The Oil Spill Models

Subjects: Engineering, Environmental

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Oil spills may have devastating effects on marine ecosystems, public health, the economy, and coastal communities. To predict in near real time oil spill transport and fate with increased reliability, these models are usually coupled operationally to synoptic meteorological, hydrodynamic, and wave models.

oil spill modeling | meteorological and hydrodynamic forcing | wave models | met-ocean data | forecasting | biogeochemical models

1. Introduction

When crude oil is accidentally released in the marine environment, an oil slick is formed appearing as a thin oily layer, floating on the sea surface [1]. The slick is shaped by the slow, low-scale, and diffusive processes, responsible for changing the contaminants' concentration, and is transported by the large-scale advective processes, advancing the center of the oil-slick mass to the direction of background currents, winds, and waves [2]. This implies that the ambient environment of the spill significantly determines its movement and fate. The amount of oil spilled in the ocean, the oil's initial physicochemical properties, the prevailing weather and sea state conditions, and other spill-specific and environmental factors affect the timing, duration, and relative importance of each physical and biochemical oil-weathering process (known as OWP), affecting the slick [3][4][5]. Since hydrocarbons are nonconservative pollutants, OWPs cause longterm changes in their physicochemical properties, such as oil density and viscosity [6]. The most important OWPs are spreading, evaporation, dispersion/diffusion, emulsification, and dissolution. Photooxidation, biodegradation, and sedimentation act over longer time periods and determine oil's ultimate behavior [7].

Planning for and responding to an oil spill requires rigorous comprehension of baseline environmental characteristics and processes [8]. Oil-spill models help the response agencies lessen the damaging impacts on the environment by predicting the path of at-sea oil spills. Predicting the spillage trajectory is the main outcome of oil-spill models, highlighting the potential for ecosystem harm as an incident develops, while, in parallel, assisting in the optimization of the cleanup efforts [9][10][11]. Any guidance that oil-spill modeling may offer could be extremely important for the authorities, given the tremendous effect and costs associated with oil spills. Risk evaluation, readiness planning and analysis of the environmental effects of the oil industry infrastructure, heavily rely on oil spill modeling [12]. When models are run, a wide range of input variables and actual met-ocean conditions might result in multiple alternative trajectories [13]. Following analysis, these trajectories are plotted on maps to create reaction strategies. Emergency responders must be knowledgeable about the type of oil, the location, and the marine and coastal habitats the spillage may affect. Thus, governments, oil exploration and production firms, insurance companies, and other stakeholders may evaluate whether the adequate resources, tools, and procedures are in place to respond to oil spill incidents. Simulating different scenarios may allow for assessing the potential environmental impacts and device plans on the movement of the response supplies to the necessary locations [14][15]. This procedure could lead to the assessment of the efficacy of various response strategies, as well as their benefits and drawbacks [10][12]. Additionally, it is expected to aid responders to organize and mobilize socioeconomic resources to limit environmental impacts along the oil's potential course [8].

As explained above, met-ocean conditions, i.e., currents, wind, and waves, represent the fundamental components influencing the spreading of oil in the marine environment [7][16][17][18]. For this reason, it is crucial to be able to illustrate that oil-spill forecasts are accurate and reliable, as well as that the constraints of a model are well-understood when evaluating the model's predicting capacity and performance [19][20]. An assessment of the ocean currents, water characteristics over the water column, and waves at a particular time and location is provided by the three-dimensional ocean-circulation models [21]. These models aid in determining how these factors will affect the transport of oil once it reaches the sea surface. Meteorological and atmospheric models provide information on air properties such as temperature, relative humidity, and barometric pressure, as well as on the surface winds that might transport and affect the evaporation rate of floating oil [22]. In parallel, wave models provide information about the significant wave height and Stokes drift fields, affecting wave turbulence, vertical mixing, and oil dispersion within the water column [23]. Furthermore, once the oil is discharged into the marine environment, the chemical and physical changes it will undergo could be predicted by the fate models [17][24].

2. Seven State-of-the-Art Oil-Spill Models

Seven state-of-the-art oil-spill models, namely: OpenOil [23][25], MEDSLIK [18][26][27], MEDSLIK-II [28][29], SIMAP [30][31], GNOME [32][33][34], BLOSOM [35][36][37], and STFM [38][39] are examined in terms of their meteorological, hydrodynamic, wave, and biogeochemical forcing in twenty-three oil accidental release cases studied worldwide. An analytical description and comparison of these oil-spill models in terms of their characteristics, capabilities, and simulated processes is presented in the comprehensive review of Keramea et al. [7].

