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How successive meteotsunami and storm activity disrupts saltmarsh vegetation

Clare Lewis [a,b,*], Jonathan Dale [a], Jessica Neumann [a], Tim Smyth [b], Hannah Cloke [a,c]

[a] Department of Geography & Environmental Science, University of Reading, Reading, UK
[b] Plymouth Marine Laboratory, Prospect Place, Devon, Plymouth, PL1 3DH, UK
[c] Department of Meteorology, University of Reading, Reading, UK

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ABSTRACT

Meteotsunami (meteorological tsunami) are globally occurring progressive shallow water waves with a period of between 2 and 120 min which result from sudden pressure changes and wind stress due to moving atmospheric systems. These waves are known to cause destruction to and loss of assets. Currently, there is no research into the impact of meteotsunami on coastal ecosystems such as saltmarshes, despite the significant role saltmarsh play in providing vital habitats for resident and migrating birds, natural flood defences and climate mitigation. As such the restoration of saltmarshes has emerged as a pivotal focus within the UK Government's environmental policy framework.

This paper examines the impact of two meteotsunami events (2016 and 2021) on saltmarsh vegetation in the southwestern UK. An assessment of the vegetation pre and post event was undertaken using high resolution satellite imagery and the Normalised Difference Vegetation Index (NDVI). Results revealed that the 2016 meteotsunami exacted minimal vegetation change with a decrease in NDVI from 0.26 to 0.23 and a temporary reduction in coverage of 40 %, suggesting a potential resilience to single episodic disturbances. In contrast, the 2021 event, compounded by multiple significant storms and additional meteotsunami, led to a decline in NDVI values from 0.44 to 0.22 and a temporary reduction in vegetation coverage of 66 %. Both events indicated a short-term disruption with a relatively rapid rebound (within one to three months). However, the longer-term effects of such a disruption on the saltmarsh ecosystem need to be investigated further.

This comparative analysis underscores the complex interactions between meteotsunami, climatic phenomena, and coastal vegetation dynamics, highlighting the necessity for ongoing monitoring and research to understand the resilience mechanisms of such ecosystems in the face of increasing climatic variability and extreme weather events.

1. Introduction

1.1. Brief overview of meteotsunami

Meteotsunami are shallow water waves with wave periods of between 2 and 120 min, they are initiated by sudden pressure changes and wind stress from moving atmospheric systems. Sources range from convective clouds, cyclones, squalls, thunderstorms, atmospheric gravity waves and strong mid-tropospheric winds (Vilibić and Šepić, 2017). The atmospheric pressure changes are typically only a few mb over a few tens of minutes and this corresponds with only a few centimetres of sea level change known as the inverse barometer effect (for example, a 3 mb pressure jump will produce a 30 cm ocean wave). The atmospheric disturbance transfers energy into the ocean initiating and amplifying a water wave and both waves travel at the same speed, in a process known as Proudman resonance (Proudman, 1929). When the water wave reaches the coastline and shallower water it is further amplified through coastal resonances. For example, if the wave reaches the entrance of a semi enclosed basin it can induce an oscillation in the basin known as harbour resonance. However, if the wave reaches a beach type environment and the along shore component of the disturbance equals the phase speed of the edge wave this is a process known as Greenspan resonance (Monserrat et al., 2006). The resultant waves can elevate the coastal water level and can substantially increase flow velocities with

* Corresponding author. Department of Geography & Environmental Science, University of Reading, Reading, UK.
E-mail address: clare.lewis@pgr.reading.ac.uk (C. Lewis).

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the potential for rip currents (Linares et al., 2019). Due to the rapid onset and unexpected nature of meteotsunami waves, they have the potential to cause destruction, injuries and even fatalities (Sibley et al., 2016).

Meteotsunami are a global phenomenon with over 98 events recorded between 1750 and 2023 in the UK alone, however this number may be a lot greater due to the lack of a high-resolution tide gauge network (Lewis et al., 2023). Previous work has suggested that meteotsunami in the UK are rare events and occur more frequently during the summer months and are usually initiated by convective storms (Thompson et al., 2020; Tappin et al., 2013; Sibley et al., 2016; Haslett et al., 2009). However, recent work has shown a prominent seasonal pattern of winter events related to mid latitude depressions with precipitating convective systems (Lewis et al., 2023; Williams et al., 2021). A geographical pattern across the UK has also emerged showing three hotspot areas along the coastline of south and southwest England and the northwest of Scotland, this is mainly due to the dominant direction of flow of UK weather systems and morphological coastal features (Lewis et al., 2023; Williams et al., 2021; Sibley et al., 2016).

1.2. Intertidal habitats in the UK

Saltmarshes are highly dynamic intertidal habitats that form on the upper parts of intertidal flats where it is low energy and sheltered but regularly inundated by water and colonised by salt tolerant (halophytic) vegetation. These habitats embody characteristics from both terrestrial and marine environments and are good indicators of the health and condition of the coastal zone (Cawkwell et al., 2007). Even though the preservation and restoration of UK saltmarshes is now a key factor in coastal management policy due to their critical role in flood protection, sea defence, in supporting biodiversity and achieving net zero carbon emissions, they have often been undervalued and subjected to urban and agricultural reclamation for economic gain. The 1950s saw a shift towards protection and natural heritage conservation with the introduction of Sites of Special Scientific Interest (SSSIs) and Nature Reserves and since the early 2000s the ecosystem services provided by saltmarshes have been more widely acknowledged, coupled with a shift towards restoration, i.e., the prioritisation of the ecological wellbeing of the marsh over profit (Ladd, 2021).

Saltmarsh vegetation is important as it plays a vital role in reducing the risk of erosion, damage, and tidal flooding of low-lying coastal areas by attenuating high water levels (Stark et al., 2015; Cobell et al., 2013; Wamsley et al., 2010) and acting as a natural buffer to wave energy (Mayor et al., 2018; Gedan et al., 2011; Costanza et al., 2008). It has been estimated that the presence of marsh vegetation such as those found along the mid to southern North Sea have the potential to attenuate storm wave energy by up to 60 % and can withstand large wave forces without substantial erosion (Möller et al., 2014). Saltmarshes also offer stability as they trap, filter, and recycle nutrients, pathogens, and pollutants (Ricart et al., 2020; Gedan et al., 2011), and the salt tolerant plants help mitigate climate change by sequestering carbon. It is estimated that the 448 saltmarshes in Great Britain (GB) which cover an area of approximately 451,66 ha contain 5.20 ± 0.65 Mt of organic carbon, with *Spartina* species outperforming the native pioneer species for sequestration (Smeaton et al., 2023). Saltmarshes are an important component of the world's "blue carbon" (McLeod et al., 2011). Another important function of saltmarsh is its position in the estuarine food web where they underpin the healthy functioning of the ecosystem by supporting a range of rare and important plants and by providing food, roosting, and nesting for resident and migratory birds (Mathot et al., 2018). Saltmarshes are considered GBs largest intertidal blue carbon resource (Smeaton et al., 2023) and provide massive benefits to society and ecology and as such are a highly valued coastal ecosystem benefiting from protection and restoration (Costanza et al., 2021). They are recognised in the UK Government's climate strategy (Environment Agency, 2023a,b), the UK's Biodiversity 2020 Strategy (DEFRA, 2011), the UK's Biodiversity Action Plan (UKBAP) (Baily and Pearson, 2007) and the Environment Agency's (EA) Restoring Meadows, Marsh and Reef (ReMeMaRe) initiative (Hudson et al., 2021). Saltmarshes that have a greater amount of high to mid vegetation can be promoted for wildlife habitat provision and saltmarshes that have a greater amount of resilient seaward vegetation can be promoted for wave attenuation (Pétillon et al., 2023).

