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| TEMPS CLIMAT EAU | **Organisation météorologique mondiale**  **COMMISSION DES SERVICES ET APPLICATIONS MÉTÉOROLOGIQUES, CLIMATOLOGIQUES, HYDROLOGIQUES, MARITIMES ET ENVIRONNEMENTAUX**  **Troisième session** Bali, Indonésie, 4-9 mars 2024 | **SERCOM-3/Doc. 4.7(1)** |
| Présenté par: Président du SC-MMO  19.XII.2023  **VERSION 1** |

**POINT 4 DE L’ORDRE DU JOUR:** **RÈGLEMENT TECHNIQUE ET AUTRES QUESTIONS TECHNIQUES**

**POINT 4.7 DE L’ORDRE DU JOUR:** **Services de météorologie maritime et d’océanographie**

**PROJET DE GUIDE SUR LES INTERVENTIONS  
EN CAS D’URGENCE MARITIME**

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| --- |
| **RÉSUMÉ** |
| **Document présenté par:** Le Président du Comité permanent des services de météorologie marine et d’océanographie (SC-MMO)  **Objectif stratégique 2020-2023:**  Objectif 1.1 – Étoffer les systèmes nationaux d’alerte précoce multidangers et étendre la couverture afin de mieux contrer les risques  Objectif 1.4 – Accroître la valeur des informations et services météorologiques d’aide à la décision et innover dans la fourniture de ces informations et services  Objectif 4.1 – Répondre aux besoins des pays en développement afin qu’ils puissent fournir et utiliser les services essentiels concernant le temps, le climat et l’eau et les domaines environnementaux connexes  **Incidences financières et administratives:** Publication dans les langues des Nations Unies pertinentes  **Principaux responsables de la mise en œuvre:** SERCOM, en collaboration avec les Membres de l’OMM qui bénéficieraient grandement d’une assistance technique et d’un soutien accrus dans leur rôle d’appui aux interventions en cas d’urgence maritime,  **Calendrier:** publication en 2024  **Mesure attendue:** Adoption de la résolution proposée par la Commission des services et applications météorologiques, climatologiques, hydrologiques, maritimes et environnementaux (SERCOM) |

# CONSIDÉRATIONS GÉNÉRALES

### Introduction

1. Conformément à la [décision 10 (SERCOM-2)](https://library.wmo.int/idviewer/66332/102) – Élaboration d’orientations sur les interventions en cas d’urgence maritime, le présent document contient une proposition de Guide sur les interventions en cas d’urgence maritime, dont l’objectif est d’aider les météorologues à mieux comprendre les facteurs qui peuvent influencer ce type d’intervention. Ce guide explique en outre comment les Services météorologiques et hydrologiques nationaux (SMHN) peuvent être amenés à apporter leur aide dans le cadre des interventions en cas d’éco-urgence maritime et des opérations de recherche et de sauvetage.

2. Dans de nombreux pays, il incombe aux SMHN d’appuyer les interventions en cas d’urgence maritime à l’aide d’informations météorologiques et océanographiques. Les incidents maritimes (marées noires, libération de radionucléides et objets à la dérive) constituent des menaces majeures pour la santé des océans et la protection du milieu marin. En outre, les opérations de recherche et de sauvetage nécessitent un soutien météorologique et océanographique précis et rapide pour sauver des vies. C’est dans cette optique que le guide proposé décrit les processus physiques et les conditions météorologiques et océanographiques qui influent sur ces opérations, ainsi que les éléments de détection, de surveillance et de modélisation qui contribuent à l’efficacité des interventions en cas d’urgence maritime.

### Mesure attendue

3. Compte tenu de ce qui précède, la Commission des services et applications météorologiques, climatologiques, hydrologiques, maritimes et environnementaux peut décider d’adopter une résolution libellée comme suit.

# PROJET DE RÉSOLUTION

## Projet de résolution 4.7(1)/1 (SERCOM-3)

**Proposition de Guide sur les interventions en cas d’urgence maritime**

LA COMMISSION DES SERVICES ET APPLICATIONS MÉTÉOROLOGIQUES, CLIMATOLOGIQUES, HYDROLOGIQUES, MARITIMES ET ENVIRONNEMENTAUX

**Rappelant:**

1. La [résolution 4 (EC-72)](https://library.wmo.int/idviewer/55339/17) – Renforcement des services de météorologie maritime,
2. La [résolution 42 (Cg-19)](https://library.wmo.int/idviewer/68194/553) – Commissions techniques et organes additionnels de l’OMM pour la dix-neuvième période financière, selon laquelle le mandat révisé de la Commission des services et applications météorologiques, climatologiques, hydrologiques, maritimes et environnementaux (SERCOM) entre en vigueur immédiatement, l’examen et la révision continus des règlements techniques de l’OMM devant être effectués par les commissions techniques compétentes,
3. La [résolution 29 (Cg-18)](https://library.wmo.int/idviewer/55219/120) – Renforcement des services météorologiques destinés aux activités maritimes et côtières,
4. La Convention internationale de 1973 pour la prévention de la pollution par les navires (MARPOL), dans sa version modifiée par les protocoles et amendements ultérieurs,
5. La Convention des Nations Unies de 1978 sur le transport de marchandises par mer (Règles de Hambourg), dans sa version modifiée par les protocoles et amendements ultérieurs,
6. La Convention internationale de 1974 pour la sauvegarde de la vie humaine en mer (SOLAS), dans sa version modifiée par les protocoles et amendements ultérieurs,
7. La Convention sur l’assistance en cas d’accident nucléaire ou de situation d’urgence radiologique,

**Ayant examiné** la [décision 10 (SERCOM-2)](https://library.wmo.int/idviewer/66332/102) – Élaboration d’orientations sur les interventions en cas d’urgence maritime,

**Ayant approuvé** la [décision 10 (SERCOM-2)](https://library.wmo.int/idviewer/66332/102) – Élaboration d’orientations sur les interventions en cas d’urgence maritime**,**

**Reconnaissant:**

1. Que les SMHN ont un rôle important à jouer dans la préservation de la santé des océans et la protection du milieu marin,
2. Que l’OMM œuvre depuis longtemps, en coordination avec l’Organisation maritime internationale (OMI), à la mise en place et à l’exploitation d’un système mondial coordonné de fourniture d’informations météorologiques et océanographiques à l’appui des interventions d’urgence en cas de pollution maritime et des opérations de recherche et de sauvetage,

**Ayant noté** que de nombreux SMHN bénéficieraient grandement de directives techniques plus élaborées pour les aider dans leur rôle d’appui aux interventions en cas d’urgence maritime,

**Tenant compte:**

1. Des travaux approfondis réalisés par le Comité permanent des services de météorologie marine et d’océanographie (SC-MMO) et des experts invités pour élaborer la présente proposition de guide,
2. De l’examen indépendant qui a été mené méthodiquement par des pairs conformément aux règles de publication de l’OMM, ainsi que des commentaires des examinateurs qui ont été incorporés dans le guide proposé,

**Demande** l’approbation et la publication du [projet de guide](#_Annex_to_draft) en conséquence.

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[Annexe: 1](#_Annex_to_draft)

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## Annex to draft Resolution 4.7(1)/1 (SERCOM-3)

## GUIDE TO MARINE EMERGENCY RESPONSE

(Draft)

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The overall responsibility for the final version of the Guide, including the final synthesis and editing, has been undertaken by SC-MMO and notably its member, Øyvind Breivik (Norwegian Meteorological Institute and University of Bergen), who acted as editor together with Alice Soares. The work was supported by the WMO Marine Services Division (Sarah Grimes, Nayeon Kim and Alice Soares). Individual chapters were produced with contributions from one or more of the co-authors listed below (alphabetical order):

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For any queries related to this publication, please contact the WMO ([mmo@wmo.int](mailto:mmo@wmo.int)).

## PREFACE

The purpose of the guide on Marine Emergency Response is to provide a comprehensive introduction to the physical and practical aspects of the metocean-related support to marine emergencies (MER), including marine *environmental* emergencies (MEER) and search and rescue (SAR) response operations.

Marine emergency response operations are hugely important to the safety of humans at sea and for the protection of the marine and coastal environment. These operations are performed, often by volunteers, under stressful conditions and with limited resources. The geophysical forcing, mainly represented by the wind, the waves and the ocean currents, is a continuous source of uncertainty, both because of our limited ability to forecast them, but also in how the target (oil recovery, a missing person, a drifting ship) behaves under such environmental conditions.

Often the uncertainties extend even to the type of incident or even whether an incident has at all occurred, and if, where and when. The search for a missing aircraft based on debris is a case in point. Here, all these uncertainties come to the fore as response agencies try to locate the site of the accident based on debris found later, sometimes much later, as in the tragic case of the MH 370 airline accident in the Indian Ocean in March 2014. A flaperon was found 16 months later on Réunion Island. Based on this, attempts were made to deduce the site of the accident. Not only are there large uncertainties in the currents and waves along the trajectory of the debris, but the drift properties of the object itself must also be investigated before a proper drift calculation can be made.

This Guide is written with the audience of WMO in mind. A typical reader of this document could be a meteorologist specializing in marine forecasting. The activities of National Meteorological and Hydrological Services (NMHSs) can involve giving support to national or international agencies responsible for MEER and SAR operations. It is with this in mind that this Guide describes the physical aspects and the meteorological and oceanographic conditions that affect such operations. The Guide is not meant as an exhaustive instruction manual nor an operational response/contingency plan for conducting MER operations. That is the remit of other agencies. It is meant to give meteorologists an understanding of which factors influence MER operations, and how an NMHS can be expected to assist.

## ACRONYMS

|  |  |
| --- | --- |
| ACTSUS | Active Search Suspended Pending Further Developments (Search and Rescue) |
| AATSR | Advanced Along-Track Scanning Radiometer |
| ADIOS | Automated Data Inquiry for Oil Spills |
| AMOCs | Area Meteorological & Oceanographic Coordinators |
| API | Application Programming Interface |
| ASA | Applied Science Associate |
| ARIANE | Particle Tracking Software |
| AISA | Airborne Imaging Spectrometer for Applications |
| AIS | Automatic Identification System |
| AVIRIS | Airborne Visible/Infrared Imaging Spectrometer |
| AVHRR | Advanced Very High-Resolution Radiometer |
| BLOSOM | Blowout and Spill Occurrence Model |
| CANSARP | Canadian Search and Rescue Planning |
| CASP | Computer Assisted Search Planning |
| CASI | Compact Airborne Spectrographic Imager |
| CDOG | Comprehensive Deepwater Oil and Gas Model |
| CMEMS | Copernicus Marine Environmental Monitoring Service |
| CMM | Commission for Marine Meteorology |
| CNRS | National Centre for Scientific Research (Centre National de la Recherche Scientifique in French) |
| CSN | Clean Sea Net |
| CSA | Canadian Space Agency |
| CSW | Catalogue Services for the Web |
| CTBTO | Comprehensive Nuclear-Test-Ban Treaty Organization |
| CWL | Crossway Leeway Component |
| DCPC | Data Collection or Production Centre |
| DIF | Directory Interchange Format |
| DOI | Digital Object Identifier |
| DWD | Deutscher Wetterdienst |
| DWL | Down-Wind Leeway |
| DSS | Decision Support Systems |
| ECDIS | Electronic Chart Display and Information System |
| EFTA | European Free Trade Association |
| EMSA | European Maritime Safety Agency |
| EPR | Emergency Preparedness and Response |
| EPPR | Emergency Prevention Preparedness and Response |
| EO | Electro-Optical |
| ERA | Emergency Response Activities |
| ET-CER | Expert Team on Coastal and Emergency Response |
| ET-ERA | Expert Team on Emergency Response Activities |
| EU | European Union |
| FAIR | Findable, Accessible, Interoperable, and Reusable |
| FLIR | Forward-Looking Infrared |
| FTP, FTPS | File Transfer Protocol, Secure |
| FOV | Field Of View |
| GCMD | Global Change Master Directory |
| GDPFS | Global Data-Processing and Forecasting System *(renamed WIPPS in June 2023)* |
| GEARN | Atmospheric Dispersion Model developed by the Japan Atomic Energy Agency (JAEA) |
| GMDSS | Global Maritime Distress Safety System |
| GNOME | General NOAA Operational Modelling Environment |
| GOOS | Global Ocean Observing System |
| GPS | Global Positioning System |
| GRIB2 | General Regularly distributed Information in Binary form, Edition 2 |
| HAZMAT | Hazardous Materials |
| HAB | Harmful Algal Blooms |
| HDF, HDF5 | Hierarchical Data Format, version 5 |
| HELCOM | Helsinki Commission |
| HF | High-Frequency |
| HFR | High-Frequency Radar |
| HNS | Hazardous and Noxious Substances |
| HTTPS | Hypertext Transfer Protocol Secure |
| HYCOM | Hybrid Coordinate Ocean Model |
| IAEA | International Atomic Energy Agency |
| IAMSAR | International Aeronautical and Maritime Search and Rescue Manual |
| ICAO | International Civil Aviation Organization |
| IEC | Incident and Emergency Centre |
| IFREMER | French Research Institute for Exploitation of the Sea (Institut Français de Recherche pour l'Exploitation de la Mer) |
| IMO | International Maritime Organization |
| IOC | Intergovernmental Oceanographic Commission |
| IOOS | US Integrated Ocean Observing System |
| IR | Infra-red |
| ISC | International Science Council |
| IWG | Inter-agency Working Group |
| JAEA | Japan Atomic Energy Agency |
| JCB | Joint WMO-IOC Collaborative Board |
| JCG | Japan Coast Guard |
| JCOMM | Joint WMO-IOC Technical Commission for Oceanography and Marine Meteorology |
| JMA | Japan Meteorological Agency |
| JPLAN | Joint Plan |
| JRCC | Joint Rescue Coordination Centre |
| LDC | Lesser Developed Country |
| LKP | Last Known Position |
| LPT | Lost Person Types |
| LRC | Lateral Range Curve |
| LURSOT | Laser-Ultrasonic Remote-Sensing of Oil Thickness |
| MAN | Management Committee of the Joint Technical Commission for Oceanography and Marine Meteorology (JCOMM) |
| MARPOL | International Convention for the Prevention of Pollution from Ships |
| MDC | More Developed Country |
| MEDESS | Mediterranean Decision Support System for Marine Safety |
| MEDSLIK | The Oil Spill Model Code |
| MEER | Marine Environmental Emergency Response |
| MEPC | Marine Environment Protection Committee |
| MER | Marine Emergency Response |
| MERRAC | Marine Environment Emergency Preparedness and Response Regional Activity Centre |
| MERIS | Medium Resolution Imaging Spectrometer |
| MIZ | Marginal Ice Zone |
| ML | Machine Learning |
| MME | Multimodel Ensemble |
| MODIS | Moderate Resolution Imaging Spectroradiometer |
| MODARIA | Modelling and Data for Radiological Impact Assessments |
| MONGOOS | Mediterranean Oceanography Network for Global Ocean Observing System |
| MOVE/ MRI.COM | Multivariate Ocean Variational Estimation system/Meteorological Research Institute Community Ocean Model, which is an ocean circulation model and assimilation system developed by the Meteorological Research Institute (MRI), Japan Meteorological Agency |
| MOSSFA | Marine oil snow sedimentation and flocculent accumulation |
| MPERSS | Marine Pollution Emergency Response Support System |
| MSC | Maritime Safety Committee |
| MSI | Maritime Safety Information |
| MSSD | Mediterranean Strategy for Sustainable Development |
| NCEP | US National Centre of Environmental Prediction |
| NCSR | Navigation, Communication, Search and Rescue |
| NCSS | NetCDF Subset Service |
| NetCDF | Network Common Data Form |
| nm | Nautical miles |
| NMHSs | National Meteorological and Hydrological Services |
| NOWPAP | Northwest Pacific Action Plan from UNEP |
| NWP | Numerical Weather Prediction |
| NVG | Night-Vision Goggles |
| NRT | Near-Real-Time |
| OPeNDAP | Open-source Project for a Network Data Access Protocol |
| OHMSETT | National Oil Spill Response Research & Renewable Energy Test Facility |
| OOSA | Online Oil Spill Advisory |
| OPRC | International Convention on Oil Pollution Preparedness, Response and Cooperation |
| OSERIT | Oil Spill Evaluation and Response Integrated Tool, a software tool developed in Belgium |
| PCBs | Polychlorinated biphenyls |
| PIW | Person-in-the-water |
| RANET | Radioactive Release Environmental Assessment and Networking:  a programme of the International Atomic Energy Agency (IAEA) |
| RBINS | Royal Belgian Institute of Natural Sciences |
| RCS | Radar cross-section |
| RCM | Radarsat Constellation Mission |
| REMPEC | Regional Marine Pollution Emergency Response Centre for the Mediterranean Sea |
| RSMC | Regional Specialized Meteorological Centre |
| RTH | Regional Telecommunication Hub |
| RTOFS | US/NCEP Real-Time Ocean Forecast System |
| SAR | Search and Rescue |
| SAR\* | Synthetic Aperture Radar |
| SAROPS | Search and Rescue Optimal Planning System |
| SaWS | Sargassum Watch System |
| SC-ESMP | Standing Committee for Earth System Monitoring and Predicting |
| SC-MMO | Standing Committee on Marine Meteorology and Oceanographic Services |
| SERCOM | The Commission for Weather, Climate, Hydrological, Marine and Related Environmental Services & Applications  (Services Commission or SERCOM) |
| SeaWiFS | Sea-viewing Wide Field-of-view Sensor |
| SIROCCO | Simulation Réaliste de l’Océan Cotier; ocean circulation model |
| SIMAP | Spill Impact Model Application Package |
| SINTEF OWM | SINTEF Ocean - Marine Operations and Emergency Response |
| SLAR | Side-Looking Airborne Radar |
| SLEAF | Scanning Laser Environmental Airborne Fluorosensor |
| SOLAS | International Convention for the Safety of Life at Sea |
| SRRs | Search & Rescue Regions |
| STW | Seatrack Web |
| SST | Sea Surface Temperature |
| TDS | THREDDS Data Server |
| THREDDS | Thematic Real-time Environmental Distributed Data Services |
| TRACMASS | TRACMASS refers to a Lagrangian particle-tracking software package |
| UNEP | UN Environment Programme |
| UAV | Unmanned Aerial Vehicles |
| UNESCO | United Nations Educational Scientific and Cultural Organization |
| URN | Uniform Resource Name |
| USCG | United States Coast Guard |
| UV | UltraViolet |
| VOC | Volatile Organic Compounds |
| WAFC | World Area Forecast Centre |
| WCS | Web Coverage Service |
| WIPPS | WMO Integrated Processing and Prediction System |
| WIS | WMO Information System |
| WMO | World Meteorological Organization |
| WFS | Web Feature Service |
| WMS | Web Mapping Service |
| WWMIWS | IMO-WMO Worldwide Metocean Information and Warning System |

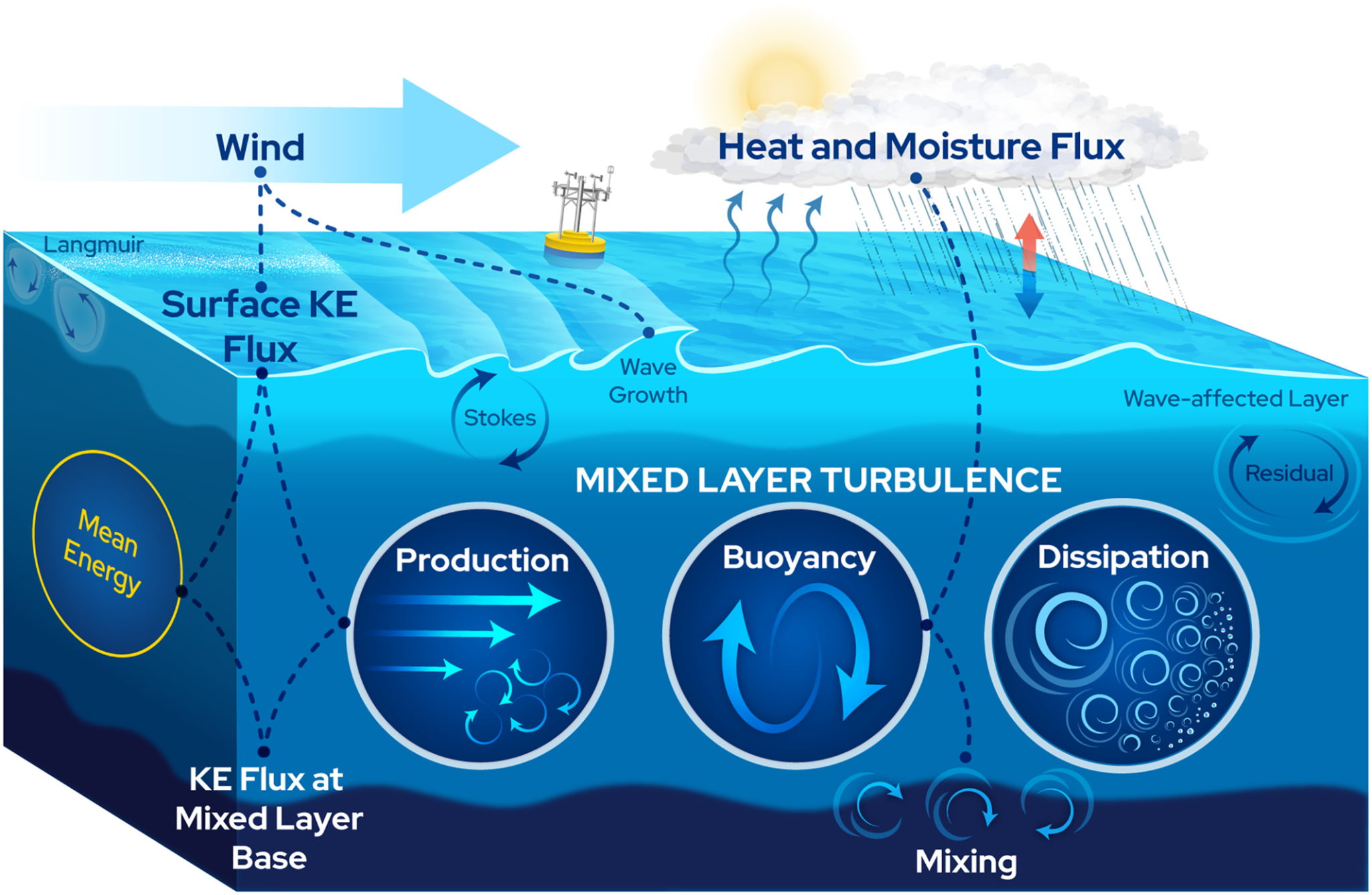
### INTRODUCTION AND GENERAL CONSIDERATIONS

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### 1.1 Overview of the Marine Emergency Response (MER)

Marine emergency response refers to the process of responding to an emergency, related to drifting substances or objects in the water, usually the ocean, in both national and international waters. The emergency response could be for environmental reasons, i.e. Marine Environment Emergency Response (MEER), and is understood as an emergency due to the threat of harm to the marine environment, e.g. an oil spill. The emergency could also relate to drifting objects (e.g. lost shipping containers) or persons, that threaten life and property, e.g. Search and Rescue (SAR) efforts for lost persons and/or vessels at sea. Both have a common variable in that substances, objects, animals or persons “drift” in a fluid environment and there is a time sensitive need to locate and/or monitor the drift, to minimize damage to the environment and/or property and/or loss of life.

The ocean surface is a busy place where a great many different processes decide the fate of a drifting object or a substance (see Figure 1.1). The waves driven by the wind, and the air-sea fluxes of mass, momentum and energy make it difficult to predict where and in what state an object would go. Substances such as oils can get mixed down by breaking waves, and objects can swamp or capsize. The current shear can then spread down-mixed oil beneath the sea surface in a different direction from oil that remains on the sea surface. A search and rescue object such as a liferaft feels the waves and the wind in addition to the surface currents.



**Figure 1.1 - A schematic representation of the multitude of upper-ocean and lower-atmosphere processes that affect the fate of substances and objects at the sea surface or in the mixed layer of the ocean (Zippel et al, 2022).**

Emergency response for marine pollution incidents can vary significantly in scale. Environmental emergencies in the marine waters can ensue when there is a marine pollution incident, which could be instigated through, for example, spills of oil and other noxious substances or radionuclide releases. When this happens, authorities respond to remove and/or minimize the hazard. MEER is an area where multiple legislative or policy frameworks and agencies are involved, either in preventing, preparing, and/or responding to such emergencies. The effectiveness of a response is highly dependent on the preparedness and ability of those involved to undertake specific emergency response and management tasks. At a minimum this requires the designation of roles and responsibilities of the various stakeholders, definition of response strategies and procedures to be followed in case of an incident, in addition to training to provide the necessary knowledge and skills.

Given the nature of ocean dynamics, the response to the environmental emergency often involves modelling and tracking (forward or backwards) the movement of the substance or object on/in water. Forward tracking calculations are conducted to support removal operations, while backtracking (also known as “reverse modelling”, “backtracking” or “reverse”) simulations are also used to identify the origin/source.

The same method of modelling and tracking applies for drifting objects (e.g. lost people, vessels and even containers at sea). Due to this, the response and preparedness for SAR is often using the same predictive and response tools as for MEER. Meteorological, oceanographic and wave observations and forecasts are the forcing data in such drift modelling. Therefore, NMHSs are among the stakeholders in emergency preparedness and response systems. In addition, meteorological data and information is effective in reducing the risk of incidents and emergencies if introduced into environmental emergency prevention programmes. Operational services of the meteorological community are important for the reduction of loss and risks in the mitigation of all kinds of disasters. Also, naturally occurring extreme events are disruptive and could trigger many kinds of incidents which can, in turn, result in spills and releases of hazardous substances to air and water, adding to the burden of emergency response to protect and secure endangered populations and contaminated environments.

The authorities in charge of responding to maritime emergencies are required to make timely decisions about the deployment of critical and limited resources mitigating the emergency. Key inputs into the responding authority’s decision-making are drift and fate predictions and on-scene operational conditions. The drift and fate predictions need to be from the earliest possible start of the emergency up through to the departure of the next round of the response resources. The on-scene oceanographic and meteorological conditions in support of operations cover the period of the response resources getting to the on-scene, operations, and return from the operations to a safe base. The on-scene conditions are important for effective decision-making for the response operations and are vital for the safety of individuals involved in the response operations. Each emergency has its own timeline that dictates the hindcast, nowcast, and forecast periods of the drift and fate predictions. The type of emergency and the associated response resources dictate the need for on-scene condition information. As the emergency unfolds, the response authorities will need the predictions and on-scene conditions updated in a timely manner.

Diagram

Description automatically generated

**Figure 1.2: The emergency timeline**

Marine emergencies share a common timeline of which there are four phases: pre-emergency conditions; the initial event conditions, the conditions during the response period, and the conclusion and post-event analysis, as illustrated in Figure 1.2. The pre-emergency conditions cover the events and conditions leading up to the actual emergency event. These are typically the root causes of the marine emergency which may include but are not limited to: extreme weather and waves, reduced visibility, shoals and currents, icing on superstructures, heavy vessel traffic, mechanical fatigue or failure, inadequate fail-safe design, human fatigue, and faulty decision-making. The initial event conditions include the probable area where the emergency occurred; the time period when the emergency might have occurred or is occurring, and the type and quantity of material or objects involved in the emergency. The conditions during the response period include the drift trajectories and fate of the material or objects from the initial probability area and time period up and through the end of the next response epoch. Critical to successful modelling are field (and remote-sensing) observations about the location of the object that is drifting[[1]](#footnote-2). Also required by the response agencies for their operations are the on-scene conditions and constraints. As the response operations continue, the initial conditions are likely to be updated and refined; the next sequence of responses defined and implemented until the final stage of the timeline is obtained; the conclusion. Active migration response measures are either terminated or evolve into long-term lower-level efforts. At this point, post-event analysis may be conducted to determine the root cause of the emergency and evaluate the response effort with the goal of reducing the chance of such an emergency happening again or improving methods to deal with this type of incident.

Diagram

Description automatically generated with medium confidence**Figure 1.3 : Typical relevant time and depth scales associated with various marine emergencies (modified from Röhrs et al, 2023)**

While the components of responding to marine emergencies are complicated, these can be broken down into two key aspects: (1) accurate estimates of the oceanographic and meteorological conditions; and (2) the drift and fate model specific to the type of emergency. The latter aspect is unique to each type of emergency response, e.g. leeway tables in SAR or oil weathering or radioactive decay of radionuclides, and these are addressed in specific sections. The former aspect, about quality estimates of meteorological and oceanographic conditions, is required for all Marine Emergency Response. It is important to keep in mind that different emergencies require data on different spatial and temporal scales. An illustration of the relevant time and depth scales associated with various marine emergencies are shown in Figure 1.3. Note that the spatial extent of the required data is linearly related to the relevant temporal scales. Oil spill mitigation and restorations typically are confined to the friction layer, while their timescales can range from half-hour for the response to years for the restoration efforts. In contrast, the mitigation of heavy oil that sinks to the bottom is confined to the bottom boundary layer. SAR survivors and survivor craft occupy the ocean boundary layer. SAR has the most immediate response timescales of minutes, but can extend out to days, but are limited by survivability. Non-SAR objects (e.g. shipping containers or their contents) can extend deeper than SAR objects and may require longer response or forecast times. Extreme weather and weather forecasts for vessels must represent conditions on the sea surface and the lower part of the atmospheric boundary layer (also known as the constant flux layer) and the ocean wave zone, while offshore structures need forecasts that extend deeper into the ocean mixed layer (the Ekman layer) and in shallow waters down to the benthic zones directly above the bottom boundary layer. At the longer, deeper end of the response and forecast scales are the transport of the radioactive particles and dissolved nuclides. Deep sea currents might also be required in case of a response to continuous release of harmful substances from sunk objects.

#### 1.1.1 Marine Environment Emergency Response (MEER)

Noxious and hazardous substances are here defined as substances that are potentially harmful to persons or to the marine environment. They may be both naturally occurring (e.g. petroleum) or man-made (e.g. polychlorinated biphenyls (PCBs)). Substances can be noxious either due to their toxic chemical characteristics or due to the extreme concentrations that occur when they are spilled into the ocean. Incidents involving petroleum products, both raw and refined oil, have received the most attention in the context of damaging spill incidents, and procedures for emergency response have been developed primarily for oil spills. Models for the drift and fate of oil in the ocean and the prediction systems built around them are described in Section 3.2.1.

The lessons learned from developing and applying oil spill drift and fate prediction tools have encouraged the application of those tools to other noxious substances, such as sewage. It should be noted that the distinction between noxious substances described here and drifting objects is not always sharp; for example, some drifting objects, such as plastics, may be considered noxious. In the present context, however, the distinction is based on what tools are deemed most applicable. Spilled fluids and very small objects, such as ash, would typically be handled with oil spill type tools, while larger floating objects, whose individual drift characteristics can be estimated, would be handled by drifting object methods.

Spills of oil on the ocean have occurred since the advent of industrial activities which have led to the building of major facilities along the coast (e.g. refineries), at sea (e.g. offshore oil platforms) and maritime transport. The need for remedial response arose already in the 1960s and 1970s after major oil spills in connection with the boom in tanker transport and offshore oil production. Public concerns about the environmental damage to coastlines, the seabed and wildlife from major oil spills (for example, Torrey Canyon in 1967, the Ekofisk Bravo blowout in 1977 and Amoco Cadiz in 1978) led to the development of emergency response capabilities in the major industrialized maritime countries.

However, ever larger tankers put into service, new oil fields opening, and pipelines laid on the seabed have increased the spill risk. Severe oil spill incidents occurred in the late 1980s: Odyssey in 1988, Exxon Valdez in 1989, Khark 5 in 1989, and ABT Summer 1991 (In 1991, one of the largest oil spills took place in the Persian Gulf during the second Gulf War.) Those spill incidents led to the International Convention on OPRC of IMO. The parties are required to establish measures for dealing with pollution incidents, either nationally or in cooperation with other countries. Even though the number of spill incidents is decreasing, huge spills still happen occasionally, such as the Prestige wreck in 2002, the Deepwater Horizon oil spill in 2010 and the Sanchi oil tanker collision in 2018. The MV Wakashio oil spill in 2020, in which great environmental damage occurred in Mauritius, is a recent case which was outlined by Daniel and Virasami (2021), and explains well the various actors involved in responding to such an emergency. In 2019, the *Grande America* container vessel, travelling between Hamburg and Casablanca, caught fire and capsized[[2]](#footnote-3), leading to both oil slicks and hazardous chemical substances in the ocean. Several meteorological services were involved in providing information to the response authorities. The Tongan volcanic eruption in January 2022 demonstrated a cascading impact of multi-hazards from the initial eruption, triggering a basin wide tsunami wave across the Pacific Ocean, where waves approaching the Peru coast damaged an oil facility, leading to an oil spill[[3]](#footnote-4).

