UNIVERSIDADE FEDERAL DO RIO GRANDE DO SUL
INSTITUTO DE GEOCIÊNCIAS
PROGRAMA DE PÓS-GRADUAÇÃO EM DE GEOCIÊNCIAS

AVALIAÇÃO DA HIDRODINÂMICA E TRANSPORTE DE SEDIMENTOS DA BAIA DE TIJUCAS – SC

MÁRCIO FABIANO DE SOUZA

ORIENTADOR – Prof. Dr. Carlos Augusto França Schettini

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Minha família que esteve sempre ao meu lado e é parte de todas as minhas conquistas.

Meu orientador e amigo professor Dr. Carlos Augusto França Schettini pela oportunidade confiada a mim, a qual me proporcionou este nível de aprendizagem.

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RESUMO

O constante aumento da população tem gerado intensa ocupação das áreas costeiras em todo mundo. A exploração dos recursos naturais de forma não sustentável proporciona um desequilíbrio que dependendo das proporções pode gerar graves prejuízos ambientais e financeiros. Diante deste cenário exploratório a pesquisa dos ambientes costeiros aparece como uma maneira de entender, planejar e desenvolver estas regiões de forma mais equilibrada. O estudo sobre hidrodinâmica costeira e transporte de sedimentos tem sido aplicado com o objetivo de gerar conhecimento e desse modo auxiliar as tomadas de decisões. A dinâmica dos ambientes costeiros é complexa e o seu entendimento aborda uma serie de variáveis as quais podem afetar as regiões costeiras de formas diferentes. A área estudada nesta tese, a baia de Tijucas, é particularmente caracterizada por apresentar alta concentração de sedimentos finos, seu comportamento proporcionou ao longo do tempo o aprisionamento de grande quantidade de sedimentos formando um ambiente muito diferente das áreas em torno da baia. O papel da baia na retenção e no transporte sedimento finos para plataforma adjacente torna-se o alvo desta pesquisas que por meio de dados de campo e modelos numéricos procuram entender os efeitos das forçantes ambientais sobre a baia. A dinâmica da baia esta diretamente relacionada a intensidade dos ventos, altura das ondas e volume da descarga fluvial, neste contexto é relevante a relação com os eventos climáticos de alta transferência de energia como a passagem de frentes frias pelo estado de Santa Catarina. O presente estudo é compreendido por três artigos; o primeiro artigo busca avaliar por meio de simulação numérica o efeito dos ventos modais e descarga fluvial anual média do rio Tijucas na hidrodinâmica da baia, a troca de água entre baia e plataforma adjacente assim como o tempo de residência da água em cenários com ventos nordeste (condição típica) e ventos sudeste (condição de frente fria), o segundo artigo avalia por meio de simulação numérica e dados de campo o comportamento da pluma de sedimentos do Rio Tijucas em cenários de alta concentração e descarga de sedimentos sob condições de ventos nordeste e sudeste, já o terceiro artigo avalia através da simulação numérica de modelos acoplados o efeito das ondas no cisalhamento do fundo, na erosão, ressuspensão e deposição de sedimentos em cenários de ventos nordeste e sudeste. A baia de Tijucas apresenta um padrão de aguas calmas a maior parte do tempo, a energia envolvida na sua dinâmica esta diretamente relacionada a intensidade das forçantes e condições climáticas. Em eventos de passagem de frente frias por esta região a

tendência é que haja maior descarga fluvial, ventos mais fortes e ondas mais altas, nestes períodos estas forçantes são capazes de afetar significativamente a hidrodinâmica da baia adicionando, ressuspendendo e transportando sedimento em maiores intensidades o que consequentemente proporciona maior troca de água entre baia e plataforma, estes períodos são marcados pela maior energia hidrodinâmica e transporte de sedimento baia afora. No entanto o balanço final do comportamento da baia evidencia um cenário geral de baixa troca com a plataforma adjacente.

ABSTRACT

The constant increase of population has generated intense occupation of coastal areas worldwide. The unsustainably exploitation of natural resources provides an unbalance that depending on the proportions can lead to serious environmental damage and financial. Given this exploratory scenario the research of coastal environments appears as a way to understand, plan and develop these areas more balanced. The study on coastal hydrodynamics and sediment transport have been implemented with the objective of generating knowledge and thereby assist decision. The dynamics of coastal environments is complex and its understanding addresses a series of variables which can affect coastal regions in different ways. The area studied in this thesis, the Tijucas bay, is particularly characterized by high concentration of fine sediments, their behavior provided over time trapping large amounts of sediments forming a very different environment of the areas around the bay. The role of the bay on retention and fine sediment transport to the adjacent platform becomes the target of this research that through field data and numerical models seek to understand the effects of environmental forces on the bay. The dynamics of the bay is directly related to the intensity of the winds, wave heights and volume of river discharge, in this context is relevant with respect to the climatic events of high energy transfer as the passage of cold fronts by the state of Santa Catarina. This study is comprised of three articles, the first article seeks to evaluate through numerical simulation the effect of modal winds and average annual river discharge of the river Tijucas on the bay hydrodynamics, the water exchange between bay and adjacent platform as well as time residence of water in scenarios with northeast winds (typical condition) and southeast winds (cold front condition), the second article evaluates through numerical simulation and field data the behavior of sediment plume River Tijucas in scenarios of high concentration and sediment discharge under conditions of winds northeast and southeast, already the third article evaluates through the numerical simulation of coupled models the effect of shear waves at the bottom of the bay, in erosion, in sediment deposition and resuspension on scenarios with northeast and southeast winds. The bay Tijucas shows a pattern of calm waters most of the time, energy involved in its dynamics is directly related to the intensity of the forces and climate conditions. In the event of cold front passage through this region the trend is that there is greater river discharge, strongest winds and highest waves, these periods these forces are able to significantly affect the hydrodynamics of the bay adding, resuspending and transporting sediment into the

higher intensities which consequently provides greater water exchange between bay and adjacent shelf, these periods are marked by higher energy hydrodynamics and sediment transport bay outside. However the final balance of the behavior of the bay shows a general scenario of low exchange with the adjacent platform.

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SUMÁRIO

INTRODUÇÃO

A partir de uma perspectiva da história humana é observado à preferência da população em ocupar as áreas costeiras, tal desenvolvimento tem efeito e consequências diretas na qualidade e preservação dos ecossistemas que compõem estas áreas. A rápida expansão das atividades socioeconômicas nas ultimas décadas principalmente as atividades industriais e o desenvolvimento urbano tem dificultado o gerenciamento e a conservação das áreas costeiras. Atualmente os ecossistemas costeiros tem sido alvo de inúmeros estudos sendo que compreensão das dinâmicas e processos envolvidos requerem conhecimentos interdisciplinares e integrados como parte de estratégias de desenvolvimento sustentável, (Neves et al., 2008). O entendimento sobre os processos relacionados ao transporte de sedimentos em estuários e regiões costeiras é crucial para tomadas de decisões na gestão de várias questões sociais que vão desde a indústria da pesca, transporte e armazenagem de contaminantes e a manutenção dos portos.

Sob ponto de vista socioeconômico e de conservação os sedimentos compõem parte fundamental no estudo dos ambientes costeiros , de acordo com Milliman et al., (1992) entre 10 e 20 bilhões de toneladas de sedimentos são transportadas pelos rios anualmente. A partir do momento em que são exportados pelos estuários, os sedimentos alcançam a plataforma continental e o comportamento dos sedimentos já em plataforma dependerá das condições hidrodinâmicas do próprio ambiente receptor e das características dos sedimentos.

O transporte de sedimentos coesivos estuarinos tem sido objeto de intensa investigação. Uma razão importante é que o movimento do sedimento coesivo está diretamente relacionado com a redistribuição de nutrientes, metais pesados e materiais contaminados. O movimento dos sedimentos é afetado pelas ondas, correntes, solução salina, condições térmicas e fatores biogeoquímicos (Mehta, 1989). Compreender o movimento de sedimentos coesivos é importante para o desenvolvimento e manutenção de portos e canais de navegação nos estuários. Sedimentos coesivos também podem servir como armazenadores ou meio de transporte de poluentes introduzidos na coluna de água. Obviamente o conhecimento sobre os comportamento dos sedimentos coesivos torna-se um ponto chave no gerenciamento dos ambientes costeiros.

As plataformas abrigadas são mais sujeitas aos processos deposicionais, especialmente em relação aos sedimentos finos. Ao chegar a uma plataforma abrigada, o sedimento fino, coesivo, tende a se depositar devido à baixa energia do ambiente. Os sedimentos podem ser erodidos, ressuspendidos, depositado, permanecer na coluna d’água, formar camadas de altas concentrações e até mesmo camadas de lama fluida, conforme a dinâmica sedimentar do ambiente.

Importante ressaltar que independentemente dos processos naturais, a atividade humana sob a forma de dragagens, canalização, barragens e estruturas costeiras também levam a alterações dos padrões circulatórios em corpos d’água costeiros, podendo minimizar ou maximizar determinadas variáveis e alterar parcialmente ou totalmente os padrões naturais de um determinado ambiente, de modo reversível (temporário) ou não.

Os sedimentos transportados pelos rios consistem em sua maior parte de argilo-minerais e silte, apresentando complexas interações físico-químicas com o ambiente. As complexidades destas interações aumentam consideravelmente quando o fluxo de água fluvial alcança os ambientes estuarinos, onde ocorre a gradual diluição da água marinha pela água fluvial nos estuários.

De acordo com Winterwerp & Kesteren, (2004), o sedimento é formado por material granular que pode decantar na água por ação da gravidade. São divididos em grosseiros (areia e seixos) e finos, sendo que os sedimentos finos são caracterizados pelo tamanho inferior a 0,062 mm, subdivididos em fração de silte (0,062 a 0,0039 mm) e fração argila (0,0039 a 0,00006 mm) contendo uma parcela significativa de argilo-minerais. A desintegração física atua sobre as linhas de fraturas e clivagem dos minerais e o sedimento produzido é eletricamente estável, apolar, ou não coesivo, sendo composto por silte, areia, grânulo e seixos. A desintegração química atua sobre a estrutura cristalina dos minerais, rompendo as ligações químicas e gerando um sedimento eletricamente carregado, polar, ou coesivo, caracterizado como argila.

Outra diferenciação dos tipos de sedimentos pode ser aplicada através do procedimento usual de análise granulométrica. Partículas sedimentares com diâmetro superior a 0,063 mm utiliza-se a técnica de peneiramento para separar as diferentes frações dos grãos. Partículas sedimentos com diâmetro inferior a 0,063 mm utiliza-se a propriedade da velocidade de decantação através da extração sucessiva de uma suspensão por pipetagens (McCave, 1979).

O principal meio de transporte dos sedimentos para os oceanos é pela ação da água através dos cursos fluviais, (Dyer, 1986). Segundo Wright & Nittrouer, (1995) em ambientes naturais ocorrem um ciclo contínuo de transporte de sedimento, processos como erosão, sedimentação, deposição e consolidação estão associados à dinâmica sedimentar assim como ressuspensão e intrusionamento em algumas condições mais específicas. Regiões de clima tropical e vegetação bem desenvolvida geram resíduos sedimentares principalmente por decomposição química, grande parte do sedimento fino originado é transportado principalmente em suspensão pelos rios. Embora os sedimentos possam ser transportados por arrasto, saltação e suspensão, o modo predominante no transporte de sedimentos finos é a suspensão. Mesmo em condições de baixa energia, velocidades baixas são capazes de fornecer turbulência necessária para manter sedimentos finos em suspensão.

O transporte de sedimentos em um fluxo depende de uma variedade de condições, por exemplo, sob a influência da maré os sedimentos finos movem-se para a frente e para trás, participando de um processo passo a passo de deposição e ressuspensão. Os efeitos adicionais de descarga do rio, ondas, e biota fazem estes processos serem muito mais complexos (Leussen 2011).

Na realidade, como o transporte sedimentar é altamente não linear no que respeita à velocidade da corrente e a amplitude das ondas, são os episódios ocasionais, provocados pela combinação da circulação devida às tempestades e ondas de grande período, que mais marcam o registo estratigráfico de uma plataforma continental. Muitas vezes, a ocorrência destes episódios menos frequentes apagam mesmo os efeitos acumulados de várias tempestades mais pequenas que ocorreram nos períodos intermédios. Efetivamente, grande parte do transporte sedimentar na plataforma ocorre em condições pouco frequentes e muito energéticas, sendo a medição dos diferentes parâmetros extraordinariamente difícil com as técnicas e equipamento atualmente disponíveis. Assim, na impossibilidade atual de medir, um dos meios mais úteis para prever as características do transporte nestas ocasiões é sem dúvida a modelação. Além disso, o sistema em consideração é extremamente complexo devido a múltiplas interações, nomeadamente as que se relacionam com as camadas limites das ondas e das correntes, à estratificação eventual da coluna de água induzida por contrastes de salinidade, de temperatura e de matéria em suspensão, à composição do fundo, e as formas sedimentares que o afetam. Face a complexidade inerente aos processos associados ao transporte sedimentar, existe uma impossibilidade prática de estudar na natureza os múltiplos processos envolvidos. Acresce ainda que frequentemente o próprio ato de "medir" altera a grandeza que se pretende medir. Assim, é necessário simplificar para compreender e para posteriormente poder efetuar previsões. Neste contexto, a modelação surge como uma "ferramenta" essencial para o estudo dos processos da dinâmica sedimentar, a qual permite isolar processos individuais utilizando a determinação teórica da contribuição específica de cada um destes complexos sistemas, (Shen et al., 2002).

Um modelo é uma esquematização da realidade, constitui portanto, aproximação aos fenômenos reais e como tal, concepção idealizada dos processos e mecanismos ocorrentes na natureza. É por consequência, hipotético, sendo tanto mais aproximativo quanto melhor for o conhecimento da realidade que pretende descrever. Os modelos revelam-se, no entanto, bastante úteis porque constituem forma racional de visualizar a realidade, método lógico de compreender e sistematizar os vários processos envolvidos e respectivas interações, e relato legível do funcionamento da natureza. Assim um modelo deve tentar ser o mais possível racional, lógico e legível sem no entanto recorrer a simplificações excessivas, (Zao et al, 2004).

Este estudo tem como objetivo avaliar através do uso de modelos numéricos e dados de campo o efeito de determinadas condições ambientais na hidrodinâmica, no transporte de sedimentos finos da Baia de Tijucas e sua relação de troca com a plataforma adjacente. A Baia de Tijucas é caracterizada como sendo um ambiente único ao longo da costa sul brasileira apresentando extensos depósitos de lamas (Buyvenich et al., 2005). Os mecanismos envolvidos no aprisionamento de sedimentos finos na baia ainda não são bem entendidos. A hidrodinâmica da baía é um somatório de forçantes como; ventos, ondas, marés e descarga fluvial. Devido ao sistema hidrodinâmico complexo é difícil afirmar qual destes agentes domina o transporte e o comportamento dos sedimentos finos dentro da baia (Schettini et al., 2010). Em condições típicas a baia tende a manter sedimentos aprisionados no seu interior, porém a hipótese é que haja transporte de sedimentos baia afora durante eventos menos frequentes de alta descarga de energia associados principalmente a passagem de frentes frias pelo estado de Santa Catarina.

Na busca por uma melhor compreensão sobre o papel da baia de Tijucas no transporte de sedimentos finos, optou-se por avaliar o efeito das forçantes hidrodinâmicas sobre o comportamento dos sedimentos. Neste contexto esta tese se desenvolveu através da elaboração de três artigos, os quais se complementam conforme a sequencia. As simulações numéricas seguiram por um período de 30 dias ou mais com análises contínuas e pontuais (marés sizígia e quadratura).

O artigo 1 procura avaliar através do modelo numérico MOHID o efeito da maré e dos ventos nordeste e sudeste na circulação da baia, as trocas de massa d’agua entre baia e plataforma adjacente e o tempo de residência da água nos cenários propostos. A baia de Tijucas apresenta na sua maior parte profundidades baixas, sendo os ventos as forçantes que mais afetam as correntes superficiais. As séries temporais de ventos modais utilizados nas simulações representam as condições típicas (nordeste) e as condições de frentes frias (sudeste), quando ocorrem os eventos de maior transferência de energia. Embora a maré desta região seja classificada como regime de micromarés seu efeito foi estudado. O limite entre baia e plataforma adjacente também foi analisado, tanto em perfil horizontal quanto em perfil vertical afim de verificar o efeito das forçantes na variação de velocidade e sentido das correntes.

O passo seguinte, artigo 2, foi avaliar o comportamento da pluma de sedimentos em momento de alta descarga do rio Tijucas (condição associada a passagem de frente fria) em cenários forçados por ventos nordeste e sudeste. O desenvolvimento da pluma, a extensão, o deslocamento (bi-direcional) e o tempo de permanencia de sedimentos suspensos são características do início do ciclo sedimentar da baia de Tijucas.

Para completar o estudo o artigo 3 buscou avaliar o efeito das ondas na ressuspensão dos sedimentos, as simulações também seguem com ventos nordeste e sudeste. Cenários de ondas de 1 e 2 metros de altura forçando a baia são pouco frequentes, quando ocorrem duram por um intervalo de tempo curto estando sempre associados a condições de alta energia. O efeito das ondas no fundo da baia é responsável pela ressuspensão de sedimentos sendo o efeito do cisalhamento no fundo proporcional a altura das ondas. A baia é uma área abrigada e o efeito das ondas, podem afetar praticamente toda a baia. Avaliar as áreas de maior estresse, maior erosão e áreas de deposição contribuem significativamente para o entendimento do papel da baia no transporte de sedimentos, sendo que ondas associadas aos ventos podem ser os principais responsáveis pela exportação de sedimentos para a plataforma adjacente.

A sequencia dos artigos teve o objetivo de avaliar inicialmente as forçantes que supostamente mais afetariam a hidrodinâmica da baia, os ventos e as marés. Estas afetam diretamente as correntes e consequentemente as trocas entre baia e plataforma ocorrem basicamente devido a interação entre marés e ventos. A descarga do rio Tijucas e a formação da pluma em condições de alta descarga e concentração de sedimentos é importante no entendimento da distribuição dos sedimentos, que através do efeito das correntes afetam os processos de transporte e deposição. Diantes das informações dos artigos anteriores a aplicação das ondas no modelo pôde complementar o entendimento da dinâmica sedimentar da baia. Os cenários propostos neste estudo tiveram como objetivo avaliar condições ambientais que ocorrem com maiores frequencias e condições ambientais menos frequentes (frentes frias), buscando desta forma testar a hipótese levantada neste estudo.

Este estudo teve fases de desenvolvimento diferente ao longo dos anos de doutorado. Inicialmente a compreenção do modelo hidrodinâmico base MOHID (water modelling system), seus módulos e suas aplicações, após a fase de esclarecimento das questões envolvidas na pesquisa seguido da interpretação das muitas informações disponibilizadas pelos cálculos numéricos. Para dar continuidade ao estudo, principalmente a utilização de ondas no modelo hidrodinâmico, foi necessário um período de 4 meses no Instituto Superior Técnico (Universidade Técnica de Lisboa) sob a orientação do professor Dr. Ramiro Neves para acoplar o modelo de ondas SWAN (Simulating Waves Nearshore) ao modelo hidrodinâmico MOHID, entretanto todos os passos até a interação e o sincronismo dos modelos levaram muitos meses. De modo geral os modelos numéricos são ferramentas muito complexas, as simulações que testam as configurações experimentais e não experimentais gastam muito tempo, dessa forma trabalhar com simulações que abrangem um longo período de análise dispende de tempo além de equipamento que favoreça a velocidade dos cálculos para análises.

Por fim esta tese pretende através das ferramentas de pesquisa utilizadas abordar o máximo de informação relacionada a dinâmica costeira da baia de Tijucas, entender como as condições ambientais mais frequentes (vento nordeste) e menos frequentes (vento sudeste) podem contribuir para a retenção e o transporte de sedimentos baia afora afim de gerar conhecimento para futuras tomadas de decisões relacionadas ao tema e a área estudada.

Anexo A

Declaração de submissão do artigo: ASSESSMENT OF TIDE AND WIND EFFECTS ON THE HYDRODNAMICS AND INTERACTIONS BETWEEN TIJUCAS BAY AND THE ADJACENT CONTINENTAL SHELF, SANTA CATARINA, BRAZIL.

Carlos A.F. Schettini,

Agradecemos a submissão do seu manuscrito "ASSESSMENT OF TIDE AND WIND EFFECTS ON THE HYDRODNAMICS AND INTERACTIONS BETWEEN TIJUCAS BAY AND THE ADJACENT CONTINENTAL SHELF, SANTA CATARINA, BRAZIL" para Revista Brasileira de Geofísica. Através da interface de administração do sistema, utilizado para a submissão, será possível acompanhar o progresso do documento dentro do processo editorial, bastanto logar no sistema localizado em: URL do Manuscrito: http://sys2.sbgf.org.br/revista/index.php/rbgf/author/submission/163 Login: guto Em caso de dúvidas, envie suas questões para este email. Agradecemos mais uma vez considerar nossa revista como meio de transmitir ao público seu trabalho.

Cleverson Guizan Silva
Revista Brasileira de Geofísica

Anexo B

Declaração de submissão do artigo: STUDY OF THE DISPERSION BEHAVIOR OF THE TIJUCAS RIVER PLUME, SANTA CATARINA, BRAZIL.

Dear Dr. Carlos Schettini:

Thank you for submitting your manuscript, "STUDY OF THE DISPERSION BEHAVIOR OF A RIVER PLUME IN A RESTRICTED EMBAYMENT: THE TIJUCAS BAY, BRAZIL.", to Estuaries and Coasts. During the review process you can keep track of the status of your manuscript by accessing the following web site: http://esco.edmgr.com/

Your username is: CSchettini-232

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Alternatively, please call us at 001-630-468-7784 (outside the US)/(630)-468-7784 (within the US) anytime from Monday to Friday.

Sincerely,

Taylor Bowen

Editorial Coordinator

Estuaries and Coasts

Anexo C

Declaração de submissão do artigo: THE EFFECTS OF WAVES AND CURRENTS ON THE REDISTRIBUTION AND EXPORT OF FINE SEDIMENTS IN A SEMI-RESTRICTED BAY: TIJUCAS BAY, BRAZIL.

Dear Dr. Schettini,

Your submission entitled "THE EFFECTS OF WAVES AND CURRENTS ON THE REDISTRIBUTION AND EXPORT OF FINE SEDIMENTS IN A SEMI-RESTRICTED BAY: TIJUCAS BAY, BRAZIL." has been received by journal Ocean Dynamics You will be able to check on the progress of your paper by logging on to Editorial Manager as an author. The URL is http://odyn.edmgr.com/. Your manuscript will be given a reference number once an Editor has been assigned.
Thank you for submitting your work to this journal.

Kind regards,

Ocean Dynamics

ASSESSMENT OF TIDE AND WIND EFFECTS ON THE HYDRODNAMICS AND INTERACTIONS BETWEEN TIJUCAS BAY AND THE ADJACENT CONTINENTAL SHELF, SANTA CATARINA, BRAZIL

AVALIAÇÃO DO EFEITO DA MARÉ E VENTO NA HIDRODINÂMICA E TROCA DE ÁGUA ENTRE A BAIA DE TIJUCAS E PLATAFORMA ADJACENTE, SANTA CATARINA, BRASIL

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ABSTRACT

The importance of understanding coastal processes and their relationships to continental shelves has become increasingly important as coastal areas experience great socio-economic growth. In this context, Tijucas Bay and its interactions with the adjacent continental shelf was a subject of study through the use of a numerical model (MOHID Water Modeling System) for analysis of its hydrodynamics, exchanges of water masses between the bay and the continental shelf and the water's residence time in the bay. Simulations were run for 30 or more days. Boundary conditions for the simulations were tides, constant river discharge (24 $m^3.s^{-1}$) and winds. Wind time series represented typical conditions in the region, with NE winds (3 $m.s^{-1}$) forcing the domain for five days, then turning in the counterclockwise direction for 12 hours until they were oriented in the SE direction (8 $m.s^{-1}$), remaining two days in this direction and again turning counterclockwise for 12 hours and ending in the NE direction. Three scenarios have been proposed for the experiment; scenario 1 was forced by tides and river discharge, and scenarios 2 and 3 were forced by tides, river discharge and winds. The difference between scenarios 2 and 3 was the wind direction at the beginning of the simulations: scenario 2 began with NE winds, and scenario 3 began with SE winds. The results showed that the hydrodynamics and water exchange of Tijucas Bay were strongly influenced by tide and wind. The tide provided the input and output water pattern in the bay, while the wind accelerated the process, increasing the speed of exchange between the bay and the adjacent shelf. Superficial layers were the most affected by the winds. The easternmost portion of the bay exhibited the greatest current speeds, with a tendency to form a gyre current with water input at one end and output at the other, depending upon wind direction. In the shallower regions, currents exhibited their greatest speeds, while in the deeper areas, the inverse was found. The residence time for scenario 1 was 75 days, and for scenarios 2 and 3, the residence times were 19 and 15 days, respectively. The hydrodynamics of Tijucas Bay is a sum of processes related to its forces; however, it is important to highlight the role of winds as one of the major determinants of the dynamics of this region, directly affecting transport throughout the bay.

