From Earth to Space and Back Again: 130 years of geophysical research as told through the titles of AGU journal articles

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Key Points

- The development of the field of geophysics is shown through the most frequent words in AGU journal article titles.
- Early on, the most frequent scientific words in titles were on Earth's magnetism and the effect that the sun, Earth's core, and Earth's atmosphere had on Earth's magnetism.
- After the 1940s, the most frequent words in titles expanded to include hydrology, water resources, oceans, and climate.
- The field of geophysics, as seen through the most frequent words, was also influenced by technological advances and sociopolitical events.

Abstract/ PLS

We present the development of the field of geophysics between 1896 and 2022 using the most frequent words in journal article titles published by the American Geophysical Union. The story, as told through most frequent words titles in these years, begins with studying the Earth's magnetic field and the sun's effects on it. The field of geophysics expanded to investigate Earth's immediate atmosphere and as technology allowed, atmospheric composition further and further away from Earth. Around the mid-twentieth century, geophysics expanded to more rigorously study Earth's aqueous environments, and title words show an increasingly deeper understanding that these environments could tell the story of Earth's past and be a harbinger of Earth's future. We group the analysis into multi-decadal years for the following journals: *Terrestrial Magnetism* (updated to *Terrestrial Magnetism and Atmospheric Electricity* in 1899 and *Journal of Geophysical Research* in 1949), *Reviews of Geophysics*, *Water Resources Research*, *Radio Science, Geophysical Research Letters* (*GRL*), *Tectonics*, *Paleoceanography*, *Global Biogeochemical Cycles (GBC)*, *Geochemistry, Geophysics, Geosystems* (*G-Cubed*), *Space Weather, Journal of Advances in Modeling Earth Systems* (*JAMES*), *JGR: Space Physics, JGR: Solid Earth, JGR: Oceans, JGR: Atmospheres, JGR: Planets, JGR: Earth Surface, JGR: Biogeosciences*, *Earth's Future*, *Earth and Space Science*, *GeoHealth*, *AGU Advances*, *Perspectives of Earth and Space Scientists*, and *Community Science*.

Introduction

In the 1896 Editorial Greeting of *Terrestrial Magnetism*, founding editor Louis A. Bauer "made no apology" for "adding one more to the already over large list of scientific periodicals" (Bauer, 1896a). This "over large list" has grown considerably in the past 130 years since the first issue of *Terrestrial Magnetism,* the American Geophysical Union's (AGU) first journal starting with Bauer at the University of Chicago, where he was an instructor of math and physics, and transferred to AGU in 1959 as the *Journal of Geophysical Research*. In his 1896 Greeting, Bauer laments that articles on terrestrial magnetism "appear anywhere

but specially nowhere," and it is this homelessness that inspires the new journal. Bauer claims that in addition to submissions on Earth's magnetism, he welcomes topics on "Earth Currents, Auroras, [and] Atmospheric Electricity." His contemporaries also understood the importance of publishing on this subject: *Nature* described *Terrestrial Magnetism*'s inaugural issue as appealing to "a large class of investigators" interested in "the magnetic needle as a promising instrument of research not only in terrestrial, but in cosmical physics" (Bauer, 1896b). *National Geographic Magazine's* 1896 issue praised *Terrestrial Magnetism*'s inception with poetic flair:

> Is it not the journal before us, then, to mark a new epoch in our knowledge of this subject? It seems strange that, when almost every other branch of science has long had its special journal or organ, we should have waited almost for the dawn of the twentieth century for the first number of the first journal devoted to a matter of such great practical moment and for four centuries known by all civilized men to be important (National Geographic Society, 1896).

And of course, for the next 126 years, AGU journals would expand to provide a home for research in fields far beyond those envisioned by Bauer and his contemporaries.

Words tell stories; titular words in AGU's journal articles narrate a story of the Earth and space sciences—accounting natural phenomena, cultural and social movements, and technological and scientific developments. This piece analyzes article titles of AGU's scientific journals for the most frequently occurring words by multidecade intervals from 1896 through 2022. The use of scientific and methods-related terms reveals how the Earth and space sciences have evolved and expanded.

Methodology

In this analysis, article titles and year of publication are used to explore topical and publication-related trends. We focus on titles because they are the only consistent pieces of metadata on articles dating back to the turn of the twentieth century. This analysis includes AGU's current and historical journals but excludes *Transactions* (now *Eos*). Though *Terrestrial Magnetism* started with a different publisher, we look at the whole of its history; other journals starting with a different publisher later transferred to AGU are only analyzed once published by AGU. We exclude titles from *Eos Transactions* but refer to articles published in *Eos* to provide context on the events and motives surrounding new journal acquisitions, launches, and other related history. Journal birth and transfer years are noted throughout. To show the evolution of geophysical and publishing trends, we grouped the articles into the following intervals: 1896-1949, 1950-1969, 1970-1989, 1990-2009, and 2010-2022. The title analysis excludes prepositions, articles (the, a, an, etc.), numbers, single letters, and symbols. Each word's frequency includes the counts of that exact word with some highly related words grouped manually at the authors' discretion (e.g., atmosphere, atmospheres, and atmospheric are grouped; water and waters are grouped). When words are grouped, it is indicated in the figures and in the discussion (e.g., "ionosphere/ic"). If words are connected by punctuation in a title (e.g. hyphenated), they are divided at each punctuation mark and analyzed separately. Compound words without hyphens or spaces are analyzed as the entire compound word (i.e., "groundwater" was not divided and counted as one instance of "ground" and another instance of "water"). The titles of the few articles published in other languages, namely German and French in the early days of *Terrestrial Magnetism,* are not translated and are excluded from the top 10 lists. Throughout the analysis, we divide scientific terms (e.g., ionospheric, geomagnetic) from non-scientific terms, such

as those describing methods and locations (e.g., when referring to the name of instrumentation/observatory), and analyzed them separately to uncover a more detailed story of doing and communicating Earth and space sciences. Some words appearing in the top 10 lists are applicable to multiple fields of research (e.g., field, wave, surface, etc.), so we selected several of these words for further analysis by extracting and counting adjacent words or, if a part of a compound word is present, extracting and counting their prefixes or suffixes (e.g., "ground" appears in the list of words most commonly adjacent to "water"). All article titles used in this analysis are available on Zenodo (Wooden, 2024).

Each following section of this article includes an overview of the years analyzed, the journals that started in those years, significant milestones, and annual article volume. We provide a graph of the top 10 scientific terms of the multidecade intervals and explore why the words appear (or might appear) at their frequency. We select some of the top 10 scientific terms to analyze adjacent words to better understand their context. Finally, we review the top 10 nonscientific terms of each period, words that indicate content types ("comment," "paper"), methods ("analysis," "data," "model"), and instrumentation (i.e., name/location of an observatory), and use them to speculate about the structures supporting the investigation and communication of the science in the sociocultural moment.

Years 1896-1949

Journals (1896-1949): Between 1896 and 1949, one journal was published. Starting in 1896 as *Terrestrial Magnetism*, it was retitled to *Terrestrial Magnetism and Atmospheric Electricity* in 1899 and retitled to *Journal of Geophysical Research* in 1949. The journal started at the University of Chicago where Bauer was a lecturer and was transferred to the Carnegie Institute of Washington in 1904 after Bauer began his directorship there in 1903.

