Projected Impacts of Climate Change on the Physical and Biogeochemical Environment in Southeast Asian Seas

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Abstract

The seas of Southeast Asia are home to some of the world's most diverse ecosystems and resources that support the livelihoods and wellbeing of millions of people. Climate change will bring temperature changes, acidification and other environmental change, with uncertain consequences for human and natural systems in the region. We present the first regional-scale projections of change in the marine environment up to the end of 21st century. A coupled physical-biogeochemical model with a resolution of 0.1° (approximately 11 km) was used to create projections of future environmental conditions under two greenhouse gas scenarios, RCP4.5 and RCP8.5. These show a sea that is warming by 1.1–2.9°C through the 21st century, with surface pH falling by up to 0.02 and dissolved oxygen decreasing by 5 to 13 mmol m^{-3}. Changes for different parts of the region, including four sensitive coastal sites, are presented. The changes reach all parts of the water column and many places are projected to experience conditions well outside the range seen at the start of the century. Altered species distribution and damage to coral reefs resulting from this environmental change would have consequences for biodiversity, for the livelihoods of small-scale fishers and for the food security of coastal communities across the region. Projections of this type are a key tool for communities planning how they will adapt to the challenge of climate change.

1. Introduction

The world's oceans are warming, acidifying and deoxygenating, leading to shifts in the geographical range of many marine species, and these changes are expected to accelerate this century (IPCC 2019). Southeast Asia is particularly vulnerable to the effects of marine climate change: a large population lives in coastal areas (Neumann et al. 2015) and relies on marine resources and marine ecosystem services (Barange et al. 2014). In some Southeast Asian countries the ocean economy can account for 15–20% of total GDP (Ebarvia 2016). In addition, the seas of this region include many sites of high ecological value, including biodiversity hotspots such as the Coral Triangle (Veron et al. 2011; Burke et al. 2012). The impact of climate change on the Southeast Asian marine environment is therefore of major social, economic and ecological concern.

The productivity of marine fisheries is likely to be affected by climate change and the associated changes in ocean conditions including water temperature, ocean currents and coastal upwelling (Brander 2010; Sumaila et al. 2011; Weatherdon et al. 2016; Lam et al. 2020). Modelling studies show a projected decrease in fish production potential and revenue in the region due to climate change (Stobutzki et al. 2006; Barange et al. 2014; Teh et al. 2019). In Southeast Asia small-scale fishers provide around half the fish that is used for human consumption (Teh and Pauly 2018) and they are also particularly vulnerable to climate change impacts (Barange 2018). Other sectors reliant on wild capture and farming may be similarly affected. Cultivation of seaweed, caged fish and shellfish are important for the marine economy, food security, human nutrition, sustainable livelihoods, and poverty alleviation, especially in Southeast Asia (FAO 2018; Monnier et al. 2020).

Climate change also poses a risk to coral reefs, which are found across Southeast Asia and are areas of particularly high biodiversity: 76% of all coral species and 37% of coral reef fish species are found in the Coral Triangle (Burke et al. 2012). Rising temperatures and ocean acidification pose threats to coral reefs worldwide (Hoegh-Guldberg et al. 2007; Lough et al. 2018). Increasingly frequent and more extreme heat-waves cause damage to reefs through mass coral bleaching reducing long-term sustainability (Hughes et al. 2018). In addition, ocean acidification is altering ocean carbonate chemistry, limiting coral growth and degrading the physical structure of reefs (Burke et al. 2012; Lam et al. 2020). Coral reef degradation in Southeast Asia threatens the associated foodweb, jeopardizing dependant biodiversity and fisheries, and threatening regional food security, coastal protection and tourism, potentially costing the region billions of dollars in lost revenue (Burke et al. 2002, 2012; Cesar et al. 2003).

There are indications that climate change is resulting in the increased intensity and frequency of typhoons and flooding in Southeast Asia (Loo et al., 2015), although considerable uncertainty remains about both historical and future trends (Lee et al. 2012; Ying et al. 2012; Knutson et al. 2020). Typhoons disrupt ocean ecosystems through water column mixing by strong winds and the freshening effect of heavy rain. They can also cause flooding and surging which may damage fishing gears and cages and cause long-term damage to coral reefs (Harmelin-Vivien 1994; Latypov and Selin 2012; Safuan et al. 2020). Increased typhoon activity leads to beach erosion, causing damage to property for communities living close to the shore. All of these effects are exacerbated by sea level rise, which poses an additional threat to the large coastal population of this region (Rowley et al. 2007; Neumann et al. 2015).

Given the potential impact of climate change on key marine ecosystems in Southeast Asia and coastal communities that depend upon them, adequately projecting the effects of climate change on Southeast Asian seas is a crucial step toward informing strategies for poverty alleviation and food security: UN Sustainable Development Goals 1 and 2. Global climate models provide a broad picture of the environmental change that may be experienced in the region (IPCC, 2019); however they have a coarse resolution and the marine ecosystem models used are typically designed for open ocean conditions. This paper presents regionally-scaled projections of change in the physical environment and lower trophic level ecosystem of Southeast Asian seas, to the end of the 21st century. The projections were created using a model with spatial resolution 0.1° (approximately 11 km) and a well-established biogeochemical/ecosystem model suited to coastal and shelf sea environments: the European Regional Seas Ecosystem Model (ERSEM, Blackford et al. 2004; Butenschon et al. 2016). This modelling system has previously been applied to coastal regions in many parts of the world, including Southeast Asia (Holt et al. 2009; Barange et al. 2014). The model was driven by outputs from a global climate model using two Representative Concentration Pathways (RCPs) of greenhouse gases in the atmosphere (van Vuuren et al. 2011): the moderate RCP4.5 scenario, under which atmospheric carbon dioxide concentration rises until mid-century and then stabilises, and the more extreme RCP8.5 scenario, under which the concentration rises throughout the 21st century.

Eight regions were selected to sample projected change across the region (Fig. 1). Four are coastal sites of key importance for biodiversity and sustainable development: UNESCO Biosphere Reserves at Cu Lao

Cham-Hoi An in Vietnam, Palawan in the Philippines and Taka Bonerate-Kepulauan Selayar in Indonesia, and Sabah coastal waters, Malaysia, which includes several marine parks. These are supplemented by four offshore sample areas, boxes A-D in Fig. 1; region-wide snapshots of change projected for the middle and the end of the 21st century under both RCPs are also presented. The next section describes the modelling system and data used; Sect. 3 presents the model outputs, first a comparison to observations for past years and then projected conditions for the rest of the 21st century; Sect. 4 discusses the implications of the projected change for people and ecosystems.

2. Methods

The projections were created using the Proudman Oceanographic Laboratory Coastal Ocean Modelling System (POLCOMS, Holt and James 2001) coupled to the European Regional Seas Ecosystem Model (ERSEM, Butenschon et al. 2016). Together these simulate the movement of water, energy and dissolved and suspended material through the sea and the cycling of nutrients and carbon through the marine ecosystem. POLCOMS is a three-dimensional model of physical processes, suitable for modelling both deep and shallow water. 40 depth levels were used at each point, regardless of total water depth, distributed more closely in the upper parts of the water column than at depth. ERSEM models the transfer of carbon, nitrogen, phosphorus and silicate through the lower trophic levels of the marine ecosystem. It is one of the more complex models of its type, with four phytoplankton functional types, three zooplankton and bacteria; the carbonate system is included, enabling changes in pH to be modelled. The model domain covered the region from 99.1 to 139.0°E and 16.7°S to 23.9°N, with all sea areas within 200 km of the shelf break included (Fig. 1). Cells close to the open boundary have been removed from the analysis presented here to avoid boundary effects.

