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# How many species in the Southern Ocean? Towards a dynamic inventory of the Antarctic marine species

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A R T I C L E I N F O

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A B S T R A C T

The IPY sister-projects CAML and SCAR-MarBIN provided a timely opportunity, a strong collaborative framework and an appropriate momentum to attempt assessing the “Known, Unknown and Unknowable” of Antarctic marine biodiversity. To allow assessing the known biodiversity, SCAR-MarBIN “Register of Antarctic Marine Species (RAMS)” was compiled and published by a panel of 64 taxonomic experts. Thanks to this outstanding expertise mobilized for the first time, an accurate list of more than 8100 valid species was compiled and an up-to-date systematic classification comprising more than 16,800 taxon names was established. This taxonomic information is progressively and systematically completed by species occurrence data, provided by literature, taxonomic and biogeographic databases, new data from CAML and other cruises, and museum collections. RAMS primary role was to establish a benchmark of the present taxonomic knowledge of the Southern Ocean biodiversity, particularly important in the context of the growing realization of potential impacts of the global change on Antarctic ecosystems. This, in turn, allowed detecting gaps in knowledge, taxonomic treatment and coverage, and estimating the importance of the taxonomic impediment, as well as the needs for more complete and efficient taxonomic tools. A second, but not less important, role of RAMS was to contribute to the “taxonomic backbone” of the SCAR-MarBIN, OBIS and GBIF networks, to establish a dynamic information system on Antarctic marine biodiversity for the future. The unknown part of the Southern Ocean biodiversity was approached by pointing out what remains to be explored and described in terms of geographical locations and bathymetric zones, habitats, or size classes of organisms. The growing importance of cryptic species is stressed, as they are more and more often detected by molecular studies in several taxa. Relying on RAMS results and on some case studies of particular model groups, the question of the potential number of species that remains to be discovered in the Southern Ocean is discussed.

In terms of taxonomic inputs to the census of Southern Ocean biodiversity, the current rate of progress in inventorying the Antarctic marine species as well as the state of taxonomic resources and capacity were assessed. Different ways of improving the taxonomic inputs are suggested.



## 1. Introduction

Given the potential impact of environmental change on the Southern Ocean ecosystems and the services they provide, it is crucial to establish comprehensive baseline information on the Antarctic marine biodiversity, as a sound benchmark against which future changes can reliably be assessed. The Census of Antarctic Marine Life (CAML, www.caml.aq) and its data and information component, the Marine Biodiversity Information Network of the Scientific Committee on Antarctic Research (SCAR-MarBIN, www.scarmarbin.be), are devoted to assembling this information and making it freely available through various channels.

In the course of the International Polar Year (IPY) 2007-2009, CAML-dedicated cruises collected a mass of new information on the diversity, occurrence and abundance of Antarctic marine species. Numerous unknown species have been discovered, in particular in the Antarctic deep sea.

Establishing a complete and accurate inventory of the presently described Antarctic marine fauna and flora has never been attempted so far, and, necessarily, requires the contribution of numerous experts. The SCAR-MarBIN initiative launched within the CAML and IPY frameworks provided the opportunity to establish such a comprehensive inventory of the Antarctic marine biodiversity, from microorganisms to whales.

The present paper focuses on the following questions:

- How many marine Antarctic species are presently described?
- What might be the real magnitude of the Antarctic marine biodiversity?

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[1] http://www.scarmarbin.be/rams.php?p=editors.

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- What is the current rate of progress in inventorying Antarctic marine biodiversity?
- What is the state of taxonomic resources and capacity?
- How to improve the taxonomic inputs?

## 2. Documenting Antarctic marine biodiversity

### 2.1. Historical background

The very first Antarctic species to be described were some birds of South Georgia and the South Shetland Islands discovered during James Cook's second voyage (1772-1775) and described by Forster (1781). They included some charismatic species such as the gentoo (*Pygoscelis papua*) and the chinstrap (*Pygoscelis antarctica*) penguins, the snow petrel (*Pagodroma nivea*) or the light-mantled sooty albatross (*Phoebetria palpebrata*). Another emblematic species, the Weddell seal (*Leptonychotes weddellii*), was discovered in the South Orkney Islands during James Weddell's 1822-1824 voyage and described by Lesson in 1826. The first invertebrates were described by James Eights from the first American exploring expedition to the Antarctic (1829-1831): the isopod *Brongniartia* (now *Ceratoserolis*) *trilobitoides* in 1833, the ten-legged pycnogonid *Decolopoda australis* in 1835, and the giant isopod *Glyptonotus antarcticus* in 1852 (Fig. 1).

The *Challenger* expedition (1872-1876) described a number of Antarctic species. Although the *Challenger* mostly collected in sub-Antarctic localities such as Kerguelen, Crozet, and Prince Edward Islands, but also around Heard Island, some of these species were later found south of the Polar Front (see *e.g.* De Broyer et al., 2007). The "heroic age" Antarctic expeditions in the late 19th and early 20th centuries mostly concentrated on the discovery of the nearly unknown Antarctic marine organisms. Expedition reports of, among others, the *Belgica*, *Discovery*, *Gauss* or *Terra Nova* comprised a high number of new species descriptions, published over the first half of the twentieth century.

The *Discovery* Investigations (resulting in the numerous *Discovery* Reports issued between 1929 and 1976), although mostly concentrating on the oceanographic and biological surveys of the whaling grounds and the biology of whales in the Southern Ocean at large, provided the opportunity to extensively sample the Antarctic plankton as well as, to a lesser extent, the benthos, and to describe a significant number of unknown taxa (Rainbow, 2005). Among the post-war campaigns results, the Soviet Antarctic Expeditions Reports (published between 1964 and 1990) and the numerous "Biology of the Antarctic Seas" monographs in the Antarctic Research Series (1971-1995) contributed extensively to documenting the Antarctic marine biodiversity.

The signature of the Rio Convention on Biological Diversity in 1992 significantly raised the public awareness of the planet's vanishing biodiversity, and of our vast ignorance of the world species richness. It generated a new interest for biodiversity issues, and stimulated the elaboration of comprehensive regional or national inventories still largely lacking. In the wake of the Rio Convention, SCAR's "Ecology of the Antarctic Sea Ice Zone (EASIZ)" programme (1994-2004) resulted in important contributions to the knowledge of the Southern Ocean biodiversity (Arntz and Clarke, 2002; Clarke et al., 2005).

The current "Census of Antarctic Marine Life (CAML)" programme (2005-2010), in the framework of the International Polar Year 2007-2009 (www.ipy.org) and the Census of Marine Life (www.coml.org), was mainly devoted to expand the current knowledge of the nature, distribution and abundance of Antarctic marine biodiversity and to investigate the evolutionary processes that resulted in the present day diversity, in order to provide a robust information basis for assessing future changes in the Southern Ocean biodiversity and ecosystem functioning.

In this context, a special mention should be given to the "ANDEEP" project ("Antarctic benthic deep-sea biodiversity: colonization and recent community patterns" 2002-2008) of the Census of the Diversity of Abyssal Marine Life (CeDAMar) and CAML, which, for the first time, systematically investigated the Antarctic deep-sea basins in the Atlantic sector and provided outstanding results (Brandt and Hilbig, 2004; Brandt and Ebbe, 2007; Brandt et al., 2007a, b).

### 2.2. Some benchmarks

Some modern syntheses have already attempted to summarize the Southern Ocean biodiversity knowledge. Hedgpeth (1969, 1970) set up the general patterns of the Southern Ocean biogeography, still largely referred to nowadays (but see Griffiths et al., 2009). Dell (1972) provided a comprehensive synthesis of the Antarctic benthos knowledge, critically reviewed the biogeographical schemes previously proposed and largely confirmed Hedgpeth's scheme.

