Assessing the vulnerability of Annex I marine habitats to climate change in Wales

Evidence Report No: 536

Author Name: J. Oaten, A. Brooks, N. Frost, S. Hull, D. Williamson.

Author Affiliation: ABPmer

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Gellir defnyddio allbynnau'r prosiect i helpu i nodi unrhyw newidiadau tebygol yn y dyfodol ym mregusrwydd cynefinoedd Atodiad I sy'n deillio o bwysau newid hinsawdd, a fydd yn ei dro yn cyfrannu at ddatblygiad opsiynau rheoli cysylltiedig â'r hinsawdd a / neu addasu safle ar lefelau nodwedd, safle a rhwydwaith yn ogystal â hyrwyddo dealltwriaeth o newidiadau posibl i wasanaethau ecosystem ymhellach.

Datblygwyd y model mewn amgylchedd GIS i ddal cynrychiolaeth ofodol bregusrwydd posibl cynefinoedd morol Atodiad I yng Nghymru i ystod o bwysau a senarios newid hinsawdd. Mae'r model yn integreiddio nifer o baramedrau mewnbwn a gynhyrchir o gyfres o gamau. Mae'r camau'n cwmpasu'n fras:

- Mapio **amlygiad** i bwysau newid hinsawdd gan ddefnyddio amcanestyniadau newid yn yr hinsawdd a biotopau cydran wedi'u mapio o gynefinoedd morol Atodiad I;

- Asesu **sensitifrwydd** biotopau cydran cynefinoedd morol Atodiad I a gosod trothwyon sensitifrwydd;

- Integreiddio'r asesiad sensitifrwydd â rhagamcanion pwysau newid hinsawdd a biotopau cydran cynefinoedd morol Atodiad I i asesu **bregusrwydd**.

Mae allbynnau'r model GIS a'r asesiad bregusrwydd yn dangos mai nodweddion morol Atodiad I rhynglanwol fel Morfeydd Heli a Fflatiau Llaid a gwastadeddau tywod nad ydynt wedi'u gorchuddio â dŵr y môr ar lanw isel, sydd fwyaf agored i newid hinsawdd. Gyrrwyd bregusrwydd y nodweddion hyn yn bennaf gan godiadau a ragwelir yn lefel y môr, a arweiniodd at asesu bron pob biotop cydran rhynglanwol yn fregusrwydd uchel erbyn diwedd y ganrif. Mae nodweddion rhynglanwol hefyd yn cael eu hystyried yn agored i bwysau newid hinsawdd eraill megis tymheredd yr aer, amlygiad tonnau, a thymheredd y môr.

Nodwyd nifer o gyfyngiadau yn y model sy'n lleihau ei allu i fapio bregusrwydd cynefinoedd Atodiad I. Mae'r rhain yn cynnwys cynrychiolaeth ofodol cynefinoedd Atodiad I, argaeledd setiau data pwysau newid hinsawdd (a'u penderfyniadau gofodol ac amserol), ac ansicrwydd sy'n gysylltiedig â senarios allyriadau a rhagamcanion hinsawdd. Mae cyfyngiadau pellach yn cynnwys y ffaith nad oes cyfrif am fesurau eraill sy'n gysylltiedig â phwysau newid hinsawdd a allai fod yn bwysig i fod yn agored i niwed (e.e. ciwiau tymhorol, cyfnod / amlder dod i gysylltiad â phwysau). Yn sgil hyn, mae'n bwysig cydnabod yr angen i fonitro effeithiau a newidiadau i gynefinoedd Atodiad I yn barhaus er mwyn llywio rheolaeth addasol, ac i gyd-ddigwydd osgoi cam-addasu.

Dyluniwyd egwyddorion y model i sicrhau y gellir diweddaru paramedrau mewnbwn wrth i ddata neu dystiolaeth newydd ddod ar gael, neu os yw polisïau'n newid a gwahanol ragdybiaethau neu senarios i gael eu profi. O'r herwydd, rhestrir argymhellion i wella model ac allbynnau'r asesiad bregusrwydd isod:

- Cynyddu cwmpas biotopau cydran sy'n cael eu mapio ledled Cymru pan ddaw data gofodol newydd ar gael. Bydd hyn yn gwella cywirdeb biotopau cydran wedi'u mapio ac yn cynrychioli bregusrwydd cynefinoedd a nodweddion morol Atodiad I yng Nghymru yn well;

- Adolygu a diweddaru rhagamcanion hinsawdd o bryd i'w gilydd a ddefnyddir yn y model gyda phenderfyniadau gofodol ac amserol a allai wella. Dylid cydnabod bob amser sut y bydd elfennau o ansicrwydd sy'n gysylltiedig â rhagamcanion hinsawdd yn effeithio ar ganlyniad asesiadau bregusrwydd;

- Adolygu a diweddaru'r asesiadau sensitifrwydd o bryd i'w gilydd i gadw i fyny â materion ac ymchwil sy'n dod i'r amlwg;

- Mireinio'r archwiliad o bwysau newid hinsawdd penodol a sensitifrwydd biotop cydran yn y model. Gellid blaenoriaethu hyn ar sail pwysau pryder penodol am rai nodweddion; ac

- Ymgorffori ffactorau eraill sy'n dylanwadu ar fregusrwydd cynefinoedd morol Atodiad I yn y model ac asesiad bregusrwydd. Gallai hyn gynnwys pwysau eraill, goblygiadau polisïau sy'n dod i'r amlwg neu newid gweithgareddau, gallu i addasu, yn ogystal â chyflwr presennol nodweddion. Fodd bynnag, gallai hyn gymhlethu ansicrwydd ymhellach a bod yn rhy gymhleth.

Er gwaethaf yr holl gyfyngiadau cydnabyddedig, mae'r allbynnau model a gynhyrchir trwy'r astudiaeth hon yn rhoi arwydd lefel uchel o ba nodweddion morol Atodiad I o fewn Ardaloedd Cadwraeth Arbennig Cymru (ACA) sy'n cael eu hystyried yn fwyaf agored i'r pwysau sy'n gysylltiedig â newid hinsawdd. Mae hyn yn rhoi syniad o ble y gellid targedu mesurau rheoli posibl orau i sicrhau'r budd mwyaf i'r rhwydwaith MPA. Fodd bynnag, byddai angen gosod unrhyw fesurau o'r fath yng nghyd-destun y graddau o ansicrwydd sy'n gysylltiedig â'r allbynnau ynghyd â dylanwadau ehangach ar nodweddion o'r fath.

Summary

The impacts of climate change pressures on Annex I marine habitats across Wales are currently poorly understood. ABPmer was commissioned by NRW to further the understanding of climate change pressures on Annex I marine habitats, and the level of vulnerability that may be experienced under various emission scenarios and management timeframes. This involved developing a Geographic Information Systems (GIS) model for assessing the vulnerability of Annex I marine habitats, using the best currently available climate projections and spatial data on marine habitats in Wales. A literature review on the sensitivities of Annex I habitats to physical and chemical pressures as a result of climate change has also informed the assessment.

The outputs of the project can be used to help identify any likely future changes in Annex I habitat vulnerability resulting from climate change pressures, which in turn will feed into the development of climate-related management and / or site adaptation options at feature, site and network levels as well as further the understanding of potential changes to ecosystem services.

The model was developed in a GIS environment to capture the spatial representation of the relative potential vulnerability of Annex I marine habitats in Wales to a range of climate change pressures and scenarios. The model integrates a number of input parameters produced from a series of steps. The steps broadly encompass:

- Mapping **exposure** to climate change pressures using climate change projections and mapped component biotopes of Annex I marine habitats;

- Assessing the **sensitivity** of component biotopes of Annex I marine habitats and setting sensitivity thresholds;

- Integrating the sensitivity assessment with the climate change pressure projections and component biotopes of Annex I marine habitats to assess **vulnerability**.

The outputs of the GIS model and vulnerability assessment indicate that intertidal Annex I marine features such as Saltmarsh and Mudflats and sandflats not covered by seawater at low tide are most vulnerable to climate change. The vulnerability of these features was mainly driven by projected rises in sea level, which resulted in nearly all intertidal component biotopes being assessed as high vulnerability by the end of the century. Intertidal features are also considered vulnerable to other climate change pressures such as air temperature, wave exposure, and sea temperature.

A number of limitations in the model were identified that reduce its ability to map potential Annex I habitat vulnerability. These include the spatial representation of Annex I habitats, the availability of climate change pressure datasets (and their spatial and temporal resolutions), and uncertainty associated with emissions scenarios and climate projections. Further limitations include the fact that other measures associated with climate change pressures that may be important to vulnerability are not accounted for (e.g. seasonal cues, period/frequency of exposure to pressures). In light of this, it is important to recognise the need for continued monitoring of impacts and changes to Annex 1 habitats to inform adaptive management, and to coincidentally avoid mal-adaptation.

The principles of the model were designed to ensure input parameters can be updated as new data or evidence becomes available, or if policies change and different assumptions or scenarios are to be tested. As such, recommendations to improve the model and outputs of the vulnerability assessment are listed below:

- Increase the coverage of component biotopes mapped across Wales when new spatial data becomes available. This will improve the accuracy of mapped component biotopes and better represent the vulnerability of Annex I marine habitats and features in Wales;

- Periodically review and update climate projections used in the model with potentially improved spatial and temporal resolutions. How elements of uncertainty associated with climate projections will affect the outcome of vulnerability assessments should always be recognised;

- Periodically review and update the sensitivity assessments to keep pace with emerging issues and research;

- Refine the examination of specific climate change pressures and component biotope sensitivity within the model. This could be prioritised on the basis of particular pressures of concern for certain features; and

- Incorporate other factors that influence the vulnerability of Annex I marine habitats into the model and vulnerability assessment. This could include other pressures, the implications of emerging policies or changing activities, adaptive capacity, as well as the current condition of features. However, this may further compound uncertainty and be prohibitively complex.

Despite all of the recognised limitations, the model outputs generated through this study provide a high-level indication of which Annex I marine features within Welsh Special Areas of Conservation (SACs) are considered to be most vulnerable to the pressures associated with climate change. This provides an indication of where potential management measures could be best targeted to achieve the greatest benefit to the MPA network. However, any such measures would need to be set in the context of the degrees of uncertainty associated with the outputs along with wider influences on such features.

1. Introduction

The impacts of climate change pressures on Annex I marine habitats across Wales are currently poorly understood. Natural Resources Wales (NRW) is looking to better understand the potential magnitude and types of change likely to occur to Annex I marine features within marine Special Areas of Conservation (SACs) that form part of the Marine Protected Area (MPA) network in Wales, as well as its future resilience and coherence in a changing climate. Whilst pressures associated with climate change are not directly manageable in the same way as pressures associated with a specific activity, there are measures that could be implemented to improve the resilience of Wales' MPA network and wider marine environment. Improving the resilience of features and site network will potentially involve reducing pressures from other anthropogenic sources, as well as restoration or wider protection of Annex I marine habitats and features where possible.

ABPmer was commissioned by NRW to further the understanding of climate change pressures on Annex I marine habitats, and the level of vulnerability that may be experienced under various emission scenarios and management timeframes. This involved developing a Geographic Information Systems (GIS) model for assessing the vulnerability of Annex I marine habitats, using the most recent climate projections and spatial data on marine habitats in Wales. A literature review on the sensitivities of Annex I habitats to physical and chemical pressures as a result of climate change also informed the assessment. The project built upon previous and ongoing work to assess the vulnerability of marine habitats and designated sites to climate change (see Section 2.1).

The outputs of the project will be used to help identify any likely future changes in Annex I habitat vulnerability resulting from climate change pressures, which in turn will feed into the development of climate-related management and / or site adaptation options at feature, site and network levels as well as further our understanding of potential changes to ecosystem services.

In summary, the key aims and objectives of the project were to:

- Develop a method and GIS model for assessing the vulnerability of Annex I marine habitats
- Review current knowledge of climate change pressures and Annex I habitat sensitivities
- Assess the spatial vulnerability of Annex I marine habitats to climate change pressures
- Produce data and GIS layers of climate changes pressures, and the relative vulnerabilities of Annex I habitats to climate changes pressures, as well as a series of spreadsheets detailing the vulnerability assessment results and values used to assess features; and
- Prepare a report to accompany the outputs of the GIS model, and to present a summary of key results.

This document forms the report that accompanies the GIS model outputs. It details the process undertaken to develop the GIS model, and provides a high-level review of the literature that informed the model and underpins the vulnerability assessment. The report also provides a summary of the key results of the vulnerability assessment and a discussion including limitations and recommendations for future assessments. The report is structured as follows:

- Section 2: Methodology – explanation of the methods used to develop a GIS model to assess the vulnerability of Annex I marine habitats in Wales to climate change pressures
- Section 3: Vulnerability assessment – summary of the literature review on climate change pressures and Annex I habitat sensitivities, and key results of the vulnerability assessment
- Section 4: Discussion – a brief discussion on the results of the assessment and any limitations and recommendations for future assessments; and
- Section 5: Conclusion – a summary of the key findings of the assessment.

2. Methodology

2.1. Overview

This section of the report outlines the methodology that was used to develop the model to assess the vulnerability of Annex I marine habitats in Wales to climate change pressures. The model was developed in a GIS environment to capture the spatial representation of the relative potential vulnerabilities of the Annex I habitats to a range of climate change pressures and scenarios.

The model was designed to ensure input parameters could be updated as new data or evidence becomes available. It builds upon previous and ongoing work to assess the vulnerability of marine habitats and designated sites to climate change. These include:

- **Countryside Council for Wales[1] (CCW) Vulnerability Assessment** – Assessing the Vulnerability of Marine Habitats in Wales to the Impacts of Climate Change (Jones *et al*., 2011).
- **Marine Climate Change Impact Partnership (MCCIP) MPA Climate Smart Adaptation Report Cards –** identified risks and vulnerabilities for a number of MPA features with potential management options.
- **UK Climate Change Risk Assessment (CCRA)** – Reports produced in 2012, 2017 and 2021 as part of a series of assessments of the risks of climate for the UK required by the UK Climate Change Act 2008.

[1] Now Natural Resources Wales

For the purposes of this project, the definition of vulnerability is consistent with that used in the Marine Life Information Network (MarLIN) Marine Evidence based Sensitivity Assessment (MarESA)[2]; '*a measure of the degree of exposure of a receptor to a pressure to which it is sensitive'*. This is presented schematically in Figure 1.

The model integrates a number of input parameters produced from a series of steps outlined in this section of the report and summarised in Figure 2. The steps encompass an assessment of 'exposure', 'sensitivity' and 'vulnerability' to reflect the components of the definition of vulnerability provided by MarESA (see above and Figure 1). It was not possible to capture all climate change pressures within the spatial model due to a lack of projection data, or a lack information on sensitivity. Therefore, for some climate change pressures, only the exposure or sensitivity element of the assessment could be completed (this is explained further in the subsequent sections).

Exposure + **Sensitivity** = **Vulnerability**

Figure 1. Representation of the defining elements of vulnerability

[2] The MarESA methodology provides a systematic process to compile and assess the best available scientific evidence to complete sensitivity assessments for habitats and species in the marine environment: https://www.marlin.ac.uk/assets/pdf/MarESA-Sensitivity-Assessment-Guidance-Rpt-Dec2018.pdf (accessed November 2020)

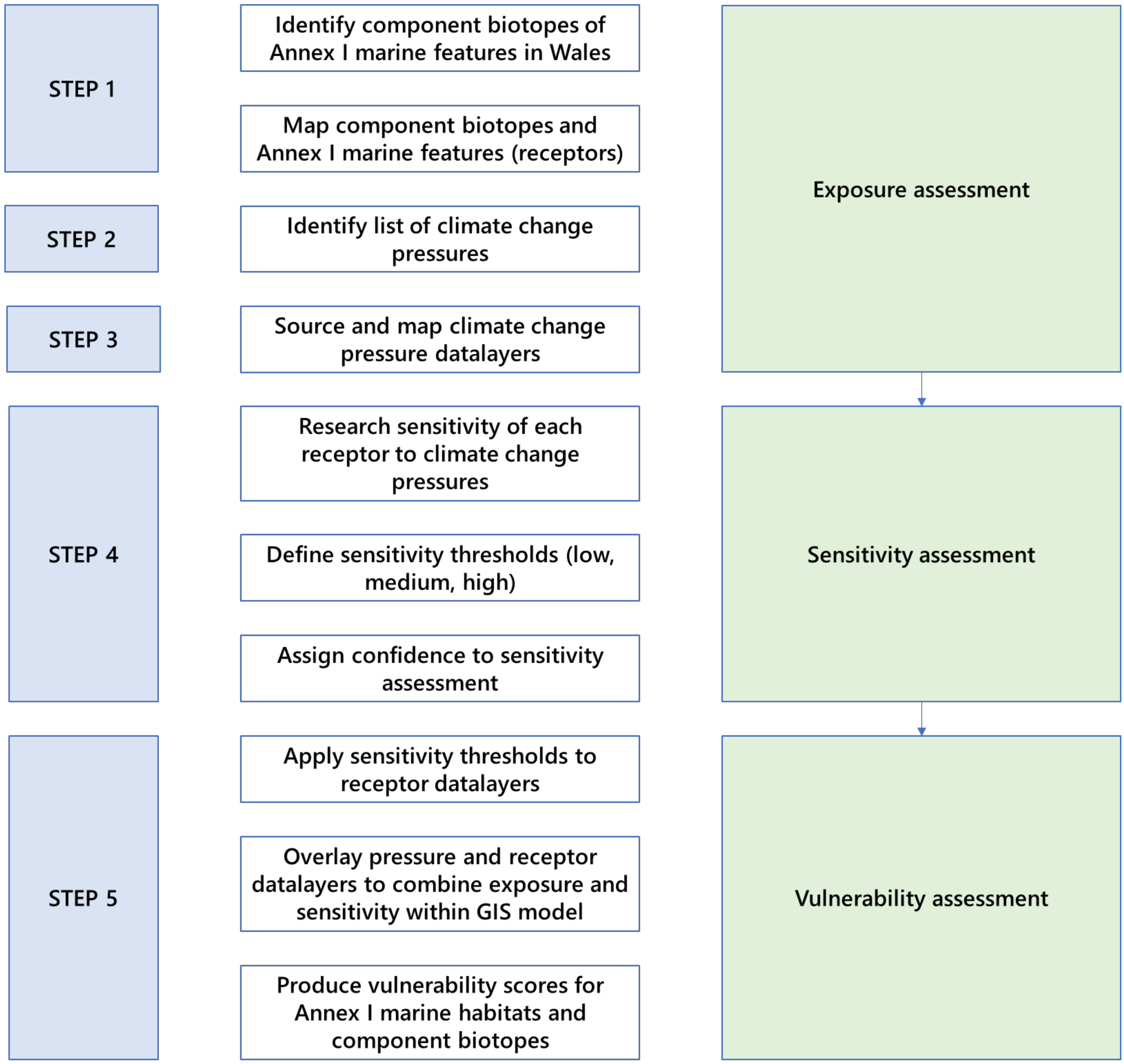

Figure 2. Methodology flow chart

2.2. Step 1: Receptors and spatial representation

The objective of this project was to assess the vulnerability of Annex I marine habitats that occur in Wales to climate change pressures. However, the biological resolution of Annex I habitats is considered too broad to undertake a meaningful vulnerability assessment, as individual biotopes within the Annex I habitats have differing sensitivities to climate change pressures. Consequently, it was decided to base the assessment on component biotopes of Annex I marine habitats in Wales. This provides a more detailed and useable assessment for the purposes of developing management and site adaptation options.

European Nature Information System (EUNIS)/Marine Habitat Classification (MHC) level 4 biotopes were selected as 'receptors' for this project, providing a good representation of varying biotopes and respective sensitivities (Figure 3). In some cases, level 5 biotopes were also included as receptors in the assessment where significant differences in sensitivity to climate change pressures were expected, compared with the broader level 4 biotopes, or where those biotopes are considered ecologically important. The inclusion of level 5 biotopes was based on the literature review of sensitivity (Step 4) and in discussion with the project team and wider NRW personnel.

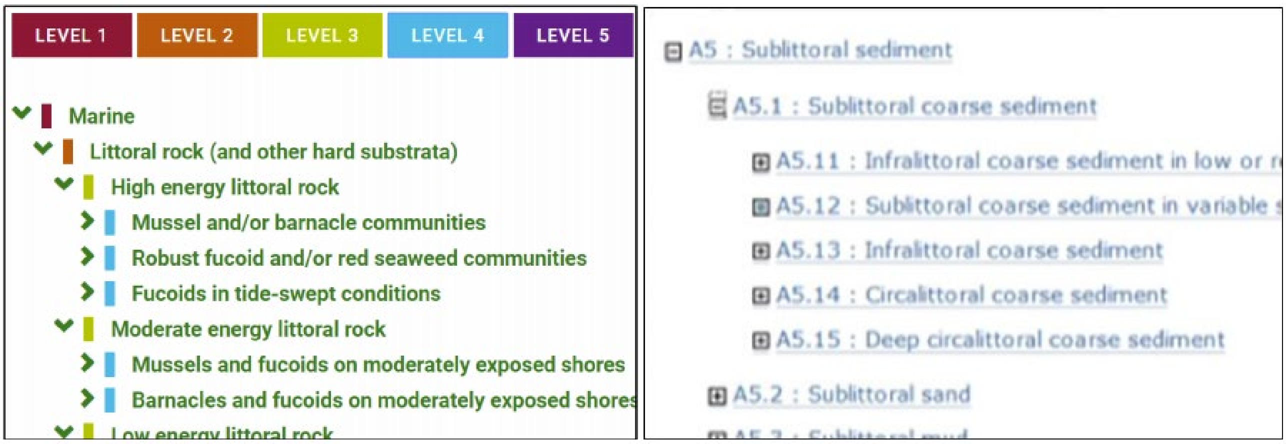

Figure 3. Examples from level 4 of Marine Habitat Classification (MHC) for Britain and Ireland (left) and European Nature Information System (EUNIS) (right). Source: Parry (2019)

The list of receptors (i.e. component biotopes within Annex I marine habitats in Wales) included in the assessment is provided in Table 1. This was provided by NRW.

Spatial representation of these biotopes within the model was primarily based on the information contained within the JNCC combined map[3] (JNCC, 2019). This is a composite product that provides a complete coverage of the UK's seafloor habitats. The focus of this data product is on providing EUNIS level 3 habitat classification, however, more detailed biotope information (i.e. level 4, level 5 and level 6) is provided where it exists. There is relatively good coverage of this more detailed information where Annex I marine habitats are located within Wales, predominantly at the coast. Biotope information at level 4 (and above) is, however, less complete for some subtidal Annex I marine habitats. To fill these gaps, HABMAP[4] was used. This is a modelled dataset that predicts habitat occurrences in areas where survey data does not currently exist, based on physical parameters. Predictive maps produced by the HABMAP project were validated using data collected during survey work in the southern Irish Sea. For use in this project, predicted biotopes with a confidence score of 8 or above (i.e. those that were predicted with high confidence) were selected from HABMAP to maintain a reasonable amount of certainty in the presence of component biotopes. Coverage of saltmarsh features remained low after these steps and therefore the Article 17 GIS feature data layer[5] for 'Atlantic salt meadows' and '*Salicornia* and other annuals colonising mud and sand features' was also used. Overall, the coverage of level 4, 5 and 6 biotopes provided by the JNCC combined map and HABMAP, as well as the Article 17 GIS feature data layer for saltmarsh features, comprised approximately 86 % coverage of Annex I marine habitats (see Table 2). Spatial

[3] https://jncc.gov.uk/our-work/marine-habitat-data-product-eunis-level-3-combined-map/
[4] https://naturalresources.wales/about-us/our-projects/marine-projects/habmap/?lang=en
[5] The Habitats Directive Article 17 reporting maps are a snapshot of the most up to date spatial data for features listed on the various Annexes of the Directive at the time of reporting both inside and outside of SACs. Downloaded from the Lle portal: https://lle.gov.wales/catalogue/item/MarineArt17Features/?lang=en

coverage of component biotopes at this resolution within intertidal Annex I habitats was generally high, for example coverage of Mudflats and sandflats not covered by seawater at high tide and Intertidal reef was 100% and 99% respectively. Spatial coverage of Coastal lagoons was low (20%). This is likely due to a lack of polygon data for this feature, which is restricted to Phase 1 intertidal survey data at the lagoon edges. Some component biotopes that are considered to comprise Annex I marine habitats were absent from these datasets (see Table 1)[6].

Level 4, 5 and 6 biotopes were extracted from the JNCC combined map using a python query to extract any features with a EUNIS code consisting of more than 3 characters (e.g. A3.2). These were then clipped to Welsh waters and cleaned further by manually removing any features that were more than 3 characters but still only represented a level 3 biotope. An example of this would be a mosaic biotope at level 3, such as 'A1.2 + A1.3'. HABMAP biotopes (with a confidence score ≥ 8) that overlapped with the extent of the extracted biotopes from the JNCC combined map were then erased, leaving HAPMAP biotopes to fill remaining gaps. These were then mapped at level 4 and level 5 of the MHC/EUNIS classification.

Biotopes (from the JNCC combined map and HABMAP) that overlapped with the Article 17 GIS feature data layer (representing Annex I marine habitats) were then extracted in order to create a receptor data layer (which also included the Article 17 GIS feature data layer for saltmarsh features) for use in the model. To ensure a consistent naming convention, EUNIS codes were then translated to MHC equivalents using JNCC's correlation spreadsheet[7]. This was undertaken to aid the sensitivity assessment (Step 4) which draws upon information contained in the MarESA database that uses the MHC system.

[6] Missing component biotopes are likely not included in the JNCC combined map or HABMAP due to a lack of accompanying data on spatial extent at the resolution required. However, the model (described in Section 2.6) is set up to produce blank feature classes for component biotopes that are missing in the receptor data layer. This allows the model to be re-run in the future with an updated receptor data layer that contains these biotopes without the need to adjust the model.

[7] https://hub.jncc.gov.uk/assets/62a16757-e0d1-4a29-a98e-948745804aec

Table 1. List of component biotopes within Annex I marine habitats in Wales included in the vulnerability assessment. (* Currently absent from the receptor data layer in Annex I marine habitats in Welsh waters)

Biotope level	MHC biotope code	MHC biotope name	Annex I habitats
4	LR.HLR.MusB	Mussel and/or barnacle communities	Estuaries / Mudflats and sandflats not covered by seawater at low tide / Large shallow inlets and bays / Reef
4	LR.HLR.FR	Robust fucoid and/or red seaweed communities	Estuaries / Large shallow inlets and bays / Reef
5	LR.HLR.FR.RPid	*Ceramium* sp. and piddocks on eulittoral fossilised peat	Large shallow inlets and bays
4	LR.HLR.FT	Fucoids in tide-swept conditions	Large shallow inlets and bays / Mudflats and sandflats not covered by seawater at low tide / Reef / Estuaries
4	LR.MLR.BF	Barnacles and fucoids on moderately exposed shores	Estuaries / Large shallow inlets and bays / Reef
4	LR.MLR.MusF	Mussels and fucoids on moderately exposed shores	Estuaries / Large shallow inlets and bays / Reef
5	LR.MLR.MusF.MytPid	*Mytilus edulis* and piddocks on eulittoral firm clay	Estuaries / Large shallow inlets and bays / Reef
4	LR.LLR.F	Fucoids on sheltered marine shores	Estuaries / Mudflats and sandflats not covered by seawater at low tide / Large shallow inlets and bays / Reef / Coastal lagoons
4	LR.LLR.FVS	Fucoids in variable salinity	Estuaries / Large shallow inlets and bays / Mudflats and sandflats not covered by seawater at low tide / Reef / Coastal lagoons
4	LR.FLR.Rkp	Rockpools	Estuaries / Large shallow inlets and bays / Reef
4	LR.FLR.CvOv	Littoral caves and overhangs	Submerged or partially submerged sea caves / Large shallow inlets and bays / Reef / Estuaries
4	LR.FLR.Eph	Ephemeral green or red seaweed communities (freshwater or sand-influenced)	Estuaries / Mudflats and sandflats not covered by seawater at low tide / Large shallow inlets and bays / Reef
4	LS.LCS.Sh	Shingle (pebble) and gravel shores	Estuaries / Large shallow inlets and bays / Reef / Coastal lagoons
4	LS.LSa.St	Strandline	Estuaries / Mudflats and sandflats not covered by seawater at low tide / Large shallow inlets and bays
4	LS.LSa.MoSa	Barren or amphipod-dominated mobile sand shores	Estuaries / Mudflats and sandflats not covered by seawater at low tide / Large shallow inlets and bays / Reef
4	LS.LSa.FiSa	Polychaete / amphipod dominated fine sand shores	Estuaries / Mudflats and sandflats not covered by seawater at low tide / Large shallow inlets and bays
4	LS.LSa.MuSa	Polychaete / bivalve dominated muddy sand shores	Estuaries / Mudflats and sandflats not covered by seawater at low tide / Large shallow inlets and bays

Biotope level	MHC biotope code	MHC biotope name	Annex I habitats
4	LS.LMu.MEst	Polychaete / bivalve dominated mid estuarine mud shores	Estuaries / Mudflats and sandflats not covered by seawater at low tide / Large shallow inlets and bays / Coastal lagoons
4	LS.LMu.UEst	Polychaete / oligochaete dominated upper estuarine mud shores	Estuaries / Mudflats and sandflats not covered by seawater at low tide / Large shallow inlets and bays
4	LS.LMx.GvMu	*Hediste diversicolor* dominated gravelly sandy mud shores	Large shallow inlets and bays / Mudflats and sandflats not covered by seawater at low tide / Estuaries
4	LS.LMx.Mx	Species-rich mixed sediment shores	Large shallow inlets and bays / Mudflats and sandflats not covered by seawater at low tide / Reef / Estuaries / Coastal lagoons
4	LS.LMp.Sm	Saltmarsh	Estuaries / Large shallow inlets and bays / Coastal lagoons / Atlantic salt meadows / *Salicornia* and other annuals colonising mud and sand
4	LS.LMp.LSgr	Seagrass beds on littoral sediments	Large shallow inlets and bays / Mudflats and sandflats not covered by seawater at low tide / Estuaries
4	LS.LBR.Sab	Littoral *Sabellaria* honeycomb worm reefs	Estuaries / Large shallow inlets and bays / Reef
4	LS.LBR.LMus	Littoral mussel beds on sediment	Estuaries / Mudflats and sandflats not covered by seawater at low tide / Large shallow inlets and bays / Reef
4	IR.HIR.KFaR	Kelp with cushion fauna and/or foliose red seaweeds	Reef / Large shallow inlets and bays / Estuaries
4	IR.HIR.KSed	Sediment-affected or disturbed kelp and seaweed communities	Reef / Large shallow inlets and bays / Estuaries
4	IR.MIR.KR	Kelp and red seaweeds (moderate energy infralittoral rock)	Reef / Large shallow inlets and bays / Estuaries
4	IR.MIR.KT	Kelp and seaweed communities in tide-swept sheltered conditions	Reef / Large shallow inlets and bays / Estuaries
4	IR.LIR.K	Silted kelp communities (sheltered infralittoral rock)	Reef / Large shallow inlets and bays / Estuaries
4	*IR.LIR.IFaVS	Faunal communities on variable or reduced salinity infralittoral rock	Reef / Large shallow inlets and bays / Estuaries
4	IR.FIR.SG	Infralittoral surge gullies and caves	Submerged or partially submerged sea caves / Large shallow inlets and bays / Reef / Estuaries
4	CR.HCR.FaT	Very tide-swept faunal communities	Reef / Large shallow inlets and bays / Estuaries
4	CR.HCR.DpSp	Deep sponge communities	Reef
4	CR.HCR.XFa	Mixed faunal turf communities	Reef / Large shallow inlets and bays / Estuaries
4	CR.MCR.EcCr	Echinoderms and crustose communities	Reef / Large shallow inlets and bays / Estuaries