For a saltmarsh to continue providing its vital ecological services and prevent the release of stored carbon, it needs to maintain its delicate balance between sediment supply, nutrients, and external forcing factors such as waves, storms, and tidal inundation (Grandjean et al., 2024). It is known that saltmarshes cycle through natural phases of vertical and lateral accretion and erosion which are influenced by seasonality, hydrological cycle, sediment regime and the ability of pioneer vegetation to establish at the marsh edge (Fagherazzi et al., 2012). Whilst vegetation establishment can aid in lateral expansion, wave forcing can led to lateral erosion (Leonardi et al., 2016). Numerical modelling has been used to help understand the stability of saltmarshes, the biogeomorphological interactions and to predict saltmarsh development and resilience under a changing climate (Fagherazzi et al., 2012). Maintaining the delicate balance of sediment supply, vegetation health and the influence of external forcing factors in the light of sea level rise, climate change and anthropogenic influence is a challenge, especially as the UK is already experiencing large scale loss of saltmarsh habitat (Ladd, 2021).

Whilst there is an understanding of saltmarsh response to morphological change, storms and tsunami (Willemsen et al., 2022; Leonardi et al., 2016; Schuerch et al., 2013) there has been no assessment of the interactions between meteotsunami and saltmarsh. Currently, there is no policy in place in the UK to cover the impacts of meteotsunami or other wave anomalies on the coastal zone apart from storm surge, leading to a need for further policy consideration (Lewis et al., 2023). There also appears to be no qualitative or quantitative studies related to the effect of meteotsunami on intertidal habitats either within the UK or globally. However, it has been found that research on the ecological impacts of tsunami has been widespread, typically using such methodological approaches as ecological field surveys (Nakaoka et al., 2006); numerical modelling (Wang and Liu, 2007); and remote sensing techniques using satellite imagery (Paterson et al., 2012).

Since 2020 there has been a comprehensive global record of saltmarsh extent and research on the single marsh scale and saltmarsh dynamics have become prevalent within Europe and North America (Pétillon et al., 2023; Worthington et al., 2024). There have also been many studies conducted highlighting saltmarsh recovery and resilience to storms, in particular along the US North Atlantic (Roman et al., 2024; Temmerman et al., 2022; Castagno et al., 2021; Schuerch et al., 2018; Ganju et al., 2015). Studies have discussed how saltmarsh is effective in attenuating short-term storm induced waves but less effective with storm surge waves (Temmerman et al., 2022). Similar to other extreme wave hazards, this attenuation rate is location and event specific (Stark et al., 2015) and is highly dependent upon elevation, vegetation characteristics and sediment dynamics (Leonardi et al., 2018). With the 2004 Indian Ocean tsunami a total of over 77 research papers related to the tsunamis ecological effects were published by Indian authors alone with many more from other global researchers (Devi and Shenoi, 2012). The extensive research that has been conducted into tsunami impacts upon mangroves gave way to a noticeable increase in demand for government policies that combine management and preservation methods to ensure future resilience (Patel et al., 2014). The ecological effects of tsunami disturbance on coastal communities have been studied in mangrove forests, the tropical equivalent of saltmarsh (Fujioka et al., 2008), seagrass beds (Whanpetch et al., 2010; Nakaoka et al., 2006), subtidal soft bottoms (Jaramillo et al., 2012), and intertidal flats (Urabe et al., 2013; Kanaya et al., 2012; Lomovasky et al., 2011).

Studies of the 2004 Indian Ocean tsunami have shown that vegetation recovered quickly, and sediment returned to pre-event levels within days to weeks of the tsunami (Paterson et al., 2012). Vegetation in Sri

Lanka responded with regrowth within 3 months of the tsunami and was found to yield better than pre tsunami conditions (Ranasinghe, 2011). In studies of the 2011 Japan tsunami, Urabe et al. (2013, 2016) a comparison of the taxon richness and community composition of macrobenthic communities revealed a 1–2-year recovery period (Urabe et al., 2013; 2016) whereas a study of the community structure of seagrass beds (*Zostera marina)* showed a decrease in vegetation coverage relative to pre-tsunami levels (Shoji and Morimoto, 2016).

Currently, the interaction of meteotsunami with saltmarsh vegetation has not been considered and as such is unknown. This lack of previous research may be due to the human-centric approach to risk assessment, with focus centred on minimising risk to built infrastructure and economic assets. Understanding the interactions between meteotsunami and ecosystems is important not just for the UK but around the world. Better understanding of these interactions especially in meteotsunami prone areas such as the Mediterranean, the Adriatic and the east coast of America can be used to take informed decisions on management of natural buffer zones to aid in minimising potential impacts (Benazir et al., 2024). A recent study by Robertson et al. (2022), highlighted the lack of knowledge on and the importance of the potential role meteotsunami could play in coastal processes and ecosystem functioning. Perez et al. (2022), also conducted a study highlighting the hydrological response of meteotsunami within the Rio de la Plata estuary in Argentina. Within their study they assessed the characteristics, atmospheric forcing, direction of propagation and amplification factors of eight meteotsunami events. Their study was a continuation of the results received from previous work where they modelled and analysed the generation and propagation of meteotsunami from gravity waves along the coastline of Buenos Aires (Perez et al., 2020; Perez and Dragani, 2021). However, without a clearer idea of the vegetation characteristics and the processes involved (especially those that enhance the efficient wave buffering capabilities), loss of infrastructure and life to meteotsunami such as those witnessed at Daytona Beach, Florida in 1992 and Dayyer, Persian Gulf in 2017 may continue into the future (Vilibić et al., 2021).

As there is no data and no literature currently available to represent the impact of meteotsunami on coastal ecosystems, this study represents a novel assessment in which to provide a starting point for further research. This study addresses this knowledge gap by using the lower Tamar estuary close to the city of Plymouth, UK (50° 22′ 35″N, 4° 8′ 38″W) (Fig. 1) as a case study site to investigate whether evidence of changes in vegetation coverage and health can be seen and attributed to meteotsunami. The study aims to.

1. Highlight the degree to which the area encounters the forcing dynamics of meteotsunami.
2. Access the robustness and the rate to which the vegetation reclaims its habitat after being disrupted by meteotsunami.
3. Finally, to take the initial steps towards highlighting if a stable intertidal ecosystem can play a vital role as a form of natural defence against hydrodynamic extremes.

2. Methodology

2.1. Study area

Between 1750 and 2023, 31 % of known UK meteotsunami events were recorded within estuarine intertidal environments and 20 % of the total UK events were recorded within the Tamar estuary, southwest UK (Lewis et al., 2023; Williams et al., 2021). St. John's Lake (50°22′9″N 4°12′57″W), to the west of Plymouth (Fig. 1), was therefore chosen as a study area or area of interest (AOI) due to its susceptibility to meteotsunami and its ecological significance as a diverse and dynamic intertidal ecosystem. The 2.66 km^2 shallow (<5 m deep) sheltered, embayment has an elevation of 0–1m relative to Ordnance Datum Newlyn (ODN) meaning the mudflat and saltmarsh are inundated by seawater at high tide and fully exposed at low tide (Fig. 1c and SP 2). The area was designated as a SSSI in 1986 under Section 28 of the Wildlife and Countryside Act 1981 and was included as part of the Tamar Estuaries Complex Special Protection Area (SPA) in 1997. Both designations are due to the area's international importance for nature conservation, as a wintering site for 6000 wildfowl and 10,000 waders, including the IUCN (International Union for Conservation of Nature) amber listed Pied Avocet (*Recurvirostra avosetta*) and the red listed European Curlew (*Numenius arquata)* (Woodward et al., 2024). The AOI also lies within the Plymouth Sound and Estuaries Special Area of Conservation (SAC) recognised for its mudflats, sublittoral sandbanks, and saltmarsh communities (Plymouth Marine Protected Area, 2024). For the location of St Johns Lake within the Plymouth area please refer to Fig. 1b and SP 1.

