
Differential vulnerability to climate change yields novel deep-reef communities

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Abstract :

The effects of climate-driven ocean change on reef habitat-forming species are diverse(1,2) and can be deleterious to the structure and functioning of seafloor communities(3-5). Although responses of shallow coral- or seaweed-based reef communities to environmental changes are a focus of ecological research in the coastal zone(1,4-6), the ecology of habitat-forming organisms on deeper mesophotic reefs remains poorly known. These reefs are typically highly biodiverses(7,8) and productive as a result of massive nutrient recycling(9). Based on seafloor imagery obtained from an autonomous underwater vehicle(8), we related change in community composition on deep reefs (30-90 m) across a latitudinal gradient (25-45 degrees S) in southeastern Australia to high-resolution environmental and oceanographic data, and predicted future changes using downscaled climate change projections for the 2060s(10-12). This region is recognized as a global hotspot for ocean warming(13). The models show an overall tropicalization trend in these deep temperate reef communities, but different functional groups associate differentially to environmental drivers and display a diversity of responses to projected ocean change. We predict the emergence of novel deep-reef assemblages by the 2060s that have no counterpart on reefs today, which is likely to underpin shifts in biodiversity and ecosystem functioning.

38 Climate-induced decay of coral colonies in the tropics⁶ or regional
39 decline^{14, 15} of kelp beds in temperate latitudes^{3, 4, 5} can precipitate community-
40 wide consequences for reef ecosystems and fisheries that are difficult to reverse^{3,}
41 ^{4, 16}. However, while community-level responses to climate-driven ocean change
42 on shallow (< 30 m depth) habitat-forming reef species are well studied and are
43 to some extent predictable^{6, 16}, the biogeography and ecology of habitat-forming
44 species on deep reefs are poorly understood. We refer here to ‘deep reefs’ as the
45 benthic communities on hard substratum in the mesophotic zone (30-90 m
46 depth), where low light limits photosynthetic activity. Similar to their shallow
47 counterparts (e.g. corals, kelps), habitat-forming organisms are also important to
48 the structure¹⁷ and functioning^{18, 19} of deep reef communities, which support
49 high biodiversity⁸ and valuable commercial species^{20, 21}. For example, large
50 suspension feeders such as sponges provide habitat structure and can dominate
51 benthic-pelagic coupling and benthic production via recycling of nutrients and
52 organic matter^{9, 18, 22}. However, despite the acknowledged importance of these
53 deep reef communities, there is limited understanding of how they will respond
54 to climate-driven ocean changes.

55

56 Here we assess the vulnerability of ‘deep’ sessile invertebrate
57 communities to environmental change on mesophotic continental shelf reefs
58 (30-90 m) from subtropical to temperate latitudes (25-45°S) in eastern Australia.
59 This region is recognised as a global hotspot for ocean warming¹³, and
60 downscaled projections for 2060 indicate substantial ongoing warming (Fig. 1).
61 For instance, surface temperatures are projected to increase by >1.2°C above
62 current annual means in the whole region with higher rates of warming expected

63 at lower latitudes (Fig. 1). We relate the present distribution of major benthic
64 functional groups to ocean environmental variables, and predict the range
65 contractions and extensions of each group in response to projected changes
66 associated with the increased southwards incursion of the tropical, nutrient-
67 poor East Australian Current for the 2060s. The projected range shifts in
68 individual functional groups are then combined to assess shifts in deep reef
69 community structure (and, by implication, ecosystem functioning) in the
70 anticipated future climate.

71

72 We developed distribution models using random forests relating (i)
73 presence/absence of 13 major functional groups across the full latitudinal range
74 of temperate eastern Australia⁷ derived from seafloor imagery at 44 independent
75 reef locations to (ii) environmental covariates of bathymetry, seafloor features,
76 and oceanographic and biogeochemical conditions for which regionally-
77 downscaled projections are available for the 2060s¹⁰ (see Fig. A2 in SI). The 13
78 functional groups (Fig. 2), which each corresponds to a variety of similar
79 species⁷, are defined based on the morphological and phyletic features of the
80 organisms recognisable from seafloor imagery²³. They include large habitat-
81 formers that are the typical dominant groups at these depths in the region (e.g.
82 sponges, ascidians, bryozoans, gorgonians and octocorals), but also rarer
83 morphotypes such as black corals⁷. Hence, while our ecological dataset does not
84 comprehensively capture community diversity at the species level, it is unique in
85 providing the first consistent quantitative survey of deep reef community
86 composition across a large latitudinal range spanning subtropical to temperate
87 latitudes⁷. Seafloor features considered were reef complexity (hereafter relief),

