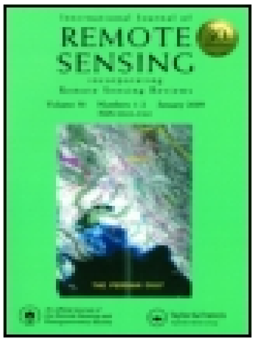

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The influence of river discharge and wind on Patos Lagoon, Brazil, Suspended Particulate Matter

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ABSTRACT

Eight years (2008–2015) of reflectance data from the Moderate Resolution Imaging Spectroradiometer (MODIS) – Aqua sensor are used to quantify Suspended Particulate Matter (SPM) distribution and variability in Brazil's Patos Lagoon. After application of an atmospheric correction suitable for extremely turbid coastal water and calculation of SPM concentrations from the reflectance values using an established algorithm, the daily remote sensing data were averaged into eight-day and monthly composites. The climatological patterns show a gradient from higher concentrations in the north to lower concentration in the south, with highest concentrations in austral spring and summer and lowest in autumn and winter. Strong interannual variability shows 2009 and 2012 to have the highest SPM concentrations and 2010 and 2014 to have the lowest. Time series of SPM were then compared with the main forces to the lagoon circulation (wind and river discharge). Peaks in SPM are associated with peaks in river discharge. Maximum SPM occurred following peaks in river discharge combined with strong northeast (NE) winds, suggesting that freshwater input and direction-specific winds are the major mechanisms of sediment transport in Patos Lagoon.

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1. Introduction

Estuaries and coastal lagoons are often characterized as sites of high concentrations of suspended matter from continental discharge or seabed resuspension (Miller and Mckee 2004). Suspended Particulate Matter (SPM) in the water column impacts the phytoplankton light regime and represents a geological and environmental issue. The ability to systematically monitor these aspects provides a valuable tool for coastal management. Conventional methodologies to monitor SPM concentrations in coastal waters use field-based approaches (Werdell et al. 2009; Chen and Quan 2013). Apart from being expensive, such methods provide data that are often limited in both space and time. Over large estuaries and coastal lagoons, the use of the daily coverage provided by oceanographic remote sensors such as MODIS (Moderate Resolution Imaging Spectroradiometer) provides

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an opportunity to systematically estimate SPM concentrations at high temporal resolution (Son and Wang 2012).

The use of remote sensing data to map SPM is well established in the literature for a variety of water types (Miller and McKee, 2004; Werdell and Bailey 2005; Son and Wang 2012). The daily coverage provided by MODIS through the Aqua sensor (Wang and Shi 2007; Son and Wang 2012) has been applied in coastal and inland waters (Kirk 1994; Mobley 1994; Franz et al. 2006; Saldías et al. 2006; Son and Wang 2012; Goyens, Jamet, and Schroeder 2013; Sokoletsky, Xianping, and Shen 2014; Fernandez-Novoa et al. 2015), allowing us to capture monthly to interannual variations of SPM.

Polito et al. (2016) comment that a higher spatial resolution provides a better understanding of SPM dynamics at the smaller scales mainly controlled by wind resuspension and regional circulation (Ody et al. 2016). However, higher resolution sensors tend to offer lower temporal resolution (e.g. Landsat 8 Operational Land Imager (Landsat 8 OLI) – 16-day repeat time). Hence, to effectively monitor dynamic changes in a turbid water system, higher temporal resolution images are required. A combination of these high temporal (MODIS-Aqua) and high spatial (Landsat 8 OLI) resolution sensors should provide optimal remote sensing observations of surface SPM dynamics in coastal waters (Ody et al. 2016). Among currently available sensors, MODIS-Aqua is operational at a global scale with a good trade-off between spatial and temporal resolution (Polito et al. 2016). MODIS data has a daily coverage and is freely available, making it applicable to monitoring SPM dynamics (Jiang et al. 2009).

SPM in the Patos Lagoon was studied by several authors using field sampled data (Toldo Jr, 1989; Hartmann and Schettini, 1991; Toldo, 1994; Hartmann and Schettini, 1996; Calliari et al. 2008; Andrade Neto et al. 2012; Avila, Moller., and Andrade 2014), modelling tools (Marques et al. 2006, 2010), and remote sensing techniques (Herz 1977; Pagot et al. 2007; Fassoni-Andrade et al. 2015). Only a few authors, however, applied remote sensing data to address the SPM variability in the Patos Lagoon. Pagot et al. (2007) demonstrated the potential of Landsat 5 Thematic Mapper (Landsat 5 TM) and Landsat 7 Enhanced Thematic Mapper (Landsat 7 ETM) to describe the spatial distribution of suspended matter associated with the dynamics of the lagoon in 1999. Fassoni-Andrade et al. (2015) analysed the spatial and temporal variability of SPM in the Patos Lagoon estuary using Landsat 8 OLI data between 2013–2014 and concluded that suspended sediments were mainly transported by wind-driven currents and river discharge. Unlike the estuarine and the coastal areas in the region (Marques et al. 2010), the spatial and temporal variability of SPM over the inner lagoon remain poorly documented.

The motivations of this study are to: 1) use MODIS-Aqua reflectance data to quantify SPM over a large coastal lagoon, 2) use time series of these data to develop a quantitative picture of the spatial, seasonal, and interannual variability of SPM over the lagoon; and 3) provide and initial examination of the relationship of these patterns to local wind and rivers discharge data.

2. Study area

The Patos Lagoon, located in southern Brazil (see Figure 1), is the largest coastal lagoon in the world, at 10 360 km^2 (Kjerfve 1986). Its margins host approximately 260 towns and cities and a population of approximately 7 000 000 habitants. The lagoon

