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Model projections of marine environmental variables’ response to climate change within England’s south west marine plan areas (MMO 1169)

MMO 1169: Model projections of marine environmental variables' response to climate change within England's south west marine plan areas

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Information about this publication and further copies are available from:

Marine Management Organisation
Lancaster House
Hampshire Court
Newcastle upon Tyne
NE4 7YH

Tel: 0300 123 1032
Email: info@marinemanagement.org.uk
Website: www.gov.uk/mmo

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1. Introduction

1.1. Background

The UK marine economy is worth over £49 billion (bn) a year with the potential for significant expansion (Marine Management Organisation 2017). It is a significant source of social benefits through recreational activity and cultural identity while also being home to over 8000 marine species which require protection for future generations.

The UK Government has a 20-year vision to achieve clean, safe, healthy, productive and biologically diverse oceans and seas. To facilitate sustainable growth while safeguarding marine ecosystems and the services they provide, the Marine and Coastal Access Act (2009) places a duty on the Marine Management Organisation to develop Marine Plans for English waters, guided by the Marine Policy Statement (MPS). Marine Plans provide a framework for decisions that affect the marine area. Marine plans inform regulators, planners and users by providing a clear and consistent framework that guides the decision making process towards this vision.

The MPS sets out 11 marine plan areas. The south west inshore marine plan area covers over 16,000 square kilometres of sea and approximately 2,000 kilometres of coastline stretching from the River Severn border with Wales to the River Dart in Devon. The south west offshore marine plan area covers approximately 68,000 square kilometres of sea and includes the marine area from 12 nautical miles extending out to the seaward limit of the Exclusive Economic Zone (EEZ).

The south west marine plan (SWMP) areas incorporates a number of marine protected areas including sites unique to England (Charting Progress 2, 2014; Gubbay 2014).They also incorporate one of the largest fishing fleets in the UK, landing 39.4 thousand tonnes into south west ports annually worth over £86 million to the regional economy (UK Sea Fisheries Annual Statistics report 2017). The south west's coastline and associated area includes eight world heritage sites and half of all English designated Heritage Coasts attracting recreational activity and tourism estimated to contribute £4-5.5 bn to the regional economy (Visit Cornwall 2011; ONS 2013). The Severn Estuary and Bristol Channel provide accessible naturally occurring sources of marine aggregates, notably sand, which support local construction. This aggregate resource may also support infrastructure projects of national significance (tidal energy, Hinkley nuclear power station). The 15 metre tidal range in the Bristol Channel is the third largest in the world, offering the potential for renewable energy exploitation. Collectively, marine sectors in the south west directly or indirectly support over 350,000 jobs and contribute £16.4 bn to gross value added in a region where the resident population is projected to increase 6.6% by 2026, relative to the resident population in 2016 (ONS 2015; 2018). Existing and projected activities are likely to place increasing pressure on the south west regions' marine environment.

The South West Marine Plans have been under development since 2016, alongside the North East, North West and South East Inshore and Offshore Marine Plans. Once developed, draft plans will be subject to a formal public consultation process and become a material consideration in decision making, before expected adoption in 2021. English marine plans cover a 20-year planning timeframe. Thus adoption of the South West Marine Plans in 2021 provides policy for decision making impacting the marine environment over the 2021 to 2041 timeframe. The Marine and Coastal Access Act (2009) requires the review of marine plans every three years.

Physical and chemical characteristics of the marine environment are responding to climate change induced by anthropogenic activities (Doney 2012; IPCC 2014; Natl. Res. Counc. 2011). It is almost certain that the rate of change will accelerate over the coming decades in the absence of dramatic and immediate mitigation efforts (Natl. Res. Counc. 2011).

Existing evidence indicates that amongst these changes, global seawater temperature has increased while global seawater pH has decreased. Such changes influence marine life, with evidence for modifications to activity and distribution of species across temporal and spatial scales, and levels of biological organisation. At regional scales, change within the marine environment influences the suitability of marine habitats for indigenous marine life and ultimately impacts upon ecosystem function, sustainability and service provision. Within the context of marine planning, there is a specific interest in the influence global climate change exerts at the regional and local scale within and among marine plan areas and within the 20-year timescales applicable to marine plans, where impacts may be least certain.

1.2. Aims

The aim of this report is to use modelling approaches to project how seawater characteristics within the SWMP areas may change over the coming decades. While model projections frequently consider potential longer-term impacts of climate change, there is a pressing need to consider changes at time scales relevant to marine planning. Potential changes in environmental variables that describe the physical, chemical and biological characteristics of seawater are presented. This report considers how these potential changes may influence specific marine sectors and receptors within the time-frame and geographical extent of the SWMP.

2. Modelling

2.1. Model description and setup

For the purpose of this study we used simulation results from a three-dimensional modelling framework consisting of an ocean circulation model coupled with a model of marine biogeochemistry and the lower trophic food web (Figure 1).

Ocean circulation model

NEMO (Nucleus for European Modelling of the Ocean) is a state-of-the-art community-led ocean modelling system which is used for research and operational applications at a range of spatial and temporal scales. Within the scientific community there are 115 research projects associated with the NEMO modelling system which have generated over 650 publications (2009-2019). NEMO outputs three-dimensional fields of velocity based on currents and tidal mixing, sea surface height, temperature and salinity. Some of this information is used by the coupled biogeochemical model (e.g. temperature modifies biological rates; velocity fields transport biogeochemical tracers in vertical and horizontal directions).

Biogeochemical model

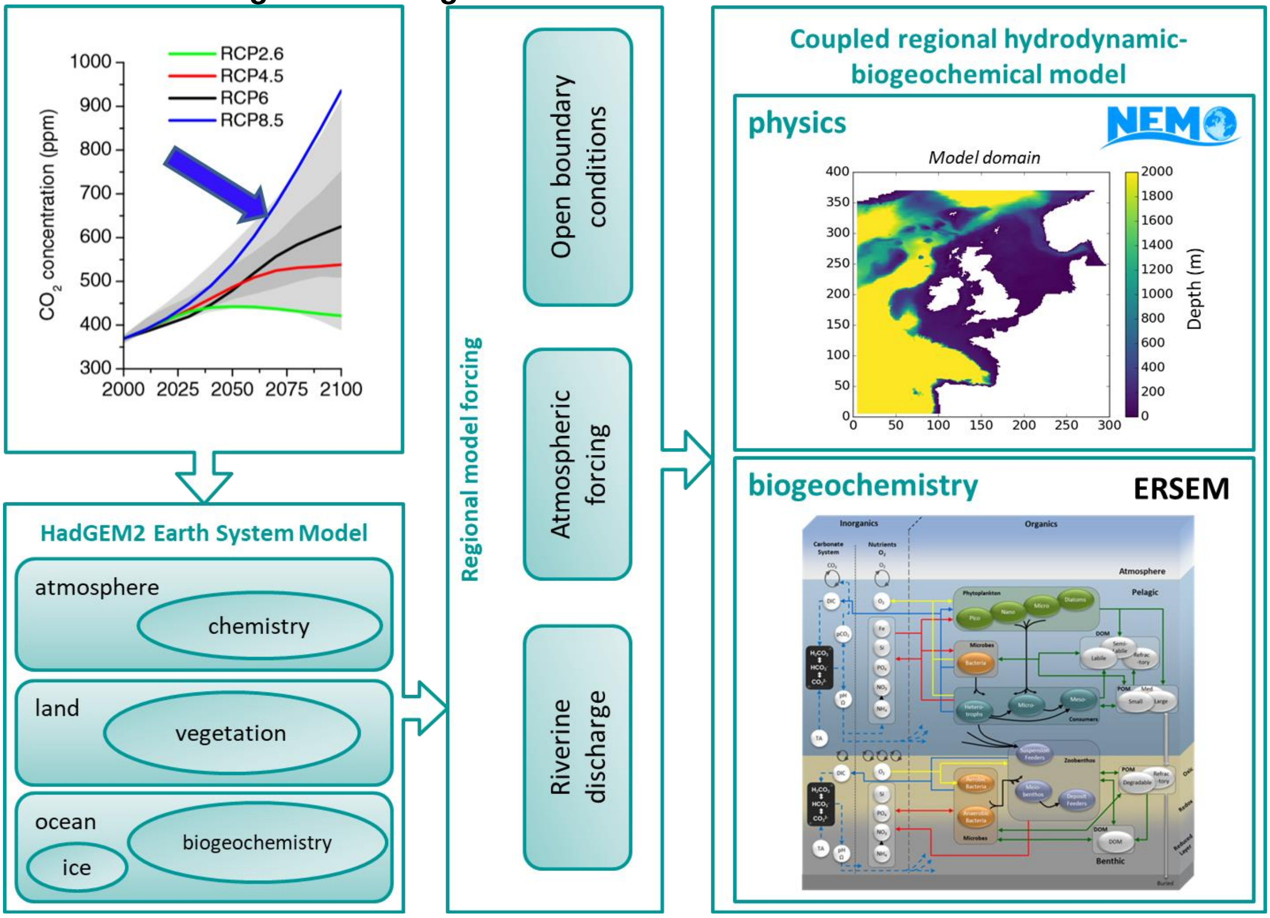
The biogeochemical and ecological model ERSEM (European Regional Seas Ecosystem Model that has been applied in over 200 publications since 1995) is a complex system that addresses both pelagic and benthic environments, including representation of the carbon, nitrogen, phosphorus, silicate, iron and oxygen biogeochemical cycles. ERSEM explicitly includes formulations of several functional types of phytoplankton, zooplankton and benthic fauna, a detailed representation of the microbial loop, as well as the carbonate system. ERSEM is a UK community model, with a wide international user-base.

Modelled area

The modelling framework used within this study was configured on the Atlantic Meridional Margin (AMM7) domain, which spatially covers an area from 20°W to 13°E and 40°N to 65°N, with a horizontal resolution of 1/15 degrees in latitudinal and of 1/9 degrees in longitudinal directions, corresponding to approximately 7 km square grids. In vertical profile at all locations, the model resolves the water column into 32 unequal terrain-following layers. Within this AMM7 domain, masks for the SWMP areas are applied; projections are presented for the SWMP area only.

Figure 1 provides a high-level overview of the structure of the coupled hydrodynamic-biogeochemical model. Of the four Relative Concentration Pathways (RCP) of atmospheric CO_2 over the 21st century (van Vuuren et al. 2011), the RCP8.5 greenhouse gas emission scenario was used to force the HadGEM2 Earth System Model (Figure 1; left). Compared to the total set of RCPs, RCP8.5 represents that with the highest greenhouse gas emissions (Section 2.2). HadGEM2-ES provided meteorology, land-based discharge and conditions at lateral boundaries of the model domain (Figure 1; middle) which forced the regional modelling system (Figure 1; right). The latter consisted of a hydrodynamic model NEMO (Figure 1; top-right) coupled with the ecological–biogeochemical model ERSEM (bottom-right). The regional model domain incorporates the North West European shelf sea area.

Figure 1 High-level overview of the structure of the coupled NEMO hydrodynamic and ERSEM biogeochemical model with forcing from the HadGEM2 Earth System Model under a RCP8.5 greenhouse gas emission scenario



Atmospheric forcing and boundary conditions

The model was driven by atmospheric forcing and open boundary conditions derived from outputs of the HadGEM2-ES global model simulation performed under the RCP8.5 greenhouse gas emission scenario (Section 2.2). HadGEM2 (Hadley Centre Global Environment Model version 2) is a global model, which includes a coupled atmosphere-ocean system with an Earth System (ES) configuration. It includes terrestrial vegetation, ocean biogeochemistry and atmospheric chemistry.

Rivers

Present-day concentrations of riverine nutrient inputs were applied, while river runoff values at each river mouth were modified according to changes in precipitation projected by the HadGEM2-ES global model.

2.2 Representative Concentration Pathway emission scenario selection

Representative Concentration Pathway (RCP) greenhouse gas concentration and emission scenarios were developed to underpin research on impacts of climate change and to inform policy on potential response and remediation measures (van Vuuren et al. 2011). The RCP8.5 scenario (for relatively high greenhouse gas emissions) was used to drive the NEMO-ERSEM modelling system used in this study and facilitate projections of marine environmental dynamics. The justification for this choice is that fossil fuel CO_2 emissions have been at the high-end of IPCC scenarios for the past decade. This has been related to the rapid growth of developing economies (Le Quéré et al. 2009). RCP8.5 (Riahi et al. 2011) is a baseline scenario that does not include any specific climate mitigation targets, assumes high population growth and a lower rate of technology development. Within this scenario the greenhouse gas emissions and concentrations increase considerably over time, leading to a radiative forcing of 8.5 $W \cdot m^{-2}$ (~1370 ppm CO_2 eq) at the end of the 21st century. In comparison, other RCP scenarios lead to radiative forcing levels of 6, 4.5 and 2.6 $W \cdot m^{-2}$, for RCP6, RCP4.5 and RCP2.6 respectively (Figure 1).

3 Environmental variables

The biological, physical and chemical variables considered within this study are outlined below. Unless otherwise stated, the discussion is restricted to the SWMP geographical area and the time frame 2021-2041, the planning horizon of the SWMP after adoption.

3.1 Dissolved Inorganic Nitrogen

Dissolved Inorganic Nitrogen (DIN) includes nitrate (NO_3^-), nitrite (NO_2^-) and ammonium (NH_4^+; which is in pH-dependant equilibrium with ammonia; NH_3). DIN supports the growth of microbial cells and higher marine plants and is essential nutrient for the growth of autotrophic cells within the benthic and pelagic environments. Within these cells, DIN is incorporated into organic molecules including amino acids, proteins, nucleic acids and photosynthetic pigments, supported by light energy captured during the process of photosynthesis. Collectively, this autotrophic activity represents primary production, which underpins marine food webs and ultimately seafood supply. The extent of primary production constrains the biomass of higher trophic levels. DIN availability is a factor that can limit the extent or rate of marine primary productivity (Wu et al. 2000). The form in which DIN is available (NO_3^- vs NH_4^+) can modify ecosystem function (Ward et al. 2011). The concentration of DIN varies across spatial and temporal scales with variability related to changes in DIN sources and sinks.

Sources of DIN to the SWMP areas include (i) riverine discharge of natural inputs of nitrogen derived from terrestrial organic matter decomposition as well as that derived from human activity (agricultural, industrial, as well as waste water treatment effluents), (ii) the water or sediment based regeneration of DIN following the decomposition of organic matter and, (iii) inputs related to water mass transport into the region.

Sinks that remove DIN from the marine environment and contribute to changes in DIN concentration include (i) the growth of biological cells; including autotrophic cells such as micro- and macro-algae and heterotrophic cells with the appropriate capacity (e.g. bacteria), (ii) denitrifying microbes, most frequently associated with marine sediments, that facilitate the conversion of nitrate (NO_3^-) to di-nitrogen gas (N_2) that is subsequently lost to the atmosphere, and (iii) export from the region associated with seawater mass movement. These source and sink terms are accounted for in the model.

Within the context of the SWMP, DIN concentration is relevant to the following sectors: (i) tourism, via its link with water quality, (ii) fisheries, via its constraint on marine productivity, and (iii) aquaculture, via its links to marine productivity and water quality. There is a particular interest in nitrates (a component of DIN) and their role in the eutrophication (the enrichment of water bodies with nutrients to a point that risks prolific and potentially undesirable or harmful microbial growth) of the coastal zone (e.g. Nitrates Directive (91/676/EEC)). Potential sources of eutrophication include waste water treatment, agricultural and industrial effluents, with consequences for water quality, habitats and human health, recreation and the potential for hypoxia (a dissolved oxygen concentration in seawater that is 1-30% of the air-equilibrated value). Future changes in land use, which influence riverine delivery of DIN to the coastal zone, are not explicitly considered within the model.

3.2 Dissolved Inorganic Phosphorus

Dissolved Inorganic Phosphorus (DIP; HPO_4^{2-}, PO_4^{3-}) supports the growth of autotrophic and heterotrophic microbial cells. Phosphorus is an essential element for living cells and accessing DIP represents one way in which this requirement can be met to achieve cell growth. In autotrophic cells, DIP is incorporated into organic molecules (e.g. nucleic acids, proteins, lipids) using energy derived from photosynthesis. In this way, DIP supports primary production and by extension, marine food webs. The availability of DIP is a factor that can limit the extent of marine primary production (Wu et al. 2000). DIP concentration varies spatially and temporally in relation to changes in its sources and sinks.

Sources of DIP to the SWMP areas include (i) weathering of terrestrial environments and delivery of DIP to the coastal environment and shelf sea via riverine flux (Paytan and McLaughlin 2007), (ii) anthropogenic riverine inputs derived from human activity including agricultural applications, waste water treatment and industrial effluent, (iii) pelagic or benthic regeneration of DIP following the decomposition of organic matter, and (iv) inputs related to seawater mass transport. Sinks that remove DIP from the region include: (i) the growth of biological cells with a capacity for DIP utilisation including photosynthetic autotrophs (e.g. phytoplankton) and heterotrophs (e.g. bacteria), (ii) physical transportation from the region via water mass movement.

Within the model, processes that directly influence DIP variability (assimilation, regeneration) are modulated by the physical environment (temperature, light, water column structure, tides, water-mass movement) leading to changes in DIP concentration across spatial and temporal scales.

Within the context of the SWMP, DIP concentration is relevant to the following sectors: (i) tourism, via its link with water quality, (ii) fisheries, via its constraint on marine productivity, (iii) aquaculture, via its links to marine productivity and water quality. There is a particular interest in the contribution that point and diffuse sources of phosphorus make to riverine and ultimately coastal DIP concentrations, including their contribution to eutrophication (e.g. the European Commission's Urban Waste Water Treatment Directive 91/271/EEC). Such enrichment can decrease ecological quality, induce ecological regime shifts and increase the potential for hypoxia in riverine and coastal environments (Hilton et al. 2006; Breitburg et al. 2018). Sources of eutrophication include agriculture, industry and waste water (notably sewage; Civan et al. 2018) disposal with consequences for water quality, habitats, human health and recreation. Future changes in land use, which influence riverine delivery of DIP to the coastal zone, are not explicitly considered within the model.

3.3 Ratio of Inorganic Nitrogen to Inorganic Phosphorus

The ratio of Dissolved Inorganic Nitrogen to Dissolved Inorganic Phosphorus (N:P) is an indication of the balance between resources that are essential for the growth of primary producers (i.e. phytoplankton). Primary producers require both resources in a relatively predictable proportion such that a limited availability of one resource restricts the use of the other. The ratio between these resources has a theoretical value of 16 (Redfield 1934), although observations at the global scale report variability around an average value of 20 (Martiny et al. 2013).

3.4 Dissolved Oxygen

Oxygen dissolved in seawater supports the respiratory metabolism of marine life in the pelagic as well as the benthic environment, including epifauna (organisms residing on the sea-floor surface) and infauna species (organisms residing within the benthic material). Oxygen is supplied by photosynthetic processes facilitated by pelagic microbial cells (phytoplankton), benthic phytoplankton (i.e. within biofilms), macrophytes (i.e. marine plants) and macroalgae (i.e. seaweeds). However, oxygen is not essential to all marine life; for example, deeper benthic sediments characterised by anoxic (oxygen deplete) conditions support specific growth strategies for marine microbes that utilise sulphate rather than oxygen to support respiration and hence growth. Such environments are critical to organic matter decomposition and nutrient regeneration. The balance between photosynthetic and respiratory processes has a major influence upon dissolved oxygen concentration in seawater, which exhibits strong seasonal variability (e.g. 190-260µM measured at the Western Channel Observatory).

The concentration of dissolved oxygen is modulated by seawater temperature as an intrinsic physical function. Dissolved oxygen concentration does not naturally approach low (i.e. hypoxic) or anoxic conditions within the shelf sea region considered, although in the global context the number of hypoxic regions has increased dramatically since the 1960's. This has been linked to lower oxygen solubility in warmer water (i.e. a climate change related impact) and also eutrophication, that places a greater demand on dissolved oxygen concentration during the microbial decomposition of organic matter (Diaz and Rosenberg 2008).

Beyond the European Shelf, sufficiently low oxygen concentrations have been measured at coastal sites to influence nutrient cycles and limit the abundance and distribution of fisheries (Bertrand et al. 2008), krill (Johnson et al. 1984) and marine animals (Breitburg et al. 2018).

