Publishing in *Nature*: *a climate science perspective*

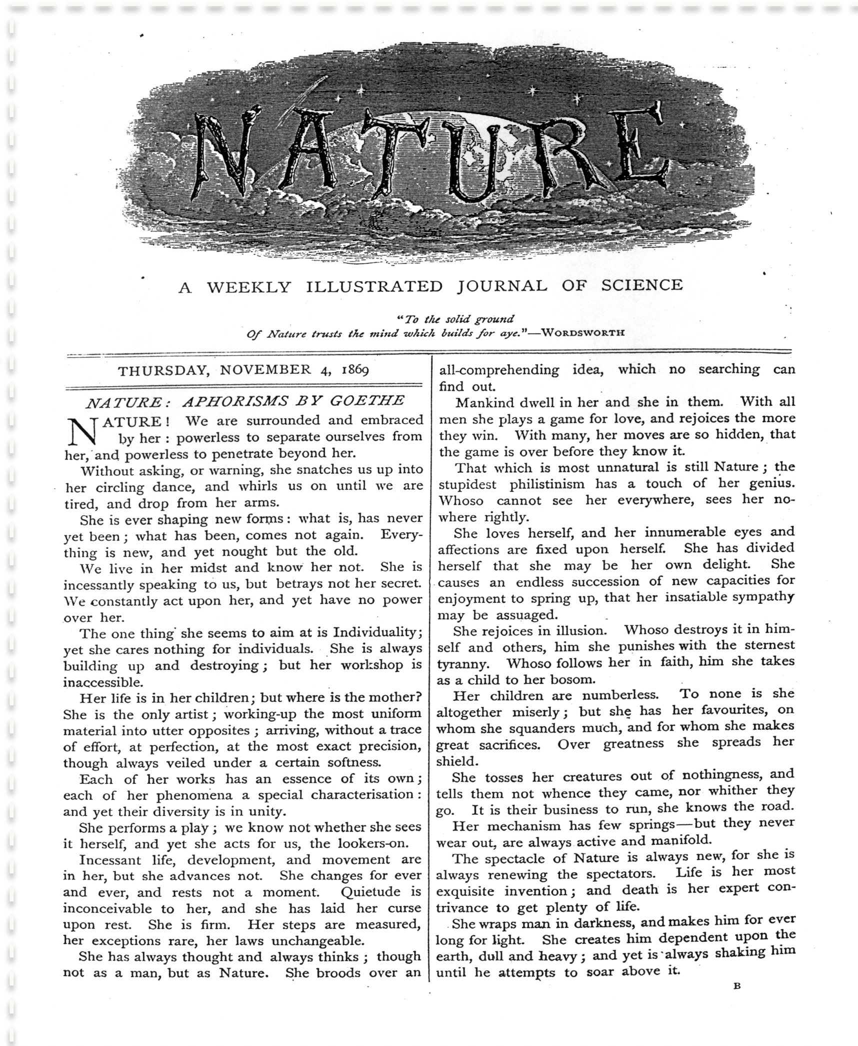
Michael White
Senior Editor
Nature

Today’s talk

Nature and Nature Publishing Group
Nature’s publication procedures

Nature's first issue

- *Nature* was launched in 1869



NATURE

A WEEKLY ILLUSTRATED JOURNAL OF SCIENCE

"To the solid ground
Of Nature trusts the mind which builds for aye."—WORDSWORTH

THURSDAY, NOVEMBER 4, 1869

NATURE: APHORISMS BY GOETHE

NATURE! We are surrounded and embraced by her: powerless to separate ourselves from her, and powerless to penetrate beyond her.

Without asking, or warning, she snatches us up into her circling dance, and whirls us on until we are tired, and drop from her arms.

She is ever shaping new forms: what is, has never yet been; what has been, comes not again. Everything is new, and yet nought but the old.

We live in her midst and know her not. She is incessantly speaking to us, but betrays not her secret. We constantly act upon her, and yet have no power over her.

The one thing she seems to aim at is Individuality; yet she cares nothing for individuals. She is always building up and destroying; but her workshop is inaccessible.

Her life is in her children; but where is the mother? She is the only artist; working-up the most uniform material into utter opposites; arriving, without a trace of effort, at perfection, at the most exact precision, though always veiled under a certain softness.

Each of her works has an essence of its own; each of her phenomena a special characterisation: and yet their diversity is in unity.

She performs a play; we know not whether she sees it herself, and yet she acts for us, the lookers-on.

Incessant life, development, and movement are in her, but she advances not. She changes for ever and ever, and rests not a moment. Quietude is inconceivable to her, and she has laid her curse upon rest. She is firm. Her steps are measured, her exceptions rare, her laws unchangeable.

She has always thought and always thinks; though not as a man, but as Nature. She broods over an all-comprehending idea, which no searching can find out.

Mankind dwell in her and she in them. With all men she plays a game for love, and rejoices the more they win. With many, her moves are so hidden, that the game is over before they know it.

That which is most unnatural is still Nature; the stupidest philistinism has a touch of her genius. Whoso cannot see her everywhere, sees her nowhere rightly.

She loves herself, and her innumerable eyes and affections are fixed upon herself. She has divided herself that she may be her own delight. She causes an endless succession of new capacities for enjoyment to spring up, that her insatiable sympathy may be assuaged.

She rejoices in illusion. Whoso destroys it in himself and others, him she punishes with the sternest tyranny. Whoso follows her in faith, him she takes as a child to her bosom.

Her children are numberless. To none is she altogether miserly; but she has her favourites, on whom she squanders much, and for whom she makes great sacrifices. Over greatness she spreads her shield.

She tosses her creatures out of nothingness, and tells them not whence they came, nor whither they go. It is their business to run, she knows the road.

Her mechanism has few springs—but they never wear out, are always active and manifold.

The spectacle of Nature is always new, for she is always renewing the spectators. Life is her most exquisite invention; and death is her expert contrivance to get plenty of life.

She wraps man in darkness, and makes him for ever long for light. She creates him dependent upon the earth, dull and heavy; and yet is always shaking him until he attempts to soar above it.

