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STEFAN CHRISTMANN/CORBIS

The aurora australis over the German Antarctic research base, Neumayer-Station III.

Six priorities for Antarctic science

Mahlon C. Kennicutt II, **Steven L. Chown** and colleagues outline the most pressing questions in southern polar research, and call for greater collaboration and environmental protection in the region.

Antarctica. The word conjures up images of mountains draped with glaciers, ferocious seas dotted with icebergs and iconic species found nowhere else. The continent includes about one-tenth of the planet's land surface, nearly 90% of Earth's ice and about 70% of its fresh water. Its encircling ocean supports Patagonian toothfish and krill fisheries, and is crucial for regulating climate and the uptake of carbon dioxide by sea water.

Antarctic scientists are unlocking the secrets of Earth's climate, revealing lakes and mountains beneath the ice, exploring the deep sea and contemplating the origins of life and the Universe. Once seen as a desolate place frozen in time, Antarctica is now known to be experiencing relentless change. Local transformations such as the loss of ice, changes in ocean circulation and recovery of atmospheric ozone have global consequences — for climate, sea level, biodiversity and society.

In April 2014, the Scientific Committee on Antarctic Research (SCAR) convened 75 scientists and policy-makers from 22 countries to agree on the priorities for Antarctic research for the next two decades and beyond. This is the first time that the international Antarctic community has formulated a collective vision, through discussions, debate and voting. The SCAR Antarctic and Southern Ocean Science Horizon Scan narrowed a list of hundreds of scientific questions to the 80 most pressing ones (see Supplementary Information; go.nature.com/iilhsa). A full report will be published in August. ▶

Here we summarize the overarching scientific themes, and outline steps that researchers and governments must take to make this vision a reality. Securing funding, as well as access to and protection for the region, will make greater international collaboration a necessity.

SIX SCIENTIFIC PRIORITIES

The questions identified fall broadly into six themes. To realize the full potential of Antarctic science we need to do the following.

Define the global reach of the Antarctic atmosphere and Southern Ocean. Changes in Antarctica's atmosphere alter the planet's energy budgets, temperature gradients, and air chemistry and circulation. Too little is known about the underlying processes. How do interactions between the atmosphere, ocean and ice control the rate of climate change? How does climate change at the pole influence tropical oceans and monsoons? How will the recovering ozone hole and rising greenhouse-gas concentrations affect regional and global atmospheric circulation and climate?

The Southern Ocean has important roles in the Earth system. It connects the world's oceans to form a global system of currents that transfers heat and CO_2 from the atmosphere to the deep ocean. Nutrients carried north support the base of the ocean's food web. The ocean is becoming more acidic as CO_2 dissolves in sea water, and cold southern waters will be the first to exhibit impacts. How will climate change alter the ocean's ability to absorb heat and CO_2 and to support ocean productivity? Will changes in the Southern Ocean result in feedbacks that accelerate or slow the pace of climate change? Why have the deepest waters of the Southern Ocean become warmer and fresher in the past four decades?

Sea ice reflects and filters sunlight. It modulates how heat, momentum and gases exchange between the ocean and atmosphere. Sea-ice formation and melt dictate the salt content of surface waters, affecting their density and freezing point. What factors control Antarctic sea-ice seasonality, distribution and volume? We need to know.

Understand how, where and why ice sheets lose mass. The Antarctic ice sheet contains about 26.5 million cubic kilometres of ice, enough to raise global sea levels by 60 metres if it returned to the ocean. Having been stable for several thousand years, the Antarctic ice sheet is now losing ice at an accelerating pace[1,2]. What controls this rate and the effect on sea level? Are there thresholds in atmospheric CO_2 concentrations beyond which ice sheets collapse and the seas rise dramatically? How do effects at the base of the ice sheet influence its flow, form and response to warming? Water bodies beneath the thick ice sheet have barely been sampled, and their effect on ice flow is unknown.