Climate change was applied by using publicly-available climate model outputs from the Coupled Model Intercomparison Project Phase 5 (CMIP5, Taylor et al. 2011): lateral boundary conditions were taken from the global model HadGEM2-ES (Jones et al. 2011) and surface conditions from a regionally-downscaled atmospheric model driven by the same global model, HadGEM2-ES-RCA4, which was sourced from CORDEX Southeast Asia (http://www.ukm.my/seaclid-cordex/). This pair of models was selected because it provided both a biogeochemical component in the ocean and a consistent regional-scale atmospheric component. The atmospheric model provided data at 0.22° resolution: temperature, pressure, wind and humidity at 6-hourly intervals and precipitation and radiation flux at daily frequency. The ocean model provided monthly values of temperature, salinity and current speed at 1° spatial resolution. It also provided annual concentrations of nitrate and inorganic carbon; concentrations of phosphate and silicate and the monthly cycle of variation in all nutrients were derived from this using ratios based on the present-day climatology from the World Ocean Atlas 2013 (Garcia et al. 2013a).

River inputs of fresh water and nutrients used average present-day values from the global model NEWS2 (Mayorga et al. 2010). Fixed values were used for nutrients; discharge values were adjusted to give a daily climatology based on historic flows reported by (Dai et al. 2009). Future values for riverine discharge were based on this climatology, adjusted each year in line with domain-average precipitation.

No information about future changes in river water quality was available, so concentrations of nutrients were kept constant at present-day values. Initial conditions of temperature, salinity, oxygen and nutrients were taken from the World Ocean Atlas 2013 (Garcia et al. 2013b, a; Locarnini et al. 2013; Zweng et al. 2013) and total alkalinity and dissolved inorganic carbon were taken from the GLODAPv2.2016b gridded dataset (Key et al. 2015; Lauvset et al. 2016). Atmospheric carbon dioxide levels for RCP4.5 and RCP8.5 were set to the global levels defined for RCP4.5 and RCP8.5 (Meinshausen et al. 2011). The model was run for a 10-year spin-up period before being run for the period 1980–2098, with RCP4.5 and RCP8.5 run separately from 2006 onwards.

Eight areas were selected for analysis (Fig. 1): coastal areas around each of the coastal case study sites and four sample 2° boxes in offshore regions. Box A is at 18–20°N, 114–116°E; Box B at 5.5–7.5°N, 109–111°E; Box C at 1.2°S-0.8°N, 125–127°E; Box D at 3.5–5.5°S, 127–129°N. These boxes were chosen to sample different parts of the region in places where observations of nutrients and oxygen are available.

Model outputs were compared to observations to assess how closely the model reproduces real-world conditions. The observational datasets used were satellite observations of sea surface temperature (OSTIA reprocessed product from the Copernicus Marine Service, Good et al. 2020) and chlorophyll concentration (Ocean Colour CCI product from the Copernicus Marine Service, Sathyendranath et al. 2019), and in situ measurements of nitrate and phosphate in the World Ocean Database (Boyer et al. 2018). Observations are sparse in some parts of the region and for some variables, so model outputs were extracted to match the date and location of observations. The mean and standard deviation of the resulting datasets over several years were compared; for a free-running climate model a close agreement between specific observations and model outputs is not expected, but there should be a match between observed and modelled average values and spread. Historic trends were compared to those seen in satellite observations and reported in the literature.

3. Results

Section 3.1 shows how the model outputs compare to observed values and trends for the period 1980–2018; Sect. 3.2 presents projections for future values to 2100.

3.1 Comparison of model outputs to observations

The mean and seasonal variation in sea surface temperature is captured well by the model (Fig. 2), though modelled April-June temperatures are higher than observed in the west and July-September temperatures are lower in the north. The model matches average values of sea surface temperature from satellite-based observations to within 0.5°C in all regions and the standard deviation is also similar (online resource, Table S1), though the model under-represents the spread in Box D, Palawan and Sabah and over-represents it in Cu Lao Cham. The agreement is less close when temperature at all depths in the water column is compared, with the model tending to underestimate sub-surface temperatures, but modelled and observed mean temperatures agree to within 2°C for most regions and the standard deviation to within 1.5°C, with closer agreement for coastal areas. The model underestimates salinity in the northern part of the region, but average values are in good agreement elsewhere (online resource, Table S1). Modelled and observed standard deviations of salinity agree to within 0.1 psu except in Box A, Box B and Cu Lao Cham, which may reflect the use of climatology for river discharge rather than annually varying values: Box B, in particular, is affected by the outflow of the Mekong River.

Model-observation agreement is less close for biogeochemical variables, but the model reproduces many features of the biogeochemical environment. Mean surface chlorophyll concentration is overestimated compared to satellite values, particularly in the north, but shows broadly the same spatial and temporal patterns (Fig. 3 and Table S2, online resource). Nitrate, phosphate and oxygen observations are sparse across the region, but are available in boxes A-D and in some of the coastal sites (Fig. 4 and Table S2, online resource). Modelled nitrate values are higher than observed in the north, but the standard deviation is in agreement with observation, as is the spatial distribution of surface values. Phosphate is overestimated in the north and underestimated in the south; the spread and spatial distribution agree with observed values. Oxygen is overestimated for the region as a whole and in most of the sample areas; the spread of values is less than observed (Table S2, online resource).

The model outputs and satellite observations both show a rising trend in sea surface temperature for the period 1985–2019 (Table 1). The observed trend is smaller than modelled, though there is closer agreement for the trend in the period 2000–2019 (Fig. 7a). The change in surface chlorophyll concentration for 1998–2017 is small in both model outputs and satellite observations. Modelled trends in dissolved oxygen concentration are smaller than observed but have the same spatial distribution, with increases in the north and west and decreases in the south and east. A global analysis of satellite and in situ observations (Kulk et al., 2020) shows little change in net primary production in this region since 1998, and the model outputs are consistent with this. There are few measurements of pH for the Southeast Asia region, but the IPCC reports a decrease of 0.013 to 0.03 pH units per decade for 1990–2014 (IPCC, 2019). The model outputs are consistent with this (-0.01 to -0.02 pH units per decade) except for shallow areas in the northwest of the region, where a small increase in pH in pH is projected by the model.

3.2 Projected future conditions

The projected 21st century change in some key variables is summarised in Fig. 5. This compares monthly mean conditions for 20 years at the start, middle and end of the century (2000–2019, 2040–2059 and 2079–2098) under the moderate RCP4.5 scenario (atmospheric greenhouse gas concentrations rising until mid-century and then stabilising) and the more extreme RCP8.5 (greenhouse gases continuing to rise throughout the century). The values show the mean difference between start and mid- or end-century, shown in grey where the difference is not statistically significant ($p > 0.05$, t-test, $n = 240$; for details of the method see Kay and Butenschön, 2018). The colours show the size of the change relative to the present-day variability, defined as the difference between the minimum and maximum monthly values for 2000–2019. Statistically significant change is seen in temperature, surface salinity and bottom-level oxygen for both carbon scenarios: temperatures rising and salinity and oxygen falling, with larger changes for RCP8.5 than for RCP4.5. There is significant change in primary production and pH for RCP8.5 but not for RCP4.5. The pattern for phytoplankton and zooplankton biomass is less consistent: there is a broad trend to decreasing biomass under RCP4.5 and increasing under RCP8.5, but the changes are only significant in a few places and well within current variability everywhere. Compared to present-day variability, the bottom level changes are larger than for the sea surface, because bottom-level conditions are more stable and the present-day variability is low: these projections show the effects of climate change reaching all depths of the sea. In the regions around Cu Lao Cham, Sabah and Palawan the water is relatively shallow, so bottom level conditions are more variable than for the other areas and the relative change is smaller.

The rest of this section discusses the changes in sea surface temperature, primary production and pH in more detail. Sea surface temperatures are projected to rise by 1-1.5°C by mid-century and 2–3°C by end century under RCP8.5, when compared to 2000–2019 (Figs. 6 and 7). Smaller increases are projected under RCP4.5: 0.5-1°C and 1-1.5°C respectively. These changes are in line with those projected by a range of CMIP5 global models, and they imply that temperatures that were average for the region in 2000–2019 will occur only in the very far north under RCP8.5 (see the contours in Fig. 6). Change under RCP4.5 is substantially smaller, with end-century conditions similar to those at mid-century under RCP8.5. The median temperature for the present-day period shows higher movement poleward in RCP 8.5 as compared to RCP 4.5.