B

Acta Pharmacologica Sinica
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Nature sections

THE FRONT HALF

News and Features [Tim Appenzeller]

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THE MIDDLE HALF

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THE BACK HALF

Primary research papers

25 September 2008 front and back cover

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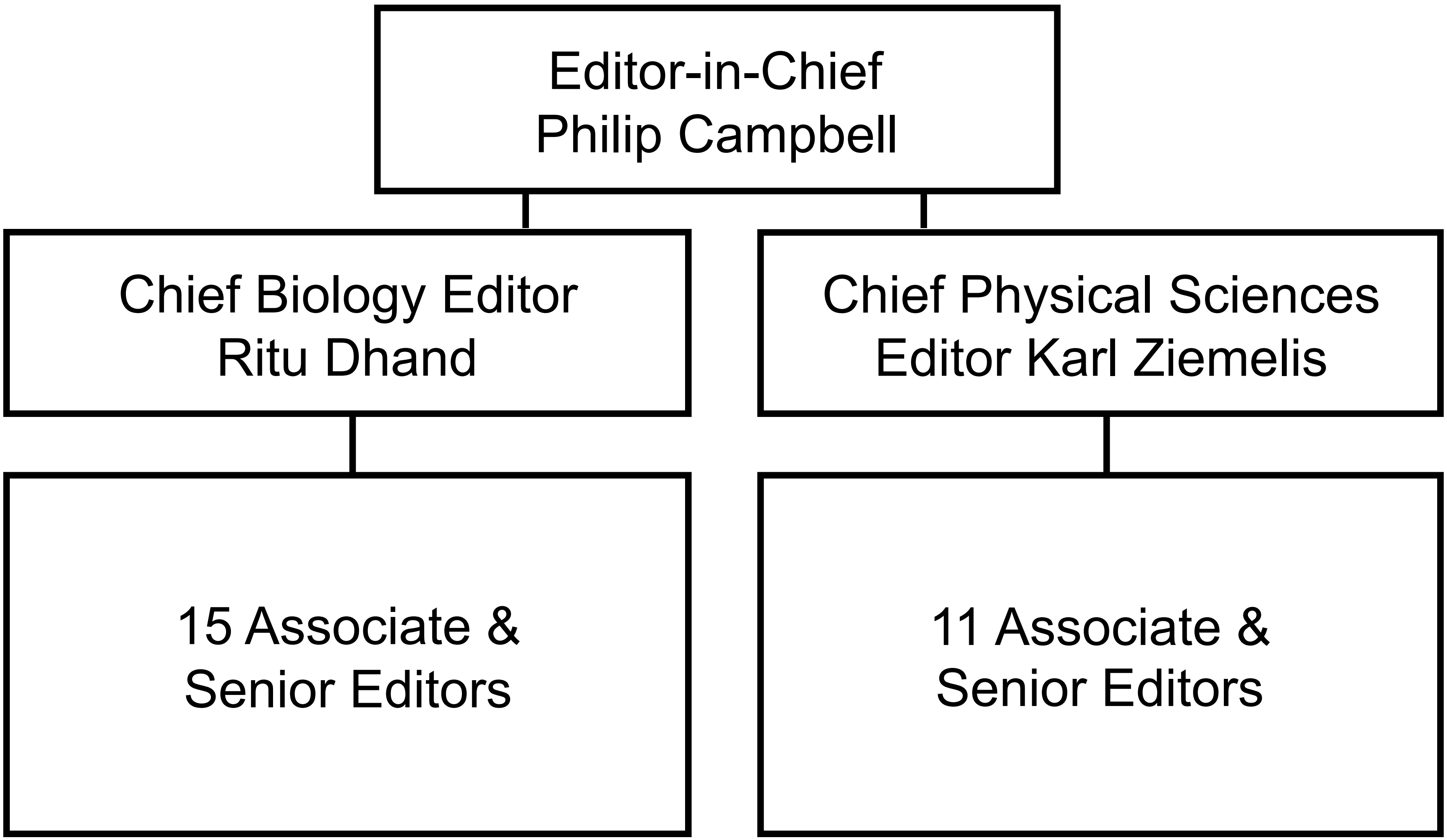

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The wee office

Editor’s responsibilities

Selection of primary research manuscripts for publication

feature

Land and wine

Competition from the New World, a changing climate and technological advances have threatened the Burgundian notion that the quality of wine depends on regional geography and culture. Only flexibility can keep the concept of *terroir* alive.

Cistercian monks began to make wine in the Clos de Vougeot region of Burgundy, France in the late Middle Ages (Fig. 1). Their traditions created the notion, described as *terroir*, that aspects of climate, geology and human culture create a unique characteristic in regional food and beverages, especially wine. The idea was advocated most strongly by the Burgundian cultural historian Gaston Roupnel[1] and cannot be defined in a quantitative manner. Nevertheless, *terroir* — as a cultural, place-based entity springing from centuries of connection between culture (epitomized by the Cistercians) and the cultivation of wine-grapes — was ideologically elevated to the level of an analytic explanation for the quality of certain wines by the mid-twentieth century. This Burgundian concept was so successful that in 1935 it led to the *appellation d’origine contrôlée* (AOC) — a French system that is still used to legally delineate geographical regions and regulate agricultural products (*produits du terroir*), and has been adapted for much of the food-obsessed world.

But the idea of *terroir* is not easily reconciled with mechanized wine production, New World winemaking (focused on wine variety rather than location) and the rise of precision agriculture, which makes use of non-traditional devices such as computer modelling and remote sensing that fall outside the classic idea of *terroir*. In addition, *terroir* is less obviously meaningful in a rapidly changing climate: if a region’s characteristics, including temperature and precipitation patterns, lead to a unique quality of its produce, then rapid and severe change in these circumstances — as expected from global warming in many regions worldwide — must affect the outcome.

Not all facets of *terroir* that comprise the modern notion of the term are supported by scientific analysis, and those that are, such as rainfall and temperature, will probably change in the next few decades. In the face of the challenges from both technology and climate change, the most successful winemakers — either Old World or New World — will be those who achieve two goals simultaneously: the use of modern technology to optimize the making and marketing of wines, and the development and advertising of location and production processes that are unique to their product. To make *terroir* useful as a classification system and marketing tool in a sustainable twenty-first-century wine market, it needs to be defined more flexibly, allowing changes in location or in the varieties of grapes produced at a certain site.