KEYWORDS: circulation; estuary-shelf interaction; residence time.

RESUMO

Atualmente a importância sobre o entendimento de processos costeiros e sua relação com a plataforma continental ganha importância à medida que as regiões costeiras tornam-se áreas de grande expansão socioeconômica. Neste contexto a baia de Tijucas e sua interação com a plataforma adjacente foi alvo de investigação através do uso de modelo numérico (MOHID) para análise da hidrodinâmica, troca de massas de água entre baia e plataforma e tempo de residência da baia. As simulações correram por 30 dias ou mais. As condições de fronteiras para as simulações foram maré, descarga fluvial constante (24 $m^3.s^{-1}$) e ventos. As séries temporais de ventos representam condições típicas da região com ventos NE (3 $m.s^{-1}$) forçando o domínio por 5 dias girando no sentido anti-horário durante 12 horas ate a direção SE (8 $m.s^{-1}$), permanecendo por 2 dias nesta direção e novamente girando no sentido anti-horário por 12 horas ate a direção NE. Três cenários foram proposto para o experimento, cenário 1 foi forçado por marés e descarga fluvial, cenário 2 e 3 forçados por marés, descarga fluvial e ventos. A diferença entre os cenários 2 e 3 é a direção do vento no início das simulações, cenário 2 começa com vento NE e cenário 3 com vento SE. Os resultados mostram que a hidrodinâmica e a troca de água da baia de Tijucas é fortemente influenciada por maré e vento. A maré proporciona um padrão de entrada e saída de água da baia enquanto o vento acelera o processo, aumentando as velocidades de troca entre baia e plataforma adjacente. As camadas superficiais são mais afetadas pelos ventos. As extremidades da baia na sua porção mais a leste apresentam as maiores velocidades das correntes, a tendência é a formação de uma corrente em forma de giro com entrada de água por uma extremidade e saída por outra, dependendo da direção do vento. Nas partes mais rasas as correntes apresentam maiores velocidades enquanto nas partes mais profundas é o inverso. O tempo de residência para o cenário 1 foi de 75 dias enquanto os cenários 2 e 3 apresentaram tempo de residência de 19 e 15 dias respectivamente. A hidrodinâmica da baia de Tijucas é um somatório de processos relacionados as suas forçantes entretanto é importante destacar o papel dos ventos como um dos principais condicionantes da dinâmica desta região afetando diretamente o transporte baia afora.

PALAVRAS-CHAVE: circulação, interação estuário- plataforma, tempo de residência.

INTRODUCTION

The understanding of processes affecting the dynamics of coastal environments, such as hydrodynamics, has gained importance as the scientific community concentrates on understanding ocean processes. In addition, the fact that coastal areas are directly involved in the activities of productive sectors, such as the oil, fisheries and civil engineering industries, as well as port activities makes them key factors in economic development. Therefore, the study of hydrodynamics in coastal environments is critical for the understanding of processes involved in their dynamics.

The study of coastal hydrodynamics comprises a set of analyses, and the dynamics of these environments are directly related to water exchange times. Residence time and other measures used in water renewal analysis have been used as parameters to classify estuaries and semi-enclosed water bodies (Dyer, 1973; Bolin & Rodhe, 1973; Zimmerman, 1976; Takeoka, 1984). The main goal of using these parameters is to quantify how long water is retained by these water bodies. These time scales can be used as indicators for the analysis of processes such as pollutant transport, sediment transport or ecological processes (Braunschweig et al., 2003). To assess these time scales, one can start from experimental studies using passive tracers (e.g., Deleerrsnijder et al., 2001) or apply Lagrangian transport models (e.g., Tartinville et al., 1997; Oliveira & Baptista, 1997).

Numerical hydrodynamic models are widely used currently to assess residence times in coastal environments (Signell & Butman, 1992; Luff & Pohlmann, 1995). These models are based on the introduction of a hypothetical mass of conservative tracers released instantaneously within an area of interest. The tracer concentration is initially set within the area; the subsequent advection and dispersion of the mass is obtained by numerically solving transport equations, while the tracers are tracked and the variation (or not) of the retention time of the tracers in the area is calculated. The analysis of residence time through numerical models and tracers is often gauged by a reduction of tracer mass to a certain level (such as 50% or 10%) of the initial mass (Choi et al., 2004).

Many hydrodynamic studies using numerical modeling are conducted using a barotropic approximation by averaging the water speed vertically and solving the resulting horizontal 2-dimensional circulation (2D models). This simplification facilitates the modeling process by minimizing the domain and significantly lowering the computational cost (e.g., Signell & Butman, 1992; Chen, 1998; Gillibrand, 2001; Wang et al., 2004; Bilgili et al., 2005; Malhadas et al., 2009b). However, improvements in numerical schemes and advances in the processing power of computers are increasingly allowing the employment of models that also solve the water column vertical structure (3D models), which provide a better representation of the circulation (e.g., Andrejev et al., 2004; Garcia, 2008).

Coastal circulation in continental shelf areas and coastal embayments is forced mainly by wind and to a lesser extent by tides and even by river input, if any (Bowden, 1983). Both wind and tides constitute boundary conditions in models: winds are considered to act on an entire domain and the tides on horizontal open borders. Many studies have demonstrated the efficiency of numerical models in the reproduction of coastal circulation forced by wind, including the effects of exchanges with coastal bays and vertical circulation (e.g., Davies, 1982; Davies & Jones, 1992; Davies & Hall, 1998; Xie & Eggleston, 1999; Suzuki & Matsuyama, 2000).

The present paper aimed to study the circulation of Tijucas Bay, state of Santa Catarina (SC), and assessed the tidal and wind roles in the exchange process between the bay and the adjacent continental shelf using a hydrodynamic numerical modeling tool. The study was based on scenario simulations of idealized wind conditions to allow clear decompositions of the phenomena involved. As in most coastal environments, there is a great lack of observational data, and the present study aimed to contribute to understanding of the local oceanography.

STUDY AREA

Tijucas Bay is located between the 27º10’ and 27º18’ S parallels (Figure 1), with an approximate area of 100 km^2. Its length and width are nearly equal at approximately 10 km. According to Buynevich et al. (2005), Tijucas Bay is a unique environment on the Southern Brazilian coast, as it is the only one exhibiting a wide intertidal mudflat area, indicating that the bay exhibits a hydrodynamic regime that favors the retention of fine sediments (Schettini et al., 2010).

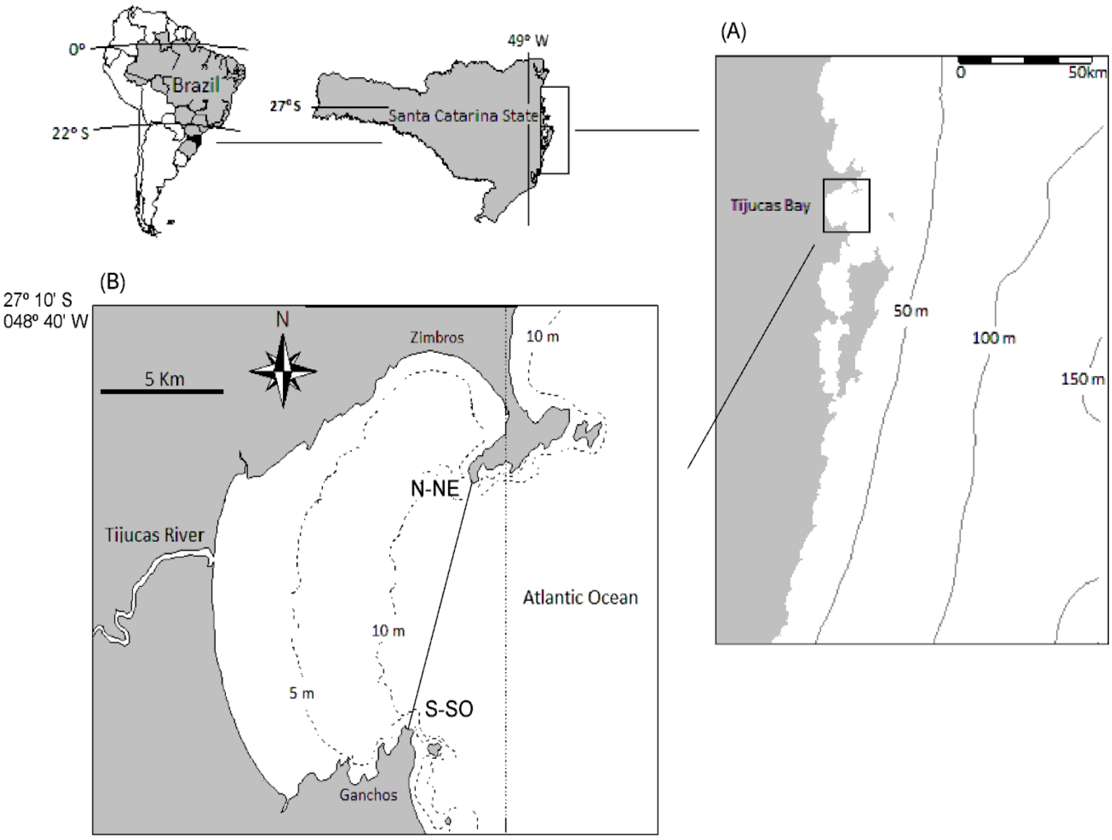

Figure 1. Study area, Tijucas bay, central coast north of Santa Catarina, Brazil, father domain (A) and son domain (B). In particular the cross section (N-NE/S-SO) delimiting the Tijucas bay.

The regional climate is characterized as subtropical mesothermic without a uniform distribution of rainy periods. It displays a positive hydrological balance, with rainfall values of approximately 1,415 mm.year^{-1} and an evaporation potential of approximately 900 mm.year^{-1}. The annual average temperature is 21.4ºC, ranging between 17.3ºC and 26ºC in August and February, respectively (Gaplan, 1986).

The wind regime is dominated by northeasterly (NE) winds throughout the year with the occurrence of periods of winds from the southern quadrant associated with cold fronts crossing the coastal region of the state of Santa Catarina (Truccolo et al., 2006). The changes in meteorological conditions observed in the Southern and Southeastern regions of Brazil are usually associated with the passage, formation or intensification of cold fronts typical of mid-latitude weather systems and active on the Brazilian coast in all seasons (Kousky, 1979 & Satyamurty et al., 1998). From 1990 to 1999, the passages of cold fronts were identified by the wind turning toward the southerly (S) direction, the persistence of the S wind for at least one day and a drop in air temperature simultaneous with the wind pattern or up to two days later (Rodrigues et al., 2004). Using the days of cold front passage in Santa Catarina as reference, one can clearly discern a climatological pattern of progression with cold fronts typically moving from southwest (SW) to northeast. According to Rodrigues et al. (2004), the passage of cold fronts can be observed year-round with little seasonal variation, although with greater frequency during spring, at approximately four per month and with wind speeds that can reach approximately 5 m.s^{-1} (measured at 10 m above the surface). Goulart (1993), analyzing historical data for the city of Florianópolis (SC) (at the Florianópolis airport meteorological station) approximately 30 km from Tijucas Bay, found wind speeds ranging from 3.4 m.s^{-1} in May (the month with the lowest average speed) to 4.7 m.s^{-1} in October (the month with the highest average speed). The abovementioned author also found a high standard deviation of the data for maximum wind speeds in May and October of 16 m.s^{-1} and 27.1 m.s^{-1}, respectively.

The bay receives river input in an area of approximately 2.800 km^2, and the Tijucas River [Rio Tijucas] is the main contributor for water and sediment transport, flowing into the central portion of the bay. Historical data for Tijucas River flow since 1945, gathered at a measuring station administered by the National Water Agency (Agencia Nacional das Águas - ANA), reported an average flow of 24.4 m^3.s^{-1} (Schettini et al., 2010). The estuary of the Tijucas River displays a highly stratified regime (Schettini and Carvalho, 1998), and its sediment balance is similar to the pattern of other nearby estuaries (e.g., Schettini et al., 2006). The estuary acts as a sediment sink during low-discharge periods and an exporter during river discharge peaks (Schettini and Toldo Jr., 2006).

The region exhibits a mixed microtidal regime with predominance of semidiurnal tides. The average height of the tide is approximately 0.8 m, ranging from 0.3 to 1.2 m during neap and spring tides, respectively (Schettini, 2002a). Meteorological effects can influence up to 30% of the tidal level variation; in events of cold front passages associated with strong winds from the southern quadrant, the level variation can reach one meter (Truccolo et al., 2006).

The wave regime in the study area is still poorly studied. Based on measurements from a wave-rider buoy located 35 km from Florianópolis Island, Araujo et al. (2003) identified five wave patterns for the island of Santa Catarina consisting of two swells and three types of waves: a southern swell (θ=162°) with a period of 11.4 s and Hs [significant wave height] between 1.25 and 2.0 m, a southeastern swell (θ=146°) with a period of 14.2 s and Hs between 1.50 and 2.0 m, eastern waves (θ=92°) with a period of 8.5 s and Hs between 0.75 and 1.75 m, northeastern waves (θ=27°) with an Hs> 0.75 m and southern waves (θ=188°) with a period of 7.7 s and Hs > 1.0 m. Overall, swells from the eastern quadrant (northeast, east and southeast) and southern quadrant predominate at the island and that southern quadrant waves can exhibit Hs values above 4 m (Araujo et. al, 2003).

The water characteristics in the bay are influenced by local continental input and by continental shelf water. The continental shelf belongs to the meridional portion of the Southeastern Brazilian Continental Shelf (SBCS) also known as the Santos Basin. The overall circulation on this portion of the shelf is characterized by the Brazil Current (BC) flow of Tropical origin and south direction; in the opposite direction is the Malvinas current (MC) of sub-Antarctic origin (Legeckis & Gordon, 1982; Olson et al., 1998). According to Resende (2003), the SBCS exhibits (1) coastal water (CW) that is characterized by low salinity values as a result of admixture between continental coastal waters and shelf waters; (2) tropical water (TW) that flows towards the S/SW in the surface layer of the BC between 0 and 200 m deep and displays low concentrations of nutrients and dissolved oxygen; and (3) South Atlantic central water (SACW), subjacent to the TW, that is also transported to the S/SW by the BC at depths between 200 and 500 m and is a nutrient-rich water mass, especially with respect to inorganic nutrients, with high concentrations of oxygen and characterized by temperature and salinity below 20ºC and 36.4, respectively (Miranda, 1982).

NUMERICAL MODELING

The MOHID 3D numerical model (http://www.mohid.com/) was used in the present study with the application of complete formulations for three-dimensional finite-difference calculations, the hydrostatic hypothesis and the Boussinesq approximation (Miranda et al., 2000; Martins et al., 2001).

A nested regular grid approach was adopted. The father-model employed a greater geographic extension and a coarser grid (500x500 m) encompassing an area of 150x180 km, providing boundary conditions for the son-model domain. The latter model covered mainly the bay area, the Tijucas River estuary and the adjacent continental shelf (20x35.5 km), with 100x100 m grid resolution. The grid used was the Arakawa C-grid. The father-model was run in barotropic mode (2D), and the son-model used the baroclinic mode (3D) with 18 vertical layers (1-m thick each layers) in Cartesian coordinates.

The hydrodynamic model was forced at its boundaries by imposing variations in the tidal level (FES2004 – *Finite Element Solution*, Lyard et al. 2006), annual average river discharge generated by the Tijucas River (24.4 $m^3.s^{-1}$) and the time series of the synthetic model winds. The wind series were created to reproduce the typical conditions of local synoptic variability (Truccolo, 2011). The predominant wind regime is NE, which is disturbed by the passage of frontal systems that rotate the wind to southeast. During the passage of cold fronts, intensification of winds also occurs, and after a few days, the winds rotate back to northeast. This cycle displays a temporal variation of 6 to 11 days (Stech & Lorenzetti, 1992).

The simulations were performed considering three scenarios: (1) a simulation forced only by tide and river discharge and (2) and (3) simulations forced by tide, river discharge and winds, although with the latter varying in different modes. The wind series was generated starting with NE winds at 3 $m.s^{-1}$ speed, remaining constant for five days and then rotating in a counterclockwise direction to the SE during 12 hours and increasing gradually in speed up to 8 $m.s^{-1}$, remaining in this condition for two days and again rotating counterclockwise back to the northeast over 12 hours, with a gradual reduction in speed until the initial conditions were reached (Figure 2). The difference between scenarios 2 and 3 was the wind direction in the beginning of the simulations: in scenario 2, the wind at the start of the simulation came from a NE direction, and in scenario 3, the wind at the start of the simulation came from the SE, with a 3-day difference in the phase of the tidal variation. All simulations started during flood tide approximately five days before the spring tidal peak. Previous assessments indicated that this is a satisfactory period for the beginning of the model. Simulations were performed for a 30-day period.

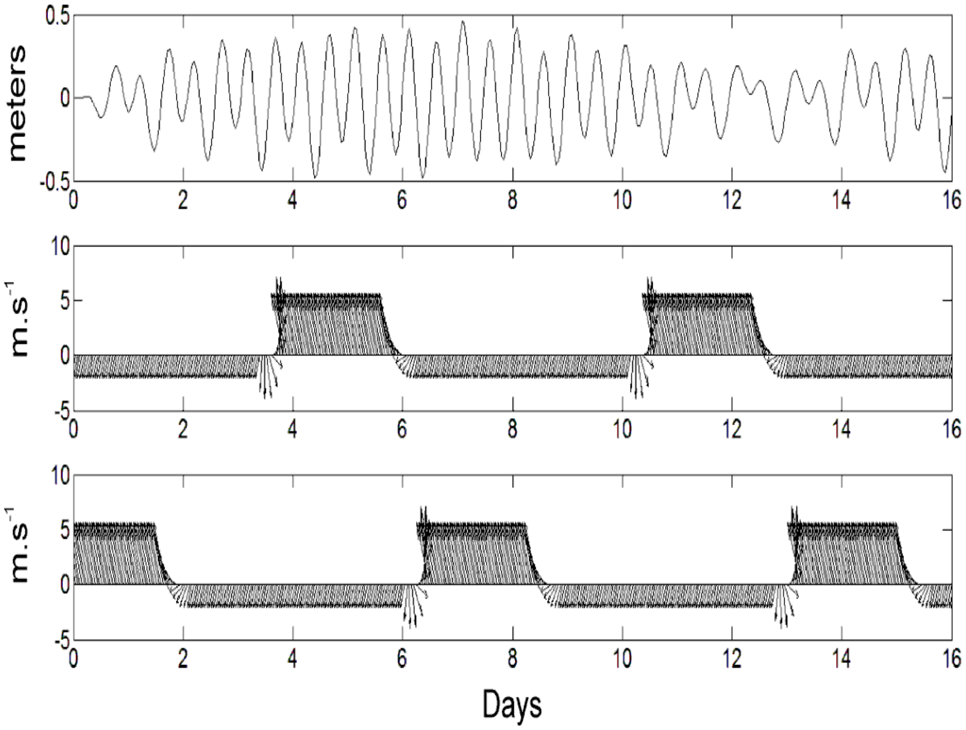

Figure 2. Variation of the tide level (above) and time series (middle and below) used in the simulations of winds.

The data analyzed to assess the water exchange between Tijucas Bay and the adjacent internal continental shelf were extracted from the cross-section of the bay, traced along the bay’s two eastern ends, near the shelf; the northern end was Zimbros Point (Ponta de Zimbros) (N-NE), and the southern end was Ganchos Point (Ponta de Ganchos) (S-SW; Figure 1). The cross-sectional profile shows depth varying from 7 m in the swallower areas to 12 m in the deeper ones, at the points and in the middle of the bay, respectively.

The residence time analysis followed the methodology proposed by Braunschweig et al. (2003), with the hydrodynamic model and Lagrangian transport using tracers and a box. The tracers released inside the box were tracked and residence time of the water enclosed by the box corresponds to the time when 80% of the tracers were outside of the box. According to Braunschweig et al. (2003), this method is used for two purposes: to release Lagrangian tracers and monitor the passage of these tracers across the box. By monitoring the tracer movements, one can answer some questions regarding the area's hydrodynamics, such as the following: (1) in which is the direction water mass displaced under certain conditions (forcings); (2) where do the tracers move when released in a certain area inside the box; and (3) what is the input and output of water from the box?

For model calibration, data for the levels of tides produced by the harmonic components of the tides at Arvoredo Island (Ilha do Arvoredo), located in front of Tijucas Bay, and the model tidal levels were used.

Visual agreement between the observations and model results for water levels was very satisfactory. To objectively assess the ability of the model (Cm) to reproduce the observations, we applied an error analysis (Eq.(1)) calculated by:

$$Cm = 1 - \frac{\sum | X_M - X_O |^2}{\sum (| X_M - \overline{X_O} | + | X_O - \overline{X_O} |)^2} \qquad \text{Eq. (1)}$$

where X_M represents the instantaneous result of the model, X_O represents a synoptic observation for this result and $\overline{X_O}$ is the average observed value (Willmott et al., 1985). In the case of perfect ability to reproduce the observation, Cm takes a value of 1, while in the case of a total lack of ability to reproduce the observation, Cm is zero. In the present study, Cm was 0.96 for the water levels. This value is not a percentage. The Cm value for the present study allows the validation of the model, and for the tidal amplitudes analyzed, the error was below 10% (Figure 3).

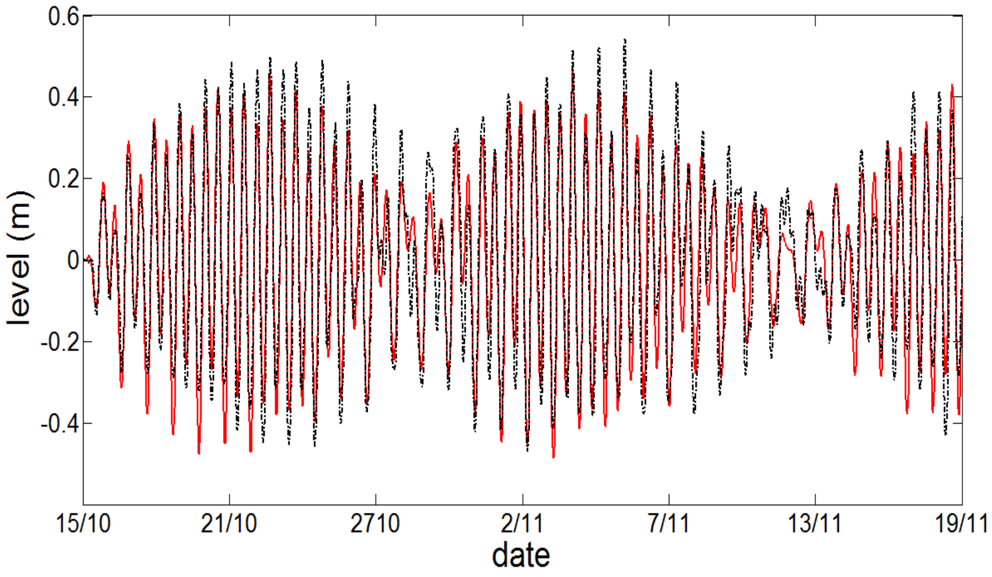

Figure 3 - Calibration curve between tide level modeling and the tide level of harmonic components at Arvoredo Island.

RESULTS

Figure 4 shows the average current patterns of the water column orthogonal to the bay mouth over time for the three simulated scenarios. As a rule, the currents running towards the outside of the bay were positive, and those towards the inside of the bay were negative. In scenario 1, forced only by the tides and river discharge, the maximum speeds of currents towards the inside and outside of the bay were 0.13 $m.s^{-1}$ and 0.11 $m.s^{-1}$, respectively, for currents during spring tide. The greatest speeds occurred near the section ends. The displacement pattern of water masses in both directions followed the tidal cycle, with water masses entering and leaving the bay every six hours, homogeneously over the entire section. During the neap tide period, water masses moved slower, with a speed of approximately 0.05 $m.s^{-1}$ in both directions.

In scenario 2, there was a wind effect in addition to the tide and the river discharge, starting with a NE wind direction. The greatest current speeds were found during the period that coincided with a SE wind and spring tide. In the period between 100 and 150 hours of the simulation occurred a pattern of inflow current in the southern portion of the bay mouth and outflow currents in the northern bay mouth. The maximum current speed of both sides was approximately 0.18 $m.s^{-1}$; however, there was also an oscillation of currents according to the tidal phase. In the neap tide period, during the time interval between 270 and 320 hours of simulation and during the second event of SE wind, the same current pattern was repeated; nevertheless, the speeds were lower, at approximately 0.10 $m.s^{-1}$. During NE wind, there was a decrease in current intensity and a reversal of predominance in current direction on each side of the bay mouth. During these periods, the maximum current speeds were approximately 0.06 $m.s^{-1}$.