Biotope level	MHC biotope code	MHC biotope name	Annex I habitats
4	CR.MCR.SfR	Soft rock communities	Reef / Large shallow inlets and bays / Estuaries
4	CR.MCR.CMus	Circalittoral mussel beds on rock	Reef / Large shallow inlets and bays / Estuaries
4	CR.MCR.CFaVS	Circalittoral faunal communities in variable salinity	Reef / Large shallow inlets and bays / Estuaries
4	*CR.LCR.BrAs	Brachiopod and ascidian communities	Estuaries / Large shallow inlets and bays
4	SS.SCS.ICS	Infralittoral coarse sediment	Estuaries / Large shallow inlets and bays / Sandbanks which are slightly covered by seawater all the time / Reef
4	SS.SCS.CCS	Circalittoral coarse sediment	Estuaries / Large shallow inlets and bays / Sandbanks which are slightly covered by seawater all the time / Reef
4	SS.SSa.IFiSa	Infralittoral fine sand	Estuaries / Large shallow inlets and bays / Mudflats and sandflats not covered by seawater at low tide / Sandbanks which are slightly covered by seawater all the time / Reef
4	SS.SSa.IMuSa	Infralittoral muddy sand	Estuaries / Mudflats and sandflats not covered by seawater at low tide / Large shallow inlets and bays / Sandbanks which are slightly covered by seawater all the time
4	SS.SSa.CFiSa	Circalittoral fine sand	Large shallow inlets and bays / Sandbanks which are slightly covered by seawater all the time / Estuaries
4	SS.SSa.CMuSa	Circalittoral muddy sand	Large shallow inlets and bays / Sandbanks which are slightly covered by seawater all the time / Estuaries
4	SS.SMu.SMuVS	Sublittoral mud in variable salinity (estuaries)	Estuaries / Large shallow inlets and bays / Sandbanks which are slightly covered by seawater all the time
4	SS.SMu.ISaMu	Infralittoral sandy mud	Large shallow inlets and bays / Sandbanks which are slightly covered by seawater all the time / Estuaries
4	SS.SMu.IFiMu	Infralittoral fine mud	Large shallow inlets and bays / Estuaries
4	SS.SMu.CSaMu	Circalittoral sandy mud	Estuaries / Large shallow inlets and bays / Sandbanks which are slightly covered by seawater all the time
4	SS.SMu.CFiMu	Circalittoral fine mud	Large shallow inlets and bays / Estuaries
4	SS.SMu.OMu	Offshore circalittoral mud	Large shallow inlets and bays
4	SS.SMx.SMxVS	Sublittoral mixed sediment in variable salinity (estuaries)	Estuaries / Large shallow inlets and bays / Reef
4	SS.SMx.IMx	Infralittoral mixed sediment	Estuaries / Large shallow inlets and bays / Sandbanks which are slightly covered by seawater all the time / Reef / Mudflats and sandflats not covered by seawater at low tide
5	SS.SMx.IMx.Ost	Ostrea edulis beds on shallow sublittoral muddy mixed sediment	Estuaries / Large shallow inlets and bays / Mudflats and sandflats not covered by seawater at low tide

Biotope level	MHC biotope code	MHC biotope name	Annex I habitats
4	SS.SMx.CMx	Circalittoral mixed sediment	Large shallow inlets and bays / Mudflats and sandflats not covered by seawater at low tide / Sandbanks which are slightly covered by seawater all the time / Reef / Estuaries
4	SS.SMx.OMx	Offshore circalittoral mixed sediment	Reef
4	SS.SMp.Mrl	Maerl beds	Estuaries / Large shallow inlets and bays
4	SS.SMp.KSwSS	Kelp and seaweed communities on sublittoral sediment	Large shallow inlets and bays / Reef / Estuaries
4	SS.SMp.SSgr	Sublittoral seagrass beds	Mudflats and sandflats not covered by seawater at low tide / Estuaries / Large shallow inlets and bays
4	SS.SBR.PoR	Polychaete worm reefs (on sublittoral sediment)	Reef / Sandbanks which are slightly covered by seawater all the timeLarge shallow inlets and bays / Estuaries
4	SS.SBR.SMus	Sublittoral mussel beds (on sublittoral sediment)	Estuaries / Large shallow inlets and bays / Reef
5	*SS.SBR.SMus.ModT	*Modiolus modiolus* beds with hydroids and red seaweeds on tide-swept circalittoral mixed substrata	Reef
5	*SS.SBR.SMus.ModMx	*Modiolus modiolus* beds on open coast circalittoral mixed sediment	Reef
5	*SS.SBR.SMus.ModHAs	*Modiolus modiolus* beds with fine hydroids and large solitary ascidians on very sheltered circalittoral mixed substrata	Reef
5	*SS.SBR.SMus.ModCvar	*Modiolus modiolus* beds with *Chlamys varia*, sponges, hydroids and bryozoans on slightly tide-swept very sheltered circalittoral mixed substrata	Reef
5	SS.SBR.SMus.MytSS	*Mytilus edulis* beds on sublittoral sediment	Estuaries / Large shallow inlets and bays / Reef
4	LR.FLR.Lic	Lichens or small green algae on supralittoral and littoral fringe rock	Estuaries / Large shallow inlets and bays / Reef / Coastal lagoons
4	*CR.FCR.Cv	Circalittoral caves and overhangs	Submerged or partially submerged sea caves / Large shallow inlets and bays / Reef
4	*CR.FCR.FouFa	Circalittoral fouling faunal communities	Reef / Large shallow inlets and bays / Estuaries
4	*CR.MCR.CSab	Circalittoral *Sabellaria* reefs (on rock)	Reef
4	*IR.FIR.IFou	Infralittoral fouling seaweed communities	Reef / Large shallow inlets and bays / Estuaries
4	*SS.SCS.SCSVS	Sublittoral coarse sediment in variable salinity (estuaries)	Estuaries / Large shallow inlets and bays / Reef
4	*SS.SMu.SMuLS	Sublittoral mud in low or reduced salinity (lagoons)	Large shallow inlets and bays / Coastal lagoons

Biotope level	MHC biotope code	MHC biotope name	Annex I habitats
4	*SS.SMx.SMxLS	Sublittoral mixed sediment in low or reduced salinity (lagoons)	Large shallow inlets and bays / Estuaries / Coastal lagoons
4	*SS.SSa.SSaVS	Sublittoral sand in variable salinity (estuaries)	Estuaries / Sandbanks which are slightly covered by seawater all the time

Table 2. Coverage of Annex I marine habitats in Wales provided by the JNCC combined map and HABMAP data layer

Annex I habitat	Total area in Wales (km²)	Receptor data layer area (km²)	Percentage coverage
Sandbanks which are slightly covered by seawater all the time	638.20	498.34	78%
Estuaries	1139.63	956.48	84%
Mudflats and sandflats not covered by seawater at low tide	433.30	431.94	100%
Coastal lagoons	0.84	0.16	20%
Large shallow inlets and bays	1520.84	1346.48	89%
Intertidal reef	77.44	76.37	99%
Subtidal reef	2935.93	2483.88	85%
Submarine structures made by leaking gases (Methane-derived authigenic carbonates)	0.077	0.077	100%
Salicornia and other annuals colonising mud and sand	2.09	2.09	100%
Atlantic salt meadows (*Glauco-Puccinellietalia maritimae*)	75.66	75.66	100%
Maerl	4.98	3.30	66%
Total for all Annex I habitats	**6923.03**	**5874.79**	**86%**

2.3. Step 2: Climate change pressures

Climate change pressures that are considered to have the potential to affect Annex I marine habitats in Wales were selected for inclusion in this project. This was informed by a high-level review of climate change impacts within the UK and Wales (this is presented in Section 3.1), as well as previous projects undertaken by Jones *et al*. (2011), LIFE Natura 2000 Programme for Wales (2015), Flavell *et al*. (2020) and Garrard and Tyler-Walters (2020). The project also acknowledged that some pressures could not be assessed due to the absence of datasets or current evidence on the nature and scale of change (e.g. changes in storm patterns), or the fact that changes (such as management interventions) cannot be predicted or quantified in a way that allowed inclusion of a spatial assessment over different timeframes and emission scenarios.

Following the review of available evidence and datasets, ten climate change pressures were selected for inclusion within this project:

- Physical
  - Sea temperature (surface and seabed)
  - Air temperature
  - Sea level rise
  - Wave exposure
  - Water quality due to run-off and pollution
  - Turbidity
  - Water column stratification
- Chemical
  - Salinity
  - Ocean acidification
  - Deoxygenation

A number of other climate change pressures were initially identified but subsequently not included in the assessment. The rationale for their exclusion is provided below:

- Storminess
  - Whilst data is available for mean sea level pressure, the key driver for potential impacts on marine habitats are the frequency, magnitude (i.e. wind and waves) and location of storms. There is significant uncertainty associated with these parameters. Therefore, storminess is discussed in terms of climate change impacts, but not taken through into the vulnerability assessment (noting wave exposure is already accommodated within the assessment).
- Water flow/currents
  - Available climate change projections focus on offshore areas and are concerned with density driven changes in flows. This is unlikely to be a dominant factor in tidal coastal areas where the majority of Annex I habitats are located.
- Precipitation
  - Other climate change pressures included in the assessment, such as changes in salinity, are affected by precipitation and thus already accommodated within the model. Exposure to decreases in water quality due to increases in run-off from land are also considered. Direct impacts to Annex I marine habitats caused by changes in precipitation are likely to be minimal.
- Irradiance
  - There is limited information on the potential effects and impacts that increased irradiation may have on marine habitats to enable a vulnerability assessment. Furthermore, air temperature is likely to present a similar risk to marine habitats and is already accommodated in the assessment.

2.4. Step 3: Pressure data layers

Climate change projections were used to assess the potential exposure of receptors (listed in Table 1) to climate change pressures within the model. Data were sourced from UK Climate Projections 2018 (UKCP18) (Palmer *et al*., 2018), UK Climate Projections 2009 (UKCP09) (Lowe *et al*., 2009), the European Regional Seas Ecosystem Model (ERSEM) and the Centre for Ecology and Hydrology (CEH) Future Flows. ERSEM is coupled to two regional ocean circulation models, Proudman Oceanographic Laboratory Coastal Ocean Modelling System (POLCOMS) and Nucleus for European Modelling of the Ocean (NEMO). Each have different temporal and spatial resolutions (see Table 3 for details, and Figures 4 and 5 for illustrations od spatial coverage and resolution).

There are several limitations in using some of these climate projections to calculate the exposure of receptors to climate change pressures. In particular, the resolution of climate projections and coverage is poor in nearshore locations. For example, coverage of ERSEM POLCOMS projections are low at the coast, where most Annex I habitats are present (Figure 4). ERSEM NEMO projections have slightly better resolutions and coverage in nearshore locations, though some up-estuary areas still lack data coverage (Figure 5). This issue was overcome in the model by applying the closest projection data point to each receptor using the ‘closest’ function in the spatial join tool in ArcGIS. This allowed the nearest projection data point to a receptor (where there were not data directly overlapping the receptor) to inform exposure to the climate change pressure.

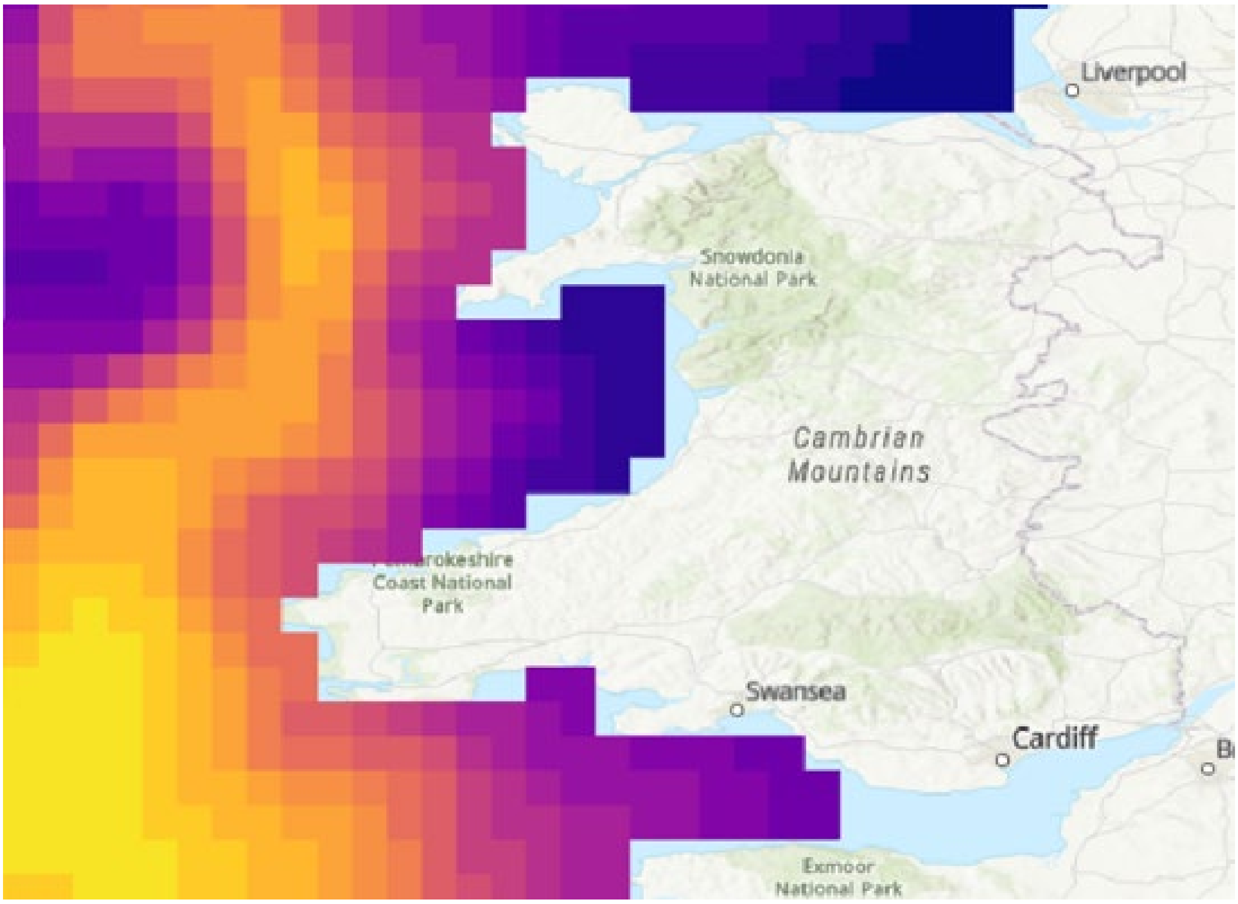

Figure 4. ERSEM POLCOMS coverage in Wales (coloured grids represent the extent of spatial coverage in the Welsh marine area for illustrative purposes only).

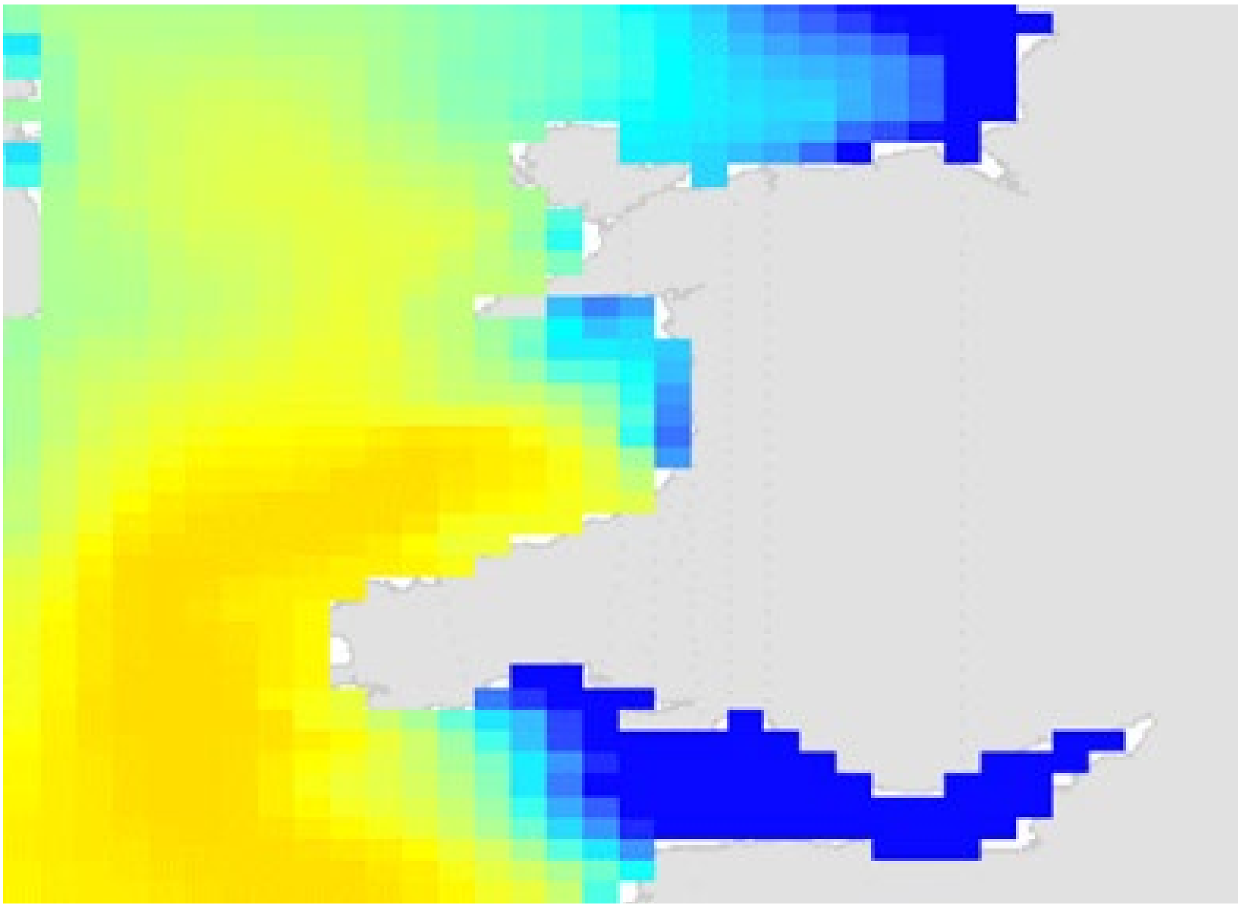

Figure 5. ERSEM NEMO coverage in Wales (coloured grids represent the extent of spatial coverage in the Welsh marine area for illustrative purposes).

Such limitations guided the selection of climate change projections to represent each climate change pressure. Table 3 provides a summary of each set of climate projections that are considered the best-available for each climate change pressure, alongside their temporal and spatial resolutions, and climate change scenarios.

Table 3. Summary of climate change pressure data layers used in the spatial assessment.

Climate change pressures	Selected data layer(s)	Temporal Resolution	Spatial resolution	Emissions scenario
Sea temperature	ERSEM NEMO UKCP09	NEMO – 2049 UKCP09 - 2083	NEMO - 7km UKCP09 - 12km	NEMO - RCP 4.5 RCP 8.5 UKCP09 - SRES A1B
Salinity	ERSEM NEMO UKCP09	NEMO – 2049 UKCP09 - 2083	NEMO - 7km UKCP09 - 12km	NEMO - RCP 4.5 RCP 8.5 UKCP09 - SRES A1B

Climate change pressures	Selected data layer(s)	Temporal Resolution	Spatial resolution	Emissions scenario
Water column stratification	ERSEM NEMO ERSEM POLCOMS	NEMO – 2049 POLCOMS - 2099	NEMO - 7km POLCOMS - 11km	RCP 4.5 RCP 8.5
Ocean acidification	ERSEM NEMO ERSEM POLCOMS	NEMO – 2049 POLCOMS - 2099	NEMO - 7km POLCOMS - 11km	RCP 4.5 RCP 8.5
Deoxygenation	ERSEM NEMO ERSEM POLCOMS	NEMO – 2049 POLCOMS - 2099	NEMO - 7km POLCOMS - 11km	RCP 4.5 RCP 8.5
Sea level rise	UKCP18	2100	12km	RCP 2.6 RCP 4.5 RCP 8.5
Wave exposure	UKCP18	2099	12km	RCP 4.5 RCP 8.5
Air temperature	UKCP18	2100	60km	RCP 8.5
Water quality due to run-off and pollution	CEH Future Flows	2098	Interpolated to WFD water body	SRES A1B emission scenario (medium)
Turbidity	No data	No data	No data	No data

As projections were not available for turbidity, this pressure was not assessed within the GIS model in Step 5. Instead, only a sensitivity assessment was undertaken as described in Step 4 (see Section 3.2).

Further processing was also required to understand changes to water quality due to run-off in the context of Annex I marine habitats. Projected values for changes in winter (DJF) and summer (JJA) mean river flow relative to the 1961 – 1990 baseline provided by CEH Future Flows were mapped across the Water Framework Directive (WFD) transitional water body in which the catchment meets the coast (i.e. areas of the marine environment that are subjected to freshwater influence). This was achieved using the ‘closest’ function in the spatial join tool in ArcGIS, and spatially joining catchment discharge data points to the ‘main rivers’ data layer[8]. This was then spatially joined to the WFD transitional water

[8] http://lle.gov.wales/catalogue/item/MainRivers?lang=en

body data layer where the projected changes in flow were mapped. A manual check was also carried out to remove catchment discharge data points that were incorrectly joined to a WFD transitional water body (i.e. where a catchment did not discharge into the WFD transitional water body).

The availability of climate change pressure data layers guided the selection of appropriate timeframes and emissions scenarios to be used in this project.

2.4.1. Timeframes

Timeframes for the vulnerability assessment were set to align with the management epochs used within the shoreline management plans (SMPs); up to 2025 (epoch 1), between 2025 and 2055 (epoch 2) and between 2055 and 2105 (epoch 3). This approach is consistent with future management timeframes of the coast over the next century. The timeframes that were selected were also guided by that available in the projection datasets.

Single years in the projection datasets were selected as timeframes for use within the model to keep the volume of data to a manageable level (daily projections were used in most cases – see Section 2.4.3). Most climate change pressure data layers were extracted for the years 2025, 2049 and 2099, as these timeframes most closely aligned with that available in the projections and the SMP epochs. For climate change pressures that relied on UKCP09, data was not available in 2099, and therefore the year 2083 was selected (see Table 3). The use of different timeframes within the assessment affects the comparability of the assessment over the next century and caution should be used when interpreting the results for these climate change pressures.

2.4.2. Emission scenarios

As described by the Met Office (2018), Representative Concentration Pathways (RCPs) are a set of scenarios to capture assumptions about the economic, social and physical changes to our environment that will influence climate change. RCPs specify concentrations of greenhouse gases that will result in increases of total radiative forcing[9] by 2.6, 4.5, 6.0 and 8.5 watts per square metre (W/m^2) by 2100 (relative to pre-industrial levels). RCP2.6, RCP4.5, RCP6.0 and RCP8.5 correspond to these increases, respectively. It is worth noting that these scenarios are referred to as ‘pathways’ to reflect their non-definitive nature and that they could be realised by a number of socioeconomic drivers.

RCPs were used in the most recent Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment report (IPCC, 2013). These are used in the ERSEM and UKCP18 projections (see Table 3). Different emission scenarios specified within the older Special Report on Emission Scenarios (SRES) (IPCC, 2000) were used in the UKCP09 and CEH Future Flows projections (see Table 3). These scenarios did not include any policies to limit climate change, and RCPs were introduced to recognise the relevance of mitigation. Figure 6 shows the relationship between RCPs and SRES.

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[9] Total radiative forcing is the difference between the incoming and outgoing radiation at the top of the atmosphere.

In this vulnerability assessment, RCP4.5, and RCP8.5 were used for most climate change pressures as the most up to date scenarios available within the datasets. In the case of sea temperature and salinity, ERSEM projections beyond 2049 use the POLCOMS model and have poor coverage at the coast (where most Annex I habitats are present) and thus UKCP09 projections were used. This uses the SRES A1B emission scenario (medium), which tracks approximately between the warming projected by RCP4.5 and RCP8.5 (see Figure 6). The use of different emissions scenarios within the assessment limits the comparability of the assessment over the next century and caution should be used when interpreting the results for these climate change pressures.

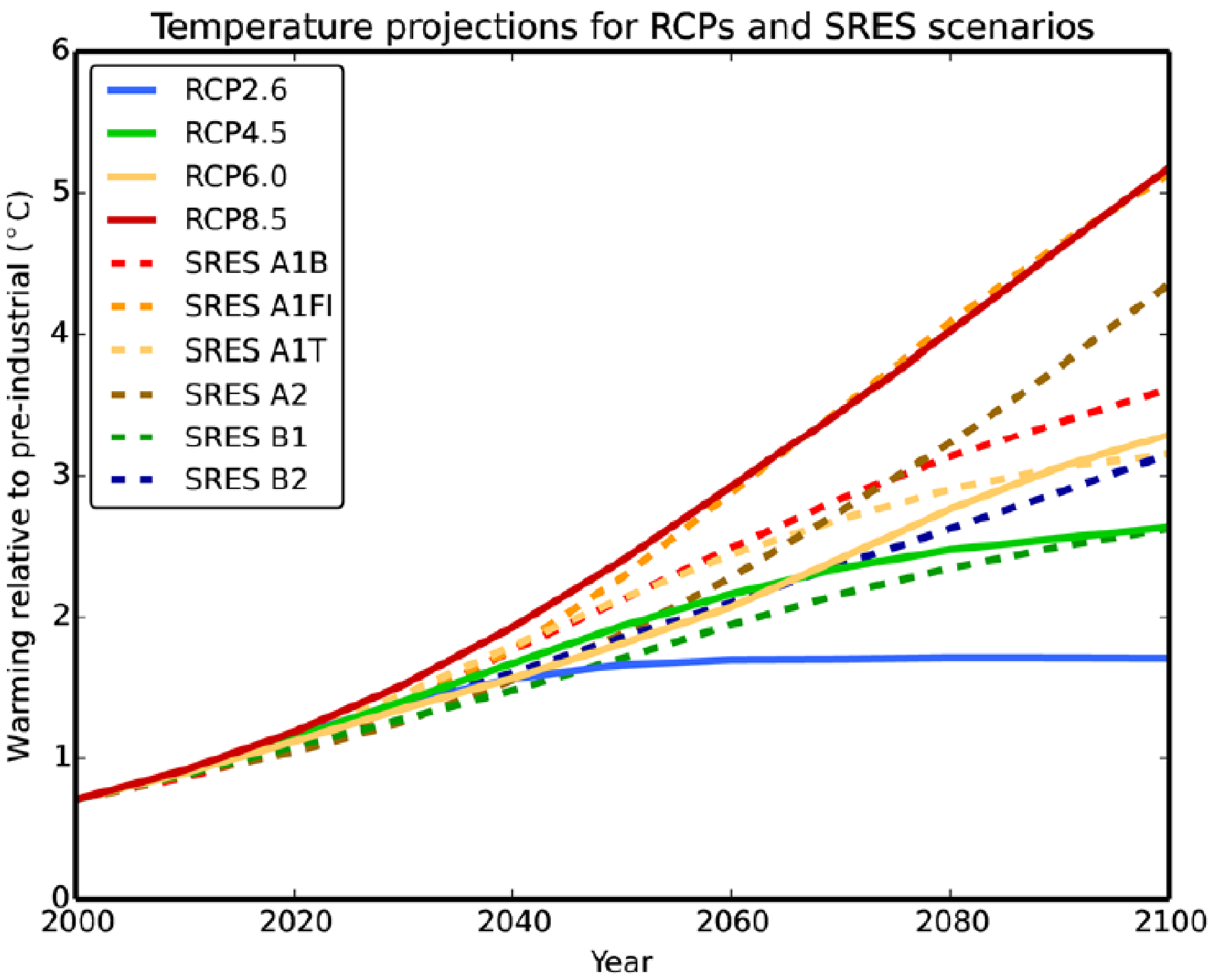

Figure 6. Global mean temperature projections from a climate model (called MAGICC6) relative to a pre-industrial average (1850-1900) for RCP2.6 (blue), RCP4.5 (green), RCP6.0 (yellow) and RCP8.5 (red) and the older SRES scenarios (dashed coloured lines) (Source: Met Office, 2018).

2.4.3. Variables

The precise variables used in the model for each climate change pressure are set out in Table 4. In most cases, where available, values were taken from the greatest depth as the component biotopes of Annex I habitats are benthic. Furthermore, daily mean values were used in the model where available to capture the most extreme projected values (as opposed to values averaged over months) to adopt a precautionary approach to the assessment. Minimum or maximum values were selected on the basis of component biotope sensitivities, and the projected changes in climate change pressures (see Section 3.1). The use of different variables for each climate change pressure also limits the comparability of assessed vulnerabilities over the next century.

Table 4. Climate change pressure variables used in the model

Climate change pressures	2025	2049	2099 (2083 for sea temperature and salinity)	Data source
Sea temperature	ERSEM NEMO RCP4.5 / RCP8.5 Max. daily mean bottom temp. (°C)	ERSEM NEMO RCP4.5 / RCP8.5 Max. daily mean bottom temp. (°C)	UKCP09 (only 2083) SRES A1B Max. daily mean sea surface temp. (°C)	ERSEM: https://cds.climate.copernicus.eu/cdsapp#!/dataset/10.24381/cds.dcc9295c?tab=overview UKCP09: https://catalogue.ceda.ac.uk/uuid/46f53c4e24f4428cba1c42a608844c82
Salinity	ERSEM NEMO RCP4.5 / RCP8.5 Min. daily mean bottom salinity (psu)	ERSEM NEMO RCP4.5 / RCP8.5 Min. daily mean bottom salinity (psu)	UKCP09 (only 2083) SRES A1B Min. daily mean salinity (psu)	ERSEM: https://cds.climate.copernicus.eu/cdsapp#!/dataset/10.24381/cds.dcc9295c?tab=overview UKCP09: https://catalogue.ceda.ac.uk/uuid/46f53c4e24f4428cba1c42a608844c82
Water column stratification	ERSEM NEMO RCP4.5 / RCP8.5 Max. monthly mean potential energy anomaly (J/m³)	ERSEM NEMO RCP4.5 / RCP8.5 Max. monthly mean potential energy anomaly (J/m³)	ERSEM POLCOMS RCP4.5 / RCP8.5 Max. monthly mean potential energy anomaly (J/m³)	https://cds.climate.copernicus.eu/cdsapp#!/dataset/10.24381/cds.dcc9295c?tab=overview
Ocean acidification	ERSEM NEMO RCP4.5 / RCP8.5 Min. daily mean bottom pH	ERSEM NEMO RCP4.5 / RCP8.5 Min. daily mean bottom pH	ERSEM POLCOMS RCP4.5 / RCP8.5 Min. daily mean bottom pH	https://cds.climate.copernicus.eu/cdsapp#!/dataset/10.24381/cds.dcc9295c?tab=overview
Deoxygenation	ERSEM NEMO RCP4.5 / RCP8.5 Min. daily mean bottom dissolved oxygen (mg/l)*	ERSEM NEMO RCP4.5 / RCP8.5 Min. daily mean bottom dissolved oxygen (mg/l)*	ERSEM POLCOMS RCP4.5 / RCP8.5 Min. daily mean bottom dissolved oxygen (mg/l)*	https://cds.climate.copernicus.eu/cdsapp#!/dataset/10.24381/cds.dcc9295c?tab=overview

Climate change pressures	2025	2049	2099 (2083 for sea temperature and salinity)	Data source
Sea level rise	UKCP18 RCP4.5 / RCP8.5 Local time-mean relative sea level anomaly (m) – 95th percentile	UKCP18 RCP4.5 / RCP8.5 Local time-mean relative sea level anomaly (m) – 95th percentile	UKCP18 RCP4.5 / RCP8.5 Local time-mean relative sea level anomaly (m) – 95th percentile	https://catalogue.ceda.ac.uk/uuid/0f8d27b1192f41088cd6983e98faa46e
Wave exposure	UKCP18 RCP4.5 / RCP8.5 Relative change in max. significant wave height (%) from 1979-2004 baseline period^	UKCP18 RCP4.5 / RCP8.5 Relative change in max. significant wave height (%) from 1979-2004 baseline period^	UKCP18 RCP4.5 / RCP8.5 Relative change in max. significant wave height (%) from 1979-2004 baseline period^	Data provided by National Oceanography Centre (Bircheno and Wolf, 2018)
Air temperature	UKCP18† RCP8.5 Max. daily mean air temp. (°C)	UKCP18† RCP8.5 Max. daily mean air temp. (°C)	UKCP18† RCP8.5 Max. daily mean air temp. (°C)	https://catalogue.ceda.ac.uk/uuid/854bb0de8a5e4bfaafe322bbfc57ea57
Water quality due to run-off and pollution	CEH Future Flows§ SRES A1B Change in winter (DJF) and summer (JJA) mean river flow compared with 1961-1990 baseline, interpolated across WFD transitional waterbodies (%)	CEH Future Flows§ SRES A1B Change in winter (DJF) and summer (JJA) mean river flow compared with 1961-1990 baseline, interpolated across WFD transitional waterbodies (%)	CEH Future Flows§ SRES A1B Change in winter (DJF) and summer (JJA) mean river flow compared with 1961-1990 baseline, interpolated across WFD transitional waterbodies (%)	https://www.ceh.ac.uk/services/future-flows-maps-and-datasets
Turbidity	No data	No data	No data	

* ERSEM projections for dissolved oxygen concentrations are provided in mol/m³. These were converted to mg/l for use in the model.
^ A historical baseline period of 1979-2004 was used to calculate relative change in mean max. significant wave height, as per the methodology used by Morim *et al.* (2019) and Morim *et al.* (2020).
† A set of 28 projections are provided for this projection dataset and consist of a combination of 15 coupled model simulations produced by the Met Office Hadley Centre, and 13 coupled simulations from CMIP5 contributed by different climate modelling centres. CMIP5 Climate Model HadGEM2-ES was selected to match that used in the ERSEM NEMO projections.

§ Future Flows Climate projections are based on HadRM3-PPE, with each ensemble member equally likely. FF-HadRM3-Q8 (afixj) ensemble was selected as it projects greater changes in flow in Wales over the next century, adopting a worse case (see: https://www.ceh.ac.uk/national-changes-river-flow#overview)

2.5. Step 4: Sensitivity assessment

A literature review of the sensitivity of the individual component biotopes of Annex I marine habitats to the pressures associated with climate change was conducted in order to understand pressure-sensitivity relationships. This information is collated in an accompanying Microsoft Excel spreadsheet (*4912_Pressure-sensitivity relationships_31Mar2021.xlsx* – see NRW metadata record NRW_DS125172).