The rise of *terroir*

Terroir achieved its greatest cultural resonance through ardent supporters in twentieth-century Burgundy. In the Burgundian sense, *terroir* is “everything that contributes to the distinction of a vineyard” (ref. 2). Burgundians originally developed the concept as an instrument for identifying the qualities of their wines in terms of geo–climatic origin and authenticated methods of production. However, in addition to marketing wine, Burgundians also used the concept to promote tourism, affirm regional traditions and obtain a comparative advantage over other wine-producing regions. Natural resources, historical memory, modern marketing strategies and revived cultural practices were assembled into an imaginative repertoire of wine festivals and gastronomical fairs that helped sell regional products in general and wine in particular.

In the early twentieth century, a time of debate on the relative importance of cultural versus physical geography, Paul Vidal de la Blache[3] (1845–1918) began to emphasize the importance of empirical and rigorous site studies — a theme that still exists in discussions of *terroir*. Although Vidal was unable to resolve the physical-versus-cultural argument, his empha[illegible]cientific factors presaged the late-twentieth-century rise of precision agriculture.

Still, for much of the twentieth century, the cultural (rather than the scientific) notion of *terroir* held prominence, largely

Figure 1 | ‘The Vintner’ (left) and ‘The Clos de Vougeot’ (right) showing idealized depictions of the rural wine making tradition — woodcuts by Louis William Graux. Reprinted with permission from ref. 1 (© 1936 Gallois family).

Commissioning Reviews

Attending meetings and visiting labs

Consulting with other *Nature* sections

Writing when time permits

Publication process

The process should not be a mystery
… and it is not a conspiracy!

Key steps

Cover letter

Editor assignment and selection

Peer review

Decisions after review

Appeals

November 26, 2002

Editor
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Dear Editor,

It is not clear why a cover letter is required except to fulfill the silly British preoccupation with letterhead and other emblems of status.

Please accept my correspondence.

Sincerely,

The cover letter

Why should *Nature* publish your study?

Suggest and exclude referees

Identify related manuscripts

Alert us to potential competition

Editor assignment and manuscript selection

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Editorial criteria

New and significant insight

?

What do Nature editors look for?

Scientific significance

- Data compellingly supports conclusions
- Novelty
- Broadly interesting for the journal's readership
- Significant step forward
- Impact in the field
- Provides new directions for research

nature Vol 459|4 June 2009|doi:10.1038/nature08024

LETTERS

The Gamburtsev mountains and the origin and early evolution of the Antarctic Ice Sheet

Sun Bo[1], Martin J. Siegert[2], Simon M. Mudd[2], David Sugden[2], Shuji Fujita[3], Cui Xiangbin[1], Jiang Yunyun[1], Tang Xueyuan[1] & Li Yuansheng[1]

Ice-sheet development in Antarctica was a result of significant and rapid global climate change about 34 million years ago[1]. Ice-sheet and climate modelling suggest reductions in atmospheric carbon dioxide (less than three times the pre-industrial level of 280 parts per million by volume) that, in conjunction with the development of the Antarctic Circumpolar Current, led to cooling and glaciation paced by changes in Earth's orbit[2]. Based on the present subglacial topography, numerical models point to ice-sheet genesis on mountain massifs of Antarctica, including the Gamburtsev mountains at Dome A, the centre of the present ice sheet[2,3]. Our lack of knowledge of the present-day topography of the Gamburtsev mountains[4] means, however, that the nature of early glaciation and subsequent development of a continental-sized ice sheet are uncertain. Here we present radar information about the base of the ice at Dome A, revealing classic Alpine topography with pre-existing river valleys overdeepened by valley glaciers formed when the mean summer surface temperature was around 3 °C. This landscape is likely to have developed during the initial phases of Antarctic glaciation. According to Antarctic climate history (estimated from offshore sediment records) the Gamburtsev mountains are probably older than 34 million years and were the main centre for ice-sheet growth. Moreover, the landscape has most probably been preserved beneath the present ice sheet for around 14 million years.

Deep-sea oxygen isotope records show that the Eocene and Oligocene epochs represent times of global cooling culminating in the development of the first Antarctic Ice Sheet and an important expansion of Antarctic ice volume[1]. The Eocene (~52 to ~34 million years (Myr) ago) is characterized by a global cooling trend which continued during the remainder of the Cenozoic era. Subsequently there were two stepped changes in the rate of cooling. The first, at the Eocene–Oligocene boundary ~34 Myr ago, saw the onset of significant glaciation in Antarctica. The second, at ~14 Myr ago, is recorded by a 6–7 °C cooling in the marine isotope record[5,6] and in terrestrial evidence of cooling of at least 8 °C in the Transantarctic mountains[7].

Two approaches to modelling the initial growth of the Antarctic Ice Sheet show that glaciation begins in the upland mountain massifs of Antarctica, at coastal Dronning Maud Land, the Transantarctic mountains, and the Gamburtsev mountains beneath Dome A[2,8]. This central dome dominates glaciation because of its high altitude and consequent cold surface temperatures. Ice-sheet modelling, ocean cores and stratigraphic evidence suggest that for 20 million years, from 34 to 14 Myr ago, Antarctica experienced orbitally driven ice-volume fluctuations similar in scale to those of the Pleistocene ice sheets of the Northern Hemisphere and that these fluctuations were accompanied by marked changes in global sea level[2,9–11]. Tundra biota survived at high altitudes during this period[7]. After 14 Myr the ice sheet, at least in higher mountain peripheries in East Antarctica, maintained its presence and control over the cold polar climate of today, leading to extremely low rates of erosion[12], cold-based local glaciers[13] and even the preservation of buried Miocene ice[14].

Our knowledge of the subglacial topography at Dome A has been obtained during only one radar flight in the 1970s[4,15,16]. Consequently, the present form and evolution of the Gamburtsev mountains are poorly understood, making models of ice-sheet inception problematic. Indeed, the morphology of the mountains is less well known than the surface of Mars.

In seasons 2004/05 and 2007/08, Chinese glaciologists made the first detailed radar survey of the Gamburtsev mountains (as part of the International Polar Year programme Chinese Antarctic Research Expedition; CHINARE). The bed was detected in the majority of radar lines (Fig. 1), and by subtracting ice thickness from surface elevation (measured by GPS) the elevation of the bed could be found. The bed elevations were then interpolated[17] onto a regular grid with pixel resolution of 140.5 m (see Methods Summary and Supplementary Methods for interpolation details). The unprecedented density of radar transects in this region means that the resulting Digital Elevation Model (DEM) provides the first detailed depiction of the topography of the central Gamburtsev mountains (Fig. 2).