Reveal Antarctica's history. Glimpses of the past from rock records collected around the continent's margins suggest that Antarctica might look markedly different in a warmer world. But rocks from the heart of the continent and the surrounding oceans have been only sparsely probed. Responses of the crust to, and the effects of volcanism and heat from Earth's interior on, overlying ice are largely undescribed. We know little about the structure of the Antarctic crust and mantle and how it influenced the creation and break-up of super-continents. Ancient landscapes beneath ice reveal the history of interactions between ice and the solid Earth. Geological signatures of past relative sea level will show when and where planetary ice has been gained or lost. We need more ice, rock and sediment records to know whether past climate states are fated to be repeated.

"Maximizing scientific return while minimizing the human footprint should be the goal."

Learn how Antarctic life evolved and survived. Antarctic ecosystems were long thought of as young, simple, species-poor and isolated. In the past decade a different picture has emerged. Some taxa, such as marine worms (polychaetes) and crustaceans (isopods and amphipods) are highly diverse, and connections between species on the continent, neighbouring islands and the deep sea are greater than thought. Molecular studies reveal that nematodes, mites, midges and freshwater crustaceans survived past glaciations.

To forecast responses to environmental change we need to learn how past events have driven diversifications and extinctions. What are the genomic, molecular and cellular bases of adaptation? How do rates of evolution in the Antarctic compare with elsewhere? Are there irreversible environmental thresholds? And which species respond first?

Observe space and the Universe. The dry, cold and stable Antarctic atmosphere creates some of the best conditions on Earth for observing space. Lakes beneath Antarctic glaciers mimic conditions on Jupiter and Saturn's icy moons, and meteorites collected on the continent reveal how the Solar System formed and inform astrobiology.

We have limited understanding of high-energy particles from solar flares that are funnelled to the poles along the Earth's magnetic field lines. What is the risk of solar events disrupting global communications and power systems? Can we prepare for them and are they predictable?

Recognize and mitigate human influences. Forecasts of human activities and their impacts on the region are required for effective Antarctic governance and regulation. Natural and human impacts must be disentangled. How effective are current regulations in controlling access? How do global policies affect people's motivations to visit the region? How will humans and pathogens affect and adapt to Antarctic environments? What is the current and potential value of Antarctic ecosystem services and how can they be preserved?

CHALLENGING ENVIRONMENT

Answering these many questions will require sustained and stable funding; access to all of Antarctica throughout the year; application of emerging technologies; strengthened protection of the region; growth in international cooperation; and improved communication among all interested parties.

Antarctic programmes are sensitive to budget uncertainties and disruptions. In the past year, US projects were deferred, delayed or reduced in scale because of the US government shutdown in October 2013. Other national programmes suffered budget cuts stemming from the economic slowdown. High fuel prices and diversions for a major search and rescue mission hindered some. Decades-long projects are difficult to sustain given short grant cycles.

Postponed projects and lost field seasons leave gaps — a missing year of data for an ice-sheet study or biodiversity monitoring is irreplaceable. Faced with such uncertainties and hurdles, and with laboratories and students to support, some Antarctic researchers choose to leave the field. This also jeopardizes the recruitment and retention of the next generation of researchers.

Access to locations needed for science is limiting. Much of the continent and the Southern Ocean remain unexplored, and most scientists visit for a only few months each year. Researchers will need to develop autonomous vehicles and observatories that can reach remote locations such as beneath ice shelves, the deep sea and under ice sheets. Miniaturized sensors deployable on floats, animals and ice tethers must be able to acquire or transmit data for months or years.

A wider range of satellite-borne sensors is needed to continuously observe the entire region. Expanded aircraft-based geophysical surveys are needed to access the continental interior and ice margins. Advanced biogeochemical and biological sensors will be crucial for establishing regional patterns. Databases and repositories that can handle vast quantities of genomic and biodiversity information will be essential.

Future data sets will require high-speed and high-volume communications over great distances. Reliable sources of energy to power

MARIA STENZEL/NATIONAL GEOGRAPHIC CREATIVE

Emperor penguins dive under a breathing hole in the Antarctic sea ice, which provides a platform for marine life.

remote observatories and better ways to store and uplink data will be needed. Improved computer models are essential for portraying the highly interconnected Antarctic and Earth system if we are to improve forecasts.