The long-term trend of sediment within the AOI is in a state of quasi-equilibrium resulting in no long-term changes in bed elevation due to erosion or deposition (Natural England, 2020). However, previously the sediment and saltmarsh vegetation on the southeastern leading edge have been less stable due to bait digging, with high levels of contaminants and poor water quality also experienced in the northern sections (Warwick, 1986; English Nature, 2000; Natural England, 2013). In 2013 the site was finally deemed to be 90 % stable with no significant changes

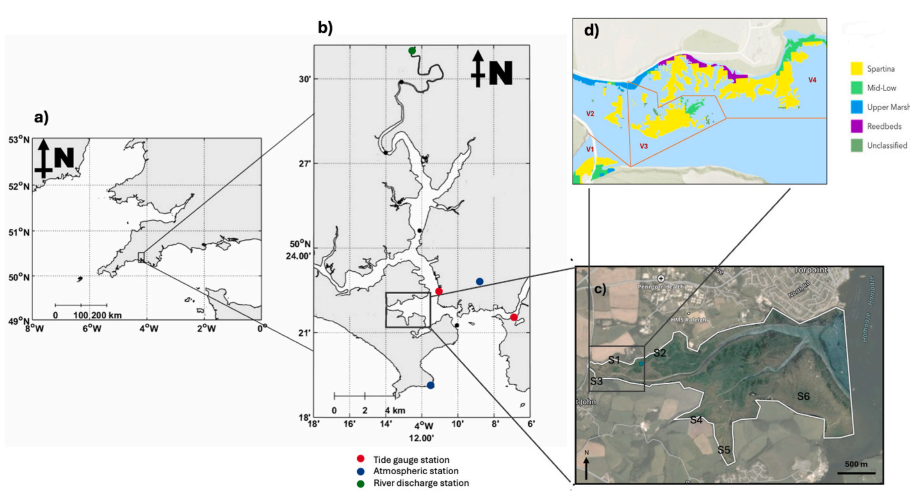

Fig. 1. a) St John's Lake study site within the southwest UK; and b) study site within the Plymouth area, with locations of atmospheric, tide gauge and river monitoring stations (© Crown copyright and database rights 2024 Ordnance survey (AC0000851941); c) Satellite image from July 2013 (Image © 2013 Planet Labs PBC) with test sites S1 to S6 highlighted and d) Salt marsh zonation and extent at S1, V1 to V4 represent the vegetation zones used in the extent analysis (© Environment Agency copyright and/or database rights 2015. All rights reserved).

in habitat zonation and an increase in species richness. The 10 % unstable conditions were due to the presence of non-native species such as Pacific Oyster *(Crassostrea gigas)* and macroalgae overlaying vegetation which reduced levels of primary production (Natural England, 2020).

Initially, six study sites (S1 – S6 on Fig. 1c) were selected within the AOI based upon their position within the intertidal zone and the vegetation type hosted within each site. Sites 1 to 3 are situated at the sheltered shallow north-western corner of the lake and host the principal pioneer species common cordgrass (*Spartina angelica*), dwarf eel grass (*Zostera noltii*) and saltmarsh rush (*Juncus gerardia*). Sites 1 to 3 also contain common salt marsh-grass (*Puccinellia maritime*), sea purslane (*Halimoine portulacoides*) and sea plantain (*Plantago maritima*). Site 4 located at Penhale and Site 5 at Insworke Creek, both at the sheltered southern portion of the lake contain common cordgrass (*Spartina angelica*), sea purslane (*Halimoine portulacoides*), sea arrow grass (*Triglochin* maritima), sea couch grass (*Puccinellia maritime*), sea milkwort (*Glaux maritima*), sea aster (*Aster tripolium*) and glasswort (*Salicornia europaea*). Finally, Site 6 which is situated out on the eastern edge of the mudflat near to the river Tamar, sustains considerable swathes of green macro algae (*Enteromorpha* sp.) (Environment Agency, 2024).

2.2. Historical meteotsunami events within the study area

A summary of meteotsunami events within the Tamar estuary was taken from Lewis et al. (2023) to enable the selection of one summer and one winter event for further analysis (Table 1). Propagations of meteotsunami into the area are by two routes northwards from the English Channel up through Plymouth Sound where one direction of flow propagates eastward into the River Plym and Hooe Lake and a second, westward up through the Narrows, into the River Tamar and St John's Lake (SP1).

2.3. Data acquisition

As this was a retrospective study with no ecological field data available due to the transient and unpredictable nature of meteotsunami, as such remote sensing was utilised. The vegetation coverage and greenness of all six sites was carried out using a series of Rapid Eye and Planet Scope satellite images provided by Planet Lab (source outlined in Table 2). Planet Scope offers high resolution imagery at a spatial resolution of 3 m (panchromatic resolution) and Rapid Eye offers imagery at a spatial resolution of 5 m (panchromatic). A total of 130 images for the AOI were used (averaging 1 to 4 images per month with a few months unavailable as shown in SP 4), the images were cropped to the defined watershed (Fig. 1c) and a ten-year seasonal baseline of the broader climatic context and NDVI were calculated, NDVI is a popular method to assess tidal marsh vegetation change and coverage as a result of hurricanes and typhoons (Nardin et al., 2021; Svejkovsky et al., 2020; Wang and Xu, 2018; Miller et al., 2017). The years surrounding the selected meteotsunami events allowed for a comparative analysis of vegetation changes, environmental variability, changing patterns in temperature, precipitation and solar radiation. By examining the external factors, the aim was to identify and isolate their impacts on NDVI fluctuations and try to discern the direct influence of the meteotsunami events. Sources for the data used are given in Table 2.

Obtaining suitable satellite images were restricted by issues of cloud cover, high tide or low light leading to limited temporal continuity. To ensure robust data, only images with a cloud cover of 10 % or less, a full coverage of the AOI and the necessary spectral bands of red, green, blue and near infra-red were selected. For cross calibration, all images were pre-processed, atmospherically corrected, with a stable calibration point selected, tidal data was assessed to ensure that water was not present on the mudflat, sensor specific spectral characteristics were accounted for such as spectral bands, swath width and radiometric resolution, and as far as availability allowed, images used were also validated against Sentinel-2 images.

Table 1
Summary of meteotsunami activity within the Tamar estuary from 1750 to 2022. ('Wm (m)' is maximum wave height in metres of the meteotsunami wave separate to the tidal level and Intensity Index value from Lewis et al., 2024). Tidal data taken from Devonport navel yard tide gauge, atmospheric data taken from stations at Crownhill and Penlee Point (Fig. 1c).

Date	Time	Wm (m)	Notes	Intensity Index	Reference
July 17, 1793	07.00	0.6	3 waves in 1 h	2.3	Lewis et al. (2023)
May 31, 1811	03.00	2.4	4 h duration, rain, low pressure, SW wind	2.4	Dawson et al. (2020)
September 13, 1821	14.00	1	Boats moved.	2.4	Long (2015)
July 13, 1824	22.00	0.6	4 m/s currents, ESE light wind	2.4	Lewis et al. (2023)
November 23, 1824	01.00	2	3 waves in 10 min, storm surge	3.4	Haslett et al. (2009)
July 5, 1843	11.00	1	4 waves in 20 min, convective activity, strong wind	2.2	Thompson et al. (2020)
August 28, 1883	09.00	0.25	Pressure wave from Krakatoa eruption	1.9	Lewis et al. (2023)
August 18, 1892	–	4	Squall line, 3 waves in 1 h, boats damaged.	3	Haslett et al. (2009)
June 27, 2011	08.30	0.3	Non-linear rainfall, North moving.	2.7	Thompson et al. (2020)
October 28, 2013	03.15	0.27	Non-linear rainfall, NE moving, 1 mb/1 h air pressure drop.	1.9	Williams et al. (2021)
December 18, 2013	19.00	0.33	Quasi linear rainfall, 2.6 mb/1 h air pressure drop.	2.7	Williams et al. (2021)
January 3, 2014	12.30	0.33	High tide, Quasi linear rainfall, 1.2 mb/1 h air pressure drop, high winds.	3	Williams et al. (2021)
February 8, 2014	20.00	0.25	Open cell, E moving, 1.3 mb/1 h air pressure drop.	2.1	Williams et al. (2021)
February 12, 2014	21.45	0.26	Quasi linear rainfall, E moving, high winds, storm.	2.2	Williams et al. (2021)
August 25, 2016	22.45	0.7 to 1	Individual cell, NE moving.	2.5	Lewis et al. (2023)
August 2, 2020	21.00	0.3	Spring tide, cold front, 0.5 mb/2 min air pressure rise	2.9	Lewis et al. (2023)
August 9, 2021	11.30	0.25	S wind, mid tide, 0.5 mb/30 min air pressure rise	2.3	Lewis et al. (2023)
September 27, 2021	03.00	0.32	Quasi-linear storm, SW moving, 1.1 mb/20 min air pressure drop.	2.2	Lewis et al. (2023)
October 2, 2021	12.00	0.29	SSE wind, non-linear, mid tide, 1.4 mb/1h air pressure drop.	2	Lewis et al. (2023)
October 20, 2021	05.00	0.36	Non-linear, SW moving, 1.5 mb/ 10 min.	2.6	Lewis et al. (2023)
November 1, 2022	09.00	0.3	Heavy ppt, thunder, 1 mb/5 min rise.	2.3	Lewis et al. (2023)

Table 2
Data source overview used for the assessment of meteotsunami on vegetation within St John's Lake.