From the sampled regions, the largest temperature changes are seen in Box C, Palawan, Sabah and Taka Bonerate-Kepulauan Selayar (Fig. 7b). Palawan shows a stronger seasonal change than other areas, with temperatures rising more in April-September than in October-March. The southernmost areas, Box D and Taka Bonerate-Kepulauan Selayar, also show a seasonal change, with smaller temperature rises in May-September than the rest of the year.

Projected changes in net primary production are smaller than for sea surface temperature and in many regions are only noticeable for RCP8.5 at the end of the century (Figs. 8 and 9). Some changes in seasonality are projected: for example, Box A shows smaller increases in production in November to February than the rest of the year; Taka Bonerate-Kepulauan Selayar show larger increases in May-September; Sabah shows slightly decreased production in November to March, except for RCP8.5 end-century when these months show the largest increases (Fig. 9b). In many cases the changes are small and are difficult to distinguish from the general variability.

Modelled changes in surface pH follow the trends in the applied atmospheric carbon dioxide levels, with pH falling until mid-century and stabilising under RCP4.5 but continuing to fall throughout the century under RCP8.5 (Fig. 10). The size of the change is similar across the sample regions, with the exception of Taka Bonerate-Kepulauan Selayar, which has static or even rising values for pH. Changes in other southern areas, Box C and Box D, are also relatively small.

4. Discussion

The agreement between modelled and observed values and trends for the period 1980–2018 is good enough to support use of the future projections. Agreement is better for physical variables than for biogeochemical, as is common in this type of modelling, but spatial and temporal trends are captured in all cases.

The projections show a sea that is, on average, warming by 1.1–2.9°C through the 21st century, with surface pH falling by up to 0.02 and dissolved oxygen decreasing by 5 to 13 mmol m^{-3}. The changes reach all parts of the water column and the bottom levels, in particular, are projected to experience conditions well outside the range seen at the start of the century. There are considerable local variations (Fig. 5), emphasising the value of using a regional rather than global model.

Warming seas mean that some parts of the region will experience temperatures not seen in the region at present (Fig. 6). As a response, some species population may be able to move with the present-day temperature contours, seeking to maintain optimum conditions for their growth, reproduction and survival (Pinsky et al. 2013; Poloczanska et al. 2013). However, this adaptation strategy has limited success near warmer regions of species distributions, and does not apply to all types of species. This is the case for corals, whose algal symbionts are tightly dependant on light near the sea surface, and where range expansion to deeper water is therefore limited.. There are clear consequences for fishing, in a region already experiencing significant challenges due to overcapacity and declining catches, exacerbated by poorly regulated fisheries (Pomeroy 2012; Teh et al. 2017). As populations re-distribute in response to changes in habitat conditions, fishers may need to travel further to find their target species, shift to catching different species, perhaps requiring an investment in new gear, or in the worst cases be faced with declining catches and no incoming new species. This is especially a concern in tropical regions, such as Southeast Asia, where declining local diversity resulting from poleward retreat of distribution leading edges is not necessarily compensated by new species arrivals. Therefore, adapting to climate change will be a significant challenge, especially for the many small-scale fishers in the region, and good management will be essential for protecting livelihoods (Lam et al. 2020).

Increased temperature and reduced salinity, as seen in these projections, may result in increased incidence of harmful algal blooms (HABs). The consequences of such HAB events include reduced water quality and toxin build-up in fish and shellfish, with potential subsequent impacts on human health (GEOHAB 2010; Young et al. 2020). Rising temperatures can also increase the risk of disease in cultured fish (Reverter et al. 2020), shellfish (Allison et al. 2011) and seaweed (Largo et al. 2017) and can lead to a rising number of jellyfish blooms or invasions that may affect aquaculture (Xu et al. 2013; Bosch-Belmar et al. 2020). Climate change driven changes in the timing of seasons is also likely to affect aquaculture production cycles, where activities are tightly timed to sharp climatic variations between monsoon/inter-monsoon periods. Such changes can be seen in the projected changes for coastal regions, notably Palawan and Taka Bonerate-Kepulauan Selayar (Fig. 7). A reduction in the predictability of seasonal cycles often leads to reduced harvests (Handisyde et al. 2006; Hamdan et al. 2015).

All the analysed coastal regions had projected end-century temperature increases close to 1.5°C under RCP4.5, enough to cause significant thermal stress leading to coral bleaching, while the 2.7°C increase seen under RCP8.5 would cause widespread loss of coral (Lough et al. 2018). The smallest temperature increases were seen at Cu Lao Cham, but at 1.5°C (RCP4.5) or 2.5°C (RCP8.5) these are still too high to prevent coral damage. Ocean acidification and the overall alteration of the ocean carbonate system resulting from rising atmospheric CO_2 levels provides further stress to coral reefs by affecting the ability of reef organisms to maintain sufficient calcification rates in the face of increased dissolution rates and, in extreme cases, prevent the deposition of carbonate minerals needed for skeleton construction through the occurrence of insufficient saturation levels (Eyre et al. 2018). Our projections show surface pH decreasing, though not beyond the range currently experienced; however any acidification will act as an additional stressor on coral reefs and make it more difficult for them to recover from bleaching events. The conditions under which coral reefs are able to recover can be complex (Graham et al. 2015) and this has not been considered in the current study.

The effect of climate change on typhoons is a key concern for coastal communities in Southeast Asia, however changes in the frequency and intensity of storms are one of the least certain climate features reported by the IPCC (IPCC 2013). Regional models can simulate stronger storms than global models, because they have higher resolution, but the uncertainty in the projections remains high. We investigated the surface wind speeds in the regional atmospheric model HadGEM2-ES-RCA4, which was used as input to the marine model reported here, for any changes in the strength, frequency or timing of storms. There was some indication of an increase in the number of days per year with strong winds, but not in maximum wind strength or in the pattern across the year. By contrast, Herrmann et al. (2020), based on a much more thorough analysis of outputs from a similar regional model (CNRM-CM5_RegCM4), found a decrease in projected wind speeds, in most of the region and all seasons, except for some increase in average speeds for December to February in the north of the region. The number of tropical cyclones also decreased in all seasons. There is a clear need for more investigation of changes in storminess in this region.

This study, using a single regional-scale model driven by a single global climate model, provides useful, novel information about the potential scale of climate change effects that may occur in the marine environment at different locations across Southeast Asia. However, it does not provide any indication of the certainty in these changes, which is of key importance for decision-making. Further projections are needed, using a range of models with different climate sensitives and alternative global emissions scenarios, to estimate the uncertainty and give confidence levels in the change projected for different variables and different locations. In a region of exceptionally high marine biodiversity, and where the sea supports the livelihoods of millions of people, such projections are a key tool for communities planning how they will adapt to the challenge of climate change.