Arntz et al. (1997) gave the first general overview of the Antarctic marine biodiversity, noting that there are no common patterns for species richness in the various Antarctic subsystems

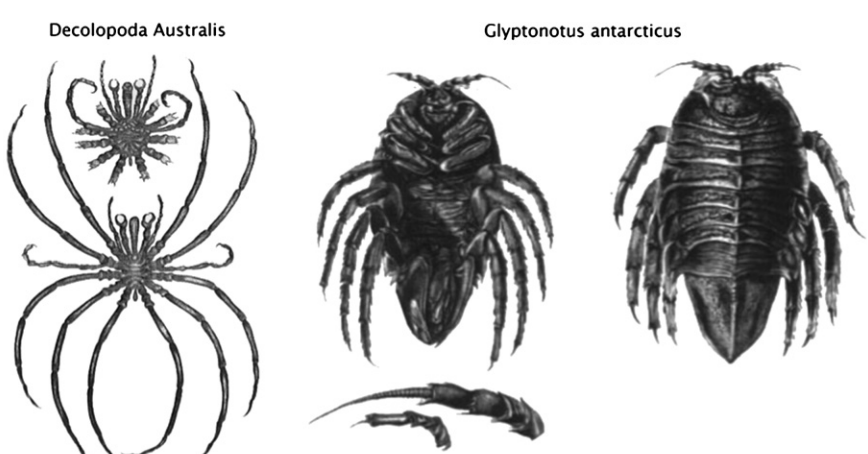


**Fig. 1.** The first Antarctic invertebrate species to be described: the pycnogonid *Decolopoda australis* by James Eights in 1835 and the giant isopod *Glyptonotus antarcticus* in 1852.

(benthic/pelagic, shallow/deep) or for different taxonomic groups. They discussed diverse ecological aspects of the Antarctic biodiversity and emphasized the difficulties in comparative analysis of the Southern Ocean species richness within its different sectors and with other oceans due to limitations in data comparability. Their synthesis was updated and extended in more details for the marine benthos by Clarke and Johnston (2003), who gave a precise estimation of the species richness of the major groups of Southern Ocean benthic invertebrates. They noted that the long period of evolutionary history *in situ* around Gondwana has resulted in a generally diverse fauna, though some taxa (such as decapods or stomatopods) are poorly represented or absent. While some groups with current low diversity were previously well represented in the Antarctic shelf fauna, some other groups (but only some of their lineages) have undergone marked radiations in the Southern Ocean. Clarke and Johnston (2003) stressed that evolutionary questions concerning the origin, diversification or extinction of the various Southern Ocean faunal groups will have no single answer, the evolutionary history of each group reflecting a different response to the tectonic, climatic and oceanographic changes over time.

## 3. How many marine Antarctic species are presently described?

In the framework of the Census of Antarctic Marine Life (CAML), a systematic and exhaustive taxonomic inventory of the Antarctic marine biodiversity was considered a necessary step towards its accurate assessment. This led to the establishment, for the first time, of the "Register of Antarctic Marine Species (RAMS)", an authoritative and dynamic taxonomic database openly accessible online, designed as a key component of an evolutive information system on Antarctic marine biodiversity (www.scarmarbin.be/scarramsabout.php).

### 3.1. RAMS, the Register of Antarctic Marine Species

The primary objective of RAMS was to establish a benchmark of the present taxonomic knowledge of the Southern Ocean biodiversity, particularly important in the context of the growing awareness of the global-change issues. Setting up RAMS allowed detecting gaps in taxonomic knowledge, treatment and coverage, and estimating the importance of the taxonomic impediment, as well as the need for more complete and more efficient taxonomic tools.

A second role of RAMS, not less important, was to compile and manage an authoritative list of species occurring in the Southern Ocean for establishing a standard reference for marine biodiversity research, conservation, monitoring and sustainable management. RAMS provides the necessary "taxonomic backbone" of SCAR-MarBIN and the Ocean Biogeographic Information System (OBIS, www.iobis.org). RAMS links in real-time to a wealth of species-level information from many different sources, *e.g.*, genetic information from GenBank (www.ncbi.nlm.nih.gov/) or Barcode of Life (www.barcodinglife.org; Grant and Linse, 2009), and, through SCAR-MarBIN's webservices, to a variety of georeferenced environmental data.

RAMS attempts to encompass all Antarctic (and sub-Antarctic: see below) marine species from micro-organisms to whales. It includes species from the three macrohabitats of the Southern Ocean: the sea floor (meio-, macro- and megabenthos), the water column (phyto-, zooplankton, nekton) and the sea ice.

RAMS was established by the SCAR community and is managed by an editorial board comprised of 64 world-renowned specialists acting as "taxonomic editors" of the Register (http://www.scarmarbin.be/rams.php?p=editors). They provided complete lists of species (with accurate nomenclature and synonyms) and up-to-date systematic classification. In case several classifications are in use, alternative classification(s) may be mentioned in RAMS, but only one classification is kept for obvious standardization purposes. Quality control is checked by crossing the information with that included in the World Register of Marine Species (WoRMS, www.marinespecies.org) managed by a complementary board of over 180 taxonomic editors, by some internal semantic controls, and by external experts and the user community. RAMS taxonomic data ultimately feeds through WoRMS into the Catalogue of Life (www.catalogueoflife.org).

The Register is by essence dynamic and evolutive: the taxonomic editors can edit, correct and update all entries online, including newly described species, taxonomic revisions, or changes in classification. RAMS is completely interoperable with WoRMS, which in some cases complements or updates Antarctic data. RAMS initially benefited from the integration of Clarke and Johnston (2003)'s macrobenthos database of 2500 Antarctic species names. The Antarctic Register also largely benefited from the experience of the European Register of Marine Species (Costello et al., 2001, 2006) hosted at the same data centre (Flanders Marine Institute, www.vliz.be). New IT developments are elaborated in common and shared on-the-fly by RAMS, ERMS, WoRMS and all associated initiatives (world species lists and thematic lists: http://marinespecies.org/about.php).

RAMS's geographic scope is the Southern Ocean in its wide sense, as used by oceanographers (e.g., Deacon, 1984; Longhurst, 1998; Rintoul, 2007), the Antarctic region south of the Antarctic Polar Front remaining the priority. Its complete geographic coverage extends from the coasts of the continent in the south, to the sub-Tropical Front in the north (Fig. 2). For facilitating data retrieval from existing databases, convenient operational limits of the RAMS' area of interest have been defined (Table 1), fitting as closely as possible, when justified, to the statistical areas used by the Convention for the Conservation of Antarctic Marine Living Resources (CCAMLR, www.ccamlr.org).

RAMS will attempt *in fine* to include also sub-Antarctic species. This is justified by the fact that in many benthic groups one quarter to one third of Antarctic species extend their distribution into the sub-Antarctic region and that most pelagic species are not restricted to the Antarctic region. On the other hand, Magellanic and other sub-Antarctic species are potentially the first candidates to invade the Antarctic region under the global warming conditions (Barnes et al., 2006, 2009; Clarke et al., 2007).

### 3.2. RAMS results

The taxonomic information is currently under the responsibility of a board of expert taxonomic editors, all with their own specialty. Five (mostly minor) taxonomic groups currently lack an editor: Gastroricha, Tardigrada, Ascothoracida, Cirripedia, and Hemichordata. Complete validated lists of Antarctic species are now available for most taxonomic groups, but part of the sub-Antarctic species lists remains to be completed, or checked by specialists.

For the Antarctic region, the Register currently (October 2010) includes 16,803 taxon names and 9463 species, among which 8193 species are considered valid. These valid species are in turn made of about 88 % of (primarily) benthic species, 11% of pelagic species and less than 2% of symbiotic species (Table 2). In comparison with previous surveys (Arntz et al., 1997; Clarke and Johnston, 2003), the multi-authored RAMS inventory showed significant progress due to the description of new taxa from recent field surveys or taxonomic revisions, or complements from additional sources, but first of all stressed the advantage of establishing a dynamic inventory of the Antarctic marine biodiversity: from the moment this paper submitted, information has probably been completed,