The model represents dissolved oxygen concentration and the biological processes that produce and consume it (photosynthesis, respiration). Temperature modulates oxygen concentration directly, via its physical constraint on gas solubility, and indirectly via its influence on the rate of biological processes.

Within the context of the SWMP, dissolved oxygen concentration is relevant to water quality with implications for aquaculture and fisheries where reduced oxygen levels impact on growth rates and ultimately the health of species. Similar issues exist for the health of many designated features or wider communities encompassed in the marine protected areas and biodiversity more generally. Low oxygen environments can facilitate invasive (non-native) species (Lagos et al. 2017) and there is a particular interest in dissolved oxygen concentration in relation to eutrophication of the coastal zone and its subsequent impact on water quality, habitats and human health and thus is also relevant to tourism. Within the context of climate change, the susceptibility of the marine environment to de-oxygenation is an issue compounded by increased water temperature, which decreases oxygen solubility and enhances water column stratification.

3.5 Chlorophyll Concentration

Chlorophyll is a collection of closely related pigments synthesised by photosynthetic cells. Chlorophyll ‘captures’ light energy which is subsequently used for the synthesis of organic molecules in support of cell growth and ultimately, primary production. Through empirical relationships, chlorophyll concentration is broadly used as a proxy for photosynthetic cell biomass. By extension, the rate of chlorophyll production is used as a proxy for primary production. A diversity of photosynthetic cells contribute to the chlorophyll concentration within seawater. In isolation, chlorophyll concentration does not describe this diversity (i.e. the photosynthetic community structure may change without an associated change in total chlorophyll concentration).

Chlorophyll concentration increases when environmental factors support the growth of photosynthetic cells. These include physical (e.g. water column structure, temperature, light), chemical (e.g. the concentration of DIN and DIP) and biological (e.g. diminished grazing pressure) factors. Although there is considerable diversity in the biological communities that contain chlorophyll as well as the factors that support their growth, there is a relatively predictable seasonality to the variability in chlorophyll concentration, (as evidenced by long-term measurements, such as those at the Western Channel Observatory, which is situated within the SWMP area. Conversely, chlorophyll concentration decreases when environmental factors do not support growth (e.g. insufficient light, depleted nutrients, enhanced grazing pressure). The model explicitly considers the biological processes that produce chlorophyll, and the factors that modulate its concentration.

Within the context of the SWMP, chlorophyll concentration is relevant to the following sectors: (i) fisheries, via its measure of potential biomass available as a food source for higher trophic levels, (ii) aquaculture, as it constrains resource availability to commercially exploitable marine-life products (e.g. shellfish) and (iii) tourism, as an aesthetic indicator of water quality. Within the context of climate change, there is an interest in chlorophyll as an indicator of potential changes in marine productivity, its spatial distribution and phenology (the timing of events such as characteristic periods of enhanced primary productivity and how these relate to the productivity cycles of higher trophic levels).

3.6 Seawater Temperature

Temperature is a fundamental physical characteristic of seawater. Meridional overturning circulation represents the global transportation of heat energy (realised via temperature), upon which regional seasonality within the shelf sea system, that incorporates the SWMP areas, is superimposed. Seawater temperature directly influences (i) the physical characteristics of seawater; seasonal changes in incident light energy modify seawater temperature and hence density leading to seasonal transitions in water column structure, (ii) seawater chemistry; the solubility of gases (e.g. oxygen) decreases as seawater temperature increases, (iii) rates of chemical processes, and (iv) for living cells within seawater, temperature directly influences the rate of metabolic processes and hence growth rate. The culmination of these impacts places temperature as a primary driver influencing the function, structure and distribution of biological communities across levels of organisation, from pelagic plankton, zooplankton and fish to benthic epifauna and infauna species (IPCC 2014; Doney 2012; Perry 2005; Hiddink et al. 2015; Kröncke et al. 2011). The model explicitly considers temperature via direct empirical relationships to parameters describing physical, chemical and biological characteristics of seawater.

Within the context of the SWMP, temperature is relevant to the following sectors: (i) aquaculture, via its influence on the growth rate of cultured species and their food sources, and indirectly via its influence on habitat suitability, (ii) fisheries, via its influence on the growth rate of fish, their food sources, and the suitability of habitats, (iii) Marine Protected Areas via its influence on habitat suitability for indigenous species, (iv) invasive (non-native) species via its influence on habitat shift, spatial range and opportunities for colonisation, (v) biodiversity via its influence on habitat suitability, habitat shift, spatial range, the size structure, phenology and seasonal abundance of populations and the nature and extent of species interactions.

3.7 Seawater pH

The pH of seawater is a measure of its acidity or alkalinity. In the open oceans seawater has a relatively stable pH of approximately 8.2, but has higher variability in coastal regions due to terrestrial influence and higher marine biological productivity; typically, values can range from 7.5 to 8.5. The pH of seawater is a crucial characteristic that influences marine life across all levels of organisation, from single cells through to marine animals. Fundamentally, for microbial cells and photosynthetic marine plants, nutrients dissolved in seawater are transported from the surrounding environment across a cell membrane into the cell. Where nutrients carry an ionic charge, this transportation incurs an energetic cost to the cell that relates to seawater pH. Changes in pH therefore directly influence the amount of energy that cells need to exert in order to maintain and grow biomass. More broadly, it is essential for the cells of all forms of marine life to actively maintain their integrity and function, which is directly influenced by submergence in seawater which has a pH that differs from that of biological cells (Lewis et al. 2011; Gomiero et al. 2018). In addition to biological impacts, seawater pH influences chemical equilibria in seawater. For example, the balance between ammonium (NH_4^+) and ammonia (NH_3) in seawater is moderated by pH and directly influences biological processes that require a specific form of nitrogenous nutrient, such as nitrification (Ward, 2008).

The Dissolved Inorganic Carbon (DIC) system of seawater is a major global reservoir of carbon. The DIC system comprises of aqueous carbon dioxide (i.e. CO_2 dissolved in seawater), bicarbonate and carbonate ions (HCO_3^- and CO_3^{2-} respectively). The balance between these carbon forms largely dictates the pH of seawater. When atmospheric CO_2 dissolves in seawater, the unstable intermediate carbonic acid (H_2CO_3) is formed which dissociates to bicarbonate, hydrogen and carbonate ions. This reversible process is responsible for the buffering capacity of seawater (i.e. the ability of seawater to resist changes in pH). The dissolution of atmospheric CO_2 into the oceans decreases the pH of seawater due to the production of hydrogen ions during the subsequent carbonate system equilibration. This process has been exacerbated by the anthropogenic increase in atmospheric CO_2 since the industrial revolution. Surface ocean pH has been estimated to have decreased by approximately 0.1 pH units since pre-industrial times, representing a 30% increase in hydrogen ion concentration (Caldeira and Wickett, 2003; SCOR 2009; Hall-Spencer et al. 2008).

Superimposed on long-term changes in seawater pH due to the oceanic uptake of anthropogenic CO_2, within the confines of the SWMP area, biological factors modify seawater pH over relatively short time frames (i.e. seasonally). For example, at the Western Channel Observatory (data available via the Global Ocean Acidification Observing Network), a seasonal variation in pH within the range 7.73-8.22 units has been derived from carbonate system parameters during 2009-2014, linked to the annual cycle in marine primary production (Cummings et al. 2015).

Within the model, pH is an emergent property of a fully described carbonate/alkalinity system, which responds to physical processes (e.g. transport, air-sea exchange) and biological (e.g. respiratory CO_2 production and CO_2 removal via photosynthetic carbon fixation) source and sink terms.

Within the context of the SWMP, the impacts on ecosystem function and the provision of goods and services that may take place as a consequence of changes in seawater pH are relevant to (i) aquaculture, via the direct impact upon the growth of commercially exploited species, particularly shellfish, and the growth and distribution of their food sources, (ii) fisheries, via the direct impact upon their growth and the growth and distribution of their food sources, (iii) Marine Protected Areas, via its influence on habitat suitability for indigenous species, (iv) invasive (non-native) species via its influence on habitat shift, spatial range and opportunities for colonisation, (v) biodiversity via its influence on habitat suitability, habitat shift, spatial range, the size structure, phenology and seasonal abundance of populations and the nature and extent of species interactions.

3.8 Seawater Salinity

Seawater salinity is a measure of dissolved salt content. Marine microbes, plants and animals are sensitive to changes in salinity, which can lead to distributional shifts and modifications to seasonal growth patterns (Weinert et al. 2016; Blackett et al. 2014). Salinity decreases in response to precipitation patterns over broad spatial scales, while riverine inputs of freshwater from the terrestrial environment influence salinity at smaller, localised scales. In both instances, freshwater inputs lead to a decrease in water density which is essentially limited to surface waters. This difference represents a barrier to vertical mixing. Conversely, seawater salinity increases due to the evaporation of water at the sea surface.

Within the model, salinity is influenced by riverine discharge, precipitation and evaporation, as well as transport at the lateral boundaries of the model domain.

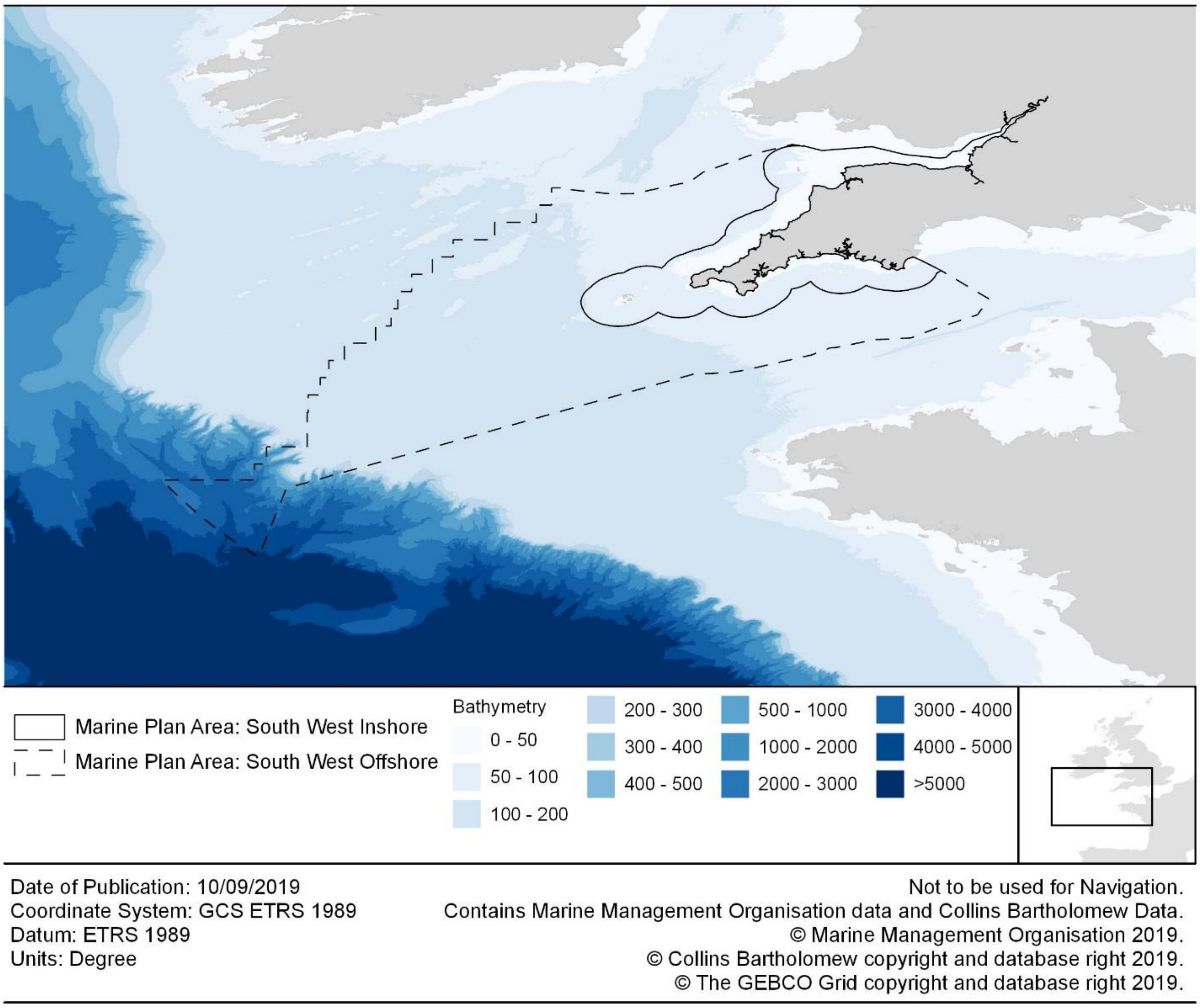
Within the context of the SWMP, the impact of changes in salinity has implications for sectors related to biological productivity including aquaculture, fisheries, Marine Protected Areas, invasive (non-native) species and biodiversity via alterations in water circulation and vertical stratification patterns, consecutively impacting on species' habitat suitability.

4. Model projections

4.1 The presentation of model data

The model data presented within this report represents a subset of the coupled regional model simulation spanning a total time frame of 1970-2100. The period 1970-1990 was considered as a time frame for internal model dynamics to stabilise. The period 1990-2021 is included for historical context to the SWMP time frame, which, for the purposes of this study is assumed to be 2021-2041. Model data is only presented for the SWMP area (Figure 2)

Figure 2 Map of the south west marine plan areas, showing the boundaries of the inshore and offshore plan areas, overlaid on the bathymetric map. Seabed depths are in metres.



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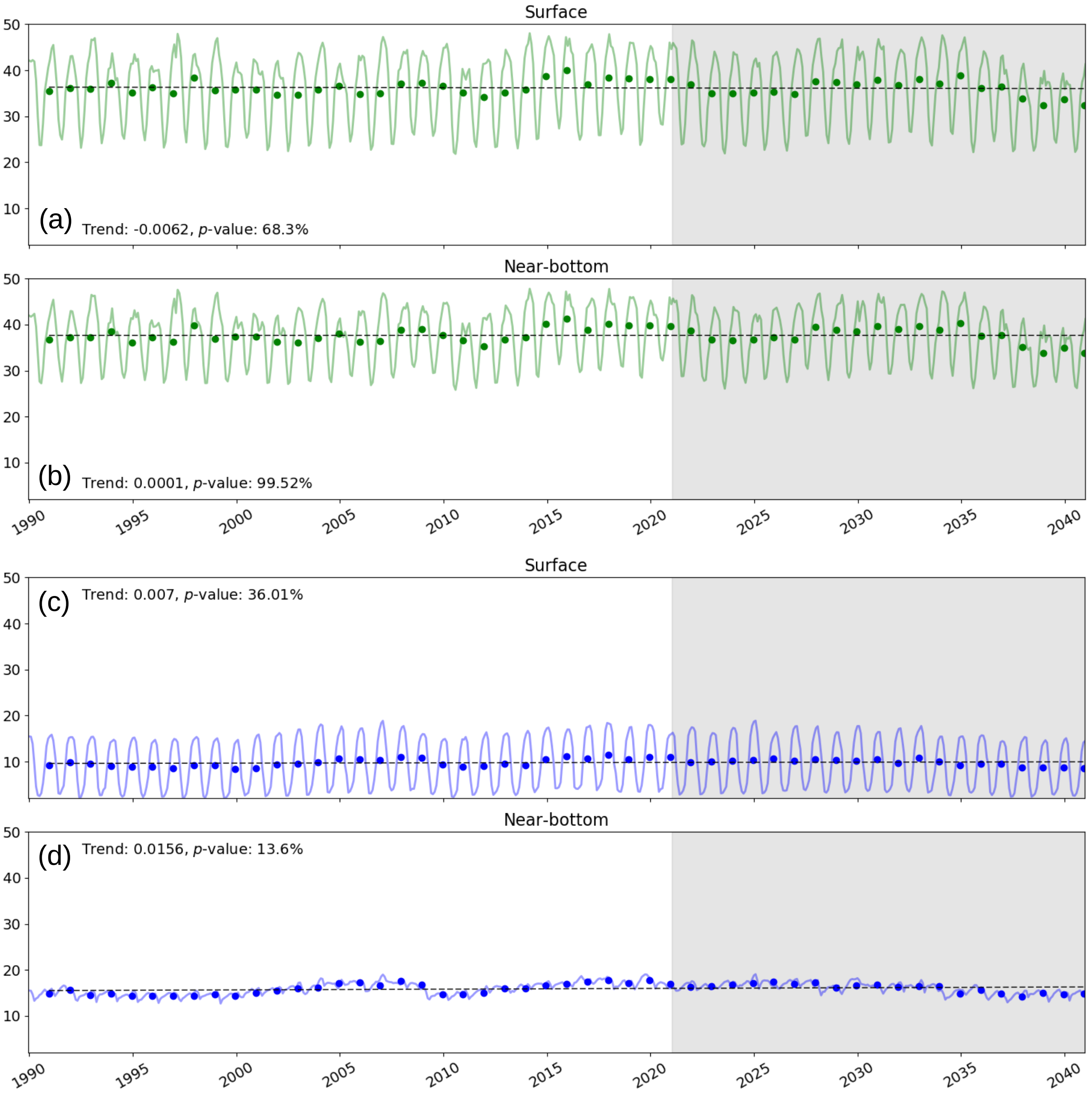
Data herein is presented in a range of formats. Data trends are derived from time-series of monthly and annual means, providing positive or negative values, which indicate a long-term increase or decrease in the parameter value, respectively. An indication of trend significance is provided by *p*-values where value ≤5% are deemed to be statistically significant. Colour coding is used for the time-series below (e.g. Figure 3), with the south west inshore marine plan area consistently represented in green, and the south west offshore marine plan area presented in blue.

Spatial variability within the data is presented as percentage difference between 5-year means for the beginning and end of considered time-frame (1990-1995 vs 2036-2041). A 5-year time-frame was used to enable a justifiable sample size to derive mean values. Spatial analysis is conducted for the surface and near-seabed depths. By adopting this resolution in space-time, we captured the main features in seasonality and long-term dynamics of environmental variables within the SWMP area (Figure 2). We note however, that the consistent application of this strategy across all variables gave rise to an anomalous feature on the North Devon Coast, which is explained through further analysis. We also note that spatial analysis for near-bottom depths considers a depth range that potentially changes over 3 orders of magnitude (4m vs 4000m) within the SWMP area, incorporating marine ecosystems that strongly contrast. Prediction confidence is lower, particularly for the extreme south west where depths exceed 200m. However, this represents a geographically small proportion of the SWMP area.

Data are also presented as line and box plots; legends contain full details of these representations.

