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Talking About the Weather: The Feasibility of Using Very High-Resolution Optical Satellite Imagery to Monitor Live and Stranded Cetaceans Around the UK and UK Overseas Territories

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ABSTRACT

Monitoring live and stranded cetaceans can be expensive and logistically challenging, resulting in knowledge gaps. Very high-resolution (VHR) optical satellites are considered a potential solution to addressing some of these gaps. Despite success at detecting live and stranded cetaceans, satellites have only been trialed on restricted spatiotemporal scales. This project presents a framework for assessing the feasibility of using VHR optical satellite-based monitoring of cetaceans at high temporal frequency and local to global scales, focusing on the UK and UK Overseas Territories as a case study. We assess the primary environmental conditions necessary for the successful application of this technology: cloud cover and wind speed. Five-year monthly median "Total cloud cover" and "10m wind speed" ERA5 global reanalysis data were analyzed to map the spatial feasibility of satellite monitoring. We found that for the United Kingdom, VHR optical satellites could complement existing monitoring methods to achieve greater spatial and temporal coverage of live cetacean surveys, particularly, offshore, during the boreal spring and summer. However, satellites cannot address gaps in UK live cetacean monitoring in winter due to high wind speeds reducing whale detection probability. Based on environmental conditions, the tropics hold the greatest promise for achieving year-round satellite-based cetacean monitoring. In the Falkland Islands, particularly, the remote, unpopulated coastlines of West Island, satellites have the potential to improve strandings monitoring, opportunistically complementing existing stranding monitoring efforts.

1 | Introduction

Cetaceans are important species for the functioning of healthy ocean ecosystems (Roman et al. 2014; Coombs et al. 2019; Gilbert et al. 2023). Several international agreements, bodies, and treaties recognize the importance of and are charged with conserving cetaceans, including the International Whaling Commission (IWC), the Convention on the Conservation of Migratory Species, and the Convention on International Trade of Wild Fauna and Flora (Simmonds and Elliott 2009; Reeves 2018; Clarke et al. 2021). Despite recognition and protection, cetaceans are threatened by a range of evolving

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and intensifying human-induced threats, including ship strikes, entanglement in fishing gear, noise, and pollution (Clapham 2016; Jepson et al. 2016; Nicol et al. 2020; Robbins et al. 2022).

To evaluate and mitigate threats to cetaceans and implement an informed policy response, in-depth knowledge of cetacean population ecology, distribution, abundance, health, and mortality is needed (Smith et al. 2020; Hammond et al. 2021; EFRA 2023). However, cetaceans are logistically and economically challenging to survey via conventional methods (visual boat and aerial-based surveys), as many inhabit the remote open ocean and are predominantly concealed at depth (Evans and Hammond 2004; Coombs et al. 2019). Current estimates of global line-transect survey effort for live (free-swimming) whales report only 25% of the world's oceans have been surveyed, with monitoring efforts biased toward waters surrounding the European and North American continents (Kaschner et al. 2012; Braulik et al. 2018). Even with additional survey effort through acoustics, citizen science campaigns, and emerging technologies like wildlife telemetry and drones, gaps remain. Complementary to live cetacean data, cetacean stranding (live stranded cetaceans and cetaceans dead upon deposition, termed beachcast) patterns offer insights that support conservation decision-making, inform cetacean diversity and distribution, and alert conservation managers to concerns for ocean, animal, and human health (Coombs et al. 2019; Clarke et al. 2021; Garcia-Bustos et al. 2024). However, stranding monitoring programs are also biased toward populated and well-resourced coastlines of the European and North American continents (Clarke et al. 2021).

Even in relatively well-surveyed and resourced regions of the world, such as the United Kingdom (UK), there are many knowledge gaps relating to cetaceans, which means that current conservation measures may be inadequate (Geelhoed et al. 2022; Taylor et al. 2022). For instance, the UK has well-established stranding monitoring programs around its shores, with one of the most continuous and systematic records dating back to 1913 (Coombs et al. 2019; SMASS 2023; CSIP 2024), but the UK coastline is extensive and varied, with remote, complex stretches that inhibit monitoring.

The UK is obligated to monitor the conservation status of all cetaceans within its waters under several legislative acts, directives, and policies, including the Wildlife and Countryside Act 1981 England and Wales, the UK Marine Strategy, and the Agreement on the Conservation of Small Cetaceans of the Baltic and North Seas (EFRA 2023). UK waters, spanning warmer southern waters and cooler Arctic currents, fall within the habitat range of 28 of the ~89 described cetacean species (Reid et al. 2003; Fordyce and Perrin 2024), including breeding, migrating, and overwintering populations, with some of these ranges likely to be impacted by climate warming and all requiring effective conservation (O'neil et al. 2019; Williamson et al. 2021). In 2018, the Joint Nature Conservation Committee (JNCC) assessed the conservation status of cetaceans within UK waters, revealing that the population status of all UK cetacean species was "unknown" (JNCC 2019). One of two principal solutions recommended by the Environment, Food and Rural Affairs Committee (EFRA) to address gaps in the UK's monitoring efforts and to establish baseline information on population trends and mortality was new technologies, with very high-resolution (VHR) optical satellites being considered the most promising (EFRA 2023).

There is a higher-level policy imperative to using VHR optical satellites for monitoring, as the tool could help resource managers achieve their goals to protect biodiversity, including mapping marine species' habitats to assist marine spatial planning (JNCC 2023). These tools can also benefit the UK's Overseas Territories (UKOTs), which include remote and sparsely populated islands in areas of rich biodiversity (DEFRA 2009).

Since their initial application to identify live whales (Abileah 2002; Fretwell et al. 2014) and their improved spatial resolution allowing defining features to be seen from space, VHR optical satellite imagery has proven to be an effective tool to detect and identify live and stranded cetaceans in remote regions (Cubaynes et al. 2019; Fretwell et al. 2019). More recently, progress has moved beyond simple detection toward satellite-derived density estimation (Bamford et al. 2020; Corrêa et al. 2022; Belanger et al. 2024), species detection (Cubaynes et al. 2019; Charry et al. 2021; Hodul et al. 2022; Ramos et al. 2022), reviews of future applications (Clarke et al. 2021; Höschle et al. 2021; Rodofili et al. 2022; Khan et al. 2023), open-access datasets (Cubaynes and Fretwell 2022), annotation protocols (Cubaynes et al. 2023), and automation pipelines (Borowicz et al. 2019; Guirado et al. 2019; Houegnigan et al. 2022; Green et al. 2023; Kapoor et al. 2023). However, the majority of studies using satellites to monitor cetaceans have been pilot studies, aiming to demonstrate the technology's potential by opportunistically acquiring images from the archives (a library of historical satellite imagery) or tasking (ordering) a satellite to collect imagery on short timescales in a single location. To date, there are no operational programs that rely on VHR satellite remote sensing to assess cetacean populations at regular intervals or at scale, in both space and time.

Great whale species are currently the most feasible group for monitoring whales at sea via VHR optical satellites due to their large size. For strandings, a broader diversity of cetaceans may be monitored, as smaller cetaceans often strand in groups and are similar in size to other dense aggregations of wildlife, such as walruses hauled out on land that have been identified from space (Sergeant 1982; Hamilton 2018; Cubaynes et al. 2024). The most commonly seen baleen whales in UK waters are fin (*Balaenoptera physalus*) and minke whales (*Balaenoptera acutorostrata*), while humpback whales (*Megaptera novaeangliae*) are occasional visitors (Charif et al. 2001). Fin whales have a mostly offshore distribution (Macleod et al. 2003), visiting UK waters on migration to and from more northerly feeding areas (Whooley et al. 2011). Minke whales are predominantly found in shallow shelf waters (Northridge et al. 1995) and feed in UK waters, particularly, during the spring and summer months (Anderwald et al. 2012). Farther south, Caribbean waters that span a number of UKOTs are important breeding grounds for North Atlantic humpback whales, which are seasonally abundant there during the winter months (Strevick et al. 2018; Heenehan et al. 2019). In the Southern Hemisphere, another UKOT, the Falkland Islands (Islas Malvinas) shelf waters are an important summer feeding area for sei whales (*Balaenoptera borealis*; Weir et al. 2021), and its EEZ is a multi-use area for southern right whales (*Eubalaena australis*), which breed and socialize

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coastally in winter and feed and travel offshore in other months (Weir and Stanworth 2020; Weir et al. 2024).

In order to achieve effective cetacean monitoring from space, we must address the feasibility of running successful systematic, long-term monitoring programs encompassing the spatial and temporal ranges (either nationally or globally) of a species and establish frameworks for identifying areas around the globe most suited to this application. Given their global coverage, there is a misconception that VHR optical satellites can collect useful imagery of any place on Earth at any time; however, in reality there are a multitude of factors that limit the quality and availability of satellite images including: (1) prevailing environmental conditions: cloud cover, wind, diverse environmental backgrounds, ice, and turbidity (Abileah 2002; Platonov et al. 2013; Fretwell et al. 2014, 2019; Larue et al. 2017; Cubaynes et al. 2019; Lennert-Cody et al. 2019; Bamford et al. 2020; Charry et al. 2021; Clarke et al. 2021; Höschle et al. 2021; Boulent et al. 2023; Gaur et al. 2023; Khan et al. 2023); (2) accessibility and sensor specification: cost of satellite imagery, access prioritization to high-paying customers, spectral and spatial resolution, nadir angle and revisit rate (Clarke et al. 2021; Khan et al. 2023; Belanger et al. 2024); (3) target species: morphological characteristics and behaviors, surface availability, presence of similar-looking species, and confounding features (objects misidentified as cetaceans) (Cubaynes et al. 2019; Clarke et al. 2021; Höschle et al. 2021; Khan et al. 2023); and (4) image quality: solar reflection/glare and image darkness (Abileah 2002; Fretwell et al. 2014; Cubaynes et al. 2019; Boulent et al. 2023; Gaur et al. 2023).