Scenario 3 was similar to 2, with differences in the occurrence of wind reversal and the starting point with a SE wind. The maximum current speed reached approximately 0.16 $m.s^{-1}$ during SE winds. Between 100 and 150 hours of simulation, a period of spring tide and NE wind, current speeds were approximately 0.10 $m.s^{-1}$ and were lower compared with the same period in scenario 2. During the neap tide period, in the time interval between 270 and 320 hours of simulation, the same pattern of currents found during spring tide was also observed, although with lower speeds of approximately 0.05 $m.s^{-1}$ in both directions.

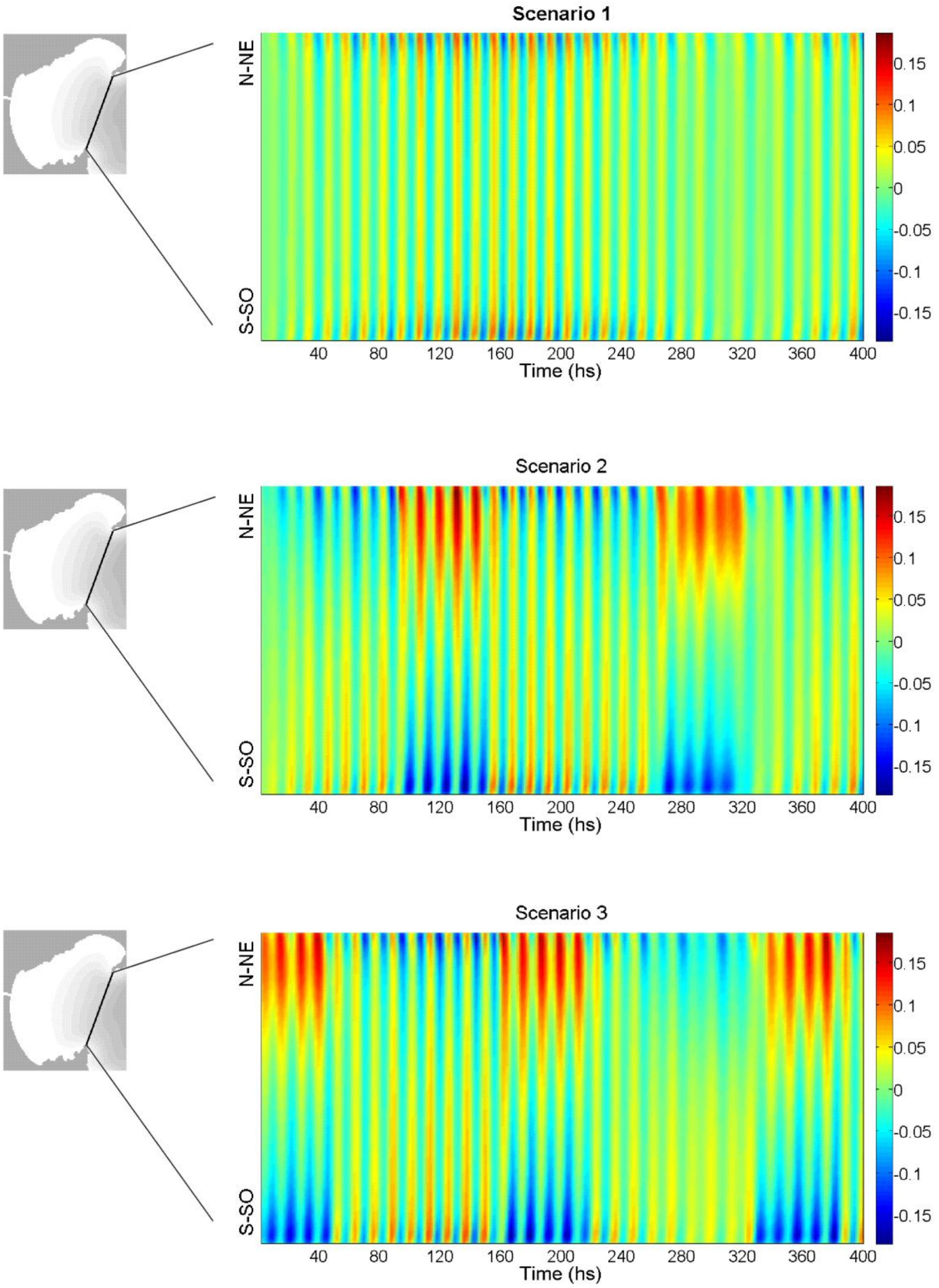

Figure 4 - Average vertical speed ($m.s^{-1}$) on the cross-sectional profile, S-SO and N-NE, positive velocities represent the output of water from the bay, the negative input of water. Scenario 1 (tides and no wind), scenario 2 (tides and winds, starting simulation with wind NE) and scenario 3 (tides and winds, starting with wind simulation SE).

Figures 5, 6, 7 and 8 show currents orthogonal to the cross-section of the bay mouth. Instantaneous currents are shown for the flood and ebb periods in the neap and spring tide conditions for the three scenarios. The greatest current speeds occurred at the ends and in the surface layers, mainly when wind was forcing the model. Current surface speeds reached their greatest values, up to 0.50 $m.s^{-1}$, both for inflow and outflow currents from the bay, when a SE wind coincided with spring tide (Figure 5). In Figure 6, current speeds reached their maximum values of approximately 0.35 $m.s^{-1}$ when SE wind forced the domain; however, this speed was observed at the northern end, indicating outflow from the bay, even at neap tide. Figures 7 and 8 show periods of flood and ebb during neap tide. The currents exhibited speeds below 0.12 $m.s^{-1}$ and the same speed distribution pattern in the cross-section.

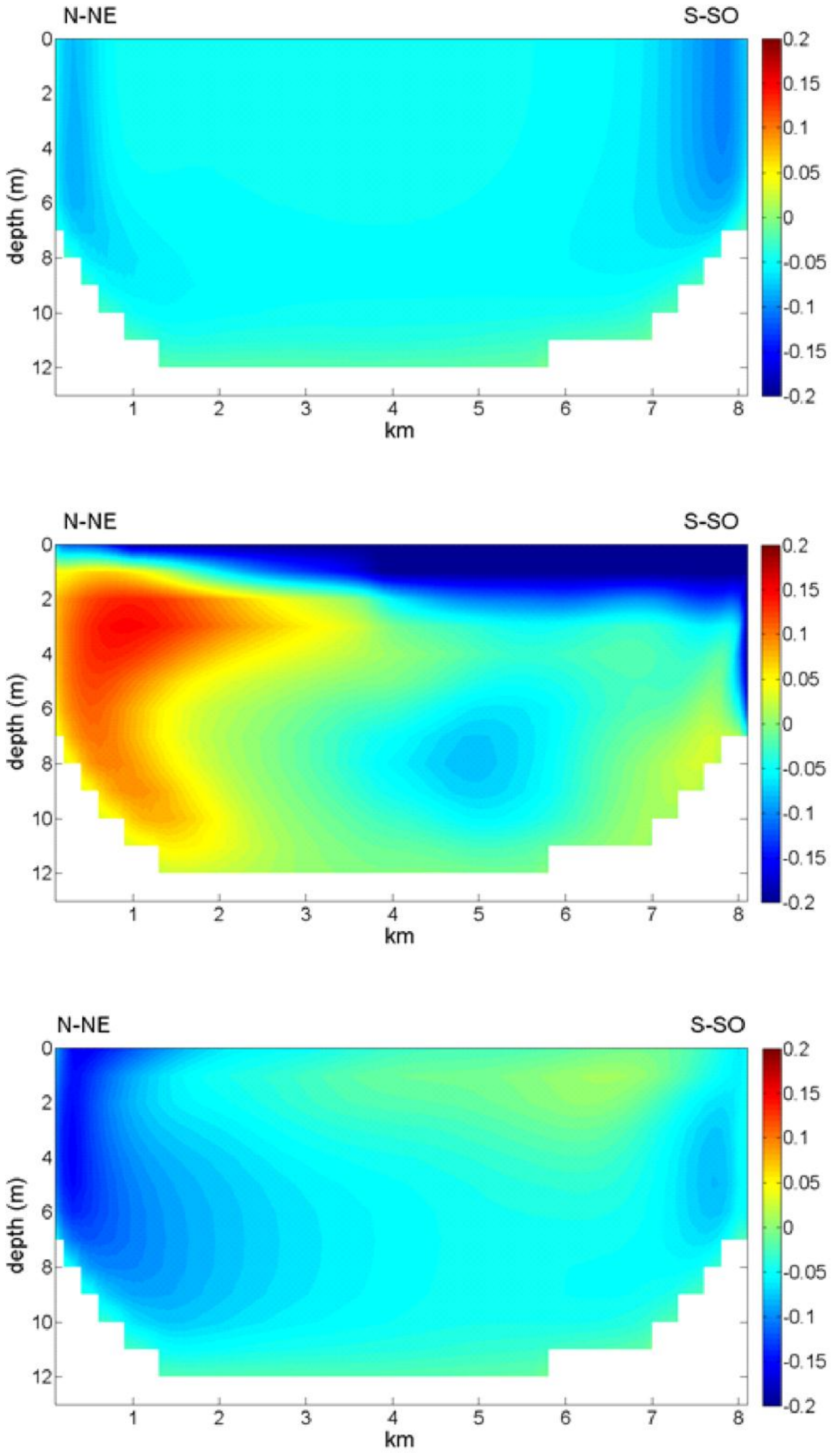

Figure 5 - Speed of currents (m.s^{-1}) orthogonal to the cross-section profile between Bay and adjacent shelf in the period of spring tide (flood), (above) tide without wind, (middle) tide and SE wind, (below) tide and NE wind. Positive velocities represent the output water of the bay, the negative velocities input.

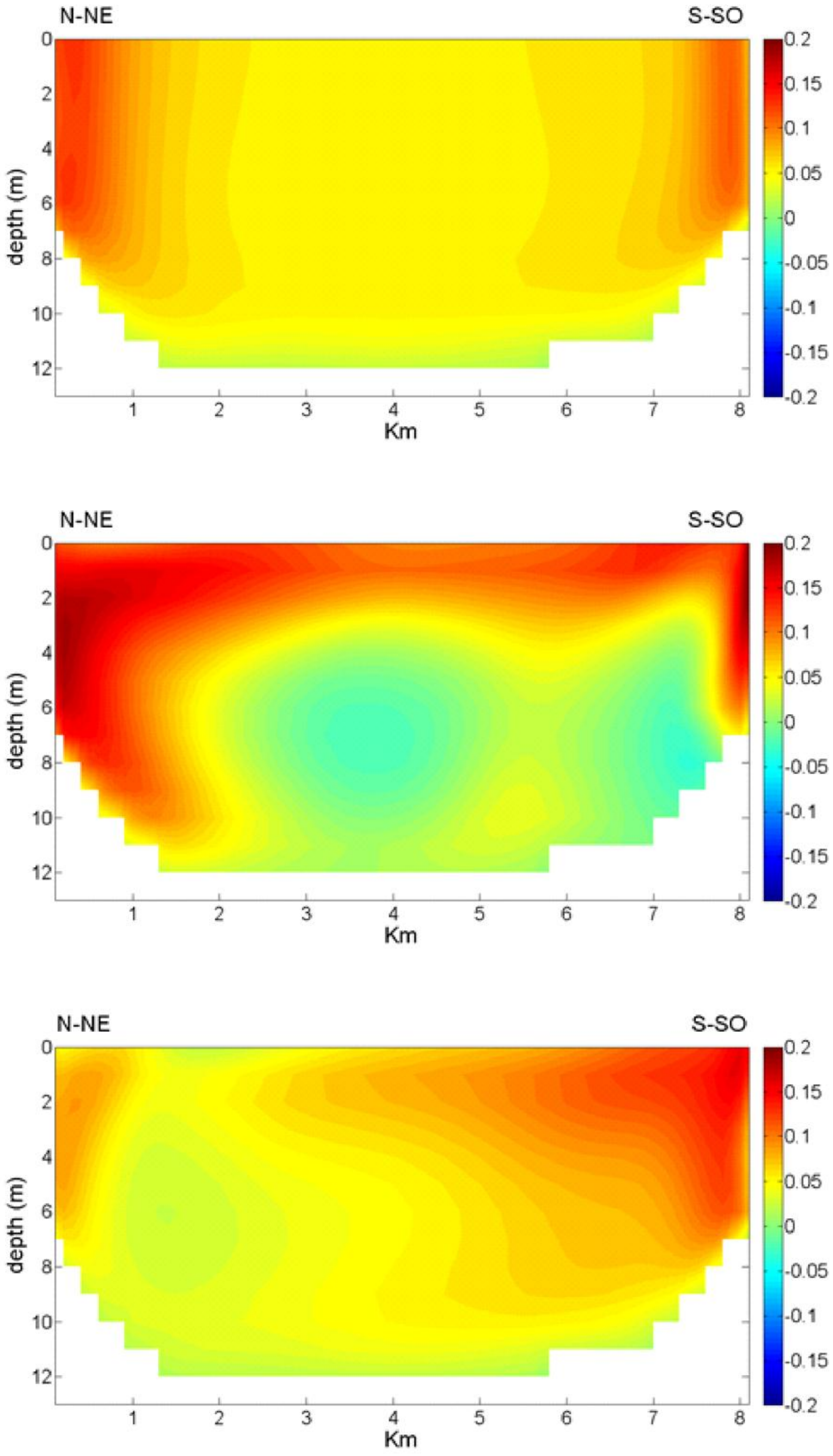

Figure 6 - Speed of currents (m.s^{-1}) orthogonal to the cross-sectional profile between Bay and adjacent shelf in the period of spring tide (ebb), (above) tide without wind, (middle) tide and SE wind, (below) tide and NE wind. Positive velocities represent the output water of the bay, the negative velocities input.

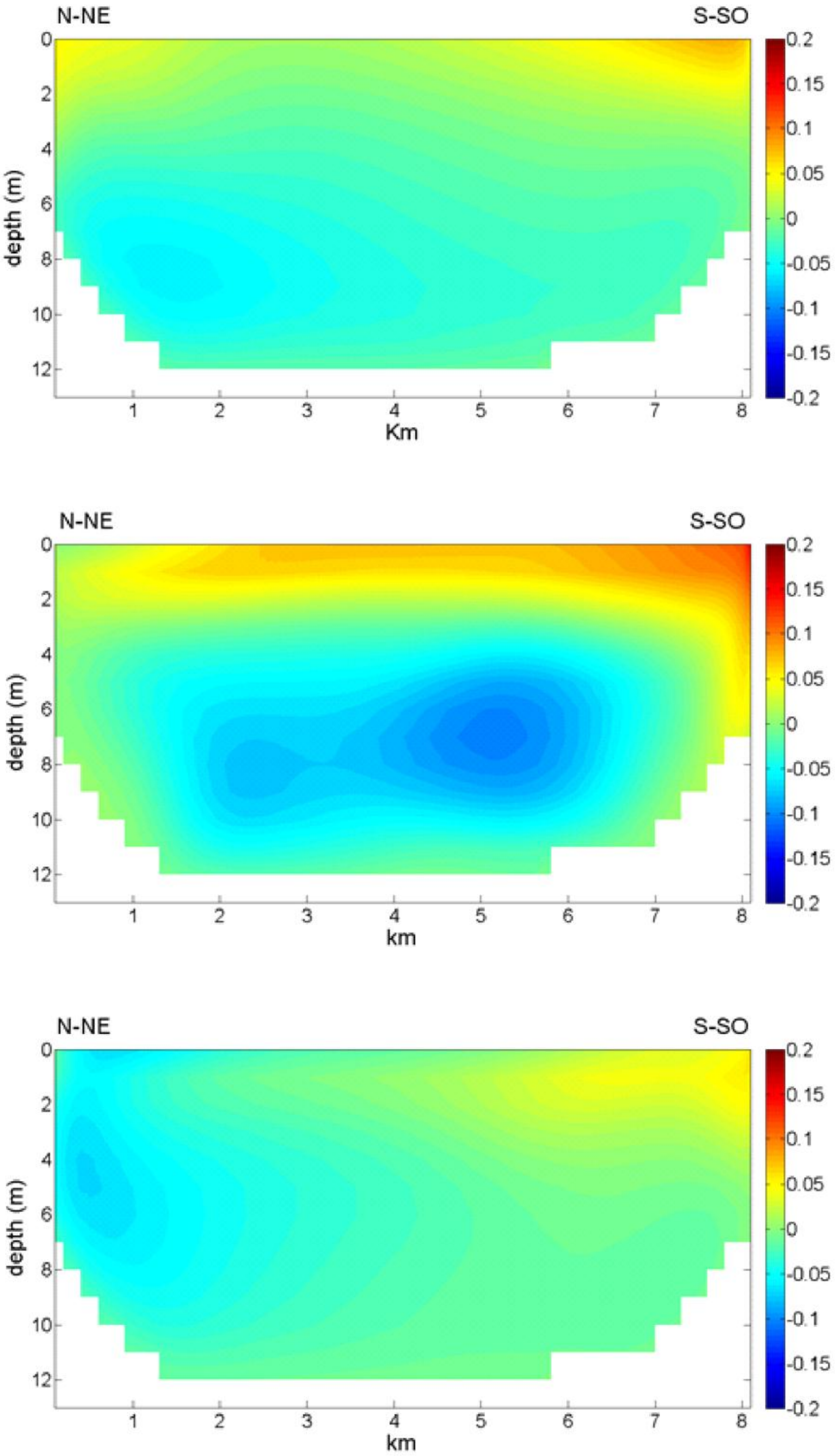

Figure 7 - Speed of currents (m.s^{-1}) orthogonal to the cross-sectional profile between Bay and adjacent shelf in the period of neap tide (flood), (above) tide without wind, (middle) tide and SE wind, (below) tide and NE wind. Positive velocities represent the output water of the bay, the negative velocities input.

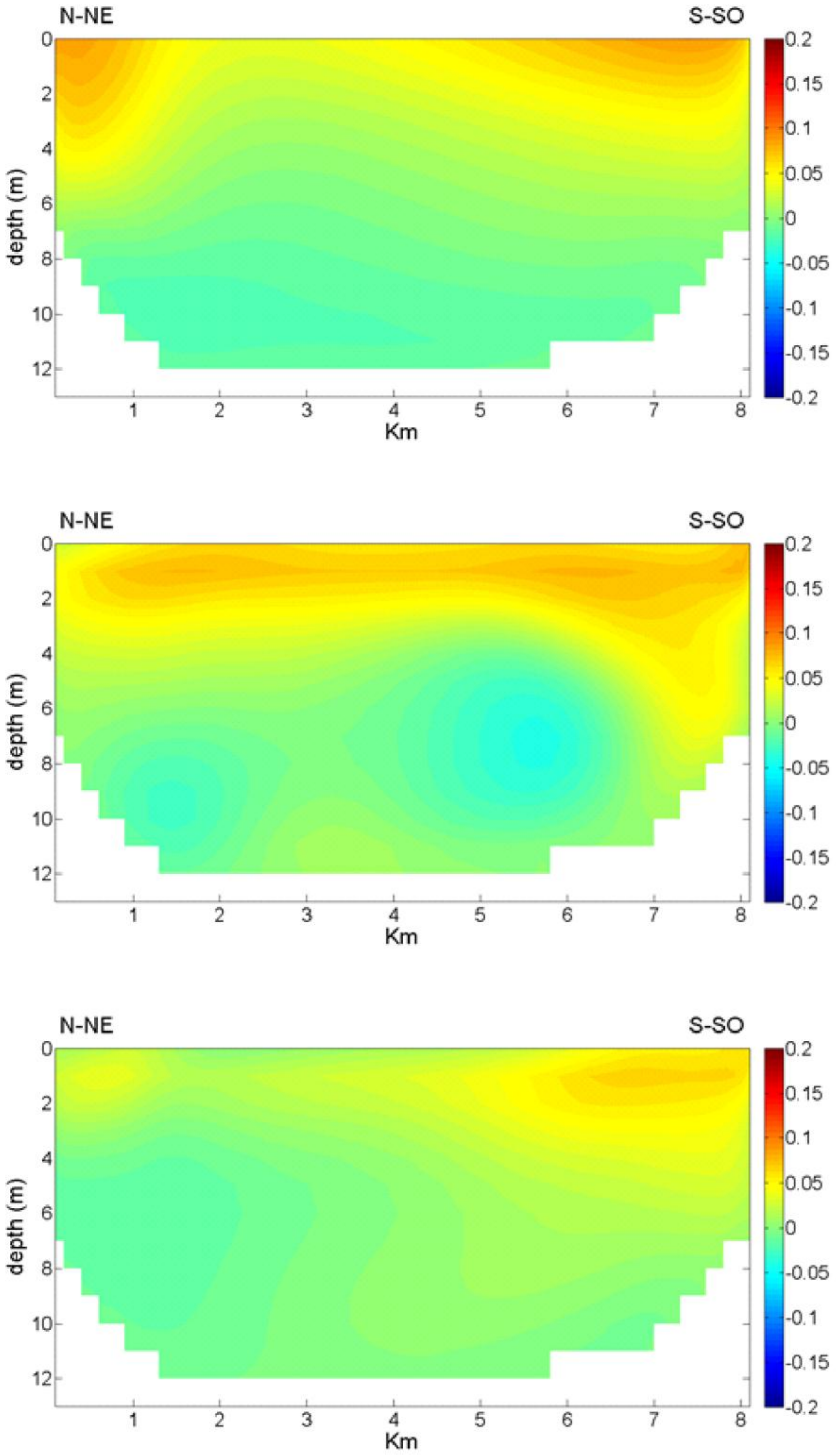

Figure 8 - Speed of currents (m.s^{-1}) orthogonal to the cross-sectional profile between Bay and adjacent shelf in the period of neap tide (ebb), (above) tide without wind, (middle) tide and SE wind, (below) tide and NE wind. Positive velocities represent the output water of the bay, the negative velocities input.

The behavior of residual, flood and ebb currents during 25 hours in the spring and neap tide periods are shown in Figures 9 and 10, respectively. During spring tide

(Figure 9), the residual speeds showed variations according to the winds. In scenario 1, with no wind, the residual speed was virtually zero and the speeds of the flood and ebb tides were equal and opposite. In scenario 2, the residual speed was low and the circulation pattern was poorly defined. In scenario 3, we noted that the residual speeds showed a movement of water in the N/S direction; the water entered from the S-SW end and exited in the N-NE end. The flood and ebb currents responded to the action of their forcings: in scenario 1, flood and ebb currents were similar but opposite; in scenario 2, flood currents characterized the water inflow into the bay at the N-NE end, while ebb current characterized the water outflow at the S-SW end. Opposite patterns were found for flood and ebb currents in scenario 3, in which flood currents entered the bay at the S-SW end and exited at the N-NE end. It is worth noting the highest speeds that the ebb current reached within the bay.

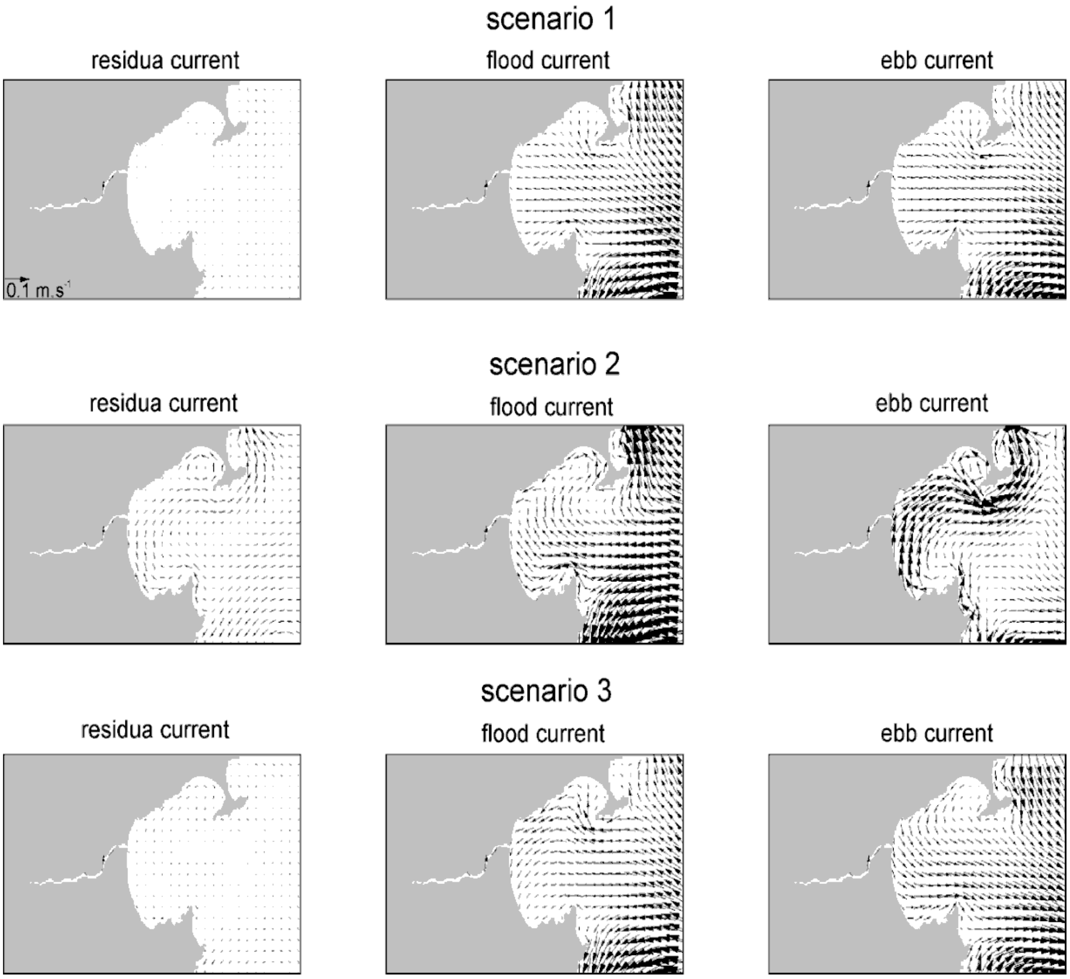

Figure 9 - Speeds of residual, flood and ebb currents for the three scenarios during 25 hours in spring tide. Scenario (1); tide and river discharge. Scenario (2); tide, river discharge and wind (SE) Scenario (3); tide, river discharge and wind (NE).

