

Geographic range shift responses to climate change by Antarctic benthos: where we should look

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Supplement 1. Testing whether hotspots are real or artefacts of sampling

INTRODUCTION

We hypothesised that most southern polar marine species would have southern geographic limits in the southern Weddell and Ross Seas, whilst many South American species would have limits at the southernmost tip of South America. Our second hypothesis was that hotspots of northernmost limits would be around the boundary of the Polar Front (PF), as this has always been found to be the biggest discontinuity in Antarctic fauna. Here, we suggest which species (amongst the taxa studied) are likely to represent the best models for monitoring change.

METHODS

The study area was continental shelf areas approximately south of 20° S. We evaluated the number and area coverage of records for different potential model taxa in the SOMBASE and SCAR-MarBIN databases. We divided the study area into a series of similar boxes, each 3 × 3 degrees of latitude and longitude, and then determined the number of boxes that contained records of each taxon and evaluated for geographic patterns of species range limit hotspots.

RESULTS AND DISCUSSION

Analysis of data from SOMBASE and SCARMarBIN revealed strong patterns in the number of records, richness and southern limits for our Southern Ocean study taxa. These are reported in the main paper together with relationships between the number of records and southernmost limits, and between species richness and the number of southernmost limits (for gastropod data). These showed that all gastropod data well above the 95% prediction intervals were in the

hotspots previously identified. Rarefaction curves for gastropod data from 4 example locations further showed that range limits increased with sampling, but accumulated 4 to 14 times faster in hotspots than in other 3 × 3 degree areas within the same regions (see Fig. S1). It is notable that numbers of range limits approached, or were at, asymptote at non-hotspot areas, whereas at 3 of the hotspots they did not approach asymptote. Thus despite significant relationships between gastropod range-limit data and those for both record and species numbers, there was strong support for the validity of all hotspots identified.

Patterns in other Southern Ocean study taxa also revealed hotspots. The number of records of species, numbers of species and numbers of southernmost limits of species for bivalve molluscs are shown in Figs. S2a–c respectively. This process was repeated for amphipod crustaceans to reveal records of species (Fig. S3a), numbers of species (Fig. S3b) and numbers of southernmost limits of species (Fig. S3c); for ophiuroid echinoderms (Figs. S4a–c) and hexacoral cnidarians (Figs. S5a–c). As with gastropods, for each of the taxa studied there were significant (Pearson) correlations between the number of range limits and species richness, and the number of records and species richness. The relationships for the bivalve molluscs, amphipods, ophiuroids and hexacorals are each shown in Fig. S6. In each plot there are a few points considerably above the 95% prediction intervals (red lines, Fig. S6) and in every case of each taxon these were the hotspots identified previously (shown in Fig. 4 of the main manuscript). It is clear that the residuals for hotspots are highly positive compared with other (non-hotspot) data, which in contrast lie within 95% prediction intervals. As southernmost range limit hotspots for Antarctic taxa were mainly around continent margins, it is argued that the greatest scope for monitoring change is by considering northernmost limits (reported in main manuscript). The validity of northernmost limits (e.g. at South