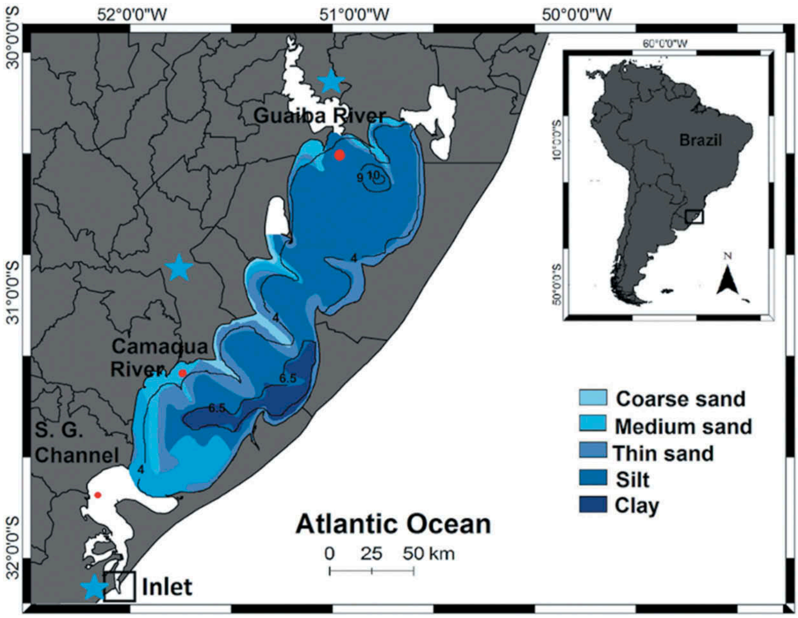

Figure 1. The Patos Lagoon in southern Brazil. Red dots indicate the three main tributaries: Guaíba River; Camaquã River, and São Gonçalo Channel (shown as S. G. Channel). Blue stars indicate wind-monitoring stations. The black box indicates the Patos Lagoon connection to the Atlantic Ocean (Patos Lagoon inlet). Bottom sediment types are shown in blue scales as adapted from Toldo Jr (1994). (white areas have no data). Black contour lines in the lagoon show bathymetry (in m).

is very important to the local economy (e.g. navigation, fishery and agriculture), but is also experiencing strongly increasing, and often environmentally detrimental, anthropogenic activities. The weather in southern Brazil is highly seasonal and strongly related to the large-scale pressure systems of the Polar Anticyclone in austral autumn and winter, and the Atlantic Anticyclone in austral spring and summer (Hasenack and Ferraro 1989).

Several studies (Moller et al. 2001; Vaz, Möller, and Almeida 2006; Calliari et al. 2008; Marques et al. 2009; Marques, Stringari, and Eidt 2014) have shown that wind and river discharge are the main forces driving circulation in the Patos Lagoon. The three major freshwater sources to the lagoon are the Guaíba and Camaquã rivers and the São Gonçalo Channel. The lagoon drains a hydrographical basin of almost 200 000 km^2 exhibiting a typical mid-latitude seasonal flow pattern: higher freshwater inflow over austral winter and spring and lower inflow over austral summer and autumn (Moller et al. 2001). The Guaíba river accounts for approximately 61% of the total river input into the lagoon, with mean discharge of 1 500 $m^3\ s^{-1}$ (Vaz, Möller, and Almeida 2006). The São Gonçalo Channel contributes with a mean discharge of about 700 $m^3\ s^{-1}$ and the Camaquã River around 300 $m^3\ s^{-1}$ (Vaz, Möller, and Almeida 2006). Peaks of high discharge (12 000 $m^3\ s^{-1}$–25 000 $m^3\ s^{-1}$) can often be observed at Guaíba River during extreme weather events related to the El Niño Southern Oscillation (ENSO) cycle (Hartman and Schetinni 1991; Marques, Stringari, and Eidt 2014). Such events drain a water volume equivalent to 7% of the total lagoon volume into the Atlantic Ocean in periods as short as 6 h (Fernandes et al. 2002).

Contrarily, when river discharge is below or near average, winds are the main forcing mechanism over the lagoon (Castelão and Moller 2003). North-easterly (NE) winds dominate throughout the year (Moller et al. 2001). Austral spring and summer cover the period from October to March, with strong and consistent winds from the east side of the lagoon, producing a sea breeze signal. Austral autumn and winter season extend from April to September. It is in this period that strong and more consistent south-westerly (SW) winds become more frequent, as observed by Tomazelli (1993). Seaward and landward exchanges between the Patos Lagoon and the adjacent ocean are the result of NE and SW winds, respectively. Reversals in the wind direction occur due to the passage of meteorological fronts at time intervals ranging from three to 15 days (synoptic time scales) (Möller et al. 2001). When long flood periods combine with changes in the main wind direction (specifically SW to NE winds), the typical saline gradient found at the estuarine region of the lower lagoon is removed. In such a combination, the lagoon can remain fresh for several months (Moller and Castaing, 1999) and only strong opposite winds can restore the salinity gradient.

Tides are mixed with diurnal dominance (24.83 hours) and their effects are restricted to the coastal zone and lower estuarine region of the Patos Lagoon, with a mean amplitude of 0.23 m (Moller et al. 2001). Astronomical tides are not only filtered at the entrance channel (Kjerfve and Knoppers 1991; Moller et al. 1996; Fernandes et al. 2004; Castelão and Moller, 2006), but are attenuated for long period oscillations generated offshore (Fernandes et al. 2004). The Patos Lagoon demonstrates a typical micro-tidal pattern (Barros, Marques, and Kirinus 2014) on which, over synoptic time scales, the wind effect is the most important forcing controlling the exchange processes between the estuarine and coastal regions (Moller et al. 2001). At longer time scales (months, years and longer), freshwater discharge becomes an important control of estuarine hydrodynamics.

The Patos Lagoon has two distinct morphological and sedimentological bottom types: the first region corresponds to sandy and narrow margins, the second, larger region is the muddy and nearly flat central bottom (Toldo et al. 2006). The 5–6 m isobaths split these regions (see Figure 1). The sandy margins show sand spits rising on average 1 m above the mean water level on the west side of the lagoon and might extend about 15 km into the water body. The east side is mainly composed of sand forming at least 40% of the total bottom area. Sandy margins on the west side are poorly selected, varying from gravel to fine sand size, while the east margin is mainly composed by well classified fine sand (Martins et al. 1989). Bottom sediments are less than 4% sand and consist of silt and silty-clay in the upper lagoon (see Figure 1). The mid/lower lagoon is mainly characterized by greyish green clay-silt and terrigenous organic matter reaching up to 30%. Deposited mud is mainly from the Guaíba River and its deposition occurs below wave-action depths which rarely exceed 4 m (Toldo 1994).

According to Rusnak (1967), the lower lagoon can be classified as a direct accumulation basin (mainly austral winter) or as an inverse accumulation basin (mainly austral summer). The transfer of SPM along the lagoon from the Guaíba River consists of a gradual deposition of sand and fine material (silts and clays). The coarser material (sand and thick silt) deposits first as the flow loses its loading power. In sequence, the finer material (medium to fine silt and clay) is transported and deposited gradually along the lagoon depending on the hydrological conditions (Hartman and Schetinni 1996). Hartmann and Schettini (1991) observed that the granulometry of the SPM in the Patos Lagoon surface waters indicate 85% silt, 10% clay and 5% or less sand. The finer SPM fraction and some silt remain suspended and are transported to the ocean as shown by sediment plumes at the Patos Lagoon inlet (Marques et al. 2006; Pagot et al. 2007; Marques et al. 2010; Fassoni-Andrade et al. 2015) or deposited at the lower lagoon creating clay facies (Paim and Moller 1986; Toldo 1989; Calliari et al. 2008).

