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Estrutura vertical e variabilidade temporal de correntes na plataforma continental interna do sul do Brasil.

Julia Gil dos Santos

Dissertação apresentada ao Programa de Pós-Graduação em Oceanografia Física, Química e Geológica, como parte dos requisitos para a obtenção do Título de Mestre.

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Resumo

Este estudo investiga o impacto dos ventos, marés e descargas fluviais nas correntes costeiras e na variabilidade da salinidade da plataforma interna do sul do Brasil. Foram utilizados medições *in situ* coletadas por uma boia meteoceanográfica do Sistema de Monitoramento da Costa Brasileira (SiMCosta) durante 315 dias consecutivos, com início em Dezembro de 2016 à Outubro de 2017. A boia de monitoramento denominada RS05 está ancorada próxima a desembocadura da Lagoa dos Patos, conhecida como a maior laguna do mundo. A série temporal de correntes pode ser interpretada como uma soma de fluxos de alta variabilidade, correlacionada com a tensão do vento local e com um fluxo residual de alguns centímetros por segundo para sul, ao longo da costa. Correntes de maré foram predominantemente diurnas, mas desprezíveis, representando aproximadamente 1,7% da variabilidade total das correntes na região. Foi encontrado a predominância de ventos de noroeste e corrente de sudeste na plataforma interna, com fluxo intermitente de corrente, tanto na componente longitudinal como na transversal, devido às passagens de frentes meteorológicas. As análises espectrais para ambas as componentes de corrente apresentam padrões similares de frequências, o que indica a prevalência de eventos de alta energia em períodos de 3 a 10 dias, para toda a séries temporal. A corrente longitudinal é altamente correlacionada (r = 0.77, p<0,05) com o vento longitudinal, com defasagem temporal de 3 horas. Nas baixas (período> 40h) e altas (período <40h) frequências, as defasagens temporais foram de 5 e 3 horas, respectivamente, com correlações de 0,83 (p <0,05) e 0,65 (p <0,05). As análises de ondeletas mostraram que eventos de alta energia na componente longitudinal do estresse do vento são mais comuns entre agosto a outubro, mas pouco frequentes entre fevereiro e março, com padrões similares nas correntes superficiais e salinidade. Foi observado um decaimento na salinidade superficial durante o inverno devido a eventos de alta vazão da Lagoa dos Patos. A salinidade média diária correlacionou-se negativamente com a vazão da Lagoa de Patos, mas parte de sua variabilidade está associada à intrusão da pluma da Lagoa de Patos e a passagens de frentes meteorológicas sobre a plataforma interna.

Palavras-chave: Circulação oceânica; Medições *in situ* de velocidade; Correntes de maré; Plataforma Continental Sul do Brasil.

Abstract

This study investigates the impact of winds, tides and river discharges on the coastal current and salinity variability of Southern Brazil’s inner shelf. This was possible through an analysis of *in situ* measurements of wind speed, current, surface salinity, and temperature taken by sensors on a meteocean buoy of the Brazilian Coastal Monitoring System (SiMCosta). The mooring RS05 buoy is anchored close to the mouth of Patos Lagoon, which is known as the largest chocked lagoon in the world. The observed current time series can be interpreted as a sum of highly variable flow correlated with local wind stress, and a residual mean current flowing southward along the coast at a few centimeters per second. Tidal currents were predominantly diurnal, however negligible, representing approximately 1.7% of the current variability in the region. The prevalence of northwest winds and southeastward current on the inner shelf were found, but also an intermittent current flow in both the alongshore and cross-shore components due to meteorological frontal system passages. The power spectrum of both current components presented similar frequency patterns, indicating the prevalence of high-energy events in periods of 3 to 10 days over the entire time series. The alongshore current is highly correlated ($r = 0.77$, $p<0,05$) with alongshore wind with a delay of 3 hours. In the low (period >40h) - and high-frequency (period <40h), the temporal lags were 5- and 3-hours, respectively, with correlations of 0.83 ($p<0.05$) and 0.65 ($p<0.05$). The wavelet analysis has shown that high-energy events in alongshore wind stress are more common between August and October and not very often between February and March, with similar patterns in surface currents and salinity. A decrease in surface salinity during the winter season was observed due to the high level of Patos Lagoon’s outflow. Mean daily salinity correlated negatively with Patos Lagoon’s outflow, however part of this variability is associated with the intrusion of Patos Lagoon’s plume and the passage of frontal systems over the inner shelf.

Keywords: Costal circulation; direct current measurements; tidal currents; south Brazilian inner shelf.

Estrutura da Dissertação

Para obter o título de Mestre pelo Programa de Pós-Graduação em Oceanologia, é solicitado que o aluno realize a submissão de pelo menos um artigo científico como primeiro autor em periódico indexado com corpo editorial. Sendo assim, o corpo da dissertação apresenta os resultados e conclusões da pesquisa em forma de artigo, composto de cinco capítulos, descritos a seguir: no capítulo I será apresentado uma breve introdução sobre a circulação oceânica em plataformas continentais e suas principais forçantes de circulação, capazes de influenciar a estrutura vertical e variabilidade das correntes locais; no capítulo II, os objetivos que esse estudo se propõe a alcançar; o capítulo III traz a descrição dos dados e métodos utilizados para atingir os objetivos geral e específicos; no capítulo IV, os resultados e discussão serão apresentados em forma de artigo. Os principais resultados e conclusões serão sumarizados no capítulo V. Por fim, encerra-se o documento com as referências utilizadas na elaboração do artigo e da dissertação.

Capítulo I: Introdução

A plataforma continental, definida como a região de águas rasas e de declive suave que circunda os continentes, estende-se desde a linha de praia até a borda da plataforma, local onde ocorre uma mudança abrupta na declividade (Castello et al, 2015). A profundidade em que termina o domínio da plataforma continental é bastante variável, ficando na média, em torno de 130 m, podendo chegar até 500 m. Costuma-se dividi-la em parte proximal e distal da plataforma que se referem, como plataforma interna e plataforma externa, respectivamente, e podem ser geologicamente separadas pela isóbata de 50m (Mendes, 1984). Contudo, ainda não há consenso sobre o limite exato entre as partes interna e externa das plataformas continentais e essa delimitação fica a critério da dinâmica local de circulação, podendo haver ainda uma plataforma continental média entre elas. Os oceanos costeiros são comumente definidos como as áreas que vão da linha da costa até a borda externa da margem continental e são, portanto, a parte oceânica sobre as plataformas continentais. As principais forçantes da circulação no oceano costeiro estão atribuídas a ação direta ou indireta do vento, forças gravitacionais astronômicas e forças devido a gradientes de densidade.

A plataforma interna pode ser entendida em oceanografia como “região nearshore” (ou próxima à costa), conforme definido por Mitchum e Clarke (1986) e é a região de transição entre a zona de surf e o meio da plataforma, abrangendo tipicamente profundidades de água de alguns metros a algumas dezenas de metros (Lenz et al, 2011). Em geral, a profundidade do perfil diminui do oceano em direção a linha de costa e os processos de circulação se modificam devido a essa variação na profundidade, diminuindo em intensidade quanto mais próximos da costa. De acordo com Lenz (1995), a plataforma interna desempenha papel fundamental na dinâmica geral da plataforma continental, uma vez que é a região onde a circulação se ajusta à presença da condição de limite costeiro. Assim, as águas em plataforma continental ao fluírem, interagem com o meio físico circundante e respondem a ele. Esse meio pode ser natural ou ter influências da ocupação humana, através de edificações costeiras, que podem fisicamente modificar as direções e intensidades dos fluxos, ou ainda através de mudanças em outras propriedades da água, como material dissolvido ou em suspensão.

Uma ampla variedade de processos conduz a circulação nas plataformas continentais internas, incluindo ventos, ondas de gravidade superficial, marés e plumas (Lenz et al, 2011), com escala de tempo semi-diurna (12h), sazonal e interanual (Castro et al., 2006) e podem variar consideravelmente dependendo do local geográfico estudado. Podem também ser processos determinísticos, como por exemplo os efeitos da maré, ou não determinísticos, como por exemplo e os efeitos do El Nino ou La Nina na vazão continental ou no regime de ventos. Os principais processos dinâmicos que afetam a circulação em plataforma interna são o efeito Coriolis, batimetria local, maré, descargas de rios, vento e ondas.

O efeito de Coriolis se dá em função da latitude e é importante para fluxos em plataforma com extensões horizontais que superam o raio de Rossby local, que sentirão o efeito de rotação da Terra e os defletirão. Em altas latitudes, a influência de Coriolis é máxima e há a deflexão para a esquerda da direção do fluxo no hemisfério sul. Para as plataformas internas, a batimetria e a forma da costa podem causar mudanças na direção ou interferir nas velocidades dos fluxos ao se adaptarem a uma barreira física. Em plataformas externas, onde em geral os perfis verticais são mais profundos e com maior circulação, pode haver movimentos verticais entre massas de água, com diferentes propriedades.

As marés criam ondas internas que quebram, criando turbulência e mistura (Talley et al, 2011). Assim, pelo seu caráter periódico, geram movimentos verticais periódicos em águas costeiras que estão associados a processos de estratificação/mistura por efeito da enchente de maré, responsável pela intrusão de água marinha no interior do estuário (Chao, 1990; Guo e Valle-Levinson, 2007) ou vazante, que pode favorecer o escoamento dos rios sobre a plataforma continental adjacente.

Por ser uma região de transição entre continente e o oceano, a plataforma continental interna apresenta desembocaduras de rios e estuários. Em geral, quanto maior a drenagem continental, maior a vazão de águas continentais em regiões costeiras. O escoamento de um rio ou estuário para o oceano pode desenvolver uma pluma que, ao avançar sobre o mar aberto, caracteriza uma frente, cuja localização é estabelecida pelos limites entre massas de água, com maiores gradientes horizontais de densidade e outras propriedades (McClimans, 1988). Plumas de estuários, produzidas pela descarga continental persistente de água salobra, são feições primárias de mesoescala em plataformas continentais (Garvine, 1987). Assim como os estuários, as plumas estuarinas são bastante dinâmicas e, segundo Garvine (1995), apresentam ampla variedade de formas e escalas. Sua extensão e morfologia são dependentes da vazão dos rios, condições da maré e tensão do vento (Morris et al., 1995). Quando suficientemente extensas, sofrem influência da rotação da Terra e tendem a aderir à costa em faixas estreitas, definidas em escala pelo raio de deformação Rossby baroclínico (~ 5-15 km), devido a sua própria tendência de vorticidade batimétrica e pressão.

A expansão de uma pluma sobre as águas costeiras depende basicamente de dois parâmetros: a diferença de densidade relativa entre a pluma e camada de água subjacente, e o número de Froude densimétrico (Wrigth e Coleman, 1971; Bowden, 1983). O número Kelvin (Rk) é utilizado para classificação quanto ao tamanho das plumas e pode ser entendido como a relação da largura da desembocadura do rio ou estuário com o raio de deformação de Rossby interno, cuja medida é usada para estimar a escala de tamanho em que um fluido estratificado passa a sentir os efeitos rotacionais. Garvine (1995) utiliza o número de Kelvin como o principal parâmetro para classificar as plumas em dois casos distintos. As plumas que se enquadram no Caso 1 (Rk<< 1) são dominadas por inércia da descarga. Já as plumas no Caso 2 (Rk >> 1), são descargas de larga escala espacial e têm a dinâmica de dispersão dominada pela rotação planetária, através do efeito de Coriolis. Casos intermediários (Rk próximos a 1) apresentam ambas as características e são, portanto, mais complexas do ponto de vista dinâmico.

Por serem menos densas as águas continentais, escoam sobre as águas oceânicas, mais densas, onde gradualmente se misturam. Contudo, fatores dinâmicos podem influenciar a expansão de uma pluma de larga escala no ambiente costeiro. Yankovsky e Chapman (1997) sugeriram dois casos distintos em relação a advecção de plumas. O primeiro caso em relação ao padrão teórico, com advecção de águas da drenagem continental sobre águas superficiais marinhas. O segundo, em relação a plumas advectadas próximas ao fundo oceânico. Nesse caso, a pluma tende a ocupar toda a coluna d'água em regiões próximas a boca do estuário. Essa advecção é normalmente associada a plumas formadas em locais (ou em eventos) com altas descargas de água salobra na plataforma. Devido a esse volume que chega à costa, forma-se um fluxo de escoamento próximo ao leito em direção ao oceano. Guo e Valle-Levinson (2007) apontam também a influência da maré como forçante importante na expansão das plumas e reportam que, em regiões onde há forte influência da maré, a pluma responde a ela e pode mudar de advectada ao fundo para advectada à superfície. De forma complementar, Kirincich e Hebert (2005) relatam que as velocidades das correntes de maré foram maiores quando relacionadas a plumas advectadas ao fundo.

Ao desembocar no mar adjacente, a base da pluma é normalmente caracterizada pela alta estratificação que, conforme a pluma avança sobre o oceano, é suavizada pela diluição e processos de mistura entre as águas. Essas frentes de densidade superficiais no oceano criam barreiras dinâmicas para transporte de *momentum* e materiais dissolvidos em direção *offshore* (Chao *et al*, 1986) e podem modificar significativamente a estrutura física das águas da plataforma continental (Osadchiev *et al*, 2013), causando forte impacto na distribuição de propriedades da água, sedimentos e biota (Xia *et al,* 2010; Acha et al, 2015). A distribuição de compostos químicos naturais e poluentes de origem continental nas águas da plataforma são fortemente influenciados pela dinâmica das plumas (Jouanneau e Latouche, 1982; Fichez et al., 1992), o que justifica a necessidade de conhecer sua variabilidade em uma região costeira. Além disso, grandes intrusões de descarga continental com salinidades menores do que as do oceano, podem induzir a formação de gradientes de densidade que promovem a formação de fluxos residuais horizontais em uma direção específica das águas sobre a plataforma continental, influenciando assim toda a dinâmica local de circulação. Da mesma forma, poderá acontecer uma estratificação vertical acentuada, forçando circulações antagônicas entre a superfície e o fundo do perfil.

A tensão do vento na superfície é o principal meio de forçar a circulação oceânica, através de uma camada de atrito (turbulência) e convergências e divergências de massa nessa camada (Talley et al, 2011). As convergências/divergências estão diretamente relacionadas à tensão do vento. Assim, os ventos que atuam na plataforma continental interna podem movimentar as águas devido ao transporte de Ekman e modificar o escoamento natural das águas. Ventos favoráveis a subsidência de água (*downwelling*) estão associados ao transporte de águas para junto a costa enquanto ventos que favorecem a ressurgência de águas (*upwelling*) tendem a favorecer o escoamento em direção *offshore.* Essa relação entre vento e transporte de águas superficiais é comumente discutida e evidenciada pela literatura quando há a presença de uma pluma costeira (Zhang *et al*, 1987; Chao, 1988; Hickey *et al*, 1998; Fong *et al*, 2002).