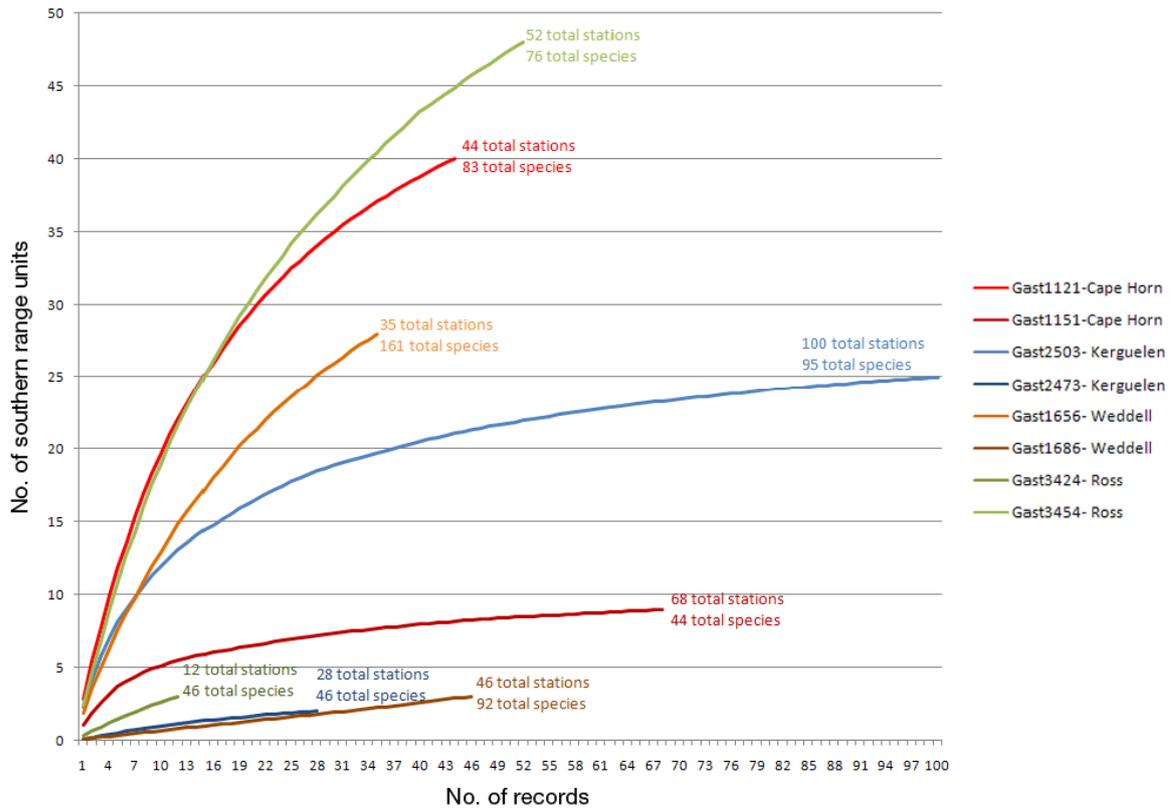


Fig. S1. Rarefaction curves showing accumulation of (southern) range limits in hotspot and non-hotspot areas for gastropod molluscs. Data are for 4 example areas; Cape Horn, Kerguelen Plateau, Weddell Sea and Ross Sea, as shown in the legend

Georgia) was supported by these same hotspots having anomalously high numbers of northern range limits for the level of sampling (Fig. S7).

Largely on the basis of being northern range limit hotspots, the study data suggests that 2 areas seem most appropriate for monitoring the response of ben-

thos to regional warming: South Georgia and the Kerguelen Plateau. However there are 2 other important criteria in considering the most appropriate sites to measure organism response. The first is how well the local fauna is known (steepness of species accumulation curves) and thus how likely actual range shifts are