88 seafloor slope, and aspect. The oceanographic and biogeochemical variables
89 included were temperature (mean, variance, skewness, minimum and
90 maximum), primary production, salinity, and nitrate concentration. We used
91 random forests (i) to model the probability of presence of each functional group
92 across the latitudinal gradient based on these environmental features and; (ii) to
93 predict climate-driven shifts in their distribution based on projected changes by
94 2060¹².

95
96 Model predictions of present-day distributions proved reliable to
97 characterise the large-scale latitudinal range of each of the 13 functional groups,
98 and indicate four broad types of biogeographic distribution across the latitudinal
99 gradient (Fig. 1 and 3; Fig. A17 in SI). Fig. 3 illustrates that the models identify
100 functional groups that manifest truncated distributions limited to (1) subtropical
101 (e.g. octocorals - Fig. 3A; rigid gorgonians, black corals – Fig. A17 in SI), (2)
102 warm temperate (e.g. ascidians; Fig. 3B), or (3) cold temperate (e.g. ball sponges
103 - Fig. 3C; massive form sponges, soft gorgonians – Fig. A17 in SI) latitudes; and,
104 (4) those that occur, either sparsely or abundantly, across the entire latitudinal
105 gradient of the study (e.g. branching sponges - Fig. 3D; bryozoans and cup,
106 tubular, laminar and palmate sponges – Fig. A17 in SI). These four groups
107 depicted in Fig. 3, in particular the former three that are characteristic of the
108 three dominant community types in the region⁷, display strong biogeographical
109 responses to projected ocean changes. Local-scale predictions for a few broadly
110 distributed and locally sparse groups, such as tubular sponges, should be
111 interpreted with caution, but overall predicted present-day latitudinal ranges
112 show good agreement with available observational data (Fig. 3, SI Fig. A17);

113 More importantly, when combined together, predictions capture the observed
114 gradient in community structure across the survey sites (Fig. 4). Importantly, the
115 modelled presence/absence of each functional group relates to a unique
116 combination of environmental covariates (Fig. 2), which suggests diverse
117 ecologies and biogeographies across all groups and raises the possibility of
118 diverse responses to environmental change. For example, the Tasmanian-bound
119 distribution of cold-temperate groups (e.g. massive and ball-shaped sponges) is
120 constrained by large-scale oceanographic variables such as ocean temperature
121 and salinity (Fig. 3); **Conversely**, the modelled occurrence of widely distributed
122 cup sponges relates to local-scale reef features of depth, seafloor relief and slope
123 **as well as larger-scale oceanographic variables** (e.g. temperature skewness) (Fig.
124 **2**). **Overall, the distribution of most of the 13 functional groups is primarily**
125 **related to ocean temperature (mean, variance, minimum and/or maximum) (Fig.**
126 **2), which suggests a certain sensitivity of present-day biogeographic patterns to**
127 **ongoing²⁴ and future²⁵ regional warming of coastal waters.**

128

129 Given that the distribution of different functional groups relates
130 differentially to environmental variables (Fig. 2), it is not surprising that
131 biogeographic responses to projected climate-driven ocean warming are diverse
132 (Fig. 3). Nonetheless, broad patterns emerge in the predicted redistribution of
133 invertebrate functional groups on these deep reefs by the 2060s (Fig. 3).
134 Subtropical groups, such as octocorals, currently restricted to the northern edge
135 of the study area (~ 25-30°S), are likely to extend their range poleward in
136 response to ocean warming (Fig. 3A). Most functional groups restricted to warm
137 temperate regions are predicted to contract their northern range boundary,

138 while the southward extension of their distribution to higher temperate latitudes
139 (> 40°S) is limited (e.g. ascidians; Fig. 3B). For most of the cold-bound habitat-
140 forming functional groups (Fig. 3C), a large southwards range contraction is
141 predicted by the 2060s and the south coast of Tasmania provides the last refuge
142 against ocean warming, i.e. there is no further continental shelf habitat to the
143 south to which these groups and species can move. For those populations
144 currently distributed across the whole study area (Fig. 3D), present-day regional
145 environmental suitability is expected to decline by the 2060s by 3% - 26% (for
146 cup sponges and bryozoans, respectively). These widely-distributed groups (e.g.
147 branching, laminar and hollow cup sponges) overall appear more resilient than
148 temperate groups to [projected ocean changes](#) (Fig. A17), [as regional warming](#)
149 [may only induce slight poleward contractions of their subtropical boundaries](#).
150 This is consistent with existing studies on mobile fish species and other marine
151 fauna^{26, 27, 28}.