A região geográfica dita a escala de variação dos ventos. Em áreas extratropicais, o vento tende a atuar em escala sinóptica (variabilidade atmosférica) que está relacionada ao período de 2 a 15 dias, os fluxos são forçados pela passagem de sistemas frontais (Castro e Lee, 1995). De acordo com Mazzini (2009), a brisa marinha também pode afetar a circulação em alta frequência. Além disso, efeitos locais e remotos do vento também podem induzir a padrões de circulação (Möller et al., 2001; Zavialov et al., 2002).

Os fluxos de água resultantes sobre a plataforma interna, ou correntes costeiras, têm um enorme impacto na área costeira. São fluxos ordenados ou não, resultantes da rotação da Terra, ventos e diferenças de densidade e pressão. Fatores como ventos, marés e descargas continentais podem intensificar ou retardar as correntes costeiras em plataforma continental. Estudos relacionados a influência das correntes costeiras em propagação de plumas de rio em plataforma reportam a ação das correntes costeiras de forma independente do vento. Garcia et al. (2002) encontraram em seus estudos que as correntes, mesmo ao redor de 1 m/s, são capazes de intensificar o escoamento de água formado pela pluma ao longo da costa e podem criar um transporte residual contrário ao sentido de propagação da pluma, independente do vento. Hickey et al. (2005) mostram que a orientação das correntes da plataforma afeta a intensidade e o sentido de propagação da pluma costeira do Rio Colúmbia (EUA), de forma independente das diferentes condições de ventos.

Assim, compreender a dinâmica de circulação de plataformas internas continentais envolve compreender seus principais agentes e processos. Por serem áreas próxima à costa e com grande ocupação humana, possuem importante papel socioeconômico. A compreensão da dinâmica desses ambientes é fundamental para pautar importantes questões relacionadas às boas práticas de gerenciamento e manejo costeiro e garantir assim a sustentabilidade dessa ocupação. O estudo da dinâmica de circulação sobre a plataforma interna continental pode ser feito através de ferramentas computacionais de modelagem numérica ou através de análises de medições diretas de propriedades meteoceanográficas.

A plataforma continental do sul do Brasil (entre 28° e 35°S) é uma região com influência de correntes costeiras originadas no extremo sul do continente Sul-Americano e de água doce devido ao aporte fluvial, principalmente, do Rio La Plata e da Lagoa dos Patos. O Rio La Plata, um dos maiores rios da Terra, descarrega no oceano águas de uma bacia de drenagem que cobre uma ampla área da América do Sul. Sua pluma estende-se ao longo do norte da Argentina, Uruguai e sul do Brasil influenciando amplamente os ecossistemas costeiros (Pimenta *et al*, 2015). A intrusão das águas do La Plata na Plataforma Continental Sul do Brasil ocorre ao longo de todo o ano, mas se reduz durante o verão em função dos ventos de nordeste, sendo intensificada durante o inverno (Matano et al., 2014). A Lagoa dos Patos está localizada na plataforma continental do sul do Brasil e é a maior laguna do mundo com aproximadamente 250 km de comprimento e 40 km de largura. Sua porção estuarina se conecta ao oceano Atlântico através de um canal longo e estreito, por onde sai a água salobra da laguna em direção ao mar, formando a pluma da Lagoa dos Patos. A pluma da Lagoa dos Patos é a segunda principal assinatura de gradientes associados à valores de baixa salinidade (Burrage et al., 2008), sendo a primeira, a pluma do La Plata. Durante eventos de fortes vazantes da Lagoa dos Patos, a água doce se mistura à água presente na plataforma, formando uma camada flutuante de baixa salinidade, que pode ser embebida na Pluma do Rio La Plata (Zavialov *et al.*, 2003; Burrage *et al.*, 2008).

A região é bastante estudada devido a sua importância socioambiental, não só em relação a recreação, que movimenta a economia local, mas principalmente pela presença do Porto de Rio Grande, bastante ativo em nível nacional. A presença da pluma é importante para a dinâmica da plataforma continental interna da região, pois é uma feição recorrente sobre a mesma. Contudo, estudos da dinâmica da circulação costeira em plataforma continental interna que se atrelam à dinâmica da pluma da Lagoa dos Patos são limitados a observações de campo (Calliari *et al*, 2009; Reed *et al*, 2009; Holland *et al*, 2009), resultados obtidos através de simulações numéricas (Zavialov *et al*, 2002; Marques *et al*, 2009; Vinzon *et al*, 2009) e análises de imagens de satélites (Hartmann *et al*, 1989). Embora existam estudos baseados em séries temporais de correntes na região (Costa, 2010), as séries são relativamente curtas (poucos meses), e não abrangem tantas propriedades meteoceanográficas. Essas observações obtidas por instrumentos e sensores fixos em plataformas flutuantes (boias) e controlados remotamente, podem fornecer uma série de informações de alta resolução temporal de parâmetros meteorológicos e oceanográficos.

Na região costeira adjacente ao estuário da Lagoa dos Patos, encontra-se fundeada a boia SiMCosta RS-05 a aproximadamente 14 km de distância da boca do canal, na cidade de Rio Grande – RS. Essa boia pertence ao Sistema de Monitoramento da Costa Brasileira (SiMCosta), um sistema observacional integrado que visa o monitoramento contínuo, automático e em tempo real de parâmetros meteorológicos e oceanográficos para estudos oceanográficos, ecológicos e climáticos (Figura 1, página 24 deste documento).

Dessa forma, esse estudo tem como finalidade caracterizar a estrutura e a variabilidade do perfil vertical de correntes em plataforma continental interna, e suas associações aos parâmetros de ventos, salinidade superficial, temperatura superficial e descarga fluvial. Séries temporais, constituídas de dados de propriedades meteoceanográficas obtidos pelos sensores da boia e dados de descarga continental dos principais rios da região, são utilizadas para alcançar os objetivos do estudo.

Capítulo II: Objetivos

Geral:

Analisar a estrutura e a variabilidade do perfil vertical de correntes fornecidos pelo ADCP da boia SiMCosta RS-05, localizada em plataforma continental interna do sul do Brasil, próxima à desembocadura da Lagoa dos Patos, ao longo de onze meses de coleta de dados contínuos, visando aprimorar o entendimento da circulação oceânica local.

Específicos:

1. Caracterizar os parâmetros meteoceanográficos fornecidos pela boia RS05, as massas de água superficiais e a descarga continental da Lagoa dos Patos durante os onze meses de dados coletados, comparando com estudos pretéritos.
2. Analisar a estrutura e a variabilidade do perfil vertical das correntes.
3. Avaliar o papel da maré na variabilidade das correntes.
4. Analisar as semelhanças e diferenças na variabilidade das correntes superficiais, estresse do vento, salinidade e temperatura superficiais.
5. Correlacionar a ação dos ventos com as correntes superficiais.

6. Correlacionar os efeitos da descarga fluvial nas propriedades oceanográficas.
7. Investigar a variabilidade da salinidade e das correntes superficiais durante passagens de frentes meteorológicas.

Capítulo III: Material e Métodos

Conjuntos de Dados

- Dados da boia SiMCosta RS05

Este trabalho baseia-se na análise de dados *in situ* de correntes verticais, vento, salinidade superficial e temperatura superficial obtidos pela boia SIMCosta RS-05, durante 315 dias consecutivos. Os registros horários variam de 15 de dezembro de 2016 a 27 de outubro de 2017. Os dados registrados foram utilizados para investigar a variabilidade dos parâmetros físicos, como também para explicar suas relações nos domínios do tempo e da frequência.

No caso das correntes, o ADCP (Acoustic Doplller Current Profiler) foi programado para medir correntes em 25 bins ao longo do perfil vertical com tamanho de célula de 1m. O ADCP está invertido, com seus transdutores acústicos apontando para o fundo. O equipamento está localizado a 0,5m da superfície livre do oceano e existe uma área em branco de 0,5m, o instrumento mede correntes de 1m de profundidade e abaixo (ou seja: o bin 1 mede correntes de 1 a 2m a profundidade de 1,5m, bin 2 de 2 a 3m na profundidade de 2,5m e assim por diante). Somente dados até o bin 17 foram usados, evitando o uso de dados espúrios próximos do fundo. A corrente de superfície foi obtida pela média das leituras de ADCP nas três células superiores (profundidade variando de 1,5 a 3,5m). Os dados de salinidade e temperatura superficiais foram medidos a 0,5 m da superfície livre do oceano. Os dados de vento são oriundos do anemômetro, instalado a aproximadamente 3,5m da superfície da água.

- Dados de descarga fluvial

A descarga da Lagoa dos Patos foi constituída pela soma dos dados diários de vazão dos rios Jacuí, Taquari e Camaquã, que de acordo com Marques (2005) são os principais afluentes da Lagoa dos Patos. Não foi incluída a vazão do rio São Gonçalo, devido à falta de dados. As descargas diárias de água doce para os sistemas dos rios Camaquã e Jacuí-Taquari foram calculadas usando valores de nível de água medidos pela Agência Nacional de Águas obtidos via (ANA). A análise da descarga continental foi realizada com dados do mesmo período temporal da boia SiMCosta RS05.

- Sensoriamento remoto

Para esse trabalho, imagens de satélites foram obtidas através da plataforma da NASA dos satélites MODIS-Aqua, processadas via software SeaDAS, um pacote abrangente para o processamento, exibição, análise e controle de qualidade de imagens da cor do oceano. Os dias selecionados para a análise das imagens dependeram da cobertura de nuvens. Da mesma forma, foi usado o aplicativo Giovanni da mesma plataforma para fins investigativos na pesquisa, que é um aplicativo baseado na Web desenvolvido pelo GES DISC que fornece uma maneira simples e intuitiva de visualizar, analisar e acessar grandes quantidades de dados de sensoriamento remoto de ciências da Terra sem ter que baixar os dados.

Processamento dos Dados

- Pré-processamento:

Inicialmente, as séries temporais de cada parâmetro foram examinadas para a identificação de *spikes*, *gaps* e de tendência. Para lidar com *spikes* foi feita a inspeção visual, adotando o critério clássico de Chauvenaut que define um intervalo de confiabilidade de ±3 desvios padrão em relação à média dos dados como referência de confiabilidade. Quaisquer valores acima ou abaixo desse intervalo foram eliminados. As lacunas (gaps) de dados foram identificadas nas séries. A maioria das lacunas foram de registros unitários e distribuídos regularmente ao longo de séries temporais. Assim, a interpolação linear foi usada e suficiente para substituir os dados ausentes em todas as séries temporais.

O número total de medições foi de 7607, coletados a cada hora, durante 315 dias consecutivos. Há dois tipos distintos de conjunto de dados obtidos pela boia utilizados no estudo: dados escalares e dados vetoriais. Para dados escalares de salinidade e temperatura superficiais, os procedimentos e análises são diretos. Os dados de descarga continental também se enquadram a este grupo. Já os dados vetoriais de vento e de correntes, que já estão referenciados em relação ao norte verdadeiro, passaram por pré-processamento secundário dividido em duas etapas.

A primeira etapa consiste na decomposição dos dados de velocidade e direção de vento e correntes, em componentes norte-sul (Y) e leste-oeste (X), corrigidos para declinação magnética. A segunda etapa consiste na rotação desses eixos para ajustá-los à linha de costa, que normalmente faz um ângulo em relação ao norte verdadeiro. A boia fornece os dados corrigidos para a declinação magnética e com orientação em relação ao norte verdadeiro. Assim, as componentes zonal e meridional dos vetores foram decompostas em componentes paralelas à costa (longitudinais) e perpendiculares à costa (transversais), de acordo com Miranda et al (2001). Para a região, a rotação foi de 37° (Möller et al., 2001) em direção horário em relação ao norte verdadeiro. Os dados de vento foram convertidos em tensão de vento nas componentes em alongshore (τy) e cross-shore (τx)

(N m^{-2}) (Csanady, 1982): τy $=\rho_{air}\ C_D W_y W$, τx$=\rho_{air}\ C_D W_x W$, onde ρ_{air} = 1,225 kgm^3, C_D= 1,4x10^{-3}), com velocidade de vento medido a 10 metros de altitude. Como o anemômetro (instrumento de aquisição dos dados de vento da boia RS-05) está colocado a 3,3 m acima do nível do mar, a fórmula de Panofsky e Dutton (1984) foi utilizada para calcular os componentes do vento a 10m, assumindo um perfil de vento logaritmo.

- Análise das séries temporais:

Após o pré-processamento, as tendências de cada série foram removidas. Para a caracterização das propriedades, foram calculadas as estatísticas básicas de cada série. A análise das massas de água se deu pelo diagrama TS, através da salinidade e temperatura superficiais. Para o estudo das correntes, todas as análises foram feitas com as componentes paralelas e perpendiculares à costa. Para compreender a estrutura do perfil vertical de correntes, foi analisado a distribuição vertical das correntes nas componentes longitudinal e transversal. Em seguida, foi analisado o perfil vertical médio de velocidade, calculado pela média em cada bin ao longo do perfil.

A análise harmônica das marés foi feita aplicando a metodologia de Pawlowicz et al (2002), utilizado o perfil médio das componentes zonais (u ou para leste) e meridionais (v ou para norte) das correntes, ambas após as tendências removidas, com duas abordagens diferentes. A primeira, o software T_Tide foi usado com as componentes zonal e meridional independentes para separar os constituintes das marés. Em seguida, o mesmo pacote foi usado com a variável complexa (u + iv) para caracterizar, não somente as principais constituintes de marés, mas também para investigar o comportamento das elipses das marés. As correntes de maré foram reconstruídas baseadas nos harmônicos de maré e subtraídas dos dados sem tendência das componentes zonal e meridional de correntes. A corrente resultante (correntes residuais) tiveram seus eixos rotacionados em 37° em direção horária em relação ao norte verdadeiro, obtendo-se assim as componentes longitudinal e transversal à costa. A corrente resultante foi usada nas análises de variabilidade no domínio do tempo e da frequência, bem como a sua correlação com as demais séries temporais das propriedades meteoceanográficas.

A variabilidade e inter-relações das correntes superficiais do perfil e demais propriedades, foram investigadas separando-se os registros em altas e baixas frequências para identificar eventos de alta energia. Nos estudos de baixa frequência, um filtro passa baixo do tipo Lanczos-Cosseno (Thompson, 1983) foi usado para remover períodos inferiores a 40 h, enquanto as variações de alta frequência foram obtidas pela remoção dos dados estimados de baixa frequência dos dados do registro original (sem filtro).

Nos estudos que envolviam a descarga continental da Lagoa dos Patos, similar filtro foi utilizado para remover períodos inferiores a 30 dias. Neste caso, medias diárias foram calculadas para os dados horários meteoceanográficos, seguido da filtragem para remoção de períodos inferiores a 30 dias, antes de estabelecer correlações com a descarga continental.

A análise espectral foi feita em todas as séries meteoceanográficas, usando dados de baixa e alta frequência, para identificar períodos de eventos de alta energia, nas séries temporais, nessas bandas de frequência. A análise espectral foi baseada no método Welch (1967), usando uma janela do tipo Hanning aplicada sobre 1/8 do comprimento total da série, com sobreposições de 50%. Os resultados estimam a média espectral da densidade calculada a partir de estimativas de 15 segmentos. Esse procedimento foi feito para preservar a variação do sinal sob a curva espectral dos dados meteoceanográficos, mantendo a forma de preservação de variância dos espectros, obtendo maior resolução espectral.

