MODIS sensor and is applied to highly turbid waters with a range of 1-1000 FNU, r = 0.97, and a mean relative error of 13.7%. However, we have to consider that for turbidity values obtained with band 1 (T < 15 FNU) the method shows uncertainties caused by particulate scattering phase function variations and bidirectional effects. Therefore, to avoid these effects we limited the region of trust with turbidity values higher than 15 FNU. All images were processed with the QGIS 2.12 Lyon software through the plugins GRASS and GDAL.

2.3 Meteorological Data

We acquired ocean surface winds direction from the NOAA's Center for Satellite Application and Research (STAR), available at their website (www.manati.star.nesdis.noaa.gov/datasets), using products from the ASCAT and WindSat sensor. The ASCAT sensor, onboard the EUMETSAT METOP satellite, utilizes the geophysical model CMOD5.5, which relates the ocean surface wind direction and speed to the normalized radar cross-section at a 10-meter height and 25 km of resolution. The WindSAT wind retrievals are at a 10 m height assuming neutral stability and are derived from WindSat microwave brightness temperatures measurements.

Ultimately, the cumulative precipitation data of the previous 7 days of each image was taken from the meteorological stations of Linhares, Povoação and Pontal do Ipiranga, in which we took the mean precipitation of the three of them. These data were provided by the National Institution of Meteorology (Inmet) and the Capixaba Institution of Research, Technical Service and Rural Extention (Incaper).

2.4 Assessment Method

We selected 71 images of the River Doce plume before the Fundao dam's collapse and 12 images after the disaster. The images contemplate the four years assessed and were chosen according to their availability and lack of cloud coverage. After the incident, we chose the first 4 images representing the plume with an interval of approximately a week from each other, and for the rest of the images we have a month of interval.

Before discussing how the plume behaved after the incident, we first identified how it responds to precipitation and wind pattern, and also how dispersion and turbidity are affected seasonally by analyzing the maximum pixel value (MPV) of all images for each season according to the standard deviation ($\alpha = 0.05$). Furthermore, to statistically quantify changes in turbidity after the collapse, we first generated an MPV image base utilizing all images from before the incident and compared with each image from after. As a result, we could elaborate a map for each day that shows the percentage increase in turbidity for each pixel after the incident by comparing it to the maximum turbidity registered before the event.

3. Results and Discussion

3.1 Plume dispersion before the disaster

After analyzing all images, 4 patterns regarding the plume behavior were identified (Figure 2). When northern winds are blowing, the plume tends to flow southward and off the coast. As this pattern predominates, both turbidity and plume area increase with the precipitation rate, showing maximum values of 926 FNU at the first 500 m adjacent to the

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river mouth. On the other hand, during cold front events, the wind pattern changes from south to north, driving the plume northwards. At cold fronts, the precipitation rate does not seem to change significantly the turbidity or the plume area. This is likely to occur for two reasons, (1) turbulence increases as the waves become more energetic (Felix, 2014), diluting the plume at the surface; or (2) the inversion of the longitudinal current lessening the plume towards north and closer to the coast.

We also observed an intense discharge in December 26th 2013 (Figure 2-e), forming a large plume different from the usual ones. It reached 19.7 km off the coast – considering the 15 FNU limit – and its turbidity showed values higher than the method could describe (T > 1,000 FNU), covering a 16.7 km² area. As documented, it happened to be the greatest precipitation event over the last 90 years, causing deaths and significantly increase of the River Doce discharge (Incaper, 2014). Hence, we did not consider this period when generating the image base and treated it separately.