OpenOil is a newly-developed, open-source oil-spill transport and fate model [40], part of the Python-based trajectory framework of OpenDrift [25]. To reach operational oil-spill forecasts with OpenOil, MET Norway employs in-house, high-resolution ocean-circulation, and meteorologic models [23]. However, the model allows the coupling with the coarser resolution forecasts from CMEMS (Copernicus Marine Environmental Service), FVCOM, SHYFEM, CYCOFOS, HYCOM, Norshelf for hydrodynamics and ocean state, and NOAA, ECMWF, and SKIRON wind fields with netCDF and many different files format. The OpenOil has been applied in several cases worldwide, such as the Norwegian Sea [23], the Gulf of Mexico and the Cuban coast [41][42][43][44], the Thracian Sea [45], and the Caribbean Sea [46].

MEDSLIK-II [28][29] is a version of the MEDSLIK oil-spill model [18][26]. MEDSLIK-II uses the experimental JONSWAP wave spectrum in terms of wind speed and fetch for the Stokes drift parameterization [47], while

MEDSLIK directly uses the wave height and period to estimate the Stokes drift. MEDSLIK-II is also coupled in terms of input format with the forecasted atmospheric fields provided by the European Center for Medium-Range Weather Forecasts (ECMWF) and the oceanographic fields provided by CMEMS (currents, temperature, salinity, and density), while MEDSLIK is coupled in addition to the CMEMS with the downscaled CYCOFOS sea currents and the SKIRON winds. MEDSLIK-II has been implemented in many case studies in recent years, such as the Northern Atlantic [48], the Northwestern Mediterranean Sea [49], the Aegean Sea [50], the offshore of Southern Italy [51], and the Brazilian coast [52]. In addition, MEDSLIK has been implemented in real oil spill incidents in the Eastern Mediterranean Levantine basin [53] and in numerous test cases in the Levantine basin [54][55][56][57], in the Black Sea [58], and in the Red Sea [59].

SIMAP, the integrated oil-spill impact oil system, developed by ASA [30][31] simulates the three-dimensional trajectory, fate, and transport of spilled oil and fuels, as well as the biological effects and other impacts [30]. SIMAP has been validated against data from over 20 major spills, including the Exxon Valdez [30]. The analytical description of the SIMAP oil trajectory and fate model is presented in McCay [30][60]. Wind-driven wave drift (i.e., Stokes drift) and Ekman transport at the surface can be modeled, based on the results of Stokes drift and the Ekman transport formula produced by Youssef and Spaulding [61]. Moreover, the model has the capability to couple with three-dimensional hydrodynamic models (HYCOM (3–4 km), POM (10 km), and SABGOM (5 km)) and with wind data from NOAA and ECMWF [62]. Currently, SIMAP has been implemented in the Gulf of Mexico [60][62].

GNOME, the general NOAA operational modeling environment, is an oil spill model that forecasts the fate and transport of pollutants, as well as the movement of oil due to winds, currents, tides, and spreading [32][33]. Furthermore, this model is highly configurable and tunable to field conditions and it can be driven by a variety of data: measured point data, meteorologic, and hydrodynamic models with a variety of meshes (structured and triangular) (NOAA, ECMWF, CMEMS, POM, CROCO, RTOFS, GLB-HYCOM, FVCOM, and Salish Sea model). Since GNOME can integrate any ocean-circulation and meteorologic model that supports forecasts in various file formats, as well as observational data, NOAA has created the GNOME Operational Oceanographic Data Server (https://gnome.orr.noaa.gov/goods, accessed on 10 April 2023), a publicly accessible system that provides access to all available driver models and data sources. Moreover, GNOME has been applied in many regions over the latest years, such as Indonesia [63], the Gulf of Suez in Egypt [64], offshore Odisha in India [65], and the Red Sea in Egypt [66].

BLOSOM, the blowout and spill occurrence model has been generated by the National Energy Technology Laboratory (NETL) of the USA (https://edx.netl.doe.gov/offshore/blosom/, accessed on 10 April 2023) [35][37][67]. The model may be coupled to wind and current data from different models (Salish Sea model, FVCOM, NOAA, and NCOM AMSEAS) with multiple flexible file formats and output types. Finally, it incorporates a number of oil types from the ADIOS oil library [68]. Recent, the BLOSOM has been applied in the Gulf of Paria in Venezuela [69].

Finally, the STFM (Spill, Transport, and Fate Model), created by the Institute of Astronomy, Geophysics and Atmospheric Sciences, University of Sao Paulo (IAG/USP) of Brazil, is a transport and weathering model of spilled oil based on Lagrangian elements for operation in marine and environmental fields [38][39]. Moreover, STFM is a fully three-dimensional model that uses the Weather Research and Forecasting (WRF) atmospheric model and the hydrodynamic Hybrid Coordinate Ocean Model (HYCOM), feeding the oil-spill module with current speed and direction, water temperature, salinity and bathymetry data. In addition, it has the capability to couple with the ADIOS oil database. It has been recently applied on the Brazilian coast by Zacharias et al. [39].

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