152

153 The combination of the projected range shifts across all functional groups
154 under future climate-driven ocean change suggests the emergence of novel deep
155 reef assemblages (Fig. 4). AUV surveys characterise north-south transitions
156 between three main community types (i.e. subtropical, warm and cold
157 temperate)⁷, which are captured accurately in the model predictions across this
158 latitudinal gradient for the present time (blue symbols and shaded ellipses on
159 PCA; Fig. 4). Consistent with ongoing and anticipated ecological changes on
160 shallow reefs in the region^{27, 28, 29}, the predicted changes in deep reef community
161 structure by the 2060s suggest an overall 'tropicalisation' (red symbols and
162 transparent ellipses on PCA; Fig. 4). The subtropical groups are predicted to

163 extend to intermediate latitudes ($\sim 32\text{-}35^\circ\text{S}$), the warm temperate groups are
164 expected to dominate community structure south of 35°S , while the occurrence
165 of cold-bound invertebrates decline at the higher latitudes ($\sim 40^\circ\text{S}$). It is
166 particularly important that model predictions also highlight that climate-driven
167 range shifts are likely to lead to novel assemblages as a result of differential
168 responses by different functional groups. For example, by the 2060s, a mix of
169 cold-water invertebrates (e.g. massive sponges) and range-extending warm
170 temperate organisms (e.g. ascidians; Fig. 4) are predicted to dominate reef
171 communities in northeastern Tasmania ($\sim 40^\circ\text{S}$). As multiple simultaneous range
172 shifts can have complex, hard-to-reverse effects on regional ecosystem
173 dynamics^{16, 28}, it is difficult to anticipate the precise ecological consequences of
174 these broad changes in the structure of deep reef communities. However, given
175 the central contribution of sessile organisms to deep reef ecosystem dynamics^{18,}
176 ¹⁹ and benthic-pelagic coupling^{9, 18, 22}, the predicted emergence of novel
177 invertebrate assemblages, which have no counterpart on the continental shelf
178 today, can be expected to also significantly modify functioning of benthic
179 communities³⁰. Changes in the productivity of benthic communities, which
180 support valuable commercial species, can be expected given that organic matter
181 recycling relies on the diversity and identity of seafloor suspension-feeding
182 communities^{19, 30}. Note that our results are based on combining statistical
183 distribution models across individual groups additively and do not account for
184 ecological interactions or species traits, which may further facilitate dramatic
185 shifts in community dynamics²⁷.
186

187 Seafloor communities are often portrayed as threatened by the long-
188 lasting impacts of physical disturbances, such as bottom trawling³¹. However,
189 similarly to terrestrial³², freshwater³³ or shallow marine²⁸ ecosystems where
190 novel ecological assemblages emerge as a result of shifts in regional climates³⁴,
191 deeper marine ecosystems are also likely to be significantly impacted by climate-
192 driven environmental changes^{35, 36}. As the ecological and/or physiological
193 knowledge required to develop a deterministic understanding of deep reef
194 community responses to climate-driven changes in ocean biogeochemistry (via
195 altered regional ocean circulation) is currently limited, our results provide a
196 valuable first insight of anticipated shifts in deep reef community structure due
197 to changes in ocean climate and particularly warming. With the emergence of
198 novel underwater sampling technologies over recent decades³⁷, there is potential
199 to monitor trends and changes in deep reef assemblages^{38, 39}, although in most
200 areas worldwide this kind of work is, at best, just beginning. Climate-driven
201 changes in deep reef ecosystems remain largely understudied relative to
202 terrestrial and coastal ecosystems, although new initiatives are attempting to
203 overcome the challenges of managing climate change impacts on deeper
204 communities in a data-poor context³⁶. While coastal reef research investment
205 and associated management effort is gradually expanding for some temperate
206 seaweed-based communities⁴⁰, our study highlights the crucial need to better
207 understand and monitor the deep reef communities pivotal to benthic ecosystem
208 diversity and productivity in temperate areas. Structural shifts in these
209 communities in response to climate change will be mediated by ecological
210 processes³ and species traits²⁷, and may have dramatic consequences for benthic
211 productivity and other aspects of ecosystem functioning. Developing