The review was primarily based on existing data and information sources, particularly the MarESA database and previous work commissioned by CCW and NRW on the vulnerability of marine habitats to climate change (e.g. Jones *et al*., 2011). MarESA was considered the best available information on the sensitivity of marine biotopes at the level of detail required for this assessment (i.e. component biotopes of Annex I habitats). For some biotopes, it also gives consideration to specific climate change pressures, namely global warming, marine heatwaves, ocean acidification, and sea level rise[10]. For other biotopes where climate change pressures were not assessed by MarESA, pressures (and benchmarks) that are not specifically climate-related were used to inform the sensitivity assessment (e.g. temperature changes, or salinity changes).

These pressures and benchmarks are considered to be in line with, or to exceed, the changes expected to be caused by climate change. However, climate change pressures are ongoing and liable to steadily increase in the future; they are not likely to be reversed in any manageable timescale (Garrard and Tyler-Walters, 2020). In this respect, resilience or recovery of biotopes (used in the assessment of sensitivity by MarESA) is unlikely to occur and thus is one limitation in applying the MarESA assessments of pressures that are not specifically climate-related. To address this, care was taken to examine the underlying literature to inform the sensitivity assessment in the context of climate change.

A sensitivity assessment was not undertaken for climate change pressures ‘water column stratification’ and ‘changes in water quality due to run-off’. This is due to the lack of information available on the sensitivity of component biotopes to these pressures which would make it difficult to assign specific sensitivity thresholds. Furthermore, changes in water quality due to run-off would be affected by land use and pollution of local water courses, and not just changes in riverine discharge. As such, it would not be appropriate to conduct a sensitivity assessment for these pressures. Instead, pressure data layers were mapped to determine exposure to these pressures across Wales, as described in Step 3, and presented in Sections 3.1.9 and 3.1.10.

2.5.1. Sensitivity thresholds and definitions

Different levels of receptor sensitivity were related to appropriate climate change pressure values, based on the evidence reviewed (mainly in MarESA). These ‘sensitivity thresholds’ were identified for each receptor and climate change pressure[11] and recorded in the sensitivity assessment spreadsheet (*4912_Pressure-sensitivity relationships_22Feb2021.xlsx*). The evidence used and sensitivity assessments conducted in MarESA provide a greater level of detail than the EUNIS/MHC level 4 biotopes selected as receptors in this project. In most cases, the evidence used in MarESA is consistent between EUNIS/MHC level 5 and level 6 biotopes (that comprise the EUNIS/MHC level 4 biotopes selected as receptors in this project). Therefore, a single set of sensitivity thresholds for each component biotope was readily inferred. Where the evidence in MarESA differed between EUNIS/MHC level 5 and level 6 biotopes, sensitivity

[10] https://www.marlin.ac.uk/sensitivity/sensitivity_rationale

[11] For saltmarsh (LS.LMp.Sm) and the wave exposure pressure, pressure values relating to sensitivity thresholds could not be deduced from the evidence; in this case the sensitivity assessment provided by MarESA (i.e. medium sensitivity) was applied to the vulnerability assessment.

thresholds assigned to receptors were based on the most sensitive biotope (i.e. adopting a worst case). Furthermore, where EUNIS/MHC level 5 biotopes were included as receptors in the assessment, level 4 biotopes were assessed separately from the level 5 biotope (i.e. the sensitivity thresholds may be different between EUNIS/MHC level 4 and level 5 biotopes). However, where the best evidence was available for the EUNIS/MHC level 5 biotope (e.g. a specific climate change pressure was assessed by MarESA), this was also applied to the level 4 counterpart biotope.

Sensitivity thresholds deduced from the literature review were matched to generic definitions of low, medium and high sensitivity. For example, a given receptor may be assigned a low sensitivity to a < 1°C rise in temperature, a medium sensitivity for a rise in temperature between 2°C and 4°C, and high sensitivity to a change of > 4°C. Generic definitions of sensitivity used in this project are provided in Table 5 and broadly follow those used by Jones *et al.* (2011).

There are different types of change that may result from climate change pressures on receptors. This can include changes in extent, distribution, species abundance, behaviour and ecosystem function. Therefore, in order to document the types of change that a receptor may be subject to, sensitivity was considered with respect to two types of change: habitat distribution and extent, and habitat quality and/or ecosystem function. This follows the methodology used by Jones *et al*. (2011) and also aligns with generic conservation objectives for SACs within Wales. The type of change that is relevant to each pressure-sensitivity relationship was highlighted in the sensitivity assessment (*4912_Pressure-sensitivity relationships_22Feb2021.xlsx*).

Definitions of 'not sensitive' and 'not relevant' were also used in the sensitivity assessment and applied in the same way as in MarESA. Component biotopes were considered 'not sensitive' where they have a high resistance or tolerance to the benchmark level of pressure used in MarESA (which for pressures that are not specifically climate-related is considered to be broadly in line with, or exceed, the changes expected to be caused by climate change and therefore applicable here, noting limitations with respect to the resilience or recovery of biotopes discussed above). Pressure-sensitivity relationships were considered 'not relevant' where the evidence suggests that there is no direct interaction between the pressure and the biotope (e.g. sea level rise and subtidal biotopes not affected by light).

Where sensitivity thresholds could not be assigned to component biotopes based on the evidence reviewed, alternative component biotopes with similar species and/or similar biotopes with the most sensitive thresholds (representing a worst case) were used as proxies. This was informed by the MHC biological comparative tables[12] which enable a rapid comparison of the species composition between sets of biotopes.

Positive impacts resulting from climate changes pressures are included within the low sensitivity definition and not assessed separately (see Table 5). However, any positive impacts to habitats arising from climate change that were identified in the literature have been are highlighted, allowing future management options to capitalise on any opportunities.

[12] https://hub.jncc.gov.uk/assets/1e129033-5336-4c5a-93fe-fe85f7e72b96

Table 5. Sensitivity definitions

Sensitivities	Distribution and extent	Quality and ecosystem function
Low	Minor adverse, positive or no impact on distribution or extent	Minor adverse, positive or no change to species composition Short-term, reversible, and localised reduction, or increase, in habitat quality, biodiversity and ecosystem function/services
Medium	Moderate adverse impact on distribution or extent (habitat likely to become slightly more localised)	Moderate adverse change to species composition Medium-term, regional reduction in habitat quality, biodiversity and ecosystem function/services
High	Significant adverse impact on distribution or extent (widespread habitat likely to become localised)	Significant adverse change to species composition, including loss of structural and key species Long-term, widespread reduction in habitat quality, biodiversity and ecosystem function/services

2.5.2. Confidence assessment

At this stage of the sensitivity assessment, the confidence in the evidence was noted and used to assign a confidence score to the sensitivity thresholds. The broad definitions of confidence are outlined in Table 6, and have been tailored to include key aspects of the confidence assessment used as part of MarESA, specifically the quality of evidence[13] (information sources), applicability of evidence, and degree of concordance (agreement between studies). The confidence associated with the sensitivity thresholds assigned to each component biotope is recorded in the sensitivity assessment (*4912_Pressure-sensitivity relationships_22Feb2021.xlsx*).

[13] Evidence is defined as expert opinion or advice, data, methodology, results from data analysis, interpretation of data analysis, and collations and interpretations of scientific information (meta-analysis), peer-reviewed papers, grey literature, industry knowledge and anecdotal evidence (adapted from JNCC, 2015).

Table 6. Confidence scores and definitions used in this project.

Confidence score	Definition
High (H)	There is a good understanding of the impact on the same species/habitats in the UK marine environment and it is well supported by peer reviewed papers (observational or experimental) or grey literature reports by established agencies. There is consensus amongst the experts on the impact (direction and magnitude).
Medium (M)	Whilst there is an understanding of the impact on species/habitats, the evidence is based on proxy information outside of the UK or in the laboratory and/or the assessment is based on limited peer-reviewed papers and relies heavily on grey literature or expert judgement. There is a majority agreement between experts on the direction of the change; but conflicting evidence/opposing views exist on the magnitude of impact.
Low (L)	There is limited or no understanding of the impact on species/habitats and the assessment is not well supported by evidence, or only by expert judgement. There is no clear agreement amongst experts on the direction or magnitude of the impact.

2.6. Step 5: Vulnerability assessment

The vulnerability assessment involved integrating the sensitivity assessment with the climate change pressure data layers and the receptor data layers (to determine exposure). This was achieved using 'ModelBuilder' within ArcGIS Pro which enabled a level of automation to process large amounts of data and re-runs for different climate change scenarios, timeframes and pressures. A flow chart of the model process is show in Figure 7.

The sensitivity thresholds of each receptor to each climate change pressure were firstly recorded as an attribute in the receptor data layers. The receptor data layers were then overlaid and spatially correlated with the pressure data layers within the GIS model (for each emission scenario and timeframe) to determine the vulnerability of each individual biotope record. The model calculated the vulnerability of the biotope by cross referencing the projected values of climate change pressures in relation to the sensitivity thresholds for each receptor. Where projections met or exceeded a sensitivity threshold, a level of vulnerability directly relating to the sensitivity threshold was assigned[14]. The resulting layer provides spatially distinct levels of vulnerability for receptors across Wales.

Individual results for each component biotope within SACs and Annex I habitat/feature boundaries were also produced (SAC and Article 17 data layers were downloaded from the Lle portal[15]). This allowed the percentage coverages of low, medium, and high (or not

[14] The sensitivity of saltmarsh (LS.LMp.Sm) to wave exposure assessed by MarESA (i.e. medium) was applied as the vulnerability to wave exposure as it was not possible to deduce pressure value sensitivity thresholds from the evidence.
[15] http://lle.gov.wales/home

sensitive/not relevant) vulnerabilities to be calculated for each SAC and Annex I feature in Wales.

Model outputs of the vulnerability assessment were collated in Microsoft Excel spreadsheets, with a separate file provided for each climate change pressure. In each spreadsheet, the vulnerability of the component biotope is recorded alongside the spatial extent (area) for which it is vulnerable. A separate worksheet provides the results per Annex I habitat and for each SAC in Wales, and pivot tables calculate the percentage coverage of Annex I habitat vulnerability (see data record NRW_DS125172).

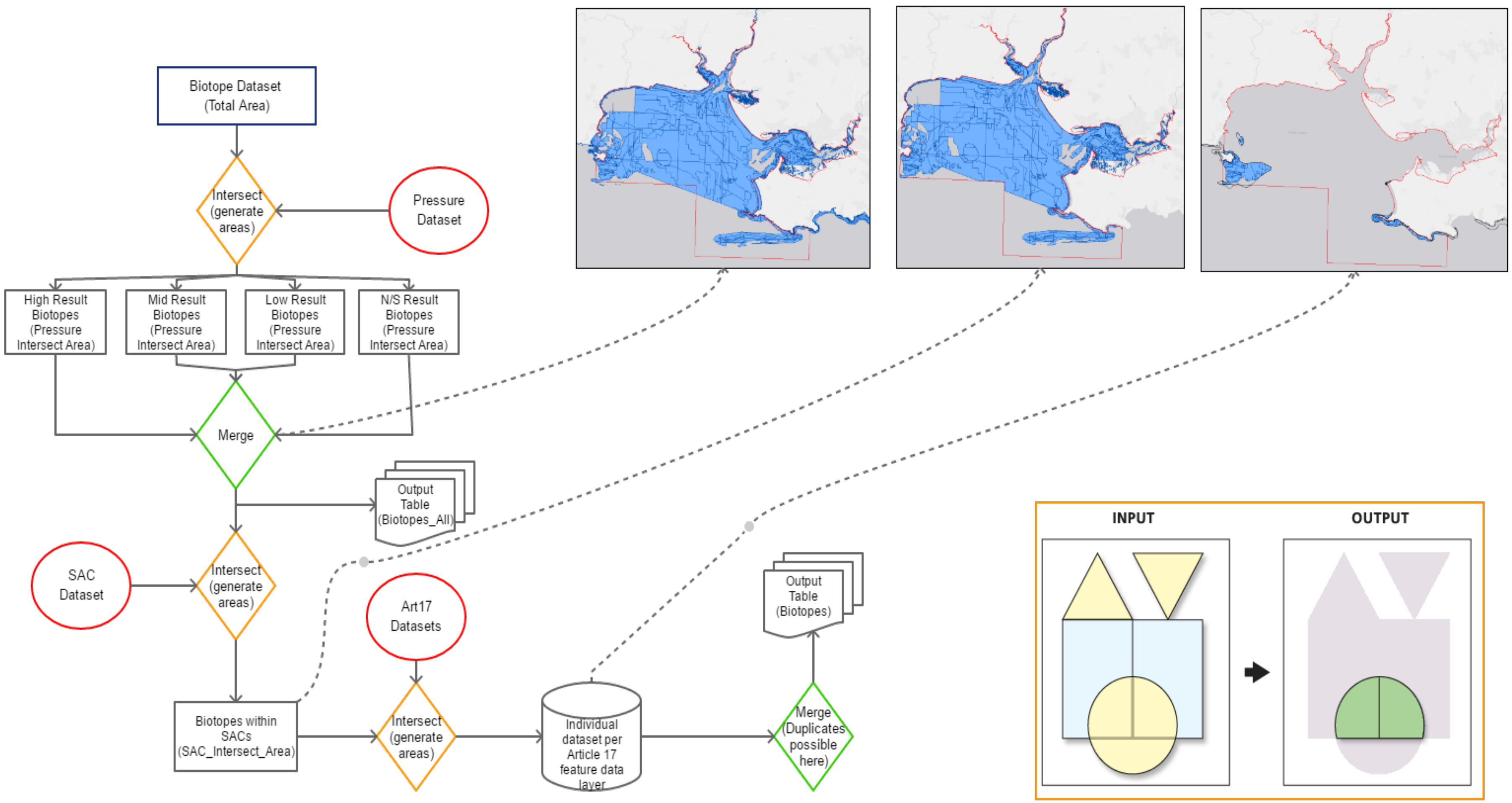

Figure 7.Flow chart showing stages in model process

3. Vulnerability assessment

The following sections provide a high-level review of the evidence used to inform each stage of the vulnerability assessment, and that fed into the GIS model. Section 3.1 describes how climate change pressures are expected to change over the next century, and presents the climate change projections used in this project (to inform the exposure element of the assessment). Section 3.2 presents a high-level summary and key examples of the findings of the sensitivity assessment of component biotopes to climate change pressures. Finally, key results from the vulnerability assessment and the GIS model outputs are provided in Section 3.3.

The full set of pressure-sensitivity tables are provided in an accompanying Microsoft Excel spreadsheet (*4912_Pressure-sensitivity relationships_31Mar2021.xlsx*). The full set of model output tables providing the vulnerability assessment results are provided in a series of Microsoft Excel spreadsheets, with a separate file provided for each climate change pressure (*4912_[Climate change pressure]_vulnerability assessment_31Mar2021.xlsx*).

3.1. Climate change pressure exposure

Exposure to climate change pressures were examined in this part of the assessment. This section provides an overview of the changes anticipated to occur to each of the selected pressures in a warming climate over the next century in the North Atlantic and in Welsh waters. The review is predominantly based on the information provided by the MCCIP Report Card (2020) and the underpinning scientific reviews, as well as the climate change projections used in the vulnerability assessment. Each pressure is discussed separately below.

However, before considering future projections in climate and the exposure of Annex I marine habitats in Wales to climate change pressures, the uncertainty associated with climate projections should be highlighted. As summarised by Tinker and Howe (2020), there are several different types of uncertainty associated with climate projections:

- Emission scenario uncertainty (how emissions will evolve over time);
- Initial condition uncertainty (how well known the conditions are at the start of the model period);
- Model structure uncertainty (differences due to modelling frameworks);
- Model parameter uncertainty (how well known the parameters are that are set in the model); and
- Model coupling approach (how do models link together different earth systems).

Climate models also consist of a variety of experimental designs, model domains, and averaging periods, and therefore it is difficult to quantitatively compare the magnitudes of projected warming and pressures (Tinker and Howes, 2020).

Furthermore, the projections shown here have been processed so that coverage across all component biotopes of Annex I habitats in Welsh waters is complete (using the ‘closest’ function in the spatial join tool in ArcGIS). Therefore, projections with poor spatial resolution in nearshore regions may be less accurate at the coast which further compounds uncertainty (see Section 2.4).

Due to the complexity in determining the uncertainty associated with climate change projections, the amount of uncertainty in the projections used in this project are not accounted for here (though uncertainty is described in reporting that accompanies the projections). This allowed resources to be focussed on sourcing and processing climate projections data and incorporating them in the GIS model. Therefore, the model outputs of the vulnerability assessment (Section 3.3) should be interpreted with an appropriate degree of caution.

3.1.1. Sea temperature

As summarised by Tinker and Howes (2020), there is high confidence that UK seas are showing an overall warming trend. Over the last 30 years, sea surface temperature (SST) warming has been most pronounced in the North Atlantic (north of 60°N) with increases of 0.4°C per decade just off the east coast of Iceland. SSTs have increased up to 0.24°C to the north of Scotland and in the majority of the North Sea.

Short term variation in UK SSTs has been observed amongst an overall long-term warming. For example, UK shelf seas were warmer in 2000–2008 than 2009–2013, but recent years have seen warmer conditions return. The warmest year on record for SSTs was 2014, and eight of the 10 warmest years have occurred since 2000.

The Western English Channel has seen average or below average SSTs in the early 1980s replaced by warmer than average waters since. Particularly warm conditions have been observed around 2007, and more recent years have been close to but slightly higher than average. The influence of cold ocean temperature anomalies observed in the mid- to high-latitude North Atlantic from winter 2013/2014 (Josey *et al*., 2018) has weakened the warming along the UK's south-west coast. In the Irish Sea, the years between 2008 and 2013 were slightly cooler than 2002–2008 but warm relative to the 1980s.

SST warming of UK shelf seas is expected to continue over the next century. Most models suggest (with medium confidence) an increase between 0.25°C and 0.4°C per decade (Tinker and Howes, 2020). Overall, most projections give a warming between 1–4°C by the end of century.

As described by McCarthy *et al*. (2020), the Atlantic Meridional Overturning Circulation (AMOC), also known as the Gulf Stream, is a system of ocean currents associated with the exchange of warm and cold water. It plays a major role in the maintenance of the climate and marine environment of the UK. A weakened AMOC state (which it is currently in) causes the subpolar North Atlantic to enter a cool (and fresh) state. Whilst there are very large uncertainties, the AMOC is predicted to weaken over the coming century and this may cause large biogeographical and climatic shifts. However, it is not thought that it will abruptly shut down completely .

Maximum daily mean sea temperature projections around the Welsh coast are shown in Figure 8. ERSEM NEMO projections in 2049 under RCP8.5 predict maximum sea bottom temperatures of up to around 25°C in shallow waters (< 10 m depth) in the Severn

Estuary, and around 21°C on the north coast (< 10 m depth). Maximum daily mean sea bottom temperatures further offshore in Cardigan Bay, for example, reach around 18°C (in about 50 m water depth). Note that sea temperatures shown in Figure 8 for 2083 are based on UKCP09 projections (which provide sea surface temperatures, rather than sea bottom temperatures as in ERSEM NEMO projections) and should not be directly compared with ERSEM NEMO projections in 2025 and 2049 (see Section 2.4).

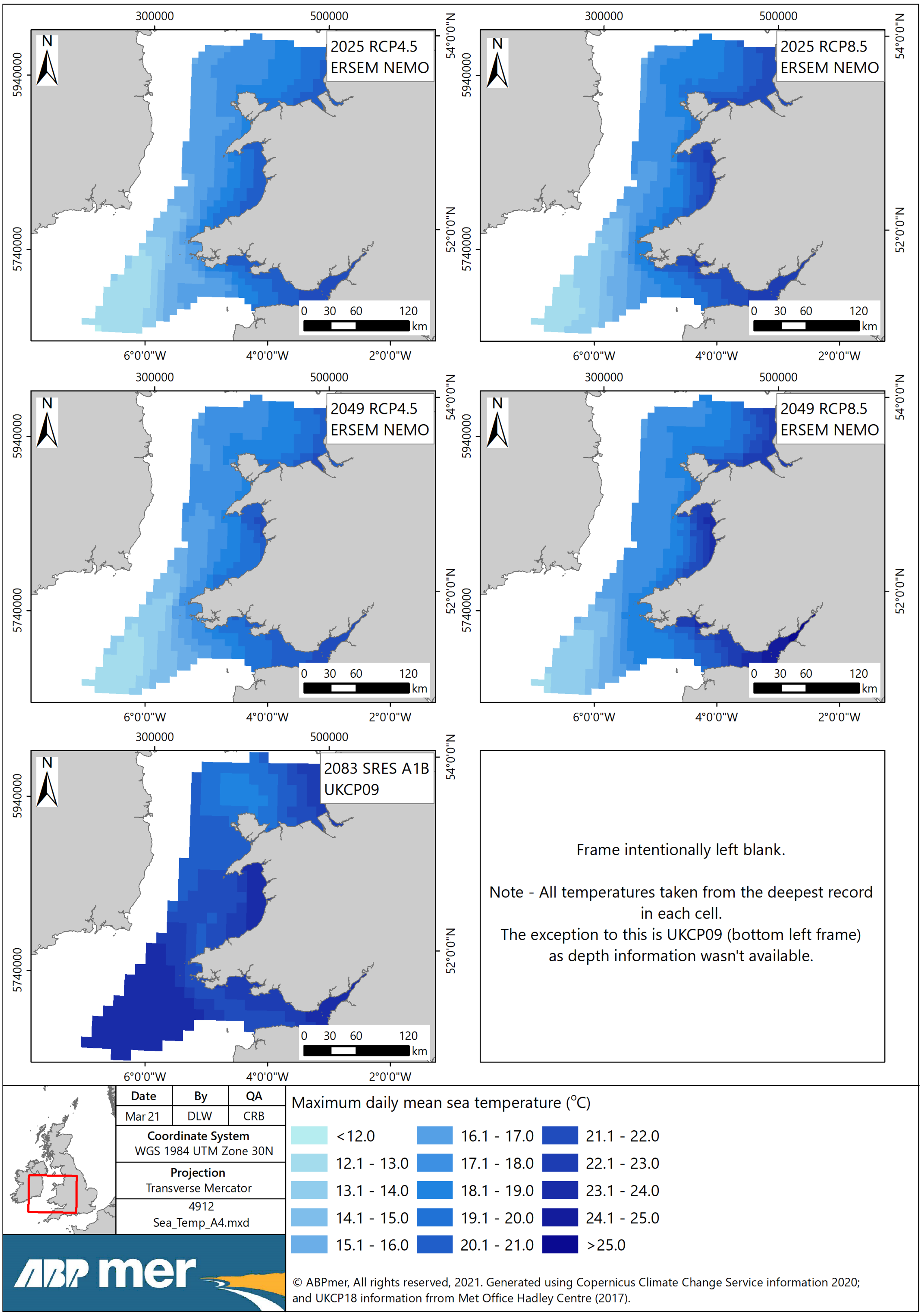

Figure 8. Maximum daily mean sea temperature (°C) projections in Welsh waters. Top left: ERSEM NEMO projections at sea bottom for the year 2025 and RCP4.5. Top right: ERSEM NEMO projections at sea bottom for the year 2025 and RCP8.5. Middle left: ERSEM NEMO projections at sea bottom for the year 2049 and RCP4.5. Middle right: ERSEM NEMO projections at sea bottom for the year 2049 and RCP8.5. Bottom left: UKCP09 projections at surface for the year 2083 and SRES A1B.

3.1.2. Air temperature

Over the last 30 years, trends in marine air temperature warming are not significant over most of the UK region; only areas around Iceland and part of the Scottish continental shelf have shown significant warming (Tinker and Howes, 2020). In these areas, trends range from an increase of 0.1–0.5°C per decade with an average of 0.3°C per decade.

The frequency of discrete periods of regional extreme temperatures has also increased and caused what are known as marine heatwaves (Tinker and Howes, 2020). Marine heatwaves are defined as a period when SSTs exceed the local 99th percentile and occur when air temperatures exceed the seasonal average (Garrabou *et al.,* 2009). They are caused by a range of factors, including air-sea heat flux when air temperatures are anomalously high as well as large-scale climate drivers (e.g. El Niño Southern Oscillation) (Smale *et al.*, 2019). Marine heatwaves have doubled in frequency since the 1860-1880 baseline; 84-90% of marine heatwaves occurring between 2005 and 2016 are thought to be attributable to anthropogenic temperature rises (Frölicher *et al.,* 2018).

Climate models predict that the frequency of marine heatwaves will increase 50-fold for RCP 8.5 and 20-fold for RCP 2.6 by 2081-2100 relative to 1850-1900 (IPCC, 2019). Marine heatwaves are also expected to increase in duration, extent and intensity (IPCC, 2019). However, substantial uncertainty remains over the frequency, scale and impact of these events are in a changing climate (MCCIP, 2020).

Around the Welsh coast, maximum daily mean air temperatures are projected to reach approximately 29°C by 2025, 30°C by 2049, and 33°C by 2099 (Figure 9). Further offshore, temperatures are projected to be 5 to 6°C cooler than at the coast.

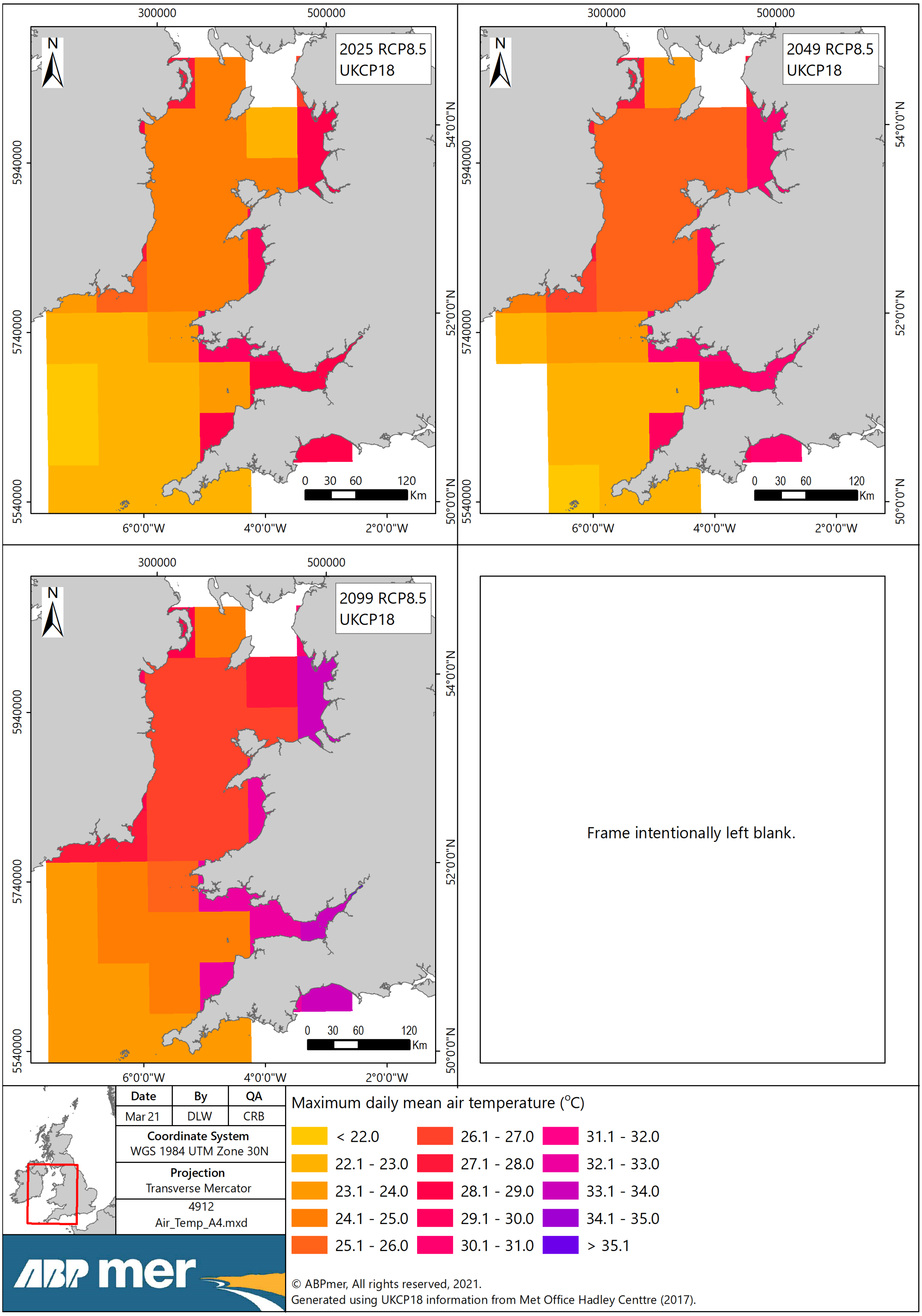

Figure 9. UKCP18 maximum daily mean air temperature (°C) projections over Welsh waters. Top left: projections for the year 2025 and RCP8.5. Top right: projections for the year 2049 and RCP8.5. Bottom left: projections for the year 2099 and RCP8.5.

3.1.3. Sea level rise

Over the last century, sea level has risen by approximately 12–16 cm around the UK. In southern regions of the UK, the net rate of sea level rise is slightly higher than in northern regions due to vertical land movement caused by glacial isostatic adjustment since the last ice age.

There is considerable uncertainty associated with future projections. The central estimate projection (medium confidence) of sea level rise for 2100 in Cardiff ranges from 0.43–0.76 cm[16], depending on emissions scenario. Increases in future extreme sea levels are expected to result in increases in flooding and erosion in the coming decades, although precise changes will vary by location (Horsburgh *et al*., 2020). Glacial isostatic rebound and the spatial pattern of sea level change related to polar ice melt is also expected to result in spatial variation in the rates of sea level rise across the UK; southern regions are expected experience greater rises in sea level compared to norther regions (Horsburgh *et al*., 2020).

Around the Welsh coast, southern regions are projected to experience slightly greater rises in sea level (Figure 10). For example, UKCP18 projects a rise in sea level of more than 1.1 m (95th percentile) in the Severn Estuary, Bristol Channel and around Pembrokeshire in the year 2099 under RCP8.5. Around Anglesey sea levels are projected to rise by around 1 m (95th percentile).

[16] This estimate is a central estimate of sea level rise and is lower than the projections used in the vulnerability assessment (shown in Figure 10) which represents the 95th percentile.

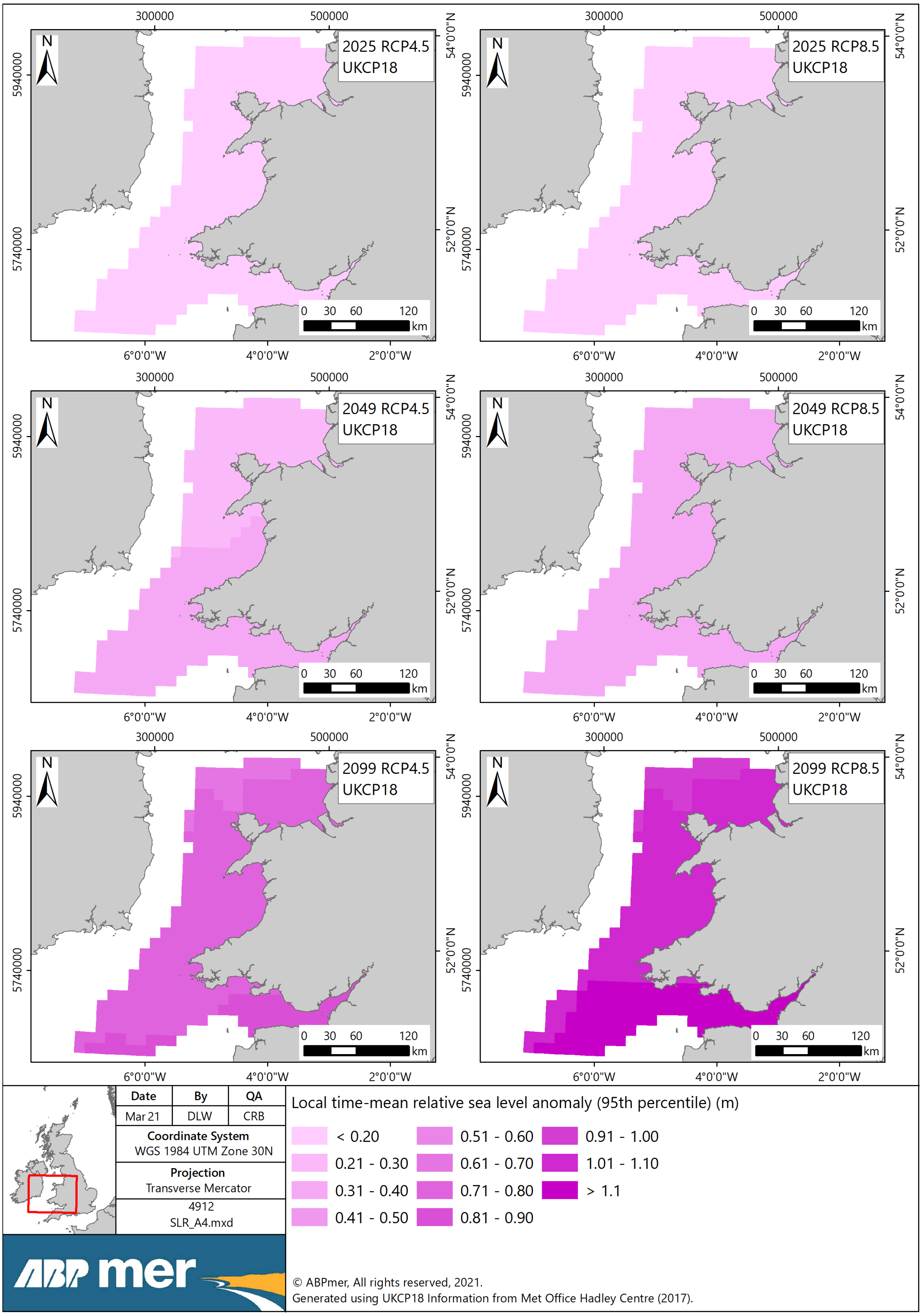

Figure 10. UKCP18 projections for the 95th percentile of local time-mean relative sea level (m) in Welsh waters. Top left: projections for the year 2025 and RCP4.5. Top right: projections for the year 2025 and RCP8.5. Middle left: projections for the year 2049 and RCP4.5. Middle right: projections for the year 2049 and RCP8.5. Bottom left: projections for the year 2099 and RCP4.5. Bottom right: projections for the year 2099 and RCP8.5.

