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A METHODOLOGY FOR RESPONSE GAP ANALYSIS IN OFFSHORE OIL SPILL EMERGENCY MANAGEMENT

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Abstract

In case of offshore oil spills, the success of emergency response largely depends on the meteorological and oceanographic conditions during and after the spill, which are expressed by a set of different environmental factors. A "gap" in the response may be caused by unfavourable environmental factors that could limit its effectiveness or even impede it. In this context, Response Gap Analysis (RGA) studies identify the environmental factors negatively influencing the emergency response in a given sea area and aim at assessing the percentage of time during which the response would be without success or impossible to deploy. In the present study, a new RGA methodology is described, based on 11 environmental factors. Different oil spill response strategies are considered: mechanical recovery, application of dispersants by vessel and by aircraft, and in-situ burning. A case-study is presented to demonstrate the methodology and discuss the outcomes obtained by its application.

Keywords: emergency response; environmental factors; Directive 2013/30/EU; oil spill; response gap analysis; response viability analysis.

1. Introduction

Oil spills at sea are among the accidental events causing the most severe damage to the environment, as evidenced by the data reported in several specific databases [ARIA, 2021; CEDRE, 2021a; REMPEC, 2021]. Very often oil tankers are the source of spills at sea, which result in huge environmental damage. Focusing on the last 25 years, it is worth mentioning the Sea Empress grounding near the coasts of Wales in 1996, the Erika sinking in the Atlantic Ocean off France in 1999, the rupture in two of the Prestige in 2002 in the Gulf of Biscay and of the MV Wakashio in 2020 nearby the lagoons of Mauritius, the Hebei Spirit collision in South Korea in 2007, and the collision of the Sanchi in the East China Sea in 2018. These disasters caused the release into the sea of a total amount of more than 280,000 tonnes of oil [Neuparth et al., 2012; Chen et al., 2019, Jin et al., 2019; CEDRE, 2021b]. However, significant oil spills at sea might occur also from offshore installations for the exploitation of oil and gas [DNV GL, 2021], and, in particular, from blowout scenarios [Holand, 1996; Schmidt Etkin et al., 2017; SINTEF, 2021]. It is worth mentioning the Montara blowout in 2009 in Australia, with a spill volume in the range 4,600 ÷ 34,000 m^3 over 75 days, as well as the Deepwater Horizon blowout, occurred in 2010 in the Gulf of Mexico, with a spill amount between 390,000 and 670,000 m^3 over nearly 3 months [Beyer et al., 2016; Schmidt Etkin et al., 2017; Spies et al., 2017].

During the last decades, the adoption of progressively stricter safety measures has determined a decrease in the frequency of oil spills, with respect to releases from both ships and fixed installations. In fact, the occurrence frequency of leakages from oil tankers has been significantly reduced by several factors, among which some of the more important are the introduction of double hulls, the adoption of electronic collision avoidance and global positioning systems, the improvement of personnel training and the enhances in marine traffic coordination [Burgherr, 2007; Chen et al., 2019; Huang et al., 2020; ITOPF, 2021a]. Similarly, in the offshore sector, growing attention has been devoted to safety barriers for preventing oil spills [Hauge et al., 2012; Hauge et al., 2016; Bucelli et al., 2018] and, in particular, to those for the prevention of blowouts and well releases [IPIECA-IOGP, 2011; Vandenbusche et al., 2014; Brandvik et al., 2018].

Nevertheless, despite the relevant technological progress aimed at assuring the integrity of ships, sealines, and offshore installations so to reduce the likelihood of any loss of containment, the possibility of oil spills at sea cannot be totally excluded, as confirmed by some recent severe accidents [IMO, 2021; Jin et al., 2019; Pan et al., 2020].

In case of an oil spill event, contingency operations are required to mitigate the contamination of the environment. The main emergency strategies to respond to an oil spill are represented by containment / deflection, mechanical recovery, spraying of dispersants by vessel or by aircraft, and in-situ burning [AMSA, 2015; IPIECA-IOGP, 2015a; IPIECA-IOGP, 2016]. Even if these techniques have been used since more than 50 years, advances in their application, also due to a continuous evolution of technologies, is documented in the technical literature and in guidelines for people involved in contingency response, as emergency planners, decision makers, and field responders [NOAA, 2013; Exxon Mobil, 2014; API, 2015]. Furthermore, the recent advent of oil exploitation in Arctic and sub-Arctic waters has posed huge challenges to oil spill response and has resulted in the funding of specific research projects on emergency response in these regions [Jørgensen et al., 2019; Tarantola et al., 2019; BSSE, 2021]. Consequently, specific oil spill emergency response guidelines have been proposed for the Arctic [ADEC, 2014; ACS, 2015; EPPR, 2017a; ARRT, 2016].

However, the effectiveness of oil spill emergency response is affected by the environmental factors during and after the spill, which could not only limit the performance of remedial actions, but also make their implementation impossible [Li et al., 2016; Kong et al., 2020; Schmidt Etkin et al., 2021]. Furthermore, the weathering phenomena decrease rapidly the thickness of the oil slick floating on the sea surface and increase its viscosity. Thus, the “window of opportunity” for the implementation of emergency actions, which are especially effective on oil slicks with a minimum thickness and a maximum viscosity, can be rather short, limited to 1 or 2 days after the spill [Nordvik, 1999; Fingas, 2004; Bullock et al., 2019]. Consequently, it is during this time span that the environmental factors should be conducive to the response. Actually, the unfavourable conditions of the environmental factors during the “window of opportunity” are the cause of “gap” periods in the response, during which contingency actions are unsuccessful or even impossible [NUKA, 2007a].

In this framework, Response Gap Analysis (RGA) studies for a given sea area aim at identifying the environmental factors which could have a negative influence on oil spill response and, based on their hindcast over a suitable time period, to statistically evaluate the percentage of time during which the response could be ineffective [PEW, 2021]. More recently, the term Response Viability Analysis (RVA) has been used for the same studies, emphasizing the percentage of time during which an effective response may be carried out [EPPR, 2017b; Dahlslett et al., 2018; NUKA & DNV GL, 2019]. Information about the percentage of time of the ineffective response is critical when assessing the risk of oil spills from a given operation. Depending on the results of RGA, additional preventive and / or protective measures may be required. For example, some oil and gas production operations could be limited to specific seasons and may be curtailed during critical biological periods or the access of oil tankers to vulnerable areas, with a relevant ecological value, may be prohibited during response gaps [PEW, 2021; NUKA, 2007a; NUKA, 2007b].

In the European Union, the Deepwater Horizon blowout has increased the awareness that oil spill events with severe environmental consequences might still occur, despite all the actions undertaken to avoid them. A specific Directive came into force in 2013 (Directive 2013/30/EU) to control major accident hazards from offshore oil and gas operations. The Directive requires offshore operators to carry out a RGA to assess the oil spill response effectiveness, including an "analysis of the frequency, duration, and timing of environmental conditions that would preclude a response. Furthermore, the assessment of oil spill response effectiveness is to be expressed as a percentage of time that such conditions are not present" [Directive 2013/30/EU]. Exploration and production of oil in the Arctic is among the factors that caused similar requirements to be issued in some sea areas in North America by the local regulatory authorities [NUKA, 2007b; SL Ross, 2011; NUKA, 2012]. Actually, in the Arctic regions on the one hand a unique and precious environment is present, on the other the weather conditions are often particularly harsh, so to preclude response actions to oil spills. Also due to the above regulations coming into force, RGA studies started in 2006, but were mostly developed after 2012.

The availability of RGA studies represents a useful support for oil spill emergency response planning. In this regard, it has to be recalled that usually the determination of the tactic (or of the combination of tactics) to be adopted to face an oil spill in a given location is based on the minimization of the environmental impact of the oil spill which could occur in the area, and on the maximisation of the benefits for the marine environment and for the socio-economic and cultural targets potentially impacted by the oil. A NEBA - Net Environmental Benefit Analysis study, which can be carried out by implementing a SIMA - Spill Impact

Mitigation Analysis, is usually performed to address this issue [IPIECA-IOGP, 2015b; IPIECA-IOGP & API, 2017]. A SIMA study is a semi-quantitative procedure for estimating the impact mitigation score of each tactic with respect to the no intervention option, finally allowing a ranking of the different response options. The evaluation of the reduction in the environmental impact of each tactic requires the simulation - without and with response actions - of the transport and fate of the oil and of the physical and chemical phenomena occurring to the oil. However, the mathematical models for simulating the fate and trajectory of the oil, which are implemented in specific software tools able to consider the response tactics, currently do not provide an estimate of their response gap [Barker et al., 2020; Keramea et al., 2021]. Hence, a separate method needs to be used to assess the gap. Thus, a RGA study is an auxiliary tool used by decision makers involved in oil spill response planning, aimed at providing the probability that the environmental conditions allow the deployment and operation of the tactics evidenced as the most suitable by the SIMA study.

The present study introduces a novel comprehensive method for RGA, suitable for application either by operators of offshore installations, or by oil tanker companies and public authorities, with the aim of reducing the risk of environmental contamination caused by oil spills, especially in ecologically sensitive areas. The paper has the following structure: the state of the art about RGA methods is presented and discussed extensively in section 2; section 3 is devoted to the description of the new RGA methodology, which, in section 4, is applied to a case-study. Section 5 and 6 provide, respectively, the presentation and the discussion of the results, while some conclusive remarks are drawn in section 7.

2. State of the art of methods for RGA

As shown in Table 1, 8 different methodologies to carry out a RGA study have been presented up to now in the open literature.