212 understanding of the physiological and ecological mechanisms that underpin
213 deep reef communities dynamics will be critical to confirm our findings, assess
214 their generality, and to adequately manage these ecosystems that appear
215 sensitive to climate-driven changes³⁶.

216

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233

234

235 **AUTHOR CONTRIBUTIONS:** All authors provided comments on the paper. MPM
236 led the research, performed the analyses and wrote the paper. ECJ provided the

237 oceanographic datasets and downscaled climate projections for the 2060s. LJ
238 analysed the seafloor imagery and consolidated the ecological dataset. SJW
239 provided guidance about statistical modelling techniques. CRJ, NSB and NJH
240 conceived the project and provided guidance in the conduct of the research.

241

242 **COMPETING FINANCIAL INTERESTS:** All authors declare no competing
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244

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413

414 MATERIAL AND METHODS

415 Study area

416 South-east Australia is a global hotspot for climate-driven ocean warming (Fig.
417 1A)¹³, where shallow temperate reef communities have been affected by rapid
418 changes in ocean conditions¹⁶ related to an increase southwards penetration of
419 the East Australian Current²⁴.

420

421 Ecological data

422 Presence and absence of 13 key habitat-forming functional groups, including
423 sponges, ascidians, bryozoans and cnidarians, were derived from ~1,800
424 seafloor images obtained from the Integrated Marine Observing System (IMOS)
425 autonomous underwater vehicle (AUV) *Sirius* between 2010 and 2013^{7, 37}. See
426 Fig. 1 for example images. Each image was scored using the standardised
427 CATAMI classification²³. Sampling occurred at depths ranging from 30 to 90 m
428 following a hierarchical design: 7 out of the 8 marine bioregions identified across
429 the eastern seaboard of Australia were surveyed from subtropical southern
430 Queensland (25°S) to temperate southern Tasmania (45°S) (Fig. 3). Individual
431 sites may be difficult to distinguish on Fig. 3, but given that they are >10s km
432 apart they constitute independent replicates and provide an assessment of local-
433 scale variability within any given bioregion⁷. Within each survey site, several
434 transects, which are 100s m apart, form the basis of our dataset. Note that
435 hierarchical sampling efforts are comparable across survey sites so our data set
436 is overall homogeneous across regions: each bioregion includes 3-5 sites; each
437 site 3-6 transects, for which there are at least 10 images each covering ~2m². We
438 based our analysis on presence/absence data of the 13 groups derived from

439 aggregating scored images (Fig. 1B-D) along 120 transects from a total of 44
440 independent reef sites (see SI). Reef habitat was surveyed at the scale of 100 m
441 by 100 m at each of these sites and images were sampled along the AUV transect
442 using a geostatified sampling design. We recognise some limitations of the
443 image-based dataset, specifically: (i) IMOS regular AUV monitoring sites are not
444 evenly distributed across the region (Fig. 1A); due to time-consuming image
445 scoring (ii) a set list of targeted easy-to-recognise benthic functional groups
446 (rather than total community diversity) was identified (iii) on a subset of
447 available imagery at each site (rather than all available images). Nonetheless, our
448 ecological dataset is unique as it provides the first systematic quantitative survey
449 of deep reef community composition across a large latitudinal range spanning
450 subtropical to temperate latitudes⁷. The description of seafloor communities
451 based on broad functional groups (i.e. using the CATAMI seafloor imagery
452 annotation scheme⁷) reliably characterises current latitudinal changes in deep
453 reef community structure⁷.