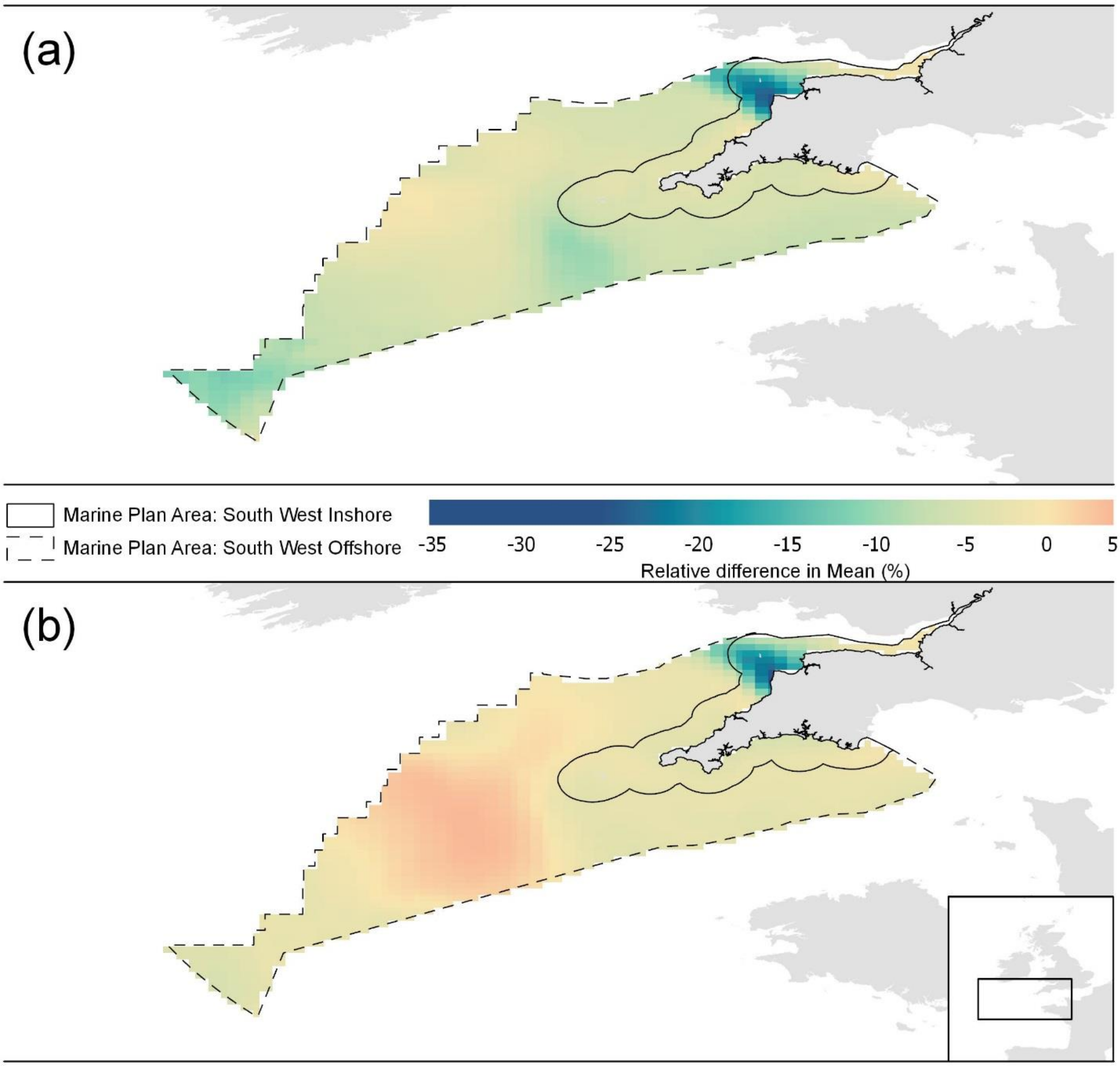
4.2 Dissolved Inorganic Nitrogen

Figure 3 Model output for Dissolved Inorganic Nitrogen concentration (1990-2041) in the south west inshore (a,b) and offshore (c,d) marine plan areas in surface (a,c) and near bottom (b,d) waters. The South West Marine Plans' 20-year time frame is shaded. Data represent monthly mean (solid line) and yearly mean (circles) values. The data trend is presented (dashed line). Trend values (mmol N $m^{-3}y^{-1}$) represent change per year. A *p*-value ≤5% is deemed to indicate that the trend is significant.



Values for DIN projected by the model are generally greater than observational measurements, by ~20 mmol N m^{-3} (http://www.westernchannelobservatory.org.uk/). This is primarily due to uncertainties in land-based nutrient input, which over a relatively long spin up period leads to the accumulation of inorganic nutrients (especially nitrogen) within the model domain. This eventually equilibrates at concentrations that exceed observations. While this influences the absolute levels of nutrients in the model, it is less likely to influence spatiotemporal trends.

Figure 4 Relative spatial change (%) in Dissolved Inorganic Nitrogen concentration for (a) the surface and (b) near-bottom waters of the south west marine plan areas. The percentage change represents the difference between 5-year averages at the boundaries of the temporal range considered (i.e. 1990-1995 compared to 2036-2041) at every resolved geographical location.



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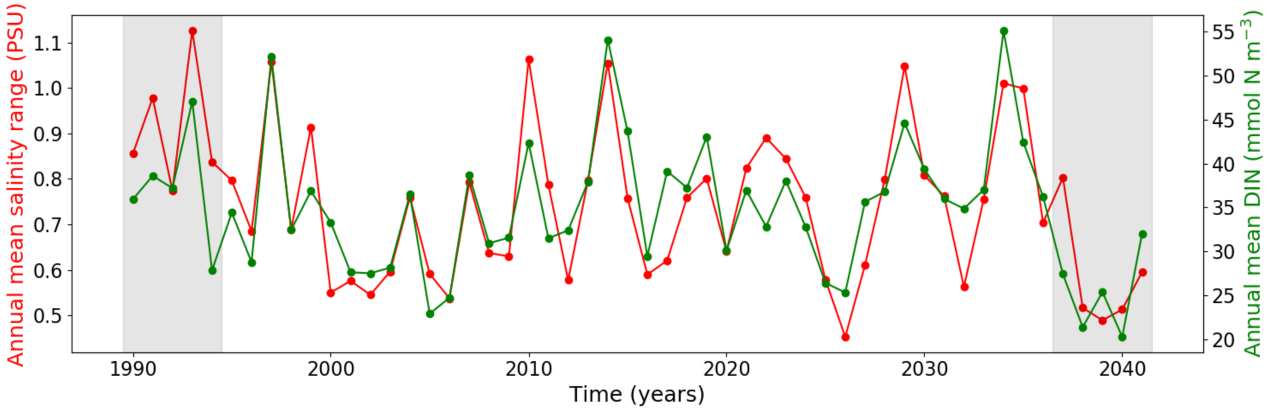
Model projections imply that there will be no significant changes in dissolved inorganic nitrogen concentration within the time frame and geographical area of the SWMP. In isolation, this result implies that dissolved inorganic nitrogen concentration will not be a factor driving change in the biological processes that relate to its availability (e.g. the extent and rate of primary production; section 3.1). By extension, this may imply that there are no consequences for aquaculture, fisheries, marine protected areas, invasive (non-native) species, biodiversity, or water quality as a direct consequence of potential changes in inorganic nitrogen concentration within the temporal and spatial limits of the SWMP.

The spatial variability in DIN is presented in Figure 4. A striking feature is the anomalously large percentage decrease in DIN concentration in the coastal North Devon region, discussed further below. Beyond this area, there are no obvious spatial trends that predict DIN concentration change within the time frame considered

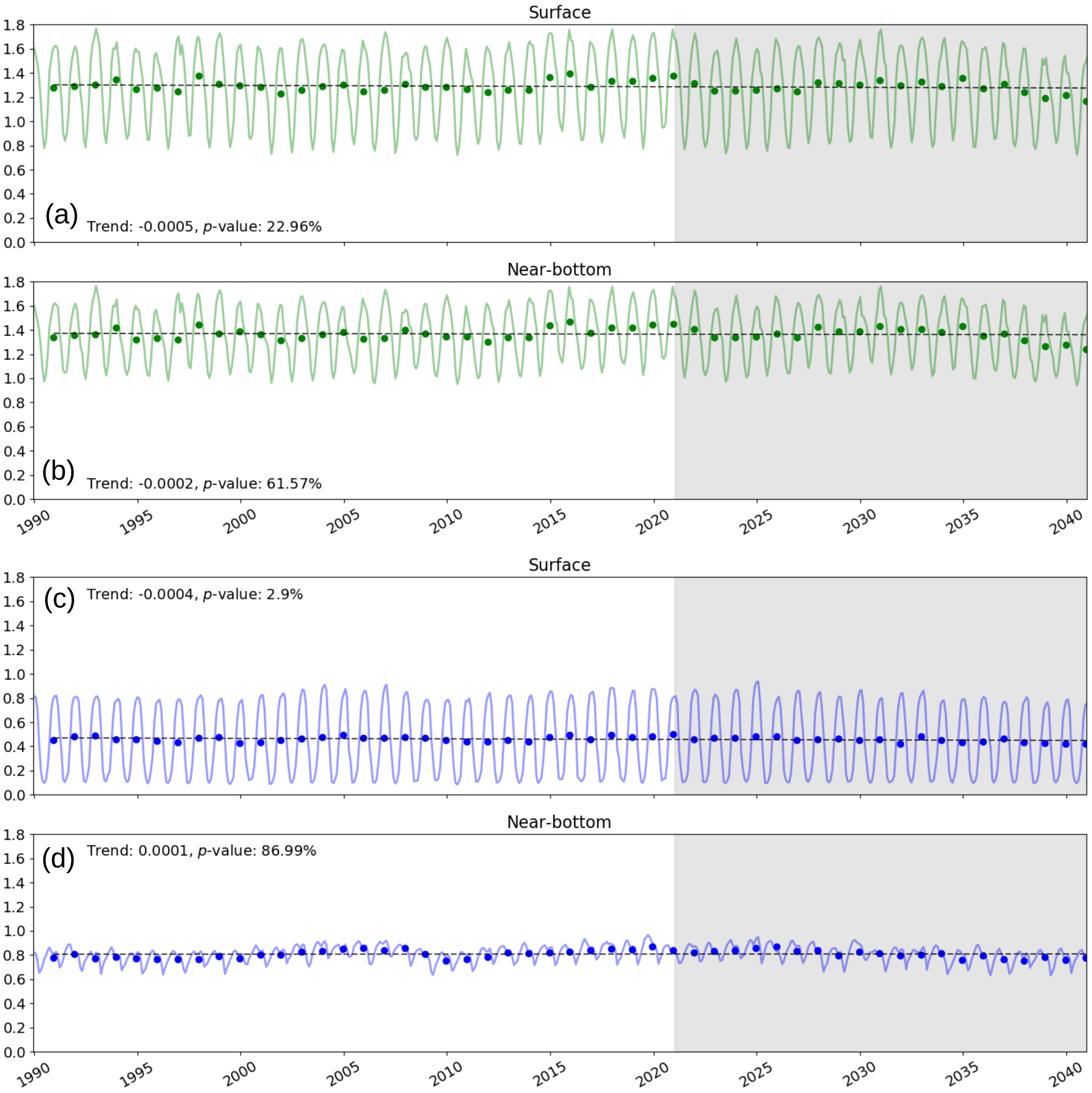
Figure 5 Change in salinity and Dissolved Inorganic Nitrogen at a specific location (51°4’N, 4°40’W) within the North Devon anomaly. The 5-year window used for averaging is shaded**.**



The cause of the North Devon anomaly becomes apparent by considering variability in specific parameters within its area. The 5-year window used to derive average values of parameters (DIN, DIP) coincided with a period of particularly low values for the period 2036-2041 within a restricted spatial range, resulting in the emergence of the anomalous area. The cause of this feature is the interaction between marine and riverine influences which exert strong inter-annual variability within estuarine areas with significant freshwater inputs, such as the Severn Estuary.

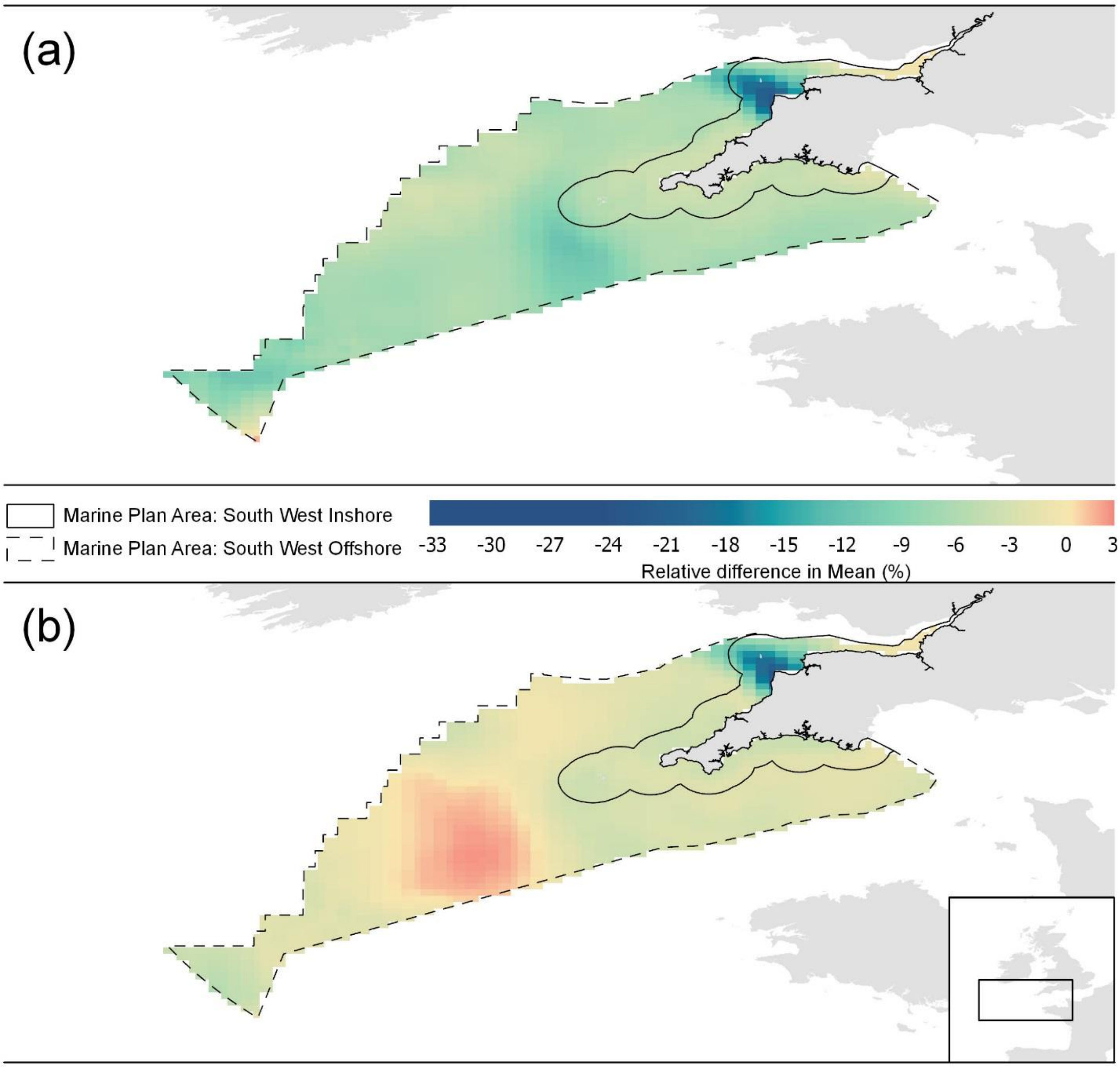
4.3 Dissolved Inorganic Phosphorus

Figure 6 Model output for Dissolved Inorganic Phosphorus concentration (1990-2041) in the south west inshore (a,b) and offshore (c,d) marine plan areas in surface (a,c) and near bottom (b,d) waters. The South West Marine Plan's 20-year time frame is shaded. Data represent monthly mean (solid line) and yearly mean (circles) values. The data trend is presented (dashed line). Trend values (mmol P $m^{-3}y^{-1}$) represent change per year. A *p*-value ≤5% is deemed to indicate that the trend is significant.



Values for DIP projected by the model are generally greater than observational measurements from the Western Channel Observatory by ~0.75 mmol P m^{-3} The causes of this discrepancy are identical to those described for DIN (above).

Figure 7 Relative spatial change (%) in Dissolved Inorganic Phosphorus concentration for (a) the surface and (b) near-bottom waters of the south west marine plan areas. The percentage change represents the difference between 5-year averages at the boundaries of the temporal range considered (i.e. 1990-1995 compared to 2036-2041) at every resolved geographical location.



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Model projections in Figure 6 imply that there will be no significant change in the dissolved inorganic phosphorus concentration within the time frame and geographical area of the inner SWMP areas. For the Offshore SWMP Area, the model projects a small, but significant decreasing trend in phosphorus concentration within surface waters, though not for near-bottom waters. In isolation, this result implies that in general, dissolved inorganic phosphorus concentration will not be a factor driving change in the biological processes that relate to its availability. However, a decreasing trend in the phosphorus concentration of surface offshore waters suggests the potential for this nutrient to become an influential factor in regions geographically distant from terrestrial influence (which is the dominant source of phosphorus to the global ocean). Depending upon geographical distribution, this may have implications for offshore fisheries, marine protected areas, invasive (non-native) species, and biodiversity beyond the time frame of the SWMP.

Spatial variablity in DIP (Figure 7) highlights the North Devon anomaly, the casue of which is discussed above. Beyond this anomaly there is limited horizontal variabilty.

4.4 Ratio of Inorganic Nitrogen to Inorganic Phosphorus

Model projections and relative spatial changes in the ratio of Inorganic Nitrogen to Inorganic Phosphorus are presented in Figure 8 and Figure 9 respectively.

Figure 8 Model output for the ratio of dissolved inorganic nitrogen to dissolved inorganic phosphorus concentration (1990-2041) in the south west inshore (a,b) and offshore (c,d) marine plan areas in surface (a,c) and near bottom (b,d) waters. The South West Marine Plans’ 20-year time frame is shaded. Data represent monthly mean (solid line) and yearly mean (circles) values. The data trend is presented (dashed line). Trend values represent change per year. A *p*-value ≤5% is deemed to indicate that the trend is significant.