Antarctica's environmental-protection measures must be strengthened[3,4]. More scientists will need to visit, and tourist numbers have almost tripled in the past decade to more than 34,000 a year plus support personnel. This growth increases the risk of introducing non-indigenous species and the likelihood of fuel spills that we are ill-equipped to respond to effectively[3,5].

The Antarctic Treaty System, which is responsible for governance of the region, is being tested by mounting environmental pressures and economic interests[3,6]. The establishment of marine protected areas, international regulation of tourism, assessing financial penalties for environmental damage and regulating bioprospecting have proved difficult to resolve. An integrated strategy for Antarctic environmental management is essential[4].

Antarctica is seen as a place to assert national interests[6]. In the past decade, countries including Belgium, China, the Czech Republic, India and South Korea have established new stations; Germany, the United Kingdom, the United States and others have replaced ageing ones; and Japan, South Korea and South Africa have built or replaced ice-capable ships.

Yet scientists from many other nations lack access to Antarctica. Twenty-nine countries participate in decision-making and another twenty-one have agreed to abide by the Antarctic Treaty. Although this represents about two-thirds of the world population, it comprises less than one-sixth of the 193 member states of the United Nations — countries in Africa and the Middle East are notably under-represented.

WORK TOGETHER

Maximizing scientific return while minimizing the human footprint should be the goal. Coordinated international efforts that engage diverse stakeholders will be crucial.

It is time for nations involved in southern polar research to embrace a renewed spirit of cooperation as espoused by the founders of the Antarctic Treaty — in actions not just words. Wider international partnerships, more coordination of science and infrastructure funding and expanded knowledge-sharing are essential.

As an interdisciplinary scientific body, but not a funder of research, SCAR should assist with and encourage coordination and planning of joint projects, sharing of data and dissemination of knowledge to policy-makers and the public. SCAR should repeat the Horizon Scan exercise every four to six years and provide the outcomes to emerging integrated science, conservation and policy efforts[3,4] (see www.environments.aq).

We urge the Antarctic Treaty and its Committee for Environmental Protection to expand use of scientific evidence in its decision-making and to apply state-of-the-art conservation measures judged on measurable outcomes[7].

Communicating the global importance of Antarctica to the public is a priority[8]. Narratives must better explain how the region affects and is influenced by our daily lives. Antarctic success stories, such as signs of ozone recovery, engender confidence in the power of changes in behaviour.

Antarctic science is globally important. The southern polar community must act together if it is to address some of the most pressing issues facing society. ■

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On behalf of attendees at the 1st SCAR Antarctic and Southern Ocean Science Horizon Scan Retreat, 20–23 April 2014, Queenstown, New Zealand. See go.nature.com/iilhsa for a full list of co-signatories.

Supplementary information to: Six priorities for Antarctic science (Comment in *Nature* 512, 23–25;2014)

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Antarctic Science Horizon Scan Method

Horizon scan methodologies[1,2,3,4] were customized for the Antarctic Science Horizon Scan aiming for broad community engagement and transparent decision-making.

A database of 866 scientific questions was generated by two open community-wide, on-line solicitations. Submitted questions were expected to: i) be answerable by an achievable research design; ii) have a factual answer independent of value judgments; iii) address important gaps in knowledge; iv) be of a spatial and temporal scale that could be addressed by a research team; v) be specifically formulated (not a general topical area) and vi) if related to impact and interventions, contain a subject, an intervention and a measurable outcome[2]. The questions were to be clearly-worded, simple and concise. Questions best addressed by research in the southern polar regions or where studies in the Antarctic provide insights unobtainable elsewhere were encouraged.

The final list of 80 priority scientific questions for future Antarctic research was developed at a 4-day meeting of experts (the Retreat) from 20-23 April 2014 in Queenstown, New Zealand**.** More than 500 potential invitees were nominated via an open, online call. Those 75 invited to attend the Retreat were selected by vote that ensured balance amongst disciplinary expertise, geographic origins, gender, stage of career, and representation from interested parties. Each attendee self-selected the topical sessions to attend at the Retreat.

