Science of the Total Environment 650 (2019) 2294–2306

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Development of physical modelling tools in support of risk scenarios: A new framework focused on deep-sea mining

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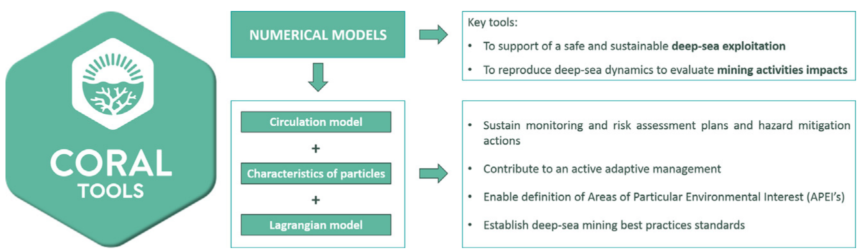
HIGHLIGHTS

- Need for reliable numerical models to reproduce deep-sea and sediment dynamics.
- Numerical models as key tools for risk management associated to deep-sea mining.
- Model simulations support definition of buffer zones around deep-sea mining spots.
- Sediments in Azores region can spread up to 192 km due to mining operations.
- Particles residence times can last for several tens of days.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 13 July 2018
Received in revised form 28 September 2018
Accepted 29 September 2018
Available online 01 October 2018

Editor: Damia Barcelo

Keywords:
Deep-sea technologies
Precautionary principles
Hazard assessment
Numerical modelling
Biological communities
Adaptive management

ABSTRACT

Deep-sea mining has gained international interest to provide materials for the worldwide industry. European oceans and, particularly, the Portuguese Exclusive Economic Zone present a recognized number of areas with polymetallic sulphides rich in metals used in high technology developments. A large part of these resources are in the vicinity of sensitive ecosystems, where the mineral extraction can potentially damage deep-ocean life services. In this context, technological research must be intensified, towards the implementation of environmental friendly solutions that mitigate the associated impacts.

To reproduce deep-sea dynamics and evaluate the effects of the mining activities, reliable numerical modelling tools should be developed. The present work highlights the usefulness of a new framework for risk and impact assessment based on oceanographic numerical models to support the adoption of good management practices for deep-sea sustainable exploitation. This tool integrates the oceanic circulation model ROMS-Agrif with the semi-Lagrangian model ICHTHYOP, allowing the representation of deep-sea dynamics and particles trajectories considering the sediments physical properties. Numerical simulations for the North Mid-Atlantic Ridge region, revealed the ability of ROMS-Agrif to simulate real deep-sea dynamics through validation with *in situ* data.

Abbreviations: APEI, Area of Particular Environmental Interest; CCZ, Clarion-Clipperton Zone; CFSR, Climate Forecast System Reanalysis; CMEMS, Copernicus Marine Environment Monitoring Service; COADS, Comprehensive Ocean Atmosphere Data Set; EDMONET, European Marine Observation and Data Network; EEZ, Economic Exclusive Zone; ISA, International Seabed Authority; LS, Lucky Strike; mbSL, m below sea level; MG, Menez Gwen; MoMAR, Monitoring the Mid Atlantic Ridge project; NMAR, North Mid-Atlantic Ridge; RB, Rainbow; REE, Rare Earth Elements; RMSD, Root Mean Square Difference; RMSE, Root Mean Square Error; ROMS, Regional Ocean Modeling System; SCOW, Scatterometer Climatology of Ocean Winds; WOA, World Ocean Database.

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https://doi.org/10.1016/j.scitotenv.2018.09.351
0048-9697/

Results showed a strong diversity in the particle residence time, with a dependency on their density and size but also on local ocean conditions and bottom topography. The highest distances are obtained for the smaller and less dense particles, although they tend to be confined by bathymetric constrains and deposited in deepest regions. This work highlights the potential of this modelling tool to forecast laden plume trajectories, allowing the definition of risk assessment scenarios for deep-sea mining activities and the implementation of sustainable exploitation plans. Furthermore, the coupling of this numerical solution with models of biota inhabiting deep-sea vent fields into ecosystem models is discussed and outlined as cost-effective tools for the management of these remote ecosystems.

1. Introduction

In recent years, deep-sea mining has become an attractive and economically viable solution to provide metals and minerals for the industry due to the large reservoir of minerals (hydrothermal sulphides, polymetallic nodules and manganese crusts), gas-hydrates and biological resources present in the European deep sea floor with biotechnological applications. Rare Earth Elements (REE) are also present in these metalliferous deposits and used in high- tech and defence applications, green technologies or communication systems (Santos et al., 2018).

