A study of sediment transport in the Madeira River, Brazil, using MODIS remote-sensing images

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ABSTRACT

The Madeira River may contribute nearly half of the Amazon River sediment discharge to the Atlantic Ocean, showing the highest erosion rates in the Amazon Basin. However, few studies have assessed the Madeira River sediment budget and the transport processes occurring in the main stem of the river. In this study, MODIS space-borne sensors were used to analyze the suspended sediment transport processes along the main stem of the Madeira River. Field measurements of suspended sediment concentration, spectral radiometry and granulometry were performed during 10 cruises from 2007 to 2011. The relationship between the spectral reflectance and the surface suspended sediment concentration (SSSC) was analyzed using both field radiometric measurements and satellite data. Ten-day SSSC samples acquired by the HYBAM monitoring network were used to match satellite observations with field measurements performed from 2000 to 2011. Over 900 MODIS images of 6 different locations were processed to monitor the SSSC dynamics in space and time. Satellite reflectance was found to be significantly correlated with the SSSC. However, a seasonal dependency was demonstrated, most likely caused by a variable granulometric distribution along the annual cycle. The ratio between the red and near-infrared bands was found to be free of the seasonal dependency ($r = 0.79$, $N = 282$), and a SSSC retrieval model was built from the satellite data using a bootstrap resampling technique. The satellite-retrieved SSSC time series showed excellent accuracy over the 11-year period and at two different stations located 800 km from each other. The satellite data were averaged to analyze the SSSC pattern temporally and spatially along the entire Madeira River, which provided evidence of significant sedimentation and resuspension. The backwater effect caused by the two-to-three-month lag between peak water in the Madeira and Amazon Rivers was used to predict local sedimentation near the Madeira River mouth. Our results facilitated a precise assessment of such sedimentation, which demonstrated an SSSC decrease 400 km upstream from the Madeira–Amazon confluence.

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1. Introduction

Sediment transport is of special significance in large tropical basins, which are known to concentrate approximately 50% of the world’s solid fluxes from continental lands to the oceans (Latrubesse et al., 2005). Among these basins, the Amazon Basin exhibits high erosion rates in which most of the sediment is derived from the Andes and from large floodplains that can store and release sediment on different time scales (Meade, 1994). The size of the basin and the fact that the basin is moderately affected by anthropogenic activities make it a valuable case study for understanding erosion and sediment transport and their relation with past and present geomorphology (Baby et al., 2009) and climate (Martinez et al., 2009).

Most studies on the sediment budget of the Amazon Basin have focused on the Amazon River main stem, where the availability of hydrological data is better than in other areas of the catchment (Filizola and Guyot, 2004; Gibbs, 1967; Martinez et al., 2009; Meade et al., 1979). The Madeira River Basin drains approximately 25% of the Amazon Basin but may account for nearly half of the sediment fluxes released to the ocean (Guyot et al., 1996). The Madeira
drainage basin forms the southwestern boundary of the Amazon Basin. It is limited to the southwest by the Cordillera Oriental, which supplies a large quantity of sediment to the rest of the basin and to the northeast by the Brazilian craton (Baby et al., 2009). Sediment yield data show that the upper basin hosts the most elevated erosion rates in the Amazon Basin, which are approximately 3200 t × km⁻² × year⁻¹ on average, with large variations ranging from 50 to 50 000 t × km⁻² × year⁻¹ (Guyot et al., 1996). The total mass of suspended sediment exported from the eastern Andes and sub-Andean drainage basins in Bolivia, excluding the Peruvian Madre de Dios subcatchment, has been estimated to be approximately 500–600 million t × year⁻¹ (Guyot et al., 1996).

Using a network of sampling stations for river sediment discharge assessment in Bolivia, GUYOT et al. (1996) estimated that the current sedimentation in the Madeira foreland basin may be approximately 270 million t × year⁻¹.

Sediment transport monitoring is critical in the Madeira River Basin because the monitoring provides valuable information for economic activity that is dependent on river flows and sediment discharge, such as ship transport. Interestingly, the construction of two large hydroelectric power-generation dams in the upper reach of the Madeira River, upstream of Porto Velho, may affect the natural sediment transport. Concerns about the impact of these dams and the future behavior of sediment discharge as a function of regional climate change (Espinoza Villar et al., 2009) require the development of robust and cost-efficient monitoring methods adapted to large rivers. It has been shown that the optical qualities of water are closely linked to certain quality parameters, such as turbidity (Dekker et al., 2002; Mertes et al., 1993), algal pigment (Gohin et al., 2002; Schalles et al., 1998) and organic matter (Vodacek et al., 1995). Recent studies on the Amazon Basin have shown that space-borne global monitoring sensors can be used to efficiently monitor river sediment discharge along the Amazon River (Martinez et al., 2009) (Espinoza et al., 2012). In this study, we analyzed the optical properties of the Madeira River waters to develop a surface suspended sediment concentration (SSSC) retrieval algorithm based on MODIS satellite data. The SSSC estimates acquired over an 11-year period were analyzed to assess the sediment transport processes along the main stream of the Madeira River. Special attention was paid to the Madeira River mouth, where backwater effects originating from the confluence with the Amazon River cause sedimentation.