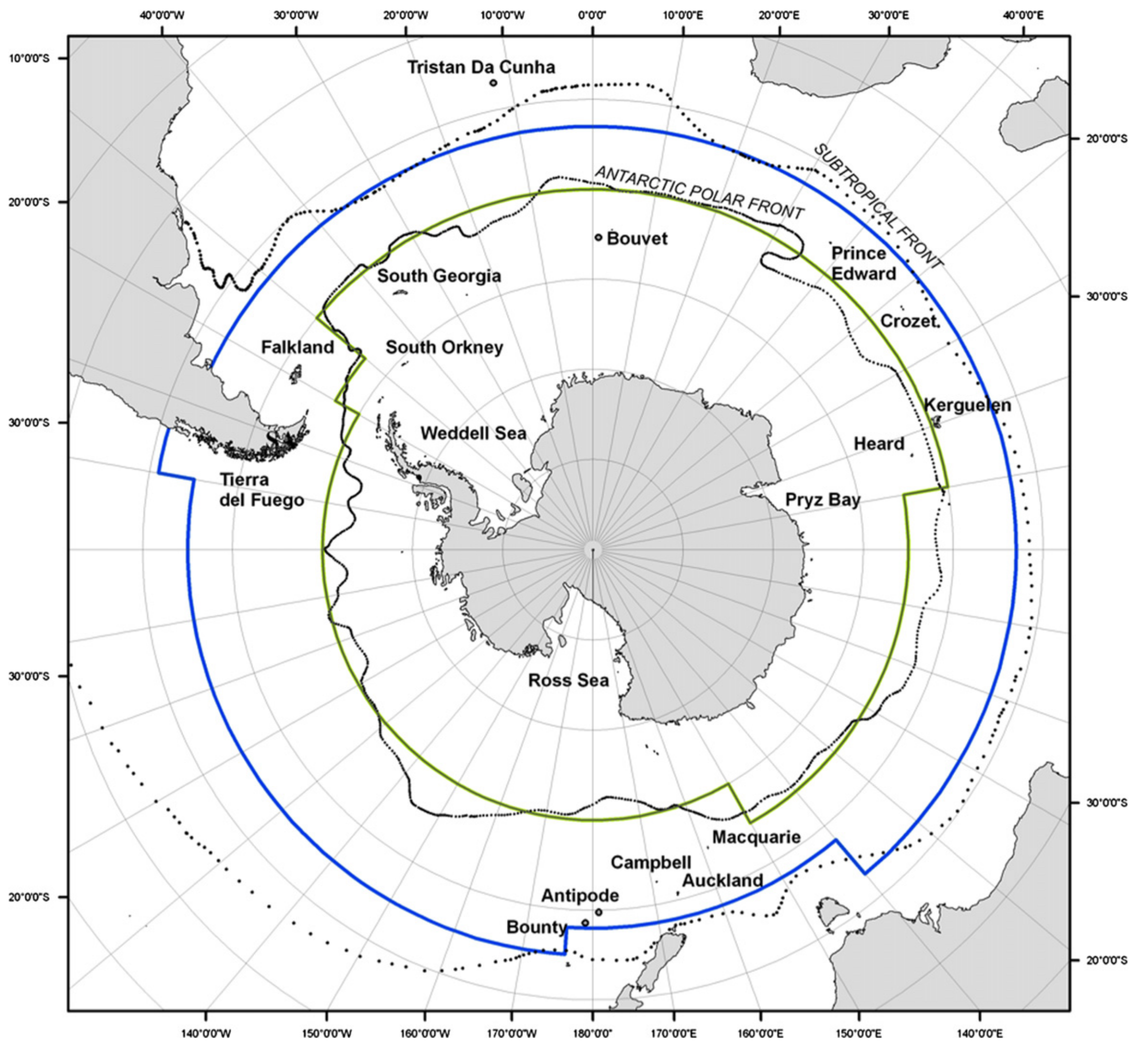


**Fig. 2.** SCAR-MarBIN's area of interest (AoI). The most inner line close to the Antarctic Polar Front indicates the operational (average) northern limit of the Antarctic AoI. The outer line close to the sub-Tropical Front indicates the operational (average) northern limit of the sub-Antarctic AoI.

**Table 1**
SCAR-MarBIN/RAMS area of interest (AoI). Operational Northern limits of the AoI, in the different sectors of the Southern Ocean for both the Antarctic and Sub-Antarctic zones.

| Sector | Longitude range | Northern limit |
|---|---|---|
| *Antarctic zone* | | |
| South Atlantic Sector | 60°W-50°W | 57°S |
| | 50°W-30°E | 50°S (same as *CCAMLR*) |
| Indian Sector | 30°E-80°E | 50°S |
| | 80°E-150°E | 55°S (same as *CCAMLR*) |
| South Pacific Sector | 150°E-60°W | 60°S (same as *CCAMLR*) |
| *Sub-Antarctic zone* | | |
| Atlantic and Indian Sectors | 60°W-140°E | 43°S |
| South Pacific Sector | 140°E-176°W | 48°S |
| | 176°W-80°W | 45°S |
| | 80°W-72°W | 41°S |

updated and/or validated a significant number of times (http://www.scarmarbin.be/rssNewsFront.php).

### 3.3. Distribution data

In addition to accurate species lists and up-to-date classification, RAMS taxonomic editors in most cases provided distribution data (occurrence records), from a critical review of literature data, or from museum collections. Complete occurrence records of species from 15 taxonomic groups are currently available online: Porifera, Anthozoa, Kynorhyncha, free living Nematoda, Gastropoda, Bivalvia, Oligochaeta, Lophogastrida, Mysida, Amphipoda, Cumacea, Bryozoa, Brachiopoda, Ophiuroidea, and Echinoidea. Occurrence records (latitude/longitude/depth combination) of other taxonomic groups are currently being compiled. This georeferencing effort included records with, however, various degrees of precision, depending on available original data.

All these distribution datasets feed the SCAR-MarBIN "ANTOBIS" database, the Antarctic section of the Ocean Biogeographic Information System (OBIS). Occurrence records are currently available for about 5200 taxa (or about 34% of all taxa) and SCAR-MarBIN currently gives access to over 1,201,000 biogeographic records from 189 interoperating databases (http://www.scarmarbin.be/scarproviders.php). These online datasets (http://www.scarmarbin.be/AntobisMapper.php), when validated by experts, constitute valuable sources of information for comparative biogeographic analyses, detection of biodiversity hotspots, bio/ecoregionalisation of the Southern Ocean, designation of marine protected areas and monitoring of the Southern Ocean biodiversity (see Griffiths et al., 2011; Sicinski et al., 2011).

**Table 2**
Estimates of Antarctic marine species richness from the Register of Antarctic Marine Species (RAMS, May 2010), as compared to data from Arntz et al. (1997) and Clarke and Johnston (2003).