RGA methods		References
1	LOS	[Terhune, 2011]
2	SL Ross	[SL Ross, 2011]
3	NUKA	[NUKA, 2006; NUKA, 2007b; NUKA, 2008; NUKA, 2012; NUKA, 2014; NUKA, 2015; NUKA, 2016]
4	DNV	[Laborde et al., 2015]
5	DNV&DCD	[Spansvoll et al., 2015; Spansvoll et al., 2016]
6	EPPR&DNV&NUKA	[EPPR, 2017a; EPPR, 2017b]
7	DNV&NCA	[Dahlslett et al., 2018]
8	NUKA&DNV	[NUKA & DNV GL, 2019]

Table 1. Response Gap Analysis methods available in the technical literature

In the following, a comparative analysis of these methods is reported.

2.1 Environmental factors

Table 2 lists the environmental factors considered in each method. A comprehensive description of the negative effects of the environmental factors on oil spill response is summarized in the Supplementary Material, while major details can be found in other studies [Fingas, 2011; NUKA, 2014; NUKA, 2015; EPPR, 2017a].

RGA METHODS / ENVIRONMENTAL FACTORS		1 LOS	2 LS Ross	3 NUKA	4 DNV	5 DNV&DCD	6 EPPR&DNV&NUKA	7 DNV&NCA	8 NUKA&DNV
Wind	Wind speed								
	Wind gusts								
Sea state	Significant wave height								
	Average wave period								
Temperature effects	Air temperature								n.r.
	Sea temperature								n.r.
	Superstructure icing								n.r.
	Wind chill								n.r.
Visibility	Daylight / darkness								
	Horizontal visibility								
	Cloud ceiling								
Sea ice	Ice coverage								n.r.
Currents and tides	Current velocity								
	Tides								
Debris	Debris								

	Environmental factors which are recognized having an impact on the success of oil spill response, but are not directly considered in the case-study to which the method is applied
	Environmental factors directly considered both in the method and in the case-study to which the method is applied
n.r.	Environmental factor not considered because not relevant (n.r.) in the area for which the method was developed

Table 2. Response Gap Analysis methods: environmental factors cited and / or considered

Table 2 shows that none of the RGA approaches described in the technical literature takes into account directly the wind gusts, the sea temperature, the currents / tides, and the presence of debris. The wind gusts probably are not considered since the effect of the wind is already expressed by the wind speed, and probably also because of the limited data available. The sea temperature is never considered directly by the methods, though it is often used to evaluate the superstructure icing. The exclusion of currents and tides is to ascribe to a different cause. In fact, if vessels used for emergency response are not anchored and not sailing, the entire response equipment at sea (booms, skimmers, vessels) is captured by the current and there is no relative movement between the components of the response system and the current, making negligible the influence of the current on the response [NUKA, 2006; NUKA & DNV GL, 2019]. In case of sailing vessels, since the speed of the current relative to the boom can always be reduced below a limit value by adjusting the speed of the vessels towing the boom, the current speed is actually not a limiting factor for the response.

With regard to debris, despite their influence on the response is recognized, their presence is a random factor, difficult to assess.

It can be noticed easily that one of the methods (method 1 - LOS) considers the wave height as the only environmental factor affecting the response. In most of the other approaches, at least the wind speed, the wave height, the superstructure icing, the daylight / darkness, and the ice coverage (a total of 5 environmental factors) are considered. It is necessary to recall that the wind speed and the wave height are directly correlated in offshore environment, as pointed out by the Beaufort wind force scale [Lindau, 1995]. However, since the available empirical correlations between the wind speed and the wave height only provide approximate and uncertain results, in all RGA methods available in the technical literature the wave height is never calculated as a function of the wind speed, but separate datasets are used for the wind speed and the wave height. Thus, this approach was used also in the methodology developed in the present study.

With respect to waves, some methods consider both the wave height and the wave period, since, at a given wave height, steeper waves impair the response more than waves having a longer period. Though, other methods take into account only the wave height. Method 3 - NUKA considers the maximum number of environmental factors (10), including also the wave period, the air temperature, the wind chill, the horizontal visibility, and the cloud ceiling (directly related to the vertical visibility).

While in the presentation of method 1 - LOS it is expressly recognized that considering only the wave height is incorrect, thus admitting that the results of this RGA approach only represent a first attempt to estimate the response effectiveness, all the other procedures do not provide detailed discussions concerning the reasons for the exclusion of some environmental factors. Only in few cases, the cause of the exclusion is related to the absence of data.

All RGA methods use historical and / or modelled hindcast data for the environmental factors referring to a multi-year period (from 5 to 20 years). In regard to the time resolution of the data, it is necessary to consider that the environmental factors have rather different dynamics. For instance, the sea temperature shows much slower variations than the wind speed. Consequently, while daily sea temperature values may be adopted, for the wind speed this resolution is not adequate. In any case, monthly values seem completely inadequate for all the environmental factors, being daily values barely acceptable even for those factors showing a slow dynamic. Focusing on the space resolution, since the methods are intended mainly for spills in open sea, a rather coarse mesh (e.g., 25 km x 25 km, as in [EPPR, 2017b]) is adopted, because gradual variations of the environmental factors are expected among contiguous points far off the coastline.

2.2 Oil spill response tactics

Oil spill emergency response may be carried out by means of 4 strategies: containment / deflection, mechanical recovery, application of dispersants, and in-situ burning. Within each strategy, several tactics are available, i.e. specific techniques for mounting the strategy, as described in [EPPR, 2017a; NUKA & DNV GL, 2019].

Table 3 reports the main strategies and the tactics for which each RGA method estimates the response effectiveness.

RGA METHODS / RESPONSE STRATEGIES AND TACTICS	1	2	3	4	5	6	7	8
	LOS	LS Ross	NUKA	DNV	DNV&DCD	EPPR&DNV&NUKA	DNV&NCA	NUKA&DNV
CONTAINMENT / DEFLECTION								
Containment booming								
Deflection booming								
MECHANICAL RECOVERY								
No tactics specified								
2 vessels with boom								
Single vessel with outrigger								
3 Vessels-Of-Opportunity								
2 vessels with active boom								
Single vessel system in ice								
DISPERSANT APPLICATION								
Vessel dispersant application								
Fixed-wing dispersant application								
Helicopter dispersant application								
Subsea dispersant injection (SSDI)								
IN-SITU BURNING								
No tactics specified								
Vessel ignition, fire-proof boom								
Fixed-wing ignition, fire-proof boom								
Helicopter ignition, fire-proof boom								
Vessel ignition, ice containment								
Fixed-wing ignition, ice containment								
Helicopter ignition, ice containment								
Helicopter ignition, herders application								

Table 3. Response Gap Analysis methods: oil spill response tactics considered

The oldest procedures only accounted for mechanical oil recovery. More recently, also the surface application of dispersants and in-situ burning have been considered. Only 2 of the RGA methods have considered also containment booming, while none of the methods has taken into account deflection booming or the subsea dispersant injection (SSDI). However, not all the methods specify the tactics adopted within each strategy. Furthermore, some methods describe the response tactics providing limited details: for instance, in case of mechanical recovery with a vessel system and a boom, the number and type of the vessels is not given and in case of aerial operations, it is not specified whether a fixed-wing aircraft or a helicopter is used.

2.3 Operational limits of the environmental factors

All the RGA methods divide the variability range of the environmental factors in 3 zones: the green zone (the factor favours a successful response), the yellow zone (the factor is marginal, i.e. it could impair the response), and the red zone (the factor is unfavourable to the response) [NUKA & DNV GL, 2019]. Thus, in each methodology 2 threshold values, or operational limits, are established for each environmental factor in each response tactic. As explained in [NUKA, 2016], the use of 3 tiers for each environmental factor is intended to acknowledge and partially overcome the challenge of representing the response degradation. Indeed, this deterioration occurs continuously (though not linearly). Thus, in theory, an even higher number of zones would be useful. However, pinpointing the operational limits for more than 3 zones is difficult and implies a significant subjectivity. For this reason, the presence of 3 levels represents an acceptable compromise between the need of a realistic description of the degradation process and the requirement of simple and robust criteria to distinguish among the tiers. It is important to remark that the deterioration of the response corresponding to the yellow and the red zones can be due either to the decreasing effectiveness of the response equipment, or to the worsening of the working conditions, which could become unsafe for the responders. Obviously, the safety of the response personnel, as well as of any other person involved in the response, is always a priority [EPPR, 2017b].

The consistency and internal coherence of an RGA method require that the same number of tiers is adopted for all the environmental factors. More specifically, the absence of the yellow zone for some environmental factors in some RGA methods is somewhat difficult to justify. The only exception is represented by daylight / darkness, since the transition time between these conditions is so short to be deemed negligible. Actually, in all RGA methods, daylight corresponds to the green zone. Instead darkness is considered either marginal (i.e. in the yellow zone) when vessels are involved, or unfavourable (i.e. in the red zone) for the tactics requiring the use of an aircraft [EPPR, 2017b; NUKA & DNV GL, 2019].

The assessment of the threshold values to delimit the zones is a delicate issue, mostly based on expert judgment. Not surprisingly, the different RGA methods apply different thresholds, usually reporting limits only for some environmental factors and adding few comments for the values adopted. These differences may be caused by the scarce experimental data available on operational limits, as documented, for instance by [Allen et al., 2011] and [NC, 2011], which report thresholds for some environmental factors derived from the Deepwater Horizon oil spill response.

It is worthwhile to stress that the operational limits mainly depend on the components of the response equipment, and that, in principle, differences could be justified by the adoption of different equipment. However, all case studies, except the one described in [NUKA & DNV GL, 2019], consider sea areas in the North of America and Europe or in the Arctic regions, and some of them refer to the same zones. Thus, large variations in the threshold values can hardly be put down to differences in the equipment. An exception applies to the differences in the horizontal visibility and cloud ceiling values in case of aerial intervention, that depend on the type of aircraft, which can be an airplane or a helicopter, and on the flight regulations: in fact, these regulations may be different from country to country.

2.4 Criteria for the determination of the response outcome

The outcome of the response deriving from the application of each method is based on the combination of the conditions of all the environmental factors. Table 4 shows the 2 criteria used by the current RGA methods to establish the overall outcome of the response.

