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INVESTIGAÇÃO DA DINÂMICA DO ÓLEO ASSOCIADO A DERRAMES NA BACIA DE CAMPOS

CAROLINA DE LIMA SANTANA

Dissertação apresentada ao Programa
de Pós-Graduação em Oceanologia,
como parte dos requisitos para a
obtenção do Título de Mestre.

Orientador: *Prof. Dr.* FABRICIO SANGUINETTI CRUZ DE OLIVEIRA

Universidade Federal do Rio Grande (FURG), Brasil.

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por

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Março 2026

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Prof^a. Dr^a Grasiela Lopes Leães Pinho
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Lista de Acrônimos e Abreviações

A

ANP – Agência Nacional do Petróleo, Gás e Biocombustível

API – Instituto Americano de Petróleo (*American Petroleum Institute*)

Previsões Meteorológicas a Médio Prazo (*European Centre for Medium-Range Weather Forecasts*)

ESA – Agência Espacial Europeia (*European Space Agency*)

B

BC – *Corrente do Brasil (Brazil Current)*

BLOSUM – *The Blowout and Spill Occurrence Model*

C

CDS – *Climate Data Store*

CMCC – *Centro Euro-Mediterraneo sui Cambiamenti Climatici*

CMEMS – *Copernicus Marine Environment Monitoring Service*

CSI – Índice Crítico de Sucesso (*Critical Success Index*)

E

ECMWF – Centro Europeu de

F

FPSO – Plataforma flutuante de produção, armazenamento e transferência de petróleo e gás natural (*Floating Production, Storage and Offloading unit*)

FPU – Unidades Flutuantes de Produção (*Floating Production Units*)

FR – Taxa de Erro (*Failure rate*)

G

GAA – Grupo de Acompanhamento e Avaliação de Incidentes

GEBCO - *General Bathymetric Chart of the Oceans*

GNOME – *General National Oceanic and Atmospheric Administration Operational Oil Modeling Environment*

GRD – *Ground Range Detected*

GSHHS – *Global Self-consistent, Hierarchical, High-resolution Shoreline*

I

IBAMA – Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis

INGV – *Istituto Nazionale di Geofisica e Vulcanologia*

ISL – Índice de Sensibilidade do Litoral

ITCZ – Zona de Convergência Intertropical (*Intertropical Convergence Zone*)

K

KM – *Quilômetros (Kilometers)*

L

LSI – Índice de Sensibilidade do Litoral (*Littoral sensitivity index*)

M

METHODS – (*METOcean Dynamic Solutions*)

N

NBC – Corrente Norte do Brasil (*North Brazil Current*)

NOAA – *National Oceanic & Atmospheric Administration*

O

OBIS – *Ocean Biodiversity Information System*

P

PNC – Plano Nacional de Contingência

PyGNOME – *Python General National Oceanic and Atmospheric Administration Operational Oil Modeling Environment*

S

SAR – Radar de Abertura Sintética

SEC – Corrente Sul Equatorial (*South Equatorial Current*)

SisMOM – Sistema Multiusuário de Detecção, Previsão e Monitoramento de Derrame de Óleo no Mar

SNAP – *Sentinel Application Platform*

SR – Taxa de Sucesso (*Success rate*)

SSM – Superintendência de Segurança Operacional e Meio Ambiente

SST – Temperatura da Superfície do Mar (*Sea surface temperature*)

SVM – *Support Vector Machine*

T

TSM – Temperatura da Superfície do Mar (*Sea surface temperature*)

U

UNESCO – *United Nations Educational, Scientific and Cultural Organization*

Z

ZCIT – Zona de Convergência Intertropical

Resumo

A indústria de óleo e gás é uma das principais forças motrizes do comércio mundial, pois viabiliza o desenvolvimento econômico de diversos países, dado seu valor como matéria-prima. As práticas referentes à extração, produção e atividades offshore, são capazes de provocar a contaminação por óleo de áreas oceânicas e desencadear impactos imensuráveis ao meio ambiente. As principais forças que governam a dispersão de óleo no oceano são: as ações dos ventos, das correntes e das ondas. Quando no oceano, o óleo, impulsionado pelos parâmetros meteo-oceanográficos, exibe comportamentos distintos, em termos da sua propriedade físico-química e da intensidade dos fenômenos atuantes. Ainda há múltiplas lacunas do conhecimento referente à dinâmica desse composto e como ele pode afetar a zona costeira brasileira. Na tentativa de melhor entender a dinâmica do óleo, o presente estudo investigou o melhor desempenho entre dois modelos de dispersão de óleo, o MEDSLIK II e PyGNOME, para a região da Bacia de Campos (RJ). Foram simulados diversos cenários para três derrames reais, e posterior análise comparativa perante a validação de dados oriundos de sensores SAR e SLAR provenientes do monitoramento do IBAMA. Os resultados alcançados elucidaram o comportamento das manchas de óleo na região, assim como elegeu o MEDSLIK como melhor opção para casos com toque de óleo na costa, enquanto o PyGNOME para ambientes majoritariamente dominado por correntes superficiais e ventos. Em virtude, pôde-se relacionar a passagem de sistemas transientes como eventos de maiores riscos para o litoral da Região dos Lagos.

Palavras-Chave: Óleo; Falso-positivo; SAR; Modelagem; Bacia de Campos.

Abstract

Oil and gas industry is one of the main driving forces of global trade, as it enables the economic development of several countries, given its value as a raw material. Practices related to extraction, production, and offshore activities can cause oil contamination in oceanic areas and triggering immeasurable impacts on the environment. The main forcing factors that govern oil dispersion in the ocean are wind, currents, and waves. Once in the ocean, oil, driven by meteorological and oceanographic parameters, exhibits distinct behaviors in terms of its physicochemical properties and the intensity of the acting phenomena. There are still multiple knowledge gaps regarding the dynamics of this compound and how it can affect the Brazilian coastal zone. To better understand oil dynamics, the present study investigated the best performance between two oil spill models, MEDSLIK II and PyGNOME, for the Campos Basin region (RJ). Several scenarios were simulated for three real spill events, followed by a comparative analysis through validation using SAR and SLAR sensor data from IBAMA monitoring. The achieved results elucidated the behavior of oil slicks in the region, as well as selecting MEDSLIK as the best option for cases with oil reaching the coast, while PyGNOME was more suitable for environments predominantly driven by surface currents and winds. Therefore, it was possible to relate the passage of transient systems as events of higher risk to the coastline of the Lakes Region.

Keywords: Oil; Look-alikes; SAR; Numerical modeling; Bacia de Campos.

Prefácio

A poluição marinha causada pelo óleo interfere em múltiplos aspectos, como os impactos ambientais e ecológicos, a economia e a saúde humana [Andrews et al. 2021]. Os efeitos ecológicos e ambientais podem ser imensuráveis, uma vez que dependem de vários fatores físico-químicos, que em conjunto às condições ambientais irão interagir entre si e resultar em que grau serão nocivos ao meio ambiente [Wang et al. 2021]. O padrão de ventos, a quantidade de óleo derramado, o cenário climático e oceanográfico, as correntes, a morfologia do local e a composição química do óleo serão responsáveis pela dispersão do óleo na superfície do oceano [Murray 2018].

De acordo com Xiao & Yang [2020], a presença do óleo na coluna d'água afeta os organismos fitoplanctônicos e inibe os processos de fotossíntese. Efeitos esses provocados pela camada de óleo que impede que a radiação solar chegue à camada eufótica. Outro agravante, segundo He [2024], é a capacidade

dos animais marinhos de concentrar toxinas expostas no meio em seus próprios organismos, à medida que avançam nos níveis tróficos, em razão da presença de metais pesados na composição do óleo. Em virtude disso, o estudo sobre a integração de fatores que compõem os processos de dispersão no oceano é imprescindível, a fim de prever a trajetória do óleo quando derramado e a formulação de estratégias mitigantes.

No intuito de suprir as lacunas relacionadas ao comportamento do óleo no oceano, o uso da modelagem numérica possibilita a simulação de diferentes cenários realísticos de derrame de óleo e suas consequências para as diferentes regiões oceânicas e/ou costeiras. Para este efeito, os modelos de dispersão de óleo mais modernos majoritariamente abordam o transporte lagrangeano das partículas de óleo [Goeury et al. 2014], e utilizam da propagação tridimensional do óleo ao longo da coluna da água para o melhor conhecimento da difusão do hidrocarboneto no mar [Fangxiang, 2012]. À vista disso, o presente estudo mostra-se pertinente no que diz respeito ao conhecimento sobre a dinâmica do óleo em uma das mais importantes bacias sedimentares marítimas do Brasil, a Bacia de Campos. Com ele será possível definir, entre dois modelos de acesso público, qual melhor representa a dispersão do óleo nesta região. Além de fornecer informações suficientes a fim de mitigar possíveis desastres ambientais com a análise de mapas de suscetibilidade para a área de estudo.

A dissertação está dividida em seis capítulos. No capítulo I é apresentada o estado da arte em relação à temática da pesquisa e seus fundamentos, seguido pelo Capítulo II, que contém os objetivos propostos para esse estudo. O Capítulo III apresenta a descrição da área de estudo e a metodologia aplicada. Os resultados e discussão são apresentados na forma de artigos científicos, que

estão presentes no Capítulo IV, seguido por uma síntese dos resultados, discussões e conclusões obtidas no Capítulo V. As referências bibliográficas utilizadas nesta dissertação estão expostas no Capítulo VI.

Capítulo I: Introdução

A poluição por óleo nos oceanos é uma consequência da grande dependência global decorrente da indústria do petróleo e seus derivados [Chen et al. 2020]. A perda desse recurso natural para o meio é quase inevitável, uma vez que estão submetidos aos constantes processos de produção, transporte, refino e uso [Blumer 1971].

No transporte do óleo, há problemas associados a colisões entre navios, rupturas nos cascos, encalhes e despejos intencionais que provocam a entrada deste poluente nos oceanos [Ketkar & Babu 1997]. Como exemplo, o episódio do navio petroleiro Exxon Valdez (1989) no Alasca, causado por uma colisão contra rochas submersas capazes de rasgar o casco do navio e despejar mais de 10 milhões de galões de óleo no mar [Robbins 1991]. Há também o

abalroamento dos navios Ro-Ro Ulysse e CSL Virginia na França (2018), que acarretou o derrame de 530 m³ no mar [Daniel et al. 2021]. Outro desafio provém de acidentes envolvendo atividades em plataformas, como a explosão da Deepwater Horizon (2010) no Golfo do México, denominado como o maior desastre da indústria petrolífera mundial [Kujawinski et al. 2020].

Acidentes relacionados a plataformas no Brasil são inúmeros, em razão do forte vínculo com a produção e extração offshore de hidrocarbonetos [Mohriak et al. 1990; Zacharias & Fornaro 2020]. Como referência, há a submersão completa da P-36 (2001) localizada na Bacia de Campos, em consequência do rompimento seguido de explosão de um dos tanques de sua instalação [Figueiredo et al. 2018]. Além disso, há também registros de vazamentos do tipo Floating and Production Unit (FPU), como a unidade P-53 (2019) localizada no campo Marlim Leste, que resultou na chegada de óleo na região dos Lagos [ANP 2020].

Outros eventos não envolvem as atividades em plataformas, tais como as misteriosas aparições de manchas de óleo no litoral nordeste do Brasil (2019) [Carreira et al. 2022], ou despejos de caráter intencional. O óleo nas praias do nordeste, após exaustivas investigações, atestou o ponto inicial do derrame sendo a mais de 700 km da costa, e um dos maiores propulsores para chegada destas manchas no litoral fora a atuação conjunta das correntes de Benguela, Corrente Equatorial Sul, e Corrente Norte do Brasil [Lessa et al. 2021; Soares et al. 2022].

Após essa situação, esforços governamentais foram elaborados a fim de aprimorarem o monitoramento e vigilância da costa brasileira. Como resultado,

em 2022, houve a criação do Grupo de Acompanhamento e Avaliação de Incidentes (GAA) que passou a integrar o Plano Nacional de Contingência (PNC) [Inojosa et al., 2022]. Subsequente, com apoio institucional elencada a tecnologias digitais deu-se origem ao Sistema Multiusuário de Detecção, Previsão e Monitoramento de Derrame de Óleo no Mar (SisMOM) desenvolvendo um papel essencial acerca da poluição por óleo no Brasil [Zacharias et al. 2024; IBAMA, 2025; Zacharias et al. 2025]. Todavia, as medidas tomadas são muito recentes e ainda carecem de dados consolidados para validação referente aos estudos da parte de diferenciação de manchas de óleo e modelagem [Possobon et al. 2021].

A identificação de manchas de óleo por imagens de sensores de satélite é majoritariamente desenvolvida pela aquisição de dados de Radar de Abertura Sintética (SAR) [Brekke & Solberg 2005; Solberg et al., 2007; Alpers et al., 2017]. Os sensores ativos têm a capacidade de adquirirem produtos independente da luminosidade do sol e condições de tempo, através das micro-ondas, elencando pelo contraste entre a superfície oceânica e a mancha de óleo [Liu et al., 2010; Migliaccio et al., 2015]. Estudos voltados a identificação das feições oleosas fazem a integração de classificadores, treinamento de redes neurais e diferenciação perante os aspectos geométricos e texturais das imagens SAR. O estudo de Conceição et al., (2019) visou a identificação das manchas de óleo por imagens de sensores de satélite, além de relacionar suas propriedades químicas, sendo essencial para predizer a trajetória do óleo no oceano.

A composição química do óleo é um fator crucial para a avaliação da sua dinâmica no mar. Além de revelar o grau de toxicidade ao meio, ela também

repercute nos eventos intempéricos [Blumer 1969]. O óleo cru possui metais pesados em sua composição, e denota uma complexa mistura de compostos aromáticos, heterocíclicos e alifáticos [Srivastava et al. 2019]. Sua permanência na coluna da água pode se estender por meses, fazendo com que o óleo sofra o processo de degradação e tenha a mancha sendo constantemente retrabalhada pela dinâmica oceânica [Teal & Haworth 1984].

A degradação do óleo, ou intemperismo, é determinada pela fusão dos efeitos biológicos, químicos e físicos que englobam juntos uma série de variáveis ambientais. Estas incluem a presença de material suspenso e particulado, da microbiota, salinidade, temperatura, pH, densidade, e solubilidade da água [Vyas & Dave 2007; Mishra & Kumar 2015]. A biodegradação está intimamente relacionada ao volume de óleo, à área de superfície ocupada por ele e às ações das bactérias e fungos degradadores que fazem o uso dos hidrocarbonetos como fonte de carbono e energia [Perry & Cerniglia 1973; Loh et al. 2020;]. Adicionalmente, a taxa de velocidade com que este processo ocorre está sujeito a disponibilidade de nutrientes e temperatura da água do mar [Higgins et al. 1981]. Consoante a pesquisa de Gustitus & Clement [2017], a interação do óleo com o material suspenso resulta em agregados de minerais de petróleo, que acabam por ser reduzidos à medida que sofrem o desgaste dos processos intempéricos.

Há múltiplas interações que irão promover o desgaste do óleo no oceano, portanto há cinco etapas físicas cruciais, sendo elas: as fases de espalhamento, emulsificação, evaporação, sedimentação e dispersão (Figura.1) [Lehr 2001; Fingas 2014; Millah et al. 2020]. A partir das informações inerentes

à propriedade do óleo, é possível compreender como os processos intempéricos alteram sua composição e implicam no seu percurso em meio marítimo [Tarr et al.2016].

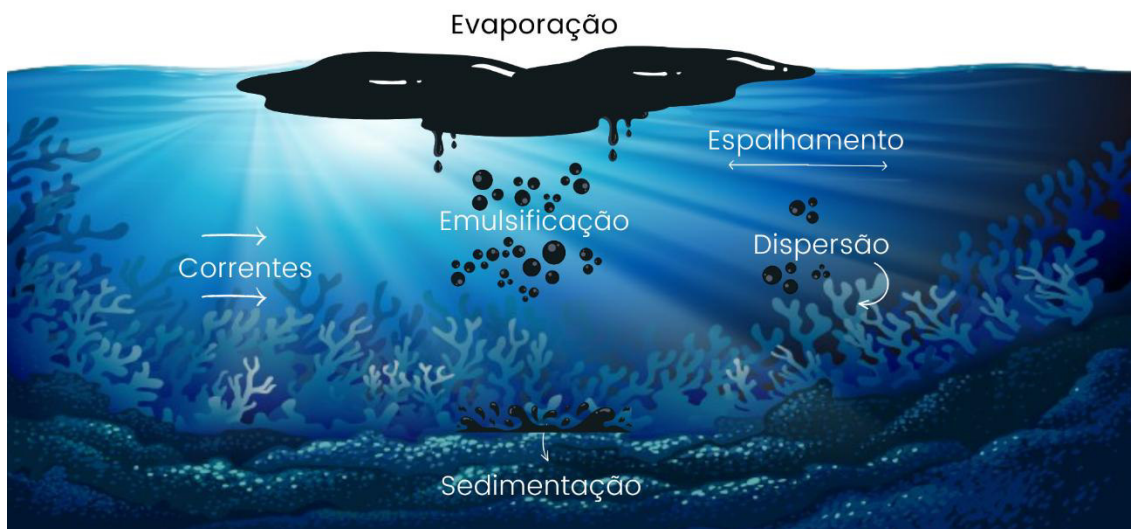


Figura 1. Processos intempéricos essenciais que ditam o comportamento do óleo no meio oceânico em meio a influência meteo-oceanográfica. Fonte Adaptada: [Woodroffe & Murray-Wallace, 2012; Bitencourt, 2019].

A dispersão do óleo é a variação de uma gama de fatores meteo-oceanográficos, com ênfase na ação dos ventos, ondas e correntes superficiais [Mearns et al. 2001; Röhrs et al. 2018; Lee et al. 2020]. Os ventos agem na forma de arrasto superficial para a difusão das manchas de óleo, via tensão de cisalhamento, conforme o óleo flui através da água. Aspecto esse que se baseia das condições de fluxo laminar ou turbulento da camada limite superficial [Wagner et al. 2022].

A velocidade dos ventos também é capaz de ditar os processos de mistura vertical, uma vez que estão dependentes das propriedades do óleo e do estado da camada superficial. É um fato que os ventos em oceano aberto

gerarão mais tensão à camada limite oceânica e potencializarão uma mistura maior [Reed et al. 1994].

A energia da quebra das ondas age diretamente no transporte de óleo emulsificado para camadas inferiores, e viabiliza a dispersão horizontal pelas correntes. A intensidade das ondas é diretamente proporcional à quebra de gotículas de óleo, entretanto, com o aumento dos processos intempéricos, a alta viscosidade acaba por implicar na mistura vertical [Tkalic & Chan 2002].

A fina camada de óleo em superfície oceânica gera o aumento de cisalhamento na camada superficial superior, e como consequência, a área circundada pela mancha amortece a ação das ondas capilares, e pode dificultar a mistura para camadas adjacentes [Dorrestein 1951]. Conforme a investigação de Christensen & Terrile [2009], a contribuição de fortes ventos é capaz de inibir a atenuação das ondas no local causada pelo óleo, o que permite a distribuição vertical da mancha de óleo em pequenas parcelas.

Na condução de estudos voltados à modelagem numérica do óleo, todos os fatores responsáveis pela trajetória do poluente, citados anteriormente, são implementados nos modelos de dispersão. Contudo, processos relevantes em escalas de médio e longo prazo ainda demandam maior detalhamento e aprimoramento em sua representação nos modelos, como a dissolução, a biodegradação e a foto-oxidação. A exemplo, a pesquisa de Balogun et al. [2021] pôde assimilar o aspecto de sazonalidade para a região da Malásia em Kota Tinggi, utilizando o modelo de dispersão de óleo GNOME. Onde, concluiu-se que a variação das estações climáticas influenciava significativamente a vulnerabilidade dos recursos costeiros ao derramamento de óleo na região.

Outro exemplo é a comparação do mesmo modelo com o Blowout and Spill Occurrence Model (BLOSOM), que segundo Duran et al. [2003] revelou um desempenho muito semelhante entre ambos. Ressalvando aspectos que poderiam ser melhorados no GNOME, referente a inclusão de uma opção de ângulo de deflexão ao parametrizar processos impulsionados pelo vento.

Adicionalmente, o modelo MEDSLIK-II simulou a evolução de derramamentos acidentais de petroleiros que viajam próximo ao Arquipélago de Fernando de Noronha. Em suma, Siqueira et al. [2022] atestou a chegada do óleo na Área do Parque Nacional Marinho de Noronha, alertando o perigo ambiental que pode ser representado pelo tráfego de hidrocarbonetos próximo a essa região. Ademais, Protasio et al. [2022] investigaram os possíveis riscos ambientais visando derrames de óleo próximos ao Parque Nacional de Abrolhos. Com os resultados foi possível correlacionar as variações sazonais ao comportamento do óleo no local. Além de elencar a complexa interação entre a circulação oceânica, o deslocamento da Zona de Convergência Intertropical (ZCIT) e a trajetória do óleo.

Capítulo II: Objetivos

2.1 Geral

Analisar o comportamento dinâmico de vazamentos de óleo no entorno da Bacia de Campos por meio da aplicação de dois modelos modernos de dispersão de óleo, a partir de três eventos reais de derramamento ocorridos na região.