To map the feasibility of using VHR optical satellites to study cetaceans, we first need to assess the variability of environmental conditions at a location since these can render a location unsuitable for the tool's application, regardless of other limiting factors. The primary environmental conditions that govern satellite use for monitoring live and stranded cetaceans are cloud cover, and in the case of live cetacean monitoring only, wind/surface roughness. Thin cloud cover (including their shadows) can obscure features of interest in optical satellite imagery, leading to false detections, and the presence of dense cloud cover can inhibit detection of live and stranded cetaceans completely (Larue et al. 2017; Clarke et al. 2021). Sea state impacts the ability to detect live free swimming marine mammals via conventional monitoring methods (Barlow 1988; Pollock et al. 2006), and is documented as a challenge when using satellites (Bamford et al. 2020; Green et al. 2023). Surface roughness and white caps associated with higher sea states reflect sunlight and confound detection by mimicking cetacean behaviors, challenging the ability to detect submerged features and generally reducing the confidence of live cetacean detections in satellite imagery (Abileah 2002; Fretwell et al. 2014; Cubaynes et al. 2019; Corrêa et al. 2022; Green et al. 2023). By establishing thresholds of environmental conditions required for successful detection, we can better identify and prioritize satellite-based conservation studies toward areas that are most suited to investment.

Marine conservation efforts are often challenged by limited funding, and our proactive approach of feasibility mapping can allow for more targeted and informed decision-making and enhanced conservation outcomes. This project aims to: (1) assess the feasibility of using VHR optical satellite imagery based on cloud and wind data and (2) establish a process for using VHR optical satellite imagery by identifying the most suitable locations for using the tool to monitor live and stranded cetaceans around UK and UKOTs. While this project uses UK and UKOT waters as a case study, these methods are transferable globally.

2 | Methods

2.1 | Study Areas

Three study areas were selected to assess the feasibility of collecting useful VHR optical satellite imagery at large temporal and spatial scales in UK and UKOT waters. (a) The entire British Isles (Supporting Information S1 and Figure 1) was selected to address the EFRA (2023) recommendation that VHR optical satellites represent a principal solution for addressing the UK's cetacean monitoring gaps. Overseas study areas (b) the Falkland Islands (Islas Malvinas), and (c) the Caribbean, encompassing five UKOTs (Supporting Information S1 and Figure 1), were also selected, given their highly diverse environmental conditions when compared with the UK. While the Falkland Islands are at a similar latitude to the UK within the Southern Hemisphere, the islands have a remote and exposed location within the Southern Atlantic Ocean, located in the path of the strongest surface winds on Earth, the Southern Hemisphere westerlies (Turney et al. 2016; Deng et al. 2022). Contrastingly, the Caribbean, situated in the tropics, was selected for its expected likelihood of lower cloud cover compared to the UK (NASA Earth Observatory 2024).

2.2 | Data Acquisition

We analyzed the spatiotemporal variability of two key environmental variables: cloud cover and wind speed. The datasets were extracted from the European Centre for Medium-range Weather Forecasts (ECMWF) reanalysis ERA5 data (Hersbach et al. 2023) (Supporting Information S2). ERA5 is a gridded dataset with a native horizontal resolution of approximately 31 km (0.28125 degrees), which, when downloaded, is reprojected to a $0.25 \times 0.25°$ latitude/longitude (Figure 2) (Gualtieri 2021). Reanalysis ERA5 data combines historical meteorological observations with modern weather models (Copernicus, n.d.). ERA5 was selected over satellite-derived cloud cover data alternatives, such as Moderate-Resolution Imaging Spectroradiometer (MODIS) cloud masks (MYD08_M3 and MOD08_M3 "Cloud_Fraction_Mean_Mean"), due to its great agreement of cloud cover assessment (Yao et al. 2020; Wu et al. 2023); the data acquisition of both environmental variables from the same data source at the same resolution, and ease of data access and interpretation, make it accessible and replicable on a global scale for ecologists, conservationists, and policymakers.

The datasets accessed were "ERA5 monthly averaged data on single levels from 1940 to present" subvariables, "Total cloud cover (TCC)" and "10m wind speed." "TCC" is the portion of a grid cell covered by cloud and integrates all cloud

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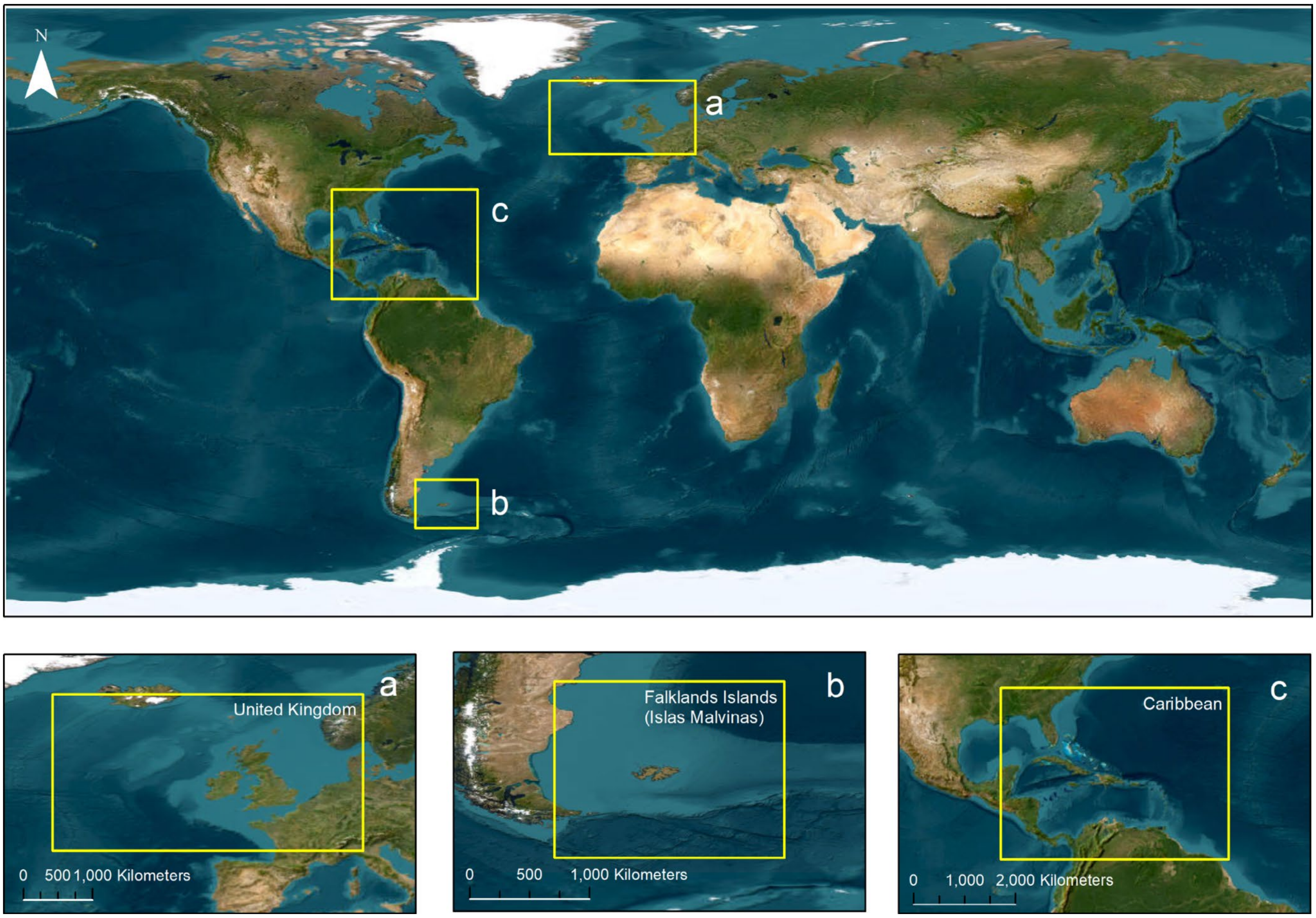

FIGURE 1 | The bounding box coordinates of the three study areas used to delineate and extract wind and cloud data from the European Centre for Medium-range Weather Forecasts (ECMWF) ERA5 reanalysis data: (a) UK, (b) the Falkland Islands (Islas Malvinas), (c) the Caribbean, including UK overseas territories the Cayman Islands, Turks and Caicos Islands, British Virgin Islands, Anguilla, and Montserrat. See Supporting Information S1 for detailed coordinates. Service layer credits: *Source:* Esri, Maxar, GeoEye, Earthstar, Geographics, CNES/Airbus, DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community.

information from the Earth's surface to the top of the atmosphere (Hersbach et al. 2023). "10m wind speed" represents horizontal wind speed in meters per second, at 10 m above the Earth's surface (Hersbach et al. 2023). As ocean surface waves are generated through an energy transfer from wind blowing over the ocean's surface, "10m wind speed" was selected to best represent wind speed with the greatest influence on ocean surface wave formation (Mitsuyasu 2015). ERA5 wind speed data are also widely recognized as a reputable information source within the wind energy sector and is regularly used in assessments of potential offshore wind energy sites (Gualtieri 2021).

Five years of data were extracted for environmental variables "TCC" and "10m wind speed" (2018–2022). The bounding box coordinates of the three study areas (Figure 1, Supporting Information S1) used to delineate and extract wind and cloud data from the ECMWF reanalysis ERA5 data were defined to encompass the entirety of the Exclusive Economic Zone (EEZ) of the study area (reference to "offshore" in this project is in line with UK guidelines as anything beyond 12 nautical miles) (Marine Management Organisation 2019; JNCC 2023).