The topography revealed beneath the ice is striking (Fig. 2 and Supplementary Fig. 1). The region consists of a south-facing elongated valley head, cutting over a kilometre into flanking mountains. The whole region is covered by ice 1,649–3,135 m thick. The maximum elevation of the topography is 2,434 m above sea level at 80° 18′ S, 76° 10′ E. The valley geometry is dendritic. We highlight this geometry by extracting a drainage network using standard methods[18] (Fig. 2, Supplementary Discussion 1). Recent numerical modelling, backed by empirical observations, has shown that ice cannot create such networks alone; subglacial topography takes this form only when ice exploits pre-existing fluvial topography (Supplementary Fig. 2)[8,19]. This fluvial landscape has subsequently been subject to intense valley glaciation, as demonstrated by overdeepening in the valley floors of up to 432 m and the presence of steep trough sides. It is also shown by details such as the location of overdeepened basins at points of valley convergence, staircases of intervening riegels or valley steps, hanging tributary valleys, and corries with steep arcuate cliffs and flat floors at the head of some tributary valleys (Fig. 3); such features are characteristic of landscapes shaped by valley glaciers[20,21]. Hanging valleys are formed when ice ponds in tributary glaciers as they enter the trunk glacier; this ponding leads to reduced ice surface slopes, which in turn reduces shear stress and sliding velocities at the glacier bed, ultimately reducing erosive capacity in the tributary glacier[20,21]. Another effect of

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Discoveries

ARTICLE

doi:10.1038/nature10915

Global warming preceded by increasing carbon dioxide concentrations during the last deglaciation

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The covariation of carbon dioxide (CO_2) concentration and temperature in Antarctic ice-core records suggests a close link between CO_2 and climate during the Pleistocene ice ages. The role and relative importance of CO_2 in producing these climate changes remains unclear, however, in part because the ice-core deuterium record reflects local rather than global temperature. Here we construct a record of global surface temperature from 80 proxy records and show that temperature is correlated with and generally lags CO_2 during the last (that is, the most recent) deglaciation. Differences between the respective temperature changes of the Northern Hemisphere and Southern Hemisphere parallel variations in the strength of the Atlantic meridional overturning circulation recorded in marine sediments. These observations, together with transient global climate model simulations, support the conclusion that an antiphased hemispheric temperature response to ocean circulation changes superimposed on globally in-phase warming driven by increasing CO_2 concentrations is an explanation for much of the temperature change at the end of the most recent ice age.

Understanding the causes of the Pleistocene ice ages has been a significant question in climate dynamics since they were discovered in the mid-nineteenth century. The identification of orbital frequencies in the marine $^{18}O/^{16}O$ record, a proxy for global ice volume, in the 1970s demonstrated that glacial cycles are ultimately paced by astronomical forcing[1]. Initial measurements of air bubbles in Antarctic ice cores in the 1980s revealed that greenhouse gas concentrations also increased and decreased over the last glacial cycle[2,3], suggesting they too may be part of the explanation. The ice-core record now extends back 800,000 yr and shows that local Antarctic temperature was strongly correlated with and seems to have slightly led changes in CO_2 concentration[4]. The implication of this relationship for understanding the role of CO_2 in glacial cycles, however, remains unclear. For instance, proxy data have variously been interpreted to suggest that CO_2 was the primary driver of the ice ages[5], a more modest feedback on warming[6,7] or, perhaps, largely a consequence rather than cause of past climate change[8]. Similarly, although climate models generally require greenhouse gases to explain globalization of the ice-age signal, they predict a wide range (one-third to two-thirds) in the contribution of greenhouse gases to ice-age cooling, with additional contributions from ice albedo and other effects[9,10]. Moreover, models have generally used prescribed forcings to simulate snapshots in time and thus by design do not distinguish the timing of changes in various forcings relative to responses.

Global temperature reconstructions and transient model simulations spanning the past century and millennium have been essential to the attribution of recent climate change, and a similar strategy would probably improve our understanding of glacial cycle dynamics. Here we use a network of proxy temperature records that provide broad spatial coverage to show that global temperature closely tracked the increase in CO_2 concentration over the last deglaciation, and that variations in the Atlantic meridional overturning circulation (AMOC) caused a seesawing of heat between the hemispheres, supporting an early hypothesis that identified potentially important roles for these mechanisms[11]. These findings, supported by transient simulations with a coupled ocean–atmosphere general circulation model, can explain the lag of CO_2 behind Antarctic temperature in the ice-core record and are consistent with an important role for CO_2 in driving global climate change over glacial cycles.

Global temperature

We calculate the area-weighted mean of 80 globally distributed, high-resolution proxy temperature records to reconstruct global surface temperature during the last deglaciation (Methods and Fig. 1). The global temperature stack shows a two-step rise, with most warming occurring during and right after the Oldest Dryas and Younger Dryas intervals and relatively little temperature change during the Last Glacial Maximum (LGM), the Bølling–Allerød interval and the early Holocene epoch (Fig. 2a). The atmospheric CO_2 record from the EPICA Dome C ice core[12], which has recently been placed on a more accurate timescale[13], has a similar two-step structure and is strongly correlated with the temperature stack ($r^2 = 0.94$ (coefficient of determination), $P = 0.03$; Fig. 2a).