Prior to the Retreat, attendees voted online for the top ten questions in each of the Day 1 sessions, to identify those questions that could be quickly eliminated. All questions were categorized into 12 topics that were assessed in separate sessions on Day 1 by small groups of Retreat attendees (4 parallel sessions with 3 discussion sessions). In each session, all questions were discussed and where necessary reworded, combined or removed from the list. The remaining questions were then rated by vote. Each session was allocated a certain number of "gold" (high priority), "silver" (very important) and "bronze" (important) questions proportionate to the number of original questions per session.

The 249 top rated questions from Day 1 were then merged and discussed among four sessions on Day 2 (2 parallel sessions with 2 discussion sessions), repeating the Day 1 process. On Day 3, the remaining 162 questions from Day 2 were merged within the gold, silver, and bronze categories for consideration by all attendees in a final, single session of everyone. The process of discussion, rewording and voting was repeated to identify the top 80 gold questions by a vote.

Post-Retreat the final questions were categorized into clusters, and edited for consistency and clarity while maintaining the essence and meaning of the agreed draft question from the Retreat (see the Final Question List).

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The1st SCAR Antarctic and Southern Ocean Science Horizon Scan - Final List of Questions

ANTARCTIC ATMOSPHERE AND GLOBAL CONNECTIONS[1,2]

1. How is climate change and variability in the high southern latitudes connected to lower latitudes including the Tropical Ocean and monsoon systems?
2. How do Antarctic processes affect mid-latitude weather and extreme events?
3. How have teleconnections, feedbacks, and thresholds in decadal and longer term climate variability affected ice sheet response since the Last Glacial Maximum, and how can this inform future climate projections?
4. What drives change in the strength and position of Westerly winds, and what are their effects on ocean circulation, carbon uptake and global teleconnections?
5. How did the climate and atmospheric composition vary prior to the oldest ice records?
6. What controls regional patterns of atmospheric and oceanic warming and cooling in the Antarctic and Southern Ocean? *(Cross-cuts "Southern Ocean")*
7. How can coupling and feedbacks between the atmosphere and the surface (land ice, sea ice and ocean) be better represented in weather and climate models? *(Cross-cuts "Southern Ocean" and "Antarctic Ice Sheet")*
8. Does past amplified warming of Antarctica provide insight into the effects of future warming on climate and ice sheets? *(Cross-cuts "Antarctica Ice Sheet")*
9. Are there CO_2 equivalent thresholds that foretell collapse of all or part of the Antarctic Ice Sheet? *(Cross-cuts "Antarctic Ice Sheet")*
10. Will there be release of greenhouse gases stored in Antarctic and Southern Ocean clathrates, sediments, soils, and permafrost as climate changes? *(Cross-cuts "Dynamic Earth"*)
11. Is the recovery of the ozone hole proceeding as expected and how will its recovery affect regional and global atmospheric circulation, climate and ecosystems? *(Cross-cuts "Antarctic Life" and "Human")*

SOUTHERN OCEAN AND SEA ICE IN A WARMING WORLD[1,2]

12. Will changes in the Southern Ocean result in feedbacks that accelerate or slow the pace of climate change?
13. Why are the properties and volume of Antarctic Bottom Water changing, and what are the consequences for global ocean circulation and climate?
14. How does Southern Ocean circulation, including exchange with lower latitudes, respond to climate forcing?
15. What processes and feedbacks drive changes in the mass, properties and distribution of Antarctic sea ice?
16. How do changes in iceberg numbers and size distribution affect Antarctica and the Southern Ocean?
17. How has Antarctic sea ice extent and volume varied over decadal to millennial time scales?
18. How will changes in ocean surface waves influence Antarctic sea ice and floating glacial ice?
19. How do changes in sea ice extent, seasonality and properties affect Antarctic atmospheric and oceanic circulation? *(Cross-cuts "Antarctic Atmosphere")*
20. How do extreme events affect the Antarctic cryosphere and Southern Ocean? *(Cross-cuts "Antarctic Ice Sheet")*
21. How did the Antarctic cryosphere and the Southern Ocean contribute to glacial-interglacial cycles? *(Cross-cuts "Antarctic Ice Sheet")*
22. How will climate change affect the physical and biological uptake of CO_2 by the Southern Ocean? *(Cross-cuts "Antarctic Life")*
23. How will changes in freshwater inputs affect ocean circulation and ecosystem processes? *(Cross-cuts "Antarctic Life*")

1 Questions are assigned numbers for ease of referencing and do not indicate relative importance or rank-order within or between clusters.
2 Questions that cross-cut clusters are indicated in red.