CRITERION	METHODS	DESCRIPTION	RESPONSE OUTCOME
A	Method 2. NUKA, before 2016	All factors green OR one factor yellow and the others green	Response favourable
		2 or more factors yellow OR one factor red	Response ineffective
B	Method 1. LOS Method 2. NUKA, since 2016 Method 3. SL Ross Method 4. DNV Method 5. DNV&DCD Method 6. EPPR&DNV&NUKA Method 7. DNV&NCA Method 8. NUKA&DNV	All factors green	Response favourable
		At least one factor yellow. All the other factors green or yellow	Response impaired
		At least one factor red	Response ineffective

Table 4. Response Gap Analysis methods: criteria to combine the environmental factors for the determination of the response outcome

Criterion A considers 2 tiers for the response, which can be favourable (green) or ineffective (red). Criterion B is based on 3 response levels, with a yellow zone (impaired response) between the green and the red ones.

2.5 Limits of the existing methods

The state of the art about RGA has evidenced some room for improvement in the existing RGA methods. The main revisable areas are the definition of the set of the environmental factors to be taken into account and the information provided about the emergency response tactics considered within each strategy, which is a key element to determine the operational limits of the environmental factors. These limits are in some cases only partially clear. Furthermore, some methods do not take into consideration some factors, which can play a role in the determination of the response, thus possibly providing an overestimate of the favourable response outcome.

A further point is that some of the methods do not define a yellow zone between the green and the red zones for some of the environmental factors. In the light of the criteria for the response outcome summarized in Table 4, not defining a yellow zone for some of the environmental factors may result in an underestimation of the impaired response.

Lastly, while all the methods provide statistical estimates of the response outcome probabilities based on hindcasts of the environmental factors, none of them seems conceived to be used as a support for real-time decision making basing on forecast data, i.e. decision making just after the occurrence of a spill event.

3. Methodology

In order to overcome the limits of the existing methods, a new RGA methodology was developed. The aim of the procedure is, on the one hand, to provide a more robust response outcome based on a systematic and detailed analysis of all the environmental factors influencing the response and on a consistent and sound definition of the threshold values for the definition of the conditions of each factor. On the other hand, the new RGA technique was conceived not only to be used for the statistical analysis of hindcast data, but also to support real-time emergency decisions to be taken just after a spill event, providing criteria for the selection of the most suitable tactic based on the forecasts of the environmental factors.

The flowchart of the new procedure is reported in Figure 1. A flexible software code written in MatLab (version R2017b) [Mathworks, 2019] was developed to support its application.

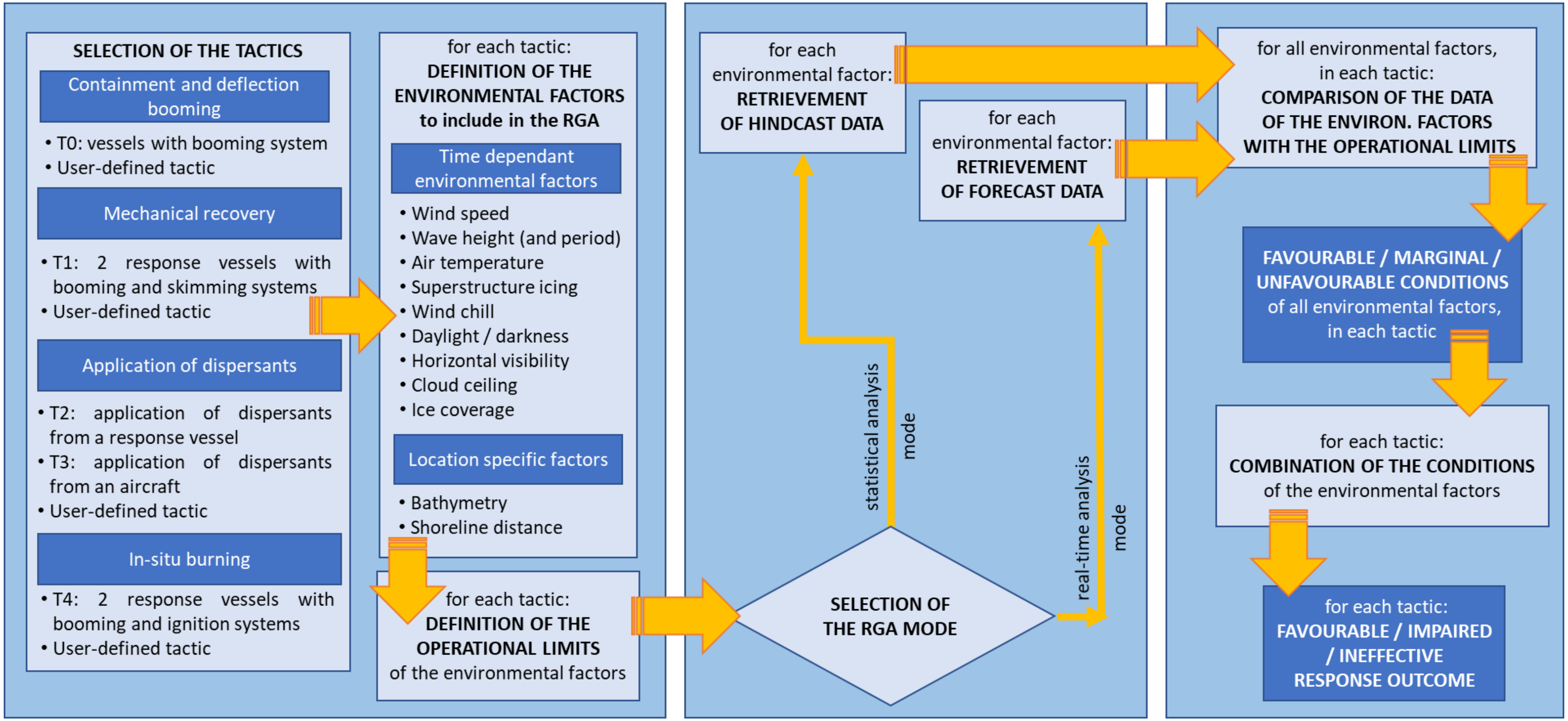


Figure 1. Flowchart of the new Response Gap Analysis methodology

The new method considers 9 environmental factors and 2 location-specific factors, as shown in Figure 1. The location-specific factors are the bathymetry and the shoreline distance, which are not time-dependent. These parameters are not considered in the RGA methods listed in Table 1, despite their influence on the response outcome in coastal areas. As regards the bathymetry, in shallow waters the size and / or the draught of the response vessel could hamper its speed and maneuverability, thus limiting the extension of the area where the vessel can operate. Furthermore, a minimum water depth may be required not only to apply dispersants, but also when using the tactics based on in-situ burning. In fact, the higher the water depth, the easier the dilution of both the oil droplets forming as a consequence of the application of dispersants and the residues of the combustion which, even in a small amount, cannot be totally recovered from the sea surface and, unavoidably, enter the water column. Lastly, the deployment of booms for oil containment in shallow-water locations with strong currents may lead to the loss of significant amounts of oil from entrainment, in particular when the draught of the boom is greater than 25% of the water depth [ADEC, 2014; ARRT, 2016; BP CEG, 2018]. With respect to the shoreline distance, in case of in-situ burning it is necessary to consider safety distances between the burning oil slick and populated areas along the coast, which could be impacted by the smoke plume forming during the combustion [ADEC, 2008].

In the following, for the sake of simplicity, all the above factors are globally indicated as “environmental factors”, also in order to align the terminology to that used in the previous RGA methods.

As shown in Figure 1, 4 oil spill response strategies (i.e. containment and deflection booming, mechanical recovery, application of dispersants, and in-situ burning) and a total of 5 baseline tactics (indicated with T0, T1, T2, T3, and T4) are considered in the method. These tactics are applicable in every geographical area and can address both surface and subsea oil spill scenarios. However, it is important to point out that the RGA methodology allows the definition of further tactics, in addition to the baseline ones considered in the present study. For instance, while the baseline tactic T4 refers to in-situ burning carried out from a response vessel with booming and ignition systems, in-situ burning can be performed also by several other tacticsm, as shown in Table 3 (e.g., with fixed-wing ignition and booming systems, or helicopter ignition and booming systems, or a vessel ignition system with ice containment, or a fixed-wing ignition system with ice containment, or a helicopter ignition system with ice containment, or a helicopter ignition system with the application of herding agents). Clearly enough, in-situ burning based on ice containment is of interest only in the Arctic regions. As a further example, subsea injection of dispersants (SSDI) for combating subsea blowouts was not included among baseline tactics but may be considered in the methodology as a user-defined tactic. This tactic usually requires the transfer by aircraft of the dispersant and the injection equipment from the location where the emergency resources for a given sea area are stockpiled to the installation experiencing the blowout. Rather intuitively, environmental factors can hamper the transfer operations.

Lastly, it is important to notice that the possibility of defining further tactics makes the methodology capable of taking into account technological progress and new tactics that could become available in future.

Within each response tactic, 2 operational limits need to be defined for each environmental factor in order to delimit the conventional 3 zones used in RGA methods, that is the green zone corresponding to favourable conditions, the yellow zone where the conditions are marginal, and the red one for the unfavourable conditions. Only in the case of daylight / darkness, 2 zones are considered, that is the green and yellow ones for the tactics using a vessel, while the green and the red zones for the tactics based on an aircraft.

The overall response outcome is obtained by combining the zones of each environmental factor through the criterion B reported in Table 4. More specifically, the assessment of the conditions of the environmental factors has to be performed in each point of the geographical area of interest and at each time within the period selected, since in general the environmental factors vary over space and over time. In the case of the bathymetry and the distance from the shoreline, only the position needs to be considered, since such factors do not change in time.