Figure 10 shows the neap tide period, in which one can note that scenarios 1, 2 and 3 showed behavior similar to the spring tide period; however, scenarios 2 and 3 displayed higher residual speeds compared to the same scenarios during spring tide.

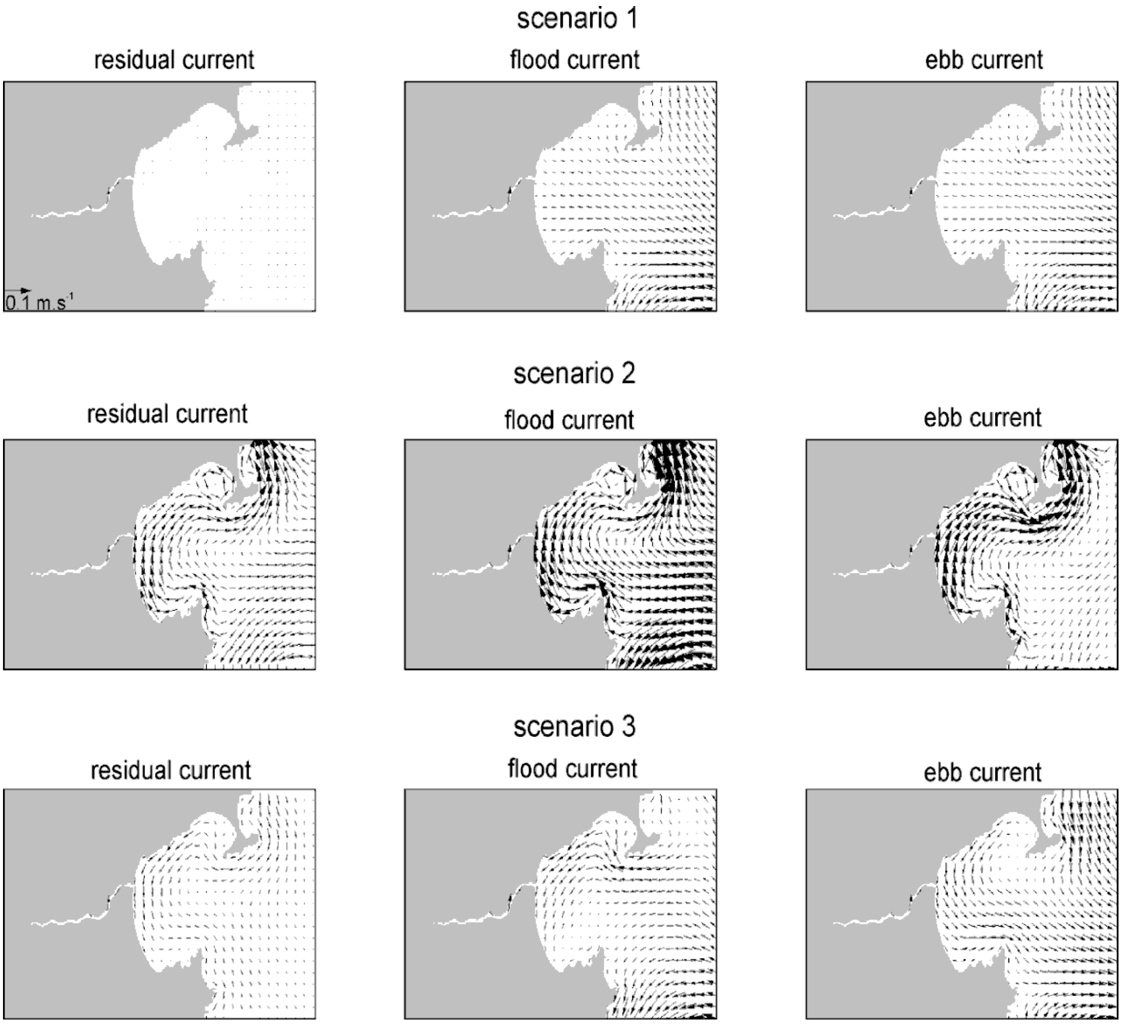

Figure 10 - Speeds of residual, flood and ebb currents for the three scenarios during 25 hours in neap tide. Scenario (1); tide and river discharge. Scenario (2); tide, river discharge and wind (SE) Scenario (3); tide, river discharge and wind (NE).

The residence time for scenarios 1, 2 and 3 were 75, 19 and 15 days, respectively. Figure 11 shows the distribution of tracers in each scenario. In scenario 1, there was a homogenous distribution throughout the domain, with motion in both south and north directions towards the outside of the bay with a very slow dispersion. The distributions of tracers in scenarios 2 and 3 were similar, with dispersion predominantly towards the north direction.

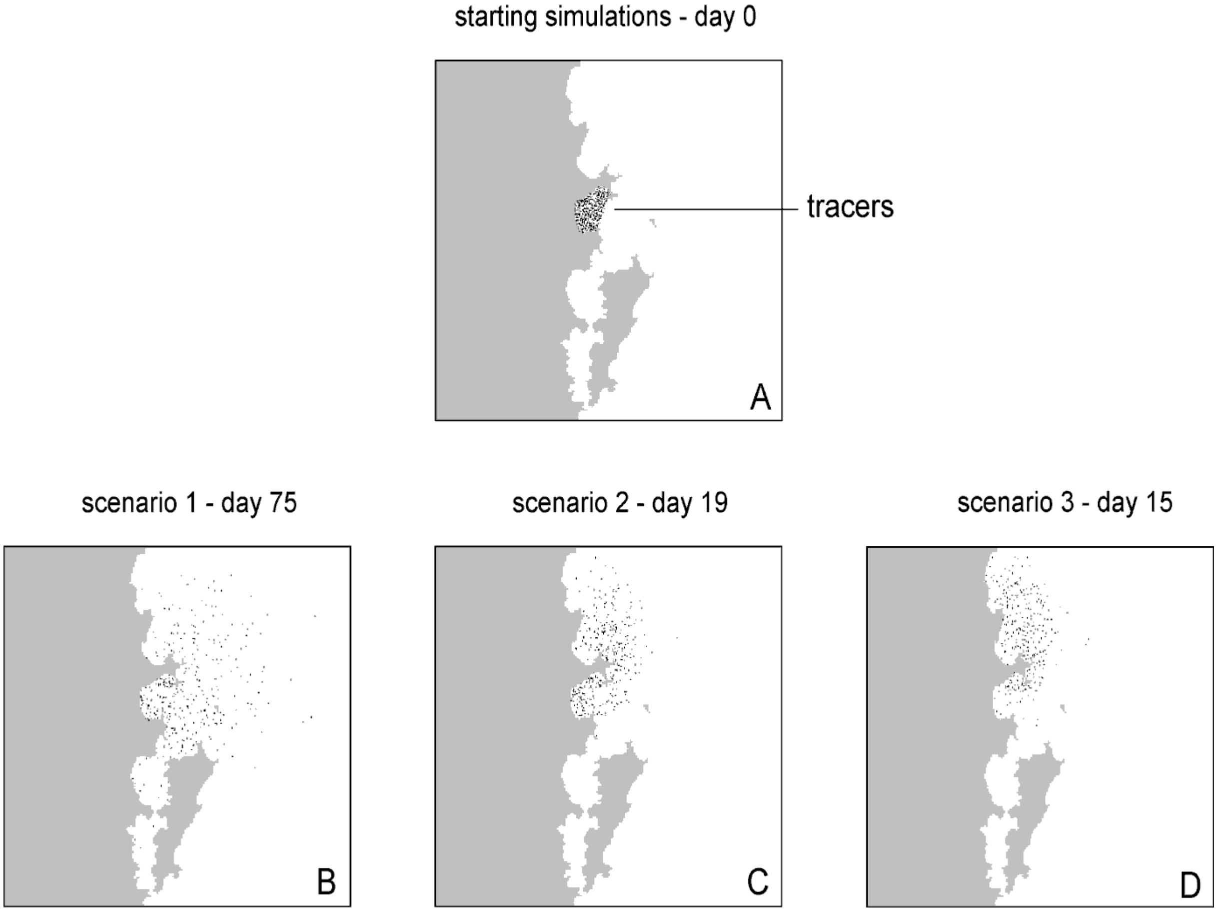

Figure 11 - Dispersion of tracers along the simulations. (A) tracers concentrates in the Tijucas bay, (B, C and D) tracers dispersed in their residence time for scenario 1, 2 and 3.

DISCUSSION

According to Fitzgerald et al. (2007), the coastal plain of Tijucas extends for approximately 5 km off of the coast, formed mainly by muddy deposits in the form of cheniers, overbank deposits and tidal mudflats. Buynevich et al. (2005) states that the bay of the Tijucas River is characterized by a high concentration of suspended material throughout most of the year, mainly due to Tijucas river discharge and the entrapment of tons of fine sediment. This high sediment input results in a decrease of wave energy in the environment and the consequent formation and deposition of slurry in the sub- and inter-tidal areas of the estuary. Tijucas Bay is a region where mud is entrapped due to its particular physiography; mudflat intertidal areas are formed in this area, despite microtidal conditions and relatively high wave energy (Asp et al., 2005; Buynevich et al., 2005). In a recent study of Tijucas Bay, Schettini et al. (2010) found the formation of mud deposits in the bottom and the presence of slurry in some areas of the bay.

The geomorphological and hydrodynamic characteristics of the Tijucas region, which is evidenced by the low hydrodynamic energy of the study area, contribute to the entrapment of fine sediment.

The richness of the geomorphological features of the SC coast and the direction of the coastline can represent a complicating factor for the study of coastal oceanographic process such as sea- and estuary-level oscillations and currents of the internal continental shelf movements induced by the atmosphere. Therefore, the assessment of the behavior of local and synoptic winds is essential to understand the factors that control the hydrodynamics and water quality in coastal areas (Trucculo, 2011).

The Tijucas Bay has as its geographical limits the mouth of the Tijucas River to the west, Zimbros beach to the north, Ganchos beach to the south and an adjacent internal continental shelf to the east. Its proximity to Florianópolis Island makes the bay a fairly sheltered and protected area, mainly with regard to waves from the southern quadrant.

The hydrodynamics of Tijucas Bay are basically the sum of several oceanographic and meteorological forcings on local and regional levels. The major local forcings are currents generated by wind and tide, and when strong winds coincide with spring tide, a greater than usual water exchange between the bay and continental shelf can occur. However, the opposite may also occur because water can be piled up against the coast, a condition that is related to SE winds, and can increase the water residence time inside the bay, decreasing the exchange with the continental shelf.

The circulation in the continental shelf region, including its innermost portion where bays and coves are located, is directly influenced by the energy transferred by the winds. The circulation pattern of the bays can directly respond to tidal variation (flood and ebb) and, mainly, to the intensity and direction of the winds. In the study area, the winds act as an intensifier of water movement, with the circulation and water exchange being accelerated according to the wind speed. The most frequent wind directions in Tijucas Bay are NE and SE, and the speed of the SE wind is generally higher compared to the NE wind, although the NE wind is the most frequent one. Analyzing the residual speeds, one can note a greater influence of the SE wind on water exchange and transport during neap tide, while during the spring tide, the exchange is lower. The circulation in the study area is more affected by SE winds because they frequently display higher speeds and thus transfer more energy to the water column and produce faster currents. In the neap tide period, the wind has more influence on the displacement of currents. Using the indicator vectors of flood and ebb speeds and, mainly, the residual speed, it was found that the SE wind has an essential role in the final transport towards the outside of the bay. When highlighting the importance of winds in the transport of water mass, it was noted that the difference between scenarios is the coincidence of the SE wind forcing the domain during neap tide and providing greater transport. The wind effect on the hydrodynamics is primarily shown by the gyre circulation pattern within Tijucas Bay. There is a gyre circulation in the clockwise direction that is noted when the SE wind forces the domain, while a counterclockwise gyre is noted when the NE wind forces the domain. In these gyres, the speeds tend to be lower in the center of the bay, which is a deeper area. The results of numerical models applied to the Chesapeake Bay using wind and river discharges have shown the influence of these forcings on its hydrodynamics, and the effect produced by the sum of these forcings is responsible for water mass exchanges and transport of both salt and sediments (North et al., 2004). dE Castro et al., (2003) found a strong influence of winds in water exchange and transport between Ría de Ferrol (Spain) and the continental shelf. According to the abovementioned authors, the exchanges depend directly on the intensities of local winds, and residence times are essentially controlled by wind regimes. In a study of Armação de Itapocoroy Bay, approximately 100 km to the north of Tijucas Bay, Schettini et al. (1999) found that the displacement of currents follows the wind more directly than the tidal regime and can usually reach speeds below 0.1 $m.s^{-1}$.

The tide directly influences the pattern of water exchange between Tijucas Bay and the adjacent continental shelf. The water input and output to the bay is a response to the tidal diurnal cycle, and every six hours, the flood and ebb tides set the direction of displacement and transport.

By analyzing the residence time, one can clearly note the influence of the wind on the hydrodynamics of the bay. The variation in wind patterns, shifting from NE to SE and vice-versa, often tends to retain the water for a longer period within the bay because the NE wind generates a current that outflows by the S portion of the bay, while the SE wind has an opposite effect. This shift in current direction during a short period of time tends to retain the water for longer within the bay. Residence time seems to be inversely proportional to wind strength. Thus, one can expect variations according to climatic and meteorological conditions because during periods of high energy, strong winds and waves and meteorological tides, the residence time tends to be shorter. Nevertheless, the hydrodynamics become even more complex if other variables are considered, even the meteorological tide that is associated with strong winds from the southern quadrant can act as a brake on the exchange flow.

In accordance with the hydrodynamic characteristics of Tijucas Bay, the exchanges and transport between the bay and the continental shelf are low over time. Short time periods related to cold front passages and strong SE winds can affect this pattern associated with calm water, increasing the exchanges. This fact can be observed in the low speeds produced by tides and winds most of the time.

Geomorphological, meteorological and oceanographic characteristics should be considered and consequently, the transport in coastal regions, especially coves, bays and estuaries, when water exchange is analyzed. Depending on the characteristics, different forcings can assume the main role in coastal hydrodynamics. Braunschweig et al., (2003) found no significant difference in residence time in numerical situations applied to the Tagus estuary (Portugal) when comparing scenarios with no wind and with constant S wind (10 $m.s^{-1}$). Malhadas et al., (2010), in a study to assess the residence time of Laguna de Óbidos [Óbidos Lagoon] (Portugal), found that the semi-diurnal tide was the main hydrodynamic forcing, followed by waves. Wang et al., (2004) found for the estuary of Danshuei (Taiwan) that the tide was responsible for approximately 50% of estuary outflow transport.

The morphology of Tijucas Bay can be another factor influencing water renewal, as the narrowing of the eastern portion of the bay where there is a connection with the adjacent continental shelf may somehow affect the water exchange between the bay and the shelf. Another factor is its proximity to Florianópolis Island, which shelters part of the bay from undertows from the S/SE.

There are indicators of the calm water hydrodynamic pattern during most of the time in the study area. Occasionally, extreme, short events of high energy with strong winds, high river discharge and waves can generate greater current movements within the bay, but sediment characteristics, such as the presence of fine sediments highlighted by some authors, show this pattern of calm waters.

CONCLUSION

Tijucas Bay is located in a sheltered area and displays characteristics of an environment of calm water hydrodynamics. The microtidal regime acts directly in the current displacement direction towards the inside or outside of the bay according to the cycle period. The wind patterns found in the study region are NE winds, which are more frequent and less intense, and SE winds, which are less frequent and more intense. The transport of water masses between the bay and the adjacent continental shelf is a direct response to the wind intensity, the same being true for the direction of the movement. Northeast winds tend to form a counterclockwise gyre current within the bay, and therefore, the currents are forced to enter by the northern end and exit by the southern end. The currents are more intense in the northern end during flood tide and more intense in the southern end during ebb tide. The opposite can be observed when SE winds force the region, with clockwise currents entering by the southern end and exiting by the northern end and the inflow currents being more intense during flood tide, while outflow currents are more intense during the ebb tide. Southeast winds are supposedly more intense, exhibit higher speeds compared to NE winds and are responsible for a greater displacement of water mass. Consequently, SE winds contribute to a greater transport to the outside of the bay, especially when coinciding with neap tide. Through the analysis of residence time, it is clear that winds are important for the transport between the bay and the adjacent continental shelf

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STUDY OF THE DISPERSION BEHAVIOR OF THE TIJUCAS RIVER PLUME, SANTA CATARINA, BRAZIL.

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ABSTRACT

The Tijucas Bay on the southern coast of Brazil has unique characteristics, such as intertidal mudflats in a microtidal region. The Tijucas River estuary is the main source of sediments for the bay. The aim of the present study was to describe the processes of estuarine plume dispersion in the bay and to assess the patterns that arise under various meteorological conditions. Data on salinity and the concentration of suspended sediments (CSS) and numerical simulations were used to analyze the plume dispersion behavior. The numerical experiments were designed to represent the conditions of a fluvial discharge pulse. The modeling results qualitatively corroborated the field observations. The dispersion of sediments liberated by the plume directly corresponded to the bay's hydrodynamics, especially as a response to the wind. The intensity and orientation of the plume dispersion corresponded to the wind, forcing dispersion both to the north (southwestern wind) and to the south (northeastern wind). The numerical simulations revealed the greatest plume development at approximately one day (~30 hours) after the discharge peak; after this period, the plume's extension and CSS tended to decrease.

RESUMO

O entendimento sobre processos costeiros sobretudo o comportamento da pluma de sedimentos dos rios vem se tornando cada vez mais importante a medida em que as zonas costeiras se desenvolvem. O Rio Tijucas é maior contribuidor de sedimentos para a baia de Tijucas, apresenta a maior parte do tempo descarga baixa, com períodos de médias e altas descargas normalmente relacionados a eventos metereológicos como passagens de frentes frias. A pluma do rio Tijucas é capaz de despejar grandes quantidades de sedimentos finos no interior da baia. Foram utilizados dados coletados de salinidade e CSS e simulações numéricas como ferramentas para análise do comportamento da pluma do Rio Tijucas. Os dados de CSS coletados e do modelo apresentaram uma relação direta, ambos mostram um desenvolvimento da pluma de sedimento ao longo da linha de costa. O comportamento da pluma do rio Tijucas é uma resposta direta a hidrodinâmica da baia, principalmente em relação ao vento, principal responsável. Os ventos influenciam diretamente a direção e intensidade das correntes, proporcionando a pluma um desenvolvimento tanto para norte quanto para sul da desembocadura. As simulações numéricas mostraram o maior desenvolvimento da pluma cerca de 32 horas após o pico de descarga, após este período a pluma tende a diminuir de extensão e CSS. O perfil vertical mostra a pluma distribuida por toda a coluna dágua. Há indícios de deposição rápida dos sedimentos da pluma, entretanto muitos processos físico-químicos, principalmente a floculação, afetam diretamente a dinâmica destes sedimentos e que possivelmente estam relacionados com a deposição da pluma.

Keywords: Numerical modeling, suspension sediments, fluvial discharge, wind.

Palavras-chave: modelo numérico, sedimentos, descarga pluvial, vento.

INTRODUCTION

The understanding of processes related to the dynamics of coastal environments, such as hydrodynamics, become relevant as the scientific community concentrates its efforts in understanding the ocean processes. In addition, because of the direct relation to several activities of the productive sectors (e.g., oil, fisheries, civil construction industries, and port activities), the coastal area has become a key piece in development. Therefore, the study of the hydrodynamics of coastal environments is fundamental for understanding the processes involved in the dynamics of these regions.

The hydrodynamics of coastal regions are directly related to oceanographic (tides), meteorological (wind), and continental (fluvial discharge; Bowden, 1983) forces. The rivers are the main mechanism of fresh water, nutrient, and sediment transport along the continent-ocean interface. Annually, ten billion tons of sediment load are transported worldwide by rivers into the oceans (Milliman et al., 1992), although these values may change rapidly due to changes in land and river use. The impacts generated by the rivers’ discharges are important on a global, continental, and regional scale, as well as, more directly, to the continental shelf that receives this sediment input (Dagg et al., 2004).

The input of sediments of fluvial origin into the coastal region is commonly visualized by the formation of a low-density water plume with a high concentration of suspended sediments near the mouths of estuaries (Stumpf et al., 1993). The low-density plumes are an important mechanism of initial distribution of the fine sediments that are brought in by the rivers. The sediment discharge into the marine environment is basically controlled by a sequence of processes, including fluvial, estuarine, and marine processes; all of these processes are substantially affected by the flow of continental fresh water. The processes that influence the sediment transport are related to the difference in density between the continental sediment-rich water and the marine water. In addition, the plume buoyancy effect caused by the contrasting densities can generate a force capable of influencing coastal circulation, affecting both the estuary and the continental shelf (Geyer et al., 2004).

The distribution of the concentration of suspended sediments brought in by the rivers relies on many factors, such as the mixing process between fresh and saltwater, the magnitude of the fluvial discharge, the coastal circulation, and the tidal and wind regimes (Stumpf et al., 1993; Arnoux-Chiavassa et al., 1999; Liu et al., 1999). In the absence of other forces, the continental waters that discharge into the continental shelf are deflected leftward in the Southern Hemisphere due to the effect of the Earth’s rotation. However, this pattern may be altered seasonally or for short periods of time by the action of dominant winds or by the temporal variability in the coastal currents (Zhang et al., 1987; Hickey et al., 1998). Although the fluvial discharge usually exhibits positive buoyancy, in some situations, the fluvial input presents very high concentrations of suspended sediments, resulting in negative buoyancy (Liu et al., 2002).

Understanding the dispersion dynamics of sediment-rich estuarine/fluvial plumes requires employing a number of experimental techniques, including field observation and numeric modeling. Numeric models have been successfully used in the study of plume behavior and have generated an extensive bibliography on this subject: Chao (1990) studied the influence of the tidal oscillation on the behavior of the sediment plume, and Chao (1988b) analyzed the effect of the wind on dispersion and mixing. Arnoux-Chiavassa et al. (1999) applied a 3D hydrodynamic numerical model to study the transport of suspended sediments in plumes. Liu et al. (2002) used a model to analyze the characteristics and behavior of the sediment plume in southern Taiwan. Maidana et al. (2002) applied a numeric three-dimensional model using field-measured wind data to observe the circulation in the Ebro Delta, Spain. Durand et al. (2002) applied a numeric model to analyze the mechanisms of mixing and stratification in the same region in Spain. Van Maren & Hoekstra (2005) used a one-dimensional model to observe the movement of the sediment plume in the Red River in northern Vietnam. Huret et al. (2005) studied the ecological processes related to the Plata River plume by means of coupled physical and biogeochemical models. Vaz et al. (2009) used a hydrodynamic model based on the wind and fluvial discharge to analyze sediment plume dispersion during the winter in the estuary of the Tejo River in Portugal. Currently, there are few published investigations of the plume systems in Brazil. Schettini et al. (1998) assessed the pattern of initial plume dispersion in the estuary of the Itajaí-Açu River [Rio Itajaí-Açu]. Marques et al. (2010) evaluated the plume dispersion in the Patos Lagoon [Lagoa dos Patos] to investigate the pattern of sediment deposition on the continental shelf. Oliveira et al. (2012) investigated the sediment plume of the rivers on the eastern coast of northeastern (NE) Brazil.

Along the coast of Santa Catarina state (SC), there are many estuaries dominated by rivers that produce coastal plumes (e.g., Schettini et al., 1998). The Tijucas River estuary is one of these systems, which discharges into the internal portion of the Tijucas Bay. The Tijucas Bay has the peculiarity of having extensive mud plains along its internal portion, which is an uncommon feature in microtidal regions (Buynevich et al., 2005), as well as areas with sediment slurry (Schettini et al., 2010s). This phenomenon suggests that mechanisms might exist for the retention of the fine sediments released by the Tijucas River. The aim of the present paper is to assess the behavior of the Tijucas River plume and verify its dynamics relative to the distinct wind patterns that occur in SC.