Analysis	Data information	Unit of analysis	Source
Tidal.	Devonport tide gauge data from 2015 to 2021 courtesy of IOC (station id: E72124)	Ordnance Datum readings in m at 15 min increments.	https://www.ioc-sealevelmonitoring.org/station.php?code=plym
Morphological and vegetation.	Rapid Eye imagery from 2015 to February 2017 and October 21, 2021, Planet Scope imagery from February 2017 to August 2024 courtesy of PlanetLab PBC.	RGB and IR (4 band combination) at 3 m and 5 m resolution.	https://www.planet.com/
Hydrological.	UK National River Flow Archive data, River Tamar at Gunnislake (station id: 47117) from 2015 to 2023 courtesy of UKCEH.	Mean gauged daily flow in m^3/s.	https://nrfa.ceh.ac.uk
Climatological.	Plymouth climatological data from 2015 to 2024 (station id: A00360)	Monthly mean air temperature in °C, monthly total sunshine in Hrs, monthly mean rainfall in mm.	http://www.bearsbythesea.co.uk/wxclimate2024.php
Saltmarsh zonation.	Saltmarsh extent and zonation shapefile download from 2017, courtesy of DEFRA.	Pioneer, upper, mid/low, reedbed, Spartina and unclassified vegetation coverage in Hectares.	https://environment.data.gov.uk/explore/6da82900-d465-11e4-8cc3-f0def148f590?download=true

2.4. NDVI calculation

The Normalised Difference Vegetation Index (NDVI) is a widely used index for assessing vegetation greenness and stress changes in coastal wetlands (Akhter and Jahid Hasan, 2025; Kusumaningrum et al., 2024; Gandhi et al., 2015; Ozyavuz et al., 2015). NDVI is a numerical indicator where values typically range from −1 to +1; the higher the value the more abundant the vegetation (Huang et al., 2021). However, it is worth noting that NDVI is a measure of chlorophyll in the leaves which signifies productivity and overall level of vegetation, this will vary depending on the vegetation's phenological stage and the species type of which NDVI cannot distinguish. Vegetation can show low levels of NDVI and be assumed to be stressed/unhealthy because it is located in an area of sparse coverage, or a dormant growth phase or of a species type with overall lower chlorophyll content such as shrubs or certain crop types (Wu et al., 2008). Barren areas and water bodies tend to have lower or negative values while dense vegetation has higher or positive values. The NDVI was calculated using the raster calculator tool within QGIS, this was done by inputting the near infrared (NIR) which in Planet Lab is Band 4 and the red band data (Band 3).

The formula used for NDVI:

$$\text{NDVI} = \frac{(NIR - RED)}{(NIR + RED)} \qquad [1]$$

The NDVI serves as an essential indicator for understanding whether the two meteotsunami events had a deleterious or beneficial impact on the vegetation within the study area.

NDVIs that have been calculated from different sensors might not be directly comparable (Kobayashi et al., 2007) and so in this study absolute values and years were not compared, but rather differences before and after events were evaluated (e.g. Saito et al., 2022) and spatial variations assessed, maximising data availability, to determine the impact and recovery of meteotsunami events on the saltmarsh. There have been several studies that have used a combination of both PlanetScope and Rapid eye images to assess NDVI and vegetation change over time. Even though PlanetScope has better accuracy for species identification, the studies found that the spatial result had no major influence on the NDVI mapping accuracy and were found to correlate with field data (Mohr et al., 2023; Rosch et al., 2022; Légaré et al., 2022; Cooley et al., 2019). It was also found that despite the lower resolution of 10 m, Sentinal-2 can also achieve comparable results with PlanetScope (Légaré et al., 2022).

Following the preliminary review of NDVI at all six sites on the intertidal flat, analysis was then focussed up on the saltmarsh extent at S1 (Fig. 1 c) ensuring the influence of variations on the mudflat e.g. the growth of algae did not influence the data. S1 was then further subdivided in four areas (V1 – 4 as shown on Fig. 1 d) to allow for a more accurate analysis, the study's subsite boundaries were based upon the pre-determined UK recognised saltmarsh zonation from Environment Agency (EA) where the zonation of marsh vegetation type and their subdivision of the site into 64 smaller sectors was adapted to ensure consistency (Environment Agency, 2020). It is worth noting in relation to the 2016 analysis, that the Environment Agency (EA) saltmarsh zonation was created from imagery in 2008 and extent was created from imagery in 2017, however discrepancy is likely to be minimal. The raster-layer shapefile from the Environment Agency (EA) saltmarsh zonation (Table 2) was imported and merged with the produced NDVI images, followed by an analysis using the QGIS 'Zonal Statistics' plugin to calculate standard deviation, mean, minimum and maximum.

2.5. Classification of vegetated and unvegetated extent

To assess the extent of saltmarsh vegetation and to evaluate whether there was a removal or masking of the marsh following the events, S1 was segmented out into areas of vegetated and unvegetated (soil or sediment), again the data used were limited to the extent recognised by the Environment Agency, which was created in 2017. This segmentation was carried out by initially calculating the Excess Green Index (EGI) a widely used index for vegetation analysis that contrasts the green part of the spectrum against the red and blue to distinguish vegetation, a recent study by (Dale et al., 2020) demonstrated its use with coastal vegetation restoration schemes. The Excess Green Index has been demonstrated to outperform other indices that work with the visible spectrum to distinguish vegetation (Larrinaga and Brotons, 2019).

This following formula was used:

$$\text{EGI} = 2 \text{ x } (G / (R + G + B)) - (R / (R + G + B)) - (B / (R + G + B)) \qquad [2]$$

(where R = red band, B = blue band and G = green band).

To visually simplify the data the calculated EGI value was assigned into two categories with contrasting colours, if the EGI value was ≤ 0.1 then a value of 0 and the colour black was allocated, representing sediment or sparse unvegetated areas. If the EGI value was ≥ 0.1 then a value of 1 and the colour green was allocated to represent densely vegetated areas. This method was adapted from concepts found in Ganju et al. (2017), 2022; in particular the separating out of vegetation, bare earth and water on a pixel-based fraction using satellite-based data and spectral indices such as NDVI (Normalised Difference Vegetation Index, NDWI (Normalised Difference Water Index) and NDBI (Normalised Difference Built-up Index).

3. Results and discussion

Seasonal weather conditions and local topography in the UK result in on average five meteotsunami per year, with over 15 occurring at St

John's Lake between 2015 and 2024 (Lewis et al., 2024). In this study the focus was upon two particular meteotsunami events (2016 and 2021) and their effect on vegetation as analysed using images from two types of satellite and an NDVI analysis which served as an indicator of plant robustness and stress.