Thus, a key point of the methodology is the determination of the operational limits of each environmental factor. An extensive analysis of the limits adopted by the existing RGA procedures and of those reported in the technical literature was carried out to define conservative reference values for the operational limits of all the baseline tactics considered. Quite different values are present in the technical literature for the operational limits. The baseline values suggested, being intended for general use, were selected to provide a conservative estimate of the ineffectiveness of the response. As discussed below, specific values can be selected, if detailed data on the area of interest and the response equipment are available.

Table 5 shows an example of the reference values proposed for the tactic T4 - In-situ burning - 2 response vessel with booming and ignition systems.

ENVIRONMENTAL FACTORS			Conditions			Reference
			Favourable	Marginal	Unfavourable	
1	Wind speed		< 5 m/s	5 m/s ÷ 10 m/s	> 10 m/s	[IPIECA-IOGP, 2016]
2	Wave height (without wave period)		< 1 m if period < 6 s < 1.2 m if period ≥ 6 s	1 m ÷ 2 m if period < 6 s 1.2 m ÷ 2 m if period ≥ 6 s	> 2 m	[SL Ross, 2011; Buist et al., 2013]
	Wave height (without wave period)		< 1 m	1 m ÷ 2 m	> 2 m	
3	Air temperature		> -5 °C	-25 °C ÷ -5 °C	< -25 °C	[EPPR, 2017a; EPPR, 2017b; EPPR, 2017c]
4	Superstructure icing		< 0.7 cm/h	0.7 cm/h ÷ 2 cm/h	> 2 cm/h	[NUKA, 2016]
5	Wind chill		> -31.7 °C	-37.2 °C ÷ -31.7 °C	< -37.2 °C	[EPPR, 2017b]
6	Daylight / darkness		daylight	darkness	not used	[NUKA & DNV GL, 2019]
7	Horizontal visibility	vessel monitoring	> 900 m	200 m ÷ 900 m	< 200 m	[EPPR, 2017a; EPPR, 2017b]
		helicopter monitoring	> 1,900 m	700 m ÷ 1,900 m	< 700 m	[EPPR, 2017a; EPPR, 2017b]
8	Cloud ceiling	vessel monitoring	not limiting			/
		helicopter monitoring	> 300 m	150 m ÷ 300 m	< 150 m	[NUKA, 2014]
9	Ice coverage		< 10%	10% ÷ 30%	> 30%	[SL Ross, 2011; Buist et al., 2013]
10	Bathymetry		> 18 m	10 m ÷ 18 m	< 10 m	[ARRT, 2016]
11	Shoreline distance		> 4,800 m	1,600 m ÷ 4,800 m	< 1,600 m	[ADEC, 2008]

Table 5. Reference values proposed for the operational limits of the environmental factors in tactic T4 - In-situ burning - 2 response vessels with booming and ignition systems

The complete sets of reference values defined for the operational limits of the environmental factors in the baseline tactics are reported in the Supplementary Material, that also includes an example of the review performed on the values of the environmental factors adopted by the existing RGA methods. Quite obviously, the reference values provided in Table 5 and in the Supplementary Material are only intended as guideline values. In fact, it is important to bear in mind that the methodology allows the user to define site-specific operational limits, substituting the reference values with less conservative thresholds, where different adoptions are justified by the features of the response equipment or of the area. For instance, in case of non-populated coastlines, the operational limits of the shoreline distance could be lowered (even to 0, which corresponds to the exclusion of this factor), if the protection of the marine environment from the oil at sea provided by in-situ burning is deemed more important than the protection of the fauna living on land from the smoke plume. Furthermore, in case the user defines a new tactic, it is necessary to specify the operational limits of the environmental factors in the tactic. For instance, if the response gap of in-situ burning with ice containment has to be analyzed, specific threshold values are necessary. Some examples of these thresholds are provided in the Supplementary Material.

In regard to the operational limits of the wave height, it is important to recall that in very rough sea conditions emergency actions could be unnecessary, because natural dispersion could be enhanced to such an extent to eliminate the oil from the sea surface. However, when the wave height is marginal, or when it assumes values just above the upper operational limit, so to be slightly unfavourable, usually natural attenuation can only reduce the amount of floating oil. Moreover, in case of oils with low dispersibility, natural attenuation could be unable to remove the oil slick quickly even in very rough sea states [Fingas, 2011].

As discussed above, the RGA method developed may be applied considering 2 different approaches: the statistical analysis mode and the real-time analysis mode.

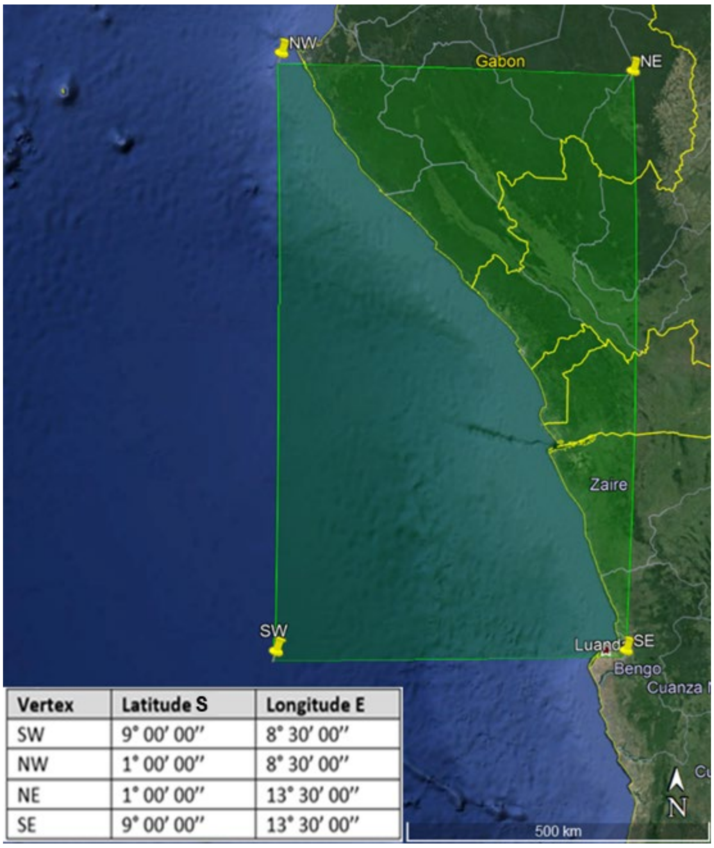
Statistical analysis is the conventional mode adopted by all the existing RGA methods. This approach is based on the analysis of multi-year hindcast data of the environmental factors for the area of interest. The probability that the response of a given tactic is favourable, impaired, or ineffective is then calculated all over the area for every week and / or month of a “typical year”. The “typical year” is obtained averaging the available hindcast data week by week and month by month in each year.

Instead, the real-time analysis mode is based on forecast data for the environmental factors in the area of interest over a period of 1 ÷ 5 days after the occurrence of an oil spill. The response outcome of the different tactics is calculated using forecast data for the area considered. The results support decision making in emergency management, allowing the selection of the tactic or of the combination of tactics having the highest probability of success.

Actually, the statistical analysis and the real-time analysis modes are complementary. During emergency response planning, the results of the statistical analysis approach support the decision process addressing the combination of the response tactics that should be made available in the area. Instead, the results of the real-time analysis are useful immediately after an oil spill event, at the beginning of the emergency response actions, to understand which tactics, when, and for how long they may be applied with success in the zones of the area where oil is present.

4. Application to a case-study

The RGA methodology developed was applied to a region of the Atlantic Ocean in front of the western coast of Africa. The map of the area selected for the case-study is shown in Figure 2.



Vertex	Latitude S	Longitude E
SW	9° 00′ 00″	8° 30′ 00″
NW	1° 00′ 00″	8° 30′ 00″
NE	1° 00′ 00″	13° 30′ 00″
SE	9° 00′ 00″	13° 30′ 00″

Figure 2. Map and coordinates of the extremes of the case-study area

The area, which was not previously analysed in the RGA studies available in the open scientific and technical literature, is located in the south of the Gulf of Guinea. It is limited eastwards by the coastline of Gabon, Congo, the Democratic Republic of Congo, and Angola, having an extension of 8° in latitude (about 889 km) and of 5° in longitude (about 554 km).

The baseline oil spill response tactics T1 (mechanical recovery - 2 response vessels with booming and skimming systems), T2 (application of dispersants from a response vessel), T3 (application of dispersants from an aircraft, specifically an airplane), and T4 (in-situ burning - 2 response vessels with booming and ignition systems) listed in Figure 1 were considered for application. The reference operational limits reported in Table 5 and in the Supplementary Material were assumed for the environmental factors. Furthermore, each tactic was supposed monitored from the same platform used as the operating platform, that is for the tactic T3 airplane monitoring was considered, while vessel monitoring was taken into account for the tactics T1, T2, and T4. The operational limits referring to the wave height without considering the wave period were taken into account, for the sake of simplicity.

The relevance of some environmental factors was excluded a-priori, since they never limit the response in the seas near the Equator: the air temperature, the wind chill, the superstructure icing, and the ice coverage. The cloud ceiling was excluded too, since it was not possible to find data for this factor. The difficulty in retrieving data for the cloud ceiling is confirmed by the fact that this factor, despite the availability of operational thresholds, so far has never been used in the RGA studies referring to wide areas in open sea [NUKA & DNV GL, 2019].