Análises de correlação cruzada foram feitas para avaliar a relação entre as séries temporais. Por essa análise estima-se também o tempo de resposta de interação entre as séries. Primeiramente, foi investigado a relação do vento com as correntes superficiais. Em seguida, a relação entre descarga continental com as correntes superficiais e salinidade superficial também foram investigadas usando os dados de baixa frequência (períodos acima de 30 dias). Mesma análise foi feita para investigação das passagens das frentes meteorológicas.

Para esse estudo, as correlações cruzadas foram feitas entre dados horários não filtrados e filtrados (frequência de corte de 40h, associadas a passagem de sistemas frontais de 2 a 15 dias) para ventos e correntes superficiais e avaliar assim a ação do vento na variabilidade das correntes superficiais. Da mesma forma, foi usado dados diários em baixa-frequência (com frequência de corte de 30 dias, associadas ao regime de chuvas locais) para descarga continental e as médias diárias de correntes superficiais e salinidade superficial, buscando entender a ação da descarga continental na variação das correntes superficiais e também compreender a variabilidade da salinidade nessa camada, que pode indicar a presença da pluma costeira na região da boia.

Testes de estacionariedade foram aplicados a cada série temporal (Emery e Thomson, 2001). A função densidade de probabilidade de cada série temporal foi dependente do tempo, portanto todas as séries temporais oceânicas e atmosféricas são não estacionárias. Devido a essa característica, a análise espectral não é a técnica mais apropriada para descrever a variabilidade de processos oceânico e atmosférico não estacionários no domínio da frequência. As séries temporais contêm sinais de diversos fenômenos oscilatórios, com períodos variáveis de dias a meses. Desta forma, a observação os sinais de alta e baixa frequência simultaneamente foram estudados durante o período de 315 dias usando análises de ondeletas (wavelets), com uma adaptação do método de Morlet descrito por Torrence e Compo (1998). As ondeletas nos fornecem informações tanto no domínio do tempo, como na frequência (Liu e Miller, 1996).

Capítulo IV: Artigo científico

Para a obtenção do título de Mestre pelo Programa de Pós-Graduação em Oceanografia Física, Química e Geológica, é solicitado que o discente realize a submissão de pelo menos um artigo científico como primeiro autor em periódico com corpo indexado. Sendo assim, os resultados da pesquisa desenvolvida durante o período de mestrado e a discussão dos resultados serão apresentados em forma de artigo neste Capítulo. O manuscrito, de autoria de Julia Gil dos Santos e Carlos Alberto Eiras Garcia, é intitulado "***Vertical structure and variability of current on the southern brazilian inner shelf***", submetido ao jornal **Regional Studies in Marine Sciences**.

VERTICAL STRUCTURE AND VARIABILITY OF CURRENT ON THE SOUTHERN BRAZILIAN INNER SHELF

1. Introduction

The continental shelf could be defined in geological terms as being a submerged continental part into the ocean. It is usually subdivided as internal platform and external platform, geologically separated by the isobath of 50m (Mendes, 1984). The internal platform, or inner shelf, could be understood in oceanography as a "nearshore region" (Mitchum and Clark,1986). According to Lentz (1995), the inner shelf plays a key role in the overall shelf dynamics because it is the region where the circulation adjusts to the conditions of the coastal boundary.

The main forcing mechanisms that generate and act over water transport dynamics are tides, local winds, impact of freshwater discharge, Coriolis effect and local bathymetry. The time scale of these processes range from semidiurnal (12h) to interannual and they could be deterministic processes (i.e. tidal) or not (i.e. year-to-year variations in wind or river discharge rates) on the water flow variations/variability. Regarding wind action, the time scale variation changes with the geographical area and could act in synoptic scale associated with the passage of frontal systems over the region, where main flows are forced by those passages (Castro and Lee, 1995; Castro *et al*., 2006).

An important impact on the circulation of shelf waters happens when freshwater derived from a hydrographical basin encounters ocean waters. According to McClimans (1988), the seaward expansion of low salinity waters is usually called a river plume, which has its limits given by a front showing differences in water color and the formation of a foam line (Mann and Lazier, 2013; Garvine, 1984). Therefore, the presence of this feature may change circulation patterns due to differences between water properties, causing variation on its physical parameters. This variation is largely due to the differences in salinity. In theory, a coastal river discharging freshwater into a saline environment forms an anomaly in both volume and density, resulting in a characteristic circulation pattern (Soares et al, 2007). Hence, freshwater tends to flow and stay at the surface while ocean water remains at the bottom, which promotes a density gradient along the water profile.

However, several studies demonstrate an opposite behavior in the spread of coastal plumes, with low salinity water flowing with close contact with the bottom (Beardsley and Hart (1978); Ikeda (1984); Chao and Boicourt (1986); Chao, 1988a; Chao, 1988b; Yankovsky and Chapman (1997); Garvine 1999). This opposite circulation pattern is normally associated with hyperpycnal plumes that have large density, while surface advected plumes are often associated with smaller plumes. Hence, a large volume of freshwater discharge can cause freshwater accumulation close to the estuary's mouth, which may occupy the entire water column, and make freshwater flow close to the ocean floor. Changes in the pressure gradient formed by this shift induces changes in the plume orientation, which will be influenced by coastal current circulation nearshore. In addition, tidal currents were reported as an important force in the propagation of plumes near the bottom (Kirincich and Hebert (2005); Guo and Valle-levinson (2007)). Salinity variations, however, could be associated to the river plume, especially at the surface. Regarding mixing process, McClimans (1988) indicates that an important engineering aspect of river plumes is the initial dilution or mixing with seawater, or brackish water, within the estuarine system. Once the plume is formed, its seaward dynamics and behavior will be assigned to the actions of the inner shelf's local current circulation.

The resulting flows over the inner shelf, or coastal currents, have a huge impact on the coastal area. They can be ordered flows or not, stemming from the Earth's rotation, winds and density differences. Problems caused by intense coastal currents associated with gravitation waves and rising sea levels are common and can lead to erosion and flooding in coastal areas, destruction of seaside buildings, as well as siltation of ports and navigation channels (Costa and Möller, 2011). Therefore, the study of coastal currents, the determination of their variability and the involved processes are essential to coastal management and environmental issues.

The hydrodynamic of southern Brazil's inner continental shelf - around 32° S - is still poorly known due to a lack of continuous data, and basic questions concerning the inner shelf circulation still persist. Until recently, the lack of consistent time series was a problem. Most of the local circulation research was made using numerical modeling and just a few studies used direct *in situ* measurements of meteocean data. Most of the studies with *in situ* data used a time series shorter than six months, hence, the seasonal characteristics were not described.

With the implementation of the Brazilian Coastal Monitoring System (SiMCosta) - an integrated observational system aimed at continuous, automatic, and real-time monitoring of meteorological and oceanographic parameters for ecological and climatic studies - the time series analysis gained strength and it became an important ally to answer a few essential questions concerning the inner shelf coastal dynamics.

Therefore, the purpose of this paper is to contribute to a better understanding of southern Brazil's inner shelf coastal current dynamics - based on a vertical current profile variation - located close to Patos Lagoon's mouth, at approximately 32°S latitude. The study focuses on the structure and variability of coastal currents caused by forcing mechanisms, particularly tides, winds, and river discharges. The article is separated in five main topics: (1) description of winds, river discharge and oceanographic properties; (2) current structure and variability; (3) analysis of tidal currents; (4) analysis of surface detided currents and its interaction with local wind and river discharge; and (5) salinity and current variability during winter cold front passages.

2. Description of Study Area

The southern Brazilian shelf is narrow in the northern part (110 km) and widens up to 170 km in the south. The shelf break is located around the 180 m isobath. The inner shelf is dominated by coastal currents originated at Patagonia's coast (Piola and Rivas, 1997) and by the La Plata River discharge (Framinan and Brown, 1996; Guerrero *et al*., 1997; Burrage *et al.*, 2008). The outer shelf is influenced by the western boundary of Brazil Current (Castro and Miranda, 1998), whilst the inner shelf receives freshwater contributions from La Plata River (depending on the season) and Patos Lagoon (Piola *et al*., 2005; Piola *et al*., 2008). The influence of the South Atlantic anticyclone, anticyclones of polar origin, and extratropical cyclones contributes to the high spatial variability of wind circulation at synoptic time scales over the southern continental shelf. The tides in the region are mixed with diurnal dominance, having a mean amplitude of 0.5 m near the entrance area (Herz, 1977), due to an amphidromic point for the M2 constituent situated off the Rio Grande do Sul coast (Vassie 1982). The tidal effects are restricted to both the coastal zone and the estuarine region of the Patos Lagoon (Möller *et al*., 2001).

Patos Lagoon is a shallow and long coastal lagoon, with nearly 275 km of extension. According to Marques (2005), the rivers Taquari and Jacuí (tributaries of the Guaíba river) along with the river Camaquã are the principal tributaries of Patos Lagoon. Möller *et al* (2001) sustain that the rivers exhibit a typical mid-latitude flow pattern with high discharge in late winter and early spring, and low to moderate discharge expected during summer and autumn. The rivers also present large year-to-year discharge variations. Patos Lagoon is connected to the South Atlantic Ocean by a natural channel (modified by training walls) that is close to 1 km wide and 12 m deep (Möller *et al*., 2001). This artificial channel is Patos Lagoon's only runoff, with an annual mean discharge of approximately 2000 m^3/s (Bordas *et al*, 1984), with seasonal averages ranging from 700 m^3/s during summer to up to 3000 m^3/s in spring (Moller *et al.*, 2001), although peaks of 8000 and 12000 m^3/s can be observed during El Niño events (Moller, 1996).

The main lagoon axis is northeast-southwest oriented and coincident with the dominant wind regime. Historical studies reported the lagoon responding to wind forcing (Bicalho, 1883;Malaval, 1922; Motta ,1969), in which NE winds contribute to seaward flow, while southerly winds, mainly those from SW, can produce the opposite effect. Therefore, NE winds are particularly important for the circulation and dynamics of the inner shelf (and buoy site), once them promote plume formation. They are dominant throughout the year, although southerly winds become more important in autumn and winter when the frontal systems constrain coastal water landward more frequently.

The southern Brazilian continental shelf (from 22º S to 34º S) is usually covered with waters involved in southward motion (with the exception of autumn and winter) due to: (1) northeasterly and easterly prevailing winds (except in the autumn and winter); (2) the continental slope in the area is occupied with the southward flow of the Brazilian current and; (3) as a number of studies focused on water mass analysis suggest (e.g. Miranda, 1972; Miranda and Castro, 1979), in all seasons the region is covered mostly by water of tropical origin, indicating the presence of southward advection. An opposite presence of a northward advection was reposted by Zavialov *et al* (2002). In addition, Pereira (1989) has predicted a dominance of southward flow which could only be overridden by sufficiently strong southern winds.

On the other hand, there is an unexpected presence of northward net transport over the shelf that sometimes can be traced as far north as 23°S (Zavialov *et al*., 1998; Campos *et al*., 1996; Piola *et al*., 1999; Stevenson *et al*., 1998). Zavialov *et al* (2002) attribute this northward flow as the Rio Grande Current. Moreover, the region has the well-known entrance of a large amount of freshwater in the coastal zone from Rio de la Plata and from the complex Patos-Mirim Lagoons, which causes a strong impact concerning the shelf dynamics, as it produces a lateral salinity gradient that induces a northward residual flow (Pereira,1989; Zavialov *et al*., 1998) usually modulated by wind action.

Previous studies presented similar conclusions concerning wind as an important forcing mechanism on the area of study (Castelão and Möller, 2006; Möller *et al.*, 2008; Marques *et al.*, 2010). Marques *et al*. (2009) used numerical modeling to investigate the influence of the principal physical forcing factors acting on Patos Lagoon's coastal plume formation and behavior. The importance of winds, acting as the main mechanism controlling the behavior of Patos Lagoon's coastal plume in synoptic time scales, was notable. The authors of such study concluded that winds of moderate intensity can mechanically reverse the plume orientation. They also concluded that the intensity of the river discharge flowing higher than 2000 m^3/s contributes to the coastal plume formation. Marques *et al*. (2010) investigated the importance that straining and advection had on the inside of Patos Lagoon's coastal plume and concluded that northeasterly and northwesterly wind conditions - associated with southwestward and southeastward transportation of the plume - contributes to spreading the brackish waters offshore, increasing the vertical stratification of the coastal area. On the other hand, southeasterly and southwesterly wind conditions, associated with the northeastward transportation of the plume, contributes to the vertical destratification of the inner continental shelf. Close to Patos Lagoon's mouth, the occurrence of stratification/destratification processes is associated with the exchange process, independently of the intensity of river discharge. The authors also concluded that the plume behaves as an hypopycnal plume covering the first meter of depth. Burrage *et al*. (2008) suggested the plume maintains its integrity over the southern Brazilian shelf as a relatively symmetric, ageostrophic, frictionally dominated plume with significant across-shelf, and modest along-shelf development.

3. Data and Methods

The SiMCosta RS05 buoy is located at latitude 32° 17' 45.6" N and longitude -052° 01' 26.4" S, at 20m depth, approximately 14km from the coast and 8km from Barra de Rio Grande (figure 1). The buoy site receives the influence of Patos Lagoon's waters due to the proximity with the coastal lagoon channel (modified by training walls).

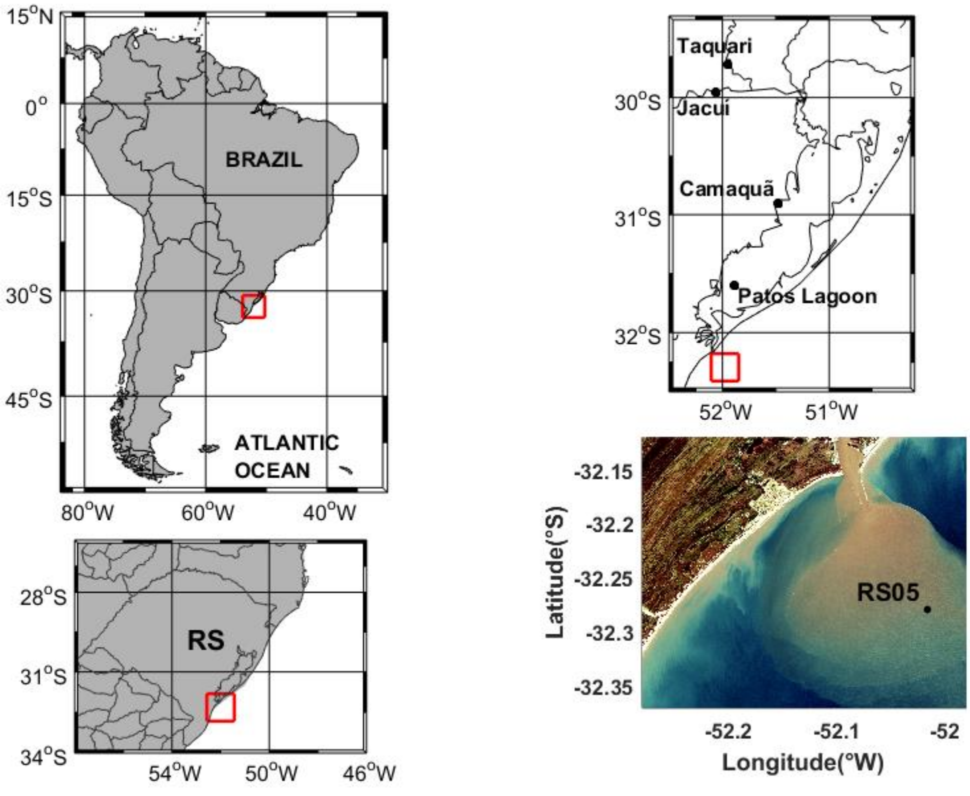


Figure 1 - Study area. The Landsat 8 true color composition image, obtained on August 25 2017, shows the location of the SiMCosta RS05 RS05 buoy, close to the mouth of Patos Lagoon. The plume is clearly seen due to its high content of suspended solids.