| Taxon | Habitat | Taxonomic Editor(s) | RAMS | Arntz | Clarke | N recs |
|---|---|---|---|---|---|---|
| **ANIMALIA** | | | 7761 | | | |
| Porifera | B | D. JANUSSEN | 284 | 300 | 233 | 8,628 |
| Calcarea | B | D. JANUSSEN | 12 | | 14 | 99 |
| Demospongiae | B | D. JANUSSEN | 243 | | 190 | 5,219** |
| Hexactinellida | B | D. JANUSSEN | 29 | | 29 | 682 |
| Cnidaria | B / P | | 448 | | | 7,908 |
| Hydrozoa (excl.Siphon.) | B / P | A. PENA-CANTERO | 260 | 200 | 186 | 2,257 |
| Siphonophorae | P | A. PENA-CANTERO | 52 | | | 2,648 |
| Anthozoa | B | P. LOPEZ-GONZALEZ and D. FAUTIN | 127 | 85 | 86 | 2,425** |
| Scyphozoa | P | D. LINDSAY | 10 | | | 565 |
| Staurozoa | B | N | 4 | | | 12 |
| Myxozoa | S | M. LONGSHAW | n.d. | | | n.d. |
| Ctenophora | P | D. LINDSAY and E. PAKHOMOV | 10 | | | 37 |
| Platyhelminthes | B / S | | 162 | | | 89 |
| Turbellaria | B | T. ARTOIS | [30] | | | 89 |
| Monogenea | S | M. LONGSHAW | [7] | | | n.d. |
| Digenea | S | K. ZDZITOWIECKI | 56 | | | n.d. |
| Cestoda | S | A. ROCKA | 69 | | | n.d. |
| GASTRORICHA | B | N | n.d. | | | n.d. |
| Nemertina | B / P | R. GIBSON | 47 | | 31 | 875 |
| Rotifera | B | H. SEGERS | 2 | | | 14 |
| Cephaloryncha | B | | 7 | | | 20 |
| Kynorhyncha | B | B. NEUHAUS | 4 | | | 11** |
| Priapulida | B | J. SAIZ-SALINAS | 3 | 3 | 3 | 9 |
| Nematoda (free living) | B | A. VANREUSEL | 367 | | | 1,374** |
| Nematoda (parasitic) | S | A. ROCKA | 13 | | | n.d. |
| Tardigrada | B | N | 10 | | | 17 |
| Acanthocephala | S | K. ZDZITOWIECKI | 31 | | | n.d. |
| Echiura | B | J. SAIZ-SALINAS | 11 | | 9 | 44 |
| Sipuncula | B | J. SAIZ-SALINAS | 14 | 15 | 15 | 500 |
| Mollusca | B / P | | 708 [740] | | | 29,727 |
| Solenogastres | B | L. SALVINI-PLAWEN | 97 | | | 39 |
| Monoplacophora | B | M. SCHRÖDL and S. SCHIAPARELLI | 3 | | | n.d. |
| Polyplacophora | B | E. SCHWABE | 10 | | 10 | 282 |
| Gastropoda | B / P | K. LINSE, S. SCHIAPARELLI, M. SCHRÖDL | 428 [543] | | 530 | 17,833** |
| Bivalvia | B | K. LINSE | 130 | | 110 | 6,617** |
| Scaphopoda | B | V. SCARABINO | 6 | | 6 | 64 |
| Cephalopoda | B / P | U. PIATKOWSKI | 37 B+29 P | | 34 | 3,247 |
| Annelida | B / P | | 627 | | | 9,344 |
| Polychaeta | B / P | J. SICINSKI | 590 | 650 | 648 | 9,178 |
| Oligochaeta | B | P. MARTIN | 22 | | | 40 |
| Hirudinea | S | A. UTEVSKI | 12 [21] | | | 85 |
| Arthropoda | | | 2,297 | | | 114,709 |
| Acarina: Halacaridae | B | I. BARTSCH | 69 | | 45 | 2 |
| Pycnogonida | B | T. MUNILLA and C. ARANGO | 192 | 150 | 175 | 1,213 |
| Crustacea | | | 2,344* | | | |
| Ascothoracida | B / S | N | 5 | | | 5 |
| Cirripedia | B | N | 44 | 37 | 50 | 67 |
| Copepoda (excl.Harpacticoida) | P | J. KOUWENBERG and C. RAZOULS | 283 | | | 18,178 |
| Harpacticoida | B | K.-H. GEORGE | 186* | | | 50 |
| Ostracoda | B / P | | 234 | | | 1,085 |
| Myodocopida (excl. Halocypridina) | B / P | S. BRANDAO | 64 | | | 260 |
| Halocypridina | P | M. ANGEL and K. BLACHOWIAK-SAMOLIK | 43 | | | 25 |
| Podocopa | B | S. BRANDAO | 127 | | | 1 |
| Leptostraca | B / P | C. DE BROYER | 5 | | | 9 |
| Lophogastrida | P | V. PETRYASHOV | 6 | | | 128** |
| Mysida | B / P | V. PETRYASHOV and T. DEPREZ | 38 | | | 1,565** |
| Amphipoda | B / P | | 601 | 520 | 496 | 14,205** |
| Gammaridea | B / P | C. DE BROYER | 477 | | | 7,725** |
| Corophiidea | B | C. DE BROYER | 59 | | | 1,080** |
| Hyperiidea | P | W. ZEIDLER | 65 | | | 4,981** |
| Isopoda | B / P | A. BRANDT | 441 | 346 | 257 | 656 |
| Tanaidacea | B | M. BLAZEWICZ | 142 | 50 | 80 | 759 |
| Cumacea | B | U. MUEHLENHARDT-SIEGEL | 86 | | | 1,883** |
| Euphausiacea | P | V. SIEGEL | 8 | | | 82,080 |
| Decapoda | B / P | S. THATJE | 26 | 19 | 13 | 134 |
| Bryozoa | B | D.K.A. BARNES and P. KUKLINSKI | 318 [393] | | 322 | 4,911 |
| Brachiopoda | B | C. EMIG | 29 | | 19 | 1,342** |
| Chaetognatha | P | A. PIERROT-BULTS | 15 | | | 3,423 |
| Hemichordata | B | N | 6 | | | 49 |
| Echinodermata | B | | 568 | | | 11,422 |
| Asteroidea | B | M. JANGOUX and B. DANIS | 208 | | 108 | 4,591** |
| Ophiuroidea | B | I. SMIRNOV | 129 | | 119 | 3,724** |
| Crinoidea | B | M. ELEAUME | 44 | 22 | 28 | 355 |

Table 2 (*continued* )

| Taxon | Habitat | Taxonomic Editor(s) | RAMS | Arntz | Clarke | N recs |
|---|---|---|---|---|---|---|
| Echinoidea | B | B. DAVID | **80** | 44 | 49 | **1,908**** |
| Holothuroidea | B | J. BOHN | **104** | 88 | 106 | **1,122** |
| Chordata | | | **555** | | | **447,728** |
| Tunicata | B / P | | **148** | | | **4,807** |
| Ascidiacea | B | E. VASQUEZ | **113** | 130 | 118 | **2,454** |
| Thaliacea | P | R. HOPCROFT and E. PAKHOMOV | **9** | | | **1,811** |
| Larvacea | P | R. HOPCROFT and E. PAKHOMOV | **26** | | | **483** |
| Pisces | B / P | | **317** | | | **11,815** |
| Agnatha | B | P. KOUBBI and. C. OZOUF-COSTAZ | **2** | | 2 | **9** |
| Elasmobranchii | B / P | P. KOUBBI and. C. OZOUF-COSTAZ | **14** | | 8 | **642** |
| Actynopterygii | B / P | P. KOUBBI and. C. OZOUF-COSTAZ | **301** | | 198 | **10,974** |
| Aves | P | E. WHOELER | **59** | | | **337,260** |
| Mammalia | | | **31** | | | **80,099** |
| Pinnipedia | P | M. BESTER | **6** | 6 | | **68,572** |
| Cetacea | P | W. PERRIN | **25** | | | **11,464** |
| **CHROMISTA** | | F. SCOTT and M. de SALAS | **281** | | | **2,483** |
| Bacillariophyta | | F. SCOTT and R. LIGOWSKI | **201** | | | **2,457** |
| Cryptophyta | | F. SCOTT | **2** | | | n.d. |
| Haptophyta | | F. SCOTT | **31** | | | n.d. |
| Heterokontophyta | | F. SCOTT and C. WIENCKE | **33** | | 26 | **24** |
| Ochrophyta | | F. SCOTT | **13** | | | **2** |
| Chromista *incertae sedis* | | F. SCOTT | **1** | | | n.d. |
| **PLANTAE** | | C. WIENCKE | **88** | | | **0** |
| Rhodophyta | | C. WIENCKE | **66** | | 75 | **41** |
| Chlorophyta | | C. WIENCKE | **22** | | 17 | **8** |
| **PROTOZOA** | | F. SCOTT and M. de SALAS | **524** | | | **171** |
| Ciliophora | | F. SCOTT | **160** | | | **2** |
| Dinophyta | | F. SCOTT | **57** | | | n.d. |
| Discomitochondria | | F. SCOTT | **2** | | | n.d. |
| Foraminifera | | A. GOODAY | **165** | | | **221** |
| Haptophyta | | F. SCOTT | **31** | | | n.d. |
| Heliozoa | | F. SCOTT | **5** | | | n.d. |
| Myzozoa | | F. SCOTT | **68** | | | **1** |
| Rhizopoda | | F. SCOTT | **3** | | | n.d. |
| Sarcomastigophora | | F. SCOTT | **32** | | | **2** |
| Xanthophyceae | | F. SCOTT | **1** | | | n.d. |
| Protozoa *incertae sedis* | | F. SCOTT | **1** | | | |

Phyla in capital letters. Classification according to Brusca and Brusca (2003) and Species 2000 and ITIS (2009).
N*: include some sub-Antarctic species.
[N]: best estimates of Antarctic species numbers from recent literature, in case RAMS coverage is incomplete.
n.d.: no data.
Habitats: B: Benthic; P: Pelagic; S: Symbiotic.
N recs: numbers of occurrence records (mostly south of 43°S) from SCAR-MarBIN (species level and higher taxa records combined). **: include complete coverage of species records from literature.