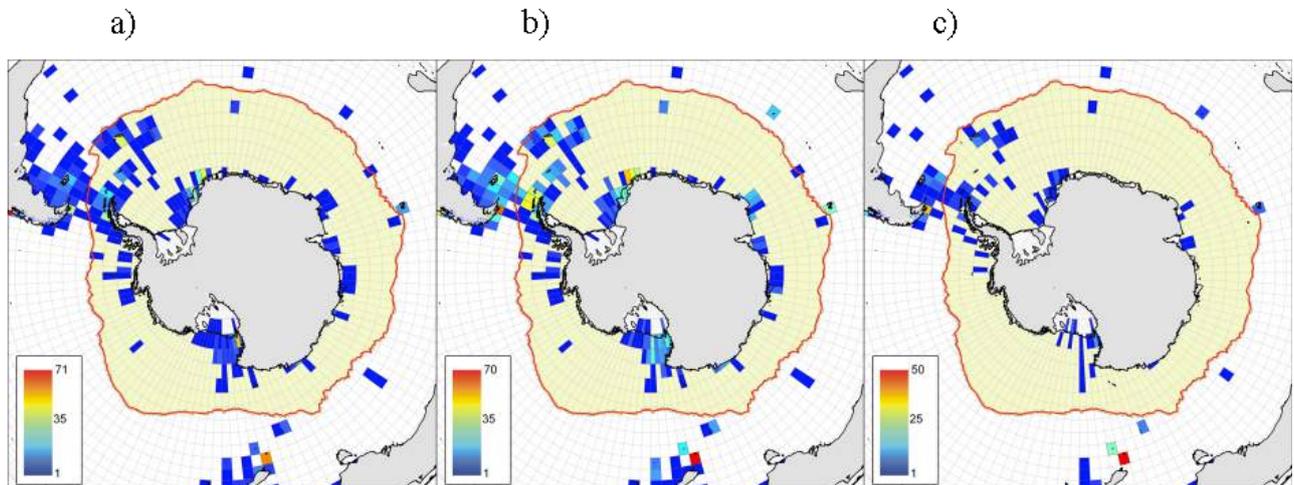


Fig. S2. Bivalve mollusc richness at high southern latitudes. (a) Numbers of records (the number of separate samples with bivalves reported), (b) numbers of species, (c) southernmost limits. Data from SOMBASE and SCAR-MarBIN databases.

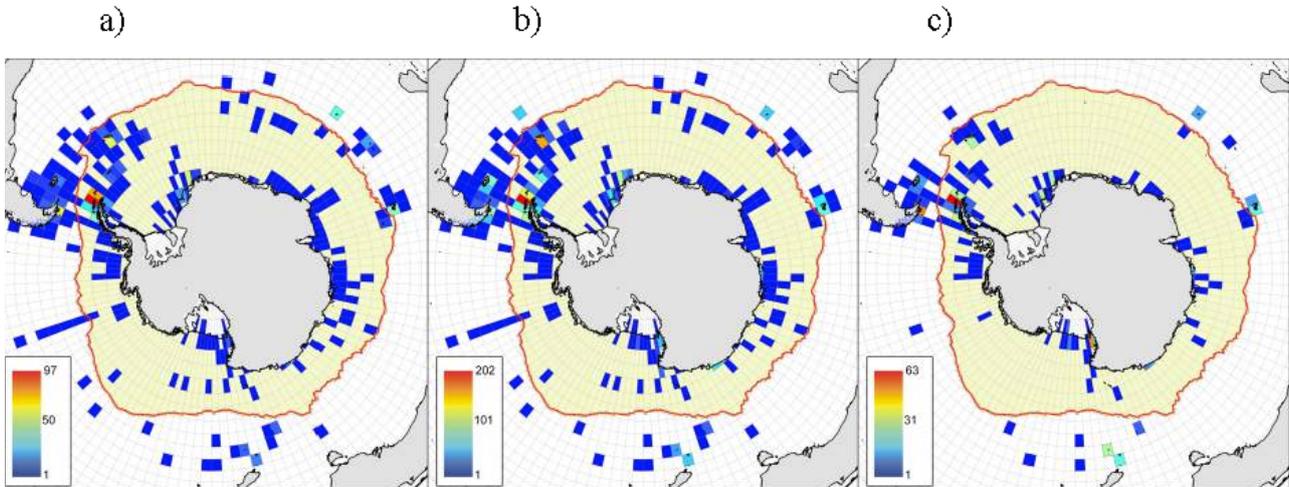


Fig. S3. Amphipod crustacean richness at high southern latitudes. (a) Numbers of records (the number of separate samples with amphipods reported), (b) numbers of species, (c) southernmost limits. Data from SCAR-MarBIN database.