Although such large spills result in serious damage to the local environment, they do not occur often. In reality, most spill cases involve small amounts of oil and they occur frequently (almost daily). Although the amount of each spill is rather small, the total amount and the cumulative impact on the affected areas are significant, especially in heavily trafficked areas. It is difficult to detect small spills, which makes the response and building of reliable statistics difficult.

#### 1.1.2 Maritime Search and Rescue (SAR) operations

SAR response is primarily concerned with finding maritime survivors, survivors’ craft and saving the survivors. SAR crosses over with oil spill response with the drift predictions of potentially dangerous floating objects like shipping containers and disabled vessels.

Timeline

Description automatically generated with medium confidence

**Figure 1.4: Typical SAR timeline**

The response time of the SAR authorities to enable resources on-scene is the shortest of all the marine emergencies. Figure 1.4 shows a generalized SAR timeline with all the major events of SAR procedures of the SAR timeline, ranging from minutes to days (and sometimes longer). However, not every SAR incident contains all these elements, but all contain the time of the incident, notification of SAR authorities, and response by the SAR resources to the incident.

Classical maritime SAR incidents start with pre-distress conditions, the distress itself, followed by the notification of SAR authorities of the distress, and response by the SAR resources to the incident. Often, the SAR incident is resolved successfully with the initial response and lives are saved. However, there are some SAR incidents that run the full spectrum of the SAR timeline due to some combination of the following; (i) complex pre-distress motion; (ii) uncertainty in the time of incident; (iii) significant delays in notification; (iv) limited information by third-party reporting sources; (v) areas remote from response resources; and (vi) hard to detect but favourable survival conditions and craft. This can lead to multiple cycles of planning and subsequent search efforts until the case is resolved or suspended. SAR response organizations have guidance, SAR planning tools, and resources for classic SAR events. The SAR planning tools established access to the necessary environment data and fields for drifting the survivors or survival craft from the time of the incident through to the end of the next search epoch. Environmental data are critical inputs into evaluation of effectiveness of the SAR visual and electronic sensors aboard the SAR response units; and for estimating the maximum survival times of the survivors. When survivors are not located, the extremely difficult decision to suspend active searching for survivors is dependent on the estimations of survival times and the additional probability of success given the previous search efforts and potential additional search efforts.

SAR also shares and overlaps with oil spill and HAZMAT[[4]](#footnote-5) response with the drift predictions of potentially dangerous floating objects like shipping containers and disabled vessels. The drift prediction of disabled vessels is primarily concerned with the potential impact and release of oil upon grounding. Semi-submerged shipping containers are hazards to navigation and alerting the maritime community to their potential locations is the primary goal. Much of the capabilities of SAR planning are used for the drift prediction of dangerous floating objects.

The growing occurrences of maritime migrants present challenges to the SAR response community. Maritime migrants are seasonal in nature, which can also be influenced by political events. Migrant vessels can generate classic SAR cases when the migrant vessel capsizes or sinks, which leads to very high-profile events both in the media and at the political levels. Migrant vessels have known voyage routes with several possible initial locations and destinations. Response organizations’ resources (vessels and aircraft) are highly stressed during the season of maritime migrants’ voyages, by maintaining a constant presence across the lanes that the migrant vessels transit. Migrant vessels do not notify the response authorities as they are trying to avoid detection, often travelling during periods of low visibility (e.g. new moon and cloud cover). Response organizations have planning tools for classic SAR events but no specific guidance or tools for the maritime migrant seasons.

### 1.2 Structure of the Guide

This Guide is organized into five chapters and four appendices. Chapter 1 gives an overview of the Marine Emergency Response. Chapter 2 describes the physical and chemical processes associated with the transport of substances and objects in the marine environment. Chapter 3 focuses on the modelling of drift of substances and objects, while Chapter 4 intends to give an overview of the methods and techniques used in the detection and monitoring. Chapter 5 provides a review of the existing capabilities and services.

Appendix I provides an overview of the international conventions and frameworks. Appendix II describes the meteorological, oceanographic and wave data required as inputs to drift and fate models. Appendix III gives an overview of the operation and response activities. Appendix IV includes the IAEA case studies with modelling and data for radiological impact assessments. There is a list of acronyms and abbreviations, and a glossary.

### PROCESSES AFFECTING SUBSTANCES AND OBJECTS IN THE MARINE ENVIRONMENT

*Authors: Graigory Sutherland (Environment and Climate Change Canada), Arthur A. Allen (US Coast Guard) and Pierre Daniel (MeteoFrance)*

Chapter 2 provides an overview of many of the theoretical aspects of drift prediction with regards to MER. First, an overview of the physical forcing by the ocean currents, the wind and the waves is given. Topics related to turbulent diffusion and advection in regions partially covered with sea ice are also mentioned in brief. The dominant processes determining the fate and drift of objects and substances (e.g. oil) are then presented.

### 2.1 Environmental forces determining ocean transport

Substances and objects in the ocean move under the combined action of the wind, ocean currents and waves. While the wind is the primary forcing for waves, the ocean currents are generated, in addition to wind, by tides, the rotation of the earth as well as bottom friction in coastal regions and, importantly, baroclinic effects due to variable thermodynamic forcing through heating and evaporation and precipitation. While the wind, the ocean currents and the waves provide the forcing for the transport, how any material and/or object is transported can differ depending on how it interacts with each of the forcing components. That is, every object has unique drift characteristics even for identical environmental forcing. An example helps illustrate the widely varying fates of substances and different drifting objects. Imagine oil leaking from a ship and a liferaft launched while the ship itself is drifting with no engine on. The oil feels the wind mostly through the surface wind drift and is in addition subject to the Stokes drift by the waves (more about this later). The liferaft has no keel and a very significant windage through its canopy and moves swiftly downwind. The ship has a large superstructure which gives it significant windage but also a deep keel which makes it move more with the average current in the upper few metres of the ocean. It is clear that the oil, the liferaft and the ship move at very different speeds and also in different directions. Another example that helps illustrate the different forces that affect a drifting object is shown in Figure 2.1. Here, a 20-ft container is deployed during a field experiment in French waters (Breivik et al, 2012). As is evident from the picture, the container is influenced by the waves, both through wave forces, but also through the Stokes drift. Its immersion ratio is also quite high, and thus it is strongly influenced by the currents in the upper 2 m of the ocean. The over-water structure (the part that sticks out of the water) also feels direct windage, so the near-surface wind is important. All of these factors must be accounted for in order to assess the total drift.



**Figure 2.1. A drifting 20-ft container in the Iroise Sea during a field experiment to establish the drift properties of shipping containers. Shipping containers represent a major risk to marine traffic and a potential source of pollution. They are also difficult to model since their immersion ratio can vary a lot. From Breivik et al. (2012b).**

The relative importance of each forcing is thus strongly dependent on the density of the drifting object and/or material and the specific shape and size of drifting objects. First, the density of the object and/or material determines whether it floats, sinks, or passively follows the water (if neutrally buoyant with density identical to the ambient water). The density of seawater is on average about 1025 kg/m3, and this varies only slightly with temperature, salinity and depth. The height of the object above the water is called the freeboard. For example, the density of sea ice is about 90% that of water, hence icebergs are typically 90% immersed and their freeboard is about 10%.

The next crucial element is the shape above and below the water, as this determines the relative drag (the surface friction forces) due to the wind and the water surface. As the drag scales as , where is the density, is the drag coefficient and is the velocity relative to the object at a fixed height (typically 10 m above the sea surface), both forces are relatively important with wind speeds typically 1 to 2 orders of magnitude greater than ocean currents and the ocean density being three orders of magnitude (about 800 times) greater than air density.

Additional forcing can occur if the object and/or substance significantly affects the surface waves. For example, oil dramatically reduces the ripples present in the wave field, which is why oil patches are smooth and are called slicks. This phenomenon leads to an additional forcing that affects the shape and motion of the slick (Christensen and Terrile, 2009). As this wave-oil interaction is dominated by the local wind-generated sea, this process is included as an additional wind-drift factor where 3% of the 10 m wind is the canonical value (Kim et al., 2014). A more dramatic impact exists for very large objects that are comparable in length to the dominant wavelengths in the wave field. These large objects can reflect the incoming waves leading to a forcing equal to up to twice the incoming wave momentum in the case of pure reflection and no wave transmission (Longuet-Higgins, 1977).

### 2.2 Physical Processes of the upper ocean and lower atmosphere

#### 2.2.1 Advection

Advection is the mean motion of a substance or object due to the wind, waves and ocean currents. In the ocean, advection is predominantly due to the earth’s rotation in combination with tidal forces (tidal currents), gravity (geostrophic currents and baroclinic effects through thermodynamic processes such as heating, cooling, freezing, evaporation and precipitation), and wind stress at the surface either due to direct forcing on the object (leeway) and on the ocean (Ekman currents). In coastal regions bottom friction is also a key component and directly influences the dynamics.

#### 2.2.2 Diffusion

Objects and substances diffuse due to the turbulent nature of the oceans. This is especially true in the upper ocean, where the effects of wind and wave forcing are the strongest. With respect to drift prediction, turbulent diffusion adds a stochastic (random) component on top of the advection and spreading (Soloviev and Lukas, 2013). These stochastic processes can vary greatly by region and environmental forcing, and are strongly impacted by motion at scales much smaller than those resolved by environmental prediction systems. For substances such as oil slicks, this turbulent diffusion makes the slick expand with time. For discrete objects, turbulent diffusion leads to expanding uncertainty about the location of a single realization in a turbulent fluid, or, in other words, the search area will expand with time.

For turbulent flows, diffusion is typically approximated by an eddy diffusivity. The eddy diffusivity can be scaled as where and are the velocity and length scales of the turbulent flow, respectively. The value of can vary by several orders of magnitude depending on the region and oceanic conditions (Nummelin et al., 2021).

#### 2.2.3 Stokes drift

The waves induce a slow drift in the direction of wave propagation known as the "Stokes' drift". Its effect is very important when dealing with the movement of floating pollutants (e.g. oil slicks). Under transient conditions the Stokes transport may become relatively more important because it can persist when a wind ceases to blow (Wu, 1983).

In progressive gravity waves of very small amplitude, it is well known that the orbits of the particles are either elliptical (shallow waters) or circular (deep waters). In steep waves, however, the orbits become quite distorted (trajectories are not closed) due to the existence of a mean horizontal drift or mass-transport in irrotational waves (Stokes 1847, 1880). Hence, floating oil droplets are subjected to the movement caused by the orbital motion of water particles (Daniel et al, 2003).

The second order Lagrangian drift due to waves is called the Stokes drift (Phillips, 1977):

where is the wave amplitude, is the water depth, and isdepth (negative) beneath the surface. The wave circular frequency and the wave number for a wave of period and wavelength . The Stokes drift can be calculated from the full wave spectrum (see for example Breivik et al, 2014, 2016), but is typically about 1 to 1.5% of the wind speed at the surface (Ardhuin et al., 2009) and decays exponentially with depth (Kenyon, 1969). As the Stokes drift is predominantly due to the local wind generated sea, it is not common to explicitly include it in the drift model and it is implicit in the leeway correction term (Breivik and Allen, 2008, Breivik et al, 2013).

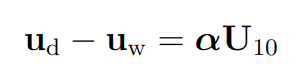
#### 2.2.4 Stratification effects

Stratification is the variation of water density with depth. A decrease in density with depth is gravitationally unstable and, therefore, instantly creates convective cells which increase turbulent mixing and remove stratification (Soloviev and Lukas, 2013). An increase in density with depth is gravitationally stable and acts to restrict vertical motion created by surface forcing (Soloviev and Lukas, 2013). Typically, the ocean surface is well mixed with little or no stratification in the upper tens to hundreds of metres. This *mixed layer depth* varies a lot by region and season. For typical conditions, stratification has no appreciable impact on near-surface substances and objects and only affects the prediction of passive substances such as radionuclides, dissolved chemicals and very small oil droplets if the water viscosity is greater than the oil buoyancy.

However, there are specific conditions that increase the stratification at shallow depths which impact the prediction of substances at the surface and objects. The two main processes are surface heating by the sun and regions where there are large freshwater flows from rivers. This can lead to the *slippery water* phenomenon where the surface water appears to slide downwind with little resistance from the mixed layer below (Houghton and Woods, 1969). This phenomenon can cause an additional increase in velocity of tens of cm/s in the case of diurnal heating (Sutherland et al., 2016) and up to 1 m/s in the case of river plumes (Röhrs et al., 2023). These surface jets are often short-lived, typically on the order of hours, but can span days in some extreme situations (Röhrs et al. 2023).

### 2.3 Leeway and wave forces on drifting objects

Leeway is the additional drift of an object relative to the ocean currents. For practical purposes Allen and Plourde (1999) defined the leeway for SAR objects as *the motion of the object induced by wind (10 m reference height) and waves relative to the ambient current (between 0.3 and 1.0 m depth).* This leeway is estimated as a linear function of the wind vector and is only applicable to objects at the surface. The leeway is expressed mathematically as:



where **u**d is the drift velocity of the object and/or substance, **u**w is the ocean surface velocity, **U**10 is the wind speed velocity at 10 m height and **α** is the leeway coefficient, which is a scalar if there only exists a down-wind leeway (DWL) component. However, **α** is often a vector *rotation* as SAR objects can have a substantial crosswind leeway component (CWL), i.e. they tend to drift at an angle (known as the leeway divergence) to the wind (see Allen and Plourde, 1999; Allen, 2005, and Chapter 3).

Values for the leeway are usually determined empirically via dedicated experiments for specific objects (Allen and Plourde, 1999; Breivik et al., 2011). This is the tried-and-true method and most values that exist in look-up tables were derived using this method. Calculating leeway coefficients using ocean currents and wind velocities from numerical models has recently been tested (Sutherland et al., 2020). This method is particularly useful if there are continuing observations of the object during the MER event as the leeway can be estimated and improved upon in real-time.

There do exist theoretical estimates of the leeway coefficient for objects if details of the object are well known. Kirwan et al. (1975) showed that the leeway can be estimated from the relative air and water drags on the object as

,

where , , and are the density of air, air-side drag coefficient, and cross-sectional area of the object above the water line respectively. Here, , , and are the density of water, water-side drag coefficient, and cross-sectional area below the water line, respectively. This method has been expanded by Wagner et al. (2022) to estimate the leeway for a broader range of objects based on the density difference of the object and the water and the aspect ratio of the object. These methods assume steady state and a simple quadratic drag law for the friction force.

There also exists a drift framework based on the Maxey-Riley equation (Beron-Vera et al., 2019) which considers the inertia of the object and other pertinent effects such as lift, drag, added mass (fluid that moves with the object) and the earth’s rotation. While the use of the Maxey-Riley equation to predict the drift of objects at the water surface looks promising, there is still work to be done to incorporate wave effects as well as buoyant substances at the surface such as oil. It is also clear that for most objects of relevance for SAR, as well as oils, the acceleration toward force balance is rapid (on the order of 30 s, see Hodgins and Hodgins, 1998), and can usually be ignored in the evolution of search areas.

Wave effects are often incorporated into leeway estimates as surface waves are strongly correlated with the wind speed. Small objects, much smaller than the dominant wavelength of the wave field, are also subject to the previously mentioned Stokes drift (van den Bremer and Breivik, 2018). For large objects, with horizontal dimensions comparable to the dominant wavelength, the object begins to influence the wave field through reflection and refraction. As waves transport momentum, this change in wave momentum creates an additional force on the object which impacts the motion and orientation (Newman, 1967; Sørgård and Vada, 1998).

### 2.4 The fate of radionuclides

Radionuclide releases in the ocean are a significant concern due to the potential environmental and health impacts they can cause. Radionuclides are unstable isotopes of elements that release radiation as they decay into more stable elements. They can be released into the ocean from a variety of sources, including nuclear accidents, nuclear testing, and nuclear waste disposal. Radioactive waste from nuclear power plants is often disposed of in the ocean ([IAEA, 2021](https://www.iaea.org/sites/default/files/publications/magazines/bulletin/bull21-4/21405942431.pdf)), either by dumping it directly or by discharging it into rivers that flow into the ocean. While these practices are regulated and monitored ([IAEA, 2023](https://www.iaea.org/topics/radioactive-waste-and-spent-fuel-management)), there is still concern about the long-term environmental and health impacts of these releases.

Radioactive material dispersion and diffusion in the ocean result from the passive advection with the ocean currents from their initial release or their deposition from the atmosphere.

### 2.5 Spreading of oils

Spreading refers to the initial movement of the oil from the point of release, as it spreads out and creates a thin film that expands over the surface of the water. The rate and extent of spreading depend on several factors, such as the quantity, density and viscosity of the oil, the interfacial tension between the oil and the water, and the wind and wave conditions. Lighter oils, such as gasoline and diesel, tend to spread more quickly and into thinner sheens than heavier oils, such as crude oil or residual fuels, which can form thick slicks that are more resistant to spreading.

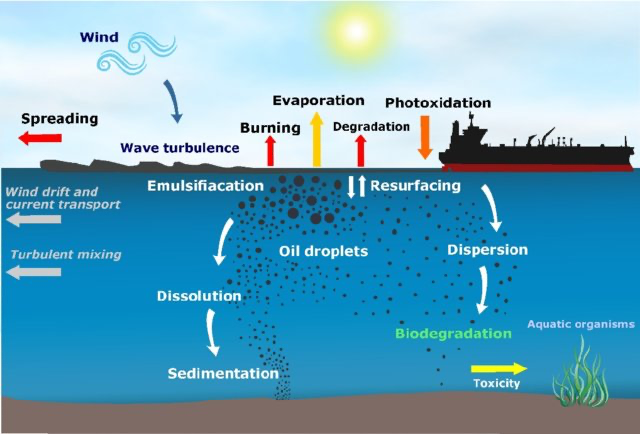
Fay (1969) developed a theory that describes the initial spreading of oil when it is spilled on water. According to the Fay theory, when oil is spilled on water, it initially spreads out in a thin layer, called the primary slick, which is characterized by a high velocity and low thickness. As the slick spreads out, it slows down and becomes thicker, forming a secondary slick. The rate of spreading is proportional to the square root of time and is influenced primarily by the size of the release, the density of the oil, and the oil-water interfacial tension. The theory describes the primary slick as having a constant velocity and thickness which allows for the calculation of the spreading rate based on the initial slick dimensions and the time since the spill. The theory also predicts that the rate of spreading slows down overtime as the slick spreads and becomes thinner. Fay’s work assumes a quiescent sea, but other factors, such as wind and wave conditions are also known to affect spreading.

Other factors, such as turbulence, can also play a role in the spreading of spilled oil. Mackay's fate theory (Mackay et al., 1980, 1982) considers gravitational spreading against viscous resistance. Spreading can also lead to advanced oil breaking and shear spreading due to turbulence, resulting in the dispersion and partial resurfacing of oil droplets (Elliot, 1986). It is important to note that from a practical forecasting point of view, the details of the initial spreading do not have a significant impact in the subsequent advection by wind and currents.

### 2.6 Weathering processes of oil

Oil, a complex mixture of thousands of different hydrocarbons, exhibits several key physical properties, including density, viscosity, and chemical composition. These properties play a significant role in the transformations that spilled oil undergoes as it interacts with the ocean environment.

Oil spills in the ocean can undergo various weathering processes which can impact the fate and behaviour of the spilled oil. The main weathering processes of oil spilled in the ocean are described below.



**Figure 2.2 – Main transport and weathering processes affecting an oil spill (Keramea, 2021)**

#### 2.6.1 Evaporation

Evaporation is one of the primary weathering processes that occurs when oil is spilled in the ocean. Evaporation depends on oil characteristics and can vary strongly between oil types. Evaporation occurs when the lighter components of the oil, such as VOCs, transition from a liquid to a gaseous state and are released into the atmosphere. The rate of evaporation depends on several factors, such as the temperature, humidity, wind speed, and the properties of the oil. In general, those oil components with a boiling point below 200°C evaporate within a period of 24 hours. The greater the proportion of components with low boiling points, the greater the degree of evaporation. The initial spreading rate of the oil affects evaporation since the larger the surface area, the faster light components evaporate. Rough seas, high wind speeds and high temperatures also increase the rate of evaporation. As the oil evaporates, it leaves behind a thicker and more viscous residue which affects subsequent weathering processes and the effectiveness of clean-up operations. Refined products such as kerosene and gasoline can completely evaporate within a few hours, while light crudes may lose up to 40% of their volume during the first day. Heavy fuel oils, on the other hand, undergo minimal evaporation. However, when highly volatile oils are spilled in enclosed spaces, they may pose a risk of fire, explosion, or health hazards to humans.

#### 2.6.2 Emulsification

The oil can mix with seawater, forming an emulsion, which is a suspension of small droplets of oil in water. In moderate to rough seas, many oils entrain water droplets and form water-in-oil emulsions under the turbulent activity of breaking waves. This can increase the volume of pollutants fourfold. These emulsions can be unstable and break down quickly, or be stable, persisting for days or longer. Whether an emulsion forms, and the stability of the emulsion, is a function of the oil’s physical and chemical properties, and the field environment – thickness of oil sheen and the nature of the turbulence. In the field, some oils will not form an emulsion when fresh, but will after having weathered for some time.

This is due to evaporation increasing the viscosity of the oil, as well as potentially photo-oxidation producing oxidized compounds that act as surfactants that stabilize the emulsion.

The most successful models for this process rely on lab experiments, so models will be most predictive if that particular oil has been studied for its emulsification potential. Easily emulsifiable oils emulsify quickly in sea states above a wind speed of 3-5 m/s. Very viscous oils entrain water droplets more slowly than less viscous oils. As the emulsion develops, the ongoing turbulence in the waves decreases the size of the water droplets in the oil, making the emulsion more viscous and stable. As the amount of water entrained increases, the density of the emulsion approaches that of seawater. This higher density and viscosity cause the emulsion to float lower in the water, resulting in less direct movement by the wind. Stable emulsions can contain up to 70-80% water and are very long-lasting. The less stable emulsions separate into oil and water when heated by sunlight under stationary conditions or when stranded. The formation of water-in-oil emulsions slows the rate of other weathering processes increasing the persistence of light and medium crude oils at the surface. Emulsified oil can be more difficult to clean up, as traditional mechanical techniques, such as skimming and booming, may be less effective, and there are larger quantities of contaminated product to manage.

#### 2.6.3 Dispersion

Dispersion involves the breaking up of the oil into smaller droplets that diffuse throughout the water column, no longer forming a surface sheen and becoming unaffected by the wind. Dispersion occurs naturally due to wave action, turbulence, and wind, and it can be facilitated by the use of dispersants, chemicals that help break up the oil into smaller droplets.

Dispersants work by reducing the interfacial tension between the oil and water, making it easier to mix with water and form smaller droplets. These small droplets rise more slowly in the water column, allowing background turbulence to keep them suspended in the water column. Once the oil is dispersed, it can be advected away from the spill site and driven deeper into the water column, making it more difficult to track. The dispersed oil can also be more easily biodegraded by bacteria, as the smaller droplets have a higher surface area to volume ratio, which allows for more efficient bacterial activity. Dispersed oil can affect subsurface biota, but will tend to reduce in concentration, and will not re-converge into high concentrations. Surface oil affects biota on the surface (birds, turtles, mammals), and can move to the shoreline where it can affect sensitive shoreline ecosystems as well as re-converge into higher concentrations in convergence zones.

Mechanical clean-up methods, such as skimming and booming, are not effective for dispersed oil because these techniques rely on the oil floating on the surface. The extent and rate of dispersion depend on various factors, including the type of oil, the environmental conditions, and the use of mitigating measures such as dispersants.

#### 2.6.4 Dissolution

Dissolution is a process by which components of the oil spilled in the ocean can dissolve into the surrounding water. The rate and extent of dissolution depend on several factors, such as the type and amount of oil spilled, the temperature and salinity of the water, and the duration of exposure. The heavy components of crude oil are nearly insoluble in seawater, while some lighter compounds, especially aromatics such as benzene and toluene, are slightly soluble. However, these compounds are also the most volatile and disappear very quickly by evaporation, usually 10 to 1000 times faster than by dissolution, and are usually only a small fraction of the total oil. Consequently, dissolved hydrocarbon concentrations in seawater rarely exceed 1 ppm, and dissolution does not contribute much to the removal of oil from the sea (ITOPFa, 2014). However, dissolution can have toxic effects on marine life, as dissolved oil can be absorbed by fish and other organisms and can cause damage to their organs and tissues (ITOPFb, 2014).

#### 2.6.5 Biodegradation

Biodegradation involves the breakdown of oil by microorganisms, such as bacteria and fungi. The rate of biodegradation depends on several factors, such as the type of oil, the environmental conditions, and the presence of nutrients and oxygen. Lighter oils, such as gasoline and diesel, are more readily biodegraded than heavier oils, such as crude oil, which contain a higher proportion of heavy hydrocarbons that are more difficult for microorganisms to break down. In the ocean, bacteria are the primary microorganisms responsible for biodegradation of oil, and oil-degrading bacteria have been found in all regions of the ocean. Biodegradation can be facilitated by the addition of nutrients, such as nitrogen and phosphorus, which can stimulate bacterial growth and activity. The use of dispersants can also facilitate biodegradation by breaking up the oil into smaller droplets that can be more easily accessed by bacteria. Biodegradation can help to reduce the volume of oil spilled in the ocean and minimize its impact on the environment. However, it can also lead to the production of harmful by-products, such as methane and hydrogen sulphide, which can further impact the marine ecosystem. Biodegradation is much slower for oil that has been adsorbed to sediments or buried on the shoreline.

#### 2.6.6 Photo-oxidation

Photo-oxidation involves the breakdown of oil by the action of sunlight and oxygen. When oil is exposed to sunlight, it can undergo a series of chemical reactions that lead to the formation of reactive oxygen species, such as hydroxyl radicals which can react with the hydrocarbons in the oil and break them down into smaller, more soluble compounds (National Research Council, 2003). These compounds can then be more easily dispersed and biodegraded by microorganisms. The rate of photo-oxidation depends on several factors, such as the type of oil, the intensity and duration of sunlight exposure, and the availability of oxygen. Lighter oils, such as gasoline and diesel, are more susceptible to photo-oxidation than heavier oils, such as crude oil, which contain a higher proportion of heavy hydrocarbons that are more resistant to break down . Recent work suggests that photo-oxidation results in more soluble compounds, and may produce surfactants that facilitate the formation of emulsions (Christoph Aeppli, 2022). Photo-oxidation can be facilitated by the use of dispersants, which can break-up the oil into smaller droplets, thereby increasing its surface area. While this greater surface area does enhance the susceptibility of the oil to sunlight and oxygen, it's important to note that these smaller droplets may be moved deeper into the water column. As a result, they become less exposed to direct sunlight. Photo-oxidation processes tend to have a more pronounced effect on the surface sheens of oil, where the oil is in direct contact with air and sunlight, rather than on the smaller, dispersed droplets located deeper in the water. The use of dispersants can also increase the production of reactive oxygen species, further facilitating photo-oxidation. However, photo-oxidation can also lead to the formation of harmful by-products, such as organic acids and aldehydes, which can have toxic effects on marine life.

### 2.7 Interactions with sea ice and shoreline

#### 2.7.1 Interaction with sea ice

The presence of sea ice has a significant effect on the surface processes of the ocean. Sea ice impacts the transfer of momentum between the atmosphere and the ocean with this modification being dependent on the concentration of sea ice. For ice concentrations greater than 80%, the physical properties of the sea ice are important as there is enough ice to compact and deform the ice cover. For ice concentrations less than 80%, commonly referred to as the *marginal ice zone* (MIZ), the sea ice is freely drifting and impacts the dynamics in a different way than at higher concentrations (Squire, 2020).

While the main processes are known, there is a lot of uncertainty with regards to MER in ice-covered water. This is especially true in the MIZ, which is highly dynamic, and prediction is strongly influenced by the representation of the ice concentration. The oil spill community has long used the “80/30” rule (Nordam et al, 2019) where the oil drifts as in open water for ice concentrations less than 30%, and with the ice for concentrations greater than 80%. For intermediate ice concentrations between 30% and 80%, the drift is assumed to be a linear combination of the two. Some work has been done to improve estimates of a more general transport drift in the MIZ and minimize errors when using the best ocean-ice-wind data available from operational centres (Sutherland et al., 2022). Oil under high ice concentrations can interact with the ice in complex ways: it can be moved relative to the ice by under-ice currents, it can be encapsulated in the ice, and even move through the ice to the surface via brine channels (Afenyo et al., 2016). Oil under ice is very difficult to detect, posing challenges to mitigation activities (Wilkinson et al., 2017).

#### 2.7.2 Interaction with the shoreline

The interaction with the shoreline depends on the type of oil spilled, the characteristics of the shoreline (e.g. sand, rocks, fine or coarse-grained beaches, wetlands and mangroves), exposure to waves and tides, and weather conditions. These characteristics, along with the combination of weathering processes (such as evaporation, photo-oxidation, and biodegradation), decide the oil behaviour (Wang et al, 2020; Huettel, 2022) in the context of oil penetration, retention, persistence, remobilization, and translocation (pathway to transport the oil into the environment).

For example, highly weathering oil on a shoreline has high viscosity and adhesiveness, which results in greater oil retention (Boufadel et al, 2019), hence would not return to the ocean and cleaning operations become more difficult. For oil with high volatility, oil removal from the shoreline could be achieved. Meanwhile, oil stranded on a shoreline goes through continual weathering processes until it is cleaned up or naturally removed, so its physical and chemical properties would change and affect the performance of response actions (Wang et al, 2020).

Oil is often mixed with sand and sediments on sand shorelines. If this mixture is washed off the shoreline back into the sea, oil sediments may sink and be buried in the seafloor. Sometimes residual oils can penetrate, depending on porosity related to sediment, the viscosity of the oil, and the presence of animal burrows in the area (Asif et al, 2022).

In the presence of high concentrations of sediments in the water, oil can stick to the sediments, forming oil-sediment aggregates (OSA). The formation of aggregates is complex and there are knowledge gaps in expressing the detailed dynamics of sedimentation in a quantitative parameterization scheme. Researchers (Khelifa et al., 2005) have developed Monte Carlo schemes and oil-particle coagulation capabilities to simulate the formation of oil-mineral aggregates.

### MODELLING OF THE DRIFT AND FATE OF SUBSTANCES AND OBJECTS

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This chapter describes dispersion modelling as it is usually developed and operated at NMHSs, as well as the forcing fields that come from operational Numerical Weather Prediction (NWP) models as well as from wave and ocean forecast models. We describe here the concepts of numerical modelling of drifting objects and substances, the required forcing fields (the geophysical data, sometimes also referred to as the environmental data) and how to design specific models (e.g. an oil spill forecast system or a drift prediction system for search and rescue objects).