3.1.4. Wave exposure

Since the 1950s, annual and winter mean significant wave heights have increased. Mid-latitude storms and depressions have also shifted poleward during winter, and the strongest storms may be becoming more intense but less frequent. However, high natural variability and poor understanding of climate-induced changes mean these trends cannot be directly attributed to climate change.

There is low confidence in how climate change could affect waves (and storms) in the future, and there is no consensus on the future storm and, hence, wave climate around UK coasts (Lowe et *al.,* 2018; Palmer *et al.,* 2018).

It is possible climate-induced change will occur with some projections suggesting an increase in storms, but natural variability could continue to dominate changes in the near future. Some projections for North Atlantic storms over the 21st Century show an overall reduced frequency of storms and some indication of a poleward shift in the tracks, in the northern hemisphere winter, but there is substantial uncertainty in projecting changes in northern hemisphere storm tracks, especially in the North Atlantic (Wolf *et al*., 2020). Under a high emissions scenario, the most severe waves could increase in height, though there could be an overall reduction in mean significant wave height in the North Atlantic by 2100. The UK may become more exposed to severe storms in Autumn if tropical cyclones become more intense and their region of origin expands northwards.

It should also be noted that the UKCP18 wave modelling is regional scale and driven by projections in future changes to the wind field. The projections are (at best) applicable to open coast settings; wave exposure in nearshore settings will be affected by the morphology of the coastline. It is possible that at the local scale in relatively sheltered nearshore settings, changes in fetch length in response to sea level rise may result in as big (or even larger) changes in wave exposure than that suggested by the regional scale model. Projections of changes to the wave regime on the open shelf are hugely uncertain, both for average and extreme waves. Therefore, there is even more uncertainty for nearshore and estuarine settings.

UKCP18 projections generally show minimal changes in wave exposure around Wales (Figure 11). On the north coast, a decrease in wave exposure is expected. For example, in 2049 under RCP8.5, decreases of around 15 % are projected. To the north and west of Anglesey and the Llŷn Peninsula, increases of around 10 % are projected.

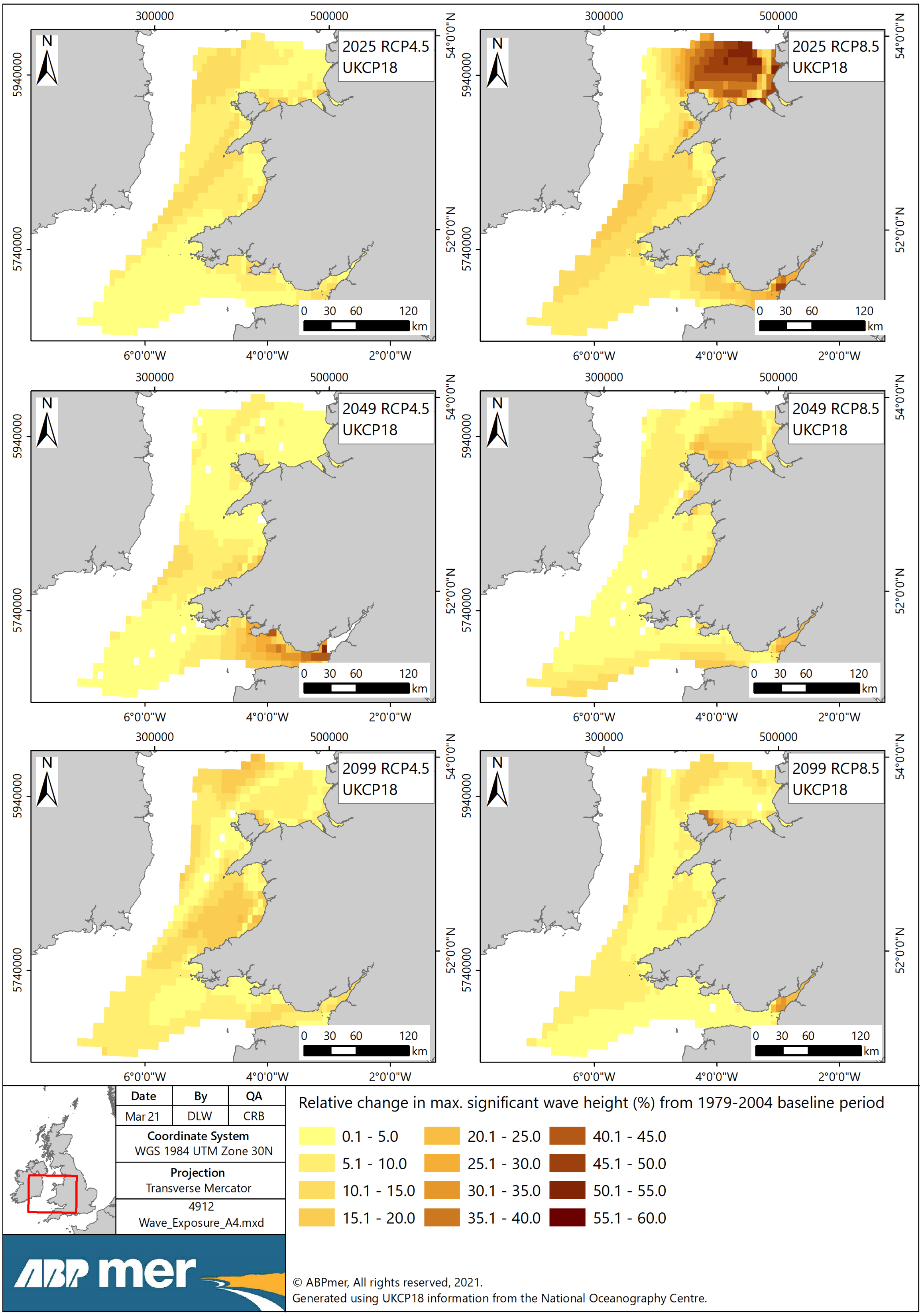

Figure 11. UKCP18 projections for the relative change in maximum significant wave height (%) from a 1979-2004 baseline period in Welsh waters. Top left: projections for the year 2025 and RCP4.5. Top right: projections for the year 2025 and RCP8.5. Middle left: projections for the year 2049 and RCP4.5. Middle right: projections for the year 2049 and RCP8.5. Bottom left: projections for the year 2099 and RCP4.5. Bottom right: projections for the year 2099 and RCP8.5.

3.1.5. Ocean acidification

The ocean absorbs anthropogenic carbon dioxide (CO_2) that is emitted into the Earth's atmosphere. Increased CO_2 concentrations affect the carbonate chemistry of seawater, and result in a reduction in pH. The average pH of sea surface waters has dropped from 8.25 in the 1700s to 8.14 in the 1990s, leading to a 25% increase in H+ ions (Jacobson, 2005). The North Atlantic contained more anthropogenic CO_2 than any other ocean basin and declined in pH by a rate of 0.0013 units per year between 1995 and 2013 (Humphreys *et al*., 2020). However, the surface water pH is highly variable over time due to seasonal cycles in photosynthesis, respiration and water mixing (Ostle *et al.*, 2016).

Models project (with medium confidence) that average continental shelf pH could drop by up to 0.366 by 2100 under a high emissions scenario; coastal areas are predicted to decline faster. Bottom waters are also expected to become corrosive to more soluble forms of calcium carbonate (aragonite). By 2100, undersaturation for at least one month of the year may occur in up to 20% of the North-west European shelf seas.

As shown in Figure 12, sea bottom pH values of around 8 are projected by ERSEM NEMO in 2025 under RCP8.5 for most regions around Wales. Sea bottom pH values are projected to decrease to around 7.9 in 2049 under RCP8.5. Minimal variation in pH values are projected around the Welsh coast. However offshore regions at depth are projected to be more acidic compared with shallower coastal regions. For example, a pH of around 7.7 is projected in 2049 under RCP8.5 in 80 m water depth. Note that pH values shown in Figure 12 for 2099 are based on ERSEM POLCOMS projections and should not be directly compared with ERSEM NEMO projections in 2025 and 2049 (see Section 2.4). A declining trend in pH is also projected by ERSEM POLCOMS over the next century (not shown here).

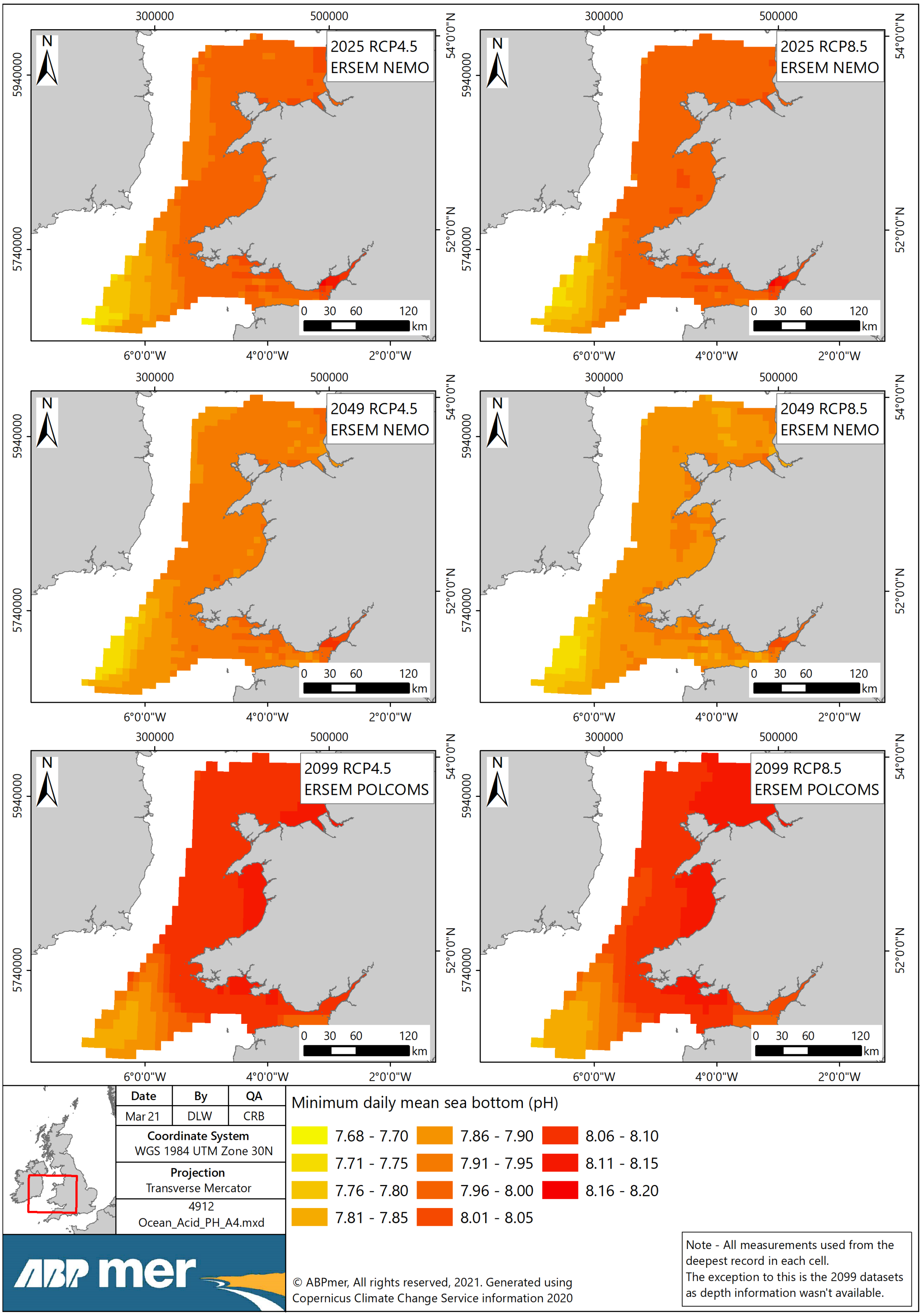

Figure 12. Minimum daily mean sea bottom pH in Welsh waters. Top left: ERSEM NEMO projections for the year 2025 and RCP4.5. Top right: ERSEM NEMO projections for the year 2025 and RCP8.5. Middle left: ERSEM NEMO projections for the year 2049 and RCP4.5. Middle right: ERSEM NEMO projections for the year 2049 and RCP8.5. Bottom left: ERSEM POLCOMS projections for the year 2099 and RCP4.5. Bottom right: ERSEM POLCOMS projections for the year 2099 and RCP8.5.

3.1.6. Deoxygenation

Increasing ocean temperatures reduce the solubility of oxygen in seawater and also enhance water column stratification (which reduces the vertical mixing of oxygenated waters). As such, global dissolved oxygen concentrations have declined by 2% since the 1960s. Approximately 15% of the global decline in oxygen has been attributed to reduced solubility, with the remaining 85% due to intensified stratification (though the relative contribution of these factors in coastal and shelf-sea waters is currently unknown) (Mahaffey *et al*., 2020). In the North Sea, oxygen concentrations and saturation has also decreased between 1990 and 2010 due to reduced oxygen solubility and an increase in oxygen utilisation.

Dissolved oxygen concentrations are predicted to continue to decrease with rising sea temperatures over the next century (medium confidence). Climate models predict concentrations could decline by up to 11.5% in the North Sea by 2100. Models also suggest there are large parts of the Celtic and Irish Sea that are prone to oxygen deficiency, but data is too sparse in time and space to support these findings (Mahaffey *et al*., 2020). The ability of models to accurately represent oxygen dynamics is still under debate due to correct representation of physical and biological processes within models.

Around Wales, minimum sea bottom dissolved oxygen concentrations projected by ERSEM over the next century (Figure 13) remain relatively high (generally around 6 mg/l). Away from the coast in deeper waters, lower dissolved oxygen concentrations are projected. In 2099 under RCP4.5 (ERSEM POLCOMS), dissolved oxygen concentrations of around 4 mg/l are projected (in 90 m water depth). Concentrations in the Bristol Channel are also projected to be relatively low, around 5 mg/l (in 25 m water depth). Note that oxygen concentrations shown in Figure 13 for 2099 are based on ERSEM POLCOMS projections and should not be directly compared with ERSEM NEMO projections in 2025 and 2049 (see Section 2.4). A declining trend in oxygen concentrations is also projected by ERSEM POLCOMS over the next century (not shown here).

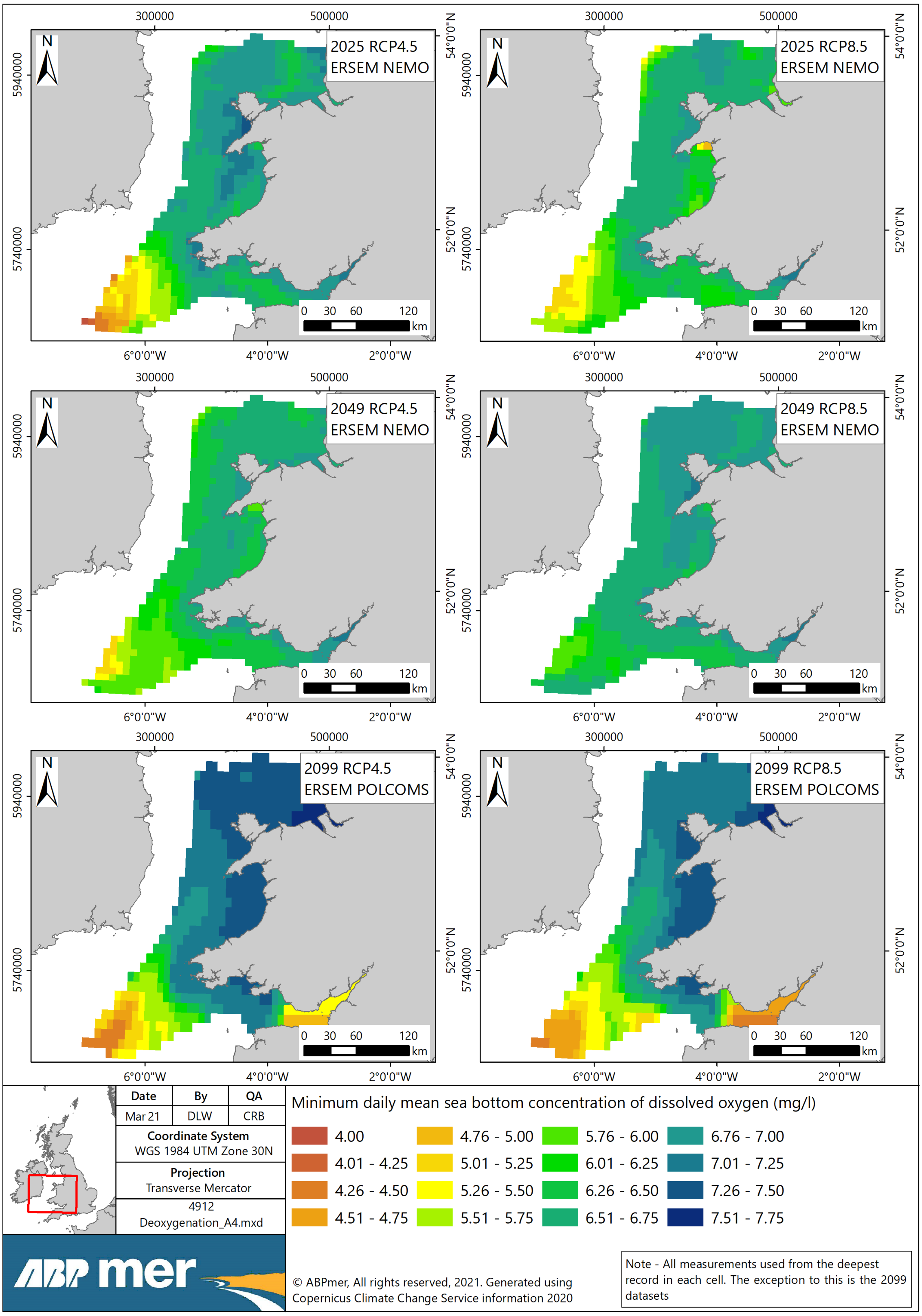

Figure 13. Minimum daily mean sea bottom concentrations of dissolved oxygen in Welsh waters. Top left: ERSEM NEMO projections for the year 2025 and RCP4.5. Top right: ERSEM NEMO projections for the year 2025 and RCP8.5. Middle left: ERSEM NEMO projections for the year 2049 and RCP4.5. Middle right: ERSEM NEMO projections for the year 2049 and RCP8.5. Bottom left: ERSEM POLCOMS projections for the year 2099 and RCP4.5. Bottom right: ERSEM POLCOMS projections for the year 2099 and RCP8.5.

3.1.7. Salinity

There are no clear long-term trends in salinity changes in UK shelf seas, with high variability on annual and decadal time scales. In the last five years, salinity has decreased in the eastern North Atlantic, probably due to atmospheric changes in the eastern North Atlantic about 10 years ago.

UK shelf seas are expected to be less saline than present, according to most model projections up to 2100 (medium confidence). This is due to changes in ocean-circulation. Greater decreases in salinity are projected for the North Sea, compared with the Celtic and Irish Sea near Wales. However, there is considerable uncertainty regarding future salinity (Dye *et al*., 2020).

Figure 14 shows projected changes in salinity in Welsh waters. The scale of projected changes is relatively small, with slight decreases projected over the next century. The lowest salinities are projected in the Severn Estuary. Projections provided by ERSEM POLCOMS differ due to the lower resolution of data which is not resolved in up-estuary locations compared with ERSEM NEMO projections (see Section 2.4). Note that salinity values shown in Figure 14 for 2083 are based on UKCP09 projections (which provide surface values, rather than values at depth as in ERSEM NEMO projections) and should not be directly compared with ERSEM NEMO projections in 2025 and 2049 (see Section 2.4).

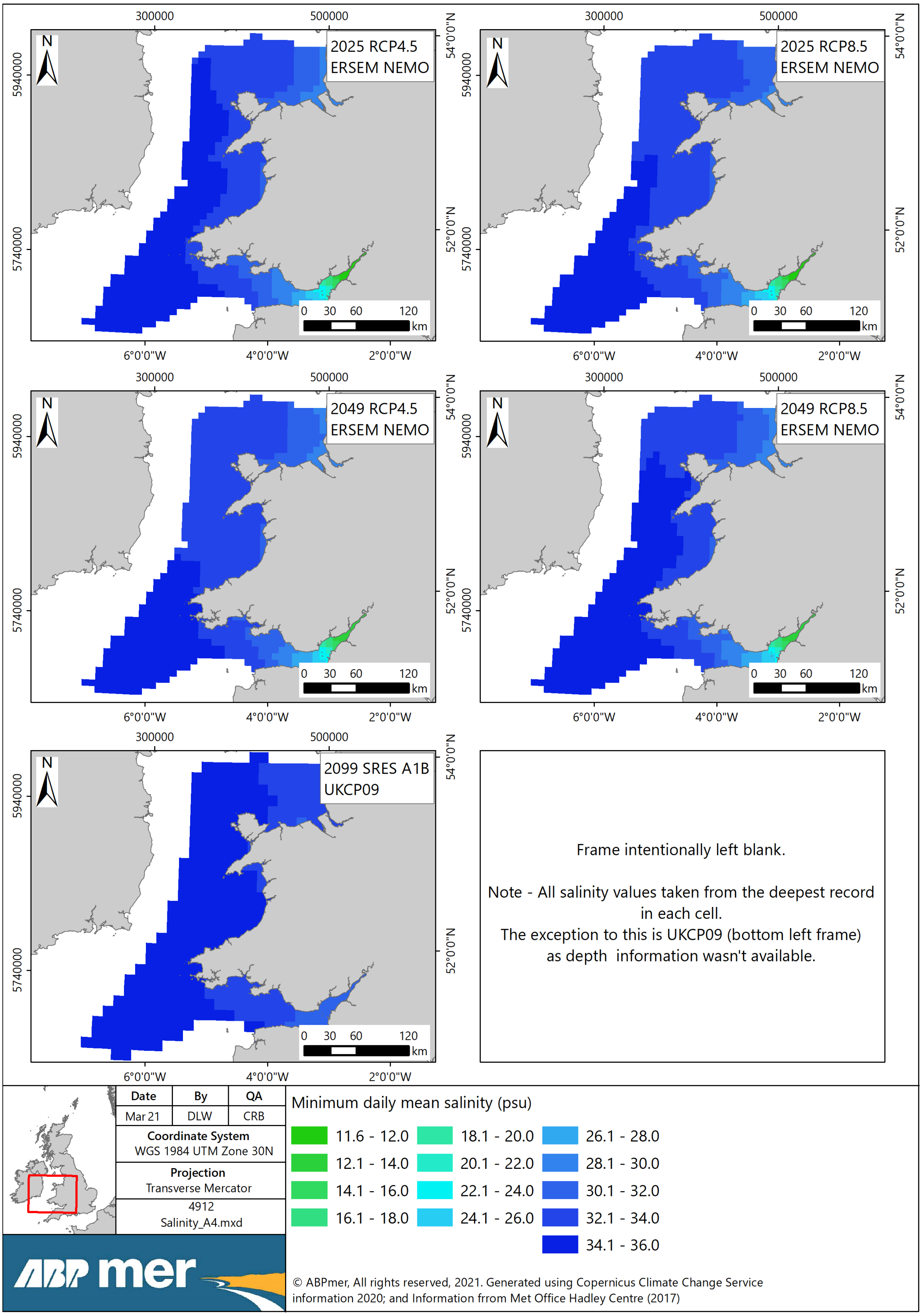

Figure 14. Minimum daily mean sea bottom salinity (psu) in Welsh waters. Top left: ERSEM NEMO projections for the year 2025 and RCP4.5. Top right: ERSEM NEMO projections for the year 2025 and RCP8.5. Middle left: ERSEM NEMO projections for the year 2049 and RCP4.5. Middle right: ERSEM NEMO projections for the year 2049 and RCP8.5. Bottom left: UKCP09 projections at surface for the year 2083 and SRES A1B.

3.1.8. Turbidity

Changes in turbidity are complex and can be driven by changes in suspended sediment and phytoplankton in the water column. Quantitative climate-induced changes in these factors are difficult to project given that they can be influenced by multiple factors such as precipitation, storminess, and riverine input (Jones *et al*., 2011). As such, the exposure of component biotopes of Annex I marine habitats to changes in turbidity cannot be considered in this project, and thus vulnerability cannot be assessed. However, the sensitivity of component biotopes to changes in turbidity is assessed in the pressure-sensitivity spreadsheet (*4912_Pressure-sensitivity relationships_22Feb2021.xlsx*) and summarised in Section 3.2.7.

3.1.9. Water column stratification

As summarised by Sharples *et al*. (2020), water column stratification occurs when less-dense water is situated above a layer of denser water. This reduces the vertical exchange of water and can act as a barrier to the transport of nutrients, oxygen, sediment and organic matter. Decreases in salinity and increases in temperature both causes seawater to be become less dense. Whether a water column becomes stratified is also influenced by effects of turbulence that act to mix the water vertically. Deep water, away from shallow coastal areas influenced by tides and waves, tends to experience stratification caused by the heating of surface waters in spring and summer. Stratification also occurs often in estuaries or regions of freshwater influence (Marine Scotland, 2020).

Trends in the strengthening of water column stratification over the past century are not evident, however, stratification is starting slightly earlier in the year over the North-West European shelf seas. Stratification influenced by freshwater in coastal regions also shows no long-term trends compared with natural variability.

It is predicted, albeit with low confidence, that by the end of this century thermal stratification will typically begin one week earlier than present in UK shelf seas, and end five to 10 days later. The strength of stratification in North-West European shelf seas is also projected to increase due to changes in seasonal heating (Sharples *et al*., 2020). This may lead to reductions in primary production and increases in eutrophication.

The strength of water column stratification is usually quantified as a potential energy anomaly. This is a quantitative measure of stratification that represents the work required to bring about complete mixing of a water column (measured as J/m^3) (Hall *et al*., 2018). The higher the potential anomaly, the more stratified the water column. A potential energy anomaly of zero is indicative of a fully mixed water column. A value of 20 J/m^3 can be considered the position of the frontal region where a transition between vertically mixed and stratified waters occurs (Marine Scotland, 2020).

In the majority of Welsh waters, projections of maximum monthly mean potential energy anomaly remain below 20 J/m^3 (and therefore considered to be mixed) (Figure 15). Only deeper waters offshore are projected to become stratified, particularly in the Celtic Sea off the south west coast of Pembrokeshire. This pattern is relatively consistent between timeframes and emissions scenarios. Note that potential energy anomaly values shown in Figure 15 for 2099 are based on ERSEM POLCOMS projections and should not be directly compared with ERSEM NEMO projections in 2025 and 2049 (see Section 2.4).

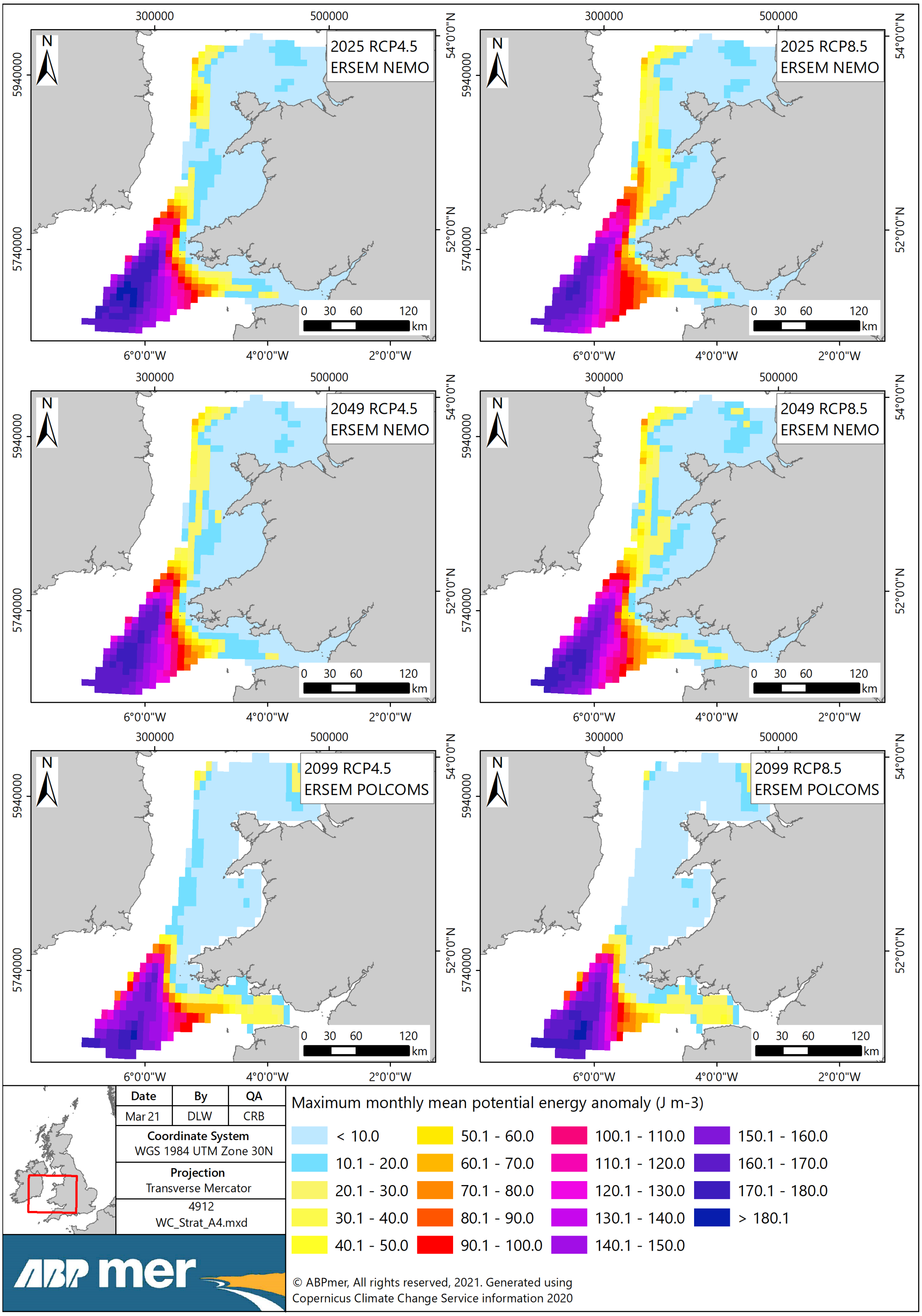

Figure 15. Maximum monthly mean potential energy anomaly (J/m³) in Welsh waters. Top left: ERSEM NEMO projections for the year 2025 and RCP4.5. Top right: ERSEM NEMO projections for the year 2025 and RCP8.5. Middle left: ERSEM NEMO projections for the year 2049 and RCP4.5. Middle right: ERSEM NEMO projections for the year 2049 and RCP8.5. Bottom left: UKCP09 projections at surface for the year 2083 and SRES A1B.

3.1.10. Water quality due to run-off

An indirect impact of increased precipitation over land (which is projected to increase over the UK and Wales in winter due to climate change) is increased delivery of sediments, nutrients and pollution by rivers. Anecdotal evidence of these effects across Wales are reported by NRW.

Projected values for changes in winter (DJF) and summer (JJA) mean river flow relative to the 1961 – 1990 baseline provided by CEH Future Flows have been used here to infer the potential exposure of Annex I habitats to changes in run-off and water quality in Welsh waters (see Section 2.4). Percentage change in winter and summer mean river flow for upstream rivers have been mapped to WFD waterbodies (Figure 16).

Projections suggest increases in Welsh riverine discharge during winter, and decreases in summer, towards the end of the century. This pattern is fairly uniform for WFD transitional waterbodies across Wales. The Severn Estuary WFD transitional waterbody, for example, is projected to receive a 27% increase in run-off in winter in 2098. In north Wales, run-off into the Glaslyn WFD transitional waterbody is projected to increase by 76%. However, projected trends in river flows and run-off are very variable, particularly in summer (e.g. a large increase in run-off is projected for 2025). As discussed by Hannaford (2015), past observations of river flows in the UK have identified a very mixed pattern in summer flows punctuated by anonymously wet summers (with no evidence of a decrease in flows as projected by most future climate studies). There is limited consensus on the cause of these anomalous summers and the relative roles of drivers such as sea surface temperature anomalies and sea ice declines.