2.2 Específicos

- I. Identificação e Caracterização de Manchas de Óleo em Imagens SAR;
- II. Investigação do padrão de ventos e correntes oceânicas na região de estudo e sua relação com o transporte do óleo em superfície;
- III. Comparar e avaliar a influência na parametrização dos ventos nos modelos Medslik e PyGNOME para casos reais;
- IV. Analisar o potencial risco a recursos biológicos e naturais sensíveis à dispersão de óleo com toque na costa.

Capítulo III: Material e Métodos

Os derrames estudados neste trabalho se concentram na Bacia de Campos, entre os limites da Bacia do Espírito Santo e da Bacia de Santos, estendendo-se entre as latitudes 20°27'29" S e 22°59'29" S e as longitudes 40°19'29" O e 42°00'49" O, como representado na Figura 2. Uma de suas principais características se dá pelo papel fundamental na indústria do óleo e gás, sendo considerada a maior bacia petrolífera do país [Jablonski, 2008; Miranda et al. 2010].

A circulação oceânica dessa área é demarcada pela presença ativa da Corrente do Brasil, da Corrente de Contorno Intermediária e pelos vórtices e meandros afiliados aos escoamentos [Da Silveira et al. 2015]. Dessa maneira,

sua posição geográfica permite uma grande influência oriunda da Corrente do Brasil (CB), sendo esta a principal responsável pelo transporte de águas no sentido sul ao longo da costa. Os ventos da região são fortemente influenciados pelo sistema de alta pressão do Atlântico Sul, o qual institui um padrão de circulação no sentido anti-horário, favorecendo a predominância de ventos de nordeste ao longo da área de estudo [Reboita et al. 2019; Dereczynski et al. 2019].

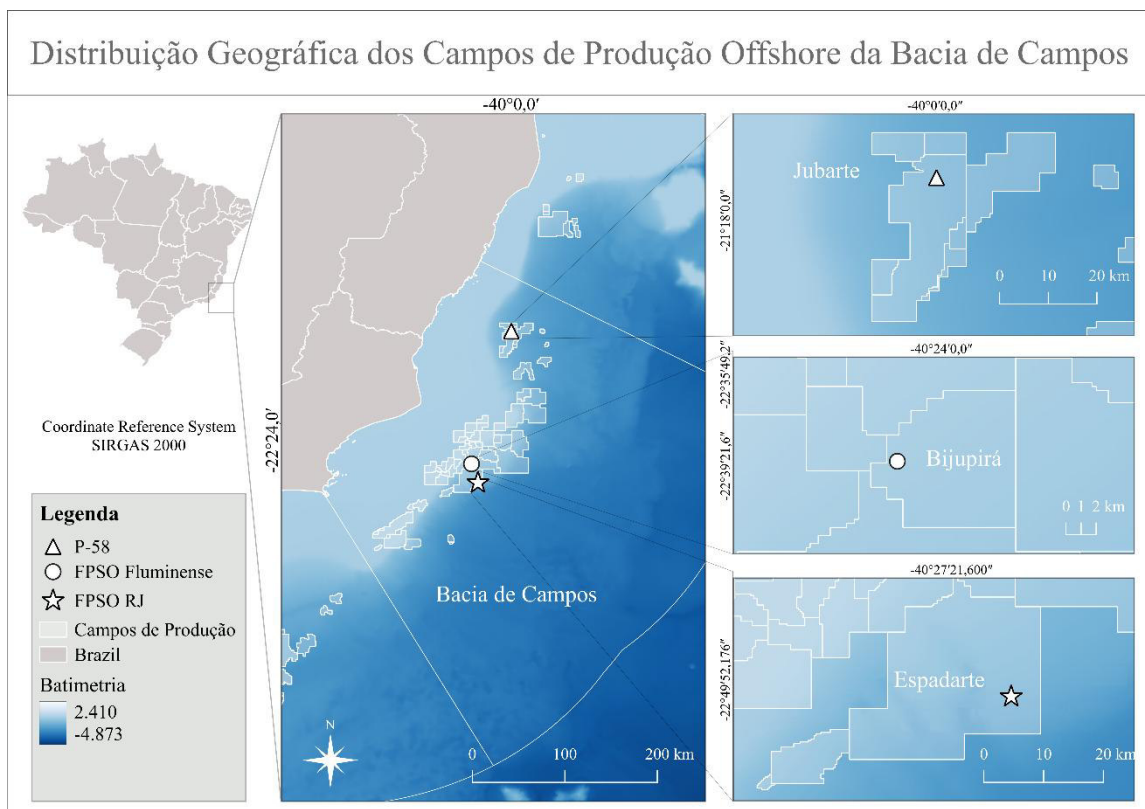


Figura 2. Distribuição geográfica dos campos de produção offshore na Bacia de Campos. O mapa expõe a localização dos campos de produção de petróleo e gás na Bacia de Campos, sudeste do Brasil, incluindo as plataformas estudadas: P-58 (campo Jubarte), FPSO Fluminense (campo Bijupirá) e FPSO Cidade do Rio de Janeiro (campo Espadarte). A profundidade batimétrica (m) e os limites dos campos de produção são indicados.

Dadas as características meteo-oceanográficas, destaca-se também a distribuição dos campos de produção, os quais exibem óleos com diferentes graus API, em razão da evolução sedimentar da bacia. Para esse efeito,

estratégias específicas são desenvolvidas para a prosperação da produção nesses campos, viabilizando a extração e a gestão de seus reservatórios [Bruhn et al. 2003; Sampaio 2018]. Portanto, é visível que os três casos aqui estudados se encontram em campos diferentes, os quais apresentam distintas propriedades físicas do óleo, como densidade, viscosidade e porosidade.

3.1. Monitoramento dos Derrames de Óleo

As observações das manchas de óleo se deram por meio de dois métodos de sensoriamento remoto, em níveis orbital e suborbital, via produtos SAR e SLAR. Os produtos SAR foram obtidos pelos sensores 1A e 1B da missão Sentinel. Esses dados são públicos e disponibilizados pela Agência Espacial Europeia (ESA) (<https://scihub.copernicus.eu/>). Os dados aqui visualizados possuem polarização VV, são do tipo GRD (Ground Range Detected) e foram pré-processados na plataforma SNAP (Sentinel Application Platform), também disponibilizada pela ESA.

Para a identificação das manchas de óleo na superfície do mar, foi inicialmente realizada uma rigorosa pesquisa acerca dos eventos de derrames envolvendo plataformas na Bacia de Campos. Esta, por sua vez, envolveu veículos de informação digital que noticiaram derrames de maiores proporções. A partir desses dados, foi realizada a procura das manchas de óleo pela rugosidade específica associada à sua presença, evidenciada por porções mais escuras nas imagens.

Em conjunto, o IBAMA disponibilizou produtos SLAR provenientes de sobrevoos do Poseidon, realizados pela empresa FOTOTERRA. Além das

manchas, também foram concedidos relatórios detalhados de cada evento, assim como o grau API do óleo, a quantidade aproximada do vazamento e o tipo de incidente envolvendo as plataformas. Essas informações garantiram que os parâmetros necessários do estado inicial do derrame fossem introduzidos nos modelos de dispersão de óleo para sua melhor eficiência.

3.1.1 FPSO Cidade do Rio de Janeiro

A plataforma flutuante de produção, armazenamento e transferência de petróleo e gás natural (FPSO) Cidade do Rio de Janeiro se localiza ao sul do campo de produção Espadarte e era operada pela empresa MODEC, através da Petrobras. Esta unidade sofreu um incidente no dia 02 de janeiro de 2019 como relatado, no relatório de investigação de novembro de 2020, pela Agência Nacional do Petróleo Gás Natural e Biocombustível (ANP). Neste momento, a unidade estava em fase de descomissionamento e sem produzir. Deste modo, o vazamento foi proveniente de furo no tanque 5C que armazenava o óleo desde o fim de suas operações em 2018. Segundo a Superintendência de Segurança Operacional e Meio Ambiente (SSM) da ANP cerca de 15,36 m³ de óleo foram observados para o incidente em questão.

Segundo informações midiáticas, o derrame ocorreu na manhã do dia 02 de janeiro, o Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis (IBAMA) cobriu todo monitoramento com sobrevoos do Poseidon, nas manhãs do dia 03 e 04, como apresentado na Figura 3. Referente as propriedades do óleo da unidade, segundo o Diário Oficial da União, o campo Espadarte apresenta o grau de densidade relativa do petróleo (API) de 21, sendo considerado um óleo mediano. Após este incidente outro vazamento foi

observado no mesmo ano, com relação a trincas no casco da embarcação. Atualmente a unidade não opera mais e foi totalmente descomissionada.

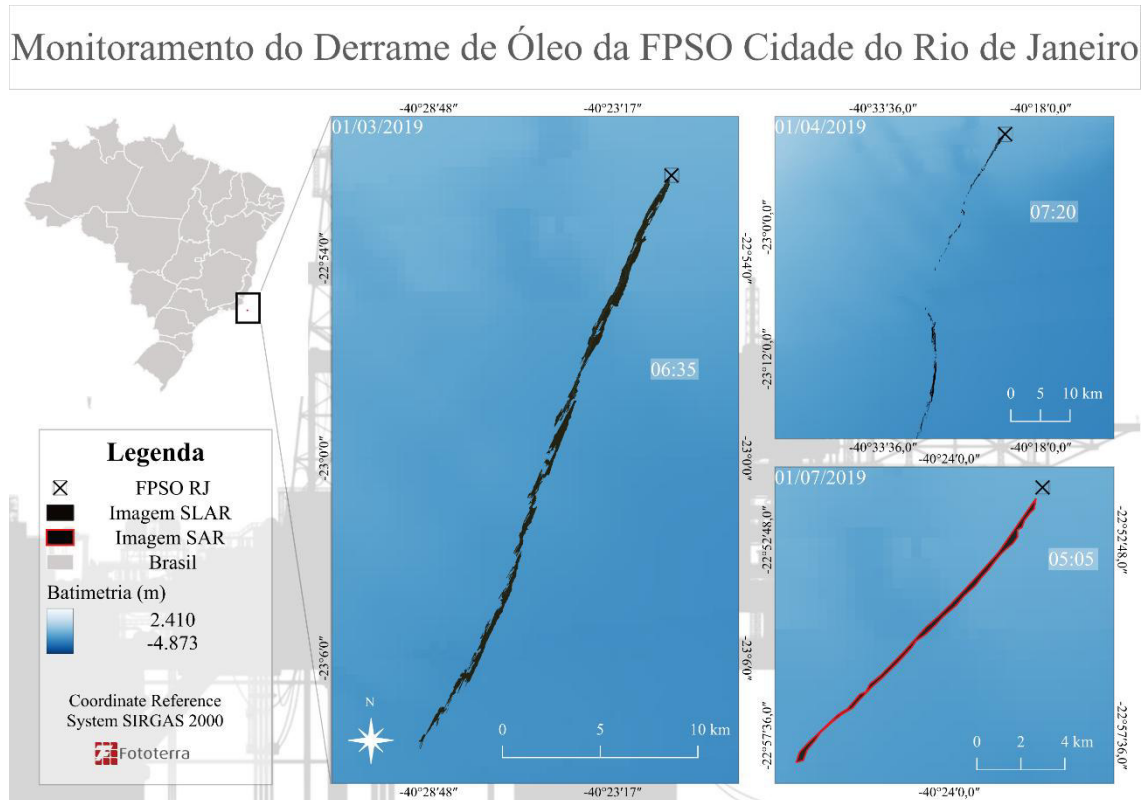


Figura 3. Monitoramento do derramamento de óleo da plataforma FPSO Cidade do Rio de Janeiro na Bacia de Campos. As detecções por SLAR e SAR dos dias 3, 4 e 7 de janeiro de 2019.

3.1.2 FPSO Petrobras 58

A P-58 está localizada no parque das Baleias a cerca de 85 km de distância do litoral capixaba, contando com uma capacidade de até 180 mil barris de petróleo por dia. Atualmente, é considerada uma das mais importantes unidades de produção nacional ranqueando entre as 35 maiores produtoras de petróleo no ano de 2025. Dentro deste estudo, este derrame foi o que apresentou maior volume, com cerca de 251,8m³ na manhã do dia 23/02/2019. A causa do evento foi proveniente da operação de offloading da unidade, durante a atividade

de transferência de óleo entre a plataforma e o navio São Sebastião. Foram verificados problemas de infraestrutura durante tal operação. Desta forma, foram feitos quatro sobrevoos nos dias 23, 24, 27 e 28 de fevereiro (Figura 4). As buscas foram finalizadas uma vez que o óleo não apresentou um comportamento que viabilizasse sua chegada ao litoral. Em adição, entre os cinco dias monitorados, foi possível identificar apenas uma imagem SAR com feições oleosas. Neste caso, o grau API escolhido foi de número 19 como previsto para o tipo de óleo encontrado no campo Jubarte.

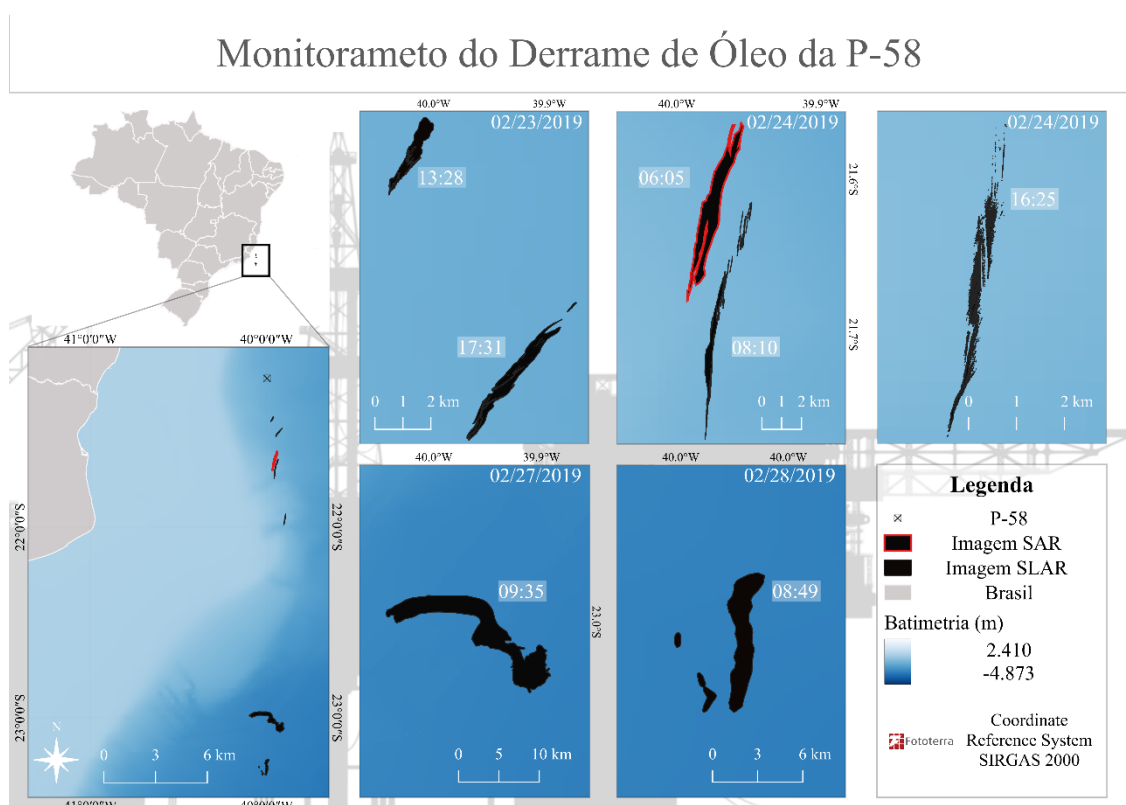


Figura 4. Monitoramento do derramamento de óleo a partir da plataforma P-58 na Bacia de Campos. Imagens SAR e SLAR adquiridas entre 23 e 28 de fevereiro de 2019 mostram a evolução temporal da mancha de óleo, destacando variações em sua extensão e morfologia.

3.1.3 FPSO Fluminense

A FPSO Fluminense teve início em suas atividades no ano de 2003 e se estendeu até o seu descomissionamento em 2021, operada pela MODEC com

responsabilidades inerentes a Shell Brasil, apresentava a capacidade de processamento de 81 mil barris de óleo por dia. A mesma, operou em dois diferentes campos de produção, o Bijupirá e o Salema. O ocorrido em questão aconteceu enquanto a unidade mantinha operações ativas no campo de Bijupirá, portanto as características de óleo atribuídas a esse evento detiveram um grau API de 27,8. Sendo considerado um óleo mais leve que os demais.

Há muitas lacunas referentes a esse derrame, já que o mesmo só foi notado em coincidência do monitoramento da P-53 no dia 4 de abril, como mostra a figura 5. Esse por sua vez, atestou a chegada de óleo no litoral da Região dos Lagos, o qual também obteve um relatório de Incidente com Toque de Óleo na Costa elaborado pela ANP. Diante disso, não há ciência sobre o tipo de ocorrência que acarretou seu vazamento, tão pouco quanto ao dia inicial do derrame. Sendo assim, assumiu-se neste trabalho as informações iniciais do derrame equivalentes com o incidente da P-53. A ideia em modelar esse evento era poder observar através dos modelos se o óleo que atingiu a costa derivado da P-53, também poderia se tratar deste vazamento em conjunto. Desta forma admitiu-se que o derrame teve início na tarde do dia 23 de março de 2019.

Monitoramento do Derrame de Óleo da FPSO Fluminense e P-53

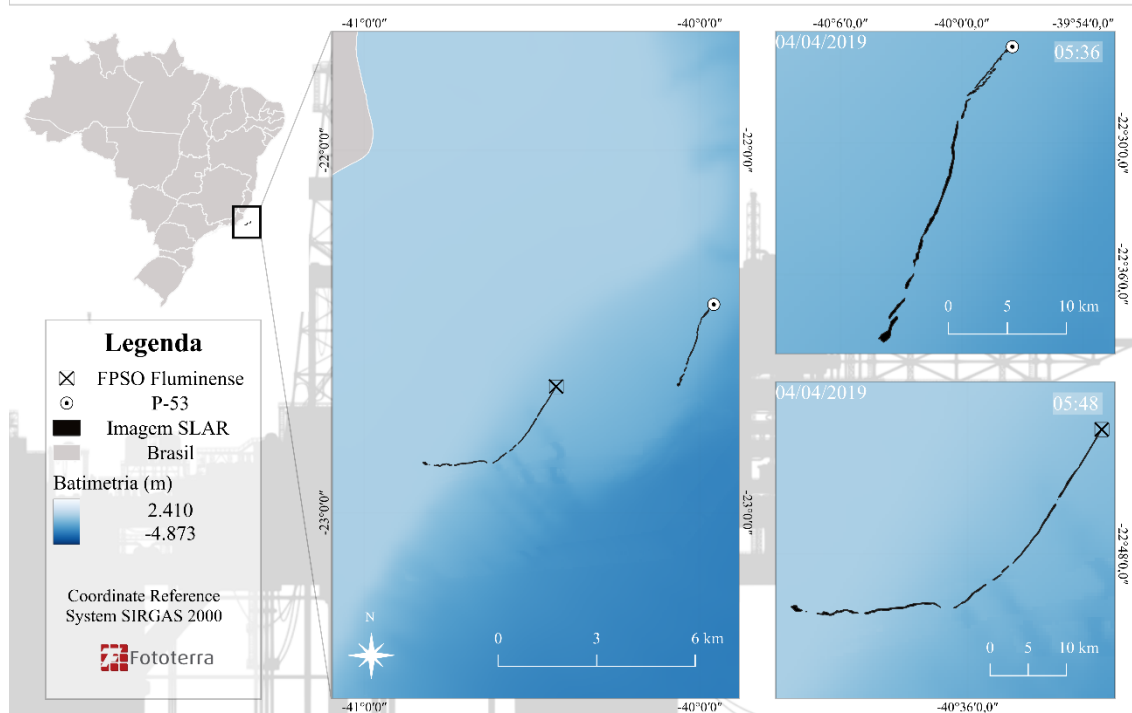


Figura 5. Monitoramento do derramamento de óleo a partir das plataformas FPSO Fluminense e P-53 na Bacia de Campos. Imagens SLAR adquiridas em 4 de abril de 2019 mostram a distribuição espacial das manchas de óleo superficiais associadas a ambas as plataformas.

3.2. Modelagem da Dispersão de Óleo

3.2.1. MEDSLIK 2.01

O código computacional MEDSLIK-II corresponde a um sistema de modelagem de dispersão de óleo de código livre, que incorpora informações de modelos hidrodinâmicos oceânicos na determinação do padrão de dispersão do óleo em superfície. Seu foco se aplica a trajetória realizada por componentes de flutuação turbulenta parametrizadas, associado a um modelo de partículas langregeanas com a aderência a processos intempéricos. O mesmo é capaz de resolver a equação de advecção, difusão e transformação do óleo em três tipos variáveis de estado sendo elas, perante as manchas, partículas e de estrutura.

Dessa forma, o modelo utiliza-se da equação geral para traçadores associando massa sobre volume durante os processos emulsificantes no oceano como apresentado na Equação 1.

$$\frac{\partial C}{\partial t} + U \cdot \nabla C = \nabla \cdot (K \nabla C) + \sum_{j=1}^M r_j(x, C(x, t), t) \quad (1)$$

Onde, $r_j(x, C(x,t),t)$ são as transformações físico-químicas sofridas pelo óleo dada sua degradação. U representará a distribuição horizontal das correntes oceânicas, as componentes u e v . E K será o tensor de difusidade turbulenta [De Dominics et al. 2013a]. O modelo possui o próprio banco de dados de óleo, com diferentes graus de API encontrados no Mar Mediterrâneo, que se faz capaz de abordar a transformação do óleo inerente a processos intempéricos como a evaporação, emulsificação, dispersão horizontal/vertical e encalhe na costa [Lardner, R., & Zodiatis 2016].