STUDY AREA

The Tijucas Bay is located between the parallels $27^{0}10'$ and $27^{0}18'$ S (Figure 1) and has an approximate area of 100 km^2 and a length and width of approximately 10 km. Tijucas Bay is a unique environment on the Brazilian coast because it has an extensive intertidal mudflat area (Buynevich et al., 2005), which indicates that the bay has a hydrodynamic regime that favors the retention of fine sediments in its interior (Schettini et al., 2010). The bathymetry of the bay has a smooth pattern with increasing depth up to its central and external portions, as well as a large shallow area along its internal edge area. The extension of the coastline to the 2 m isobath is 2.5 km. From the 2 m depth, the bathymetry tends to follow a steeper gradient, reaching a depth of 12 m at the estuary's mouth.

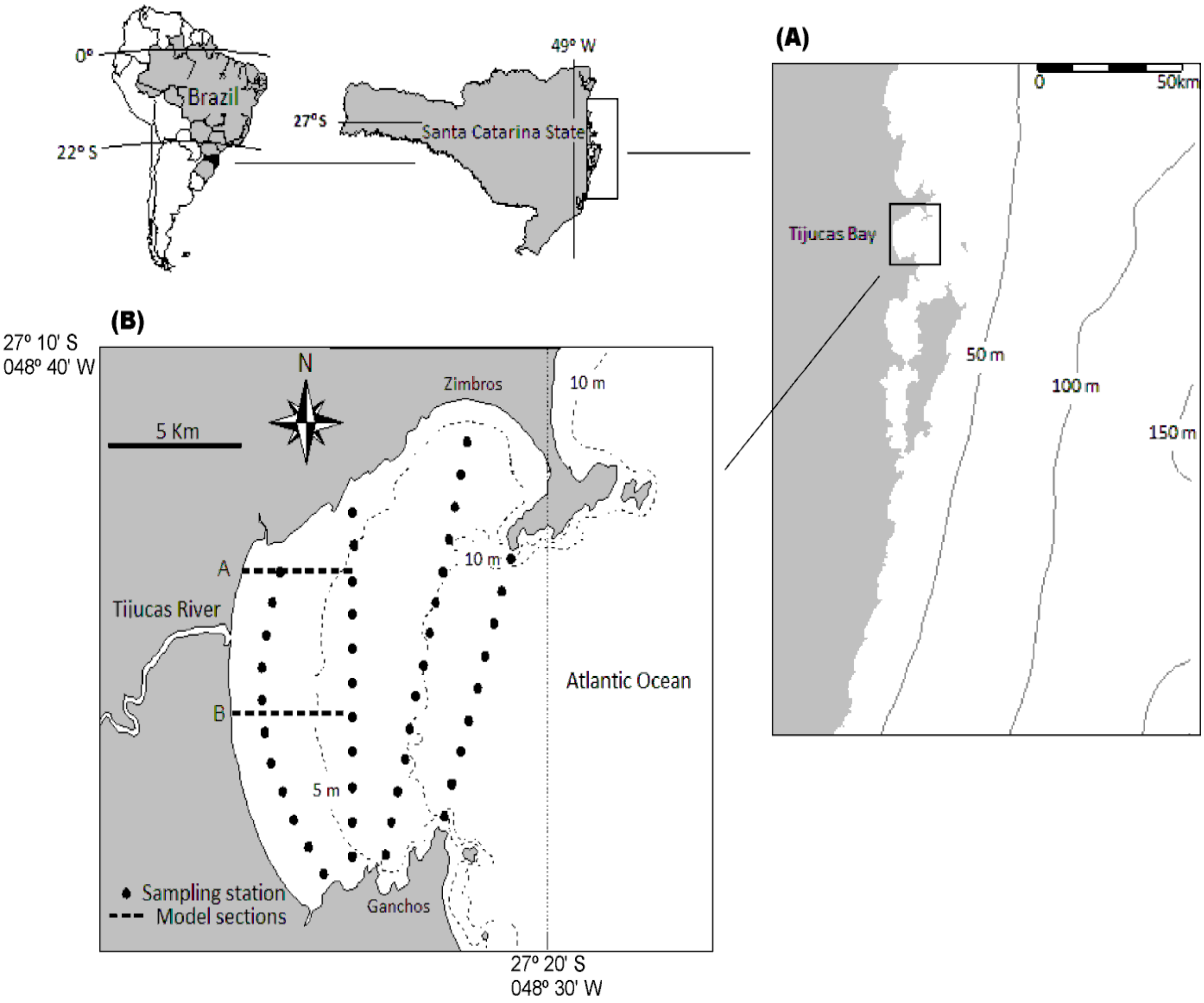

Figure 1. Location of the study area. (A) area of the model domain, (B) Tijucas Bay with the location of sampling stations (points) and the sections of data extraction model (dashed line).

The climate in this region is characterized as subtropical mesothermic, with rainfall distributed throughout the year. The hydrological balance is positive, with a total rainfall of approximately 1,415 mm.year^{-1} and a potential evapotranspiration of approximately 900 mm.year^{-1}. The average annual temperature is 21.4 ºC, with maximum and minimum temperatures of 17.3 ºC and 26 ºC in August and February, respectively (Gaplan, 1986).

The wind regime is dominated by NE winds throughout the year, with the occurrence of winds coming from the southern quadrant related to cold fronts crossing the coast of SC (Truccolo, 1998). The changes in the meteorological conditions observed in the southern and southeastern (SE) regions of Brazil are usually related to the passage, formation, or intensification of cold fronts, which are typical of mid-latitude weather systems and are active on the Brazilian coast in all seasons (Kousky, 1979; Satyamurty et al., 1998). The cold fronts travel from SE to NE and exhibit a rotating wind pattern initially from the NE towards the south; this pattern persists for at least one day and is followed by a decreased temperature up to two days after the cold front’s passage (Rodrigues et al., 2004). In the city of Florianópolis, which is approximately 30 km south of Tijucas Bay, the average wind speed varies from 3.4 m.s^{-1} in May to 4.7 m.s^{-1} in October, with maximum values of 16 and 27.1 m.s^{-1}, respectively (Goulart, 1993).

The hydrographic basin of the Tijucas River has a drainage area of 2800 km^{2}, and the river is the main transporter of water and sediment into the bay, discharging into the central portion of the inner edge of the bay. Historical data on the flow of the Tijucas River, which has been monitored since 1945, indicate an average discharge of 24.4 m^{3}.s^{-1}. However, the hydrograph primarily reveals values below the average discharge, with flood peaks that are randomly distributed in time. This phenomenon is caused by the response to the rainfall regime and to the relatively small area of the drainage basin. The flood peaks may last from several hours to a few days during prolonged rain periods.

The area has a mixed microtidal regime (< 2 m high) with dominant semidiurnal tides. The average tidal height is 0.8 m and varies between 0.3 and 1.2 m during the neap and spring tides, respectively (Schettini, 2002a). Meteorological effects can influence the variation in the tidal level (up to 30%), and during the passage of cold fronts that are associated with strong southern winds, the variation in the tidal level can reach 1 m (Truccolo et al., 2006).

Araújo et al. (2003) described the regional wave climate based on the measurements from an ondograph anchored 35 km off Florianópolis Island. Five wave patterns were identified, consisting of two swells and three types of wind waves. The most important patterns are the southern swell (direction of 162°), with a period of 11.4 s and a significant height between 1.5 and 2 m, and the NE wind waves (direction of 27°), with a period of less than 8 s and a significant height greater than 0.75 m.

The region is located in the southern portion of the Southeastern Brazilian Continental Shelf (SBCS), which is also known as Santos Bay. The overall ocean circulation in this portion of the continental shelf is characterized by the flow of the Brazil Current (BC), which is of tropical original and southerly direction, whereas the flow in the opposite direction is that of the Malvinas Current (MC), which is of sub-Antarctic origin (Legeckis & Gordon, 1982; Olson et al., 1998). The SBCS is characterized by the following: Coastal Water (CW), which results from the mixture of coastal water of continental origin and continental shelf water with low salinity values; Tropical Water (TW) associated with the BC; and South Atlantic Central Water (SACW), which is subjacent to the TW and characterized by temperatures and salinities below 20 ºC and 36.4, respectively (Miranda, 1982; Resende, 2003). From May to September, the region is influenced by the Prata Plume, which moves northward and may travel as far as Rio de Janeiro state (Piola, 2005). During this period, the salinity in the inner continental shelf decreases to values of approximately 30, and the water temperature is below 20 °C (Schettini et al., 2005).

MATERIALS AND METHODS

Field activities

Four field campaigns were performed in the Tijucas Bay to assess the spatial distribution of salinity and the concentration of suspended sediments (CSS) on June 20 and 27 and on July 3 and 31, 2010. The temporal proximity of the campaigns was chosen to obtain an overview of the variables' variability on a short time scale. The data were recorded with an SAIV A/S CTD-type probe, model SD202, with a SeaPoint turbidity sensor (Optical Backscatter Sensor – OBS). Forty-five vertical conductivity/temperature/depth (CTD) profiles were sampled and distributed among four sections, which were approximately transversal to the longitudinal axis of the bay (Figure 1). The data were processed and reduced to a vertical resolution of 0.5 m. The turbidity data were registered in nephelometric turbidity units (NTU) and converted to CSS by calibration with samples that were collected *in situ* (Schettini et al., 2010). Fluvial discharge data were obtained from the Hidroweb website of the National Water Agency (Agência Nacional de Águas – ANA) for the Major Ercino Station (Figure 2). This station represents the discharge for a drainage of 1,010 km^2, and the discharge data were linearly normalized for the total drainage area.

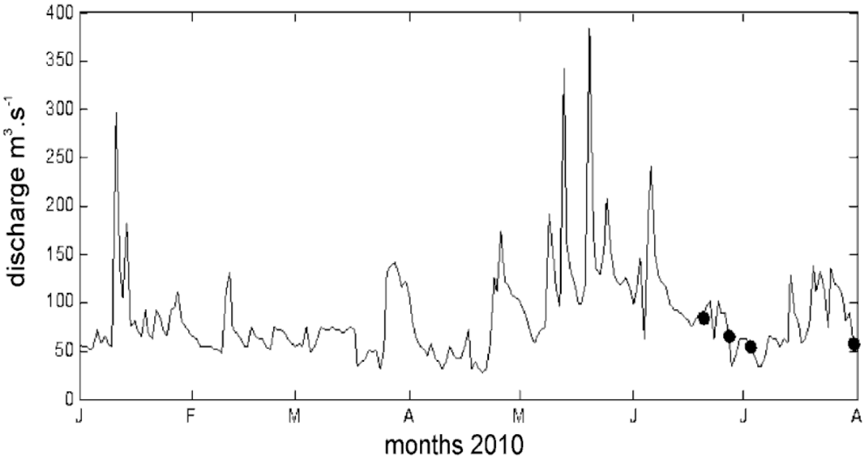

Figure 2: Data from the Tijucas River daily discharge for 2010, and an indication of the days that were performed field campaigns in the Tijucas Bay.

Numerical modeling

The hydrodynamic numerical model MOHID 3D (water modeling system, http://www.mohid.com/) was used for the present study, with the application of full formulations for three dimensions, the hydrostatic hypothesis, and the Boussinesq approximation (Miranda et al. 2000; Martins et al. 2001). A nested-mesh model was utilized.

The father-domain, which represents a region that encompasses a large part of the SC coast (150 x 180 km), generates border conditions for the subordinate domain, which is restricted to the area of greatest importance for the present study (20 x 35.5 km), namely, the Tijucas Bay and part of the inner continental shelf. The grid is 500 x 500 m Arakawa C type for the father-domain and 100 x 100 m for the subordinate domain. The hydrodynamic model was forced through its border by imposing tidal level variations generated by the FES2004 – (Finite Element Solution; Lyard et al., 2006).

The model was calibrated with the tide level data produced by the harmonic components of Arvoredo Island (Ilha do Arvoredo), located in front of the Tijucas Bay, and with the tide level data produced by the model.

For the water level, the visual agreement between the observations and the model results were considered very satisfactory. Error analysis (Eq.1) was employed to objectively evaluate the ability of the model (Cm) to reproduce the observations, as calculated by:

$$Cm = 1 - \frac{\sum |X_M - X_O|^2}{\sum (|X_M - \overline{X_O}| + |X_O - \overline{X_O}|)^2} \qquad \text{Eq. (1)}$$

where X_M is an instant result of the model, X_O represents a synoptic observation to this result, and $\overline{X_O}$ is the mean of the observed values (Willmott et al., 1985). In the case of a perfect capability to reproduce the observation, Cm will be 1. In the present case, the Cm value was 0.96 for the water level. This value is not a percentage. The Cm value for the present study allows for the validation of the model; for the tide amplitudes that were analyzed, the error was below 10% (Figure 3).

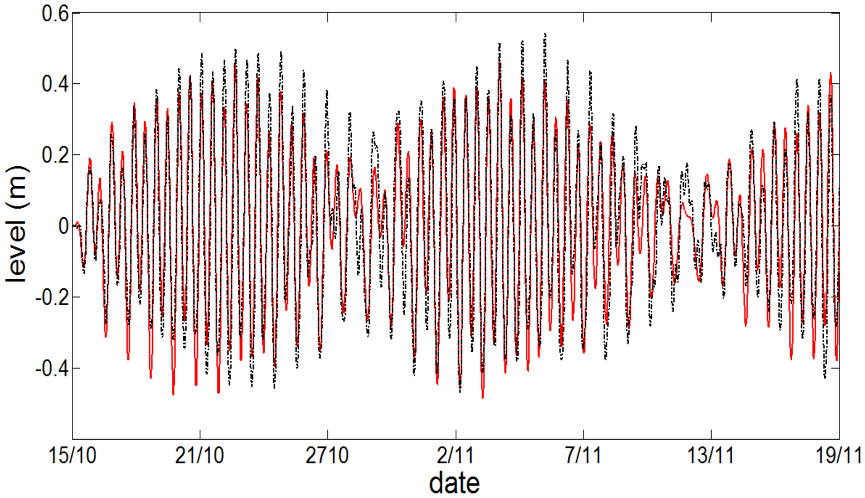

Figure 3 - Calibration curve between tide level modeling (···· Mohid) and tide level of harmonic components at Arvoredo Island (— Arvoredo).

Two scenarios were simulated to assess the response of a fluvial discharge pulse in the Tijucas Bay under various wind conditions. These conditions are typical of the hydrological events of freshwater inflow into the bay. The concentration of suspended sediments transported by the river is linearly and directly related to the fluvial discharge (e.g., Schettini, 2002a). The simulations begin with an initial fluvial discharge of 25 $m^3.s^{-1}$; after 24 hours, the discharge increases continuously for 8 hours until reaching 500 $m^3.s^{-1}$. After the peak, the output decreases over 20 hours until returning to the initial values. The variation in CSS follows the variation in the water discharge, but its values are measured in $mg.l^{-1}$ (Figure 4). The same water discharge condition was simulated for two different modal wind conditions, which are typical for the region: NE wind with a speed of 3 $m.s^{-1}$ (standard condition) and SE wind with a speed of 8 $m.s^{-1}$ (cold front condition). The values used for the fluvial discharge, CSS, and wind were based on values that were consistent with the observed local data (Schettini et al., 1996; Schettini et al., 2010).

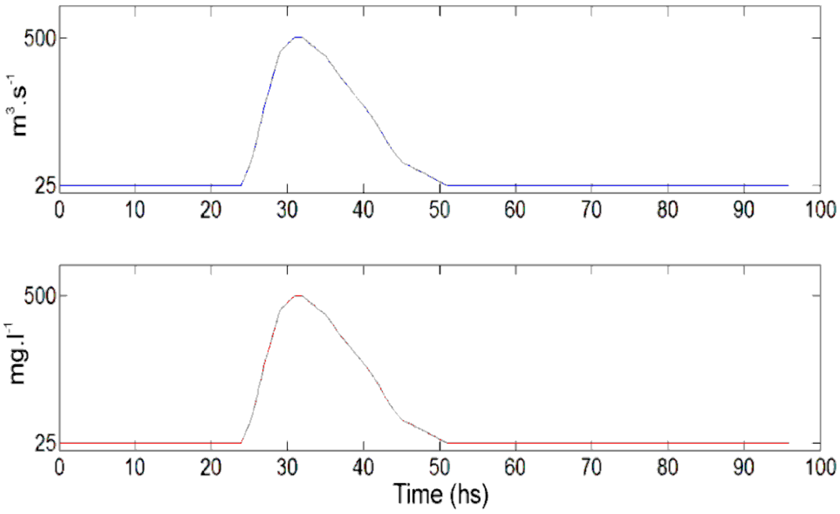

Figure 4. Schematic representation of the variation of the Tijucas River discharge (—) and sediment concentration (—) used in the simulations.

RESULTS

The fluvial discharge during the field campaigns was not high; however, all of the campaigns were performed when the fluvial discharge was over 50 $m^3.s^{-1}$. The hydrograph for 2010 displayed no excessive discharge peaks, with one isolated peak in January and a subsequent, wetter period in May, which ended in June, with outputs of approximately 300 $m^3.s^{-1}$. Therefore, no campaign registered a discharge pulse, as they all recorded average discharge conditions.

Figures 5 and 6 present the distributions of salinity and superficial CSS, respectively, which were recorded during the field campaigns. The first three campaigns were performed in weekly intervals, whereas the fourth campaign was performed only three weeks after the third campaign due to logistical problems. Each campaign lasted one day and spanned different phases of the tidal cycle. However, the tidal currents played only a secondary role in the circulation within the bay (Souza and Schettini, unpublished data), and the results represent a realistic pictures of the distribution of these parameters.

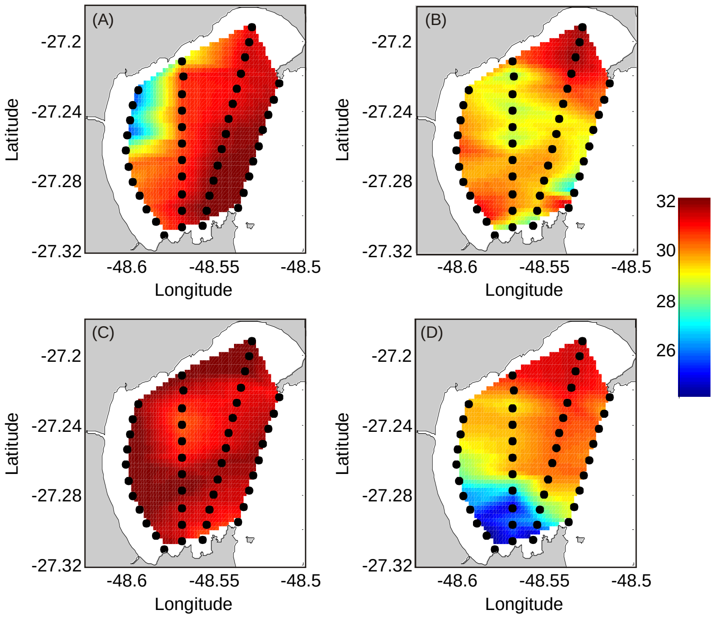

Figure 5. Distribution of surface salinity in the Tijucas Bay during the four cruises.

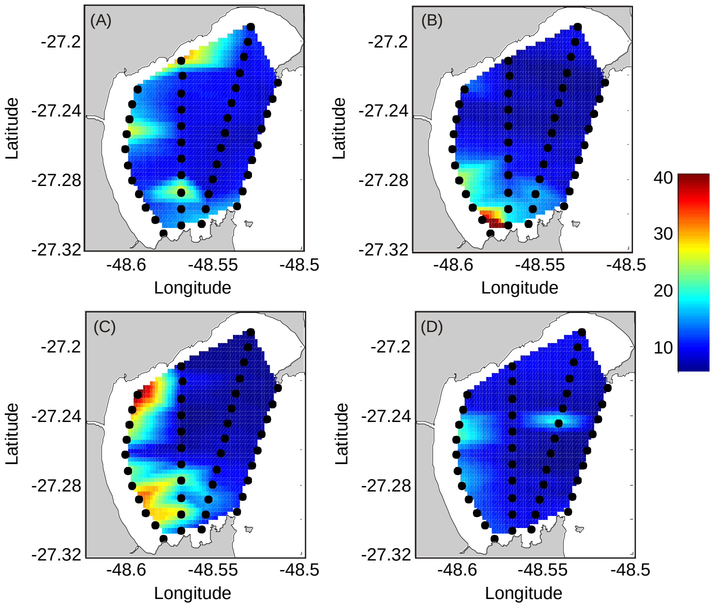

Figure 6. Distribution of suspended sediment concentration (mg.l^{-1}) in the Tijucas Bay during the four cruises.

The maximum salinity for all of the campaigns was 33, which is the typical condition for this season in coastal waters influenced by the northward current of the Prata (Piola et al., 2005; Schettini et al., 2005). The direct river influence may be indicated by the lower salinity values (below 28), which were mainly recorded for the first and last field campaigns and, to a lesser extent, in the second campaign. The results for the first and last campaigns were especially relevant for the present study. In the first campaign, the dispersion of the fluvial waters of the Tijucas River occurred northward from the mouth, whereas for the second campaign, the dispersion occurred southward. In both cases, the lowest salinity region was located inside the bay and did not reach the mouth of the bay. The distribution of the superficial CSS was different from that of the salinity. The CSS ranged from less than 10 to slightly over 40 mg.l^{-1}, with the greatest values observed near the coast. This result is similar to the findings of Schettini et al. (2010) and indicates that the sediment reworking is due to the wave action more than to the contribution of the fluvial plume itself. The poor relationship between the salinity and the CSS indicates that suspended sediments precipitate rapidly once they are released into the river plume (e.g., Schettini et al., 1998) and that the plume's water mingles and forms higher-salinity water, which disperses more slowly as a result of the dominant forces.

Figure 7 illustrates the dispersion of the Lagrangian tracers in the simulations. The movement pattern and the behavior of the cohesive sediments may be represented by the temporal evolution of tracers in the domain. The dispersion of the sediment plume for the proposed scenarios was observed 8, 32, and 56 hours after the beginning of the discharge pulse. Under NE wind conditions, the particles tended to remain along the coastline in the shallower parts of the bay, dispersing both northward and southward from the river's mouth. Under SE wind conditions, the distribution of the particles also tended to follow the coastline; however, the distribution was directed towards the northern part of the bay because of the currents. In these scenarios, some of the particles tended to remain close to the river's mouth under both wind conditions. During the simulations, the first particles began to be discharged after the first 8 hours, and after 32 hours, the plume was fully developed, and the particles were distributed. The movement of the particles between 32 and 56 hours was practically null, and at this point, we could observe the areas in which the sediments (tracers) were deposited after the discharge pulse of the Tijucas River.

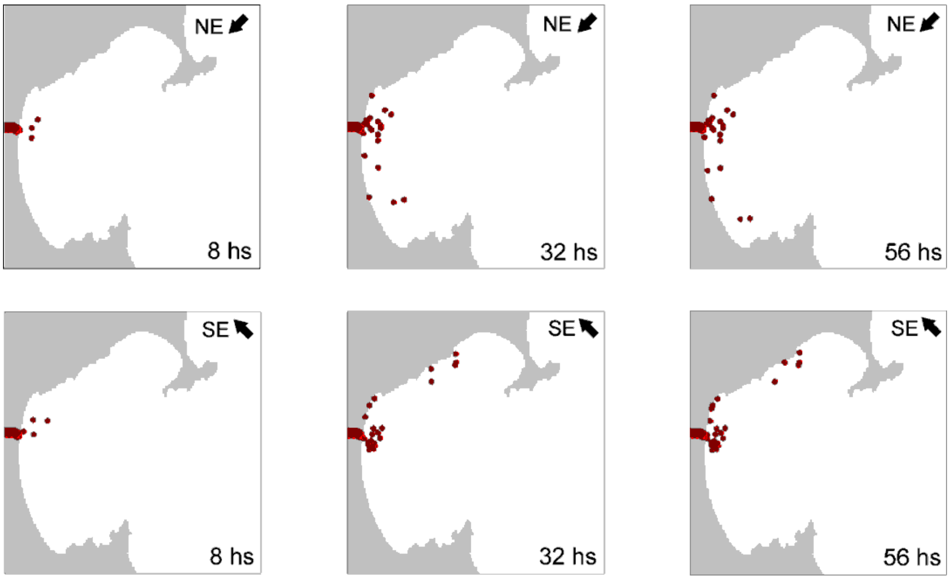

Figure 7. Lagrangian tracers characterizing the behavior of sediment discharged by Tijucas River on 8, 32 and 56 hours after the peak discharge in northeast wind conditions (above) and southeast (below).

Figures 8 and 9 display the distribution of the simulated CSS for the different wind scenarios and a vertical profile (A and B) for the observation of the behavior of CSS throughout the water column. The plume developed towards the bay's interior and reached its maximum size 32 hours after the beginning of the discharge. The concentration of the suspended sediments after 32 hours was high, reaching values of hundreds of mg.l^{-1}; this outcome was observed in both scenarios. Subsequently, the extension of the plume and CSS decreased. Under NE wind conditions, the plume dispersed northward and southward from the river's mouth, although its southward dispersion was more intense due to the currents' directions. Under SE wind conditions, the plume developed only towards the northern margin due to the currents generated by the SE wind, which were more intense than those generated by the NE wind. In the vertical profile, both scenarios were characterized by the plume's evolution in the entire coastal strip, forming a strip of lower-salinity water near to the coast, with a preferential dispersion related to the wind-generated coastal currents (Figure 10).