Lag correlations quantify the timing of change in the temperature stack relative to CO_2 from 20–10 kyr ago, an interval that spans the period during which low LGM CO_2 concentrations increased to almost pre-industrial values. Our results indicate that CO_2 probably leads global warming over the course of the deglaciation (Fig. 2b). A comparison of the global temperature stack with Antarctic temperature provides further support for this relative timing, in showing that

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Fundamental revisions to our framework of understanding

LETTER

doi:10.1038/nature10891

Collapse of polar ice sheets during the stage 11 interglacial

Maureen E. Raymo[1] & Jerry X. Mitrovica[2]

Contentious observations of Pleistocene shoreline features on the tectonically stable islands of Bermuda and the Bahamas have suggested that sea level about 400,000 years ago was more than 20 metres higher than it is today[1–4]. Geochronologic and geomorphic evidence indicates that these features formed during interglacial marine isotope stage (MIS) 11, an unusually long interval of warmth during the ice age[1–4]. Previous work has advanced two divergent hypotheses for these shoreline features: first, significant melting of the East Antarctic Ice Sheet, in addition to the collapse of the West Antarctic Ice Sheet and the Greenland Ice Sheet[1–3]; or second, emplacement by a mega-tsunami during MIS 11 (ref. 4, 5). Here we show that the elevations of these features are corrected downwards by ~10 metres when we account for post-glacial crustal subsidence of these sites over the course of the anomalously long interglacial. On the basis of this correction, we estimate that eustatic sea level rose to ~6–13 m above the present-day value in the second half of MIS 11. This suggests that both the Greenland Ice Sheet and the West Antarctic Ice Sheet collapsed during the protracted warm period while changes in the volume of the East Antarctic Ice Sheet were relatively minor, thereby resolving the long-standing controversy over the stability of the East Antarctic Ice Sheet during MIS 11.

The stability of ice sheets in the face of continuing global warming is an issue of significant societal concern. Satellite gravity measurements indicate that the Greenland Ice Sheet (GIS) and the West Antarctic Ice Sheet (WAIS), the two ice sheets most susceptible to climate change, are experiencing a net mass loss[6–9], with evidence of an accelerating pace[9–12]. In contrast, the current mass balance of the much larger East Antarctic Ice Sheet (EAIS) is uncertain, even in sign[6,9], though a recent study[11] has inferred EAIS mass loss localized to coastal regions. This uncertainty about the stability of the EAIS in a progressively warming world has been a key motivation for studies of the palaeoclimate record during past warm intervals.

One such study, a statistical analysis of widely distributed sea-level markers related to the last interglacial (MIS 5e; about 120,000 years ago), concluded with 95% confidence that eustatic sea level (ESL; defined as the globally averaged sea-level change) was >6.6 m higher during MIS 5e than at the present day, and with 66% confidence that ESL was >8.0 m higher[13]. (This inference, higher than earlier estimates[14], is supported by a recent analysis of MIS 5e sea-level records from Florida[15].) Estimates of the ESL rise associated with collapse of polar ice sheets range from 3.4 m (ref. 16) to 7 m for the GIS, and from 3.2 m (ref. 17) to 5 m for the WAIS, where the upper bounds refer to the complete disappearance of the ice sheet. Thus, whereas the estimate of peak ESL during MIS 5e implies significant collapse of both the GIS and the WAIS, it also implies that the EAIS remained relatively stable.

It is within this context of assessing potential future instability of the EAIS that the sea-level highstand features found at ~20 m (here and elsewhere, height above present-day sea level is meant) in Bermuda and the Bahamas, and which formed during the MIS 11 interglacial (~424–395 kyr ago), have taken on great significance. MIS 11 spanned two precession cycles and was the longest interglacial of the past 500 kyr (refs 18, 19), including the current interglacial MIS 1 (Fig. 1) and MIS 5e (Supplementary Fig. 4). If the ESL during the MIS 11 interglacial peaked at a level 20 m higher than today[1–3], then at least 8 m of that rise must have come from melting of the EAIS. Geologic evidence for a ~20-m sea-level highstand in Bermuda and the Bahamas is convincing. In Bermuda, reasonably well-dated deposits with thalassinidean shrimp burrows, foraminifera, and gastropods characteristic of littoral and intertidal environments constrain relative sea level at 21.3 ± 1.0 m during MIS 11 (refs. 2, 3). On Eleuthera, in the Bahamas, a gently sloping erosion surface capped with fenestrae-rich intertidal beach deposits provides a maximum sea-level estimate of 20 ± 3 m, and the occurrence of pendant fibrous cements suggests a minimum sea level of 17 ± 2 m (we will henceforth quote a sea-level estimate of 18.5 ± 3.6 m for this site); multiple dating methods suggest that these deposits were formed during MIS 11 (ref. 1).

How do these observations compare to other MIS 11 sea-level indicators or proxies? In a recent survey of MIS 11 sea-level records worldwide (most of which are located in tectonically active regions), Bowen[5] estimated peak MIS 11 sea level using a range of tectonic uplift

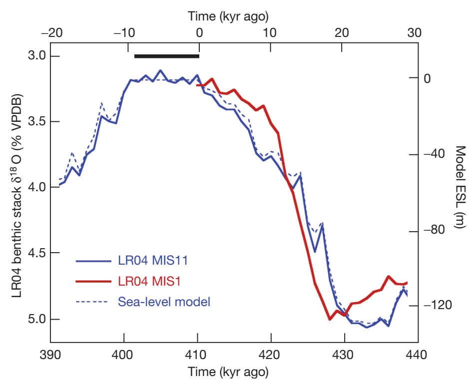

Figure 1 | Comparison of the duration of the MIS 11 and MIS 1 interglacials. Plot of the LR04 benthic oxygen isotope stack[28] (left-hand vertical axis) over a time window spanning the MIS 11 (blue; bottom time scale) and MIS 1 (red; top time scale) interglacials. The mean standard error on $\delta^{18}O$ in the LR04 stack is 0.06‰ with an age error of ±4 kyr for the intervals considered here. The juxtaposition illustrates the significantly longer duration of maximum interglacial conditions during MIS 11 relative to MIS 1. ESL associated with the model ice history used to calculate GIA effects during MIS 11 is shown by dashed line (right-hand vertical axis). Note the hiatus in model ice volume changes from 410 to 401 kyr ago (black bar). An analogous comparison between the duration of MIS 11 with MIS 5e can be found in Supplementary Fig. 4.

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Resolution of a controversy

ARTICLE

doi:10.1038/nature10556

Unprecedented Arctic ozone loss in 2011

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Chemical ozone destruction occurs over both polar regions in local winter–spring. In the Antarctic, essentially complete removal of lower-stratospheric ozone currently results in an ozone hole every year, whereas in the Arctic, ozone loss is highly variable and has until now been much more limited. Here we demonstrate that chemical ozone destruction over the Arctic in early 2011 was—for the first time in the observational record—comparable to that in the Antarctic ozone hole. Unusually long-lasting cold conditions in the Arctic lower stratosphere led to persistent enhancement in ozone-destroying forms of chlorine and to unprecedented ozone loss, which exceeded 80 per cent over 18–20 kilometres altitude. Our results show that Arctic ozone holes are possible even with temperatures much milder than those in the Antarctic. We cannot at present predict when such severe Arctic ozone depletion may be matched or exceeded.