Calliari et al. (2008) affirm that a considerable fluvial input of fine sediments (silt and clay) from the drainage basin accumulates in the estuary from a variety of sources. The hydrodynamic erosion of estuarine margins, especially from lagoon terraces, marshes and benthic estuarine fauna and flora represent a source of organic matter (phytoplankton, zooplankton, detritus, algae, and others). Organic matter data acquired during flooding and ebbing periods (Pereira 2003) show a constant behaviour from the Guaíba to the Camaquã Rivers (average around 13 g m^{-3}). The author explains that such behaviour indicates that sources of organic carbon (dissolved or particulate) are equivalent to the withdrawals of this same nutrient by the respiration of living organisms, bacteriological consumption and other processes. Pereira (2003) shows the percentage of organic matter in the austral summer season, when biological productivity is usually high. The data were acquired in the whole extension of the Patos Lagoon including the main rivers and shows values not higher than 21.30% for Guaíba River, 15.40% for Camaquã River, and 23.90% for Sao Goncalo Channel suggesting that inorganic particles dominate.

Pereira (2003) also shows that the organic matter content in the lagoon does not necessarily increase with river discharge. That same pattern was observed for phytoplankton in terms of chlorophyll-*a*. Abreu et al. (2010) show that phytoplankton growth and biomass accumulation in the estuary are closely related to freshwater discharge and water residence time. However, this relationship disappears when large amounts of freshwater are discharged from the basin as it flushes the phytoplankton biomass (and organic matter) out of the lagoon.

It is known that the processes governing SPM transport and deposition at the lower lagoon, as well as its concentration, may be associated with the estuarine circulation patterns (Hartman and Schetinni 1996). The SPM concentrations on the surface depend on the freshwater discharge from the main tributaries, as well as on the entrance of salt water which, depending on its intensity, can resuspend benthic material.

The Patos Lagoon has averaged SPM concentration values between 50 and 150 g m^{-3} (Toldo et al. 1989) depending on the year. However, SPM concentrations up to 1 000 g m^{-3} have been recorded at the Guaíba River mouth when heavy rain events coincide with NE winds. Another aspect of the sedimentary dynamics of the Patos Lagoon is anthropogenic. Every two years about 3 000 000 m^3 of deposited particulate matter are dredged from the navigation channel of the lower lagoon (Bemvenuti, Angonesi, and Gandra 2005; Torres and Philomena 2013).

The potential for wave resuspension is weak. Toldo et al. (2006) showed that most winds blowing in the Patos Lagoon area are unable to generate waves greater than 0.10 m. The wave energy growth and propagation are limited by the shallow water and also by the unusual fetch characteristics of the lagoon, where the sand spits provide important limitations to wave growth. Toldo et al. (2006) have also demonstrated the dominance of short duration (<2 hours) and weak winds (0–2 m s^{-1}) on controlling and limiting the wave growth in the Patos Lagoon.

3. Data and methods

3.1. *Ocean colour data*

For the eight-year study period 2008–2015, all available daily, full resolution, level 1A data from MODIS-Aqua for the study area (swaths inside the box 29.8–33.8 S; 54.2–50.1 W) were obtained from the National Aeronautics and Space Administration (NASA) Goddard Space Flight Centre data archive (http://oceancolor.gsfc.nasa.gov/). Because processing to level-2 colour products depends on the choice of atmospheric correction, three different options for the MODIS data processing were considered: (Gordon 1997; Ruddick, Ovidio, and Rijkeboer 2000; Wang and Shi 2007).

The difference between these procedures is how the aerosol contributes to the data recorded at the sensor. The standard method of atmospheric correction is based on the use of Near Infra-Red (NIR) bands (748 and 869 nm for MODIS) to identify aerosol contributions (Gordon 1997). These wavelengths are suitable for open ocean applications, where there is no significant in-water contribution to radiance. However, in coastal ocean applications with turbid conditions, substantial errors can result in the final products that lead to remote sensing reflectance underestimations. The algorithm proposed by Ruddick, Ovidio, and Rijkeboer (2000), called Management Unit of the North Sea Mathematical Models – MUMM algorithm, replaces the assumption of zero water-leaving radiance (no significant contribution of radiance) in the NIR bands by assuming spatial homogeneity of the 748/869 nm reflectance ratio for aerosol and water reflectance. This ratio calculated for aerosol and water reflectance is used to determine the aerosol model. However, such approaches do not work well over extremely turbid coastal waters. For that, a NIR-SWIR (Short Wave Infrared) combined algorithm (Wang and Shi 2007) that discriminates between turbid and clear oceanic waters is used as an index. The NIR-SWIR atmospheric correction reduces the signal-to-noise ratio, obtaining improved high-resolution products.

Figure 2 summarizes the result of two random dates on which the three atmospheric correction algorithms were tested. Figure 2(a) shows remote sensing reflectance at 645 nm by Gordon (1997) where masked areas represent highly turbid waters in the lagoon, for both dates. Figure 2(b) shows improvements in atmospheric corrections by applying the Ruddick, Ovidio, and Rijkeboer (2000) algorithm but masks cloudy zones, and Figure 2(c) (Wang and Shi 2007) shows better estimations of remote sensing reflectance over turbid waters and through cloudy regions. We chose this latter method to process each daily scene over the study period from level-1A data to level-2 using NASA's SeaDAS (SeaWiFS Data Analysis System) ocean data processing software (https://seadas.gsfc.nasa.gov – version 7.02).

Daily averages were calculated when more than one image occurred in a 24-h period. Daily data were then composited into eight-day and monthly means for the eight-year period, increasing cloud-free available data from about 18% to over 62% (see Table 1). Satellite eight-day composites have been widely used in studies of coastal and inland waters (e. g. Thomas and Weatherbee 2006; Venegas et al. 2008; Saldías et al. 2006). Although, this procedure reduces the potential variance produced by very short term (e.g. day-long) events.