The European Centre for the Medium-Range Weather Forecast (ECMWF) - ERA 5 data source, which contains data from 1979 to present, provided the data about the wind speed, the air temperature, the dew point temperature, and the wave height [ECMWF, 2021a]. Even if the air temperature is among the factors not taken into account for the case-study area, and the dew point temperature is not in the list of the factors influencing the response directly, these temperatures were used to estimate the horizontal visibility values. Indeed, since no data for the horizontal visibility are available in the ERA 5 database, this factor was calculated as follows [EPPR, 2017b; Gultepe et al., 2010; Perry, 2008]:

$$Hor\ Vis = max\{0.05;\ -0.000114 \cdot RH\%^{2.715} + 27.0\ \} \qquad \text{eq. (1)}$$

$$RH\% = \frac{P^*(T_d)}{P^*(T_a)} \cdot 100 \qquad \text{eq. (2)}$$

$$P^*(\mathrm{T}) = \ exp(73.649 - \frac{7258.2}{T} - 7.3037 \cdot lnT + 4.1653 \cdot 10^{-6} \cdot T^2) \qquad \text{eq. (3)}$$

where:

HorVis = horizontal visibility (km)

RH % = percentage relative humidity

T_a = air temperature (K)

T_d = dew point temperature (K)

P(T)* = vapour pressure of water (Pa) at temperature *T* (K).

Information about daylight / darkness in the area was obtained through a model developed by the Institut de Physique du Globe de Paris, using the date and the latitude and longitude coordinates of the area [IPGP, 2021]. As usual in RGA studies, the civil twilights were included in daylight hours, since during these time periods illumination is sufficient to carry out oil spill contingency interventions [NUKA, 2016; EPPR, 2017b]. Morning civil twilight begins when the geometric centre of the sun is 6° below the horizon and ends at the successive sunrise. Evening civil twilight starts at sunset and ends when the geometric centre of the sun gets 6° below the horizon [NOAA-NWS, 2021]. Information about the bathymetry was extracted from the General Bathymetric Chart of the Oceans [GEBCO, 2021], whereas for the shoreline distance the Global Self-Consistent, Hierarchical, High-Resolution Geography Database was adopted [GSHHG, 2021].

A 10 years period ending with the most recent data available (2009 ÷ 2018) was considered for all the time-dependent environmental factors. Using longer periods in a RGA study may be questionable, due to climate change issues [EPPR, 2017b].

Table 6 summarizes the data of the environmental factors retrieved for the case-study area. Since most of the available data for the environmental factors have a space resolution of 0.25° x 0.25° (about 27.8 km x 27.8 km) and a time resolution of 1 hour, these resolutions were adopted in the RGA analysis.

ENVIRONMENTAL FACTORS		**DATA SOURCE**	**SPACE RESOLUTION**	**TIME RESOLUTION**	**TIME PERIOD**
1	Wind speed	European Centre for the Medium-Range Weather Forecast (ECMWF) – ERA 5 [ECMWF, 2021a]	0.25° x 0.25°	1 hour	10 years (01/01/2009 to 31/12/2018)
2	Wave height		0.50° x 0.50°		
3	Air temperature				
/	Dew point temperature				
6	Daylight / darkness	Institut de Physique du Globe de Paris [IPGP, 2021]	0.25° x 0.25°		
10	Bathymetry	General Bathymetric Chart of the Oceans [GEBCO, 2021]	1/60° x 1/60°	/	/
11	Shoreline distance	Global Self-Consistent, Hierarchical, High-Resolution Geography Database [GSHHG, 2021]	1/60° x 1/60°	/	/

Table 6. Data sources for the environmental factors considered for the case-study area

5. Results

Table 7 reports the average, minimum and maximum values calculated for each environmental factor over the whole area and the entire time period considered in the analysis.

ENVIRONMENTAL FACTORS			MINIMUM	AVERAGE	MAXIMUM
1	Wind speed	m/s	0	3	11.7
2	Wave height	m	0.2	1.4	3.7
3	Air temperature	°C	13.1	25	37.6
/	Dew point temperature	°C	7.6	21.8	29.5
6	Daylight / darkness	/	not applicable		
7	Horizontal visibility	km	0.1	8.1	26.5
8	Cloud ceiling	m	not considered		
10	Bathymetry	m	1.4	2,212	4,582
11	Shoreline distance	m	412	182,346	495,469

Table 7. Minimum, average, and maximum values of the environmental factors in the case-study area in the period 2009 ÷ 2018

It can be observed that all environmental factors present a rather wide variability spectrum. In order to compare each environmental factor included in the RGA with its operational limits, both the simple and the cumulative occurrence probabilities of the factors have been calculated and plotted versus the operational limits. Figure 3 reports the results obtained for wave height and the horizontal visibility, and shows the values of the range of each factor that are favourable, marginal, and unfavourable to the response for each tactic considered.

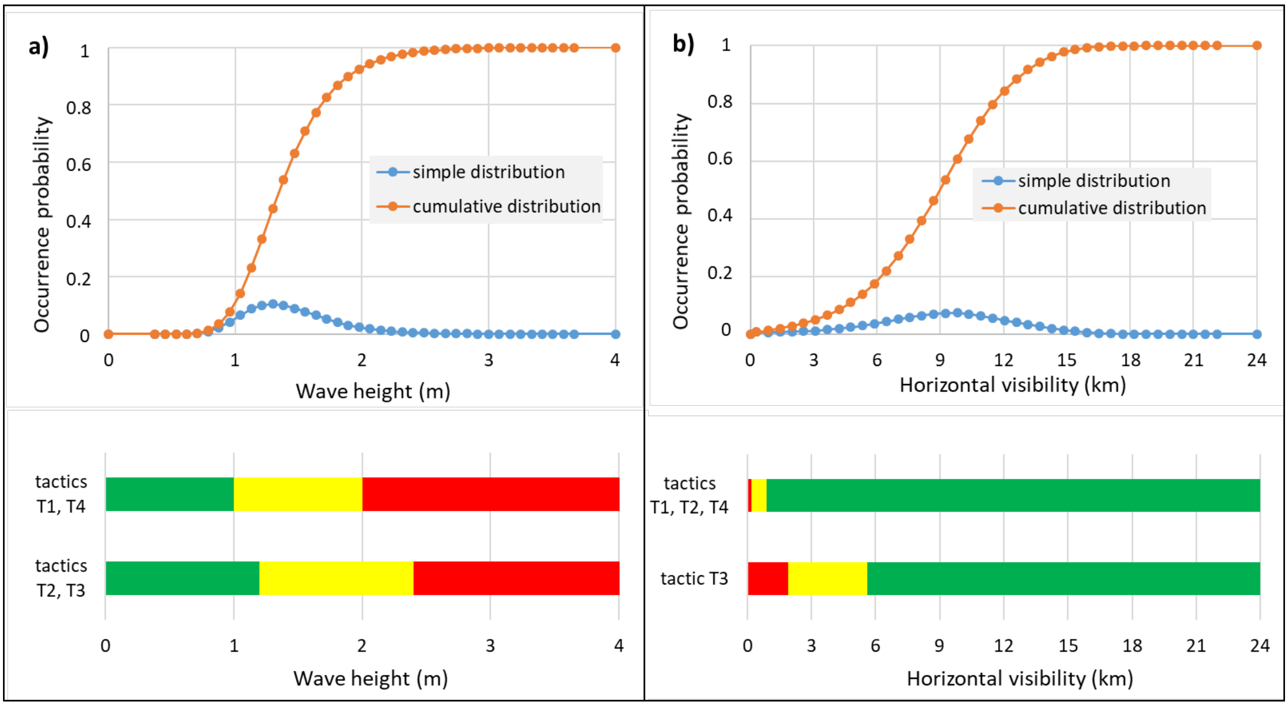


Figure 3. Occurrence probability and response of the different tactics with respect to the conditions of the environmental factors in the case-study area in the period 2009 ÷ 2018: a) wave height; b) horizontal visibility (favourable conditions: green; marginal conditions: yellow; unfavourable conditions: red)

As shown in Figure 3a), the wave height is mostly marginal or favourable to all the tactics, while unfavourable conditions occur rarely. Figure 3b) shows that also the horizontal visibility is largely favourable, or at least marginal, for the all the tactics.

Figures 4 to 7 report an example of the results obtained for the statistical analysis application of the new RGA method to the whole case-study area. Further results, which refer to the sub-zones, in which the area can be divided, are reported in the Supplementary Material.

Figure 4 reports the yearly % probabilities of the response over the entire area for all the tactics considered.

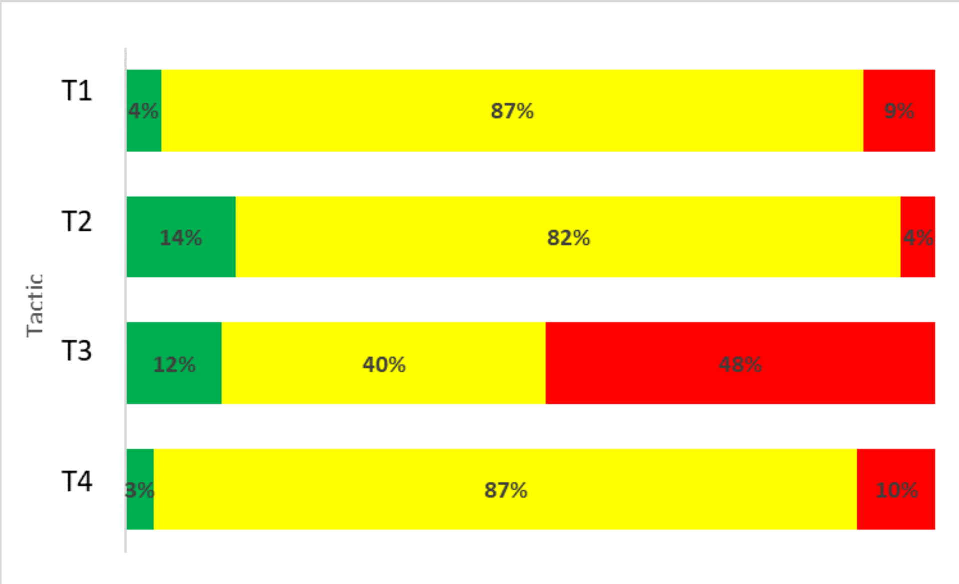


Figure 4. Response outcome in the case-study area: yearly % probabilities of favourable (green), impaired (yellow), and ineffective (red) response

It can be noticed that the % probabilities of the favourable response have low values for all the tactics, with a maximum of 14%. The tactics T1, T2, and T4 present similar values of the impaired response probability (82% ÷ 87%) and of the ineffective response probability (4% ÷ 10%). In the case of the tactic T3, the % probability of the impaired and of the ineffective response are equal, respectively, to 40% and 48%.