Since the emergence of the Antarctic 'ozone hole' in the 1980s[1] and elucidation of the chemical mechanisms[2–5] and meteorological conditions[6] involved in its formation, the likelihood of extreme ozone depletion over the Arctic has been debated. Similar processes are at work in the polar lower stratosphere in both hemispheres, but differences in the evolution of the winter polar vortex and associated polar temperatures have in the past led to vastly disparate degrees of springtime ozone destruction in the Arctic and Antarctic. We show that chemical ozone loss in spring 2011 far exceeded any previously observed over the Arctic. For the first time, sufficient loss occurred to reasonably be described as an Arctic ozone hole.

Arctic polar processing in 2010–11

In the winter polar lower stratosphere, low temperatures induce condensation of water vapour and nitric acid (HNO_3) into polar stratospheric clouds (PSCs). PSCs and other cold aerosols provide surfaces for heterogeneous conversion of chlorine from longer-lived reservoir species, such as chlorine nitrate ($ClONO_2$) and hydrogen chloride (HCl), into reactive (ozone-destroying) forms, with chlorine monoxide (ClO) predominant in daylight[5,7].

In the Antarctic, enhanced ClO is usually present for 4–5 months (through to the end of September)[8–11], leading to destruction of most of the ozone in the polar vortex between ~14 and 20 km altitude[7]. Although ClO enhancement comparable to that in the Antarctic occurs at some times and altitudes in most Arctic winters[9], it rarely persists for more than 2–3 months, even in the coldest years[10]. Thus chemical ozone loss in the Arctic has until now been limited, with largest previous losses observed in 2005, 2000 and 1996[7,12–14].

The 2010–11 Arctic winter–spring was characterized by an anomalously strong stratospheric polar vortex and an atypically long continuously cold period. In February–March 2011, the barrier to transport at the Arctic vortex edge was the strongest in either hemisphere in the last ~30 years (Fig. 1a, Supplementary Discussion).

The persistence of a strong, cold vortex from December through to the end of March was unprecedented. In the previous years with most ozone loss, temperatures (T) rose above the threshold associated with chlorine activation (T_{act}, near 196 K, roughly the threshold for the potential existence of PSCs) by early March (Fig. 1b, Supplementary Figs 1, 2). Only in 2011 and 1997 have Arctic temperatures below T_{act} persisted through to the end of March, sporadically approaching a vortex volume fraction similar in size to that in some Antarctic winters (Fig. 1b). In 1996–97, however, the cold volume remained very limited until mid-January and was smaller than that in 2011 at most times during late January through to the end of March (Fig. 1b, Supplementary Figs 1, 2).

Daily minimum temperatures in the 2010–11 Arctic winter were not unusually low, but the persistently cold region was remarkably deep (Supplementary Figs 1, 2). Temperatures were below T_{act} for more than 100 days over an altitude range of ~15–23 km, compared to a similarly prolonged cold period over only ~20–23 km altitude in 1997; below ~19 km altitude, $T < T_{act}$ continued for ~30 days longer in 2011 than in 1997 (Supplementary Fig. 1b). In 2005, the previous year with largest Arctic ozone loss[7], $T < T_{act}$ occurred for more than 100 days over ~17–23 km altitude, but all before early March.

The winter mean volume of air in which PSCs may form (that is, with $T < T_{act}$), V_{psc}, is closely correlated with the potential for ozone loss[7,15–17]. In 2011, V_{psc} (as a fraction of the vortex volume) was the largest on record (Fig. 1c). Both large V_{psc} and cold lingering well into spring are important in producing severe chemical loss[7,15,16], and 2010–11 was the only Arctic winter during which both conditions have been met. Much lower fractional V_{psc} in 1997 than in 1996, 2000, 2005 or 2011 (Fig. 1c) is consistent with less ozone loss that year[16,17].

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Startling findings with immediate relevance

LETTER

doi:10.1038/nature10847

Recent contributions of glaciers and ice caps to sea level rise

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Glaciers and ice caps (GICs) are important contributors to present-day global mean sea level rise[1–4]. Most previous global mass balance estimates for GICs rely on extrapolation of sparse mass balance measurements[1,2,4] representing only a small fraction of the GIC area, leaving their overall contribution to sea level rise unclear. Here we show that GICs, excluding the Greenland and Antarctic peripheral GICs, lost mass at a rate of 148 ± 30 Gt yr^{-1} from January 2003 to December 2010, contributing 0.41 ± 0.08 mm yr^{-1} to sea level rise. Our results are based on a global, simultaneous inversion of monthly GRACE-derived satellite gravity fields, from which we calculate the mass change over all ice-covered regions greater in area than 100 km^2. The GIC rate for 2003–2010 is about 30 per cent smaller than the previous mass balance estimate that most closely matches our study period[2]. The high mountains of Asia, in particular, show a mass loss of only 4 ± 20 Gt yr^{-1} for 2003–2010, compared with 47–55 Gt yr^{-1} in previously published estimates[2,5]. For completeness, we also estimate that the Greenland and Antarctic ice sheets, including their peripheral GICs, contributed 1.06 ± 0.19 mm yr^{-1} to sea level rise over the same time period. The total contribution to sea level rise from all ice-covered regions is thus 1.48 ± 0.26 mm yr^{-1}, which agrees well with independent estimates of sea level rise originating from land ice loss and other terrestrial sources[6].

Interpolation of sparse mass balance measurements on selected glaciers is usually used to estimate global GIC mass balance[1,2,4]. Models are also used[3,7], but these depend on the quality of input climate data and include simplified glacial processes. Excluding Greenland and Antarctic peripheral GICs (PGICs), GICs have variously been reported to have contributed 0.43–0.51 mm yr^{-1} to sea level rise (SLR) during 1961–2004[3,7,8], 0.77 mm yr^{-1} during 2001–2004[8], 1.12 mm yr^{-1} during 2001–2005[1] and 0.95 mm yr^{-1} during 2002–2006[2].

The Gravity Recovery and Climate Experiment (GRACE) satellite mission[9] has provided monthly, global gravity field solutions since 2002, allowing users to calculate mass variations at the Earth's surface[10]. GRACE has been used to monitor the mass balance of selected GIC regions[11–14] that show large ice mass loss, as well as of Antarctica and Greenland[15].