2. The study area

With an area of 6.2 × 10⁶ km², the Amazon Basin is the world’s largest catchment, delivering a water discharge of 6600 km³ × year⁻¹ (Molinier et al., 1996) and a sediment discharge of 800 million t × year⁻¹ based on measurements at the last gauged station along the Amazon River that is not disturbed by sea tides (Martinez et al., 2009). Sediments are transported principally from the Andes, which surround 12% of the Amazon Basin. One of the most important tributaries is the Madeira River, which contributes 16% of the Amazon River water budget and approximately 50% of the sediment discharge (Filizola, 1999). According to the Sioli classification system (1957), the Madeira River is a white-water river that is rich in dissolved material and suspension solids.

The Madeira River drains an area of approximately 1.4 × 10⁶ km² and has a mean annual discharge of 32 000 m³ × s⁻¹ (Molinier et al., 1993). This river is among the ten largest rivers in the world and was classified as a mega river (Latrubesse, 2008). The Madeira River is formed at the confluence of the Beni and Mamore Rivers near the border between Brazil and Bolivia. These rivers are of Andean origin and present high sediment loads of approximately 690 and 280 mg × l⁻¹ at the river surface, respectively (Guyot et al., 1996). The lower load of the Mamore River results from low sediment load tributaries that drain the lowlands (e.g., the Guapore River) and strong sedimentation processes in the Andean Piedmont (Guyot et al., 1996). Downstream from the Beni-Mamore confluence, all of the tributaries are characterized by low sediment concentrations because they drain the Amazonian lowlands on the Brazilian Shield (Fig. 1). In Brazil, most of the tributaries from the Abunã River down to the Aripuanã River confluence flow into the Madeira River from its right bank as the Madeira River nears the Purus River catchment.

Fig. 1. A map of the Madeira River and the major tributaries showing the water-gauge stations along the river main stem maintained by the Brazilian Water Agency. The relief data were extracted from the SRTM digital elevation model.

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The Madeira River sediment budget estimates show significant variations from one study to another because some studies use sediment discharge-water discharge relationships, whereas others are based on a network of stations at which the river water was sampled for particle concentration assessment but with different sampling frequencies or sampling methods (i.e., integrated vs. surface sampling). Based on a limited set of sampling field campaigns, Gibbs (1967) reported suspended sediment yields of approximately $217 \times 10^6 \text{ t} \times \text{ year}^{-1}$ at the mouth of the Madeira River in the Amazon. Subsequent studies reevaluated the previous estimates and calculated a yield of 550 million $\text{ t} \times \text{ year}^{-1}$ (Ferreira et al., 1988; Martellini et al., 1993). In Bolivia, the results obtained by the Climatological and Hydrological Program of the Bolivian Amazon basin (PHICAB) for the Upper Madeira Basin from 1983 to 1990 showed that the Beni and Mamore Rivers contribute a suspended sediment yield of 223 million $\text{ t} \times \text{ year}^{-1}$ to the Madeira River (Guyot et al., 1993; Roche and Fernandez Jauregui, 1988). Using the quarterly integrated suspended sediment concentration data from the Brazilian Water Agency, Guyot et al. (1996) calculated the sediment discharge at the Porto Velho station to be 320 million $\text{ t} \times \text{ year}^{-1}$, which is significantly higher than the value directly assessed upstream. Finally, using 10 years of sampling records from the HYBAM network, Guyot et al. (2010) determined a sediment discharge of 411 million $\text{ t} \times \text{ year}^{-1}$. However, the authors suggest that the sediment discharge-water discharge relationships they used for the Brazilian data should be disregarded for the Madeira Basin because the relationships show strong dispersion.