Figure 5 shows the contributions of the different environmental factors to the yearly % probabilities of the response of the tactic T4. Annual cycle graphics are reported too, showing how these probabilities vary during the "typical year" resulting from the statistical analysis.

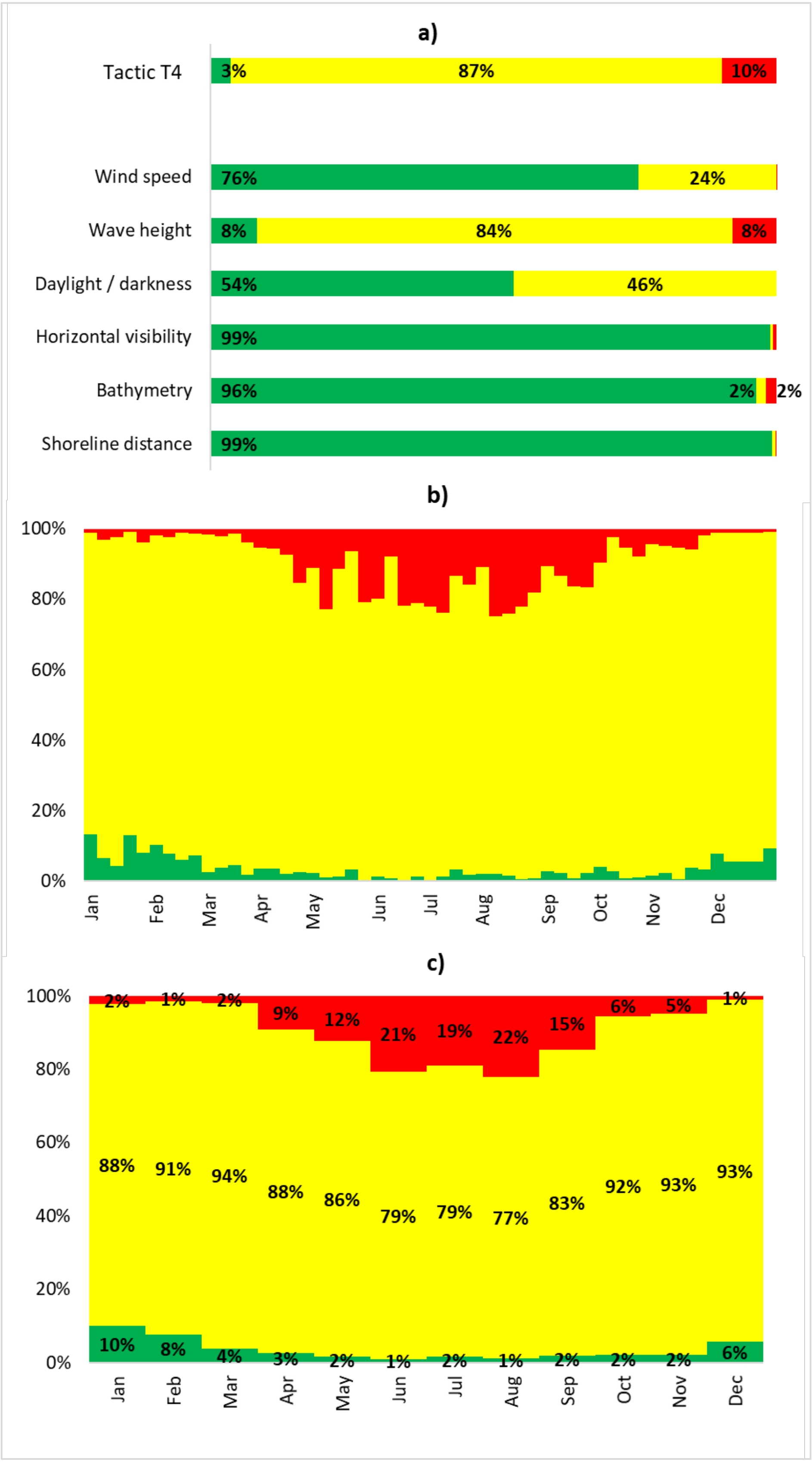


Figure 5. Application of the tactic T4 to the case-study area: a) yearly % probabilities of the response outcome and of the conditions of each environmental factor; b) weekly and c) monthly % probabilities of the response outcome (favourable conditions / favourable response: green; marginal conditions / impaired response: yellow; unfavourable conditions / ineffective response: red)

Figure 5a) allows understanding which environmental factors determine the impaired and the ineffective response of the tactic T4. The unfavourable conditions of the wave height (8%) and of the bathymetry (2%) provide the most important contributions to the overall probability of the ineffective response (10%). The % probability of the impaired response (87%) is primarily due to the marginal conditions of the wave height (84%), and, secondarily, of the daylight / darkness conditions (46%) and of the wind speed (24%). Figure 5b) and 5c) show that, as expected, the % probabilities of the response outcome are strongly dependent on the season, with the highest values of the unfavourable response occurring in June, July, and August.

Quite obviously, the variation of the % probabilities of the response outcome of a given tactic across the year is the consequence of the variations of all time-dependent environmental factors, as shown for all the tactics by the annual cycle graphics reported in Figure 6. For the sake of completeness, Figure 6 reports also the % probabilities of the conditions of the bathymetry and the shoreline distance, which are not time-dependent.

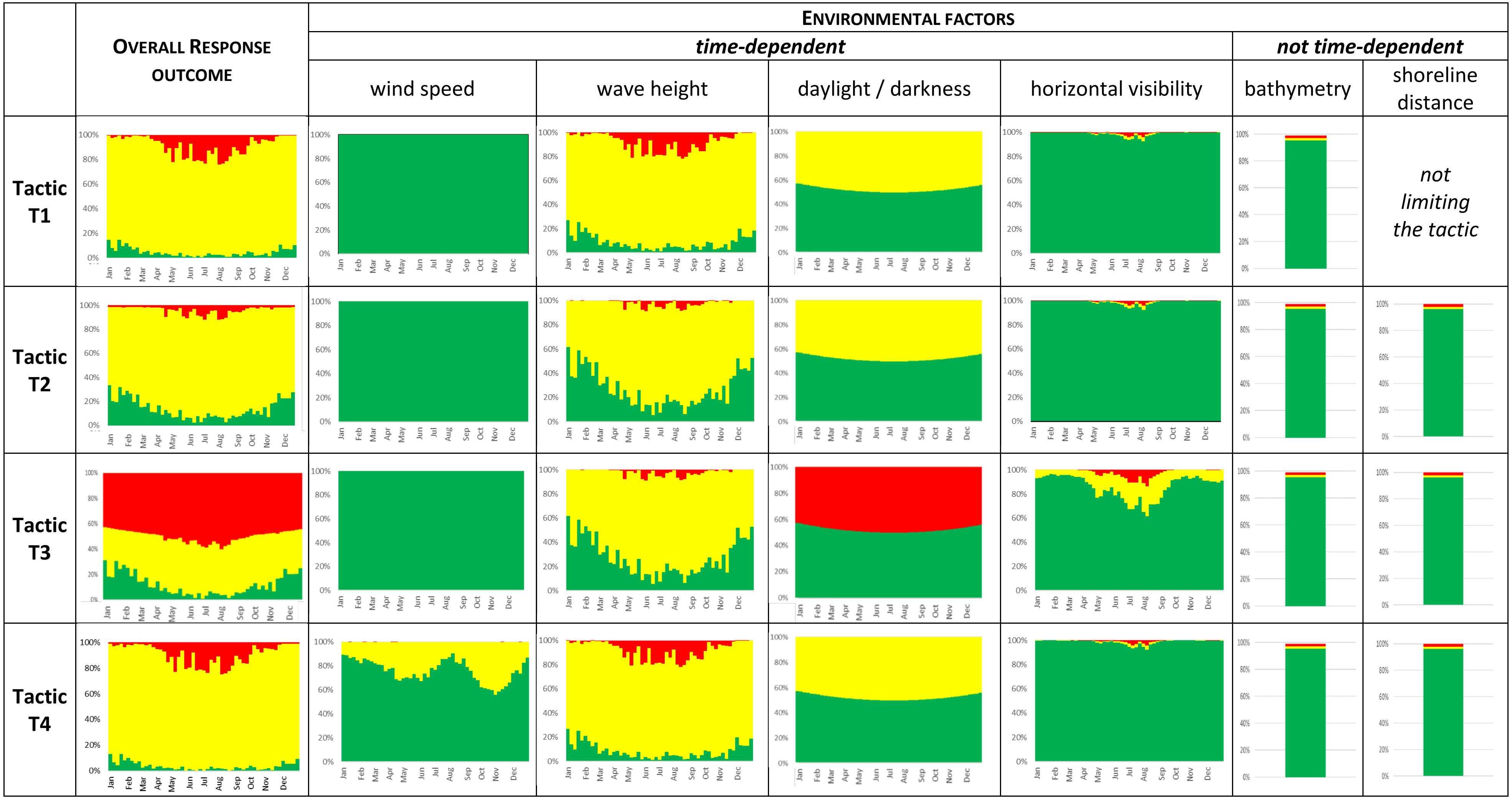


Figure 6. Weekly % probabilities of the response outcome and of the conditions of the time-varying environmental factors and % probabilities of the conditions of the time-independent environmental factors in each tactic in the case-study area (favourable conditions / favourable response: green; marginal conditions / impaired response: yellow; unfavourable conditions / ineffective response: red)

Looking at Figure 6, it can be noticed that the daylight / darkness conditions show a minor variability over the year, as typical in the regions near the Equator. The % probability of daylight and darkness over the year are equal, respectively, to 54% and 46%, being daylight slightly more probable because it includes the twilights. Daylight is favourable to the response of all the tactics, thus it corresponds to the green area in the graphs of the daylight / darkness conditions. Instead, darkness is marginal for the tactics T1, T2, and T4, as evidenced by the yellow area in those graphs, while it is unfavourable for the tactic T3, as confirmed by the presence of the red zone. Moreover, Figure 6 evidences that the wave height affects the response of all the tactics, although the tactics T2 and T3 are slightly less sensitive to this factor than the tactics T1 and T4, as shown also in Figure 3a). This causes a little higher effectiveness of the response of the tactics T2 and T3 with respect to the tactics T1 and T4. Moreover, Figure 6 shows that the wind speed impairs only the tactic T4. The tactic T3 is the only made ineffective by darkness and it is also slightly more sensitive than the other ones to the horizontal visibility conditions. In fact, while the tactics T1, T2, and T4 use a vessel as the operating platform, the tactic T3 is based on an airplane, which, quite obviously, has significantly stricter visibility requirements than a vessel. It can be noticed that for the tactic T3 the red zone of the overall response outcome nearly coincides with the red zone of the daylight / darkness conditions, thus pointing out that the ineffectiveness of the response of this tactic is mostly caused by darkness. In fact, the % probability of the ineffective response of tactic T3 is equal to 48%, as evidenced in Figure 4, only slightly higher than the % probability of darkness, which is equal to 46%.