Published articles (1896-1949): Between 1896 and 1949, 3185 articles were published. Figure 1 shows the annual published article count in these decades. In its first year, *Terrestrial Magnetism* published 61 articles, and after that, it published 30-50 articles per year until 1928. After 1928, annual output increased, and between 1932 and 1949, an average of 100 articles were published each year until 1949, when the newly retitle *Journal of Geophysical Research* (*JGR*) published 126 articles (see Fleming, 1948, for a description of this transition).

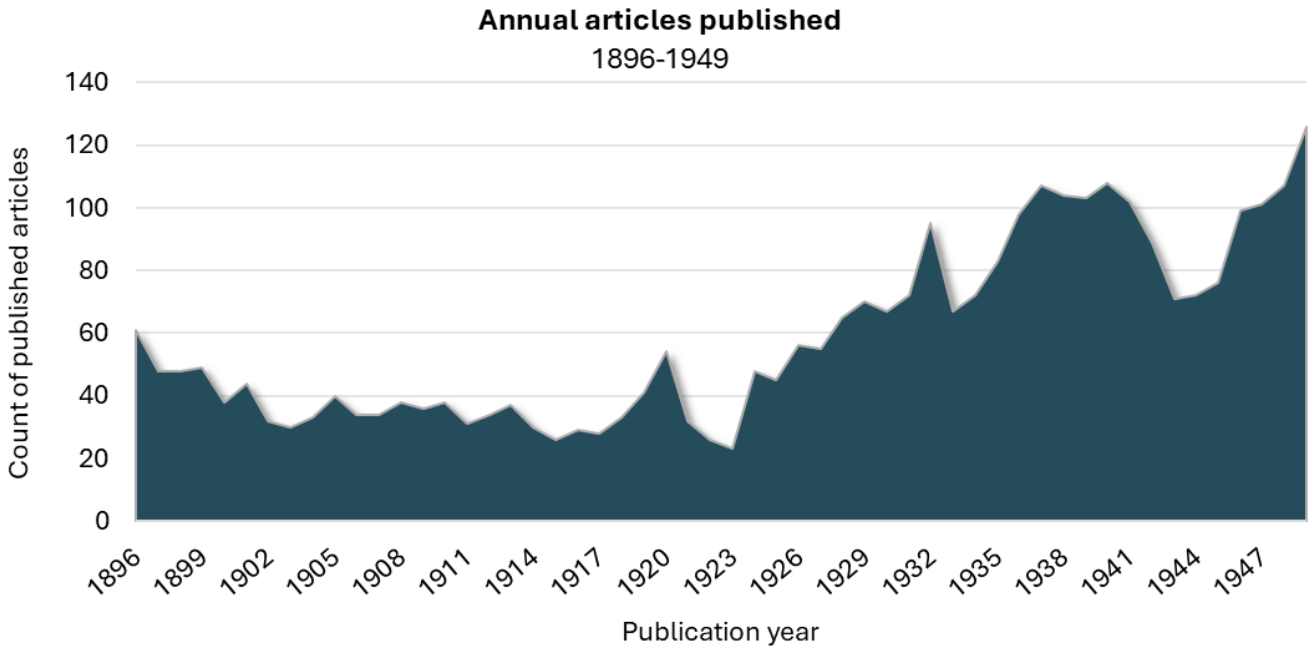

Figure 1: Count of articles published annually between 1896 and 1949.

Scientific terms (1896-1949):

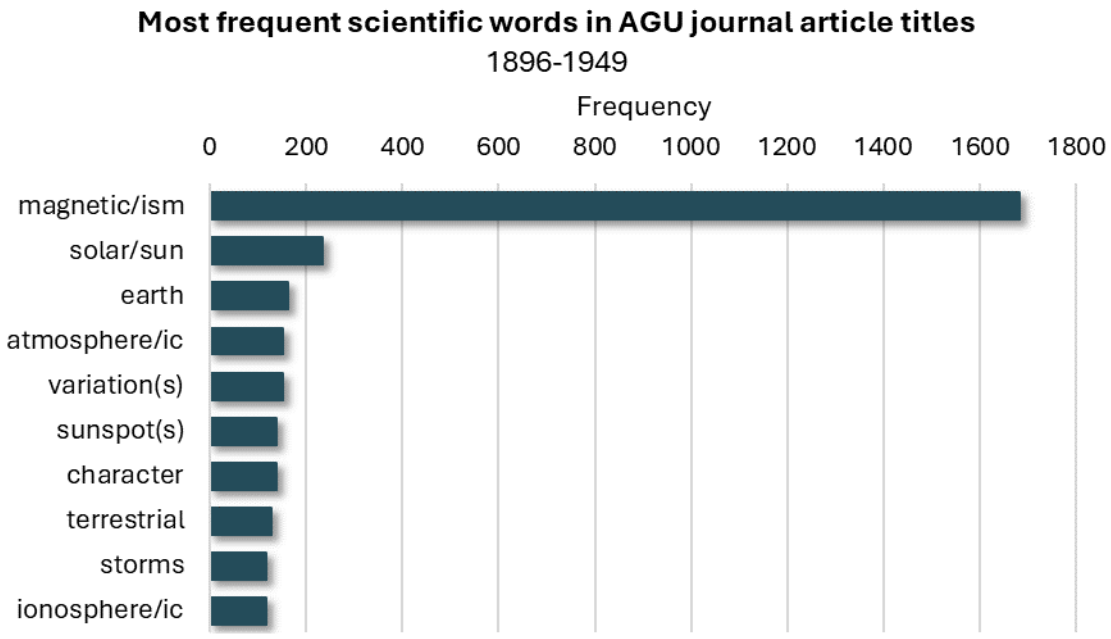

Figure 2: Most frequently occurring scientific terms in titles of articles published between 1896 and 1949.

Figure 2 shows the top 10 scientific terms used in paper titles for this 54-year window. Unsurprisingly, the eponymous "magnetic" was the most frequent word. Bauer's ambition was to map Earth's entire geomagnetic field, and he asked his readers to record their magnetic field observations and mail in the data (Bauer, 1904). He published much of the data in the journal and used it in more extensive research articles of his own (see Bauer, 1900, for an example). "Variation" refers to variations of the Earth's

magnetic field, known as “secular variations.” “Solar” and “sun” come in second with articles primarily on sunspots (appearing in titles as “sun-spots,” thus analyzed as separate words) but also articles on magnetic observations during solar eclipses and ponderings on the electric charge or magnetic field of the sun (Arrhenius, 1905). The popularity of “sunspot(s)” in titles shows that scientists understood that Earth’s magnetism was connected to the activities of the sun: as Bauer puts it, “the Earth’s magnetism is in sympathetic touch not alone with terrestrial but also with *cosmical* influences” (Bauer, 1896, emphasis Bauer’s). First noted in 1609 by Galileo and others, sunspots were not vigorously studied again until the 1820s, when Heinrich Schwabe discovered the 11-year solar cycle when the magnetic field of the sun flipped (Stern, 2002). Finally connecting the sun’s magnetism to Earth’s was Kristian Birkeland who postulated in the early 1900s that “magnetic disturbances on the earth, and aurora borealis, are due to corpuscular rays emitted by the sun” (Birkeland, 1902). In 1908, George E. Hale reported that sunspots are characterized by “solar flares,” which are highly magnetic, so sunspots can be used to describe the magnetism of the sun (Stern, 2002). Observatories around the world all noted periodic magnetic disturbances and were dubbed “magnetic storms.” “Storms” enters our top 10 list, as Bauer was interested in publishing data from observatories across the world on magnetic storms. Most articles with the word “storm” referred to specific magnetic storms with locations and dates, for example, “Magnetic storm of October 31-November 1, 1903, in Japan” (Okada, 1904).