This study is based on an analysis of data related to time series of vertical currents, wind, surface salinity, and surface temperature, recorded at an hourly interval during 315 consecutive days by the following instruments on the SiMCosta RS05 buoy: Temperature and Salinity/Conductivity type Seabird SBE 37-SMP, Acoustic Doppler Current Profiler type Nortek Aquadopp Z-Cell 600kHz, and Ultrasonic Anemometer type Gill Instruments WindSonic. The hourly records span from 15-Dec-2016 to 27-Oct-2017.

An inverted ADCP was programmed to measure currents in 25 bins along with the vertical profile with a cell size of 1m. As the head of the ADCP is located 0.5m from the free surface of the ocean, and there is a blank area of 0,5m, the instrument measures currents from 1m deep and below (i.e.: bin 1 measures currents from 1 to 2m at the depth of 1.5m, bin 2 from 2 to 3 m at the depth of 2.5m, and so on). Only data up to bin 17 were analyzed in this study, to avoid the use of spurious data from the bottom. All recorded data were used to investigate the structure and variability of the physical parameters but also to explain their relationships in time and frequency domains. Surface salinity and surface temperature data were measured at 0.5m from the free surface of the ocean. Surface current was obtained by averaging the ADCP readings in the upper three bins (depth varying from 1.5 to 3.5m).

Initially, those data with values well above and below the threshold criteria (± 3 standard deviation) were eliminated. Most of the gaps were unitary and evenly distributed over the time series. Linear interpolation was used to replace missing data. The main gap occurred between 9 and 12 Dec 2016, with 53 hours of extension (representing 0.68% of total time series). The maximum gap found in ADCP measurements represents 3.6% of total time series for current velocity and direction.

Wind and current vectors were decomposed into longitudinal (y) and transverse (x) components, through a magnetic declination correction and a 37° clockwise axis rotation from true north, making the y-component parallel to the coast (alongshore component) and x-component perpendicular to the coast (cross-shore component). The wind data were converted into alongshore (τy) and cross-shelf (τx) wind stress components (Nm^{-2}) (Csanady, 1982): τy $=\rho_{air}\ C_D W_y W$, τx$=\rho_{air}\ C_D W_x W$, onde ρ_{air} = 1,225 kgm^3, C_D= 1,4x10^{-3}) with wind velocities measured at 10 m height. Since the anemometer is placed at 3.3 m above sea level, we assumed a logarithm wind profile (Panofsky and Dutton, 1984) to compute the wind components at 10m.

Basic statistics were calculated for all hydrological, oceanic, and atmospheric parameters. A full tidal harmonic analysis was performed applying the methodology of Pawlowicz *et al.* (2002) using the mean profile of the detrended zonal (u or eastward) and meridional (v or northward) components of the current. The T_Tide toolbox was performed using the complex variable (u + iv) to characterize the tidal ellipses. The tidally driven currents were reconstructed based on the harmonic constituents and subtracted from the detrended zonal and meridional components of the current. The resulted currents had their axes rotated in 37° clockwise from true north to obtain the along- and cross-shore components, which were used to study the structure and variability of currents and their relationship with other properties.

Trends were removed from each time series. A Lanczos-squared low pass filter was used to remove periods shorter than 40h, while the high-frequency variations were obtained by removing the estimated low-frequency data from the original (not filtered) recorded data. Spectral analysis was made using low and high-frequency data to identify periods of high-energy events in the time series. The spectral analysis was based on Welch (1967), using a Hanning type window applied over 1/8 of the series total length with 50% overlap. Therefore, the average of spectral power density was estimated over 15 segments of the time series.

Studies concerned with the relationship between the components of detided surface currents and wind stress were further investigated by means of cross-correlation analysis using original, low- and high-frequency data.

Patos Lagoon's runoff comprehends the sum of daily discharge data from its main tributaries: Jacuí, Taquari, and Camaquã rivers (Marques, 2005). Daily freshwater discharges of the river systems Camaquã and Jacuí-Taquari were calculated using values of water level measured by the National Agency of Waters (Agência Nacional de Águas - ANA).

Stationarity tests were applied to each time series (Emery and Thomson, 2001). The probability density function of each time series was found time-dependent, so all the oceanic and atmospheric time series were considered non-stationary. Hence, the main cycles and the changes in the seasonal pattern were also studied using wavelet analysis with an adaptation of the Morlet wavelet method, as described by Torrence and Compo (1998).

4. Results and discussion

This section is organized as follows: at first, a brief statistical description is provided regarding winds, river discharge, and oceanographic properties; secondly, current structure and variability are examined, followed by tidal analysis of mean current profile. Then, an emphasis is given to surface current variability and its relationship with winds and river discharge, with special focus on the winter period when cold frontal systems crossed the study area.

4.1 Description of winds, river discharge and oceanographic properties

The description of properties and comparisons with previous studies are situated in this section. Only surface currents (mean of bins 1 to 3, varying from 1.5m to 4.5m) was used. Figure 2 shows the 315 days continuous observations of original (not filtered) wind stress (figures 2A and 2B), alongshore and cross-shore currents (figures 2C and 2D), surface salinity (figure 2E), and surface temperature (figure 2F) records.

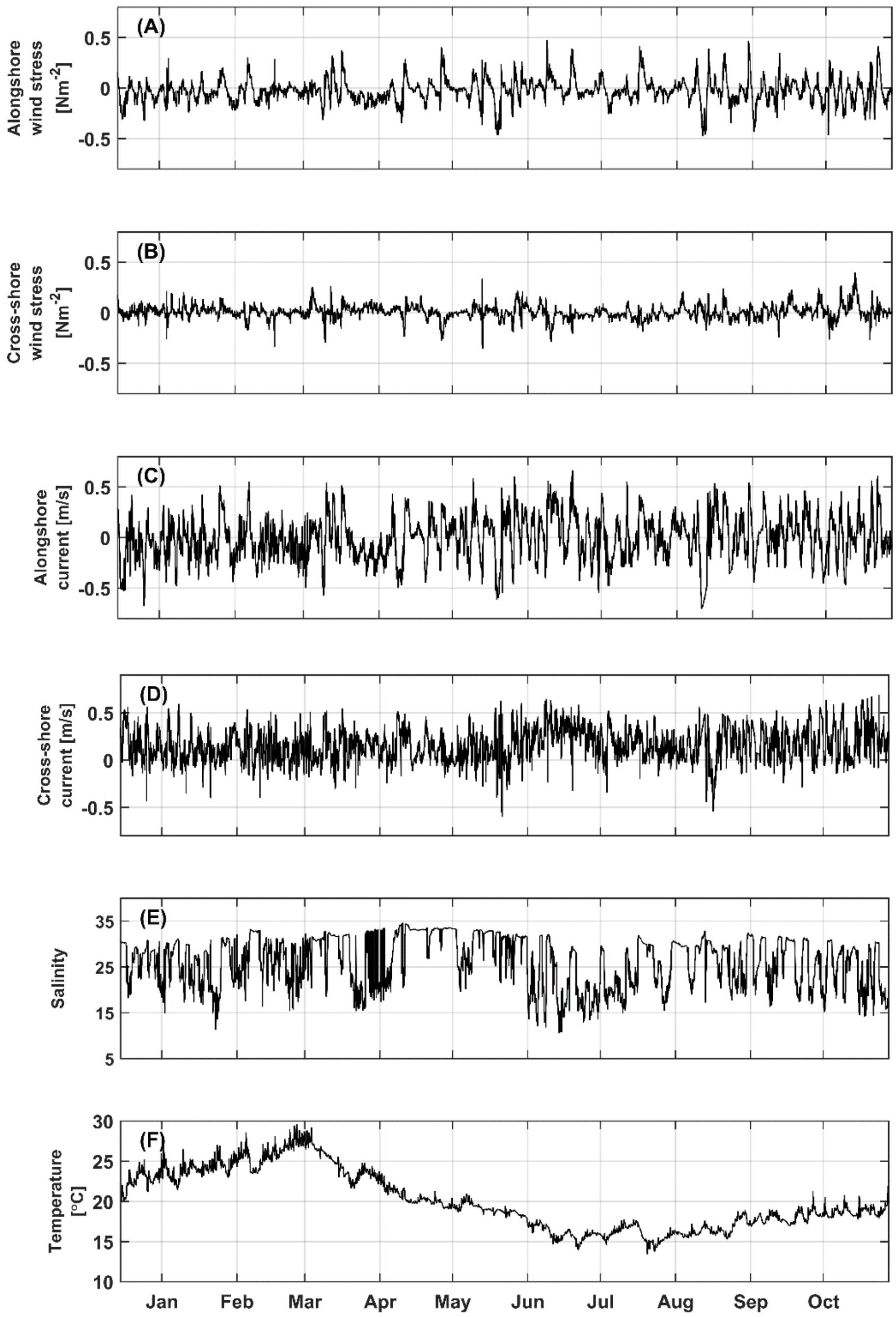


Figure 2 – Hourly time series of: (A) alongshore wind stress; (B) cross-shore wind stress; (C) alongshore surface current; (D) cross-shore surface current; (E) surface salinity and; (F) surface temperature.

The daily freshwater discharges of the river systems Camaquã and Jacuí-Taquari, and mean daily salinity measured at buoy RS05 (figure 3), also presented certain variability within the studied period. The mean daily average discharge over the period was 1984.3 m^3/s, with a standard deviation of 1794.0 m^3/s. The maximum (minimum) daily discharge happened in July (May) with a river discharge of 9345.5 (491.0) m³/s (figure 3). The cross-correlation between daily river discharge and daily salinity was -0.41 ($p<0.05$), indicating that river discharge lead salinity in 11 days. Observe that minimum salinity (figure 3) was reached (middle of June) after the maximum river discharge (beginning of June).

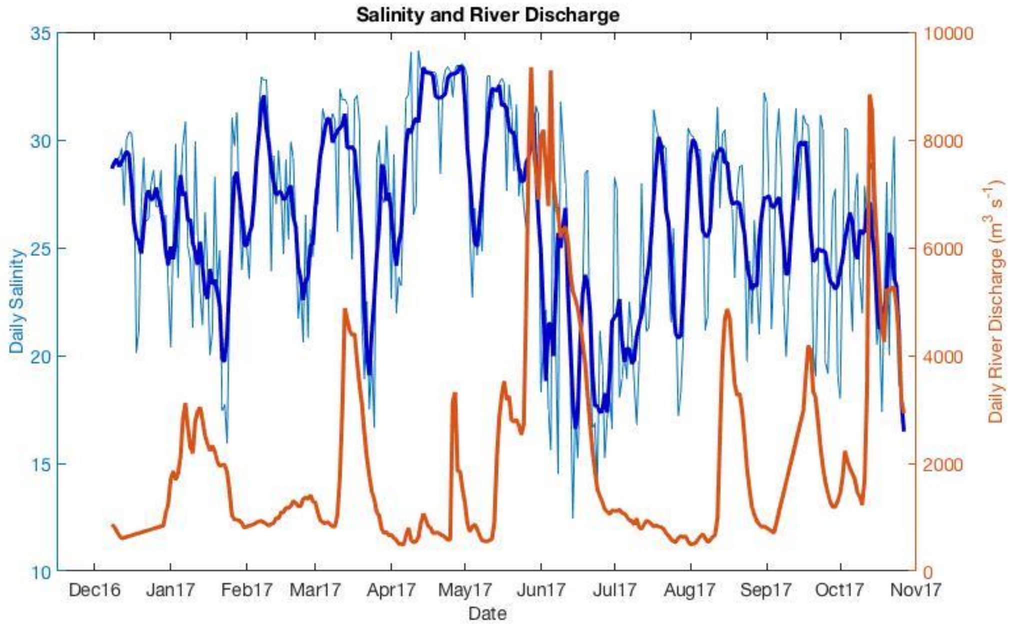


Figure 3 - Time series daily discharge (red line) of river discharge and daily mean salinity (light blue line) at buoy RS05 from 2016 Dec 8 to 2017 Oct 27. The thick blue color is a moving average filter with a 5-day span to smooth the salinity data.

The wind rose (figure 4A) exhibits the well-known prevalence of northwest winds, with the incursion of southwestern winds due to cold frontal systems, while the surface current rose (figure 4B) shows the dominance of southeastern/eastern velocity at the inner shelf, as exposed and discussed in previous studies (Pereira, 1989; Zavialov *et al*. 2002; Marques *et al*. 2009).

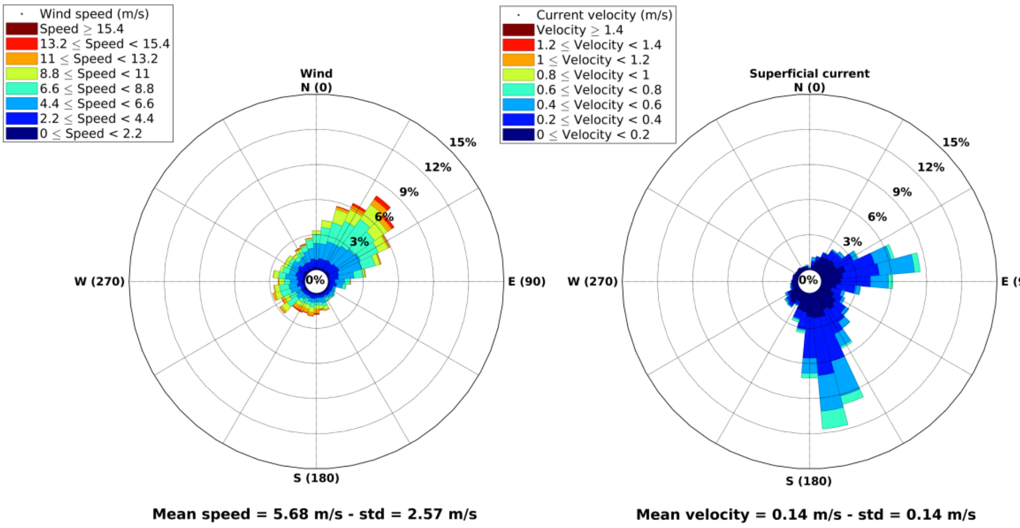


Figure 4 - The (A) wind and (B) surface current roses. Wind follows the meteorological convention and superficial current follow the oceanic convention.