2.3 | Data Processing and Analysis

To perform a threshold analysis, for each month, first we calculated the 5-year monthly median for "TCC" and "10m wind speed" from 2018 to 2022. Median was selected for its greater representation of central tendency (herein referred to as "average"). The monthly median outputs were then masked to retain only those areas that met or were below the predefined threshold. The masked areas of both variables were converted into a vector (polygon shapefile). To assess the feasibility of live cetacean monitoring, both vectors are used to perform an intersection (extraction of overlapping features from the two input layers) of the matching monthly "TCC" and "10m wind speed." The resulting final "suitable area(s)," where both 5-year monthly average environmental variables met the predefined threshold, were mapped to the study area to develop feasibility maps. For stranded cetaceans, the outputs for "TCC" alone, masked by the coastline (to include a 2 km buffer either side of the coastline), form the resulting final "suitable area(s)" to develop feasibility maps. For resource managers interested in evaluating the feasibility of satellites for monitoring live (or floating dead) and stranded cetaceans, the "suitable area(s)"

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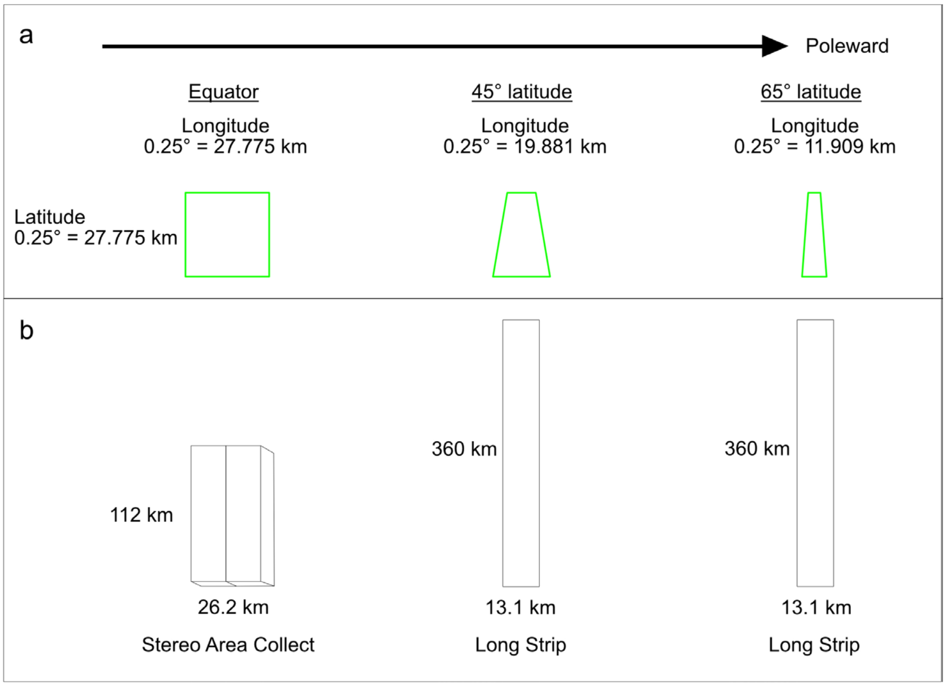

FIGURE 2 | (a) Green cells depict the equivalent ground distance of a 0.25 × 0.25° latitude and longitude in kilometers, where polewards longitude becomes smaller (the resolution of the data in kilometers is consistent across latitude, however, longitude decreases poleward due to convergence) and (b) black boxes represent the swath width (width of an image collection) of a Maxar WorldView-3 satellite image feasibly collected within an ERA5 grid cell at a given latitude.

TABLE 1 | ERA5 "Total cloud cover" ("TCC") monthly average thresholds (%) and associated likelihood of achieving a suitable image collection.

ERA5 "Total cloud cover (TCC)" monthly average threshold (%)	Likelihood of achieving a suitable image collection based on "TCC"
≤ 20	Certain
21–40	Almost certain
41–60	Likely
61–80	Possible
81–99	Unlikely
100	Impossible

Note: "TCC" is given as a value between 0 and 1, as probability is a value between 0 and 1 or 0% and 100% inclusive, therefore, to assess the probability (percentage likelihood) of achieving a suitable image collection based on "TCC," in this project the ERA5 grid cell values were evaluated as a percentage (between 0% and 100%).

for both live and stranded cetaceans were merged and boundaries dissolved to develop a single "suitable area(s)" vector. In addition, to understand the (interannual) variability in the dataset, the standard deviation was extracted and mapped. To evaluate monthly average "TCC," we devised thresholds to define the likelihood of achieving a suitable image collection (Table 1). The term suitable image is used to describe an image that is cloud-free or contains thin or spatially restricted cloud, which does not render an image unusable.

To determine a suitable wind speed threshold in satellite surveys, we reviewed Beaufort scale requirements for traditional boat and aerial-based live cetacean surveys, in addition to recommendations from early efforts using satellites. The Beaufort scale is widely used in traditional live cetacean surveys as a measure for defining sea state based on wind intensity (Aragones et al. 1997; Hodgson et al. 2013; Gilles et al. 2023; Met Office 2024). Sighting probabilities tend to decrease ordinally with increasing sea state (Anderson 2001). As a definitive threshold for sea state is not agreed for live cetacean satellite surveys (Borowicz et al. 2019; Cubaynes et al. 2019; Cubaynes 2020; Corrêa et al. 2022; Fretwell et al. 2022), we opted to set a threshold for mapping feasibility at Beaufort 4; in line with the UK SCANS surveys (Gilles et al. 2023). Borowicz et al. (Borowicz et al. 2019) recommendation that at Beaufort 4, white caps would be in the range of a single pixel and so allow for the feasible discrimination of individual cetaceans; and given that the most suitable species for satellite monitoring will be larger whale species or aggregations of smaller cetacean species. We used the Beaufort scale to directly infer ERA5 "10m wind speed" in meters per second, therefore, for this project we set the wind speed threshold as 8 ms^{-1} in accordance with Beaufort wind scale 4 (Met Office 2024).

The assessment of all data was conducted using open source QGIS 3.28 pyQGIS console. An open-source pipeline to identify areas that meet a threshold of environmental variables in extracted ERA5 data is archived with Zenodo at https://doi.org/10.5281/zenodo.17106752 (Clarke and Skachkova 2025), and the latest version can be found on GitHub at https://github.com/PennyJClarke/feasibility-mapping. A visual representation of the steps within the code is available as pseudo code in Supporting Information S3.

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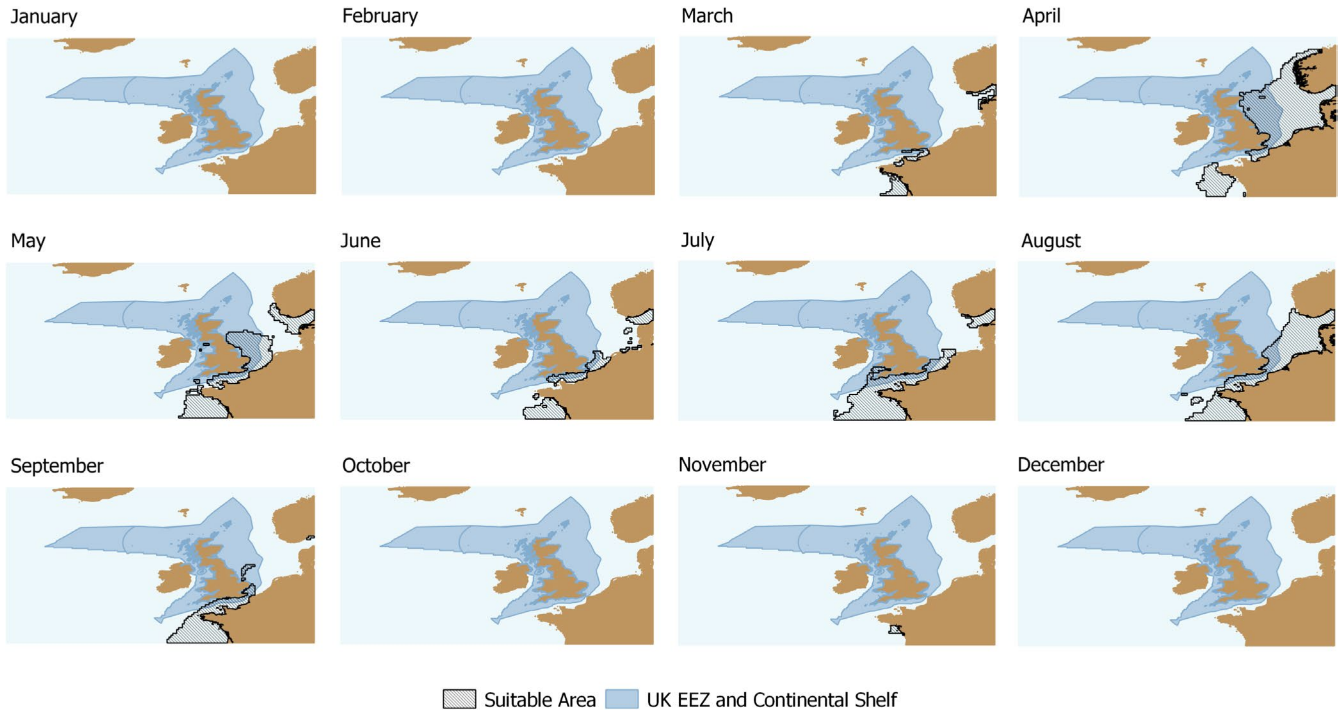

FIGURE 3 | A map detailing the "suitable area(s)" for live cetaceans with ≤60% average "TCC" and wind speeds ≤8 ms^{-1} per month around the UK. UK EEZ and Continental Shelf data UK Hydrographic Office (published date: June 20, 2024) (Admiralty 2024) and Flanders Marine Institute (version: World_EEZ_v12_20231025) (Flanders Marine Institute 2023). Land shapefile (large scale data 1:10 m) Natural Earth (access date: September 7, 2023) (Natural Earth 2024).