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Tables

Table 1 Comparison of modelled and observed historical trends in selected variables. (N = north; E = east; NW = northwest; SE = southeast)

Variable	Modelled trend	Observed trend	Source	Period
Sea surface temperature (SST) (°C per decade)	0.22	0.15	OSTIA satellite (Good et al. 2020)	1985–2018
Surface chlorophyll ($mg\ m^{-3}$ per decade)	-0.001	-0.005	CCI satellite (Sathyendranath et al. 2019)	1998–2017
Dissolved oxygen ($mmol\ m^{-3}$ per decade)	0-1200m depth: change < 1 in most areas, some increase in NW, decrease in SE below 1200 m depth: +1–3, 0 in far SE	0-1200 m depth: +1.5 in NW, -3 to -5 in central E, mixed in SE below 1200m depth: +3–4 in NW, 0 to 3 in SE	(Oschlies et al. 2018)	Modelled 1980–2010, observed 1960–2010
Net primary production	Close to 0 most areas, some increase in far N and some coastal areas.	No trend or small decrease in most areas (< 1% per year); small increase in some coastal areas	(Kulk et al. 2020)	1998–2018
Surface pH	-0.01 to -0.02 in most areas; +0.01 in shallow NW; -0.0013 overall	global: -0.013 to -0.03 pH units per decade	(IPCC 2019)	1990–2014

Figures

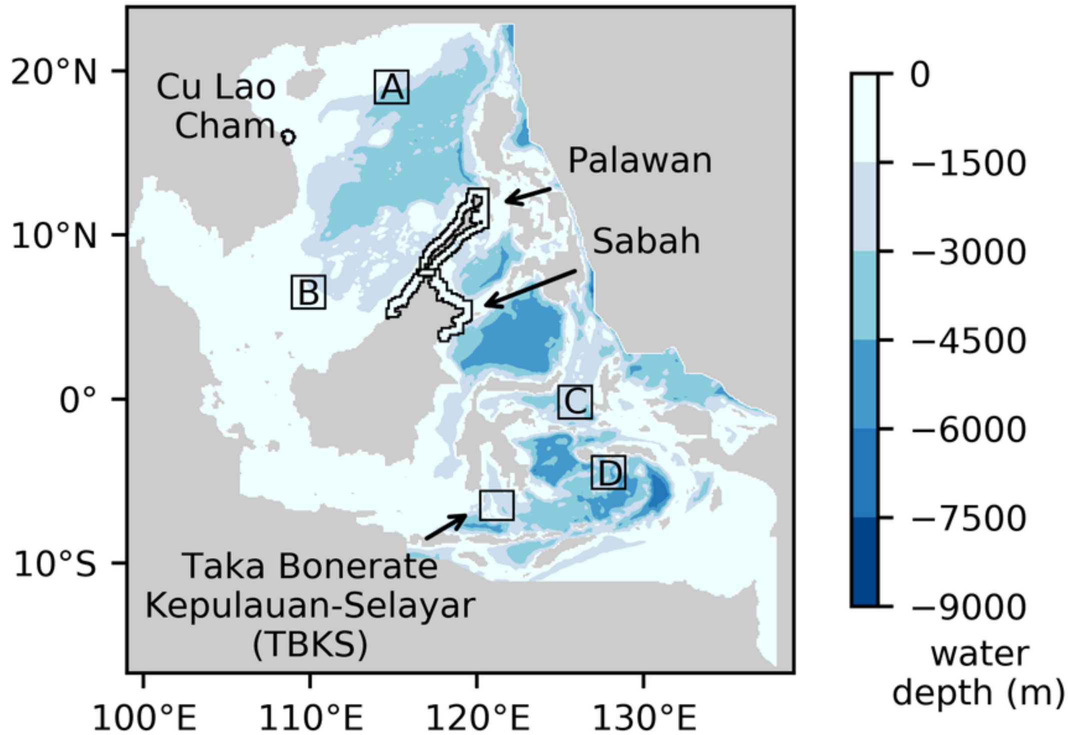


Figure 1

The model domain and regions referred to in the text. Boxes A, B, C and D are sample areas for four different offshore parts of the domain; the labels show regions around the four coastal study sites. The shading shows bathymetry. Box A is at 18-20°N, 114-116°E; Box B at 5.5-7.5°N, 109-111°E; Box C at 1.2°S-0.8°N, 125-127°E and Box D at 3.5-5.5°S, 127-129°N. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

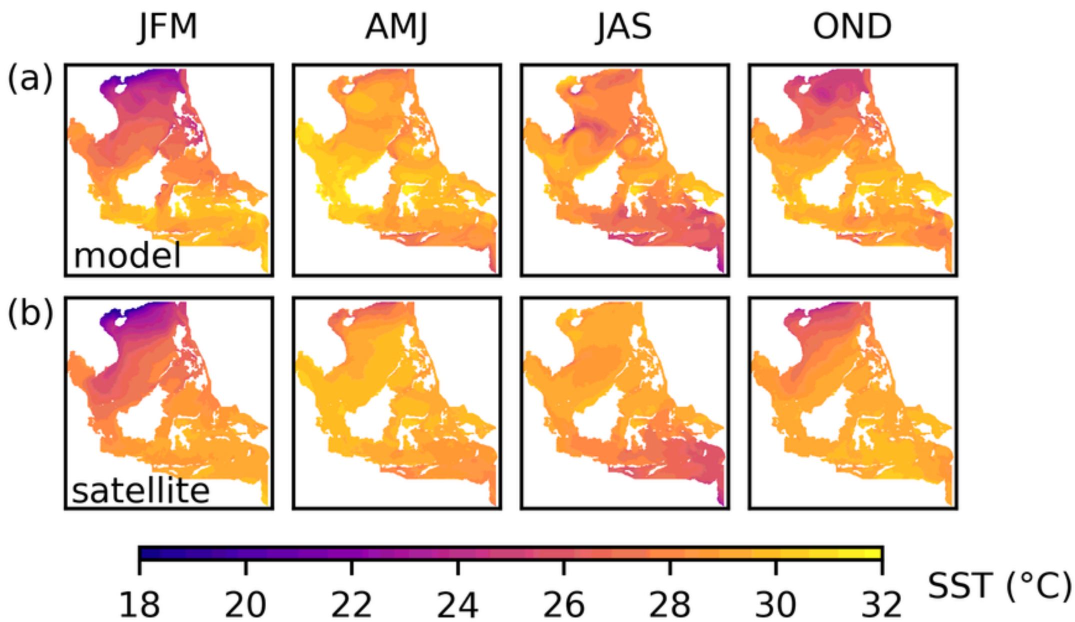


Figure 2

Three-month mean surface temperature for 1985-2018 from (a) the model and (b) OSTIA satellite-based observations. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

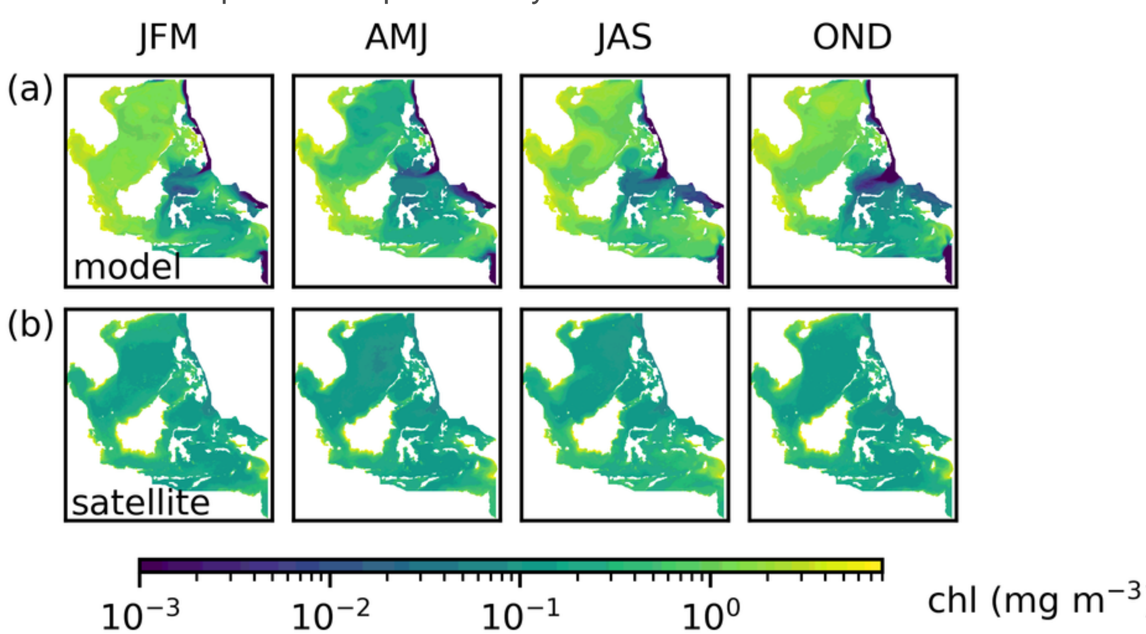


Figure 3

Three-month mean surface chlorophyll concentration for 1998-2017 from (a) the model and (b) CCI satellite observations. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