Table 1 presents the basic statistics for the meteocean properties measured by the mooring buoy. The averaged properties over depth and time of each time series suggests negative (southward) alongshore velocity flow of about -0.006 m/s, with negative alongshore wind stress (southward) of about -0.026 N/m^2. The measured data supports the once popular conception of the mean southward flow of tropical origin over the inner shelf.

Table 1 - Basic statistics for alongshore and cross-shore winds, alongshore and cross-shore surface currents, temperature, and salinity for all the time series. Positive (negative) values for both alongshore surface currents and wind stress mean northeastward (southwestward) fluxes. Positive (negative) values for both cross-shore surface currents and wind stress mean southeastward (northwestward) fluxes.

Property	Mean	Standard Deviation	Minimum	Maximum
Alongshore wind stress (N/m²)	-0.026	0.115	-0.472	0.473
Cross-shore wind stress (N/m²)	0.008	0.067	-0.355	0.398
Surface alongshore current (m/s)	-0.006	0.220	-0.704	0.666
Surface cross-shore current (m/s)	0.157	0.170	-0.601	0.694
Salinity	26.218	5.318	10.610	34.570
Temperature (℃)	20.103	3.619	13.410	29.600

On the other hand, a northern flow occurrence was reported in previous studies (Campos *et al*., 1996; Zavialov *et al*., 1998; Piola *et al*., 1999; Zavialov *et al*., 2002). Zavialov *et al*. (2002) is considered the first study with *in situ* data using two current meters, one at 15 and the other at 40 m depth in a mooring station (32°41'S– 51°27'W) for the period of March 4 to August 2, 1997. Contrary to the results showed in Figure 4 on this study, the authors reported a northward current at the Brazilian continental shelf, despite the negative wind stress (southward), using a 151 days long time series for a 15m current analysis. The mooring station in Zavialov *et al*, (2002) is located at 32°17.76'S and 52°1.44' W, 20 nm away from the SiMCosta RS05 mooring buoy. In order to investigate a northern flow occurrence reported by Zavialov *et al*, (2002) and identify possible similar patterns in the behavior of current between their time series and this study, a comparative investigation was made using a similar time period (March 4 to August 2, 2017). The mean depth over the entire series suggests positive (northward) alongshore velocity flow of approximately 1.3 cm/s with negative wind stress (southward) alongshore of about -0.014 N/m². For the time frame of March 4th to August 2nd, 2017, the results are similar to those found by Zavialov *et al.* (2002) and indicate a northern flow occurrence on the Brazilian continental inner shelf in that period.

4.2 Surface water mass

We used both low-frequency (period>40h) surface salinity and temperature to examine the temporal evolution of both properties. Figure 5 shows the TS-time diagram, where surface temperature and surface salinity varied from 13.99 to 28.25ºC and from 11.33 to 35.16, respectively. The colored TS dotted lines are mostly orientated along the horizontal axis (constant temperature), due to the intrusion of Patos Lagoon's plume. Once the plume spread offshore reaching the RS05 buoy, salinity decreases rapidly with a small change in temperature.

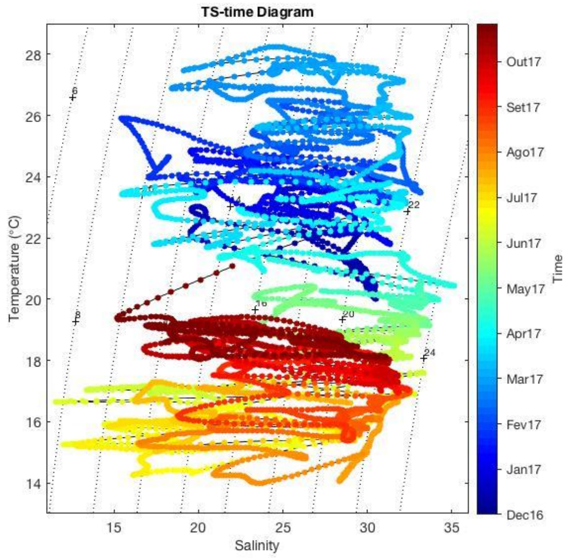


Figure 5 – TS-time diagram.

During wintertime, a combined outflow of La Plata estuary (situated approximately 36º S) and southerly winds originate a buoyant coastal plume (La Plata plume) that extends northward along the Uruguayan and southern Brazilian continental shelf (Piola *et al*., 2008). Depending on wind and discharge conditions, the La Plata plume can reach the southern Brazilian inner continental shelf around 32º S. When this happens, Patos Lagoon's plume is embedded into this low salinity plume derived from La Plata estuary (Burrage *et al.*, 2008). A close examination of TS-time diagram shows thermohaline indices similar to La Plata's plume when Patos Lagoon's plume is away from the RS05 buoy location.

Piola *et al.* (2000) used historical hydrographic data to suggest that in the austral winter La Plata's plume reaches Cape Santa Marta Grande (28º S), while it retracts to 32º S in the summer. Numerical experiments conducted by Pimenta *et al*, (2005) have shown that under steady southwesterly winds around 8 m/s and La Plata flow of nearly 15000 m^3/s, La Plata's plume extended northeastward, reaching 32º S (30º S) after approximately 5 (10) days. A close inspection on alongshore wind records (figure 2C) showed, after a short period (March 18 to April 6 2017) of northeast winds, that several meteorological frontal systems crossed the southern Brazilian region. La Plata's outflow on June 6th 2017, was about 22500 m^3/s (O. Möller, personal communication) and southwesterly winds near 5m/s. Afterwards, a successive meteorological frontal system with southwestern winds crossed the region, which certainly pushed the low salinity further downshelf. The inspection of several of MODIS weekly (4 km resolution) sea surface temperature images from April (figure 6) to August 2017 (not shown) led to believe that La Plata's plume occupied most of the Brazilian inner shelf during most of the winter season and, therefore, Patos Lagoon's plume was embedded into this relatively low salinity plume derived from the La Plata estuary. In other periods of time, the Patos Lagoon's plume was embedded into Subtropical Shelf Water, a mixture of La Plata water and Tropical Water (Möller et al, 2008).

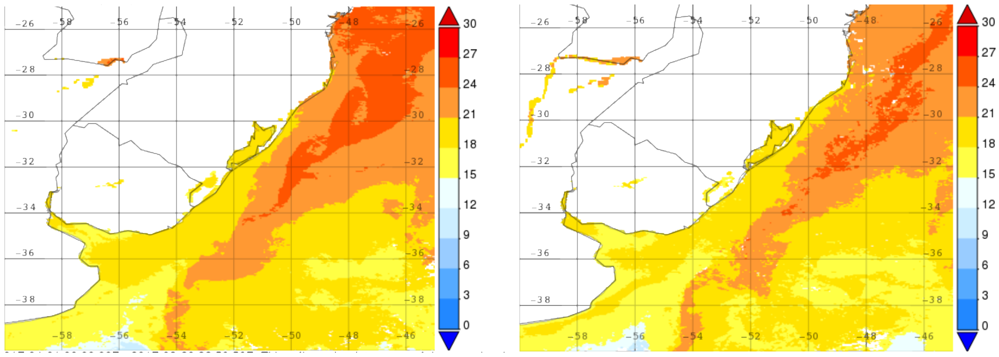


Figure 6 – Weekly (8 days) MODIS SST image showing the La Plata incursion northwards along the southern Brazilian coast. Images are from 6 to 14 April (A) and 22 to 30 (B) April 2017. Source: Giovanni (NASA).

4.3 Current structure and variability

The vertical current profile's structure and variability are discussed in this section using original (not filtered) and low-frequency filtered data. The RS05 buoy is placed at 20m depth but only depths between 1.5m to 17.5m were analyzed (bin 1 to bin 17) to avoid spurious data close to the ocean bottom, as aforementioned. The vertical profile was analyzed using the along- and cross-shore components of current. To understand the vertical profile structure, two approaches were chosen: (a) wind stress and the vertical profile of current velocity in alongshore and cross-shore was made to represent the similarities between wind and the currents' distribution along with the profile. A low-pass filtered data was used to improve visualization and analysis; (b) usage of the mean vertical profile to understand the main flow along with the profile (bins 1 to 17).

Figure 7 shows the wind stress and vertical distribution of currents in alongshore (7A and 7B) and in cross-shore (7C and 7D). Isoline zero represents changes in the flow's direction. It can be intuitively observed that both vertical distribution profiles are intermittent and vary quite often through time. The vertical distribution in the alongshore component exhibit a similar behavior to the profile with slightly larger (smaller) velocities in surface/intermediate (bottom) waters. The southern main flow seems predominant, especially during December to May which has higher velocities in intermediated waters. In mid-June to October, southern flows are more intense and are associated to the typical seasonal cold front passages. Northern flows were predominant during mid-June. In addition, the results point out similarities between variations in wind and the vertical distribution in alongshore (7A and 7B). Strong NE winds events (peaks close to -0.4 Nm^{-2}) are associated with more intense southern main flow, as observed between May and June and between August and September. Likewise, the main peaks of southern winds (peaks close to 0.2 Nm^{-2}), are associated with northern flows.

On the other hand, the cross-shore velocities behave differently than in the alongshore. Overall, velocity variations were close to zero throughout time and, consequently, smaller (7C). Differently from what is observed in alongshore velocities, in which velocities are similar along the profile, in cross-shore component, velocities exhibit sometimes the same flow orientation along with the profile. Although, mostly surface waters have different or opposite orientation comparing to intermediate and bottom velocities. In general, the first half of the vertical profile (1.5m to 10.5m depth) presents eastern oriented velocities, while the second half (10.5m to 17.5m depth) exhibits a western orientation. This behavior is particularly visible during austral winter (June to September) and may be associated with river discharges. Zavialov *et al*. (2002) reported a drastic decay on currents during the austral winter, time in which no significant reduction of wind forcing was evident. They hypothetically attributed this to the impact of a very stable salinity-controlled stratification that forms in a narrow subsurface layer due to enhanced river discharges from Patos-Mirim and Plata estuaries, effectively isolating deeper layers from the atmospheric forcing. A decrease in monthly average in salinity was found during Austral winter, which might be associated with cross-shore current behavior. Similarities between cross-shore wind and the vertical distribution (7C and 7D) are not easily observed as in alongshore component.

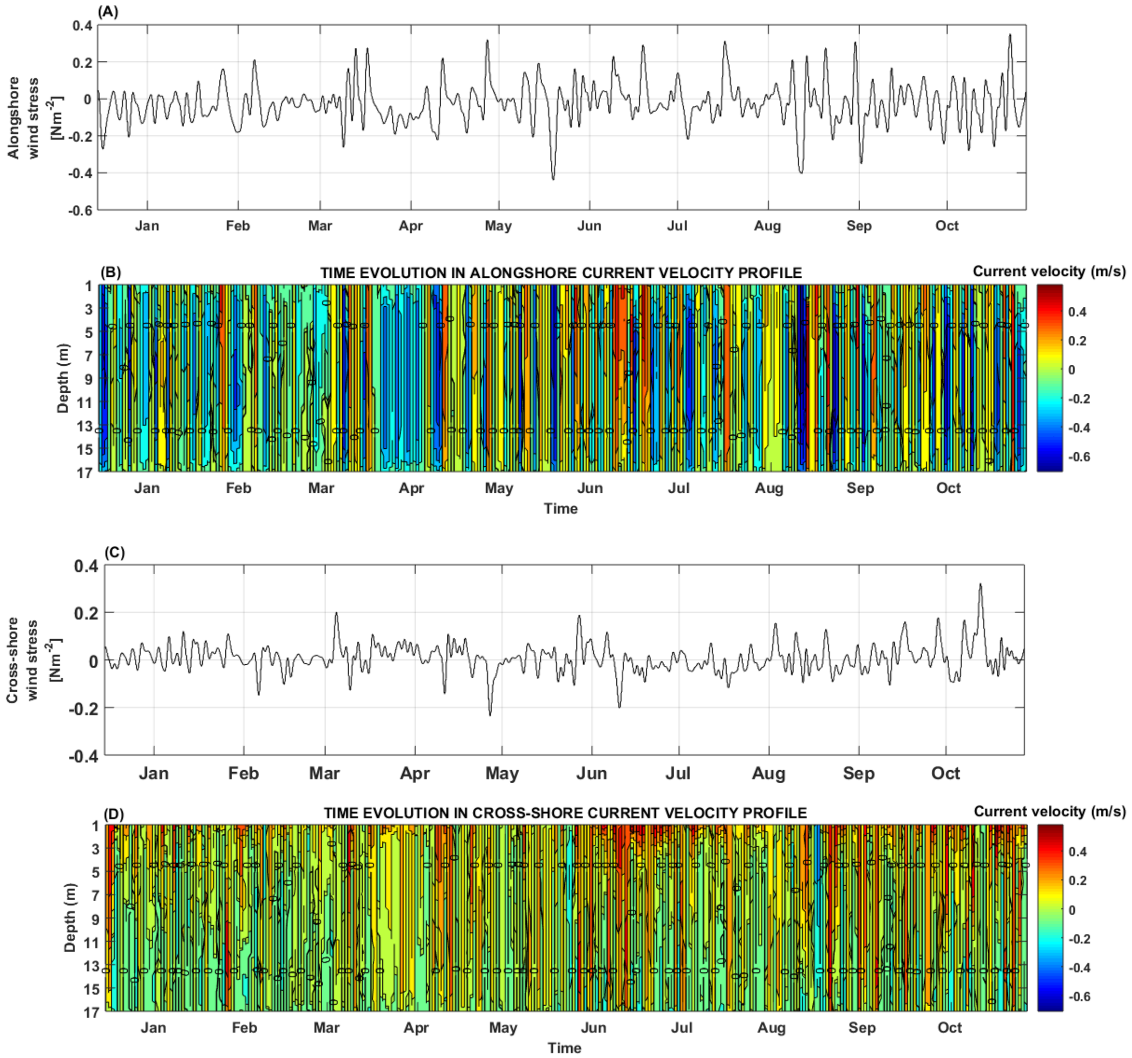


Figure 7 – Wind stress in alongshore (A) and vertical distribution of the alongshore (B). Wind stress in cross-shore (C) and vertical distribution of the cross-shore (D). The components data were filtered using a Lanczos low-pass filter (periods>40 h).

The wind stress and mean vertical profile for alongshore and cross-shore velocities in the entire time series (figure 8) show negative and positive values for the alongshore (southwestward flow) and cross-shore (southeastward flow) components, respectively. The mean alongshore current in the water column is -3 cm/s for the entire period (figure 8A). The overall southward oriented current has been found in previous studies in the Brazilian southern inner shelf where the buoy is located (Palma *et al*., 2008; Costa and Möller, 2011). The mean cross-shore current for the entire period (figure 8B) has shown dominant positive (southeastward) values with larger velocities in surface waters. The mean cross-shore current in the water column is 7 cm/s for the entire period. The vertical distribution of alongshore and cross-shore currents were not uniform from surface to bottom. Wind and bed stresses change the mean current profile in the near-surface and bottom, respectively. Slightly higher velocities are found in intermediate depths. The mean cross-shore vertical profile is southeastward oriented with smaller velocities (close to zero) near the bottom. Continental discharges also contribute to the variability of surface currents in the locality.