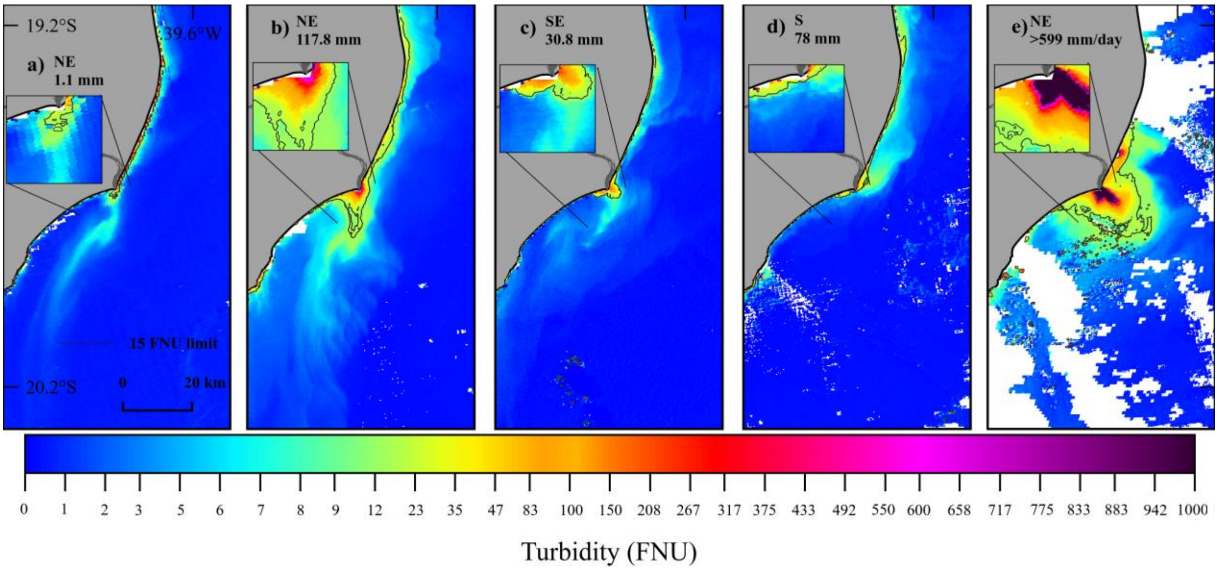

Figure 2. Example of the River Doce's plume behavior in response to winds and precipitation rates (indicated at the top). Northeastern winds with **(a)** low precipitation and **(b)** high precipitation rates. During cold fronts, southeastern winds with **(c)** low precipitation and **(d)** high precipitation. **(e)** Extreme flood event that happened in December 2013. Blank pixels correspond to cloud coverage or corrupted data.

Despite the climatic differences between rainy and dry seasons, the plume dispersion seems almost invariable, in terms of MPV (Figure 3). The results show that during rainy seasons, the plume usually reaches 9.4 km off coast, and 10.5 km during dry seasons. Therefore, a plausible explanation could be that winds are more efficient in driving dispersion in the area, whereas precipitation rates would affect more significantly the maximum turbidity values, inducing higher turbidity at rainy seasons. Considering the first 500 m off the coast turbidity reaches the same value for both seasons; however, if we consider the entire plume extension, it shows higher turbidity values during the rainy season.

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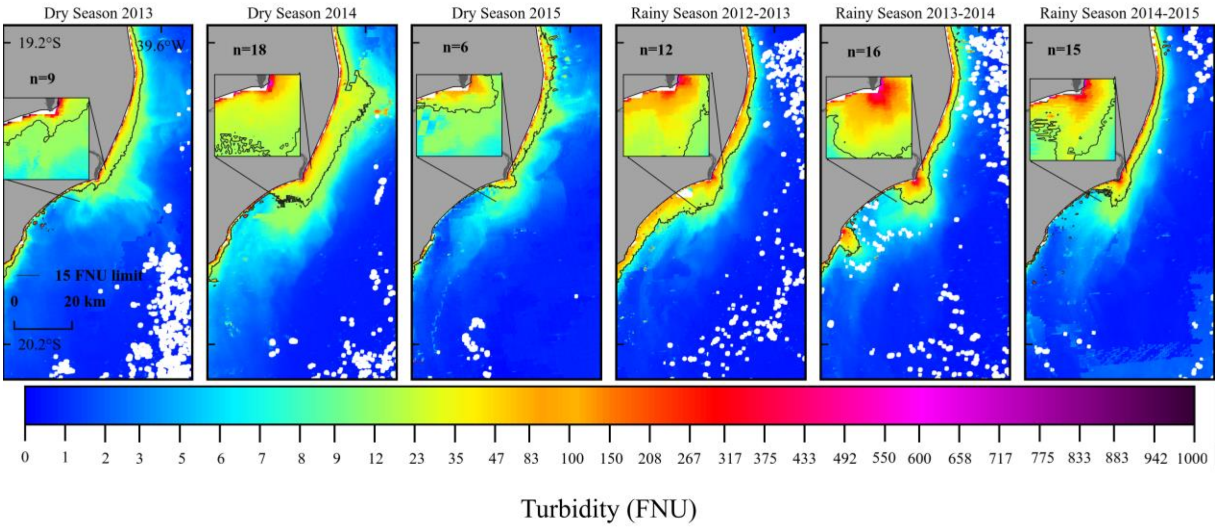

Figure 3. MPV turbidity values for dry and rainy seasons in 2013, 2014 and 2015, within the 15 FNU limit.