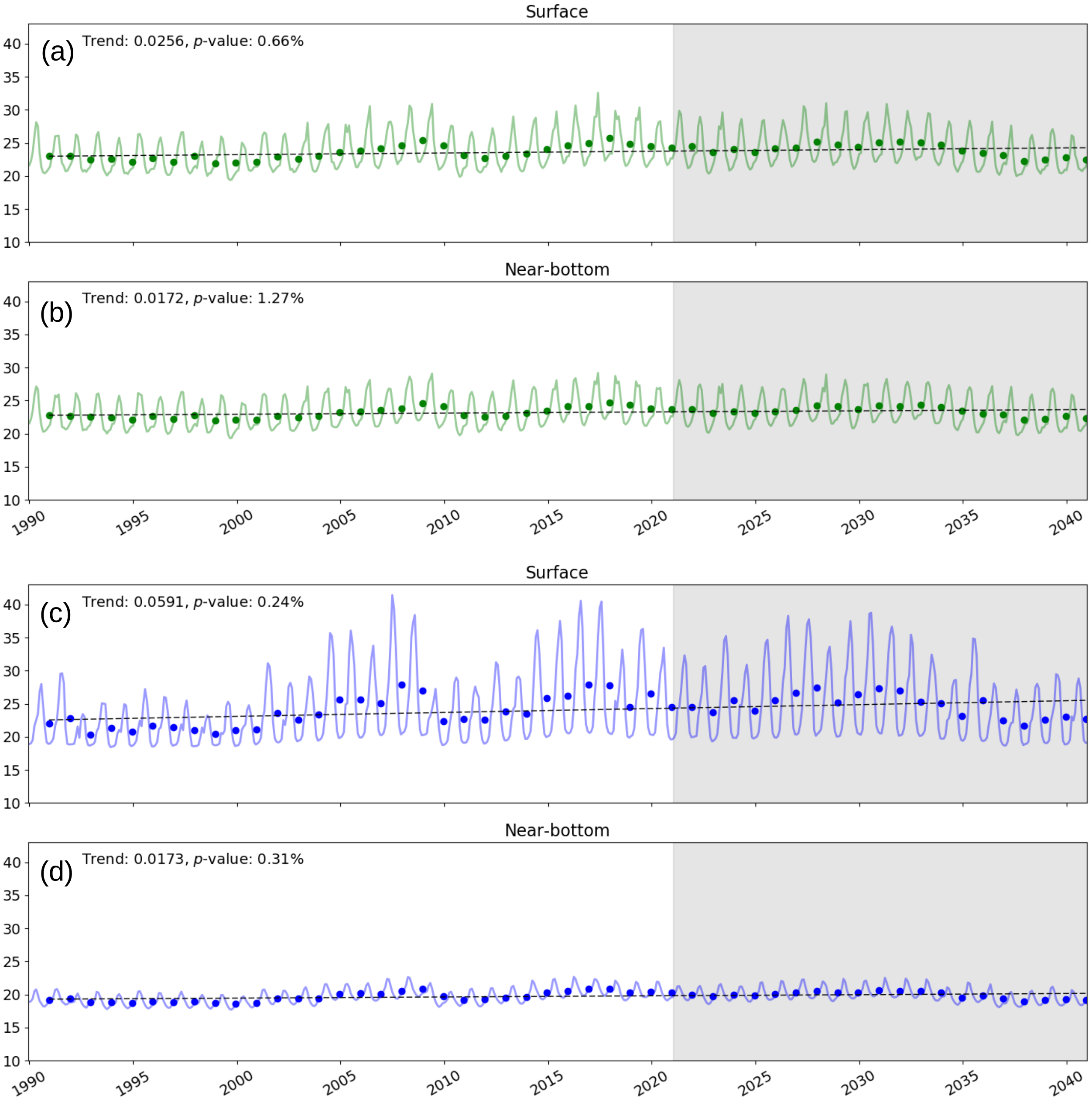
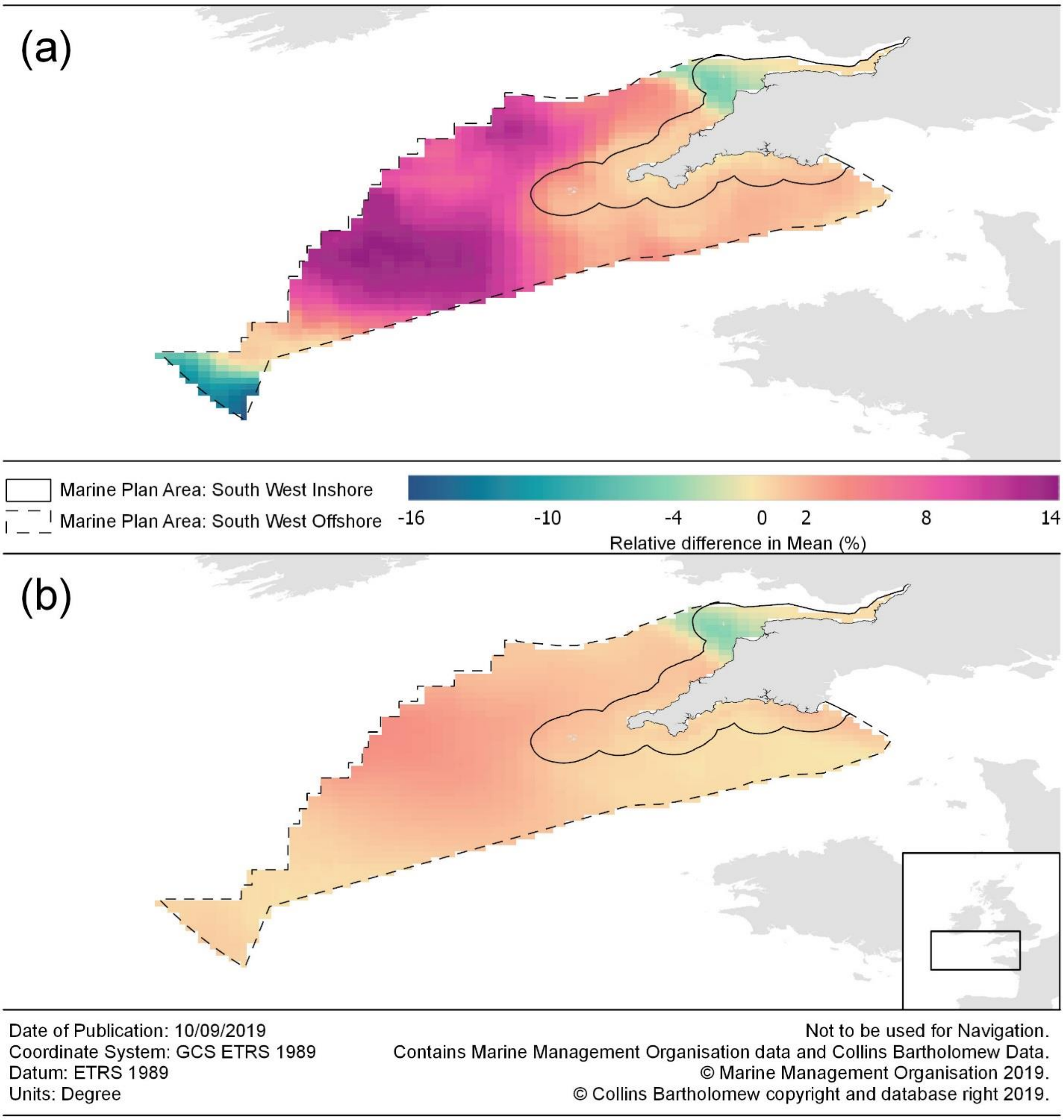


Figure 9 Relative spatial changes in the ratio of Dissolved Inorganic Nitrogen to Dissolved Inorganic Phosphorus concentration for (a) the surface and (b) near-bottom waters of the south west marine plan areas. The percentage change represents the difference between 5-year averages at the boundaries of the temporal range considered (i.e. 1990-1995 compared to 2036-2041) at every resolved geographical location.



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Model projections (Figure 8) indicate a N:P ratio of approximately 23, with a significant trend towards increasing values over time for both surface and near-bottom layer within the SWMP areas.

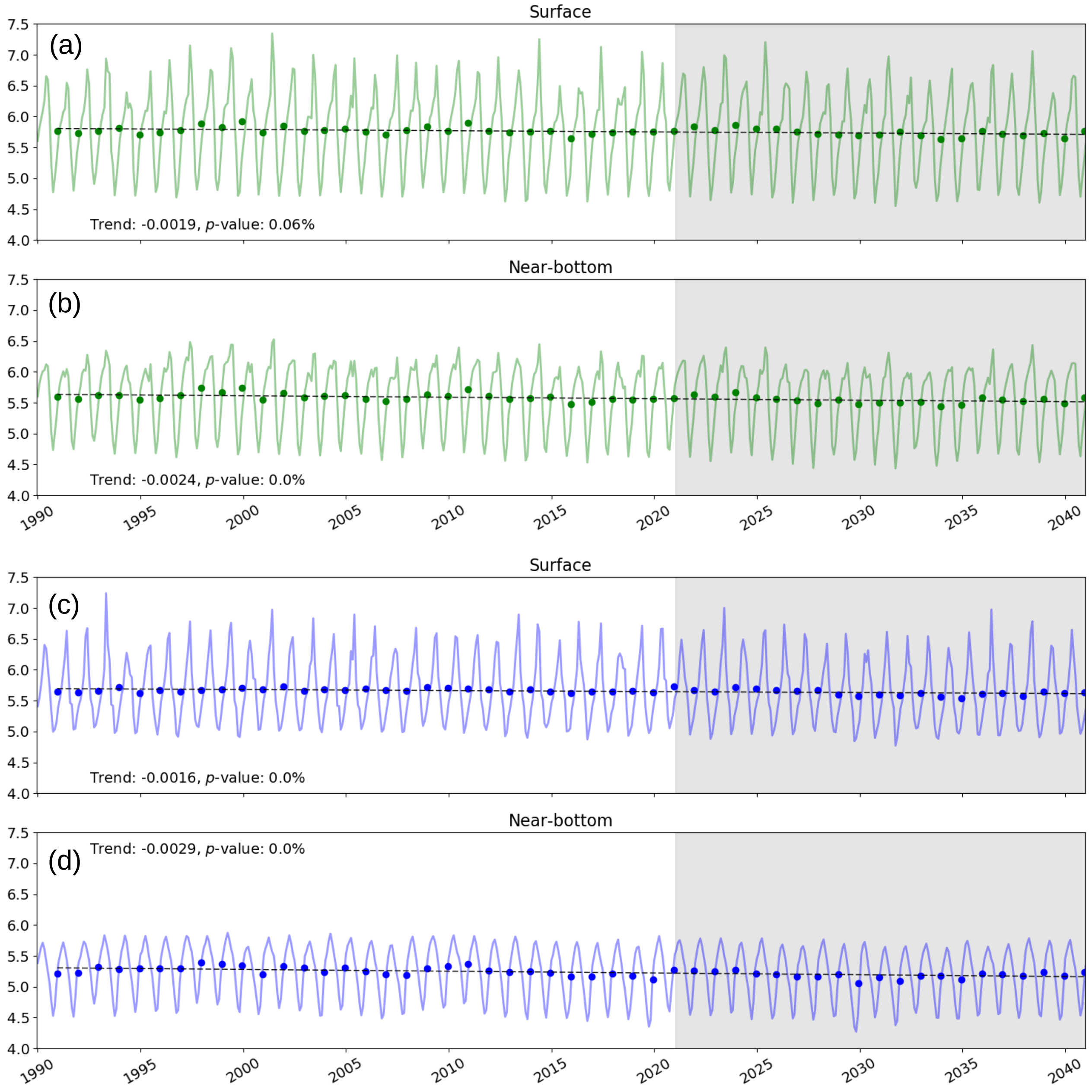
Though the rate of increase is small, the implication is that the SWMP area will progressively shift towards a condition of relative phosphorus limitation (nitrate excess) for primary producers. Projections do not imply that Phosphorus will necessarily become limiting (i.e. that the absolute concentration of phosphorus will approach zero, although there is some support for this in the surface waters of the outer SWMP area). Rather, that the availability of nitrate relative to phosphorus will increase. In isolation, this change may directly influence primary producers. A shift in the composition of phytoplankton communities may take place towards species with the capacity to exploit a relative excess of nitrate. Such species tend to be those capable of prolific growth, and may include harmful, or otherwise nuisance, algal bloom species (Glibert 2017). This may ultimately have implications for higher trophic levels (via palatability, toxicity), and consecutively ecosystem function, diversity and potentially human health.

Within the timeframe of the SWMP, the projected shift will not be greater than the natural variability experienced by ecosystems during seasonal transitions. Consequently, it is unlikely that changes in nutrient regime (N:P) will have an impact upon ecosystems within the geographical and temporal extent of the SWMP.

The offshore region associated with the shelf break appears to be linked with strong contrasts in N:P within surface waters, a feature related to the transition between shelf and open ocean conditions.

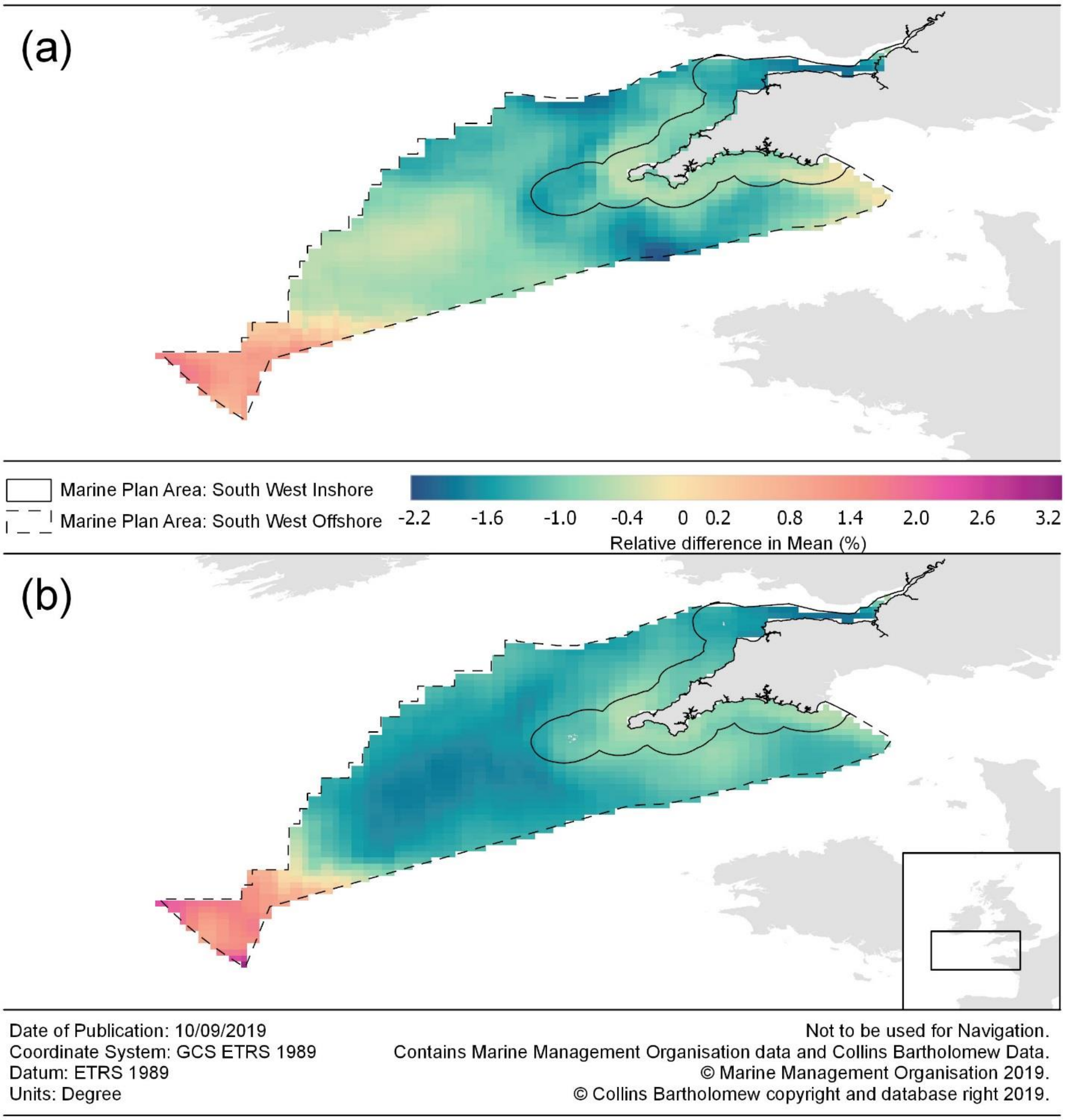
4.5 Dissolved Oxygen

Figure 10 Model output for Dissolved Oxygen concentration (1990-2041) in the south west inshore (a,b) and offshore (c,d) marine plan areas in surface (a,c) and near bottom (b,d) waters. The South West Marine Plans' 20-year time frame is shaded. Data represent monthly mean (solid line) and yearly mean (circles) values. The data trend is presented (dashed line). Trend values represent change per year (ml $L^{-1}y^{-1}$). A *p*-value ≤5% is deemed to indicate that the trend is significant.



For the SWMP area, a significant trend of decreasing dissolved oxygen concentration was projected for surface and near-seabed depths (Figure 10). Within this decreasing trend, a higher seasonal range in dissolved oxygen concentration is apparent in surface than near-seabed waters for both plan areas. This reflects the difference in temperature and productivity cycles, which differentially influence oxygen solubility and oxygen production/consumption respectively.

Figure 11 Relative spatial change (%) in Dissolved Oxygen concentration for (a) the surface and (b) near-bottom waters of the south west marine plan areas. The percentage change represents the difference between 5-year averages at the boundaries of the temporal range considered (i.e. 1990-1995 compared to 2036-2041) at every resolved geographical location.

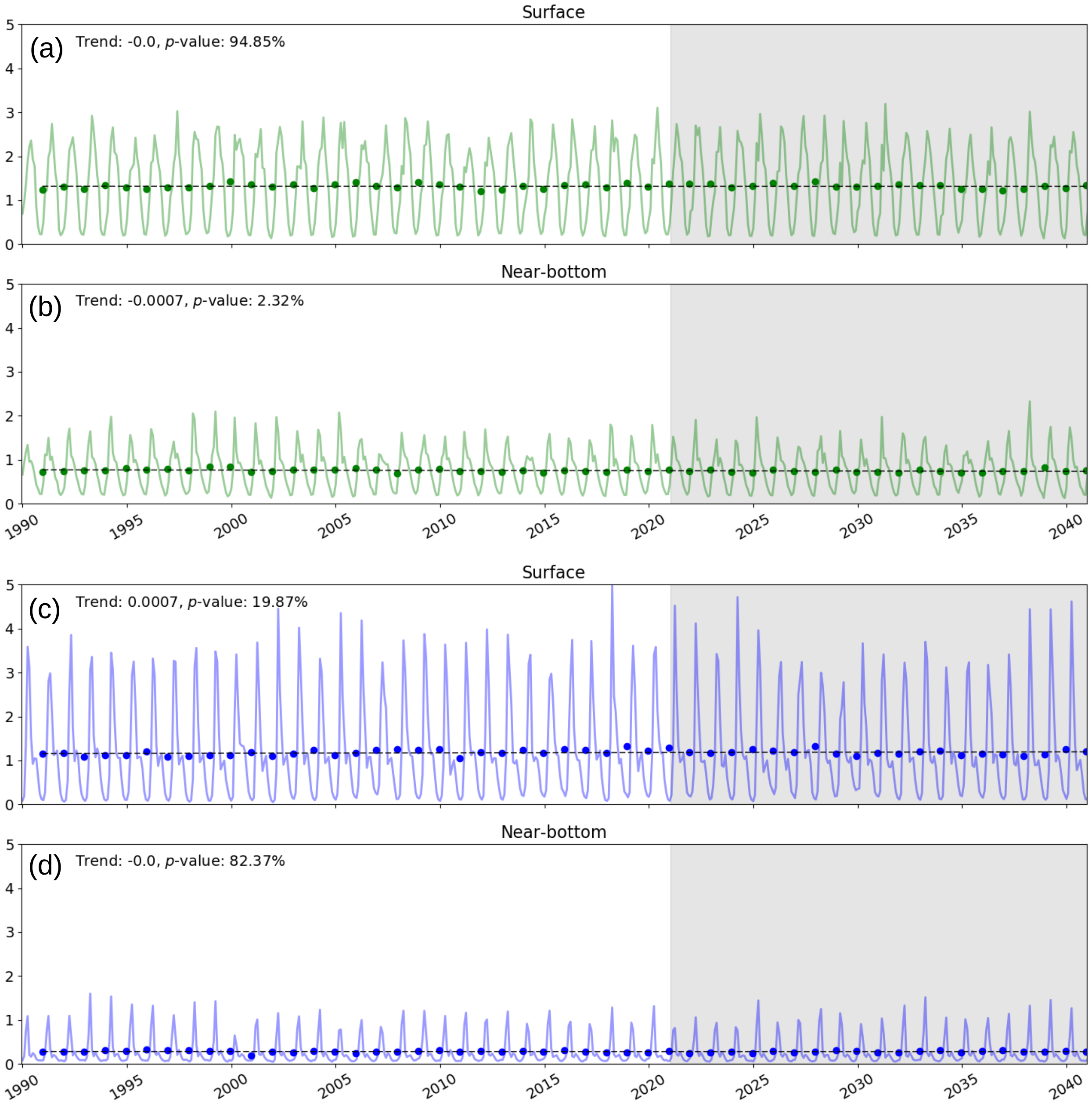


Dissolved oxygen values generally fall within the range of seasonal variability directly measured within the Western English Channel (Western Channel Observatory). In isolation, projections imply that dissolved oxygen concentration will not reach and maintain extreme values beyond those which ecosystems have been seasonally exposed to in the recent past (order of decades). Projections imply that sub-oxic (low-oxygen) or hypoxic water column conditions do not present a risk within the SWMP time frame. However, this does not exclude the possibility of localised risks and impacts related to the interaction between multiple factors compounding this trend.

Projections indicate that mixing with deep (i.e. cooler, with a greater capacity to dissolve gas) waters beyond the shelf break lessen or mitigate the downward trend in dissolved oxygen concentration implying that the impact will be most apparent in the relatively shallow waters on-shelf, including all of the inshore and the majority of the offshore south west marine plan areas.