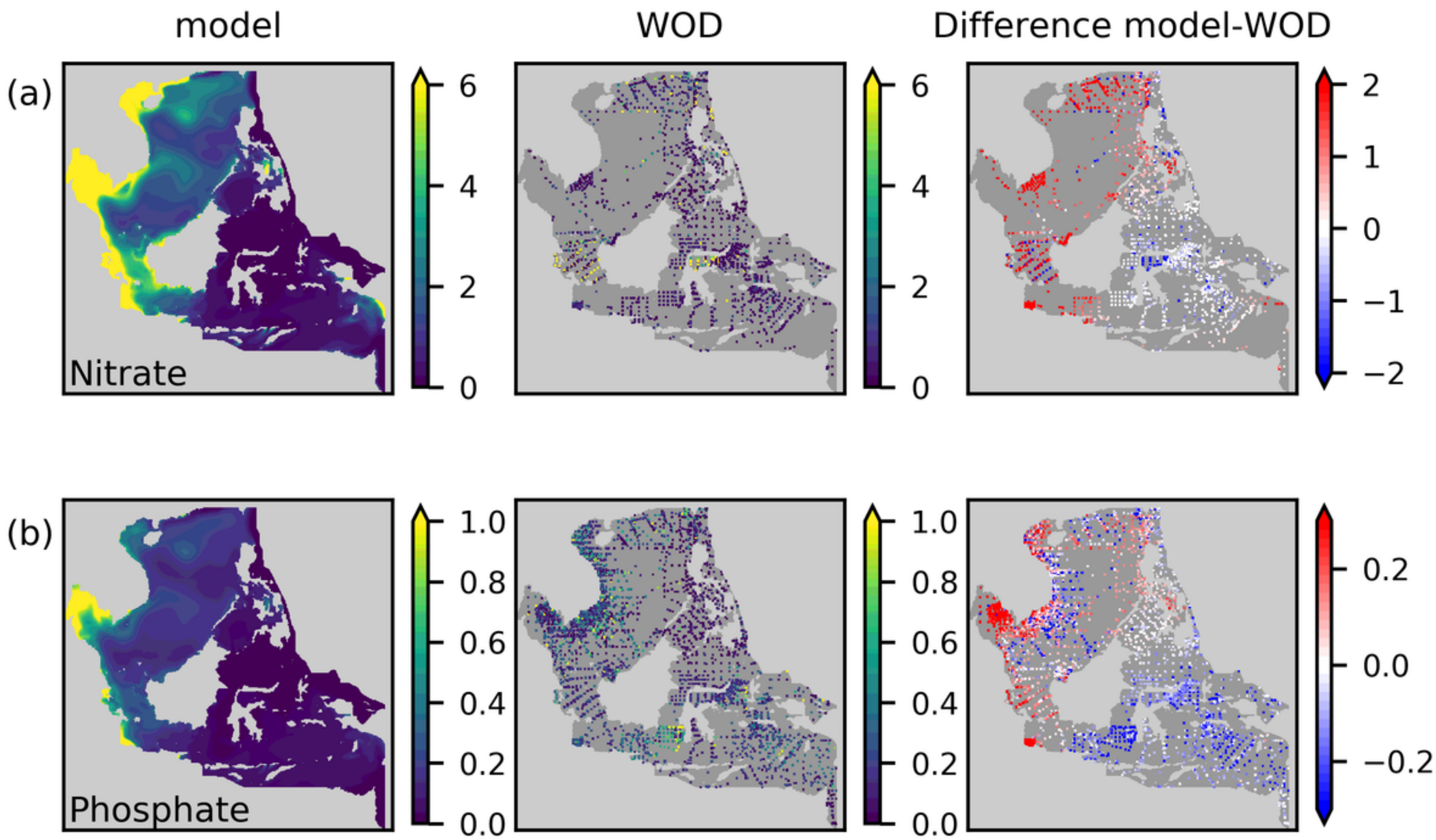
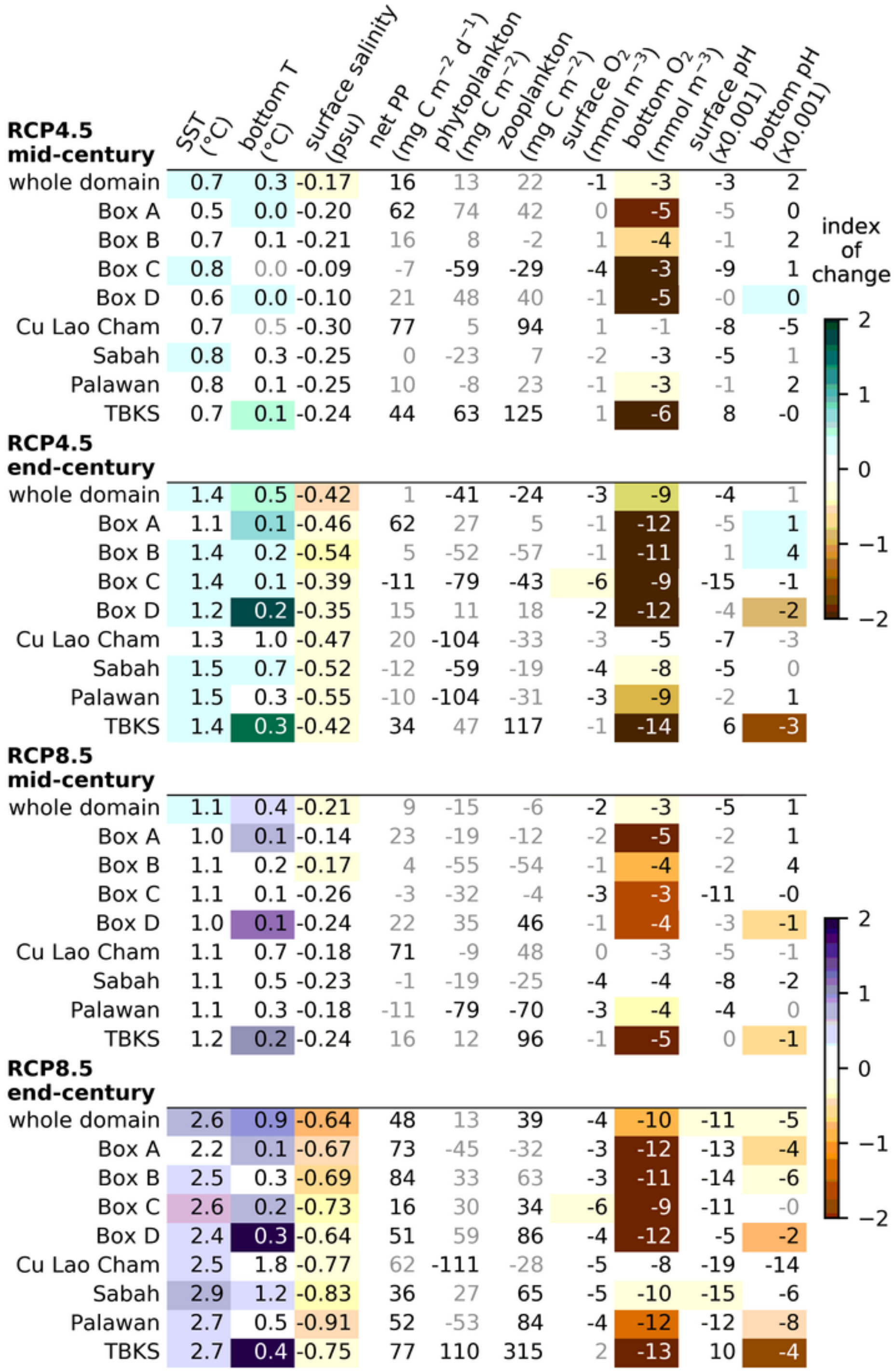


Figure 4

Comparison of modelled values of (a) surface nitrate and (b) surface phosphate concentration to in situ observations from the World Ocean Database. All values are in mmol m-3. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.