Although promising, a large proportion of these metals and mineral resources are located in the vicinity of important and sensitive ecosystems, still poorly studied (Bell et al., 2016; Bluhm, 2001; Purser et al., 2016; Van Dover, 2014). As an example, metal enriched minerals exists in hydrothermal vents of the Portuguese Economic Exclusive Zone (EEZ; InterRidge: https://www.interridge.org/). Several endemic taxa thrive only in these hydrothermal-vents, displaying an array of adaptation to this unique environment (Duperron et al., 2016). The mineral extraction may theoretically change the biogeochemical equilibrium of the surrounding area, altering deep-sea life-support services with potentially negative impacts (Bluhm, 2001; Jones et al., 2017; Purser et al., 2016; Vanreusel et al., 2016). Furthermore, impacts can have repercussions over non-local species. Marsh et al. (2018) showed recently geological past interactions between large vertebrates and abyssal sea floor (~4000 m depth) on the Clarion-Clipperton Zone (CCZ) in the Pacific, a region full of targeted mineral resources with granted exploration contracts. Nevertheless, the International Seabed Authority (ISA; ISA, 2011), which regulates mining claims at international waters, has received an increase in the number of applications to exploit polymetallic nodules (Jones et al., 2017). However, the scientific international community has raised concern about the hazard associated with mining activities, supported in results of research projects related with the impact of mining activities like Blue Mining (http://www.bluemining.eu/), MIDAS (http://www.eu-midas.net/), Mining Impact (https://jpio-miningimpact.geomar.de/), Blue Nodules (http://www.blue-nodules.eu/), Deep Sea Minerals Project (http://dsm.gsd.spc.int/) or Coral. There is a large consensus that before deep-sea mining starts, there is a need to establish environmental and management guidelines integrated in functioning governance and regulatory frameworks (Durden et al., 2017; Santos et al., 2018; Van Dover, 2011).

The foreseen increase in noise, light, sediment laden plumes and trace elements can potentially impact these ecosystems leading to habitat fragmentation and loss of biome and biodiversity (Moskvitch, 2014). It should be highlighted that frameworks and guidelines for the deep-sea mining that could mitigate these impacts have not yet been established (Volkmann and Lehnen, 2018). The equilibrium between trace elements in solution and particulate forms under high pressure is poorly documented, as well as the impact in organisms due to trace elements accumulation at various levels of the food-chains. Mining activities are predicted to promote particle dispersion from the mining area, potentially impacting not only the adjacent habitats but also spreading far away to other sensitive ecosystems. Nevertheless, it must be highlighted that particle aggregation effects are also unknown at these environmental conditions. The time and space scales of these impacts depend on the local dynamics and its associated ecosystems, and on the mining technology. Thus, deep-sea mining will potentially affect extensive areas and will likely origin near-bottom, mid-water or near-surface sediment plumes, threatening benthic communities through the spreading of trace elements in toxic levels or fine particulate materials into the ocean. Therefore, there is an urgent need to develop new frameworks and guidelines to assess potential impacts of deep-sea mining, and how they will affect the surrounding ecosystems.

Ocean circulation numerical models are one of the key technological advances needed as a basis for the development of risk and impact assessment tools (Santos et al., 2018). This is also important to support the establishment of legal instruments and management practices for a sustainable environmental exploitation of deep-sea mineral resources. Modelling tools reproducing the dynamics of deep-sea areas can support the implementation of scenarios, before, during and after deep-sea mining operations, depicting the particles spreading patterns and forecasting impacts in the environment.

The lack of *in situ* data to initiate and force the models and validate the obtained results raised additional difficulties in the implementation of such models. Previous studies were developed for restricted areas representing the circulation of deep-sea water masses (Dinniman et al., 2011; Hermann et al., 2008; Pickart et al., 2003; Thoma et al., 2008; Wu and Haines, 1996). Being the availability of different types of information a fundamental aspect for building an accurate model, and due to the lack of deep-ocean areas knowledge, international organizations have acknowledged the interest in, and the need for, deep-oceanic observations, aimed at surpass the high depth and technological limitations of running monitoring and *in situ* studies. Several initiatives, projects and programs focused on deep-sea data should be remarked as ESONET (http://www.esonet-noe.org/), EMSO (Favali and Beranzoli, 2009), NEPTUNE and VENUS (Ocean Networks Canada; Martin Taylor, 2009) and the U.S. Cabled Array Fiber-Optic Ocean Observatory among others, providing morpho-hydrodynamic parameters needed to realistic reproduce sediment transport at deep-sea locations.

Deep-sea mining particle's circulation cannot be simulated without considering the physical properties of the generated sediment particles and the relation between surface processes and deep ocean circulation (Bonaldo et al., 2016; Rosburg et al., 2016; Turnewitsch et al., 2017; Yahagi et al., 2017). To represent the behaviour of these particles in the water column, including their physical properties (size, density, concentration, buoyancy, roughness, etc.), sediment transport or Lagrangian models should be considered. Nevertheless, these tools need circulation models to provide the oceanic conditions (velocity, temperature and salinity) at the area where the simulations are performed, justifying the coupling of both kind of models to accurately reproduce the sediment transport patterns at deep-sea locations (Jankowski et al., 1996; Jankowski and Zielke, 2001; Rolinski et al., 2001; Siegel and Deuser, 1997).

In the frame of project "Coral - Sustainable Ocean Exploitation: Tools and Technologies for management of Deep-Sea resource exploitation", a collaborative project between CIIMAR and INESC-TEC, developed under the Norte2020 programme, we provide a new conceptual approach to forecast the dispersion of the sediment plumes generated during deep-sea mining activities. This approach was developed based on the