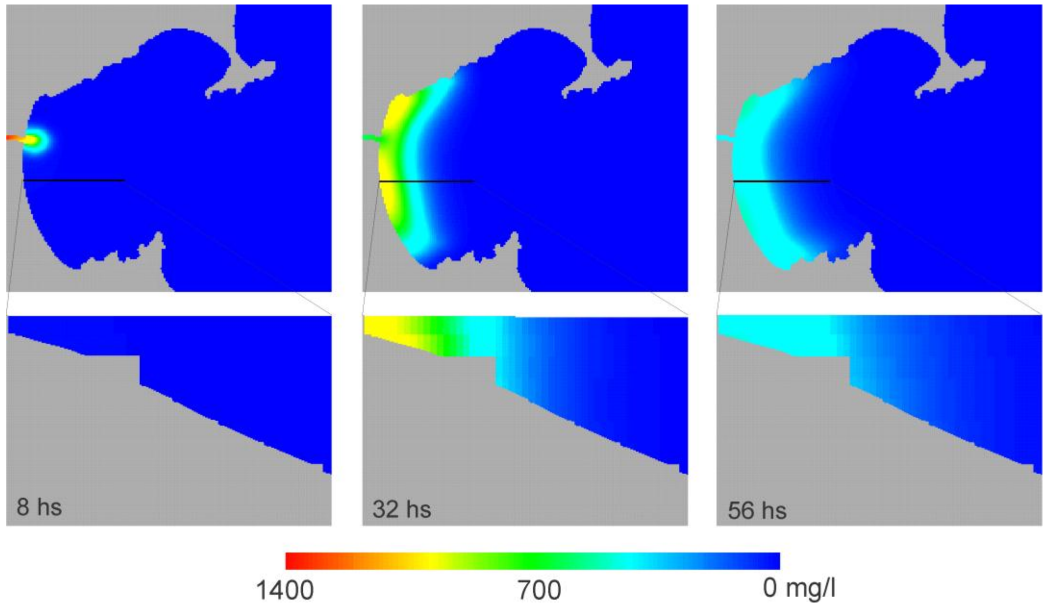

Figure 8. Tijucas River sediment plume measured on 8, 32 and 56 hours after the start of the discharge pulse, under conditions of wind northeast (NE). Vertical profile (below) of the sediment plume in section (B) south of the Tijucas River mouth.

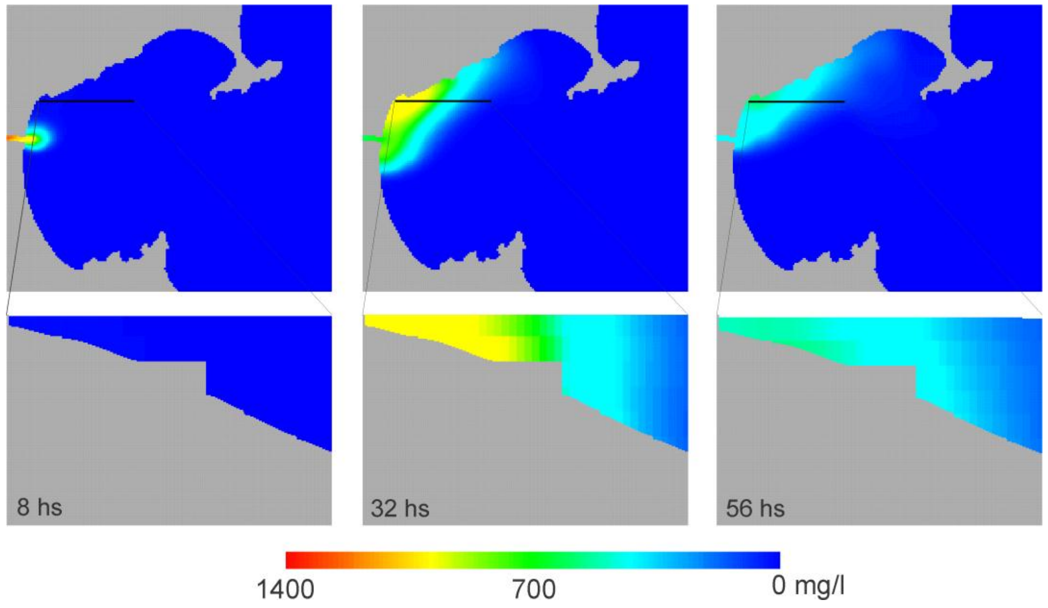

Figure 9. Tijucas River sediment plume measured on 8, 32 and 56 hours after the start of the discharge pulse, under windy conditions southeast (SE). Vertical profile (below) of the sediment plume in section (A) south of the Tijucas River mouth.

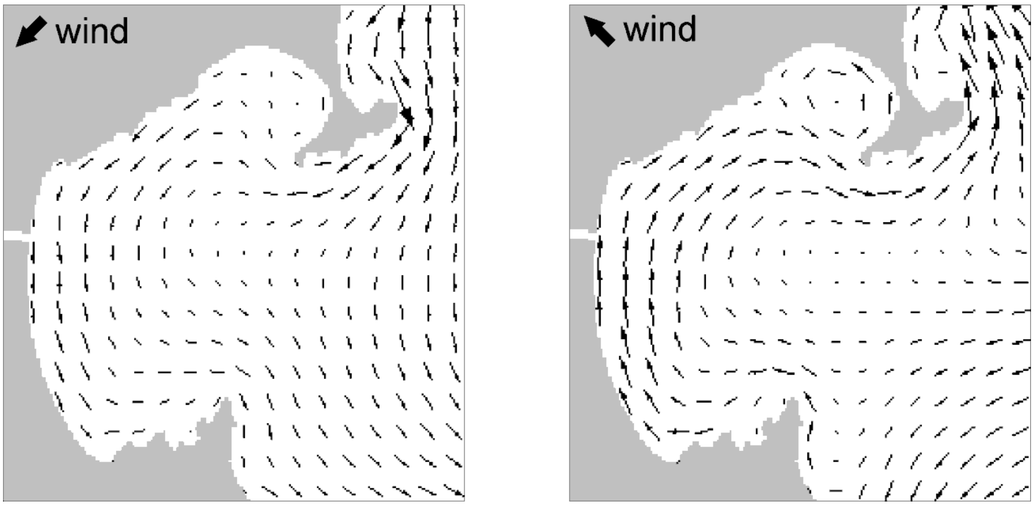

Figure 10. Patterns of currents in the Tijucas Bay generated by winds of the northeast (NE) and southeast (SE).

DISCUSSION

SC does not exhibit a characteristic pattern of rainy periods. Analysis of the historical data (ANA – National Water Agency) of the Tijucas River output from 1983 to 2006 indicates maximum output values of 900 m^3s^{-1}, which occur in short-duration episodes interspersed with long low-discharge periods (Schettini, 2002). The high-discharge periods usually last several hours to a few days and are related to cold fronts coming from the SE in the winter and to storms occurring in the summer. The cold fronts are the main causes of precipitation in southern Brazil, and due to their spatial and temporal variability, the rainfall varies throughout the year because of factors including (but not limited to) irregular topography, latitude, and circulation dynamics.

The Tijucas River is the main transporter of fine sediments into the bay (Schettini et al., 2010). The CSS of the Tijucas River estuary is four times greater than those of nearby estuaries with similar hydrological conditions (Schettini et al., 1996), which indicates a relatively high level of sediment formation in the hydrographic basin. This greater concentration may be related to the characteristics of the bay, which has a higher slope and friable rocks, such as recent sedimentary and metasedimentary rocks (Asp et al., 2009).

The behavior of the Tijucas River plume is related to the hydrological regime of the river and to the hydrodynamics of the bay and should be more pronounced after periods of high discharge and low hydrodynamic energy in the environment

(Traykovski et al., 2000). High river discharges imply a longer transport, a greater CSS, and longer and more fully developed plumes.

The Tijucas River plume tends to develop parallel to the coastline and, depending on the hydrodynamic conditions (especially the wind direction), can stretch northward under SE wind conditions or southward under NE wind conditions. The salinity and CSS within the bay vary mainly as a function of the river's discharge and hydrodynamics. The collected data revealed areas of lower salinity (Figure 4 A and D) after periods of greater discharge, which characterized the displacement of the plume. Regarding the data on the suspended sediments, it is possible to emphasize the greater sediment concentration in the shallower areas. In this case, the results of the numeric model and collected data are correlated, as both present a greater CSS along the coastline, which is characteristic of the plume's behavior. The simulation represented conditions typical of high-discharge peaks and winds, and these results demonstrated that the plume exhibited greater development approximately 32 hours after the discharge peak and displayed no stratification. After 56 hours, the plume's parameters decrease, especially with regard to CSS. At this point, the physical-chemical processes, including flocculation, act until the sediments are completely dispersed; these sediments are then integrated into the processes of coastal transport and deposition. However, we noted that the sediment plume tended to accumulate quickly; this process might be critical for the retention of a large part of the river-discharged sediment within the bay.

The Tijucas coastal plain extends for approximately 5 km into the coast and is mainly composed of muddy deposits in the form of cheniers, overbank deposits, and tidal mudflats (Fitzgerald et al., 2005). Approximately 1,000 years ago, the deposition processes on the Tijucas plain changed from a sand-dominated system to a mud-dominated system. This change was most likely related to modifications in the fluvial sedimentation rate due to climate change that led to modifications in the vegetation, erosion, and soil-formation patterns and the consequent increase in the fine sediment input into the estuary (Fitzgerald et al., 2005). In addition to the greater input of fine sediments, the gradual filling of the estuary, with the consequent reduction of the bathymetry of the bay, led to a decrease in the wave energy, favoring the deposition of these sediments. The Tijucas River bay is currently characterized by a high concentration of suspended material throughout most of the year, mostly due to discharge from the Tijucas River and the imprisonment of tons of fine sediments (Buynevich et al., 2005). Based on the characteristics of the bay, it is important to highlight the role of the sediment plume in its formation; throughout its history, the plume has carried tons of sediments into the bay. Short high-discharge periods associated with long low-discharge periods controlled the distribution of the sediments within the bay via its hydrodynamics, which consisted of increasingly calm waters. Periods of heavy rainfall, such as the El Niño climatic event, contributed to the transport of sediments into the bay. Currently, one can observe that the wind pattern, which is mainly responsible for the bay's hydrodynamics, also favors the transport of sediments between the bay and the adjacent continental shelf. Sediment retention, which is also primarily controlled by hydrodynamics, may also have a substantial effect on the behavior of the Tijucas River plume. The sediments of the plume precipitate rapidly, as demonstrated by the present study's results; this rapid precipitation significantly decreases the availability of suspended sediments for transport. Notably, areas adjacent to the Tijucas Bay, both to the north and to the south, are clear-water areas that are used for tourism (including diving). The retention of sediments within the bay is related to its dynamics (i.e., the behavior of the plume).

The behavior of plumes is complex; once discharged by the river, the sediments become part of a cycle of erosion, transport, and deposition before they reach deeper water, and they may subsequently participate in a remobilization process (Wright et al., 1995). Some processes appear to be consistent within the plumes, such as (a) aggregation, flocculation, and adsorption-desorption; (b) increased light penetration; and (c) photo-chemical and microbial transformations, which affect the transformation and the transport (vertical and horizontal) along the plume (Dagg et al., 2004). The dynamics of the plumes are also related to biogeochemical processes that vary based upon the timescale. The seasonality, fluvial discharge intensity, solar radiation, and wind are key forces that are responsible for modifying the spatial and temporal extension of the plumes (Dagg et al., 2004). The difference in density and salinity between the discharged freshwater and the saltwater of the ocean tend to increase the complexity of the processes. As the river plume mingles with the ocean's saltwater, flocculation and aggregation of the dissolved and colloidal material become the major physical-chemical processes (Sharp et al., 1983; Stumm, 1990) that are responsible for modifying the plumes.

Flocculation is a dynamic process that depends on the sediments' aggregation and disaggregation rates, which vary over time. The shear tensions of the current are essential for disaggregation, as the current may cause floc break-down even without collisions. The aggregation of the particles by collisions reduces the number of particles and increases the average aggregate diameter. There are at least five processes that may be involved in flocculation, including the compensation of the negative charge of the particles by the addition of positive ions (cations) from the surrounding water (saline flocculation), adhesion of the particles by the adsorption of organic matter, collision of the particles due to different sedimentation speeds (gravity), collision of the particles due to Brownian motion (which moves the particles randomly), and collision of the particles due to water turbulence (Krone, 1978; Eisma, 1986).

The effect of salinity on the size of the aggregates should also be considered. Until a few years ago, there was a generalized consensus within the scientific community that the cohesive sediments transported by riverine freshwater tended to flocculate because of salinity and to precipitate as they expanded into the waters of estuaries (Mehta et al., 1975). However, some authors have reported that maximum turbidity depends essentially on the hydrodynamic conditions (Postma, 1967). Notwithstanding the substantial evidence of increasing flocculation with increasing salinity, several authors have questioned the role of salinity as the main factor accelerating the flocculation processes (Van Leussen, 1999; Thill et al., 2001; Fox et al., 2004). Thus, the influence of salinity on flocculation can be related to a threshold value, and flocculation may also be controlled by other related factors (Gibbs, 1983; Mikes et al., 2004). Flocculation has been recognized for decades as a key process in the rapid removal of suspended sediments from turbid coastal waters (Krone, 1962; Postma, 1967). Some authors have demonstrated that the formation of flakes substantially increases the deposition of fine sediments present in the coastal water and the river plumes (Dyer et al., 1999; Hill et al. 2000).

The action of the described physical-chemical processes directly affects the deposition rate of the plume because the sediments, once discharged, are transported to deeper regions of the bay, where the currents are slower. The Tijucas Bay exhibits a higher CSS in its shallower portions and in its deeper portions. The opposite phenomenon is observed in the interior of the Bay, where the shallower portions have lower concentrations of fine sediments and the deeper portions have higher concentrations; some portions of the latter even exhibit the formation of a slurry (Schettini et al., 2010). While in suspension, some of the Tijucas River plume’s sediments should reach the adjacent continental shelf through the northern and southern edges of the bay due to the relatively high current speed in these areas

(Souza and Schettini, unpublished data). The sediments could also reach the adjacent continental shelf via currents on the bottom of the Bay, which contain a high concentration of sediments displaced by gravity. A cohesive seabed that has been made fluid by the action of waves or currents may move upon the continental slope as turbidity currents because of the force of gravity, filling deeper areas (McAnally et al., 2007). This process may affect the sediment balance between the bay and the adjacent continental shelf over a long period; however, additional studies are necessary to verify this outcome. As the Tijucas Bay exhibits low-energy hydrodynamics (predominantly with a low amount of river discharge), during these low-discharge periods, the dynamics most likely favor the selection and deposition of sediments. By contrast, during periods related to storms and cold fronts arising from the southern quadrant and characterized by strong winds, some of the sediments tend to be resuspended and transported onto the adjacent continental shelf.

The development of the Tijucas River plumes responds directly to the fluvial discharge. However, it is unlikely that the plume reaches the adjacent continental shelf. Therefore, the role of the plume in the dynamics of the bay sediments is crucial for the process of distribution and deposition. After deposition, a large portion of the sediments is likely to be retained inside the bay and imprisoned until an extreme event is capable of resuspending and releasing them once again for the process of transport and deposition. The greater exchange of sediments between the bay and the adjacent continental shelf depends on higher-energy meteorological and oceanographic conditions, such as intense winds and higher wave energies.

CONCLUSION

The Tijucas River is the largest source of sediments for the bay. Most of the time, the amount of discharge is low, with short periods of high discharge that are associated with the passage of cold fronts. During these events, there is an output of fluvial water and sediments in the form of a plume into the bay. The dispersion of the plume is directly influenced by the river’s discharge energy and by the wind; additionally, the plume can travel both southward and northward within the bay in response to the wind, and most of the plume is retained within the inner portion of the bay. The development of the plume along the coastline and throughout the entire water column is a characteristic of the Tijucas River plume during events of high sediment discharge. During these episodes, the plume reaches its maximum development approximately one day after the discharge peak, and the suspended sediments subsequently undergo rapid deposition. As the morphological characteristic that protects the bay from direct wave action, the position of the mouth of the estuary combined with the hydrodynamics transform the bay into a trap for sediments that are discharged by the river.

ACKNOWLEDGMENTS

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THE EFFECTS OF WAVES AND CURRENTS ON THE REDISTRIBUTION AND EXPORT OF FINE SEDIMENTS IN A SEMI-RESTRICTED BAY: TIJUCAS BAY, BRAZIL.

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ABSTRACT

Tijucas Bay is a unique restricted coastal system on the southern coast of Brazil because it includes muddy intertidal plains in an area characterized by a microtidal regime. The bay receives inputs of water and sediments from the Tijucas River, and its morphology favors the retention of materials. This study aimed to investigate the role of waves in the transport and redistribution of sediments within the bay and the conditions that favor the export of materials. The Swan wave model coupled with the Mohid hydrodynamic model was used to evaluate the capacity for sediment resuspension by waves in typological scenarios, with waves of 1 and 2 m in height and periods of 8 and 12 s, respectively, originating from the northeast and southeast directions. These scenarios are an approximation for modal energy conditions. Local hydrodynamics are most often of low energy interspersed with events of higher energy, primarily associated with the passage of cold fronts. The stress on the bottom of the bay generated by the waves can reach values higher than 0.6 Pa, which leads to erosion and sediment resuspension. However, some portions of the bay are sheltered from the influence of waves, especially in the northern portion, which functions as a depositional area. The synergetic effect of the waves combined with wind-generated currents drives the internal redistribution of sediments and can also generate export conditions to the adjacent platform. Sediment transport throughout the bay occurs primarily along the edges and depends on the wind direction. The most favorable conditions for export are associated with events of higher wave energy, and most of the time, the bay acts as a sediment trap.

KEYWORDS: Erosion, deposition, numerical model, Mohid, Swan.

INTRODUCTION

The understanding of the processes related to the dynamics of coastal environments, among them hydrodynamics, is essential because the increase in coastal occupation has led to rising demands for knowledge to support planning for sustainable development. The hydrodynamics of coastal areas are very complex and involve an important anthropic element because these areas support various economic activities such as oil extraction, fishing, construction and port activities among others and are therefore key areas for social and economic development.

The hydrodynamics of sediment in coastal areas is determined by the interaction of different forces acting on different time scales, as, wind, tides and waves (Stanev et al, 2006). Superficial waves are particularly relevant in shallow coastal environments; their effects are easily observed because they occur on a scale of seconds, they are very important due to their impacts on coastal and offshore structures, they play an essential role in sediment transport and coastal morphology, and their global effects are related to the energy exchange between the atmosphere and ocean (Garcia et al. 2005).

Despite the importance of knowledge of wave dynamics for many purposes, observational data are rarely available in a desirable quality and quantity. Even when records exist, they tend to have limited spatial coverage. In this context, numerical models become an alternative for obtaining information with wide spatial coverage (Pontes et al. 2003). Current wave models have high quality standards and have been widely used as a tool for the analysis of the behavior and effects of waves in ocean and coastal environments (Biausser et al. 2003).

Waves interacting with the sea floor, especially in coastal areas, tend to generate a force capable of modifying the behavior of sediments on the bottom as well as hydrodynamics through energy dissipation. The dynamics of erosion, resuspension, transport and deposition are directly influenced by wave energy. Gradients in flow velocity over the depth cause turbulent mixing of sediment. In the case of large flow velocities, the sediment becomes fully mixed over the water column, resulting in a uniform concentration profile (Vijverberg et al, 2011). Wave dynamics and their interactions with muddy sediments are still complex topics. The understanding of wave evolution on sheltered and muddy shelves forms the basis for the development of models that interpret the pattern of erosion and deposition for these environments. Scheremet et al. 2005 observed the effect of waves on the resuspension of fine sediments in Atchafalaya Bay during Hurricane Claudette, and according to their data, the storm caused sediment resuspension and the formation of a layer of mud 1 m in thickness with a concentration of tens of kilograms per cubic meter in an area 5 m in depth. Fluid mud, in turn, has the ability to suppress wave energy and reduce the drag of fine sediment (Winterwerp et al, 2004; Winterwerp et al, 2009). Morphology is particularly important for refraction and other wave properties when waves reach coastal areas (Rodriguez et al. 2001). Mathew et al. (1995) observed a decrease in wave energy by approximately 95% after the waves reached a 5-m depth on the Kerala coast on the western coast of India. Muddy bottoms are currently modeled using a variety of rheological descriptions, such as the viscoelasticity of the material (Jiang et al. 1995), and their characteristics can also be attributed to different sediment layers with different thicknesses and properties, such as shear stress.

Bottom sediments in sheltered bays can undergo resuspension by tidal currents, waves and the interaction between the two (Schoellhamer 1995). Bottom sediment resuspension by waves has been observed in water between 5 and 10 m deep in Long Island Sound (Lavelle et al. 1978), less than 2 m deep in Chesapeake Bay (Ward et al. 1984) and between 4 and 10 m deep in Start Bay, U.K. (Davies 1985). Bohlen (1987) observed the effect of tidal currents and waves on the resuspension of bottom sediments at a depth of 12 m in Chesapeake Bay. According to Cacchione et al. (1987) and Drake et al. (1992), the resuspension of sediments is the primary factor controlling sediment distribution in the northeast of the California coastal shelf due to the interaction between waves and currents during extreme high-energy events in the winter. Sediment resuspension is also an important process in the shallow estuaries of Tampa Bay in western Florida, being responsible for modifying the turbidity and consequently the ecological processes in this region (Schoellhamer 1995).

Tijucas Bay is a coastal embayment with a unique characteristic in southern Brazil, the presence of wide muddy intertidal plains, even though it is characterized by a microtidal regime and the formation of chenier plains (Buynevich et al. 2005; Asp et al. 2009). The bay receives a relatively high sediment input from the Tijucas

River, the dispersion of which is mostly restricted to within the bay. The bottom of the bay is predominantly muddy, and there are areas of the formation of fluid-mud layers (Schettini et al. 2010). These facts indicate that the bay acts as an efficient trap for the sediments discharged by the river even though it presents significant sediment dynamics. The objective of this study was to evaluate the effects of waves and circulation in sediment redistribution and the capacity for sediment export in this system, using numerical modeling to solve modal scenarios of environmental conditions.

STUDY AREA

Tijucas Bay is located between 27°10’ and 27°18’ S (Figure 1), with an area of approximately 100 km^2 and a length and width of approximately 10 km. Tijucas Bay is an unique environment along the Brazilian southern coast because it includes a wide intertidal mudflat area (Buynevich et al. 2005; Asp et al. 2009), which indicates that this system has a hydrodynamic regime that favors the retention of fine sediments within the bay (Schettini et al. 2010). The bathymetry of the bay features an extensive shallow area along its inner portion. The distance from the coastline to the 2-m isoline is approximately 2.5 km. After reaching a depth of 2 m, the bathymetry tends to follow a steeper gradient, increasing in depth towards the central area until reaching approximately 12 m.

The climate of this region is considered subtropical and mesothermal without a uniform distribution of rainy periods. It has a positive hydrological balance with a mean annual precipitation of approximately 1,415 $mm.year^{-1}$ and annual potential evapotranspiration of approximately 900 $mm.year^{-1}$. Rainfall is distributed throughout the year with no clear seasonality. The average annual temperature is 21.4°C with minimum and maximum temperatures of 17.3°C and 26°C in the months of August and February, respectively (Gaplan 1986).