Here we present a GRACE solution that details individual mass balance results for every region of Earth with large ice-covered areas. The main focus of this paper is on GICs, excluding Antarctic and Greenland PGICs. For completeness, however, we also include results for the Antarctic and Greenland ice sheets with their PGICs. GRACE does not have the resolution to separate the Greenland and Antarctic ice sheets from their PGICs. All results are computed for the same 8-yr time period (2003–2010).

To determine losses of individual GIC regions, we cover each region with one or more 'mascons' (small, arbitrarily defined regions of Earth) and fit mass values for each mascon (ref. 16 and Supplementary Information) to the GRACE gravity fields, after correcting for hydrology and for glacial isostatic adjustment (GIA) computed using the ICE-5G deglaciation model. We use 94 monthly GRACE solutions from the University of Texas Center for Space Research, spanning January 2003 to December 2010. The GIA corrections do not include the effects of post-Little Ice Age (LIA) isostatic rebound, which we separately evaluate and remove. All above contributions and their effects on the GRACE solutions are discussed in Supplementary Information.

Figure 1 shows mascons for all ice-covered regions, constructed from the Digital Chart of the World[17] and the Circum-Arctic Map of Permafrost and Ground-Ice Conditions[18]. Each ice-covered region is chosen as a single mascon, or as the union of several non-overlapping mascons. We group 175 mascons into 20 regions. Geographically isolated regions with glacierized areas less than 100 km^2 in area are excluded. Because GRACE detects total mass change, its results for an ice-covered region are independent of the glacierized surface area (Supplementary Information).

Mass balance rates for each region are shown in Table 1 (see Supplementary Information for details on the computation of the rates and uncertainties). We note that Table 1 includes a few positive rates, but none are significantly different from zero. We also performed an inversion with GRACE fields from the GFZ German Research Centre for Geosciences and obtained results that agreed with those from the Center for Space Research (Table 1) to within 5% for each region.

The results in Table 1 are in general agreement with previous GRACE studies for the large mass loss regions of the Canadian Arctic[12] and Patagonia[11], as well as for the Greenland and Antarctic ice sheets with

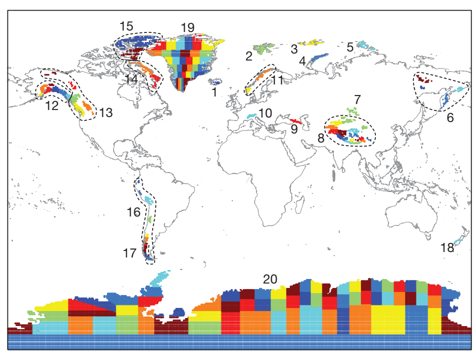

Figure 1 | Mascons for the ice-covered regions considered here. Each coloured region represents a single mascon. Numbers correspond to regions shown in Table 1. Regions containing more than one mascon are outlined with a dashed line.

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Important quantifications

LETTER

doi:10.1038/nature10946

Aerosols implicated as a prime driver of twentieth-century North Atlantic climate variability

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Systematic climate shifts have been linked to multidecadal variability in observed sea surface temperatures in the North Atlantic Ocean[1]. These links are extensive, influencing a range of climate processes such as hurricane activity[2] and African Sahel[3–5] and Amazonian[5] droughts. The variability is distinct from historical global-mean temperature changes and is commonly attributed to natural ocean oscillations[6–10]. A number of studies have provided evidence that aerosols can influence long-term changes in sea surface temperatures[11,12], but climate models have so far failed to reproduce these interactions[6,9] and the role of aerosols in decadal variability remains unclear. Here we use a state-of-the-art Earth system climate model to show that aerosol emissions and periods of volcanic activity explain 76 per cent of the simulated multidecadal variance in detrended 1860–2005 North Atlantic sea surface temperatures. After 1950, simulated variability is within observational estimates; our estimates for 1910–1940 capture twice the warming of previous generation models but do not explain the entire observed trend. Other processes, such as ocean circulation, may also have contributed to variability in the early twentieth century. Mechanistically, we find that inclusion of aerosol–cloud microphysical effects, which were included in few previous multimodel ensembles, dominates the magnitude (80 per cent) and the spatial pattern of the total surface aerosol forcing in the North Atlantic. Our findings suggest that anthropogenic aerosol emissions influenced a range of societally important historical climate events such as peaks in hurricane activity and Sahel drought. Decadal-scale model predictions of regional Atlantic climate will probably be improved by incorporating aerosol–cloud microphysical interactions and estimates of future concentrations of aerosols, emissions of which are directly addressable by policy actions.

An understanding of North Atlantic sea surface temperature (NASST) variability is critical to society because historical Atlantic temperature changes are strongly linked to the climate, and its impacts, in neighbouring continental regions. For example, strong links between NASST variability and periods of African Sahel drought are found in observations[4,13] and physical climate models[3,5,14]. Similar covariation between NASSTs and rainfall in eastern South America has been found[5], as have links to changes in both mean rainfall[15] and rainfall extremes[16], Atlantic hurricane activity[2,10,14] and European summer climate[8]. These changes are not solely limited to the regions bordering the Atlantic, but also have links to Indian monsoon rainfall[14], Arctic and Antarctic temperatures[17], Hadley circulation[1], El Niño/Southern Oscillation[18] and relationships between El Niño/Southern Oscillation and the Asian monsoon[19].

A link between multidecadal variability in NASST and circulation changes internal to the ocean was first proposed in 1964 (ref. 20) and later named the Atlantic Multidecadal Oscillation[21]. This variability is often characterized as the detrended NASST between the equator and latitude 60° N (longitude 7.5–75° W; ref. 8). Although it has recently been questioned[22], the present consensus remains that most of the observed Atlantic temperature variations occur in response to the ocean's internal variability. This picture emerged from general circulation models, a number of which inherently produce multidecadal Atlantic variability in the absence of external climate forcing[7] and, when considered together as a multimodel mean, have shown little evidence of forced changes projecting onto the NASSTs[6,9]. Observationally, this interpretation has been accepted because the Atlantic temperature changes seem to be oscillatory, both around any secular long-term trend and when calculated as anomalies from the global-mean change.