3. Data acquisition and method

3.1. General Hydrology

Five water-gauge stations providing river-flow estimates are currently maintained by the National Water Agency (ANA) along the Madeira River in Brazil. Starting from the Bolivia-Brazil border, the stations are Abunã (ABU; upstream of the Abunã River confluence), Porto Velho (PV), Humaita (HUM), Manicore (MAN), and Fazenda Vista Alegre (FVA) (see www.ana.gov.br/hydroweb). Near-real-time data are available at the PV and FVA stations, whereas at the other stations, the river water level is measured twice a day. The water level was calibrated to the water discharge using the mechanical current-meter method at all of the stations except for the PV and FVA stations, where acoustic doppler current profiler (ADCP) measurements were also used (Filizola and Guyot, 2004). Fig. 2 shows the Madeira River water discharge time series at the ABU, PV, HUM, MAN and FVA stations for the studied period. We note well-defined monomodal hydrographs with peaks in March–April and low water between August and September. At the FVA station, the maximum water discharge recorded over the period is $60 000 \text{ m}^3 \times \text{ s}^{-1}$, the minimum is $3500 \text{ m}^3 \times \text{ s}^{-1}$, and the average discharge is approximately $27 000 \text{ m}^3 \times \text{ s}^{-1}$.

The water discharge increase between the ABU and FVA stations is 62% on average with the inputs of the tributaries. The increase is relatively larger in May, up to 100%, and smaller between October and December, down to 20%. For the main tributary of the Madeira River, the ANA data show that the mean annual water discharge is 700, 1400, 1000 and 3300 $\text{ m}^3 \times \text{ s}^{-1}$ for the Abunã, Jí-Parana, Marbelos and Aripuana Rivers, respectively. These rivers have similar hydrological cycles with a high water level between February and April and a low water level in September, similar to the behavior of the main stem of the Madeira River.

Comparisons of water discharge data from the tributaries and the river main stem show inconsistencies that may result from insufficiently accurate water level-river discharge relationships. The main problem occurs at the MAN station, where the flow is much higher (i.e., 25% from June to December) than measured at the next downstream station on the Madeira River, FVA.

The large volume of the Amazon River affects the Madeira River water level in the lower courses of the tributary, producing what is known as the backwater effect. This effect is amplified by the two-to-three-month lag between peak water in the Madeira and Amazon Rivers, resulting in a hysteresis effect in the stage-discharge relationship, as shown in Fig. 3 for the FVA station. While the backwater effect in the HUM station records is not measurable, it can be detected downstream at the MAN station (Meade et al., 1991) and becomes significant at the FVA station, where the water level varies between 2 and 3 m for the same discharge amount, depending on the hydrological period.

3.2. The suspended sediment from the monitoring networks

The ANA protocol requires quarterly measurements of the suspended sediment concentration at five stations in its network using the depth integration method (using integrating USD-49 samplers). However, the data are scarce for the 2000–2010 period. The HYBAM network maintained by the ANA and the Institut de Recherche pour le Développement (IRD) at the PV and FVA stations has been providing 10-day samples from the river surface since 1995. To obtain the HYBAM data (see www.ore-network.org), a local operator samples the SSSC every 10 days at a fixed point. The

Fig. 2. The monthly water discharges for the ABU, PV, HUM, MAN, and FVA stations along the main stem of the Madeira River recorded during 2000–2009, which were provided by the Brazilian water agency.
The suspended sediment samples were processed using the same protocol as that used for the 10-day HYBAM measurement network. The measurements were performed with three TriOS-RAMSES hyperspectral spectroradiometers, two measuring radiance and one measuring downwelling irradiance. The instruments were mounted on a steel frame that was fixed to the prow of the ship, facing forward to minimize ship shadow and reflection. A cosine irradiance sensor detected the incident daylight. One radiance sensor detected the reflected light from the upper water column at a nadir angle of 30°, and another measured the diffuse radiance originating from the region of the sky that reflects into the water-viewing radiance sensor. The acquisition geometry recommended by Mobley (1999) from numerical modeling was followed. The results are provided as the remote-sensing reflectance, which is the ratio of reflected light from the upper water column (upwelling radiance) to incident light from the sky (downwelling solar irradiance). Field reflectance data were used to simulate the MODIS surface reflectance in the red and near-infrared (NIR) channels.

3.4. Satellite images

The Collection 5 atmospherically corrected surface reflectance products from the Terra and Aqua MODIS space-borne sensors were used in this study. The MODIS data products MOD09Q1 (Terra on-board sensor) and MYD09Q1 (Aqua on-board sensor) provide calibrated reflectance for two radiometric bands measured at a 250-m pixel resolution while offering near-daily time coverage over tropical areas (http://modis.gsfc.nasa.gov). Bands 1 and 2 are centered at 645 and 858.5 nm, respectively (Fig. 5). The MODIS surface reflectance 8-day composite data were acquired for March 2000 to July 2011 from the NASA Warehouse Inventory Search Tool (WIST) data gateway. We chose composite images for three reasons: i) the 8-day composite images are compatible with the 10-day field measurement sampling frequency; ii) the 8-day composite images reduce the quantity of data to be analyzed because persistent cloud cover renders a large number of daily images unusable; and iii) the 8-day composite images significantly reduce the directional reflectance effects and atmospheric artifacts. For each date, the composites from Terra and Aqua are automatically scanned, and the image with the lowest cloud cover is selected. When both composites exhibit low cloud cover, the composite acquired with the lowest satellite viewing angle is preferred.