454

455 **Environmental data**

456 To characterise the environmental niche of each group, we considered a range of
457 environmental covariates related to seafloor features (depth, relief, slope,
458 aspect), sea surface temperature (SST; mean, variance, skewness, minimum and
459 maximum), and biogeochemical conditions (mean salinity, nitrate concentration,
460 and phytoplankton concentration as a proxy for primary production) for which
461 high resolution projections through the 2060s were available^{10,11,12} (See SI Fig.
462 A2). Note that temperature-depth profiles through the water column suggest
463 high mixing on the continental shelf, which legitimises the use of SST as a proxy

464 for bottom temperature⁴¹ (See SI Fig. A1). Ocean variables are derived from
465 available 9-year time series for the 1990s and 2060s, and projections through
466 the 2060s are based on dynamically downscaled ocean climate change
467 projections from a coupled climate model taking account of CO₂ increases
468 according to the IPCC AR4 'business as usual' A1B scenario^{11, 12}. Mean SST was
469 further statistically downscaled to the coast⁴² while the other variables were
470 taken directly from the high-resolution ocean dynamical model^{11, 12}. We do not
471 account for the long-term effects of ocean acidification, which might further alter
472 community structure by impacting pH-sensitive groups (e.g. calcifying
473 octocorals, or sponges with limited acid-base regulation capacities)⁴³. However,
474 our predictions capture the effects of coastal ocean warming, which is expected
475 to be a major signature of climate-driven changes in the next decades in the
476 region²⁵.

477

478 **Analyses**

479 *Distribution Modelling and prediction of climate-driven range shifts.* We compared
480 the alternative statistical modelling techniques of bootstrapped-aggregated
481 binomial generalised linear models (GLMs), bootstrapped-aggregated binomial
482 generalised additive models (GAMs), and Random Forests, which all performed
483 consistently and provided similar results. However, across all groups the
484 Random Forest models were more accurate based on cross-validation, hence we
485 only present results based on Random Forests here (see SI for details).
486 Following sensitivity analyses on Random Forest parameters (i.e. forest size,
487 depth of the trees), all models presented here rely on aggregating 500 individual
488 classification trees grown on bootstrapped samples of the ecological data using

489 random selection of features to split each node, up to a maximum of 4 levels of
490 branching. Thus, the number of nodes per tree varied from 2 to 16, with a mean
491 of 7 (+/- 2.5 standard deviation). Model performance was assessed based on
492 cross-validation using bootstrapping (i.e. subsampling of the data into 2 sets for
493 model training and testing, respectively). Misclassification error rate, which
494 accounts for both false positives and false negatives, was 16% (mean across all
495 groups) and varied from ~2% for octocorals to ~33% for laminar sponges (see
496 SI section 2). The accuracy of models varied from 'excellent' (see SI Fig. A3 and
497 Table A1), to 'fair' for the few functional groups that occurred across the entire
498 latitudinal range but were not detected at successive survey sites, either due to
499 local environmental conditions (not captured in our predictors) or their low
500 detectability (related to their sparse occurrence and/or the random sampling
501 design). Despite some inaccuracy in local-scale prediction for these groups,
502 Random Forests meaningfully characterised the broad latitudinal distribution of
503 the 13 functional groups (Fig. 3; see also SI Fig. A17). Models fits, predictions,
504 and permutation-based accuracy indices (Figs. 2-4) were implemented in R's
505 Random Forest package⁴⁴. Statistical modelling of the distribution of major deep
506 reef habitat-formers across space and time has limitations, including that model
507 predictions do not explicitly account for ecologically- or physiologically-
508 mediated responses to ocean changes^{16, 27}. However, in a data-poor context, in
509 particular given the lack of mechanistic understanding of the ecological
510 processes driving the ecological dynamics of these deep reef communities,
511 statistical distribution modelling with Random Forests provides unique first
512 insights on potential deep reef community responses to climate-driven ocean
513 warming across the broad latitudinal gradient considered in our study. Our

514 models predict, in a consistent manner, both the current and 2060
515 biogeographical ranges of each functional group so we can interpret increase
516 and/or decrease in predicted probabilities of presence [at large scales](#) as range
517 extensions and/or contractions, respectively (Fig. 3; SI Fig. A17). Only at the edge
518 of our study domain (i.e. in the northernmost subtropical areas), where limited
519 data were used to train the models, predicted changes need to be interpreted
520 with caution. In addition to commenting on predicted climate-driven changes in
521 the leading and trailing edges of population ranges, we also characterise
522 latitudinal shifts in the core distribution of each group by tracking the latitudinal
523 change between 2010 and 2060 in the median and the maximum probability of
524 presence integrated across depth (Fig. 3; SI Fig. A18).