## 4. What remains to be discovered (and described) in the Southern Ocean?

Current knowledge of the Antarctic marine biodiversity remains highly patchy in terms of coverage of geographical areas, bathymetric zones, habitats, taxonomic groups, ecofunctional groups, or size categories.

### 4.1. The known biodiversity: only the tip of the iceberg?

Any new exploring expedition in the Southern Ocean - even in previously visited areas – may bring back a number of invertebrates or micro-organisms that are new to science. As the last ocean to be discovered and the most difficult to access, the Southern Ocean and its biodiversity remain, not unexpectedly, still partially known, but as noted by Clarke and Johnston (2003), the (benthic) fauna is better known than might be thought, at least for the major taxa on the continental shelves.

Estimating the magnitude of the unknown biodiversity in the Southern Ocean is a challenging task, but it can be indirectly approached, among other ways, by analyzing the sampling effort and the related number of species sampled (Fig. 3 - see also discussion and details in Griffiths et al., 2011). This analysis clearly showed that a large number of areas remain poorly sampled or not sampled at all. Large parts of the Southern Ocean still require a basic biodiversity inventory. In the Maritime Antarctic for example, the littoral and shallow sublittoral zones have been relatively well studied in several places (see e.g. Sicinski et al., 2011) but the diversity of environments along the Scotia Arc and the Antarctic Peninsula suggests that more complete sampling is required before gaining a more definitive idea of the faunal richness and its precise distribution patterns. The deeper continental shelf in the West Antarctic is still largely under-sampled and the eastern side of the Peninsula and the western Weddell Sea remain poorly known, but recent exploration of the former Larsen Ice-shelf area,for example, provided new insights on the local biodiversity (Gutt et al., 2010). Until recently, the Bellingshausen Sea had been investigated by only a very few expeditions such as the historical *Belgica* expedition, and the Amundsen Sea remained a nearly complete white spot. However, recent EASIZ and CAML surveys significantly increased our knowledge of some

(A)

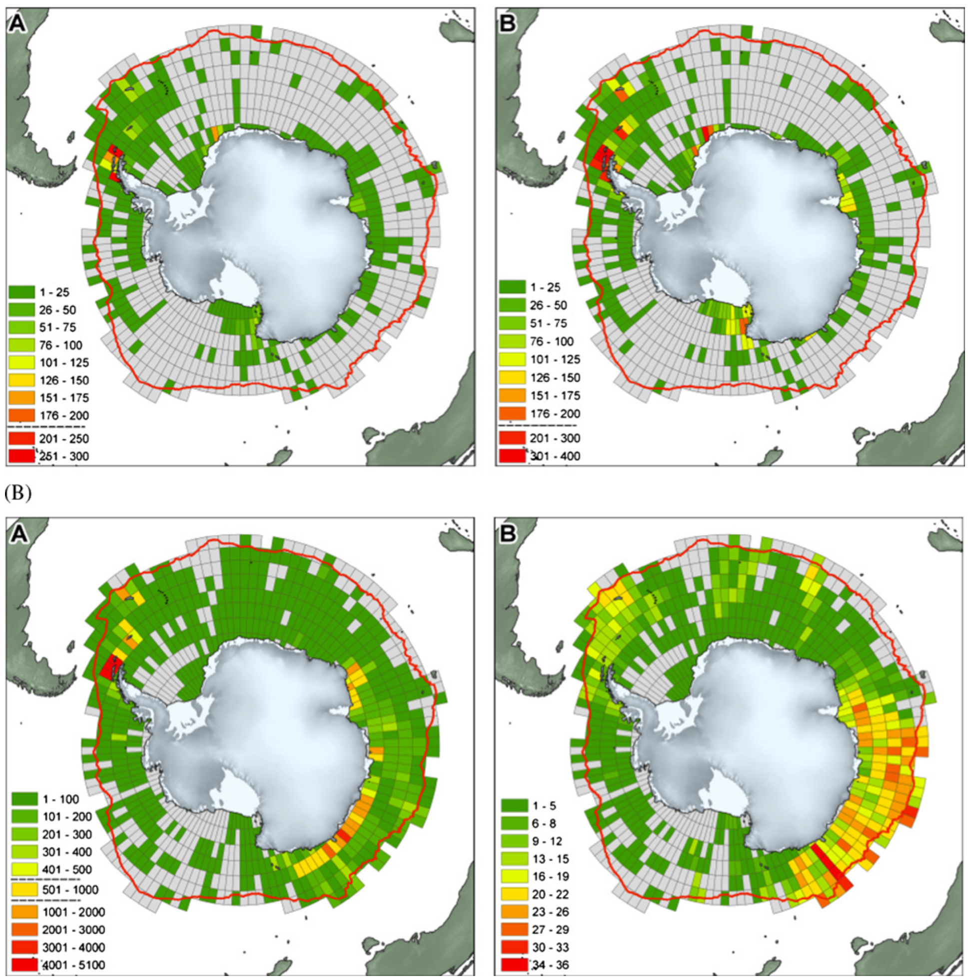


**Fig. 3.** The total numbers of sample sites (A) and species (B) found within each 3° of latitude by 3° of longitude grid square, from all distribution records in SCAR-MarBIN (as of August 2009). The two top figures are the total numbers of all benthic sample sites and species found within each grid square. The two bottom figures are the total numbers of all plankton sample sites and species found within each grid square.
Courtesy of Griffiths et al., 2011.

of these regions (e.g., Bouvet Island: Arntz et al., 2006; Bellingshausen Sea: Corbera et al., 2009; Amundsen Sea: Kaiser et al., 2009).

Obviously, the most important gaps in the Antarctic biodiversity survey remained the zone between the Bellingshausen Sea/ Amundsen Sea and the Ross Sea, and also large parts of the East Antarctic (between 0° and 150°E) where only few spots have been reasonably well sampled (Fig. 3; see Griffiths et al., 2011, for a macroanalysis of the sampling effort). Only few of the Antarctic deep-sea basins have been explored by some scattered Russian and American investigations mostly in the sixties (Malyutina, 2004; Clarke, 2003) and, more significantly, by the recent ANDEEP expeditions in the Atlantic Sector (Brandt et al., 2007a, b) and by the NZ IPY-CAML expedition in the Ross Sea (Profitt, 2008). For the first time, the CeDAMar/CAML "ANDEEP" project ("Antarctic benthic deep-sea biodiversity: colonization and recent community patterns" 2002-08) systematically investigated the Antarctic deep-sea basins in the Atlantic sector, revealing high species richness in most animal groups. The 40 collecting stations of the ANDEEP cruises, for example, yielded more than 1400 species (so far identified) with more than half of them assumed to be new to science (Brandt et al., 2007a, b; Brandt and Hilbig, 2004). One of the most spectacular cases is undoubtedly the richness and ubiquity of the deep sea isopods: the ANDEEP expeditions raised the number of Antarctic isopod families from 25 to 27, of genera from 128 to 151 and of species from 371 to 954, with about 90% of the new findings representing unknown species, many of them remaining to be described (Brandt et al., 2007b).

Another source of unknown biodiversity is to be found in the symbiotic associations. Endo- and ectosymbionts in general remain to be more systematically investigated in the Southern Ocean, in particular in benthic invertebrates (see, e.g., Hétérier et al., 2008; Linse, 2008) and, as emphasized by Bouchet (2006), symbionts of symbionts might also be expected. There is also a common bias in biodiversity knowledge against the smaller size categories: the meiobenthos is a good example (not mentioning the microorganisms), with, e.g., most nematodes usually identified only to genus level.

In terms of future biogeographic exploration, it is necessary, as emphasized by Gutt et al. (2010), to reach a systematic coverage as even as possible for as many as possible relevant regions and not so much to accumulate perfectly detailed results at a single location. However, to allow substantiated statistical extrapolations, information on rare species is required, "*consequently, not only presences but also information on the absence and abundance of species is strongly needed*" (Gutt et al., 2010).