“Earth” and “terrestrial” appear primarily in articles on Earth’s magnetism but also in reference to activities of the Department of Terrestrial Magnetism at the Carnegie Institute, which Bauer became director of in 1903. Most of these accounts describe the lab and field work of department employees or advertise job openings for physicists, magnetic observers, and “computers” (actual humans at this time), offering an annual salary of $1000-$2500 USD (Bauer, 1905).

“Atmosphere” appears in titles referring to the electrical composition of the atmosphere. “Ionosphere” barely makes it to the list, as the study of the ionosphere was still nascent in the late 19th century. In fact, early studies referred to it as “the upper” or “outer” atmosphere and speculated about its electric charge. In 1927, Edward Appleton confirmed the existence and makeup of the ionosphere (Hulbert, 1935) and won a Nobel Prize in 1947 for his discovery, but the journal must wait until 1934 to publish articles with “ionosphere” in the titles, with the first appearing in “F-region ionosphere- investigations at low latitudes” (Berker and Wells, 1934).

In 1908, the journal started publishing articles with titles following the pattern “The magnetic character of the year [year of observation],” which helps usher “character” to the top 10 list. Publishing such data was spurred by a resolution adopted in 1905 at a meeting of the International Commission for Terrestrial Magnetism requesting that observatories classify each day’s magnetic character as 0-“quiet,” 1-“moderately disturbed,” or 2-“severely disturbed” and sending in their data. This resulted in the major magnetic observatories sending quarterly reports to the Netherlands Meteorological Institute, which published the data with the resolution of “making the data available for all” (Hazard, 1921).

Nonscientific terms (1896-1949):

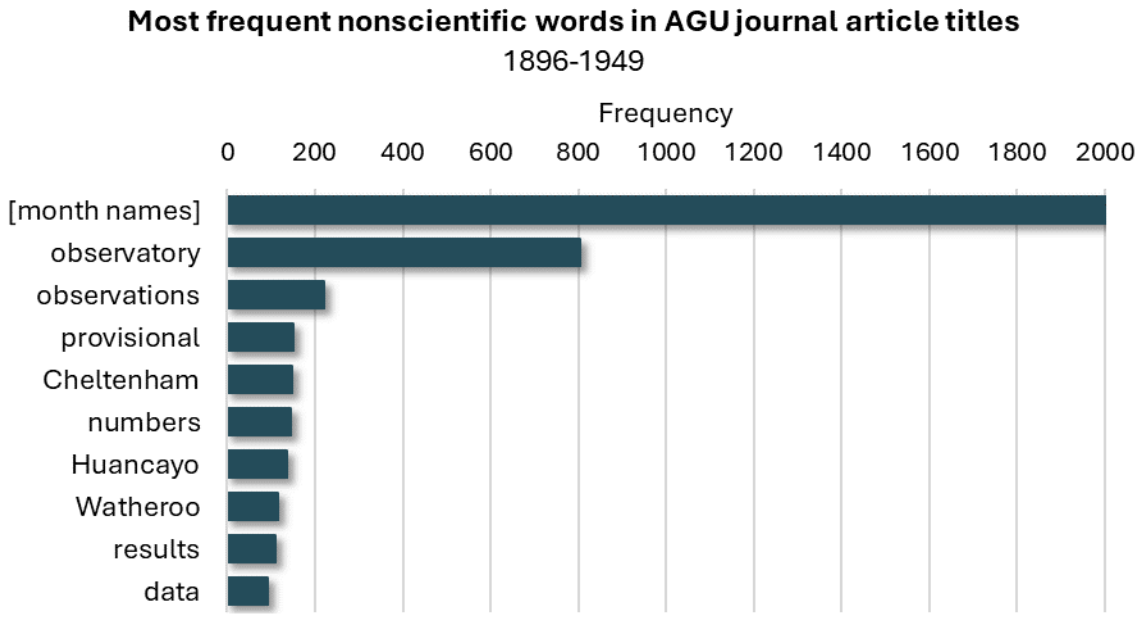

Figure 3: Most frequently occurring nonscientific terms in titles of articles published between 1896 and 1949.

Terms not related to science expose an equally interesting history of writing style, methods, and types of content published in the journal. Figure 3 shows the most common nonscientific terms in titles between 1896 and 1949. In these years, the most common terms are months of the year, with January, June, and December being the most frequent, as many articles were observations made during a specific date range, which was included in the title. The limited technology of the early 20th century restricted data collection to primarily ground observations, and the frequency of "observatory" and "observations" further illustrates this site-specific method of data collection.

"Provisional" sunspot "numbers" were a feature in the journal starting in 1919 that printed tables of sunspots observed each day during the time period indicated in the title (e.g., "Wolfer provisional sun-spot numbers for 1920"; "Wolfer" indicated the author-observer's name) (vanDijk, 1920).

Cheltenham, Huancayo, and Watheroo were all major observatories and appeared in articles composed of tables of numbers, such as "Principal magnetic disturbances recorded at Cheltenham Magnetic Observatory, Sept. 1-Nov. 30, 1904" (Wallis, 1904). "Results" appears as results of magnetic observations, especially as observations from a specific observatory or expedition.

"Data" appears in a few article titles reporting magnetic observation data but is pushed to the top 10 list by articles starting in 1930 reporting "American URSI broadcasts of cosmic data." The URSI (Union Radio-Scientifique Internationale) cosmic radio broadcast started on August 1, 1930, and was a transmission of data to a centralized station in Washington D.C. hosted by an organization called Science Service. The data included observations of solar electromagnetic radiation, magnetic conditions, and sunspots (Davis, 1931).

Years 1950-1969

Journals (1950-1969): In 1959, the Carnegie Institute transferred *Journal of Geophysical Research* (JGR) to AGU as a publisher. Prior to that, AGU's only publication had been *Transactions, AGU* (later becoming *Eos*), which covered both scientific content and nonscientific content, such as Union business, membership information, special projects, meeting reports, and geoscience news. In 1958, AGU leadership decided to separate out ever-growing scientific content and maintain *Transactions* as the AGU member newsletter but debated the title of the new scientific journal (Peoples, 1958). However, soon after deciding on this division, in 1958, the Carnegie Institute offered to transfer *JGR* to AGU, which provided the perfect receptacle for *Transactions'* scientific articles. AGU and the Carnegie Institute representatives secured financial support from the United States' National Science Foundation (NSF) to merge and expand the journals (Ewing, 1959).