The retrieval of river stream reflectance using the MODIS data is hampered by the low spatial resolution that may result in few pure (non-mixed) water pixels, depending on the river width and image acquisition geometry. Spectral mixing has been described...
extensively in the literature and occurs when different materials are present in the same pixel. In the context of this study, spectral mixing may occur between water, riverine vegetation or sand banks. Accordingly, specific algorithms have been developed that enable the derivation of the water endmember reflectance in each image. First, river pixels are partitioned into homogeneous clusters using the K-means algorithm (Martinez et al., submitted, 2009). Next, the fraction of each endmember in each cluster is obtained by applying a least squares technique to minimize the un-modeled residual. The testing of every cluster as a possible pure water endmember is performed to solve the set of linear equations. The cluster leading to the lowest residual is retained as the water endmember (Martinez et al., submitted).

The MODIS surface reflectance was retrieved for six different locations along the main stem of the river (Fig. 1) to create 11-year time series. For each station, 936 8-day composites were processed from the MODIS Terra and Aqua sensors. The locations match the five ANA water-gauge stations. An additional virtual station (i.e., the FOZ station) was added to analyze the SSSC near the Madeira River mouth at the confluence with the Amazon River. Data from the PV and FVA stations were used to analyze reflectance-SSSC matchups with the HYBAM network data, whereas the other stations enabled the study of the SSSC behavior in space and time.

4. Results

4.1. The SSSC and granulometry

Table 1 summarizes the measurements acquired during the 10 field-sampling campaigns at each station along the Madeira River.

<table>
<thead>
<tr>
<th>Stations</th>
<th>Sample number</th>
<th>SSSC range (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low water</td>
<td>Peak water</td>
</tr>
<tr>
<td>ABU</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>PV</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>HUM</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>MAN</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>FVA</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>FOZ</td>
<td>4</td>
<td>2</td>
</tr>
</tbody>
</table>

The measurements consisted of the simultaneous recording of spectroradiometric data and surface-water sampling. Three field campaigns were conducted to visit most of the stations in the downstream direction (i.e., the PV station to the FOZ station) in November 2009, March–April 2010 and July 2011. The stations more easily accessible from Manaus (i.e., the FOZ and FVA stations) were visited more often, namely up to 10 times. At the FVA station, multiple sampling was performed during 3 campaigns. The 40 SSSC records show a large range of values, from 25 to 622 mg x 1\(^{-1}\).

Particle-size distribution analyses were performed on 5-liter surface-suspended sediment samples collected during the 2009 rising-water cruise and the 2010 flood-peak cruise. Granulometric data were obtained using a laser grain-size measuring device (a Mastersizer 2000 with a sample dispersion unit) at the CPRM Laboratory for Sediment and Water Quality. Fig. 4 shows the grain-size distribution at the HUM and MAN stations during the 2009 and 2010 cruises. Fine-grained silt dominated the surface samples (95% of the grains are finer than 63 m). However, the distribution appeared to shift toward larger sizes during the flood peak. The median particle-size distribution (D50) was 9 m in April and 5 m in November at the MAN station, whereas the D50 decreased from 7 m in April to 5 m in November at the HUM station.

4.2. The optical properties of the Madeira River

The analysis of the spectroradiometric measurements enables the registering of the variations of the Madeira River spectra at different periods during the hydrological cycle. Fig. 5 shows the remote-sensing reflectance as a function of wavelength at 3 different periods at the PV station. The sediment-loaded Madeira River waters present low reflectance values in the blue–green spectra, followed by high reflectance values between 560 and 705 nm and a strong decrease in the reflectance at longer wavelengths. The reflectance level seems to be directly related to the SSSC, with higher values occurring during the rising-water period, particularly in the red and infrared parts of the spectra. Fig. 5 shows the location of the MODIS red and NIR bands. The MODIS bands match the parts of the spectra where the reflectance shows greater sensitivity as a function of the SSSC.