3.2 Plume dispersion after the disaster

The tailings' dam arrived at coast on November 21st 2015; however, the first image available is dated from December 14th (Figure 4). It flowed southward influenced mainly by the northern winds, reaching 15.6 km off the coast and covering an area of 4.7 km² with turbidity above the 1,000 FNU limit. The same pattern was observed on the 21 and 28 December, as it flowed 14.4 km and 12.3 km off the coast, respectively, though the plumes were less turbid. The precipitation rates for these three days were low (9.7 mm, 12 mm and 7 mm, respectively) and if we compare with the usual river plume, it shows similar turbidity values during high precipitation rates, as seen on December 4th 2014 (Figure 2-a). Therefore, we discarded the possibility that precipitation was the responsible for the high turbidity, and attributed this behavior to the tailings discharge.

On January 6th 2016, a cold front arrived and the plume area got reduced and reached 7.1 km from the coast, with most turbidity values lower than 30 FNU. As stated before on section 3.1, the high turbulence generated by wave trains associated with cold fronts is able to enhance vertical mixture and to dilute the plume at the surface. On January 31st, with northern winds taking place, the plume got enlarged again and reached 11.3 km off the coast. The area shows values above 1,000 FNU covering 4.3 km². Again, we did not consider turbidity being influenced by precipitation, since it rained about 18.8 mm, which is less than one-fifth observed in December 4th, 2014.

After February the plume reduced its dispersion and turbidity, even with northern winds predominating, suggesting lower influence of the tailings dam than before. All data from February to June show that turbidity values were mostly lower than 340 FNU, and did not surpass the 379 FNU. These changeable behaviors happened in response to precipitation, which is a similar pattern observed during regular dry seasons.

An exception happened in July and August, when the plume expanded again, reaching 10.1 km in both north and south direction with values between 40 and 150 FNU. Both days showed low precipitation values (3 mm and 10.9 mm, respectively) and winds predominated from northeast, characterizing an unusual dispersion behavior at the region. We could not find any evidence of physical processes that could explain this behavior, leaving us with the hypothesis that these variations are related to other processes, such as algae blooms or even upwelling, though we do not have data to confirm.