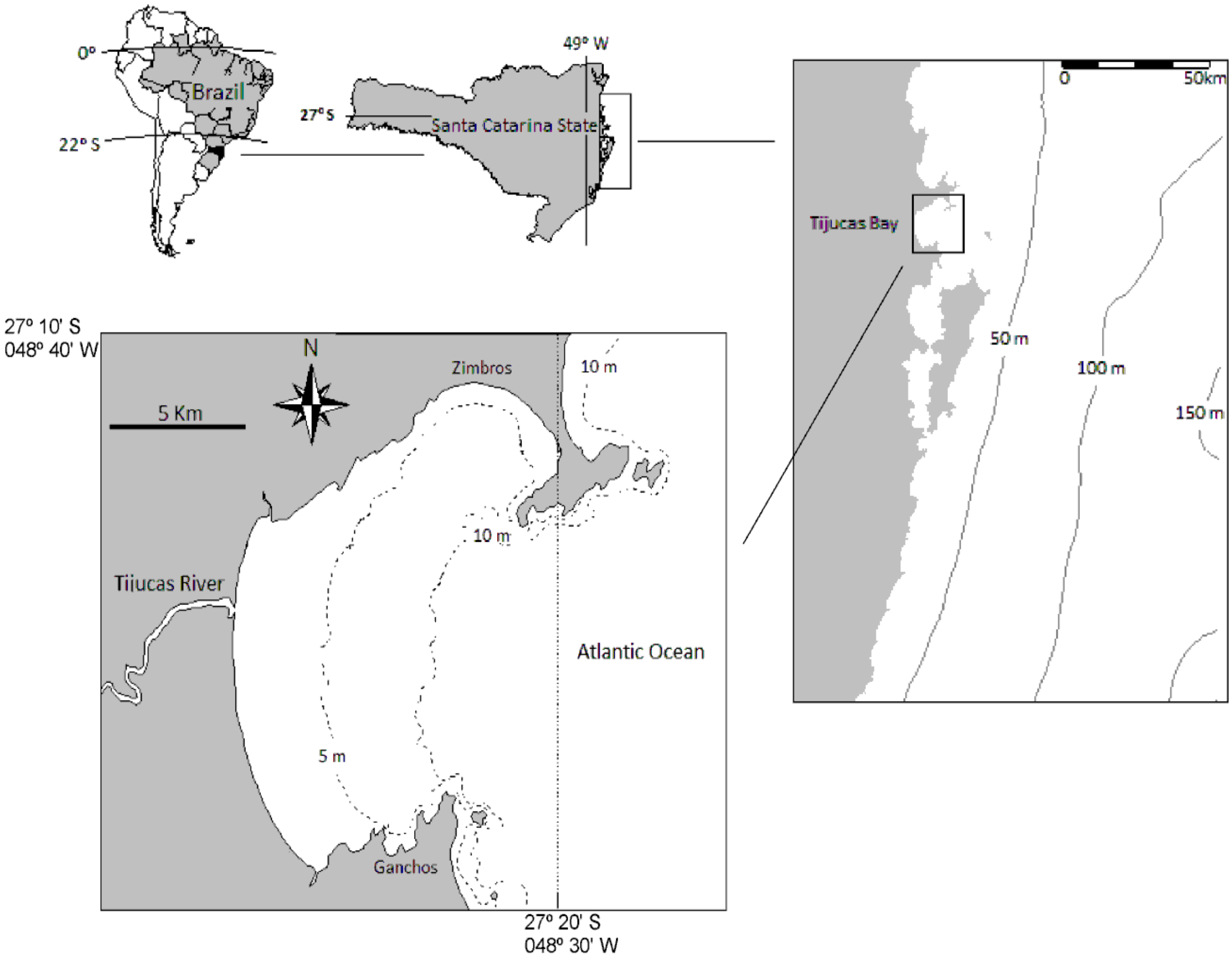

Figure 1 – Study Area, Tijucas Bay, north central coast of Santa Catarina state, Brazil, father domain (right) and son domain (below).

The wind regime is dominated by northeast winds throughout the year, with periods of winds from the south quadrant associated with the passage of cold fronts along the Santa Catarina coast (Truccolo 2011). Changes in the weather conditions observed in the south and southeast regions of Brazil are usually associated with the passage, formation or intensification of cold fronts, which are weather systems typical of intermediate latitudes that act on the Brazilian coast in every season of the year (Kousky 1979; Satyamurty et al. 1998). The cold fronts move from southwest to northeast and exhibit a pattern of wind turning, initially from the northeast to the south direction, continuing for at least 1 day and followed by a drop in air temperature up to 2 days later (Rodrigues et al. 2004). For the city of Florianópolis, approximately 30 km south of Tijucas Bay, the average wind speed ranges from 3.4 $m.s^{-1}$ in May to 4.7 $m.s^{-1}$ in October with maximum values of 16 and 27.1 $m.s^{-1}$, respectively (Goulart 1993).

The fluvial input into the bay originates from a drainage area of approximately 2,800 km^2, and the Tijucas River is the main contributor to the transport of water and sediment, flowing into the central portion of the inner bay. The historical flow rate data for the Tijucas River, monitored since 1945, indicate an average discharge of 24.4 m^3.s^{-1} (Schettini et al 2010). However, in response to the rainfall regime and the relatively small size of the drainage basin, the hydrograph mostly shows a low discharge value interspersed with flood peaks that are randomly distributed over time. Flood peaks may last from a few hours to a few days in periods of continued rainfall. The hydrodynamics of the Tijucas River estuary are similar to those of other nearby systems (e.g., Schettini et al. 2006), namely, a system dominated by flash floods. During the short discharge pulses, large amounts of sediment are released into the coastal zone (Schettini & Toldo 2006).

The regional tidal regime is of the microtidal type (< 2 m in height) and is mixed, predominantly semidiurnal. The average tide height is approximately 0.8 m, ranging between 0.3 and 1.2 m during the periods of neap and spring tides, respectively (Schettini 2002a). Weather can have an effect of up to 30% of the tidal level variation, and during cold front events associated with strong winds originating from the south quadrant, the tidal variation can reach up to 1 m (Truccolo et al. 2006).

The regional wave climate is described by Araújo et al. (2003). Based on measurements from a wave rider buoy anchored 35 km off of Florianópolis, five wave patterns were identified, consisting of two types of swells and three types of sea waves. The most important patterns are a south swell (162° direction) with a period of 11.4 s and significant height between 1.25 and 2 m, a southeast swell (146° direction) with a period of 14.2 s and significant height between 1.5 and 2 m, and northeast sea waves (27° direction) with a period of less than 8 s and significant height greater than 0.75 m.

The region is located in the southern portion of the South Brazil Bight (SBB), also called the Santos Basin. The ocean circulation in this portion of the shelf is generally characterized by the flow of the Brazilian Current (BC), of tropical origin and a southerly direction, and in the opposite direction, the flow from the Malvinas Current (MC) of subantarctic origin (Legeckis & Gordon 1982; Olson et al. 1998). The SBB includes low-salinity coastal water (CW) resulting from the mixture between coastal waters of continental origin and continental shelf waters, tropical water (TW) associated with the BC, and south Atlantic central water (SACW), underlying the TW and characterized by temperature and salinity lower than 20°C and 36.4, respectively (Miranda 1982; Resende 2003). During the period from May to September, the region is influenced by the Plata River plume, which moves north and can reach Rio de Janeiro (Piola 2005). In this period, there is a decrease in the salinity of the inner shelf to approximately 30, and the temperature drops below 20°C (Schettini et al. 2005).

NUMERICAL MODELING

The numerical models MOHID (Water Modelling System) and SWAN (Simulating Waves Nearshore) were used in this study. The first model simulated hydrodynamics and the transport of fine sediments, and the latter generated the wave data, which were assimilated by MOHID as boundary conditions for the dynamics and transport of fine sediments.

MOHID (Miranda et al. 2000; Martins et al. 2001) is a numerical model that was developed by the MARETEC research group of the School of Engineering (Instituto Superior Técnico - IST) at the Technical University of Lisbon (Universidade Técnica de Lisboa - UTL). MOHID development began in 1985. Since then, an effort to continuously develop new features has been maintained. Its modular system with a finite volume approach is an integrated modeling tool that is able to simulate physical and biogeochemical processes in the water column as well as in the sediments, including the transport of fine sediments. MOHID is also able to simulate the coupling between these two domains and the atmosphere. The model solves the three-dimensional primary equations in Cartesian coordinates for an incompressible fluid with Boussinesq approximation, hydrostatic hypothesis and Reynolds approximations. The algorithms used for the calculations of processes related to erosion, deposition and sediment transport adopt currently established formulations (e.g., Huang et al. 2006).

The SWAN model (Booij et al. 1999) is a numerical model for the generation, propagation and dissipation of sea waves based on the wave action conservation equation. SWAN is a public domain model under constant development led by Delft University of Technology in the Netherlands. This model propagates sea waves from the open sea to near shore, considering the physical processes of refraction, diffraction and shoaling due to variations in the sea bottom and the presence of currents, wind-induced wave growth, depth-induced breaking and excessive steepness (whitecapping), energy dissipation due to bottom friction, blocking and reflection by opposite currents and transmission through obstacles. The wave field in the study area is characterized by a two-dimensional wave action density spectrum. With this representation, it is possible to apply the model in areas where wind-induced wave growth is noticeable or where sea states, or even swells, are present. Wave propagation, in stationary or nonstationary modes, in geographic and spectral spaces is conducted using implicit numerical schemes. The necessary data for the execution of SWAN are the bathymetric mesh of the zone to be modeled and the wave conditions in the domain input boundary, in addition to a set of other calculation parameters. Among the results generated by the model are the significant wave height, peak and mean periods, peak and mean propagation directions, directional dispersion, bandwidth parameter and the water level at any point in the domain.

MOHID was used with the study area (20 x 35.5 km; child domain) nested within a region spanning most of the Santa Catarina coast (150 x 180 km; parent domain) to generate the boundary conditions for the child domain (Figure 1). The grid used in the model is the Arakawa C type with 500 x 500 m spacing for the parent domain and 100 x 100 m for the child domain. Tidal level variations at boundary were generated by FES2004 – (*Finite Element Solution;* Lyard et al. 2006).

The hydrodynamic model was calibrated by comparing the water level data produced by the harmonic components of Arvoredo Island with those generated by the model for the same location. The island is located 15 km offshore in front of Tijucas Bay and in a relatively central portion of the parent domain. Figure 2 illustrates the harmonic and simulated series. The model's capacity (Cm) to reproduce the observations was given by the following:

$$Cm = 1 - \frac{\sum |X_M - X_O|^2}{\sum (|X_M - \overline{X_O}| + |X_O - \overline{X_O}|)^2} \qquad \text{Eq. (1)}$$

where X_M represents an instant result of the model, X_0 represents an observation synoptic to this result, and $\overline{X_O}$ is the mean observed value (Willmott et al. 1985). The perfect reproduction of the observations by the model results in Cm = 1, and in this case, a Cm of 0.96 was obtained.

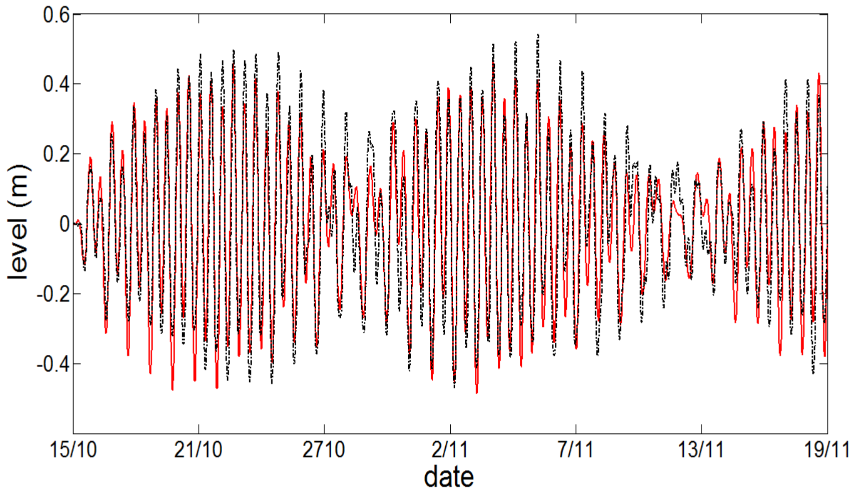

Figure 2 – Calibration curve between tide level modeling (···· Mohid) and tide level of harmonic components at Arvoredo Island (— Arvoredo).

Six scenarios were simulated, each lasting for 48 h. The scenarios were divided into two groups with modal wind conditions of 3 m.s^{-1} and 8 m.s^{-1} from the NE and SE directions, respectively, acting uniformly throughout the domain. These wind conditions represent normal periods and periods of passage of cold fronts (Truccolo 2011). For each wind condition, three sea states were prescribed: no waves; waves with a significant wave height (H_S) of 1 m and period (T) of 8 s; and waves of H_S = 2 m and T = 12 s. These wave conditions represent typical patterns of local sea and swell (Araújo et al. 2003). The bottom was defined as cohesive material in 5 layers with critical erosion stress increasing from 0.6 Pa in the upper layer to 2 Pa in the deepest layer, varying as shown in Figure 3. The thickness of the resuspendable layer was established by approximating the results of Schettini et al. (2011) for the distribution of the thickness of the fluid-mud layer in the bay.

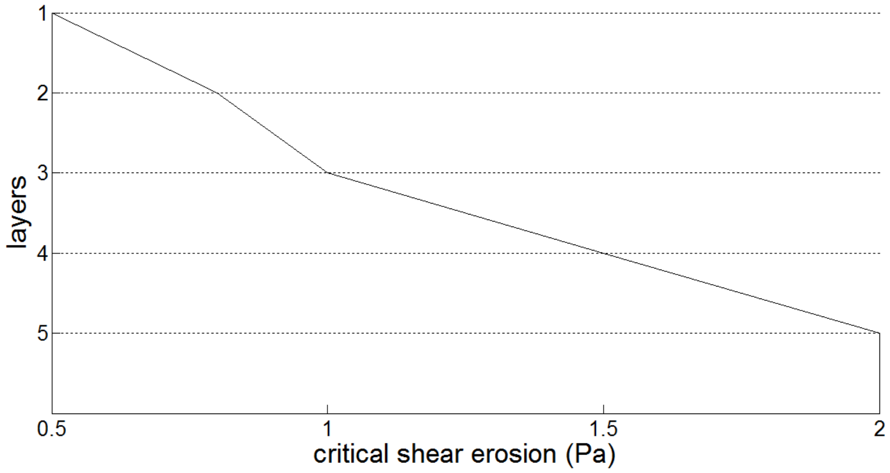

Figure 3. Variation level of critical erosion stress of the 5 layers of sediment. Each layer has a thickness of 4 cm depth.

RESULTS

The SE wave propagation pattern was similar for both of the sea states imposed on the domain boundary. When southeast waves of H_0 = 1 m forced the model at its boundary, a wave height of approximately 0.5 m was observed in most of the bay. When H_0 = 2 m, there was a greater height variation within the bay; in the deepest areas, the height ranged from 1.5 to 1 m, whereas in the shallower areas, the height was approximately 0.5 m. The NE waves showed a similar propagation pattern. Waves of H_0 = 1 m generated waves of approximately 0.5 m in the central portion of the bay, and waves of H_0 = 2 m generated waves between 0.5 and 1 m (Figure 4).

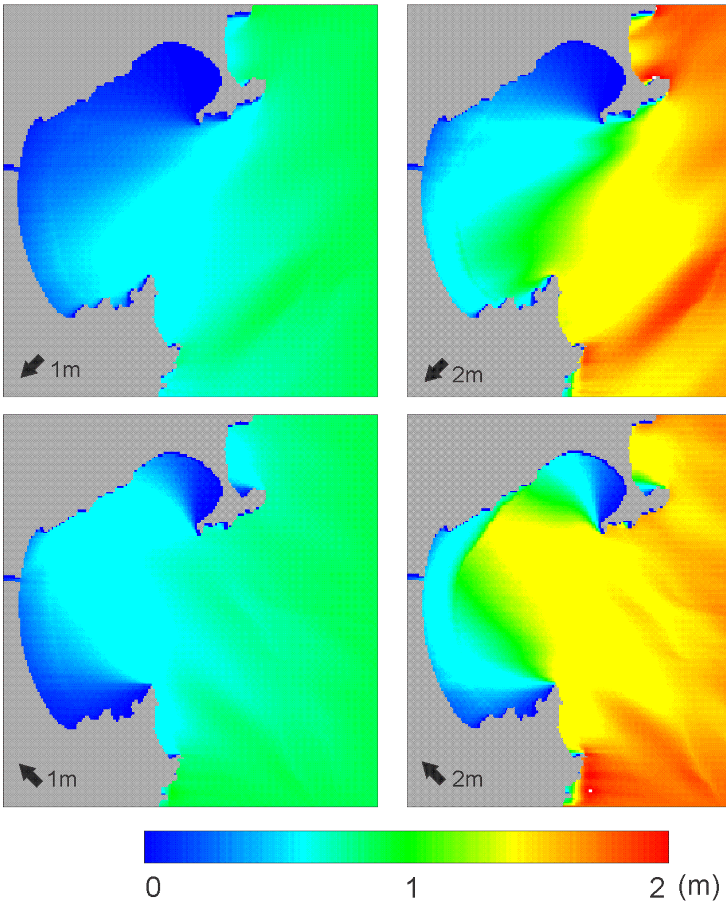

Figure 4. Height and direction of waves acting on the Tijucas Bay in scenarios with waves (1 and 2 meters high). Arrows indicate the directions of the waves.

The bottom shear stress exhibited a pattern similar to that of wave propagation. In all scenarios, the values exceeded the critical erosion stress threshold (0.6 Pa) in portions of the bay. The stresses generated in the bottom surface layer were greater in the simulation of waves of H_0 = 2 m. Waves of H_0 = 1 m from the SE affected the bottom of the bay more strongly compared to those of the same height originating from the NE, primarily in the central portion. The effects of the H_0 = 2 m conditions were similar for both sources, affecting virtually the entire inner portion of the bay. The only sheltered region was in the north part of the bay, especially for NE waves. The effects of the currents were negligible in comparison with the wave effects in all scenarios (figure 5).

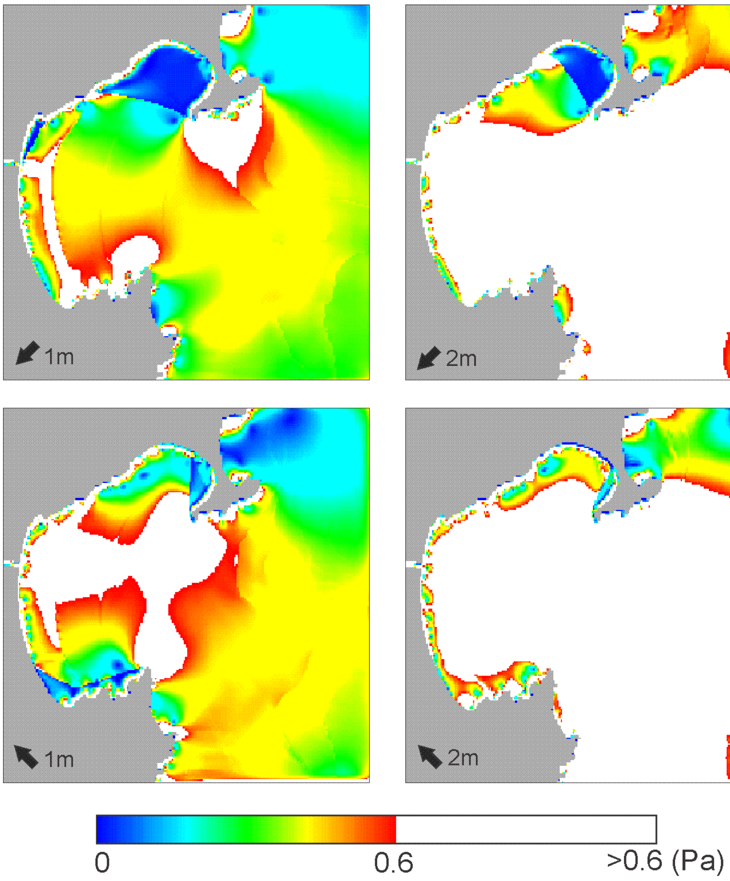

Figure 5. Variation of shear stress at deep bay in condition forced by waves of 1 and 2 meters (high). Arrows indicate the directions of the waves. Blank areas mean stress greater than 0.6 Pa.

Figure 6 shows the combined effect of waves and currents in the processes of erosion and deposition throughout the bay based on the spatial variation of the stress in the sediment layers. The areas of maximum erosion and deposition are indicated. For H_0 = 1 m from the SE, the maximum erosion areas occurred near the Tijucas River's mouth and also formed a strip parallel to the coastline, where a steeper bathymetric gradient, between 2 and 3 m, was observed. Erosion occurred in most of the bay, with deposition occurring at the north and south ends. For H_0 = 2 m, there was erosion in virtually the entire bay, with only a small deposition area to the north. Waves from the NE and H_0 = 1 m produced a small area of maximum erosion in the southern portion of the bay, and similarly to what was observed for SE waves of an equal H_0, erosion occurred along a strip parallel to the coast line. A deposition area was present in a central portion of the bay and extended to the northern end. In H_0 = 2 m conditions, erosion occurred in the central and southern portions and deposition in the northern portion of the bay.

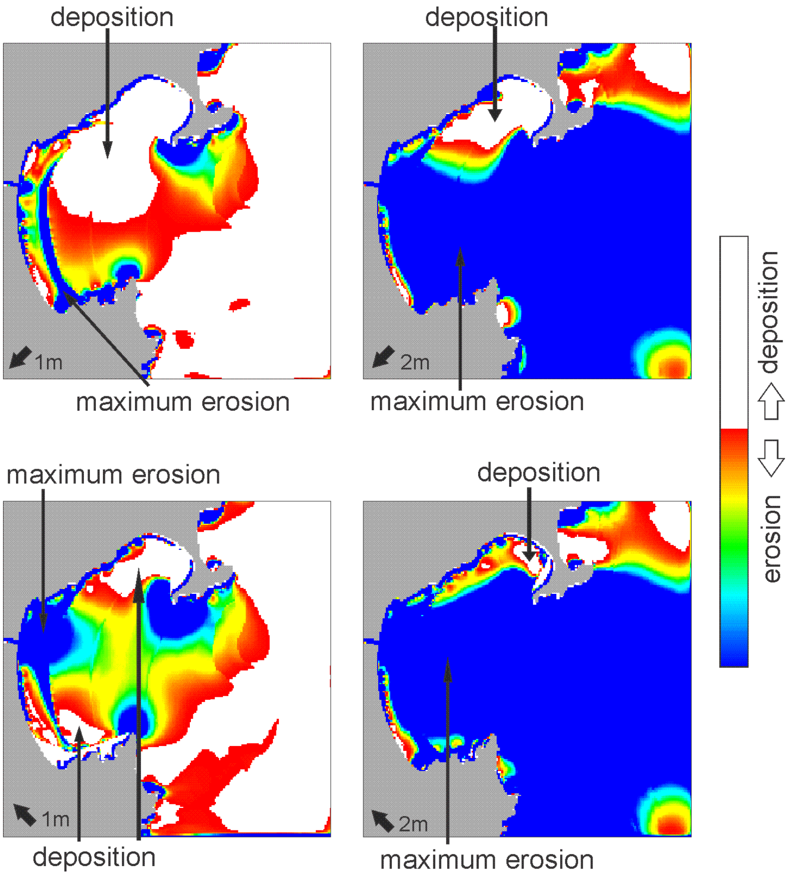

Figure 6. Variation of sediment concentration at deep bay after 2 days of simulation, scenario with waves of 1 and 2 meters (high). The arrows represent the directions of the waves. The blank areas represent deposition while the blue maximum erosion of sediments.

DISCUSSION

Sheltered shelves are usually more prone to depositional processes than erosive ones. The lower levels of wave and current energy favor the accumulation of sediments. Still, depending on environmental conditions such as the sea state and its effect on the bottom, the sediment may be remobilized; it can then be transported to other areas or remain in suspension near the bottom, forming layers of high sediment concentration or fluid mud (Winterwerp et al. 2004).

Bottom sediments erode when the shear stress applied by the action of currents and/or waves is higher than the critical erosion stress, whose value depends on characteristics such as sediment composition, bottom surface structure, the chemical composition of pores and fluids, deposition history, organic matter concentration and oxidation state (Ariathurai et al. 1976; Metha et al. 1989). However, depending on the characteristics of the sediment and environment, processes of erosion and sedimentation can occur simultaneously, as observed in Tijucas Bay.

Realistic values for critical erosion stress are difficult to determine with accuracy. Different methods have been tested for determining values for this parameter, but the many associated variables hinder precise estimation. Wang et al. (2000) found critical erosion stress values ranging from 1.5 to 3 Pa for fine sediments. Lau et al. (2000) observed in the laboratory that clayey fine sediments only began to erode at a critical erosion stress level of 0.13 Pa. In studies with different sediment densities, Van Rijn (1993) observed critical erosion stress ranging from approximately 0.1 to 1 Pa. The only regional study that offers an indicator of critical erosion stress values is by Schettini (2002b), who evaluated the erosion in the Itajaí-Açu River estuary and obtained values between 0.4 and 0.6 Pa; the maximum value from that study was the one used in the present study.

The sediment dynamics in Tijucas Bay are a response to multiple hydrodynamic driving forces. The local sediment cycle begins with the input of sediments from the Tijucas River discharge. The sediment load depends on the river flow rate, which is directly related to the amount of rainfall in the hydrographic basin. Given that there is no seasonality of precipitation in the study area, the sediment input is distributed throughout the year in pulses (e.g., Schettini and Toldo 2006). A discharge pulse forms a fluvial plume that initially distributes the material in the bay. The plume dispersion pattern is parallel to the coast, and sediments are eventually directed north or south of the estuary mouth due to the currents generated by the wind (Souza et al., submitted). This process induces the initial entrapment of materials in the inner portions of the bay (e.g., Geyer et al. 2000).