The low values in the blue and green parts of the spectra are characteristic of the light absorption by CDOM and suspended sediment that is known to decrease exponentially from ultraviolet wavelengths toward higher wavelengths (Kirk, 1994). In the red part of the spectrum, light scattering and absorption are controlled by the concentration of inorganic suspended matter, and the reflectance reaches its highest value, which seems to depend on the TSS load. The contribution of pure water absorption increases rapidly in the near infrared (NIR) region of the spectrum, which results in a significant decrease in reflectance beyond 705 nm. Although the concentrations in November 2009 and April 2010 were similar (i.e., a 5% variation), there is a significant difference between both spectra, indicating a possible seasonal dependence. Additionally, the light attenuation in the water column was measured by assessing downwelling irradiance as a function of depth in the euphotic zone. The data show that the light penetration in the water column in the red and NIR is directly linked to the SSSC, with the euphotic zone varying between 20 cm and 1 m. This result confirms that the riverbed does not affect the water’s spectral response because the main channel is on average more than 15 m deep.

4.3. The seasonal control of the SSSC-reflectance relationship

The field spectroradiometric measurements collected along the Madeira River were used to simulate the MODIS radiometric band
behavior as a function of the SSSC using the MODIS spectral response functions. Fig. 6 shows the simulation of the MODIS near-infrared band as a function of the SSSC, where each point is labeled with the month of collection. Samples were collected during 10 field sampling cruises that covered a large range of SSSCs (i.e., 25–622 mg L⁻¹). Low concentration or reflectance values correspond to the low-water period (May–October), whereas higher values were found during the rising-water and flood-peak period (November–April). The SSSC-remote-sensing reflectance relationship appears to be linear for most of the SSSC range except during the rising-water period (i.e., the November samples). For similar SSSC levels, the November samples exhibit a significantly higher reflectance than the flood-peak samples (principally, the March and April samples). This difference confirms our analysis in the previous section, where the reflectance in the red and NIR part of the spectrum was much higher in November than in April for the same range of SSSC. However, the limited number of field radiometric samples makes a full assessment of this seasonal dependency difficult.

We now analyze the SSSC-near-infrared reflectance matchups between the MODIS images and the HYBAM network samples to improve our understanding of the relationship variation for the entire SSSC range and in all of the periods of the hydrological cycle. Fig. 7 shows the average reflectance derived from MODIS for each month during the 2000–2011 period as a function of the average SSSC over the same period. The error bars indicate the standard deviation of the reflectance and of the SSSC of all of the samples collected during each month. The data are plotted for the PV and FVA stations. The seasonal dependency is obvious, with a stronger reflectance during the rising-water period (from October to January) than during the flood-peak period (February–April). The SSSC-reflectance relationship seems to vary similarly for both stations. However, the effect seems to be less pronounced downstream following the sediment dilution by the sediment-poor waters from the lowland tributaries between the PV and FVA stations. Separate studies performed on the Amazon River did not show this seasonal pattern, neither upstream in the Peruvian Amazon River tributaries (Espinoza et al., 2012) nor downstream near the Amazon River mouth at the Obidos station (Martinez et al., 2009).

A significant number of studies have been conducted concerning SSSC and remote-sensing reflectance, mostly over oceanic and coastal waters. Forget et al. (1999) showed that the way in which the light is scattered and absorbed by inorganic suspended sediment is a function of particle concentration, size distribution and the refraction index. Therefore, for the same SSSC level, a difference in the measured reflectance may indicate a differential suspended sediment type. Guyot et al. (1999) measured the suspended sediment grain size from the Andes downstream near the Beni-Mamore confluence. They showed that, downstream of the Andean Piedmont where strong sedimentation processes occur for the larger grains, the suspended sediment granulometric distribution exhibits reduced variability at different flood stages. Our results suggest the same behavior but with certain slight variations between the hydrological phases. The silt-dominated suspended sediment exhibited a finer distribution during rising water than during the flood-peak stage. Analyzing the spectral reflectance from different soil textures, Han and Rundquist (1996) showed that as SSSC increased, the reflectance from the finest particles increased faster than that from the coarser soil. Additionally, mineralogical differences in the suspended sediment may exhibit different reflectance responses because the river flow may be dominated by several different upstream sources. Guyot et al. (2007) suggested that the sediment from the Andes is enriched in smectite as the river flows through the lowlands during the flood peak. Analyzing the HYBAM samples acquired during one hydrological cycle, Viers et al. (2008) found that the Solimões and the Madeira Rivers exhibit distinct suspended sediment chemical compositions, although the same researchers did not detect seasonal variations in the mineralogical composition of the rivers. Nevertheless, the same authors found significant strontium isotopic composition variations over time in the suspended sediments, with a difference between the high-water period and the remainder of the year. This seasonal variation in the Sr isotopic composition remains unclear and may be caused by increasing physical weathering during the rainy season, i.e., when landslides and riverbank erosion may facilitate the input of radiogenic sediments not easily mobilized during periods of low water. These observations highlight a limited but significant variability in suspended sediment type and size distribution. This variability may be used to explain the seasonal dependency of the reflectance over time. However, more research is necessary, using optical modeling, to fully assess the phenomenon.