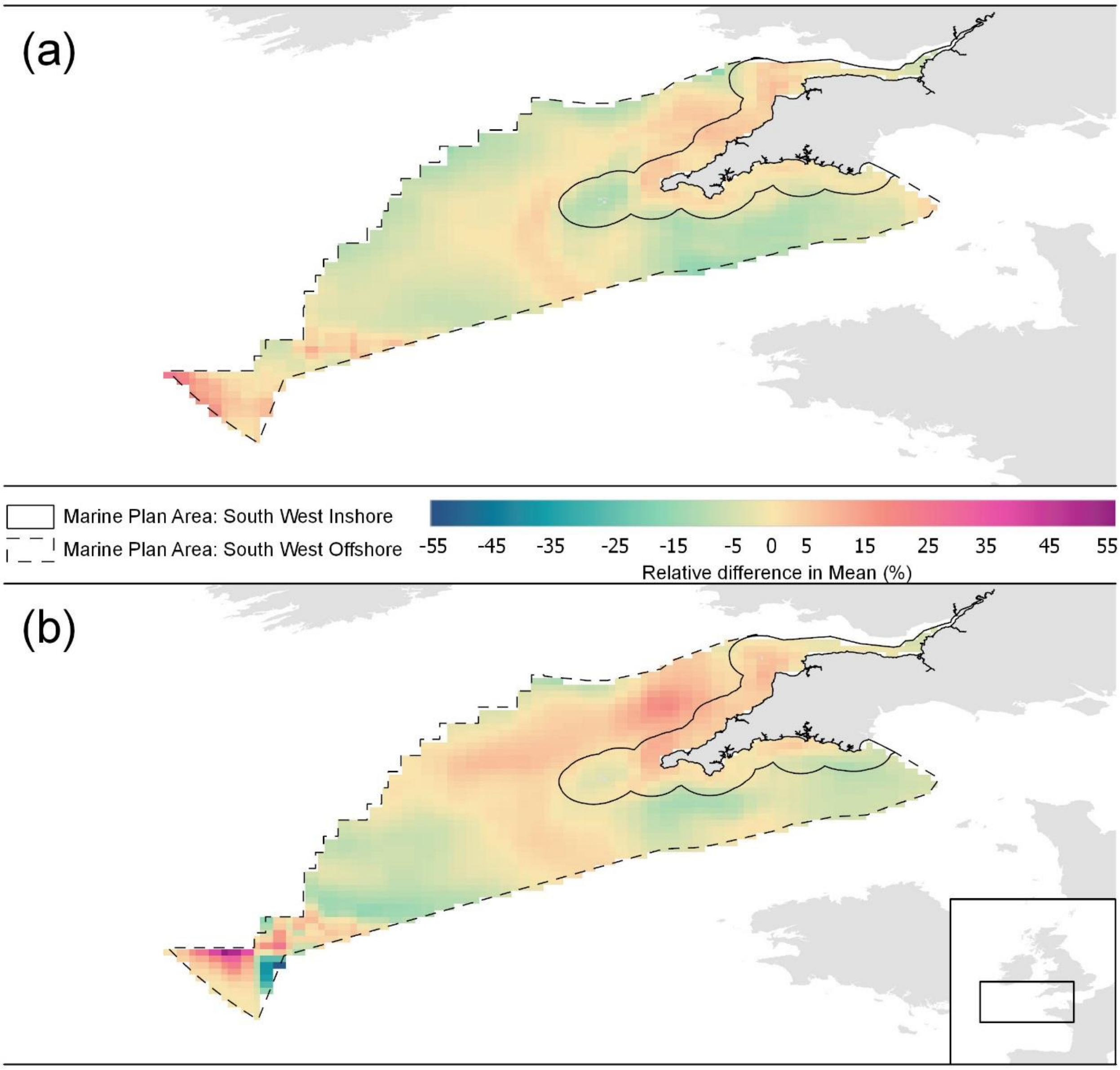
4.6 Chlorophyll Concentration

Figure 12 Model output for chlorophyll concentration (1990-2041) in the south west inshore (a,b) and offshore (c,d) marine plan areas in surface (a,c) and near bottom (b,d) waters. The South West Marine Plans' 20-year time frame is shaded. Data represent monthly mean (solid line) and yearly mean (circles) values. The data trend is presented (dashed line). Trend values represent change per year (mg Chl m^{-3} y^{-1}). A *p*-value ≤5% is deemed to indicate that the trend is significant.



Projections generally indicate no significant trend in chlorophyll concentration over time in the SWMP area with the exception of near-bottom waters of the inshore SWMP area. The lower variation in chlorophyll in near bottom relative to surface water has resulted in greater ability to detect trends against inter or intra-annual variation. As a consequence, while significant, trend gradients are essentially zero, implying that there will be no ecologically meaningful change in the seawater concentration of chlorophyll over the period of study.

Figure 13 Relative spatial change (%) in chlorophyll concentration for (a) the surface and (b) near-bottom waters of the south west marine plan areas. The percentage change represents the difference between 5-year averages at the boundaries of the temporal range considered (i.e. 1990-1995 compared to 2036-2041) at every resolved geographical location.



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Within the SWMP area, there are no clear spatial trends in chlorophyll concentration. Extremely low concentrations of chlorophyll are projected for some locations, notably the near-bottom waters of the shelf break region (associated with sedimenting particles), such that very small differences in chlorophyll concentration lead to large percentage changes (Figure 13).

A lack of any notable change in chlorophyll over time or in space does not exclude the possibility that the community structure of chlorophyll containing cells (phytoplankton) will change, merely that their cumulative contribution to total chlorophyll concentration does not change. While this could imply that there will be no change in the primary productivity that supports fisheries and aquaculture, it should be noted that multiple factors influence the extent to which these higher trophic levels access primary productivity.

4.7 Seawater Temperature

Model predictions for trends in seawater temperature through time (Figure 14) and changes between time periods spatially (Figure 15) across the SWMP areas are detailed below.

Figure 14 Model output for seawater temperature (1990-2041) in the south west inshore (a,b) and offshore (c,d) marine plan areas in surface (a,c) and near bottom (b,d) waters. The South West Marine Plans' 20-year time frame is shaded. Data represent monthly mean (solid line) and yearly mean (circles) values. The data trend is presented (dashed line). Trend values represent change per year (°C y^{-1}). A *p*-value ≤5% is deemed to indicate that the trend is significant.

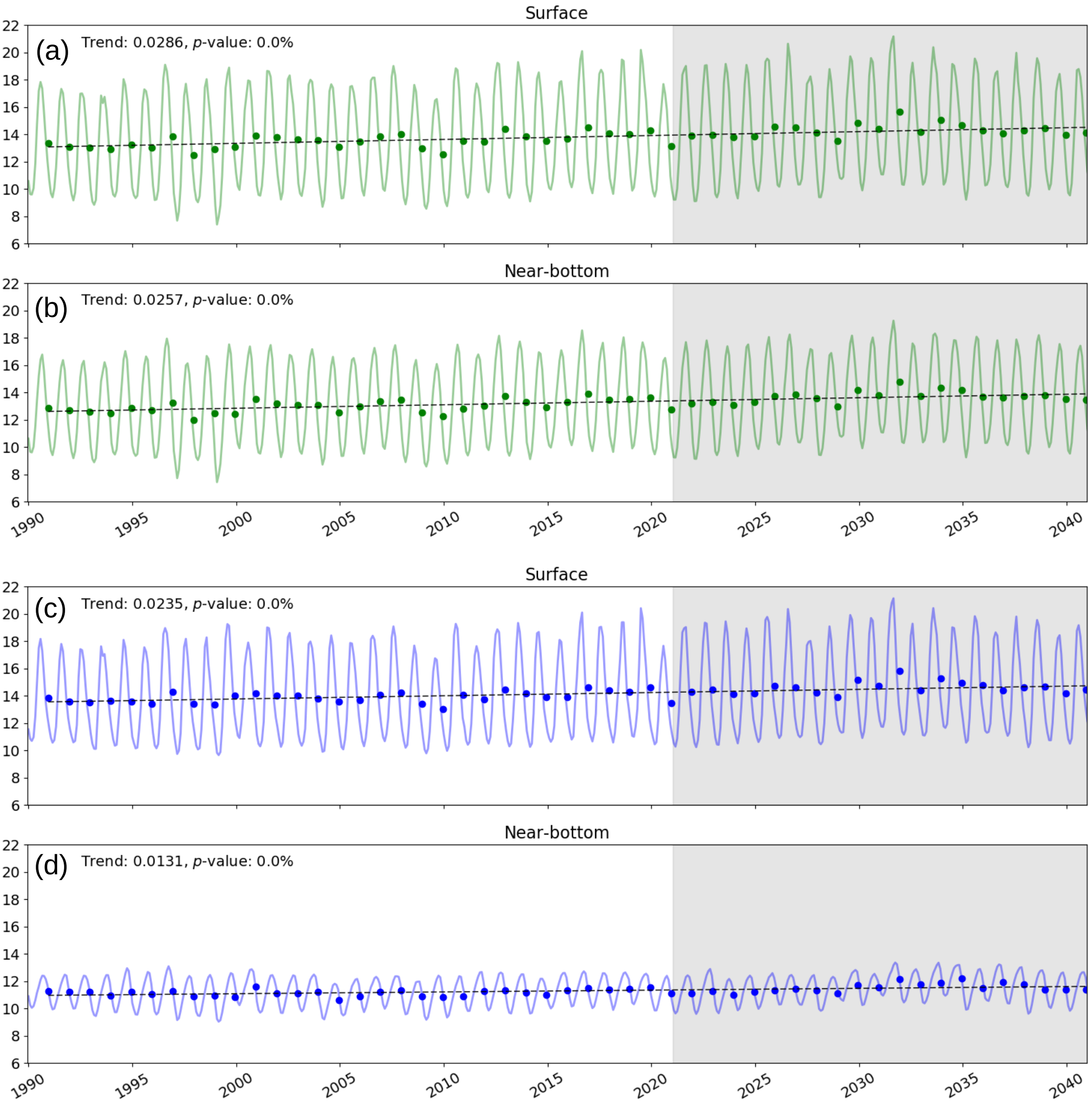
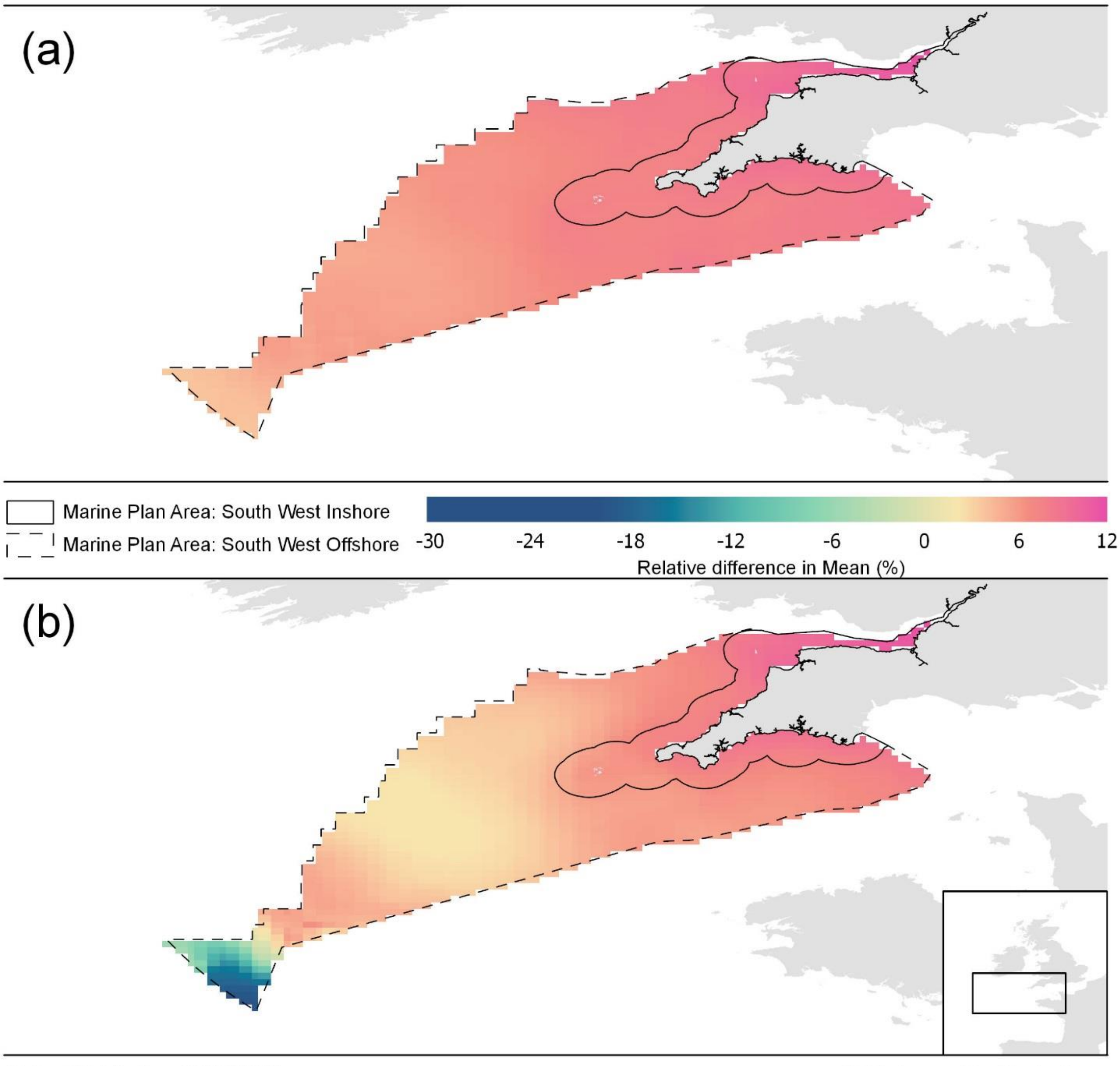


Figure 15 Relative spatial change (%) in temperature for (a) the surface and (b) near-bottom waters of the south west marine plan areas. The percentage change represents the difference between 5-year averages at the boundaries of the temporal range considered (i.e. 1990-1995 compared to 2036-2041) at every resolved geographical location.



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For the geographical and temporal extent of the SWMP, model projections indicate a significant rising trend in seawater temperature. This trend is consistent with global and regional observations (MacKenzie and Schiedek, 2007; Doney et al. 2012; Smyth et al. 2010). Seawater temperature is a fundamental characteristic that influences biological processes at all levels of organisation, from single cells to ecosystems. Consequently, it is likely that an increase in temperature will have broad implications for biological communities within the SWMP areas which incorporates a transitional region between the geographical domains for Lusitanian and Boreal species (Southward et al. 2005).

Existing evidence already indicates that increased temperature over recent decades has led to distributional shifts in benthic species, plankton and fish within the European shelf seas (Kröncke et al. 2013; Ehrich et al. 2007; Neumann et al. 2013; Blackett et al. 2014). Further increase in seawater temperature, as projected here, may have implications extending to aquaculture, biodiversity, ecosystem function, ecosystem suitability and the incidence of invasive (non-indigenous) species.

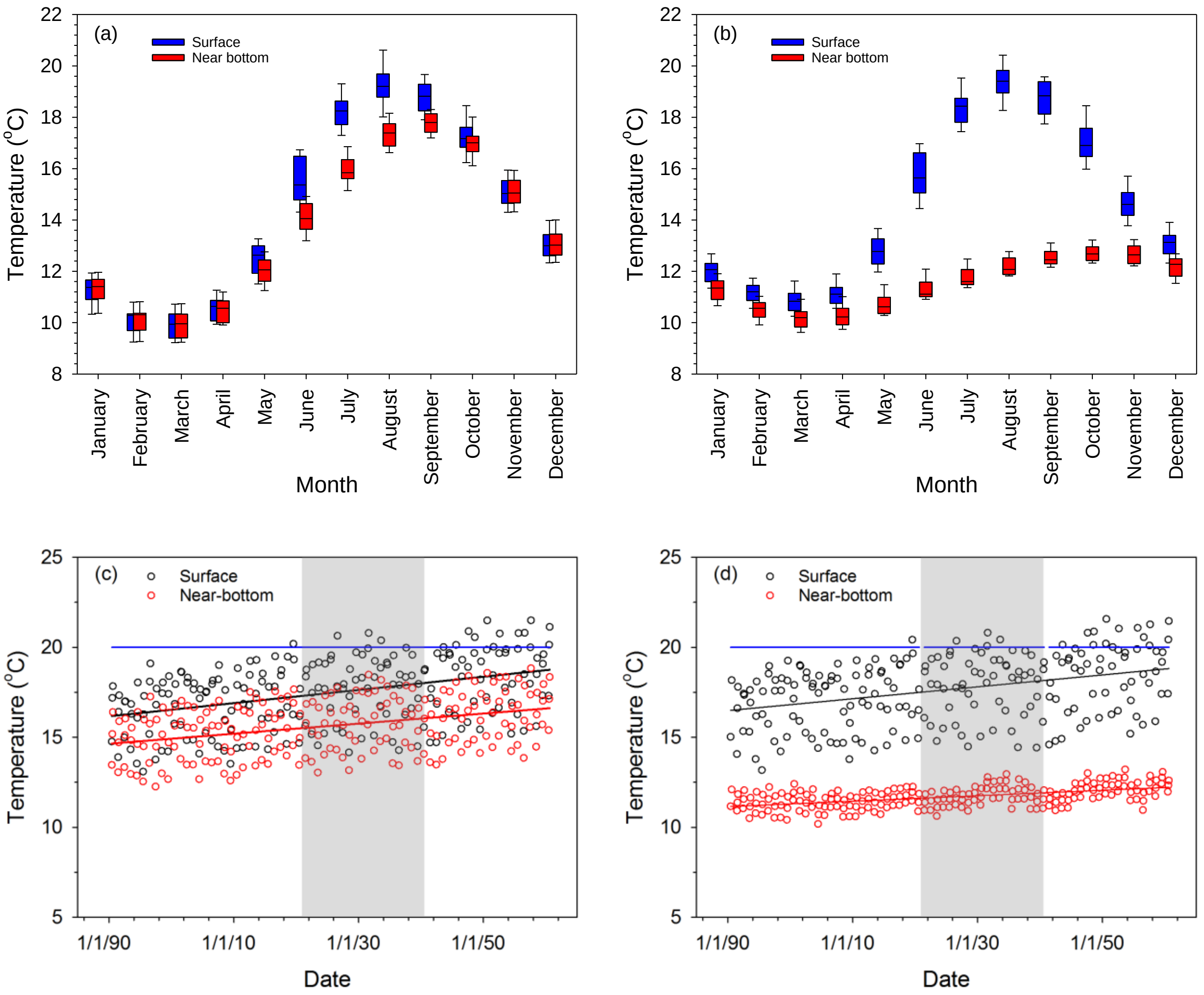
For surface waters, all areas experience a general increase, which is greatest for the inshore area of the SWMP that is associated with shallower depths. In that area increases are projected to be in excess of 0.57°C over the 20-year timeframe of plans. A comparable trend is evident for near-bottom waters within the continental shelf area. Within the shelf break region, changes in temperature at great depth relate to far-field forcing (i.e. modelled ocean circulation).

Considering seawater temperature in relation to aquaculture, existing mussel and oyster aquaculture sites within the south west region account for a significant fraction of UK shellfish production (27,000 tonnes worth £33 million in 2012; Ellis et al. 2012). These sites include the Fal fishery, the river Camel mussel and oyster fishery, and the river Taw mussel fishery. With sufficient time, an increase in temperature may present opportunities for further commercial exploitation by targeting species that may be more suitably adapted to higher seawater temperatures projected for the longer term (i.e. the order of decades). Within the time frame of the SWMP, it is more likely that projected changes in temperature will influence the growth rate of indigenous species within established aquaculture locations, rather than illicit a dramatic change in community composition.

In a study of North Atlantic commercially and ecologically important bivalves, elevated temperature positively or negatively modified bivalve performance (Stevens and Gobler 2018). For *Mytilus edulis*, 4 week exposure to a temperature of 26°C (summer heat-wave conditions associated with the sampling site in the Northeast USA) significantly decreased weight and shell growth rates by > 50%. Similarly, for *M. edulis* samples collected from the North Sea, exposure to temperatures above 25°C elicited detrimental effects, with critical effects observed above 28°C (Zitter et al. 2015). Temperature also drives distributional shifts, with evidence suggesting that the geographical range of *M. edulis* has contracted in the western Atlantic, linked to air temperatures persistently higher than 32°C (Jones et al. 2010). While these observations relate to higher temperatures than projected for the SWMP time frame, they allude to issues that may become more pressing, as episodic excursions towards this temperature range become increasingly probable.

Native oyster (*Ostrea edulis*) stocks have been in broad decline for decades, due to over-exploitation, pollution and disease. This has rendered many European commercial ventures non-viable and lead to a ‘threatened species’ listing in the UK and conservation action under the Biodiversity Action Plan. As a protandrous alternating hermaphrodite, individuals of the species change sex in response to environmental conditions, including temperature. A study of populations at contrasting sites (Lock Ryan, Scotland and Chichester Harbour, England) indicated that the proportion of male phase oysters positively correlated with temperature (Eagling et al. 2017). Cooler waters featured a more balanced population sex ratio, which was observed ~75% of the study period time in Loch Ryan compared to ~15% of the study period time in Chichester. A critical temperature threshold for sex determination of 16.5°C was derived for Loch Ryan populations of the native oyster, above which population skew towards male oysters took place. For the SWMP areas, seasonally elevated temperatures superimposed upon an increasing long-term trend may further challenge the commercial viability of this aquaculture species, due to its unbalancing impact upon population sex ratios (Figure 16).