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ANTARCTIC ICE SHEET AND SEA LEVEL[1,2]

24. How does small-scale morphology in subglacial and continental shelf bathymetry affect Antarctic Ice Sheet response to changing environmental conditions? *(Cross-cuts "Dynamic Earth")*
25. What are the processes and properties that control the form and flow of the Antarctic Ice Sheet?
26. How does subglacial hydrology affect ice sheet dynamics, and how important is it? *(Cross-cuts "Dynamic Earth")*
27. How do the characteristics of the ice sheet bed, such as geothermal heat flux and sediment distribution, affect ice flow and ice sheet stability? *(Cross-cuts Dynamic Earth")*
28. What are the thresholds that lead to irreversible loss of all or part of the Antarctic ice sheet?
29. How will changes in surface melt over the ice shelves and ice sheet evolve, and what will be the impact of these changes?
30. How do oceanic processes beneath ice shelves vary in space and time, how are they modified by sea ice, and do they affect ice loss and ice sheet mass balance? *(Cross-cuts "Southern Ocean")*
31. How will large-scale processes in the Southern Ocean and atmosphere affect the Antarctic Ice Sheet, particularly the rapid disintegration of ice shelves and ice sheet margins? *(Cross-cuts "Antarctic Atmosphere" and "Southern Ocean")*
32. How fast has the Antarctic Ice Sheet changed in the past and what does that tell us about the future?
33. How did marine-based Antarctic ice sheets change during previous inter-glacial periods?
34. How will the sedimentary record beneath the ice sheet inform our knowledge of the presence or absence of continental ice? *(Cross-cuts "Dynamic Earth")*

DYNAMIC EARTH - PROBING BENEATH ANTARCTIC ICE[1,2]

35. How does the bedrock geology under the Antarctic Ice Sheet inform our understanding of supercontinent assembly and break-up through Earth history?
36. Do variations in geothermal heat flux in Antarctica provide a diagnostic signature of sub-ice geology?
37. What is the crust and mantle structure of Antarctica and the Southern Ocean, and how do they affect surface motions due to glacial isostatic adjustment?
38. How does volcanism affect the evolution of the Antarctic lithosphere, ice sheet dynamics, and global climate? *(Cross-cuts "Antarctic Atmosphere" and "Antarctic Ice Sheet")*
39. What are and have been the rates of geomorphic change in different Antarctic regions, and what are the ages of preserved landscapes?
40. How do tectonics, dynamic topography, ice loading and isostatic adjustment affect the spatial pattern of sea level change on all time scales? *(Cross-cuts "Antarctic Ice Sheet")*
41. Will increased deformation and volcanism characterize Antarctica when ice mass is reduced in a warmer world, and if so, how will glacial- and ecosystems be affected? *(Cross-cuts "Antarctic Life")*
42. How will permafrost, the active layer and water availability in Antarctic soils and marine sediments change in a warming climate, and what are the effects on ecosystems and biogeochemical cycles? *(Cross-cuts "Antarctic Life")*

ANTARCTIC LIFE ON THE PRECIPICE[1,2]

43. What is the genomic basis of adaptation in Antarctic and Southern Ocean organisms and communities?
44. How fast are mutation rates and how extensive is gene flow in the Antarctic and the Southern Ocean?
45. How have ecosystems in the Antarctic and the Southern Ocean responded to warmer climate conditions in the past? *(Cross-cuts "Antarctic Atmosphere" and "Oceans")*
46. How has life evolved in the Antarctic in response to dramatic events in the Earth's history? *(Cross-cuts "Dynamic Earth")*
47. How do subglacial systems inform models for the development of life on Earth and elsewhere? *(Cross-cuts "Eyes on the Sky")*
48. Which ecosystems and food webs are most vulnerable in the Antarctic and Southern Ocean, and which organisms are most likely to go extinct?
49. How will threshold transitions vary over different spatial and temporal scales, and how will they impact ecosystem functioning under future environmental conditions?