3.1. Meteotsunami event of August 25, 2016

The first meteotsunami event to be assessed was the summer event of August 25, 2016. With high tide predicted at 23.02 UTC, the first meteotsunami wave arrived at Devonport tide gauge (Fig. 1b, SP 1 and SP 5a) at 21.30 UTC and was followed by two more distinct waves reaching a maximum wave height of 0.35m (meteotsunami wave component) before subsiding at 23.45 UTC. A series of five waves were recorded at Turnchapel tide gauge at Hooe Lake (SP 1 and SP 5b) starting at 22.45 UTC and subsiding at 00.25 UTC reaching a maximum wave height of between 0.7 and 1 m (Lewis et al., 2023). This event was allocated a hazard intensity level of 2.5 (moderate level) based upon the criteria presented in Lewis et al. (2024) and this led to severe damage to and overturning of a dozen boats moored within Hooe Lake (The Plymouth Herald, Aug 27, 2016).

This meteotsunami was generated by two intense squall lines and a cold front on the continental shelf edge, west of Brittany at 20.41 UTC on 25 August, where an individual cell then detached and travelled northeast to the UK (Lewis et al., 2023; Ventusky, 2025). The atmospheric observatory at Penlee Point, Plymouth (station Id: af2ffcd2-3e6s-eb11-8fed0003ff59sf97, Fig. 1b and SP 1) recorded the weather cell at 23.56 UTC releasing a maximum rainfall of 0.2 mm/min, followed by a rapid air pressure rise of 1.5 mb over a 4-min period and a maximum windspeed of +6 m/s (Lewis et al., 2023).

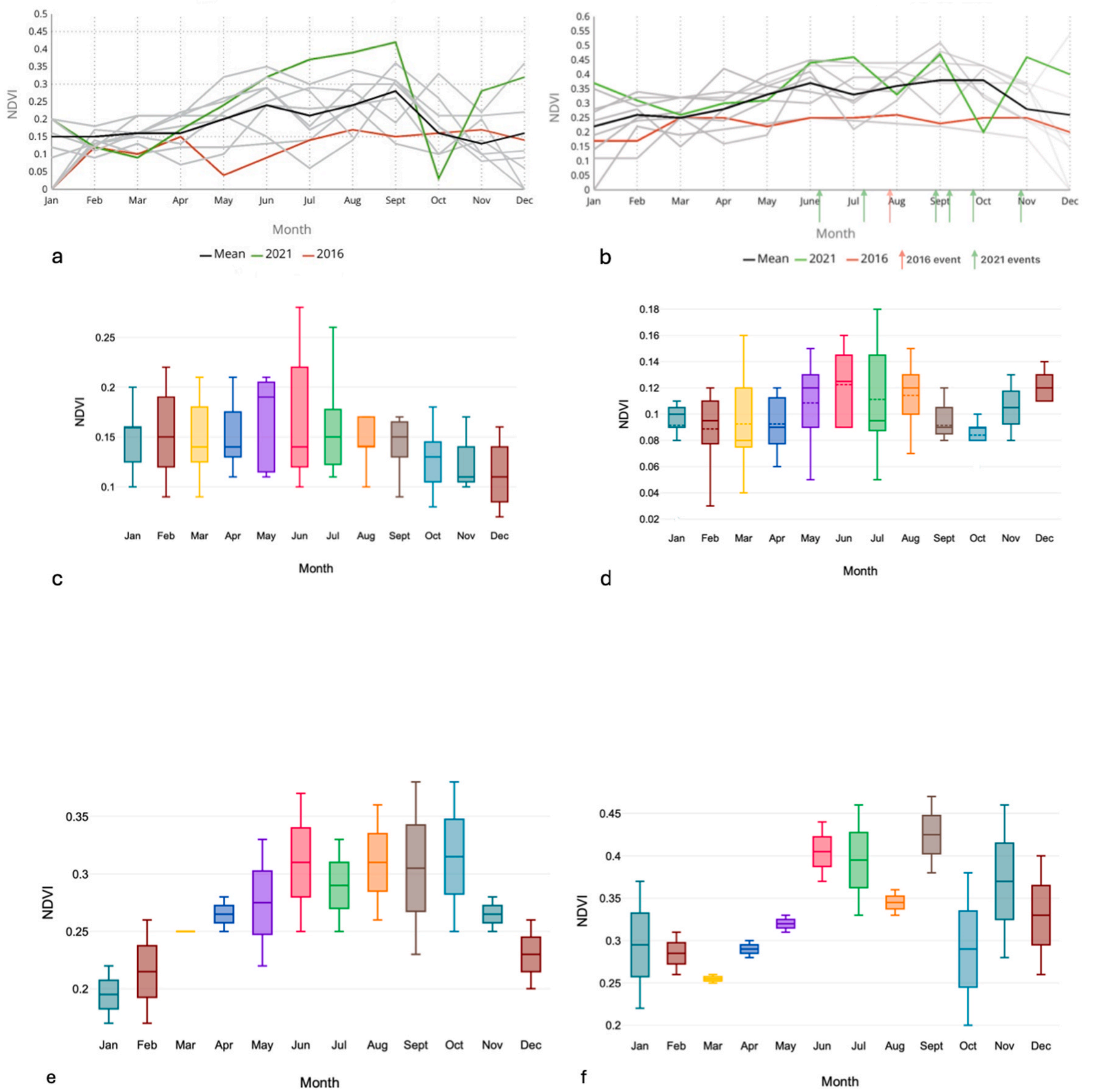

Fig. 2. Monthly mean NDVI results for St Johns Lake intertidal flat as a whole system (a) and for the upper saltmarsh, S1 (b) for the period 2015 to 2024. Study years of 2016 (derived from Rapid Eye) and 2021 (derived from Planet Scope except for 21 October which was from Rapid Eye) are highlighted in red and green respectively, the baseline mean is in black, and the other baseline years within the 10-year study period are *in grey.*
Standard deviation for mean monthly NDVI data for the period 2015 to 2024, for the whole system (c) and the upper saltmarsh, S1 (d). Median is represented by a solid line on each boxplot.
Monthly mean NDVI variance for 2016 (e) and 2021 (f) against baseline monthly mean for study period (2015–2024). Median is represented by a solid line on each boxplot. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3.2. Meteotsunami event of October 20, 2021

The second meteotsunami event was the winter event of October 20, 2021. This event was the fourth in a series of five successive meteotsunami events to occur in the area, starting in August and ending in November 2021 (SP 5). It arrived at 16.00 UTC with a mid-latitude depression named Aurore accompanied by heavy precipitation, convective activity, and strong winds (32 m/s) veering rapidly from west to south. This system also initiated a sharp air pressure rise of 0.5 mb over 2 min which coincided with a spring tide. Wave anomalies were recorded at the Devonport tide gauge (station Id: E72124) at 16.45 UTC (SP 5c) and Turnchapel (station Id: 1609) at 17.00 UTC with a maximum meteotsunami wave height of 0.36 m (SP 5d) (Lewis et al., 2023). This event was also allocated an intensity score of Level 2.6 (moderate) again based upon the criteria laid out in Lewis et al. (2024).

Given the reported impacts of the 2016 event at Hooe Lake on the eastern side of Plymouth (SP 1) this study anticipated impacts within St John's Lake which could have included: physical damage of vegetated habitats due to the succession of strong water currents (Greve and Binzer, 2004). A short-term increase in turbidity from the re-suspension of sediment and the introduction and establishment of alien or invasive plant species. Saltmarsh could be negatively affected by nutrient overload leading to ammonium toxicity and an increase in nuisance algal blooms restricting oxygen levels. However, periodic and less severe ocean influxes can also be beneficial to estuarine environments by flushing out of the system and through the introduction of oxygen, sediment, and nutrients (El-Hacen et al., 2019).

3.3. NDVI

Analysis of the NDVI data spanning from 2015 to 2024 (as shown in Fig. 2 and SP 6) indicates a variability that correlates with temperate vegetation seasonal patterns, reflecting the typical cycle of greening up or biomass increase influenced by climatic conditions during the spring and summer months and a decline during the autumn and winter months (Townend et al., 2011). External factors of air temperature, precipitation, solar radiation and river flow also play a critical role in normal vegetation dynamics (Fig. 3 and SP 7). It was noted that there were dips in NDVI during the test period that can be attributed to changes in external forcing factors. The first noticeable dip in NDVI on the intertidal zone was in March and September of 2017. This correlates with high rainfall and a low number of sunshine hours. In February to April and again in June to August of 2018, substantial dips in the NDVI occurred, which correlate with a cold wet start to spring followed by a hot dry summer (Fig. 3 b/c and SP 7).