3 | Results

All "suitable area(s)" (.shp shapefiles) identified in this study are available to download at the British Antarctic Survey Polar Data Centre (PDC) (https://doi.org/10.5285/451a6a5d-a17b-4d71-aad0-188739403d8c, Clarke et al. 2025).

3.1 | UK

No area within the jurisdiction of the UK, for any given month, met the parameters of a ≤40% monthly average "TCC" and ≤8 ms^{-1} monthly average wind speed, for monitoring of live cetaceans. When the cloud cover threshold was increased to ≤60% monthly average "TCC," areas in the English Channel and North Sea met the parameters during boreal spring and summer months, April to September (Figure 3).

When the monthly average "TCC" was increased to ≤80% (meaning a 20% "possible" chance that a single image collected within a given month is suitable for monitoring live cetaceans) for the boreal spring and summer months, much of the waters surrounding the UK, including the North, West, and offshore regions, met the thresholds. There was low interannual variability in cloud and wind conditions during these months over the 5-year period, with the exception of cloud cover over the English Channel during April (Supporting Information S3, Figure S4, (5)). The boreal autumn and winter months, October to March, also had areas meeting the threshold for cloud cover and wind speed conditions; however, these are restricted to coastal regions due to high average wind speeds around the UK associated with weather changes during these months (Figure 4).

When assessing cloud cover only in evaluation of "suitable area(s)" for strandings monitoring, most of the UK coastline, year-round, met the parameter of ≤80% monthly average "TCC" (exceptions include parts of the western Scotland coastline during the winter months) (Figure 5).

3.2 | Caribbean

Given the expected lower cloud cover average compared with the UK, the Caribbean was first assessed at a ≤20% monthly average "TCC" and ≤8 ms^{-1} monthly average wind speed for the suitability of live cetacean monitoring. Limited areas of the Caribbean Sea met the threshold of environmental conditions; these were restricted to the tropical dry season in the months of December through to March. Of the UKOTs, only offshore of the Cayman Islands during February and March and nearshore north of the Cayman Islands in February were identified as suitable (Figure 6).

By increasing the cloud cover threshold to ≤40% monthly average "TCC," much of the Caribbean Sea, for the entire tropical dry season (including all UKOTs, January–April), met the threshold of "TCC" and wind speed. In contrast, few areas met the parameters during the wet season (Figure 7). While wind speeds were largely below the threshold during this season, the "TCC" was generally high, particularly, during May, June, September, and October (Supporting Information S4, Figure S4 (7) and (9)).

When the cloud cover threshold was further increased to ≤60% monthly average "TCC," much of the Caribbean Sea jurisdiction fell below the threshold of "TCC" and wind speed for all

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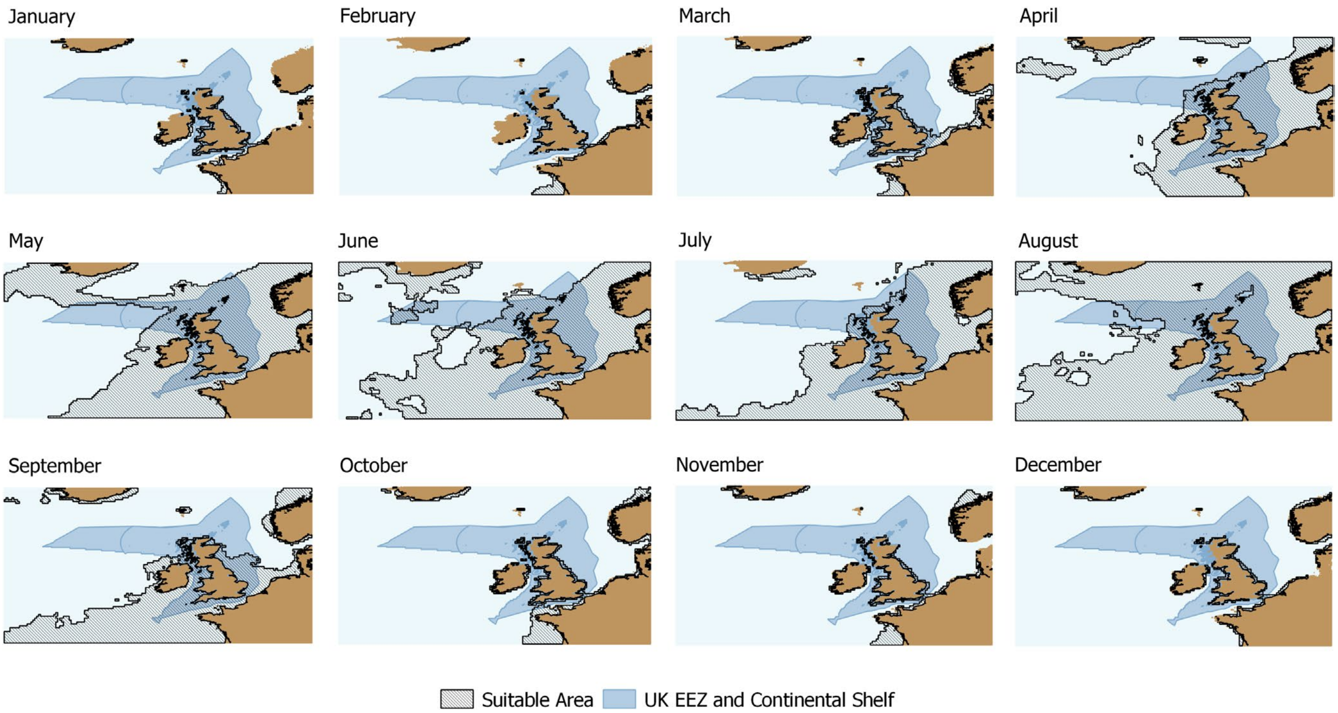

FIGURE 4 | A map detailing the "suitable area(s)" for live cetaceans with ≤80% average "TCC" and wind speeds ≤8 ms^{-1} per month around the UK.

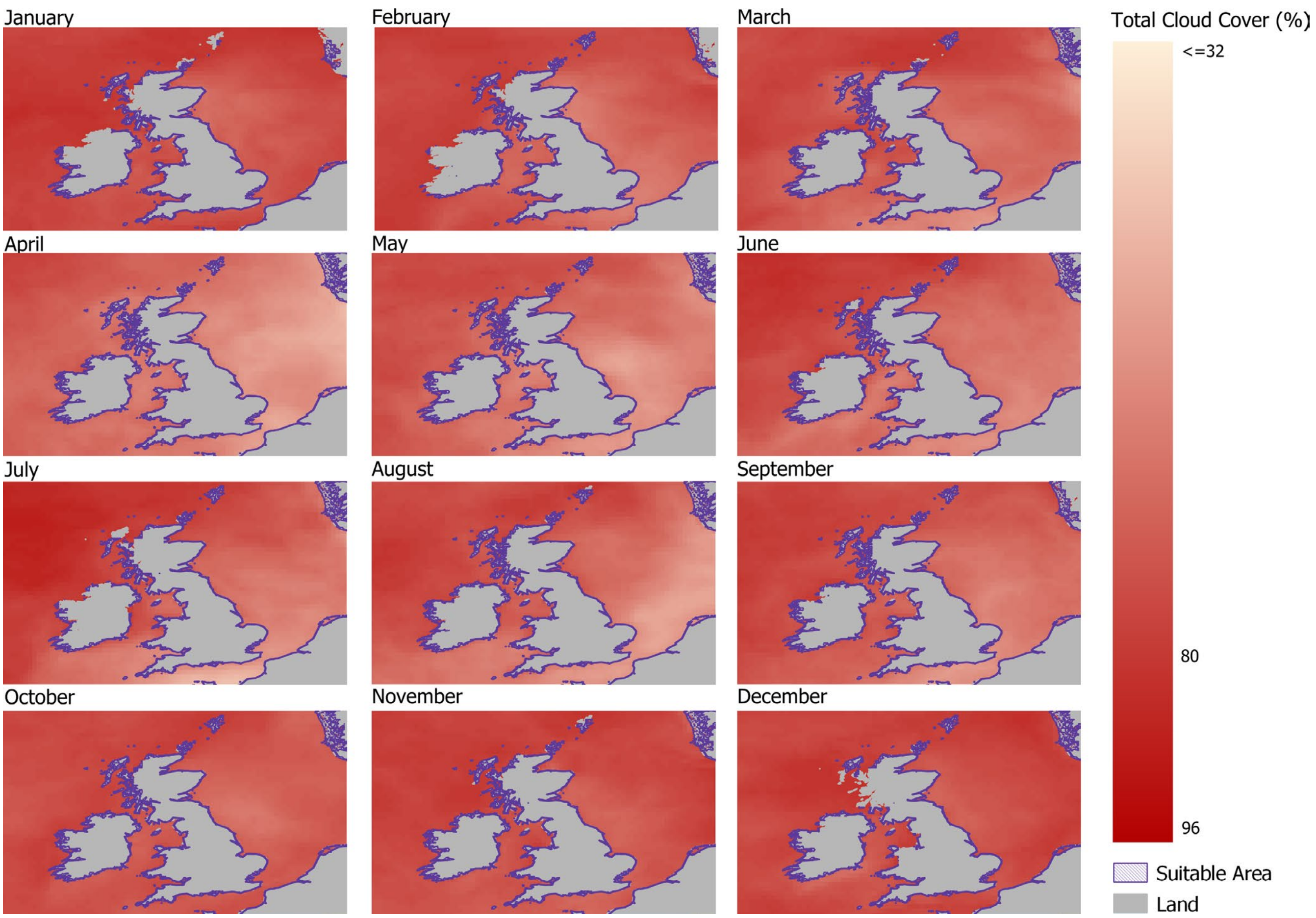

FIGURE 5 | A map detailing the "suitable area(s)" for stranded cetaceans with ≤80% average "TCC" per month around the UK, within 2 km either side of the coastline.