Figure 16 Model projected median seasonal variability in seawater temperature for the south west inshore (a) and offshore (b) marine plan areas (2021-2041). Summertime monthly mean temperature for the south west inshore (c) and offshore (d) marine plan areas indicating the increasing frequency with which mean temperature exceeds 20°C (indicated by the blue reference line). Horizon is indicated by the grey shading. Summer months include June, July, and August.



Voluntary introduction of the Pacific Oyster (*Crassostrea gigas*) to northern temperate countries was undertaken for aquaculture due to the decline of native species, and because of its resilience to environmental variation, disease and its rapid growth rate (Grizel and Héral, 1991). Water temperatures constrained the geographical distribution, as optimal larval development required temperatures of 22°C for at least 2 weeks (Rico-Villa et al. 2008). Evidence now supports the hypothesis that low median seawater temperatures between 1970-1995 suppressed the proliferation of *C. gigas* but that seasonal excursions in seawater temperature above 20°C critically supported larval survival and the subsequent recruitment of feral oysters (Dutertre et al. 2010). From the late 1990's, feral oyster northerly proliferation along European coastlines has taken place, where it alters geomorphology of coastal areas and competes with native species for natural resources. *C. gigas* is now considered to be an invasive organism, with a range that extends from Spain to the North Sea (Brandt et al. 2008).

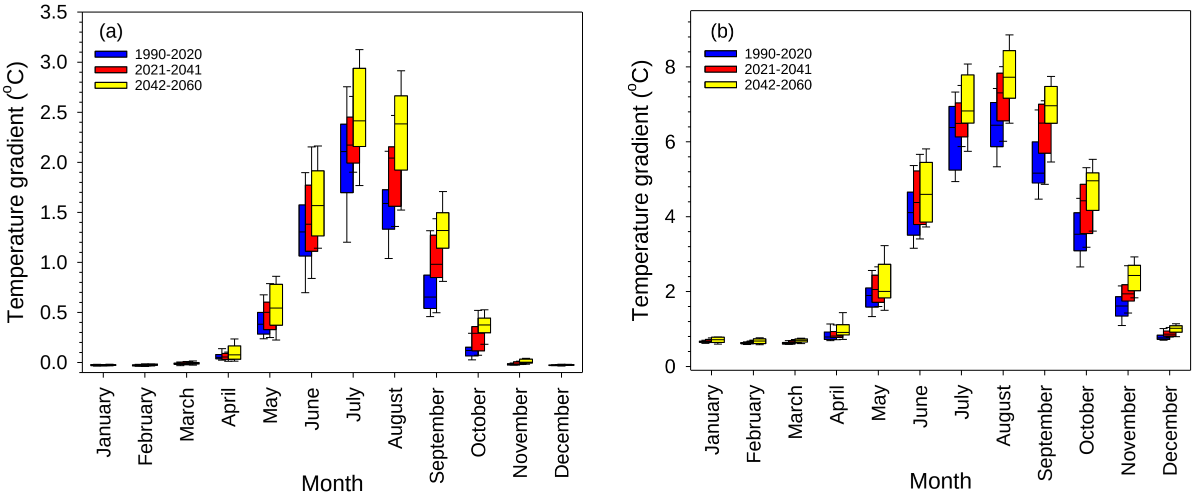
The projected increase in seawater temperature, with seasonal excursions that approach 20°C, will support and potentially intensify the proliferation and geographical range extension of this invasive (non-native) species. For reference, projections for the inshore area of the SWMP indicate an increasing frequency of summertime (June, July, August) monthly mean sea surface temperature excursions above 20°C (once in 2010-2020, once in 2020-2030, twice in 2030-2040, four times in 2040-2050, seven times in 2050-2060) with a mean summertime surface sea temperature above 20°C projected for 2090's (by linear interpolation; Figure 16).

The annual cycle of water column stratification and subsequent mixing is evident in the model data (Figure 17), varying between gradient values of ~0°C (fully mixed) and >2 °C (stratified). Considering historical and future time frames, model projections indicate a progressive increase in both strength and duration of stratification for the inner and outer SWMP area. Stratification leads to modifications in multiple environmental characteristics, as illustrated by directly observed data derived from the Western Channel Observatory during 2017 (Figure 18).

During March the water column is fully mixed (Figure 18a). Surface ocean warming due to increased incident radiation through spring and into summer sees the development of strong thermal stratification, with a difference in temperature of >2°C between the surface ocean and near bottom depths. During 2017, the upper mixed layer depth was ~20 metres. Beyond the summer solstice, a progressive decrease in incident radiation leads to a net loss of heat from the ocean's surface and a gradual erosion of the thermal gradient between the surface ocean and greater depths. An increase in turbulent mixing due to winds and storm events further erodes the thermal gradient by increasing the upper mixed layer depth, until the water column returns to its fully mixed state in November (Figure 18b). The water column continues to lose heat until the following March. This cycle in physical structure has a profound impact on the nutrient regime (Figure 18c; d). The onset of water-column stabilisation in April represents a barrier to physical vertical mixing. Phytoplankton, which require both light and nutrients for growth, are physically retained within the well-lit surface ocean, leading to a proliferation of growth and draw-down of inorganic nutrients; nitrate is depleted within weeks during the 'spring bloom' period. A surface ocean deplete of nutrients is characteristic of this phase, as water column stability prevents nutrient replenishment through physical mixing. Only when thermal stratification begins to erode (September-October) are nutrients returned to the surface ocean.

Combining these insights (Figure 17; 18), the implications of these model projections may be summarised as follows: (i) the water column will be warmer than previously observed. This will have implications for all biological life within the water, most notably for their growth rates. (ii) The barrier to vertical mixing will be strengthened. Following the removal of nutrients from the surface ocean during spring, the barrier to their reintroduction will be intensified, potentially increasing the severity of nutrient limitation for phytoplankton growth within the well-lit region throughout the productive period (May-September). This may have implications for phytoplankton community structure, and for higher trophic levels that directly depend upon phytoplankton productivity (e.g. mussels, oysters, zooplankton and planktivorous fish). (iii) The period of convective winter mixing will be compressed – this period is crucial to nutrient regeneration and resetting of the shelf system nutrient regime (Kröger et al. 2018). Progressive compression of this phase of the annual cycle may have profound implications for productivity over subsequent cycles.

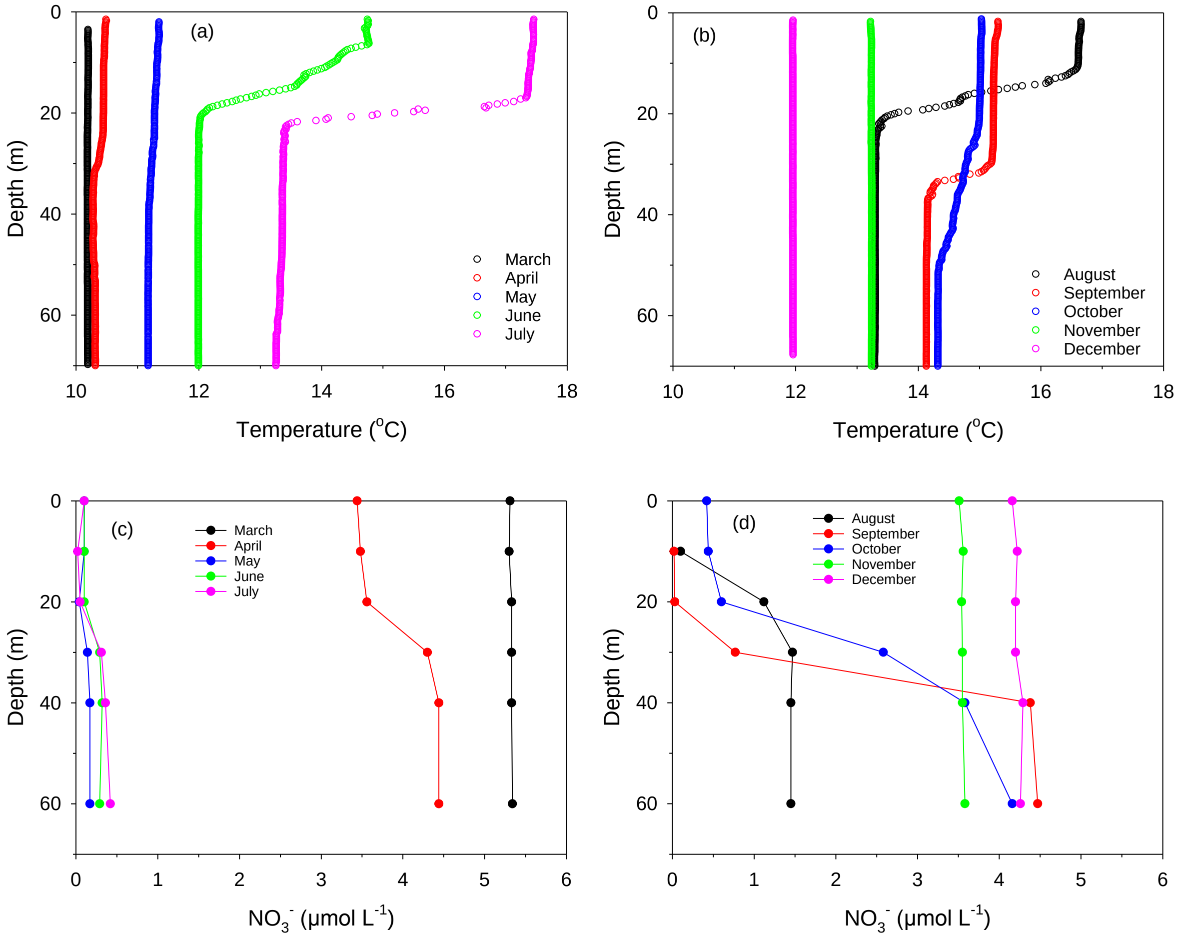
Figure 17 The strength of seasonal stratification is derived by considering the difference between the mean water column temperature projected for surface and near-bottom depths for the south west inshore (a) and offshore (b) marine plan areas. Three time frames are considered; a pre-plan time frame of 1990-2020 (blue) provides historical context to the plan time frame (2021-2041; red) and a further projection for the period 2042-2060 (yellow). Vertical box plots represent the data mean, 10th, 25th, 75th and 90th percentiles. Error bars indicate standard error while data outliers (circles) are also included.



Relating these insights to observations and their biological impact, existing studies of historical data for the English Channel provide evidence of water column warming and changes to phytoplankton community structure, specifically a decrease in diatom abundance and increase in specific dinoflagellate species (Smyth et al. 2010; Widdicombe et al. 2010). These changes are of interest as they incorporate Harmful Algal Bloom (HAB) species; those that directly or indirectly have detrimental impacts upon marine ecosystems, human health and aquaculture.

In the eastern English Channel-North Sea region, the HAB species *Pseudo-nitzschia* spp. is identified as a dominant diatom of the spring bloom (Klein et al. 2010; Hasle et al. 2002). *Pseudo-nitzschia* spp. has also been recorded in the Western English Channel, with variable abundance that seasonally dominates the diatom community. Following recognition in 1987, domoic acid (a potent neurotoxin) production by *Psuedo-nitzschia* spp. has become a global threat in temperate regions (Bates 1998), eliciting both acute and chronic effects on marine mammals, seabirds and humans (Bates 2000). Zooplankton, planktivorous fish, and shellfish are common vectors (Lefebvre et al. 2002a, b), with potential impacts on coastal ecosystems and commercial interests (Klein et al. 2010). Domoic acid production by *Psuedo-nitzschia* spp. at the Western Channel Observatory (within the SWMP area) has been reported (Downes-Tettmar et al. 2013). Although factors supporting this production broadly relate to environmental characteristics (including nutrient availability, salinity, temperature), specific details remain unclear. Though likely to remain of concern, the implications of model projections for the growth and impact of this species will only be possible when clear links between domoic acid production and environmental variables are established.

Figure 18 Changes in water column temperature and nutrient regime during the annual cycle at WCO station E1 (50.026° latitude; -4.225° longitude; January and February are omitted for clarity). Data present the transition towards water column stratification and the subsequent erosion of this vertical structure, with associated changes in nutrient regime.



The dinoflagellate *Karenia mikimotoi* frequently dominates phytoplankton carbon biomass during the summer (Barnes et al. 2015), and is known to display slow-acting toxicity or to otherwise have direct detrimental effects on microalgae, fauna and fish (Chang 2011, Arzul et al. 1993; Silke et al. 2005; Davidson et al. 2009). Exposure to localised high cell density can lead to direct negative impacts upon fish gills (Davidson et al. 2009). Following an accumulation of cells, the palatability of *K. mikimtoi* for zooplankton grazers has been questioned (Turner and Tester 1997; though not comprehensively supported by Fileman et al. 2010), potentially leading to the vertical export of un-grazed particulate organic matter from the surface ocean to the benthos. The decomposition of this material has been linked to significant oxygen under-saturation below the seasonal thermocline in the English Channel (Barnes et al. 2015), with potentially greater impacts in shallower water. Mass fish kills and microbenthic mortalities in Cornish estuaries were potentially linked to deoxygenation following the decomposition of *K. mikimtoi* blooms, directly impacting commercial interests (Coates et al. 2009).

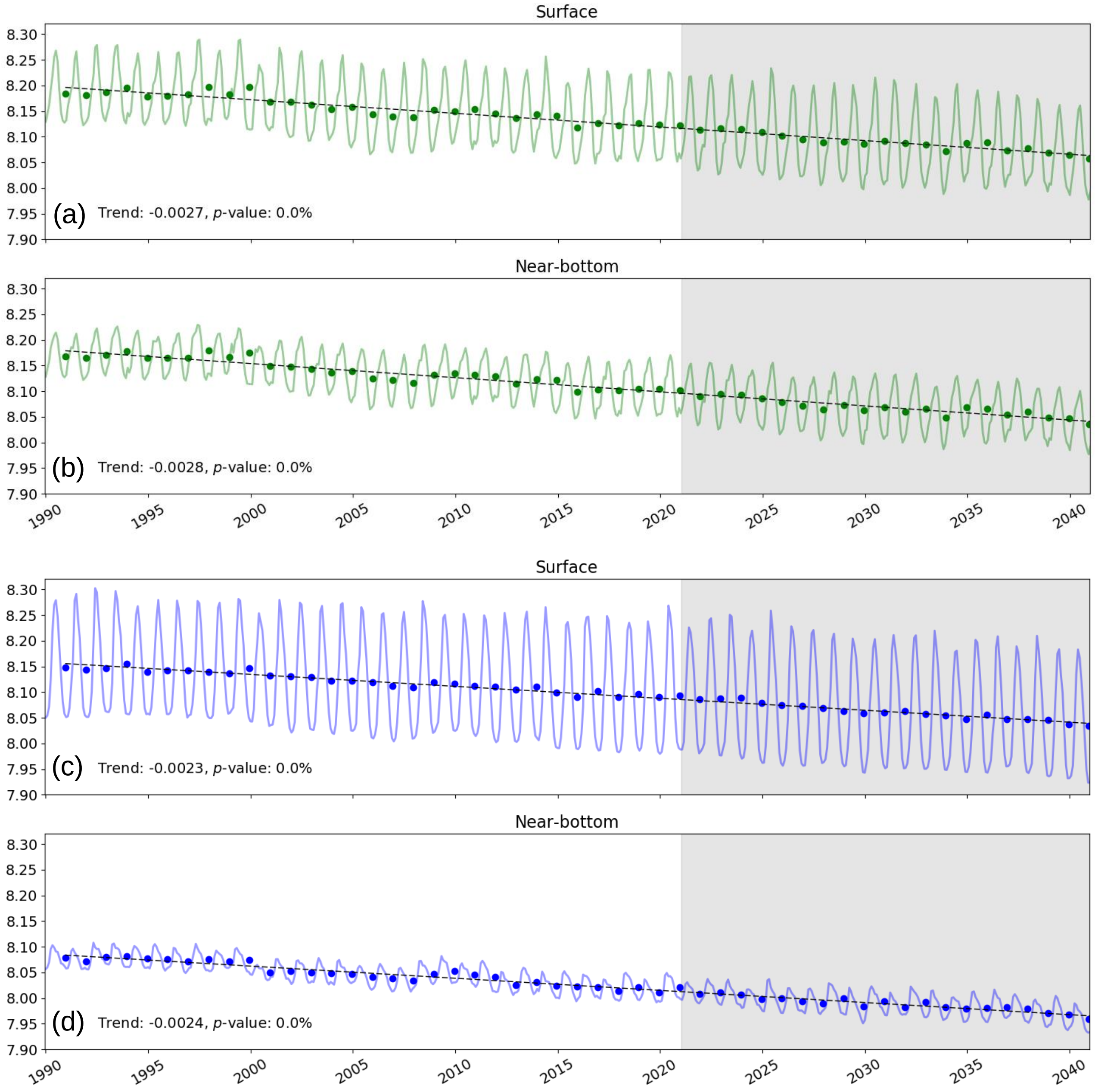
The factors that directly support the growth and proliferation of *K. mikimotoi* are poorly understood. Evidence suggests that bloom initiation takes place in continental shelf regions that exhibit both summer stratification and weak tidal current, before advection in coastal currents that support growth and distribution across large areas of the coastal zone (Brand et al. 2012; Davidson et al. 2009). During growth, significant links have been demonstrated between *K. mikimotoi* proliferation and nutrient supply, notably following periods of enhanced rainfall and the delivery of terrestrially derived nutrients to the coastal zone (Barnes et al. 2015; Davidson et al. 2014; Silke 2009). However, no significant relationships to a broader range of environmental parameters (temperature, irradiance, wind speed or direction) have been derived (Davidson et al. 2009). Localised factors (topography, hydrography) may have an important role in supporting bloom formation; this possibility requires further investigation drawing upon fine scale observations beyond those presently available. However, once growth is supported, evidence suggests that water column physical structure may influence the behaviour of *K. mikimotoi* cells (Gentien 1998); surface accumulation of cells may be enhanced during periods of strong stratification such as those projected for the SWMP area, potentially increasing the risk of harmful impacts related to localised toxin production and physical contact (e.g. gill damage for fish) at the sea-surface (Davidson et al. 2009). HAB species that may benefit, or otherwise extend their range due to increased sea temperature and the associated water column stability include the toxic dinoflagellate *Gymnodinium catenatum* (Hallegraeff 2010). The benthic dinoflagellate genus *Ostreopsis* has a geographical range that now extends beyond the Mediterranean (Hallegraeff 2010); projected temperature increases for the SWMP may render this region more susceptible to colonisation by this species.

The historical trend of increasing seawater temperature has been identified as a factor supporting the geographical range expansion of the siphonophore *Muggiaea atlantica*, a species of jellyfish that has progressively colonised the western Mediterranean (Licandro et al. 2012) and only sporadically resided in the western English Channel prior to the 1960’s. It has now established a self-sustaining population within the SWMP area, as noted for other phytoplankton and zooplankton species (Blackett et al. 2014; Hays et al. 2005; Beaugrand et al. 2002). Blackett et al. (2014) identified a minimum seawater temperature of 9°C below which *M. atlantica* populations would not develop, a value comparable to the minimum observed during the SWMP annual cycle (Figure 16). For the remainder of the year, water temperature is within the thermal optima for this species, which can cause significant ecological and economic impacts. These have included a restructuring of the zooplankton community with cascading ecosystem impacts (Greve 1994) and mass farmed fish mortalities (Cronin et al. 2004). Projections, in combination with observational data, suggest that the trend for increased seawater temperature may enhance overwintering success and enable this species to further expand its geographical range throughout the English Channel/Celtic Sea and into the North Sea.

For higher trophic levels, historical increases in seawater temperature have been shown to drive changes in abundance, body size, geographical distribution and phenology, leading to changes in community structure, predator-prey interactions and modifications to entire foods webs (Montero-Serra et al. 2015; Cheung et al. 2013; Simpson et al. 211). The projected continuation of this warming trend implies that further ecosystem responses should be anticipated across higher trophic levels.