It is important to recognise that this assessment of exposure to changes in run-off should be considered indicative only. The spatial coverage of the projections data was relatively poor and only accounted for a small number of catchments or tributaries that discharge into WFD transitional waterbodies. Furthermore, as described in Section 2.5, changes in water quality due to run-off would be affected by other factors such as land use and pollution of local water courses, and not just changes in riverine discharge.

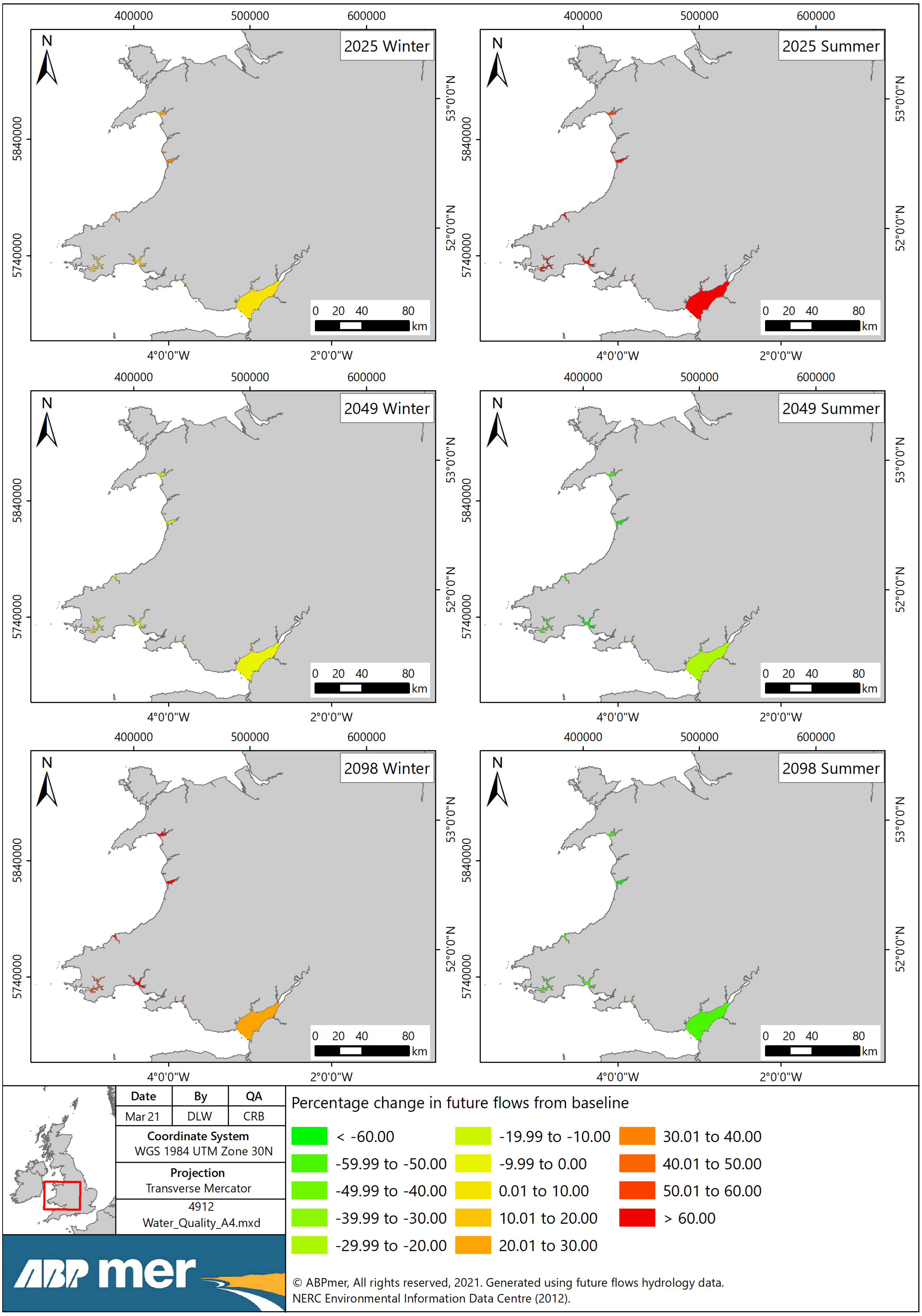

Figure 16. Projected changes in winter (DJF) and summer (JJA) mean river flow relative to the 1961 – 1990 baseline provided by CEH Future Flows mapped to WFD waterbodies

3.2. Sensitivity to climate change pressures

Sensitivities to climate change pressures differ for each component biotope of Annex I habitats. Therefore, a high-level summary and key examples of the findings of the sensitivity assessment are provided in this section. The sensitivity thresholds and supporting evidence for each component biotope are documented in an accompanying Microsoft Excel spreadsheet (*4912_Pressure-sensitivity relationships_31Mar2021.xlsx*).

3.2.1. Air and sea temperature

In terms of sensitivities to a warming climate, one key factor is the current distribution of component biotopes. Those at the southern limit of their distribution in Wales are likely to be most sensitive to increases in temperature (Hiscock *et al*., 2004). For example, *Semibalanus balanoides* (present in biotopes LR.MLR.BF, LR.LLR.F, LR.LLR.FVS, for example, which are component biotopes of Estuaries, Large shallow inlets and bays, and Reef) is found closer to the southern extent of its range in Wales and higher temperatures could reduce its reproductive capacity and cause this species to contract its range northwards (Perry and Hill, 2015). *Modiolus modiolus* (present in biotopes SS.SBR.SMus, which is a component biotope of Reef features in the Pen Llyn a'r Sarnau SAC) is a boreal species, and the fact that dense aggregations reach their southern limit in the North East Atlantic around Welsh, Scottish and Irish shores suggests this species is sensitive to ocean warming (Tillin *et al*., 2020a). Biotopes with distributions further south than Wales (e.g. on the south coast of England, France and Spain/Portugal) have the potential to increase their distribution further north as sea and air temperatures warm. Many of the intertidal algae characteristic of shores in Wales, such as species of *Fucus* (present in biotope LR.MLR.BF, for example, which is a component biotope of Estuaries, Large shallow inlets and bays, and Reef), occur extensively further south (and north) on the coasts of the northeast Atlantic, suggesting that they are unlikely to be adversely affected by increased air and sea temperatures (Hiscock *et al*., 2004).

Equally, range expansion of competitors to native species may cause climate related impacts. Ocean warming has caused poleward range expansion of the warm temperate kelp *Laminaria ochroleuca* and led to competition with cold-water kelp *Laminaria hyperborea* (present in biotope IR.HIR.KFaR, for example, which is a component biotope of Reef, Large shallow inlets and bays, and Estuaries) in the south west of England and west coast of Ireland waters this century (Smale *et al*., 2015). *L. hyperborea* has suffered a 250 km range constriction since 1970 at its southern extent (Assis *et al*., 2016). Replacement of *L. hyperborea* with *L. ochroleuca* in Wales may alter ecological function and ecosystem services as *L. ochroleuca* is known to be less resistant to storms and may support less diverse biological communities (Smale and Vance, 2015).

Another key driver in the sensitivity of component biotopes is where they occur in the tidal/subtidal zone. Component biotopes that comprise intertidal Annex I marine habitats are generally considered more tolerant of higher temperatures and were assigned higher value sensitivity thresholds (i.e. less sensitive) or were considered not sensitive to temperature changes. This is because these biotopes are regularly exposed to temperature fluctuations, and higher temperatures when exposed to the air. Therefore, the characterising species of these biotopes are often well adapted to higher temperatures (though they may still be sensitive to extreme temperatures during marine heatwaves). For example, *Mytilus edulis* is a eurytopic species found in the intertidal and subtidal zone (present in biotope LS.LBR.LMus, for example, comprising part of Estuaries, Large shallow inlets and bays, and Reef) and tolerates wide temperature ranges from mild, subtropical regions to areas which frequently experience freezing conditions (Tillin and Tyler-Walters, 2015). *M. modiolus* beds (present in biotope SS.SBR.SMus which is a component biotope of Reef) occur in the subtidal environment and are less tolerant of higher temperatures; the depth range of *M. modiolus* increases at higher latitudes with intertidal specimens more common on northern Norwegian shores where air temperatures are lower (Davenport & Kjørsvik, 1982). However, intertidal biotopes would be exposed to increased air temperatures over the next century and could suffer impacts such as desiccation, whereas subtidal biotopes would be largely protected from this pressure (aside from increased sea temperatures during marine heatwaves from air-sea flux (see Section 3.1.2)).

Some biotopes might specifically benefit from increased temperatures. *Sabellaria alveolata* (present in biotope LS.LBR.Sab, comprising part of Estuaries, Large shallow inlets and bays, and Reef) is distributed as far south as Morocco where air temperatures regularly reach 28°C (Tillin *et al*., 2020b). The growth of tubes in winter was also observed to be greater in the cooling water outfall at Hinkley Point, Somerset, where the water temperature was raised by around 8-10°C compared to a control site (Bamber and Irving, 1997). The sea fan *Eunicella verrucosa* is also at the northern limit of its distribution in Skomer, Wales, and therefore may increase in extent northwards with increasing temperatures (Hiscock *et al*., 2004).

3.2.2. Sea level rise

For the purposes of this assessment, it was assumed that landward migration of biotopes is not possible (see Section 4.2.2). Intertidal component biotopes are therefore considered sensitive to changes in sea level, whereas subtidal biotopes are generally not sensitive to this pressure. Only subtidal biotopes that are light dependent are considered to have a degree of sensitivity to sea level rise. For example, light availability and water turbidity are principle factors in determining kelp depth range, with laminarians being reported to be able to withstand light levels of up to 1% surface irradiance (Stamp and Garrard, 2020). If landward migration is not possible, it is expected that depth distribution of this biotope will shrink substantially in response to sea-level rise.

The most sensitive biotopes to sea level rise are considered to be littoral sand, mud and saltmarsh biotopes on the upper and mid-shore of broad estuaries (i.e. comprising Estuaries, Mudflats and sandflats not covered by seawater at low tide, Large shallow inlets and bays, Atlantic salt meadows, *Salicornia* and other annuals colonising mud and sand). Assuming landward migration is not possible (e.g. where there is a cliff or hard defence backing the intertidal habitat), an increase in sea level height could have severe repercussions for the extent of these biotopes as they are likely to be submerged, eroded, or moved through a mechanism known as coastal squeeze[17]. The effects of sea level rise could be amplified by increases in wave action due to storms and storm surges. However, it is important to recognise that each shoreline profile would exhibit different behaviours, and the effect of sea level rise will be very site-specific and largely dependent on the geomorphological settings (Jolley *et al*., 2013). For example, on sedimentary shorelines rates of sedimentation would influence whether the extent of intertidal habitat would be lost due to sea level rises, or whether vertical accretion would keep pace with rises in sea level

[17] See report entitled 'What is coastal squeeze?' (Pontee *et al.,* 2021)

(Bouma *et al*., 2016). Flat rocky shore platforms may also be vulnerable to loss where steeper backing cliffs do not erode as sea levels rise (Jolley *et al*., 2013).

Where biotopes occupy the lower to mid shore (e.g. biotope LS.LMu.UEst, which is a component biotope of Estuaries, Mudflats and sandflats not covered by seawater at low tide, and Large shallow inlets and bays), it is possible that sea level rise could extend the upper extent of the biotope as the species recolonise or migrate to favourable conditions (Ashley, 2016a). However, for the purposes of the sensitivity assessment, landward migration was assumed not to be possible.

3.2.3. Wave exposure

Only biotopes in the intertidal zone and shallow sublittoral zone were considered sensitive to changes in wave exposure, and therefore a considerable number of biotopes were considered not sensitive to changes in wave exposure. Where a pressure-sensitivity relationship has been identified, most component biotopes are considered to tolerate changes in wave exposure < 3% but be highly sensitive to changes > 5% to wave exposure.

Sensitivity to wave exposure is a product of mechanical damage to organisms and dislodging of flora and fauna from the substratum, which can affect the extent and distribution of biotopes. Fucoids (present in biotope LR.HLR.FT, for example, which is a component biotope of Estuaries, Mudflats and sandflats not covered by seawater at low tide, Large shallow inlets and bays, and Reef) are susceptible to this, as they are highly flexible but not physically robust, and cannot reattach once the holdfast is dislodged (Perry and Hill, 2020). Wave energy can also affect the underlying sediment of some biotopes. *Zostera* beds (biotopes LS.LMp.LSgr and SS.SMp.SSgr, which are component biotopes of Large shallow inlets and bays, Estuaries, and Mudflats and sandflats not covered by seawater at low tide) may suffer from wave-induced mobilisation of sediments in coastal areas causing sediment resuspension and reduced photosynthesis (see Section 3.2.7), but also coarser sediment grain size with lower nutrient concentrations (D'Avack *et al*., 2020). Wave exposure will also affect accretion and erosion rates in saltmarsh (i.e. biotope LS.LMp.Sm, the component of Atlantic salt meadows, *Salicornia* and other annuals colonising mud and sand); wave action may erode areas at the face of the raised salt marsh, resulting in a 'cliff' which may undermine the edges of creeks (Tyler-Walters, 2001).

3.2.4. Ocean acidification

Limited evidence is available on the sensitivity of Annex I marine habitat component biotopes to ocean acidification. Many species show variation in their response to acidification independent of their taxonomic group or habitat preference (Kroeker *et al*., 2013). In general, it is thought that calcifying invertebrates will be more sensitive to ocean acidification than non-calcifying invertebrates (Hofmann *et al*., 2010). Coralline algae, such as maerl (biotope SS.SMp.Mrl, which is a component biotope of the Large shallow inlets and bays feature in the Pembrokeshire Marine SAC; this is the only known maerl bed in Wales), are thought to be one of the groups of species most vulnerable to ocean acidification due to the solubility of their high magnesium-calcite skeletons (Martin and Hall-Spencer, 2017). Circalittoral mixed sediment (biotope SS.SMx.CMx, which is a component biotopes of Estuaries, Large shallow inlets and bays, Sandbanks which are slightly covered by seawater all the time, and Reef) containing brittlestars *Ophiothrix* *fragilis* and *Ophiocomina nigra* is also considered to be sensitive to low pH; a 0.2-unit pH decrease led to almost 100% mortality in *Ophiothrix fragilis* larvae after one week's exposure, and in low pH conditions surviving larvae of *Ophiothrix fragilis* show skeletal malformations (De-Bastos *et al*., 2020).

Not all calcified organisms (and their respective biotopes) were considered to be sensitive to ocean acidification. *Mytilus edulis* (present in biotope LR.MLR.MusF, for example, which is a component biotope of Estuaries, Large shallow inlets and bays, Reef) is a calcified organism but acidification does not appear to lead to mortality, even at levels which exceed those expected for the end of this century (pH 7.6 – 7.7) (Berge *et al.,* 2006, Melzner *et al.,* 2011).

However, marine autotrophs (e.g. kelp present in biotope IR.HIR.KFaR, for example, which is a component biotope of Estuaries, Large shallow inlets and bays, Reef) are likely to benefit from ocean acidification, through an increased availability of dissolved CO_2 for photosynthesis (Koch *et al.,* 2013). Many species of algae, such as *Pelvetia canaliculata*, also appear to be under-saturated in respect to CO_2 (Koch *et al.,* 2013).

3.2.5. Deoxygenation

Oxygen concentrations above 6 mg/l are considered to be sufficient to support healthy marine communities with minimal problems (OSPAR, 2017). Cole *et al.* (1999) suggested possible adverse effects on marine species exposed to dissolved oxygen concentrations below 4 mg/l and probable adverse effects below 2 mg/l.

Most intertidal biotopes and characterising species are considered either not sensitive to deoxygenation or have a high degree of tolerance to low dissolved oxygen concentrations. For example, *Arenicola marina* (present in biotopes LS.LSa.FiSa and LS.LSa.MuSa, for example, comprising part of the Estuaries, Large shallow inlets and bays, and Mudflats and sandflats not covered by seawater at low tide) is subject to reduced oxygen concentrations regularly at low tide and is capable of anaerobic respiration (Ashley, 2016b). Some species are also mobile and able to migrate to escape unsuitable conditions.

3.2.6. Salinity

Component biotopes found in variable salinities regimes are more tolerant of fluctuations in salinity (e.g. biotope LR.LLR.FVS, which is a component biotope of Estuaries, Large shallow inlets and bays, Mudflats and sandflats not covered by seawater at low tide, Reef and Coastal lagoons). These tend to be located in estuaries and in the intertidal environment where evaporation increases salinity and inputs of rainwater expose individuals to freshwater (Perry and Garrard, 2020). Characterising species of these biotopes tend to be euryhaline and able to withstand very low salinity levels. Some species found in the intertidal biotopes have behavioural or physiological adaptations to changes in salinity. For example, *S. balanoides* (present in biotope LR.MLR.BF, which is a component biotope of Estuaries, Large shallow inlets and bays, and Reef) has the ability to isolate itself from water by closing their opercula valves and can withstand large changes in salinity over moderately long periods of time by falling into a "salt sleep" (Perry and Garrard, 2020).

The sensitivities of biotopes may also depend on local adaptations and acclimatisation to the prevailing salinity regime.

3.2.7. Turbidity

Sensitivities to increased suspended sediment concentrations vary between component biotopes of Annex I marine habitats. In general, increased suspended particles have the potential to increase light attenuation. Therefore, biotopes that are dependent on light are considered more sensitive to this pressure. For example, an increase in water clarity from clear to intermediate (10-100 mg/l) represents a change in light attenuation of *ca.* 0.67-6.7 Kd/m and is likely to result in a greater than 50% reduction in photosynthesis of *Laminaria* spp. (present in biotope IR.HIR.KFaR, for example, which is a component biotope of Reef, Large shallow inlets and bays, and Estuaries) (Stamp *et al*., 2020). Similarly, seagrass populations (present in biotopes LS.LMp.LSgr and SS.SMp.SSgr, which are component biotopes of Large shallow inlets and bays, Estuaries, and Mudflats and sandflats not covered by seawater at low tide) are likely to survive short-term increases in turbidity, however, a prolonged increase in light attenuation, especially at the lower depths of its distribution, will impair photosynthesis and probably result in loss of or damage to the population (D'Avack *et al*., 2019). Increased turbidity can also reduce the amount of oxygen available for respiration by the roots and rhizomes thus lowering nutrient uptake.

Other mechanisms caused by increased turbidity that biotopes can be sensitive to include increase scour and deposition. This can adversely affect foliose red algae in rock pools (biotope LR.FLR.Rkp, a component biotope of Reef, Large shallow inlets and bays, and Estuaries), for example, and interfere with settling spores and recruitment (Tillin and Budd, 2016). Increased suspended particulate matter may also enhance food supply to filter or deposit feeders (where the particles are organic in origin) or decrease feeding efficiency (where the particles are inorganic and require greater filtration efforts). For example, concentrations of suspended sediments above 250 mg/l have been shown to impair the growth of filter-feeding organisms (Essink, 1999).

3.3. Vulnerability to climate change pressures

The full set of model output tables providing the vulnerability assessment results are presented in a series of Microsoft Excel spreadsheets, with a separate file provided for each climate change pressure (*4912_[Climate change pressure]_vulnerability assessment_31Mar2021.xlsx*). A sub-set of the vulnerability assessment for each climate change pressure is provided in this section, highlighting key results with a focus on Annex I features (i.e. Annex I habitats that are designated features within SACs) that are particularly vulnerable. Results for the year 2049 and RCP 8.5 are reported for each pressure.

3.3.1. Sea temperature

In general, the majority of the spatial coverage of component biotopes of Annex I features (within SACs) to projected changes in sea temperature was mapped as low vulnerability, or they were considered not sensitive (Figure 17). Only a small percentage coverage of the component biotopes was assessed as having a high vulnerability in any year or scenario. The spatial coverage of component biotopes scored as having a medium vulnerability increased for RCP8.5 compared with RCP4.5, for both 2025 and 2049.

A sub-set of the vulnerability assessment results for sea temperature change by 2049 under RCP8.5 is presented in Table 7, and described below (based on sites that have features containing biotopes sensitive to this pressure). The percentage values shown in the table represent the predicted spatial coverage of component biotopes with differing vulnerabilities to projected changes in sea temperature within an Annex I feature (within a SAC).

The component biotopes of Mudflats and sandflats not covered by seawater at low tide were mostly assessed as not sensitive with respect to spatial coverage (70%), 3% were assessed as low vulnerability, 25% as medium vulnerability, and 2% high vulnerability. The Dee Estuary SAC, Menai Strait and Conwy Bay SAC, Pen Llŷn a`r Sarnau SAC and Carmarthen Bay and Estuaries SAC had a greater extent of biotopes assessed as medium vulnerability at 46%, 37%, 34% and 32% respectively. A small percentage (8%) of Mudflats and sandflats not covered by seawater at low tide component biotopes in the Severn Estuary SAC were assessed as high vulnerability. Component biotopes assessed as highly vulnerable include polychaete/bivalve dominated muddy sand shores (biotope LS.LSa.MuSa). This biotope was given a high sensitivity threshold of 24°C and is projected to be exposed to maximum daily mean sea bottom temperatures of around 25°C in the Severn Estuary.

Sandbanks which are slightly covered by seawater all the time were mostly assessed as medium vulnerability (43% coverage). 18% coverage was assessed as not sensitive, 39% low, and 0% high. The Severn Estuary SAC, Menai Strait and Conway Bay SAC, and Cardigan Bay SAC had the greatest extent of Sandbank biotopes assessed as medium vulnerability at 78%, 67% and 65% respectively. Component biotopes assessed as medium vulnerability include infralittoral muddy sand (biotope SS.SSa.IMuSa), which was given a medium sensitivity threshold of between 20°C and 25°C.

The difference between Mudflats and sandflats not covered by seawater at low tide and Sandbanks which are slightly covered by seawater all the time may be partly attributable to the fact that intertidal biotopes tend to be tolerant of high and variable temperatures, whereas subtidal biotopes are less adapted to high temperatures (as they are constantly submerged and not exposed to variations in temperature like intertidal biotopes) (see Section 3.2.1).

67% of the extent of *Salicornia* and other annuals colonising mud and sand within SACs was also assessed as medium vulnerability, with 33% assessed as low vulnerability overall. Within the Pen Llŷn a`r Sarnau SAC, 99% of the spatial coverage of *Salicornia* and other annuals colonising mud and sand was assessed as medium vulnerability. Similarly, 61% of the extent of Atlantic salt meadow within SACs was assessed as medium vulnerability, with 39% assessed as low vulnerability overall. Atlantic salt meadow features within the Severn Estuary SAC, Carmarthen Bay and Estuaries SAC, and Pen Llyn a'r Sarnau SAC were assessed as medium vulnerability for 100%, 79% and 74% of its spatial coverage, respectively. Saltmarsh (biotope LS.LMp.Sm) was assigned a medium sensitivity threshold of between 23.25°C and 28.25°C.

Component biotopes within Large shallow inlets and bays were also mainly assessed as medium vulnerability (52%). Carmarthen Bay and Estuaries SAC had the greatest extent of medium vulnerability Large shallow inlets and bays component biotopes at 71%.

The component biotopes of Subtidal reef features were assessed as less vulnerable. 80% coverage was assessed a low vulnerability, 15% medium, and 1% high, whilst 4% coverage was assessed as not sensitive. Subtidal reef features in the Severn Estuary SAC were assessed as most vulnerable with 52% of the spatial coverage of component biotopes assessed as medium vulnerability. Circalittoral coarse sediment (biotope SS.SCS.CCS) is an example component biotope, which was assigned a medium sensitivity threshold of between 24°C and 25°C and is projected to be exposed to similar maximum daily mean sea bottom temperatures in the Severn Estuary. Notably, *M. modiolus* component biotopes (i.e. biotope SS.SBR.SMus) of Subtidal reef features found in Pen Llŷn a`r Sarnau SAC were assessed a low vulnerability (assigned a low sensitivity threshold of < 20°C, exposed to projected maximum daily mean sea bottom temperatures of around 18°C). This is despite them being considered sensitive to warming as they are a boreal species and north Wales is their southernmost extent (see Section 3.2.1). However, *M. modiolus* may be more sensitive to increases in winter temperature rather than maximum temperatures used in this assessment (see Section 4.3).

Component biotopes of Submarine structures made by leaking gases (Methane-derived authigenic carbonates) were mostly assessed as medium vulnerability (84% coverage) with 16% coverage assessed as high, all in Pen Llyn a'r Sarnau SAC (methane-derived authigenic carbonates are not a designated feature of the Pen Llyn a'r Sarnau SAC though they are found within the site and included in Article 17 reporting).

For RCP4.5 the vulnerability of some biotopes (e.g. biotope SS.SSa.IMuSa in Carmarthen Bay and Estuaries SAC) decreased slightly from medium to low between 2025 and 2049. This is counterintuitive, but temperatures decreased very slightly in the projections (*ca*. 0.3°C) to below the prescribed sensitivity for some biotopes. This highlights the sensitivity of the model to the sensitivity thresholds that are set and the underlying projections (see Section 4.3).

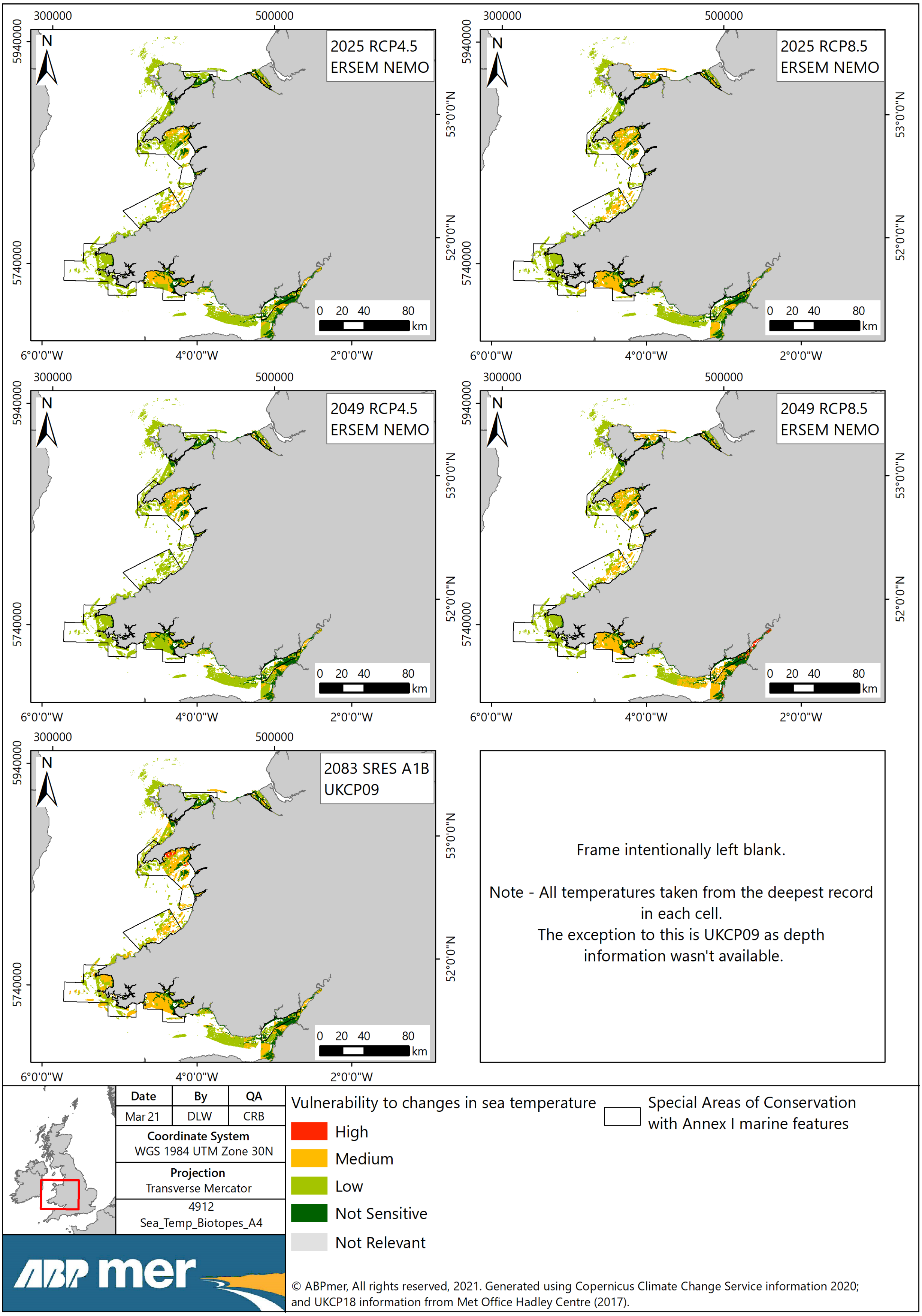

Figure 17. Vulnerability of component biotopes of Annex I marine habitats to projections of sea temperature.

Table 7. Sub-set of vulnerability assessment results (given as percentage areas of features in each site) for sea temperature change expected by 2049 under RCP8.5 (red boxes highlight largest percent areas in each category)

Vulnerable features in SACs	Not vulnerable	Low	Medium	High	Not relevant
Mudflats and sandbanks not covered by seawater at low tide	-	-	-	-	-
Carmarthen Bay and Estuaries / Bae Caerfyrddin ac Aberoedd	68%	0%	32%	0%	0%
Dee Estuary / Aber Dyfrdwy (Wales)	54%	0%	46%	0%	0%
Glannau Mon: Cors heli / Anglesey Coast: Saltmarsh	49%	51%	0%	0%	0%
Pembrokeshire Marine / Sir Benfro Forol	74%	24%	2%	0%	0%
Pen Llyn a'r Sarnau / Lleyn Peninsula and the Sarnau	65%	1%	34%	0%	0%
Severn Estuary (Wales)	88%	0%	3%	8%	0%
Y Fenai a Bae Conwy / Menai Strait and Conwy Bay	59%	4%	37%	0%	0%
Overall	**70%**	**3%**	**25%**	**2%**	**0%**
Sandbanks which are slightly covered by seawater all the time	-	-	-	-	-
Cardigan Bay / Bae Ceredigion	2%	32%	65%	0%	0%
Carmarthen Bay and Estuaries / Bae Caerfyrddin ac Aberoedd	5%	62%	33%	0%	0%
Pembrokeshire Marine / Sir Benfro Forol	0%	100%	0%	0%	0%
Pen Llyn a'r Sarnau / Lleyn Peninsula and the Sarnau	31%	44%	25%	0%	0%
Severn Estuary (Wales)	19%	0%	78%	3%	0%
Y Fenai a Bae Conwy / Menai Strait and Conwy Bay	23%	10%	67%	0%	0%
Overall	**18%**	**39%**	**43%**	**0%**	**0%**
Large shallow inlets and bays	-	-	-	-	-
Carmarthen Bay and Estuaries / Bae Caerfyrddin ac Aberoedd	23%	5%	71%	0%	0%
Pembrokeshire Marine / Sir Benfro Forol	9%	90%	1%	0%	0%
Pen Llyn a'r Sarnau / Lleyn Peninsula and the Sarnau	15%	26%	58%	0%	0%
Y Fenai a Bae Conwy / Menai Strait and Conwy Bay	37%	7%	55%	0%	0%
Overall	**20%**	**28%**	**52%**	**0%**	**0%**
Salicornia and other annuals colonising mud and sand	-	-	-	-	-
Carmarthen Bay and Estuaries / Bae Caerfyrddin ac Aberoedd	0%	66%	34%	0%	0%
Dee Estuary / Aber Dyfrdwy (Wales)	0%	100%	0%	0%	0%
Glannau Mon: Cors heli / Anglesey Coast: Saltmarsh	0%	100%	0%	0%	0%
Pen Llyn a'r Sarnau / Lleyn Peninsula and the Sarnau	0%	1%	99%	0%	0%
Overall	**0%**	**33%**	**67%**	**0%**	**0%**
Atlantic salt meadows	-	-	-	-	
Carmarthen Bay and Estuaries / Bae Caerfyrddin ac Aberoedd	0%	21%	79%	0%	0%

Vulnerable features in SACs	Not vulnerable	Low	Medium	High	Not relevant
Dee Estuary / Aber Dyfrdwy (Wales)	0%	100%	0%	0%	0%
Glannau Mon: Cors heli / Anglesey Coast: Saltmarsh	0%	100%	0%	0%	0%
Pembrokeshire Marine / Sir Benfro Forol	0%	100%	0%	0%	0%
Pen Llyn a'r Sarnau / Lleyn Peninsula and the Sarnau	0%	26%	74%	0%	0%
Severn Estuary (Wales)	0%	0%	100%	0%	0%
Overall	**0%**	**39%**	**61%**	**0%**	**0%**
Subtidal reef	-	-	-	-	-
Cardigan Bay / Bae Ceredigion	2%	80%	17%	0%	0%
Pembrokeshire Marine / Sir Benfro Forol	1%	96%	3%	0%	0%
Pen Llyn a'r Sarnau / Lleyn Peninsula and the Sarnau	2%	77%	19%	1%	0%
Severn Estuary (Wales)	47%	0%	52%	0%	0%
Y Fenai a Bae Conwy / Menai Strait and Conwy Bay	33%	38%	27%	3%	0%
Overall	**4%**	**80%**	**15%**	**1%**	**0%**
Submarine structures made by leaking gases (Methane-derived authigenic carbonates)	-	-	-	-	-
*Pen Llyn a'r Sarnau / Lleyn Peninsula and the Sarnau	0%	0%	84%	16%	0%
Overall	**0%**	**0%**	**84%**	**16%**	**0%**

*Submarine structures made by leaking gases (Methane-derived authigenic carbonates) is not a feature of the Pen Llyn a'r Sarnau SAC, but they are found within the site and included in Article 17 reporting. Methane-derived authigenic carbonates is a feature offshore in the Croker Carbonate Slabs SAC.