525

526 *Principal Component Analysis (PCA) and prediction of changes in community*
527 *structure.* To describe large-scale changes in the community structure of deep
528 reef assemblages, we performed a PCA on the predicted current and future
529 probability of presence of each of the 13 functional groups at 15 monitoring sites
530 (Fig. 4). Error bars represent the 95% confidence intervals of the PC scores, and
531 were derived from Monte-Carlo sampling (100 samples) of current and future
532 community structure as characterised by predicted probabilities of presence
533 across the 13 functional groups. Predicted climate-driven changes across the
534 different groups translate into regional changes in functional diversity; The
535 probability of occurrence of the different functional groups is predicted to
536 change locally (and in certain region go from present to absent; or conversely),
537 which implies significant shifts in community composition and emergence of
538 assemblages that do not resemble any of the currently described community

539 types (Fig. 4). These predicted changes in community structure are largely
540 related to differential vulnerability of region-characteristic groups, which are
541 likely to display responses similar to other sessile benthic taxa that share similar
542 environmental niches but were not considered in our study. While our current
543 understanding of the different groups' ecology is limited, we can nevertheless by
544 definition, expect changes in ecosystem functioning if there is a major change in
545 functional diversity. A number of functional traits, which differ across the
546 different groups, have direct implications for ecosystem functioning, such as
547 nutrient recycling and provision of shelter via formation of complex three-
548 dimensional habitat. Filter feeding rates are likely to vary across the different
549 functional groups but apart for sponges⁹, there is limited quantitative
550 information about organic matter and nutrient recycling functions filled by the
551 different functional groups. Moreover, complex interactions between the
552 different functional groups are likely to contribute to overall ecosystem
553 functioning (e.g. synergy between cold-water corals and sponges)⁴⁵. Another
554 important function associated with the different groups relates to their different
555 abilities to form complex biogenic habitats, which has direct implications in
556 terms of shelter from predation for the macro- and megafauna⁴⁶.

557

558 **Supplementary Information** This document provides technical details
559 concerning the distribution models, specifically concerning: environmental
560 covariates; random forest model fits; projections of current and 2060s
561 distributions for all groups; and projected change in latitudinal distributions.

562

563 **Data Availability** The ecological dataset derived from AUV imagery is
564 extensively described⁷. All environmental datasets are available from public
565 sources as referenced above. Estimates of ecological and environmental
566 variables associated with each transect, and which were used to fit the random
567 forest models, are provided as online supplementary material. All the data that
568 support the findings of this study, including R scripts, are available from the
569 corresponding author upon request.

570

571 **METHODS-ONLY REFERENCES**

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596

597

598 **FIGURE LEGENDS**

599

600 Figure 1. (a) Predicted warming in mean sea surface temperature between the
601 1990s and 2060s of up to ~ 2 °C confirms the region as a global ‘hotspot’, and
602 shows that the absolute magnitude of warming is expected to be greater in the
603 subtropics than temperate regions. Survey sites where the autonomous
604 underwater vehicle collected seafloor imagery on multiple transects are shown
605 as open circles. AUV images show examples of organisms that are largely
606 restricted to particular regions, viz. (b) subtropical octocorals, (c) warm
607 temperate stalked solitary ascidians, and (d) cold temperate yellow ball sponges,
608 illustrating large-scale variability in sessile benthic communities. Each photo
609 covers $\sim 1.2 \times 1.4$ m of the seafloor. Credits: AUV *Sirius*, Australian Centre for
610 Field Robotics, University of Sydney.

611

612 Figure 2. Relative importance of environmental predictors (x-axis) to the
613 accuracy of random forest predictions reflects diverse relationships between the
614 occurrence of the 13 functional groups (y-axis) and environmental conditions.
615 ‘White’ symbolises no influence of predictor. The regional occurrence of certain
616 groups, such as soft gorgonians or bryozoans, associates with local seafloor
617 features (i.e. depth, slope, aspect and relief). Conversely, the overall distribution
618 of other groups, such as cold-bound massive or ball sponges, relates tightly to
619 regional-scale gradients in oceanographic conditions, e.g. sea surface
620 temperature characteristics. Abbreviated x-axis labels stand for: sea surface
621 temperature (‘Temp.’); variance (‘var.’); skewness (‘skew.’); maximum (‘max.’);
622 minimum (‘min.’); and, primary productivity (‘Prim. Prod.’).