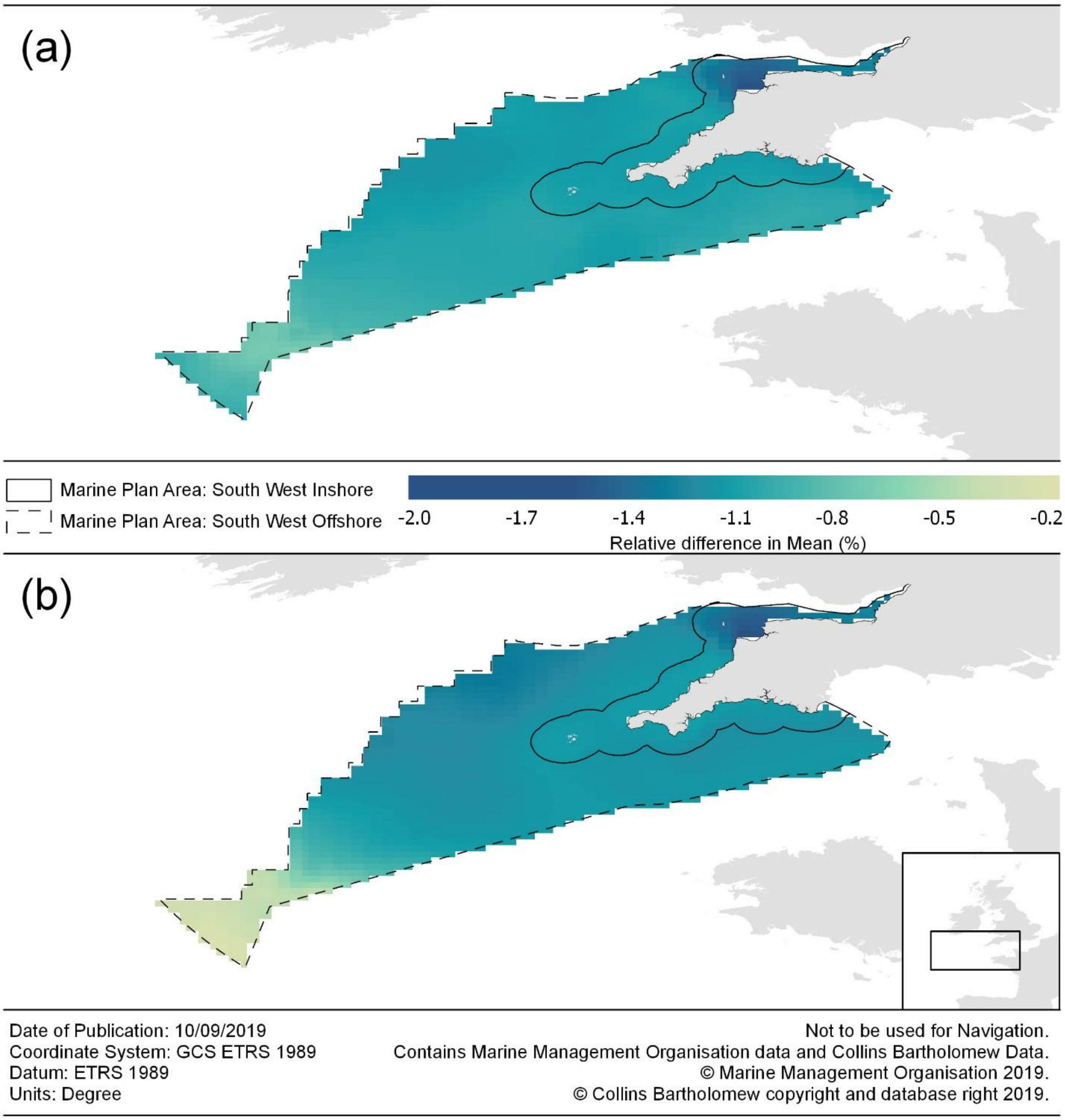
4.8 Seawater pH

Figure 19 Model output for seawater pH (1990-2041) in the south west inshore (a,b) and offshore (c,d) marine plan areas in surface (a,c) and near bottom (b,d) waters. The South West Marine Plans' 20-year time frame is shaded. Data represent monthly mean (solid line) and yearly mean (circles) values. The data trend is presented (dashed line). Trend values represent change per year (meq y^{-1}). A *p*-value ≤5% is deemed to indicate that the trend is significant.



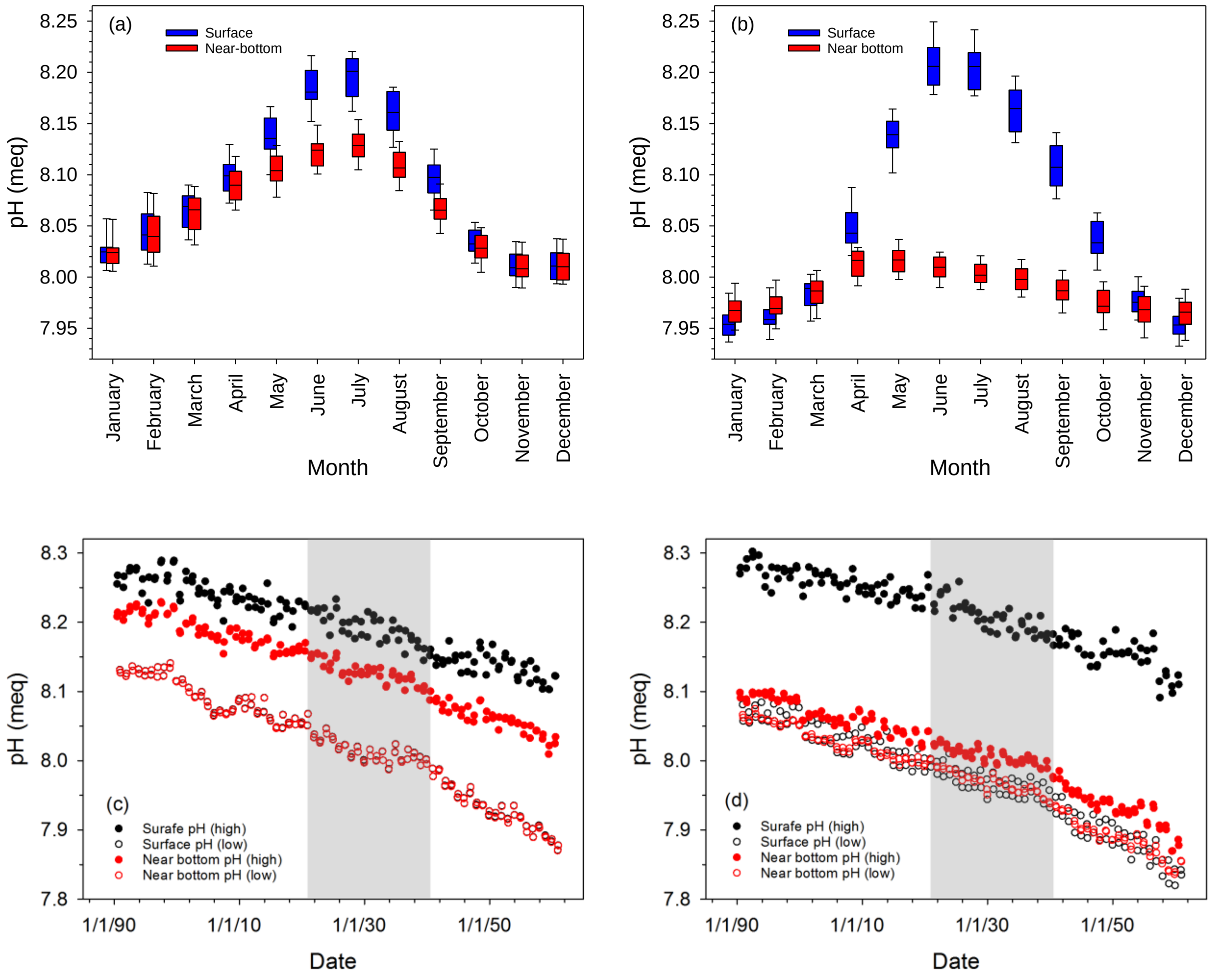
The model projects a consistent and significant decrease in seawater pH for the geographical and temporal extent of the SWMP. This regional trend is consistent with projections for the global ocean (Doney et al. 2012).

Figure 20 Relative spatial change (%) in seawater pH for (a) the surface and (b) near-bottom waters of the south west marine plan areas. The percentage change represents the difference between 5-year averages at the boundaries of the temporal range considered (i.e. 1990-1995 compared to 2036-2041) at every resolved geographical location.



The North Devon anomaly is evident in the spatial analysis, the causes of which are discussed above. For surface waters, spatial analysis indicates a general decrease in pH across both plan areas with no clear geographical features. For near-bottom depths, a comparable decrease in pH is projected for on-shelf regions. As water column depth increases considerably over the shelf break, the change in pH decreases, reflecting the progressively diminishing interaction between deep and surface waters.

Figure 21 Seasonal variability in pH, presented as box plots of monthly values for the south west inshore (a) and offshore (b) marine plan areas and 20-year time horizon (2021-2041). Seasonal high (June/July) and low (November/December) are presented for the south west inshore (c) and offshore (d) marine plan areas which define the limits of seasonal variability for the time period 1990-2060. SWMP time horizon is indicated by the grey shading.



There is a strong seasonal variability in the pH of seawater within the SWMP area; the inner and outer SWMP areas are defined by summer peaks, with troughs in autumn/winter. Variability is largely driven by biological processes (Litt et al. 2010). The greater connectivity across depths for the inner SWMP area leads to peak summertime near-bottom pH values that approach those expected for the surface. In contrast, there is a strong distinction between summertime pH values projected for surface and near-bottom depths of the outer SWMP area, reflecting physical separation and limited (or non-existent) mixing between the specific depths considered in this analysis, which can represent a vertical separation of >2km for off-shelf region.

Seasonal variability in pH, which covers a range of up to ~0.2 meq, may imply that resident biological communities have a degree of resilience to Ocean Acidification (OA) conditions, which have equated to a decrease in seawater pH of ~0.1 meq since pre-industrial times (Caldeira and Wickett, 2003). However, projections indicate that for short periods of time within the seasonal cycle, the marine environment will experience lower pH values than experienced previously within the order of decades to centuries. Consequently, set against a background trend of progressively decreasing average pH, seasonal excursions into levels of seawater acidity previously unexperienced is likely to have implications for the marine environment.

Ocean acidification is increasingly impacting marine organisms and ecosystems (Fabry et al. 2008). While studies of the response of specific marine species to simulated ocean acidification conditions have been undertaken across levels of organisation, a conclusion frequently reached is that broad generalisations regarding the response of test organisms is challenging; the extrapolation of responses to natural communities carries uncertainty (O'Donnell et al. 2013; Zhao et al. 2017; Doney et al. 2012). For example, divergent responses to OA from different strains of the world's most important pelagic calcifier *Emiliania Huxleyi* (a marine phytoplankton species) questions the extrapolation of results from selected strains through to population and community responses (Langer et al. 2009). In a meta-analysis of experimental data of marine phytoplankton, a wide range of responses to OA between taxa, between functional groups and also between strains of the same species were reported (Dutkiewicz et al. 2015). These authors suggested that competitive differences between phytoplankton species were sufficient to induce a shift in phytoplankton community composition, and hence function, over the coming decades. However, Lohbeck et al. (2012) argue that such short-term studies do not incorporate adaptive evolution, which could help to maintain functionality of microbial processes with on-going climate change. The debate continues to develop.

Specifically in relation to HAB species, the impact of OA is largely unknown (Bresnan et al. 2013) although an analysis of historical data from the western English Channel, combined with microcosm studies, suggested that the spring bloom biomass of the (non-toxic) HAB *Pheaocystis* spp. may increase in response to elevated CO_2 (and associated OA; pH ~7.9; Keys et al. 2017).

As observed for marine phytoplankton, broad generalisations regarding the response of marine bivalves to ocean acidification are not supported, as evidence suggests species-specific responses (O'Donnell et al. 2013; Zhao et al. 2017). Zittier et al. (2015) found that adult North Sea mussels (*Mytilus edulis*) had high physiological resilience to projected OA conditions (experimental OA pH 7.91 and 7.81 were investigated, values only achieved in the SWMP area beyond the 2021-2041 time frame) leaving thermal stress as the most relevant factor shaping future populations. A study of the anchoring ability of the edible mussel (*M. edulis*) demonstrated that the byssal threads used to attach mussels to surfaces (ropes, seabed) were not significantly impacted by OA conditions (Dickey et al. 2018). Significant effects of OA (across the pH range 8.1-7.5) upon marine bivalves have been reported (Gazeau et al. 2007), which included a progressive decrease in calcification (shell formation) for the edible mussel (*M. edulis*) and the Pacific Oyster (*Crassostrea gigas*), both of which are commercially cultured in the UK.

4.9 Seawater Salinity

Figure 22 Model output for seawater salinity (1990-2041) in the south west inshore (a,b) and offshore (c,d) marine plan areas in surface (a,c) and near bottom (b,d) waters. The South West Marine Plans’ 20-year time frame is shaded. Data represent monthly mean (solid line) and yearly mean (circles) values. The data trend is presented (dashed line). Trend values represent change per year (PSU y^{-1}). A *p*-value ≤5% is deemed to indicate that the trend is significant.

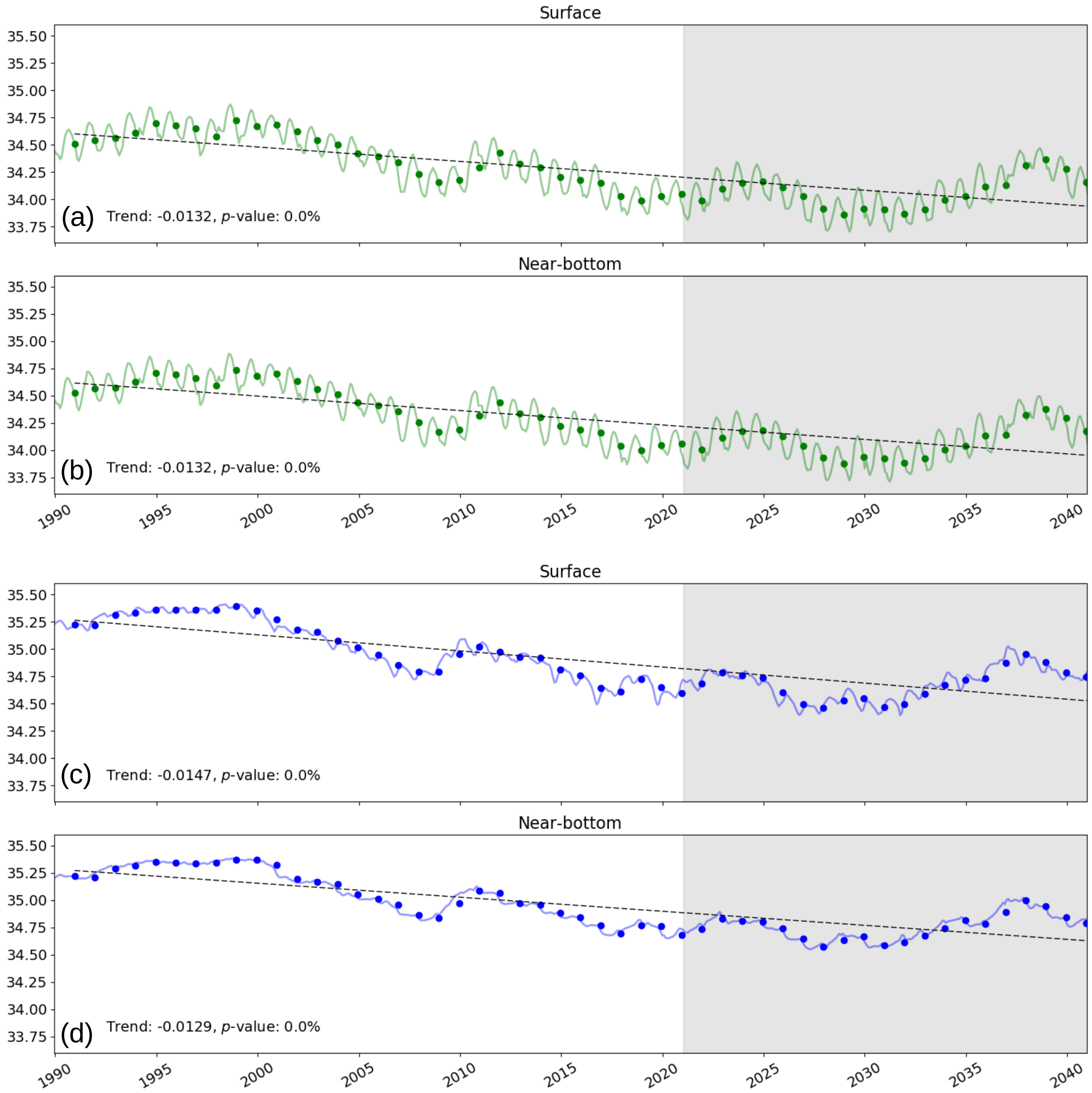
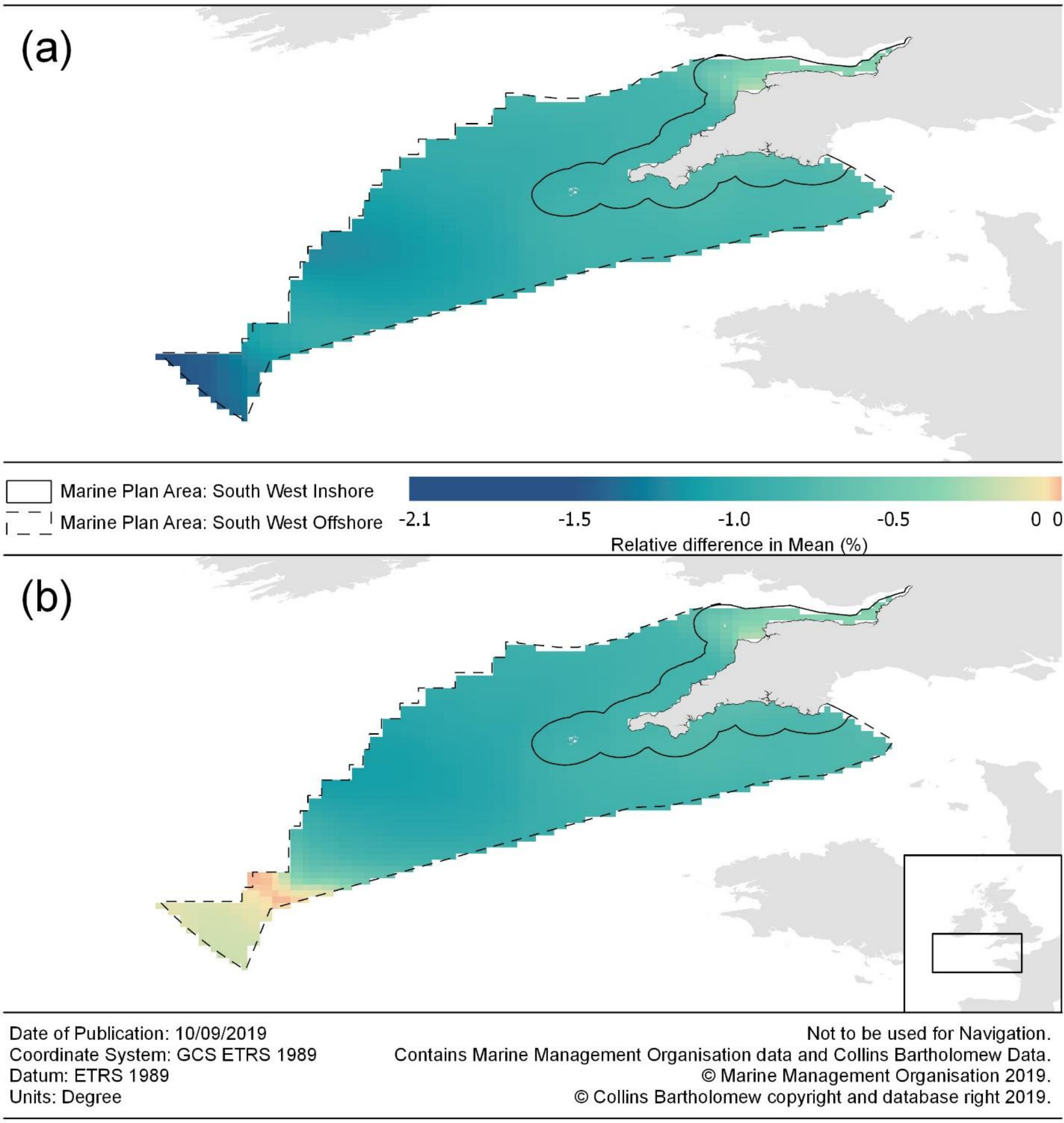


Figure 23 Relative spatial change (%) in seawater salinity for (a) the surface and (b) near-bottom waters of the south west marine plan areas. The percentage change represents the difference between 5-year averages at the boundaries of the temporal range considered (i.e. 1990-1995 compared to 2036-2041) at every resolved geographical location.



