Perspectives of Earth and Space Scientists

PERSPECTIVE
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Earth Sciences Are the Model Sciences of the Anthropocene

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Key Points:

- Human beings are changing Earth's systems from local to global scales in ways that are not well understood, quantified, or modeled
- There is dire need to prioritize the Earth sciences and engineering to advance environmental policy for a more sustainable future

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Abstract

After 4.5 billion years as an evolving and dynamic planet, the Earth continues to evolve but with human-altered dynamics. Earth scientists have special opportunities and responsibilities to accelerate our understanding of Earth's changes that are transforming our most remarkable home.

Since 2000 when atmospheric chemist Paul Crutzen and ecologist Eugene Stoermer proclaimed that we live in the Anthropocene (Crutzen, 2002; Crutzen & Stoermer, 2000), a burgeoning Anthropocene literature has erupted across the fields of anthropology (Mathews, 2020), archeology (Edgeworth et al., 2015), biology (Kidwell, 2015), ecology (McDowell et al., 2019; Wilson, 2016), engineering (Allenby et al., 2009), environmental humanities (Castree, 2014), finance (Shrivastava et al., 2019), fine arts (May & Price, 2024), geography (Cook et al., 2015), history (Chakrabarty, 2009), literature (Menely & Taylor, 2017), philosophy (Raffnsoe, 2016), science studies (Latour, 2017), soil science (Richter, 2020), and stratigraphy (Waters et al., 2016). Reaction to the Anthropocene extends to newspaper editorial cartoons (Figure 1). By Anthropocene, we refer not to the currently contested mid-20th century Anthropocene Epoch but to all the many time-transgressive interactions of human beings with Earth's systems.

Notably absent are comprehensive assessments for how the Earth sciences (*all geo- and eco-system sciences, and related social sciences and fields of engineering*, hereafter "Earth sciences") can best address the many open scientific questions about our planet's changing and interconnected systems. These questions encompass our climate, atmosphere, hydrosphere, pedosphere, lithosphere, biosphere, cryosphere, magnetosphere, and techno-sphere, indeed all of Earth's "tangled banks," Darwin's (1859) still stunning metaphor for life on Earth, whether on land and its freshwaters, at sea, or in the air.

Here, we open this much-needed assessment of the Earth sciences by asserting that to understand these gathering changes requires a new integration of our scientific and engineering disciplines, *and* the prioritization of these

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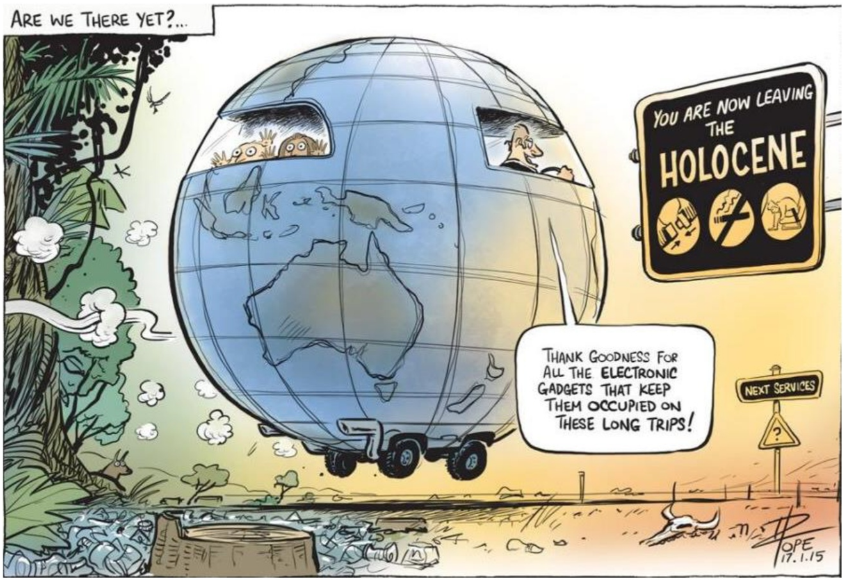