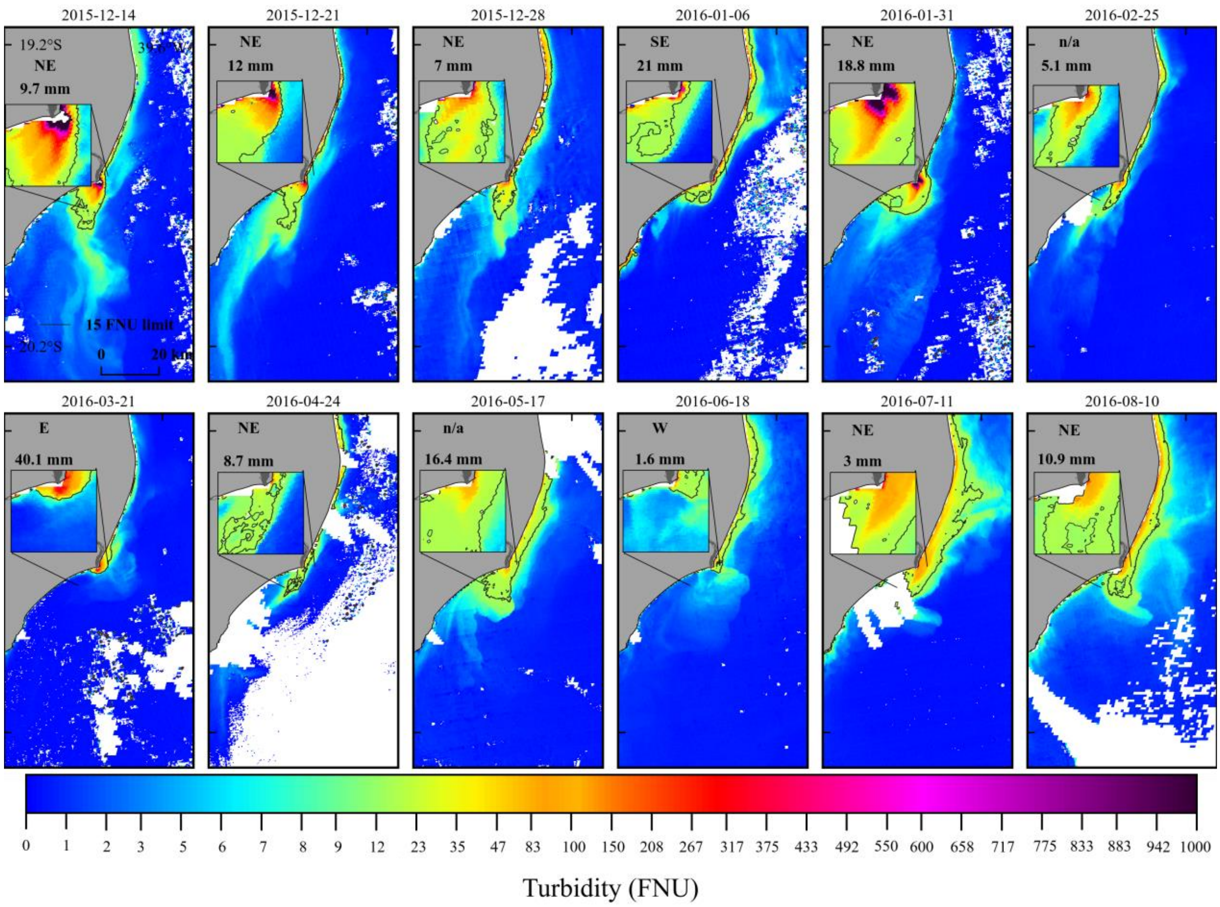

Figure 4. Dispersion and turbidity values after the tailings dam arrived in the Atlantic Ocean. Wind direction and precipitation rates for each day are also shown.

3.3 Percentage Changes in Turbidity

Finally, we generated maps to calculate the percentage change of turbidity after the disaster. As a result, 12 maps were made that show the percentage increase in turbidity after the collapse (Figure 5) by comparing it with MPV from the image base. The main results for turbidity changes are shown on Table 1. We defined the quantification of turbidity changes for within the 15 FNU limit, as we previously explained. For this reason, we could not quantify for sure turbidity changes for values below the 15 FNU. However, it is known that the relationship between reflectance (Rrs) and turbidity is always positive (Chen et al., 2007) what makes us affirm that turbidity indeed was affected, though we cannot tell by how much exactly. For this reason, we considered areas with turbidity values above the 15 FNU as affected zones (AZ), whereas those with values below the 15 FNU we considered as possibly affected zones (PAZ). In this section we also emphasize the effects at the conservation units of CA and SC.

On December 14th the AZ showed great changes in turbidity concentrated close to the river mouth (> 600%). As the plume got further from the coast, these changes reduced drastically to 100%, covering the major AZ. On the other hand, the PAZ reached 91.1 km south from the river mouth and showed the largest coverage area of all images (1,454 km^2), affecting CA. A week later, on December 21st, there was a considerable decrease in the AZ area; however, it still showed values around 600% close to the river mouth. The PAZ became thinner and longer, achieving 103 km southwards and covering both conservation units. In late December, the AZ did not show changes close to the river mouth, but only 5 km from it. The PAZ partially achieved CA (92.8 km southwards). In sum, the dispersion during December is in accordance to Marta-Almeida *et al.* (2016), who states the plume could reach until 100 km south of the river mouth. Consequently, the plume observed in December not only achieved this distance, but was also capable of altering the local turbidity.