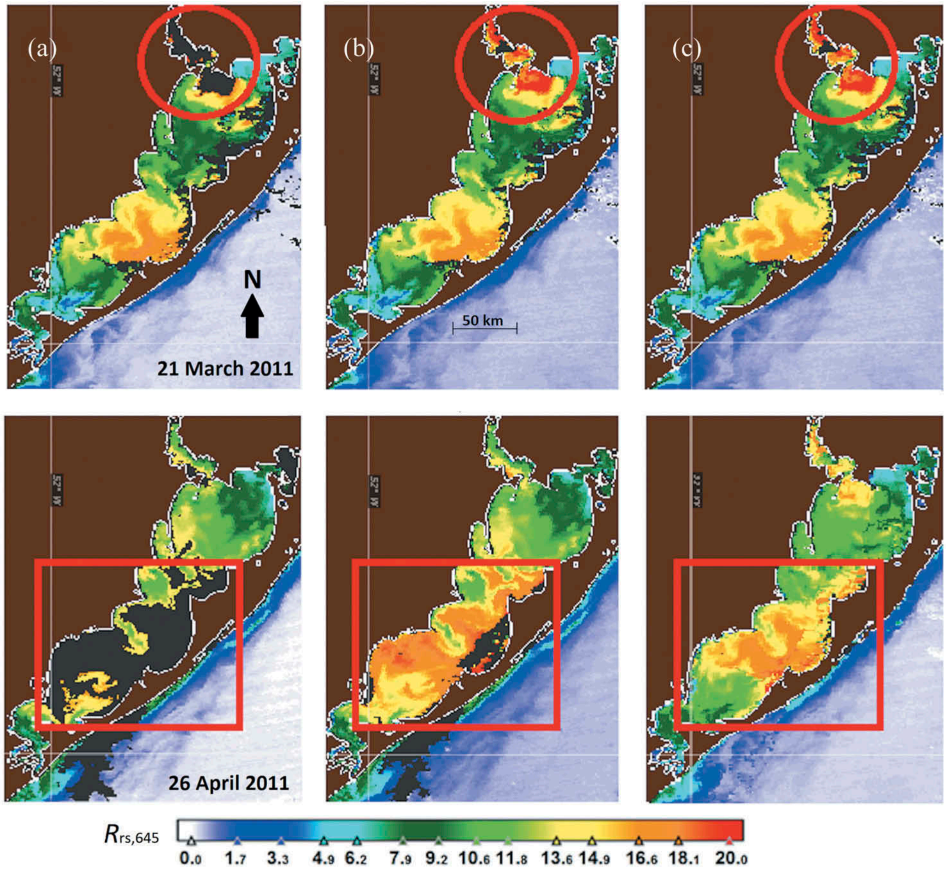

Figure 2. Atmospheric correction tests using (a) (first column, Gordon 1997); (b) (second column, Ruddick, Ovidio, and Rijkeboer 2000); and (c) (third column, Wang and Shi 2007) of $R_{rs,645}$ band (units are sr^{-1}).

Table 1. Average percentage of cloud-free available data for daily and 8-day composites.

Average (%)	Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Daily	**18.66**	18.95	15.35	27.42	26.67	22.18	18.33	16.94	15.73	16.67	16.53	14.17	14.52
8-day	**62.50**	64.29	67.86	67.86	69.05	57.14	42.86	57.14	64.29	72.62	76.19	52.38	58.33

3.2. *Suspended Particulate Matter estimates*

Estimates of SPM concentrations were obtained using the algorithm (Equation 1) proposed by Nechad, Ruddick, and Park (2010) and applied to MODIS-Aqua remote sensing reflectance at band 645 nm ($R_{rs,645}$). Nechad, Ruddick, and Park (2010) algorithm is a broadly applicable method to other turbid waters, such as the Patos Lagoon, due to is its semi-analytical approach. The method is based on the physical knowledge of the relationship between reflectance and SPM. Such an approach overcomes the possible limitation in accuracy by empirical models when environmental conditions are not in the range of the calibration set.

The algorithm for SPM is:

$$\mathrm{SPM} = C^{\rho} A^{\rho} \left(\rho_{\mathrm{w}} / C^{\rho} - \rho_{\mathrm{w}} \right) \tag{1}$$

where ρ_{w} is the water reflectance at 645 nm, and $C^{\rho} = 0.1641$, and $A^{\rho} = 258.8$ are dimensionless variables given by Nechad, Ruddick, and Park (2010) in their tables 2 and 6, respectively.

SPM is mapped for all 2008–2015 eight-day images. Their climatological anomalies were then calculated by subtracting the averaged period of each respective year from the eight-year mean composite map.

3.3. *Wind and river discharge data*

Wind data were retrieved from the Meteorology National Institute – INMET (www.inmet.gov.br) monitoring stations close to each tributary (see Figure 1 – blue stars). The INMET database provides wind speed and wind direction recorded every 8 h. All wind data were transformed to $\boldsymbol{U}$ and $\boldsymbol{V}$ components and then corrected to a 10 m elevation, by applying the standard one-seventh power law on the wind velocity profile, according to the Shore Protection Manual (1984):

$$\boldsymbol{U}_{10} = \boldsymbol{U}_{Z} (10/Z)^{1/7} \tag{2}$$

where $\boldsymbol{U}_{10}$ estimates wind velocity at 10 m from the observed $\boldsymbol{U}$ at elevation Z. Equation 2 was also applied to $\boldsymbol{V}_{10}$ at elevation Z.

Daily river discharge data were obtained from the National Water Agency (www.hidroweb.ana.gov.br) for each of the three main tributaries.

4. Results

Remote sensing of estimated SPM in Patos Lagoon revealed strong spatial and temporal variability over the eight-year period. Climatological MODIS SPM distributions are shown in Figure 3. In general (Figure 3, left panel), SPM decreases from the upper lagoon segments (near Guaíba River) through the mid lagoon (Camaquã River surroundings) and to the lower lagoon (from São Gonçalo Channel to the inlet). The upper lagoon has mean concentrations up to 38 g m^{-3}, while the lower lagoon reaches a maximum of 16 g m^{-3}, evidence of the SPM filtering and settling. Offshore, the Patos Lagoon coastal plume reaches 12 g m^{-3}. SPM in the Guaíba River area was consistently higher than in other segments, followed by the Camaquã River area and Patos Lagoon coastal zone. The southern estuarine region of the Patos Lagoon shows the lowest SPM concentration in the study area (approximately 10 g m^{-3}).

Distinct seasonal differences in distributions of SPM are evident in Figure 3- right panels. Lower SPM (approximately 20 g m^{-3}) usually occurs during austral autumn and winter. During austral spring, SPM doubles in concentration, with the upper and mid lagoon showing approximately 40 g m^{-3}. Austral summer, however, shows a different pattern: stronger SPM concentration (around 50 g m^{-3}) in the mid to the lower lagoon.