Para as parametrizações dos ventos e correntes o próprio modelo consegue fazer as calibrações necessárias internamente a depender do usuário, para isto, são utilizados os módulos ângulo de deriva, fator de deriva, redução fracionaria dos ventos e deriva de Stokes. O ângulo de deriva induz a mancha ser impulsionada pelo vento devido ao efeito de Ekman, para o caso em questão, à esquerda do movimento. O fator de deriva é utilizado para escalar a velocidade de deriva da mancha, uma vez que consegue definir a intensidade com que os ventos agem sobre ela. Em seguida, a redução fracionária dos ventos ocorre para que o modelo possa responder melhor, este por sua vez é utilizado quando há dados para validação, em que é possível linkar a redução da velocidade dos ventos sob influência do estado meteorológico. Por fim as correções inerentes a

deriva de Stokes são pertinentes para que se possa fazer aproximações das velocidades induzidas pelas ondas, de forma simplificada e empírica, como descrita na equação 2.

$$D_s(z=0)2 \int_0^{\infty} \omega k(\omega) S(\omega) d\omega \quad (2)$$

Onde D_s é a magnitude da velocidade da deriva de Stokes, ω é a frequência angular, k é o número de onda e $S(\omega)$ é o espectro de ondas. Deste modo, considerando a direção do vento para propagação das ondas as componentes de velocidade da deriva de stokes serão (Equação 3):

$$U_s = D_s \cos \vartheta \quad e \quad v_s = D_s \sin \vartheta \quad (3)$$

onde $\vartheta = \arctg\left(\frac{w_x}{w_y}\right)$ é a direção do vento, e w_x e w_y são as componentes zonal e meridional do vento a 10 m de altura, enquanto que D_s é a magnitude da velocidade de deriva [De Dominicis et al. 2013b].

Atualmente, diversos órgãos em conjunto apoiam o desenvolvimento e distribuição do modelo, tais como CMCC (Centro Euro-Mediterraneo sui Cambiamenti Climatici), INGV (Istituto Nazionale di Geofisica e Vulcanologia), METODS – (METOcean Dynamic Solutions), e entre outros. Hoje em dia, ele está entre os dez modelos mais utilizados para a análise da dispersão de óleo no Mediterrâneo. Sua versão atual, conta com a aquisição de dados batimétricos disponibilizados pela GEBCO (General Bathymetric Chart of the Oceans) e linha de costa oriundas do conjunto de dados da NOAA (National Oceanic & Atmospheric Administration) e GSHHS (Global Self-consistent, Hierarchical, High-resolution Shoreline).

3.2.2. PyGNOME 1.1.15

O General National Oceanic and Atmospheric Administration Operational Oil Modeling Environment (GNOME) é um modelo de dispersão de óleo com livre acesso, disponibilizado pela NOAA, que permite simulações em diferentes regiões do globo. Ele também é um modelo lagrangeano, portanto resolve a dispersão do óleo por considerar a mancha um conjunto de partículas, onde seu movimento é calculado a partir da trajetória de cada uma delas [Pradhan et al. 2020]. Entretanto para a obtenção do movimento total das partículas é utilizado o método Runge-Kutta de 1ª ordem somado as componentes de velocidade das correntes (u e v), ventos (u e v) e difusão. Tal como descrito na equação 4.

$$\Delta x = \frac{dx * \sqrt{6 * \frac{D}{10,000} * \Delta t}}{1,11 \times 10^5 \cos(y)}, \Delta y = dy * \frac{\sqrt{6 * \frac{D}{10,000} * \Delta t}}{1,11 \times 10^5} e \Delta z = 0 \quad (4)$$

Onde, Δt é o tempo decorrido, y será a latitude em radianos e $1,11 \times 10^5$ é o valor dos metros por grau de latitude e Δz é a profundidade. Portanto Δx e Δy são denotados como o deslocamento 2D em longitude e latitude a considerar a difusão [Zelenke et al. 2012].

Em relação as parametrizações dos ventos, há dois módulos principais o windage, conhecido como fator de deriva, e o parâmetro de ventos persistentes. Além de outras correções diretas aplicadas ao vento, como o ângulo de deflexão. As principais correções atuam diretamente na mancha de óleo e podem ser representadas pela Equação 5:

$$\frac{d\sigma^2}{dt} = S(t) \quad (5)$$

Onde, σ^2 é a variação dos elementos langregeanos, enquanto $S(t)$ é o parâmetro de espalhamento em função do tempo.

Para melhor representação dos processos intempéricos do óleo e suas propriedades físicas e químicas, foi utilizado o ADIOS Oil database. Tal banco de dados fornece uma gama de API para diferentes regiões, que visa os processos de evaporação, dispersão, sedimentação, encalhe e flutuação. Esse último, detalha fatores como a flutuabilidade e viscosidade do óleo na coluna da água durante a permanência do óleo no mar.

Essa ferramenta é comumente utilizada pela NOAA como suporte a derrames de óleo à respostas rápidas, mas também pode ser utilizado na dispersão de larvas de peixe, detritos marinhos como microplásticos e entre outros componentes.

3.3. Forçantes Meteo-oceanográficas

O transporte da mancha de óleo no oceano é fortemente dependente da dinâmica oceânica superior, ou seja, do campo de vento e velocidade das correntes oceânicas. Adicionalmente, a temperatura da superfície do mar (TSM) também foi utilizada como dado de entrada em ambos os modelos. Os dados das componentes da velocidade das correntes oceânicas superficiais e TSM são diários e foram adquiridos a partir da reanálise GLORYS12V1, distribuída pelo Copernicus Marine Service (CMEMS) no site <https://data.marine.copernicus.eu/>, na resolução horizontal de 1/12 (~8 km) e 50 níveis verticais. Já os dados do campo de ventos, horários, correspondem a reanálise ERA5, desenvolvida pelo ECMWF (European Centre for Medium-Range Weather Forecasts) e

disponibilizado pelo Climate Data Store (CDS) através do site <https://cds.climate.copernicus.eu>, na resolução horizontal 1/4 (~30 km) com 137 níveis de pressão desde a superfície até 80km de altura.

3.4. Método de Comparação entre os Derrames

Este estudo trata de três derrames diferentes, envolvendo períodos, duração, e óleo distintos. Portanto, a comparação entre as simulações e as verdades de campo foram realizadas via análise visual da mancha de óleo e sobre seu comportamento durante todo o monitoramento. Neste caso, ao observar os três incidentes foi elaborado uma árvore de decisão apresentada na Figura 6.

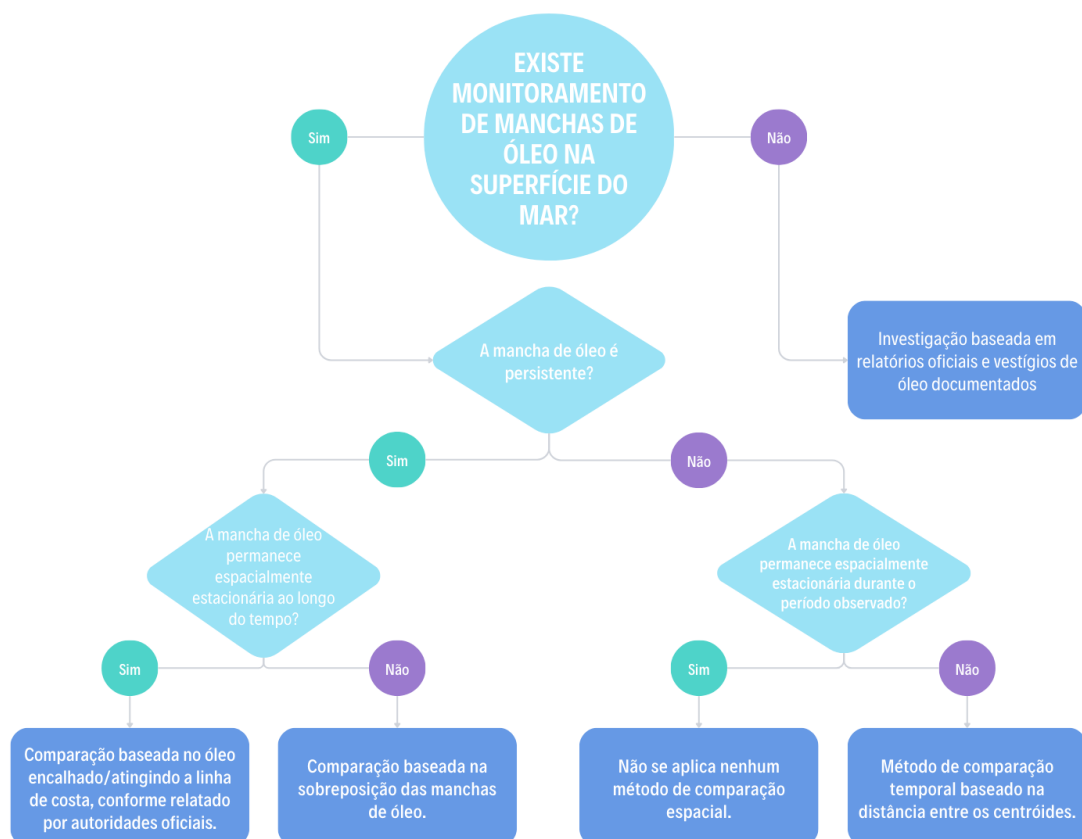


Figura 6. Árvore de decisão para seleção do método de comparação entre dados de sensoriamento remoto e saídas do modelo. O diagrama ilustra o processo de tomada de decisão utilizado para determinar o método de comparação mais adequado entre detecções de manchas de óleo por sensoriamento remoto e previsões de modelos numéricos.

As manchas de óleo persistentes referem-se à trajetória da mancha que deixa uma assinatura superficial de sua passagem, evidenciando o rastro do deslocamento do óleo na superfície. Já as manchas estacionárias são caracterizadas pelo comportamento praticamente fixo ao longo de todo o período de monitoramento, permanecendo próximas à área inicial do derrame.

3.4.1. Sobreposição de Mancha

Nos casos de manchas de óleo persistentes e não estacionárias foi definido o método de sobreposição de manchas para analisar as melhores performances. Esse método é utilizado em diversos estudos com a temática de poluição no mar e monitoramento de plumas de sedimento em superfície [Evans et al. 2012; Tavora et al. 2023], particularmente a metodologia aqui desenvolvida se baseou no estudo de Keramea et al. [2023]. Desta forma, perante os produtos SLAR e SAR foi possível traçar um grau de concordância espacial entre os resultados dos modelos e as observações por sensoriamento remoto. A primeira métrica a ser utilizada se chama taxa de sucesso (SR), que descreve o quão coerente o modelo é em relação à área real afetada pelo derrame, descrita na Equação 6.

$$SR = \frac{\text{Área sobreposta}}{\text{Área total efetiva}} \quad (6)$$

A taxa de falha (FR), ou taxa de erro, também foi utilizada para descrever o quanto o modelo superestimou a mancha real (Equação 7).

$$FR = \frac{\text{Área não sobreposta}}{\text{Área total modelada}} \quad (7)$$

Por fim, o índice de sucesso crítico foi mensurado através da razão entre

a área sobreposta e a soma das áreas reais e modeladas. Este relaciona o desempenho dos modelos perante a combinação de acertos e erros em extensão espacial (Equação 8).

$$CSI = \frac{\text{Área sobreposta}}{\text{Área real} + \text{Área modelada}} \quad (8)$$

3.4.2. Distância entre os Centróides das Manchas

As manchas de caráter não persistentes e não estacionárias foram denominadas como manchas dinâmicas, sendo possível observar o distanciamento das plataformas conforme o período de monitoramento, sem deixar rastros de sua origem. Para essas, os desempenhos foram mensurados perante a distância de centroides entre as manchas reais e os resultados dos modelos. Para as menores distâncias entre centroides com o passar do tempo descreveria uma melhor concordância.

3.4.3. Relatórios de Órgãos Oficiais de Monitoramento

Atualmente há três principais órgãos para o monitoramento, fiscalização e investigação de poluição por óleo nas águas de jurisdição brasileira, sendo eles a Agência Nacional do Petróleo, gás natural e biocombustível (ANP), IBAMA e a Marinha do Brasil. Em conjunto, é formado o Grupo de Acompanhamento e Avaliação (GAA) responsável pela investigação de incidentes com maiores proporções. Deste modo, quando há uma ocorrência de toque de óleo na costa, ou de recorrentes eventos, há a elaboração de relatórios por esses órgãos detalhando os incidentes. Os relatórios são de livre acesso, através do website (<https://www.gov.br/anp/pt-br/assuntos/comunicacao-de-incidentes/relatorios->

de-investigacao-de-incidentes), e disponibilizam informações sobre a origem do vazamento, tipo de óleo, condições meteorológicas, causas, cronologia do incidente, localidades atingidas, quantidade de óleo derramado e medidas de mitigação e contingenciamento.

3.5. Levantamento da Sensibilidade ao Óleo da Bacia de Campos

As Cartas de Sensibilidade Ambiental a Derramamentos de Óleo (Cartas SAO) foram elaboradas no intuito de servir como apoio estratégico em meio a incidentes. Nelas, é possível observar a relação dos recursos naturais, biológicos e socioeconômicos com base nos índices de sensibilidade do litoral (ISL) [de Aquino Martins et al. 2014; da Silva Baptista et al. 2015]. Esses dados estão disponíveis gratuitamente no site <https://www.gov.br/mma/pt-br/assuntos/meio-ambiente-urbano-recursos-hidricos-qualidade-ambiental/emergencias-ambientais/repositorio/cartas-de-sensibilidade-ao-oleo/atlas-cartas-e-mapas>, juntamente com seus respectivos atlas. Esses atlas enumeram as espécies locais sensíveis a possíveis derrames. A partir dessas informações, houve o levantamento dos recursos biológicos marinhos para a Bacia de Campos através da plataforma de acesso livre Ocean Biodiversity Information System (OBIS), disponível no site <https://obis.org/> mantida pela United Nations Educational, Scientific and Cultural Organization (UNESCO). Já para o levantamento de aves, foi utilizado a plataforma de acesso livre de observação e ocorrência de aves, WikiAves disponível em <https://www.wikiaves.com.br/>.

Capítulo IV: Artigos Científicos

Para a obtenção do título de Mestre pelo Programa de Pós-Graduação em Oceanologia, é requerido que o discente realize a submissão de pelo menos um artigo científico como primeiro autor em periódico com corpo indexado. Desse modo, os resultados da pesquisa desenvolvida durante o período de mestrado e a discussão dos resultados serão apresentados em forma de artigos neste Capítulo. O primeiro manuscrito, de autoria de Carolina de Lima Santana, Fernanda Cunha Pirillo Inojosa e Fabricio Sanguinetti Cruz de Oliveira, é intitulado “***Use of SAR Images for Discriminating Between Oil Spill Events and Natural Oceanic Phenomena***” foi submetido para publicação no periódico “***Ocean and Coastal Research***”. O segundo manuscrito, de mesma autoria, é intitulado “***Performance Comparison of MEDSLIK and PyGNOME for Real Oil Spill Events in the Campos Basin, Brazil***” e será submetido no periódico “***Marine Pollution Bulletin***”.

Use of SAR Images for Discriminating Between Oil Spill Events and Natural Oceanic Phenomena

Carolina de Lima Santana ¹, Fernanda Cunha Pirillo Inojosa ², Fabricio
Sanguinetti Cruz de Oliveira ¹

C.D.L.S.: [ORCID®](#) 0009-0009-0164-5816

F.C.P.I.: [ORCID®](#) 0000-0003-1312-6262

F.S.C.D.O.: [ORCID®](#) 0000-0002-9997-4926

¹ Universidade Federal do Rio Grande, Avenida Itália, nº 1750/1751, Instituto de Oceanografia, Laboratório de Oceanografia Dinâmica e por Satélites, Brasil, CEP 96203-000

² Casa Civil da Presidência da República, Secretaria Especial de Análise Governamental, Secretaria Adjunta IV, Brasília, DF, Brasil

* Corresponding author: carolinasantana@furg.br

ABSTRACT

Accidents involving oil spills in the ocean are often underreported due to the challenges of monitoring, despite mandatory reporting requirements under Law 9966/2000 and Decree 10950/2022. In this context, remote sensing imagery offers a broader perspective of the ocean, making it a valuable tool for detection and analysis. Synthetic Aperture Radar (SAR) imagery is particularly effective in

distinguishing oil slicks from similar-looking natural oceanic phenomena that can lead to misidentifications. These look-alikes result from natural oceanic processes and often resemble oil slicks, appearing as dark spots on SAR images. Therefore, accurate qualification and characterization of detected features is essential. The scattering coefficient signatures of oil exhibit distinct behaviors, enabling comparisons with other unconfirmed features based on these values. This analysis involves statistical assessments of scattering coefficient values, along with the frequency curve behavior of the corresponding pixels. In this study, two SAR images of confirmed oil slicks, serving as ground truth, were compared with images from the northeastern region of Brazil, the Santos Basin, and the Campos Basin. The results showed that 72% of the analyzed images corresponded to look-alikes, including two from the northeastern region, two from the Campos Basin, and one from the Santos Basin.

KEYWORDS: OIL SPILL, REMOTE SENSING, SAR, LOOK-ALIKES, BRAZIL.

INTRODUCTION

An estimated 4.5 million tons of oil enters the ocean every year, polluting and damaging marine and coastal ecosystems. There are numerous oil spills incidents worldwide (Fingas, 2016), however they are often poorly reported due to the challenges of monitoring oceanic areas (Ning et al., 2018). In Brazil, a major spill occurred in 2000 when more than 1.3 million liters of oil were discharged into Guanabara Bay due to pipeline failures (Sousa et al., 2013). The largest environmental accident involving oil spills in the Brazilian coast occurred in August 2019, affecting 11 states and 130 cities with the most impacted areas

located in the northeastern region. The Federal Government allocated approximately 187 million reais for cleaning operations on the beaches (Marinha do Brasil, 2020). Brazil has also experienced accidents related to platforms due to its strong reliance on offshore hydrocarbon production and extraction (Mohriak et al., 1990; Zacharias and Fornaro, 2020). A notable example is the complete submersion of the P-36 platform in 2001 in the Campos Basin, following the rupture and subsequent explosion of one of its installation tanks (Figueiredo et al., 2018). Additionally, there have been recorded leaks from Floating Production Units (FPU), such as the P-53 unit in 2019 located in the Marlim Leste field, which resulted in oil reaching the Lagos region (ANP, 2020). However, accidents involving oil platforms and tankers account for only seven percent of the total oil pollution. The primary concern lies in deliberate discharges into the sea during tanker cleaning and discharges originating from land (Murugan et al., 2023).

The spread of oil in the ocean is harmful to organisms inhabiting the affected areas, primarily because crude oil is a complex mixture of aromatic, heterocyclic, and aliphatic compounds (Srivastava et al., 2019). The residence time of oil in the water column depends on various chemical and physical factors. Oil dispersion of oil at the surface can facilitate natural degradation processes. On the other hand, phenomena that lead to the formation of emulsifying droplets can prolong their presence in the ocean (ITOPF, 2024). When crude oil and its derivatives meet water, they can form a thin layer on the surface, affecting the exchange of oxygen between the ocean and the atmosphere (Liu et al., 2023). This oil barrier results in a series of environmental consequences, ranging from intoxication and a lack of oxygen for the respiration of phytoplanktonic, planktonic,

and nektonic organisms to mortality caused by to entrapment in seabirds (Saadoun, 2015; Ma et al., 2023).

Due to the persistent challenge of oil pollution, remote sensing is widely used as an effective monitoring tool, allowing marine pollution to be detected through satellite imagery (Li et al., 2023). The most suitable satellite images for this purpose are derived from synthetic aperture radar (SAR) (Solberg et al., 2007) however optical images can also be used for this purpose (Lavrova and Kostianoy, 2011; Lee et al., 2016). Sentinel-1 is a satellite mission that provides free and open access SAR images (ESA 2024), whose main objective includes environmental monitoring of both oceanic and land environments, climate and other natural resources (Potin et al., 2019). Additionally, monitoring can be carried out using aircraft equipped with SAR systems (Brekke et al., 2021; Sriya and Rawat, 2022; Wang et al., 2023).

SAR is the most effective space sensor for the operational detection of oil spills (Brekke and Solberg, 2005). Its advantage is that it does not require larger antennas to achieve high resolution, as the sensor collects data from a specific target over time. As the satellite moves, a synthetic aperture is created, and the larger this aperture, the higher the resolution of the acquired images (Soergel et al., 2006). SAR images provide wide area coverage in near real time and are unaffected by weather conditions or nighttime. This capability enables the detection and identification of potential oil slicks on the ocean surface, while also allowing for the differentiation between oil slicks and look-alikes, as similar natural phenomena can also appear as dark patches (Topouzelis, 2008).