In 1963, AGU started its first native journal *Reviews of Geophysics* (*Reviews*), which was intended to "bridge the span between advances on the frontiers of geophysics and conventional textbook material" and aimed to appeal to both "students entering the field" and to the "mature geophysicist" (Malone, 1962). *Water Resources Research* (*WRR*) soon followed in 1965 to support "the intrinsic scientific interest and the practical importance of the water problem in all its aspects" (Malone, 1964). In 1969, the increasing volume of *JGR* impelled AGU to start publishing in separate sections "*JGR-A*"- space physics, "*JGR-B*"- solid earth and planets, and "*JGR-C*"-oceans and atmospheres in alternating issues, but all articles were still published under the title *Journal of Geophysical Research* (Landsberg, 1969) until 1978, when Space Physics, Solid Earth, and Oceans were published under distinct titles. *Radio Science* began in 1966 by the United States' Environmental Science Services Administration under the Department of Commerce and was transferred to AGU in 1969 but was published under the control of the U.S. National Committee of the International Union of Radio Science (URSI) (Jordan, 1969).

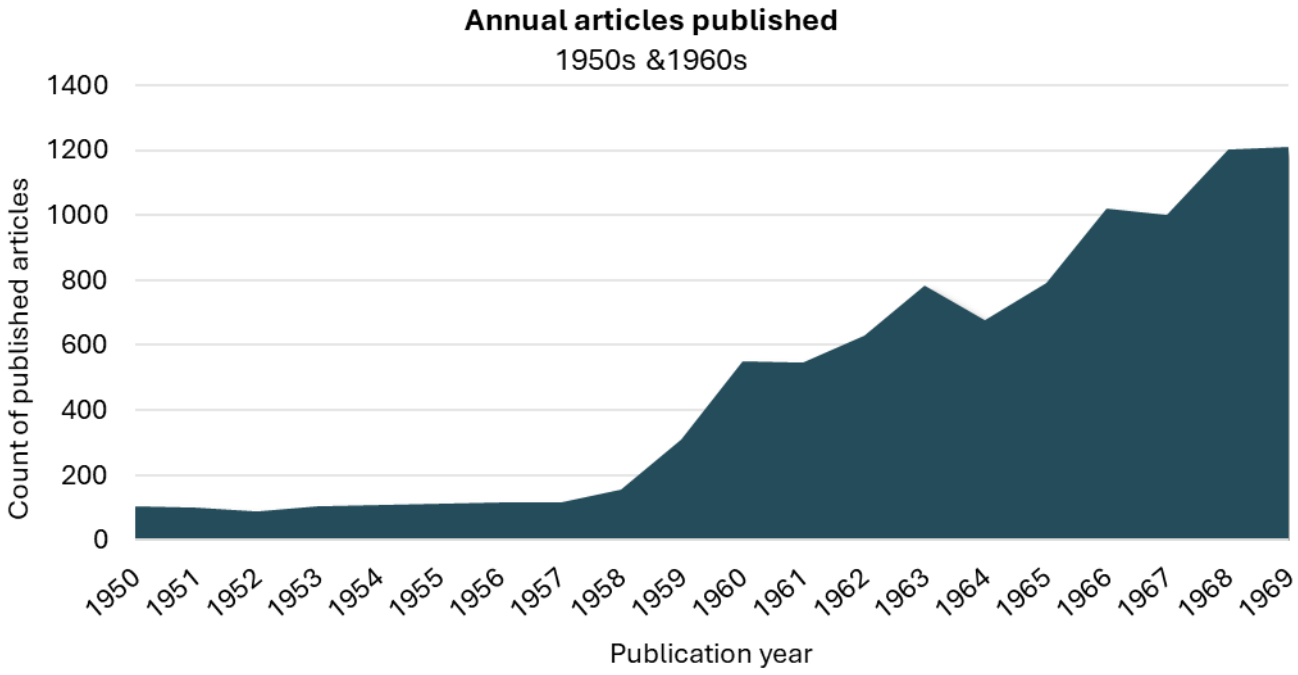

Figure 4: Count of articles published annually between 1950 and 1969.

Published articles (1950-1969): 9732 total articles were published during these two decades, with Figure 4 showing annual article publication counts between 1950 and 1969. After AGU started publishing *JGR*, the journal's output doubled from 155 articles in 1958 to 311 articles in 1959. Scientific content previously published in *Transactions* could now be published in *JGR*. The following year, content almost doubled again to 551 articles in 1960. Compared to *JGR*, *Reviews* started small, with 17 articles in its inaugural year, and remained relatively small by the end of the 1960s, with 32 articles in 1969. *Radio Science* shouldered a heftier load than *Reviews,* with 187 articles when transferred to AGU in 1966, and ended the decade with 172. *WRR* published 56 articles in its first year but more than tripled in output by the end of the 60s, with 185.

Scientific terms (1950-1969):

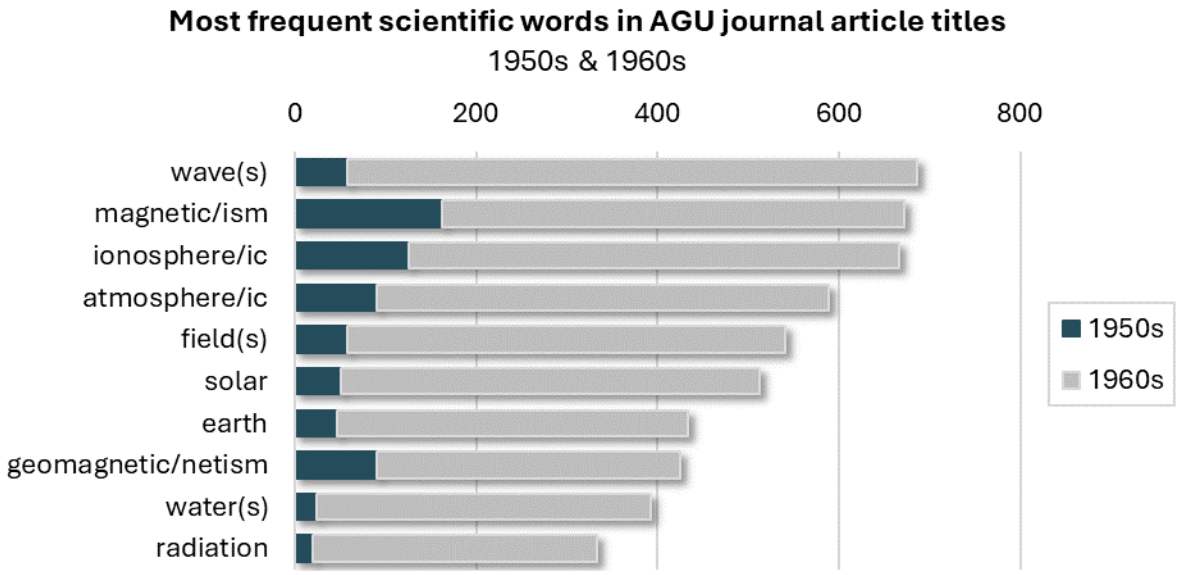

Figure 5: Most frequently occurring scientific terms in titles of articles published between 1950- and 1969.

The most frequent scientific term in titles became "wave" in these years, as shown in Figure 5, mostly contributed by articles published in the 60s. "Wave(s)" enters the list partly from the addition of *Radio Science* to AGU's portfolio, but *JGR* still contained more articles than *Radio Science* with the word "wave" in the title. A closer look at the words preceding "wave(s)" as presented in Figure 6.