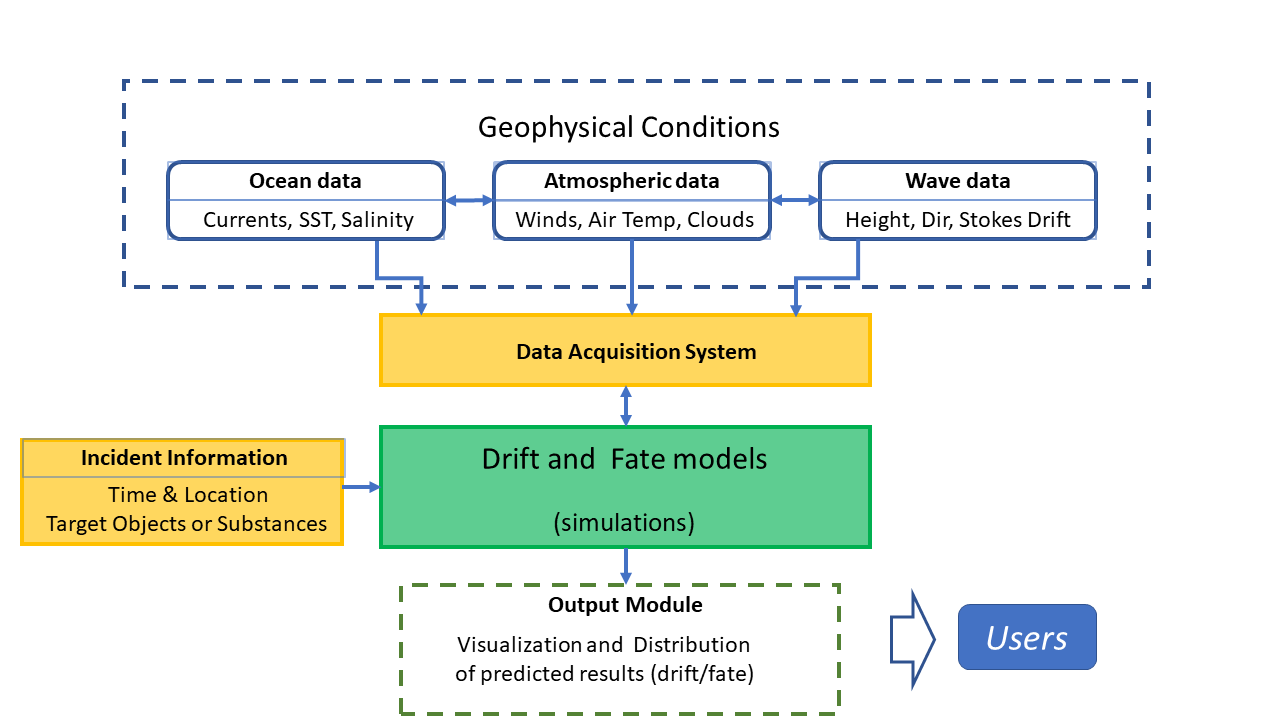
### 3.1 Basic Drift Modelling

This section covers some of the basic aspects of drift and dispersion modelling common to all marine environmental emergencies, including oil spills, search and rescue (SAR) of objects and radioactivity in the ocean. This includes aspects about the data required and how the predicted drift and dispersion is calculated.

The drift of objects and substances (the target) is an initial value problem. In other words, we need to know or assume something about the initial state (the last known position where we think the target started drifting and what sort of object or substance we are talking about). However, it is also a boundary value problem. That is, what forces will buffet the object or substance around must also be known (the wind, the waves, the currents, and potentially a host of other geophysical variables such as temperature and precipitation). This is information which must be taken from measurements or, more commonly, from forecast systems. The required information (initial conditions and boundary conditions) differs from one target (a solid object or a substance) to another.

Drift modelling of different types of targets share certain commonalities, but each obviously have specific features (e.g. both oil and SAR objects are advected with the surface current, but oil weathers, whereas a SAR object may capsize). The former can be summarized as a basic advection-diffusion process, mainly determined by atmospheric and oceanographic conditions, while the latter depends on various processes specific to the target in question, such as the chemical processes of oil fate, the chemical reactions and the decay of radioactive materials, or the leeway of a floating object. Therefore, drift models tend to handle the advection-diffusion process in a similar manner, but may differ greatly in how the target-specific processes are represented.

The drift models thus need information on the atmospheric and oceanographic conditions (their boundary conditions). Specifically, surface winds, near-surface ocean currents, surface waves, and other oceanographic and meteorological variables such as temperature go into the calculations (Figure 3.1). These are the essential forcing fields for drift simulations. The trajectories and search areas depend crucially on the quality of those geophysical fields. The search area of objects and the concentration of substances advect (move), disperse (diffuse) and change state (e.g. capsizing or evaporation for a SAR object or an oil spill) in response to the forcing by those geophysical conditions. Appendix I provides detailed information on the required geophysical forcing data.



**Figure 3.1: The flow chart of drift and fate model simulations**

#### 3.1.1 Data Required

Ocean currents are a key component for MER. Most marine emergencies involve buoyant objects and/or substances that are thus found at or very near the surface. Typically, a mean current over the upper metre is required. This depth resolution is becoming commonplace, but it is important to check the vertical resolution of the particular forcing fields being used. If the data source has a vertical resolution coarser than one metre, it is likely that the shear of the current, typically the wind-induced (Ekman) current, is underestimated and the leeway may need to be increased to compensate.

Oil spill modelling often requires more than just the surface current as the oil can be entrained to a depth, thus altering the trajectory before the oil resurfaces (Röhrs et al., 2018) compared to the trajectory of a surface slick. This process is typically modelled as a function of the waves and depends strongly on the type of oil. Radionuclides, and other tracers, are assumed to drift passively with the ocean currents and are subject to the vertical mixing and motion of the ocean.

For surface targets, the wind over the ocean as well as surface waves have a major impact on their fate and drift. The leeway parameters (how fast and in what direction an object moves through the water under the influence of the wind) normally require the wind field to be referenced to 10  m height. This corresponds to the standard forecast and measurement height used in meteorology. If for some reason it is not at the reference height, it must be adjusted assuming a certain (normally logarithmic) wind profile (see Fairall et al., 2003). It is standard practice in SAR (Breivik et al., 2011) to calculate leeway coefficients as a percentage of the wind. These coefficients vary greatly with the size and shape of the search object, as mentioned in Chapter 2. A leeway is also common in oil spill modelling where the typical value is 3% of the wind (Spaulding, 1988).

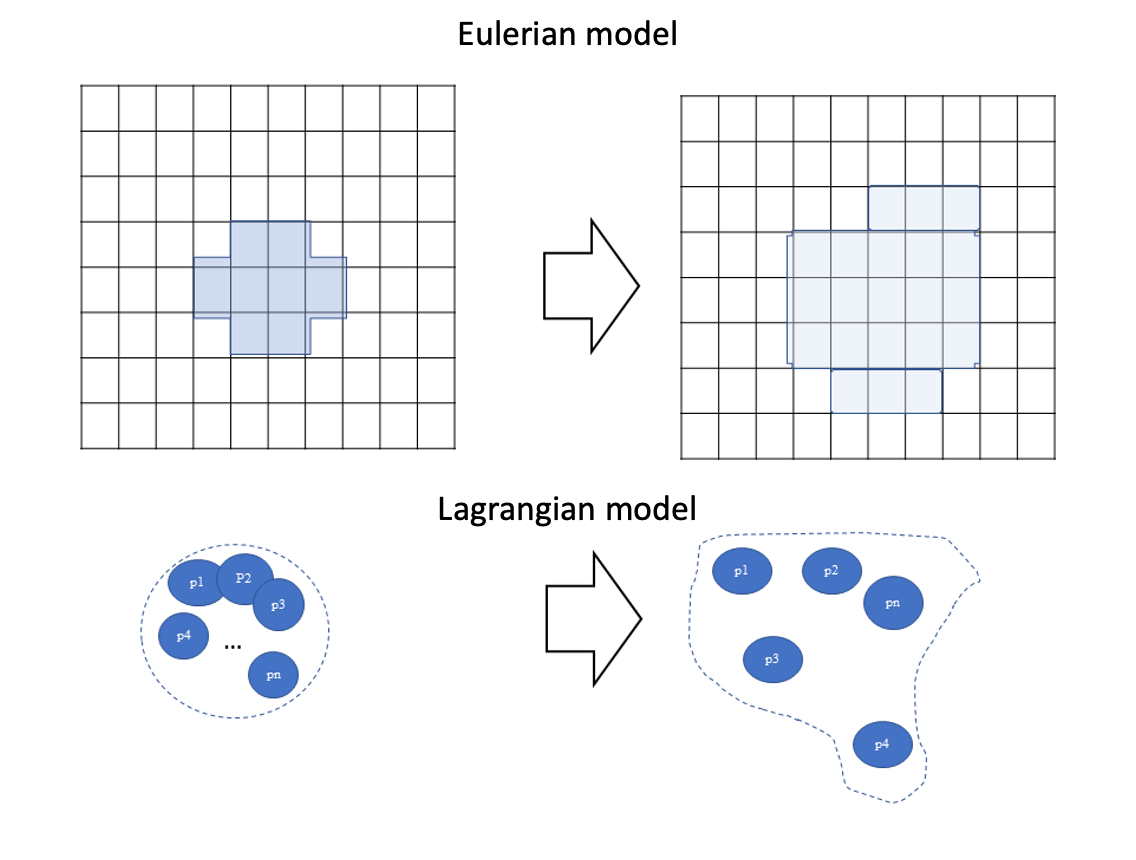
Surface waves are also important for MER, but for simplicity their contribution is often incorporated into the wind effect since wind and waves are closely correlated in strength and direction outside swell-dominated regions. For surface targets, there is also an additional Lagrangian drift, known as the Stokes drift, which is typically in the range of 1 to 1.5% of the wind speed (Ardhuin et al, 2009, van den Bremer and Breivik, 2018) and is normally included in leeway parameters (Allen and Plourde, 1999). Waves are also important for oil spill modelling where they enter parameterizations of weathering and entrainment of oil from the surface slick into the water column by wave breaking.

For oil spill modelling, the sea surface temperature strongly affects the viscosity, density, and evaporation rate of the oil which determines how the oil weathers and the ability of oil to be entrained in the water column.

Geophysical forcing fields for drift and fate models are described in Appendix I.

#### 3.1.2 Lagrangian and Eulerian modelling of substances and objects

There are two fundamental ways to conduct drift modelling, namely the Eulerian and the Lagrangian approach, illustrated in Figure 3.2.



**Figure 3.2: The two fundamental representations of a fluid or a concentration of a substance within a fluid, the Eulerian and the Lagrangian. The Eulerian approach represents the fluid motion in a fixed position, for example on a regular grid, as shown here. The Lagrangian representation follows fluid “particles” or elements (the blue blobs) as they are advected.**

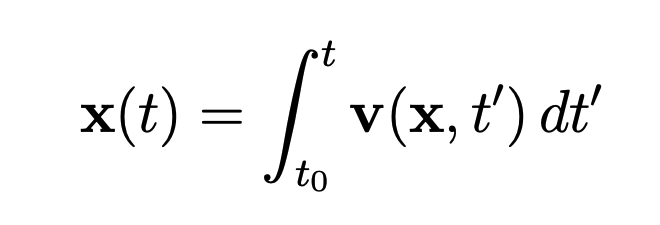
**Eulerian Modelling**

Eulerian models calculate the transport of objects or substances using an advection-diffusion equation for a tracer concentration on a model grid. The model directly calculates changes to the concentrations on the grid. This is convenient when the properties of the substance depend on its concentration as the local “thickness” of the substance is immediately available (Lynch et al, 2014). The primary disadvantage of Eulerian models is the numerical diffusion which can rapidly diffuse the concentration field. It can also be difficult to model state changes such as evaporation or capsizing. The Eulerian approach can also be inefficient since the model must calculate the condition of all grid points including those where no target substance or object is likely to exist.

**Lagrangian Modelling**

Lagrangian models represent the concentration of a substance (or fluid particle) or the probable location of an object by a large number of “particles” or elements. These particles can then be thought of as either representing a certain amount of a substance such as oil or a certain probability of finding an object such as a person in water. It should be noted that the particles do not represent real objects even if they can be represented by points, their exact shapes are not usually considered. We can then calculate the behaviour of the individual particles. Even continuous fields like oil slicks can be well approximated by an ensemble of discrete particles. Most drift simulation models apply the Lagrangian approach, since it is more cost-effective than the Eulerian model. Lagrangian models are cheap as they deal with individual particles that do not interact. However, if the concentration is of importance (say, if the “thickness” of the field affects the behaviour of the substance), it is necessary to compute this concentration from the particle distribution illustrated in Fig. 3.2. The main disadvantage to Lagrangian models is the need to repeatedly do a potentially costly “gridding” where concentrations are needed (Lynch et al, 2014).

Lagrangian modelling involves integrating particle velocities to obtain a trajectory. The fundamental equation in Lagrangian modelling is thus very simple,



Here, x(t) is the displacement at a time of the particle from the start of the drift (time ). The velocity of the particle, v, is a function of all the forces that act on the particle (typically from the wind, the waves, and surface currents). The relative contribution from the different forcing fields is determined by the shape and properties of the substance or object that the particle is assumed to represent and can vary greatly. These particles can thus represent a portion of oil, a discrete object, or the probability associated with a discrete object. The velocity field exists in the form of a gridded field from the ocean model space and time and must be interpolated to the particle location and integrated in time to obtain the particle trajectory. To minimize errors associated with the integration, a higher-order scheme such as Runge-Kutta integration method is used, although there may be reasons, especially if the input environmental fields are particularly coarse, to use other methods (Nordam and Duran, 2020).

In addition to the advection, turbulent motion exists on spatial and timescales smaller than those resolved by the environmental prediction systems. These must be parameterized, i.e. their effect must be inferred from larger scale, resolved processes. These turbulent processes contribute to the outspread of the Lagrangian particles and are modelled as stochastic processes (Griffa et al., 1995). The most common of these stochastic processes is the “random walk”, where the random motion is governed by a horizontal/vertical diffusivity uncorrelated in time. Higher-order stochastic models require additional parameters, for example the “random flight” model which includes a memory term which requires a correlation timescale in addition to the diffusivity (Berloff and McWilliams, 2002 and van Sebille et al, 2018).

#### 3.1.3 Online and offline drift modelling

There are two ways of doing drift model calculations, online and offline. In online calculations, drift processes are included or dynamically coupled with a background ocean model. Offline calculation, on the other hand, means that drift models are separated from ocean models and run with forcing data from (often several) environmental models.

Online calculations can use forcing conditions at each calculation step of the environmental model. The environmental models are selected by considering key forcing factors. The ocean model is the base model for marine drift simulation, and atmospheric models are used for air drift simulations. The main advantage of online models is that it is possible to account for interactions between an object or a substance and its ambient environment. However, online models need large computational resources since the forcing model must be rerun every time the drift calculation is done. The other disadvantage is more fundamental: a Lagrangian (or Eulerian) drift model that depends on several types of environmental forcing (waves, wind) cannot be run as part of a stand-alone ocean model unless that model has full access to those fields as well. An exception are fully coupled models, such as atmosphere-ocean models or earth system models that have recently gone operational in several NMHSs, as they are capable of providing all the necessary elements. However, such coupled models require far more computational resources than stand-alone ocean models, and it is not yet practical to operationally use those models for online calculations. For this reason, online models are mainly used for research purposes.

Offline drift models can be forced with fields from numerical models of the atmosphere, the ocean and the wave field. As these are run operationally by many NMHSs, it is a much cheaper and faster alternative for operational services. Those operational geophysical fields are not as well resolved in time as an online model would be, but this does not normally affect the accuracy of the Lagrangian representation much (and is a much smaller cause of uncertainty than the uncertainties inherent to the forcing fields themselves). The other merit of offline models is that they can easily handle the output from ensemble forecast systems, and can be used with a variety of forcing models from many services and locations.

#### 3.1.4 Forward and reverse simulations

Usually, drift and fate models calculate how targets will change their positions or characteristics in time, and thus the models are used to make forecasts of the fate of an object or a substance. However, sometimes backward simulations in time are required. For example, when spilled oil or radioactive materials is reported, it may be necessary to locate the source of the spill. It may also be necessary to go back and search an area based on a debris field, as was the case after the AF 447 airline accident (Kratzke et al, 2010, Davey et al, 2016) to try to identify the location of the accident. Therefore, such calculations, often referred to as “backtracking” or “reverse” simulations (Breivik et al, 2012), are sometimes conducted to seek the original source of pollution or the location of an incident (Drevillon et al, 2012). Authentic reverse models could be developed by an adjoint code of forward models, but such calculations can also be conducted by reversing all signs and integrating backwards in time (Thygesen 2011, Shah et al, 2017, van Sebille et al, 2018 and van Duinen et al, 2022). It should be noted that it is problematic to run models in reverse when nonlinear processes are present. The ocean is highly nonlinear, and advection, diffusion and dispersion are nonlinear processes. Moreover, there are many other nonlinear processes specific to search objects and suspended particles such as evaporation of oil and state changes like swamping and capsizing of solid objects. It is also clear that a divergent flow field also affects the search area of the incident in ways that a simple reverse model cannot handle. If more detailed information is available about the initial incident (a non-uniform prior), then this is most easily incorporated by running the model forward (Stone et al, 2023). In this case, the trajectory from a large range of initial locations can be analysed, and the results can indicate which might be the likely source. This is more robust, but also more computationally expensive than a reverse run.

### 3.2 Specific Functionalities (fate modelling)

While advection and diffusion are common processes in drift modelling, there are a number of other processes that must be considered for predicting the fate of specific targets. Before looking at the different drift models in detail, the processes necessary for modelling the fate of substances and objects are briefly introduced.

The processes common to substances and objects deal with the advection and diffusion of objects and substances, while fate modelling deals with state changes in physical or chemical characteristics, the condition of objects and so on.

For example, oil removal operations differ according to the type and state of the spilled oil. If the spilled oil is volatile, a significant portion is quickly lost due to evaporation (cf. Section 2.6.1), while heavier oils only gradually reduce in volume. The other important condition is emulsification (cf. Section 2.6.2). By emulsification, spilled oil changes its characteristics from liquid to semi-solid and its drift characteristics change as well.

For radioactive materials, it is necessary to properly evaluate the full three-dimensional current field, such as sinking/deposition due to high density and adhesion to particles. The half-life of radioactive decay may also be of importance. In addition to the direct release of radioactive materials into the sea, there are also cases in which radioactive materials are emitted to the air and then fall to the ocean by deposition.

As for SAR or drifting objects, advection is the most important factor. Floating objects are influenced by currents, winds, and waves. It is essential to assess the relative contributions. For example, life rafts are much more likely to be displaced by wind than by ocean currents, whereas submerged objects are mainly forced by ocean currents at the relevant depths. Also, the air/sea ratio may change with time. A ship or a shipping container may be sinking as water enters the hull (Daniel et al, 2002, Breivik et al, 2012b).

#### 3.2.1 Oil spills

As described in Chapter 2, oil spills in the ocean are governed by a very wide variety of processes (Zodiatis et al., 2017). The inclusion of all these processes in a model makes it very complex and impractical to run in an operational mode. Hence, only the most dominant processes are typically considered to ensure timely support of response operations. The process selection to be implemented in oil spill drift and fate models depends on the target situation and local requirements. While spreading, diffusion, evaporation and emulsification are all considered essential for long-term simulations, advection is the most critical process for short-range predictions that support MER.

Advection and diffusion determine the evolution of oil in the ocean and are common for all drifting substances and objects. Most oil spill models are formulated in a Lagrangian framework in which oil slicks are represented by a cloud of particles. The movement of those particles is dependent on the physical environmental conditions. As discussed in Appendix I, the geophysical forcing data, which are usually provided by numerical models of the atmosphere, the ocean circulation and the wave field, are key factors for the accuracy of oil spill simulations. These processes are described above, while the most common oil-specific processes that are handled in the oil drift and fate model are outlined below.

**Spreading**

Several algorithms have been developed for the initial spreading of oil on the sea surface (Fay, 1969, 1971 and Hoult, 1972). Fay (1971) classified the spreading into three phases, considering the effect of gravity, viscosity, and interfacial tension. Mackay's fate algorithms (Mackay et al., 1980, 1982) follow the theory of gravitational spreading against viscous resistance, and modified versions of these are the most common spreading representations used in operational oil spill models. Spreading can also lead to the oil slick breaking up through two processes known as spreading break-up and shear spreading. The first involves the fragmentation of the oil slick into smaller patches that are subsequently dispersed over a wider area. Shear spreading is the stretching and elongation of the oil slick due to the shearing forces generated by wind and currents, resulting in the dispersion and partial resurfacing of oil droplets (Elliot, 1986). Recent modifications and improvements have been made to spill spreading estimation (Lehr et al., 2002; Galt et al., 2009). Wind speed and wave action also affect spreading (Geng et al., 2016), and existing algorithms only partially approximate the actual surface area of real spills. Langmuir circulation models can be used to approximate the merging of oil streaks and modify existing oil spreading parametrizations (Lehr et al., 2002). The spreading is mostly important for estimating the exposed surface area when modelling the evaporation process, and has less impact on the overall advection of the oil.

**Dispersion**

Empirical formulations have been developed to parameterize the oil entrainment rate into the water column as a function of the dissipation of wave energy, fractional area of the sea surface enclosed through breaking waves, and volume of oil entrained per unit of water volume (Mackay, 1980; Delvigne and Sweeney, 1988). These empirical formulations are widely used in operational oil spill models. However, they have specific limitations associated with the simplistic representation of the wave effects, which brings a large uncertainty in the estimation of oil dispersion. The inclusion of the wave spectrum and white capping could improve the dispersion parameterizations and droplet formation; hence reducing the dispersion uncertainty. This in turn could improve the estimation of dissolution and biodegradation in the water column, as well as surface processes such as evaporation and oil partitioning.

**Evaporation**

Evaporation depends on oil characteristics and can vary strongly between oil types. There are several ways to estimate evaporation. The most widely used analytical method for assessing oil evaporation rates is the mass-transfer coefficient model of Stiver and Mackay (1984), which calculates the rate based on wind speed, oil spill coverage, oil vapour pressure, and sea surface temperature. However, this method treats oil as a uniform element, which may decrease precision and accuracy in estimating evaporation rates. A more accurate model is the pseudo-component evaporation model such as Jones (1997), which assumes petroleum to be made up of discrete, non-interacting components with relative vapour pressure and molecular weight. Alternatively, Fingas (2012) proposed an empirical oil evaporation modelling that focuses on the temperature of oil as the main factor determining the rate rather than wind action on slick thickness.

**Emulsification**

Mackay et al. (1980) developed a simple emulsification algorithm that is included in several oil spill models, while Fingas and Fieldhouse (2014) introduced a stability index to classify the emulsification tendency of oil. However, a more reliable emulsification forecasting algorithm based on environmental conditions and oil properties still needs to be developed for use in oil spill models (Keramea et al., 2021). In practice, the emulsification behaviour of a particular oil can be assessed in the lab, and these results can be extrapolated to field conditions – but only for oils that have been suitably analysed.

**Dissolution**

The Mackay (1977) algorithm is commonly used to estimate dissolution from surface slick, while the pseudo-component approach in models (French-McCay, 2003) is used to estimate oil weathering processes including dissolution, evaporation and the toxic effects of lower molecular weight induced by aromatic compounds to ecosystems.

**Biodegradation**

Biodegradation was typically not included in operational oil spill models, but recent research has been incorporated into some models, including a new biodegradation algorithm that depends on the surface area of oil droplets (Brakstad et al., 2015). However, there is a need for a more realistic description of biodegradation kinetics in oil spill models, including oil composition, dispersed oil droplets-water interface, microbial population, biofilm formation, and availability of dissolved oxygen and nutrients, to enable a more accurate prediction and evaluation of possible bioremediation scenarios and risk assessment in the mid- and long-term. Recent developments include the adoption of a pseudo-component approach to simulate weathering processes and model the biodegradation of petroleum via Monod kinetics (Zodiatis et al., 2021). The kinetics of oil droplets size reduction due to the microbe-mediated degradation at the water-oil particle interface are described by the shrinking core model (Vilcáez and Hubbard, 2013).

**Photo-oxidation**

Current numerical models do not take into account photo-oxidation, as the process is not yet fully understood, and there are no parametric expressions for it. Kolpack developed a formulation for the rate of photo-oxidation (Kolpack et al., 1977), although it has not yet been validated. In addition, photo-oxidation is not a significant loss mechanism, but rather transforms the oil – it is not yet understood how these transformations might affect other processes, such as emulsification.

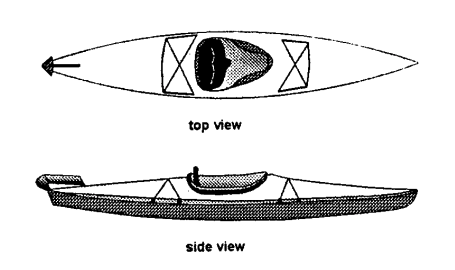
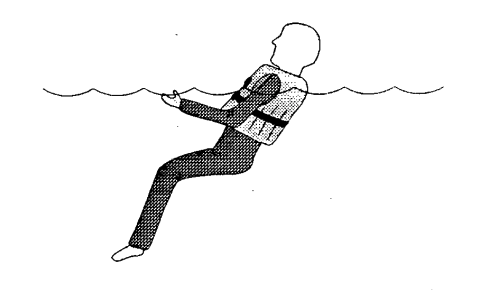
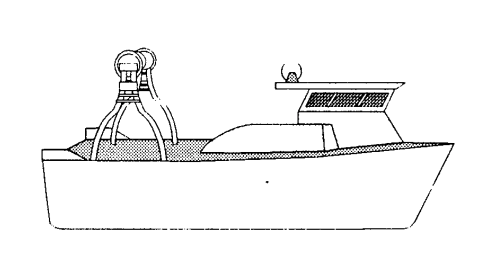
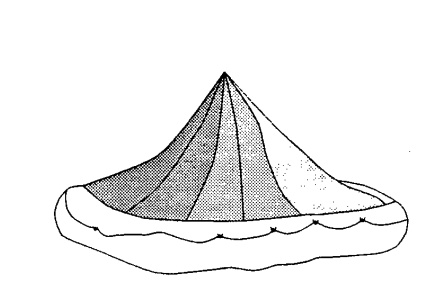
**Sedimentation**

The sedimentation of oil droplets is influenced by various processes, including increased density, incorporation of faecal pellets, and adherence to suspended particulate matter aggregates (Li et al., 2020). Sedimentation of oil has significant impacts on the marine environment, making it a critical process for biological impact analysis and response oil spill modelling. Interactions between oil and sediments play a vital role in the dispersion and degradation of oil spills (Gong et al., 2014). Several parameters such as temperature, salinity, wave energy, and physico-chemical oil properties control the formation of aggregates (Loh et al., 2014; Gao et al., 2018). However, there are knowledge gaps in expressing the detailed dynamics of sedimentation in a quantitative parameterization scheme. Researchers (Khelifa et al., 2005) have developed Monte Carlo schemes and oil-particle coagulation capabilities to simulate the formation of oil-mineral aggregates. MOSSFA, a new term for marine oil snow sedimentation and flocculent accumulation, was introduced after the Deepwater Horizon accident to assess the procedures affecting the formation and fate of oil-associated marine snow (Daly et al., 2016). Despite its importance, the MOSSFA process has not been incorporated into any existing operational oil spill model.

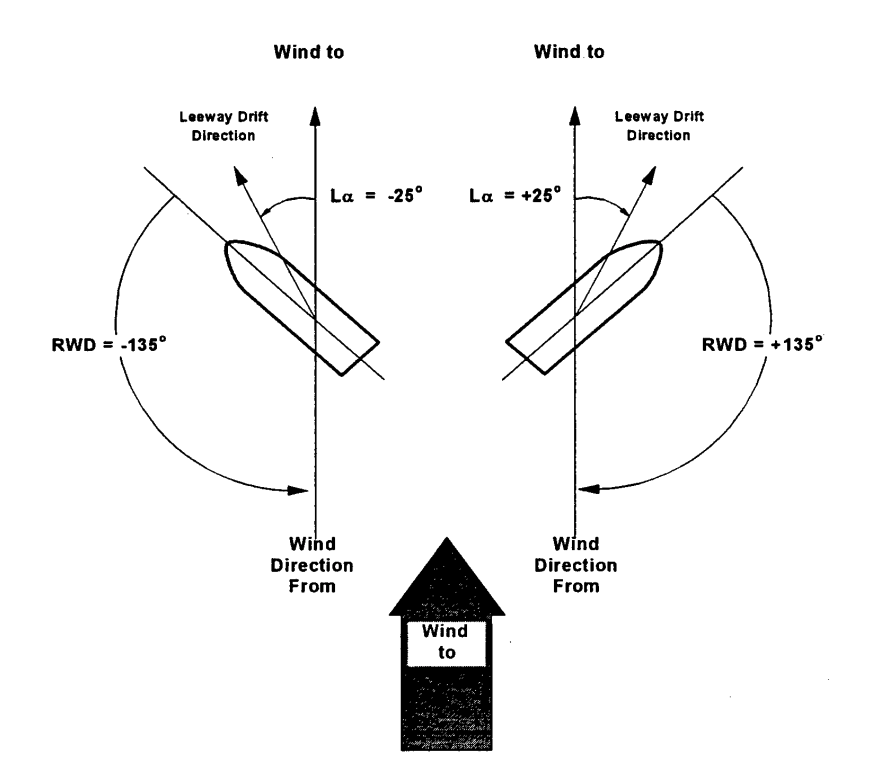
Much effort has been dedicated to oil spill model development, and state-of-the-art oil spill modelling systems are able to simulate the basic behaviour of oil slicks required for planning the mitigation. For a more detailed overview of oil spill modelling and prediction systems (including their histories), see for example Spaulding (1988), Reed et al. (1999), Hackett et al. (2006), Jones et al (2016), Zodiatis et al. (2017), and Keramea et al. (2021).

#### 3.2.2 The drift of objects, including SAR objects

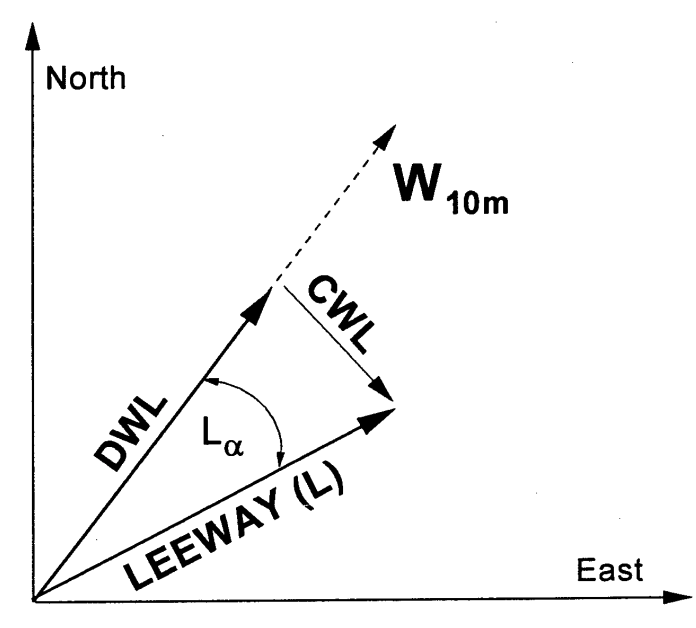
The drift of SAR objects (see Figure 3.3) across the surface of the ocean is always due to a combination of the sea surface currents, wind, and waves (Breivik et al., 2013; Futch and Allen, 2019). The forces on a common SAR craft are described by Anderson et al. (1998), Hodgins and Hodgins (1998) and Hodgins and Mak (1995). These studies looked at the relationship between the forces, drag coefficients, and wind and current velocity profiles over the height and depth of the objects. The key points of these studies are: (1) wind and water forces quickly reach equilibrium (i.e. acceleration is negligible); (2) the wind drag is equal and opposite to the water drag in the downwind direction; (3) wind torque and current torque about the craft are opposite and balance, which (4) results in a lift or crosswind term, and (5) total drift is due to both the surface currents and leeway components of drift.



**Figure 3.3. Typical search and rescue objects. Clockwise from upper left: A life raft with canopy, a 15 m fishing vessel, a sea kayak and a person in water with life jacket (also known as a personal flotation device, PFD). From Allen and Plourde (1999)**



**Figure 3.4 illustrates how two identical objects (eg. a small boat) can move to either side of the downwind direction due to the symmetry of the object. This will with time lead to an expansion of the search area as both cases must normally be accounted for (Allen and Plourde, 1999). The leeway of a drifting object is the drift through the water caused by the wind (and the waves). The direction and speed of the object can differ greatly, but common to all is a tendency to move at an angle relative to the downwind direction (the leeway divergence angle, Lα). The drift can be both left and right of the downwind direction. Here, RWD is the relative wind direction of the object referred to the direction the wind is coming from. This can be different from the direction the object is bearing. From Allen and Plourde (1999).**



**Figure 3.5. The speed and direction of the object (the leeway) is here decomposed into a downwind component (DWL) and a crosswind component of leeway (CWL). The leeway divergence angle, Lα, is small if the crosswind component is weak. From Allen and Plourde (1999).**

Total drift is predicted from the leeway. Following the definitions put forth by Allen (2005), wind forcing is treated as a vector with a direction and magnitude. Leeway speed is the velocity given to a drifting object from the wind, relative to the ambient currents. It is usually noted as a percentage of the wind speed. Leeway angle represents the angular offset from the downwind direction. This angle, when combined with the downwind component leeway, and the crosswind component, creates the full leeway vector. A thorough discussion of these principles is given in many key publications (Allen, 2005; Hackett et al., 2006; Breivik and Allen, 2008; Breivik et al., 2013).