The wind is the primary agent controlling bay hydrodynamics and also affects the water exchange between the bay and the shelf. It has a relevant role in sediment distribution, both of the sediments that flow from the estuary (plume) and of those suspended by wave action. The action of waves and currents significantly changes the behavior of cohesive sediments, either through modifications of the boundary layer due to the increase in vertical mixing or through changes in shear stress due to the increase in bottom friction (Winterwerp et al., 2004). The dissipation of wave energy has a significant impact on muddy bottoms, and its behavior in muddy shelves governs the patterns of erosion and deposition (Sheremet et al. 2005).

The generation center of the swells that reach southern Brazil is the subpolar storm track from the South Atlantic, located at latitude 60° south. The swells in southern Brazil propagate from the SE and are associated with the passage of cold fronts, primarily during the winter period (Strauch 1996; Coli 2000; Tozzi et al. 2000). Sea waves are waves generated by local winds and are primarily associated with NE winds related to the South Atlantic semi-permanent high pressure center. NE winds predominate throughout the year (Tomazelli 1990 and 1993; Braga & Krusche 2000), and the sea waves associated with this wind exhibit an incidence angle between 80° and 120° (Strauch 1996; Coli 2000). Erosion events in Tijucas Bay are related to higher-energy events associated with the passage of cold fronts, with strong local winds and waves.

The analyzed scenarios represent modal conditions from moderate to high energy for this region. Waves with $H_0 \geq 2$ m occur for short time periods, and the sea state in Tijucas Bay is mostly characterized by calm waters with a predominance of local waves. However, the periods of higher energy provide extreme conditions and are responsible for more significant changes in local hydrodynamics, driving intense resuspension of sediment, which is either advected to more remote zones within the bay or even exported to the adjacent shelf (e.g., Traykovski et al. 2000). Figure 7 conceptually illustrates residual sediment transport within the bay and the export modes. According to the circulation induced by the wind, sediment transport outside of the bay tends to occur primarily at the north and south ends. In NE wind/wave conditions, there is erosion of the entire inner coastal portion of the bay with internal transport to the north in the sheltered area in the Zimbros peninsula, with the possibility of sediment export through the south end. In SE wind/wave conditions, the erosion is more intense in the inner portion of the bay, but only on the north side. There is internal transport to both the north and south in moderate-energy conditions versus only to the north in higher-energy conditions. Potential transport to the adjacent shelf occurs via the north end.

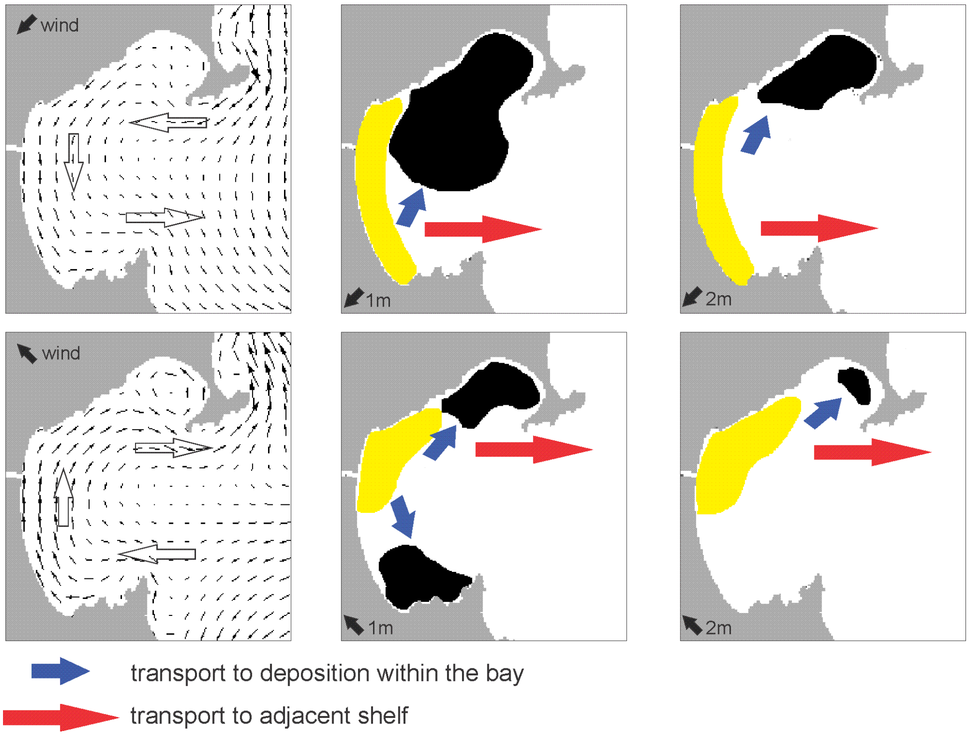

Figure 7. Movement pattern in windy conditions northeast and southeast (left column). Scenarios with waves of 1 and 2 meters high (middle and right column). The red arrows indicate the resuspended sediment transport to adjacent shelf and the blue arrows indicate the resuspended sediment transport to areas of deposition within the bay (black). Tijucas river plume (yellow) represent high discharge events.

Other processes involving the effect of waves on muddy bottoms can also affect the sediment transport balance. Cohesive sediments, after being fluidized by waves, can move as gravity currents along the slope and the bottom, moving towards deeper areas (McAnally et al. 2007). This could be another mechanism of sediment distribution in Tijucas Bay that has not been addressed in the present study.

CONCLUSION

Waves play an essential role in the process of sediment resuspension inside Tijucas Bay. Higher-energy events are associated with passing storms. Greater sediment mobilization occurs during these periods, with internal transport and potential export to the adjacent shelf. The waves appear as a disturbing force to the bottom, fluidizing the bottom and making it available to the water column, and the role of the currents is to advect the material to calmer areas. The bay's physiography makes it a sediment trap, especially its northern portion. It is likely that the majority of the time, the bay under its typical hydrodynamic pattern tends to trap the sediments discharged by the Tijucas River, whereas the deposited sediments are only made available for transport to adjacent shelf during restricted storm events.

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CONSIDERAÇÕES FINAIS

A Baia de Tijucas esta localizada em uma área abrigada e apresenta características de um ambiente com hidrodinâmica de águas calmas e grande quantidade de sedimentos finos.

O regime de micro maré atua diretamente no sentido de deslocamento das correntes, baia afora ou baia adentro conforme o ciclo. O padrão de ventos observados nesta região é ventos nordeste mais frequentes e menos intensos e ventos sudeste menos frequentes e mais intensos. O transporte de massas d’água entre baia e plataforma adjacente é uma resposta direta a intensidade dos ventos, assim como o sentido e a direção do deslocamento. Os ventos nordestes tendem a formar uma corrente em forma de giro dentro da baia, no sentido antihorário, nestas condições as correntes são forçadas a entrar pela extremidade norte e sair pela extremidade sul, sendo mais intensas na extremidade norte na mare enchente e mais intensas na extremidade sul na mare vazante. O oposto pode-se observar quando os ventos sudestes forçam a região, correntes no sentido horário entrando pela extremidade sul e saindo pela extremidade norte, sendo as correntes de entrada mais intensas na mare enchente enquanto as correntes de saída são mais intensas na mare vazante. Os ventos sudestes supostamente são mais intensos, apresentam maiores velocidades se comparados aos ventos nordestes e são responsáveis por um maior deslocamento de massa d’água, consequentemente contribuem para um maior transporte baia afora, principalmente quando coincide com mare quadratura. Através da análise do tempo de residência fica evidente a importância dos ventos no transporte entre baia e plataforma adjacente.

O Rio Tijucas é o maior contribuidor de sedimentos para a baia e apresenta a maior parte do tempo descarga baixa, com períodos de médias e altas descargas normalmente relacionados a eventos meteorológicos como passagens de frentes frias. A pluma é diretamente influenciada pela energia de descarga do rio e pelo vento, sendo deslocada para ambos os lados, assumindo um perfil bidirecional conforme a direção e o sentido dos ventos que afetam a direção da corrente dentro da baia. O desenvolvimento junto à linha da costa e ao longo de toda a coluna d’água é uma característica do comportamento da pluma do rio Tijucas em eventos de alta descarga de sedimento, nestes episódios a pluma tem seu máximo desenvolvimento cerca de 32 horas após o pico de descarga seguindo de uma rápida deposição. A atuação de processos físico-químicos como a floculação está diretamente relacionada à dinâmica dos sedimentos da pluma e podem ser um dos principais responsáveis pela rápida deposição. A baia de Tijucas tem a característica de aprisionar sedimentos finos e a rápida deposição da pluma associada a hidrodinâmica da baia devem ser um dos responsáveis por esta característica.

As ondas exercem papel fundamental no processo de ressuspensão de sedimentos dentro da baia de Tijucas. Tal processo esta relacionado a eventos de intensa energia, associados a passagem de tempestades pelo litoral catarinense. Estes podem ser os momentos de maior troca de sedimento entre baia e plataforma, ou seja, possivelmente a exportação de sedimentos da baia esta associado a eventos extremos. As ondas neste contexto aparecem como uma força perturbadora do fundo, disponibilizando para a coluna d'água parte do sedimento depositado em condições de baixa energia hidrodinâmica. A baia de Tijucas é uma área abrigada e a influencia das ondas não abrange sua área total, há indícios de áreas totalmente ou parcialmente protegida.

Possivelmente a maior parte do tempo a baia em seu padrão hidrodinâmico típico tende a aprisionar os sedimentos descarregado pelo rio Tijucas ficando restrito a alguns períodos a função de disponibilizar o sedimento depositado para o transporte.

O balanço final desta pesquisa nos mostra um ambiente com característica bastante distinta das demais áreas em torno, a baia de Tijucas tende a reter grande parte dos sedimentos que nela chegam, seu comportamento é uma resposta direta as suas forçantes, principalmente os ventos responsáveis pela advecção dos sedimentos suspensos, assim como as suas características geomorfológicas. Como área abrigada, esta baia tem poucos períodos onde as forçantes são capazes de promover uma maior troca com a plataforma adjacente, desse modo o transporte de sedimentos finos baia afora em maior intensidade esta restrito a determinados momentos, os quais são importantes na redistribuição de sedimentos dentro da baia, erodindo, transportando e depositando sedimentos.

Por fim é interessante destacar o significado do nome Tijucas, que na língua Tupy Guarani “Ty-Yuca” significa lama preta, característica já observada pelos povos mais antigos.

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ANEXO I

Título: Avaliação da Hidrodinâmica e Transporte de Sedimentos da Baia de Tijucas

Autor: Marcio Fabiano de Souza

Orientador: Prof. Dr. Carlos A. F. Schettini

Examinador: Elírio Ernestino Toldo Júnior

Data: 08 de julho de 2013

Conceito: **B**

PARECER:

O autor demonstrou claramente e ordenadamente que possui conhecimento metodológico e científico sobre o tema da Tese, relacionado a dinâmica de sedimentos finos. O tema da Tese é atual e aplicado a uma região costeira com interesses científicos e socioeconômicos, relacionados a questões de evolução geológica recente da baia, e também por causa da sua intensa ocupação.

A Tese está bem estruturada em 03 artigos e a redação é suficientemente clara, o que torna compreensível as descrições de modo geral. As figuras em geral não são adequadas em tamanho e definições, como por exemplo: figuras 9, 10 e 11 no primeiro artigo.

O capítulo de Introdução não contem uma síntese do tema e da proposta do Plano de Tese, nem uma breve revisão do estado da arte sobre o tema da Tese e dos resultados pretendidos, em acordo com as Normas do Programa (Norma 103).

O autor não desenvolveu suficientemente a hipótese de estudo/problema de investigação, associado aos objetivos da Tese.

O autor não fez uma descrição da área de estudo suficientemente completa: faltou a descrição da morfologia de fundo da baia e dos entornos (é uma baia?), e também do critério morfológico para delimitação da área de transição entre a baia e a plataforma continental adjacente. E, principalmente o autor não fez uma descrição do objeto de estudo: a lama. Não existe ao longo da Tese qualquer referência sobre a concentração e distribuição dos sedimentos lamosos no fundo da baia, nem do rio Tijucas. Descrever "......grande quantidade de sedimentos finos" (página 100, #1) não é suficiente para comprovar a existência de sedimentos finos na baia.

O autor não aprofundou a discussão em torno do volume de água contido na baia, nem sobre o tempo de residência, e as implicações sobre a taxa de deposição no fundo da baia. Os tempos de residência encontrados, para os 03 cenários, são suficientemente longos para favorecerem o processo de deposição.

As conclusões nos 3 artigos foram por vezes genéricas, faltaram algumas afirmações mais significativas (concordantes com os importantes resultados encontrados na modelagem matemática).

O autor não apresentou uma discussão entre os resultados da modelagem com aqueles medidos no campo, por exemplo, entre os resultados modelados e o mapa de fundo da baia (principalmente dos resultados apresentadas no artigo 3). Por exemplo, qual o grau de correlação da pluma de sedimentos com os sedimentos de fundo na baia? E também com as áreas de deposição/erosão?

Para a questão da ressuspensão dos sedimentos de fundo é necessário a apresentação do método utilizado (qual a rugosidade do fundo, cálculo da tensão de cisalhamento, níveis de turbulência), e não simplesmente a apresentação dos resultados obtidos com o modelo. E, muito importante, a ausência de dados de campo (tanto de ondas, como de ressuspensão) para calibrar os resultados do modelo. Efetivamente, permanece a questão: ocorre ressuspensão no interior da baia? E sob que condições de turbulência?

É recomendável a inclusão dos parceiros do IST na coautoria dos artigos.

ANEXO I

Título: **Avaliação da hidrodinâmica e transporte de sedimentos da baía de Tijucas, SC**

Área de Concentração: **Geologia Marinha**

Autor: **Márcio Fabiano de Souza**

Orientador: **Prof. Dr. Carlos Augusto França Schettini**

Examinador: **Prof. Dr. Osmar O. Möller Jr**

Data: **08/07/2013**

Conceito: **B**

A tese está organizada em cinco capítulos principais que incluem: a) introdução; b) três capítulos em forma de artigos escritos em inglês que foram submetidos a revistas referenciadas e que aparecem na forma de ANEXOS; c) considerações finais. Todo o trabalho está bem organizado em estudos que envolvem modelagem numérica e, em um dos artigos, tratamento de dados de cruzeiros. A revisão bibliográfica é extensa e atual e os resultados são interessantes. Por isso, considero a tese com nível de um título de Doutorado. A seguir, são apontadas as correções e esclarecimentos necessários.

I) Introdução

Contém as principais hipóteses e descreve a sequência do trabalho. Recomendo revisar a parte escrita e separar os objetivos, deixando claros os objetivos específicos. Há erros de português que necessitam ser corrigidos (eles também aparecem no resumo), por exemplo: baía em vez de baia; frequência em vez de frequencia.

II) Assessment of the tide and wind effects on the hydrodynamics and interactions between Tijucas Bay and the adjacent continental shelf, Santa Catarina.

- Revisar o texto em inglês: em várias frases se tem uma tradução literal do português o que deixa o texto longo e, por vezes, complicado. Cuidado com greater no lugar de higher ou maximum como em (....) *although with greater frequency during spring* (....) que aparece no segundo parágrafo da página 25 e em várias vezes no texto. O outro é o uso do possessivo como o que aparece na página 28, segundo parágrafo: (...) traced along the bay's two eastern ends (...). Isso é repetido ao longo da tese.
- Na página 26 é afirmado, com base no trabalho de Truccolo e colaboradores de 2006 que o vento influencia em 30% a variação do nível que pode chegar a 1 m durante ventos fortes. Como os ventos foram impostos na grade maior. Qual o nível gerado na costa? Esclarecer estes aspectos.
- Página 26, último parágrafo: The continental shelf belongs to the meridional (...) – melhor escrever is part of the meridional (...).
- Página 26, mesmo parágrafo: descrever melhor as massas de água da área. No texto é falado em Corrente de Malvinas. Retirar essa parte, pois a Corrente das Malvinas está longe demais dessa região (36° S). Há também uma imprecisão na descrição da SACW (ACAS) dizendo que ela tem alta concentração de OD. É o oposto. O valor dado de S e T por Miranda (1982) vale para a região de 22°S. Aqui vale o de Piola et al. (2000). Isso tem que ser corrigido nos outros artigos.
- Seria importante caracterizar a variação de salinidade e temperatura da área e mostrar como isso foi considerado no modelo ou explicar porque não foi. Isso tem que aparecer nas condições impostas no modelo.

- Resultados:

1) padronizar a escala temporal das figuras 2, 3 e 4. Uma está em dias, outra em data e outra em horas. Fica difícil seguir cada situação em relação às forças.

2) usar letras A, B, C em vez de above, middle e below.

3) A figura 5 representa um instantâneo? Se sim, de que momento? Poderia ser marcado na Figura 2 os momentos em que se extraem os dados. Porque não se integra num período de

maré para se ver a resultante?

4) página 38 é afirmado que: the residual speed was low and the circulation pattern was poorly defined. Eu vejo essa situação no cenário 3, na parte residual. Verificar se não houve uma inversão.

- Discussão

1) Deveria haver comparações com outras baías mais abertas e não com Chesapeake Bay;

2) explicar melhor o que é afirmado na página 43 onde se diz que outro fator que influencia é a proximidade com a Ilha de Santa Catarina (e não Florianópolis como está no texto) que produz abrigos contra undertows provenientes de S/SE. Undertows são correntes geradas por ondas e elas não foram analisadas aqui.

Referências bibliográficas – checar em toda a tese

III) Study of the dispersion behavior of the Tijucas River plume, Santa Catarina, Brazil

- Revisar texto em inglês desde o Abstract. Por exemplo: Data on salinity deve ser data of salinity. No abstract, separe dado de modelagem, na continuação da mesma frase. Revisar erros de digitação em todo o texto, como vírgulas e palavras juntas.

- Por que o abstract e o resumo são diferentes? O resumo apresenta mais resultados que o abstract.

- Seria importante caracterizar a variação de salinidade e temperatura da área e mostrar como isso foi considerado no modelo ou explicar porque não foi. Isso tem que aparecer nas condições impostas no modelo.

- Introdução

Tem todo um texto que pode ser dispensado, isso diz respeito aos dois primeiros parágrafos.

Novamente os problemas de redação.

Chao deve ser uma referência constante. Ele foi que iniciou o estudo de plumas de estuários com um trabalho simples intitulado "The onset of river plumes" onde analisa o efeito da descarga e de Coriolis. Após ele vai colocando a maré e o vento, num trabalho publicado com Bill Boicourt. Eu recomendo os trabalhos de Richard Garvine que definiu critérios para a classificação da pluma. No Brasil, Soares e outros de 2007 (JGR) utilizaram os mesmos critérios. Além desses, tem os trabalhos de Steve Lorentz, clássicos sobre pluma. Eles são aqui recomendados pela necessidade que eu vejo de se explorar mais a questão da estrutura física da pluma, do seu comportamento frente a estes fatores moduladores e de mostrar como o modelo reproduz a pluma. É uma forma de validação dos resultados.

- Área de estudo

Página 55, penúltima linha, primeiro parágrafo: deve ser The distance between the coastline and the 2 m isobath em vez de The extension of the coastline to the 2 m isobath...

Página 55, última linha – se refere à baía como estuário (novamente o artigo possessivo errado). São ambientes diferentes.

Página 57 – corrigir informações oceanográficas.

- Material e métodos

Na quarta linha está escrito variable's variability. Se são variáveis, elas têm variabilidade. Melhorar o texto, talvez falar em variação temporal e espacial das propriedades em menor escala de tempo.

Por que usar 500 m³/s quando os dados de descarga mostram valores de 350 m³/s? Por que o pico de descarga dura 20 horas quando isso pode acontecer por vários dias, conforme a Fig. 2?

- Resultados

Página 60, segunda frase: The hydrograph for 2010 – Referir-se à Fig. 2.

Página 61 é citado Souza e Schettini, (unpublished results) é o trabalho anterior? Se sim, deveria ser citado como submetido. Na relação bibliográfica ele não aparece. Assim como Piola et al., 2005 citado nas páginas 62 e 83 (Piola 2005) e Asp et al. 2009, página 65.

Quais as condições de vento nas campanhas mostradas nas Figs. 5 e 6? É dito no texto que a primeira e a quarta campanha são relevantes para o desenvolvimento do trabalho. O que houve de excepcional para se ter mínimos de salinidade em posições opostas entre elas?

Recomendação: dividir os resultados em itens: campanhas e modelo e explicar como se complementam.

- Discussão

Talvez, resumir um pouco a discussão. Há muito texto com informações que está sem referência com o estudo e que são extrapolações. Isso fica claro na página 69 com suposições sobre períodos de calma e de tempestade forçando transporte de sedimentos finos para a plataforma.

- Conclusões:

Assim como no primeiro artigo, aqui se fala no efeito de ondas sem que estas tenham sido estudadas. Isso deveria funcionar para dizer que esse é o próximo passo neste estudo.

IV) The effect of waves and currents on the redistribution and export of fine sediments in a semi-restricted bay: Tijucas Bay, Brazil.
- Revisar
Como é calculada a tensão de cisalhamento pelo modelo?
-

Rio Grande, 10 de julho de 2013

Osmar O. Möller Jr.

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Examinador: Eduardo Siegle

Data: 08/07/2013

Conceito: **Bom (B)**

A dissertação é apresentada na forma de três artigos, conectados de forma a responder as questões propostas. O artigo 1 aborda a hidrodinâmica local com base em aplicação de modelo numérico, com estimativas de tempo de residência na baía. O segundo artigo aborda processos que controlam e como se distribui a pluma do rio Tijucas na baía. O artigo 3 aborda a ação das ondas sobre o processo de resuspensão de material na baía de Tijucas. Os artigos foram submetidos e se encontram em fase de revisão.

O problema apresentado é bastante interessante e relevante, abordado no presente trabalho principalmente a partir da aplicação de modelo numérico. Essa abordagem certamente constitui uma importante fonte de informação e de subsídios para trabalhos na região.

No entanto, de forma geral, acredito que os resultados poderiam estar mais aprofundadamente discutidos em cada artigo. Nos artigos apresentados, a discussão está bastante extensa e repetitiva em relação aos resultados apresentados. Uma discussão mais concisa e focada facilita a leitura e auxilia a descrição de conclusões mais específicas, destacando os resultados mais relevantes de cada artigo.

Abaixo estão algumas observações específicas separadas por capítulo da tese:

Introdução

A introdução do trabalho está fraca. O problema e a motivação do trabalho não são apresentados de forma a situar o leitor em relação às questões abordadas. Os objetivos e a hipótese do trabalho deveriam ser apresentados de forma mais clara e com destaque no texto. Alguns parágrafos estão sem as devidas citações, cuidado que deve ser tomado na elaboração do texto.

Artigo 1 – (submetido a Revista Brasileira de Geofísica)

De forma geral, nos três artigos, questiono a calibração do modelo numérico. O modelo numérico é calibrado apenas para o nível de água, e em relação a uma série temporal para a Ilha do Arvoredo, fora da área de interesse principal do trabalho. Seria importante validar o modelo para mais variáveis e na área de interesse do trabalho. Em todos os casos, essa limitação deve ser destacada no trabalho.

A discussão do artigo é bastante extensa e repetitiva em relação aos resultados. Pode ser mais focada e com destaques aos resultados encontrados no trabalho.

A discussão poderia ser mais aprofundada destacando aspectos relacionados ao tempo de residência da baía. Em relação ao limite externo definido na análise da baía, importante mencionar quais aspectos levaram a definição dessa linha que separa a baía da área oceânica adjacente.

Acredito que a discussão mais focada também levaria a conclusões mais específicas.

Artigo 2 (submetido para a revista Estuaries and Coasts)

A introdução é muito similar a do Artigo 1. Em relação a calibração do modelo numérico, mesmos comentários do Artigo 1. A discussão e conclusões também podem ser mais objetivas e focadas nos resultados obtidos no trabalho.

Chama a atenção o degrau existente na morfologia de fundo, visualizado nos perfis apresentados nas Figuras 8 e 9 (pg. 64). A batimetria está corretamente representada no experimento numérico?

Artigo 3 (submetido para a revista Ocean Dynamics)

Nesse artigo, questiono principalmente aspectos relacionados ao clima de ondas utilizado para as simulações, e a representatividade das mesmas para o ambiente estudado. Não fica claro para o leitor se a intenção do trabalho é reproduzir as condições realísticas para o ambiente, ou apresentar cenários que descrevam os fenômenos que controlam o ambiente. Isso deve ficar claro no artigo, pois com a descrição e adoção do clima de ondas, o leitor é induzido a pensar que o trabalho visa a apresentação de condições reais na representação. Se essa foi a intenção, acredito que foram poucos os cenários representados.

Na estimativa da tensão crítica para o transporte/resuspensão de sedimentos, qual foi o tamanho de grão considerado?

A discussão deve relacionar os achados do trabalho com os resultados do trabalho de Schettini et al. (2010), que também considerou a distribuição de energia de ondas na baía de Tijucas.

Considerações finais

As considerações finais poderiam fazer um fechamento melhor em relação aos resultados dos três artigos apresentados, incluindo uma lista de limitações do trabalho.

Eduardo Siegle
IOUSP

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