623

624 Figure 3. Random Forest predictions of present-day distributions (1st column),
625 2060s distributions (2nd column), and the relative change in the probability of
626 presence (3rd column) indicate 4 broad types of range shift response across the
627 13 functional groups: (a) southwards range extension (e.g. subtropical
628 octocorals, rigid gorgonians, black corals); (b) retraction of northern range (e.g.
629 stalked solitary warm-temperate ascidians); (c) retraction of northern range (e.g.
630 cold-temperate ball sponges and massive sponges); and (d) marginal regional
631 decline (e.g. broadly distributed branching sponges, bryozoans, soft gorgonians,
632 hollow cup sponges, tubular sponges, palmate sponges, and laminar sponges).
633 The longitudinally-integrated latitudinal distributions (i.e. predicted probability
634 of presence) are shown in the 4th column for the present-day (black solid line)
635 and 2060s (red dashed line). The grey arrow reflects relative change in the
636 probability of presence across the entire study region; red and orange arrows
637 symbolise latitudinal shifts in, respectively, the median and the maximum of the
638 predicted distribution.

639

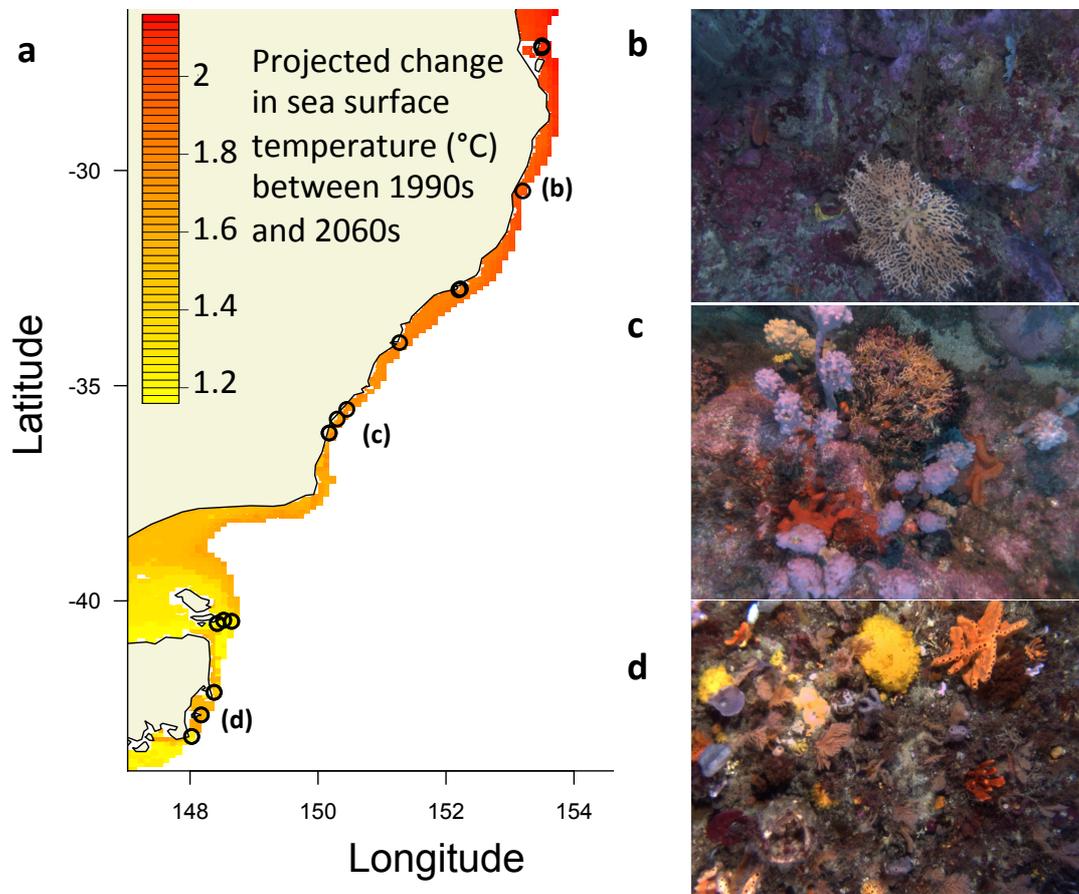
640 Figure 4. Predicted present-day (blue) and 2060s (red) community structures for
641 deep temperate reef communities in eastern Australia reveal the emergence of
642 novel ecological assemblages under projected climate-driven ocean changes.