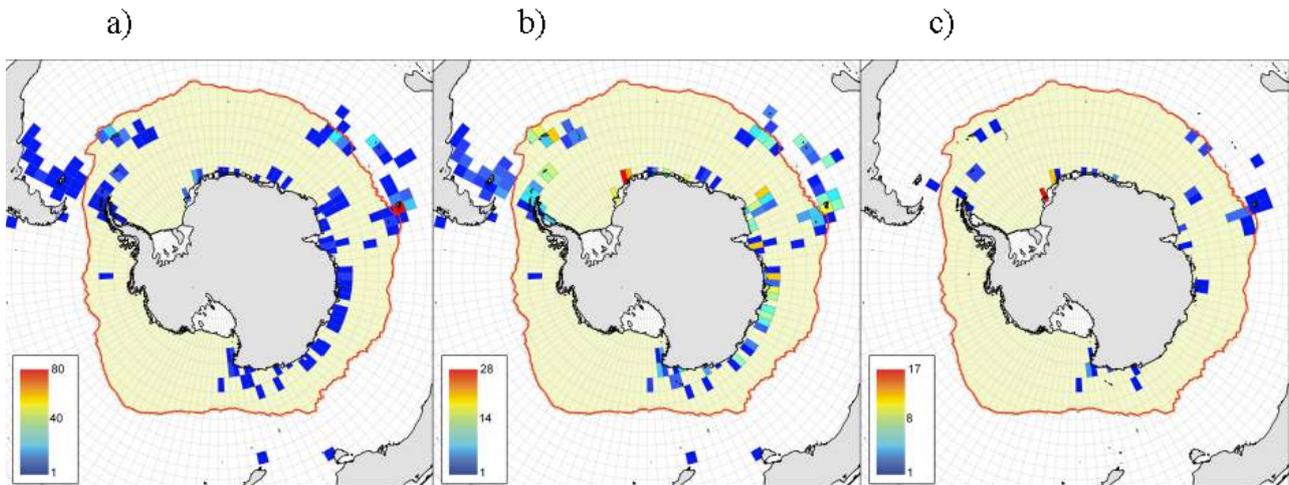


Fig. S4. Ophiuroid echinoderm (brittlestar) richness at high southern latitudes. (a) Numbers of records (the number of separate samples with ophiuroids reported), (b) numbers of species, (c) southernmost limits. Data from SCAR-MarBIN database.

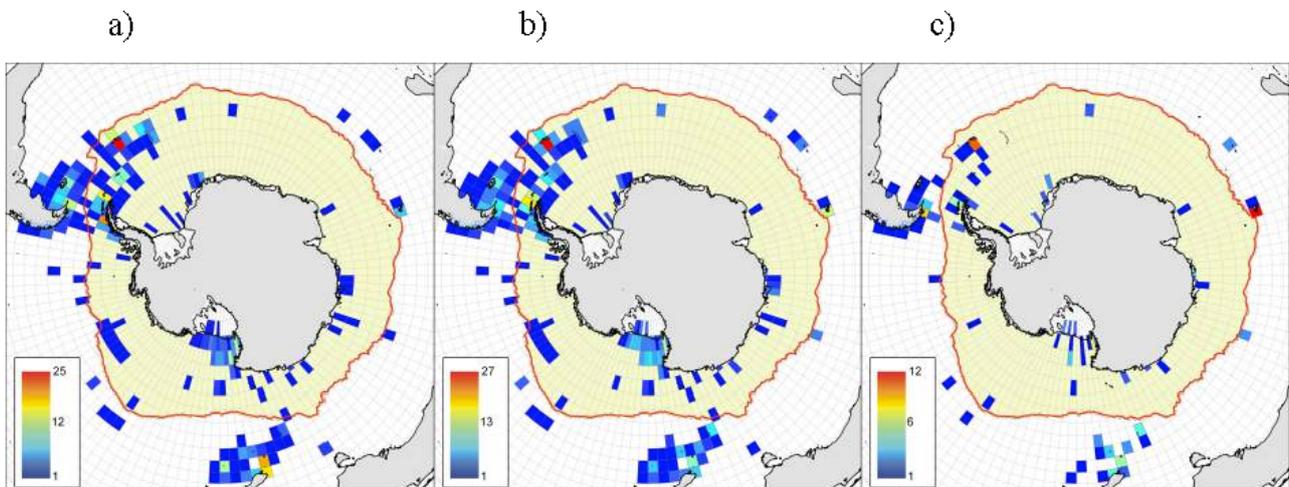


Fig. S5. Hexacoral cnidarians (hard coral) richness at high southern latitudes. (a) Numbers of records (the number of separate samples with hexacorals reported), (b) numbers of species, (c) southernmost limits. Data from SCAR-MarBIN database.