SAR images operate in the microwave range and display dark spots

based on the attenuation of the backscattered signal, caused by the high viscosity of the sea surface and changes in the pattern of capillary waves (Fujimura et al., 2016). This phenomenon is referred to as wave damping and leads to reduced surface roughness on the ocean surface. The damping of waves or the absence of surface disturbance results in darker grayscale tones, which highlight the presence of oil stain and facilitate visual inspection of the images (Misra and Balaji, 2017). However, calm wind zones can generate a similar appearance, as can several other factors that contribute to low backscattering coefficient values (De Moura et al., 2020). These factors include regions of upwelling, phytoplankton blooms, zooplankton community blooms, high water fertilization by organic compounds and rain cells, among others. In summary, many natural processes can attenuate the radar signal, often creating appearances like oil spills, known as look-alikes (Carvalho et al., 2021).

The detection of dark patches in SAR images involves various methods, such as segmentation strategies, classification based on geometric features, and classification based on texture properties (Back and Jeon, 2020; Villamil Lopez and Stilla, 2021; Vasconcelos et al., 2022; Hasimoto-Beltran et al., 2023). Zhang et al. (2008) explored oil patch identification using the textural information in SAR images, employing the Support Vector Machine (SVM) classifier, which proved effective in discriminating between similar oil patches. However, it was noted that combining the SVM method with morphological filtering analysis would yield more accurate results. The use of Sentinel Application Platform (SNAP) for identifying oil patches off the coast of Mumbai revealed that estimating the spatial spread of oil patches from satellite images significantly improved texture analysis.

However, incorporating wind field data would further enhance identification accuracy (Misra and Balaji, 2017). While fully automated patch detection approaches can produce unsatisfactory results, oil patches in the Bay of Balikpapan were successfully detected using SNAP and a semi-automatic approach (Gancheva and Peneva, 2019). However, some similar structures were partially detected as oil, requiring classification or visual inspection by the operator for verification.

For this purpose, it is essential to accurately distinguish between oil spills and natural processes in the ocean. Therefore, the main objective of this study is to characterize and estimate look-alike's backscattering values in SAR images from Brazilian coast that are typically associated with oil spills events. Accurately identifying these patches in SAR images helps reduce false alarms and save costs. Look-alikes, when mistaken for actual oil spills, can result in the unnecessary deployment of response teams and expenditures for incidents that do not exist, diverting resources away from addressing real oil spills (Bayindir et al., 2018). Therefore, integrating prevention and preparedness strategies into the management plans for activities in the oil and gas sector are essential (Carrillo, 2004).

METHODS

The detection and analysis of SAR images were conducted for the offshore sedimentary basins in the northeastern region of Brazil, as well as for the two largest oil and gas producing basins, the Santos Basin and the Campos Basin, located along the southeastern coast (Figure V(I)-1). The northeastern

region of Brazil is home to the Potiguar, Ceará, Pernambuco-Paraíba, SEAL, Jacuípe, Camamu-Alamada, Jequitinhonha, Cumuruxatiba, and Mucuri basins. The main characteristic shared by these basins is the influence of the North Brazil Current (NBC), originating from the bifurcation of the South Equatorial Current (SEC) (Da Silveira et al., 1994). The NBC plays a significant role in transporting large volumes of surface water, carrying heat and salt northward along the Brazilian coast (Barnier et al., 2001). Additionally, NBC can generate rings in these regions due to its retroflexion, contributing to the mixing of water (Garzoli et al., 2004). The predominance of southeast trade winds in the northeastern region of Brazil (Ferreira and Mello, 2005) further delineates the absence of oceanic upwelling processes in these areas, which are typically caused by water piling.

Both Campos and Santos Basins share similar characteristics regarding the oceanic flows that influence transportation within the continental shelf. Their geographical location allows for significant influence from the Brazil Current (BC), transporting water southward along the coast (Marta-Almeida et al., 2021). BC, which also originates from the bifurcation of the Equatorial South Current and flows southward along the continental margin, as a relatively weaker western boundary current.

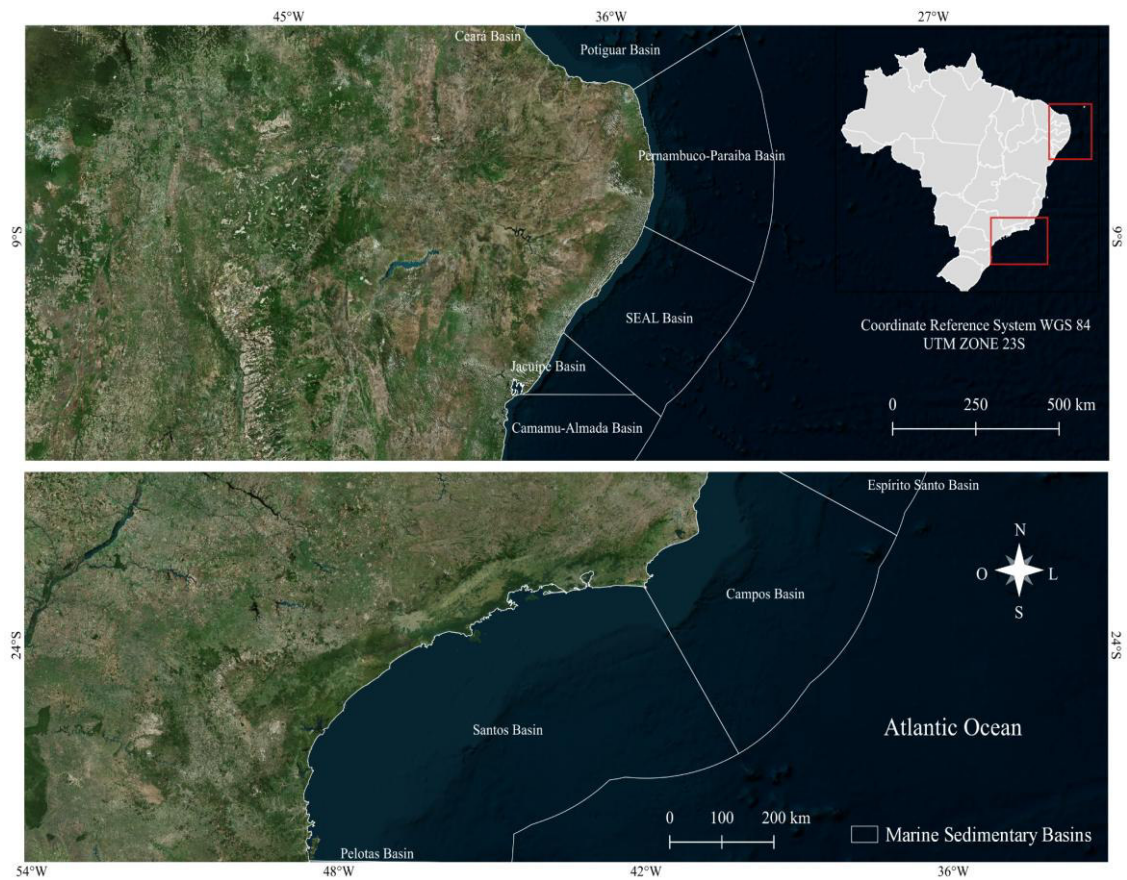


Figure V(I)-1. Map showing the study area regions along the Brazilian coast, including the Potiguar, Ceará, Pernambuco-Paraíba, SEAL, Jacuípe, Camamu-Almada, Jequitinhonha, Cumuruxatiba, and Mucuri sedimentary basins in the Northeast, as well as the Campos and Santos basins in the Southeast. The basin's boundaries are indicated.

DATA ACQUISITION AND PROCESSING

SAR data from Sentinel-1A and 1B satellites were obtained from the Copernicus Open Access Hub portal (<https://scihub.copernicus.eu/>), maintained by the European Space Agency (ESA). The Sentinel-1 mission consists of two satellites, A and B, equipped with C-band SAR sensors. The acquisition period of these data extends from August 2016 to March 2023. SAR images were acquired in Ground Range Detected (GRD) format to preserve the detected

amplitude, multi-looked to minimize speckle effects, and with VV polarization to enhance the distinction between oil patches and look-alikes. Additionally, they were preprocessed to remove inherent acquisition noise, as described in Figure V(I)-2. All processing steps were based on the study by, (Filipponi, 2019) and the extraction of backscattering values and other calculations were carried out using the SNAP software, also provided by ESA.

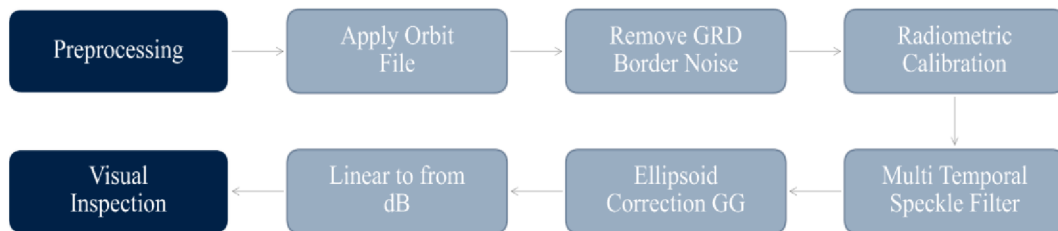


Figure V(I)-2. Workflow diagram describing the preprocessing steps applied to Sentinel-1 SAR images prior to backscattering coefficient analysis. Main steps include orbit file application, border noise removal, radiometric calibration, conversion from linear to dB scale, ellipsoid correction, multi-temporal speckle filtering, and visual inspection. All procedures follow the recommendations of Filipponi (2019) and were performed using SNAP ESA software.

DATA ANALYSIS

Backscattering is termed as the reflection of waves or signals emitted by radar. Thus, all the characteristics mentioned earlier will interact and result in specific values for each target. Consequently, it is possible to distinguish between oil stains and similar features. The presence of substances with different viscosities on the sea surface alters the propagation of oceanic waves,

consequently affecting the backscattering values in oil slicks. These substances exhibit distinct spectral responses, allowing for differentiation. Since the ocean generally behaves as a homogeneous plane, images of the sea surface typically appear in lighter shades. This property, known as the Bragg scattering, results from capillary and gravity waves generated by winds on the surface (Prastyani and Basith, 2018; Zheng et al., 2022). The scattering process is directly influenced by the radar's angle of incidence, causing its pulses to produce a resonant effect that impacts the backscattering values in the region (Equation 1).

$$\lambda_B = \frac{\lambda_R}{2\sin\theta} \quad (1)$$

where λ_B represents the Bragg resonant wavelength, λ_R is the wavelength of the radar itself, and θ is the angle of incidence. In this context, four images were initially analyzed, capturing actual oil slicks from the Campos Basin, which served as our ground truth dataset. Next, six images likely containing oil leaks from the 2019 accident in Northeast Brazil were selected. A second set of 12 images was then chosen, focusing on patches identified in the Campos and Santos Basin regions. As a result, the backscattering values from the initial database will be compared with those from the study area by extracting two polygons, respectively one coming from the central and another from edges of the stains.

RESULTS

The control database with real oil spill images was analyzed using data from different spill events in Brazil. The oil originating from the FPSO Cidade do Rio de Janeiro (Figure V(I)-3a), located in the Espadarte Field, Campos Basin,

resulted from a spill of approximately 15.36 m³ as a minimum estimated volume. The oil slick shown in Figure V(I)-3b originated from a spill of 252 m³ reported by the P-58 platform, caused by the rupture of a hose during offloading operations on February 23, 2019. Additionally, Figure V(I)-3c represents an oil spill associated with Petrobras activities on March 25, 2019, approximately 122m³ of oil. A joint report by IBAMA and ANP documented the arrival of oil in the Lagos region, attributing the incident to the P-53 platform.

The last oil slick (Figure V(I)-3d) occurred on January 20, 2021, near the coast of Arraial do Cabo. According to the Agência Nacional do Petróleo, Gás Natural e Biocombustíveis (ANP), the spill originated from the Trident Energy platform (P-65). Although the leaked volume was relatively small, approximately 0.110 m³ of hydrocarbons were released into the sea.

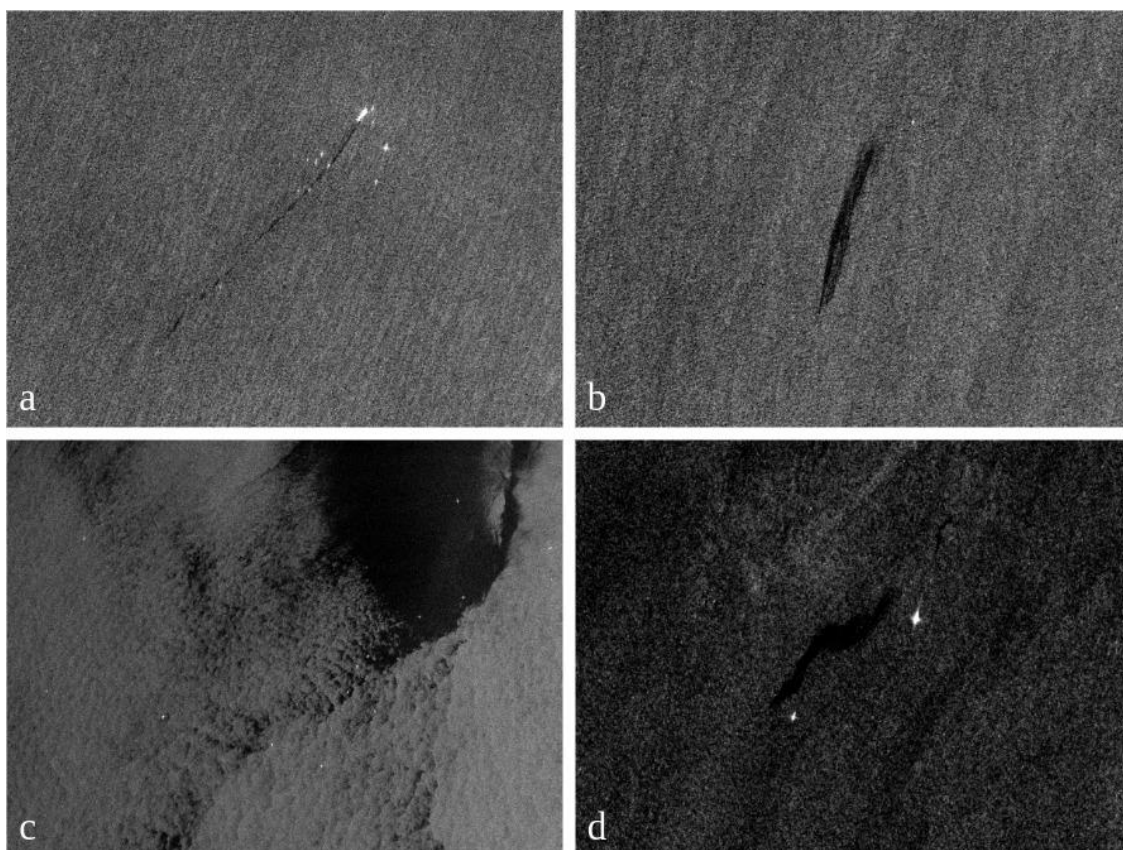


Figure V(I)-3. Sentinel-1 SAR images of confirmed oil spill events in the Campos Basin, Southeast Brazil. The dark spots in each image indicate the presence of oil slicks: (a) FPSO Cidade do Rio de Janeiro (volume: 15.4m³), (b) P-58 platform spill during offloading operations (252m³, February 23, 2019), (c) P-53 platform spill associated with Petrobras activities (122m³, March 25, 2019), and (d) P-65 (Trident Energy, 0.11m³, January 20, 2021).

A descriptive statistical analysis was performed from the scattering values presented in Figures V(I)-3a, 3b, 3c and 3d, and is summarized in Table V(I)1. The maximum values are associated with the polygons extracted at the edge of the oil stain, while the minimum values correspond to the central regions.

Table V(I)1. Statistical analysis of the scattering values from oil spills at the FPSO Cidade do Rio de Janeiro, P-58, P-65 and P-53 platforms

Image	Min (dB)	Max (dB)	Average (dB)	Std. Dev.	Med. (dB)	Coeff. of Var.
a	-58.72	29.13	-17.75	2.68	-17.87	-0.15
b	-78.92	25.50	-18.62	2.24	-18.88	-0.12
c	-70.05	30.58	-17.64	4.88	-19.14	-0.28
d	-76.95	29.14	-18.21	3.14	-18.28	-0.17

¹ Values of the dispersion coefficients of the central and edge portions of the slicks

All SAR images analyzed in this study are presented in Figures V-4, V-5,

and V-6. Most of the slicks in Figure V-4(b-f) belong to the period when oil stains reached the northeastern coast of Brazil, except for image (a), which is from a different period. Accordingly, Figure V(I)5(a-f) is from the Campos Basin, while Figure V-6(a-f) is obtained from the Santos Basin. Figure V(I)-4(a), (c), and (e), V(I)-5(a), (b), (d) and (f), and V(I)-6(d), (e) and (f) show characteristics indicative of spills likely resulting from intentional discharges by vessels. In the Campos Basin, stains V(I)-5(a), (b), (d) and (f) feature bright spots, predominantly corresponding to ships. In contrast, Figure V(I)-6(e) and (f) from the Santos Basin show dark stains but lack the distinct geometries typically associated with oil spills. As for the other images, which do not exhibit clear distinguishing features, statistical analysis is necessary to determine their origin, as summarized in Table V(I)2.

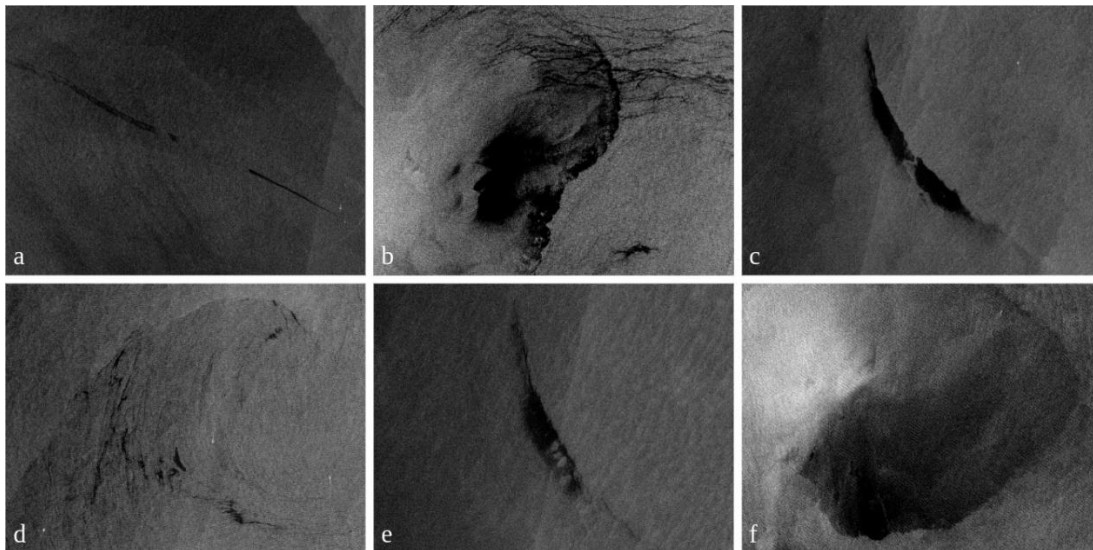


Figure V(I)-4. Sentinel-1 SAR images from the Northeast region of Brazil showing dark features classified as either oil spills or look-alike phenomena (such as rain cells and biogenic films). Images (a)-(f) display the analyzed patches, with classification confirmed via backscattering coefficient analysis. of Brazil.

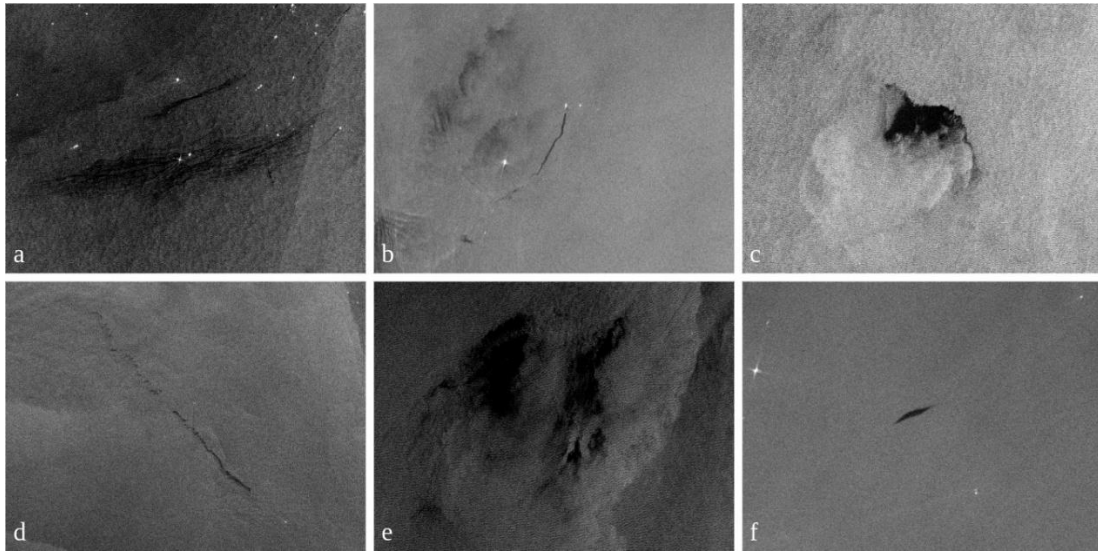


Figure V(I)-5. Sentinel-1 SAR images from the Campos Basin region illustrating dark features classified as either oil spills or look-alike phenomena (such as vessels, bright spots and rain cells). Images (a)-(f) display the analyzed patches, with classification confirmed via backscattering coefficient analysis.