643 Scores shown in principal components space correspond to rocky reef
644 community structure along a large latitudinal gradient (25-45°S) as
645 characterised by predicted probabilities of presence of 13 major functional
646 groups at the 15 regular AUV monitoring locations. Symbols and continuous lines
647 represent the north-south gradient in AUV monitoring sites from southern

648 Queensland (▲) to southeastern Tasmania (○). Error bars represent 95%
649 confidence intervals. Ellipses characterise shifts in community structure from
650 present-day (filled and solid lines) to future (dashed lines) assemblages
651 associated with cold temperate (blue), warm temperate (orange) and subtropical
652 (red) sites. The green circle overlay represents projected scores (>.3) of
653 individual groups (with associated pictures) onto the first and second principal
654 component axes, and identified as cold temperate, warm temperate, or
655 subtropical groups (colour coding as above).
656

657 **FIGURES**

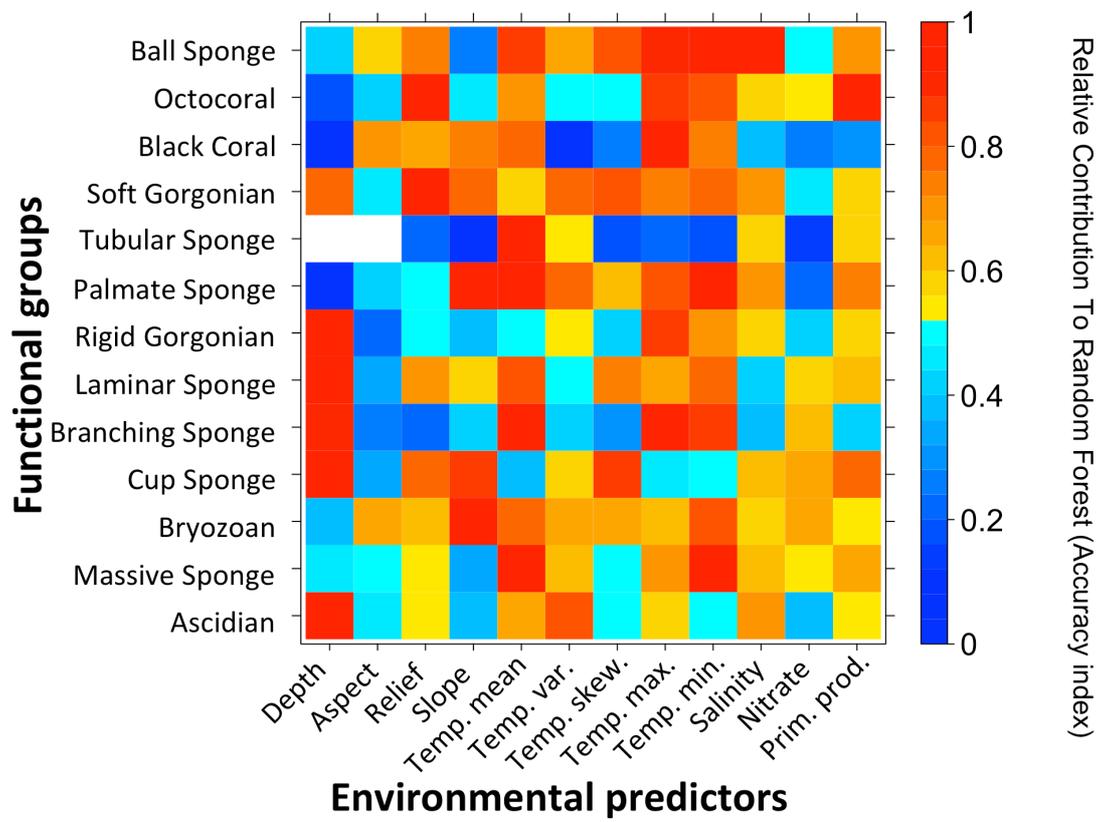
658 Fig. 1



659

660

661 Fig. 2



662

663