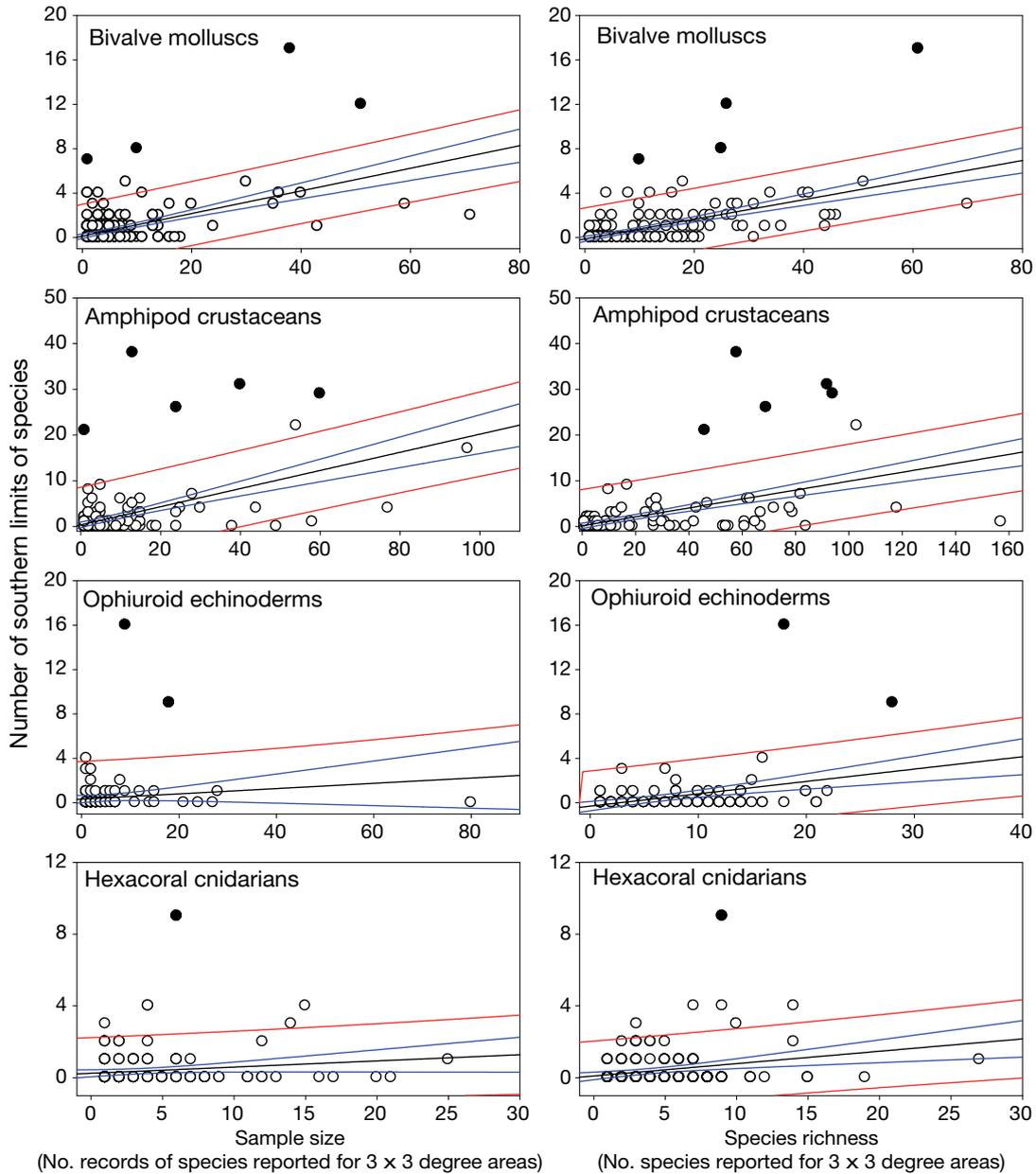


Fig. S6. Relationship between sample intensity, species richness and southern range limits per geographic sampling area for bivalve molluscs, amphipod crustaceans, ophiuroid echinoderms and hexacoral cnidarians. Solid black line: Significant regressions, blue lines: 95% confidence interval, and red lines: 95% prediction lines. Filled circles: hotspots of (southernmost) range limits all lie above the upper 95% prediction line.

to be detected. On this basis the South Orkney Islands are amongst the most suitable sites for mapping change and response, as species accumulation curves there are approaching asymptote (Barnes et al. 2009). It is also worth considering where temperate species increasing their southern limits (i.e. non-indigenous invaders) are most likely to arrive. Amongst the most important vectors are shipping, and the website www.iaato.org/tourism_stats.html lists the most visited sites. Two sites are by far the most visited, Goudier Island

(Port Lockroy) and Deception Island (Port Foster); the latter of which is the only known site for established marine aliens in the SO (Clayton et al. 1997).