4.4. The satellite-based SSSC retrieval model

Light scattering by inorganic particles varies little as a function of wavelength. However, the light absorption decreases exponentially toward higher wavelengths (Kirk, 1994). Therefore, the optical
properties of the suspended sediment may vary from one part of the spectrum to another. Different authors (Doxaran et al., 2002; Froidefond et al., 2002; Topliss et al., 1990) have proposed that the use of the ratio of the reflectance in at least two different channels should reduce the overall sensitivity of the remote-sensing reflectance to the inorganic particle type. We computed the ratio between the NIR and the red MODIS bands for the entire dataset. Fig. 8 shows the matchups between the MODIS NIR/red surface reflectance ratios and the HYBAM samples from the PV and FVA stations. The matchups were selected when the delay between the MODIS acquisitions and the field samples was less than 4 days. The SSSC exhibited a wide range, from 4 to 1832 mg x 1^{-1} with a mean value of 300 mg x 1^{-1}, for 282 field samples. There is a significant positive relationship (r = 0.79, p < 0.05) between the SSSC and the reflectance ratio. The determination coefficient shows that 61% of the variation in the reflectance ratio is explained by the variation in the SSSC. Most of the residual dispersion may be attributed to the differences in the spatial scale between the remote-sensing data, averaged over tens of pixels and representing several square kilometers, and the field samples acquired at the riverside in 250-ml bottles. Additional dispersion may be caused by the time delay between the sampling and the closest cloud-free satellite image, which rarely matches the exact day of sampling. Finally, natural SSSC heterogeneity across the river reach is likely to increase the dispersion in the relationships between the satellite and field samples. To provide a better view of the impact of these different dispersion factors, Fig. 8 shows the reflectance ratio-SSSC matchups based on the field spectroradiometric measurements that should be free of most of the scale problems, provided that the spectroradiometric measurements and water sampling were performed simultaneously from a boat. For these field spectroradiometric measurements, 40 matches are available, with an SSSC variation of 25–622 mg x 1^{-1} and a mean value of 198 mg x 1^{-1}. The correlation factor is 0.96 and 91% of the variation in the field spectroradiometric measurements are explained by the SSSC variations.

The best-fit model was assessed using least squares regression. To assess the variability in the model parameters, we used the bootstrap resampling technique (Wehrens et al., 2000). This technique proves particularly useful in cases where the sample data are limited. Its main uses are the estimation of accuracy measures and the construction of confidence sets. Least squares regression shows that a power law model, SSSC = a (R_{NIR}/R_{Red})^b, provides the best-fit values, with a = 1020 ± 150 (95% confidence interval) and b = 2.94 ± 0.37 computed using 1000 bootstrap samples.

4.5. SSSC time series from satellite data vs. those from conventional networks

The SSSCs were retrieved from the MODIS 8-day time composite time series using the model defined in the previous section at the PV and FVA stations. Fig. 9 compares the satellite-derived and network SSSC samples at PV and FVA over the 2000–2011 period. Good agreement was found, which shows that satellite data enable the monitoring of the temporal variability regardless of cloud cover, even when the cloud cover is persistent during the rainy period. Over the common period of analysis between February 2000 and March 2009, MODIS 8-day composites enabled the calculation of 372 SSSC estimates at the PV station, representing a 90% time coverage, which is the same percentage that the HYBAM 10-day network achieved with 296 samples. At the FVA station, the MODIS coverage outperformed the HYBAM network by more than 10%, with an 81% time coverage over the 2000–2009 period. These results demonstrate the potential use of satellite time series to study the spatial and temporal variability in sediment transport. The PV and FVA stations are located 880 km from each other but exhibit similar temporal behavior. However, we noted a significant SSSC decrease from upstream to downstream, which we will analyze in the next section.