3.3.2. Air temperature

There was little change in component biotope vulnerability to air temperature over the next century under RCP 8.5. Air temperature is considered not relevant to component biotopes that are subtidal; some intertidal features were assessed as highly vulnerable (Figure 18).

A sub-set of the vulnerability assessment results for air temperature in 2049 under RCP8.5 is presented in Table 8 and are described below. These percentage values represent the predicted spatial coverage of component biotopes with differing vulnerabilities to projected changes in air temperature within an Annex I feature (within an SAC).

Atlantic salt meadows and *Salicornia* and other annuals colonising mud and sand features were assessed as highly vulnerable to projected changes in air temperature. 97% and 98% overall of the spatial extent of these features were assessed as highly vulnerable, respectively. A high sensitivity threshold for saltmarsh (biotope LS.LMp.Sm) was set at > 28°C. Within the majority of SACs (with the exception of Anglesey Coast: Saltmarsh SAC), 100% coverage of saltmarsh features was assessed as high vulnerability as maximum daily air temperatures are projected to exceed 30°C in these locations.

Submerged or partially submerged sea cave feature biotopes were also assessed as relatively vulnerable to air temperature; 113 sea cave biotopes[18] were considered to have a high vulnerability, 26 low, and 6 not relevant. The Limestone Coast of South West Wales SAC had the highest number of sea caves assessed as highly vulnerable (66). In SACs located on the south coast (e.g. Pembrokeshire Marine SAC, Limestone Coast of South West Wales SAC) maximum daily mean air temperatures are projected to exceed 30°C, which exceeds the high threshold assigned to littoral caves and overhangs (biotope LR.FLR.CvOv; the main component biotope of Submerged or partially submerged sea cave feature).

For Intertidal reef, 41% of the total spatial extent of biotopes comprising this feature in Wales was assessed as being not sensitive to this pressure. At the other end of the scale, 26% of intertidal reef biotopes in sites across Wales was assessed as having high vulnerability. On an individual site basis, Pembrokeshire Marine SAC had the highest spatial extent of intertidal reef biotopes assessed as highly vulnerable at 38%. This was due to the relatively large coverage of component biotopes with fucoid species (namely biotopes LL.LLR.F and LL.MLR.BF) for which high sensitivity thresholds were set at 26°C and 30°C (with projected maximum daily mean air temperatures exceeding 30°C).

Although the period of exposure to pressures has not been accounted for in the model (see Section 4.3), it is worth noting that spatial vulnerability to air temperature may be influenced by the timing of low water on spring tides which varies around the coast. The regular motion of the sun, moon and earth cause spring tides to occur at roughly the same time of day for any given location (NTSLF, 2021). In north Wales (e.g. in the Dee Estuary, Menai Strait, Cemlyn Bay, Anglesey) neap tides coincide with peak solar irradiance (i.e. around midday and also around midnight). In south Wales (e.g. in the Severn Estuary, and Carmarthen Bay), low tide occurs either side of peak solar irradiance during neap tides (i.e. in the morning and evening). The opposite is the case during spring tides; in north Wales low tide occurs either side of peak solar irradiance, and in south Wales low tide coincides with peak solar irradiance. Therefore, as low spring tides expose the greatest extent of intertidal biotopes in the lower littoral zone to air, intertidal Annex I features in south Wales may be particularly vulnerable to increases in air temperature over the next century. Further analysis on this is presented in Appendix A.

[18] Sea cave features were counted, rather than considered by percentage coverage.

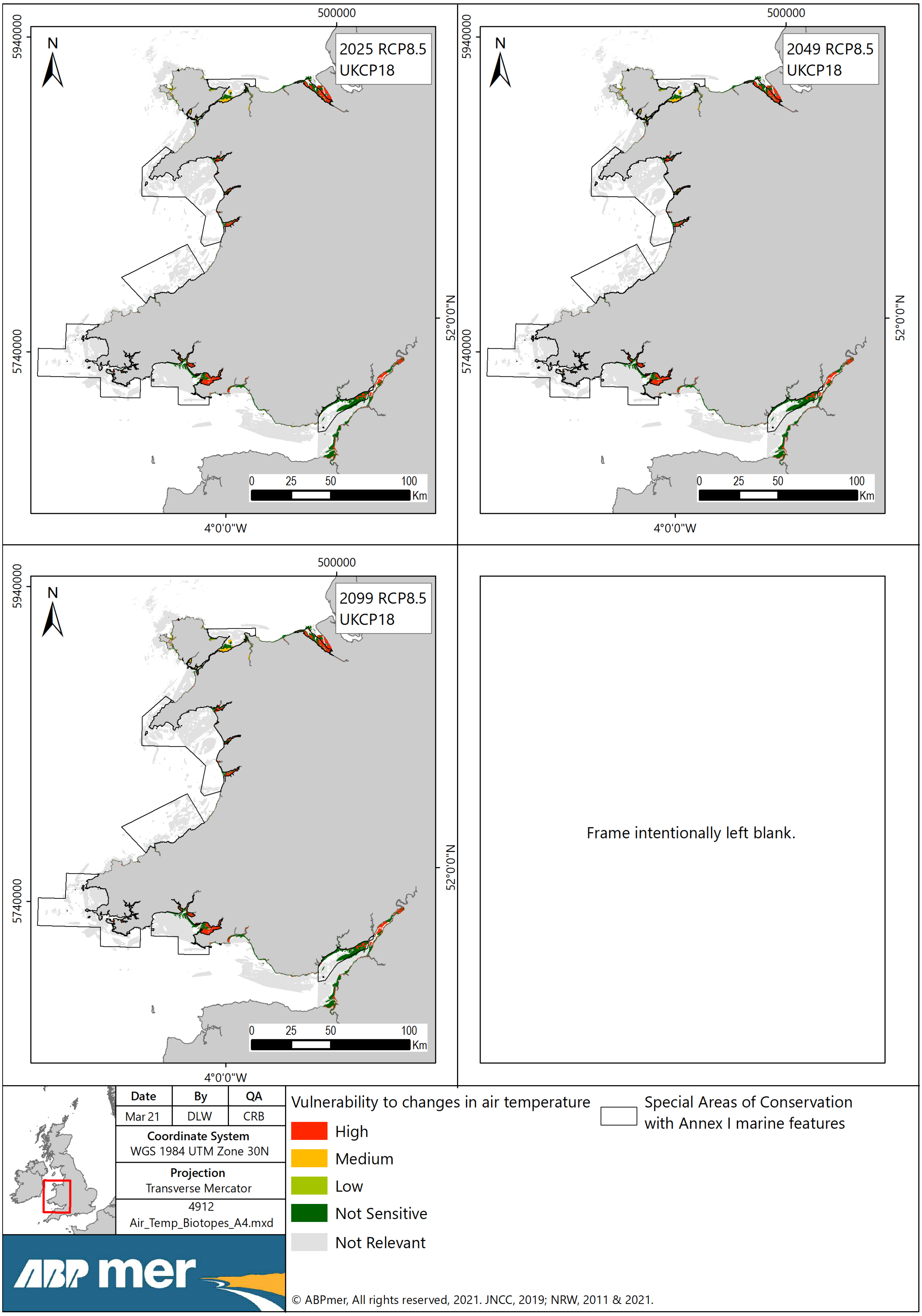

Figure 18. Vulnerability of component biotopes of Annex I marine habitats to projections of air temperature

Table 8. Sub-set of vulnerability assessment results (percent coverage/sea cave count) for air temperature in 2049 under RCP8.5 (red boxes highlight largest percent coverage/sea cave count)

Vulnerable features in SACs	Not vulnerable	Low	Medium	High	Not relevant
Submerged or partially submerged sea caves	-	-	-	-	-
Cardigan Bay / Bae Ceredigion	0	10	0	0	0
Limestone Coast of South West Wales / Arfordir Calchfaen De Orllewin Cymru	0	0	0	66	4
Pembrokeshire Marine / Sir Benfro Forol	0	2	0	46	2
Pen Llyn a'r Sarnau / Lleyn Peninsula and the Sarnau	0	6	0	1	0
Y Fenai a Bae Conwy / Menai Strait and Conwy Bay	0	8	0	0	0
Overall	**0**	**26**	**0**	**113**	**6**
Atlantic salt meadows	-	-	-	-	-
Carmarthen Bay and Estuaries / Bae Caerfyrddin ac Aberoedd	0%	0%	0%	100%	0%
Dee Estuary / Aber Dyfrdwy (Wales)	0%	0%	0%	100%	0%
Glannau Mon: Cors heli / Anglesey Coast: Saltmarsh	0%	0%	100%	0%	0%
Pembrokeshire Marine / Sir Benfro Forol	0%	0%	0%	100%	0%
Pen Llyn a'r Sarnau / Lleyn Peninsula and the Sarnau	0%	0%	0%	100%	0%
Severn Estuary (Wales)	0%	0%	0%	100%	0%
Overall	**0%**	**0%**	3%	**97%**	**0%**
Salicornia and other annuals colonising mud and sand	-	-	-	-	-
Carmarthen Bay and Estuaries / Bae Caerfyrddin ac Aberoedd	0%	0%	0%	100%	0%
Dee Estuary / Aber Dyfrdwy (Wales)	0%	0%	0%	100%	0%
Glannau Mon: Cors heli / Anglesey Coast: Saltmarsh	0%	0%	100%	0%	0%
Pen Llyn a'r Sarnau / Lleyn Peninsula and the Sarnau	0%	0%	0%	100%	0%
Overall	0%	0%	2%	98%	0%
Intertidal reef	-	-	-	-	-
Cardigan Bay / Bae Ceredigion	42%	7%	4%	5%	42%
Pembrokeshire Marine / Sir Benfro Forol	34%	6%	0%	38%	21%
Pen Llyn a'r Sarnau / Lleyn Peninsula and the Sarnau	41%	10%	3%	26%	20%
Severn Estuary (Wales)	66%	0%	0%	31%	2%
Y Fenai a Bae Conwy / Menai Strait and Conwy Bay	15%	57%	20%	2%	6%
Overall	**41%**	**13%**	**4%**	**26%**	**16%**

3.3.3. Sea level rise

The sea level rise pressure-sensitivity relationship for the majority of subtidal features was assessed as not relevant aside from those dependant on light (e.g. kelp beds), however intertidal biotopes were generally assessed as having a medium or high vulnerability (Figure 19). Overall biotope vulnerability to sea level rise increased towards the end of the century. Vulnerabilities under RCP8.5 were slightly higher compared with RCP4.5. As mentioned elsewhere in the report, landward migration of biotopes has been assumed to not be possible for this assessment (see Sections 3.2.2 and 4.2.2).

A sub-set of the vulnerability assessment results for sea level rise in 2049 under RCP8.5 is presented in Table 9 and are described below. These percentage values represent the predicted spatial coverage of component biotopes with differing vulnerabilities to projected changes in sea level rise within an Annex I feature (within an SAC).

The most vulnerable features were Atlantic salt meadows, *Salicornia* and other annuals colonising mud and sand, and Coastal lagoons; 100%, 100% and 50% coverage of the comprising component biotopes were assessed as having a high vulnerability, respectively. The high sensitivity threshold for saltmarsh (biotope LS.LMp.Sm) was set at > 0.3 m of sea level rise, which is projected to be exceeded by the mid-century.

Mudflats and sandflats not covered by seawater at low tide features were assessed as medium vulnerability (81% across all mapped component biotopes). An example component biotope is polychaete/bivalve dominated muddy sand shores (biotope LS.LSa.MuSa), which was assigned a medium sensitivity threshold of between 0.05 m and 0.5 m sea level rise. Component biotopes assessed as highly vulnerable in the Pembrokeshire Marine SAC and Severn Estuary SAC (e.g. biotopes LS.LMu.MEst and LS.LMu.UEst, assigned a high sensitivity threshold of > 0.3 m) covered 49% and 29% of the mapped extent respectively. Estuaries features were also predominantly assessed as medium vulnerability (51% across all mapped component biotopes).

Intertidal reef features were assessed as less vulnerable, with percentage coverage of low vulnerability component biotopes ranging from 87 to 95% in every SAC. Component biotopes of these features generally had low sensitivity thresholds set at < 0.5 m (e.g. barnacles and fucoids on moderately exposed shores, biotope LR.MLR.BF). Maerl (biotope SS.SMp.Mrl, assigned a low sensitivity threshold of < 0.7 m) was also assessed as having a low vulnerability to sea level rise (100% of component biotope coverage, all in the Pembrokeshire Marine SAC).

Submerged or partially submerged sea cave feature[19] biotopes were also assessed as having a low vulnerability to sea level rise; 166 sea cave biotopes (littoral caves and overhangs, biotope LR.FLR.CvOv, assigned a low sensitivity threshold of < 0.5 m) were considered to have a low vulnerability, and 6 not relevant (infralittoral surge gullies and caves, biotope IR.FIR.SG, is a component biotope of Submerged or partially submerged sea cave features; sea level rise is considered not relevant to this biotope as it occurs in the infralittoral zone).

It is important to note that by 2099, most of the spatial extent of component biotopes comprising intertidal features (i.e. Intertidal reef, Estuaries, Mudflats and sandflats not covered by seawater at low tide and Submerged or partially submerged sea caves) were assessed as highly vulnerable to sea level rise. This is due to the large rises in sea level (around 1 m) projected by the end of the century (see Section 3.1.3).

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[19] Sea cave features were counted, rather than considered by percentage coverage.

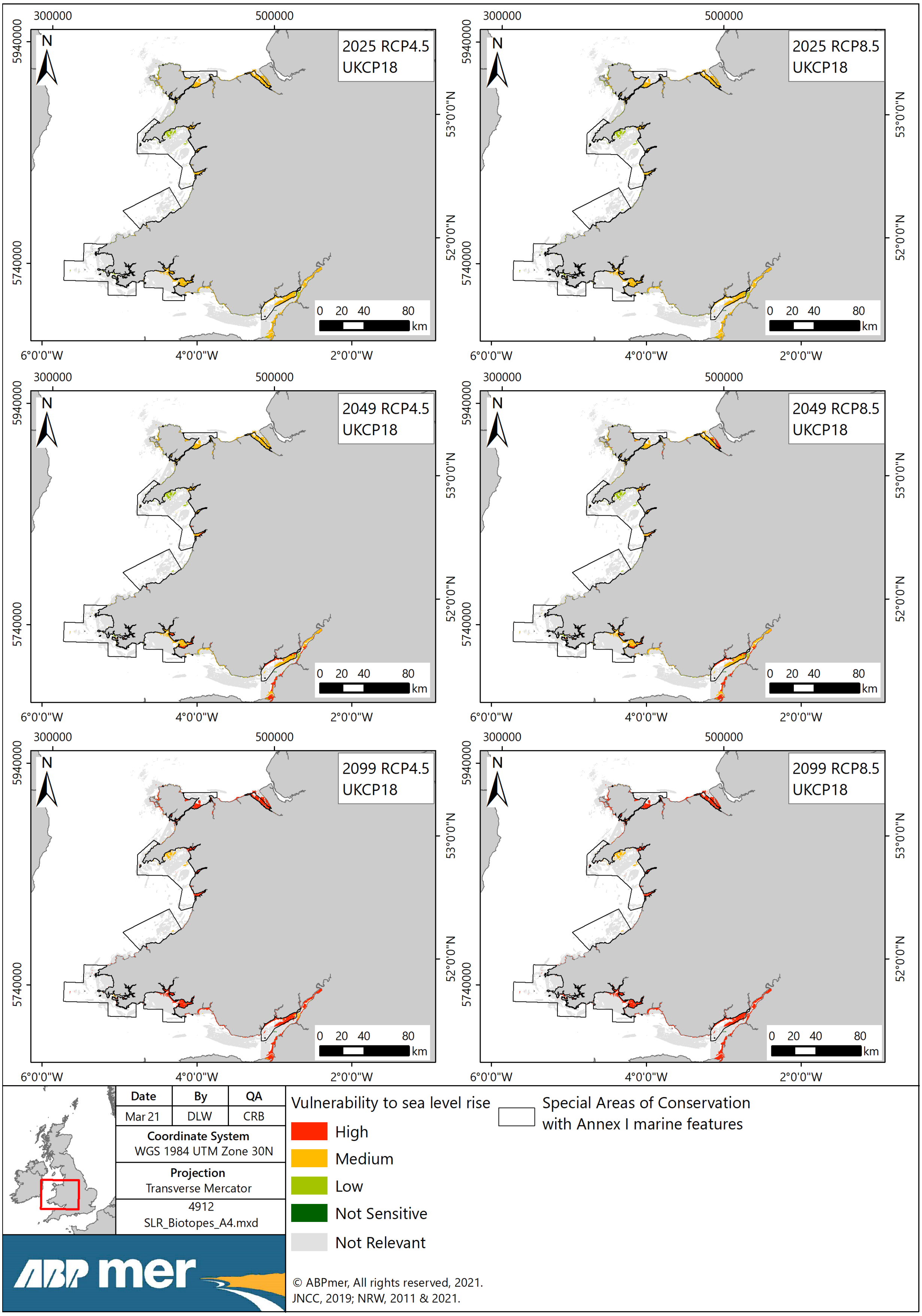

Figure 19. Vulnerability of component biotopes of Annex I marine habitats to projections of sea level rise

Table 9. Sub-set of vulnerability assessment results (percent coverage/sea cave count) for sea level rise in 2049 under RCP8.5 (red boxes highlight largest percent coverage/sea cave count)

Vulnerable features in SACs	Not vulnerable	Low	Medium	High	Not relevant
Atlantic salt meadows	-	-	-	-	-
Carmarthen Bay and Estuaries / Bae Caerfyrddin ac Aberoedd	0%	0%	0%	100%	0%
Dee Estuary / Aber Dyfrdwy (Wales)	0%	0%	0%	100%	0%
Pembrokeshire Marine / Sir Benfro Forol	0%	0%	0%	100%	0%
Pen Llyn a'r Sarnau / Lleyn Peninsula and the Sarnau	0%	0%	0%	100%	0%
Severn Estuary (Wales)	0%	0%	0%	100%	0%
Glannau Mon: Cors heli / Anglesey Coast: Saltmarsh	0%	0%	0%	100%	0%
Overall	**0%**	**0%**	**0%**	**100%**	**0%**
Salicornia and other annuals colonising mud and sand	-	-	-	-	-
Carmarthen Bay and Estuaries / Bae Caerfyrddin ac Aberoedd	0%	0%	0%	100%	0%
Dee Estuary / Aber Dyfrdwy (Wales)	0%	0%	0%	100%	0%
Pen Llyn a'r Sarnau / Lleyn Peninsula and the Sarnau	0%	0%	0%	100%	0%
Glannau Mon: Cors heli / Anglesey Coast: Saltmarsh	0%	0%	0%	100%	0%
Overall	**0%**	**0%**	**0%**	**100%**	**0%**
Coastal lagoons	-	-	-	-	-
Bae Cemlyn / Cemlyn Bay	0%	100%	0%	0%	0%
Pembrokeshire Marine / Sir Benfro Forol	0%	37%	12%	51%	0%
Overall	**0%**	**37%**	**12%**	**50%**	**0%**
Intertidal reef	-	-	-	-	-
Cardigan Bay / Bae Ceredigion	0%	90%	8%	0%	2%
Pembrokeshire Marine / Sir Benfro Forol	0%	87%	12%	0%	1%
Pen Llyn a'r Sarnau / Lleyn Peninsula and the Sarnau	0%	91%	8%	0%	1%
Severn Estuary (Wales)	0%	89%	9%	0%	2%
Y Fenai a Bae Conwy / Menai Strait and Conwy Bay	0%	95%	5%	0%	1%
Overall	**0%**	**90%**	**9%**	**0%**	**1%**
Mudflats and sandflats not covered by sea at low tide	-	-	-	-	-
Carmarthen Bay and Estuaries / Bae Caerfyrddin ac Aberoedd	0%	1%	91%	4%	3%
Dee Estuary / Aber Dyfrdwy (Wales)	0%	0%	94%	4%	2%
Pembrokeshire Marine / Sir Benfro Forol	0%	13%	38%	49%	0%
Pen Llyn a'r Sarnau / Lleyn Peninsula and the Sarnau	0%	2%	89%	5%	3%
Severn Estuary (Wales)	0%	5%	66%	29%	0%
Y Fenai a Bae Conwy / Menai Strait and Conwy Bay	0%	9%	87%	2%	2%
Glannau Mon: Cors heli / Anglesey Coast: Saltmarsh	0%	3%	93%	4%	0%
Overall	**0%**	**4%**	**81%**	**13%**	**2%**
Estuaries	-	-	-	-	-

Vulnerable features in SACs	Not vulnerable	Low	Medium	High	Not relevant
Carmarthen Bay and Estuaries / Bae Caerfyrddin ac Aberoedd	0%	4%	81%	8%	7%
Dee Estuary / Aber Dyfrdwy (Wales)	0%	1%	80%	4%	16%
Pembrokeshire Marine / Sir Benfro Forol	0%	28%	15%	26%	30%
Pen Llyn a'r Sarnau / Lleyn Peninsula and the Sarnau	0%	3%	82%	10%	5%
Severn Estuary (Wales)	0%	4%	31%	17%	48%
Glannau Mon: Cors heli / Anglesey Coast: Saltmarsh	0%	4%	89%	6%	1%
Overall	**0%**	**5%**	**51%**	**14%**	**30%**
Maerl	-	-	-	-	-
Pembrokeshire Marine / Sir Benfro Forol	0%	100%	0%	0%	0%
Overall	**0%**	**100%**	**0%**	**0%**	**0%**
Submerged or partially submerged sea caves	-	-	-	-	-
Cardigan Bay / Bae Ceredigion	0	10	0	0	0
Limestone Coast of South West Wales / Arfordir Calchfaen De Orllewin Cymru	0	66	0	0	4
Pembrokeshire Marine / Sir Benfro Forol	0	48	0	0	2
Pen Llyn a'r Sarnau / Lleyn Peninsula and the Sarnau	0	7	0	0	0
Y Fenai a Bae Conwy / Menai Strait and Conwy Bay	0	8	0	0	0
Overall	**0**	**166**	**0**	**0**	**6**

3.3.4. Wave exposure

The majority of biotopes were assessed as not sensitive to changes in wave exposure (Figure 20). Vulnerabilities were very similar between years and emissions scenarios.

A sub-set of the vulnerability assessment results for wave exposure in 2049 under RCP8.5 is presented in Table 10 and are described below. These percentage values represent the predicted spatial coverage of component biotopes with differing vulnerabilities to projected changes in wave exposure within an Annex I feature (within an SAC).

Intertidal reef biotopes had the greatest extent of component biotopes assessed as high vulnerability overall (23%). This is likely explained by the exposure to breaking waves at the coast. 62% of the total coverage of the component biotopes mapped within this feature within SACs were assessed as not sensitive, 14% low and 1% medium. The Menai Strait and Conwy Bay SAC had the greatest extent of high vulnerability biotopes at 78%, probably because the greatest relative change in wave exposure is projected for north Wales (see Section 3.1.4). An example biotope that was assessed as highly vulnerable in this location is fucoids on sheltered marine shores (biotope LR.LLR.F), which was given a high sensitivity threshold of > 5% change in wave exposure.

Subtidal reef component biotope vulnerability was much lower compared with Intertidal reef. 98% of the total extent of component biotopes within this feature (within an SAC) was considered not sensitive, and 2% low. Again, Menai Strait and Conwy Bay SAC had the greatest coverage of high vulnerability biotopes at 11%.

Atlantic salt meadows and *Salicornia* and other annuals colonising mud and sand features were assessed as medium vulnerability, with 100% coverage in all SACs (in this case a medium sensitivity of saltmarsh, biotope LS.SMp.Sm, assessed by MarESA was applied as the vulnerability to wave exposure as it was not possible to deduce pressure value sensitivity thresholds).

Component biotopes of Estuaries and Mudflats and sandflats not covered by seawater at low tide also had a relatively large extent of medium vulnerability biotopes (13 and 16% overall respectively). Again, with respect to component biotopes of the Mudflats and sandflats not covered by seawater feature, Menai Strait and Conwy Bay SAC had the greatest extent of high vulnerability biotopes at 10%.

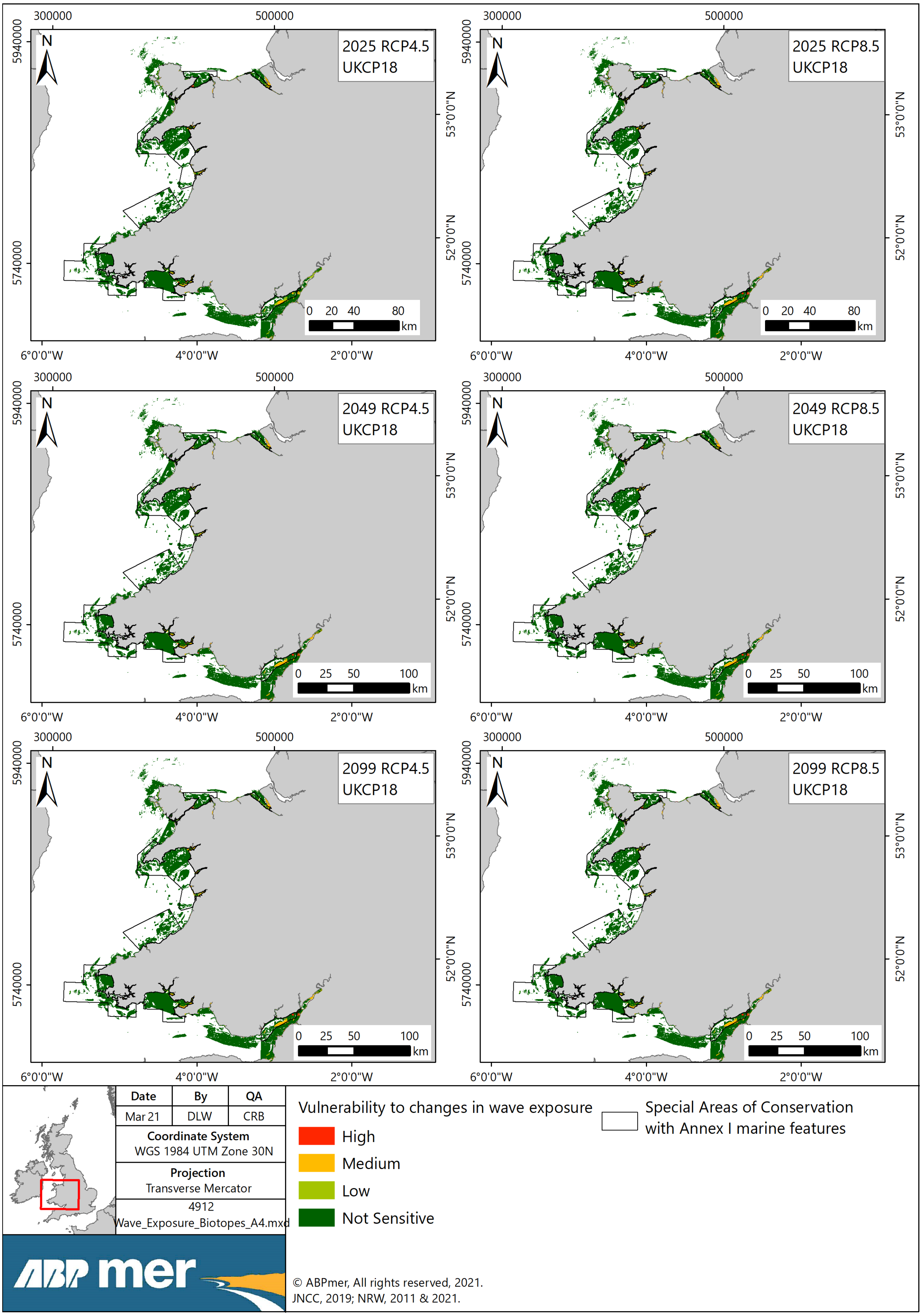

Figure 20. Vulnerability of component biotopes of Annex I marine habitats to projections of wave exposure

Table 10. Sub-set of vulnerability assessment results (percent coverage) for wave exposure in 2025 under RCP8.5 (red boxes highlight largest percent coverage)

Vulnerable features in SACs	Not vulnerable	Low	Medium	High	Not relevant
Intertidal reef	-	-	-	-	-
Cardigan Bay / Bae Ceredigion	85%	10%	0%	5%	0%
Pembrokeshire Marine / Sir Benfro Forol	63%	32%	0%	5%	0%
Pen Llyn a'r Sarnau / Lleyn Peninsula and the Sarnau	71%	6%	4%	19%	0%
Severn Estuary (Wales)	73%	0%	0%	27%	0%
Y Fenai a Bae Conwy / Menai Strait and Conwy Bay	19%	3%	0%	78%	0%
Overall	**62%**	**14%**	**1%**	**23%**	**0%**
Atlantic salt meadows	-	-	-	-	-
Carmarthen Bay and Estuaries / Bae Caerfyrddin ac Aberoedd	0%	0%	100%	0%	0%
Dee Estuary / Aber Dyfrdwy (Wales)	0%	0%	100%	0%	0%
Glannau Mon: Cors heli / Anglesey Coast: Saltmarsh	0%	0%	100%	0%	0%
Pembrokeshire Marine / Sir Benfro Forol	0%	0%	100%	0%	0%
Pen Llyn a'r Sarnau / Lleyn Peninsula and the Sarnau	0%	0%	100%	0%	0%
Severn Estuary (Wales)	0%	0%	100%	0%	0%
Overall	**0%**	**0%**	**100%**	**0%**	**0%**
Salicornia and other annuals colonising mud and sand	-	-	-	-	-
Carmarthen Bay and Estuaries / Bae Caerfyrddin ac Aberoedd	0%	0%	100%	0%	0%
Dee Estuary / Aber Dyfrdwy (Wales)	0%	0%	100%	0%	0%
Glannau Mon: Cors heli / Anglesey Coast: Saltmarsh	0%	0%	100%	0%	0%
Pen Llyn a'r Sarnau / Lleyn Peninsula and the Sarnau	0%	0%	100%	0%	0%
Overall	**0%**	**0%**	**100%**	**0%**	**0%**
Subtidal reef	-	-	-	-	-
Cardigan Bay / Bae Ceredigion	100%	0%	0%	0%	0%
Pembrokeshire Marine / Sir Benfro Forol	97%	3%	0%	0%	0%
Pen Llyn a'r Sarnau / Lleyn Peninsula and the Sarnau	98%	2%	0%	0%	0%
Severn Estuary (Wales)	100%	0%	0%	0%	0%
Y Fenai a Bae Conwy / Menai Strait and Conwy Bay	87%	3%	0%	11%	0%
Overall	**98%**	**2%**	**0%**	**0%**	**0%**
Estuaries	-	-	-	-	-
Carmarthen Bay and Estuaries / Bae Caerfyrddin ac Aberoedd	88%	5%	3%	4%	0%
Dee Estuary / Aber Dyfrdwy (Wales)	90%	6%	4%	0%	0%
Glannau Mon: Cors heli / Anglesey Coast: Saltmarsh	84%	16%	0%	0%	0%
Pembrokeshire Marine / Sir Benfro Forol	84%	12%	0%	4%	0%
Pen Llyn a'r Sarnau / Lleyn Peninsula and the Sarnau	55%	7%	36%	1%	0%

Vulnerable features in SACs	Not vulnerable	Low	Medium	High	Not relevant
*Severn Estuary (Wales)	80%	0%	17%	3%	0%
Overall	**81%**	**4%**	**13%**	**2%**	**0%**
Mudflats and sandflats not covered by sea at low tide	-	-	-	-	-
Carmarthen Bay and Estuaries / Bae Caerfyrddin ac Aberoedd	89%	5%	4%	2%	0%
Dee Estuary / Aber Dyfrdwy (Wales)	88%	7%	5%	0%	0%
Glannau Mon: Cors heli / Anglesey Coast: Saltmarsh	80%	14%	5%	1%	0%
Pembrokeshire Marine / Sir Benfro Forol	73%	20%	0%	6%	0%
Pen Llyn a'r Sarnau / Lleyn Peninsula and the Sarnau	58%	7%	33%	2%	0%
Severn Estuary (Wales)	60%	0%	36%	4%	0%
Y Fenai a Bae Conwy / Menai Strait and Conwy Bay	83%	0%	7%	10%	0%
Overall	**76%**	**5%**	**16%**	**3%**	**0%**

3.3.5. Ocean acidification

Most component biotopes were assessed as being not sensitive to changes in ocean pH (Figure 21).

A sub-set of the vulnerability assessment results for ocean acidification in 2049 under RCP8.5 is presented in Table 11 and are described below. These percentage values represent the predicted spatial coverage of component biotopes with differing vulnerabilities to projected changes in ocean acidification within an Annex I feature (within an SAC).