Leeway is normally calculated using either the *direct method*, by measuring drift through water using attached current metres and anemometers, or the *indirect method* of subtracting the estimate of current drift from the total drift (Allen and Plourde, 1999). For different drift objects such as a person-in-the-water, a liferaft, or a sailboat, leeway parameters specific to each object need to be measured and recorded for use during SAR operations (e.g. IAMSAR manual). Presently there are 89 different leeway categories available. New advancements in leeway calculation have shown that it is possible to create a model of leeway drift using the balance of hydrodynamic and aerodynamic forces. This was conducted by Di Maio et al. (2016) on a person-in-the-water, with the modelled leeway performing better than the statistical approach described above. If this model proves accurate with other objects, it could reduce the need for direct measurement of leeway parameters.

The meteorological standard of the 10 min vector-averaged wind speed and wind direction is used for determining the leeway coefficients and by the operational SAR drift models. An assumption about the logarithmic wind profile above the sea surface must be made to scale the wind up to 10 m height. The drag coefficients presented by Smith (1988), Large et al. (1995) and more recently Edson (2008, 2013) (which relies on the work by Fairall et al. (2003)) are also frequently used for adjusting wind speed at the anemometer height to the standard 10 m level. It is assumed in the leeway definition that the motion through the ambient water results from the joint action of wind and waves. The wind works directly on the over-water structure while waves exert a force on the structure in addition to advection with the Stokes drift. It can be shown (Breivik and Allen, 2008) that wave drift forces on small objects (less than 30 m), such as cargo containers or oil drums, decay rapidly as the ratio of the dominant wavelength over the object’s length increases and can be neglected compared to wind forces as soon as the wavelength is more than about six times the object’s length (see also Hodgins and Hodgins, 1998; Mei, 1989). It can thus be assumed that for objects even as large as a cargo container or a small boat, leeway can be expressed in most sea states as a function of the wind only. Furthermore, the Stokes drift can under normal circumstances be assumed to be aligned with the wind direction and is confined to a narrow layer near the surface (except in swell-dominated regions in the Tropics). It is therefore practical to have an operational definition of leeway which does not distinguish between the wind and the wave influence.

Establishing an operational definition of the leeway (see Chapter 2) is important for two distinct reasons. First, in order to carry out leeway experiments in a consistent fashion it is important to agree on a standard for measuring the wind and wave-induced response of the object and its motion relative to the ambient water. Second, in order to use the measurements in trajectory models it is important to select the most pertinent wind and current vectors available from numerical models. The current between 0.3 m and 1.0 m depth is roughly corresponding to the typical measurement depth of high-frequency (HF) coastal radars, which is typically 0.5 m, although depending on the electromagnetic wavelength (see Fernandez et al., 1996; Breivik and Sætra, 2001). Surface layer drifters observe currents at the same depth too. Thus, observations by HF radars or surface layer drifters have been used to verify calculations. Moreover, observed data can be used to derive more accurate leeway coefficients, as suggested by Sutherland et al. (2020). It also means that where HF radar observations are available in real time, short-term current forecasts based on HF currents can be used to compute the evolution of search areas, as shown in Ullman et al (2006) and Ohlmann (2007). Such systems using observations for correcting forcing or parameters will surely give more reliable forecasts than just model predictions.

**Maritime migrants**

Standard SAR drift prediction and detection tools are based upon the basic premise that the survivors or survivor craft are both passively drifting and are passive detection objects. The SAR response also assumes a passive object which is neither cooperative nor non-cooperative, i.e. it neither aids nor actively hides from the search units. In contrast, maritime migrant vessels are initially active (under their own power) and are also sometimes non-cooperative, actively avoiding detection. Active craft modelling requires assumptions and inputs regarding the craft’s own velocity vectors and how they might be affected by waves and other environmental factors such as visibility and moon phase that might aid in their ability to hide from detection. There are presently no tools specifically designed to address maritime migrant voyages and detection. Unfortunately, maritime migrant voyages are a growing global problem that places a great deal of stress on the maritime response community.

**Estimation of survival time of a person immersed in water**

The probability of survival of persons immersed in water is estimated by statistical and physiological models.

A variety of methods have been employed to estimate the cooling rate of a person in water including: statistics from actual incidents (Molnar, 1946; Xu and Giesbrecht, 2018, Tipton et al, 2022); extrapolations from laboratory or field experimental data (Hayward et al, 1975; Hayward and Eckersen, 1984; Golden and Tipton, 2002); and the use of mathematical models of the human thermoregulatory system (Wissler, 2003; Xu and Tikuisis, 2014). As a result of this work, different predictions of *survival time* (ST) for those accidentally immersed have been developed. What these statistical models have in common is that ST is, unsurprisingly, a function of sea surface temperature (SST). The importance of ocean temperature cannot be overstated, and it is clear that any search operation for a person in water has, sadly, a much shorter time horizon than a similar search for people in a liferaft or vessel.

This work has also resulted in predictive models such as the Cold Exposure Survival Model (Tikuisis, 1995; Tikuisis & Keefe, 1996; Keefe & Tikuisis, 2008, Tikuisis, 1997), the Probability of survival Decision Aid (PSDA) (Xu and Werner, 1997, Xu et al., 2005, Xu et al., 2011, and Xu et al 2014) widely to estimate ST in cold and cold/wet conditions for the Canadian and US Coast Guards. Each approach has strengths and weaknesses, the main weakness, and therefore source of error being the numerous individual (e.g. size, age, gender, fitness, body fat percentage, thermoregulatory responses, clothing, and use of a lifejacket) and environmental (e.g. air and water temperatures, wind velocity, sea state, relative humidity, solar radiation, total cloud cover, and precipitation rate) sources of variability in actual ST. In absolute terms, the various predictions of ST tend to agree more closely for very low water temperatures, and vary more as water temperature increases. This is because at the lowest temperatures, the various individual physiological factors that might cause differences between individuals tend to be overwhelmed by the intense cooling of the environment. In higher water temperatures, these factors (e.g. shivering intensity and duration) are more likely to act as a significant source of variation between individuals. It is the variation between individuals and incidents that complicates the determination of search time on the basis of the prediction of ST in water. As a result, the authorities responsible for SAR activity extend search times to beyond that which they can “reasonably expect” anyone to survive.

#### 3.2.3 Radionuclide releases

The radionuclide dispersion model calculates the movement of the materials based on the ocean structure by the circulation model, taking the information of release source term (time of release, quantity, and chemical form of material) both for a direct release into the sea and from the atmospheric deposition.

For an accident in a seaside nuclear plant, such as Fukushima in March 2011, radioactive pollution of the sea may happen in three distinct ways:

1. The direct release of contaminated water from the plant;
2. The transport of contaminated water through rivers and groundwater from radioactive pollutants deposited on the ground as a result of atmospheric deposition and rainwater runoff;
3. The deposition on the ocean surface of radioactive particles transported in the atmosphere.

It is important to have specific information to distinguish the sources in order to model such releases properly. Direct release is the simplest, and the most immediate, while release to rivers and groundwater requires detailed knowledge of the ambient environment of the plant. Finally, the deposition of particles from releases to the atmosphere requires the use of specific atmospheric dispersion models.

The simplest models presently in operational use employ passive tracers, while more sophisticated models distinguish between various radioactive isotopes, surface and depth concentrations, their deposition in sediments, and potentially a human risk analysis.

Presuming the release occurs at the coast, it is important that the ocean circulation models be sufficiently accurate in the coastal zone. This is less critical for the redeposition of the radioactive plume that occurs over a larger area and possibly far from the coast. Some of these radionuclides are soluble and are transported over very long distances by ocean currents and dissipated in oceanic water masses. Others tend to aggregate to suspended particles, causing sedimentary contamination by deposition on the ocean floor. Short-lived radioactive elements, such as iodine-131, is only detectable for a few months (iodine-131 has a half-life of about eight days and thus decays by a factor of 1000 every 80 days). Others, such as ruthenium-106 and cesium-134, persist in the marine environment for several years. Cesium-137 has a half-life of 30 years, justifying careful long-term monitoring in coastal areas where it is likely to be present in sediments.

#### 3.2.4 Other hazardous materials

In addition to the major classes of MER cases listed above, there exist a number of drifting objects, natural or man-made, that can be hazardous. Specific modelling may be required for certain objects, whereas others can be handled like regular drifting objects. Which objects should be considered differs among regions and countries. Sargassum and pumice are examples of other hazardous materials that can easily be modelled as drifting objects.

### DETECTION AND MONITORING

*Authors: Alice Soares (WMO) and Arthur A Allen (US Coast Guard)*

This chapter reviews the methodologies used in the detection and monitoring of oil slicks at sea, recognition and search objects, and examination of radioactivity in the ocean; it is not meant to provide any guidance to oil spill clean-up or search and rescue (SAR) operations.

The detection of oil slicks and objects in the ocean can be carried out with visual and in situ methods and remote-sensing observations, using sensors installed on vessels, in aircraft or on satellites. Each sensor has different detection characteristics which, in turn, can describe different features of the slick or the object. The choice of sensor to be used depends on the purpose of the study. On the other hand, only in situ measurement systems are currently applied to the detection of radioactivity in the ocean.

### 4.1 Oil spills

Fingas and Brown (1997, 2000, 2002, 2005, 2011), Brekke and Solberg (2005), and Jha et al. (2008) present detailed reviews on the use of remote-sensing applied to oil slick monitoring. Below, a summary of the various sensors that can be used in the detection of and monitoring of oil slicks at sea is presented.

#### 4.1.1 Visual/Aerial Observations

Aerial observations from helicopters and fixed wing aircraft are very important for operational oil spill response. These observations are performed by well trained and experienced observers. Primarily limitations of aerial observation are coverage (both spatial and temporal), and observing conditions. At night or in adverse weather conditions (such as fog), visual observation becomes impractical. The thickness of the slick is also a constraint for its visual detection, since if the slick is very "thin" (i.e. less than 0.05 μm thick), it cannot easily be seen. For these reasons, remote observation by satellite and aircraft is a particularly important tool in the detection and monitoring of oil slicks at sea.

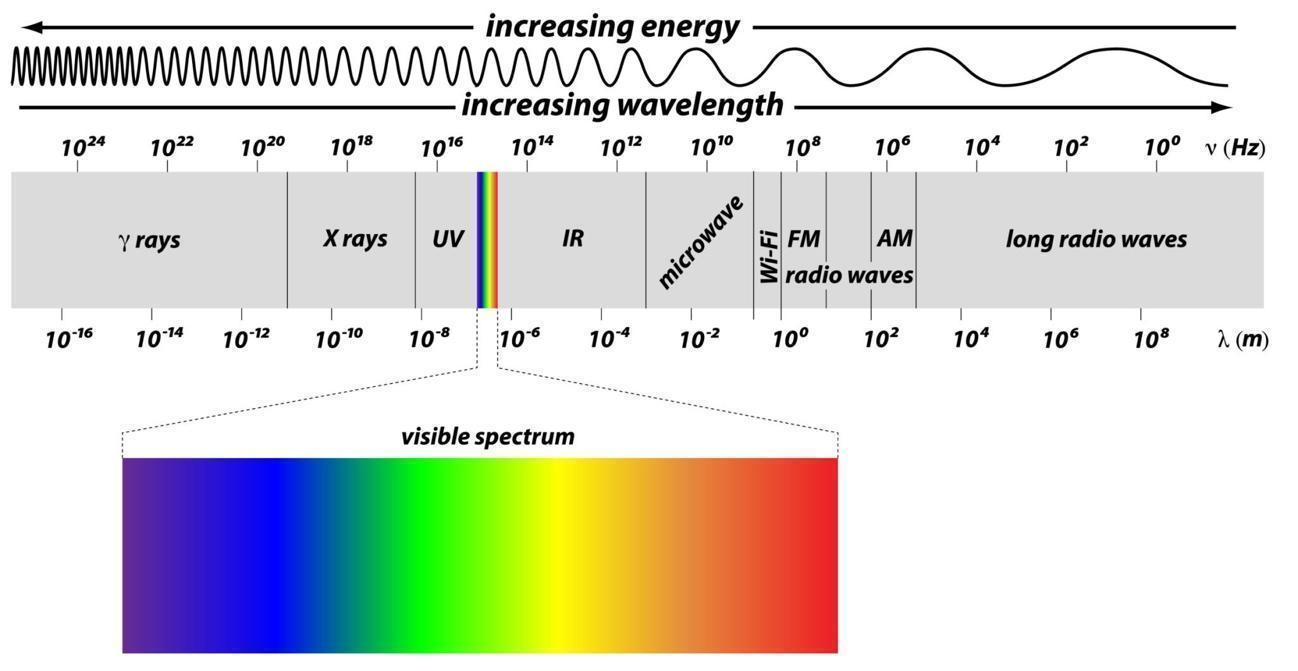
Fingas (2001) describes the guidelines for estimating oil slick thickness using the in situ visual method, as shown in Table 4.1. The appearance of the slick ranges from bright silver to dark brown, with an approximate thickness of 0.05 to 50 μm, respectively. The appearance of water-in-oil compound emulsions is usually orange brown. Note that the 50 μm estimate is a minimum thickness, oil thicker than that has the same appearance. This effect is also applicable to remote-sensing systems. Estimating oil thickness / volume from appearance is highly inaccurate and should only be used for broad order of magnitude assessments.

**Table 4.1: Appearance and respective thickness of the oil slick in calm seas (adapted from Jha et al, 2008)**

|  |  |
| --- | --- |
| Appearance | Approximate thickness (μm) |
| Shiny silver | 0.05 |
| Shining rainbow | 0.15 |
| Brilliant reddish brown | 0.50 |
| Glossy brownish | 2.00 |
| Dark | 10.00 |
| Dark brown | 50.00 |

#### 4.1.2 Remote-Sensing Instrument Methods

Remote observation using an instrument/sensor is the entire process of gathering information on a certain object or event without there being any kind of direct physical contact between the detector and the target under study. The information is obtained by measuring the electromagnetic radiation reflected or emitted by the target. Figure 4.1 shows the spectrum of electromagnetic radiation. This type of observation refers to the measurement and analysis of data obtained with instruments installed on board of aeroplanes and satellites, although observations made on ships, using sonar and echo sounders, are also considered remote observation methods.



**Figure 4.1: Electromagnetic spectrum (adapted from CFP, 2012)**

Remote observation by satellite and airborne means allows continuous and systematic analysis of large areas of the earth's surface and is therefore considered the preferred method for monitoring both the atmosphere and the ocean. This includes the detection and spatial-temporal monitoring of oil slicks and objects in the sea. This is done using different sensors installed on satellites and airborne means. Grüner et al (1991) show that remote sensors can provide the following information about the oil slick:

* The location and spread of the oil slick at sea;
* The rough distribution of thickness in the slick; and
* The classification of the type of oil within broad categories.

Table 4.2 shows the sensors used in the detection of oil slicks on the sea, and the respective bands of the electromagnetic radiation spectrum (Figure 4.1) where they operate. Remote-sensing of oils is mostly performed by sensors operating in the microwave band, due to their ability to operate under adverse weather conditions, regardless of the time (the received signal is not affected by solar radiation), and for their high spatial coverage (Brekke and Solberg, 2005). Note that remote sensors may be passive, if they receive radiation emitted or re-emitted by the sea surface (for instance, radiometers), or active, if they "illuminate" the surface with their own radiation and receive from it the corresponding reflected or backscattered signals (for instance, radars and lasers) (Fiúza, 1991b). The following sections present brief reviews on the use of various remote-sensing sensors applied to oil slick monitoring.

**Table 4.2: Instruments and the respective bands of the electromagnetic radiation spectrum in which they operate (adapted from Goodman, 1994).**

|  |  |  |
| --- | --- | --- |
| Instrument | Wavelength | Electromagnetic spectrum band |
| Photo and video cameras, scanners and lasers | 250-350 nm | Ultraviolet |
| Photo and video cameras and spectrometers | 350-750 nm | Visible |
| Photo and video cameras | 1-3 μm | Near Infrared |
| Video cameras and scanners | 3-5 μm | Mid-band Infrared |
| Video cameras and scanners | 8-14 μm | Thermal infrared |
| Radiometers | 2-8 mm | Microwave (passive sensor) |
| SLAR – Slide-Looking Airborne Radar/  SAR – Synthetic Aperture Radar | 1-30 cm | Radar (active sensor) |

##### 4.1.2.1 Passive Sensors

***Sensors operating in the visible band***

Optical techniques (e.g. photo and video cameras) are widely used in the detection and monitoring of oil slicks at sea. Figure 4.2 is an example of an aerial photograph of oil slicks with bright reddish brown and bright silver hues, corresponding to thicknesses of the order of 0.50 and 0.05 μm respectively (see Table 4.1), visualized from approximately 300 m height.



**Figure 4.2: Aerial photograph of oil slicks at sea (ITOPF, 2010)**

The sensors operating in the visible band (passive sensors), i.e. in the range of the electromagnetic spectrum between 350 – 750 nm (Figure 4.1), installed on board satellites, can be used for the detection and monitoring of oil slicks in the sea. Although oil has a higher reflectance than seawater, some of their components absorb part of the radiation in this band of the spectrum (Fingas and Brown, 1997). Typically, images in the visible band represent the ocean as a dark blue colour, making it difficult to detect oil slicks, as they are confused with seawater pixels (Figure 4.3). On the other hand, sensors operating in the visible band are dependent on the solar radiation and cloud cover of the study region. The sun reflects the ocean surface at the same angle as sensors operating in the visible band (sun glint phenomenon), so in their images in the visible band, the affected area and the seawater sometimes appear represented by a bright silvery shade, as shown in Figure 4.3. Therefore, these sensors usually do not operate at night. Even considering these constraints, images obtained through sensors operating in the visible band usually make it possible to visualize the full extent of the slick, due to the excellent spatial coverage capacity of these sensors. Examples are images obtained by MODIS (Moderate Resolution Imaging Spectroradiometer) and MERIS (Medium Resolution Imaging Spectrometer) sensors, with resolutions of 250 – 500 m and 300 m, respectively.

Some types of airborne multispectral scanners operating in the visible and near infrared bands (e.g. the passive Compact Airborne Spectrographic Imager, CASI) have been used for the detection and monitoring of oil slicks at sea (Palmer et al, 1994).

More recently, hyperspectral sensors, such as the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) and the Airborne Imaging Spectrometer for Applications (AISA) have been developed. A hyperspectral image consists of tens to hundreds of spectral bands and can provide a detailed spectral signature of an object (Landgrebe, 2003). Plaza et al (2001), and Salem and Kafatos (2001) demonstrated using hyperspectral imaging in the detection and characterization of the properties of offshore oil slicks.

In summary, although sensors operating in the visible band do not provide detailed information in the detection and monitoring of oil slicks, they are widely available on aircraft and are widely used, due to their substantially reduced costs compared to other sensors.

(a) 

(b) 

**Figure 4.3: (a) Representative example of the detection of the oil slick and the sunglint phenomenon in the visible band image obtained with the NASA MODIS sensor in the Gulf of Mexico on 13 May 2006; and (b) Enlargement of the previous image to show the oil slick in the form of "streaks" probably caused by the Langmuir cell effect (NASA, 2009)**

***Sensors operating in the infrared (IR) band***

Sensors operating in the infrared band (passive sensors), normally used to measure the temperature of seawater at the surface (e.g. Advanced Very High-Resolution Radiometer, AVHRR, and the Advanced Along-Track Scanning Radiometer, AATSR), can also be used for the detection and monitoring of oil slicks. However, as the thermal radiation released by seaweed and the shore is similar to the radiation emitted by oil slicks, the use of sensors operating in the infrared band may lead to large numbers of false positives (false alarms). Oil slicks absorb solar radiation, subsequently emitting part of this radiation in the form of thermal energy, mainly in the thermal infrared region (i.e. 8-14 μm). Oil slicks have a lower emissivity than water in the thermal infrared region, so oil slicks exhibit a distinct spectral signature in this region of the spectrum compared to that of water (Salisbury et al, 1993). During the day, thick oil slicks are observed by the sensor in the thermal infrared region as “hot” zones (i.e. these exhibit a higher thermal signature than adjacent water zones). Oil slicks with intermediate thicknesses are observed as “cold” zones and thin slicks are not detectable by the sensor. The minimum thickness of detectable slicks varies between 20 and 70 μm, depending on the environmental conditions, and the transition from “hot” zones (thick slicks) to “cold” zones (slicks of intermediate thickness) takes place approximately between 50 and 150 μm (Fingas and Brown, 1997). During the night, the release of energy by the oil slick is carried out faster than by the surrounding water, thus a thick oil slick appears “colder” than the water (Samberg, 2005).

As sensors operating in the infrared band are relatively inexpensive compared to other remote-sensing technologies that can be used to detect and monitor oil slicks at sea, they are therefore widely used in offshore oil spill surveillance systems (Brown and Fingas, 2005). However, it is known that these sensors enable the detection of slicks in adequate light conditions and whenever the sea state conditions allow it. Therefore, during the night, this type of sensor presents great limitations in the detection of oil slicks. Furthermore, these sensors are unable to detect water-in-oil compound emulsions, when these contain about 70% water and thermal properties similar to those of water (Brown and Fingas, 1997).

***Sensors operating in the ultraviolet band***

Oil slicks show high reflectance values in the ultraviolet band, compared to those of water. Even a very “thin” slick (i.e. less than 0.1 μm thick) can be detected using a sensor operating in the ultraviolet band. However, these cannot detect slicks whose thickness is greater than 10 μm (Grüner et al, 1991). The use of sensors operating in the ultraviolet band for oil slicks detection is strongly conditioned by environmental conditions, i.e. the images capture not only the oil slicks, but also areas of strong wind, the sunglint phenomenon and seaweed (Fingas and Brown, 1997). These interferences may cause false positives in the detection of oil slicks in the sea in images obtained by sensors operating in the ultraviolet band. These interferences show different signatures in images obtained in the ultraviolet and infrared bands, so the synergy between the two bands (i.e. IR/UV) is widely used in determining the relative thickness of oil slicks (Fingas and Brown, 1997; Goodman, 1994).

***Radiometer***

The radiometer (passive sensor) measures the radiation emitted by the ocean in the microwave band. The levels of radiation emitted in this band are higher for oils than for seawater. The difference in emissivity between seawater and oils allows radiometric distinction between these two fluids, so that, in the images, this fact translates into a characteristic pattern in which oil slicks are observed as light regions on a dark background (which corresponds to the sea surface). Biogenic materials in the sea may produce signals similar to oil slicks, which may lead to false alarms. On the other hand, since the microwave band signal of oils varies with the upper and lower limits of the slick, such sensors can be used to determine the thickness of oil slicks (Fingas and Brown, 1997).

This sensor can work well in adverse weather conditions, and works both day and night. However, it requires a special antenna on the aircraft to receive the radiation emitted in the microwave band. Radiometers are expensive sensors and are therefore rarely deployed in operation, and they require additional information (such as environmental characteristics and properties of the spilled oil) in order to accurately detect oil slicks at sea. Another disadvantage (perhaps the main one) of using radiometers is their low spatial resolution (Jha et al, 2008).

##### 4.1.2.2 Active Sensors

***Radar***

Radar (active sensor, also known as "scatterometer") operates in the microwave and radio wave band. These are scattered by capillary and capillary-gravity waves in the ocean, mainly through Bragg scattering, and therefore seawater looks bright on radar images. Oils diminish these short ocean waves and therefore if they are present in the sea, the reflectance is reduced. Thus, oil slicks can be detected and appear dark in the bright ocean image (Brown et al, 2003).

Synthetic Aperture Radar (SAR\*) and Side-Looking Airborne Radar (SLAR) are the two most widely used types of radar for the detection of oil slicks at sea. SAR\* has a higher spatial resolution and range than SLAR (Brown and Fingas, 1997), however, SLAR is less expensive and therefore widely used in remote-sensing applications. Brekke and Solberg (2005) conclude that the SAR\* sensor is the most efficient for oil spill monitoring and detection. Although the SAR sensor does not allow the determination of the slick thickness and the type of spilled oils, this sensor can observe vast study areas, and can operate day and night, even with thick cloud cover, with only some limitations resulting from wind speed. On the other hand, the presence of organic substances on the sea surface may lead to false positives, since the slicks of biological origin present the same type of signature as oil slicks in SAR\* images. Images from the Sea-viewing Wide Field-of-view Sensor (SeaWiFS), which measures chlorophyll concentrations in the visible band, are very useful as they can be used to validate the cases of false positives in SAR\* images (DiGiacomo and Holt, 2001).

***Fluorescence laser (lidar)***

The fluorescence laser (lidar), an active sensor, is commonly used to determine the fluorescence and in some cases the thickness of oil slicks. The sensor measures the fluorescence of aromatic oil compounds which, on absorbing ultraviolet radiation, become "electrically excited". This "excitation" is released through the emission of fluorescence by the compounds, mainly in the visible region (Figure 4.1). The fluorescence spectrum is then obtained via a multichannel sensor (Goodman, 1994). The fluorescence laser cannot measure oil spill thicknesses greater than 10-20 μm because the ultraviolet laser radiation is completely absorbed by the oils and therefore cannot reach the underlying water (Brown and Fingas, 2003 a).

The fluorescence laser is a more useful and reliable sensor for detecting oil slicks on various surfaces, including at sea (Brown and Fingas, 2003b), plus it is one of the few sensors that successfully detects water-in-oil emulsions (Brown et al, 2004). This laser can be used for day and night operations; however the atmosphere must be reasonably clean, i.e. free of cloudiness. The "excitation" wavelength for this laser is typically between 308-355 nm (Grüner et al, 1991).

***Acoustic laser for measuring slick thickness***

The acoustic laser (active sensor) detects oil slicks based on their acoustic and mechanical properties, rather than optical and electromagnetic properties, as is the case with previous sensors. This technique allows determining the absolute thickness of the oil slick, and can operate both during the day and at night (Goodman, 1994).

The LURSOT sensor, developed by a group of agencies and institutes (including Environment and Climate Change Canada, the National Research Council of Canada, the Industrial Materials Institute, Imperial Oil Limited, and the United States Bureau of Safety and Environmental Enforcement). The sensor’s ability to measure the thickness of the oil slick is based on the time-of-flight and the time required (measured by three lasers) for the ultrasonic waves to pass through the oil slick. Laboratory tests of the calculation of the slick thickness using LURSOT are promising (Brown and Fingas, 2003 a). In 2006, the LURSOT sensor, placed on board an Environment Canada aircraft, was successfully tested in the measurement of oil slicks. However, these sensors are typically bulky and expensive, and cannot operate in fog and hazy conditions (Goodman, 1994).

Since 2010, experiments carried out at the National Oil Spill Response Research & Renewable Energy Test Facility (OHMSETT) in New Jersey have demonstrated that under specific viewing conditions, a single polarization satellite SAR image can record a signal variance between thick stable emulsions and non-emulsified oil. In particular, during a series of field campaigns in the Gulf of Mexico within situ measurements of oil thickness, multiple satellite data were obtained that allowed the generation of an oil/emulsion thickness classification product based on RADARSAT-2 polarimetric imagery using entropy and the damping ratio derivations (Garcia-Pineda et al, 2020).

#### 4.1.3 Comparison of remote-sensing systems in the monitoring of oil slicks at sea

The spatial and temporal resolutions, as well as the collection and processing time, and the possibility of capturing in a comprehensive view the area concerned, and the day and night operability to ensure continuous surveillance, are some of the important factors in the choice of the sensor to be used in the detection of oil slicks at sea. Sensors operating in the visible and ultraviolet bands cannot operate at night, which is a major disadvantage in monitoring oil spills. Atmospheric conditions (namely cloud cover, precipitation, fog and mist, and wind) can also constrain continuous surveillance. Radars are the sensors that operate best under these conditions. The price, size and portability of the sensors are also considered when choosing the system to be used for the detection and monitoring of oil slicks at sea. Sensors operating in the infrared band are considered cheap and are therefore widely used; fluorescence lasers, on the other hand, are rarely used due to their high cost.

The simple detection and mapping of the oil slick is not sufficient for contingency planning in case of an oil spill at sea, because it does not allow estimating the amount of product spilled. Measuring the thickness of the slick is important but difficult and uncertain. As for now, most methods can only distinguish between “thick” and “thin”. As described previously, the superposition of images in the infrared band with images in the ultraviolet band (IR/UV) can give an idea of the relative thickness of the oil slick. Fluorescence lasers are limited in their ability to measure slick thickness greater than 10-20 μm. Radiometers can measure slick thickness from 50 mm to a few millimetres, but suffer from coarse spatial resolution. LURSOT, developed by Environment Canada, is the only sensor available that enables the measurement of absolute offshore oil slick thickness (Brown et al, 2006).

Table 4.3 shows a comparison of the various sensors used in the surveillance (detecting and monitoring) of oil spills at sea. Based on this table and the discussion above, it can be concluded that there is currently no single sensor that can give an accurate estimate for all parameters of the oil slick required for spill response.

**Table 4.3: Description of some sensors (adapted from Jha et al, 2008)**

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
|  | Visual | Infrared | Ultraviolet | Radar | Radiometer | Fluorescence laser | Laser acoustics |
| False detection | Seaweed, coastal | Seaweed, coastal | Wind, sunlight, seaweed | Too much interference | Non-significant interferences | Can detect in various media | Little interference |
| Thickness | No | Relative thickness | No | Relative thickness under some conditions | 50 μm – a few mm | < 20 μm | Absolute thickness |
| Spatial resolution | High | High | High | High | Low | High | High |
| Required atmospheric conditions | Clear sky or few clouds | Cloudlessness, precipitation and fog | Clean atmosphere | Any, depends on wind speed | Any, except heavy precipitation | Does not penetrate clouds or fog | Does not penetrate clouds or fog |
| Operates 24h | No | Yes | No | Yes | Yes | Yes | Yes |
| Horizontal cover | Average | ±250 m | ±250 m | ±30 m | ±250 m | ±75 m | Small |
| Dedicated aircraft | No | No | No | Yes | Yes | Yes | Yes |
| Classification of oils | No | No | No | No | No | Yes | No |

### 4.2 Object detection

In Search and Rescue (SAR), the first part of the problem is to develop an estimated area or probability density distribution of the location of the survivors or survivor craft during the period of the next search epoch. The second part is the optimization of the limited and time critical search resources during the next search epoch based upon their capabilities (speed, endurance, detection sensors effectiveness), and the effectiveness of previous searching efforts on the probability density distribution. The effectiveness of each sensor used for SAR is dependent upon the signal of the SAR object above the background noise of the sea surface and the ability of the crew to detect the SAR object.

There are visual and electronic sensors used aboard both surface vessels and aircraft. The effectiveness of sensors for SAR missions has been evaluated in extensive field campaigns where SAR objects are distributed throughout the test area with locations known to the control team, but not to search units. The search units then run or fly their assigned patterns through the test region marking detections. This is repeated several times until enough detection opportunities are achieved across the maximum lateral (sideways) detection range from the search unit. In each lateral range from the search unit’s straight track line, the total number detections in that lateral range bin is divided by the opportunities (detections plus misses) in the lateral range bin. From these field tests the probability detection function of lateral range from the search unit’s track line is calibrated for specific search platform, sensor, search object, and environmental conditions during the search. The probability detection function of lateral range is known as the Lateral Range Curve (LRC) for that search unit’s sensor, search object and under a set of environmental conditions.