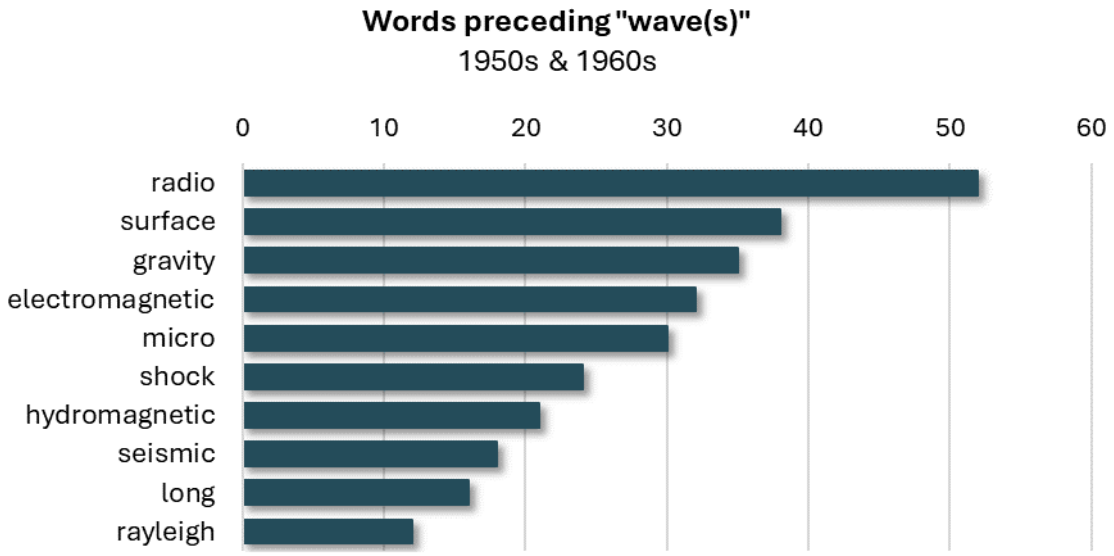

Figure 6: Most frequent words and prefixes preceding "wave(s)" in the titles of AGU articles published from 1950-1969.

“Radio” waves were the most frequently occurring types of waves mentioned in titles during these years. However, only 7 articles in the 1950s contained the titular phrase “radio wave(s),” while the rest were in articles published in the 60s as the use of sounding rockets and satellites increased. Research and resulting articles on “surface waves” were partly spurred by the increase in seismological research as a means for detecting underground nuclear explosions, which was recommended in 1958 by the Geneva Conference (Press, 1959). “Gravity” waves appear only a few times in article titles in 1959, with a large increase in the 60s on gravity waves on water, in the atmosphere, and in acoustic gravity waves.

Returning to the top 10 scientific terms, “magnetic” or “magnetism” appeared more frequently in titles in the 50s than any other scientific term (taken over by “wave” in the 60s). Articles hosting “magnetic” in the title included magnetic surveys, disturbances, and magnetic storms.

“Ionospheric” again appears as a frequent term but with a much higher frequency than in previous decades, as sounding rockets became a more accessible technology and were used for *in situ* observations of the Earth’s upper atmosphere. The ionosphere also provided the medium needed for satellite communication, integral to the U.S.’s space race with Russia. And with the U.S.’s first successful satellite launch of Explorer 1 in 1958, scientists discovered the Van Allen belt, an extension of Earth’s ionosphere, which further drove research on the physics of what lay beyond Earth’s immediate atmosphere (Li & Hudson, 2018). The increase in space-related terms was accompanied by unprecedented levels of U.S.-funded space research, one reason why AGU’s president explained that it was “inevitable” that *JGR* was devoting a “disproportionate share of pages to the planetary sciences” (Woollard, 1964).

“Atmosphere/ic” also appears on the most frequent word list, most often seen with the word “upper” in titles of both decades. “Electron” appears in article titles, and we see a sizable increase in the 60s compared to the 50s, with a high proportion of articles on electron density and the ionosphere, likely also spurred by an increase in the use of rocket technology.

Returning to the top 10 list, “field” appears mid-list and is most frequently paired with the journal’s bread-and-butter topic of magnetic and geomagnetic but also “electric field” and “field-aligned.” “Field-aligned” predominantly describes ionization or the ionosphere in titles, with the first article in *JGR* on this topic appearing in 1955 by M.A. Peterson and colleagues (Peterson et al., 1955).

“Water” appears first on this list thanks in part to the launch of *WRR,* but *JGR*, which was still the larger journal, published more total articles with this word in titles. A close look at words adjacent to “water” shows that watershed and groundwater were the most common topics, paralleling a booming population’s need for this essential resource and the increasing awareness of environmental pollutants. Other words adjacent to “water” are shown in Figure 7.

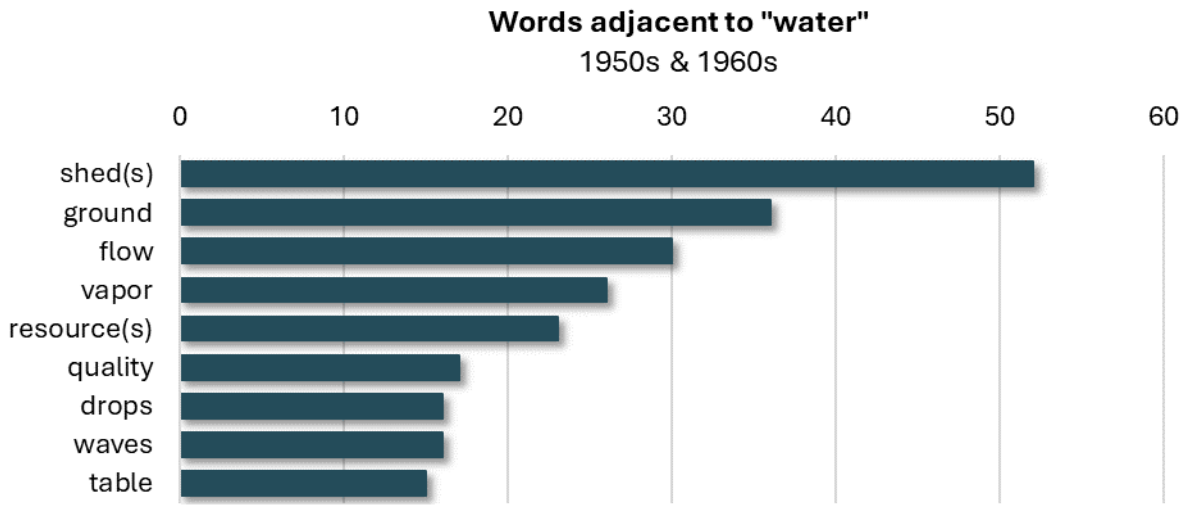

Figure 7: Most frequent words, prefixes, and suffixes adjacent to "water" in the titles of AGU articles published from 1950-1969.