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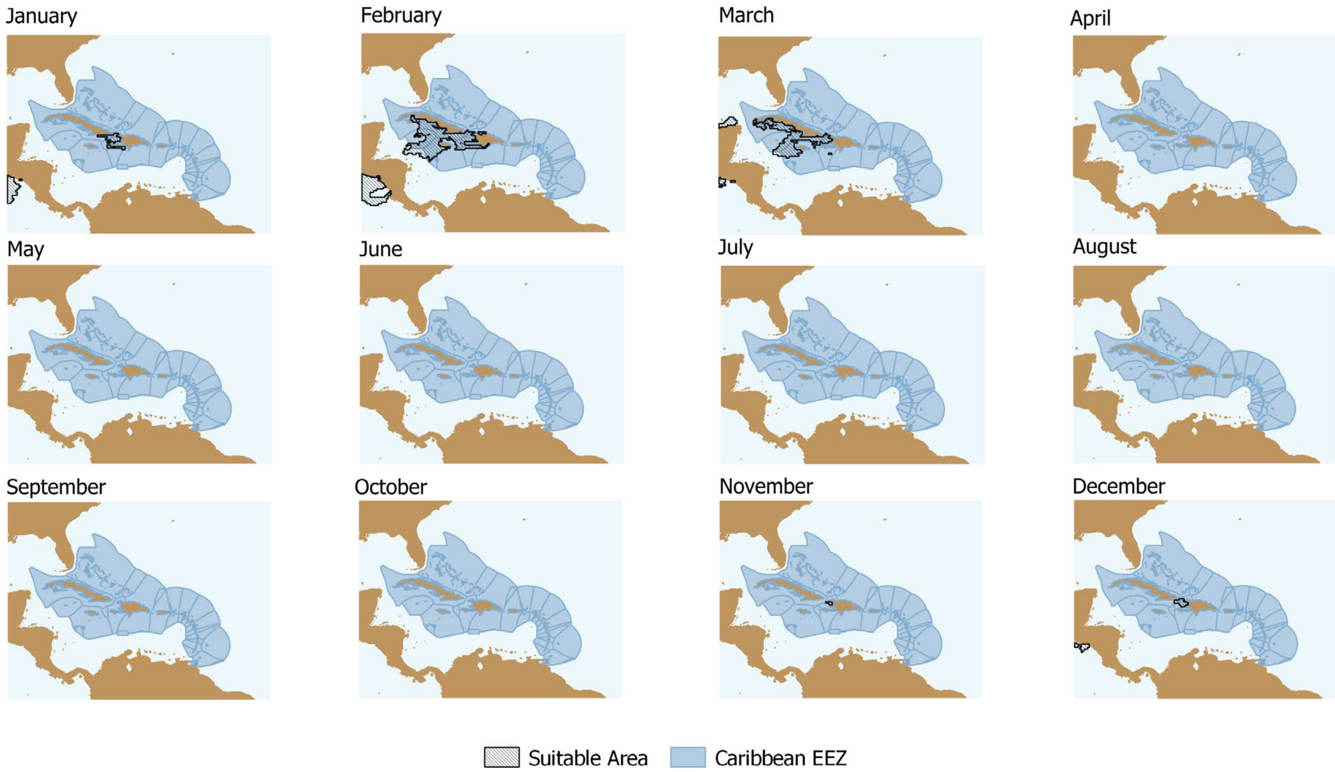

FIGURE 6 | A map detailing the "suitable area(s)" for live cetaceans with $\leq 20\%$ average "TCC" and wind speeds $\leq 8^{-1}$ per month around the Caribbean Islands. Caribbean Islands EEZ data Flanders Marine Institute (version: World_EEZ_v12_20231025) (Flanders Marine Institute 2023). Land shapefile (large scale data 1:10 m) Natural Earth (access date: September 7, 2023) (Natural Earth 2024).

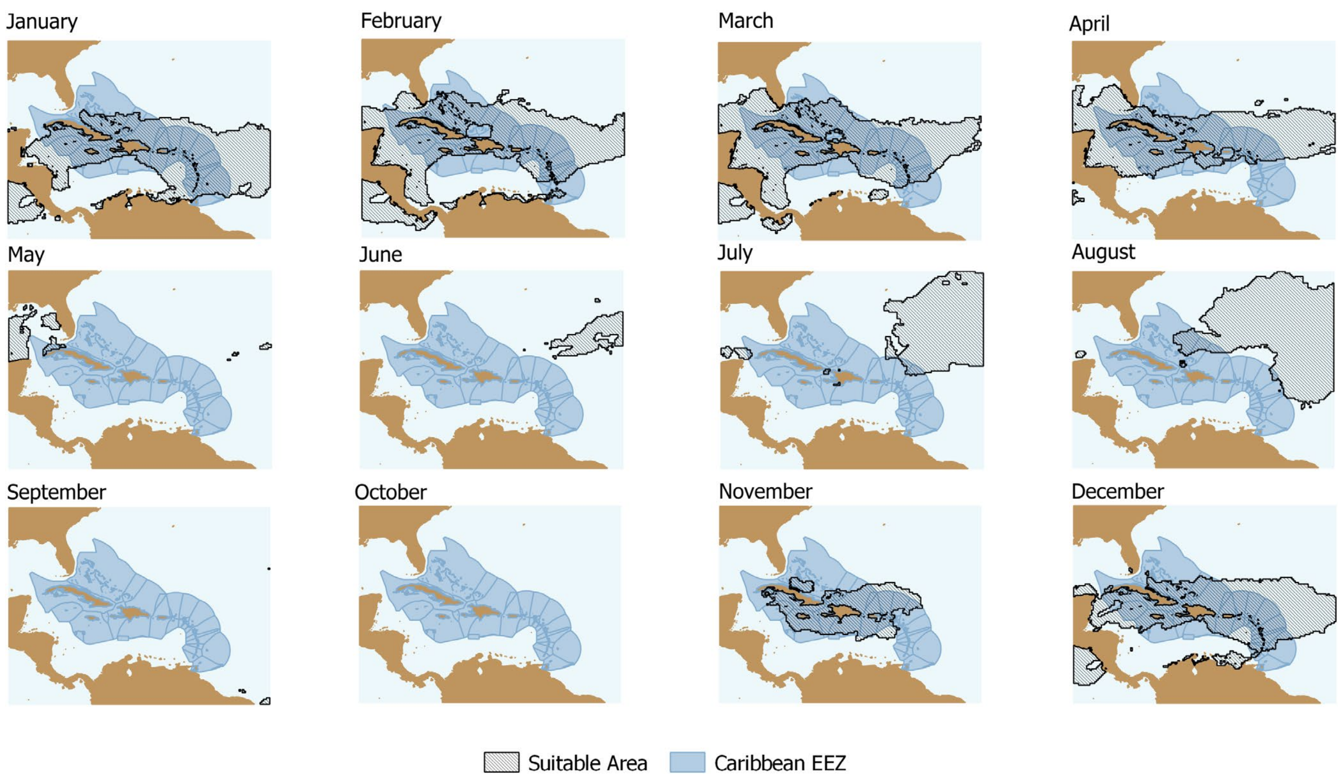

FIGURE 7 | A map detailing the "suitable area(s)" for live cetaceans with $\leq 40\%$ average "TCC" and wind speeds $\leq 8\,ms^{-1}$ per month around the Caribbean Islands.

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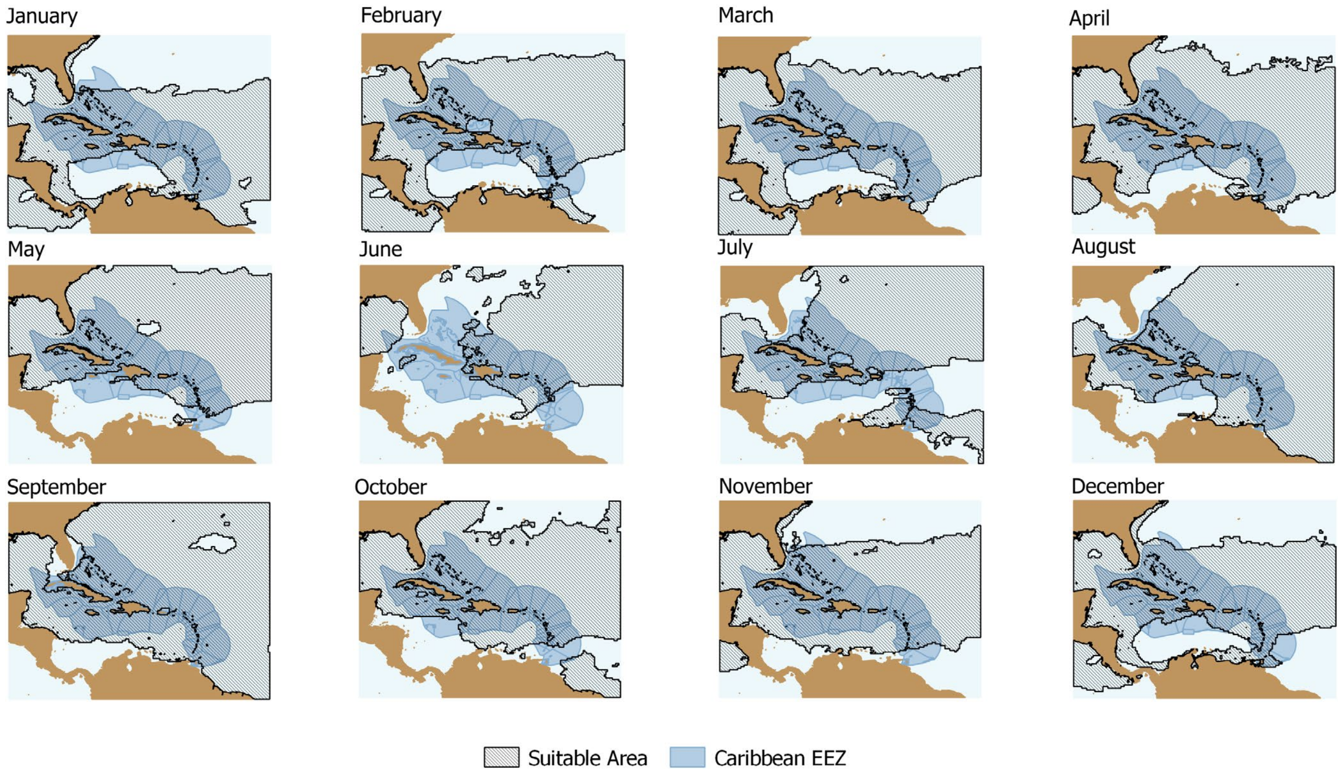