Figure 1. "Are We There Yet?…" Reactions to the Anthropocene have even reached newspaper editorial cartoons (reproduced with permission, © David Pope/*The Canberra Times*).

fields within universities, colleges, and research institutes, funding agencies, scholarly journals, and pre-University (K-12) education. To keep pace with our planet's changing dynamics that are so intimately joined by human forcings (Figure 1) and so deeply geological (Figure 2), we seek broad international support for an upscaling of the Earth sciences, which we argue, is critically important to a more sustainable future for all.

The Earth sciences have shaped human history, thinking, and behavior as much as any of the sciences (Wootten, 2015). Stephen Jay Gould (1987), for example, ranked deep geological time to be one of science's most important contributions to human development. The promotion of the Earth sciences to what historians of science call the model sciences (Cayley, 2009) will benefit the future well being of the planet and the societies we are a part of, draw much needed attention from oncoming students and scholars across academia, and present major interdisciplinary opportunities because the Earth sciences are rooted in physics, chemistry, biology, and even the social sciences and humanities (White et al., 2017). To support this realignment of the sciences, major reforms will be required in the science education of teachers and professors from K-12 to graduate school.

To those skeptical about the need to prioritize the Earth sciences, consider that the Earth sciences have the temporal and spatial scope needed to understand how human beings have been interacting with Earth's systems for millennia (Barnosky et al., 2004; Edgeworth et al., 2015; Hochella et al., 2019; Ruddiman, 2017; Schlesinger & Bernhardt, 2020; Wolfe & Broughton, 2020). Consider also that all we know *quantitatively* about our planet comes from observations, analyses, and modeling by Earth scientists who are taking full advantage of ongoing technological revolutions in advanced computer-assisted instrumentation, environmental analyses and sensors, drone and satellite observatories, artificial intelligence, and digitalization (Brantley et al., 2019; Reichstein et al., 2019), advances claimed by some to be making the 21st century unique in the history of science and technology (OECD, 2020). Consider lastly that interactions of human health with our Earth's diverse environments are increasingly identifiable with geo-spatial and geo-temporal analyses (Mielke et al., 2019).

This is no time to be complacent about the current state of the sciences. The 25-year-old argument from policy advocates that "climate science is settled" (Cushman, 1998) belies the ancient wisdom that "the sun is daily new and old" and the reality that our planet evolves in response to dynamic, high-order interactions that are difficult to predict. Transitioning energy systems for example, from fossil-carbon to wind, solar, biomass, geothermal, and nuclear will significantly affect Earth's many systems in ways that are not well understood from local to global scales. *There will always be important Earth science to do* and we promote our science and engineering crafts to ensure that future environmental policy and governance are based on the best that science and engineering can offer.

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Figure 2. The February 2023 Kahramanmaras earthquake affecting Turkey and Syria reminds us that our 8-billion person world is highly vulnerable to Earth disasters such as earthquakes, volcanic explosions, tsunamis, epidemics, floods, landslides, and windstorms (reproduced with permission from Getty Photos).

Most pertinent are the perspectives of veteran IPCC climate-scientists Tim Palmer and Bjorn Stevens (2019), who argue that climate-modeling science has reached global-scale limits. Palmer and Stevens contend that it will be next-generation climate modeling, observations, and analyses that will address how and why regional climate changes are altering the functioning of regional and local ecosystems. Their perspective underscores that Earth scientists prioritize for example, the dependencies of local and regional ecosystems and their coupled socio-economic systems on:

- Water supplies including storage, quality, and recharge of surface and groundwaters, that are subject to weather and climates but also to land-uses, vegetation, soils, and geology (Duncombe, 2022; Fan et al., 2013; Grafton et al., 2023; Porporato & Yin, 2022; Taylor et al., 2013);
- Sustainability and restoration of managed landscapes and soils that today produce food and fiber for more than 8 billion people. Many of these agro-ecosystems are managed at an intensity and geographic scale never before attempted, and risk long-lasting degradation of landscape biogeochemistry, food security, physical structures, and biodiversity (Gaffney et al., 2019; Richardson et al., 2022; Sachs et al., 2010; Thomas et al., 2023; Udvardi et al., 2021);
- Sea-level changes that vary widely along continental margins and render some coastal communities far more vulnerable than others (Frederikse et al., 2020; Hamlington et al., 2020);
- Responses of marine ecosystems and fisheries to climate forcings that will require adaptive climate-informed management (Heenan et al., 2015);
- Externalities from mineral exploration and mining on land and at sea that need scientific and engineering improvements given accelerating demands on Earth's critical minerals such as Li, Ni, Co, Cu, P, and the lanthanides (Jung & Choi, 2021; Labay et al., 2017; Schlesinger et al., 2021; Sharpley et al., 2018);
- Reducing the staggering human and financial costs of earthquakes, volcanic explosions, tsunamis, epidemics, floods, landslides, and windstorms and improving disaster prediction and warning systems (e.g., Costa et al., 2020; Wald, 2023);
- Accelerating research on the potential regional consequences of solar geoengineering, to date understudied (Irvine et al., 2010), and broadening the field of geoengineering to include all pro-active engineering of Earth's systems whether to improve the efficiency of nutrient and water cycling in crop fields or forests (Chen & Liao, 2017), or to advance carbon-cycle science and innovative carbon usage and capture technologies (Dziejarski et al., 2023).

As scientists and supporting scholars, we thus propose an ambitious international program of Earth sciences, engineering, and education. This new effort must be led by national academies of science and engineering, and national science foundations and their equivalents in many nations and make multi-decadal and multi-billion dollar commitments to international networks of research observatories that focus on the highest priority questions about our evolving planet across local, regional, and global scales.

What can individual Earth scientists and like-minded research administrators do to promote such an emboldened research and education program? We can learn much from the histories of the 1957–1958 International Geophysical Year (Sullivan, 1961), the 1964–1974 International Biological Program (Coleman, 2010), the 1987–2015 International Geosphere-Biosphere Program (Daniel, 1990), the ongoing Intergovernmental Panel on Climate Change (Agrawala, 1998) and the UN Decade of Ecological Restoration (Fischer et al., 2021), and the new International Decade of Sciences for Sustainable Development. We can continue to train highly talented Earth scientists from many nations, seek major financial support for new science organizations such as the Earth Observatory of Singapore, and participate in regional Earth science assessments, for example, of the Amazon (Albert et al., 2023). We can also collaborate with colleagues across the arts and humanities to circulate our ongoing findings and create new venues for our sciences.

Among the co-authors of this paper, one proposed the concept of Earth's critical zone in an oral presentation at an annual geological society meeting (Ashley, 1998), and over the following decade other coauthors wrote critical-zone white papers and scientific manuscripts, staged discussions with research funders, and built what are today the international research and education programs based at critical zone observatories on six continents (Arènes et al., 2018; Banwart et al., 2013; Brantley et al., 2007; Grant & Dietrich, 2017; Latour & Weibel, 2019; National Research Council, 2001; Schroeder, 2018). Not only has this program brought together geophysicists, geochemists, geomorphologists, pedologists, hydrologists, ecosystem ecologists, physical geographers, social scientists, and even humanities scholars, thousands of students have been educated in an integrative approach to place-and network-base Earth science from “treetops to bedrock” or from “rocks to the sky” (Gaillardet et al., 2018; Lee et al., 2023).

We must thus organize ourselves across the full breadth and scale of the Earth sciences to marshal unprecedented support for research and education to accelerate our understanding of Earth's changes that are transforming our most remarkable home.

The stakes are high. Let the new work begin!

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

No pre-existing or original data, software, or code were used or created in the writing of this manuscript.

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