#### 4.2.1 Visual detection

Visual sensors include the naked human eye during daylight hours and night-vision goggles (NVGs) during nighttime hours (half-hour after sunset and before sunrise). Visual detection is the primary operational means of detecting SAR objects from both aircraft and surface vessels. Visual LRCs are dependent on the search unit’s speed and altitude of the observers, search object’s size and contrast, on-scene visibility or moon phase and cloud cover (for NVGs), and sea state.

#### 4.2.2 Remote-sensing observations

Electronic sensors include airborne surface search radars and stabilized infrared (IR) sensors (see Figure 4.1 for the electromagnetic spectrum) aboard helicopters. Both radar and IR sensors require *double detection, i.e.* first the search object’s signal has to appear as “hot” pixels above the background noise and then those pixels must be detected by the sensor operator. Electronic sensors have maximum ranges determined by the sensor and its range scale setting. With airborne radars larger scales are generally not preferred for the small SAR search objects, and often large numbers of non-SAR vessels are producing radar hits. Airborne radars for SAR typically have radii of 37-46 km, while searching at 75-90 m/s (150-180 knots). Common SAR search objects typically have very small radar cross-sections (RCS), and therefore relatively weak signals. Larger less common SAR objects (vessels) do have reasonable RCS. Whitecaps present considerable background noise to airborne radars.

Stabilized infrared (IR) sensors aboard helicopters provide night-time capabilities searching for persons-in-the-water. The IR sensor is aimed 90o to the track line of the helicopter and swings 180o on every search pattern leg to always be looking in the same direction. The field of view (FOV) of the IR sensor is very narrow and reaches from a 1 km out to 4-13 km depending on settings. As with airborne radar, the IR sensor must generate a “hot” pixel that is above the background noise of the sea surface, which then has to be detected by the IR sensor operator, who has 3-12 seconds to have objects pass across the FOV. Sea surface noise is primarily from whitecaps and from a surprising amount of IR radiation from the moon; thus wind and moon-phase combined with cloud cover are important environmental inputs into the effectiveness of IR sensors.

### 4.3 Radioactivity

The detection of radioactivity in the ocean is done through collection of seawater, sediment and fish samples, and their preparation and analysis in laboratory; or in situ measurement systems deployed on vessels and oceanographic buoys. In particular, in situ gamma-ray spectrometry has been usefully applied to assess environmental radioactivity because of its ability to directly measure radioactivity on-site, although it generally has a higher detection limit than the sampling and laboratory analysis method. This in situ measurement system can be useful for continuously monitoring the radioactivity at static points. However, stationary monitoring systems may be insufficient for the early detection of abnormal radioactivity over a wide area (Byun et al, 2021).

### REVIEW OF EXISTING CAPABILITIES AND SERVICES

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Chapter 5 provides an overview of the existing capabilities and services relevant to MER. The chapter is divided into three sections: detection and monitoring, operational transport and fate models, and data access and distribution.

### 5.1 Introduction

In the previous chapters, the current best practices in constructing operational prediction systems for the drift and fate of objects and substances in the ocean have been presented. The focus has been on the elements common to systems specialized for oil spills, drifting objects and radionuclide dispersion: geophysical forcing data and the models that produce them, and transport models that estimate how the objects and substances move, spread and diffuse. It has been shown that there are well-established models and services that can be deployed and utilized by new actors and for new classes of objects and substances. The current section presents some important developments that aim to improve the efficiency of prediction services and the quality of their products.

1. Improved ocean circulation forcing data. Improving the accuracy of the ocean circulation models is undoubtedly the single factor that would most improve the quality of any Lagrangian dispersion modelling system. This is a major area of oceanographic research and encompasses not only model development, but also the deployment and maintenance of observation systems and development of the data assimilation schemes that tie them together (Le Traon et al, 2019). Services providing predictions of the drift and fate of objects and substances can, in principle, avail themselves of the best ocean circulation data for their particular area from a variety of sources, from global models to near coastal models – most often in nested combinations. In practice, however, individual operational services continue to rely primarily on their established sources of forcing data, for reasons of reliability. Use of other forcing datasets provide an alternative or supplement to their nominal forcing datasets.

2. Multinational collaboration for model development. Since the development of numerical models and data assimilation schemes of the atmosphere and the ocean is very demanding, the development of open community models supported by distributed development groups has become well established. This is especially advantageous in the context of the deployment drift and fate prediction systems in developing maritime nations. An important requirement for model development is the identification of benchmark tests and cases. In the present context, it is especially valuable to establish a few well-described real cases for which geophysical forcing and verification data are readily available.

3. Access to geophysical forcing data. Suitable technological protocols for data access and transfer are now available to ensure timely and reliable access to forecasts in standardized formats and protocols (especially OpENDAP), and a growing number of data providers are making their operational data accessible online and through machine-machine interfaces, e.g. WIS2.0. It is now possible to download data from numerical prediction models for the atmosphere, waves and the ocean for any part of the world ocean, freely. There is however a caveat: mixing ocean circulation, wave and meteorological datasets from different sources can result in inconsistent forcing data; i.e. the meteorological data applied should be the same as those used to force the wave and ocean circulation models. Lack of consistency is a source of uncertainty in the drift prediction that is difficult to estimate.

Overall, the timely access to geophysical forcing data is improving and is making it more and more feasible to implement drift and fate services in new areas as well as to improve existing services. Still, for many emergency responders and NMHSs, operationally reliable provision of geophysical forcing data through an RSMC type of network would be beneficial.

4. Uncertainty information. Responders usually seek the most likely and the worst-case trajectory predictions. Assessing the accuracy of drift and fate predictions is valuable for responders, but it poses challenges for producers. One significant challenge is quantifying this uncertainty as it increases with time.

Overtime, uncertainties accumulate and can escalate rapidly, even in the early stages of drift prediction, such as within a few days. These uncertainties can result from a variety of factors, including the inherent complexity of ocean dynamics and the challenges associated with obtaining precise forcing data. Consequently, it becomes difficult to provide accurate estimates for trajectory predictions, whether derived theoretically by combining the accuracies of the forcing data or through direct comparisons of model predictions with observed drifts during real events.

Understanding the dynamics of uncertainty growth overtime is essential for both responders and prediction model developers as they strive to make informed decisions during oil spill incidents.

Also, it is a challenge to convey the uncertainty information to the users in an effective manner. In operational systems today, addressing this challenge often involves employing various strategies and tools. These may include visual representations, probabilistic forecasts, and the use of uncertainty quantification techniques.

For instance, probabilistic modelling can provide users with a range of possible outcomes, acknowledging the inherent uncertainty in predictions. Visual aids, such as uncertainty cones or error ellipses, can help users understand the potential variability in trajectory forecasts. Additionally, real-time updates and communication channels are essential for keeping users informed of any changes or updates to the uncertainty estimates.

Drawing on the experience of organizations like the French Drift Committee, which brings together experts in the field to provide unique information to authorities, we can see how collaboration and expertise-sharing can enhance the communication of uncertainty information. Such committees play a crucial role in refining prediction models and conveying the complexities of uncertainty to decision-makers.

Overall, successfully conveying uncertainty information is a critical aspect of operational systems, allowing users to make informed decisions in response to oil spill incidents.

A commonly used approach to the problem is the use of ensemble prediction methods, where several different but equally realistic simulations of the same situation are performed. The distribution of the results gives information about the most probable prediction and about its uncertainty; a narrow distribution indicates higher certainty than a wider distribution. In NWP, wave and ocean forecasting, two avenues of implementation are currently being pursued:

(a) Ensembles generated by the same model using various perturbations of the model system (initial conditions, boundary conditions, model parameters, etc.). Typically, 30–100 ensemble members are run in order to attain sufficient statistical significance. Consequently, this type of ensemble is computationally expensive, and the ensemble production is usually performed at somewhat lower resolution than the main deterministic model run;

(b) Multimodel Ensemble (MME) methods attempt to combine simulations run with different model codes, usually by collating output from several existing prediction systems that cover the same area. The number of ensemble members is usually much smaller (<10), so the focus is more on qualitative assessment of differences rather than statistical uncertainty. The computational cost is less than for the first type, and it is distributed.

Ensemble methods of the first type have been in use in NWP for several decades (see, e.g. Molteni et al., 1996). More recently, they have trickled down to wave and ocean circulation prediction. Even so, it is still a challenge to translate the probabilities into readily understandable information for users.

[5](http://www.ntis.gov/). Ocean surface data. The response to most marine emergency incidents is focused on the ocean surface or the near-surface layer (typically the upper metre). Some ocean model systems do not resolve the vertical column to that resolution, but most model systems have a vertical resolution of a few tens of centimetres near the sea surface. The drift and fate models for MEER and SAR are dependent on accurate knowledge of the near-surface layer, preferably with a finely resolved profile of the currents. Lacking such resolution from the numerical ocean model output, the near-surface variables can be determined by post processing the model output. Such calculations can be done in the transport model or prior to ingestion in the transport model. The major providers of global and regional circulation data should be encouraged to provide near-surface data and/or provide best-practice algorithms for calculating near-surface profiles.

### 5.2 Detection and Monitoring

#### 5.2.1 Marine pollution

As described in Chapter 4, the main way to monitor oil spills is through aerial observation conducted by trained observers. This method is commonly considered essential for an effective response.

Aerial means are commonly used for the detection and monitoring of oil slicks on the surface of the water. Here are some of the aerial methods and instruments used for this purpose:

1. **Visual Observations**: Aerial observers visually scan the water surface from an aircraft to detect the presence of oil slicks. Trained observers look for distinctive visual characteristics such as sheen, discolouration, and patterns on the water surface.
2. **Multispectral Imaging** **systems** are equipped with cameras that capture images in multiple spectral bands, including the visible, near infrared, and thermal infrared regions. These images help distinguish between oil slicks and natural water features by analysing the unique spectral signatures of oil.
3. **Synthetic Aperture Radar (SAR\*)** (not to be confused with search and rescue) mounted on aircraft use microwave signals to capture radar images of the ocean surface. SAR\* is particularly useful for detecting oil slicks, as oil behaves differently from water and produces a distinct signature in the radar imagery.
4. **Hyperspectral imaging systems** capture images across numerous narrow and contiguous spectral bands, allowing for detailed analysis of the reflected light. These systems help identify and differentiate oil slicks based on their unique spectral properties.
5. **Laser Fluorosensors** emit laser beams at specific wavelengths to excite the fluorescence properties of oil on the water surface. By analysing the resulting fluorescence emissions, the presence and characteristics of oil slicks can be determined.
6. **UAVs** equipped with various sensors, such as visible and thermal cameras or multispectral imaging systems, are used for oil slick detection. UAVs provide the advantage of flexibility, manoeuvrability, and lower operational costs compared to manned aircraft.

The choice of aerial means and instruments depends on factors such as the scale of the operation, available resources, environmental conditions, and the desired level of accuracy and resolution. Often, a combination of these methods and instruments is used to enhance the effectiveness of oil slick detection and monitoring efforts.

Depending on the specifics of the situation, additional surveillance methods and tools may be necessary to complement and enhance this primary approach, and to create a comprehensive monitoring strategy. In instances where the area to be monitored is extensive, other tools like satellites may be able to provide swift and broad coverage of the affected area.

Examples of satellite-based monitoring systems are listed in the dynamic part of the Guide.

#### 5.2.2 Search and Rescue (SAR)

Marine search and rescue (SAR) operations involve a range of means to locate and assist individuals in distress at sea. Some common means used for marine SAR purposes and the instruments they are typically equipped with are listed below.

1. **Ships and Vessels** are vital resources for marine SAR operations, offering mobility, stability, and the capacity to carry SAR teams and equipment. They are equipped with various instruments, including:
   * Radar: Vessels are equipped with radar systems to detect and track other vessels, obstacles, or distress signals in the vicinity.
   * Global Navigation Satellite System (GNSS): GNSS (including GPS) devices are used to accurately determine the vessel's position, aiding in navigation and coordinating SAR efforts.
   * Communication Systems: Vessels are equipped with radio communication systems to establish contact with distressed individuals, other vessels, or SAR coordination centres.
   * Searchlights: Powerful searchlights assist in illuminating the search area, enhancing visibility during SAR operations, especially in low-light or nighttime conditions.
2. **Automatic Identification System (AIS)** systems receive signals from vessels equipped with AIS transponders, allowing ships and vessels to track and locate nearby vessels.
3. **Search and Rescue Craft:** Dedicated search and rescue craft, such as lifeboats, fast response vessels, or rescue boats, are specifically designed and equipped for SAR operations. They are equipped with instruments such as:
   * Sonar: Some search and rescue craft are equipped with sonar systems to detect submerged objects or individuals, particularly useful in underwater search scenarios.
   * Navigation Systems: These systems include GPS, radar, and electronic chart displays to ensure accurate navigation and effective search coverage.
   * Rescue Equipment: SAR craft carry specialized rescue equipment, such as life rafts, life jackets, rescue lines, and medical kits, to aid in the rescue and provision of immediate assistance to survivors.
4. **Aircraft:** Aerial means play a crucial role in marine SAR operations, providing rapid and extensive coverage of large areas. Here are some aerial means commonly used for marine SAR purposes along with the instruments they are equipped with:
   * Helicopters are versatile aerial platforms for SAR operations, capable of hovering, manoeuvring in confined spaces, and performing precise rescue operations. They are equipped with various instruments, including:
     + Forward-Looking Infrared (FLIR) cameras: These cameras detect heat signatures and help locate survivors in the water, even during low-light or nighttime conditions.
     + Searchlights: Powerful searchlights assist in illuminating the search area, enhancing visibility for both the crew and survivors.
     + Winches: Helicopters equipped with winches allow for the extraction of survivors from the water or challenging terrain.
   * Fixed-wing aircraft, such as aeroplanes, are utilized for covering larger search areas efficiently. They are equipped with instruments such as:
     + Radar: Aircraft-mounted radar systems, including maritime surveillance radar, are employed to detect and track vessels or objects in the water, assisting in search operations.
     + Electro-optical/Infrared (EO/IR) sensors: EO/IR sensors capture visual and thermal imagery, aiding in the identification of survivors, vessels, or debris.
     + AIS receivers: AIS receivers receive signals from vessels equipped with AIS transponders, allowing aircraft to track and locate nearby vessels.
   * Unmanned Aerial Vehicles (UAVs), commonly known as drones, are increasingly being utilized in SAR operations due to their manoeuvrability, versatility, and lower operational costs. They can be equipped with various instruments, including:
     + High-resolution cameras: These cameras provide detailed imagery of the search area, allowing operators to spot survivors or distressed vessels.
     + Thermal cameras: Thermal imaging sensors mounted on drones can detect body heat signatures, aiding in the detection and location of survivors in the water.
     + Real-time video transmission: UAVs equipped with video transmission capabilities enable SAR personnel to view live aerial footage, facilitating real-time decision-making.

The specific instruments and equipment used can vary based on the resources, technology, and operational requirements of each SAR organization or country. Additionally, specialized SAR teams may have access to additional equipment like rescue hoists, medical equipment, and survival gear to facilitate effective rescue operations.

#### 5.2.3 Radionuclides in the ocean

The main way to detect and monitor radionuclides in the ocean is through in situ measurement systems. Examples of marine radioactivity information systems are provided in the dynamic part of the Guide and mentioned in Chapter 4.

### 5.3 Operational Transport and Fate Models

#### 5.3.1 Oil spill

The response to oil spill incidents includes the discovery, monitoring and assessment of the spill; deployment of equipment to reduce the scope of the spill (e.g. booms and chemical treatment); remedial actions like the clean-up of coastlines, bottom sediments and wildlife; and legal and financial repercussions.

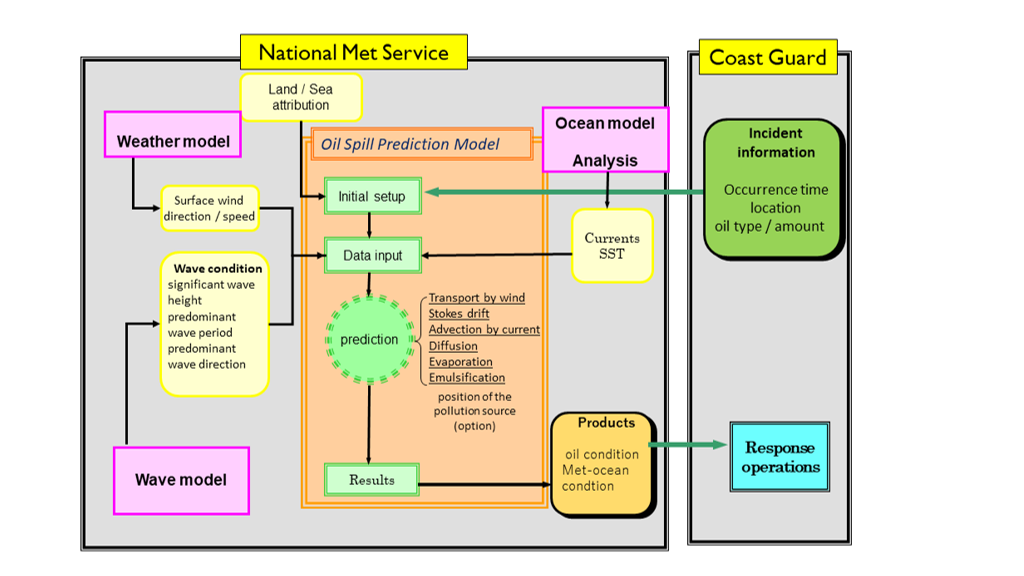
Traditionally, prediction of the drift of substances spilled in the ocean has been based on local knowledge of currents, wind and wave conditions, tidal charts and static current charts, as available. In many countries, this is, in reality, still the case, but over the past few decades, more sophisticated prediction systems have been developed and implemented in many countries around the world. These systems are based on numerical models that utilize available numerical forecasts of winds, currents and waves to calculate the likely drift and spreading of a spilled substance.

From a handful of pioneering services in the 1980s, there are today oil spill forecasting services in operation in most of the developed maritime countries and more are under development. Since nation-states are responsible for the protection of their coasts and of resources in their exclusive economic zones, oil spill forecasting is primarily implemented as a national public service. Regional or other transboundary services are feasible and are being actively explored, e.g. within the WMO framework (Appendix II) and regional examples presented below. However, global operational services are few, but, for example, Météo-France is running one. On the other hand, there are a number of commercial providers delivering special services to, for example, oil companies, and some have an international scope (see Hackett et al., 2009, for an example). However, the advent of openly accessible global ocean and atmosphere forecasts (see, e.g. the Copernicus Marine Service presented by Le Traon et al, 2019) means that users can now easily set up new services for arbitrary regions of the world. This can be done using open-source trajectory models (see, e.g. Dagestad et al, 2018), albeit typically with coarser resolution than what regional forecast systems can provide.

##### 5.3.1.1 Review of existing capabilities

The model settings and the forecast performance are also dependent on the nature of the spill. If a large oil spill incident occurs offshore, a wider region is required for the simulation, so that all potentially affected areas are covered. It also requires long-range predictions, including chemical weathering. On the other hand, a limited area could be sufficient for minor spills, but here high-resolution forcing fields are required. In this case, weathering processes might even be unnecessary if remedial action can be carried out quickly. As time is of the essence, a simplified forecast based on limited information is very often how the first oil spill simulations are performed after an incident is reported.

As noted in Section 2.1 and Appendix II, the forecast fields used to force the oil drift simulations may have large errors, which in turn propagate into the forecasts of the oil drift and fate model, which in turn has its own inaccuracies. For the emergency responders, information about the uncertainties in the predictions is valuable. The use of ensemble prediction methods is one approach that is gaining traction in modern oil spill prediction.



**Figure 5.1: Outline of an oil spill prediction operation exemplified by the system at JMA.**

A typical oil spill prediction operation is indicated in Figure 5.1. Once an oil spill incident is reported, relevant information about the spill necessary for initializing the oil spill model is acquired or estimated. The oil spill prediction is then conducted with the available input data, and the predicted results are provided to the emergency response authorities. A critical process to ensure accuracy for ongoing events is for the field responders to report back any observations of oil locations or conditions from aerial observations or other means. These observations can be used to calibrate the oil spill model, and improve future forecasts.

Spill characteristics vary from incident to incident, e.g. the amount of oil, whether it is a simultaneous or continuous spill, and the location (sea-surface, deep water, fixed point, floating vessel, etc.). How to set the initial conditions depends on the system and the information provided. As for monitoring, oil slicks have long been detected and tracked from aircraft and ships. In the last couple of decades, satellite-based Synthetic Aperture Radar (SAR\*) has proven to be a powerful tool for analysing the spill situation, and the information can be used as initial conditions in some advanced oil spill models (Klemas 2010; Zodiatis et al. 2012).

Rapid and reliable access to the required forcing data is essential for an operational oil spill prediction system, so it is common that such systems are run by NMHSs, or a close affiliate, using in-house operational forcing data.

At the start and end of the production chain is the important task of communication with responders and other users, including dissemination of results. In most national services this is tasked to a team of duty operators with 24/7/365 availability. They run the forecast models, deliver results to users in agreed forms and consult with in-house experts for interpretation and advisories. In some cases, users are offered a web-based online service so that they can perform their own simulations and download results directly to, for instance, their onboard ECDIS.

##### 5.3.1.2 Multinational efforts on oil spill monitoring and forecasting

Best practices of coordination and integration at multinational level have been developed in several regional seas for supporting the management of oil spill forecasting. Examples of multinational efforts on oil spill monitoring and forecasting systems are provided in the dynamic part of the Guide.

##### 5.3.1.3 Model intercomparison initiative

Knowing and predicting the behaviour and transport of oil slicks in the event of a spill is crucial for directing resources and preparing coastal sites. Cedre[[5]](#footnote-6) established an intercomparison programme in 2019 to analyse the performance and limitations of various oil drift models through testing and comparing different scenarios. The programme was conducted with the assistance of the French Drift Committee, which included Cedre, Météo-France, Shom, and IFREMER. Out of the 26 models tested, 11 were selected for analysis, and eight were chosen for operational use. Since 2021, exercises with oil slick tracking buoys have been held in French Guiana, the Mediterranean, and the Bay of Biscay, with plans for an annual exercise. The Drift Committee compared multiple models and found that using different oil transport models was important. However, to maintain efficiency, a maximum of three or four models were analysed, while the possibility of using multiple meteorological and oceanic data sets for the same drift model was not excluded. Monitoring the drift of buoys in near-real-time was deemed important to recalibrate models in case of a lack of pollution observations. Such exercises provide an excellent opportunity to deepen knowledge of models and hydrodynamic conditions in little-studied or complex regions, thereby enhancing preparation for real pollution management.

##### 5.3.1.4 Examples of existing capabilities

Examples of oil spill monitoring and forecasting systems are provided in the dynamic part of the Guide.

##### 5.3.1.5 Expected developments for improved services

This section presents some important developments that aim to improve the efficiency of oil spill prediction services and the quality of their products.

1. Multinational collaboration for oil spill model development. Operational oil spill modelling started with proprietary model codes for use in a commercial market. Only in the last decade has collaboration on model development and the development of open codes made real progress. The development of open community model codes is especially advantageous in the context of deployment of spill models in developing maritime nations. A few collaborative efforts of this type have been established, but there is scope for expanding the development framework (Barker et al., 2020).

An important requirement for model development is the identification of benchmark tests and cases. It would be especially valuable to establish a few well-described real oil spill cases for which forcing and validation data are readily available.

2. Multinational collaboration for improved services. The advantage of collaboration between national drift prediction services has already been mentioned in the context of multimodel ensemble forecasting (MME). Beyond the exchange of model outputs, there is potential advantage in collaboration on other links in the production chain. For example, robust exchange of forcing data, initial conditions (detection data), agreed file formats, visualization methods, archiving of test case data, etc.

Another aspect of multinational collaboration is support of development in maritime nations that currently lack adequate spill prediction services of their own. Alternatively, sharing services at regional level is feasible, given the improving access to forcing data and drift model codes, and can be a cost-effective way forward. While all of the world's oceans can be covered by global systems run in a few developed countries, the need for detailed information near the coast implies that there is ultimately a need for drift prediction services at local scales in support of local response to emergencies.

3. Specific oil spill model functionalities. Spill fate models have been developed with somewhat different functionalities depending on the most important local requirements. However, there is a movement toward more comprehensive model capabilities. The following is a list of model capabilities that have been seen limited implementation, but that should be made more widely available:

* characteristics of noxious substances other than oil
* oil in sea-ice
* coupling of substance drift model to ship drift model
* subsurface source (and three-dimensional modelling)
* reinitialization of spill geometry according to observations
* include tidal currents in areas where available ocean model data do not
* reverse (backward) calculation option, or ideally forward runs from a prior distribution with the ability to update a posterior search for the origin based on observed pollution
* include access to climatological forcing data for long-range (weeks to months) prediction

4. Standard framework for spill information exchange. Currently, there are no standards for how oil spill information is formatted and exchanged. Schemes vary among national services and regional alliances. The differences may come from specific requirements, but it is desirable to define a common standard that is independent of specific forecasting systems. This can promote cooperation between information providers and users, as well as facilitating collaboration among forecast producers at national, regional and international levels. The Trajectory NetCDF format is a promising candidate for the exchange of trajectories from Lagrangian models. It is also compliant with the Climate and Forecast convention (CF), but is still under development[[6]](#footnote-7).

#### 5.3.2 Search and Rescue (SAR)

In the following, the focus is primarily on SAR response methods since they are certainly the most comprehensive and well-established and form the basis for treating all other drifting objects. Responses to non-SAR drifting objects are more specific to regions and industries and are not (yet) covered by global frameworks similar to those for SAR. Non-SAR objects are, however, increasingly in the public awareness and more object classes are now being addressed by various response agencies, e.g. cargo containers, plastics, sargassum, pumice and ash. Non-SAR objects are briefly discussed at the end of this section.

##### 5.3.2.1 Review of existing capabilities

With the advent of high-resolution operational ocean models and the continued improvement of NWP, the potential for making more detailed predictions of the fate of drifting objects has grown tremendously in the past two decades (Breivik et al., 2013). However, although the improved weather forecasts led to better forcing, drift models have remained somewhat impervious to the advances in ocean modelling and numerical weather forecasting. This can perhaps best be understood in light of the large uncertainties in the drift properties of SAR objects as well as the accuracy of the forcing data used.

Firstly, without a proper estimate of the basic drift properties and their associated uncertainties, forecasting the drift and expansion of a search area remains difficult. An important change came when the direct method for measuring the leeway of a drifting object became common practice (Allen and Plourde, 1999; Allen, 2005; Breivik et al., 2011; Hodgins and Mak, 1995; Hodgins and Hodgins, 1998), as explained in Chapter 3.

Secondly, as with oil spill prediction modelling, there is a crucial dependence on the accuracy of the wind and current data. Again, it is the currents that are the least accurate and represent the larger source of uncertainty in the drift predictions (Breivik et al, 2013).

It was not until the 2000s that all the necessary components required for fully stochastic modelling using high-quality drift coefficients and detailed current and wind forecasts were in place. The first operational leeway model to employ the USCG table of drift coefficients (Allen and Plourde, 1999) with high-resolution ocean model current fields and near-surface wind fields went operational in 2001 (see Hackett et al. 2006; Breivik and Allen 2008; Davidson et al. 2009). The modern era of SAR planning involving the Bayesian posterior updates after the search began in earnest in 2007 when USCG launched the Search and Rescue Optimal Planning System (SAROPS), see Kratzke et al. (2010). SAROPS employs an environmental data server that obtains wind and current predictions from a number of sources. It recommends search paths for multiple search units that maximize the increase in probability of detection from an increment of search. It computes Bayesian posterior distributions on object location accounting for unsuccessful search and object motion. Recent work in the Mediterranean Sea (Coppini et al. 2016) demonstrated the operational capability to support SAR operations through the implementation of the Leeway model (Breivik and Allen, 2008) with CMEMS forecast fields of surface currents.

Although the level of sophistication and detail has grown dramatically in the past two decades, the uncertainties in SAR predictions remain stubbornly high. The fundamental challenge of estimating and forecasting search areas in the presence of large uncertainties remains essentially the same, even though certain error sources have been diminished. The slow progress that has been made over the past decades in reducing the rate of expansion of search areas (perhaps the single best estimate of improvement) is an unavoidable consequence of SAR planning being affected by a variety of errors in the current fields, the wind fields, missing physical processes (e.g. wave effects, see Breivik and Allen 2008; Röhrs et al. 2012), the uncertainty in the LKP and not least from poor estimates of the real drift properties of the object. Indeed, sometimes the type of object may not even be known, effectively making the modelling exercise into an ensemble integration spanning a range of object categories. All these error sources accumulate and make SAR planning as much art as science, where rescuers still often rely as much on their “hunches” as on the output of sophisticated prediction tools. The fact that most SAR cases occur near the shoreline and in partially sheltered waters (Breivik and Allen, 2008) compounds the difficulties as the resolution of operational ocean models in many places of the world is still insufficient to resolve nearshore features. These advances and obstacles to further progress were presented through a series of workshops organized on "Technologies for Search and Rescue and other Emergency Marine Operations" (2004, 2006, 2008 and 2011) organized by the French marine research institute IFREMER with support from the Norwegian Meteorological Institute, USCG, the French-Norwegian Foundation and the Joint WMO-IOC Technical Commission for Oceanography and Marine Meteorology (JCOMM).

##### 5.3.2.3 Examples of existing capabilities

Most search and rescue software are Monte Carlo based systems that use ensembles of large numbers of simulated objects to define search areas. Examples of SAR systems are provided in the dynamic part of the Guide.

##### [5.3.2.4 Expected developments for improved services](https://docs.google.com/document/d/1W4j_y19GhirfnG-6c9I3ERuI3TnrZ070/edit?usp=sharing&ouid=108964075871566208871&rtpof=true&sd=true)

The current section presents some important developments that aim to improve the efficiency of prediction services and the quality of their products.

1. Continued field work is crucial to expand the taxonomy of search objects and to revisit objects that have only been studied with older field methods.
2. Higher horizontal resolution forcing data is still a major issue given that most SAR cases occur near the coast (Breivik et al., 2013). Increased model resolution for operational data helps the system to “see” more details of the coastal waters (islands, fjords, etc.), and also holds the promise of producing more realistic motion of the objects.
3. Deployment of HF coastal radars. Since SAR operations tend to occur near the coast, there is also potential benefit in using observed current fields from HF radar. These observations may be used directly or blended with ocean model results to give a short-range forecast, although their time horizon is limited to about 24 hours (see, e.g. Barrick et al., 2012). What is more, the data may be assimilated into the ocean model to improve the current forecasts.
4. Ensemble modelling of surface currents are increasingly used to get a handle on the uncertainty associated with the forcing fields. As most operational SAR models are ensemble (particle) based, spreading ensemble members on a variety of forcing fields is straightforward. Ensembles of wind fields would also be useful, but the uncertainties are smaller in the first 48 hours, and most searches require relatively short forecasts.
5. Multinational collaboration for improved services. The advantage of collaboration between national drift prediction services has already been mentioned in connection with oil spills. The same benefits may be attained for SAR operations, particularly at the regional level since most of them take place near the coast.
6. Archived model fields and hindcasts – Reverse trajectories and forward runs are useful for rescue teams trying to identify the site of an accident or incident. Archives of past forecast and/or analysis fields of winds and currents at regular time steps may assist authorities to quickly determine the most likely search areas.

##### 5.3.2.5 Marine Debris and Hazards to Navigation

Similar to typical SAR objects and oil spills, floating marine debris may need to be tracked to enable clean-up or to mitigate their danger to vessels. These objects include shipping containers lost overboard, the floating contents of damaged shipping containers, plastic trash transported into the ocean from rivers or thrown overboard, debris from aircraft crashes and sinking vessels, excessive sargassum, as well as natural debris from floods or flooded rivers (e.g. tree trunks) and from volcanoes (pumice and ash). Other than shipping containers, the direct measurement of the leeway characteristics of marine debris has not been possible due to their typical size (i.e. smaller than the present generation of current metres).  However, a technique suggested by Sutherland et al. (2020) might be applied in specific cases to back out the leeway of the drift objects in question.

The response to non-SAR objects is closer to the response to oil spills than to SAR craft and survivors. This is due to the diversity of non-SAR objects and lack of knowledge of their leeway characteristics. Furthermore, the goal is mitigation of damage and a focus on clean-up, rather than the saving of lives. Many of these objects do not deteriorate very fast or at all, except for shipping containers that eventually sink and dead whales that bloat, deflate, or are consumed before sinking or beaching. As with oil spill modelling, many thousands of objects can be involved in an incident, thereby generating a distribution of the actual objects that can be compared with the modelled particle distribution.