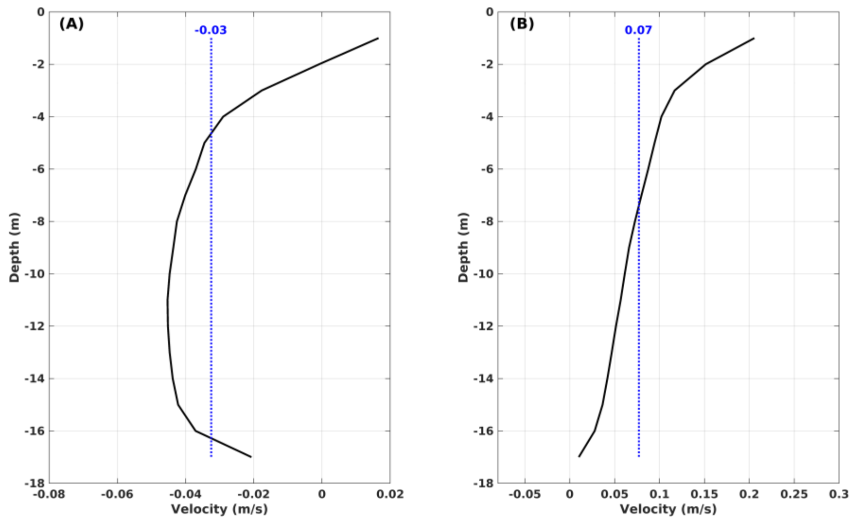


Figure 8 - The mean vertical of (A) alongshore and (B) cross-shore currents for the entire 315 days period. Positive (negative) alongshore currents are directed to the northeast (southwest) while positive (negative) cross-shore currents are southeastward (northwestward). The vertically averaged values are shown in dashed blue vertical lines.

4.4 Analysis of tidal currents

Tides are one of the main forcing mechanisms acting on the inner shelf's circulation and they may have a great influence on the vertical current profile variability. To investigate tidal influence on current variability, a harmonic analysis was made using T_Tide toolbox (Pawlowicz *et al*, 2002). Only constituents whose signal to noise ratios (SNR) are greater than 5 were considered as significant in this work. We used the original (not filtered) data of both mean zonal and meridional currents in the tidal analysis.

Table 2 shows the tidal constituents and ellipse parameters. The diurnal tidal constituent O1 (major amplitude = 3.81 cm/s) confirms as dominant for the location, followed by M4 (1.82 cm/s), K1 (1.80 cm/s) and M2 (1.42 cm/s). The tidal current resulting from the combination of the ten main tidal constituents can explain only 1.7% of the total variance of current, a clear indication that tides play a negligible role in the local current variability. Similar results were found in previous works (Möller *et al*., 2001; Costa and Möller, 2011; Zavialov *et al*., 2002), in which tidal currents were seen as very weak and predominantly diurnal. Note that the M4 amplitude (and energy) is higher than its parental M2 amplitude. Green *et al* (2018), using Topex TPXO9 data, found that the beat of the diurnal spring-neap and the semi-diurnal spring-neap cycle is very close to the period of M4. Therefore, an increase in M4 amplitude is expected when a timed combination exists between M4 and both the diurnal neap and semi-diurnal spring cycle. Our results agree with Green *et al.* (2018).

Table 2 – Ellipse characteristics from harmonic tidal analysis of currents (u + iv) at the location at SiMCosta RS05 buoy location.

Tidal	Frequency (Hz)	Period (hours)	Major axis (cm/s)	Minor axis (cm/s)	Inc (degree)	Pha (degree)	SNR
O1	0.0387307	25.81	3.81	-0.59	41.90	139.32	52
K1	0.0417807	23.93	1.80	-0.28	35.30	330.59	11
M2	0.0805114	12.42	1.42	-0.01	44.98	50.96	23
S2	0.0833333	12.00	0.72	-0.06	103.39	109.56	6.2
MN4	0.1595106	6.26	0.95	-0.06	25.00	323.09	20
M4	0.1610228	6.21	1.82	-0.33	17.41	8.89	73
MS4	0.1638447	6.10	0.64	-0.13	32.83	92.35	9.1
2MN6	0.2400221	4.16	0.38	0.04	35.38	249.76	8.5
M6	0.2415342	4.14	0.54	0.11	39.51	291.3	17
2MS6	0.2443561	4.09	0.51	0.08	54.23	20.77	15

Obs.: The ellipse parameters are frequency, period, amplitudes of the major and minor axes, inclination, and phase. Positive values of minor axis mean clockwise current circulation along the ellipses and negative values are associated with counterclockwise current circulation. The parameter pha is the ellipse phase (relative to Greenwich) of the major axes. Inc is the angle of the major axes relative to the east, being positive counterclockwise. SNR stands for signal to noise ratio. Percent total variance predicted/variance original = 1.7%. A positive minor axis means clockwise circulation. Only constituents with SNRs ≥ 5 are listed.

The power density spectra of the original and detided current data (figure 10) for both zonal (figure 10A) and meridional (figure 10B) components have shown peaks associated with periods of diurnal (D), semi-diurnal (SD), quarter-diurnal (QD) and sixth-diurnal (D/6) tidal constituents. The diurnal harmonic is the most expressive followed by the quarter-diurnal and semi-diurnal, respectively. The detided current was calculated by subtracting the tidally-driven currents from the original (not filtered) data.

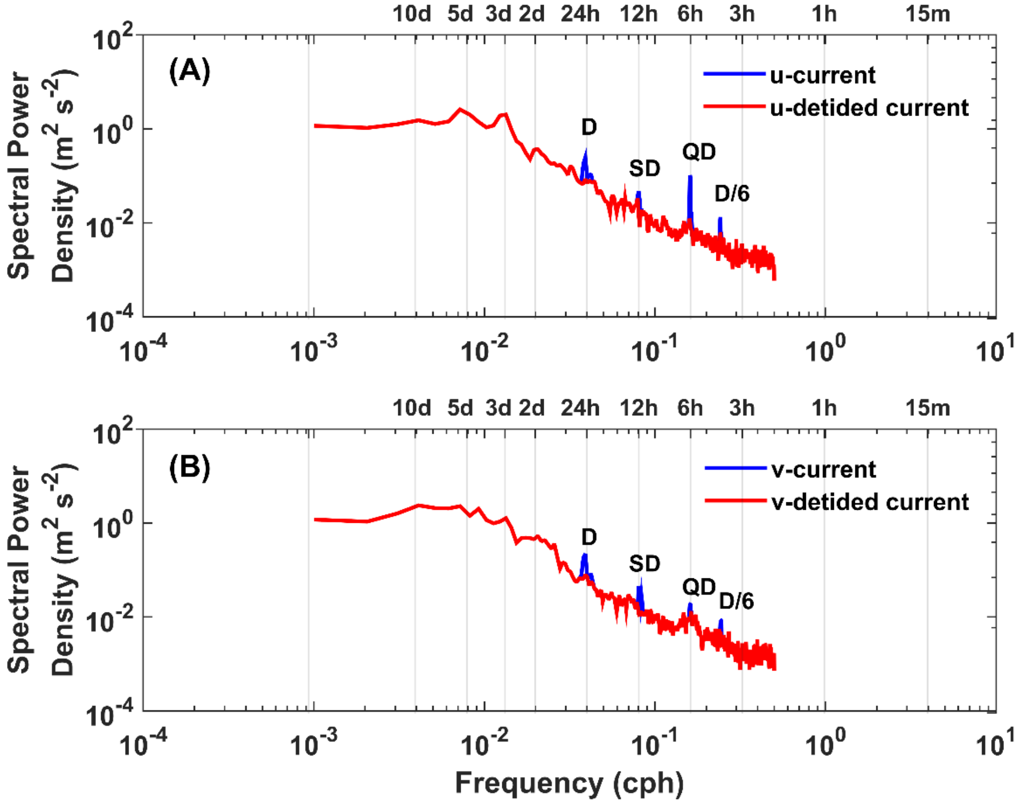


Figure 10 – The spectral power density of the mean zonal (A) and mean meridional (B) components of current. Original and detided mean currents are in blue and red lines, respectively. The diurnal (D), semi-diurnal (SD), quarter-diurnal (QD), and sixth-diurnal (D/6) frequencies are shown in the figure.

4.5 Analysis of surface current variability

This section is organized in three cases: 1) the structure and variability of surface currents (mean of bins 1 to 3, varying from 1.5 to 4.5m) and their differences and similarities with wind stress, salinity, and temperature; 2) the impact of wind and 3) river discharge on surface currents. We used only the detided along- and cross-shore surface currents in the analysis.

In cases 1 and 2, periods of high-energy events in the time series were identified through spectral analysis using low (period ≥ 40h) and high (period ≤ 40h) frequency filtered data. In case 3, high-energy events periods in the time series were identified through spectral analysis, as well as using original data. Finally, wavelet analysis was made using original (not filtered) data to investigate the main cycles and the changes in seasonal patterns of all the time series.

Afterwards, wind stress and river discharge action on surface currents are further investigated utilizing cross-correlation analysis using hourly data. The lagged cross-correlation was calculated between low-frequency (period ≥ 30 days) daily river discharge and daily averaged surface.

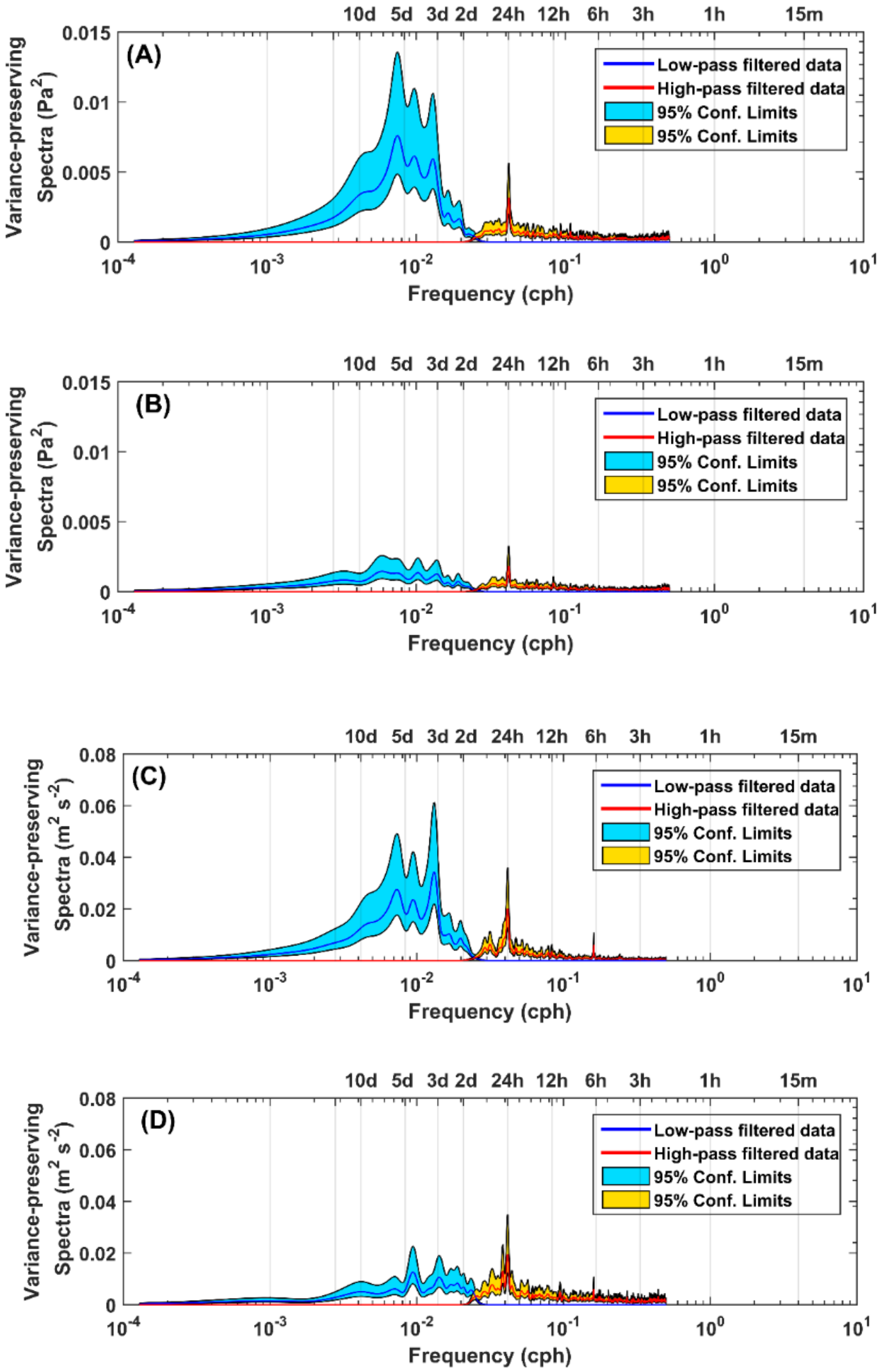
4.5.1 Surface currents

To preserve the meteocean signal variance under the spectral curve, we decided to use the variance-preserving form of the spectra for the wind stress, surface detided current, surface salinity, and surface temperature (figure 11). The surface temperature analysis (not show) presented a strong signal at low frequencies due to seasonal variation in solar radiation, we removed this seasonal signal from the time series. All the time series presented similar frequency patterns indicating the prevalence of high-energy events in common frequencies.

In the low-frequency band (period > 40h), periods of approximately 3 to 10 days for all the time series were common for both alongshore wind (figure 11A) and current (figure 11C). The salinity preserving-variance spectrum (figure 11E) also presented a peak of around 11 days. The above time series presented common main peaks in 3 and 5.5 days. On the other hand, no relevant energy was found in the low-frequency temperature (figure 11F), cross-shore wind (figure 11B) and surface cross-shore current (figure 11D) spectra.

In the high-frequency band (period < 24h), the alongshore and cross-shore wind stress spectra have shown peaks at 24h, which is associated to sea breeze (figure 11A and 11B). Both mean along- and cross-shore component spectra (figure 11C and 11D) also presented a 24h peak, however, the most energetic peak is associated to the mean cross-shore current. The influence of wind as the main forcing mechanism acting on the local circulation was mentioned in previous studies (Castelão and Möller, 2006; Möller *et al.*, 2008; Marques *et al.*, 2009; Marques *et al.*, 2010). Since we are using detided currents, the existence of a 24h energy peak, especially for the cross-shore component, suggests the existence of a daily forcing circulation associated to wind behavior.

The salinity preserving-variance spectrum (figure 11E) shows high-energy events with periods of nearly 12 to 36 hours, with the main peak at 24h as well, while the temperature spectrum (figure 11F) shows high-energy events with periods at 12 and 24h, which are related to daily variation of solar heating.