FIGURE 8 | A map detailing the "suitable area(s)" for live cetaceans with ≤ 60% average "TCC" and wind speeds ≤ 8 ms^{-1} per month around the Caribbean Islands.

months (Figure 8). Therefore, there is a 40% "likely" chance of achieving a suitable collection for live cetacean monitoring throughout the year, across all of the UKOTs (exceptions include nearshore waters of the Turks and Caicos Islands in February and the entire Cayman Islands jurisdiction in June). The same pattern of year-round suitability across all of the UKOTs (exceptions include the entire coastline of the Cayman Islands in June) was found for stranded cetacean monitoring when assessing cloud cover only, at a threshold of ≤ 60% monthly average "TCC" (Figure 9). The area of exception in the broader feasibility of the Caribbean Sea for live cetacean monitoring is the Colombian Caribbean, which has higher average wind speeds than the rest of the Caribbean Sea, except during the months of September–November, when the wind speed subsides (Supporting Information S4, Figure S4, (9)). The cloud and wind conditions for the Caribbean Sea exhibited low interannual variability across the 5-year period for most of the year (exceptions are a higher interannual variability in cloud cover during January and November, around the Cayman Islands and the Turks and Caicos Islands, which could limit the feasibility of these regions), highlighting the accuracy of the feasibility maps (as shown by the standard deviation, Supporting Information S4, Figure S4, (10)).

3.3 | Falkland Islands (Islas Malvinas)

Average monthly wind speeds for almost all areas within the jurisdiction of the Falkland Islands, except for near-shore coastal waters, exceeded the threshold of ≤ 8 ms^{-1} for all months of the year (Supporting Information S4, Figure S4, (12)). Therefore, regardless of cloud cover suitability, even at ≤ 80% monthly average "TCC," only limited nearshore areas around the Falkland Islands met the threshold of suitable environmental conditions for application of satellite imagery to live cetacean monitoring (Figure 10a,b). By contrast, when only assessing cloud cover at ≤ 80% monthly average "TCC," there is a 20% "possible" chance of achieving a suitable collection throughout the year for strandings monitoring (Figure 10c). The low interannual variability in cloud and wind conditions across all months in the 5-year period validates the limited feasibility of using optical satellite imagery in this region to monitor live cetaceans (as shown by the standard deviation, Supporting Information S4, Figure S4, (13)).

4 | Discussion

4.1 | Feasibility of Monitoring Cetaceans by Satellite by Area

4.1.1 | UK

VHR optical satellites could opportunistically support the UK in gathering baseline data where there is little to no monitoring and complement the UK's existing surveying efforts. However, it is not likely to be the revolutionary tool to achieving year-round, UK jurisdiction-wide cetacean surveillance, as contemplated by EFRA (EFRA 2023). Conventional methods of monitoring live cetaceans around the UK are inherently biased toward the spring and summer months, when the weather is more favorable. For example, SCANS cetacean surveys are conducted during the summer to maximize the potential for good coverage and conditions (Gilles et al. 2023). Based on our feasibility mapping of environmental conditions, VHR optical satellites are not

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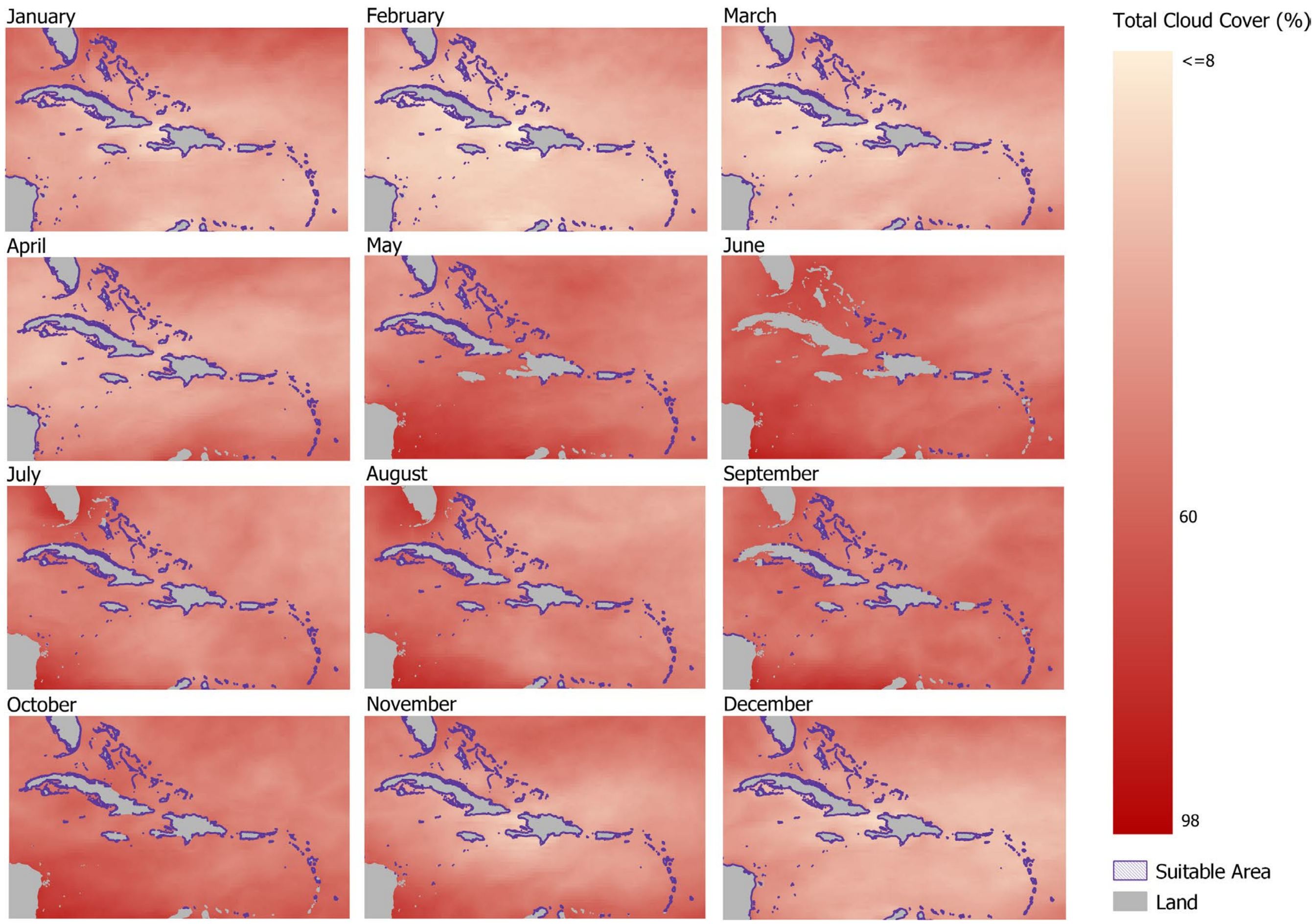

FIGURE 9 | A map detailing the "suitable area(s)" for stranded cetaceans with ≤ 60% average "TCC" per month around the Caribbean Islands, within 2 km either side of the coastline.

likely to address the current seasonal bias in monitoring efforts in the UK owing to persistent high winds in the autumn and winter months, restricting "suitable area(s)" to within kilometers of the coastline.

Satellites could complement conventional monitoring efforts, to extend surveillance in UK waters to the offshore regions opportunistically during the spring and summer months. The "possible" year-round suitability of environmental conditions in the near shore regions could present the UK with an opportunity for satellite-based strandings detection, to complement existing efforts of stranding networks along its shores. The UK's well-established stranding networks make investing in satellites inefficient and redundant for most of the UK coastline. However, satellite surveillance could support monitoring along remote and inaccessible areas of the UK coast with little footfall, for example, the Hebridean Islands. Due to the frequency of image collection required for regular monitoring, such investment would need strong justification and policy drive. Regardless, the UK's stranding networks present an opportunity for the UK to become an important place for testing and validating strandings detected from space with information on the ground (for different species and decomposition phases). In these early stages of satellite-based surveys such validations are invaluable to increasing the confidence of the tool's application along remote coastlines.