The overall NDVI trend for the 10-year study period also shows variability (Fig. 2 b SP 6), with an increase in mean NDVI as time progresses. This increase may be due to an increase in vegetation denseness, greener vegetation due to younger stems, changes in species composition and/or changes to the dredging frequency in the surrounding waters, all of which without field data a conclusion cannot be drawn, however, what can be seen are warmer summers with wetter winters occurring over this period of time (SP 7).

3.3.1. NDVI surrounding the 2016 event

During the preceding months up to the 2016 event (i.e. May to August) the NDVI values on the intertidal flat and at the saltmarsh (S1) were increasing as per normal seasonal growth patterns however they were below the expected seasonal levels (Fig. 2 a/b and SP 6). NDVI on the intertidal flat experienced a decline in May (Fig. 2 a) which correlates with low rainfall (36.4 mm total, Fig. 3, SP 7) and low mean temperatures (8.4 °C) (Fig. 3 b/c and SP 7).

NDVI values on the intertidal flat and at S1 declined following the meteotsunami event and then increased to above the pre-event levels (Fig. 2 a/b and SP 6). Two weeks post event (September) saw a slight decline in NDVI on both the intertidal flat and at S1 (0.17–0.15 and 0.26 to 0.23 respectively, see SP 6). At S1, all subsites (V1 to V4) saw a decline in the NDVI. At sites V1 and V2 this decline was predominately on the western (landward) fringes and at V3 and V4 on the eastern (seaward) fringes, however, there was a delayed decline in NDVI at the upper marsh in V2 (Fig. 4 a). Six weeks post event (October) the NDVI at all subsites had risen back to pre-event levels (0.25, see SP 6) By November the whole intertidal flat including S1 (V1 to V3) had increased back to its pre-event greenness levels (0.25), however NDVI at subsite V4 had increased and was now subject to the start of natural seasonal dieback (Fig. 4 a). Results show that the 2016 meteotsunami may have potentially been beneficial to the vegetation. The temporary additional inundation from the meteotsunami on top of the tidal regime (exceptional high-water level), may have helped flush out and bring in extra nutrients to the area as suggested by El-Hacen et al. (2019) and Temmerman et al. (2003), thus alleviating the stress on the vegetation posed by a particularly dry July. This may have resulted in high winter NDVI values equalling that of the summer pre-event levels.

3.3.2. NDVI surrounding the 2021 event

During 2021 the NDVI values on the intertidal flat and at S1 were

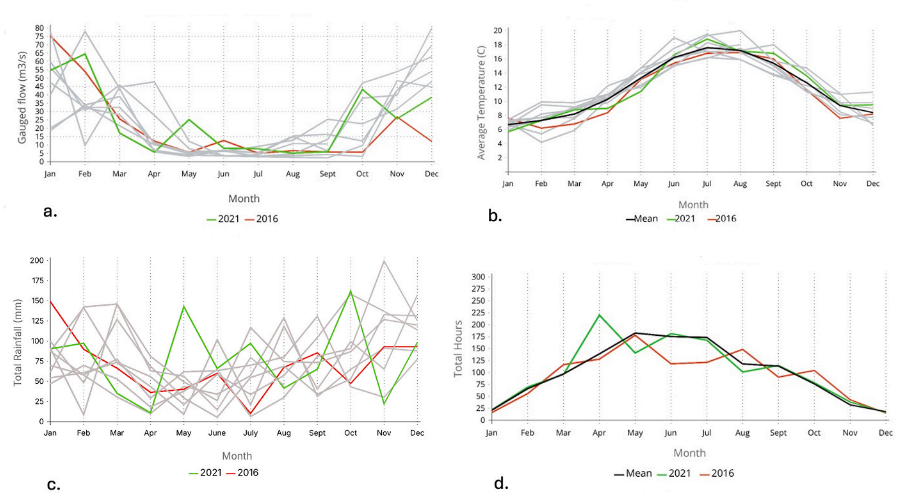

Fig. 3. Monthly mean for the external forcing factors occurring at St Johns Lake for the study period of 2015 to 2024, with the study years of 2016 and 2021 shown in red and green respectively. (a) River Tamar monthly mean flow, (b) average monthly air temperature, (c) total monthly rainfall and (d) total monthly sunshine hours. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

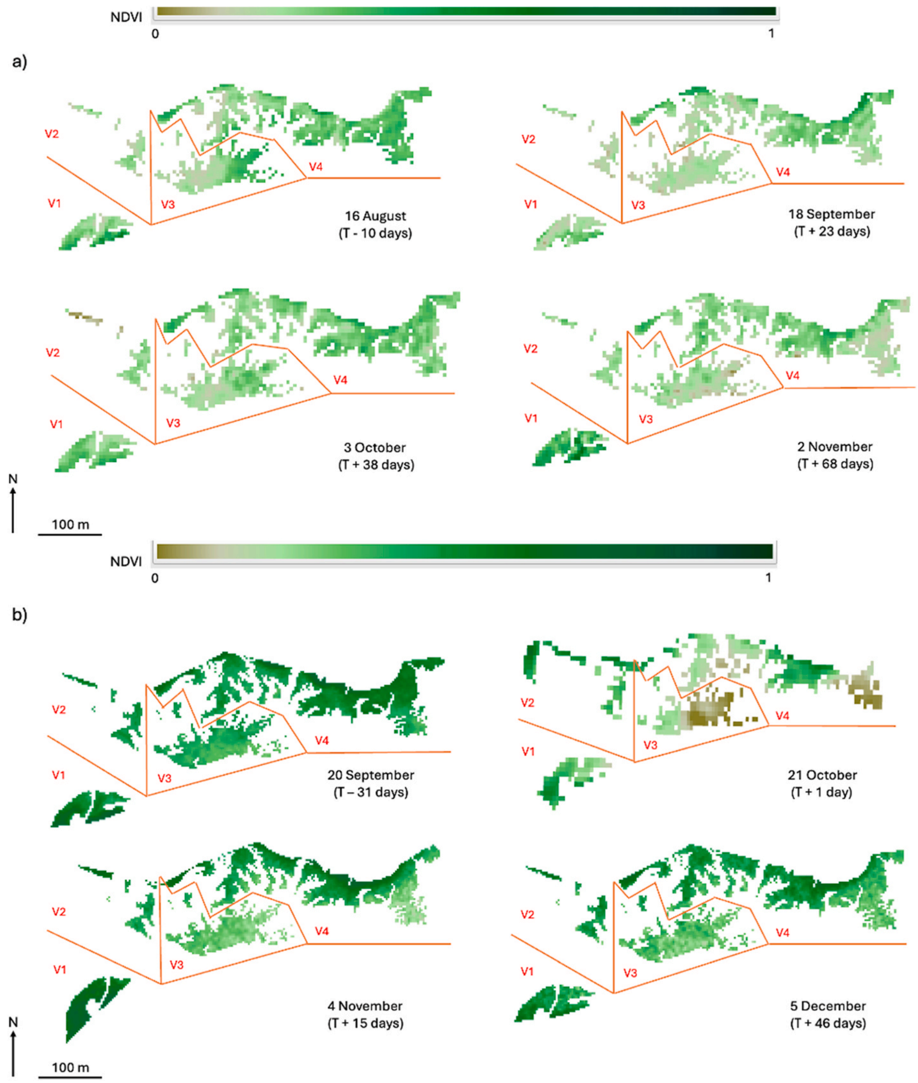

Fig. 4. NDVI for St John's Lake saltmarsh (S1) in a) 2016 (Rapid Eye data) and b) 2021 (Planet Scope data except for 21 October which was Rapid Eye data hence the lower resolution). Images show subsites V1 to V4 with boundaries in red correlating to Fig. 1c and d. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

higher than the seasonal mean indicating dense green vegetation (Fig. 2 a/b). This relatively high NDVI could have been attributed to the sunny, warm and wet summer (May to July) that was experienced during 2021 (Fig. 3 b/d).