**Sargassum**

Sargassum is a type of seaweed that is found in the open ocean. It is an important habitat for fish, turtles, and sea birds. However, in recent years, there has been a significant increase in the amount of sargassum washing up on the shores of the Caribbean islands. This phenomenon, known as the sargassum invasion, has caused significant economic, environmental, and social impact on the region. The sargassum invasion in the Caribbean islands began in 2011 and has continued to worsen each year. In 2018, the invasion reached unprecedented levels, with over 20 million metric tons of sargassum washing up on the shores of the Caribbean islands (Wang et al., 2019). This has caused significant damage to the tourism industry, as many tourists are deterred by the sight and smell of the seaweed. The sargassum invasion has also had negative effects on the environment. As the seaweed decomposes, it depletes the oxygen levels in the water, which can lead to the death of marine life such as fish and corals. The invasion has also disrupted the nesting habitats of sea turtles, which has had a significant impact on their populations. The invasion has also had social impacts on the local communities in the Caribbean islands. The seaweed can make it difficult for fishermen to access the ocean, as it can clog their nets and propellers of their motors.

To help mitigate the impacts of the sargassum invasion, several agencies have developed observation and forecasting systems to help track the movement of the seaweed and predict where it will wash up on shore. These systems use satellite imagery, oceanographic models, and field measurements to gather data on the location, concentration, and movement of sargassum in the ocean.

The Sargassum Watch System (SaWS) of the University of South Florida (USF) – a satellite-image based model – serves as an early warning system for Sargassum blooms (Wang and al., 2019). Monthly outlooks of Sargassum occurrence, based on model outputs, are made available on its website[[7]](#footnote-8).

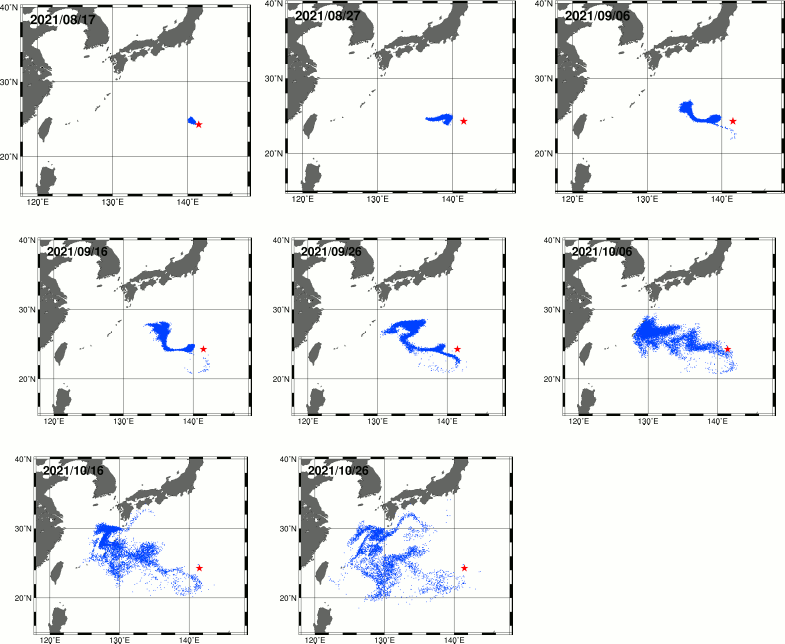
Since 2019, Météo-France has provided weekly Sargassum surveillance updates for local authorities in the French Antilles to predict the risk of upcoming landings of Sargassum mats and help organize timely clean-up crews. The bulletins present a simple cartography of the coasts concerned, with a risk index and 4-day, 2-week and 2 month forecasts of Sargassum inundation. These bulletins are produced using the MOTHY drift model of Météo-France fed by Copernicus satellite observation data and Mercator Ocean International ocean forecasting models.

Example of a sargassum stranding risk map for Martinique based on satellite observations and forecasts by the MOTHY drift model (<https://meteofrance.mq/fr/sargasses>).

**Pumice**

Pumice is a type of porous, floating volcanic rock produced by volcanic eruptions. From 13 to 16 August 2021, the submarine volcano Fukutoku-Oka-no-Ba in the Ogasawara Islands erupted and emitted huge amounts of pumice (Yoshida et al., 2022). The pumice floated westward in the south Sea of Japan for a couple of months, and arrived at coasts and bays in Okinawa Islands, 1,400 km west of the volcano. The pumice caused engine troubles for local fishing vessels and obstructed ship traffic for weeks. The beaches covered by pumice affected tourism, and many daily activities were suspended. The pumice usually floats for considerable amounts of time although it will sink eventually. Pumice can easily be modelled as drifting objects, but long-term monitoring and repeated simulations are required.

Figure 5.2 depicts a trial simulation result for the pumice drift in 2021, conducted at JMA. The large emission of pumice by the volcano Fukutoku-Oka-no-Ba was set on 16 August as the initial condition, the pumice basically floated in the south of Japan. It gradually moved westward but largely spread in early October, by stormy conditions caused by a passing typhoon. The considerable amount of pumice arrived at the coast of Okinawa on 6 October in simulation, but pumice was detected on 15 October in reality. The floating pumice headed to the main island of Japan due to Kuroshio current too.



**Figure 5.2 10-day drift simulation results for the case of pumice in 2021. A calculation for 90 days conducted from 16 August**

#### 5.3.3 Radioactive material

A marine modelling system for the simulation of radioactive material dispersion consists of ocean circulation model and radionuclide dispersion model (see, e.g. Simonsen et al., 2017, 2019). The ocean circulation model provides the structure of the ocean, such as currents, eddies, and water densities from the sea surface to the bottom.  The radionuclide dispersion model calculates the movement of the materials based on the ocean structure by the circulation model, taking the information of release source term (time of release, quantity, and chemical form of material) both for a direct release into the sea and from the atmospheric deposition. Since 2012, there have been a number of studies coordinated by the International Atomic Energy Agency (IAEA), which are related to two marine releases of radionuclides: (i) the release of Chernobyl with fallout into the Baltic Sea (Periáñez et al., 2015 a); and (ii) the release from the Fukushima Daiichi nuclear power plant into the Pacific Ocean (Periáñez et al., 2015b). These studies are summarized in Appendix IV. As for the agreement between IAEA and WMO regarding shared and individual responsibilities for radionuclide scenario simulations and result dissemination, the details can be found in Appendix I.2.

As has been shown from these studies (see Appendix IV), there are useful models for the drift and fate of radioactivity in the ocean. Prediction services can readily be adapted from existing drift and fate services for, e.g. oil spills, and can be deployed and utilized by new actors and for new regions. The current section presents some important developments that aim to improve the efficiency of radionuclide dispersion prediction services and the quality of their products.

1. Access to source data, radionuclide field measurements, and development of inverse technique for evaluation of source term. The information of release source term (location and time of release, duration and quantity of release, and chemical form of radioactive material) both for a direct release into the sea and from the atmospheric deposition is a key element. Accessing the output from current atmospheric models has become significantly more accessible and convenient than in the past. Many research organizations and government agencies have embraced open data initiatives, making their model outputs openly accessible to the broader scientific community and the public.

2. Uncertainty information. For radioactive material drift and dispersion prediction modelling, both single model ensemble and MME methods are viable. For example, it is quite feasible to obtain a suite of forcing data sets to force the same radioactive material drift and dispersion model. Conversely, in some areas there are already a number of operational radioactive material drift and dispersion prediction systems that overlap geographically; agreements need to be made about performing forecasts for events within the common area.

3. Multinational collaboration for model development. The development of open community model codes is especially advantageous in the context of deployment of radioactive material drift and dispersion models in developing maritime nations. An important requirement for model development is the identification of benchmark tests and cases. It would be especially valuable to establish a few well-described real cases for which forcing and validation data are readily available.

4. Multinational collaboration for improved services. The advantage of collaboration between national drift prediction services has already been mentioned in connection with the Fukushima accident above, and in the more formal context of multimodel ensemble forecasting (MME). Beyond the exchange of model outputs, there is potential advantage in collaboration on other links in the production chain. For example, robust exchange of forcing data, initial conditions (detection data), agreed file formats, visualization methods, archiving of test case data, etc.

Another aspect of multinational collaboration is support of development in maritime nations that currently lack adequate radioactive material drift and dispersion prediction services of their own. Sharing services at regional level is a feasible alternative, given the improving access to geophysical forcing data and drift model codes, and can be a cost-effective way forward. While all of the world's oceans can be covered by global systems run in a few developed countries, the need for more detailed information near the coast implies that there is ultimately a need for drift prediction services at local scales in support of local response to emergencies. A regionalized support system, along the lines of the RSMC network, could be an effective instrument for WMO support to developing Member States, especially for radionuclide emergency response.

5. Specific model functionalities. Radioactive material drift and dispersion models have been developed with somewhat different functionalities depending on the most important local requirements. However, there is a movement toward more comprehensive model capabilities. (The IAEA’s Programme on MOdelling and DAta for Radiological Impact Assessments (MODARIA), WP10: Modelling of marine dispersion and transfer of radionuclides accidentally released from land-based facilities.) The following is a list of model capabilities that have seen limited implementation, but that should be made more widely available:

* Radioactive material in sea-ice
* Combination of direct release into the sea (surface or subsurface) and atmospheric deposition
* Development of a radionuclides’ database including 137Cs, 134Cs, 90Sr, 131I, T, 99Tc, etc., that provides the parameters of interaction with particulate material, biota and humans in the water column and atmosphere/sea water/sediment interfaces
* Reinitialization of radioactive material volume and location according to observations
* Transfers to the biological and sedimentary compartments
* Include tidal currents in areas where available ocean model data do not
* Include access to climatological geophysical forcing data for long-range (weeks to months) prediction
* Standards for radioactive material drift and dispersion model data exchange

### 5.4 Data Access and Distribution

#### 5.4.1 Atmosphere and ocean data

The progress in technological solutions for accessing and transferring data from the atmosphere and ocean has revolutionized the field of drift modelling. With the advent of OPeNDAP and specific APIs for accessing ocean model output, combined with the increasing number of data providers offering online access and machine-machine interfaces like WIS2.0, users can now effortlessly download the necessary data from numerical prediction models.

There are several services and platforms that provide access to numerical data from atmosphere and ocean models. Here are a few examples:

NCEP[[8]](#footnote-9), operated by the National Weather Service (NWS) in the United States, offers access to a wide range of atmospheric and oceanic numerical prediction models. Their website provides access to datasets such as weather forecasts and oceanic data.

The European Centre for Medium-Range Weather Forecasts (ECMWF)[[9]](#footnote-10) is an international organization that provides access to state-of-the-art atmospheric models and data. They offer a range of services, including the ECMWF Web API, which allows users to access and retrieve atmospheric model data programmatically.

The Copernicus Marine Service (CMEMS)[[10]](#footnote-11) is a European initiative that provides access to a wealth of oceanographic data and products. It offers both free and premium subscription services, allowing users to access ocean model data, satellite observations, and other marine-related information.

The Integrated Ocean Observing System (IOOS)[[11]](#footnote-12)is a U.S.-based programme that integrates data from various sources, including atmospheric and oceanic models, to support ocean observation and forecasting. They provide access to a diverse range of datasets through their Data Catalogue, which includes atmospheric and oceanic numerical model outputs.

These examples represent just a fraction of the services available worldwide. Many national meteorological and oceanographic agencies also provide access to their respective numerical models and datasets through online platforms, APIs, and data portals.

#### 5.4.2 Drift prediction data

The distribution of drift model predictions to end users can occur through various channels depending on the specific context and requirements. Here are some common methods of distributing drift model predictions:

1. Web-based Platforms: Drift models can be integrated into web-based platforms or portals accessible to end users. These platforms provide interactive interfaces where users can input parameters, such as location and time, and view the corresponding drift predictions. The predictions can be displayed as maps, graphs, or other visualizations.
2. Decision Support Systems (DSS): Drift models can be integrated into dedicated decision support systems. These systems provide a comprehensive framework for oil spill or SAR response and management, including data input, model integration, and visualization of predictions. The DSS can be accessed through specialized software installed on users' computers or via web-based interfaces.
3. Mobile Applications: Drift predictions can be distributed through mobile applications that are specifically developed for oil spill or SAR response and management. These applications can provide real-time access to model predictions, allowing users to monitor and track oil spill/SAR targets movement on their mobile devices.
4. Email Alerts or Notifications: Users can subscribe to email alerts or notifications from the drift model system. When significant changes occur in the predicted drift patterns or when certain thresholds are exceeded, automated email alerts can be sent to the subscribed users, providing them with the latest predictions and updates.
5. Data Sharing Platforms: Drift model predictions can be shared through data sharing platforms or repositories, where users can access and download the predictions in standardized formats. These platforms facilitate the exchange of information and allow users to incorporate the predictions into their own systems or analysis.
6. Dedicated APIs: Drift model systems can provide APIs (Application Programming Interfaces) that allow users to programmatically access the model predictions. By integrating these APIs into their own applications or systems, end users can retrieve the predictions and use them for their specific purposes.

The specific method of distribution depends on factors such as the target audience, the technical capabilities of the end users, the level of interactivity required, and the existing infrastructure in place. Organizations responsible for oil spill / SAR response and management typically choose the most appropriate distribution method to ensure that end users can access and utilize the drift model predictions effectively.

## APPENDIX I – GLOBAL AND INTERNATIONAL FRAMEWORK/INTERNATIONAL CONVENTIONS

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### I.1 Relevant International Conventions and International Framework for Emergency Response

***Marine Pollution (Oil spills) Operations***

|  |  |
| --- | --- |
| Responsible international organization | The **International Maritime Organization (IMO)** is the United Nations specialized agency responsible,inter alia, for preventing pollution from ships. It is responsible for an International Convention directly relevant to Marine Environmental Emergency Response (MEER) - see Convention below.  The IMO’s Marine Environment Protection Committee (MEPC) is the subsidiary body of the IMO Assembly that considers all matters concerning the prevention and control of marine pollution from ships, covered by the Convention. Marine pollution includes: oil, chemicals carried in bulk, sewage, garbage and emissions from ships. Ballast water management, anti-fouling systems, ship recycling, pollution preparedness and response and identification of special areas and sensitive sea areas are also considered. In particular, it is concerned with the adoption and amendment of Convention and other regulations and measures to ensure their enforcement. Several Subcommittees support the MEPC work, of which the Subcommittee on Pollution Prevention and Response (PPR) has most directly relevant to the MEER agenda. |
| [International Conventions and documentation](https://www.imo.org/en/about/Conventions/Pages/ListOfConventions.aspx) | **INTERNATIONAL CONVENTION RELATING TO INTERVENTION ON THE HIGH SEAS IN CASES OF OIL POLLUTION CAUSALITIES, (1969) and PROTOCOL RELATING TO INTERVENTION ON THE HIGH SEAS IN CASE OF POLLUTION BY SUBSTANCES OTHER THAN OIL (1973)** aims to confer power on the Coastal State to intervene on the high seas in the event of a pollution causality threatening to damage, or damaging its coastline or related interests.  **INTERNATIONAL CONVENTION FOR THE PROTECTION OF POLLUTION FROM SHIPS (MARPOL 73/78)** aims to eliminate marine pollution by oil and other harmful substances, and sewage and garbage. Improvement of control of operational discharges of oil and reduction of the amount of oil released through incidents are the most important issues in the Emergency Prevention Preparedness and Response (EPPR)-area. Certain valuable areas are designated MARPOL-Special Areas. The Arctic Area has not yet been designated as such an area.  **INTERNATIONAL CONVENTION ON OIL POLLUTION PREPAREDNESS, RESPONSE AND COOPERATION (OPRC 1990) and PROTOCOL ON THE PREPAREDNESS, RESPONSE AND COOPERATION ON POLLUTION INCIDENTS BY HAZARDOUS AND NOXIOUS SUBSTANCES (OPRC-HNS Protocol 2000)** cover two of the areas in EPPRs purview but also discusses contingency planning, training and cooperation in research programmes. |
| Any international coordination boundaries | Nil, deferred to Coastal State. |
| Responsibility for responding | National |
| Operational response requirements | Safety and efficiency of clean-up crews, assessment of lifetime for oil to disperse, forecast movement of oil. |
| How is the incident reported | Ships are responsible for reporting oil spills to the national authority. |
| How is the response coordinated | The national authority is responsible for initiating their response plan and arranging for metocean information support. |

***Search and Rescue (SAR) Operations***

|  |  |
| --- | --- |
| Responsible international organization | **IMO** is the United Nations specialized agency responsible,inter alia, for safety and security of international shipping. It is responsible for an International Convention directly relevant to MER and Search and Rescue (SAR) - see Convention below.  The IMO’s Maritime Safety Committee (MSC) is the subsidiary body of the IMO Assembly that consider all matters concerning with aids to navigation, construction and equipment of vessels, manning from a safety standpoint, rules for the prevention of collisions, handling of dangerous cargoes, maritime safety procedures and requirements, hydrographic information, log-books and navigational records, marine casualty investigations, salvage and rescue and any other matters directly affecting maritime safety. The MSC has several Subcommittees to support its mandate, including the Navigation, Communication, Search and Rescue (NCSR), which in turn has an ICAO/IMO Joint Working Group on Harmonization of aeronautical and maritime search and rescue. |
| [International documentation](https://www.imo.org/en/about/Conventions/Pages/ListOfConventions.aspx) | The **International Convention for the Safety of Life at Sea, 1974 (SOLAS) (the Safety Convention)** includes all IMO Member States as well as those countries which are party to conventions such as SOLAS even if they are not IMO Member States.  The **International Convention on Maritime Search and Rescue, 1979 (the SAR Convention)**.  The **International Aeronautical and Maritime Search and Rescue Manual (IAMSAR)** outlines the procedures for coordinating SAR operations. The Manual defines the drift characteristics of objects in relation to the effects of winds and currents. |
| Any international coordination boundaries | Both the IMO and the International Civil Aviation Organization (ICAO) sponsor global SAR plans, allocating Search and Rescue Regions (SRRs) to nations.  SRR were developed by the ICAO and IMO in consultation with member nations, and often reflect existing flight regions and proximity to countries.  A SAR Authority is responsible for the coordination of SAR during a maritime or aviation distress situation in their allocated SRR. |
| Responsibility for responding | Joint Rescue Coordination Centre (JRCC) or designated national authority. |
| Operational response requirements | Safety and efficiency of search crews, assessment of person ST, forecast movement of object or person. |
| How is the incident reported | Ships are responsible for reporting persons overboard to the national authority. Missing vessels or persons may be reported to the JRCC through the Global Maritime Distress and Safety System (GMDSS). |
| How is the response coordinated | The JRCC or designated national authority is responsible for coordinating the search operation and arranging for metocean information to support drift assessments and search planning. |

***Emergency response to Radionuclide Dispersion in the Oceans***

|  |  |
| --- | --- |
| Responsible international organization | **IAEA** is the intergovernmental agency focused on scientific and technical cooperation in the nuclear field. This includes working towards safe, secure and peaceful uses of nuclear science technology. Given the high risk of nuclear hazards, it plays a role in environmental emergency response, especially through safeguarding measures and monitoring of hazardous substances.  The IAEA carries out R&D activities addressing marine pollution at its Marine Environmental Studies Laboratory. The Laboratory’s work focuses on developing and validating analytical methods for the measurement of contaminants in marine samples. |
| [International documentation](https://www.iaea.org/topics/conventions) | The **International Convention on Early Notification of a Nuclear Accident**, adopted in 1986 following the Chernobyl nuclear plant accident, establishes a notification system for nuclear accidents from which a release of radioactive material occurs or is likely to occur and which has resulted or may result in an international transboundary release that could be of radiological safety significance for another State.  The **Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency**, also adopted in 1986 following the Chernobyl nuclear plant accident, sets out an international framework for cooperation among States Parties and with the IAEA to facilitate prompt assistance and support in the event of nuclear accidents or radiological emergencies.  Good planning in advance of an emergency can substantially improve the response. To this end, the [Joint Radiation Emergency Management Plan of the International Organizations](https://www.iaea.org/publications/11163/joint-radiation-emergency-management-plan-of-the-international-organizations) was developed. It is maintained by the IAEA and includes the international organizations that are party to the Conventions (including WMO), as well as some international organizations that participate in the activities of the Inter-agency Committee on Response to Nuclear Accidents.  The IAEA established the Incident and Emergency Centre (IEC) in 2005 to provide round-the-clock assistance to its Member States in dealing with nuclear and radiological events, including security-related threats, by coordinating the efforts, contributions and actions of experts within the IAEA, Member States and international organizations. IEC is the global focal point for international emergency preparedness, communication and response to nuclear and radiological incidents and emergencies, regardless of whether they arise from accident, negligence or deliberate act. It is the world’s centre for the coordination of international emergency preparedness and response assistance. |
| Any international coordination boundaries | Nil. Deferred to coastal states. |
| Responsibility for responding | IAEA or designated national authority. |
| Operational response requirements | Safety and efficiency of response crews, forecast movement of particles. |
| How is the incident reported | In the framework of the Convention on Early Notification of a Nuclear Accident, the IAEA informs the WMO Secretariat and DCPC Offenbach (Germany) of the status of the emergency. |
| How is the response coordinated | The IAEA or designated national authority is responsible for arranging for information to support drift assessments. |

### I.2 WMO Activities and Roles in support of Emergency Response

WMO is a United Nations specialized agency with the authoritative voice for climate, weather, water and environment-related matters, especially linked to sustainable development and safety of people and property.

***WMO Nuclear and Non-nuclear Environmental Emergency Response***

WMO’s nuclear and non-nuclear environmental Emergency Response Activities includes, in general terms, the broad area of the application of specialized atmospheric dispersion modelling techniques to track and predict the spread of airborne hazardous substances in the event of an environmental emergency. This kind of specialized application depends directly on the operational infrastructure of the NWP systems that are implemented and maintained at many of WMO’s global, regional and national centres within the framework of WMO Integrated Processing and Prediction System (WIPPS). This framework was established to assist NMHSs, their respective national agencies, as well as relevant international organizations, to respond effectively to environmental emergencies with large-scale dispersion of airborne hazardous substances.

In particular, WMO has in place operational international arrangements with the IAEA to trigger specialized meteorological support to environmental emergency response related to nuclear accidents and radiological emergencies, when needed. WMO has a network of RSMCs which are prepared at all times to provide highly specialized computer-based simulations of the atmosphere that predicts the long-range movement of airborne radioactivity.

WMO has expanded the scope and capabilities of its Emergency Response Activities to include non-nuclear environmental emergencies – the area of chemical incidents and emergencies is one under exploration and development. The services range from weather observations, forecasts and warnings provided to field operations, to the provision of specialized products and expert advice on the atmospheric dispersal of pollutants.

***Marine Pollution Emergency Response***

In coordination with IMO, WMO established the [Marine Pollution Emergency Response Support System (MPERSS)](https://community.wmo.int/en/activity-areas/Marine/MEER#MPERSS) in 1993, with the objective of putting in place a coordinated, global system for the provision of meteorological and oceanographic information for marine pollution emergency response operations outside waters under national jurisdiction. The world’s oceans were divided into Marine Pollution Incident (MPIs) areas, similar to the METAREAs/NAVAREAs for the [Global Maritime Distress and Safety System (GMDSS)](https://wwmiws.wmo.int/), andArea Meteorological and Oceanographic Coordinators (AMOCs)have been identified for all of them to provide marine pollution related products and services, including basic meteorological forecasts and warnings tailored for the area(s) concerned. Additional products include: (i) basic oceanographic forecasts for the area(s) concerned; (ii) the observation, analysis and forecasting of the values of specific meteorological and oceanographic variables required as input to models describing the movement, dispersion, dissipation and dissolution of marine pollution; (iii) in some cases, the operation of these models; (iv) in some cases, access to national and international telecommunications facilities; and (v) other operational support, as required. The issued information may have been prepared solely by the AMOC, or by another supporting Service, or a combination of both, on the basis of an agreement between the Services concerned.

The AMOC functions, expanded to cover support to SAR, have been integrated within the framework of the WMO WIPPS, with the establishment of RSMCs for MER.

## APPENDIX II – GEOPHYSICAL FORCING DATA

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### II.1 Introduction

The numerical drift and fate prediction models discussed in Chapters 2 and 3 require forcing data that describe the metocean conditions, i.e. the meteorological, oceanographic and wave fields, acting on the specific substances and objects moving in the ocean or at the ocean surface. Winds, currents and surface waves are the basic types of forcing data, but several other variables are also of relevance, depending on the drift and fate model formulation. Collectively, these data are referred to as *geophysical forcing data.* They are most commonly produced by numerical prediction models, but useful data are also available from other sources, such as observations. The basic requirements for geophysical forcing data are described in Section 3.1.

Note that *sea ice* can be a factor in MER response in polar regions and could be considered an element of geophysical forcing data. Indeed, in recent years, the ability to detect, monitor and model sea ice has advanced significantly, so that sea ice data have become much more available and are used to support maritime navigation and shipping emergencies. However, due to the low capability for MER drift and fate models to realistically represent the effects of sea ice on substances and objects, as well as the difficulties in handling MER incidents in ice-infested waters and the relatively rare occurrence of such emergencies, the use of sea ice data in MER support is still very limited. Therefore, sea ice data will not be discussed in detail in this Guide.

The drift and fate models are fundamentally dependent on the quality of the forcing data that drive them. The basic requirements on the geophysical forcing data include:

* highest available prediction accuracy
* cover the incident area with sufficient spatial resolution and topographic detail
* cover the time period of the incident with sufficient temporal resolution
* include all the variables needed by the drift and fate model
* include uncertainty information
* deliver initial datasets quickly and provide updated forecasts
* provide long historical time series to support scenario and impact studies
* ensure robust operational delivery of data

This is clearly more of a wish list and in practice the operators of MER drift and fate models have to assemble a forcing data set from what is available. For many operators, the best solution for their national or regional responsibilities is to employ their national operational metocean forecast products. If such forecasts are lacking, and for support in other waters, a judicious choice of geophysical forcing data must be made among available external sources. The data requirement issues raised here are addressed in the rest of this appendix.

### II.2 Common aspects

In the following subsection, the common features of forecast systems that produce geophysical forcing data are presented. This reflects the fact that these models address components of a coupled system of geophysical fluid dynamics (but are not necessarily themselves coupled). They have broad similarities in numerical formulation, are in various ways coupled numerically, and are subject to similar requirements for operationality. Consequently, the models share many methods and requirements for production and dissemination, are commonly run in the same numerical environment, and, hence, are currently the dominant method in state-of-the-art MER prediction systems. Brief discussions of the common aspects of observational data products and data access follow thereafter in II.2.2 and II.2.3.

#### II.2.1 Geophysical forcing data from numerical models

*Atmosphere, wave and ocean models.* As pointed out in Section 3.1.1, geophysical forcing data are typically produced by three numerical model types: *NWP models* that provide atmospheric data, *ocean circulation models* that provide ocean data, such as currents, and *wave models* that provide information about the surface wave field. The role of these models in a MER prediction system is shown schematically in Figure 3.1, where they are data providers of the three components of “Geophysical Conditions”. NWP models are the key component, since they provide the basic forcing data for both ocean circulation and wave models. Also, as alluded to above, sea ice models are an important element in the model suite for metocean forecasting in polar regions, but there is currently little use of sea ice data as input to drift and fate models.

*Coupling of atmosphere, wave and ocean models.* In current operational services, the three model types are often run individually and sequentially in a system following a set operational schedule. In that approach, a model delivers forcing data to downstream models without any feedback from them. The NWP model must be run to completion before its forcing data can be applied to the ocean circulation and wave models, which are run immediately after. *Coupling* is a two-way process in which two or all three models are run concurrently with exchange of relevant data at given intervals during the model run (see, e.g. Mogensen et al, 2012, for a description of the coupled integrated forecast system of ECMWF). In principle, this is physically advantageous scheme, since it resolves the real-time interactions between the ocean and atmosphere[[12]](#footnote-13). For example, coupling of NWP and wave models has come into operational use in several forecasting centres with success. While coupled systems are conceptually simpler – in terms of Figure 3.1, the three Geophysical Conditions components would be merged into one or two model run(s) – coupling is much more complex to implement and requires substantial modifications to the component models. Fully coupled models, i.e. including atmosphere, ocean circulation, sea ice and waves, were developed for and are mainly used in climate simulations, although they have gained some traction in recent years for use in short- to medium-range forecasting at global (Breivik et al, 2015, Mogensen et al., 2017) and regional scales (Bruneau and Toumi, 2016, Wu et al., 2019). While coupled modelling is expected to significantly improve forecasts, for the present, almost all operational geophysical forcing data are produced in uncoupled model runs (with the noted exception of ocean - sea ice models).

*Consistency of metocean data*. This is an issue related to forcing data exchanged between the metocean models. As shown later in this document, one can readily pick and choose among geophysical forcing data products from many different providers. However, it is generally advantageous to utilize *consistent* datasets, wherein the downstream models use forcing data from the same upstream model. Specifically, the same atmospheric fields should be used to force ocean circulation and wave models. For example, the Stokes drift currents from the wave model and the surface currents from the ocean circulation model are more consistent when both models are driven by the same NWP wind fields. Even greater consistency can be expected of fully coupled models.

*Nesting of ocean and atmosphere models*. Most MER operations take place in a quite limited region of the ocean. For example, the majority of SAR incidents occur within a few nautical miles of the coast. Therefore, MER predictions are most often needed at high horizontal resolution with detailed representation of the coastline. This level of resolution is not achievable with currently operational global models. To achieve higher resolution in sub-areas of interest, all three types of metocean modelling systems are commonly configured with a high-resolution grid (10 s to 1000s of metres) of the sub-area embedded (*nested*) in a larger grid at coarser resolution. The coarse resolution model serves open boundary conditions to the high-resolution model, thereby imposing far-field effects on the sub-area. The nesting may also consist of several stages; this is particularly the case for coastal ocean circulation models. For example, the nesting configuration may include a high-resolution coastal model embedded in a regional (basin-scale) model, which in turn is embedded in a global model. In some major centres, the same model code is run on all grids, but most practitioners of MER services rely on external providers of global and/or regional data for open boundary input to their local models.

*Data assimilation*. An important aspect of modern numerical prediction modelling is the assimilation of observations, which improves the accuracy of the predictions. Successful use of assimilation is heavily dependent on the availability of observations, in time, space and by variable. As a consequence, the positive impact of assimilation is greater for NWP and wave models, and smaller for ocean circulation models. NWP benefits from what is by far the most comprehensive observing system, and wave models, which are strongly forced by the wind from NWPs, share indirectly from assimilation of atmospheric observations. In contrast, there are comparatively few observations of the ocean, especially below the surface and for resolving the ocean mesoscale. On the other hand, in most MER incidents the focus is on the conditions at the sea surface, which fortuitously is the best observed part of the ocean. Assimilation of high-resolution SST from satellites and especially current fields from HF coastal radar (where available; cf. Section II.4.2.1) can greatly improve the short-term prediction skill of the ocean circulation model (Sperrevik et al., 2015).

*Forecast – hindcast – reanalysis*. MER drift and fate modelling is mainly used in forecast mode to support ongoing emergency response; forcing data are fetched from the most recent operational runs of the metocean models. Yet, there is very often a need for stored simulations of the recent past, for example in connection with “backtracking” simulations (cf. Section 3.1.4). Furthermore, simulations of multi-year periods are valuable for overall MER preparedness, e.g. for impact studies and for building climatology. To this end, archives of geophysical forcing data are needed. These data may be an archive of data from operational model runs. Alternatively, they may be produced by dedicated runs using the same model setup throughout the simulation period. In the latter case, there are two classes of such datasets: *hindcast* (model simulation without data assimilation) and *reanalysis* (model simulation with data assimilation); reanalysis is inherently more accurate, but significantly more costly to produce.