The overall seasonal variation of the MODIS SPM maps suggests that highly turbid waters are formed in the Guaíba River mouth region starting in spring and disperse

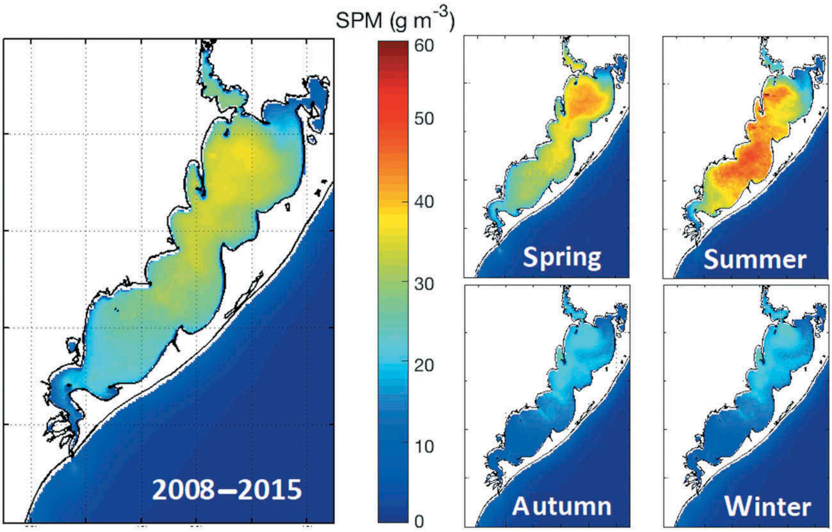

Figure 3. Overall mean SPM concentration over 8-year (left) climatological seasonal composites of austral summer, autumns, winter, and spring for a period of 2008–2015.

southwards through the Patos Lagoon, with the SPM decreasing gradually with distance down the lagoon and then with the coastal zone and offshore. In autumn and winter, the extension of highly turbid waters is narrowed and limited to the upper/mid lagoon and the highly turbid water in the lower lagoon decreases. During the wet season (spring months), the turbid Guaíba River plume extends and becomes more identifiable than during winter or autumn months. The waters are more turbid in summer months, with an enlarged extension of highly turbid waters that covers almost the whole study area.

Comparison of the eight-day mean values for wind and river flow with SPM over the eight-year period shows that the time series follow similar trends at both seasonal and interannual scales. Winds are predominantly from the northeast, with approximately 35% of occurrence (see Figure 4 – wind rose), and from southwest (around 25%). NE winds mostly ranged from 2.50 to 5 m s^{-1}, occurring throughout the year while SW winds ranged from 1 to 6 m s^{-1} occurring mainly over autumn and winter. Maximal discharge rates are recorded from the winter to the spring season with interannual variability, while dryer conditions are annually observed from late summer to autumn periods. Among rivers, Guaíba River has an average discharge of 1 340.50 m^3 s^{-1}, followed by São Gonçalo Channel (506.70 m^3 s^{-1}) and Camaquã River (263.60 m^3 s^{-1}) with maxima in austral spring (October-November-December).

Over the study period, SPM values showed strong fluctuations, generally tracking river discharge (Figure 4(a–c)). The general spatial and temporal SPM patterns showed a clear seasonality with lower SPM in the dry season and higher SPM in the wet season during which the strongest turbid values often surpass 60 g m^{-3}. Strong values of freshwater discharge during 2009 (October–December) triggered the highest values of SPM in the Guaíba River mouth in the eight years of observations.

While stronger signals of SPM are clearly related to intensify river discharge events, it appears that wind also plays a role. SPM values drop when NE winds become weaker

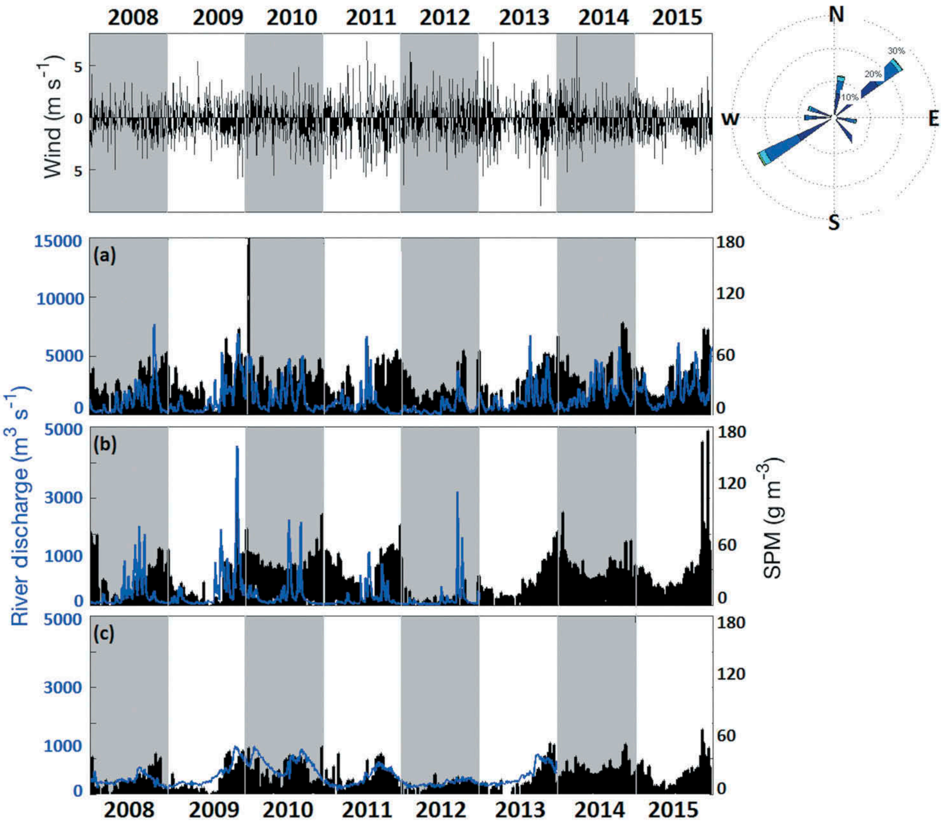

Figure 4. Panel on the top show mean wind speed and direction. Panels (a)-(c) are time series of river discharge (blue line) and SPM (black bars). Panel (a) is for Guaíba River, (b) Camaquã River, and (c) São Gonçalo Channel (boxes in Figure 1). Thus, panel (a) (river discharge) present different scale due to the distinct order of magnitude in comparison with other panels.