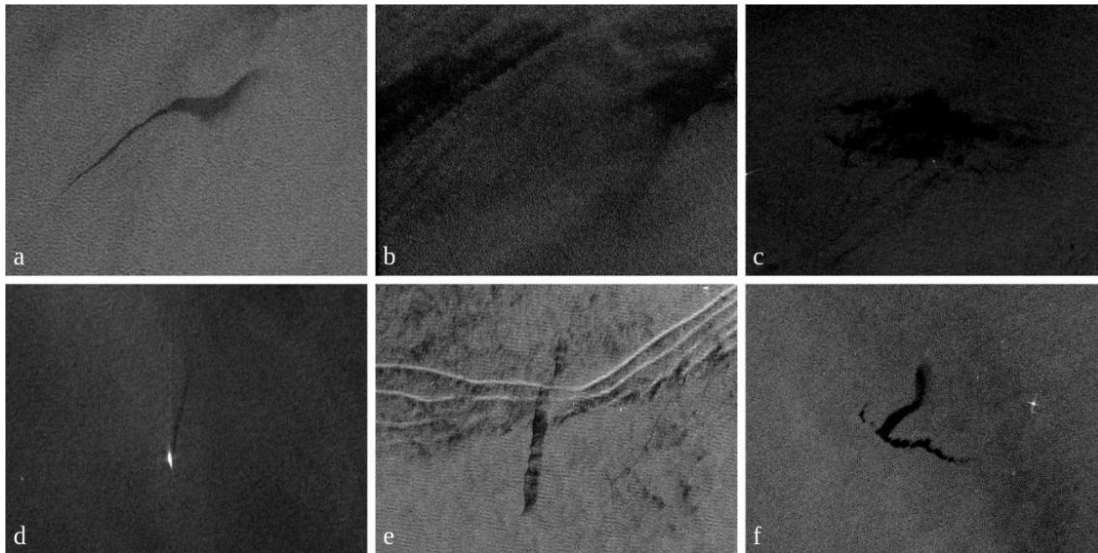


Figure V(I)-6. Sentinel-1 SAR images from the Santos Basin region illustrating dark features classified as either oil spills or look-alike phenomena (such as suspended particulate material and intentional discharge). Images (a)–(f) display the analyzed patches, with classification confirmed via backscattering coefficient analysis.

Table V(I)2. A set of SAR images, presenting dark stains, were used in the present study. Panels 4(a-f) correspond to images from the northeastern region of Brazil, while panels 5(a-f) and 6(a-f) represent the Campos and Santos Basins, respectively.

Region	Imag	Min	Max	Avg.	Std.	Med.	Coeff. of
	e	(dB)	(dB)	(dB)	Dev.	(dB)	Var.
Northeastern	4a	-61.23	33.11	-15.83	4.30	-16.64	-0.27
	4b	-74.57	16.91	-21.32	2.76	-21.52	-0.13
	4c	-55.31	19.86	-18.10	3.38	-18.63	-0.19
	4d	-62.11	28.66	-19.52	3.52	-19.73	-0.18
	4e	-64.11	20.67	-17.69	3.48	-18.06	-0.20
	4f	-63.98	-2.36	-17.35	2.72	-17.29	-0.16
Campos Basin	5a	-70.05	30.58	-17.64	4.88	-19.14	-0.28
	5b	-112.00	36.64	-17.45	5.72	-17.99	-0.33
	5c	-76.20	41.28	-20.23	2.62	-20.63	-0.13
	5d	-68.93	29.22	-13.30	3.78	-13.38	0.28

	5e	-89.28	28.12	-16.77	4.51	-17.78	-0.27
	5f	-85.76	28.10	-16.92	4.83	-17.71	-0.29
Santos Basin	6a	-77.91	29.53	-20.22	5.63	-20.70	-0.28
	6b	-98.35	12.75	-18.81	3.22	-18.78	-0.17
	6c	-69.52	30.64	-11.54	5.06	-10.33	-0.44
	6d	-67.40	32.90	-11.42	5.85	-9.63	0.51
	6e	-85.03	17.99	-18.53	3.98	-19.20	-0.21
	6f	-81.68	35.65	-18.48	4.49	-19.14	-0.24

¹ Values of the dispersion coefficients of the central and edge portions of the slicks

The percentage distribution of oil spill events and look-alikes across the analyzed regions reveals notable differences in their occurrence (Figure V(I)-7). The Santos Basin stands out with the highest prevalence of look-alikes, where most detected features resemble oil spills but were ultimately classified as false positives, leaving only one image closely matching a confirmed spill. In contrast, the Northeast region and the Campos Basin exhibit a more balanced distribution between natural phenomena and actual oil spill events. Each of these regions contains two verified cases of true oil spills, while the remaining detections correspond to look-alikes, likely influenced by biogenic films, low wind areas, or

other phenomena unrelated to oil. These findings underscore regional variations in detected features, highlighting the importance of complementary analyses to accurately distinguish real spills from patterns that look similar.

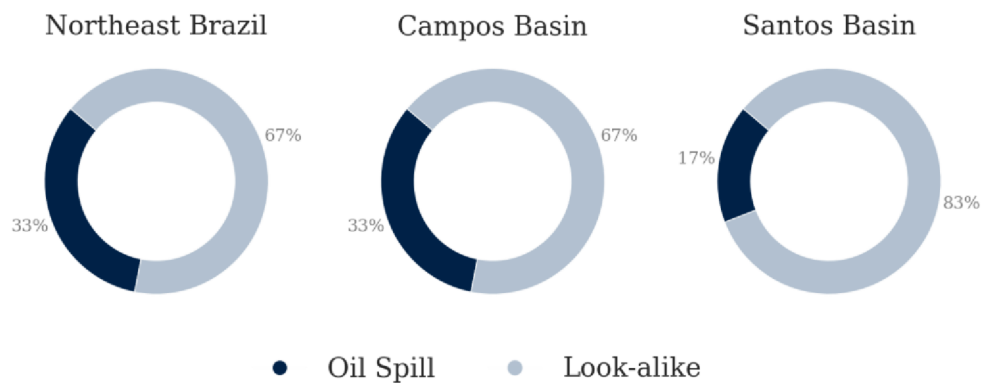


Figure V(l)-7. Pie chart showing the percentage of confirmed oil spills versus look-alike features identified in each study region: Northeast Brazil, Campos Basin, and Santos Basin, based on backscattering coefficient values. Higher oil spill detection rates are observed in the Northeast region and Campos Basin, whereas look-alikes prevail in the Santos Basin.

DISCUSSION

This study is among the first to estimate and characterize SAR backscatter values of dark features along the Brazilian coast, specifically in the Northeast Region, Campos Basin, and Santos Basin, focusing on the differentiation between oil slicks and look-alikes phenomena. Of the analyzed images, only 27% were classified as oil slicks. The remaining features were visually attributed to phenomena such as rain cells, low wind conditions, and biological films. The results confirm that backscatter coefficients of verified oil slicks along the Brazilian coast exhibit a consistent and distinct pattern, in

agreement with SAR oil signatures reported in previous studies (Alpers et al., 2017; Guo et al., 2018). This outcome directly addresses the primary objective of this work: to improve the distinction between actual oil slicks and natural oceanic features based on their backscatter behavior under local environmental conditions.

In the Northeast Region, two probable oil slicks were identified (Figure 4d and e). A major limitation during this period was the subsurface transport of oil, which hindered its detection by SAR sensors (Lourenço et al., 2020). The slicks only became visible as they approached the coastline. Since most of the analyzed images were from offshore areas, surface oil was rarely observed. Furthermore, the SAR backscatter response of oil varies depending on its physicochemical composition, resulting in distinct image signatures. Neves De Souza Júnior et al. (2023) analyzed eight SAR images of confirmed oil slicks and demonstrated that geochemical characteristics significantly influence backscatter behavior. Among those eight cases, only one, originating from the Gulf of Mexico, presented average backscatter values similar to those found in this study.

However, the minimum and maximum values differed substantially, likely due to methodological differences in the extraction of backscatter coefficients. These findings underscore the importance of using confirmed Brazilian oil slicks to derive parameters specific to the region, rather than relying on data from other oceanic regions with differing environmental and oil type characteristics. Additionally, (Lentini et al., 2022) analyzed image 4c, initially classified as an oil slick under low wind conditions by the RIOSS algorithm. Their final interpretation identified the feature as a biofilm, which aligns with our classification of this image

as a look-alikes based on backscatter values.

In the Campos Basin (Figure 5a, b, d, and f), several bright spots are observed, most of which likely correspond to vessels, highlighting the region's intense maritime traffic (Paes et al., 2010). In addition to incidents related to platforms, intentional discharges from vessels are more frequent. This study investigated both potential sources of oil slicks. It was expected that a greater number of oil slicks would be identified in this area; however, only two slicks (5a and f) were consistent with oil spill characteristics. This outcome is unexpected, particularly given the high hydrocarbon concentrations reported in the sediments of the Campos Basin, which suggest that oil leaks in these areas are not uncommon (Appolinario et al., 2020).

Regarding the other features classified as look-alikes (images 5c and e), their visual signatures are highly like interferences typically caused by rain cells. These atmospheric phenomena generate distinctive signatures in SAR imagery and are frequently observed in marine environments (Wang et al., 2024). Theoretical models describe how rain cells interact with microwaves emitted by satellites through atmospheric water condensation, resulting in variations in phase propagation and signal attenuation (Melsheimer et al., 1998). Consequently, these effects can alter backscatter coefficients and complicate the remote sensing detection of oil slicks (Danklmayer et al., 2009).

In the Santos Basin, the detected slicks do not resemble convective rain cells. However, some areas closer to the coast may be associated with suspended particulate material (Malenovský et al., 2012). Using the defined parameters, only one oil slick, Figure 6f, was identified among the six analyzed

scenes. Another noteworthy case is slick 6e, whose values closely approach those of the control slick. However, its maximum backscatter values diverge significantly. This image was acquired on April 11, 2019, approximately 53 km off the coast of Rio de Janeiro. The geometry of this slick strongly suggests intentional discharge, likely related to tank cleaning operations, and may fall under the legal provisions regarding oil pollution established by Federal Decree (De Oliveira, 2015). A more accurate classification of this feature would require the use of complementary approaches.

In this study, we applied a method to extract two polygons per feature, followed by statistical parameter analysis. We focused on minimum and maximum backscatter values, which revealed that weathering tends to be more intense at the edges of oil slicks. In other words, lower backscatter values, associated with the presence of oil, were observed in the central portions, while surrounding areas exhibited higher values. According to Solberg (2012), oil slicks typically appear more concentrated in the center and less dispersed, resembling a biofilm. The average backscatter measurements showed similar behavior in both reference images, supporting the interpretation that many of the unidentified cases in this study may represent actual oil slicks. However, although this parameter is one of the most used for slick discrimination, it should not be used as the sole criterion for distinguishing oil spills from natural phenomena, as it may lead to misclassification due to sampling errors (Loureiro and Gameiro, 2011).

Our findings indicate that most of the analyzed images do not resemble confirmed oil spill events, underscoring the difficulty of acquiring such data. As highlighted by previous studies (Bui et al., 2024; D'Ugo et al., 2024; Ivanov et

al., 2024), this challenge may be attributed to the limited spatial and temporal resolution of satellite sensors, the high cost of SAR image acquisition, and the lack of detailed information about actual spill events. One strategy to overcome this limitation is to bridge temporal gaps by integrating data from multiple sources (Falih et al., 2024), or to obtain additional information directly from regulatory agencies. Another critical challenge lies not only in the availability of SAR imagery depicting oil spills but also in their accurate identification, reinforcing the need for a standardized and widely accessible dataset for oil spill detection (Chen et al., 2024).

The method developed in this study provides encouraging preliminary results within the investigated context. Nevertheless, results could be significantly improved if a larger and more robust reference dataset were available, ideally integrated with algorithmic approaches. Even studies relying on identification based on geometry face challenges, given the dynamic nature of the marine environment, where currents, wind, and wave action can substantially modify the initial characteristics of oil slicks (Barker et al., 2020; Zodiatis et al., 2021).

Moreover, establishing a robust and region-specific reference dataset of oil slicks along the Brazilian coast is essential. Such a dataset could support the characterization of slick behavior near offshore platforms by integrating information about oil type, wind regimes, and regional ocean currents. Knowledge of these variables would reduce misclassification errors and support future studies, ultimately contributing to the development of more accurate oil detection algorithms for the Brazilian continental shelf.

CONCLUSION

This study demonstrated the effectiveness of analyzing backscatter coefficients in SAR images to distinguish between oil spills and natural oceanic phenomena along the Brazilian coast. Of the 18 cases analyzed, only 27% were classified as confirmed oil slicks, while the remaining were identified as look-alikes, underscoring the inherent challenges of remote detection in marine environments. The adopted approach, based on the extraction of statistical parameters from backscatter values, proved useful but limited when applied in isolation. The results highlight the need for a robust reference database of confirmed oil spill events, as well as a deeper understanding of regional patterns associated with natural interferences, such as rain cells, biological films, and low wind areas. Therefore, the integration of multiple classification techniques and data sources is essential to improve the accuracy of oil slick detection algorithms, particularly within the Brazilian context.

DATA AVAILABILITY STATEMENT

All SAR images used in this study were acquired from the Copernicus Sentinel-1A/B mission and are publicly available through the European Space Agency's Copernicus Open Access Hub (<https://scihub.copernicus.eu/>).

CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

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AUTHOR CONTRIBUTION

C.D.L.S.: Conceptualization; Investigation; Writing – original draft; Writing – review and editing;

F.C.P.I.: Methodology; Software; Formal Analysis; Investigation; Writing – review and editing;

F.S.C.O.: Supervision; Resources; Project Administration; Funding Acquisition; Writing – review and editing.

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Performance Comparison of MEDSLIK and PyGNOME for Real Oil Spill
Events in the Campos Basin, Brazil

Carolina de L. Santana¹, Fernanda C. P. Inojosa², Fabricio S. C. De Oliveira¹

(1) Lab. de Oceanografia Dinâmica e por Satélites, Universidade. Federal do
Rio Grande (FURG), Av. Itália, Km 8, Carreiros, CEP: 96203-900, Rio Grande,
RS, Brazil;

(2) Casa Civil da Presidência da República, Brasília, DF, CEP: 70.150-
900, Brazil.

*Corresponding author

Email address: carolinasantana@furg.br

Abstract

Oil and gas industry is one of the main driver of global trade, supporting the economic development of several countries, due to its value as a raw material. Practices related to extraction, production, and offshore activities can lead to oil contamination in oceanic areas, with significant unpredictable environmental impacts. The main forcings affecting oil dispersion in the ocean are wind, currents, and waves. Once in the ocean, oil, influenced by meteo-oceanographic conditions, exhibits distinct behaviors that depends on its physicochemical properties and the intensity of the driving processes. Significant knowledge gaps remain regarding the dynamics of oil and how it can affect the Brazilian coastal zone. To address these uncertainties, the present study investigated the best performance between two oil spill models, MEDSLIK II and PyGNOME, for the Campos Basin region (RJ). Several scenarios were simulated for three real spill

events, followed by validation using remotely sensed data from satellite SAR and airborne SLAR sensors. Results from the study elucidated oil slick behavior in the region, with MEDSLIK performing best for coastal-reaching spills, while PyGNOME was more effective in offshore regions dominated by surface currents and wind. Consequently, the passage of transient systems was identified as a major risk factor for the coastline of the Lakes Region.

1. Introduction

Oil pollution in the oceans is a consequence of the global dependence on the petroleum industry and its derivatives [Chen et al. 2020]. The loss of this natural resource to the environment is almost inevitable, as oil is continuously subjected to processes of production, transportation, refining, and consumption [Blumer, 1971]. During oil transportation, incidents associated with ship collisions, hull ruptures, groundings, and intentional discharges contribute significantly to the introduction of this pollutant into the marine environment [Ketkar & Babu, 1997].

In Brazil, accidents related to offshore platforms are numerous due to its strong reliance on offshore hydrocarbon production and extraction [Mohriak et al. 1990; Zacharias & Fornaro, 2020]. Effective management of such risks requires detailed understanding of oil composition, spill volume, and meteo-oceanographic conditions, which are essential for the application of oil spill dispersion models.

Oil dispersion is governed by the interaction of multiple meteo-oceanographic conditions, with particular emphasis on the influence of waves,

wind, and surface currents [Mearns et al. 2001; Röhrs et al. 2018; Lee et al. 2020]. Wind contributes to surface drag-driven advection and diffusion of oil slicks through shear stress as the oil moves relative to the water, a process dependent on the laminar or turbulent flow conditions within the surface boundary layer [Wagner et al. 2022]. Wave-breaking energy directly promotes the transport of emulsified oil into subsurface layers and enhances horizontal dispersion through currents. Wave intensity is directly proportional to the fragmentation of oil droplets; however, under intensified weathering processes, increased oil viscosity may hinder vertical mixing [Tkalic & Chan, 2002].

A thin oil film on the ocean surface increases shear stress in the upper surface layer and, consequently, the area covered by the slick dampens capillary wave activity, potentially inhibiting mixing with adjacent layers [Dorrestein, 1951]. According to Christensen and Terrile [2009], strong wind conditions can suppress the wave attenuation effect induced by oil, thereby enabling the vertical redistribution of the oil slick into smaller fractions.

In numerical oil spill modeling studies, all factors governing pollutant trajectories, as described above, are incorporated into dispersion models. For instance, Balogun et al. [2021] accounted for seasonal variability in the Kota Tinggi region of Malaysia using the GNOME oil spill model, concluding that seasonal climatic variations significantly influence the vulnerability of coastal resources to oil spills. Another example is the comparison between GNOME and the Blowout and Spill Occurrence Model (BLOSOM), which, according to Duran et al. [2003], demonstrated very similar performance between the two models. Nevertheless, the authors highlighted aspects that could be improved in GNOME,

particularly the inclusion of a wind-driven deflection angle option during parameterization.

MEDSLIK-II has been widely applied to simulate the evolution of accidental oil spills from tankers operating in environmentally sensitive regions. For instance, simulations conducted near the Fernando de Noronha Archipelago, Brazil, demonstrated the potential for oil to reach the boundaries of the Fernando de Noronha Marine National Park, highlighting the environmental risks associated with hydrocarbon shipping activities near this protected area [Siqueira et al. 2022]. Similarly, Protasio et al. [2022] assessed potential environmental risks related to oil spills in the vicinity of the Abrolhos Marine National Park, where the results allowed for the correlation of seasonal variability with oil behavior in the region. These findings further emphasized the complex interplay between regional ocean circulation, the latitudinal displacement of the Intertropical Convergence Zone (ITCZ), and oil spill trajectories.

Keramea et al. [2023], using satellite imagery, analyzed the responses of the MEDSLIK and OpenDrift models during the Syrian oil spill crisis in the summer of 2021. Their results indicated that both models performed well, achieving moderate accuracy, while also highlighting the role of regional circulation patterns and the influence of mesoscale eddies on oil dispersion under conditions dominated by such features.

To address gaps related to oil behavior in the ocean, the use of numerical modeling enables the simulation of different realistic oil spill scenarios and their consequences for distinct oceanic and coastal regions. In this context, the present study has as its main objective the understanding of oil dynamics in one

of the most important marine sedimentary basins in Brazil, the Campos Basin. Through this approach, it is possible to determine, between two publicly accessible models, which one better represents oil dispersion in this region. In addition, the study provides sufficient information to support the mitigation of potential environmental disasters related to oil behavior under different spill scenarios.

2. Material and Methods

2.1. Study area

The spills investigated in this study are concentrated in the Campos Basin, located between the boundaries of the Espírito Santo Basin and the Santos Basin, extending between latitudes 20°27'29" S and 22°59'29" S and longitudes 40°19'29" W and 42°00'49" W, (Figure V-(II)1). One of its main characteristics lies in its fundamental role in the oil and gas industry, being considered the largest petroleum basin in the country [Jablonski 2008; Miranda et al. 2010]

The ocean circulation in this area is characterized by the active presence of the Brazil Current, the Intermediate Western Boundary Current, and the eddies and meanders associated with these flows [Da Silveira et al. 2015]. In this way, its geographical position allows for a strong influence from the Brazil Current (BC), which is primarily responsible for the southward transport of waters along the coast. The winds in the region are strongly influenced by the South Atlantic subtropical high-pressure system, which establishes an anticyclonic circulation pattern, favoring the predominance of northeasterly winds throughout the study

area [Reboita et al., 2019; Dereczynski et al. 2019].