Motivated by the recent identification of the importance of aerosol process complexity in interhemispheric Atlantic temperature changes[23], apparent aerosol correlation[1,11] and volcanic modulation of Atlantic variability[22], we use new general circulation model simulations to question whether the CMIP3 (Climate Model Intercomparison Project phase 3) models contained the complexity necessary to represent a forced Atlantic Multidecadal Oscillation[7,9]. We use HadGEM2-ES (the Hadley Centre Global Environmental Model version 2 Earth System configuration[24]), a next-generation CMIP5 (Climate Model Intercomparison Project phase 5) model, which represents a wider range of Earth system processes (in particular aerosol interactions[25]) than do CMIP3 models.

To separate internal variability from forced changes, we present climate model ensemble-mean NASSTs, averaged over parallel model simulations started from different initial conditions[26]. If external forcing dominates the NASST evolution then ensemble members will evolve in phase and thus combine to produce a robust ensemble-mean response. If internal ocean dynamics dominate then each member will evolve separately and the resulting ensemble mean will show little residual variation around the underlying warming trend. This approach allows identification of physical mechanisms linking forced changes to Atlantic temperatures and was used in previous CMIP3 studies[6,9].

In Fig. 1a, we reproduce the multimodel-mean NASST response of the six CMIP3 models used in ref. 9 (ENS1, blue) and the eleven models used in ref. 6 (ENS2, green) (Supplementary Table 2). The observations (Fig. 1) show marked multidecadal variations. The multimodel-mean responses in both ENS1 and ENS2 do capture the underlying trend through the century; they capture only weak multidecadal variability. For example, the ensembles' 1950–1975 cooling is only a small fraction of the observed value (Fig. 1a and Supplementary Fig. 4). Therefore, the unexplained multidecadal signal was previously attributed to internal ocean variability[6,9].

By contrast, HadGEM2-ES (Fig. 1b) reproduces much more of the observed NASST variability (correlation, 0.65; 75% of detrended standard deviation (smoothed over 10-yr intervals to highlight multidecadal component)). The post-1950s cooling and subsequent warming now falls within the observed trends (Supplementary Table 1). Observed warming in the earlier period (1910–1940) is larger than simulated by HadGEM2-ES (Fig. 1b and Supplementary Table 1); however, these new simulations capture roughly twice the early-twentieth-century warming of previous CMIP3 generation models.

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(Tesfa G. Gebremeddhin and Luther G. Tweeten, *Research Methods and Communication in the Social Sciences)*

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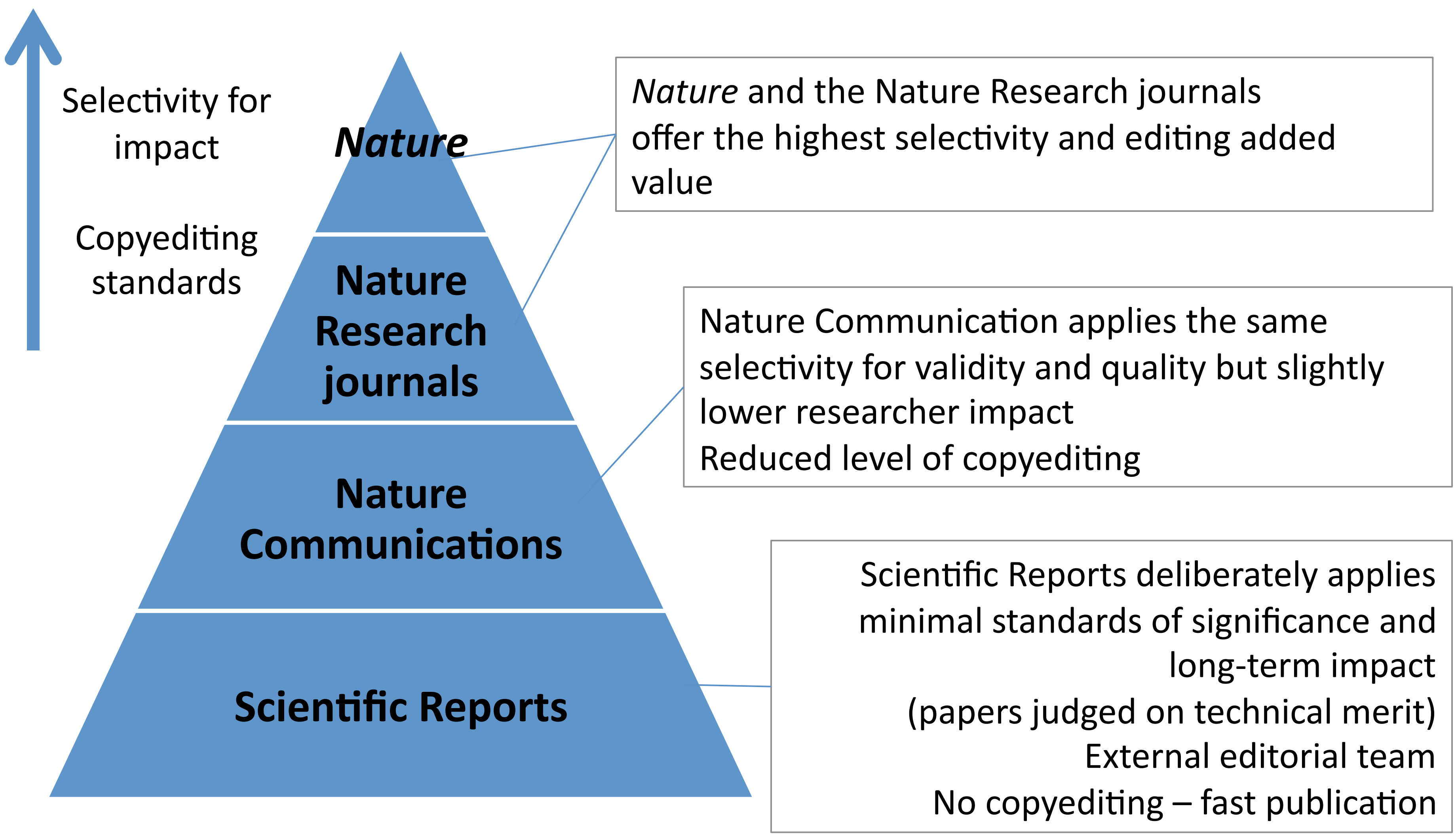

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