### 4.2. Can we predict the unknown biodiversity?

Based on their experience, most taxonomists may have their own 'guestimates' of the potential number of species remaining to be described or even discovered in their group(s) (see e.g., Winston, 1992). It has been estimated for instance that there could be as many as 2000 free-living nematode species in the Southern Ocean as a whole, where 366 species are presently known (Vanhove, in De Broyer et al., 2001).

The rate of description of new species can provide some indications on the potential state of completion of the biodiversity inventory. The contrasting accumulation curves of the descriptions of the Southern Ocean Amphipoda and Stelleroidea along time (Fig. 4) showed that, in the former, the curve is far from reaching an asymptote whilst the latter curve indicates that the inventory is close to completion. However, such interpretation should be made with caution as the taxonomic productivity may be influenced by other unknowable factors, such as the public interest in a particular group, shifting of funding priorities, or the experts' personal motivations.

In-depth taxonomic revisions may result in synonymizations but often resulted in growing species number. An illustrative example is given by the detailed revision of the Southern Ocean species of the amphipod genus *Liljeborgia* by Udekem d'Acoz (2008, 2009). Before the revision 15 species were known; after the revision of most existing museum collections, 12 species were considered valid and 13 new species described (including 5 species from new ANDEEP material). As most of the diverse and abundant Antarctic and sub-Antarctic amphipod fauna remains to be revised (De Broyer et al., 2007), we can expect substantial increase of species richness estimates from revision work only.

Extrapolations based on species-area relationships can provide a more statistically-supported approach of potential species richness. Few estimations of such kind have been done so far. For the macrozoobenthos, Gutt et al. (2004) conducted such a study, relying on substantial catch data from the *Polarstern* EASIZ I expedition to the eastern Weddell Sea (16 trawling stations, with total sampled area of 0.1 km$^2$; Gutt et al., 2000), and using various species richness estimators (species accumulation, jack-knife, incidence-based coverage). They extrapolated that the total species richness of the Antarctic shelf macrozoobenthos may comprise between 11,000 and 17,000 species, of which over 4100 species (Clarke and Johnston, 2003) or 5800 (based on current RAMS results) were presently known and described.

At the global level, the total marine species richness (Prokaryota, Algae, Protozoa, Fungi and Animalia) reaches 230,000 to 275,000 described species, or 15% of the described global biodiversity (Bouchet, 2006). The total number of potential marine species has been variously estimated by different authors, and was the subject of intense debate (e.g., Grassle and Maciolek, 1992, estimating a total of 10 million macrofaunal species; Poore and Wilson, 1993, around 5 million; May, 1993, 2004, less than 1 million; see discussion in Snelgrove and Smith, 2002). More recently, Bouchet (2006) estimated this number at 1.4 to 1.6 million, or 5 to 7 times the presently known biodiversity.

Another difficulty in assessing species richness came from the recent discovery of the potentially common occurrence of cryptic species in different Southern Ocean invertebrate taxa. DNA analysis of some widely distributed invertebrate species revealed the existence of several cryptic species, with restricted distribution, where only one often circum-Antarctic species was previously known (e.g. Held, 2003; Wilson et al., 2007; Allcock et al., 2011). A new significant example is given by the lysianassid amphipods of the genus *Orchomene* s.l., in which the molecular analysis (based on CO1 and 28S) resulted in the detection of two or three cryptic species in some common taxa but, at the same time, confirmed the circum-Antarctic occurrence of some other species (see Havermans et al., 2011).

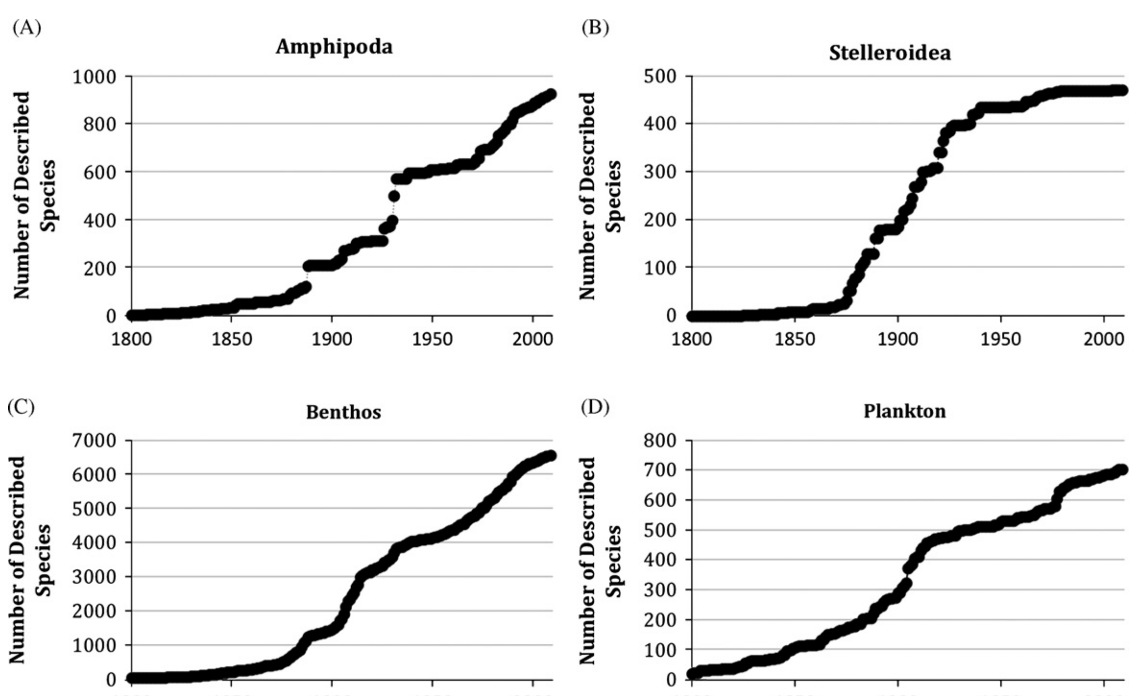


**Fig. 4.** Rate of species description for Antarctic Amphipoda, Stelleroidea, Benthos and Plankton along time (yrs), according to the data available in the Register of Antarctic Marine Species (as of March 2010).

## 5. Progress in inventorying and describing the Antarctic marine biodiversity

### 5.1. The taxonomic productivity

It has been estimated that the number of new marine species described in the world (including Prokaryota, Algae, Protozoa, Fungi and Animalia) reached 1300 to 1500 species per year (based on 2002-03 statistics), involving more than 2000 authors (Bouchet, 2006). For the Southern Ocean biodiversity (Protozoa, Algae and mostly Animalia) as recorded in RAMS, during the last decade, on average 25 species were described each year and more than 250 authors were involved in this task (Fig. 5).

If we consider the number of authors involved in the description of the Antarctic marine biodiversity from the beginning of Antarctic exploration (Fig. 6), it is interesting to note that during the period following the pioneer and heroic age expeditions (1870-1910) the number of authors was usually lower than the number of authors from the period 1960-2004. From 1990 onwards a regular decrease in the number of active Antarctic taxonomists is clearly observable.

The comparison between the taxonomic productivity for benthos and plankton (Fig. 4) showed that the description rate of the 7137 Southern Ocean benthic species was on average of 44 species per year and tends to remain linear, and that the description rate of the 883 pelagic species was of 4 per year and showed a decreasing trend. As an example of benthic group, the Isopoda description rate (on average 2.8 species per year from the beginning of Antarctic exploration verses 3.8 species during the last decade) clearly did not show any sign of reaching the asymptote (Fig. 7). At the present rate, describing the almost 600 putatively new isopod species yielded by the ANDEEP expeditions would take almost 160 years!

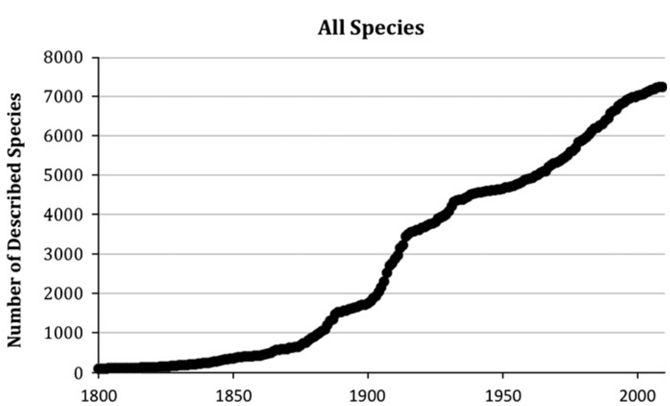


**Fig. 5.** Rate of description for all Antarctic species along time (yrs), according to the data available in the Register of Antarctic Marine Species (as of March 2010).