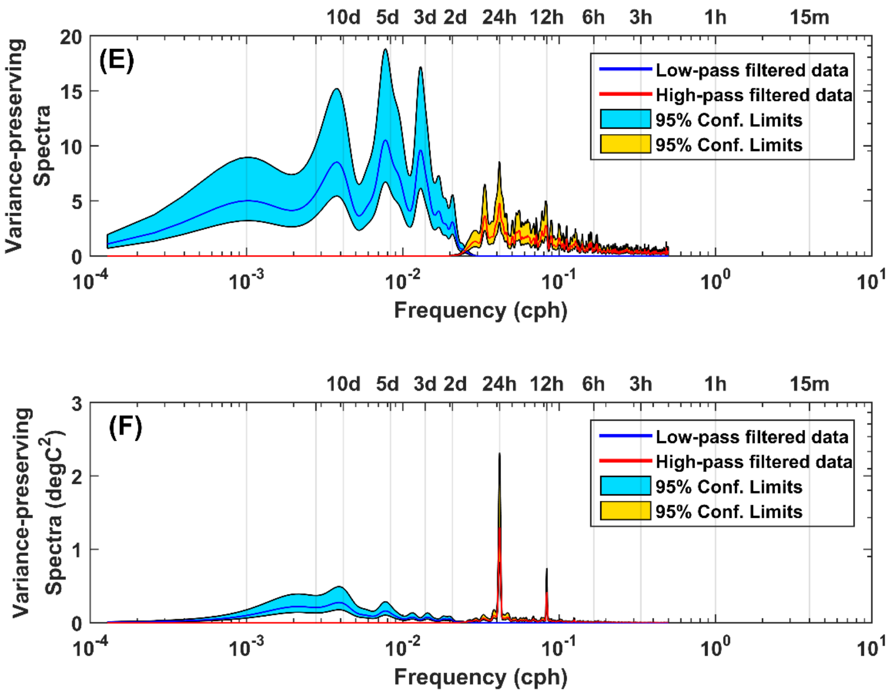


Figure 11 – The variance-preserving spectra for the low (in blue) and high-frequency (in red) filtered data: (A) alongshore wind stress, (B) cross-shore wind stress, (C) alongshore detided surface current, (D) cross-shore detided surface current, (E) surface salinity, and (F) surface temperature (after removal of seasonal variation).

The results of the wavelet analysis using the data of detrended time series indicates the importance of low-frequency processes and, once again, it highlights that the most important events occurred in periods shorter than 8 days (figure 12), except for the temperature time series (figure 12F). The main energetic peak occurred at approximately 5.5 days, coincident with the well-known passage of meteorological systems, that can vary from 3 to 17 days (figure 12A) over the study region (Möller *et al*., 1996, 2001; Fernandes *et al*., 2001, 2002, 2004, 2005; Castelão and Möller, 2006; Marques *et al*., 2010). The local energy spectrum of the alongshore wind stress shows maximum intensities between August to October and minimum between February and March (figure 12A). Similar patterns are found in surface currents and surface salinity (figure 12C e 12D).

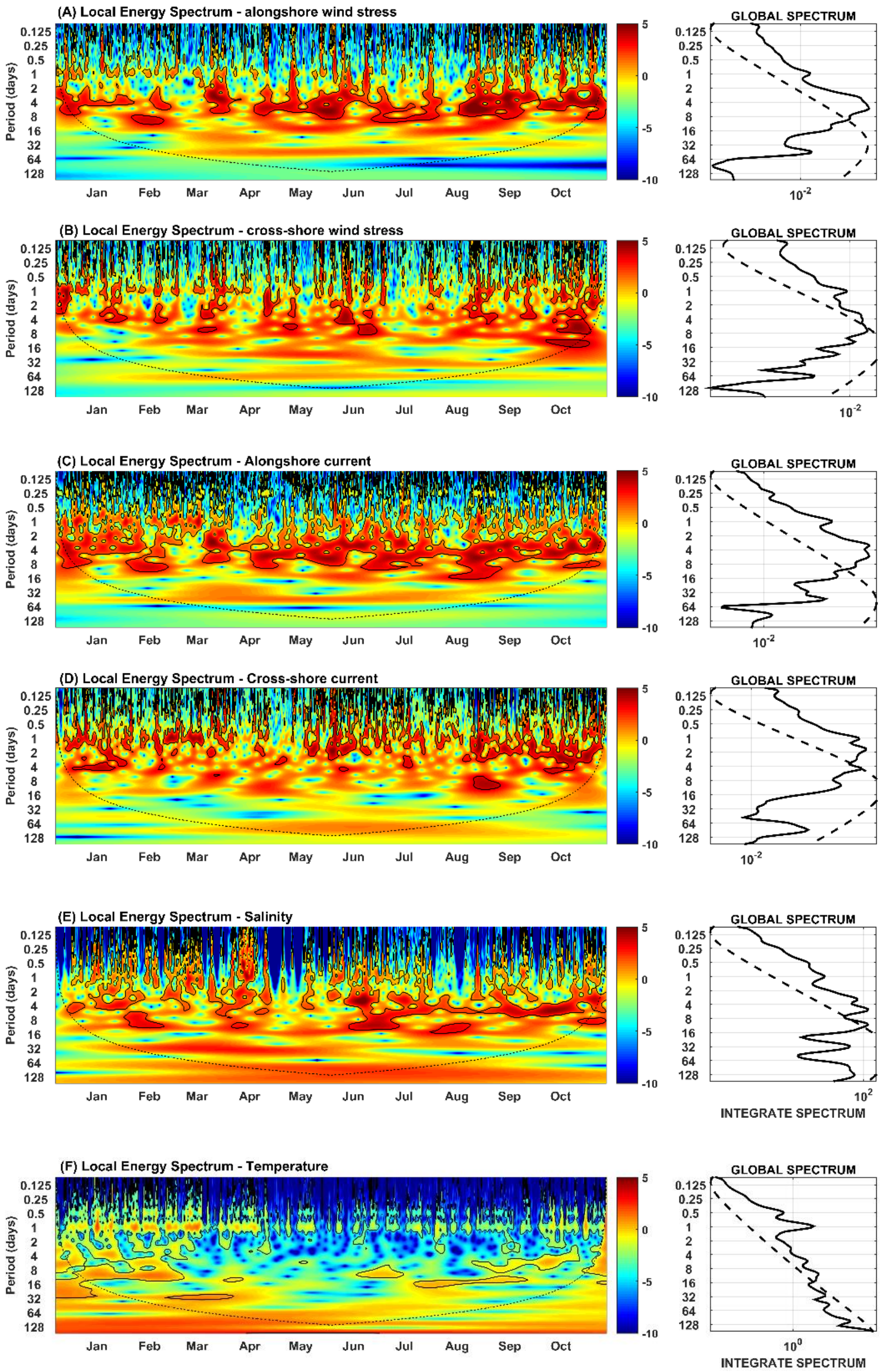


Figure 12 - The local wavelet power spectrum of original (not filtered) time series using Morlet wavelet for (A) alongshore wind stress, (B) cross-shore wind stress, (C) alongshore detided surface current, (D) cross-shore detided surface current, (E) surface salinity, and (F) surface temperature. Thick contour lines enclose regions of greater than 95% confidence for a red noise process with a lag 1 coefficient of 0.25. Cross-hatched regions indicate the cone of influence where edge effects become important. To the right of each local spectrum, the global wavelet power spectrum of the time series where the dotted lines indicate the 95% confidence level. The wavelet spectra for currents refer to surface currents.

4.5.2 Wind action on surface currents

Wind stress impact on surface currents are further investigated using temporal cross-correlation between original, low- and high-filtered hourly data, in four different scenarios: 1) both alongshore wind and current; 2) both cross-shore wind and current; 3) alongshore wind and cross-shore current and; 4) alongshore wind and cross-shore current.

The lagged cross-correlations between both alongshore wind and current have shown maximum positive correlation for original ($r = 0.77$, $p<0.05$) at lag 3h, low-frequency ($r = 0.83$, $p<0.05$) at lag 5h, and high-frequency filtered data (0.65, $p<0.05$) at lag 3h. On the other hand, weakly negative correlations between both cross-shore wind and cross-current were found for original (-0.23, $p<0.05$), low-frequency (-0.27, $p<0.05$) and high-frequency (-0.19, $p<0.05$). Alongshore winds were even less correlated with cross-shore currents.

The results highlight the importance of alongshore wind in the local circulation with surface waters quickly responding to wind action. On the other hand, the cross-shore wind has little impact to the local circulation. Previous studies reported similar results (Zavialov *at al*., 2002; Marques *et al*., 2009). Consequently, surface circulation along the coastline is mostly driven by the alongshore wind while cross-shore surface circulation is partly driven by wind and may suffer the influence of other forcing elements, such as continental discharge. The results suggest that superficial waters' circulation in the buoy site follows the standard pattern, in which the wind plays a relevant driving mechanism for surface currents and coastal plumes (Piola *et al*., 2005; Zavialov *et al*., 2002; Möller *et al*., 2008).

4.5.3 River discharge effects on oceanic properties

In this section, the effects of daily river discharge on daily oceanographic parameters are discussed. In this case, the sum of daily discharges of Jacuí, Taquari, and Camaquã rivers was employed, while the hourly surface salinity, wind stress, and surface currents were converted into daily averages prior to the analysis. Then, lagged cross-correlations were calculated between daily river discharge and daily averages of surface salinity, alongshore and cross-shore components of wind stress and surface currents.

Regarding the relationship between total river discharge and salinity, a negative correlation is expected based on the proximity of the buoy site to the mouth of Patos Lagoon, since higher discharges imply flows towards the sea and, consequently, lower salinities at the buoy site. A negative correlation ($r = -0.41$, $p<0.05$) was found between daily river discharge and daily salinity records, with discharge leading salinity by 11 days. A good lagged cross-correlation ($r = 0.68$, $p <0.05$) between river flow and sea level at Rio Grande tide station was found using data from Dec 1st, 2016 to Nov 30, 2017 with a lag of 10 days (O. Möller, personal communication). Because freshwaters from Jacuí, Taquari, and Camaquã rivers had to flow along the Patos Lagoon to reach the buoy position, a temporal delay exists in records of river discharges and salinity at buoy RS05. Those results suggest that freshwater flows, measured at the three main tributaries, took 10 days to the tide station and an extra day to reach the RS05 buoy.

However, salinity variation can be influenced by other factors as well, such as advection of water masses, tides, evaporation, precipitation, and wind-driven advection and mixing (Whitney, 2010). The La Plata plume can propagate northwards depending on wind and discharge conditions (Piola *et al*., 2005; Pimenta *et al*, 2005) lowering salinity records at the RS05 position in a certain period of the year. Tidal effects are minimal in the region. Evaporation and precipitation can also be negligible compared to the very dynamic process caused by wind that might play an important rule on the behavior of Patos Lagoon's plume, and therefore, on the high-frequency salinity data.

For instance, previous studies (Malaval,1922; Motta, 1969; Möller *et al*, 2001) reported that Patos Lagoon's discharges respond to wind forcing in a way that northeast winds contribute to lagoon "emptying", producing a seaward flow, while southerly winds, mainly those from southwestern, produce the opposite effect. These effects of wind on the outflow of Patos Lagoon occur at a temporal scale of hours (Möller *et al.*, 2001), which can be undetected within the daily mean river discharge. The results indicated that river discharge acts as an important factor in salinity variations at RS05 buoy's position because lower (higher) surface salinity records were associated with fresh (oceanic) waters. Wind forcing also plays a significant impact on salinity records at RS05 buoy, which will be further examined in the next section.

4.6 Variability of salinity and currents during the passages of cold frontal systems

The results of the spectral and wavelet analysis indicate that winds are the main physical forcing mechanism acting on oceanic property variability. The dominance of north quadrant winds over the study region contributes to the prevailing southwestward migration pattern of the plume, while the passage of frontal systems over the area tends to transport the brackish waters to the north of Patos Lagoon's mouth. The time scale of this spreading is less than 1 day (Marques e*t al*, 2010).

To illustrate how wind stress and surface currents acted over Patos Lagoon's plume, we examined the plume's behavior during the passages of five frontal systems between June to mid-August 2017 using true color composition of MODIS-Aqua images. The cloud-free images were obtained before and during (or just after) the passage of each meteorological event. The five (F1 to F5) frontal systems crossed the study area in the following periods: 08 Jun 2017 to 13 Jun 2017 (F1), 17 Jun 2017 to 21 Jun 2017 (F2), 29 Jun 2017 to 02 Jul 2017 (F3), 15 Jul 2017 to 22 Jul 2017 (F4) and 08 Aug 2017 to 10 Aug 2017 (F5). During this approximately 2.5-month period, the hourly winds, surface salinity, and surface currents were fully investigated.

Figure 13 shows the time series of surface salinity (figure 13A), alongshore and cross-shore wind stress (figures 13B and 13C, respectively), alongshore and cross-shore surface currents (figure 13D and 13E, respectively). The periods of the 5 cold front passages are highlighted (figure 13).

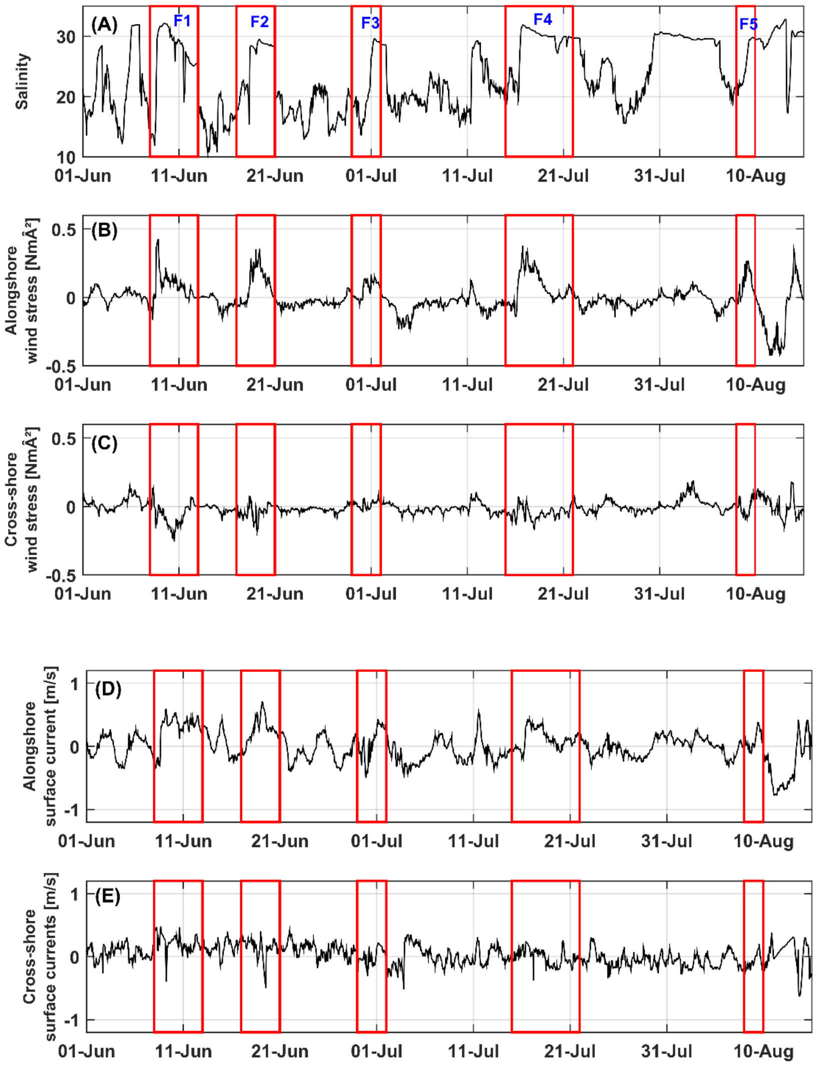


Figure 13 – Time series of: (A) surface salinity; (B) alongshore wind stress; (C) cross-shore wind stress; (D) alongshore surface current and; (E) cross-shore surface current. Fronts 1 to 5 are highlighted by the red squares.