(from late autumn to winter) while stronger SPM values are recorded once such winds become more frequent and stronger. Additionally, turbid river plumes are rare in autumn (April–June), occurring around 9% of the time in the Guaíba and 7% in the Camaquã River. Autumn SPM values in the riverine plumes are weaker. In winters, river discharge rapidly increases through spring until early summer.

The eight years of river discharge and sampled SPM data show strong seasonality but also shows that event-scale variability plays an important role, especially in SPM signals. Overall, SPM in the upper lagoon and mid lagoon was higher than in the lower segment. While a thorough analysis of all the driving forces of the observed patterns in both climatological scale and short-term variations has yet to be conducted, wind and river discharge appear to be two major, and likely linked natural mechanisms responsible for the seasonal SPM patterns.

Anomalies formed from annual means of MODIS SPM also showed intense interannual variability over the eight-year study period (see Figure 5). The strongest negative anomalies were observed in 2010, 2011 and 2014, while 2009 and 2012 had strong positive anomalies. Years 2008, 2013, and 2015 represented intermediate years.

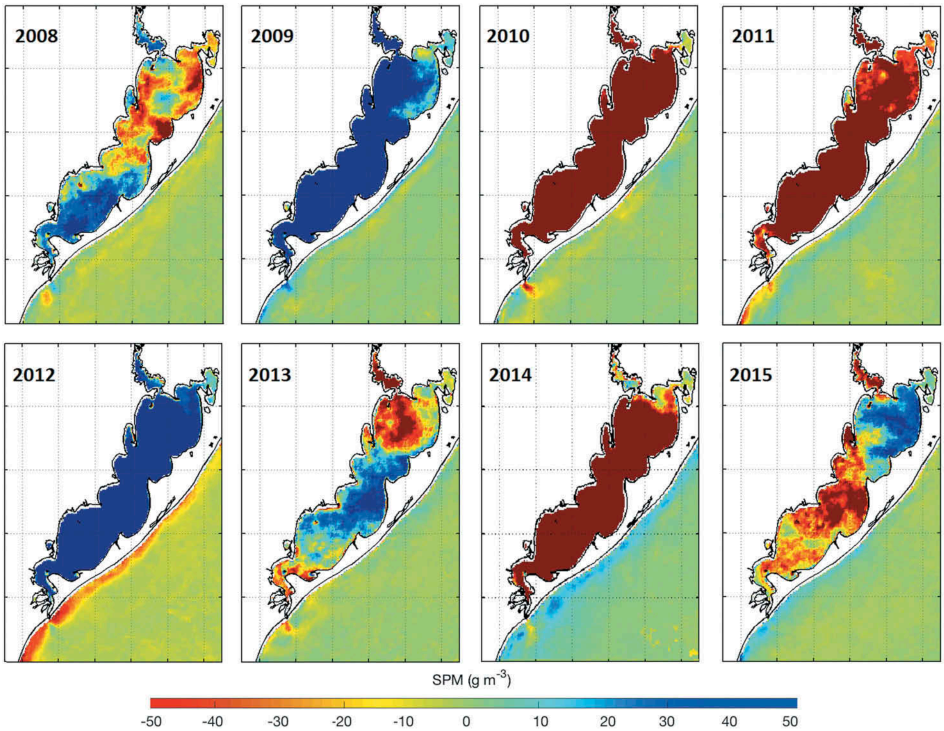

Figure 5. Annual anomaly turbidity maps illustrating the interannual variability.

In 2010 the total river outflow (2 697 m^3 s^{-1}) was about twice the mean outflow (1 340.50 m^3 s^{-1}). In turn, in 2012, the total mean outflow reached a value around 1 115.60 m^3 s^{-1} (below average). Unfortunately, the years of 2013, 2014 and 2015 cannot be compared due to the lack of data for Camaquã River and Sao Goncalo Channel (see Figure 4).

Interannual variability of SPM is also visible in the coastal zone immediately offshore of Patos Lagoon (Figure 5). The strongest features are evident in 2012 (along the entire coast) and in 2010 and 2011 (in the lagoon coastal plume) when negative anomalies were observed. Overall, coastal anomalies do not reach the strength of those in the lagoon.

Interannual variability afforded by monthly composites of SPM is presented, using two example months that represent seasonal extremes in river discharge and wind forcing. January SPM patterns (Figure 6) over the eight-year period represent summer below average discharge conditions but strong NE wind forcing (southward). The most obvious SPM variability is weaker concentrations in 2013 and 2015. Spatial patterns of SPM indicate similar concentrations over most of the lagoon in most years. In 2009 and 2012, however, there is a strong difference between the upper and lower lagoon. August SPM patterns over the eight-year period (see Figure 6) represent conditions during the winter maximum in discharge and after the wind has switched to the winter-dominant direction (SW). In most years, August values of SPM are lower (usually <40 g m^{-3}) than summer and the SPM gradient is less well defined. Over the eight-year period, winter

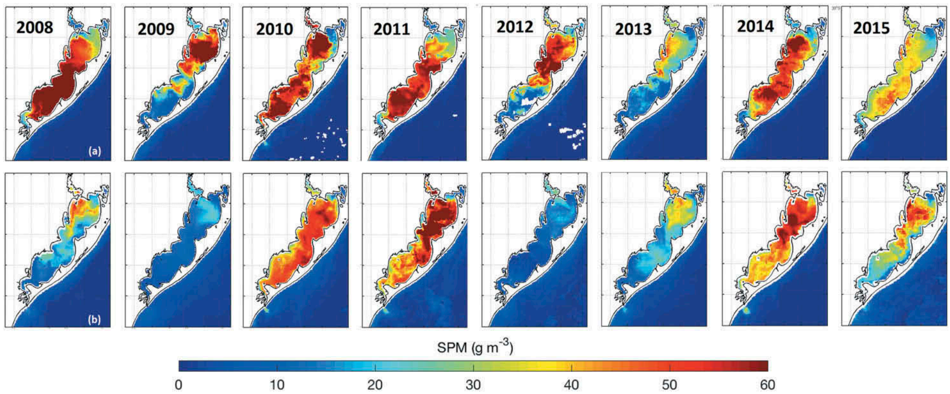

Figure 6. Interannual variability in SPM distribution in a typical summer month (a) and winter (b) over the eight-year study period for monthly means in each year.

concentrations are weaker in 2009, 2012, and 2013 but strong in the years of 2010, 2011, and 2014. These years also show stronger coastal plumes (approximately 30 g m^{-3}).