82% of the extent of component biotopes within Estuaries within SACs was assessed as not sensitive to ocean acidification. In the Pembrokeshire Marine SAC and Severn Estuary SAC, 20% and 18% of the extent of component biotopes within Estuaries were assessed as medium vulnerability, respectively.

Mudflats and sandflats not covered by seawater at low tide were also mostly not sensitive. Menai Strait and Conwy Bay SAC had the highest percentage coverage of medium vulnerability mudflat biotopes (8%).

Subtidal reef was assessed as more vulnerable to ocean acidification, with 21% of the extent of component biotopes was assessed as medium, 30% assessed as high, and 49% assessed as not sensitive. Subtidal reef features within the Pembrokeshire Marine SAC were assessed as particularly vulnerable, with 44% of component biotopes assessed as high. This may be explained by the presence of circalittoral mixed sediment (biotope SS.SMx.CMx) in this site. Brittlestar *Ophiothrix fragilis* is a characterising species of this biotope and pH decreases can lead to mortality and changes to developmental dynamics (e.g. skeletal malformations in surviving larvae) (see Section 3.2.4). This was considered the most sensitive biotope to acidification (high sensitivity < 7.99 pH). Intertidal reef was less vulnerable as pH (and the saturation state of calcite) decreases with depth.

Maerl was assessed as medium vulnerability (100% coverage) in the Pembrokeshire Marine SAC. This is also considered one of the more sensitive biotopes to low pH.

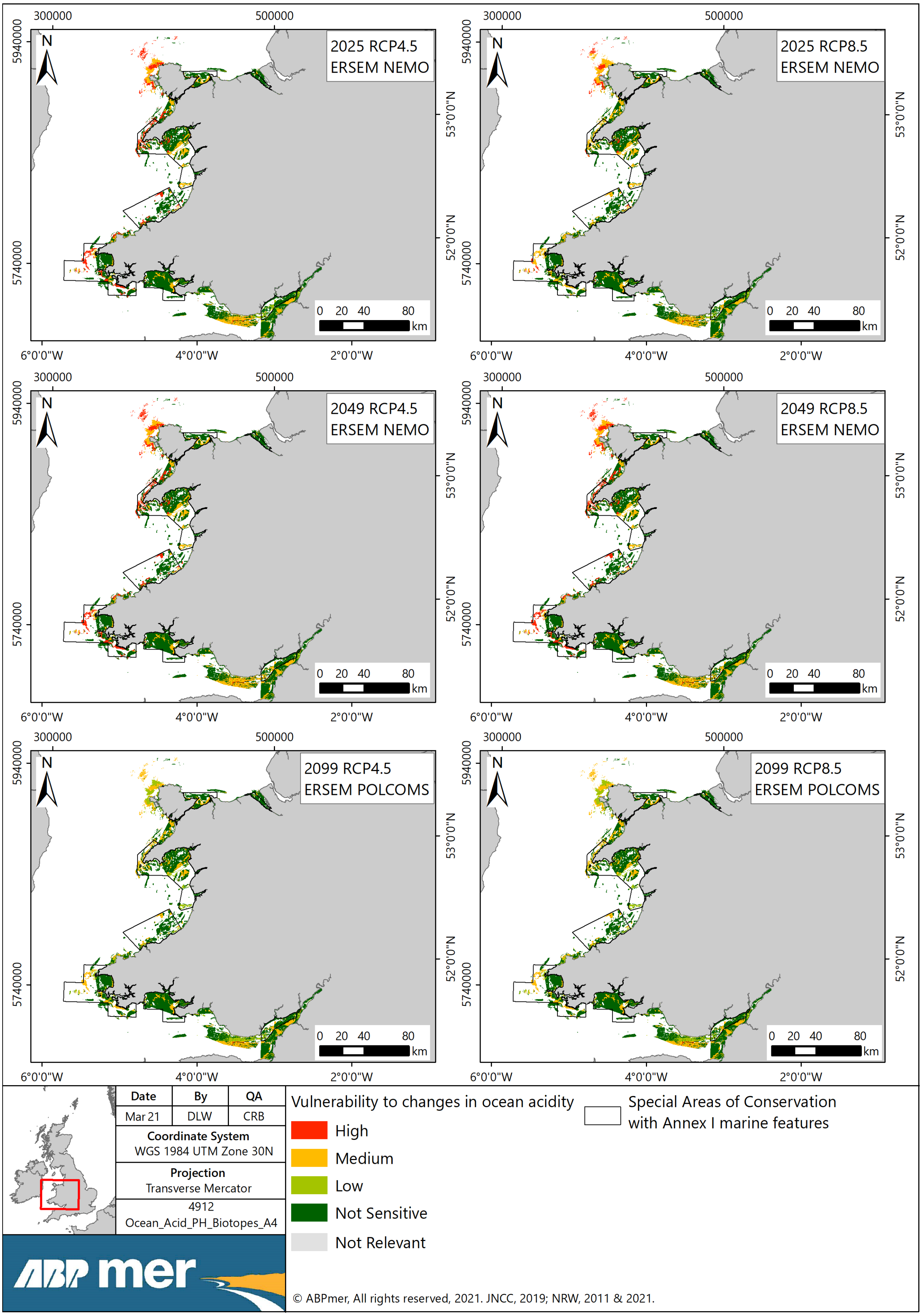

Figure 21. Vulnerability of component biotopes of Annex I marine habitats to projections of ocean acidification

Table 11. Sub-set of vulnerability assessment results (percent coverage) for ocean acidification in 2049 under RCP8.5 (red boxes highlight largest percent coverage)

Vulnerable features in SACs	Not vulnerable	Low	Medium	High	Not relevant
Estuaries	-	-	-	-	-
Carmarthen Bay and Estuaries / Bae Caerfyrddin ac Aberoedd	87%	2%	10%	0%	1%
Dee Estuary / Aber Dyfrdwy (Wales)	95%	0%	3%	0%	1%
Glannau Mon: Cors heli / Anglesey Coast: Saltmarsh	95%	3%	2%	0%	0%
Pembrokeshire Marine / Sir Benfro Forol	66%	12%	20%	0%	1%
Pen Llyn a'r Sarnau / Lleyn Peninsula and the Sarnau	92%	1%	3%	0%	4%
Severn Estuary (Wales)	77%	4%	19%	0%	0%
Overall	**82%**	**4%**	**13%**	**0%**	**1%**
Mudflats and sandbanks not covered by seawater at low tide	-	-	-	-	-
Carmarthen Bay and Estuaries / Bae Caerfyrddin ac Aberoedd	96%	1%	4%	0%	0%
Dee Estuary / Aber Dyfrdwy (Wales)	100%	0%	0%	0%	0%
Glannau Mon: Cors heli / Anglesey Coast: Saltmarsh	97%	2%	1%	0%	0%
Pembrokeshire Marine / Sir Benfro Forol	85%	13%	2%	0%	0%
Pen Llyn a'r Sarnau / Lleyn Peninsula and the Sarnau	98%	1%	1%	0%	0%
Severn Estuary (Wales)	94%	6%	0%	0%	0%
Y Fenai a Bae Conwy / Menai Strait and Conwy Bay	88%	3%	8%	0%	0%
Overall	**95%**	**3%**	**2%**	**0%**	**0%**
Subtidal reef	-	-	-	-	-
Cardigan Bay / Bae Ceredigion	67%	0%	8%	24%	0%
Pembrokeshire Marine / Sir Benfro Forol	37%	0%	19%	44%	0%
Pen Llyn a'r Sarnau / Lleyn Peninsula and the Sarnau	49%	0%	25%	25%	0%
Severn Estuary (Wales)	44%	0%	53%	3%	0%
Y Fenai a Bae Conwy / Menai Strait and Conwy Bay	37%	3%	49%	11%	0%
Overall	**49%**	**0%**	**21%**	**30%**	**0%**
Maerl	-	-	-	-	-
Pembrokeshire Marine / Sir Benfro Forol	0%	0%	100%	0%	0%
Overall	**0%**	**0%**	**100%**	**0%**	**0%**

3.3.6. Deoxygenation

There was no difference in vulnerabilities across years and scenarios. This is because minimum dissolved oxygen concentration projections do not differ significantly between years and emissions scenarios (see Section 3.1.6). No component biotopes were assessed as having a medium or high vulnerability, with most assessed as low vulnerability (Figure 22).

A sub-set of the vulnerability assessment results for deoxygenation in 2049 under RCP8.5 is presented in Table 12 and are described below. These percentage values represent the predicted spatial coverage of component biotopes with differing vulnerabilities to projected changes in deoxygenation within an Annex I feature (within an SAC).

Component biotopes of Large shallow inlets and bays were mostly assessed as low vulnerability (93% coverage). Most Large shallow inlets and bays features across SACs in Wales follow a similar pattern. An example component biotope within this feature assessed as low vulnerability is circalittoral faunal communities in variable salinity (biotope CR.MCR.CFaVS). This was assigned a low sensitivity threshold of > 2 mg/l and is projected to be exposed to oxygen concentrations above 6 mg/l.

All component biotopes of Sandbanks which are slightly covered by seawater all the time were also assessed as low vulnerability. Again, there was no spatial variation in this result across the SACs in Wales.

Intertidal features are less sensitive to deoxygenation as they are exposed at low tide. For example, compared with subtidal features a greater extent of component biotopes of Mudflats and sandflats not covered by seawater at low tide were considered not sensitive, 39%, and 61% coverage was assessed as low vulnerability. Most Mudflat features across SACs in Wales followed a similar pattern (i.e. were mostly low or not sensitive). Intertidal reef was also assessed as less vulnerable, with 82% of the extent of component biotopes within SACs assessed as not sensitive.

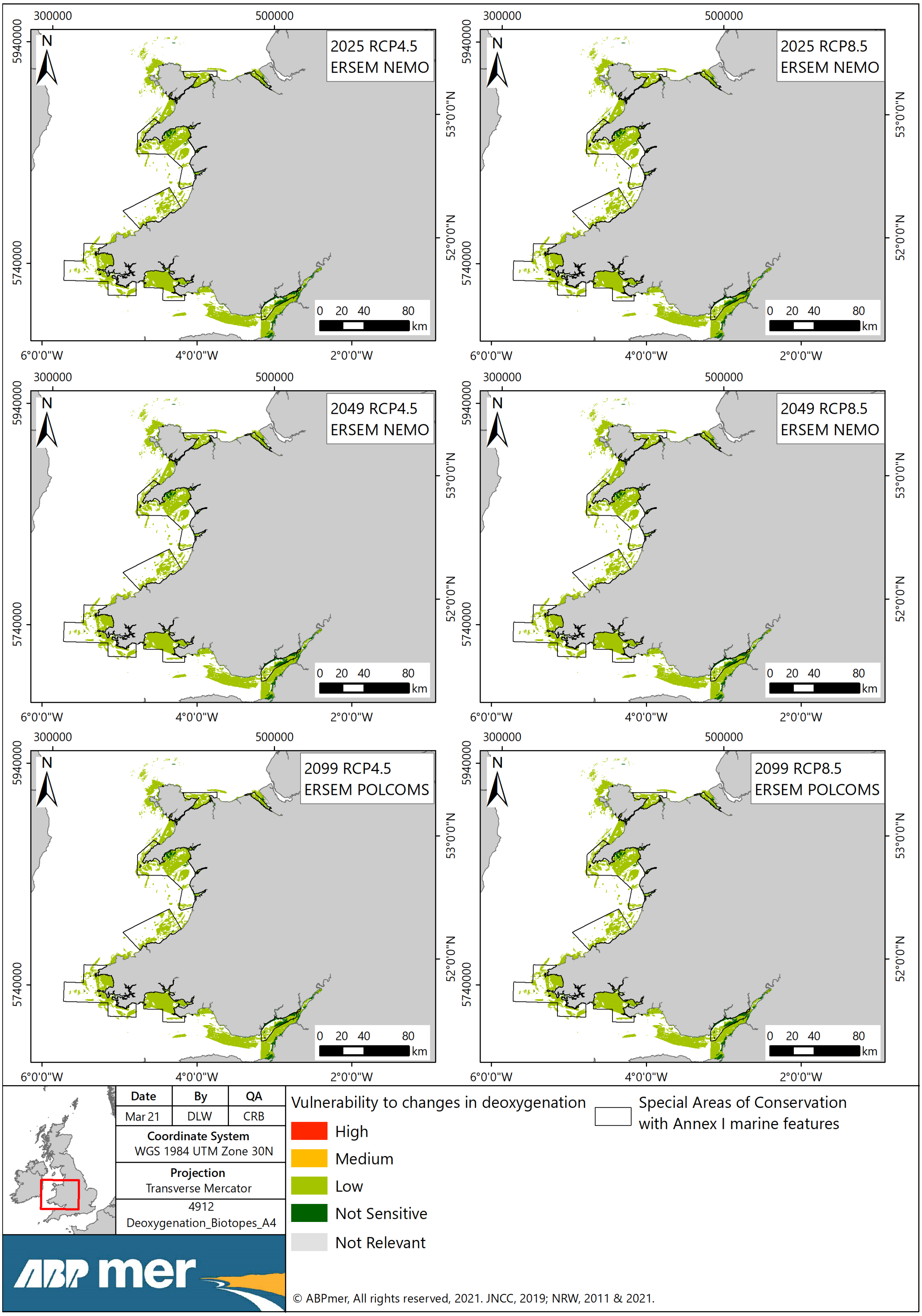

Figure 22. Vulnerability of component biotopes of Annex I marine habitats to projections of dissolved oxygen concentrations

Table 12. Sub-set of vulnerability assessment results (percent coverage) for deoxygenation in 2049 under RCP8.5 (red boxes highlight largest percent coverage)

Vulnerable features in SACs	Not vulnerable	Low	Medium	High	Not relevant
Large shallow inlets and bays	-	-	-	-	-
Carmarthen Bay and Estuaries / Bae Caerfyrddin ac Aberoedd	1%	99%	0%	0%	0%
Pembrokeshire Marine / Sir Benfro Forol	7%	92%	0%	0%	0%
Pen Llyn a'r Sarnau / Lleyn Peninsula and the Sarnau	12%	88%	0%	0%	0%
Y Fenai a Bae Conwy / Menai Strait and Conwy Bay	3%	97%	0%	0%	0%
Overall	**6%**	**93%**	**0%**	**0%**	**0%**
Sandbanks which are slightly covered by seawater all the time	-	-	-	-	-
Cardigan Bay / Bae Ceredigion	0%	100%	0%	0%	0%
Carmarthen Bay and Estuaries / Bae Caerfyrddin ac Aberoedd	0%	100%	0%	0%	0%
Pembrokeshire Marine / Sir Benfro Forol	0%	100%	0%	0%	0%
Pen Llyn a'r Sarnau / Lleyn Peninsula and the Sarnau	0%	100%	0%	0%	0%
Severn Estuary (Wales)	0%	100%	0%	0%	0%
Y Fenai a Bae Conwy / Menai Strait and Conwy Bay	0%	100%	0%	0%	0%
Overall	**0%**	**100%**	**0%**	**0%**	**0%**
Mudflats and sandflats not covered by seawater at low tide	-	-	-	-	-
Carmarthen Bay and Estuaries / Bae Caerfyrddin ac Aberoedd	16%	84%	0%	0%	0%
Dee Estuary / Aber Dyfrdwy (Wales)	16%	84%	0%	0%	0%
Glannau Mon: Cors heli / Anglesey Coast: Saltmarsh	25%	75%	0%	0%	1%
Pembrokeshire Marine / Sir Benfro Forol	77%	23%	0%	0%	1%
Pen Llyn a'r Sarnau / Lleyn Peninsula and the Sarnau	48%	52%	0%	0%	1%
Severn Estuary (Wales)	74%	26%	0%	0%	0%
Y Fenai a Bae Conwy / Menai Strait and Conwy Bay	19%	81%	0%	0%	0%
Overall	**39%**	**61%**	**0%**	**0%**	**0%**
Intertidal reef	-	-	-	-	-
Cardigan Bay / Bae Ceredigion	50%	16%	0%	0%	34%
Pembrokeshire Marine / Sir Benfro Forol	83%	5%	0%	0%	12%
Pen Llyn a'r Sarnau / Lleyn Peninsula and the Sarnau	67%	19%	0%	0%	14%
Severn Estuary (Wales)	94%	5%	0%	0%	1%
Y Fenai a Bae Conwy / Menai Strait and Conwy Bay	95%	4%	0%	0%	1%
Overall	**82%**	**8%**	**0%**	**0%**	**10%**

3.3.7. Salinity

The majority of component biotopes were assessed as having a low vulnerability to changes in salinity (Figure 23). Vulnerabilities were the same between years and emissions scenarios (except in 2083 where UKCP09 projections are used).

A sub-set of the vulnerability assessment results for salinity in 2049 under RCP8.5 is presented in Table 13 and are described below. These percentage values represent the predicted spatial coverage of component biotopes with differing vulnerabilities to projected changes in salinity within an Annex I feature (within an SAC).

With respect to the spatial extent of component biotopes comprising Estuaries features,18% was assessed as not sensitive, 44% low, 33% medium, and 6% high. In the Severn Estuary SAC, 62% of the coverage of Estuaries biotopes was assessed as medium, and 11% high. Littoral *Sabellaria* honeycomb worm reefs (biotope LS.LBR.Sab) is an example of a component biotope of the Severn Estuary SAC Estuaries feature assessed as highly vulnerable. It was assigned a high sensitivity threshold of < 18 psu and is projected to be exposed to salinities around 13 psu.

Mudflats and sandflats not covered by seawater at low tide biotopes were mainly assessed as low vulnerability (44% coverage), or not sensitive (38% coverage). In the Severn Estuary SAC, 63% of the extent of Mudflat biotopes was assessed as having a medium vulnerability.

Other features, such as Atlantic salt meadows, Intertidal reef, Subtidal reef, and Sandbanks which are slightly covered by seawater all the time were also mostly assessed as having a low vulnerability (or considered not sensitive) except in the Severn Estuary SAC. 100%, 8%, 2%, and 35% of the coverage of component biotopes of these features were assessed as high vulnerability, respectively.

The increased vulnerability of component biotopes of Annex I marine features in the Severn Estuary is likely due to low salinity projections in this region (see Section 3.1.7).

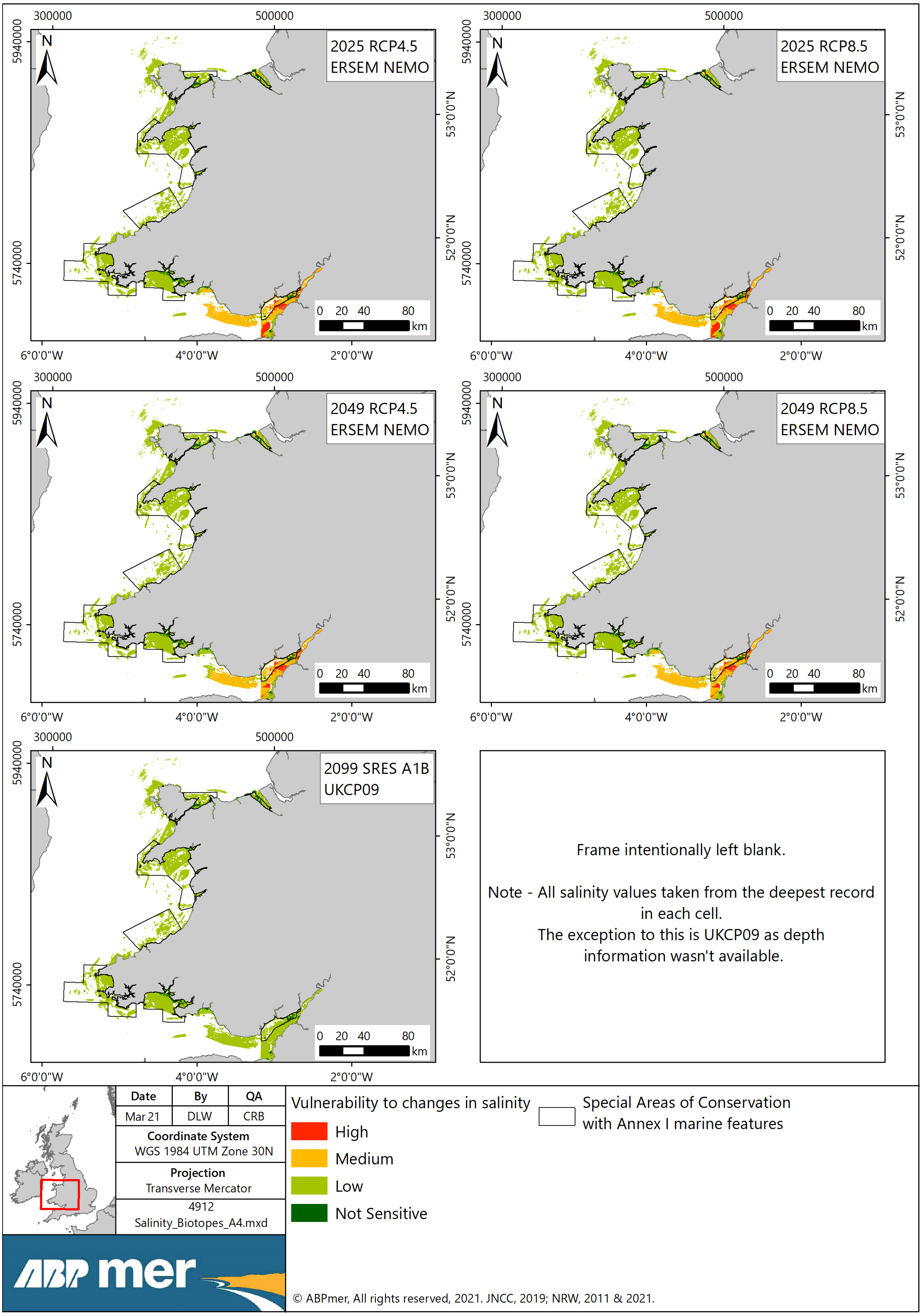

Figure 23. Vulnerability of component biotopes of Annex I marine habitats to projections of salinity

Table 13. Sub-set of vulnerability assessment results (percent coverage) for salinity in 2049 under RCP8.5 (red boxes highlight largest percent coverage)

Vulnerable features in SACs	Not vulnerable	Low	Medium	High	Not relevant
Estuaries	-	-	-	-	-
Carmarthen Bay and Estuaries / Bae Caerfyrddin ac Aberoedd	33%	67%	0%	0%	0%
Dee Estuary / Aber Dyfrdwy (Wales)	29%	63%	8%	0%	0%
Glannau Mon: Cors heli / Anglesey Coast: Saltmarsh	38%	62%	0%	0%	0%
Pembrokeshire Marine / Sir Benfro Forol	9%	91%	0%	0%	0%
Pen Llyn a'r Sarnau / Lleyn Peninsula and the Sarnau	17%	83%	0%	0%	0%
Severn Estuary (Wales)	12%	15%	62%	11%	0%
Overall	**18%**	**44%**	**33%**	**6%**	**0%**
Mudflats and sandbanks not covered by seawater at low tide	-	-	-	-	-
Carmarthen Bay and Estuaries / Bae Caerfyrddin ac Aberoedd	56%	44%	0%	0%	0%
Dee Estuary / Aber Dyfrdwy (Wales)	38%	62%	0%	0%	0%
Glannau Mon: Cors heli / Anglesey Coast: Saltmarsh	28%	72%	0%	0%	0%
Pembrokeshire Marine / Sir Benfro Forol	22%	78%	0%	0%	0%
Pen Llyn a'r Sarnau / Lleyn Peninsula and the Sarnau	20%	80%	0%	0%	0%
Severn Estuary (Wales)	25%	11%	63%	0%	0%
Y Fenai a Bae Conwy / Menai Strait and Conwy Bay	54%	46%	0%	0%	0%
Overall	**38%**	**44%**	**17%**	**0%**	**0%**
Atlantic salt meadows	-	-	-	-	-
Carmarthen Bay and Estuaries / Bae Caerfyrddin ac Aberoedd	0%	100%	0%	0%	0%
Dee Estuary / Aber Dyfrdwy (Wales)	0%	100%	0%	0%	0%
Glannau Mon: Cors heli / Anglesey Coast: Saltmarsh	0%	100%	0%	0%	0%
Pembrokeshire Marine / Sir Benfro Forol	0%	100%	0%	0%	0%
Pen Llyn a'r Sarnau / Lleyn Peninsula and the Sarnau	0%	100%	0%	0%	0%
Severn Estuary (Wales)	0%	0%	0%	100%	0%
Overall	**0%**	**95%**	**0%**	**5%**	**0%**
Intertidal reef	-	-	-	-	-
Cardigan Bay / Bae Ceredigion	9%	91%	0%	0%	0%
Pembrokeshire Marine / Sir Benfro Forol	8%	92%	0%	0%	0%
Pen Llyn a'r Sarnau / Lleyn Peninsula and the Sarnau	15%	85%	0%	0%	0%
Severn Estuary (Wales)	46%	11%	34%	8%	0%
Y Fenai a Bae Conwy / Menai Strait and Conwy Bay	59%	41%	0%	0%	0%
Overall	**26%**	**64%**	**8%**	**2%**	**0%**
Subtidal reef	-	-	-	-	-
Cardigan Bay / Bae Ceredigion	0%	100%	0%	0%	0%
Pembrokeshire Marine / Sir Benfro Forol	0%	100%	0%	0%	0%

Vulnerable features in SACs	Not vulnerable	Low	Medium	High	Not relevant
Pen Llyn a'r Sarnau / Lleyn Peninsula and the Sarnau	0%	100%	0%	0%	0%
Severn Estuary (Wales)	0%	47%	51%	2%	0%
Y Fenai a Bae Conwy / Menai Strait and Conwy Bay	9%	91%	0%	0%	0%
Overall	**0%**	**98%**	**2%**	**0%**	**0%**
Sandbanks which are slightly covered by seawater all the time	-	-	-	-	-
Cardigan Bay / Bae Ceredigion	0%	100%	0%	0%	0%
Carmarthen Bay and Estuaries / Bae Caerfyrddin ac Aberoedd	0%	100%	0%	0%	0%
Pembrokeshire Marine / Sir Benfro Forol	0%	100%	0%	0%	0%
Pen Llyn a'r Sarnau / Lleyn Peninsula and the Sarnau	0%	100%	0%	0%	0%
Severn Estuary (Wales)	0%	7%	58%	35%	0%
Y Fenai a Bae Conwy / Menai Strait and Conwy Bay	0%	100%	0%	0%	0%
Overall	**0%**	**94%**	**4%**	**2%**	**0%**

3.3.8. Multiple pressures

Annex I marine features that are exposed to multiple pressures to which they are sensitive may be especially vulnerable to climate change. Table 14 presents a cumulative assessment that identifies Annex I marine features that were assessed as vulnerable to more than one climate change pressure over the next century (for the purposes of this analysis, a feature was deemed ‘vulnerable’ if > 20% of component biotope coverage was assessed as medium and/or high). Saltmarsh (including *Salicornia* and other annuals colonising mud and sand, and Atlantic salt meadows (*Glauco-Puccinellietalia maritimae*)) and Intertidal reef were assessed as vulnerable to four climate change pressures: sea temperature, air temperature, sea level rise, and wave exposure. Estuaries were also assessed as vulnerable to four pressures: sea temperature, air temperature, sea level rise, salinity.

Across SACs around Wales, Annex I marine features were assessed as being vulnerable (again, for the purposes of this analysis, a feature was deemed ‘vulnerable’ if > 20% of component biotope coverage was assessed as medium and/or high) to multiple climate change pressures over the next century. This is shown in Table 15. Annex I marine features in the Menai Strait and Conwy Bay SAC and the Pen Llyn a'r Sarnau SAC are projected to be vulnerable to five climate change pressures: sea temperature, air temperature, sea level rise, wave exposure and ocean acidification. Severn Estuary SAC Annex I marine features are assessed as vulnerable to six climate change pressure: sea temperature, air temperature, sea level rise, wave exposure, ocean acidification, and salinity.

Table 14. Annex I features in Wales that are vulnerable (> 20% of component biotope coverage/sea cave count was assessed as medium and/or high) to multiple climate change pressures over the 21st century

Medium or High Vulnerability

	Sea temperature	Air temperature	Sea level rise	Wave exposure	Ocean acidification	Dissolved oxygen	Salinity
Sandbanks which are slightly covered by seawater all the time	✓	-	-	-	✓	-	-
Estuaries	✓	✓	✓	-	-	-	✓
Mudflats and sandflats not covered by seawater at low tide	-	✓	✓	-	-	-	-
Coastal lagoons	-	-	✓	-	-	-	-
Large shallow inlets and bays	✓	-	-	-	-	-	-
Intertidal reef	✓	✓	✓	✓	-	-	-
Subtidal reef	✓	-	-	-	✓	-	-
Submarine structures made by leaking gases (Methane-derived authigenic carbonates)	✓	-	-	-	-	-	-
Salicornia and other annuals colonising mud and sand	✓	✓	✓	✓	-	-	-
Atlantic salt meadows (*Glauco-Puccinellietalia maritimae*))	✓	✓	✓	✓	-	-	-
Submerged or partially submerged sea caves	-	✓	✓	-	-	-	-
Maerl	-	-	✓	-	✓	-	-

Table 15. SACs in Wales with Annex I features vulnerable (> 20% of component biotope coverage/sea cave count was assessed as medium and/or high) to multiple climate change pressures over the 21st century

Medium or High Vulnerability

	Sea temperature	Air temperature	Sea level rise	Wave exposure	Ocean acidification	Dissolved oxygen	Salinity
Bae Cemlyn / Cemlyn Bay	-	-	✓	-	-	-	-
Cardigan Bay / Bae Ceredigion	✓	-	✓	-	✓	-	-
Carmarthen Bay and Estuaries / Bae Caerfyrddin ac Aberoedd	✓	✓	✓	✓	-	-	-
Dee Estuary / Aber Dyfrdwy (Wales)	✓	✓	✓	✓	-	-	-
Glannau Mon: Cors heli / Anglesey Coast: Saltmarsh	-	✓	✓	✓	-	-	-
Limestone Coast of South West Wales / Arfordir Calchfaen De Orllewin Cymru	-	✓	✓	-	-	-	-
Pembrokeshire Marine / Sir Benfro Forol	-	✓	✓	✓	✓	-	-
Pen Llyn a'r Sarnau / Lleyn Peninsula and the Sarnau	✓	✓	✓	✓	✓	-	-
Severn Estuary (Wales)	✓	✓	✓	✓	✓	-	✓
Y Fenai a Bae Conwy / Menai Strait and Conwy Bay	✓	✓	✓	✓	✓	-	-

4. Discussion

4.1. Key findings

Based on the preceding assessment, the Annex I marine features within SACs that are considered most vulnerable to climate change are intertidal features such as Saltmarsh and Mudflats and sandflats not covered by seawater at low tide. The assessed vulnerability of these features is mainly driven by projected rises in sea level, which resulted in nearly all intertidal component biotopes being assessed as high vulnerability by the end of the century. Intertidal features are also considered vulnerable to other climate change pressures such as air temperature, wave exposure, and sea temperature (to a more limited extent).

Subtidal Annex I marine features in SACs are generally assessed as being less vulnerable to climate change pressures, mainly because they are not exposed to changes in sea level or air temperature (unless they occupy the shallow sublittoral zone and are light dependent). However, some subtidal features such as Subtidal reef (comprising, for example, biotope SS.SMx.CMx) and Maerl (biotope SS.SMp.Mrl) are more vulnerable to pressures such as ocean acidification as they are exposed to lower pH values at depth.

The results also suggest that both deoxygenation and changes in salinity pose the least amount of risk to component biotopes of Annex I marine features due to climate change.

The level of vulnerability that was predicted across Wales was affected by exposure to climate change pressures projections, as well as the presence of sensitive component biotopes within SACs. As such, there are some examples of spatial variation in the vulnerability of component biotopes to climate change pressures (e.g. mostly high vulnerability of Subtidal reef features comprising SS.SMx.CMx biotopes to ocean acidification in the Pembrokeshire Marine SAC, but mostly medium vulnerability or not sensitive in the Menai Strait and Conwy Bay SAC comprising various Subtidal reef biotopes). However, generally speaking, there was no consistent spatial pattern in the vulnerability of Annex I marine features to climate change pressures around Wales or within SACs.

4.2. Other factors influencing vulnerability to climate change

In addition to climate change pressures, there are a number of other factors, particularly policy factors, that could influence the overall vulnerability of Annex I marine habitats to climate change.

4.2.1. Management of feature condition

The existing condition of Annex I marine habitats is important when considering the vulnerability to climate change pressures. Features in unfavourable condition are less likely to be resistant to, or recover from, a climate change pressure because their ecological functioning may be compromised. Features already in favourable condition are more likely to withstand pressures and be resilient to climate change.

Current feature condition was not included as a parameter in the model to assess vulnerability. Although vulnerability would not necessarily be lessened for all features' if they were in favourable condition, taking management action to maintain or restore features to favourable condition could help to reduce vulnerability to climate change. This might include reducing existing anthropogenic pressures on Annex I marine habitats or interventions to recreate or restore such habitats where this is practicable.