Overall northeasterly winds prevailed before all 5 cold front passages. The beginning of the 5 frontal passages was characterized by southernly winds which resulted in currents towards the northeast. Salinity values were low before the frontal passages because RS05 was immersed in Patos Lagoon's plume (figures 14A and 14C). For instance, before the first front passage, Patos Lagoon's plume was southwestward oriented (figure 14A). During its passage, wind stress and surface current turned northeastward (figure 13B and 13D), with an increase in salinity (figure 13A) due to the displacement of brackish waters towards the northeast (figure 14B). Similar behavior of winds, current, and plume displacement occurred during the passage of front 2 (figure 14C and 14D).

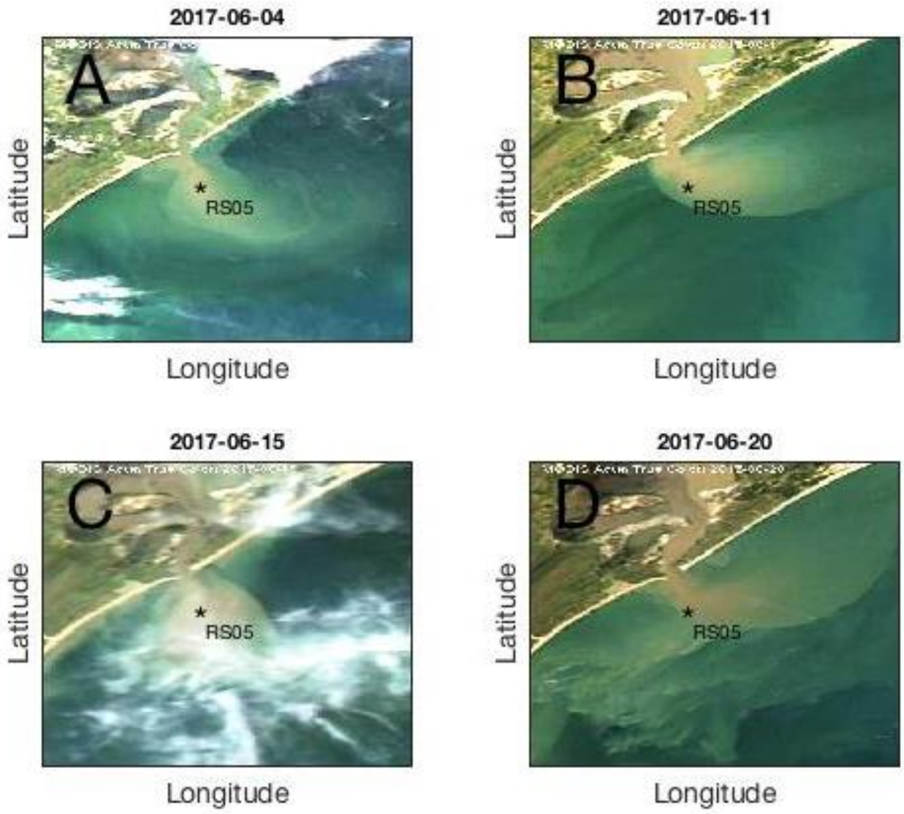


Figure 14 –True color AQUA/MODIS images before (A) and during (B) F1 passage (right) and before (C) and during (D) F2 passage. Duration of Front 1: 2017-06-04 to 2017-06-13. Duration of Front 2: 2017-06-29 to 2017-07-02.

Northeasterly winds were also predominantly present before the passage of fronts 3, 4, and 5 (figure 13B), with surface currents flowing towards the northwest (figure 13D) and a southwestward-oriented plume (figures 15A, 15C and 15E). During the passage of frontal systems 3 and 4 (figures 15B and 15D), winds were blown from southwest, currents changed to northwestern, and the plume spread northwestward. In the case of cold front 5, Patos Lagoon’s plume was attached to the coastline at the end of the front’s passage (figure 15F).

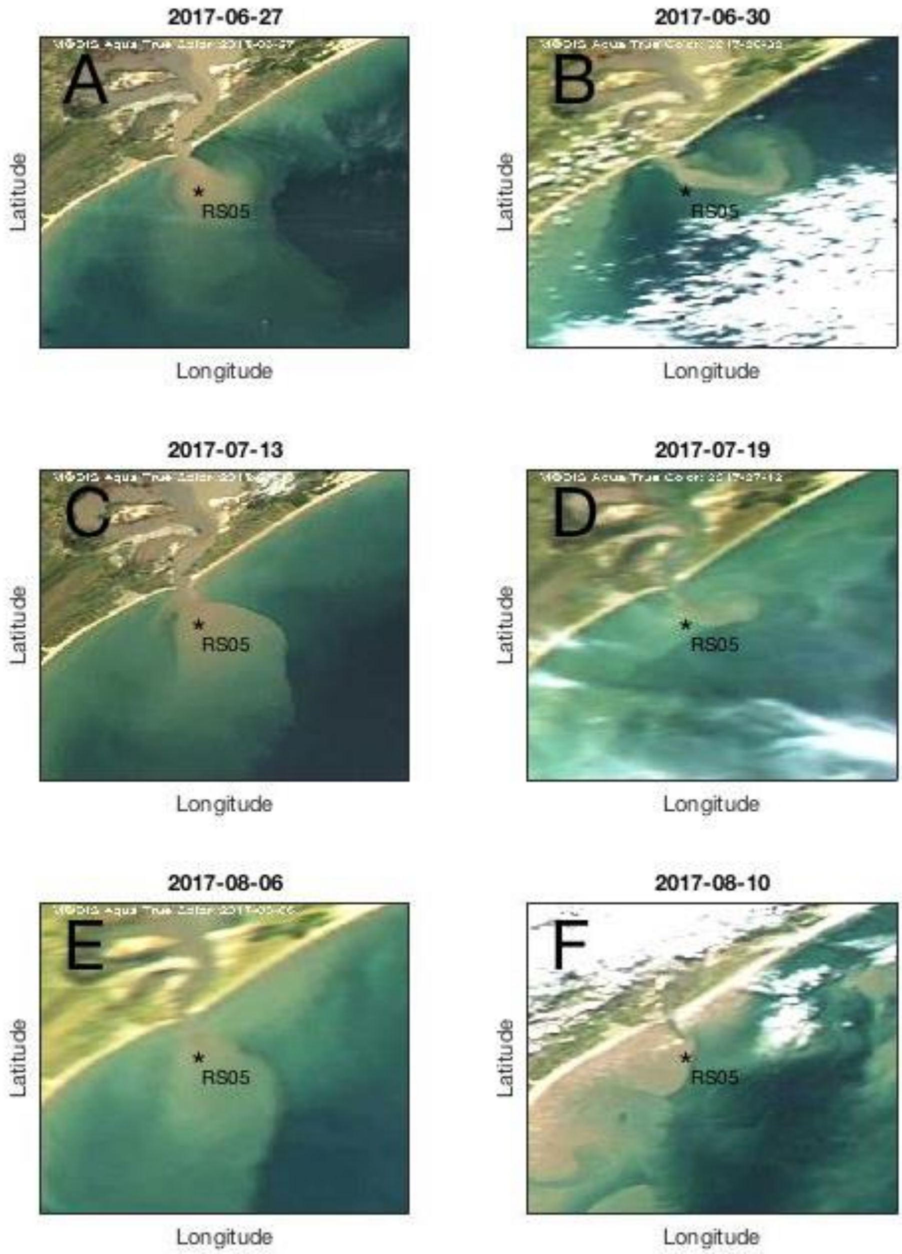


Figure 15 –True color AQUA/MODIS images before (A, C, and E) and during (B, D, and C) frontal system passages. Patos Lagoon's plume is attached to the shore (F) at the end of the front 5 passage. The duration of F3: 2017-06-29 to 2017-07-02; Duration of F4: 2017-06-29 to 2017-07-02; Duration of F5: 2017-08-08 to 2017-08-10.

Surface and mean alongshore current are highly correlated ($r=0.79$ in both cases, $p<0.05$) with alongshore winds, with 1h and 3h delays, respectively. This is expected since it takes longer for the entire water column to be influenced by wind stress. Surface salinity correlates with surface alongshore current ($r=0.51$, $p<0.05$) at lag 6h and mean alongshore current ($r=0.50$, $p<0.05$) at lag 7h. This relatively high time interval indicates that the RS05 buoy was completely immersed in the Lagoa dos Patos' plume (figures 14A, 14C, 15A, 15C and 15E) and that a certain interval of time (~ 6-7h) was necessary for the entire plume to be displaced northward, which left the RS05 buoy immersed in La Plata's plume waters. Consequently, the oscillating behavior of salinity (see TS-time diagram, figure 5), reaching low and high values in a relatively shorter interval of time, is associated with the presence/absence of Patos Lagoon's plume over the position of RS05, with the displacement of the plume being caused by southernly wind stress.

5. Conclusion

Meteocean data collected during 315 days by several instruments placed on a mooring buoy were used to study the vertical structure and variability of current in the southern Brazilian inner shelf. The vertical distribution of the alongshore current was not uniform from the surface to the bottom, with slightly higher velocities in intermediate waters than surface and bottom. The mean vertical alongshore and cross-shore current are southwestward and southeastward oriented with velocities of 3 and 7 cm/s, respectively.

The diurnal O1 tidal constituent is the major tidal constituent in both zonal and meridional components of the mean current profile, while the M4 harmonic presented the second most expressive amplitude in the zonal current component and mean current profile. Nevertheless, the tidal signal is negligible in the study area and represents approximately 1.7% of the variability of currents in the locality.

In the low-frequency band (period >40h), alongshore wind stress, alongshore surface current, and surface salinity time series presented similar frequency patterns indicating the prevalence of high-energy events in periods of approximately 3 to 10 days, with a major peak around 5.5 days. In the high-frequency band (period < 40h), cross-shore wind stress, cross-shore surface current and surface temperature presented similar frequency patterns with a prevalence of high-energy events in periods of nearly 24h. After the removal of seasonal solar heating, the temperature exhibits high-energy events in high-frequency (12 and 24 h) due to daily solar heating.

A high positive correlation between wind stress and surface currents was found only for both alongshore wind and current, whereas cross-shore winds were weakly correlated with surface currents. A lag of approximately 3h was found between both alongshore surface current and wind. The alongshore surface current was mostly driven by the alongshore wind while its cross-shore component was also driven by other mechanisms, such as continental discharge. The cross-shore wind seems to have insignificant participation to both along- and cross-shore surface current circulation.

Patos Lagoon's outflow is responsible for variations in low-frequency surface salinity, as lower (higher) surface salinity records are associated with fresh (oceanic) waters.

The wavelet analysis for the metocean time series has shown that high-energy events for the alongshore wind stress are more common between August to October and not very often between February and March, with similar patterns in surface currents and salinity.

Northeastern winds and southwestward-oriented plumes were a common pattern before the passage of cold frontal systems in the study region. The entrance of the frontal system with southwestern winds changed the current's orientation to northwestward. An increase in surface salinity was observed during the frontal passages, which is a clear indication that salinity variations at the buoy site were mainly steered by the behavior of Patos Lagoon's coastal plume in time scales of hours.

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As referências serão apresentadas no final do documento, junto com as utilizadas nos capítulos anteriores.

Capítulo V: Considerações Finais

Este trabalho teve como objetivo analisar dados meteoceanográficos de uma plataforma instrumentada fixa (boia) de monitoramento, coletados durante 315 dias consecutivos, para analisar a estrutura e a variablidade de um perfil vertical de correntes localizado na plataforma continental interna do sul do Brasil. A distribuição vertical longitudinal das correntes não foi uniforme da superfície e fundo, com velocidades ligeiramente mais altas nas águas intermediárias do perfil. A média do perfil vertical longitudinal e tranversal orientou-se para sudoeste e sudeste com velocidades de 3cm/s e 7cm/s, respectivamente.

A componente diurna O1 e a principal constituinte de maré nas componentes zonal e meridional do perfil médio de correntes, enquanto o harmônico M4 apresentou a segunda amplitude mais expressiva na componente zonal e no perfil médio vetical. No entanto, o sinal da maré é insignificante para a região e representa apenas 1,7% da variabilidade das correntes locais.

Nas faixas de baixa-frequencia, as séries temporais de estresse do vento longitudinal, correntes superficiais e salinidade superficial apresentaram padrões similares de frequência, indicando a prevalência de eventos de alta-energia em períodos de 3 a 10 dias, com picos maiores de 5.5 dias. Nas faixas de alta-frequencia, a componente transversal do estresse do vento, das correntes superficiais, da salinidade e temperatura superficiais apresentaram padrões similares de de frequência, indicando a prevalencia de eventos de alta-energia em períodos de 24 horas. Após a remoção do aquecimento solar sazonal, a temperatura exibe eventos de alta energia na faixa de alta frequência de 12h e 24 h devido ao aquecimento solar.

Foi encontrado uma alta correlação positiva entre as componentes longitudinais do estresse do vento e das correntes superficiais, enquanto que para a componentes transversal do estresse de vento e das correntes superficias são fracamente correlacionadas. As correntes superficias longitudinais possuem uma defasagem de tempo em relação ao estresse do vento longitudinal de 3 horas. As correntes superficias longitudinais é impulsionada principalmente pelo vento longitudinal, enquanto que as correntes superficias transversais são impulsionadas por outros mecanismos, como a descarga fluvial. Os ventos transversais parecem ser insignificantes na circulação das componentes longitudinais e também transversais das correntes superficiais.

A vazão da lagoa de Patos é responsável por variações na salinidade superficial de baixa frequência, já que registros de salinidade superficial mais baixos (mais altos) estão associados a águas doce (oceânicas).

A análise de ondeletas para as séries temporais metoceanográficas mostrou que os eventos de alta energia para o estresse do vento ao longo da costa são mais comuns entre agosto e outubro, mas não muito frequentemente entre fevereiro e março, com padrões semelhantes de correntes de superfície e salinidade.

Os ventos de nordeste e a pluma da Lagoa dos Patos voltada para sudoeste foi um padrão comum antes das passagens de sistemas meteorológicos na região da boia. A entrada do sistema frontal com ventos do sudoeste mudou a orientação padrão para noroeste. Houve um aumento na salinidade superficial durante as passagens frontais, o que indica que as variações de salinidade no local da boia são dirigidas principalmente pelo comportamento e passagem da pluma costeira da Lagoa de Patos pela região da boia em escala temporal de horas.

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