The NDVI at S1 saw two declines both following meteotsunami and storm features, the first decline was in August (0.46 down to 0.33, see SP 6) followed by a second decline in October (0.44 down to 0.2, see SP 6) (Fig. 4 b). At the saltmarsh, subsites V1 and V2 saw no discernible change in NDVI, however, V3 and V4 saw a decline in the NDVI of the mid/low marsh on the eastern (seaward) fringes (Fig. 3 b). Vegetation NDVI did not start to increase until the following month (November) where S1 reached 0.46 (Fig. 4b and SP 6). As a point of note, the large decline in NDVI from 0.42 to 0.03 (Fig. 2a and SP 6) experienced on the intertidal flat was likely to have been due to the loss of macroalgae at S6 not saltmarsh vegetation.

The NDVI values in 2021 displayed a steep decline (Fig. 2 a/b and SP6). On the 21 October (one day following the meteotsunami and storm event) the Rapid Eye RGB imagery shows that the intertidal zone was turbid with sediment that covered the vegetation. Analysing monthly river flow data for the River Tamar during the two events revealed striking variations in water level dynamics (Fig. 3 a, SP 7). August 2016 had a low river flow of only 6.6 m^3/s which was a percentile of flow of Q75 %, October 2021; however, had a high river flow of 43.3 m^3/s which was a percentile of flow of Q2 %. This increase in freshwater would have shifted the turbidity maxima of the river downstream (SP 4) which would have led to a potential sudden influx of sediment and freshwater on to the intertidal flat and into the saltmarsh. As the event coincided with a spring tide the turbidity only lasted a few days before its removal by the subsequent high to neap tidal actions (NTSFL, Planet Labs PBC). In the wake of any mechanical disturbances and/or sediment adjustments, opportunistic species such as macroalgae may have been quick to take hold and proliferate due to the favourable conditions, potentially overwhelming the slower-regrowing pre-event vegetation (Newton and Thornber, 2013).

It was noted that when the extreme events occurred in isolation from one another there appeared to be a minimal disruption to NDVI values. Aside from August 2016 this is also demonstrated in February and March 2020 which experienced three storms in succession but no meteotsunami and again in June and July 2022 which experienced two meteotsunami in succession but no storm activity (SP 6).

The NDVI results (SP 6) have highlighted that when meteotsunami and storms occur concurrently there is a decline in NDVI followed by a rapid regreening. Aside from 2021 it was found that other dates within the study period may have exhibited a similar result. For example, there was a significant decline in NDVI at S1 between August and September 2020 from 0.39 to 0.26 (SP 6). During this period one meteotsunami and two named storms occurred in combination with high monthly rainfall of 118 mm and high river discharge of 15 m^3/s (SP 6/7). Recovery of greeness back up to an NDVI of 0.42 had occurred within one month, which was slightly above the monthly mean of 0.38. There is an absence of evidence for any meteotsunami events in 2017 and 2018, so a robust assessment of this time period was not possible. Finally, one period of interest for this study would have been the winter season of 2013/2014 which was particularly stormy (Kendon and McCarthy, 2015) with many associated meteotsunami (Lewis et al., 2023). However, there were very limited imagery data available and thus again a robust assessment was not possible.

3.4. Saltmarsh extent

In relation to saltmarsh extent results show that there were also notable changes in vegetation extent at S1 following both meteotsunami events in 2016 and 2021 (Fig. 5).

3.4.1. Changes in extent surrounding the 2016 event

On August 16, 2016 (pre-event) 85 % of the saltmarsh boundary as defined by the Environment Agency (EA) (Fig. 1d) was classified as vegetated. However, by September 18 this had dropped to 40 %, with subsites V1 and V4 suffering a change in extent of mid/low marsh and V2 and V3 suffering a change in extent along its eastern (seaward) fringes. There was no change in upper marsh on the landward fringes of V2 and V4. By October vegetation had rebound back to the pre-event levels of extent (80 %) but with less fragmentation, seeing only two large patches of potentially unvegetated areas remaining, seaward at V3 and landward at V4. Seasonal dieback (30 %) was then visible in November and December (Fig. 5).

3.4.2. Changes in extent surrounding the 2021 event

For the 2021 event, 18 September (pre-event) saw 92 % of the saltmarsh boundary as defined by the Environment Agency (EA) was classified as vegetated (Fig. 1d), with minimal patchiness and slight fragmentation along the seaward side (Fig. 5). On October 21 (one day post event) saltmarsh extent had dropped to 26 % principally along the eastern (seaward) fringes of all subsites, in particular at the upper marsh in V2 and the reedbeds in V4. This change in extent may be principally due to smothering by sediment and/or mechanical loss. Recovery was minimal and had occurred by November (2 weeks post event), with 38 % of the site vegetated, there was still no indications of vegetation in the mid/low marsh at V1 and at V3, however, this was change occurred later than at subsites V2 and V4, this may have been accounted for as natural seasonal dieback. Recovery resulted in dissection and fragmentation of the saltmarsh leaving a greater number of small, isolated patches of vegetation within the mud (Fig. 5).

4. The importance of understanding meteotsunami impacts for saltmarsh management

It has been well documented that saltmarshes can recover from storms (Leonardi et al., 2018; Pannozzo et al., 2021; Castagno et al., 2021; Temmerman et al., 2022), and with this study it can now be seen that saltmarsh have the potential to rebound from moderate intensity meteotsunami (Lewis et al., 2024) within weeks of an event and depending on the surrounding circumstances the rebound may exceed pre-event levels.

The occurrence of a solitary meteotsunami on the August 25, 2016, which occurred in the absence of any storm activity resulted in a minimal disturbance within the mid/low marsh and on the seaward edge of the marsh, in fact after a rapid period of regreening (4–5 weeks) the event may have even promoted growth. Similar results were found post 2004 for the Indian Ocean tsunami, where vegetation recovered within months and yielded better than pre-event conditions (Ranasinghe, 2011). Periodic less severe influxes of water are known to be beneficial to estuarine environments through flushing and the introduction of valuable nutrients and sediment (El-Hacen et al., 2019; Tang et al., 2020) and vegetation is known to serve as a natural buffer to extreme waves (Möller et al., 2014; Grandjean et al., 2024).

This study has shown that the stability of St John's Lake as accounted for in Natural England's report in 2020 and its unique morphology, may be reflected in the vegetation's capabilities to withstand and potentially thrive from a solitary event. Hooe Lake (see SP 1 for location) also impacted by meteotsunami is an embayment on the eastern side of Plymouth Sound with a narrow entrance and no vegetation, its morphology allowed for an increase in resonance and wave amplification which accounted for the damage to boats moored within the area. Whereas at St John's Lake which is a flat embayment with a wide entrance and the presence of saltmarsh vegetation all of which may have

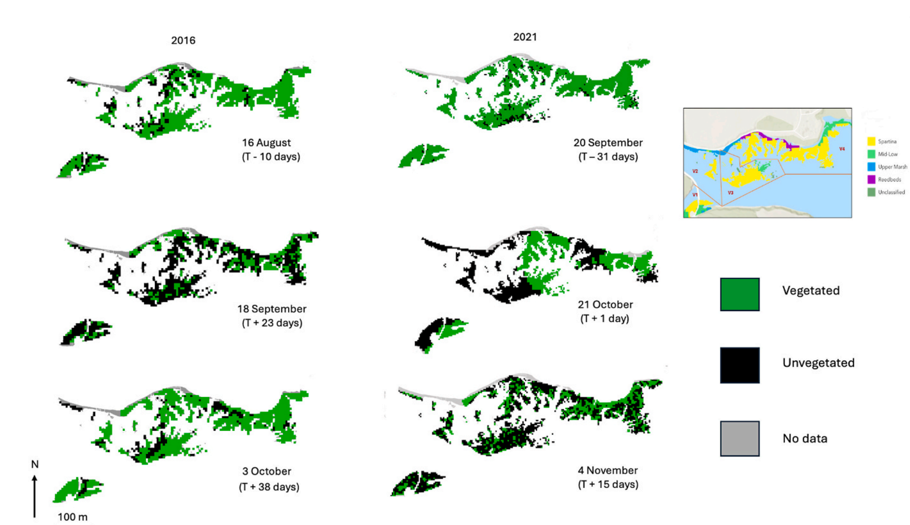

Fig. 5. Vegetated verses unvegetated zones of Site 1 (S1 saltmarsh) in the northwestern corner of St Johns Lake (see Fig. 1c). Vegetation is represented in green (0.1> EGI) and unvegetated is in black (<0.1 EGI), areas with no available data are represented in grey. Environment Agency saltmarsh zonation map given for reference. Images are for 2016 (Rapid Eye) with the meteotsunami occurring on 26 August and for 2021 (Planet Scope and Rapid Eye) with the meteotsunami occurring on 20 October. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