4.6. An analysis of the SSSC seasonal pattern along the Madeira River based on MODIS images

The sediment concentration at the virtual stations was calculated using MODIS 8-day composites. The SSSC estimates were averaged for each month of the year, enabling study of the seasonality of sediment transport along the main stem of the river during 2000–2011. Fig. 10 shows the variation of the SSSC along the Madeira River from the ABU station downstream to the Madeira River mouth at the FOZ station in 3 periods: rising water, flood peak and decreasing water. The SSSC exhibited a decreasing trend from upstream to downstream in all of the periods. However, strong spatial variations were detected from one part of the seasonal cycle to another. For the rising-water period (October to January), we noted the following: 1) a consistent increase in the SSSC level as the water level rose and 2) a sharp SSSC decrease from upstream to downstream. The SSSC decrease was considerable, particularly in the upper reaches (i.e., between the ABU, PV and HUM stations), with a mean decrease of approximately 30% between ABU and PV from October to January. Downstream, the SSSC decrease was weak, with a diminution of 4% between the FVA and FOZ stations in December and January. During the flood peak, from February to May, the overall SSSC level was lower and the relative decrease was reduced compared with the rising-water period. The concentration diminished by approximately 12% between the ABU and PV stations on average from February to May. The strongest SSSC decrease occurred between the PV and HUM stations, with a reduction of approximately 26% on average over the same period. Downstream from the PV–to–HUM reach, the SSSC decrease was lower, with a reduction of approximately 22% between the HUM and FVA stations. In the last reach, between the FVA and FOZ stations, the decrease was on average 8%. During the low-water period (i.e., June to September), the SSSC level was much lower along the entire Madeira River, and the SSSC variation along the river main stem was reduced upstream. The SSSC decrease between the ABU and FVA stations was on average 51% between June and August and 28% in September. However, downstream from the MAN station, the SSSC...
decrease was strong; namely, there was a 50% decrease from the MAN to FOZ stations from June to August. This decrease was the strongest for that reach of the river in all of the periods; namely, from June to August, the SSSC decrease between the FVA and FOZ stations was 22%, whereas the decrease was limited to 5% on average from October to May.

5. Discussion

5.1. Hydro-sedimentary processes along the Madeira River

The Madeira River sediment budget may include different inputs, such as bed load, suspended sediment load, sediment from tributaries and bank erosion. The suspended sediment load is delivered almost entirely by the Andean tributaries, whereas the local tributaries drain mostly forested lowlands with reduced erosion. From the quarterly suspended sediment concentration data acquired in Brazil between 1981 and 1994, Guyot et al. (1996) estimated that the Ji-Parana and Aripuana sediment discharge masses may not exceed 1.2 million and 2.9 million t year\(^{-1}\), respectively, representing approximately 1% of the Madeira River sediment discharge that the same authors assessed at the PV station. The measurements performed during our field sampling trips suggest that this budget may not have changed since then. Few studies have been conducted on riverbed transport in the Amazon. However, studies on the Amazon River main stem suggest that this transport varies depending on the season but may not exceed more than 5% of the total sediment budget of the river (Mertes, 1985; Strasser et al., 2004).

The SSSC decrease assessed by satellite data agrees with our field observations and with previous results, such as those obtained by Martinelli et al. (1993) during two cruises from PV to FOZ in January 1986 and April 1984. Although these authors used a depth-integrating sampler, which prevents the direct comparison of the SSSC levels, the trends obtained from the satellite data and from these field measurements exhibit similar behavior. Both datasets demonstrate a much higher SSSC level in January than in April and a pronounced SSSC decrease from PV to FVA, followed by stabilization downstream at the FOZ station in January.

In the Madeira catchment, previous studies have shown that the SSSC is closely related to the average concentration in a river reach (Guyot et al., 1996). Therefore, the SSSC data can be used as a proxy to detect sedimentation or resuspension along the main stem of a river. Our satellite-derived SSSC climatology data enable the definition of three different regions exhibiting distinct sediment transport processes.

1) Upstream, from the ABU station to the PV station, where the water discharge inputs from the local tributaries are limited, there is a sedimentation zone during the rising-water period with a 30% SSSC decrease from October to January (Fig. 9a), while the Madeira River discharge exhibits a very low increase (+1% from the ANA data). For the remainder of the period, the SSSC decrease is consistent with the river-water discharge increase resulting from the inputs of the low sediment-load tributaries (Abunã, Jaci parana).

2) Between the PV and FVA stations, dilution and sedimentation appear to occur during the rising-water period; the SSSC decreases by 53%, whereas the water discharge increases by 17%. However, resuspension is likely to occur during the flood peak from February to May; the SSSC decreases by 42%, while the water discharge increases by 59%. In April, when the Madeira River discharge is strongest, approximately 53 000 m\(^3\) s\(^{-1}\) on average at the FVA station, the SSSC decrease between the PV and FVA stations is 34%, whereas the river discharge increases by 78% with the inputs of the Marmelos and Aripuanã Rivers. During the period of decreasing water, resuspension continues but at a slower rate than during other periods.