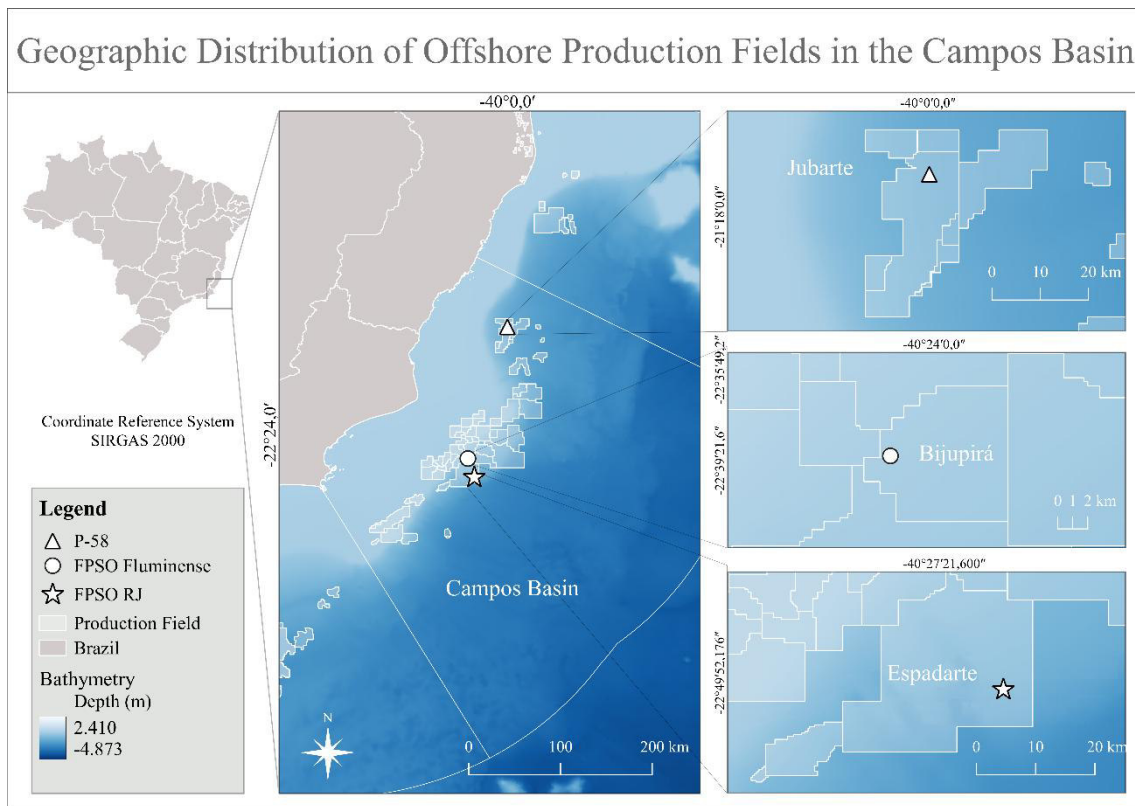


Figure V(II)1. Geographic distribution of offshore production fields in the Campos Basin.

The map shows the location of oil and gas production fields in the Campos Basin, southeastern Brazil, including the studied platforms: P-58 (Jubarte field), FPSO Fluminense (Bijupirá field), and FPSO Cidade do Rio de Janeiro (Espadarte field). Bathymetric depth (m) and production field boundaries are indicated.

2.2. Monitoring Oil Spill Cases

The observation of oil slicks was carried out using two remote sensing methods, at orbital and suborbital levels, through SAR and SLAR products. The SAR products were obtained from the 1A and 1B sensors of the Sentinel mission. These data are publicly available from the European Space Agency (ESA) (<https://scihub.copernicus.eu/>). The data analyzed here have VV polarization, are of the GRD (Ground Range Detected) type, and were pre-processed using the

SNAP (Sentinel Application Platform) software, also provided by ESA.

Additionally, IBAMA provided SLAR products acquired from Poseidon overflights conducted by the company FOTOTERRA. Along with the slicks, detailed reports for each event were also supplied, including the oil's API gravity, the estimated spill volume, and the type of incident involving the platforms. This information ensured that the necessary parameters defining the initial state of the spill were accurately introduced into the oil dispersion models, enhancing their overall efficiency.

2.2.1. FPSO Cidade do Rio de Janeiro

The floating production, storage, and offloading unit (FPSO) Cidade do Rio de Janeiro is located to the south of the Espadarte production field and was operated by the company MODEC, under Petrobras's concession. This unit experienced an incident on the morning of January 2, 2019, as reported in the investigation report issued in November 2020 by the Brazilian National Agency of Petroleum, Natural Gas and Biofuels (ANP). The spill originated from a rupture in tank 5C, which had been storing oil since the end of operations in 2018. According to the ANP's Superintendence of Operational Safety and Environment (SSM), approximately 15.36 m³ of oil were observed in relation to this incident. For model calibration, the parameters used for this spill are described in Table V(II)1.

Table V(II)1. Input Parameters Adopted for the FPSO Cidade do Rio de Janeiro Oil Spill Simulation

Case	Duration (h)	Oil API	Oil Name	Deflection by model	Wind Halved (m/s)	Angle Factor (°)	Drift Factor (%)	Oil Discharge (m ³)
M01	120	20.7	Lloyd	Yes	0	45	2	15,36
G01	120	21.5	Neptune	Yes	-	25	2	15.36
M02	120	20.7	Lloyd	Yes	10	45	2	15.36
G02	120	21.5	Neptune	No	-	25	2	15.36
M03	120	20.7	Lloyd	Yes	0	45	3	15.36
G03	120	21.5	Neptune	Yes	-	25	3	15.36
M04	120	20.7	Lloyd	Yes	10	45	3	15.36
G04	120	21.5	Neptune	No	-	25	3	15.36

2.2.2. P-58

The P-58 unit is located in the Parque das Baleias field, approximately 85 km off the coast of Espírito Santo, with a production capacity of up to 180 thousand barrels of oil per day. It is currently considered one of the most important production facilities in Brazil, ranking among the 35 largest oil producers in 2025. In this study, this spill was the one that presented the highest volume, with approximately 251.8 m³ (Table V(II)2) recorded on the morning of February 23, 2019. The cause of the event was associated with an offloading operation carried out during the oil transfer activity between the platform and the vessel São Sebastião.

Table V(II)2. Input Parameters Adopted for the FPSO P-58 Oil Spill Simulation

Case	Duration (h)	Oil API	Oil Name	Deflection by model	Wind Halved (m/s)	Angle Factor (°)	Drift Factor (%)	Oil Discharge (m ³)
M05	140	18.7	Klamono	Yes	0	45	4	251.8
G05	140	19.3	Djeno Monterey	Yes	-	25	4	251.8
M06	140	18.7	Klamono	Yes	10	45	4	251.8
G06	140	19.3	Djeno Monterey	No	-	25	4	251.8
M07	140	18.7	Klamono	Yes	0	45	6	251.8
G07	140	19.3	Djeno Monterey	Yes	-	25	6	251.8
M08	140	18.7	Klamono	Yes	10	45	6	251.8
G08	140	19.3	Djeno Monterey	No	-	25	6	251.8

2.2.3. FPSO Fluminense

The FPSO Fluminense began operations in 2003 and continued until its decommissioning in 2021. Operated by MODEC under Shell Brasil's concession, it had a processing capacity of 81 thousand barrels of oil per day. This unit operated in two distinct production fields: Bijupirá and Salema. There are many gaps regarding this spill, as it was only detected coinciding with P-53 monitoring on April 4, when oil was observed reaching the coastline of the Região dos Lagos area. An official "Incident with Oil Contact on the Coast" report was subsequently

issued by the ANP. Therefore, no information is available regarding the type of occurrence that caused the spill or the exact date when it began. Consequently, in this study, the initial conditions of this spill were assumed to be equivalent to those of the P-53 incident, except for the oil API gravity, which was adjusted to represent the typical value of the corresponding production field (Table V(II)3).

Table V(II) 3. Input Parameters Adopted for the FPSO Fluminense Oil Spill Simulation

Case	Durati on (h)	Oil API	Oil Name	Deflection by model	Wind Halved (m/s)	Angle Factor (°)	Drift Factor (%)	Oil Discharge (m ³)
M09	300	28.40	Sylvestre	Yes	No	45	2	122
G09	300	27.8	Djeno Phillips	Yes	-	45	2	122
M10	300	28.40	Sylvestre	Yes	6	45	2	122
G10	300	27.8	Djeno Phillips	No	-	45	2	122
M11	300	28.40	Sylvestre	Yes	No	45	3	122
G11	300	27.8	Djeno Phillips	Yes	-	45	3	122
M12	300	28.40	Sylvestre	Yes	6	45	3	122
G12	300	27.8	Djeno Phillips	No	-	45	3	122

2.3. Oil spill models

2.3.1. MEDSLIK 2.01

The MEDSLIK-II computational code is a free and open-source oil spill

dispersion modeling system that integrates information from ocean hydrodynamic models to determine the surface oil dispersion pattern. Its focus lies on tracking the trajectory of parametrized turbulent floating components, coupled with a Lagrangian particle model that incorporates weathering processes. The model can solve the advection–diffusion–transformation equation for oil in three variable states, namely slicks, particles, and structural components. In this way, the model employs the general tracer equation, associating mass and volume during emulsification processes in the ocean, as shown in Equation 1.

$$\frac{\partial C}{\partial t} + U \cdot \nabla C = \nabla \cdot (K \nabla C) + \sum_{j=1}^M r_j(x, C(x, t), t), \quad (1)$$

Where $r_j(x, C(x, t), t)$ represents the physicochemical transformations that the oil undergoes due to degradation; U denotes the horizontal current field components (u and v); and K represents the turbulent diffusivity tensor [De Dominicis et al., 2013]. The model includes its own oil database, with a range of API gravity values based on samples from the Mediterranean Sea, allowing it to simulate oil transformation processes related to weathering, such as evaporation, emulsification, horizontal/vertical dispersion, and beaching [Lardner & Zodiatis, 2016].

2.3.2. *Gnome 1.1.15*

The General NOAA Operational Modeling Environment (GNOME) is a freely accessible oil spill dispersion model developed and distributed by NOAA, allowing simulations to be performed in various regions across the globe. It is also a Lagrangian model and, therefore, solves oil dispersion by representing the

slick as a collection of particles, where the motion of each particle is computed based on its individual trajectory [Pradhan et al., 2020]. However, to determine the total particle displacement, the model employs the first-order Runge–Kutta method combined with the velocity components of currents (u and v), winds (u and v), and diffusion, as described in Equation 2.

$$\Delta x = \frac{dx * \sqrt{6 * \frac{D}{10,000} * \Delta t}}{1,11 \times 10^5 \cos(y)}, \Delta y = dy * \frac{\sqrt{6 * \frac{D}{10,000} * \Delta t}}{1,11 \times 10^5} \text{ and } \Delta z = 0 \quad (2)$$

Where Δt is the elapsed time, y is the latitude in radians, and $1,11 \times 10^5$ represents the number of meters per degree of latitude, while Δz denotes the depth. Therefore, Δx and Δy correspond to the 2D displacements in longitude and latitude, accounting for the diffusion process [Zelenke et al., 2012]

2.4. Atmospheric and ocean forcing

The ocean current velocity components and sea surface temperature (SST) data are provided daily and were obtained from the GLORYS12V1 reanalysis, distributed by the Copernicus Marine Service (CMEMS) through <https://data.marine.copernicus.eu/>, with a horizontal resolution of $1/12^\circ$ (~ 8 km) and 50 vertical levels. The wind field data, available on an hourly basis, correspond to the ERA5 reanalysis developed by the European Centre for Medium-Range Weather Forecasts (ECMWF) and made available through the Climate Data Store (CDS) at <https://cds.climate.copernicus.eu>, with a horizontal resolution of $1/4^\circ$ (~ 30 km) and 137 pressure levels from the surface up to 80 km in altitude.

2.5. Comparative Method

This study addresses three different oil spill events, involving distinct periods, durations, and oil types. Therefore, the comparison between simulations and field observations was conducted through visual analysis of the oil slicks and their behavior throughout the entire monitoring period. In this context, after analyzing the three incidents, a decision tree was developed, as presented in Figure V(II)2.

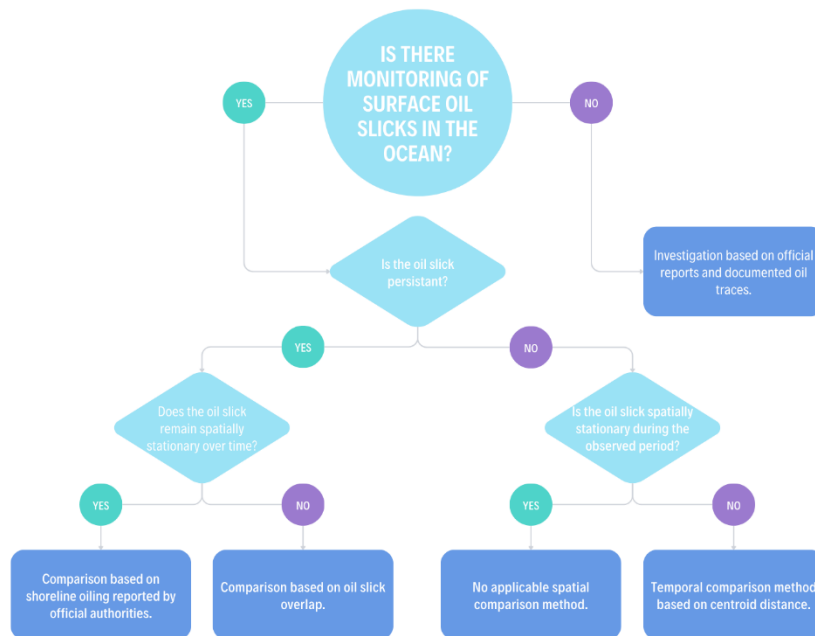


Figure V(II)2. Decision tree for selecting the comparison method between remote sensing data and model outputs. The diagram illustrates the decision-making process used to determine the most suitable comparison method between oil slick detections from remote sensing and predictions from numerical models. The selection depends on the persistence and spatial stability of the observed slicks, resulting in either spatial or temporal comparison approaches depending on data characteristics.

2.5.1. The Slick Overlap

For cases of persistent and non-stationary oil slicks, the slick-overlapping

method was defined to assess model performance. This approach has been widely applied in studies related to marine pollution and the monitoring of surface sediment plumes [Evans et al. 2012; Tavora et al. 2023], and the present methodology was developed based on the framework proposed by Keramea et al. [2023]. Accordingly, using the SLAR and SAR products, it was possible to establish a degree of spatial agreement between the model results and the remote sensing observations. The first performance metric applied, known as the Success Rate (SR), assesses how accurately the model represents the area affected by the spill, as described in Equation 3.

$$SR = \frac{\text{Overlapping area}}{\text{Total observed area}} \quad (3)$$

The Failure Rate (FR), or error rate, was also used to quantify the extent to which the model overestimated the real slick area (Equation 4).

$$FR = \frac{\text{Non – overlapping area}}{\text{Total modeled area}} \quad (4)$$

Finally, the Critical Success Index (CSI) was calculated as the ratio between the overlapping area and the sum of the real and modeled areas. This index evaluates model performance by integrating both correct predictions and spatial discrepancies.

$$CSI = \frac{\text{Overlapping area}}{\text{Observed area} + \text{Modeled area}} \quad (5)$$

2.5.2. Distance Between Slick Centroids

Oil slicks characterized as non-persistent and non-stationary were

classified as more dynamic, as it was possible to observe their displacement away from the platforms throughout the monitoring period, in a way that did not leave clear traces of their origin. For these cases, model performance was assessed based on the centroid distance between the observed slick and the model outputs. In this context, smaller centroid distances over time indicate a better agreement between the modeled and observed results.

2.5.3. Reports from Official Monitoring Agencies

There are currently three main institutions responsible for monitoring, inspection, and investigation of oil pollution in waters under Brazilian jurisdiction: the National Agency of Petroleum, Natural Gas and Biofuels (ANP), IBAMA, and the Brazilian Navy. Together, they compose the Monitoring and Evaluation Group (GAA), which is responsible for investigating large-scale incidents. Thus, whenever an oil landfall event occurs on the coast, or when recurrent events are observed, these institutions prepare reports detailing the incidents. These reports are publicly available through the website (<https://www.gov.br/anp/pt-br/assuntos/comunicacao-de-incidentes/relatorios-de-investigacao-de-incidentes>) and provide information on the source of the spill, oil type, meteorological conditions, causes, incident timeline, affected locations, volume of oil released, and mitigation and contingency measures.

2.5.4. Assessment of Oil Sensitivity in the Campos Basin

The Environmental Sensitivity Maps to for Oil Spills (SAO) were developed to provide strategic support in the event of incidents. They present the distribution of natural, biological, and socio-economic resources based on Littoral

Sensitivity Index (LSI) classifications [de Aquino Martins et al., 2013; da Silva Baptista et al., 2015]. These data are freely available at <https://www.gov.br/mma/pt-br/assuntos/meio-ambiente-urbano-recursos-hidricos-qualidade-ambiental/emergencias-ambientais/repositorio/cartas-de-sensibilidade-ao-oleo/atlas-cartas-e-mapas>, together with their corresponding atlases. These atlases list local species that are sensitive to potential spills.

Based on this information, marine biological resources in the Campos Basin were compiled using the open-access Ocean Biodiversity Information System (OBIS) platform, available at <https://obis.org/> and maintained by the United Nations Educational, Scientific and Cultural Organization (UNESCO). For bird records, the open-access bird observation and occurrence platform WikiAves was used, available at <https://www.wikiaves.com.br/>.

3. Results

3.1. Metocean conditions

The meteo-oceanographic conditions during the spill periods were consistent with what is typically expected for the region. At the initial points of each spill, ocean currents were strongly influenced by the passage of the Brazil Current (Figure V(II)3). Consequently, the surface displacement shows a predominantly southward orientation in Figures V(II)3a and V(II)3b, with not only similar flow patterns but also comparable current velocities. In contrast, for the FPSO Fluminense case (Figure V(II)3c), current velocities are higher, and the predominance of a southwestward direction is more pronounced than in the other cases.

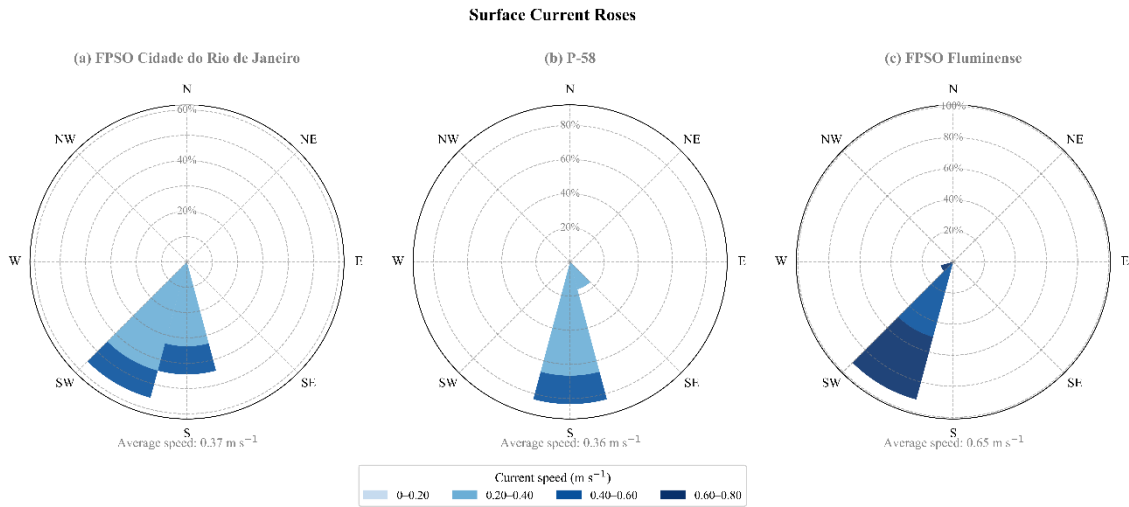


Figure V(II)3. Surface current roses derived from the GLORYS12V1 reanalysis at the locations of the FPSO Cidade do Rio de Janeiro, P-58, and FPSO Fluminense platforms. The plots show the predominant directions and intensity classes of ocean surface currents, indicating the local flow regime associated with the Brazil Current. Average current speeds for each site are shown below the respective panels.

For the wind patterns, the predominance of northeasterly winds in the region was also observed, as shown by the wind rose in Figure V(II)4. The FPSO Cidade do Rio de Janeiro (Figure V(II)4a) and P-58 (Figure V(II)4b) once again showed very similar behaviors, with a well-defined predominance of northeasterly winds. In contrast, for the FPSO Fluminense event (Figure V(II)4c), there was a marked difference between northeaster and southeasterly winds. During this event, the wind regime was predominantly southeasterly from the beginning of the simulations, while toward the end, the northeasterly winds regained predominance. Regarding wind intensity, the FPSO Cidade do Rio de Janeiro can be associated with the period that exhibited the highest surface wind speeds, whereas the lowest wind speeds were observed during the P-58 event. Finally, the FPSO Fluminense displayed a rather heterogeneous pattern, both in terms

of wind direction and speed intensity.