	SST (°C)	bottom T (°C)	surface salinity (psu)	net PP ($mg\ C\ m^{-2}\ d^{-1}$)	phytoplankton ($mg\ C\ m^{-2}$)	zooplankton ($mg\ C\ m^{-2}$)	surface O_2 ($mmol\ m^{-3}$)	bottom O_2 ($mmol\ m^{-3}$)	surface pH (x0.001)	bottom pH (x0.001)
RCP4.5 mid-century										
whole domain	0.7	0.3	-0.17	16	13	22	-1	-3	-3	2
Box A	0.5	0.0	-0.20	62	74	42	0	-5	-5	0
Box B	0.7	0.1	-0.21	16	8	-2	1	-4	-1	2
Box C	0.8	0.0	-0.09	-7	-59	-29	-4	-3	-9	1
Box D	0.6	0.0	-0.10	21	48	40	-1	-5	-0	0
Cu Lao Cham	0.7	0.5	-0.30	77	5	94	1	-1	-8	-5
Sabah	0.8	0.3	-0.25	0	-23	7	-2	-3	-5	1
Palawan	0.8	0.1	-0.25	10	-8	23	-1	-3	-1	2
TBKS	0.7	0.1	-0.24	44	63	125	1	-6	8	-0
RCP4.5 end-century										
whole domain	1.4	0.5	-0.42	1	-41	-24	-3	-9	-4	1
Box A	1.1	0.1	-0.46	62	27	5	-1	-12	-5	1
Box B	1.4	0.2	-0.54	5	-52	-57	-1	-11	1	4
Box C	1.4	0.1	-0.39	-11	-79	-43	-6	-9	-15	-1
Box D	1.2	0.2	-0.35	15	11	18	-2	-12	-4	-2
Cu Lao Cham	1.3	1.0	-0.47	20	-104	-33	-3	-5	-7	-3
Sabah	1.5	0.7	-0.52	-12	-59	-19	-4	-8	-5	0
Palawan	1.5	0.3	-0.55	-10	-104	-31	-3	-9	-2	1
TBKS	1.4	0.3	-0.42	34	47	117	-1	-14	6	-3
RCP8.5 mid-century										
whole domain	1.1	0.4	-0.21	9	-15	-6	-2	-3	-5	1
Box A	1.0	0.1	-0.14	23	-19	-12	-2	-5	-2	1
Box B	1.1	0.2	-0.17	4	-55	-54	-1	-4	-2	4
Box C	1.1	0.1	-0.26	-3	-32	-4	-3	-3	-11	-0
Box D	1.0	0.1	-0.24	22	35	46	-1	-4	-3	-1
Cu Lao Cham	1.1	0.7	-0.18	71	-9	48	0	-3	-5	-1
Sabah	1.1	0.5	-0.23	-1	-19	-25	-4	-4	-8	-2
Palawan	1.1	0.3	-0.18	-11	-79	-70	-3	-4	-4	0
TBKS	1.2	0.2	-0.24	16	12	96	-1	-5	0	-1
RCP8.5 end-century										
whole domain	2.6	0.9	-0.64	48	13	39	-4	-10	-11	-5
Box A	2.2	0.1	-0.67	73	-45	-32	-3	-12	-13	-4
Box B	2.5	0.3	-0.69	84	33	63	-3	-11	-14	-6
Box C	2.6	0.2	-0.73	16	30	34	-6	-9	-11	-0
Box D	2.4	0.3	-0.64	51	59	86	-4	-12	-5	-2
Cu Lao Cham	2.5	1.8	-0.77	62	-111	-28	-5	-8	-19	-14
Sabah	2.9	1.2	-0.83	36	27	65	-5	-10	-15	-6
Palawan	2.7	0.5	-0.91	52	-53	84	-4	-12	-12	-8
TBKS	2.7	0.4	-0.75	77	110	315	2	-13	10	-4

Figure 5

Summary of projected change in selected variables under RCP4.5 and RCP8.5, for the whole domain and sample regions. Mid-century change is for 2040-2059 compared to 2000-2019, end-century change is 2079-2098 compared to 2000 to 2019. Values for primary production, phytoplankton and zooplankton are totals for the water column. Text in grey means the change is not statistically significant. The index of change shows how large the change is compared to the present-day range. See Figure 1 for the locations of the regions.

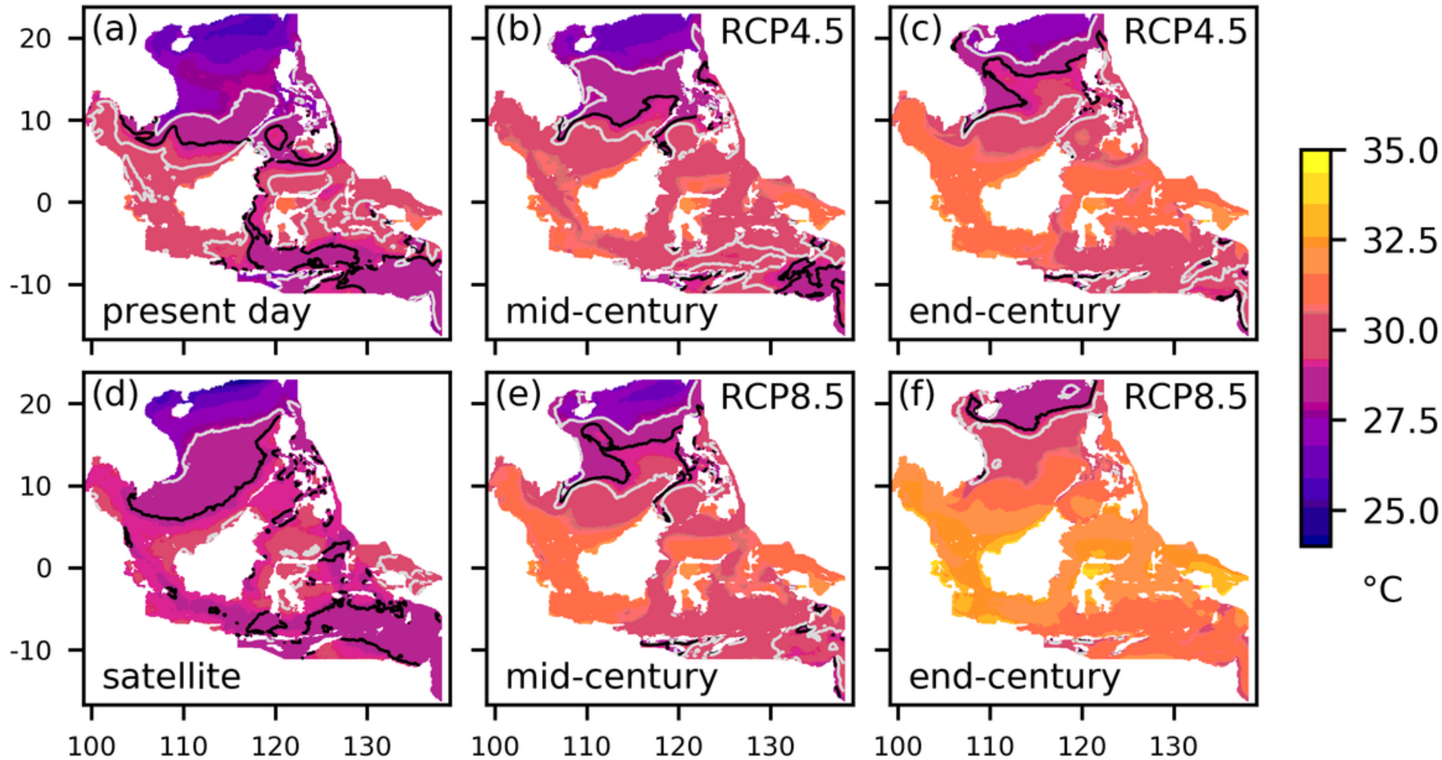


Figure 6

Sea surface temperature: (a) modelled and (d) observed for 2000-2019; (b,e) projected for 2040-2059 under RCP4.5 and RCP8.5; (c,f) projected for 2079-2098. The black contour shows the median for the present-day period, the grey contours show the 25th and 75th percentiles. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