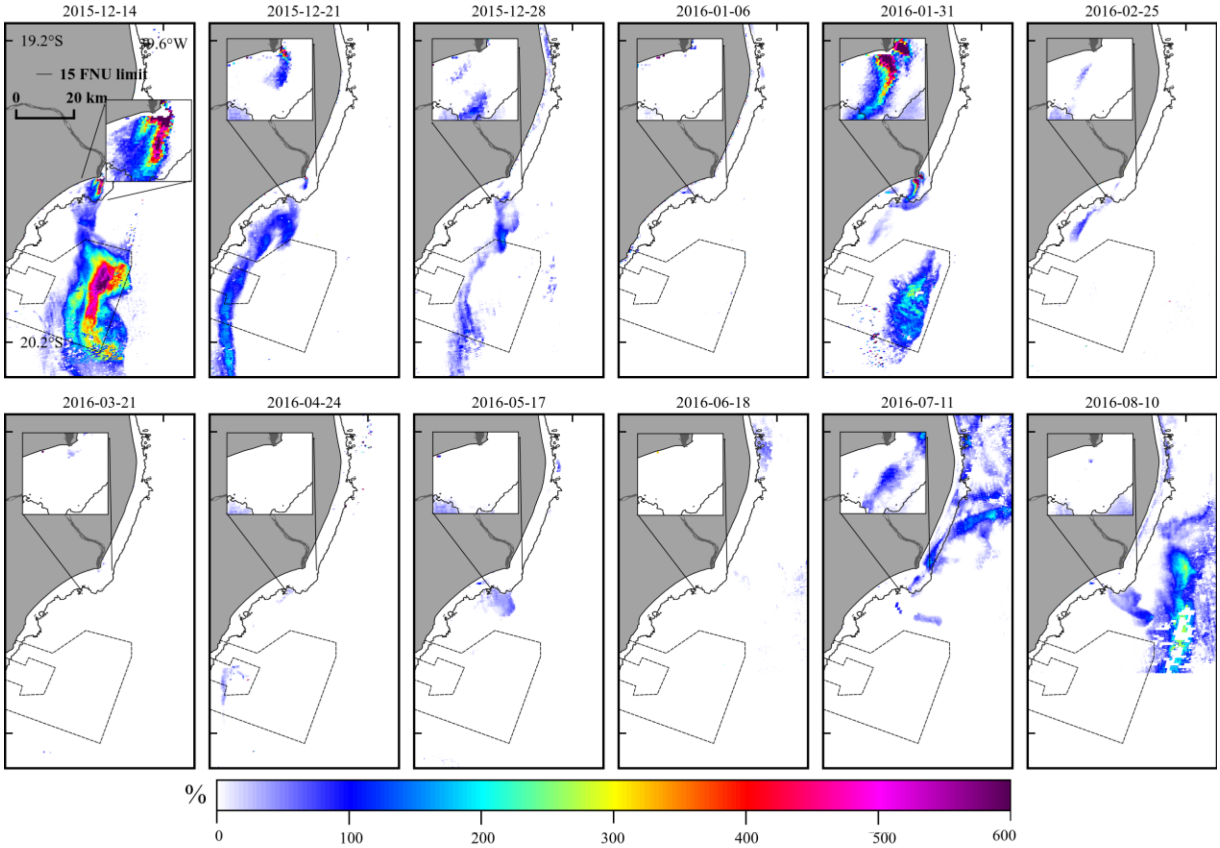

Figure 5. Percentage turbidity increase in respect to MPV of the image base.

On January 2016, the AZ barely appears close to the river mouth and at 9 km southwards, whereas we did not see any occurrence of a PAZ. However, on January 31st, the AZ area and values increased and followed the same pattern observed on December 14th, with the highest values close to the river mouth and changes until 100% for the predominating AZ. The PAZ in this day was the second largest (517.6 km²), concentrated within the CA limit.

From February on, there was a restraint for both AZ and PAZ. In fact, we could say that during these four months turbidity was already close to its normal behavior. Nevertheless, in July and August, the AZ and PAZ reached again a vast area. Thus, we suggest that this pattern is not necessarily related to the tailings' dam, as shown on section 3.2.

Table 1. Turbidity changes (%) and AZ/PAZ coverage for all 12 images after the disaster.

Date	AZ (km²)	PAZ (km²)	Maximum range (km)	Maximum change (%)	Costa das Algas coverage (km²)	Santa Cruz coverage (km²)
2015-12-14	47.6	1,454	91.1	> 600	730	-
2015-12-21	9.9	665	103	654	77.2	71.1
2015-12-28	10.5	352	92.8	145	136	-
2016-01-06	6	-	9	135	-	-
2016-01-31	46.5	517.6	68	> 600	407.6	-
2016-02-25	1.4	28.6	29.3	84.9	-	-
2016-03-21	2.4	-	2.8	61	-	-
2016-04-24	-	60.9	56.7	-	12.2	30.9
2016-05-17	4.5	71.4	17	128	-	-
2016-06-18	-	64.5	52.2	-	-	-

2016-07-11	78.5	1,213	93.8	170	-	-
2016-08-10	5	1076	38.9	145	-	-

4. Conclusion

The River Doce's plume has its turbidity and dispersion strongly influenced by precipitation rate and wind pattern, which makes the water more turbid during rainy seasons. When the mudflow arrived at the river mouth, turbidity showed an excessive increase in its values, compared to what we would expect with the regular wind pattern and precipitation rates.

The highest changes in turbidity occurred close to the river mouth, showing values over 1,000 FNU, a percentual increase of at least 600% compared to the maximum turbidity registered before the disaster. Values with this magnitude are most likely to happen in response to extreme events, such as the River Doce's flood in December of 2013.

Our data suggest that turbidity was indeed altered at further regions (approximately 103 km south), reaching both conservation units of CA and SC. The bulk of particles show an influence on turbidity until late January of 2016, weakening from February on. Therefore, since it is a very dynamic region, it is indispensable the further assessment of these particles in order to confirm their origin and associate them with either the disaster or with usual processes happening in the area.

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