Figure 7 presents two example scenes showing that variations in SPM concentration were not only events but could also be due to short-term events trough combinations of wind and river discharge. Figure 7(a) represents a late austral autumn (May 2012) period of low river outflow (about 300 m^{3} s^{-1}) under W-SW winds, while Figure 7(b) shows an austral summer (January 2010) period of high river outflow (approximately 4 500 m^{3} s^{-1}) under N-NE winds. SPM patterns in May (Figure 7(a)) show lower concentrations overall

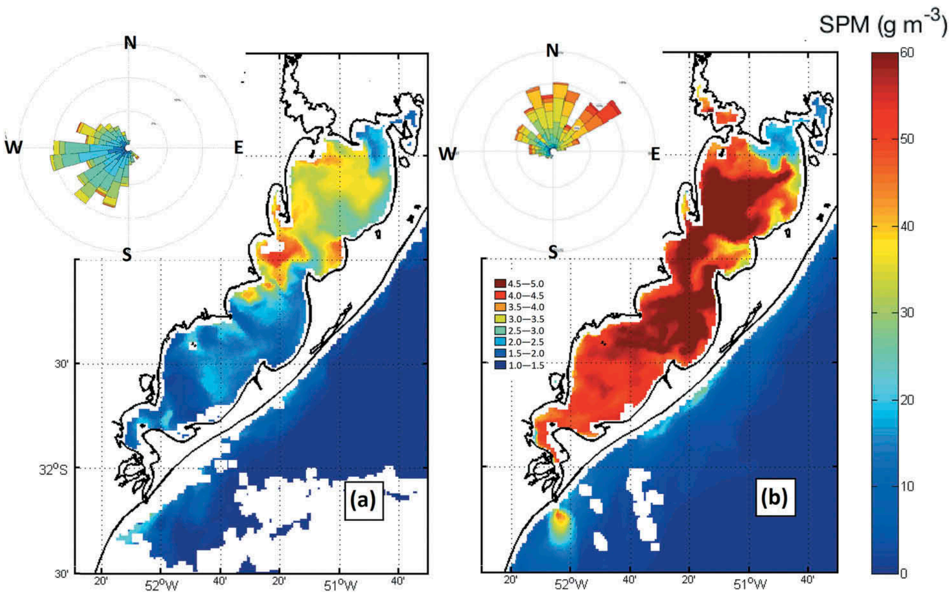

Figure 7. SPM concentrations for eight-day periods of low river discharge condition and SW blowing winds ((a) – May 2012) and high river discharge with NE blowing winds ((b) – January 2010). Wind speed is in (m s^{-1}). White spots are masked clouds.

and a strong difference in concentrations between the north and south parts of the lagoon. January patterns (Figure 7(b)) show high SPM concentration over the entire lagoon during a high discharge period (14 days of river outflow above average) and a dominant NE wind (14 days with maximum of approximately 12 m s^{-1}) that injects SPM into the entire lagoon.

5. Discussion

MODIS-Aqua data proved to be an effective tool to estimate SPM concentrations, allowing detailed analysis of spatial and temporal patterns and contributing to a better understanding of SPM dynamics in the Patos Lagoon. While we have no field matchups with MODIS imagery from 2008 to 2015, the magnitudes and spatial patterns of SPM returned from Equation 1 were consistent with existing field observations. SPM ranged from approximately 5 g m^{-3} to several hundred g $m^{-3,}$ consistent with field observations by Calliari (1980); Baisch (1997); Hartman and Schetinni (1991); Hartman and Schetinni (1996); datasets in Pereira (2003), and Andrade Neto et al. (2012). After atmospheric correction for highly turbid water, we feel that Equation 1 performed well at 645 nm.

Propagation of highly turbid waters and their variability in time and space is intimately related to particulate matter transport and remobilization (Achete et al. 2015; Göransson, Larson, and Bendz 2013). Mapping of SPM can be used to derive important statistics, observe the extension of river plumes and resuspension of particulate matter in shallow waters. Beyond the strong variability of mean SPM values evident in Patos Lagoon on event, seasonal, and interannual timescales, there is a strong spatial variability on the SPM signal from the three regions (see Figure 3). We document spatial and temporal variabilities that are the result of a combination of short-term events (e.g. Figure 7), as well as seasonal river outflow intensity and wind action (e.g. Figure 4).

Spatial patterns of Patos Lagoon show increased SPM values in the upper lagoon from late September to March. SPM values decrease towards the south probably due to sedimentation processes as they are transported to the coast by local hydrodynamical processes (Calliari 1998). SW winds, from May to September, that usually act to reduce flood flux due to non-local wind processes (Moller et al. 2001), do not seem to resuspend sediments along the lagoon as observed by Niencheski and Windom, 1994; and argued by Hartmann and Schetinni, 1996.

The seasonal differences in SPM appear related to the alternating dominance of wind and river discharge over the circulation of the lagoon, results consistent with Castelão and Moller (2006). River discharge, mainly at the upper lagoon, has moderate to strong outflow over austral winter, spring and summer (see Figure 5). Strong SPM concentrations throughout the three seasons were expected (see Figure 4). The observed low SPM in winter might be related to frontal system passages from the south that are historically frequent over this time of year (see Figure 6(b)). Such meteorological phenomena increase SW winds and change the flux of SPM. The flow that normally keeps fine-grained sediments suspended in the water column weakens and sediments flux to the bottom more easily.

Another potentially important factor is the sea breeze that develops mainly in austral spring and summer, from the east. These easterly winds impact SPM concentrations by promoting wind-driven waves at the west side of the Patos Lagoon that are responsible for erosion. Calliari et al. (2008) describe erosional processes by easterly winds as a source of suspended matter at the west side of the lagoon. Unfortunately, it was not possible to separate these patterns from other in our data

Sondergaard (1992) demonstrated that a large and relatively shallow inland water body such as the Patos Lagoon can have its spectral reflectance significantly changed by wind-driven currents that increase flux between sediment and water column. The finer particles of SPM, once disturbed, can remain suspended for longer periods contributing to the overall high concentrations of SPM along the lagoon (Hartman and Schetinni 1991).