Model projection indicates a significant trend for a decrease in salinity for both inshore and offshore SWMP areas. This long term trend is only evident by considering a time frame greater than that of the SWMP (i.e. 1990-2041). Seasonal variability, most clearly demonstrated for the inshore SWMP area, relates to both precipitation and the influence of terrestrial freshwater (riverine) inputs. Multi-year variability is also evident in the data, which is caused by large-scale processes outside of the model domain, driven by global model dynamics such as those of the Atlantic gyre system (Becker et al. 1997).

The spatial analysis for both depths of the SWMP area reflect geographical gradients related to large-scale processes outside of the model domain, which are fully described by Becker et al. (1997), and beyond the scope of the present report. Though less evidence is available, salinity has been identified as a driving factor contributing to biogeographical shifts on the European continental shelf (Blackett et al. 2014; Weinert et al. 2016).

5. Data synthesis

Table 1 Summary of model projections, presented as an annual change and the change projected within the planning horizon of the South West Marine Plans. Significant trends are highlighted in light blue.

Environmental variables	Plan area	Change per year		Change during SWMP (2021-2041)	
		Surface	Near bottom	Surface	Near bottom
Dissolved Inorganic Nitrogen (DIN) (mmol N m^{-3})	Inshore	-0.0062	0.0001	-0.124	0.002
	Offshore	0.0070	0.0156	0.140	0.312
Dissolved Inorganic Phosphorus (DIP) (mmol N m^{-3})	Inshore	-0.0005	-0.0002	-0.010	-0.004
	Offshore	-0.0004	0.0001	-0.008	0.002
N:P ratio (DIN:DIP)	Inshore	0.0265	0.0172	0.512	0.344
	Offshore	0.0591	0.0173	1.182	0.346
Dissolved Oxygen (mL L^{-1})	Inshore	-0.0019	-0.0024	-0.038	-0.048
	Offshore	-0.0016	-0.0029	-0.032	-0.058
Chlorophyll (mg Chl m^{-3})	Inshore	<0.0001	-0.0007	<0.001	-0.014
	Offshore	0.0007	<0.0001	0.014	<0.001
Temperature (°C)	Inshore	0.0286	0.0257	0.572	0.514
	Offshore	0.0235	0.0131	0.470	0.262
pH (meq)	Inshore	-0.0027	-0.0028	-0.054	-0.056
	Offshore	-0.0023	-0.0024	-0.046	-0.048
Salinity (PSU)	Inshore	-0.0132	-0.0132	-0.264	-0.264
	Offshore	-0.0147	-0.0129	-0.294	-0.258

5.1 Summary of the insights derived from this study

Model projections identify a set of environmental factors that do not change significantly within the SWMP time frame and are therefore unlikely to influence ecosystem function. These include dissolved inorganic nitrogen, dissolved inorganic phosphorus and chlorophyll. Projections also identify significant changes in a set of environmental factors with seasonal variability within the SWMP time frame that is not beyond the range experienced in the recent past. These factors include N:P ratio, dissolved oxygen, temperature and salinity. Changes in these factors have been reported to individually influence marine species physiology, distribution, and diversity (IPCC 2014; Neumann et al. 2013). Finally, projections highlight trends in seawater pH for the SWMP time frame that are both significant and extend beyond seasonal variability of the recent past. It is important to note that in natural marine systems such as the European shelf, all of these environmental factors will change simultaneously. It is feasible that such simultaneous and progressive change in multiple factors (Table 1; illustrated over decadal time frames in Figures 24, 25, 26 and 27) will lead to an environment that differs from that of the present day. However, the way in which these multiple factors interact to exert an effect on marine ecosystems is both complex and uncertain (Doney et al. 2012; IPCC 2014; Briery and Kingsford 2009). By integrating best knowledge and state-of-the-art understanding of marine systems, models contribute to decreasing this uncertainty and improving our understanding of system complexity, in turn supporting regional economies and policy development.

Figure 24 Annual variability in salinity, temperature, pH and Dissolved Oxygen concentration for surface waters of the south west inshore marine plan area. Three decadal periods prior to (top), during (middle), and beyond (bottom) the South West Inshore Marine Plan planning horizon are considered. Data are presented as monthly mean values for each time period.

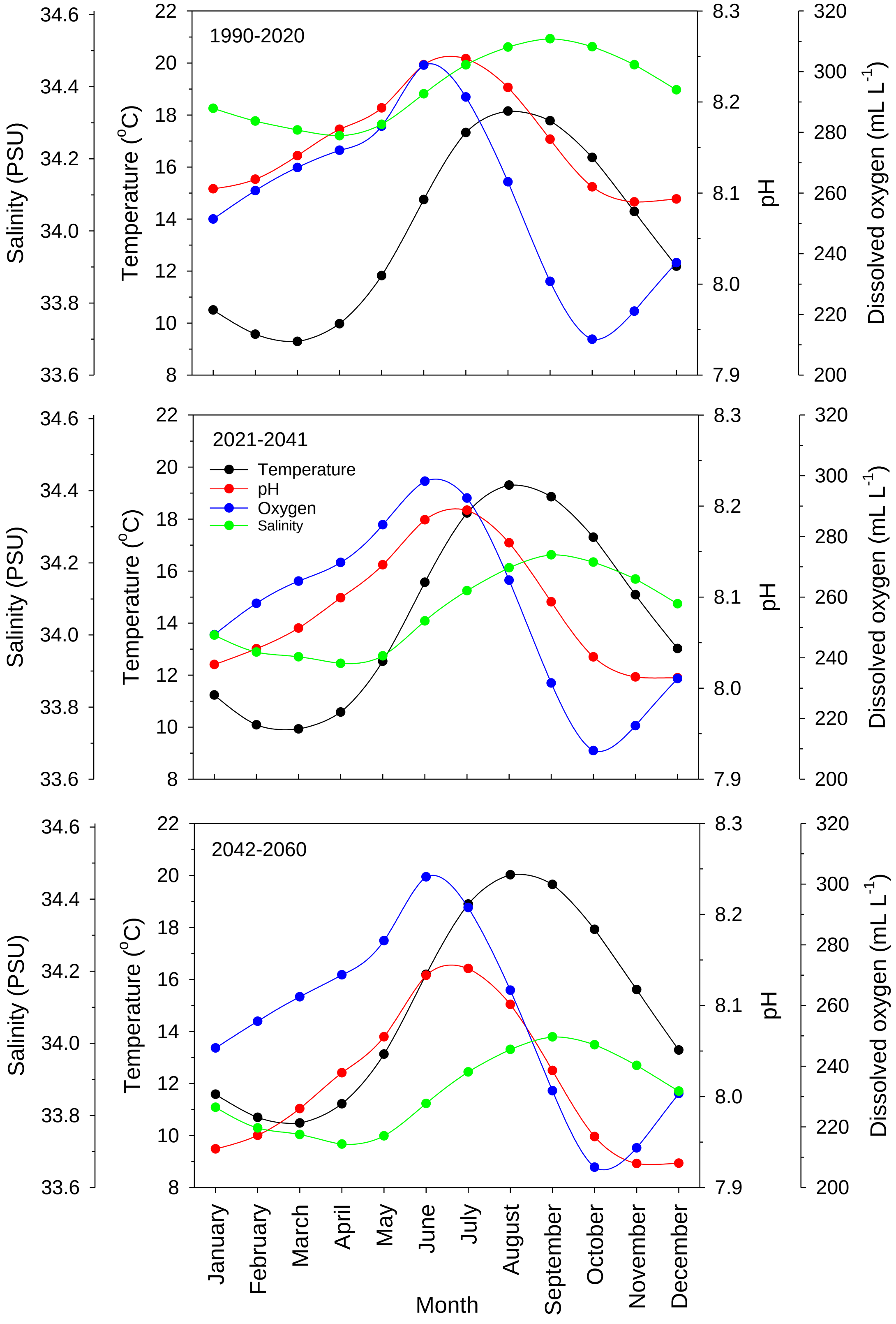


Figure 25 Annual variability in salinity, temperature, pH and Dissolved Oxygen concentration for near-bottom waters of the south west inshore marine plan area. Three decadal periods prior to (top), during (middle), and beyond (bottom) the South West Inshore Marine Plan planning horizon are considered. Data are presented as monthly mean values for each time period.

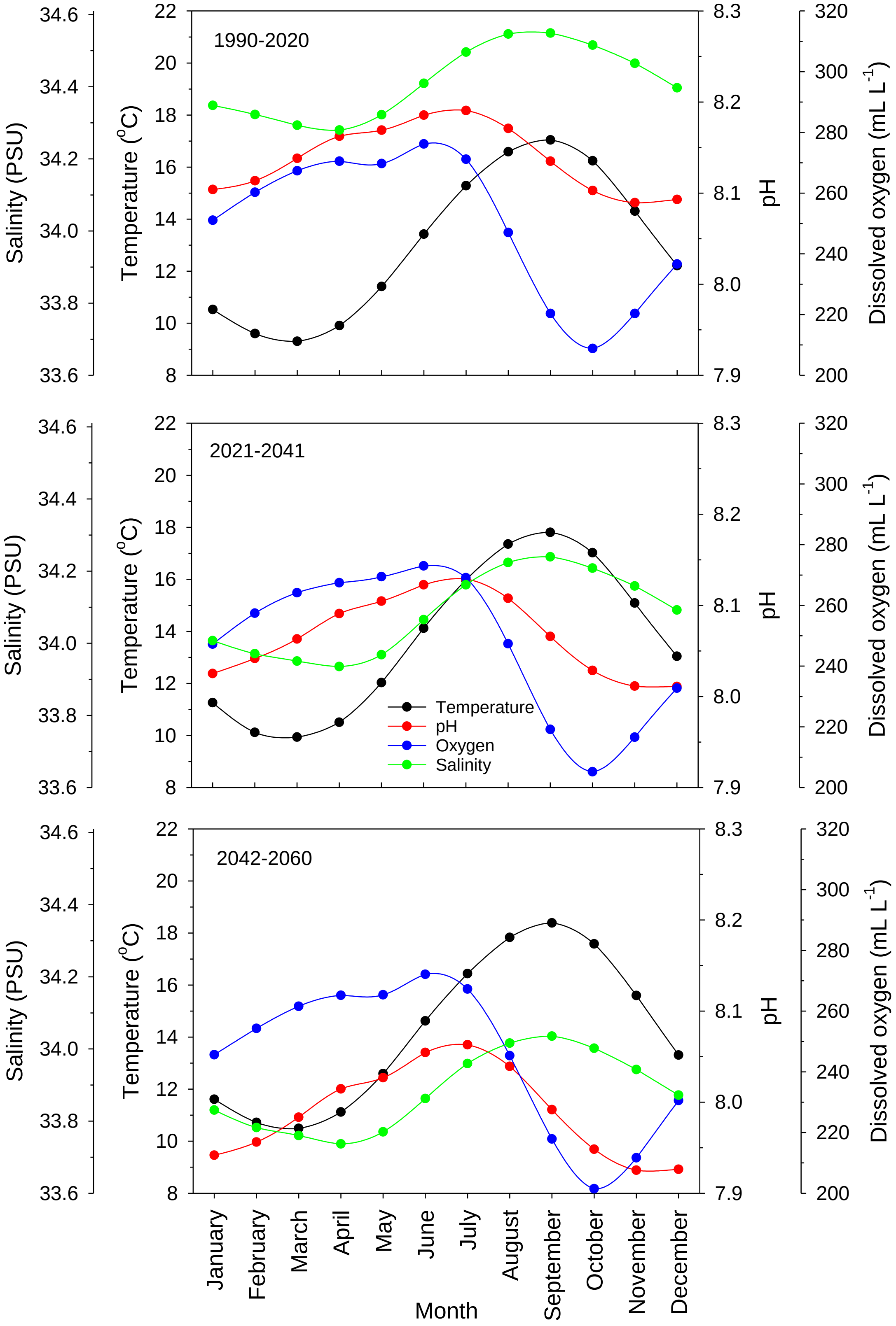


Figure 26 Annual variability in salinity, temperature, pH and Dissolved Oxygen concentration for surface waters of the south west offshore marine plan area. Three decadal periods prior to (top), during (middle), and beyond (bottom) the South West Marine Offshore Marine Plan planning horizon are considered. Data are presented as monthly mean values for each time period.

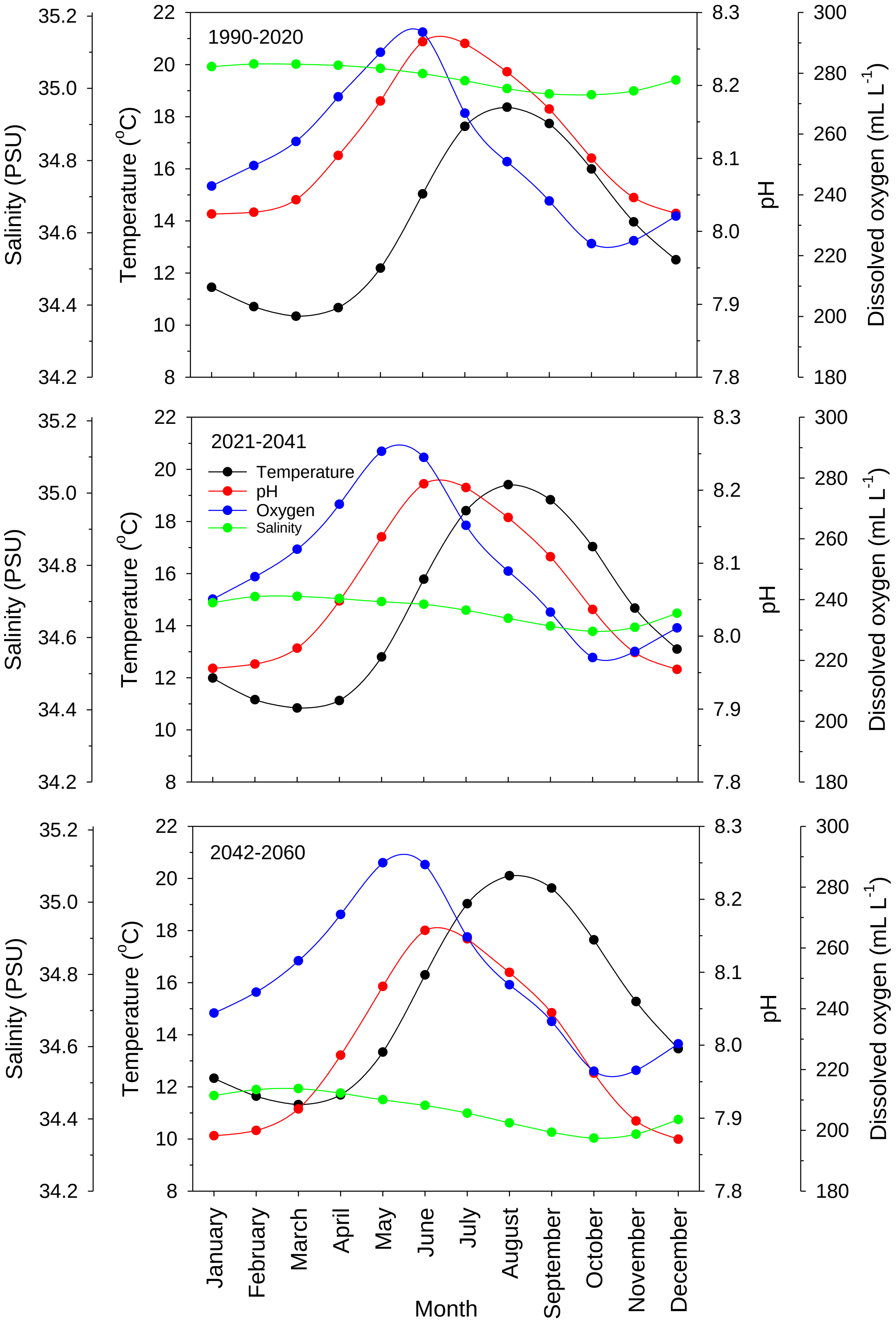
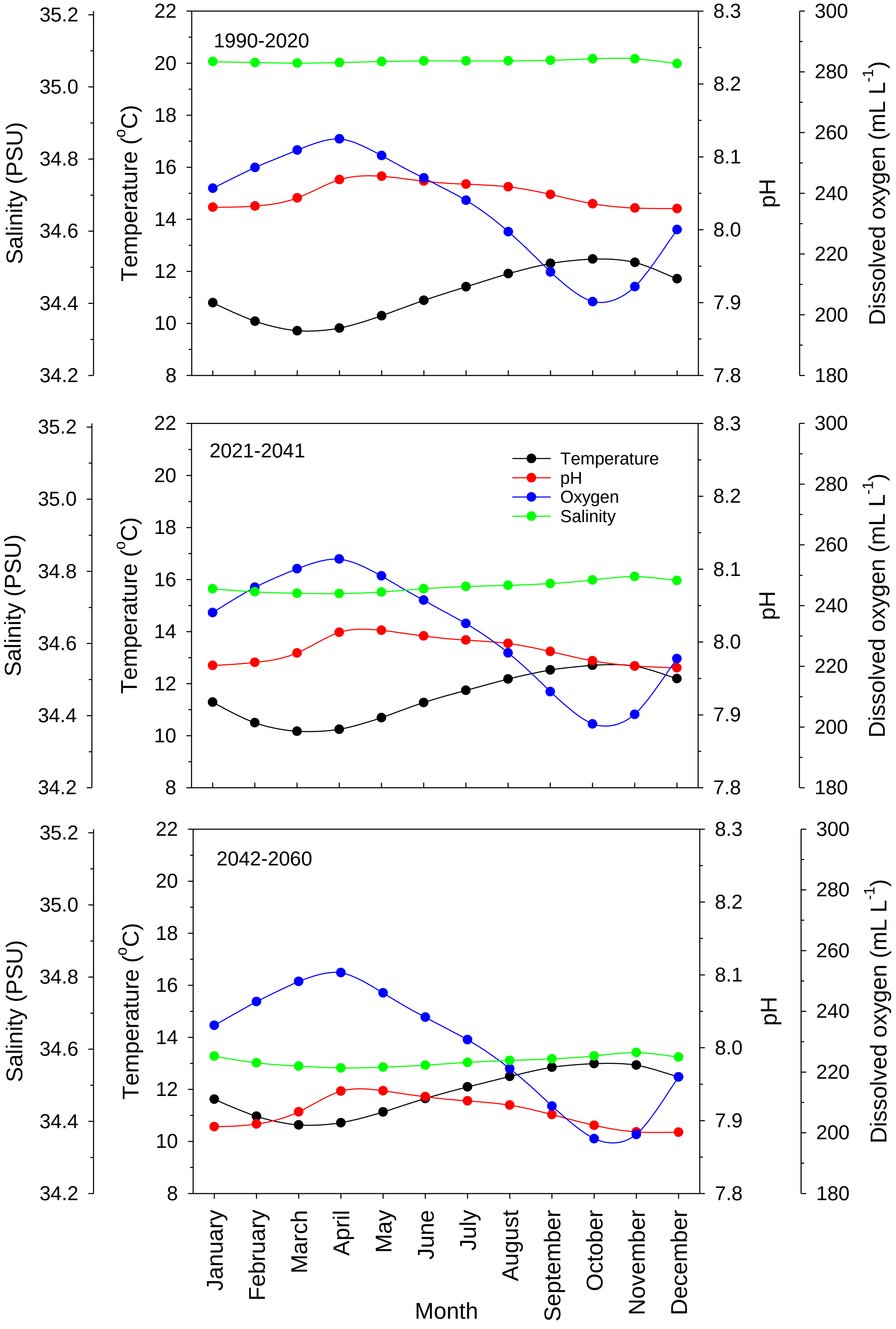


Figure 27 Annual variability in salinity, temperature, pH and Dissolved Oxygen concentration for near-bottom waters of the south west offshore marine plan area. Three decadal periods prior to (top), during (middle), and beyond (bottom) the South West Marine Offshore Marine Plan planning horizon are considered. Data are presented as monthly mean values for each time period.



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