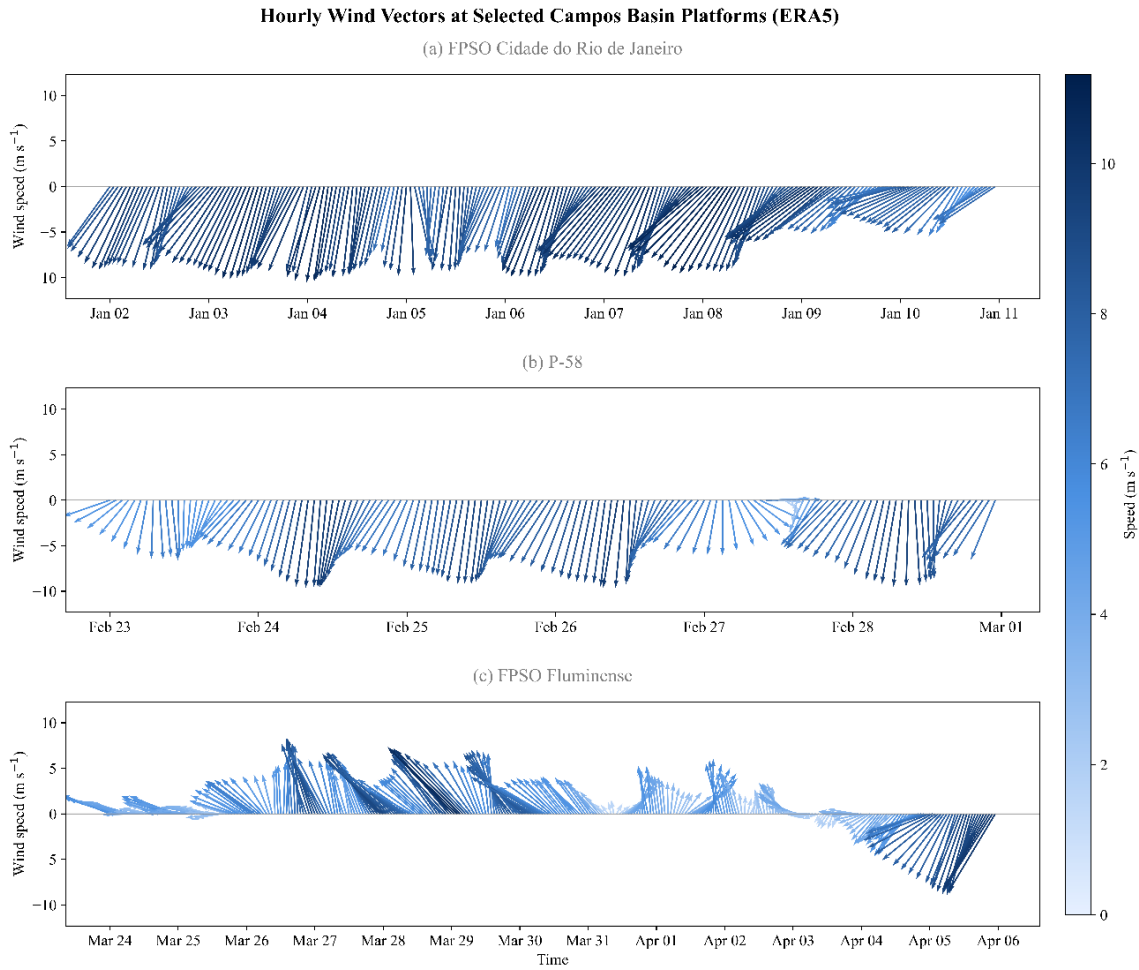


Figure V(II)4. Hourly wind vectors at the FPSO Cidade do Rio de Janeiro, P-58, and FPSO Fluminense platforms, derived from the ERA5 reanalysis dataset. Each panel represents the temporal variation in wind direction and intensity during the corresponding monitoring period of the oil spill events. The color scale indicates wind speed in meters per second (m s^{-1}).

3.2. Oil Spill Modelling

3.2.1 FPSO Cidade do Rio de Janeiro

The first spill event originating from the FPSO Cidade do Rio de Janeiro was identified as the incident that exhibited the greatest overlap with the actual

oil slick (Figure V(II)5). This observation can be attributed to the persistence of the oil patch and its distinct physicochemical characteristics. Moreover, it was possible to observe that oil residues remained near the platform even five days after the incident, which hindered comparison using the selected monitoring method for that specific day.

The simulations performed with the MEDSLIK model, corresponding to the first two parameterizations (M01 and M02) with a 20% drift factor, demonstrated superior performance. As shown in Figure V(II)5a, the centroids represented by triangles closely followed the spatial extent of the real oil slick. In contrast, the last two cases M03 and M04, which employed a higher drift factor (30%), overestimated the distance traveled by the oil from the release point to the monitoring time. Another noteworthy aspect concerns the use of the wind halved parameter in M01 and M03, which produced results more consistent with field observations for this more offshore spill event.

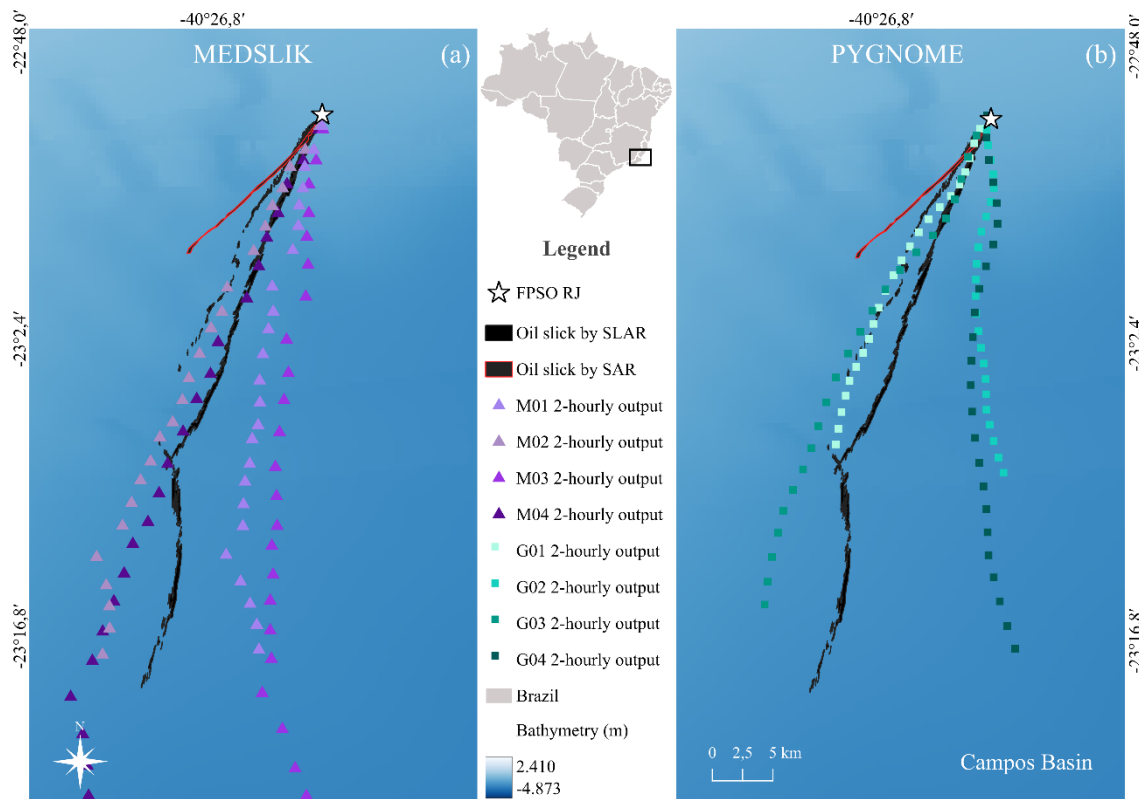


Figure V(II)5. Comparison of model outputs for the oil spill event from the FPSO Cidade do Rio de Janeiro in the Campos Basin. Panels (a) and (b) show simulated surface oil trajectories from the MEDSLIK and PYGNOME models, respectively. Model outputs at two-hour intervals are represented by triangles (MEDSLIK) and squares (PYGNOME), overlaid on the observed oil slicks detected by SLAR (black) and SAR (red).

The PyGNOME simulations visually demonstrated considerable performance (Figure V(II)5b). For the lower drift factor in G01 and G02, the simulated oil slick exhibited minimal displacement from the platform. However, simulations with a higher drift factor provided a more realistic representation of the actual distance traveled by the oil, without overestimation.

The most significant discrepancy among parameters was observed in the drift angle. While the MEDSLIK model achieved better results with a 45° deflection, PyGNOME, using its own internal calibration, proved to be more

effective. Consequently, the 25° deflection exceeded expectations (G01 and G03), and non-rotated wind fields were ultimately adopted for this case. This configuration in G02 and G04 yielded results that were more consistent with the oil slick observed during the second day of monitoring conducted by IBAMA.

3.2.2. *P-58*

The P-58 case presents distinct characteristics compared to the other spill events analyzed. The released oil exhibited a less persistent nature and a more dynamic dispersion pattern, allowing for a clearer delineation of its trajectory at each monitoring stage (Figure V(II)6). Accordingly, MEDSLIK simulations were performed using drift factors between 4% and 6%, slightly higher than those previously assessed. Although neither configuration fully reproduced the real extent of the slick displacement, the higher drift factor yielded the closest agreement with field observations.

The implementation of the wind halved parameter improved model performance during the later monitoring days, with simulation M08 displaying a centroid nearly overlapping the penultimate observed slick position. In contrast, the early monitoring stages were better represented without the wind halved correction, as illustrated by simulations M05 and M07, which closely matched the real oil slick patterns.

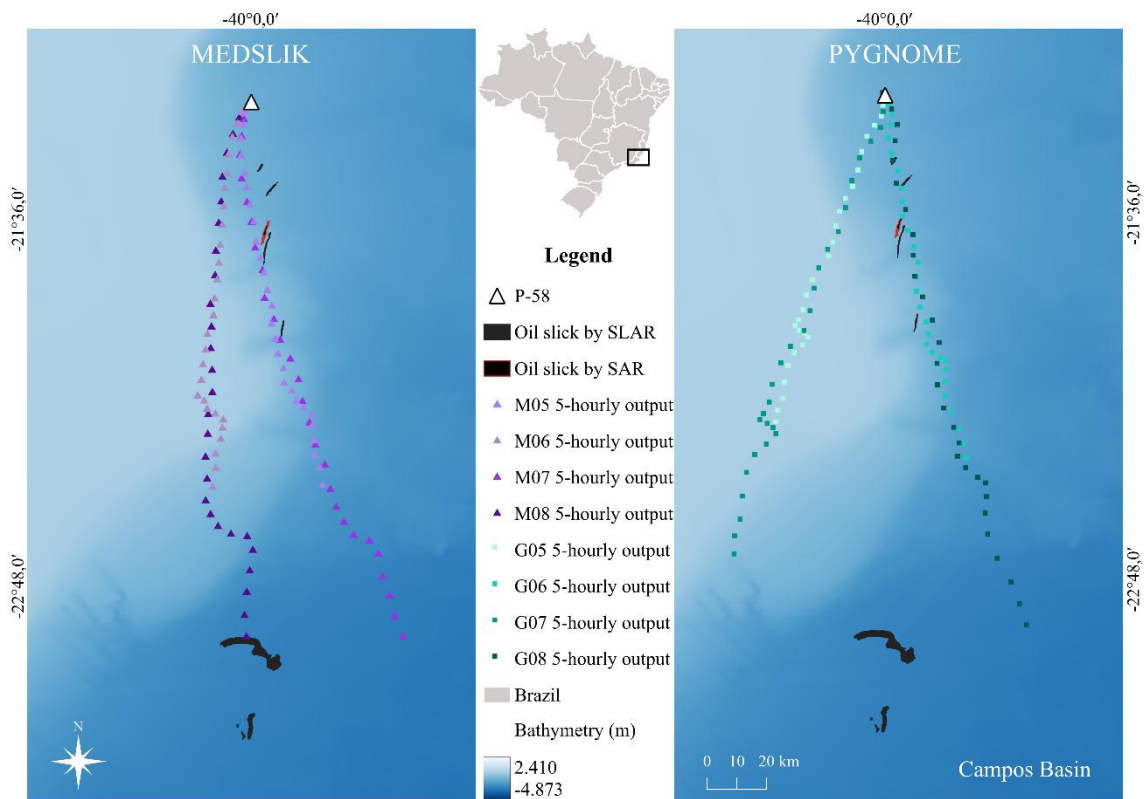


Figure V(II)6. Comparison of model outputs for the oil spill event from the P-58 platform in the Campos Basin. Panels (a) and (b) show simulated surface oil trajectories from the MEDSLIK and PYGNOME models, respectively. Model outputs at five-hour intervals are represented by triangles (MEDSLIK) and squares (PYGNOME), overlaid on the observed oil slicks detected by SLAR (black) and SAR (red).

Simulations G05 and G07, which employed a 25° deflection angle, produced trajectories that extended significantly farther than expected. Therefore, once again, the model performed better in the absence of such corrections, as demonstrated by scenarios G06 and G08. The latter simulations exhibited behavior closely resembling that of the MEDSLIK model, particularly regarding the drift factor. Simulations G07 and G08 showed displacement distances approaching 200 km from the initial release point, representing a closer approximation to the observed slick extent.

3.2.3. FPSO Fluminense

The FPSO Fluminense event revealed clear distinctions in the simulated trajectories produced by both modeling frameworks (Figure V(II)7a). Simulations M09 and M11 exhibited a high degree of similarity, as their parameterizations did not include the wind halving effect. The primary difference between them lies in the shoreline arrival time: M11, using a drift factor of 3%, reached the coast of Armação de Búzios on 2 April 2019, representing the scenario that most closely matches the timeline reported in the official P-53 investigation report. In contrast, simulations M10 and M12 showed trajectories displaced further north than expected. For oil spill scenarios in which slicks reached the coastal zone, the wind halving parameter proved to be less effective, contrasting with its performance in events characterized by fully offshore spills.

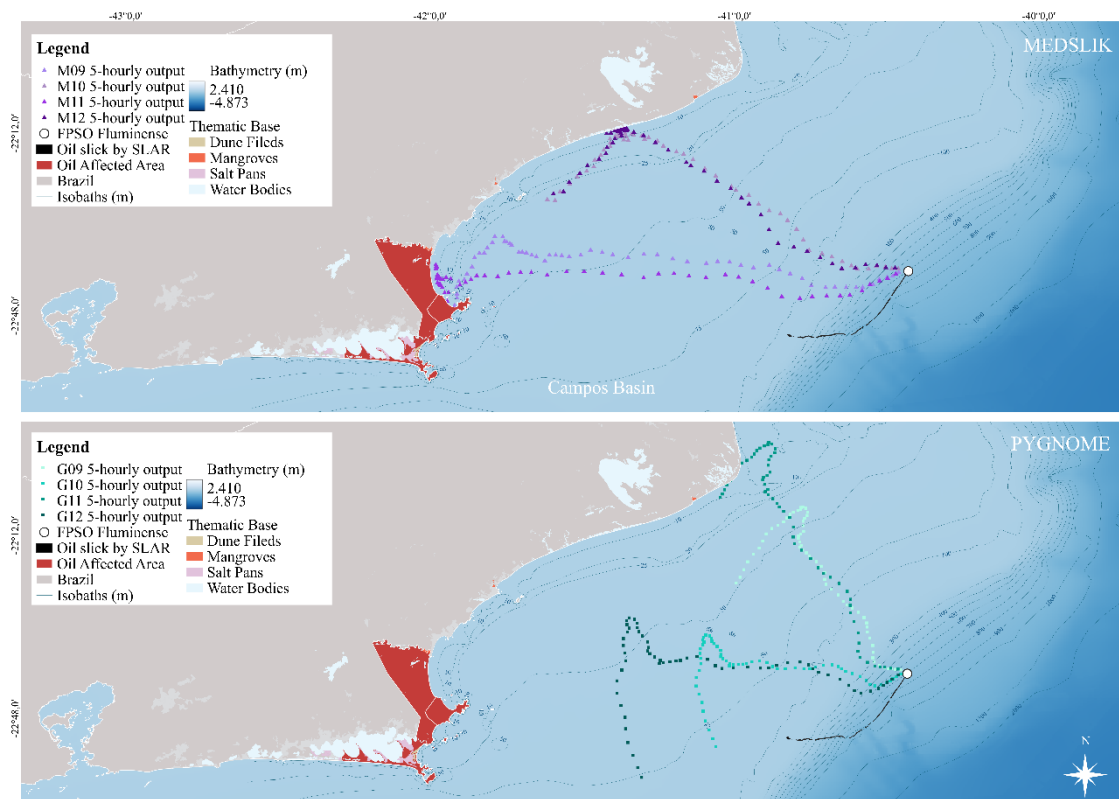


Figure V(II)7. Comparison of model outputs for the oil spill event from the FPSO

Fluminense platform in the Campos Basin. Panels (a) and (b) show the results of the MEDSLIK and PYGNOME models, respectively, with five-hour output intervals represented by triangles (MEDSLIK) and squares (PYGNOME). The Lakes Region, highlighted in red, indicates the coastal area reached by the real oil drift from P-53, according to the ANP (National Petroleum Agency) report. The observed oil slick detected by SLAR (black) is shown for reference.

The simulations conducted with PyGNOME in Figure V(II)7b exhibited different responses. Under the certain method, the model did not reproduce oil stranding along the target coastline. Simulation G11 was the only case that resulted in shoreline oiling; however, the affected area was located more than 120 km away from the Lakes Region. Regarding trajectory duration, simulations G09 and G11 produced the shortest paths, which can be attributed to their lower drift factors. Among these scenarios, simulation G12 yielded the most satisfactory results, as it resulted in oil reaching the coastline at a comparatively shorter distance from the study area.

3.3. Comparative Method Between MEDSLIK and PyGNOME

The FPSO Cidade do Rio de Janeiro incident enabled the comparison method due to principles inherent to oil slick overlap. The results described in Figure V(II)8 show a better performance of the MEDSLIK model with respect to the success rate. For the slick overlap on the second day of monitoring, the best performance was obtained in simulation M04 (Figure V(II)8 a), whereas for the first day of monitoring, M02 presented the highest success rate. For the PyGNOME model, the success rate was lower, with G01 and G03 respectively demonstrating the best responses.

Regarding the failure rate, Figure V(II)8 b shows that MEDSLIK presented the highest rates on the second day of monitoring, that is, poorer responses; however, this behavior was also observed for the PyGNOME model, in which both models performed poorly on the second day of monitoring. For the first monitored day, MEDSLIK simulations M04, M02, and M01 exhibited better performance, whereas PyGNOME presented the best responses among both models for scenarios G01 and G03, respectively.

For the Critical Success Index, values much lower than those commonly reported were observed for both models (Figure V(II)8C). Nevertheless, the highest values for MEDSLIK simulations were associated with M04, M02, and M01, all better represented on the first day of monitoring. In the case of PyGNOME, the best results remained the same as previously observed, namely G01 and G03. Among all cases, PyGNOME showed better performance for this metric with the values obtained in G01.

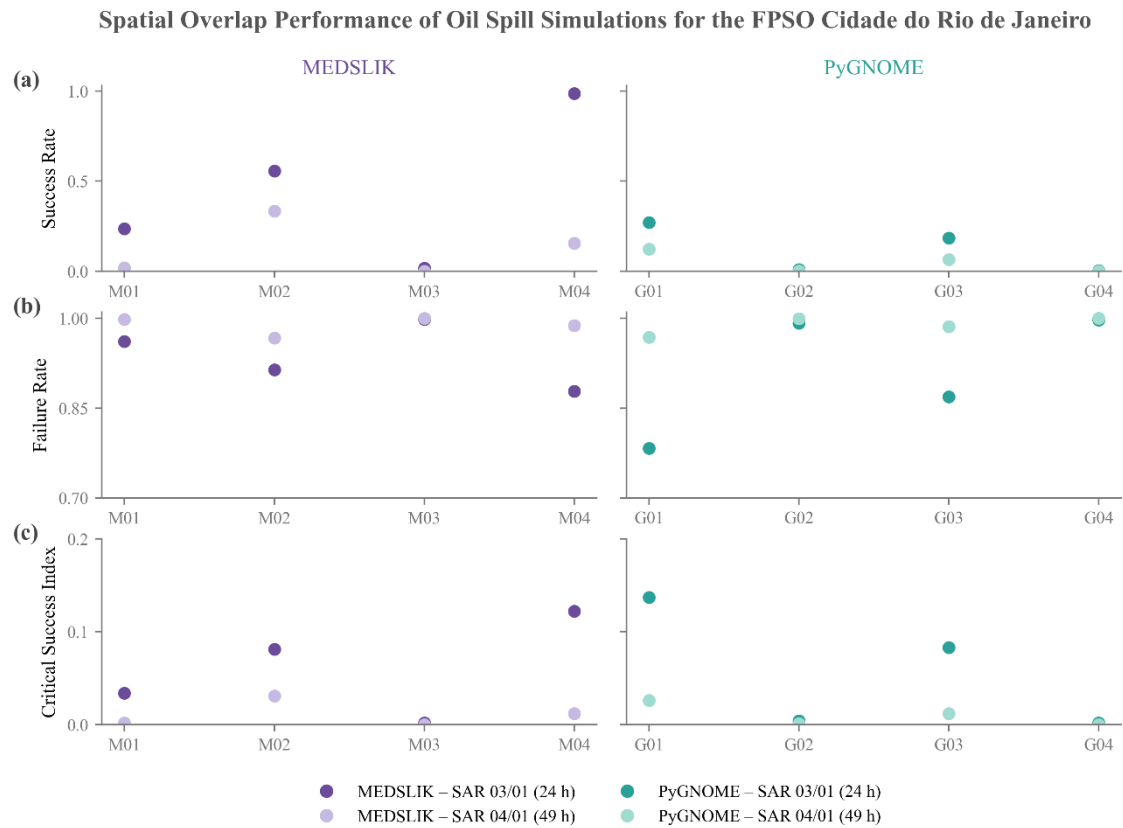


Figure V(II)8. Spatial overlap performance of oil spill simulations for the FPSO Cidade do Rio de Janeiro event. Panels (a), (b), and (c) show the Success Rate, Failure Rate, and Critical Success Index (CSI), respectively, for the MEDSLIK and PYGNOME models. The metrics are based on comparisons between simulated slicks and observed oil extents detected by SAR on March 3rd (24 h) and April 4th (49 h), 2019.