promoted wave dissipation and reduction. However, a more detailed and long-term analysis of the saltmarsh in the context of external forcing factors and sediment dynamics is required to substantiate this resilience. Saltmarshes that exhibit this type of response to disturbances can be harnessed for restoration efforts that are prioritised at both national and international levels through such initiatives as the Convention on Wetlands of International Importance (RAMSAR) and the United Nations Convention on Biological Diversity (Pétillon et al., 2023).

In contrast, the October 21, 2021 meteotsunami which occurred in a succession of five meteotsunami events and three storm events led to a devastating disruption upon vegetation. Even though regreening was rapid (2–3 weeks), this time it was limited, potentially due to insufficient time between events to allow for full re-establishment (van Belzen et al., 2017). Couple this series of events with sediment resuspension, high rainfall and high river discharge leading to an increase in water turbidity, reduced light and oxygen may have led to temporary hypoxic conditions and a smothering of the vegetation (Moore et al., 2021). The overall result was a temporary impedance of the vegetation's effectiveness and adaptability (Natural England, 2022).

In the UK, saltmarshes are being promoted as important carbon stores and biodiversity havens as well as buffer zones for wave energy. These multiple roles underscore the importance of identifying forcing factors, implementing active restoration and preservation especially in light of substantial losses and an uncertain future (Smeaton et al., 2023) and this pattern is indicative of many other locations around the world (Pétillon et al., 2023). Saltmarshes are indeed dynamic and naturally attempt to adjust in response to climate change and wind/wave energy changes, but this adaptability is not infinite. As humans continue to put pressure upon saltmarshes and with accelerated sea level rise and climate change set to heighten the intensity and frequency of extreme weather events such as storms (Bricheno et al., 2023) and meteotsunami (Lewis et al., 2024) any further loss or degradation will narrow the threshold for saltmarsh to adapt and continue to provide vital eco services.

As saltmarshes are geographically widespread around the world (Pétillon et al., 2023) so are meteotsunami (Vilibić and Šepić, 2017). Hotspot locations for both include: The Adriatic, The Mediterranean, northwest Europe, Australia and the east coast of North America, highlighting that this is not just a UK issue but one of global concern. This study focussed on the interaction between meteotsunami and saltmarsh, however, other coastal ecosystems such as mangroves, coral reefs, dunes and beaches could also be evaluated against meteotsunami. The establishment of long-term international monitoring systems that can provide data on the health and transient nature of coastal vegetation, shifts in species composition, alterations in sediment levels, nutrient cycling, elevation and bio geomorphology are needed. Couple that with the addition of ground-based observations both pre and post meteotsunami can all play a vital role in the understanding of vegetation response to meteotsunami and other stressors. Ecological monitoring can then augment this data by predicting future responses based upon observed impacts from past meteotsunami events and it may then be possible to model the attenuation of meteotsunami by saltmarsh vegetation. By collating this data, coastal managers will be able to gauge the resilience of coastal habitats and re-forecast potential changes in the carbon sequestration capacity as well as biodiversity levels and then take measures to adapt coastal management strategies accordingly.

This study has demonstrated that it is crucial to adopt a more holistic approach to ecosystem management, one that considers the cumulative impacts of multiple stressors. The UK government with the assistance of the Environment Agency has recently acknowledged the need to restore other habitats seaward of saltmarsh to attenuate waves and reduce erosion and to also better understand the cumulative impacts of winter storms on saltmarsh and tidal flats, but they still do not consider the impacts of meteotsunami within this scenario (Environment Agency, 2025). Global research into meteotsunami is an ever-growing field and whilst this study is indeed limited by the lack of current research and the availability of baseline data reflecting the processes occurring on coastal wetlands when impacted by meteotsunami, it attempts to provide a significant contribution by offering data where there was none, however, further work is needed to fully evaluate the impact of meteotsunami and to advance the field of research.

5. Conclusions

Saltmarshes perform critical ecological roles, including habitat provision, climate regulation and flood/coastal risk management. However, in the UK like many other locations around the globe saltmarsh are in decline and face an uncertain future. Efforts to restore and enhance coastal ecosystems are a priority for global governments, however, unlike storms, the potential impacts of meteotsunami on saltmarsh vegetation are unknown and under researched resulting in a gap that will challenge the successful adaption of saltmarsh to future climate change. This study therefore focused on the impacts of two meteotsunami events (one on August 26, 2016 and a second on October 20, 2021) on an area of saltmarsh in the River Tamar estuary, near Plymouth UK. With the use of satellite imagery and calculation of NDVI, contrasting responses were observed within the saltmarsh vegetation.

Findings from the 2016 meteotsunami indicated minimal disruption with a decrease in NDVI from 0.26 to 0.23 and a temporary decrease in vegetation extent of 40 %, this was followed by a period of regreening which saw an increase in both NDVI values and vegetation extent to that of pre-event levels, resulting in minor fragmentation of the saltmarsh ecosystem. The findings suggest a potential adaptability of the vegetation to this specific disturbance which can be attributed to the isolation and timing of the event, the specific stable conditions of the intertidal flat and the beneficial redistribution of sediments and nutrients that may have occurred during the meteotsunami.

In contrast, the 2021 meteotsunami presented a starkly different narrative. Characterised by a substantial decline in NDVI values from 0.46 to 0.22 and a temporary decrease in vegetation extent of 66 %. NDVI values recovered fast post event but not as effectively as those following the 2016 event, the series of events resulted in a fragmented patchy saltmarsh. This decline can be attributed to the cumulative impacts of multiple meteotsunami and storms within a period of three months leading to elevated sediment and water levels challenging the vegetations adaptability.

The data presented confirms a disruption to saltmarsh vegetation that coincides with meteotsunami following a comparison of vegetation greeness and extent before and after both events. However, the authors acknowledge that this may be biased due to limited data availability and lack of previous studies, as a result the influence of hydrodynamic processes and sediment supply on this disruption cannot be assessed. However, this study does strengthen the underlying argument that long term monitoring, data collection and further research are needed to assess the influence of meteotsunami on coastal vegetation.

As we move forward into an era of increasing global climatic uncertainty with sea level rise and increasing meteotsunami and storm activity, coupled with the continual demands of human development, saltmarsh loss is likely to accelerate. The 2021 event presented in this study can serve as a proxy for the future, an example of how multiple natural stressors can negatively impact an otherwise stable saltmarsh, a case to be used as a basis for further and more in-depth research. There is a need to promote the potential that coastal ecosystems such as saltmarsh provide in the mitigation of the impacts of such extreme natural events. More importantly, as national governments intensify their commitment to achieving net-zero emissions and attempt to create biodiversity policies that safeguard species, it is imperative that they are aware of and understand the role that extreme natural events such as meteotsunami play in coastal geomorphology processes, in hydrodynamic budgets and in the ecology of coastal ecosystems.

CRediT authorship contribution statement

Clare Lewis: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jonathan Dale:** Writing – review & editing, Supervision, Resources, Formal analysis, Data curation. **Jessica Neumann:** Writing – review & editing, Supervision, Resources. **Tim Smyth:** Writing – review & editing, Supervision. **Hannah Cloke:** Writing – review & editing, Supervision.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecss.2025.109495.

Data availability

Data will be made available on request.

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