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50. What are the synergistic effects of multiple stressors and environmental change drivers on Antarctic and Southern Ocean biota?
51. How will organism and ecosystems respond to a changing soundscape in the Southern Ocean?" *(Cross-cuts "Human")*
52. How will next-generation contaminants affect Antarctic and Southern Ocean biota and ecosystems?
53. What is the exposure and response of Antarctic organisms and ecosystems to atmospheric contaminants (e.g. black carbon, mercury, sulphur, etc.), and are the sources and distributions of these contaminants changing? *(Cross-cuts "Antarctic Atmosphere" and "Human")*
54. How will the sources and mechanisms of dispersal of propagules into and around the Antarctic and Southern Ocean change in the future?
55. How will invasive species and range shifts of indigenous species change Antarctic and Southern Ocean ecosystems? *(Cross-cuts "Human")*
56. How will climate change affect the risk of spreading emerging infectious diseases in Antarctica? *(Cross-cuts "Human")*
57. How will increases in the ice-free Antarctic intertidal zone impact biodiversity and the likelihood of biological invasions?
58. How will climate change affect existing and future Southern Ocean fisheries, especially krill stocks? *(Cross-cuts "Human")*
59. How will linkages between marine and terrestrial systems change in the future?
60. What are the impacts of changing seasonality and transitional events on Antarctic and Southern Ocean marine ecology, biogeochemistry, and energy flow?
61. How will increased marine resource harvesting impact Southern Ocean biogeochemical cycles? *(Cross-cuts "Human")*
62. How will deep sea ecosystems respond to modifications of deep water formation, and how will deep sea species interact with shallow water ecosystems as the environment changes?
63. How can changes in the form and frequency of extreme events be used to improve biological understanding and forecasting? *(Cross-cuts "Antarctic Atmosphere")*
64. How can temporal and spatial "omic-level" analyses of Antarctic and Southern Ocean biodiversity inform ecological forecasting?
65. What will key marine species tell us about trophic interactions and their oceanographic drivers such as future shifts in frontal dynamics and stratification?
66. How successful will Southern Ocean Marine Protected Areas be in meeting their protection objectives, and how will they affect ecosystem processes and resource extraction? *(Cross-cuts "Human")*
67. What ex situ conservation measures, such as genetic repositories, are required for the Antarctic and Southern Ocean? *(Cross-cuts "Human")*
68. How effective are Antarctic and Southern Ocean conservation measures for preserving evolutionary potential? *(Cross-cuts "Human")*

NEAR-EARTH SPACE AND BEYOND - EYES ON THE SKY[1,2]

69. What happened in the first second after the Universe began?
70. What is the nature of the dark Universe and how is it affecting us?
71. What are the differences in the inter-hemispheric conjugacy between the ionosphere and that in the lower, middle and upper atmospheres, and what causes those differences?
72. How does space weather influence the polar ionosphere and what are the wider implications for the global atmosphere? *(Cross-cuts "Antarctic Atmosphere")*
73. How do the generation, propagation, variability and climatology of atmospheric waves affect atmospheric processes over Antarctica and the Southern Ocean? *(Cross-cuts "Antarctic Atmosphere")*

HUMAN PRESENCE IN ANTARCTICA[1,2]

74. How can natural and human-induced environmental changes be distinguished, and how will this knowledge affect Antarctic governance? *(Cross-cuts all other Clusters)*
75. What will be the impacts of large-scale, direct human modification of the Antarctic environment? *(Cross-cuts "Antarctic Life")*

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76. How will external pressures and changes in the geopolitical configurations of power affect Antarctic governance and science?
77. How will the use of Antarctica for peaceful purposes and science be maintained as barriers to access change?
78. How will regulatory mechanisms evolve to keep pace with Antarctic tourism?
79. What is the current and potential value of Antarctic ecosystem services?
80. How will humans, diseases and pathogens change, impact and adapt to the extreme Antarctic environment? *(Cross-cuts "Antarctic Life")*

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