The P-58 spill resulted in seven different monitoring products and the comparison was extended based on the centroids of the slicks for each monitored time. Therefore, Figure V(II)9 shows the performance of both models for the seven studied slicks.

Scenarios M05 and M06 presented the most discrepant responses in terms of distance traveled when compared to the real case, which occurred due to the lower drift factor. The value of 6% was more representative in terms of

temporal periods, as demonstrated by cases M07 and M08.

Regarding the PyGNOME simulations, a very similar behavior can be observed, in which G05 and G06 were considered the poorest results due to the lower drift factor. Therefore, the smallest differences in centroid distances were observed, respectively, for scenarios G08 and G07. Among these, G08 presented the lowest overall mean of these distances, followed by scenario M08.

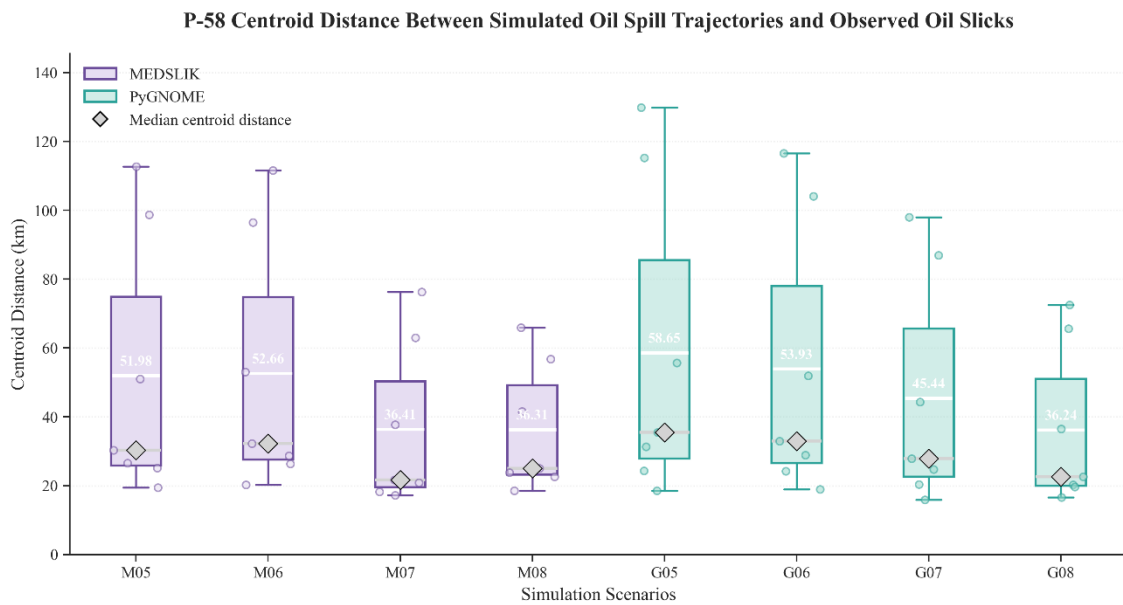


Figure V(II)9. Comparison of centroid distances between simulated oil spill trajectories and observed oil slicks for the P-58 event. Boxplots summarize the distribution of centroid-to-centroid distances (km) calculated between numerical simulations performed with the MEDSLIK and PyGNOME models and remote sensing oil slick observations for each simulation scenario. The diamond symbols indicate the median centroid distance for each case. This metric was adopted due to the non-persistent and non-stationary behavior of the oil slick, as monitoring data indicate a displacement exceeding 200 km during the event, precluding reliable spatial overlap analyses.

3.4. Responses of the models considering the sensitivity of the affected coastline

Beyond the visualization of the centroids of each simulated trajectory for the FPSO Fluminense, as shown in Figure V(II)7, a new representation was produced considering every oil particle that reached the coastline. For this purpose, the simulations that best approximated the affected cities were selected.

For the MEDSLIK model, M11 was the simulation that most closely matched the field observations; therefore, it is presented in figure Figure V(II)10a. For PyGNOME (Figure Figure V(II)10b), the best response was obtained from simulation G12 operating in uncertain mode. Additionally, Figure V(II)10 presents the Coastal Sensitivity Index (LSI) of the affected environments, as well as the thematic layers of the region and the main local biological resources. For the assessment of the affected biological resources, the species are listed in Table V(II)4.

MEDSLIK indicates that the affected locations are mostly within the municipality of Cabo Frio, followed by the municipalities of Armação de Búzios and Arraial do Cabo. According to PyGNOME, shoreline oiling would be predominantly concentrated in the municipality of Armação de Búzios, while a small portion would also affect an island belonging to the municipality of Cabo Frio.

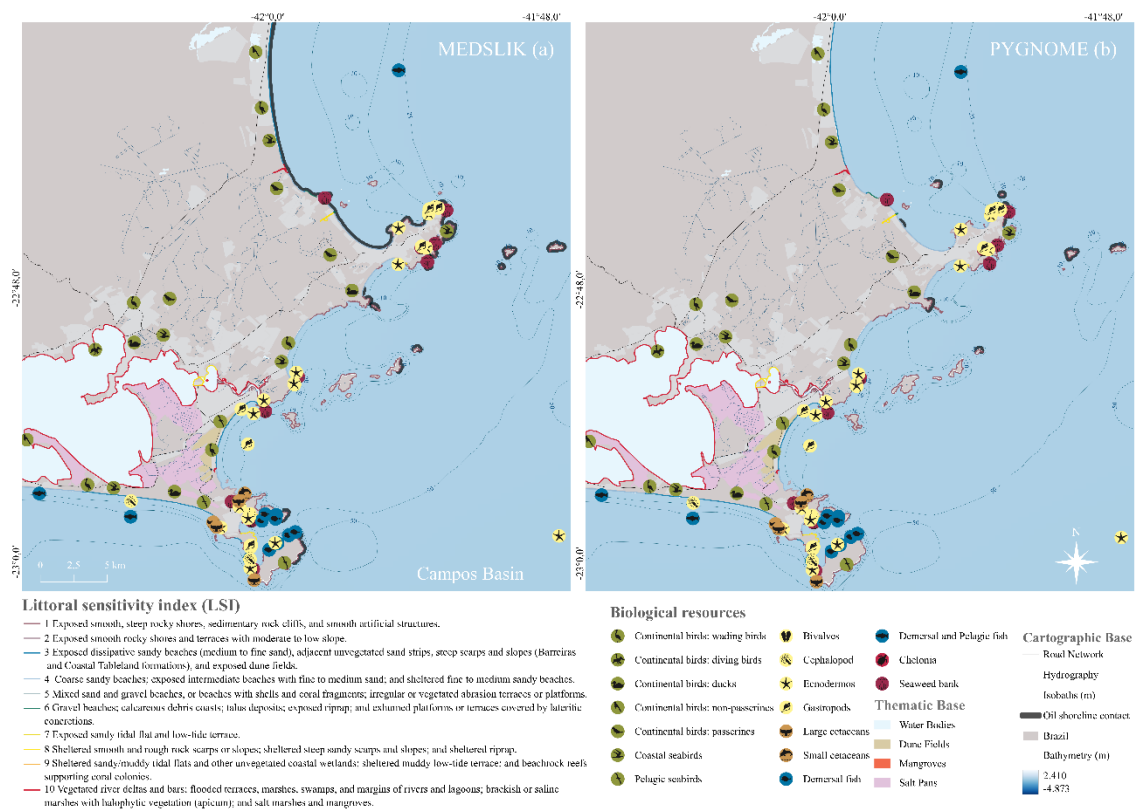


Figure V(II)10. Coastal environmental sensitivity map for the Campos Basin, southeastern Brazil, based on the Brazilian Environmental Sensitivity Index to Oil Spills (SAO). Panels show oil shoreline contact locations derived from trajectory simulations using (a) MEDSLIK and (b) PyGNOME oil models. Black line segments indicate coastal stretches where simulated oil slicks reached the shoreline. The map integrates the Index of Shoreline Sensitivity (LSI) classification, represented by color-coded coastal segments ranging from ISL 1 (lowest sensitivity) to LSI 10 (highest sensitivity), according to shoreline geomorphology, substrate type, exposure to wave energy, and ecological vulnerability. Biological resources mapped along the coast include coastal and pelagic seabirds, continental and marine birds, fish, crustaceans, cephalopods, echinoderms, large and small cetaceans, sea turtles, and seaweed banks, compiled from SAO biological sensitivity datasets. The thematic base comprises urban areas, water bodies, dune systems, mangrove areas, and salt pans, while the cartographic base includes the road and railway networks, hydrography, and bathymetric isobaths (m). This integrated

representation supports the comparative assessment of oil spill shoreline impacts and environmental sensitivity under different numerical modeling approaches in the Campos Basin.

The LSI values most affected according to MEDSLIK, in order, were 3, 4, 1, 6, and 10. These environments receive such indices due to the characteristics of the region. The LSI 10 value, which is the most critical, corresponds to a fluvial discharge area with vegetation and delta formation located in Armação de Búzios. For LSI 6, the affected areas were in Cabo Frio and are characterized by gravel beaches, talus deposits, and riprap structures, as observed at Manguinhos Beach.

PyGNOME, in turn, affected LSI classes at Manguinhos Beach and Ponta das Emergências, with values of 1 and 4, which correspond to environments characterized by smooth rocky shores with high slopes and high exposure, as well as exposed intermediate beaches composed of fine to medium sand.

Table V(II)4

Integration of Oil Spill Simulations and Environmental Sensitivity Maps for Biological Resource Identification

Group	Biological resources	Species
Aquatic Algae and Plants	Seaweed bank	<i>Dictyopteris</i>
		<i>delicatula</i>
		<i>Dictyopteris</i>
		<i>plagiogramma</i>
		<i>Dictyota menstrualis</i>

Invertebrates	Bivalves	<i>Euvola ziczac</i>
		<i>Lytechinus</i>
		<i>variegatus</i>
	Ecnoderms	<i>Astropecten</i>
		<i>brasiliensis</i>
		<i>Coscinasterias</i>
		<i>tenuispina</i>
	Cephalopods	<i>Doryteuthis</i>
		<i>sanpaulensis</i>
	Gastropods	<i>Anachis isabellei</i>
Fishes		<i>Bostrycapulus odites</i>
		<i>Hydrolagus</i>
		<i>matallanasi</i>
	Demersal	<i>Chaetodon striatus</i>
		<i>Abudefduf saxatilis</i>
		<i>Scarus zelindae</i>
Reptiles		<i>Micropogonias</i>
	Demersal/Pelagic	<i>furnieri</i>
		<i>Cynoscion guatucupa</i>
	Chelonia	<i>Dermochelys</i>
		<i>coriácea</i>
Mammals		<i>Grampus griséus</i>
		<i>Lagenodelphis hosei</i>
	Small cetaceans	<i>Peponocephala</i>
		<i>Electra</i>
		<i>Stenella longirostris</i>

Birds	Large cetaceans	<i>Eubalaena australis</i>
		<i>Megaptera</i>
		<i>novaeangliae</i>
	Wading birds	<i>Mysticeti flower</i>
		<i>Ciconia maguari</i>
	Diving birds	<i>Anhinga anhinga</i>
	Ducks	<i>Cairina moschata</i>
		<i>Dendrocygna bicolor</i>
	Passerines	<i>Formicivora</i>
		<i>littoralis</i>
		<i>Mimus gilvus</i>
		<i>Sporophila collaris</i>
		<i>Amadonastur</i>
		<i>lacernulatus</i>
	Non-passerines	<i>Amazona</i>
		<i>rhodocorytha</i>
		<i>Touit melanonotus</i>
	Coastal	<i>Sterna hirundinacea</i>
		<i>Thalasseus maximus</i>
	Pelagic	<i>Procellaria</i>
		<i>aequinotialis</i>
		<i>Thalassarche</i>
		<i>chlororhynchos</i>

The results indicate that the oil trajectories intersect areas containing a wide diversity of biological resources. For the MEDSLIK model, continental birds

and coastal seabirds have the potential to be affected in the Búzios region, as well as the group of crustaceans, gastropods, and echinoderms in the Cabo Frio region. The seaweed bank group and demersal fish may also be affected in Arraial do Cabo. Finally, PyGNOME indicates a potential impact on resources related to crustaceans, coastal seabirds, and seaweed banks located in Cabo Frio. In addition, regarding thematic areas such as dune fields, water bodies, salt pans, and mangroves, none were directly affected by the simulations.

4. Discussion

The main results of this study indicate that, in the event associated with P-53 in 2019, multiple offshore platforms may have contributed to the oil presence along the coastline of the Lakes Region. This evidence was consistent across both models, considering a scenario with an initial spill at the FPSO Fluminense. MEDSLIK exhibited greater skill in representing coastal impacts, whereas PyGNOME demonstrated superior performance in simulating offshore trajectories. The results reinforce the importance of integrating data from official incident reports for model calibration, as well as the combined application of remote sensing and numerical modeling, while acknowledging the inherent limitations of these approaches [Yan et al. 2015; Yekeen and Balogun 2020; De Souza Júnior et al. 2024]. Beyond the inter-model relationships, meteorological and oceanographic conditions acted as a key factor in differentiating spills with critical coastal impacts.

The predominance of northeasterly winds during the FPSO Cidade do Rio de Janeiro and P-58 spill periods presented the lowest risks to the coastal environment. In contrast, southwesterly winds, associated with the passage of

transient systems such as cold fronts and cyclones [Dereczynski & Menezes, 2015], may have been the primary drivers of oil reaching the shoreline in the FPSO Fluminense and P-53 cases. In particular, the occurrence of the tropical cyclone Iba during the spill period may have contributed to the intensification and shift of the wind field, favoring conditions that enhanced the transport of oil toward the coastal region [Reboita et al. 2021].

The effects of winds on oil dispersion are widely discussed in the literature. Shen et al. [2019] highlight wind attenuation in Ekman drift due to the presence of oil at the surface. In the present study, the Ekman drift deflection angle associated with transport showed variations between models. Additionally, in PyGNOME, the Ekman effect correction module proved ineffective, consistent with findings reported by Balogun et al. [2018], as an alternative, wind preprocessing was performed prior to simulations, whereas no such adjustment was required for MEDSLIK.

Wind drift factor corrections in both models varied between events, consistent with findings of Samuel et al. [1982]. This difference is likely attributable to how each model scales wind inputs or estimates wave influence on current velocities [Hackett et al. 2006; Yang et al. 2021]. Thus, model sensitivity assessment to parameterization becomes a critical factor.

The study by Carvalho et al. [2025] categorically enumerates MEDSLIK's sensitivity to wind corrections for the P-53 case and corroborates the present findings regarding coastal oil arrival, differing only in affected coastal locations. Subsequently, Correia Lima et al. [2025] incorporates fractional wind reduction parameterizations and demonstrates reasonable results in coastal environments,

consistent with the present results, as optimal responses were obtained without this correction for coastal oil contact incidents.

However, more satisfactory results for offshore spills were achieved with this parameter. This can be explained by coastal processes exerting dominant influence over wind action nearshore [Chao et al. 2001; Wu et al. 2018], underscoring the importance of temporal variability in input data combined with deterministic and probabilistic oil spill modeling.

PyGNOME in deterministic mode failed to correctly identify impacted coastal locations; however, its uncertainty mode succeeded, consistent with Cheng et al. [2011] for coastal environments. The latter emphasizes the critical role of surface currents in oil trajectories, aligning with differences observed in offshore trajectories predominantly governed by winds and currents [Zheng 2011; Cheng et al. 2014; Nukapothula et al. 2025]. Another aspect explaining model response variations may relate to their fundamental applicability.

PyGNOME was designed for rapid response, whereas MEDSLIK addresses greater coastal process complexities, such as Stokes drift parameterization and vertical turbulent mixing [Keramea et al. 2021; De Dominics et al. 2016]. Weathering processes absent in MEDSLIK but present in PyGNOME, such as oil dissolution and biodegradation, may account for improved offshore performance in cases like FPSO Cidade do Rio de Janeiro and P-58 [Varona et al. 2023], as they capture slick behavior linked to compositional degradation.

The FPSO Cidade do Rio de Janeiro and FPSO Fluminense exhibited persistent and stationary slicks. This slick type facilitates leak source

visualization. Conversely, SAR products were unsuitable for validation, as slicks remained near platforms. This resulted in only slight slick deflection toward the coast from spill initiation to detection. Therefore, for the P-58 case with heavier oil, oil trajectory identification was more clearly defined.

These results demonstrate implications of combining SAR imagery as validation data with oil modeling. One challenge relates to temporal variability potentially expressing unusual slick behavior [Solberg, 2007], compounded by limited availability of free data, posing greater challenges. Furthermore, temporal variability of surface current data is essential for improving model responses [Vasconcelos et al., 2025].

In summary, this study successfully compared two oil dispersion models for Campos Basin spills, highlighting their optimal applicability contexts. Performance was shown to be conditioned by each spill's meteorological-oceanographic characteristics and wind treatment within models. For offshore spills dominated by northeasterly winds, PyGNOME yielded superior responses, whereas MEDSLIK excelled in coastal regions. These findings strengthen the proposition that both models provide fully applicable solutions for supporting contingency planning and decision-making in surface oil spill forecasting.

5. Conclusion

In this study, it was observed that the best model performances were not always associated with the same wind parameterizations, indicating that each spill event requires individual calibration to achieve accurate results. Nevertheless, both models proved capable of adequately representing the main dispersion patterns observed in the three cases analyzed in the Campos Basin, highlighting

the differences in the response between fully offshore spills and those occurring closer to the coast. Although it remains a challenge to obtain comprehensive validation data from oil spills beyond a single metocean condition, comparative analyses across different scenarios are essential. Therefore, developing a more consistent and logical methodological framework is indispensable and could become feasible in the future, which in turn would represent a significant advance for oil spill modeling in the Campos Basin.

Future studies should focus on refining parameterization schemes and incorporating, in real time, the specific properties of the oil handled at each production platform to improve predictive accuracy under varying oceanographic conditions. It is also important to acknowledge that beyond the inherent limitations of satellite and aerial monitoring, which may not adequately capture surface dispersion, oil density and physicochemical behavior can promote subsurface transport, particularly through emulsification processes. Overall, the results presented here contribute to a better understanding of oil dispersion dynamics in the Campos Basin, attributed to different production field characteristics, and provide support for future improvements in operational modeling and environmental response strategies.

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Capítulo V: Síntese da Discussão e Conclusões

Os principais resultados deste estudo indicam que, no evento associado à P-53 em 2019, múltiplas plataformas offshore podem ter contribuído para a ocorrência de óleo na linha de costa da Região dos Lagos. Essa evidência foi consistente em ambos os modelos, considerando um cenário com derrame inicial na FPSO Fluminense. O MEDSLIK apresentou maior habilidade na representação de impactos costeiros, enquanto o PyGNOME demonstrou melhor desempenho na simulação de trajetórias em ambiente offshore. Os resultados reforçam a importância da integração de dados provenientes de relatórios oficiais de incidentes para a calibração dos modelos, bem como da aplicação conjunta de sensoriamento remoto e modelagem numérica,

reconhecendo-se as limitações inerentes a essas abordagens [Yan et al. 2015; Yekeen & Balogun 2020; de Souza Júnior et al. 2023].

A FPSO Cidade do Rio de Janeiro e a FPSO Fluminense apresentaram manchas persistentes e estacionárias. Esse tipo de mancha viabiliza a visualização da origem do vazamento. Em contrapartida, os produtos SAR não serviram como dados validatórios, pois a mancha permaneceu próxima à plataforma. Isso fez com que, desde o período inicial do derrame até o momento do registro, fosse observada apenas uma ligeira deflexão da mancha em direção ao litoral.

Esses resultados demonstram as implicações na combinação das imagens SAR como dados validatórios e modelagem de óleo. Uma das adversidades recorre à variabilidade temporal que pode expressar um comportamento inusitado da mancha [Solberg 2007], e como há uma escassez de dados disponíveis gratuitamente se torna um desafio maior. Ademais a variabilidade temporal dos dados de correntes superficiais é essencial para a melhora nas respostas dos modelos [Vasconcelos et al. 2025].

Em suma, o presente estudo teve o potencial de comparar dois modelos de dispersão de óleo para derrames na Bacia de Campos, exprimindo suas melhores aplicabilidades. Destacou-se que um bom desempenho está condicionado as características meteo-oceanográficas de cada derrame, além de como os ventos são tratados dentro dos modelos. Em derrames mais offshore e com a predominância de ventos nordeste as melhores respostas foram provenientes do PyGNOME, enquanto, em regiões costeiras, o MEDSLIK demonstrou um melhor desempenho. Esses dados fortalecem a ideia de que

para o uso de previsões de derrames de óleo superficiais ambos os modelos oferecem respostas totalmente aplicáveis ao suporte de planos de contingenciamento e tomada de decisões.

No contexto de sensibilidade ambiental ao derramamento de óleo, o estudo contribui para o primeiro levantamento dos recursos biológicos feito para o incidente da P-53. O que abre perspectivas para futuros estudos correlacionando a mudança das populações de cada espécie ao longo do litoral de Armação de Búzios, Cabo Frio e Arraial do Cabo, que de certa forma sofreu o impacto pela poluição causada. Outro viés deste trabalho, que não tinha sido delimitado como um dos seus objetivos, foi a elaboração de uma metodologia comparativa entre respostas de modelos com dados de monitoramento remoto.

Capítulo VI: Referências Bibliográficas da Dissertação

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