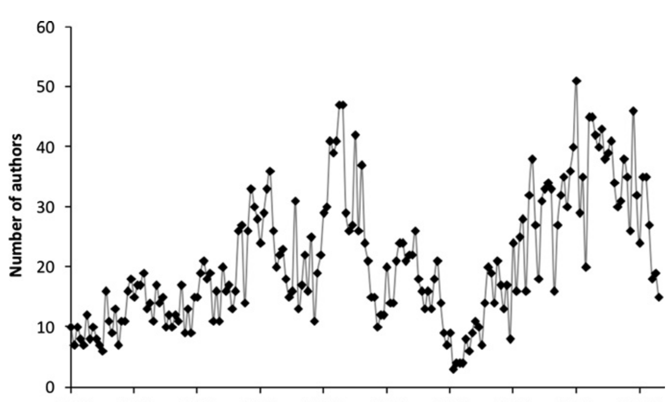


**Fig. 6.** Variation in the number of authors describing Antarctic species since 1822, based upon literature data.

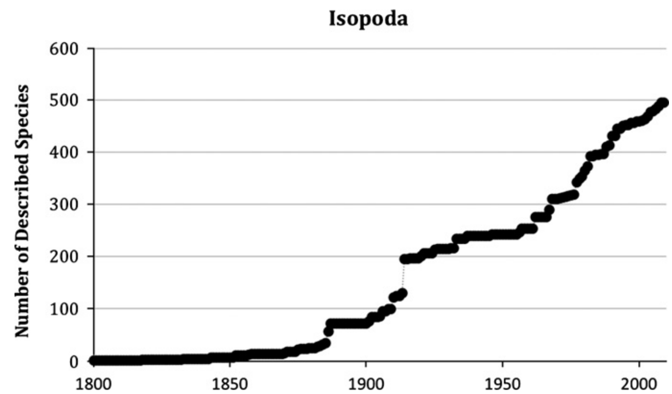


**Fig. 7.** Rate of species description for Antarctic Isopoda along time (yrs), according to the data available in the Register of Antarctic Marine Species (as of March 2010).

### 5.2. The IPY-CAML input

If it is possible to already measure the input of the multiple IPY-CAML voyages in terms of progress of the sampling coverage of the Southern Ocean, then it is too early to evaluate the whole CAML impact on the discovery and knowledge of Antarctic biodiversity. CAML-dedicated cruises explored some unknown parts of the Southern Ocean (deep-sea basins, under shelf communities, etc.) and discovered or investigated unknown or poorly known taxa, e.g. ,gelatinous zooplankton, calcareous or carnivorous sponges, peracarid crustaceans, octopi, etc. This emphasizes the necessity to keep operational the strong CAML/SCAR-MarBIN collaborative network to allow continued access to Antarctic marine biodiversity information and optimization of future collaborations.

## 6. How to improve the taxonomic inputs?

The large number of putative new species discovered by CAML and, more generally, the need to describe the unknown biodiversity before it disappears in a changing world requires imagining and developing new strategies for applied taxonomy.

### 6.1. Improve the taxonomic resources

Biodiversity studies require three different kinds of taxonomic resources: faunistic and floristic inventories, taxonomic systems of reference (classification, nomenclature, synonymy, bibliography), and appropriate identification tools such as monographs, guides, keys, photographic atlases, image recognition software (MacLeod, 2007), or DNA barcoding (Meier, 2008).

Inventorying biodiversity is an -almost- endless activity, but comprehensive and timely benchmarks have to be established when needed. The Rio Convention (even if not directly applicable in the Antarctic Treaty area: see De Broyer et al., 2003), the Millenium Ecosystem Assessment (2005), and the current 2010 International Biodiversity Year (www.cbd.int/2010), have recalled the urgent need to compensate the large gaps in the world biodiversity knowledge and to establish accurate inventories at country and regional levels (Yoon, 1993). CAML and IPY provided the appropriate framework for establishing the benchmark requested by the environmental change perspective in the Southern Ocean.

Openly accessible and dynamic taxonomic systems of reference are currently established in the RAMS and WoRMS frameworks, but systematic revisions remain necessary in many groups. Moreover, these revisions are strongly required in particular by the new phylogenetic insights brought by the developing molecular approaches. A much stronger support should, in general, be given to in-depth taxonomic revision work, which can be useful for decades.

A bibliographical survey of all the available identification guides and tools for the Southern Ocean revealed the lack of efficient and up-to-date identification tools for many invertebrate groups. However, some notable exceptions are worth mentioning, such as the useful series "Synopses of the Antarctic Benthos" (edited by Sieg and Wägele, 1990), Hayward's (1995) monograph on cheilostomous bryozoans, Scott and Marchant's (2005) "Antarctic Marine Protists", Coleman's (2007) synopsis of spinose amphipod families, and very few others. In terms of zooplankton biodiversity, a series of group-specific summaries and keys appears within the Australian Antarctic Research Expedition Notes (e.g., Kirkwood, 1982; O'Sullivan, 1986), and separately for the copepoda (Razouls,1994). The multi-authored extensive monograph "South Atlantic Zooplankton" (Boltovskoy, 1999), provides a substantial overview of the Antarctic pelagic fauna as well as useful identification keys for 30 taxonomic groups. The coverage of ID guides for the Southern Ocean biodiversity should be systematically expanded in order to progressively include the most species-rich and ecologically important groups (such as, for instance, polychaetes, gastropods, amphipods or copepods).

### 6.2. Develop cybertaxonomy

As shown by the RAMS, WoRMS and ERMS (www.marbef.org/data/erms.php) examples, the taxonomic reference systems accessible online have largely proved their usefulness: since its inception, the SCAR-MarBIN website has surpassed 820,000 visitors, 6,200,000 hits, and a total of over 39,000,000 downloaded taxonomic and biogeographic records (Fig. 8, for SCAR-MarBIN online access). A next step is to offer web-based ID tools. Developing electronic interactive keys, such as Delta Intkey (see for instance. www.crustacea.net), Lucid (www.lucidcentral.com), or few other advanced tools, is the way forward in terms of ID tools: they can integrate numerous illustrations, handle multiple-entries, are easy to update, and easier to use by non-specialists. Integrated taxonomic and biogeographic databases including identification capabilities have been recently developed for some taxa (e.g., the "Antarctic Echinoid Database"; David et al., 2004) and are unanimously recognized as extremely useful. In the same line, to facilitate field identifications and in particular ROV images interpretation, an online "Antarctic Field Guide" is being developed in connection with RAMS on the SCAR-MarBIN portal. It will be based on pictures taken in situ or from live or fresh samples (Fig. 9), with identifications checked by experts, and will in turn constitute a main CAML contribution to the Encyclopedia of Life (www.eol.org).

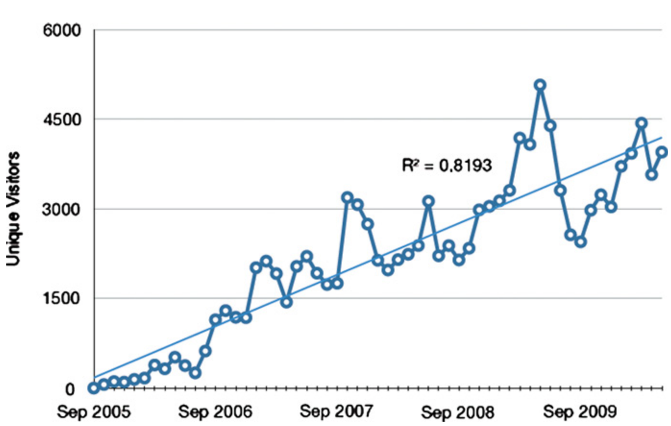


**Fig. 8.** Statistics of use of the www.scarmarbin.be webportal. Number of unique visitors per month along time (yrs). The line describes the best linear fitting of the data, including its associated determination coefficient ($R^2$).