*Ensemble modelling*. Knowledge of the uncertainty of a numerical forecast is valuable to a user’s confidence in the results, not least in MER actions. In the present context, an ensemble is a collection of several runs – typically 10 to 50 – of the same prediction model code, but using slightly different (perturbed) initial and/or boundary conditions for each run (Molteni et al., 1996). In order to keep the computational load acceptable, the ensemble runs are usually performed at lower spatial resolution than the main model run (a.k.a. the *deterministic run)*. From the resulting ensemble members, statistics can be calculated for each grid-point and variable. Specifically, the spread of values at a point can be associated with a probability distribution and, consequently, yield an estimate of the uncertainty in the ensemble mean. The uncertainties in the ensemble may also be assumed to inform about the uncertainties in the deterministic forecast. More importantly, the ensemble mean forecast constitutes a lower-resolution alternative to the deterministic forecast with the added benefit of uncertainty estimates. For MER prediction modelling, an ensemble approach to geophysical forcing data production can facilitate building a corresponding ensemble of drift and fate model runs, with known uncertainty estimates on the input data.

#### II.2.2 Observational sources of geophysical forcing data

While it may be argued that observations have greatest positive impact when assimilated into a skilful numerical model, useful forcing data products can be obtained directly or derived from satellite and in situ observations. These can be expeditious in emergency situations occurring in constricted waters, such as archipelagos, fjords, estuaries and harbours, where the resolution of available numerical models is too coarse and local knowledge may be considerable. In such cases, observational products are often more readily available and updated more rapidly than model-based data, and can be very useful in an initial, rapid-response phase of an emergency. Some drift and fate models include facilities for ingesting point observations and applying the same forcing everywhere (e.g. OpenDrift, see Dagestad et al., 2018).

On the other hand, observations are intrinsically non-predictive so that their value decreases with forecast lead time. Use of conventional statistical methods can improve the predictive capability to a certain degree, and machine learning techniques may improve it further, cf. Section II.2.2.1. An additional problem is that there may be few or no observations of the required variables in the emergency area. The scarcity of direct observations is especially problematic for ocean currents, cf. Section II.4.2, below. In practice, MER operators seek to leverage all available information, be it observations or model-based predictions, in order to decide a course of action.

In the production chains for model-based metocean data, observations are used to provide ground-truth for the verification of the model predictions. In the present context, the resulting accuracy metrics can be used to inform on the uncertainty of the downstream drift and fate predictions.

##### II.2.2.1 Machine learning models

Machine learning (ML) techniques have been applied in the geosciences as flexible methods that are able to model, predict, and represent effects that are hard to capture with traditional methods and algorithms, based on large datasets representing the phenomena to model. ML modelling is still an emerging technology, but has very recently reported newsworthy gains in meteorology by demonstrating significant skill in forecasting some key weather variables. Several works have claimed to match or beat conventional NWP models on short-term nowcasting (Agrawal et al., 2019; Sønderby et al., 2020), where the ability of ML based models to run much faster than state-of-the-art predictive models allows for a higher update rate of the predictions, higher resolution, and, according to some works, higher absolute accuracy. A few studies have claimed, similarly, to rival classical weather models on forecasts up to 10 days forward (Chen et al., 2023 ; Bi et al., 2022, 2023; Pathak et al., 2022; Lam et al., 2022). This rapid progress is a result of advances in ML model complexity, algorithms, computing power and access to very large sets of training and observational data. On the other hand, there are many challenges and open questions to be answered before ML models can replace conventional NWP models (Schultz et al., 2021). It is most likely that ML-based methods increasingly become part of forecast systems in the years to come, especially where closure models or complex, possibly ill-understood and imperfectly modelled physics are involved. The key questions lie in which parts of the systems in use can benefit from either being replaced or post-processed by ML methods, and how to balance the complexity versus explainability and robustness of the ML modules deployed.

In the present context, ML methods promise to dramatically change how geophysical forcing data are produced, accessed and applied in MER drift and fate modelling, by drastically reducing the cost of forecast production, improving accuracy and increasing resolution. Computational resources can be reallocated to other parts of the workflow to improve the overall service. Lower costs can also facilitate in-house production by LDC WMO Members and in small private enterprises.

#### II.2.3 Access to geophysical forcing data

Support to MER operations requires quick and reliable access to geophysical forcing data of the highest possible detail and accuracy. There are several alternatives to fulfilling this:

1. All required forcing data are provided by in-house operational metocean models. This is the preferred solution for NMHSs in many maritime nations, as it has several advantages:

* Since the region of responsibility is limited to national waters, well-tuned high-resolution regional/coastal models are already implemented and operational.
* Knowledge of the strengths and weaknesses of the models is generally very good.
* The forcing data are consistent.
* The operational routine can be adjusted to optimize the delivery time to drift and fate models.
* Data transport is efficient and flexible, since data are largely moved in the internal network, which is fully under the control of the operational centre.

1. Some or all required forcing data are fetched from external providers. The data provision may be managed by bilateral agreements or contracts, through WMO collaboration structures, such as the RSMC network (WIS2.0), or by accessing free online data services. This alternative can provide geophysical forcing data to NMHSs lacking in-house production of forcing data. It can also provide supplemental data to NMHSs for supporting MER incidents occurring outside their normal region of interest. The drawback to this approach is that the imported data may not be tuned to the region of interest or may, in the case of non-public providers, involve licence or subscription fees. A further caveat is that the NWP, wave and ocean circulation data obtained from different sources are prone to inconsistency.   
   Some or all required forcing data are obtained from local, national or regional sources in the form of non-model data. This includes low-cost, readily available information that may be acquired when the need arises or be extracted from in-house data. This can be a viable solution for MER incidents occurring in near-coastal waters where a few pieces of key metocean information obtained and applied quickly can be more effective than complex numerical model simulations. Data sources include: static datasets like climatologies and current charts; nearby observations, for example from buoys, weather stations and ships; sea-state bulletins from WIPPS, formerly the GDPFS); online weather forecasts (mobile and web apps); etc. The caveat of inconsistent forcing data mentioned in alternative b) is applicable here as well.

An important development in the present context is the increasing implementation of internationally accepted protocols and standards for data access, governance and documentation in the atmospheric and oceanographic communities, which contributes to making more geophysical forcing data available. These protocols and standards attempt to enforce the FAIR principles for data management: data shall be Findable, Accessible, Interoperable, and Reusable (Wilkinson et al., 2016). A basic aim of FAIR data is making data easily accessible and increasingly useful to users, anywhere. Important technologies currently used to implement FAIR principles include catalogue services (for finding datasets), self-describing file formats (NetCDF, HDF, HDF5), data access services (such as THREDDS, data access protocols (such as OPeNDAP, API, WMS, WCS, WFS), metadata standards (such as Climate and Forecast Convention, ISO 19115, GCMD DIF), catalogue services (CSW) and persistent identifiers (DOI, URN). In tandem with this development, several national, regional and global production centres for meteorological and oceanographic data have matured into efficient public data services and are actively implementing data policies and data management facilities following the FAIR principles. This includes many WMO Member centres and also is reflected in the design and implementation of WIS2.0 (cf. Section II.3.1.1). Some examples are listed in the following Sections.

### II.3 Meteorological data

#### II.3.1 Numerical Weather Prediction (NWP) Models

Operational NWP data products cover the world ocean from global to very local scales, at horizontal resolutions of hundreds of metres to several kilometres, and on timescales from hours to several days (typically 10). Access to advanced computing facilities, comprehensive observation networks, as well as research-driven technological development, is generally assured by strong public demand. The NWP-related scientific literature and documentation of NWP models is voluminous, so that any comprehensive description of NWP modelling is beyond the scope of this guidance document. The reader is referred to, for example Coiffier (2011) and Bauer et al. (2015), for overviews of the field. For more specific guidance on NWP, see the following WMO documents: WMO (2017 a), WMO (2021c) and WMO (2018c, Chapter 2).

In the present context, it is important to keep in mind that both ocean circulation and wave models are forced by NWP fields (winds, pressure, heat fluxes, etc.), especially at synoptic timescales. There is a particularly close connection in the case of the wave models. Furthermore, the drift and fate models utilize some data from the NWP model directly, as itemized in the following table. Therefore, the accuracy of the NWP forcing data is decisive for the accuracy of all the other models in the system.

**Table II.1: Meteorological variables typically used by drift and fate models. Winds are required for all models, while air temperature is infrequently called for by model codes.**

| Variables | Usage |
| --- | --- |
| Near-surface wind as meridional and zonal velocity components, or as speed and direction | Oil spill, drifting objects, radionuclide, HazMat |
| Near-surface air temperature | Oil spill, drifting objects (SAR) |

##### II.3.1.1 Access to atmospheric forcing data from WMO members

The NMHSs of WMO arguably constitute the most comprehensive, interconnected and advanced community for operational NWP data production at all spatial scales. Many NMHSs in maritime member states are producers of NWP data at global and/or national/regional scales, primarily for their own forecasting services (including MER support), but also as contributions to the whole community. Thus, any NMHS lacking in-house data for an area of interest is able to access and utilize NWP data of high quality in their own national activities, such as support to MER incidents. Note that WMO Members are generally subject to authentication to gain access to data.

WMO forecast data is currently organized in WIPPS[[13]](#footnote-14), in which designated global and regional centres manage data collection and provision by theme (*aka.* “WIPPS Activity”) and region. The [WIPPS](https://wmo.maps.arcgis.com/apps/dashboards/7c3d45e5003a417988bad63e91ad8748) [portal](https://wmo.maps.arcgis.com/apps/dashboards/7c3d45e5003a417988bad63e91ad8748) provides access to data via the responsible centres. The obligations of Members in managing and operating the system are laid out in the [GDPFS Manual](https://library.wmo.int/records/item/35703-manual-on-the-global-data-processing-and-forecasting-system?offset=1) (WMO-No. 485, 2021 a). In the current context, the most relevant WIPPS Activities are: “*Global deterministic NWP*”, “*Global ensemble NWP*”, “*Limited-area deterministic NWP*” and “*Limited-area ensemble NWP*”. A centre delivering such a data set is called a *Regional Specialized Meteorological Centre* (RSMC). Note that limited-area, i.e. regional, NWP datasets are currently available for just six regions. Not only NWP data, but also some wave model data are included in the WIPPS Activities (inclusion of ocean model data is under consideration).

Modernization of the WMO data management system to exploit the internet and international standards has been ongoing since 2007; see Giraud et al. (2021) for an historical overview. The first major upgrade is the WMO Information System ([WIS](https://community.wmo.int/en/activity-areas/wis/wis-manuals); *WMO, 2019 a,b*), the aim of which is to provide a more modern platform for managing all data produced and disseminated in the WMO community, including observational data. WIS implementation is organized in participating [WIS Centres](https://community.wmo.int/en/activity-areas/wis/database-of-wis-centres) that manage and provide data. Starting in October 2022, the second version, [WIS 2.0](https://library.wmo.int/idviewer/56019/1) (*WMO, 2017b*), has started implementation among WMO Members (although development activities are continuing). In the present context, the important aims are to make “*international, regional, and national data sharing simple, effective, and inexpensive*” and to adopt “*open standards and Web technologies to facilitate sharing of [an] increasing variety and volume of real-time data”*.

##### II.3.1.2 Examples of specific data providers

Examples of WMO centres offering global data that may be accessed directly are listed in the dynamic part of the Guide. [Note that the data may also be accessed via WIS.](https://docs.google.com/document/d/1W4j_y19GhirfnG-6c9I3ERuI3TnrZ070/edit?usp=sharing&ouid=108964075871566208871&rtpof=true&sd=true)

#### II.3.2 Observational meteorological data

The ready availability of NWP data from many WMO Member providers, at many resolutions, and constrained by almost all available observations, largely obviates the need for purely observational products. As alluded to in Appendix II.2.2, the use of observational products as forcing data is mainly attractive for localities where the available NWP data are much less accurate than local observations, or for organizations who lack access to the available NWP datasets.

The former case may occur, for example, in very constricted waters where the detailed topography is unresolved by the NWP data. Local wind observations can, in such cases, provide useful data to a drift model (if the model is able to ingest the wind data). As noted in Section II.2.2, statistical methods and ML techniques may improve the predictive capability of the observing station. Note that many “local” observations are readily available through the WMO system (GTS, WIS). In the present context, the assimilation scheme and resolution of an NWP system tend to filter out detailed local variability at the observation site, while it is retained in the observations themselves. In the latter case, the primary alternative to NWP wind fields is satellite data products from scatterometers and microwave instruments.

As mentioned in Section II.2.2, much progress has recently been reported on the application of machine learning technology to weather forecasting. A question that arises is whether observation-based ML models can soon replace traditional NWP modelling systems. Schultz et al. (2021) argued that this is in principle possible, but several conditions remain to be met and the question cannot be answered definitively. ML in weather forecasting has been under investigation at several major WMO Member centres. A good example is the ECMWF, who have highlighted ML technology in the ECMWF strategy document for the current decade[[14]](#footnote-15). There, the main focus is on using AI and ML to improve the existing (model-based) production chain (so-called hybrid chains). In the present context, the promise of improved accuracy, lower costs and faster production for winds and surface temperature is very positive.

*Examples of currently available data products are provided in* the dynamic part of the Guide.

### II.4 Oceanographic data

#### II.4.1 Ocean circulation model data

Ocean circulation models are a key component of the forecast model suite as they provide all-important surface currents in addition to other important parameters such as sea-surface temperature. A list of oceanographic data variables typically used by drift and fate models is given in Table II.2. Note that commonly used drift and fate models do not necessarily require all the variables listed in order to provide useful results. For example, in most oil spill cases focus is on the situation at the surface, so that depth and vertical profile data are not essential. In colder climates it is also common practice to couple a sea-ice model with the ocean circulation model to provide estimates of the sea-ice variables.

A comprehensive guide for implementing operational ocean circulation models may be found in a recent Global Ocean Observing System (GOOS[[15]](#footnote-16)) publication (*GOOS-275, 2022*), co-sponsored by the Intergovernmental Oceanographic Commission of the UN Educational, Scientific and Cultural Organization (IOC-UNESCO[[16]](#footnote-17)), WMO, the UN Environment Programme (UNEP[[17]](#footnote-18)) and the International Science Council (ISC[[18]](#footnote-19)). The guide document also describes the use of ocean model data in some downstream applications including oil spill. The reader is further referred to the review article by Röhrs et al. (2023) who give key technical details about the application of surface current data in operational oceanography.

The issue of accuracy is particularly serious for ocean circulation models, in the context of a drift and fate prediction system. As indicated elsewhere, the accuracy of NWP model is fundamental to the system (cf. Section II.2.1). While the wave model predictions are closely determined by the NWP winds (cf. Section II.4.1), there are physical processes in the ocean that can significantly contribute to the total current field. Topographic steering, density gradients with their accompanying instability mechanisms, and tides are processes that modify and generate current components that can match, even overwhelm, the wind-driven current component. What is more, the oceanographic mesoscale, i.e. the scale of eddies and meanders, is barely resolved by current model resolutions and there are few observations that resolve it reliably. These factors explain why the ocean circulation model data are arguably the least accurate of the three geophysical forcing components. This is a serious issue for short-term marine emergency responses, especially SAR and oil spills, which rely heavily on accurate high-resolution surface current predictions.

The use of data assimilation can greatly improve the accuracy of the mean state of the ocean, but there are limits as to how small scales the improvement extends to. It is largely dependent on the resolution of the data that are assimilated as well as the model. Jacobs et al. (2021) demonstrated that assimilation of low-resolution observations does not improve the prediction of mesoscale features even in an eddy-resolving model. It was shown in the Gulf of Mexico that using a spatial filter with an e-folding scale of 58 km on the model surface currents actually reduced the errors in the mean trajectories compared to using the full 1 km resolution model data. As noted above, the variability of these small scales is paramount for emergency response and higher-resolution models and observations are important to replicating this variability. This makes short-term prediction in the ocean a challenge (Christensen et al., 2018).

In the context of coastal response, the models are predominantly of a limited domain to increase resolution of the coastlines and bathymetry. These often share an open boundary with an operational global model and are forced by high-resolution wind products. These coastal models can be sensitive to uncertainties on the boundaries as well as bathymetry. Some advances have been made to assimilate HF radar data (Breivik and Sætra, 2001; Sperrevik et al., 2015; Hernandez-Lasheras et al., 2021) or two-way nesting in narrow channels (Herzfeld and Rizwi, 2019; Ding et al., 2021) to improve the accuracy and resolution in coastal regions. There is some potential with newer high-resolution altimetry products such as SWOT (Carrier et al., 2016) and the wave glider 5 Hz Sea-Surface Height (SSH) product (Penna et al., 2018) that may also lead to constraining more of the small-scale variability.

**Table II.2: Oceanographic variables typically used by drift and fate models. Note that not all ocean circulation models produce data at the very surface or at fixed depths; for use in drift and fate models, the ocean model output can be post-processed to more suitable depths.**

| Variables | Usage |
| --- | --- |
| Currents: near-surface | Oil spill, drifting objects, radionuclide, HazMat |
| Currents: vertical profile | Oil spill, radionuclide, HazMat |
| Temperature: vertical profile | Oil spill, radionuclide, HazMat |
| Salinity: vertical profile | Oil spill, radionuclide, HazMat |
| Water depth | Oil spill, radionuclide, HazMat |
| Vertical diffusivity: vertical profile | Oil spill, radionuclide, HazMat |
| Mixed layer depth | Oil spill, radionuclide, HazMat |
| Sea ice concentration | Oil spill (some models) |
| Sea ice velocity | Oil spill (some models) |

##### II.4.1.1 Access to ocean circulation model forcing data

There is currently relatively little data from operational ocean circulation models available from WMO WIPPS, described above (Section II.3.1), despite the fact that many of the centres are major producers. Their data are mainly accessible through the centres’ own websites and other portals. However, it is expected that more ocean prediction data will become available as WIS 2.0 implementation progresses.

##### II.4.1.2 Examples of specific data providers

The oceanographic community has over the last decades established several portals that offer a range of relevant, freely available, model and observational data at global and regional scales. Examples of global providers are listed in the dynamic part of the Guide.

#### II.4.2 Observational oceanographic data

Classical in situ observations of the ocean – temperature and salinity from water samples and lowered and autonomous digital instruments (e.g. CTD, drifting buoys, gliders), moored current metres, tide gauges – have been delivering data for over a century, but never with the spatial and temporal coverage needed by drift and fate models, except in very fortuitous circumstances, such as highly constricted waters (cf. Section II.2.2 ). In the last few decades, a number of remote-sensing technologies have been developed and demonstrated the capability of providing more suitable data (Dohan and Maximenko, 2010). With respect to Table II.2, the earliest gains came from satellite-based SST, which is now a robust, well-understood and readily available operational data type. On the other hand, it is not the most essential parameter in the present context.

Of more interest are the observing systems that can provide the all-important surface currents, which are currently the weakest element in the modelled forcing data suite. While no observations are capable of fully meeting the resolution and coverage requirements of modern drift and fate models (cf. Section II.1), not to mention their innate lack of forecast information, some have the capability of providing useful data either as an alternative or as a supplement to numerical model products. It should be noted that, although these observational datasets do not provide forecasts, it is possible to use statistical methods to create short-term predictions on the order of 1-2 days; Barrick et al. (2012) and Solabarrieta et al. (2021) provide examples in the case of high-frequency coastal radar.

It is also common to deploy drifters during emergency response operations as these data can be used to “track” the marine emergency (so-called self-locating datum marker buoys, SLDMBs, are routinely deployed by the US Coast Guard at the last known position of a search object), assuming that their drift characteristics are similar to the object or material one wishes to track. The deployment of these drifters also provides a quick assessment of the numerical model output in the region that can be qualitatively related to the uncertainty in the prediction of the local surface currents.

In the following, some of the more accessible observational data types are described.

##### II.4.2.1 High-frequency coastal radar (HFR)

HFR is a coastal instrument that provides measurements of the surface currents over a coastal area (Barrick, 1979; Paduan and Washburn, 2013). Deployment of an array of HFR antennae can provide gridded surface current – more specifically an average over the upper 0.3 to 2.5 m – data out to about 200 km from the coast, depending on the radar transmission frequency. Note that a single HFR antenna only measures the radial current speed, i.e. toward and away from the antenna within the range of the signal. Therefore, an additional antenna must be located at a suitable distance along the coast in order to provide an overlapping region and thereby allow calculation of the two-dimensional current velocity. Coverage along the coast is determined by how many antenna nodes are deployed. HFR data are subject to the fundamental play-off between range and resolution, i.e. longer range (lower radar frequency) means coarser horizontal resolution. A typical long-range system provides hourly data over a range of up to 250 km with about 7 km resolution. As alluded to above, the development of statistical methods for prediction of the current field from observations was largely initiated by the early interest in HFR data.

An HFR array is relatively costly to procure, install and maintain in light of the very specific information it provides: surface currents over a limited coastal area. It is therefore often challenging to justify on a cost-benefit basis. Consequently, HFR deployments are currently found on only a small fraction of the world coastline, and almost exclusively in coastal MDCs (a global overview map is maintained online[[19]](#footnote-20)*)*. The drivers for monitoring coastal surface currents by HFR vary among the countries where deployments are found. For example, in the USA, SAR operations and academic interest have been important; in Europe, focus has been more on port surveillance and oil spill preparedness. Recent overviews of the deployments in North America and Europe may be viewed online[[20]](#footnote-21)[[21]](#footnote-22).

Nonetheless, in the MER context, HFR is a very attractive source of real-time information, inasmuch as it provides high-resolution gridded observations for near-surface currents, which are currently the least accurate of the modelled forcing data variables, but at the same time the most crucial for drift and fate models – and provides those data in the important coastal region.

*Examples of currently available data products are provided in the* dynamic part of the Guide.

##### II.4.2.2 Geostrophic currents from satellite altimetry

Satellite altimeter data are routinely processed to provide estimates of the *geostrophic* current, i.e. the component of the current field that is due to the balancing of the sea surface gradient and the earth’s rotation (Coriolis force). The geostrophic component explains a major portion of the total surface current field in the global ocean, but is generally inadequate in the context of operational drift and fate modelling, viz., the most recent “NRT” altimeter-based field represents the previous seven days with a horizontal resolution of 0.25° (see examples below). In addition, the altimeter misses up to 50 km of coastal waters when flying from land to ocean. Furthermore, in coastal waters bottom friction and topographic effects due to shallow depths can be important factors influencing geostrophic currents (which, strictly speaking, would no longer be geostrophic because of the additional friction term).

Often, the geostrophic current is supplemented by an estimate of the wind-driven current component (the *Ekman current*), derived from modelled or satellite scatterometer winds, to give a fuller estimate of the total surface current. It is estimated by Ralph and Niiler (1999) that the geostrophic and Ekman components together account for 78% of the current variance (63% and 15%, respectively).

*Examples of currently available data products are provided in the* dynamic part of the Guide.

##### II.4.2.3 Automatic Identification System (AIS)

Another source of near real-time current data is ship track information gleaned from the AIS. By combining heading, speed-over-ground and tracking data, estimates of the near-surface current can be calculated (Jakub, 2013). In heavily trafficked regions, the data coverage makes it possible to build useful maps of the currents representative of a given time period – typically one to several days – using conventional statistical methods (Guichoux et al., 2016, Le Goff et al., 2021, Christodoulou et al., 2022). Recently, machine learning methods have begun to be applied (Benaïchouche et al., 2021). The applications reported so far produce estimates of the present state of the current field, e.g. the most recent day.

*Examples of currently available data products are listed in the* dynamic part of the Guide.

##### II.4.2.4 Tidal constituent data

Tidal currents are an important source of current variability, especially in coastal waters where tides may dominate the current field. A tidal signal is present in satellite altimetry data, but is commonly filtered out in order to expose the dynamic height signal, from which the geostrophic current component is calculated, cf. Section II.4.2.2 above. However, since the constituents of the barotropic tide are stationary in time, many unfiltered altimeter passes can be used to create a data-driven model for tidal heights and currents.

The most accurate modern tide estimates are not produced independently of numerical ocean models, but use a numerical model of the tides to provide a prior estimate and then make an empirical adjustment by using (assimilating) altimeter data (and some other observations). The results are stored as a static data set containing tidal constituent parameters on a grid. Stammer et al. (2014) provide a relevant review of eight such models. Tidal models are sensitive to the accuracy and resolution in coastlines and bathymetry. However, once the constituent data are calculated, it is then trivial to create a time series for any time period in the past or future. In tide-dominated waters, one can calculate useful current data very quickly using readily available tools. In such regions, tidal data can also be used to drive long-term predictions of drift.

*Examples of currently available data products are provided in the dynamic part of the Guide.*

### II.5 Wave data

The *WMO-No.702 Guide to Wave Analysis and Forecasting*[[22]](#footnote-23) (WMO, 2018c) is a comprehensive document that contains a wealth of knowledge on ocean surface waves and on how NMHSs can provide relevant wave information to the public. In addition to a thorough review of the science of surface waves, there are specific chapters that are relevant for the present document: *Numerical wave modelling* (Ch. 5), *Operational wave models* (Ch. 6) and *Wave data: observed, measured and modelled* (Ch. 7). A perusal of the wave guide document is strongly recommended for the interested reader. In this Section, the focus is on the practical aspects of wave data as forcing for MER drift and fate models. Information similar to that found in WMO (2018c) is not repeated here.

#### II.5.1 Wave model data

Historically, numerical wave prediction followed closely on the heels of NWP. Given that waves are strongly determined by the surface wind field, adding a wave model to the NWP production chain is a straightforward task that produces results that are about as good as the NWP winds. That, along with the demand for good wave forecasts from mariners, was a strong motivation for many NMHSs to add waves to the operational model suite. For maritime forecasting, the basic wave variables required are wave height (usually as significant wave height, SWH), mean direction and period. For MER drift and fate modelling, the Stokes drift component (van der Bremer and Breivik, 2018) is of particular interest (Table II.3), but is often not included in “standard” datasets from numerical wave prediction providers.

The wave model prediction accuracy is most strongly determined by the accuracy of the local NWP winds in the case of wind waves. On the other hand, the swell component of the wave field, i.e. “old” waves generated by distant storms that propagate into the area of interest, are almost unaffected by the local winds. In a coastal or regional wave model, the swell characteristics – and prediction accuracy – are thus largely determined by the lateral boundary conditions coming from a larger-scale wave model. It may be noted that the relative contributions of wind waves and swell to the total wave field varies with latitude: the tropics are generally swell-dominated, while in the extratropics there is a mix of wind waves and swell (Semedo et al., 2011).

**Table II.3: Wave variables typically used by drift and fate models.**

| Variables | Usage |
| --- | --- |
| Wave height | Oil spill, SAR |
| Wave period | Oil spill, SAR |
| Currents: Stokes drift | Oil spill, SAR, radionuclide, HazMat |

##### II.5.1.1 Access to wave model forcing data

A considerable selection of operational wave model data is available from the WIPPS and from Member centres, and may be discovered and accessed in very much the same manner as for NWP data; the reader is therefore referred to Section II.3.1.1.

##### II.5.1.2 Examples of specific data providers

Examples of centres offering global wave data that may be accessed directly are listed in the dynamic part of the Guide.

#### II.5.2 Observational wave data

Since operational wave forecasting has developed much in the same environment as NWP, many of the arguments concerning the need for observational alternatives to NWP in Section II.3.2 largely apply to wave observations as well. Essentially all operational wave observations are assimilated into the operational wave models run by the major WMO Member centres, whose data are readily available to all Members. On the other hand, the amount and types of wave observations are much less comprehensive than those for the atmosphere, so that the observational constraints on the wave model are weaker. It is, again, in situations where, due to for example unresolved topography or lack of key variables, the modelled wave predictions prove to be inferior to direct observations that those observations can be useful input (if the drift and fate model can ingest them). Common sources of observational wave data include the following:

* In situ wave measurements, e.g. from wave buoys and “ship-borne” wave radars, have very restricted spatial coverage and are essentially point measurements. In very constricted waters they can be useful. Note that many in situ wave instruments do not provide directional wave spectrum information, from which the Stokes drift can be calculated.
* Satellite observations from altimeters and Synthetic Aperture Radar (SAR\*) have a global coverage over the ocean, but with very coarse spatial resolution and long repeat intervals. Processing data from several concurrent satellites is used to build products with somewhat better resolutions and use regular grids, but alone the products are still too coarse for most MER modelling needs. Furthermore, each instrument is lacking in some key variables, cf. Table II.3. Altimeters measure total significant wave height only; in particular, the Stokes drift cannot be calculated. SAR\*) produce directional wave spectrum variables, but only for swell (wavelengths > 200 m) and not for wind waves; the Stokes drift vector can, in principle, be calculated but only for swell. Despite their limited applicability to MER modelling, example datasets are presented in the next subsection.

##### II.5.2.1 Examples of specific data providers

Examples of available satellite products are provided in the dynamic part of the Guide.

## APPENDIX III – MER OPERATIONS

*Authors: Arthur A. Allen (USA Coast Guard) and Alice Soares (WMO)*

### Oil Spill Operations

Every country should have an effective spill response plan to prevent incidents from becoming disasters. Stocking the appropriate spill response equipment and providing the proper training for all relevant employees and volunteers is important before a spill response plan can be implemented. Combining the correct equipment and training with a clear spill response guide helps raise the general preparedness.

When an oil spill occurs, the issue of health and safety, both for the public and oil spill responders, is the most critical consideration. There is no simple answer to how dangerous a spill is, because the hazard level depends on a variety of factors. Beyond the properties of the actual material itself, the degree of hazard may also depend on just how much material was spilled, where the spill occurred and what surface received the spill, and the geophysical forcing conditions. Depending on the specific hazards involved, it may be necessary to evacuate the area or to take steps to prevent an environmental disaster.

Regardless of the level of hazard involved, there are five basic steps involved with dealing with spills (IPIECA, 2016):

1. Identify the hazardous event and its characteristics – this step includes the identification of the oil type, event location, prevailing conditions (i.e. the meteorological and oceanographic (metocean) conditions affecting oil spill operations as described in Table III.1), etc. Visual and remote-sensing detection, which can also be affected by metocean conditions, are part of this step.
2. Communicate the hazard – this step includes immediate notification of the hazard by the vessel concerned or other(s), and if the situation warrants it, evacuate the vessel. Make sure that anyone who is injured or has been contaminated is removed from the immediate area and taken to a safe place. Metocean conditions are critical to ensure safety of operations.
3. Control the spill – this step focuses on ensuring that the spill does not become any worse, by identifying the oil spill scenarios through drift and fate modelling and sensitivity mapping, and by evaluating the risk.
4. Contain the hazard and apply the response plan – once the immediate situation has been addressed, this step includes keeping the spill from spreading and contaminating the shoreline, if the incident happened near the coast. Depending on the material and situation, this usually involves confining the spilled material to a small area with floating booms, or by applying some type of absorbent material or neutralizer, and using a skimmer. Carrying out these activities also depends on the geophysical conditions.
5. Clean up the spill and any damage – this step includes collecting the material used to contain or neutralize the spill, and dispose of it in the specified manner. Clean the surfaces that were affected by the spill with the correct material.