Our identified UK "suitable area(s)" with a ≤60% monthly average "TCC" threshold span the English Channel and North Sea and coincide with the main modeled distribution and abundance of harbor porpoise (*Phocoena phocoena*; Evans et al. 2021). However, with the current advancement of satellite technology, this species is unsuitable for satellite detection based on size (< 2 m in length) and low contrast with their surroundings (MCR 2012). If conducting a feasibility assessment for smaller cetacean species, it is also important to consider lowering the wind speed threshold during feasibility mapping (Gilles et al. 2023). Large cetacean species (most suitable for the application of satellites) are less frequently observed in these regions (Evans et al. 2021). However, humpback whale sightings within the Southern North Sea/English Channel are increasing (Berrow and Whooley 2022). The coincidence of their return within a major shipping route presents an opportunity for satellites to support measurements and mitigation of cetacean strike risk across these shipping lanes by providing maps of whale distribution that can help identify hotspots. When the monthly average "TCC" threshold is increased to ≤80%, the extension of the "suitable area(s)" to the North and West of the UK for much of the boreal spring and summer coincides with the distribution of fin, sperm (*Physeter macrocephalus*), and minke whale species (Evans et al. 2021). The higher cloud threshold poses a greater risk for effective tasking but does not prohibit collection. This necessitates that

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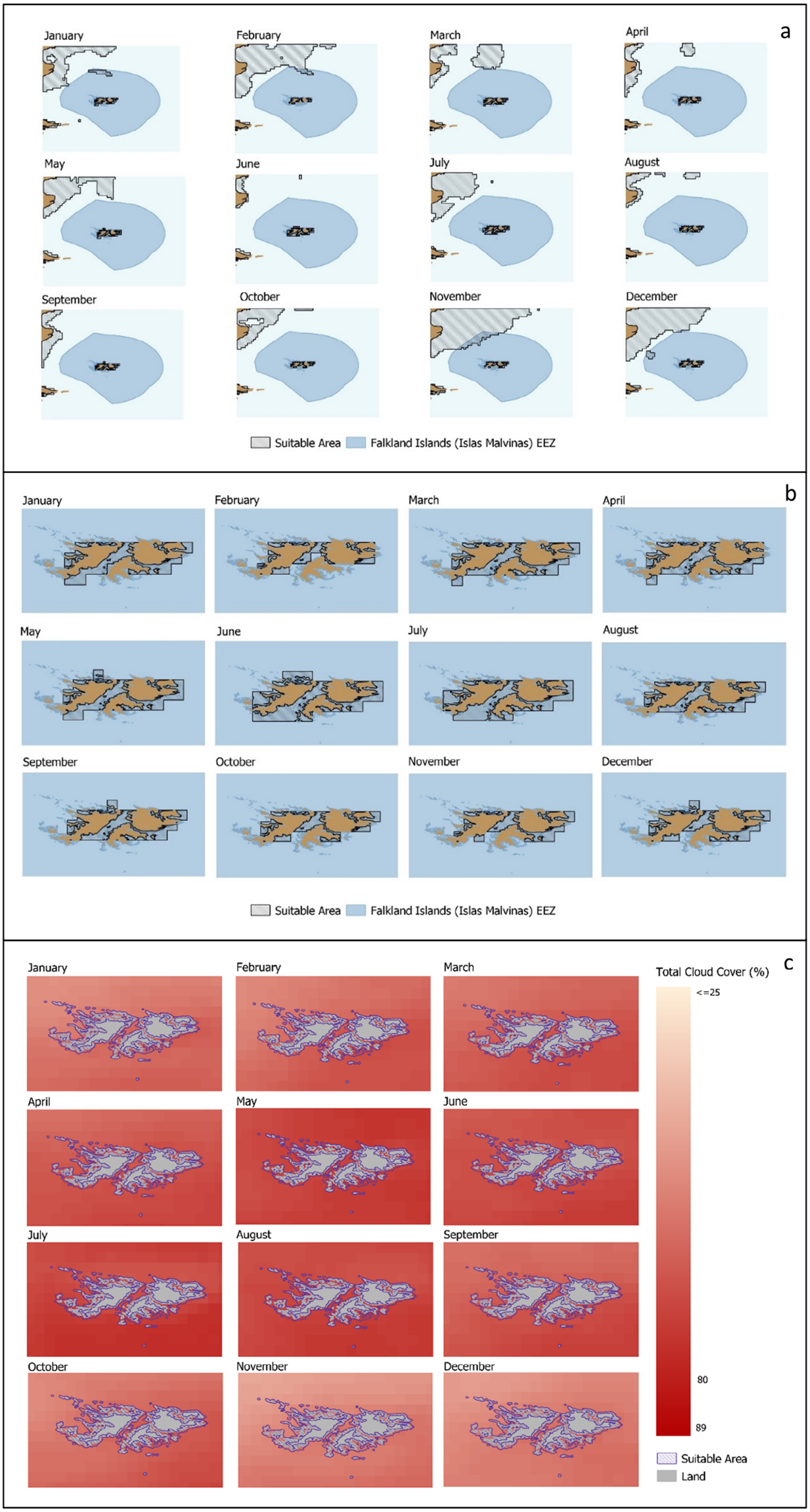

FIGURE 10 | Legend on next page.

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FIGURE 10 | (a) A map detailing the "suitable area(s)" for live cetaceans with ≤80% average "TCC" and wind speeds ≤8 ms^{-1} per month around the Falkland Islands (Islas Malvinas) (full EEZ view), (b) a zoomed version of map (a), and (c) a map detailing the "suitable area(s)" for stranded cetaceans with ≤80% average "TCC" within 2 km of the coastline. Falkland Islands (Islas Malvinas) EEZ data Flanders Marine Institute (version: World_EEZ_v12_20231025) (Flanders Marine Institute 2023). Land shapefile (large scale data 1:10 m) Natural Earth (access date: September 7, 2023) (Natural Earth 2024).

monitoring programs apply as much flexibility as possible in the timings and regularity of satellite collections.

4.1.2 | Caribbean

The Caribbean is home to more than 26 cetacean species, including larger whale species like humpback whales, which breed there during the Northern Hemisphere winter/ Caribbean dry season (Roden and Mullen 2000). Feasibility mapping revealed the Caribbean UKOTs and Caribbean Sea more broadly as a good candidates for investment in year-round regional satellite monitoring programs for live and stranded cetaceans, particularly, during the dry season from December/January to April/May (CIMH, 2024). The lower suitability identified during the feasibility mapping between May and November can be attributed to the wet season, which coincides with Atlantic hurricane season (June–November) and is characterized by high cloud cover (CIMH, n.d.). The more pronounced reduction in suitability during May, September, October, and November is the result of a shift in the Intertropical Convergence Zone (ITCZ) (Pérez et al. 2018; Bastidas-Salamanca and Rueda-Bayona 2021). Although this shift is characterized by a decrease in wind speeds, it brings high rainfall and accompanying dense cloud cover (Bastidas-Salamanca and Rueda-Bayona 2021). Despite the reduced likelihood of achieving a suitable image collection in the wet season compared with the dry season, especially the opportunity for systematic satellite surveillance programs, there is still a 40% "likely" chance of opportunistically acquiring monthly collections for much of the Caribbean UKOTs and Caribbean Sea jurisdiction. The Colombian Caribbean, however, is an exception. The region is largely unsuitable for satellite monitoring of live cetaceans for most of the year due to high wind speeds (Devis-Morales et al. 2017; Pérez et al. 2018; Bastidas-Salamanca and Rueda-Bayona 2021).

Humpback whale size and morphology make them ideal candidates for satellite surveillance, and features like their long pectoral flippers are often a unique identifier for the species. Based on our feasibility assessments, the arrival of humpback whales to the Caribbean occurs when environmental conditions are optimal for satellite image collection. However, humpback whales can be acrobatic, and splashes can obscure key features and prohibit their detection (Cubaynes et al. 2019). The above examples demonstrate the value of extending feasibility assessments beyond the basic primary environmental conditions to identify and map live cetacean distribution and abundance, and breeding and feeding grounds. For the Caribbean, a monitoring program using satellites to map cetacean densities is feasible and could be beneficial in the designation and management of Marine Protected Areas and advising policy (Knowles et al. 2015). We recommend further study to establish how well they can be detected in the local environment.

4.1.3 | Falkland Islands (Islas Malvinas)

The Falklands (Islas Malvinas) are important for resident and migratory cetacean populations (Augé, Dias, et al. 2018; Weir and Stanworth 2020; Weir et al. 2021). Based on year-round cloud cover (20% "possible" likelihood of suitable cloud cover), the Falkland Islands may be appropriate for satellite-based stranding monitoring programs. Due to the islands' remoteness, low human population density, complex coastlines, and high wind speeds, conventionally derived stranding records have been an invaluable source of information in understanding the local species composition (Augé, Otley, et al. 2018). VHR optical satellites could opportunistically complement existing efforts of the Falklands Conservation stranding monitoring program, particularly, for the remote, unpopulated coastlines of the West Island (Figure 10c). Contrastingly, feasibility mapping of the Falkland Islands also revealed the unsuitability of the region for live cetacean monitoring using VHR optical satellite imagery. The islands' location at the core of the strongest surface winds on Earth was reflected in high average wind speeds resulting in a lack of "suitable area(s)."

4.2 | Feasibility Mapping of Environmental Conditions: Data Limitations

We present first steps to map the feasibility of using VHR optical satellites to study cetaceans at scale; however, the data, analyses, and interpretations presented here have limitations.

Firstly, the ERA5 data used in the feasibility mapping exercise is a synthetic version of Earth's atmospheric conditions, and its performance is dependent upon the quality of observed and modeled data. As observation records are spatially and temporally biased and inconsistent in their standards, modeled data will be less accurate in regions with fewer observations (Copernicus, n.d.; ECMWF 2020, Hersbach 2017). It would be useful to compare ERA5 data with alternative global data sources available through satellite-derived observations, such as MODIS cloud mask level two and three products, to explore which product gives more accurate feasibility assessments.