Nonscientific terms (1950-1969):

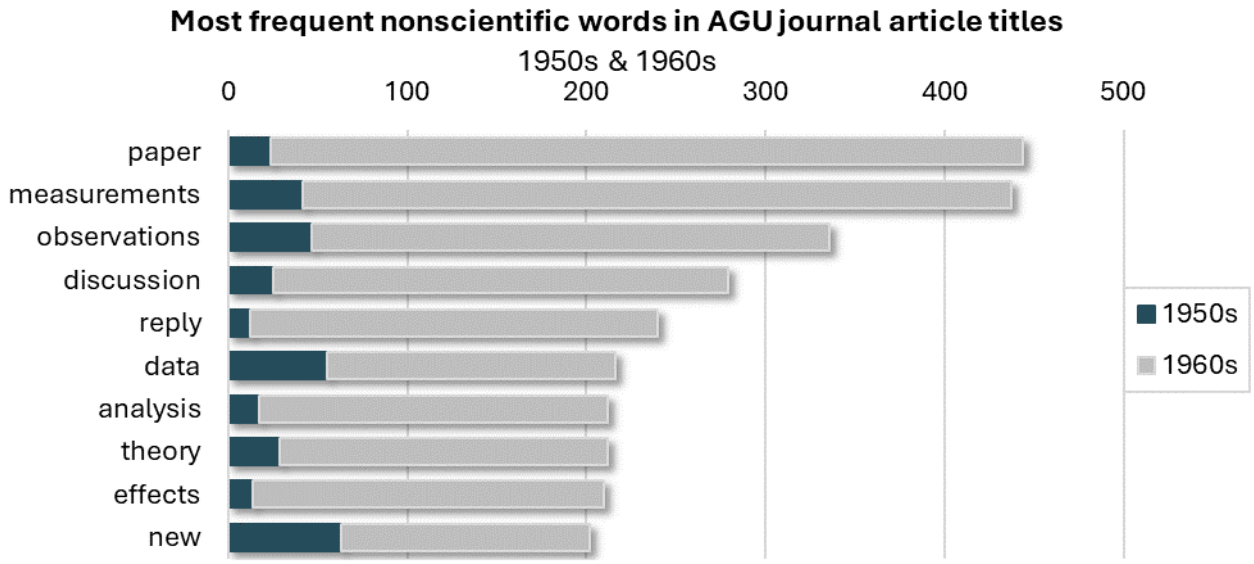

Figure 8: Most frequently occurring nonscientific terms in titles of articles published between 1950 and 1969.

Words related to the methodology and content give us a glimpse of the technology and communication styles developing in the mid-20th century. Figure 8 shows that the words "paper," "comment," "discussion," and "reply" appear on this list because they frequently appeared together in titles such as "Discussion of Paper…," "Reply to 'Discussion of Paper…," or "Comments on Paper…" Some of these articles were critiques of articles published in the same journal and pointed to an error or serious limitation, while others were a supportive commentary on the topic, pointing out additional potential lines of inquiry. Perhaps the increase in scientific dialectic in the printed pages of the journals was fueled by the large increase in printed content in general or even an academic manifestation of increased societal debate undergirded by the countercultural movement in the 60s across the U.S. and Europe.

"Measurements" appears much more frequently in titles than in previous years and was commonly seen with the use of rockets to study Earth's upper atmosphere. Although "observations" is behind "measurements" in the top 10 list, it occurs more frequently in the 50s than "measurements." In the 50s, "observations" is commonly seen in titles with "magnetic," but in the 60s, they were more commonly seen with "satellite," showing that this developing technology was adopted by the Earth and space science research community. The first title with the word "satellite" was in a small subsection in the Notes section of *JGR*. It explains that the U.S.'s National Academy of Sciences and NSF funded the construction of a "basketball-sized" satellite "filled with recording and transmitting devices" that would "telemeter information to earth about conditions in the outer edge of the atmosphere" at a height of 200-300 miles ("United States' proposed satellite program," 1955).

"Data" also appears on this list, supported by a dedicated section of each issue listing geomagnetic data from observatories around the world. Although we do see "data" in titles in previous years, the word starts to overtake "observations" starting in the late 40s and into the 50s and 60s. When previous top 10 terms such as "notes," "publications," and "list" connoted brevity and superficiality, the content-related terms of the 50s and 60s such as "analysis" imply a thorough and dedicated focus on data and details of increasingly specialized topics. Indeed, the increase in the word "data" is accompanied by an increase in

the word “analysis,” a verb we must enact on data to make sense of it and communicate it to others. “Theory” appears about as often as “analysis,” but represents a bolder stand about the conclusions than do titles with “observations,” “data,” and “analysis”: the ever-accumulating data and emerging technologies allowed geoscientists the luxury to develop theories on topics such as radio waves, dynamo theory, molecular diffusion in the atmosphere, electrostatic fields, and much more. Both “theory” and “new” also suggest that authors wanted to highlight the importance of their research to the editors and readers to indicate the importance of publishing *their* findings.

Years 1970-1989:

Journals (1970-1989): AGU began 1970 with four journals and grew to 11 by 1989. *Geophysical Research Letters* entered the scene in 1974 after author outcry for publishing important results more quickly (Abelson, 1974). Ten years later in 1984, *JGR: Atmospheres* was distinguished from the *JGR* family to accommodate increased research results in atmospheric sciences, previously subsumed under JGR: C covering oceans *and* atmospheres. Although the discovery of plate tectonics in the mid-60s was monumental to piecing together the history of our current Earth, it wasn’t until 1982 that AGU founded a separate journal, *Tectonics*, to absorb the growth of articles on a topic that the founding editor John Dewey claimed was too important to not have its own journal. *Tectonics* was copublished by the European Geophysical Society in hopes of establishing stronger relationships with geophysical organizations outside the U.S. (Kisslinger, 1981). In 1986, the annuagural issue of *Paleoceanography* (now *Paleoceanography and Paleoclimatology*) was published for many of the same reasons as *Tectonics*: a growing field was too important for articles to be scattered throughout a wide range of journals (Kennett, 1985). And in 1987, the AGU started *Global Biogeochemical Cycles* (*GBC*) to suport the growth in research on interdisciplinary topics related to physical, chemical, and biological processes in Earth’s chemical environment (Katzoff, 1987).

Published articles (1970-1989): 34,632 were published with Figure 9 showing the slow but steady growth in annual published articles. The growth in research on Earth, space, and planetary science compelled AGU to add new journals to its portfolio. From 1970 to 1989, annual output almost doubled from approximately 1300 articles to more than 2300. *JGR: Space Physics* and *JGR: Solid Earth and Planets* (a single *JGR* section at this time) had the largest outputs of all AGU journals, even though they were still considered “sections” of the more emcompassing journal *JGR*.