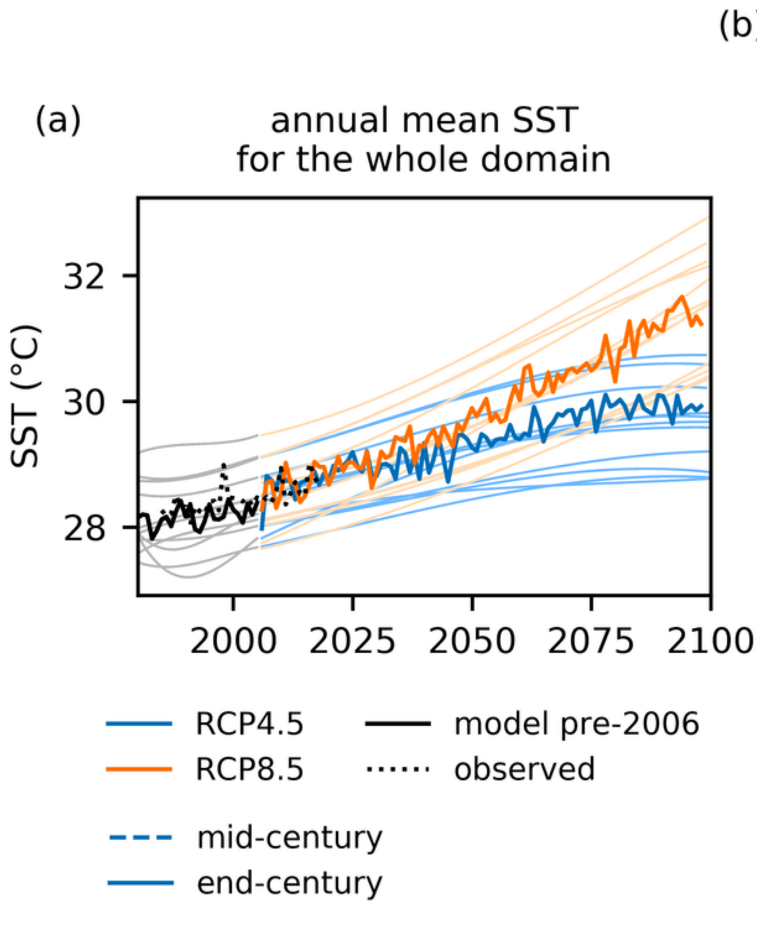


Figure 7

(a) Annual mean sea surface temperature averaged for the whole domain. The observed values are from the satellite-based OSTIA product. The fainter lines show smoothed trends from a number of CMIP5 global climate models. (b) Projected change in monthly mean sea surface temperature for 8 sample regions, for mid-century (dashed lines) and end-century (solid lines) compared to the present day. The time periods are 2000-2019, 2040-2059 and 2079-2098. See Figure 1 for region locations.

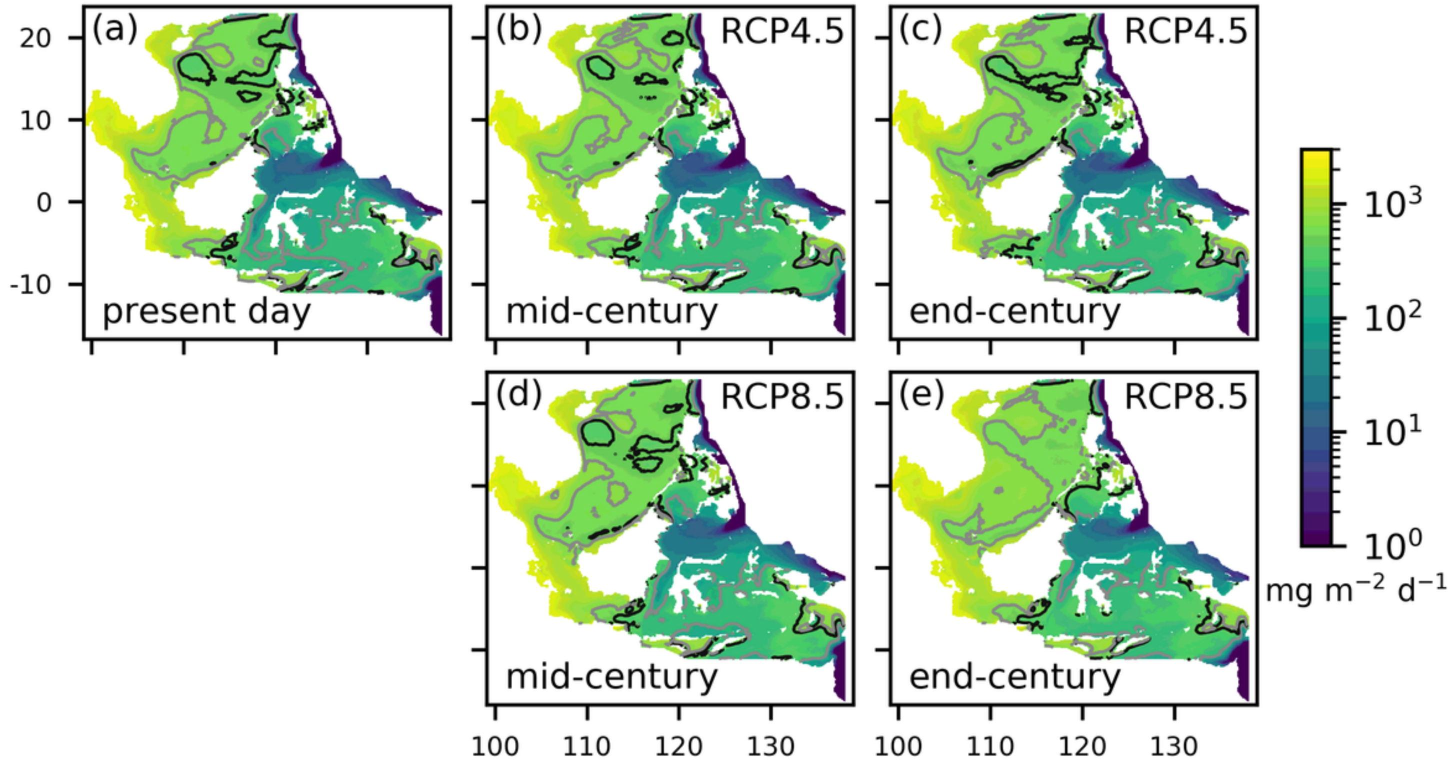


Figure 8

Column total net primary production: (a) modelled for 2000-2019; (b,d) projected for 2040-2059 under RCP4.5 and RCP8.5; (c,e) projected for 2079-2098. The black contour shows the median for the present-day period, the grey contours show the 25th and 75th percentiles. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