Several species are highlighted as potentially good indicator species to monitor (for South Georgia: the gastropods *Margarella steineni* and *Nacella concinna*, the bivalve *Laternula elliptica*, the ascidian *Pyura discoveryi*, the bryozoans *Aimulosia antarctica*, *Cellepora antarctica* and *Escharoides tridens* and the fish *Chaenocephalus aceratus*, *Champscephalus gunnari*,

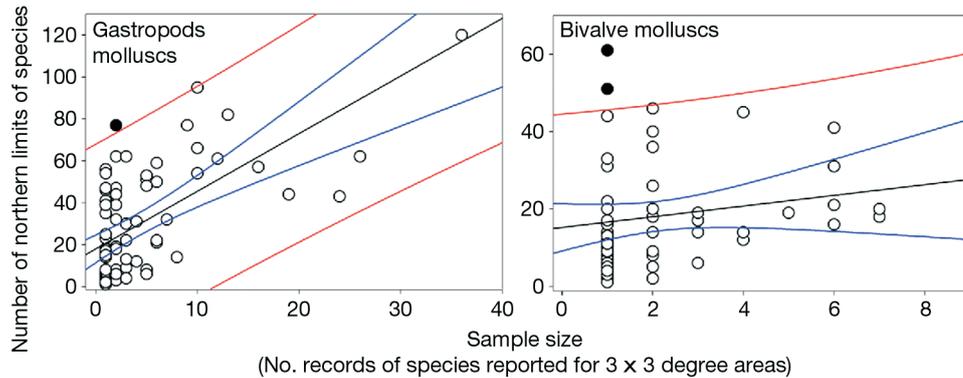


Fig. S7. Relationship between sample intensity and northern range limits per geographic sampling area for gastropod and bivalve molluscs. Solid black line: Significant regressions, blue lines: 95% confidence interval, and red lines: 95% prediction lines. Hotspots of (northernmost) range limits, shown by filled circles, all lie above the upper 95% prediction line

Lepidonotothen squamifrons, *Notothenia rossii* and *Trematomus hansonii*. The depth ranges of these species are *M. steineni* (1–53 m), *N. concinna* (0–195 m), *L. elliptica* (0–1100 m), *P. discoveryi* (46–2350 m), *A. antarctica* (0–1500 m), *C. antarctica* (6–229 m), *E. tri-dens* (13–200 m), *C. aceratus* (5–770 m), *C. gunnari* (0–700 m), *L. squamifrons* (10–900 m), *N. rossii* (5–350 m) and *T. hansonii* (6–549 m: SOMBASE, SCAR-MarBIN, FISHBASE, JR109 and JR144 unpubl. scientific cruise data, and other authors unpubl. data). There is an increasing body of work on the thermal tolerance of Antarctic species, but what constitutes a limit is complex. The wide physiological literature suggests a short term experimental limit of 5 to 10°C (Peck et al. 2009). However the longer term limits are narrower and some such as the bivalve *Limopsis marionensis* seem unable to survive beyond 2°C (Portner et al. 1999). Of the key species identified, *N. concinna* and *L. elliptica* are unable to survive more than 3 mo at 3°C (Peck et al. 2009). Fish such as *Chaenocephalus aceratus* and *Notothenia rossii* have a limit at 6°C (Somero & DeVries 1967), but these may not have fully acclimated (L. Peck pers. comm.). The functional limits for many of these species are even lower, but in all cases, the limit depends on the rate of warming. Arguably the knowledge most needed is how much temperature rise an individual of a species can cope with, such that they can complete a life cycle and produce a viable F1 generation; this is currently unknown for any Antarctic species. Identifying the identity and location of species at range limits should make geographic and taxonomic targeting of future physiological work more productive for elucidating likely responses to climate change.

Meaningful interpretation of any apparent range shift data on any model species will depend, not just on linkage to physiological data on thermal biology, but also on prior establishment of their phylogeographic status by location. This is crucial, as it has become ap-

parent that (as elsewhere) some widespread southern polar species are actually complexes of at least 2 species (e.g. see Hunter & Halanych 2008). Cryptic speciation also occurs with depth (e.g. in *N. concinna*: Carla de Aranzamendi et al. 2008) and it is likely that many range shifts will be bathymetric as well as geographic. This is particularly the case at South Georgia where there are no connected shelf areas for organisms to migrate south, and where water temperature decreases by up to 6°C with depth (Holeton et al. 2005).

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