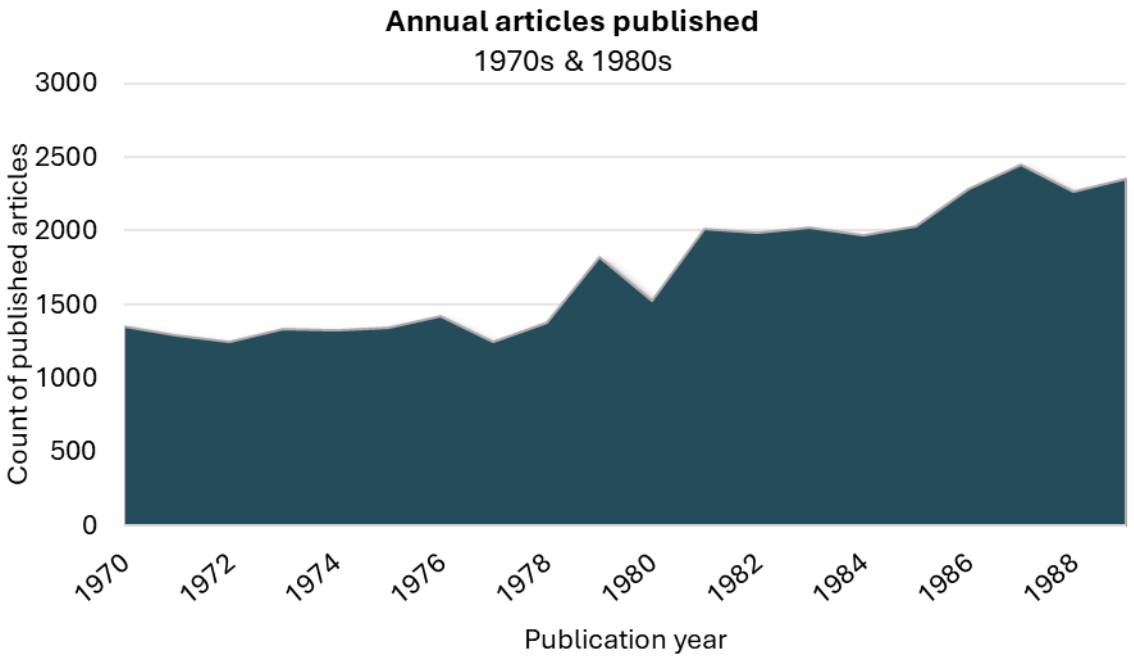

Figure 9: Counts of articles published annually between 1950 and 1969.

Scientific terms (1970-1989):

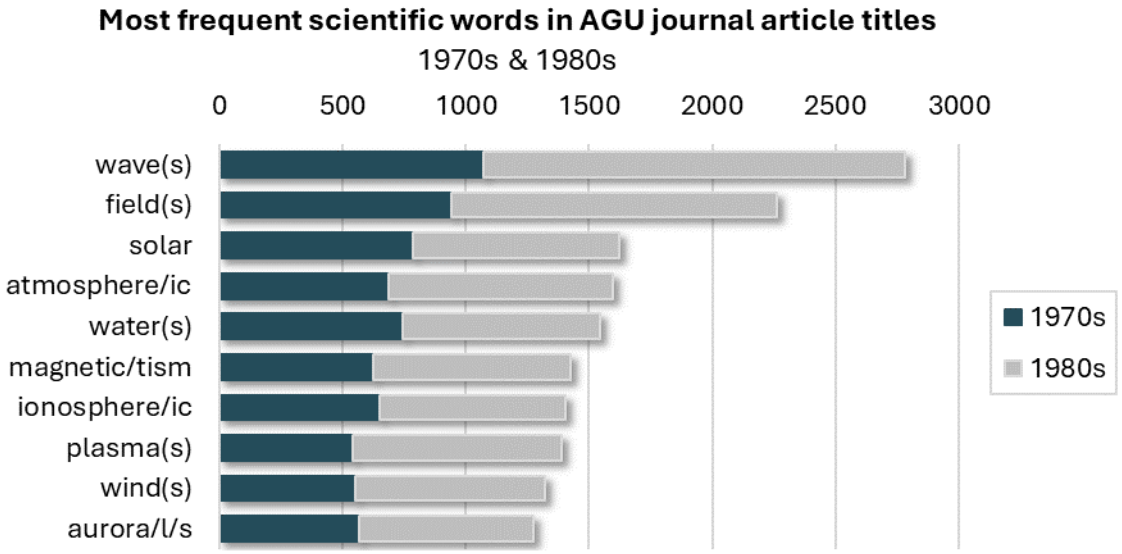

Figure 10: Most frequently occurring scientific terms in titles of articles published between 1970 and 1989.

Figure 10 shows that the previously dominant “magnetic” dropped to seventh place as technology and innovation allowed scientists to explore previously invisible or unreachable subjects. “Waves” dominated the list in these two decades with *Radio Science* and *JGR: Space Physics* contributing the most. *Radio Science* articles focused on microwaves, propagation, and electromagnetic waves, while

JGR: Space Physics contributed articles on plasma waves and shock waves. A more detailed look at words occurring before “wave” in the title is shown in Figure 11.

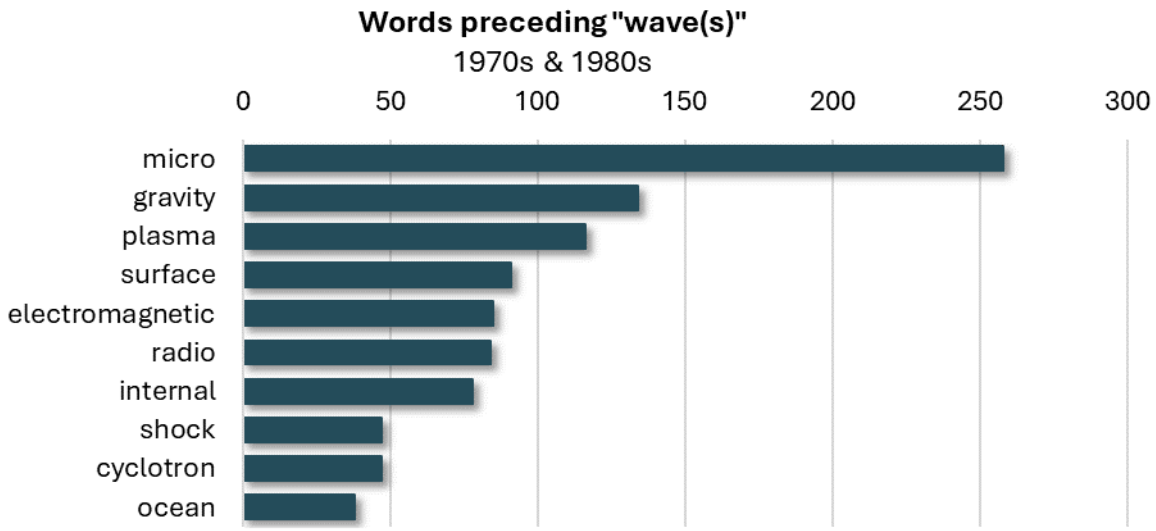

Figure 11: Most frequent words and prefixes preceding "wave(s)" in the titles of AGU articles published from 1970–1989.

“Field” again appears on these years’ top 10 list but in a higher position than in the previous two decades, with many articles on interplanetary magnetic fields, primarily contributed by *JGR: Space Physics*. Words in titles adjacent to “field” are shown in Figure 12.