Interannual variability of SPM is clearly observed in the lagoon and seems to be related to river discharge anomalies (see Figure 5). Eastern South America is subject to ENSO-triggered floods (Grimm, Ferraz, and Gomes 1998; Dogliotti et al. 2016). It has been shown that the river discharge at the Patos Lagoon has interannual variability in phase with ENSO cycles, with increased river outflow during El Niño and normal to low outflow during La Niña (Grimm, Ferraz, and Gomes 1998; Fernandes et al. 2002; Marques and Moller 2008; Marques, Stringari, and Eidt 2014). This is consistent with previous studies in South America by Robertson and Mechoso (1998) for the Rio Negro and Paraguay River and southern South America (Uruguay River) by Krepper, Garcia, and Jones (2003). In the southern-most estuarine region of Patos Lagoon, Marques et al. (2010) showed a direct relationship between river discharge and SPM. They used numerical simulations to evaluate an intensified transport of SPM towards the Atlantic Ocean in 1998 during a strong El Niño compared to a normal year (1999).

Pereira and Niencheski (2004) concluded that the combined intensities of wind and river discharge have different effects on the residence time of local SPM, showing that fine SPM transport through the lagoon is mainly observed during periods of NE winds and high freshwater discharge, consistent with our Figure 7(b). These fine SPM are likely to be transported in 18 days in the form of plumes (Calliari et al. 2008). Meanwhile, SW winds and low river outflows (e.g. our Figure 7(a)) increase the residence time to 38 days (Pereira and Niencheski 2004). This suggests that residence time of the Patos Lagoon depends on both wind and river discharge, especially from Guaíba River (Pereira and Niencheski 2004). Based on the distribution of SPM values and their relation to freshwater input, SPM patterns appeared as more dependent on intensified Guaíba River discharge than on other rivers (see Figure 4). Moreover, significant exchange flows can be generated between the estuary and coastal area through the inlet (see Figure 1) due to barotropic pressure gradients established as a function of the main physical forcing (Moller et al. 2001).

SPM in the Patos Lagoon is mainly composed of silt (decreasing towards the lower lagoon) and clay (increasing towards the lower lagoon) as seen in Figure 1, (Toldo 1989; Hartman and Schettini, 1996; Baisch and Wasserman,1998; Calliari et al. 2008). Bottom sediments mainly consist of a mixture of fine-grained sediments originating from the Guaíba River and coarse-grained sediments from the Camaquã River. An increase in clay content in the lower lagoon and in the estuarine region coincides with periods of low discharge associated with SW winds (Calliari et al. 2008). The amount of SPM carried to the Patos Lagoon by the main tributaries, as well as the patterns of seasonal variations of freshwater and wind, make the estuary predominantly dominated by ebb flows (Fernandes et al. 2002). Active ebb-flow plumes of turbid water extending both offshore and alongshore have been well documented on the coastal shelf by satellite imagery (according to Calliari et al. 2008) and numerical modelling (Marques et al. 2010).

While river discharge and the winds can affect the circulation of the lagoon and SPM patterns, these factors could also influence the spatial and temporal variation of primary production in the region (Seiler et al. 2015). The relationship of river discharge and wind stress to phytoplankton concentrations is interfered mostly from the residence time of the lagoon (Pereira and Niencheski 2004), in light availability in the water column (Kirk 1994), and in nutrient input (Azevedo, Bordalo, and Duarte 2014). A longitudinal gradient of phytoplankton in the lagoon is reported by Odebrecht et al. (2005) and Seiler et al. (2015). The authors found a decreasing gradient from the Guaíba River towards the Camaquã River region and an increasing biomass again towards the estuarine region (São Gonçalo Channel region). The authors speculate that this increase might be caused by a new discharge of nutrients from these rivers. One possible explanation for such behaviour is that the river discharge rates at the upper lagoon are much higher, increasing the turbidity and SPM in the water column and reducing light availability and phytoplankton biomass as consequence. In addition, higher flow rates may also cause stronger flushing, reducing nutrient concentrations and phytoplankton residence time (Zouiten et al. 2013).

We can place limits on biological productivity influences on SPM estimates in terms of organic matter for the Patos Lagoon based on the dataset shown in Pereira (2003). Assuming that all measured organic matter comes from biological productivity, it is reasonable to think that it cannot contribute to our SPM estimates more than 25% in the river's mouth (regions where inland sediment plumes are formed) and approximately 35% along the lagoon. As our study focuses on total SPM we can only speculate on possible contributions of biological particles to SPM estimates. We acknowledge its possible importance and suggest future studies in the field.

Finally, studies of synoptic variability and associated hydrodynamics would assist in better understanding of plumes behaviour (riverine and offshore plumes), including complete determination of the importance of extreme weather events. The interannual variability of SPM is likely to be important in this region given the influence of ENSO cycles on river discharge (Grimm, Ferraz, and Gomes 1998; Montecinos, Diaz, and Aceituno 2000; Moller, Castello, and Vaz 2009) winds (Moller et al. 1996, 2001, 2009), and coastal zone processes (Fernandes et al. 2002, 2004; Marques et al. 2010; Marques, Stringari, and Eidt 2014). Previous studies have already shown that ENSO cycles lead to changes in the estuarine circulation (Möller et al. 1996; Fernandes et al. 2002), fishing activity (Moller, Castello, and Vaz 2009), nutrient availability, and the distribution and growth of phytoplankton (Abreu et al. 2010).

6. Conclusion

The eight years of data covered by this work is a demonstration of the value of satellite remote sensing as a tool for long term monitoring and management of inland waters. Our results show that the use of information with daily temporal coverage and spatial resolution appropriate to large coastal environments provided by MODIS is an effective alternative to study SPM concentration patterns in turbid coastal waters over monthly, seasonal and interannual time scales. The MODIS surface reflectance data appears well suited to investigations of SPM concentration in the lagoon and allows quantification of patterns over space and time. The main limitations of such a remote sensing study are the persistent cloudiness present in the region as well as the lack of continuous concurrent hydrological or field SPM data for the region for validation of absolute concentration.

This study contributes toward our ability to systematically monitor SPM concentrations in the Patos Lagoon and advances our understanding of the suspended sediment dynamics. This study also contributes to the understanding of sedimentary exchange processes between the Rio Grande do Sul basin and the continental shelf through the Patos Lagoon.

SPM from MODIS images for Patos Lagoon was generally in agreement with published measurements of SPM concentration and its spatiotemporal distributions. These patterns are co-dependent on river flow (from at least the three main tributaries – Guaíba, Camaquã and São Gonçalo Channel) and wind direction (mainly from NE or SW). Seasonal dynamics of Patos Lagoon show that suspended sediment concentration in the Guaíba River, Camaquã River and São Gonçalo Channel are driven by stronger river discharge and its transport is controlled by NE winds (transport towards the estuary) and by SW winds (opposite direction). At longer time scales, interannual variability in SPM might be related to ENSO cycles (El Niño/La Niña events) and associated changes in local precipitation.

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