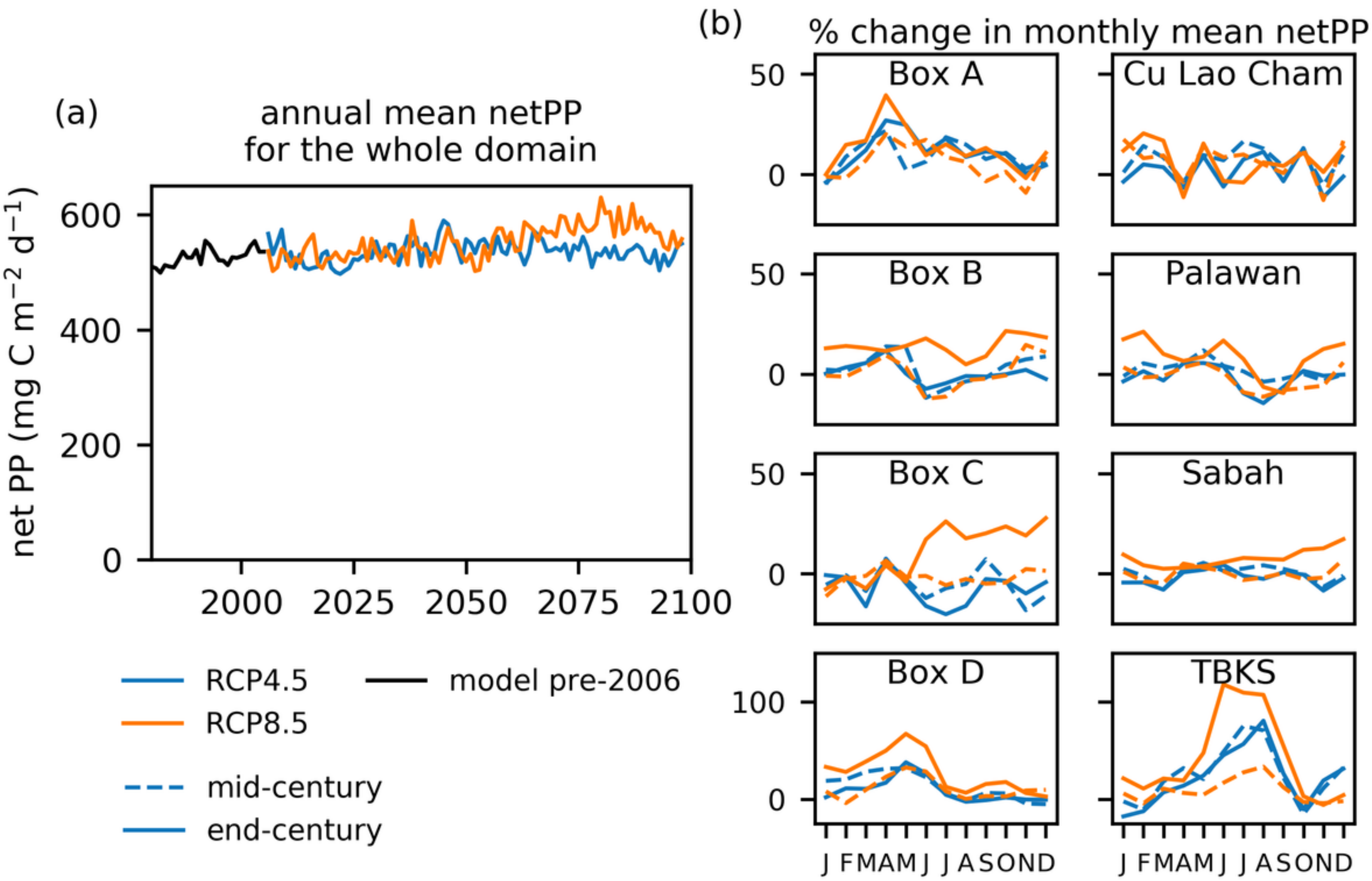


Figure 9

(a) Annual mean column total net primary production averaged for the whole domain. (b) Projected change in monthly mean column total net primary production for 8 sample regions, for mid-century (dashed lines) and end-century (solid lines) compared to the present day. The time periods are 2000-2019, 2040-2059 and 2079-2098. See Figure 1 for region locations.

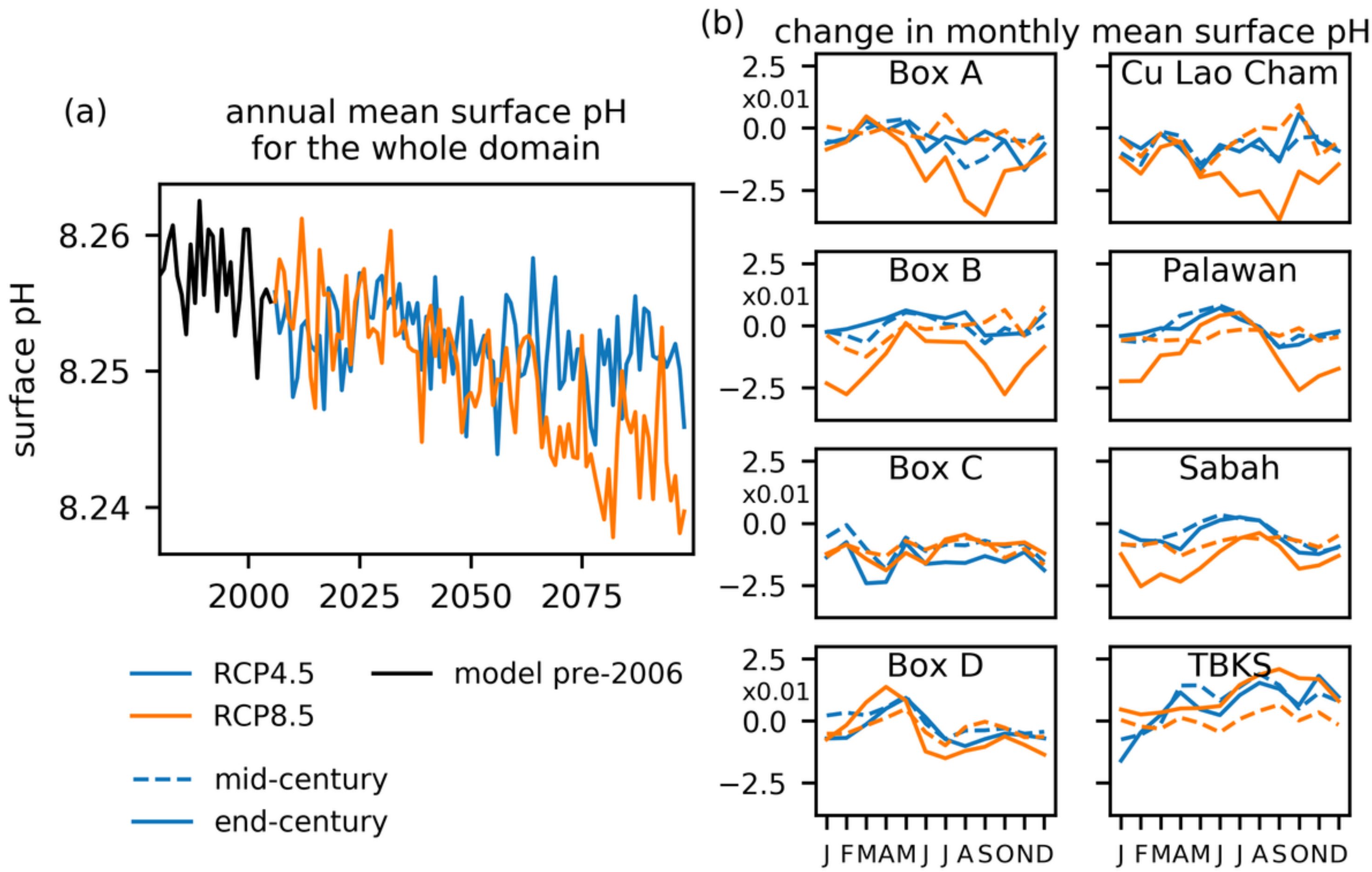


Figure 10

(a) Annual mean sea surface pH averaged for the whole domain. (b) Projected change in monthly mean surface pH for 8 sample regions, for mid-century (dashed lines) and end-century (solid lines) compared to the present day. The time periods are 2000-2019, 2040-2059 and 2079-2098. See Figure 1 for region locations.

Supplementary Files

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