We used monthly averages of wind speed and cloud cover to map feasibility; more refined daily products available through ERA5 could provide higher resolution information about satellite imaging feasibility than our exploration. In addition, ERA5 data is a global climate reanalysis dataset, which is advantageous for the standardization of these feasibility assessments on a global scale. However, in the future, regional climate reanalysis datasets or locally derived observation datasets may provide a higher resolution alternative to ERA5, which, when combined with local knowledge of weather conditions and local cetacean populations, could achieve more accurate local-level assessments (Gualtieri 2021).

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The spatial resolution of ERA5 data is much coarser than the VHR optical satellite imagery we are assessing (Figure 2). The data are also much coarser than the conditions with which they are representing, and which conservation managers require to make informed decisions (Karger et al. 2021). For example, ERA5 "10m wind speed" data does not account for complex flow regimes at the coastal land–water interface, and the direction of wind, which can affect wave formation (Gualtieri 2021). For nearshore cetacean surveys, it will be important to ground truth the local conditions rather than rely solely on ERA5 predictions.

While we opted to use a 5-year (2018–2022) climate average, future studies may find a shorter or longer timespan to be more accurate. Regardless of the timescale, analyzing averages can conceal anomalous periods. Many cells identified as not feasible on average will allow for successful image collection at certain times. Therefore, this mapping exercise should not discourage opportunistic satellite studies in regions where median environmental thresholds are not met.

Finally, further work is needed to understand the effect of sea state on the detection of cetaceans in VHR optical satellite imagery to achieve more accurate feasibility assessments (Bamford et al. 2020; Green et al. 2023). Exploration could include satellite image collection simultaneous to boat or aerial cetacean surveys to validate sea states from space and their impact on cetacean detection.

4.3 | Future Directions

The feasibility mapping exercise presented here focuses only on cloud cover and wind speed, around the UK and environmentally contrasting UKOTs. Assessments of environmental conditions should be scaled to guide where satellites will be most beneficial globally. To truly understand the feasibility of an area for satellite survey, further assessments need to be made to review the technical capabilities of satellites for collection and how future planned missions may advance monitoring capabilities (e.g., satellite spectral and spatial resolution and revisit rate), additional environmental and image quality parameters (e.g., turbidity and glare), and the costs of accessing imagery (see detailed recommendations in Supporting Information S5). The next logical step to map feasibility would be evaluating the local cetacean populations present in a "suitable area(s)" to determine suitability of species for detection. Of interest is whether the expected species are sufficiently large or morphologically unique to be confidently detected, whether the species contrasts well with its surroundings, and whether there are expected confounding features; for example, rocks may be misidentified as a stranded cetacean (Cubaynes et al. 2019; Charry et al. 2021; Clarke et al. 2021). Finally, does the species exhibit behaviors that would increase or decrease detectability (Cubaynes et al. 2019). Knowledge of overlaps in the timing and location of species known feeding, breeding, or calving grounds would be necessary. While the current generation of satellites has a spatial resolution most suited to the detection of larger cetacean species, high contrast with environments (e.g., beluga (*Delphinapterus leucas*) and narwhal (*Monodon monoceros*)) and unusual behaviors (e.g., aggregations of cetaceans in groups or large-scale features like mud rings associated with common bottlenose dolphin (*Tursiops truncatus*)) feeding (Ramos et al. 2022) can increase the likelihood of detecting smaller cetacean species.

It is evident that for many locations around the world, cloud cover will be a limiting factor for the establishment of monitoring programs using VHR optical satellite imagery. Future efforts in the use of satellites to study cetaceans should explore the use of Synthetic Aperture Radar (SAR) due to its increased capacity to observe earth through cloud (Woodhouse 2006). SAR uses longer wave radiation that penetrates cloud to identify surface roughness, which through image differencing (identifying change between images over time), could be useful to detect cetaceans. SAR will likely not be suitable for live whale monitoring due to the natural surface roughness of the ocean. However, SAR may be able to identify changes in surface roughness associated with whale behaviors and blows of super pods or dense aggregations of hundreds of whales in relatively calm waters. SAR could be of greatest value in supporting strandings monitoring, especially where spatially dense mass stranding and mass mortality events occur (Fischbach and Douglas 2021).

From existing knowledge of global climate and cloud cover (NASA Earth Observatory 2024) and evidence from the three feasibility mapped areas in this project, global year-round long-term monitoring programs using VHR optical satellites will be most practical in the tropics. There is a strong conservation rationale for satellite application in these regions, given that most of the world's biodiversity and most ocean-dependent communities are found in these regions (Spalding et al. 2023). However, most of the tropics (and more broadly, 70% of global coastlines) are low-to middle-income countries where there has been limited capacity to study local cetacean populations or systematically record strandings; and for which the current costing structure of commercially operated VHR optical satellites is restrictive (Clarke et al. 2021). The application of VHR optical satellites in cetacean research risks preserving colonial narratives already prevalent in the tropics, which see nations external to the tropics hold power in governance, research, education, technologies, and funding of conservation efforts (Braulik et al. 2018; De Vos 2020, 2022; Clarke et al. 2021; De Vos and Schwartz 2022; Spalding et al. 2023). Without local involvement, the application of VHR optical satellites could undermine local expertise and those best placed to inform the realities on the ground and lead conservation efforts (Spalding et al. 2023). This highlights the need for equitable access to VHR optical satellite imagery and its analysis, perhaps through the development of partnerships with satellite image providers as endorsed by the IWC (IWC 2023).

5 | Conclusion

We have developed a framework for assessing the suitability of a region for implementing scalable VHR optical satellite monitoring programs of live and stranded cetaceans based on key environmental variables. This framework is intended to support resource managers to deliver on their conservation policies for cetaceans, target areas and species for additional surveillance, and make more efficient use of funding. Feasibility mapping can add to the UK's efforts to apply new technologies to underpin management plans in the UK and UKOTs. More broadly, the framework can be extended to assess and inform surveillance

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strategies of cetaceans globally. While this feasibility study looks at live and stranded cetaceans, it may be expanded to assess the occurrence of floating dead cetaceans (Moore et al. 2020). In addition, the feasibility mapping exercise conducted here could act as a framework for the wider remote sensing community using VHR optical satellite imagery. For example, for non-cetacean marine features like marine plastics (Biermann et al. 2020; Cózar et al. 2024), abandoned, lost or discarded fishing gear (Elliott et al. 2021), and illegal, unreported, and unregulated fishing activity (European Association of Remote Sensing Companies 2022). It could also be adapted to evaluate the feasibility of remotely sensed data in similar terrestrial applications, like broad-scale assessments of large mammals (Durporge et al. 2021). Future efforts should focus on determining the feasibility of monitoring the most biodiverse and vulnerable places around the globe, such as the tropics and polar regions; to protect and promote their conservation.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

This framework uses open-source data, accessed through the European Centre for Medium-range Weather Forecasts (ECMWF) reanalysis ERA5 data. Guidance on how to access and download ERA5 data and all code required to replicate the analysis here (and for application to new study areas) is archived with Zenodo at https://doi.org/10.5281/zenodo.17106752 (Clarke and Skachkova 2025), and the latest version can be found on GitHub at https://github.com/PennyJClarke/feasibility-mapping. All "suitable area(s)" (.shp shapefiles) identified in this study are available to download at the British Antarctic Survey Polar Data Centre (PDC): https://doi.org/10.5285/451a6a5d-a17b-4d71-aad0-188739403d8c.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Supporting Information S1:** Bounding box coordinates. **Table S1:** The bounding box coordinates of the three study areas used delineate and extract wind and cloud data from the European Centre for Medium-range Weather Forecasts (ECMWF) ERA5 reanalysis data. **Supporting Information S2:** Downloading ERA5 data. **Supporting Information S3:** Pseudo code for processing ERA5 data. **Figure S3:** Pseudo code providing a visual representation of the steps in the code for processing ERA5 data. **Supporting Information S4:** Additional maps ("Total cloud cover," "10 m wind speed," and standard deviation). **Figure S4:** (1) A map detailing the "suitable area(s)" for live cetaceans with ≤40% average "TCC" per month around the UK. (2) A map detailing the "suitable area(s)" for live cetaceans with ≤60% average "TCC" per month around the UK. (3) A map detailing the "suitable area(s)" for live cetaceans with ≤80% average "TCC" per month around the UK. (4) A map detailing the "suitable area(s)" for live cetaceans with wind speeds ≤8 ms^{-1} per month around the UK. (5) A map detailing standard deviation of "TCC" (%) and wind speed (ms^{-1}) per month around the UK. (6) A map detailing the "suitable area(s)" for live cetaceans with ≤20% average "TCC" per month around the Caribbean. (7) A map detailing the "suitable area(s)" for live cetaceans with ≤40% average "TCC" per month around the Caribbean. (8) A map detailing the "suitable area(s)" for live cetaceans with ≤60% average "TCC" per month around the Caribbean. (9) A map detailing the "suitable area(s)" for live cetaceans with wind speeds ≤8 ms^{-1} per month around the Caribbean. (10) A map detailing standard deviation of "TCC" (%) and wind speed (ms^{-1}) per month around the Caribbean. (11) A map detailing the "suitable area(s)" for live cetaceans with ≤80% average "TCC" per month around the Falkland Islands (Islas Malvinas). (12) A map detailing the "suitable area(s)" for live cetaceans with wind speeds ≤8 ms^{-1} per month around the Falkland Islands (Islas Malvinas). (13) A map detailing standard deviation of "TCC" (%) and wind speed (ms^{-1}) per month around the Falkland Islands (Islas Malvinas). **Supporting Information S5:** Detailed next steps for a satellite feasibility assessment.

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