4.2.2. Shoreline management plans

SMPs in Wales have been developed jointly by local authorities and NRW in order to describe how a stretch of shoreline is most likely to be managed to address future coastal flood and/or erosion risk. Where a hold the line (HTL) policy is implemented there is increased potential to impact on the extent (and condition) of Annex I marine habitats through coastal squeeze. In these locations, therefore, the impacts of sea level rise (which is considered the most important pressure in driving Annex I habitat vulnerability to climate change) and the vulnerability of Annex I marine habitats would be highest. Actual impacts would of course be site specific and dependent on geomorphological settings and shore profiles (see Section 3.2.2). Jolley *et al.* (2013) provides a detailed assessment of four case study areas of different shore types from around the coast of Wales.

Equally, in locations where managed realignment (MR) is adopted (or indeed where no active intervention (NAI) is adopted provided the shoreline is able to migrate landward at the same pace as sea level rise), coastal squeeze related impacts to intertidal habitats can be offset. The vulnerability of Annex I marine habitats would potentially be lessened in these locations as intertidal habitat could move landwards and maintain or increase in extent.

The Welsh coastline has been split into four areas (North Wales; West Wales, South Wales and Severn Estuary) for the purposes of the SMP2s. Each area is further divided into management units, and again into policy units for which different management policies are defined for future management of the coastline over three epochs: 20 years; 50 years and 100 years (Figure 24). Approximately 417 km of the Welsh coast within SACs is prescribed a HTL policy in the short term (in Epoch 1, up to 2025) (Oaten *et al*., 2018).

The SMP2s were subject to Appropriate Assessments under the requirements of the Habitats Directive (which is transposed in Wales through the Conservation and Habitats and Species Regulations 2017 (as amended)). This provided the most comprehensive view of predicted habitat losses in Welsh SACs due to HTL polices and sea level rise (Table 16). Given that an Adverse Effect On Integrity (AEOI) could not be ruled out, a strategic approach to securing compensatory measures was required to offset predicted habitat loss. The National Habitat Creation Programme (NHCP) was set up by the Welsh Government (implemented by NRW) to scope for and provide any necessary coastal habitat compensation as a result of the plans or projects funded through its flood and coastal erosion risk management programme(s) related to SMP policies. It can also be a delivery mechanism of compensation for third party schemes subject to partnership agreements.

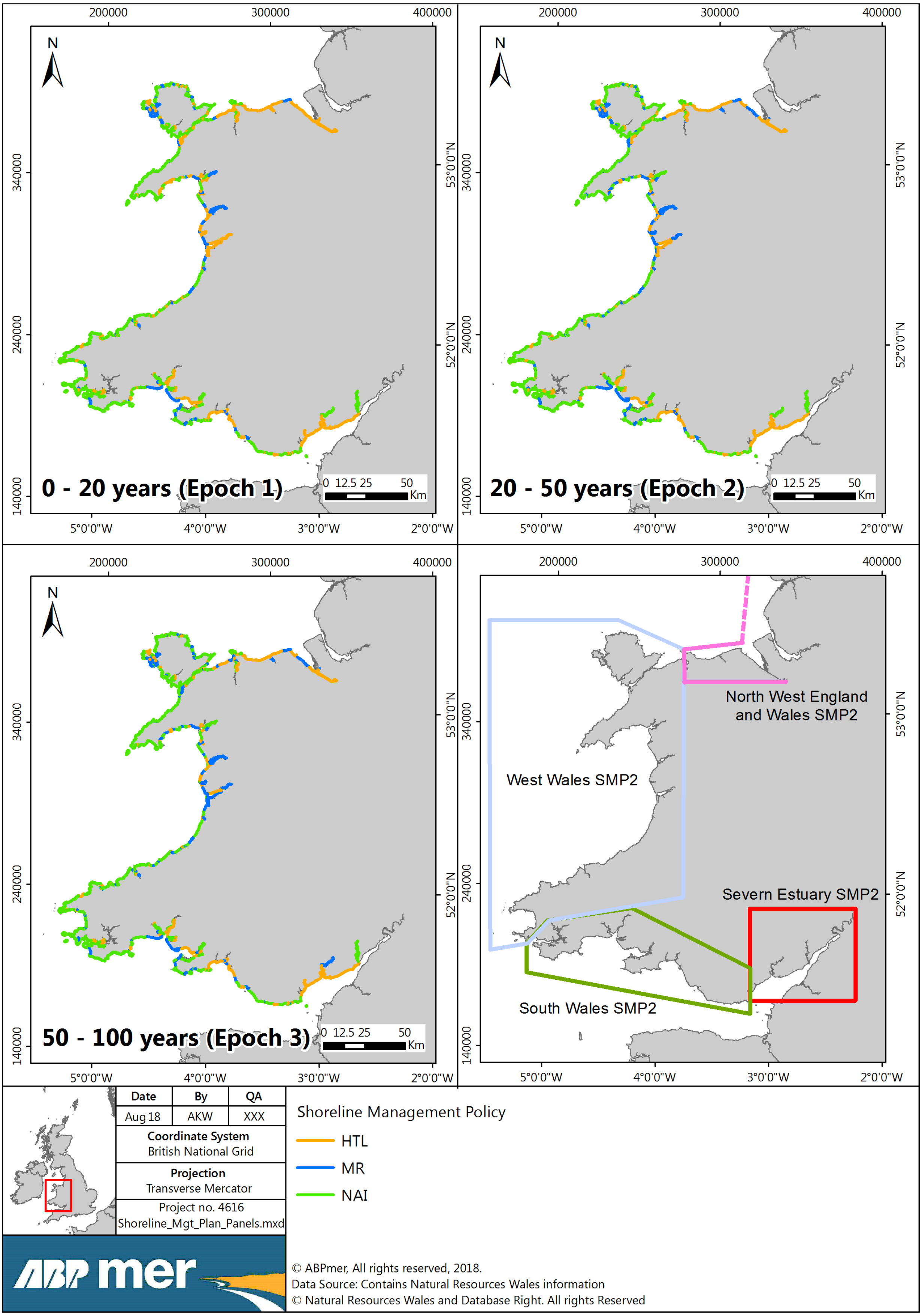

Figure 24. SMP2 policies for each epoch along the Welsh coast (Policies shown as HTL Hold the Line; MR Managed Realignment; NAI No Active Intervention)

Table 16. Predicted intertidal habitat losses in Welsh Natura 2000 sites as reported by NRW

Designated site name	Coastal Squeeze Intertidal Losses (ha) - Wales By 2025	Coastal Squeeze Intertidal Losses (ha) - Wales By 2055	Coastal Squeeze Intertidal Losses (ha) - Wales By 2105	Coastal Squeeze Intertidal Losses (ha) - Wales Total
Severn Estuary SAC/SPA (in Wales*)	226	463	1223	1912
Burry Inlet/Carmarthen Bay SAC/SPA	59	163	411	633
Pembrokeshire Marine SAC	2	4	5	11
Lleyn Peninsula and the Sarnau SAC	40	150	111	440**
Anglesey Coast Saltmarsh SAC	1	4	11	16
Menai Strait and Conwy Bay SAC	3	12	1	12***
Dee Estuary SPA	0	140	454	594
Total	**331**	**936**	**2216**	**3618**

* Predictions for Severn Estuary losses in both England and Wales are approximately three times these areas (679 ha by 2025, 1388 ha by 2055, and 3670 ha by 2105, totalling 5737 ha).

** Total figure understood to be updated to from 300 ha following review by JBA consulting (Rick Park, personal communication, 28/06/2018).

*** Total figure understood to be updated from 16 ha following review by JBA consulting (Rick Park, personal communication, 28/06/2018).

As reported in the Marine Area Statement coastal theme page (NRW, 2021), there is a planned shift from continuing to defend the coast, to a more adaptive approach in some locations (e.g. MR) (Figure 25). Furthermore, where HTL polices remain, such as in densely populated locations, other nature-based solutions (e.g. beach replenishment or saltmarsh protection) may be sought to offer coastal protection. These types of solutions offer coastal defence as well as providing other benefits such as creating or maintaining habitats for wildlife and attracting tourism to boost local economies. This allows for better integration of conservation management with flood risk planning.

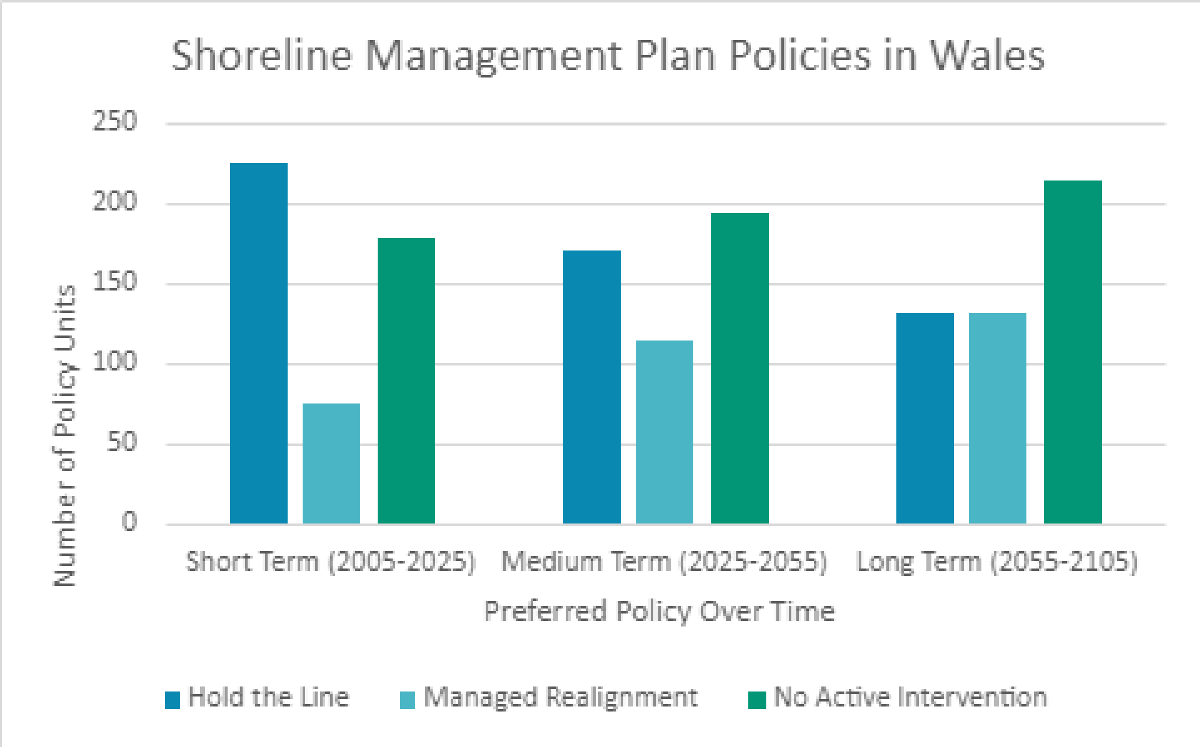

Figure 25. Shoreline management plan policies in Wales. Source: NRW (2021)

4.2.3. Adaptive capacity

The IPCC defines adaptive capacity as '*the ability of systems, institutions, humans, and other organisms to adjust to potential damage, to take advantage of opportunities, or to respond to consequences*'. The term is also built into the definition and assessment of vulnerability in climate change frameworks and studies. The UK CCRA (2012) and Jones *et al.* (2011) use the vulnerability definition of: '*[…] the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity*'.

The adaptive capacity of Annex I marine habitats can influence their vulnerability to climate change (Jones *et al*., 2011). Biotopes considered to have a low adaptive capacity include circalittoral mixed sediments as they cannot be recreated easily and some climate change pressures affecting this receptor (e.g. ocean acidification) are difficult to mitigate. For other features, such as saltmarsh and intertidal mud and sand flats, adaptive management action is more feasible.

Partly linked to the concept of adaptive capacity is how biotope function may change (or adapt) following climate change-induced affects to community composition and structure. In some instances, a species may be replaced by another with similar ecological importance and function formerly provided by the adversely affected species (Hiscock *et al*., 2004). For example, an increase in temperature may create a competitive edge for *Chthalamus montagui* which may replace *S. balanoides*; this is unlikely to cause any significant changes in the biotope as the functional niche will still be filled (Perry, 2015). However, if the abundance of a key structural species such as *M. modiolus* declined, then there may be significant effects on the associated fauna and flora (e.g. its function as a nursery areas for scallops would be compromised) (Hiscock *et al*., 2004). Another example is replacement of *L. hyperborea* with *L. ochroleuca* in Wales and changes in resistance to storms and waves, along with potential changes in ecological value (see Section 3.2.1). This is an important additional consideration when determining how Annex I marine habitats and their composite biotopes may be affected by, or adapt to, climate change.

4.3. Limitations

The GIS model provides a high-level assessment of the vulnerability of component biotopes that comprise Annex I marine habitats. There are limitations in the model that affect its ability to accurately predict vulnerability. These relate to:

- Spatial extent of Annex I marine habitat features;
- Knowledge of biotope distribution and extents within some Annex 1 features;
- Availability and spatial coverage of climate change pressure data layers;
- Uncertainty associated with emissions scenarios and climate projections;
- Synergistic effects of multiple pressures;
- Sensitivity thresholds and the oversimplification of pressure-sensitivity relationships; and
- Indirect effects of climate change.

These limitations are discussed further below.

The spatial coverage of component biotopes that were used to form the receptor data layer was poor for some Annex I marine habitats (e.g. Coastal lagoons) (see Section 2.2). For these Annex I marine habitats, the vulnerability assessment results (presented as percentage coverage of component biotopes) would be based on the sensitivity of only the component biotopes that are mapped within these features. This may therefore skew the vulnerability results and not be representative of the Annex I marine habitat as a whole. The receptor data layer should therefore be updated as new spatial data becomes available on marine biotopes in Wales.

A number of climate change pressure data layers were used in the GIS model. The appropriateness of each pressure data layer was judged and considered the best available to model future projections, however, some key limitations have been identified (as described in Section 2). Differences in the timeframes, emissions scenarios and variables used in each pressure data layer limits the comparability of assessed vulnerability over the next century. Furthermore, the resolution and coverage of some climate projections is poor in nearshore locations. To resolve this, further processing of some pressure data layers was undertaken so that coverage across all component biotopes of Annex I marine habitats in Welsh waters was complete. This further limits the accuracy of the vulnerability assessment, particularly where environmental conditions are likely to be significantly different in nearshore locations (e.g. estuaries, coastal lagoons) compared to offshore locations or the open coast.

There is a large degree of uncertainty associated with emissions scenarios and climate projections. Several factors contribute to the uncertainty in climate models relating to the current understanding of climatic conditions, how climate parameters are represented in the model, and how accurately earth systems are modelled (see Section 3.1). Projections are also based on emissions scenarios which are inherently uncertain and could be affected by a number of socioeconomic drivers. It is important to recognise this uncertainty when interpreting the vulnerability assessment results.

Where features are exposed to multiple pressures (identified in Section 3.3.8), more severe impacts and a deterioration in condition status may result. The GIS model assessed single pressures individually and does not take into account the cumulative effect of multiple pressures and the extent to which these might be synergistic. However, there is uncertainty associated with how climate change pressures may interact and therefore calculating an overall vulnerability to climate change would further compound uncertainty and is considered to be prohibitively complex.

The sensitivity thresholds set for each component biotope had a large influence over the resulting model outputs for the vulnerability of component biotopes of Annex I marine habitats. As highlighted by Jones *et al*. (2011), sensitivity thresholds that spanned a wide range of projected pressure values were more likely to result in spatially and temporally (across the projection timeframes) homogenous vulnerability outputs. Likewise, where the range of sensitivity thresholds align closely with the projected pressure values, then even small changes in the projections could result in a change in vulnerability. Furthermore, the climate projections used to form the pressure data layers will govern the vulnerability outputs from the model. This should be recognised in the context of the uncertainty in projections (particularly where uncertainty is high e.g. wave exposure) or where spatial coverage of the projections is poor and has to be interpolated. It is recommended, therefore, that the sensitivity assessments and pressure data layers are kept under regular review to keep pace with emerging issues, research and climate projections.

The sensitivity thresholds that are applied to component biotopes in the GIS model, as well as the pressure variables that are used, are also predominantly based on minimum and maximum daily mean values. However, it does not account for other measures that may be important in determining a biotope's pressure-sensitivity-relationship. An example of this is for *S. balanoides* that requires a low temperature 'trigger' to reproduce. Temperatures above 10 to 12°C inhibit reproduction (Barnes, 1957, 1963; Crisp and Patel, 1969). A laboratory study also suggests temperatures at or below 10°C for 4 to 6 weeks are required in winter for reproduction, although the precise threshold temperatures are not clear (Rognstad *et al*., 2014). Therefore, if winter temperatures increase and fail to fall below this level than the species might be unable to breed and may alter biotope extent and functioning (Hiscock *et al*., 2004). There are other examples of this: *Arenicola marina* spawning success is dependent upon spring and autumn temperatures (the seasons when spawning occurs in relation to spring and neap tides) remaining below 13-15°C (Ashley, 2016c); *Caryophyllia smithii* reproduction is cued by seasonal increases in seawater temperature (Tranter *et al*., 1982); and *M. modiolus* recruitment appears to occur in a narrow temperature range (7-10°C) (likely to be the most limiting factor for this species as seawater temperatures rise) (Tillin *et al*., 2020a). The vulnerability of biotopes to changes in seasonal cues is not accounted for in the GIS model, and therefore the vulnerability may in some instances be underestimated.

The period and frequency of exposure to extreme climate change pressures is also likely to be important for determining vulnerability. For example, gradual warming, or indeed high temperatures over short periods, may be tolerated by some biotopes. However, prolonged exposure to extreme temperatures will have larger consequences for some species and habitats, particularly if these result in marine heatwaves (see Section 3.1.2). *Zostera noltei* has been shown to withstand a gradual increase in temperatures but is susceptible to marine heatwaves (D'Avack *et al*., 2020). An experimental sharp increase in temperature from 18 to 22°C for 30 days led to a drastic decrease in shoot density (Repolho *et al.,* 2017). The GIS model currently does not take account of the period of time that a sensitivity threshold is projected to be exceeded for. To address this issue, it would require an extra level of detail in the sensitivity assessment to determine the length of exposure to a given pressure level that a biotope would be sensitive to. This is in addition to an extra step in the processing and modelling of projection data to determine the number of consecutive days a projected pressure value exceeds a sensitivity threshold. This was not undertaken in this project as it was considered to be beyond the scope of the work.

Local populations of species can also exhibit acclimation to prevailing environmental conditions (e.g. temperature, salinity etc.). This means biotopes in different locales may have different tolerances that are aligned to local conditions. For example, localised physiological adaption of brittle stars to reduced or variable salinities (despite echinoderm being stenohaline) has been suggested in near shore areas subject to freshwater runoffs (Pagett, 1981). *Chorda filum* and *Gracilaria gracilis* also show localised adaptation to the prevailing salinity regime (Stamp, 2015). This is problematic when inferring tolerances and setting blanket sensitivity thresholds to component biotopes of Annex I marine habitats across Wales.

As well as the pressures identified in this project, it is worth noting that climate change may cause other indirect impacts that could impact Annex I marine habitats in Wales but are not specifically taken into account in this assessment of vulnerability. For example, whilst climate change may cause the range of biotopes and species to recede or expand in Wales due to changes in temperature (see Section 3.2.1), it may also indirectly contribute to increased interspecific specific competition and also the proliferation of invasive non-native species (INNS). For example, *L. hyperborea* is a northern (boreal) kelp species and increases in sea temperature may limit extent and ecological functioning at its southern limit of distribution (Smale *et al*., 2013; Stenneck *et al*., 2002). As temperatures increase further, competition from INNS *Undaria pinnatifida* (Smale *et al*., 2013; Brodie *et al.,* 2014; Heiser *et al.,* 2014), and/or the Lusitanian kelp *L. ochroleuca* (Brodie *et al*., 2014) may alter *L. hyperborea* biotope structure. Evidence suggests *U. pinnatifida* is already competing with *L. hyperborea* on the UK south coast though the ecological consequences are not yet known (Stamp and Hiscock, 2015).

Another example of indirect effects include a reduction in water quality in coastal areas due to increased run-off (exposure to this is already discussed in Section 3.1.10, but vulnerability of Annex I marine habitats is not considered). Concerns are mostly associated with eutrophication and the proliferation of nuisance algae due to nutrient loading, increased amounts of marine litter, and the delivery of chemical pollutants to coastal environments (e.g. metals, pesticides).

5. Conclusions

The GIS model provides a method to capture the spatial representation of the relative potential vulnerability of individual Annex I marine habitats in Wales to a range of climate change pressures and scenarios. The model outputs of the vulnerability assessment suggest that intertidal/coastal component biotopes of Annex I features are the most vulnerable to climate change. This is mainly in relation to changes in sea level, but also air temperature, wave exposure, and sea temperature to a lesser extent.

However, a number of limitations in the model were identified that limit its ability to map potential Annex I marine habitat vulnerability. These include the spatial representation of Annex I marine habitats, the availability of climate change pressure data layers (and their spatial and temporal resolutions), and uncertainty associated with emissions scenarios and climate projections. Further limitations include the fact that other measures associated with climate change pressures that may be important to vulnerability are not accounted for (e.g. seasonal cues, period/frequency of exposure to pressures), as well as indirect effects associated with climate change.

The principles of the model were designed to ensure input parameters can be updated as new data or evidence becomes available, or if policies change and different assumptions or scenarios are to be tested. As such, recommendations to improve the model and outputs of the vulnerability assessment are listed below:

- Increase the coverage of the receptor data layer when new spatial data becomes available at the resolution required (i.e. Level 4/5 biotopes of the MHC). This will improve the accuracy of mapped component biotopes and better represent the vulnerability of Annex I marine habitats in Wales;

- Periodically review and update pressure data layers to keep abreast of new climate projections with potentially improved spatial and temporal resolution. How elements of uncertainty associated with climate projections could affect the outcome of vulnerability assessments should always be recognised;

- Periodically review and update sensitivity assessments and thresholds to keep pace with emerging issues and research. The use of biotope sensitivity assessments within MarLIN MarESA would be particularly beneficial as more component biotopes are assessed for climate change pressure;

- Refine the examination of specific climate change pressures and component biotope sensitivity within the model (e.g. account for winter minimum temperatures and seasonal cues where relevant for component biotopes). This could be prioritised on the basis of particular pressures of concern for certain features.

- Incorporate other factors that influence the vulnerability of Annex I marine habitats into the model and vulnerability assessment. This could include other pressures, the implications of emerging policies or changing activities, adaptive capacity, as well as the current condition of features. However, this may further compound uncertainty and be prohibitively complex.

Implementation of these recommendations will help better inform climate-related management and/or site adaptation options at feature, site and network level. However, it is recognised that this adds further complexity to the vulnerability assessment and is challenging due to the number of climate change pressures that need to be analysed, multiple climate model projections, emissions scenarios, and timeframes available, and the diversity of component biotopes of Annex I marine habitats that are sensitive to climate change.

Despite all of the recognised limitations, the model outputs generated through this study provide a high-level indication of which Annex I marine features within Welsh SACs are considered to be most vulnerable to the pressures associated with climate change. They provide an indication of where potential management measures could be best targeted to achieve the greatest benefit to the MPA network. However, any such measures would need to be set in the context of the degrees of uncertainty associated with the outputs along with wider influences and other pressures on the features. In light of this uncertainty, it is important to recognise the need for continued monitoring of impacts on and changes to Annex 1 habitats to inform adaptive management going forwards, and coincidentally to avoid mal-adaptation.

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Appendices

Appendix A: Tidal water levels

The regular motion of the sun, moon and earth cause spring tides to occur at roughly the same time of day for any given location (NTSLF, 2021). The diel timings of spring and neap tides, and the proportion of time different parts of intertidal habitats are exposed to varying intensities of solar heating, has the potential to influence the vulnerability of Annex I marine features exposed to air. Where spring low tides coincide with peak intensities of solar heating (i.e. midday to late afternoon) then impacts may be exacerbated.

To investigate this phenomenon in Wales, solar energy intensity was chosen as a proxy for the relative temperature of intertidal habitat surfaces. This is because it closely represents the factor driving the main seasonal and diurnal variation in temperature on the surface of the intertidal habitat. Air temperature also has an effect on surface temperature but is a slightly less direct proxy because it can also change with other local and regional scale meteorological processes. Air temperature is expected to broadly follow seasonal and diurnal patterns but is largely independent of the processes controlling tidal water levels. Air also has a low specific heat capacity and so can take some time to heat or cool a wet rock or sediment substrate. Solar radiation can heat the surface directly more efficiently, and surfaces will cool rapidly due to sensible heat loss when solar radiation is weak or absent.

A timeseries of coincident historical tidal water level and solar radiation intensity data were obtained for locations on the Welsh coast representative of SACs with Annex I marine features (i.e. central locations within SACs). Tidal water level data were obtained from the ABPmer SEASTATES European Shelf Tide and Surge Hindcast Database (ABPmer, 2017). The tidal water levels are expressed as metres above lowest astronomical tide (mLAT), where LAT is the minimum tidal water level in the timeseries. The database provides 40 years of timeseries data (1979 to 2018) at 10-minute intervals (approximately 2.1 million data points).

Solar radiation intensity timeseries data was calculated using the ‘suncycle’ Matlab function library (Scripps, 2009). The routine uses expressions from Appendix E in the 1978 edition of Almanac for Computers, Nautical Almanac Office, U.S. Naval Observatory. The solar constant (1368.0 W/m²) represents a mean of satellite measurements (of incident solar radiation intensity at the edge of Earth’s atmosphere) made over the last sunspot cycle (1979-1995) taken from Coffey *et al.* (1995), Earth System Monitor, 6, 6-10”. The routine calculates a time series of radiation intensity at a location on the earth surface based on the solar declination, radiation and altitude from the position (the angle of the sun overhead in the sky) and the corresponding reduction in radiation intensity caused by transmission through the atmosphere, and the angle of incidence to the ground (assuming a horizontal ground level). The resulting value does not however take account of the effect of time varying cloud cover, rain, and weather.

Figure and Figure A show the outputs of this analysis for neap and spring tides in summer, respectively. During neap tides, it is demonstrated that low tide in north Wales (e.g. in the Dee Estuary, Menai Strait, Cemlyn Bay, Anglesey) coincides with peak solar irradiance (i.e. around midday and also around midnight). In south Wales (e.g. in the Severn

Estuary, and Carmarthen Bay), low tide occurs either side of peak solar irradiance (i.e. in the morning and evening). The opposite is the case during spring tides; in north Wales low tide occurs either side of peak solar irradiance, and in south Wales low tide coincides with peak solar irradiance. Therefore, as low spring tides expose the greatest extent of intertidal biotopes in the lower littoral zone to air, intertidal Annex I features in south Wales may be particularly vulnerable to increases in air temperature over the next century.

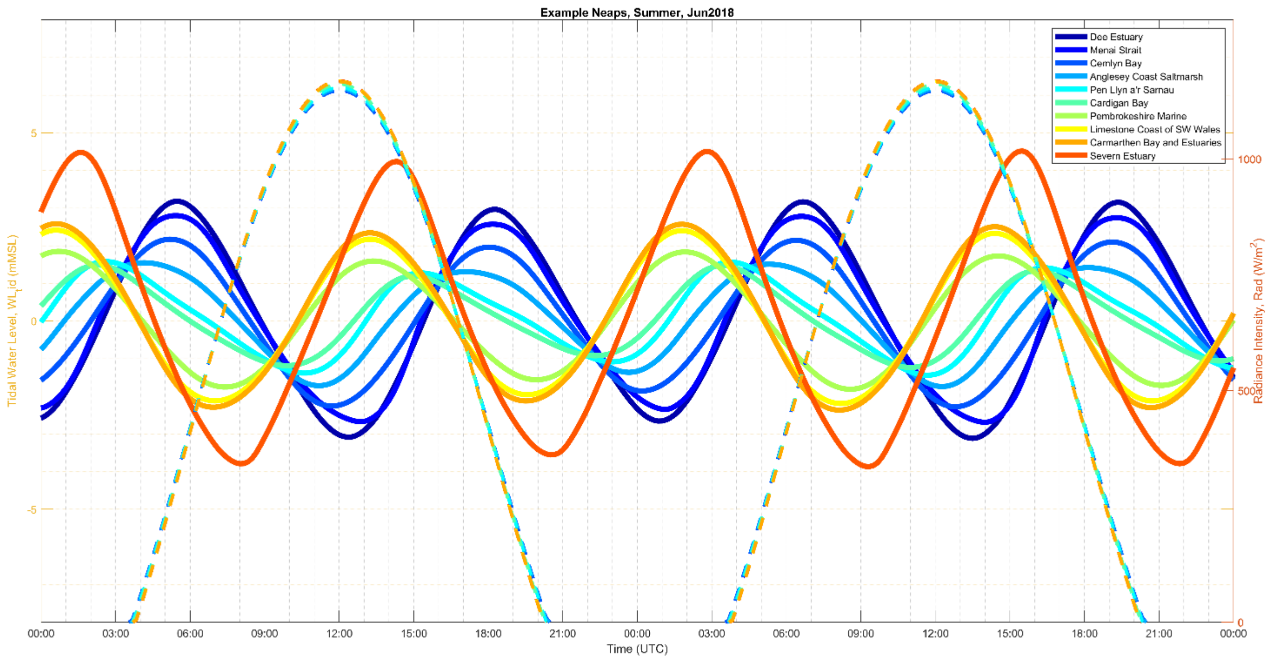

Figure A1. Diel timing of water levels during neap tides and radiance intensity for representative locations around the Welsh coast (solid lines represent water levels, left axis, and dotted lines represent radiance intensity, right axis)

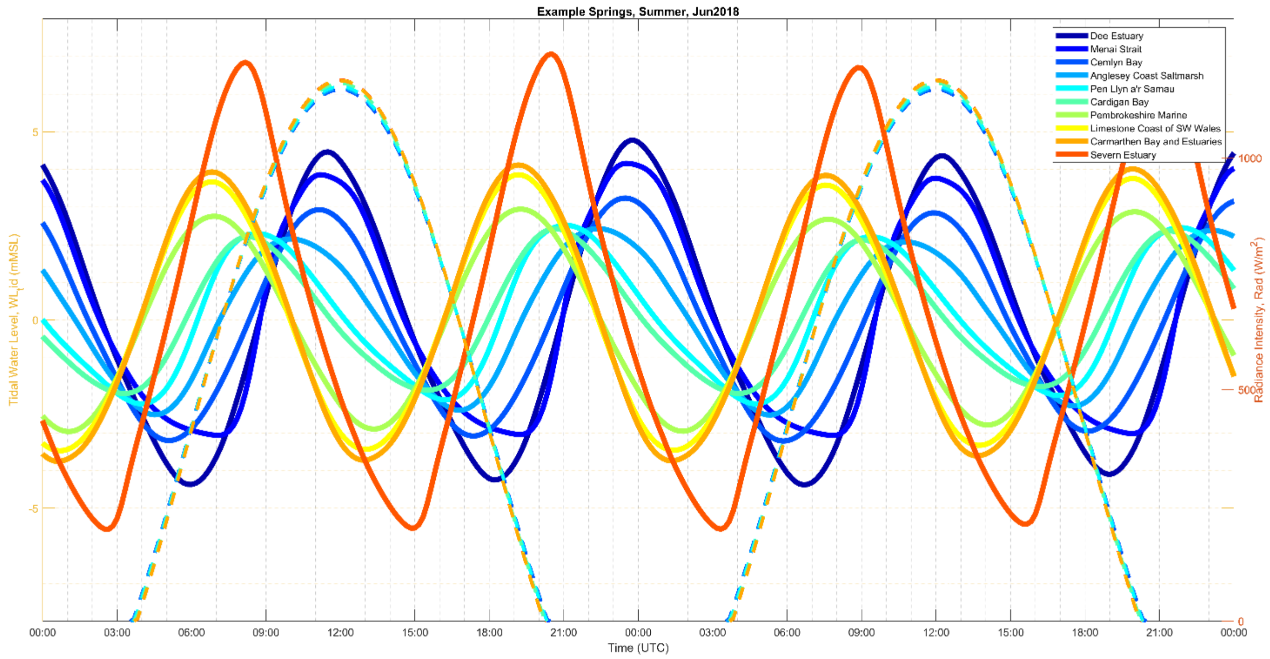

Figure A2. Diel timing of water levels during spring tides and radiance intensity for representative locations around the Welsh coast (solid lines represent water levels, left axis, and dotted lines represent radiance intensity, right axis)

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Appendix B: Data Archive Appendix

Data outputs associated with this project are archived on server–based storage at Natural Resources Wales within the NRW data archive (Z drive).

The data archive contains:

[A] The final report in Microsoft Word and Adobe PDF formats.

[B] A sensitivity assessment of component biotopes of Annex I marine habitats to climate change pressures in Microsoft Excel format.

[C] A full set of vulnerability assessment model outputs in Microsoft Excel format.

[D] A series of GIS layers on climate change pressures and Annex I marine habitat vulnerabilities on which the maps in the report and model outputs are based with a OneNote file detailing the data processing and structure of the GIS layers

Metadata for this project is publicly accessible through Natural Resources Wales' Library Catalogue https://libcat.naturalresources.wales (English Version) and https://catllyfr.cyfoethnaturiol.cymru (Welsh Version) by searching 'Dataset Titles'. The metadata is held as record no NRW_DS125172 (Record Title *Assessing the vulnerability of Annex I marine habitats to climate change in Wales 2021*).