Another common need concerns the online availability of pertinent biodiversity literature related to the Southern Ocean. Diverse initiatives, in particular the Biodiversity Heritage Library (http://www.biodiversitylibrary.org/), are contributing to meeting this demand.

In the same line, CAML and SCAR-MarBIN, with the support of the Total Foundation, have launched an "Antarctic Cybertaxonomy Initiative" to further support the development of electronic interactive keys, integrated taxonomic and biogeographic databases, and monographic revisions available online (http://www.scarmarbin.be/news.php?p=show&id=1223).

### 6.3. Speed up the taxonomic description process

If more efficient and complete identification tools and a better availability of taxonomic information should improve and speed up the identification process, taxonomic description of new taxa still remains a (too) time-consuming process. Improved collaboration and the sharing of tasks (*e.g.* taxa groups) among specialists, and with aid from parataxonomists, may allow saving some time, but more attention should be given to the development of information technology applications, such as automated taxonomic description softwares (e.g., Delta: Dallwitz, 2005).

### 6.4. Develop integrative taxonomy

It is a well-known paradox that there is a general lack of support for (classical) taxonomy and that around the world taxonomic expertise in many groups is vanishing (*e.g.*, Guerra-Garcia et al., 2008; Linse, 2008; Boero, 2010). At the same time there has never been a greater demand on taxonomy to supply the needs of biodiversity knowledge for fundamental and applied science, environmental management, conservation, bio-prospection, or sustainable exploitation purposes. There is obviously a strong need to revitalize taxonomy, and integrating its different approaches is a key element of the way forward (Dayrat, 2005; Wheeler, 2008a).

We are now actively entering the molecular taxonomy era. CAML significantly contributed to the Barcode of Life project (www.barcododinglife.org), trying to obtain a true representation of the Southern Ocean genetic diversity of micro-organisms, macroalgae, invertebrates, seabirds and mammals (Grant and Linse, 2009). Molecular "barcoding" was proved largely useful in providing a molecular diagnostic for species-level identification, particularly in the case of cryptic species. It can also be essential in the identification of different life history stages, strongly sexually dimorphic forms, and undetermined fragments, such as biological tissues, damaged specimens and food items, all of which may be impossible to identify morphologically. On the other hand, beyond the strict barcoding approach, molecular phylogeny insights can significantly contribute building Hennig's (1966) phylogenetic classification system, largely followed today (Wägele, 2004).

However, molecular "barcoding", while bringing invaluable new opportunities, brings also new challenges and has its limitations (Will et al., 2005; Meier, 2008). It should not be seen as an alternative of classical morphology-based taxonomy, or as a unique solution to the taxonomic impediment. The sensible development of the barcoding approach necessarily requires the input of classical, morphology-based taxonomy (Meier, 2008). As

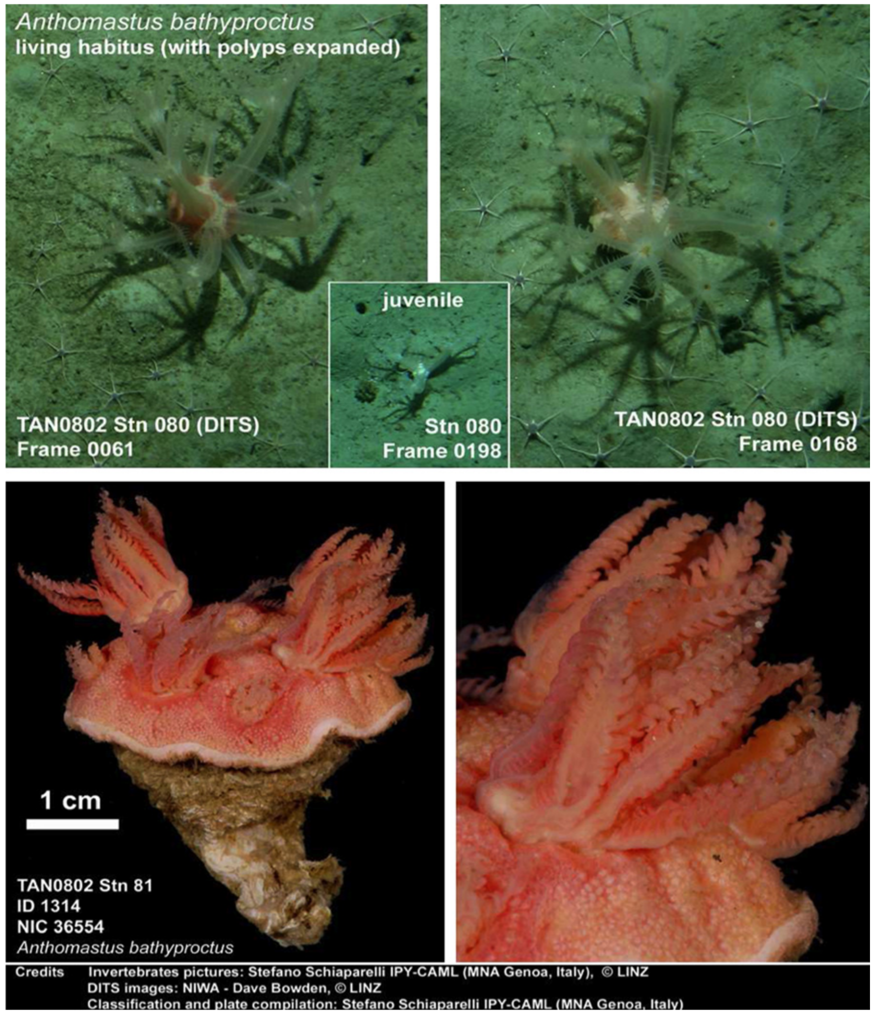


**Fig. 9.** An example of plate illustration that will be available through the new collaborative Antarctic Field Guide initiative.

emphasized by Gutt et al. (2010), *before pretending to replace the classical taxonomy*, the new genetic technology should become "*as applicable as the traditional methods*" for all biologists, and as informative in terms of "*including the accessibility of information about the so far described species*". In addition, "*it must also be guaranteed that genetically defined species serve as proxies for the biologically defined species with at least the same quality as morphologically defined species did in the past*" (Gutt et al., 2010).

## 7. Conclusions: the tip of the iceberg

The Census of Marine Life (CoML) 2000–10 was the largest programme ever devoted to the exploration and understanding of the world marine biodiversity. In addition to significantly improving our knowledge of distribution and abundance of marine life, CoML allowed discovering a substantial number of unknown marine species in an unprecedented way. CAML, as other components of CoML, did recognize and support the key role of taxonomy in a census-oriented program, conducted in the midst of the world biodiversity crisis.

The present paper described how the Register of Antarctic Marine Species (RAMS) has enabled the establishment of the first collaborative, open-access inventory of our present knowledge of Antarctic marine biodiversity, in terms of taxonomy and systematics. Even if the result is tangible, it probably only represents the tip of the iceberg, as RAMS also revealed the scale of our ignorance and the impressive amount of work still to be undertaken to describe all taxa new to science, and to explore the large gaps (spatial and taxonomic) remaining in our knowledge. Among other aspects of the taxonomic impediment, the present rate of description of new taxa is far too slow, and only an extremely sound approach will allow tackling the magnitude of the task (see Wheeler, 2008b). A few elements of this design are described herein, including immediate access to high-quality information, optimized taxonomic revisions, new identification tools, development of cybertaxonomy and ad-hoc information technology applications, involvement of specialists *and* non-specialists, revitalization of morphology-based taxonomy together with the development of molecular approach in an integrative taxonomy perspective.

But most of all, the critical importance of building large databases of biodiversity information should be stressed. Only these large databases, resulting from efficient collaborative efforts, will allow important pure and applied ecological and evolutionary questions to be addressed (see, e.g., Somerfield et al., 2009). Given the fast pace of environmental change in certain regions of the Southern Ocean, and the challenge it represents for its ecosystems, there is a urgent need to document the effect of climate change on life in Antarctic waters. As a significant legacy of the International Polar Year, a Southern Ocean Observing System is being designed, to provide a sustainable network of observatories for physical and biological monitoring (http://www.scar.org/soos). The CAML data, progressively published in SCAR-MarBIN, will contribute to assessing the effects of change on the biota.

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