Figure 7 reports an example of the maps with the position-based results obtained for the case-study area. The figure shows the spatial distribution of the monthly probabilities of the favourable, impaired, and ineffective response for the tactic T4 in the months of January and August, that are the months in which the conditions of the environmental factors are, respectively, the most and least likely to be favourable to the response of the tactic considered.

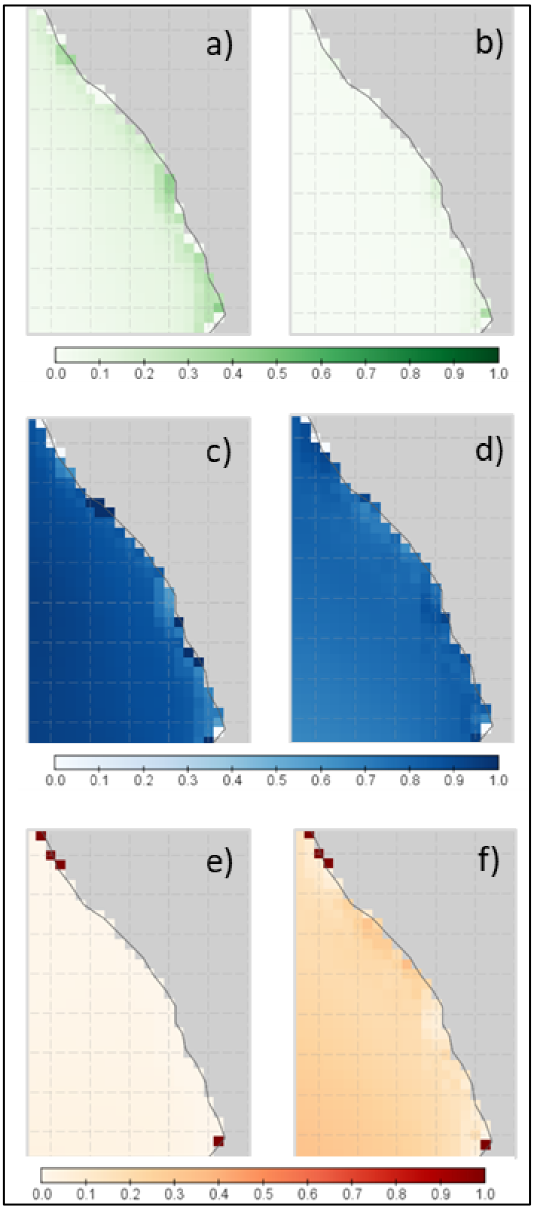


Figure 7. Maps of the case-study area reporting the monthly probabilities of the response outcome of the tactic T4 (onshore area in grey): a) favourable response in January; b) favourable response in August; c) impaired response in January; d) impaired response in August; e) ineffective response in January; f) ineffective response in August

Figure 7e) and Figure 7f) show that in a few zones along the coastline, the probability of the unfavourable response is always equal to 1, due to the unfavourable conditions of the bathymetry and / or of the shoreline distance in the proximity of the coast.

Figure 8 and Figure 9 present some results of RGA application in the real-time mode, while further results are reported in the Supplementary Material. The real-time analysis was applied assuming a spill occurring in the area on 01/08/2009 at 00:00. The values of the environmental factors from 01/08/2009 00:00 to

05/08/2009 23:00 were considered as the forecast data for a time period of 5 days after the spill. Figure 8 reports the evolution of the response outcome in the area during the 5 days period after the spill.

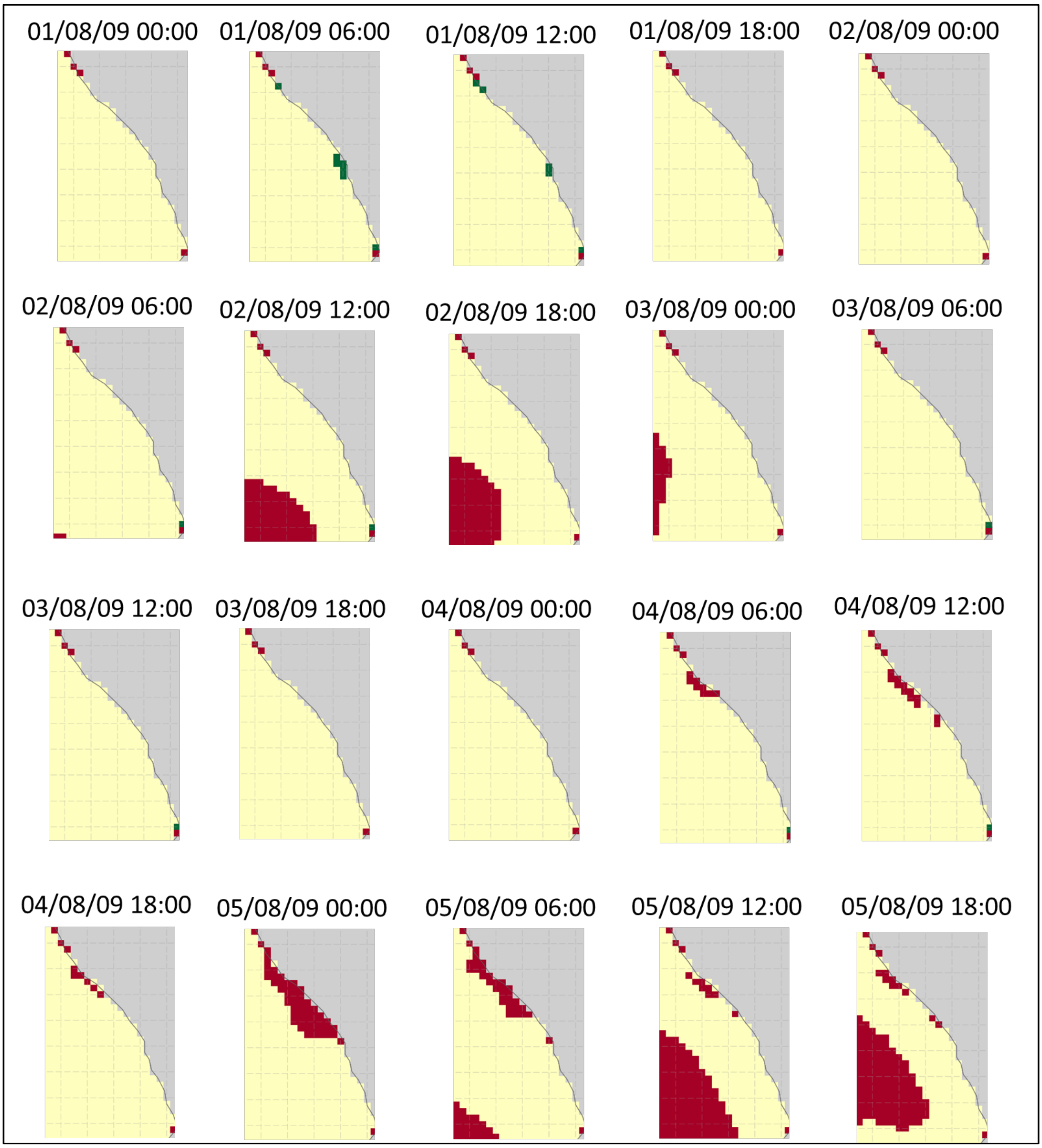


Figure 8. Maps of the case-study area reporting the response outcome of the tactic T4 at given time values during the 5 days after the spill start, assumed on 01/08/2009 at 00:00 (favourable response: green; impaired response: yellow; ineffective response: red; onshore area in grey)

The results of Figure 8 allow the identification of the locations in the area where the response of the tactic T4 is favourable, impaired, or ineffective. As expected, the response outcome changes with time in the different locations of the area.

Figure 9 reports the variation of the response outcome with time for the tactic T4 in a specific location of the case-study area, that is the grid cell centred in point (10°E longitude; 8.5°S latitude). The figure also shows the trend over time of the forecasted values of the environmental factors affecting the response of the tactic.