3) Downstream, the backwater effect caused by the Amazon River water (Meade et al., 1991) has been predicted to produce temporal sedimentation as the slope of the water line diminishes near the Madeira-Amazon confluence (Martinelli et al., 1993). The systematic satellite observations demonstrate the following: 1) the backwater effect is significant from May to
August, with a 22% decrease in the SSSC in the last reach of this river; and 2) sedimentation affects river reaches far from the confluence, more than 400 km upstream between the MAN and FVA stations, where the SSSC decreases by 36% during the months of June, July, and August. The SSSC increases slightly between the FVA and FOZ stations in September and October by approximately 12%. This increase can occur because of the resuspension of recently deposited sediments during the early stage of a flood, when the Amazon River reaches its low level, generally in October.

To determine a precise budget of the sedimentation and resuspension occurring along a stream, accurate estimates of each tributary flow near its confluence with the Madeira River and a vertical distribution model for suspended sediment concentration in the water column are necessary. However, the number of gauge stations providing river flow information is reduced along the main stem, with a mean between-station distance along the stream of approximately 200 km. Furthermore, only three tributaries are gauged for river flow, and their stations are, in two cases, remote from the Madeira confluence (i.e., the Aripuana and Ji-Parana Rivers). Water-flow modeling may enable the gap between field measurements and satellite observations to be closed. However, this topic remains beyond the scope of the present study.

5.2. Remote-sensing monitoring

Although there is a limited amount of research on the remote-sensing monitoring of the Amazon Basin waters, the advantage of using satellite data for such a task has been foreseen for more than 3 decades. Bradley et al. (1979) reported the first study to demonstrate the possibility of detecting the main water type in the Amazon Basin from Landsat imagery. Several years later, Mertes et al. (1993) estimated sediment concentration using spectral mixture analysis of Landsat images. In that study, spectral end-members were calibrated from a set of spectroradiometric laboratory measurements of Mississippi River water samples. Mertes et al. (1995) proposed a qualitative retrieval algorithm to identify five types of water depending on the concentration of sediments in three Landsat scenes and at three different locations along the Amazon River but without quantitative retrieval. More generally, a significant quantity of research exists on the determination of the optical properties of suspended sediment in oceanic and coastal waters. Forget et al. (1999) presented an analytical reflectance model showing the dependency of the optical properties on the granulometry, mineralogy and concentration of turbid coastal waters. However, such a model cannot be inverted for operational retrieval because the model depends on a large set of input data that are difficult to measure in different locations and periods. Instead, the use of empirical or semi-analytical algorithms derived from the simplification of the radiative transfer theory applied to the interaction of sunlight and a water column has been proposed (Gordon et al., 1983). Using SPOT satellite data for the Gironde estuary, Doxaran et al. (2002) used the empirical relationship between the visible SPOT bands of the near-infrared and red channels to reduce the effects of sediment type (grain size and refractive index) on reflectance. Nechad et al. (2010) developed a semi-analytical generic model to retrieve the SSSC in coastal waters from superspectral ocean color sensors. In contrast to previous studies on the Amazon Basin, our work uses the latest available satellite data that enables both global and frequent monitoring. Following the results presented by Martinez et al. (2009) and Espinoza (2012), the present study confirms that the MODIS time series enables robust monitoring of the SSSC and facilitates the integration of this information in conventional monitoring networks.

6. Conclusions

The relationship between optical properties and suspended sediment was investigated using field spectroradiometric measurements and remote-sensing images. Remote-sensing reflectance proved to be a robust predictor of SSSC. However, a seasonal control was detected that most likely resulted from the differential granulometric distribution of the suspended sediment. Using the red and near-infrared reflectance channels to retrieve SSSC, a retrieval model was developed that demonstrated precise accuracy with field spectral radiometry ($r = 0.95 - N = 40$) and satellite data ($r = 0.78 - N = 282$). Time series of surface samples from the HYBAM network were compared at two stations and showed excellent agreement. The 11-year MODIS time series were processed at six different locations along the Madeira River to analyze the monthly average SSSC at each station. The statistics enabled the identification of two depositional areas, namely the upper reach of the Madeira River in Brazil and an area near the Madeira River mouth in a location influenced by the backwater effect of the confluence with the Amazon River. This study demonstrates...
the utility and robustness of remote-sensing data for sediment-transport monitoring. In particular, this new tool may be useful for the monitoring of future changes resulting from the construction of two large hydroelectric dams along the Madeira River.

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