**Table III.1**

**Oceanographic and Meteorological Parameters affecting Oil Spill Operations. Priorities were defined with the help of Cedre**

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Parameter  Oil spill Operation | 10 m Wind vectors | 1 m Surface currents | Sub- surface currents | Significant wave height and direction | White cap cover [%] | Sea surface temperature | Surface air temp | Visibility | Lunar Phase & Cloud Cover | Precipitation rate & type | Frost | Icing & Ice cover | Solar Radiation |
| Incident  Prediction | **1st** | **1st** | 3rd | **1st** |  | **1st** | 2nd | 2nd | 3rd | 2nd | 2nd | 2nd |  |
| Drift Prediction | **1st** | **1st** | 2nd | **2nd** | 2nd | 3rd | 3rd |  |  |  |  | **1st** |  |
| Visual Detection | 2nd |  |  | **1st** | 2nd |  |  | **1st** | **1st** | 2nd |  | **1st** | 2nd |
| Aircraft Operations for Detection | **1st** |  |  | 2nd | 2nd |  |  | **1st** | **1st** | 2nd |  | **1st** | **1st** |
| Skimmer  Operations | **1st** | **1st** |  | **1st** | 2nd | **1st** | 2nd | 2nd |  | 2nd | 2nd | **1st** | 2nd |
| Ice Operations | 2nd | 2nd |  |  |  | 2nd |  |  |  |  | 2nd | **1st** |  |
| Post Incident  Analysis | **1st** | **1st** | 2nd | **1st** |  | 2nd | 2nd |  | 3rd | 2nd | 2nd | 2nd |  |

**‘1st**’ is a First Order environmental parameter affecting Oil Spill operations.

**‘2nd’** is a Secondary Order environmental parameter affecting this Oil Spill operation.

**‘3rd’** is a Tertiary Order environmental parameter affecting this Oil Spill operation.

### SAR Operations

The initiation of a SAR case begins with notification of the SAR authorities who need to address three primary questions:

1. When did the incident occur?
2. Where did the incident occur?
3. What are the number and types of SAR objects?

These three questions combined are the initial conditions or the possible *scenarios* for a particular SAR case. If the reporting source is from the distress vessel itself, the uncertainty in when, where, and what can often be very precise or limited. However, with third-party reporting sources, there can be considerable uncertainty in the scenario or possible scenarios. Most SAR cases can be represented by a limited set of scenario types. The most fundamental scenario is a bivariate normal distribution about the last known position (LKP), where the distribution reflects the uncertainty in the position system and any additional uncertainties (e.g. misreporting, time delay). The second basic scenario is a well-formed polygon covered by a uniform distribution (the area scenario). The area scenario works well when the originating craft (e.g. a fishing boat) frequents a known region (e.g. fishing grounds). A voyage scenario is the transit between a series of points (LKPs) or areas with the possible time periods of activity within the areas (e.g. loitering, fishing). Voyages can either be influenced by metocean conditions (environmentally interactive) or not. Other, more specialized, scenarios are used for flare observations; single or crossing lines from radio direction reporting high-sites; and dead reckoning from an LKP.

In these scenarios, there is also uncertainty about the time of incident. Again, if there is direct reporting, this uncertainty is reduced. In other cases, the uncertainty in time can extend from the last known time the vessel was safe up until a notification was delivered by a third-party. This can be from hours to a day or more. In some SAR cases, there is uncertainty about the object being searched for: upright or swamped or capsized life-raft or craft, with or without persons-on-board; PIW in a life jacket, survival suit, deceased, or swimming. Environmentally interactive scenarios take into account the impact of the metocean conditions on either the voyage itself, the probability of an originating craft becoming a SAR object, the distribution of an aircraft incident (break-up in flight or loss of fuel leading to controlled gliding), or trajectory modification due to limited propulsion (e.g. an active swimmer or paddler). A voyage scenario mimics the voyage of the originating craft along a series of track-lines from start to end where each track line has uniform probability of turning into the distressed drift object. However, “hazards” can be introduced to increase the probability of generating a distress drift object particle as the originating craft transits the time and location of the hazard. A hazard can either be permanent or temporary. For example, three aircraft scenarios have been prototyped to account for the three principal types of aircraft incidents: a loss-of-control at altitude that generates a LKP distribution as a function of the altitude at incident; a break-up in flight with the scattering of debris by the dynamics and wind field profile to the sea surface; and an aircraft running out of fuel and gliding on a heading or towards a destination, but affected by the upper-level winds. The last type of interactive scenario is a swimmer (typically scuba or skin diver) in distress who actively swims on a heading towards a destination. The Active Swimmer Scenario has both a swim vector, which is affected by the waves, plus a current drift vector. It may revert to a passive PIW, e.g. at night. All these scenarios require access to metocean data to be implemented.

Once scenarios are provided to the trajectory model and probability drift predictions are returned, the SAR planners can proceed to plan the search efforts of each of the search units. For the first search epoch, a SAR planner is quite capable of planning an optimized search effort for the available resources, accounting for the different capabilities of the search units and their sensors, on-scene conditions, and the search objects that each unit might focus their efforts on. If, however, the initial search effort is unsuccessful, and subsequent search efforts are required, then a SAR planning tool is required to account for the initial unsuccessful search effort and update the probability distribution, which will need a new drift update. In order to plan and account for search effort, environmental data are required based upon which parameters influence the performance of the sensors. These data parameters include, but are not limited to, visibility, precipitation, air and sea-surface temperatures, wind speed, wave height, white capping percentage, sun angle, moon phase and cloud cover.

Not all searches are successful, and the SAR planner must at some point consider whether to continue or suspend the search (“Active Search Suspended Pending Further Developments” or ACTSUS). This decision is a critical juncture for the victims, their families, and the SAR authorities. Predictions of the survivor’s deteriorating physiological condition and future ST are essential to the SAR planner during the search. The SAR planner uses these predictions to optimize the search resources, and for consideration along with other aspects of the search to make the ACTSUS decision (Turner et al, 2009). Fate models for estimating survival at sea are at the present time limited to physiological heat generation versus heat loss. These hypothermic models of survivability rely on air and sea-surface temperatures, along with wind speed, relative humidity, waves, and solar radiation for the environmental input parameters, and are needed for 5 days beyond the time of the incident (Tipton et al., 2022).

Since the incident has occurred prior to notification, drift predictions will be needed from the earliest possible time up until the next set of resources conclude their search efforts. The drift trajectory model will need the initial conditions, i.e. the scenarios and drift objects, and the projected timeline of the resources.

When the notification of a SAR incident reaches the SAR authorities, their immediate goal is to trigger SAR resources as soon as possible, with an initial or preliminary tasking, whether a drift prediction is available and necessary or not. This requires that the turn-around time from the SAR authorities’ request or need for a drift prediction to the delivery of that drift prediction is operationally acceptable to the SAR authorities. Of the three general schemes for data systems for SAR emergencies, the first or third systems are employed. The one-to-one data system has been and is still widely used to support SAR drift trajectory calculations. The limitation of this approach is that SAR controllers are typically limited in the scope and complexities of the input scenario.

**Table III.2**

**Oceanographic and Meteorological Parameters affecting SAR Operations**

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Parameter SAR Operation | 10 m Wind vectors | 1 m Surface currents | Significant wave height | White cap cover [%] | Sea surface temp | Surface air temp | Visibility | Lunar Phase & Cloud Cover | Precipitation rate & type | Relative humidity | Icing & Ice cover | Solar Radiation |
| Incident Prediction | **1st** | **1st** | **1st** |  | 2nd | 2nd | 2nd | 3rd | 2nd |  | 2nd |  |
| Drift Prediction | **1st** | **1st** | 2nd |  |  |  |  |  |  |  |  |  |
| Visual Detection | **1st** |  | **1st** | 2nd |  |  | **1st** |  |  |  |  |  |
| NVG Detection | **1st** |  | **1st** | **1st** |  |  |  | 2nd | 2nd |  |  |  |
| Radar Detection | 2nd |  | **1st** |  |  |  |  |  | 2nd |  |  |  |
| Infrared Detection | **1st** |  | **1st** | **1st** | 2nd | 2nd |  | 2nd | 2nd |  |  |  |
| Survival Estimation | 2nd |  |  |  | **1st** | 2nd |  |  |  | 3rd |  | 3rd |
| Small Boat Operations | 2nd |  | **1st** |  | 2nd | 3rd | 3rd |  |  |  |  |  |
| Vessel  Operations | 2nd |  | 2nd |  |  |  |  |  |  |  |  |  |
| Aircraft Operations | 2nd |  | 2nd | 2nd |  |  | **1st** |  |  |  |  |  |
| Helicopter Operations | **1st** |  | **1st** |  | 2nd | 2nd | **1st** |  |  |  |  |  |
| Ice Operations | 2nd | 2nd |  |  | 2nd |  | 2nd |  |  |  | **1st** |  |
| Post-Incident Analysis | **1st** |  | **1st** |  | 2nd | 2nd |  | 3rd |  |  | 2nd |  |

**‘1st**’ is a First Order environmental parameter affecting this SAR operation.

**‘2nd’** is a Secondary Order environmental parameter affecting this SAR operation.

**‘3rd’** is a Tertiary Order environmental parameter affecting this SAR operation

## APPENDIX IV – MODELLING AND DATA FOR RADIOLOGICAL IMPACT ASSESSMENTS (SUMMARY OF CASE STUDIES COORDINATED BY IAEA)

*Author: Pierre Daniel (MétéoFrance)*

From 2012 to 2015, the IAEA implemented the Modelling and Data for Radiological Impact Assessments (MODARIA) programme, which concentrated on testing the performance of models; developing and improving models for particular environments; reaching consensus on datasets that are generally applicable in environmental transfer models; and providing an international forum for the exchange of experience, ideas and research information. Different aspects were addressed by 10 working groups within MODARIA, covering four thematic areas: remediation of contaminated areas; uncertainties and variability; exposures and effects on biota; and marine modelling. The work of Working Group 10 addresses Modelling of Marine Dispersion and Transfer of Radionuclides Accidentally Released from Land-based Facilities.

The group studied two marine releases of radionuclides: (i) the release of Chernobyl fallout into the Baltic Sea (Periáñez et al., 2015 a); and the release from the Fukushima Daiichi nuclear power plant into the Pacific Ocean (Periáñez et al., 2015b).

In Japan, several groups conducted simulations of oceanic dispersion after the Fukushima accident. Though each group used a different set of models and showed different results, by reviewing them, it was found that the weak southward current along the Fukushima coast determined the initial transport direction, and that mesoscale eddy-like structures and surface current systems contributed to the dispersion in areas beyond the continental shelf. Among them, Japan Atomic Energy Agency (JAEA) carried out the simulation and validation of 137Cs dispersion to describe its medium to long-term transition in the ocean, using a nuclear dispersion model (GEARN) developed by JAEA and an ocean circulation model (MOVE/MRI.COM, 1/10◦ for north-western Pacific) developed by Meteorological Research Institute (MRI/JMA). It shows that the directly released 137Cs advances eastward along the Kuroshio Extension, being mixed and diluted by mesoscale eddies, and arrives at 170⁰ W after one year.

In the USA, the National Centre of Environmental Prediction (NCEP) of the National Weather Service (NWS) used particle tracing to predict the movement of radionuclides in the ocean shortly after the nuclear accident near Fukushima. Daily nowcast/forecast fields from 1/12° HYbrid Coordinate Ocean Model (HYCOM), implemented at NCEP as the Global Real-Time Ocean Forecast System (RTOFS-Global), were used to track inert particles at the ocean surface, assuming that the surface behaviour is reasonably represented by the ocean mixed layer, which, by definition, is nearly homogeneous in the vertical dimension. Thus, radionuclides are expected to be homogeneously distributed within the entire mixed layer of the ocean. This distribution occurs either immediately or within a few days following their release. The focus was on producing actionable information for a governmental Inter-agency Working Group (IWG) in near real-time using available resources.

With the particle tracing information, NCEP produced estimates of the retention time of radionuclides near the coast, as well as the dispersion timescale of these materials through the Pacific Ocean, particularly by persistent current systems like the Kuroshio and its extension, and the Oyashio. This helped identify both potentially safe areas in the Pacific, and areas of potential exposure on the timescales of weeks to months. Using particle tracking combined with atmospheric deposition of radionuclides, a first guess at the contamination of ocean surface water was produced.

First particle tracking products were routinely delivered to the IWG within four weeks of the first significant release of radionuclides The first quantitative offshore contamination estimates were made available to the IWG in approximately 6 weeks (Tolman et al., 2013).

In France, the SIROCCO group (from CNRS and University of Toulouse) performed, at the request of the IAEA, simulations using the 3D SIROCCO ocean circulation model to investigate the dispersion in seawater of radionuclides released by the Fukushima nuclear accident. The model uses a stretched horizontal grid with a variable horizontal resolution, from 600 m near Fukushima, to 5 km offshore. The initial fields and the lateral open boundary conditions are provided by the 1/12° Mercator global system. The SIROCCO group was the first to publish on the web results on marine dispersion of radionuclides (Estournel et al., 2012).

From 2012 to 2014, the Science Council of Japan organized an intercomparison of atmospheric and oceanic dispersion models that simulated the future of radioactive releases from Fukushima. The findings were published in late 2014 (Science Council of Japan, 2014)[[23]](#footnote-24).

The report concludes that, although there are similarities between the different simulated dispersions, significant differences are found between models concerning distributions in space and time that result from different approaches and source terms applied. It is not possible to identify which model produces the results closest to measurements. The variability of marine circulation in the mixing zone between the Kuroshio and Oyashio east of Fukushima largely explains this variability due to the presence of unstable eddies.

This intercomparison shows that there are currently several models able to perform simulations of the drift of radionuclides in the ocean. The differences between the simulations on a limited dispersal period (from March to June 2011) illustrate how their use is hazardous for assessing the dispersion of radionuclide releases in the medium term. The measurements on samples at sea remain the only reliable way to estimate the dispersion in this area.

The estimates of the source term for the Fukushima simulations are highly variable. The estimated direct discharge to the sea in April 2011 remains a subject of debate between the different investigators. Many assessments were performed on inputs of 137Cs. Atmospheric deposition on the sea-surface accounted for amounts of about the same size, but with a wide distribution in the North Pacific in the first months after the accident.

The IAEA – MODARIA Working Group on Modelling of marine dispersion and transfer of radionuclides accidentally released from land-based facilities published a paper on models applied to simulate 137Cs marine dispersion after recent nuclear accidents (Periáñez et al., 2014). State-of-the-art dispersion models were applied to simulate 137Cs dispersion from the Chernobyl nuclear power plant disaster fallout on the Baltic Sea and from Fukushima Daiichi nuclear plant releases in the Pacific Ocean after the 2011 tsunami. A wide variety of models were used, from box to fully three-dimensional models, and all included water/sediment interactions. Agreement between models was very good in the Baltic. In the case of Fukushima, results from models could be considered to be in acceptable agreement only after a model harmonization process consisting of using exactly the same forcing (water circulation and parameters) in all models. It was found that the dynamics of the considered system (magnitude and variability of currents) was essential in obtaining a good agreement between models. The difficulties in developing operative models for decision-making support in these dynamic environments were highlighted. They defined three stages to be considered after an emergency, each of them requiring specific modelling approaches. They are the emergency, the post-emergency and the long-term phases.

* + - 1. Emergency phase: The temporal scale of the simulation extends from hours to a few days and the spatial scale to be solved from tens to a few hundred km. In this case a very rapid response (in matter of seconds to a few minutes) should be given by the model to decide, for instance, if swimming must be immediately banned in a beach, or the area where fishing should be banned. This rapid response may be achieved using data on forecast of currents and waves diffusivity from operational marine models and using Lagrangian models to predict the transport of radioactivity. The temporal horizon of such water current and wave prediction is limited by the temporal scale of weather forecasts, which is about 7–10 days. Examples of this approach are given by Periáñez and Pascual-Granged (2008), Estournel et al. (2012), Duffa et al. (2016), Garraffo et al. (2016), and Maderich et al. (2016). Marine product contamination can also be estimated using biota dynamic models, as was done by Duffa et al. (2016). In this initial stage, the model output would also help to develop sampling strategies for monitoring.
      2. Post-emergency phase: the temporal scale extends to a few weeks and the spatial one to the order of 100 – 1000 km. We may consider a desalination plant that produces fresh water for irrigation a few hundred km from the nuclear facility. It should be decided whether taking seawater should be stopped. While more time is available for decision-making compared to the initial emergency phase, relying solely on short-term ocean forecasts may not be feasible due to their limited temporal and spatial accuracy. The potential solution is using data from analogous periods of previous years and the formation of an ensemble of radioactivity predictions to estimate future contamination of water, sediments and biota. With respect to the dispersion model, both Lagrangian and Eulerian approaches could be used (for instance Kawamura et al., 2011, Simonsen et al (2017) and Periáñez et al., 2012). Interactions with suspended matter and seabed sediments have been shown to affect the transport pattern after the Fukushima accident (Choi et al., 2013; Min et al, 2013). Additionally, it is worth considering the use of seasonal-to-interannual prediction ocean-atmosphere models during this phase. While these models operate at a coarse resolution and primarily simulate large-scale advection and dispersion of radionuclides, they can provide valuable information to emergency response teams over longer timescales, helping to enhance decision-making and risk assessment processes.
      3. Long-term phase: this phase would imply the assessment of the long-term consequences of the accident, including transfers of radionuclides to sediments and biota, as well as evaluating the potential role of sediments as a source of contamination once radionuclide concentrations in seawater have decreased (Periáñez, 2003). This assessment may be carried out with Eulerian models, in which these complex processes are more easily included than in Lagrangian systems and coupled dynamic biota models (Vives i Batlle et al., 2016). Ocean current fields are obtained by time-averaging ocean circulation model fields. Simulations over several months may be carried out for spatial scales of some hundreds of km. For even longer-term assessments (years to decades and thousands of km), some authors recommend using box models (Lepicard et al., 2004; Iosjpe et al., 2009). For such timescales, the computational cost of using 3-D models becomes prohibitive and the results are not better than cheaper box models.

In any case, for highly dynamic environments, it was found that model output is extremely sensitive to the choice of model used to predict the ocean circulation. Thus, the ocean model should be selected with great care and after a detailed comparison with local measurements of currents. In this sense, Duffa et al. (2016) indicate that high-resolution local forecasts of marine circulation should be used for emergency modelling. Although global ocean circulation models produce realistic pictures of the general circulation in the ocean, their outputs differ in the local scale in dynamic environments, due, at least in part, to their relatively coarse spatial resolution.

Overall, models to be used for radionuclide release emergencies in the marine environment should be carefully tuned for each particular location, i.e. for each nuclear facility for which it is decided to have a modelling tool to support decision-making after a potential emergency occurring there. In other words, we cannot be a priori confident in generic models which import ocean forecasts of currents if a highly dynamic environment is involved.

### TERMINOLOGY

| Terminology | Definition |
| --- | --- |
| Acoustic laser | A sensor that makes use of the acoustic excitation to vibrate the object and the laser beam to measure the vibrational frequency response to determine the physical characteristics. |
| Advection | The mean transport due to the bulk motion of the fluid. |
| Aircraft Operations | Fixed wing aircraft, including helicopters, can conduct extended nearshore and offshore searches. The primary sensor capabilities of large aircraft are surface search radars, combined with visual or NVG searching. Aircraft have the capabilities to deploy rescue equipment to survivors. Small aircraft are limited to nearshore visual searching. |
| Air-side drag | The friction on a partially submerged object due to forces from the atmosphere (wind). |
| Aldehydes | An organic compound containing a functional group with the structure R−CH=O |
| Capillary waves | A wave travelling along the phase boundary of a fluid, whose dynamics and phase velocity are dominated by the effects of surface tension. |
| Common processes | Processes such as advection commonly used in various drift simulations |
| Constant flux layer | A layer of air tens of metres thick at the bottom of the atmosphere where the variation of vertical turbulent flux with altitude is less than 10% of its magnitude |
| Data assimilation | Algorithms that seek to optimally combine numerical model calculations with observations, with the aim of improving prediction accuracy. |
| Data assimilation schemes | Data assimilation schemes refer to the methods used to assimilate observations into numerical weather prediction models. |
| Deep-water blowouts | A deep-water blowout refers to an uncontrolled release of oil and gas from an underwater well in deep-water environments, typically in offshore drilling operations. |
| Deterministic drift simulation | Oil characteristics especially on viscosity and density |
| Down-wind leeway | The component of the leeway of an object due to wind in the down-wind directions |
| Drift and fate predictions | Transport and weathering numerical forecasts |
| Drift Prediction | Drift Predictions are conducted on the individual particles of the Monte Carlo Simulation from the earliest possible time of the incident through to the end of the next search effort. Drift predictions account for the surface current and leeway portions of displacements. |
| Eddy diffusivity | Is the rate of change of the dispersion of objects or material. Used to describe the spread of material due to eddy (turbulent) motion. |
| Ekman layer | Ekman layers are boundary layers in which there is a balance between the viscous force and the Coriolis acceleration |
| Ensemble members | Ensemble members refer to individual weather forecasts that are part of an ensemble forecast. |
| Ensemble modelling | A process where multiple diverse model runs are performed to predict an ensemble of results, either by using many different modelling algorithms or by using different setups for the same model, e.g. perturbations of initial conditions, boundary conditions, forcing fields, etc. It is expected that the ensemble mean is a more robust estimate than the individual ensemble members, and that the ensemble spread informs about the uncertainty of the mean. |
| Eulerian modelling | A modelling method that focuses on the state of the fluid at fixed points. |
| Fate modelling | Models focusing on characteristic/condition changes of objects or materials. |
| Field of view | The extent of the observable world that is seen at any given moment. |
| Forward-Looking Infrared (FLIR) cameras | These cameras detect heat signatures and help locate survivors in the water. |
| Freeboard | The distance from the mean waterline to the top of a small boat or object, or top deck of a large ship. |
| Geophysical forcing data, | Meteorological and oceanographic data that act as drivers or forcings for geophysical processes. |
| Geostrophic current | The component of the current field that is due to the balancing of the sea surface gradient and the earth’s rotation (Coriolis force). |
| Hazardous substances | Noxious and other marine environmental hazards (e.g. Harmful algal blooms). |
| HAZMAT | An abbreviation for “hazardous materials". Hazmats include such substances as toxic chemicals, fuels, nuclear waste products, and biological, chemical, and radiological agents. |
| Helicopter Operations | Rotary wing aircraft can conduct nearshore and limited offshore searches. The primary sensor capabilities of large aircraft are daylight visual or NVG and Infrared searching at night. Helicopters have the capabilities to conduct rescues. Wind speeds and gusts, wave height, and air/sea temperatures all impact helicopter operations. |
| High-frequency coastal radar | Land-based remote-sensing instruments capable of measuring surface currents and ocean waves at ranges up to 200 km or more. Usually implemented as an array of high-frequency radio antennae along the coast. |
| Hindcast | A simulation of a past time period using a numerical model with no influence of observations during the time period. |
| Hydroxyl radicals | An important chemical species throughout the atmosphere. In the troposphere it is the primary oxidant of both natural and anthropogenic hydrocarbons, leading to the production of pollutant ozone. |
| Ice Operations | Specialized vessels conduct search and rescue operations on 100% ice-covered waters. Visibility is a key parameter for these operations. |
| Incident | This refers to the accident or event that occurred and resulted in a vessel or aircraft and their person being in distress. The incident is characterized by when, where and what went into distress and their associated uncertainties. |
| Infrared Detection | Electro-optical stabilized airborne mounted sensors combine optical with IR sensing to allow for night-time searching for person-in-the-water and persons on or in small craft. IR sensors that scan small areas are negatively impacted by whitecaps and other IR noise, and since they depend upon thermal signal of the search object above the background and its noise level is impacted by sea surface and air temperatures; moon phase combined with cloud cover and the presence of precipitation. However, when the conditions are ideal (low winds with cloudy night during new moon) the IR sensors can detect at night. |
| Lagrangian drift | The drift following a particle in the ocean. |
| Lagrangian modelling | A modelling method that focuses on the state of the fluid at specific moving points. |
| Langmuir circulation | A series of shallow counter rotating vortices at the ocean surface generated by wind. It can form visible rows of floating material, known as windrows. |
| Laser fluorosensor | Laser fluorosensor is a device that emits laser beams at specific wavelengths to excite the fluorescence properties of oil on the water surface. |
| Lateral Range Curve | Lateral range function of a sensor which is a plot of the probability of detecting the target (object) on a single pass as a function of its lateral range from the sensor's track. |
| Leeway model | A model for surface drift which includes wind and wave forces as a linear function of the wind speed. |
| Marginal ice zone | Region of the cryosphere between open ocean and pack ice. Typically defined by ice coverage between 15% and 80% by area. |
| Maxey-Riley equation | The equation of motion for a spherical inertial object in an ambient fluid. Includes direct forcing on object from fluid, in addition to lift, drag and an added mass force due to part of the fluid being transported with the sphere. |
| METAREA | Geographical sea region for the purpose of coordinating the transmission of meteorological information to mariners on international voyages through international and territorial waters. |
| Metocean models | Numerical models of the atmosphere, ocean circulation, sea ice and surface waves. |
| MOTHY | Modèle Océanique de Transport d’hydrocarbures. |
| Multimodel Ensemble | Multimodel Ensemble (MME) methods combine ensemble simulations run with different model codes. |
| Near-surface variables | Near-surface variables refer to atmospheric conditions or measurements taken in close proximity to the sea surface. |
| Numerical model codes | A numerical model code is the set of computer instructions used to solve the algorithms and equations used to capture the behaviour of the modelled system. |
| NVG Detection | Visual observation of oil objects using night-vision goggles. |
| Oil fate | Change of oil conditions by environmental condition, such as evaporation / emulsification. |
| Oil rheology | Viscosity and density. |
| Opendrift | Opendrift is a software package for modelling the trajectories and fate of objects or substances drifting in the ocean. |
| OSERIT | Oil Spill Evaluation and Response Integrated Tool. |
| Passive tracers | Ocean particles that move freely with the water and are not directly affected by forces. Objects moving with only forcing of outer conditions. |
| Photo-oxidation | A chemical reaction that can change the composition of an oil. It occurs when the sun's action on an oil slick causes oxygen and carbons to combine and form new products. |
| Post-Incident Analysis | Upon completion of an incident, an analysis may be conducted to determine the cause of the incident and what actions the survivor took during the incident. The analysis can be used to update procedures and modelling efforts on all aspects of the incident. |
| Pseudo-component models | Pseudo-component models are oil weathering models in which pure components are grouped into a set of simplified components, known as pseudo-components, based on their chemical properties and behaviour during weathering. |
| Pumice | A very light and porous volcanic rock formed when a gas-rich froth of glassy lava solidifies rapidly. |
| Quadratic drag law | The friction is proportional to the squared velocity of the fluid (air or water) relative to the object. |
| Radar cross-section | The area intercepting that amount of power which, if radiated isotropically, produces the same received power in the radar. |
| Radar Detection | Active sensor (also known as "scatterometer") that operates in the microwave and radio wave band. |
| Radionuclide releases | Radioactive gases and liquids from nuclear power plants released to the environment. |
| Reanalysis | A simulation of a past time period using a numerical model with assimilation of observations during the time period. |
| Relative drag | The drag is calculated from the motion of the fluid relative to the motion of the object. |
| River plumes | Where rivers enter the sea and the freshwater begins to mix with the seawater. |
| Runge-Kutta integration | A numerical method for ordinary differential equations (ODEs), which has 4th order accuracy. |
| Sargassum | A genus of brown macroalgae (seaweed). |
| Satellite altimeter data | The measurements of the sea surface height obtained from the vertical distance between the satellite and the nadir surface of the Earth. These measurements are collected by satellite-based altimeter sensors that are designed to measure the time taken by radar pulses to travel from the satellite antenna to surface and back to the altimeter. |
| Scatterometers | Active remote-sensing instruments for deriving wind direction and speed from the roughness of the sea. |
| Search and Rescue Optimal Planning System | Search and Rescue Optimal Planning System (SAROPS) is a comprehensive search and rescue planning system utilized by the United States Coast Guard. |
| Searchlights | A searchlight is an apparatus that combines an extremely bright source with a mirrored parabolic reflector to project a powerful beam of light of approximately parallel rays in a particular direction. |
| Shear diffusion | Shear diffusion of oil refers to the process by which oil spreads and diffuses horizontally across the water surface under the influence of wind and currents. |
| Slippery water | A term coined to describe shallow layers of water that are observed to “slip” over the bulk fluid. Related to regions with high vertical stratification, typically due to salinity. |
| Small boat Operations | Shore-based vessels typically 10-20 m in length conduct inshore or nearshore operations and are often called motor-lifeboats. They are impacted by sea state while on scene with sea state operating thresholds. Tides interacting with the incoming swell at the inlets can prevent the small boat from either transiting the inlet on the way out or back in. Protective thermal clothing is determined by a combination of sea and air temperatures. The primary sensor capability of Motor-lifeboat is visual searching. Motor-lifeboats provide recovery capabilities. |
| Stokes drift | A near-surface current velocity component due to propagating surface waves. It is defined as the difference between the Lagrangian and Eulerian average of the flow field. It is calculated as an average of the Lagrangian particle displacement over many wave periods, and follows the mean wave direction. |
| Stratification | Change in density with distance. In the ocean, stratification is typically referred to as the increase in density with increasing depth. |
| Surface jets | See slippery water. Typically, surface jets are used to describe the motion when the stratification is due to temperature. |
| Survival Estimation | Estimates of potential ST of survivors in the water and onboard the survival craft is a key input to the suspension of the search if the survivors are not found. Sea surface temperature is the primary driver for estimating ST both statistically and by physiological modelling. The physiological models also account for wind speed, relative humidity, air temperature, and solar radiation. |
| Synthetic Aperture Radar | A form of radar that is used to create two-dimensional images or three-dimensional reconstructions of objects, such as landscapes. |
| The drift and fate model | Transport and weathering numerical models. |
| Vessel Operations | Vessels greater than 20 m in length can conduct extended nearshore and offshore operations and are often called cutters. They are impacted by sea state primarily by having to reduce speed. The primary sensor capabilities of Cutters are visual and NVG searching. Cutters provide both search and recovery capabilities. |
| Visual Detection | Visual observation of oil spills or objects traditionally performed by an experienced observer. |
| Water-side drag | The friction on a partially submerged object due to forces from the ocean (currents). |
| Winches | A winch is a mechanical device that is used to pull in (wind up) or let out (wind out) or otherwise adjust the tension of a rope or wire rope. |

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# DYNAMIC PART OF THE GUIDE

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The Dynamic part of the guide is available [here](https://wmoomm.sharepoint.com/:w:/s/wmocpdb/Efok4bdxAKtJs4mEASaSqRMBIROzIsZ3IenmvStysPnF-Q?e=Scc4A2).

1. Field (and remote-sensing) observations – in SAR, that might be sightings of debris, as well as locations that were searched with no sightings. For oil spills, observations of the slick location and conditions are critical, and for drifting objects, observations and more rarely, a GPS locator on the objects. [↑](#footnote-ref-2)
2. <https://www.bbc.com/news/world-europe-47574143> [↑](#footnote-ref-3)
3. <https://www.bbc.com/news/world-latin-america-60180226> [↑](#footnote-ref-4)
4. HAZMAT is an abbreviation for “hazardous materials". HAZMATs include such substances as toxic chemicals, fuels, nuclear waste products, and biological, chemical, and radiological agents. [↑](#footnote-ref-5)
5. Cedre is a state-approved association which provides advice and expertise to French and foreign public and private authorities and organizations in charge of the response to accidental water pollution. [↑](#footnote-ref-6)
6. <https://cfconventions.org/cf-conventions/cf-conventions.html> [↑](#footnote-ref-7)
7. <https://optics.marine.usf.edu/projects/SaWS.html> [↑](#footnote-ref-8)
8. <https://www.weather.gov/ncep/> [↑](#footnote-ref-9)
9. <https://www.ecmwf.int> [↑](#footnote-ref-10)
10. <https://marine.copernicus.eu/> [↑](#footnote-ref-11)
11. <https://ioos.noaa.gov/> [↑](#footnote-ref-12)
12. Note that operational sea ice models are nearly always coupled with an ocean circulation model. This means that, while data describing the sea ice itself are little used in drift and fate modelling, the effects of sea ice on the ocean circulation are included in the currents, water temperature, etc. [↑](#footnote-ref-13)
13. Formerly known as the Global Data-Processing and Forecasting System (GDPFS). Renamed WIPPS in June 2023. [↑](#footnote-ref-14)
14. <https://www.ecmwf.int/sites/default/files/elibrary/2021/ecmwf-strategy-2021-2030-en.pdf> [↑](#footnote-ref-15)
15. <https://www.goosocean.org/> [↑](#footnote-ref-16)
16. <https://ioc.unesco.org/> [↑](#footnote-ref-17)
17. <https://www.unep.org/> [↑](#footnote-ref-18)
18. <https://council.science/> [↑](#footnote-ref-19)
19. <https://rucool.marine.rutgers.edu/geohfr/index.html> [↑](#footnote-ref-20)
20. <https://ioos.noaa.gov/project/hf-radar/> [↑](#footnote-ref-21)
21. <https://eurogoos.eu/high-frequency-radar-task-team/> [↑](#footnote-ref-22)
22. <https://library.wmo.int/?lvl=notice_display&id=7700> [↑](#footnote-ref-23)
23. Freely available here: http://cesd.aori.u-tokyo.ac.jp/cesddb/scj\_fukushima/index\_j.html [↑](#footnote-ref-24)