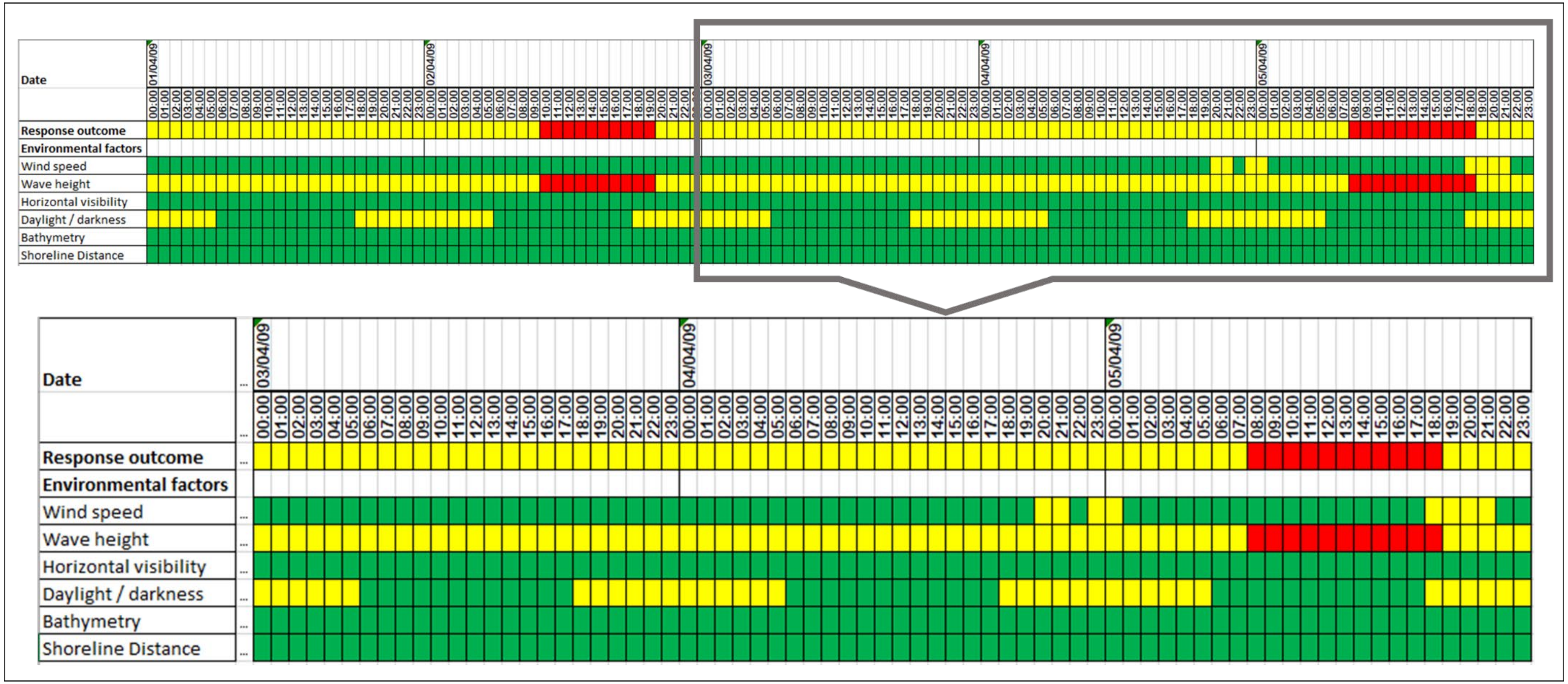


Figure 9. Response outcome and conditions of the environmental factors for the tactic T4 in a specific point of the case-study area (10°E longitude; 8.5°S latitude) during the 5 days after the spill start assumed on 01/08/2009 at 00:00 (favourable conditions / favourable response: green; marginal conditions / impaired response: yellow; unfavourable conditions / ineffective response: red)

Figure 9 evidences that the response of the tactic T4 is always impaired or ineffective in the location considered during the 5 days after the start of the spill, due to the wave height. Marginal conditions are present for the wind speed, the wave height, and the daylight / darkness. The conditions of the horizontal visibility, the bathymetry, and the shoreline distance are always favourable. Figure 9 also allows the assessment of the duration of the periods for which the different types of conditions and response outcome are present. It is possible to notice that during the 5 days examined, the duration of the periods where the conditions are marginal varies from 2 to 56 hours, while the duration of the period where the response is ineffective is equal to 11 hours.

6. Discussion

The results of the case-study confirm that the RGA method developed is able to evaluate the gap of different tactics in the emergency response to oil spills in a sea area. Actually, the approach quantifies weekly, monthly, and yearly averaged values of the response outcome probabilities based on the statistical analysis of hindcast data available for the environmental factors. The method thus provides a comprehensive assessment of the influence of the different environmental factors, allowing the identification of those factors that mostly determine the impairment and the ineffectiveness of the response. The results of the “statistical analysis” mode are of the utmost importance for the effective planning of the oil spill contingency tactics to adopt in an area.

Moreover, provided the availability of reliable forecast data for the environmental factors, the RGA method developed can be used to conduct a real-time analysis of the response gap. In this regard, it has to be acknowledged that there is an ongoing progress in weather modelling, which determines the constantly increasing accuracy of short-term forecasts. In fact, the accuracy correlation of 5-days forecasts has already reached 90% [ECMWF, 2021b]. Therefore, it is plausible that in the next future real-time RGA could help operational decision making after an oil spill more and more. The results of the real-time analysis mode provide real-time information for the deployment and operation of the tactics in the different positions of an area where oil might be recovered of treated. These results may also allow the scheduling and the authorisation of specific activities in the area, as for instance the transit of oil tankers, maintenance operations of oil wells, or the ship transfer of oil from an offshore installation to the coast, in order to avoid carrying out activities at risk in time periods where there would not be the possibility to respond to a spill.

With respect to the existing methodologies, the RGA method developed allows to take into account all environmental factors affecting the response, as well as the bathymetry and the shoreline distance, without poorly justified a-priori exclusions. Furthermore, the application of the procedure is straightforward, given the availability of a set of baseline oil spill response tactics, as well as of consistent reference values of the operational limits of the environmental factors. Moreover, the RGA method allows to add other tactics, to exclude some factors, and to tailor the operational thresholds of the environmental factors. This feature is of particular importance in the real-time analysis mode. Actually, some components of the response equipment deployed to face a spill need to be selected also considering the properties of the spilled oil. Thus, the operational limits considered in the RGA carried out in the real-time analysis mode can be modified to consider the specific equipment used to clean up the oil type spilled.

Finally, besides outlining the potentialities of the new RGA methodology, the results of the case-study also highlight the usefulness of conducting RGA studies even in non-Arctic regions, as evidenced by the low values of the probabilities of an effective response for all the baseline tactics in an Equatorial area. Actually, as shown in Figure 4, in the area considered for the case-study, the % probabilities of an effective response correspond, in decreasing order, to the tactics T2 (14%), T3 (12%), T1 (4%), and T4 (3%). However, this has not to be intended as a final order of preference of the tactics. In fact, it has to be remarked that the various oil spill response tactics have different goals and a different effectiveness in reaching these goals. For instance, while the aim of mechanical recovery is to remove the oil from the environment, the goal of the use of dispersants is to transfer the oil (and, thus, the environmental risk) from the sea surface to the water column. Furthermore, the application of dispersants can determine the dispersion of large amounts of floating oil, while mechanical recovery usually allows removing from the sea only a low fraction of the spilled oil. As already mentioned previously, the definition of the tactics to be made available to face oil spills in a given area has to take into account the results of both the NEBA - Net Environmental Benefit Analysis and the RGA studies. In fact, currently oil spill emergency response planning requires decision makers to integrate the results of different kinds of analyses, weighting up the advantages and disadvantages of the different tactics. In this regard, a further remark is that RGA methods only assess the possibility of the response based on the environmental factors. Though, it has to be recalled that the actual effectiveness of the response also depends on the complex interaction among the oil (mainly, in terms of type of oil, geographic coordinates, depth, rate and duration of the spill) and the features of the contingency actions (mainly, in terms of location, number and characteristics of the emergency equipment). Thus, RGA studies aim at evaluating a "theoretical" maximum effectiveness of the response, based only on the environmental factors. In order to respond more effectively to oil spills, it would be useful to define a "practical effectiveness" and a procedure for assessing it, taking into account all the additional elements mentioned above. In perspective, the evaluation of a "practical effectiveness" would require including a RGA method in the procedure used to evaluate the fate and the transport of the oil, as well as its impact on the environmental and socio-economic targets. In fact, only in this way it will be possible to perform a thoroughly quantitative assessment of the risk reduction of oil spills due to the deployment and operation of emergency actions. This would improve also the compliance with regulatory requirements, as those deriving from Directive 2013/30/EU, that imposes to reduce as far as possible the occurrence of major accidents relating to offshore oil and gas operations and to limit their consequences.

Finally, it is important to remark that the quantification of the occurrence probabilities of oil spill emergency response gaps is an explicit admission that it might not always be possible to treat the oil spilled at sea. However hard to accept this admission could be, it has to be recognized that all over the world regulations impose more and more to operators to lower the risk to an acceptable level, that is to a level for which the time, cost or effort of further decreasing it would be grossly disproportionate to the benefits of such a reduction. In this context, RGA studies are actually a part of the complex risk management system that needs to be implemented to mitigate the risk of oil spills at sea.

7. Conclusions

A new RGA method was developed, based on robust theoretical fundamentals, in order to estimate when and where, in a given area, there could be a gap in the deployment and effective operation of oil spill emergency response due to unfavourable conditions of the environmental factors. The new RGA method provides a sound assessment of the expected response outcome for the different tactics considered in emergency management, based on a statistical analysis of hindcast data for the environmental factors. In addition, the method was specifically conceived to conduct also real-time analyses based on forecast data, in order to support the selection of the response tactics after the occurrence of a spill. The real-time mode results are useful also for planning activities at risk or for scheduling the transit of ships in environmentally sensitive areas. Lastly, the case-study application evidences the importance of carrying out RGA studies also in sea areas different from the Arctic zones, where such studies have been applied more frequently to date. Overall, the new methodology provides an enhanced support to Response Gap Analysis as required by regulatory authorities in several sea areas, representing a further step towards a more effective protection of the environment from oil spills at sea.

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