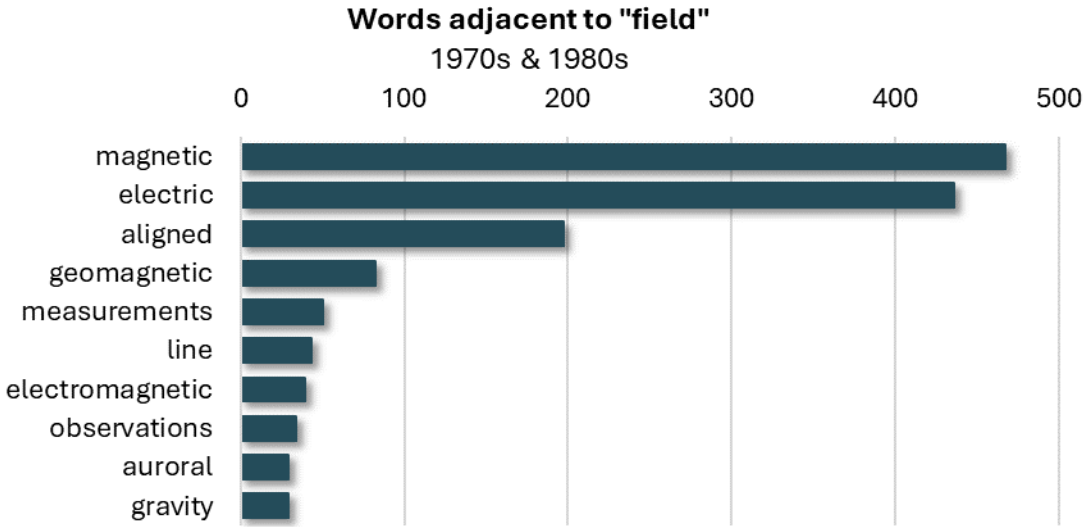

Figure 12: Most frequent words, prefixes, and suffixes adjacent to "field(s)" in titles of AGU articles published from 1970–1989.

Articles with “field aligned” in the title mostly referred to field-aligned “currents” or “current,” primarily in *JGR: Space Physics*. As more scientific spacecraft were launched in the early 1970s, the field-aligned

currents electrically connecting the upper atmosphere to the rest of near-Earth space became a topic of great interest to the research community, including the famous paper detailing the pattern of these current systems by Ijima and Potemra (1976).

“Solar” drops in the list from previous years but still holds a place in the top 10 with articles on solar wind and geomagnetic and solar data. “Atmospheric” again appears, primarily from titles in *JGR: Oceans* and then *JGR: Space Physics* but followed closely behind by contributions from *GRL*. Topics ranged widely and included soil and atmospheric boundary layer, microwave imagery of ocean waves, atmospheric nitrates, radiation, aerosols, gravity waves, and the atmospheric spectrum.

“Water” appears on the most frequent list as *WRR* started to grow; WRR contributed 62% of the articles with this word in these two decades. The top water-specific topics, as shown in Figure 13, were ground water, water flow, and water resources, perhaps related to the establishment of the Environmental Protection Agency and an increase in water-related U.S. policy; the development of hydrology computer models and codes from the U.S. Geological Survey in 1970 may also have increased the amount of data and content appropriate for AGU’s water resources journal (Reilley, 2004).

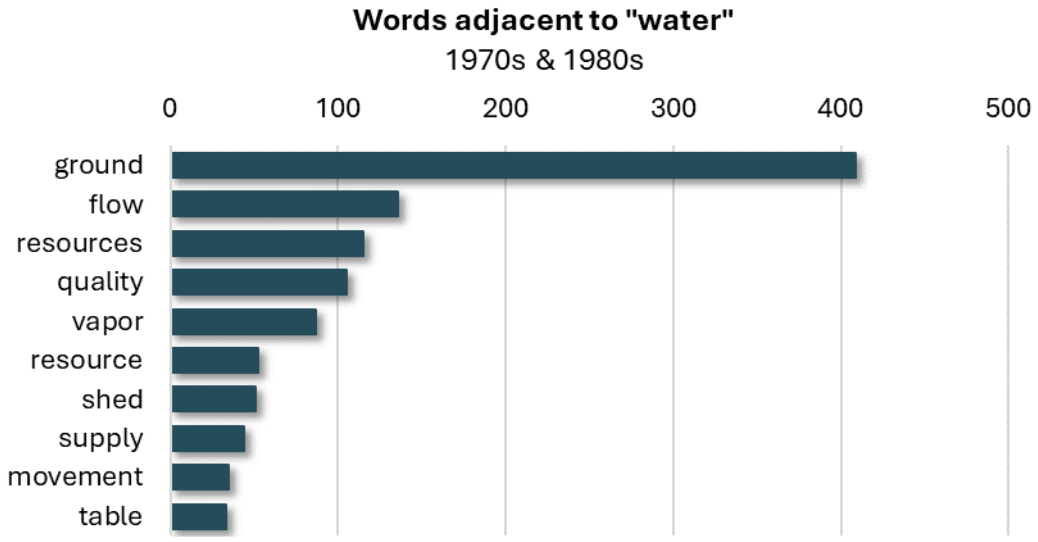

Figure 13: Most frequent words, prefixes, and suffixes adjacent to "water" in titles of AGU articles published from 1970–1989.

“Plasma” makes an exciting debut on the top 10 list and is most associated with the word “sheet”, spurred by the discovery of the plasmasphere in the mid-60s by Carpenter and colleagues and first referred to as a “knee” in the magnetosphere (Carpenter, 1963). In the early 70s, more sophisticated satellite measurements allowed scientists to confirm that a plasma sheet existed between the northern and southern portions of the Earth’s magneotail (Hill, 1974).

Nonscientific terms (1970-1989):

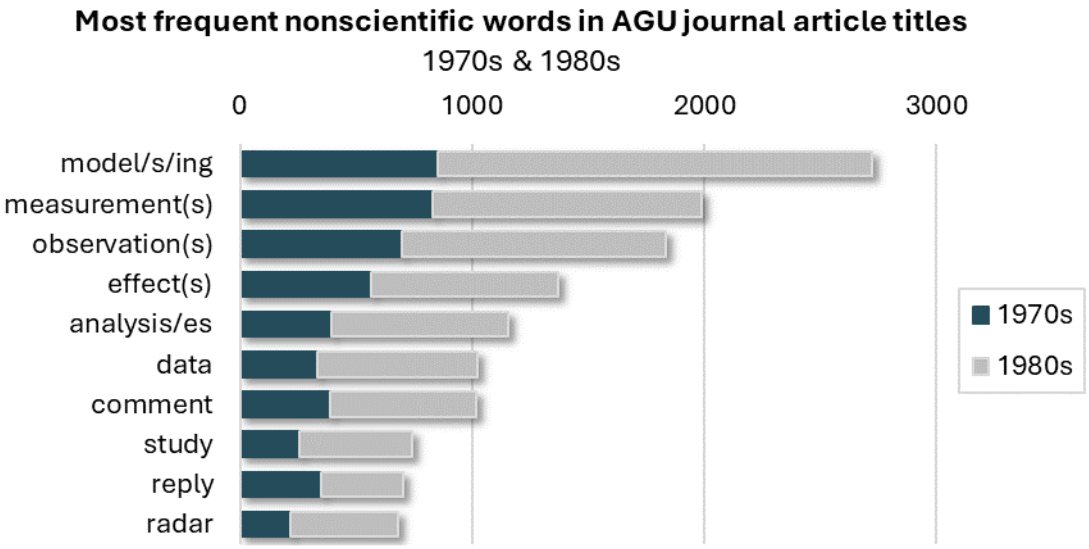

Figure 14: Most frequently occurring nonscientific terms in titles of AGU articles published between 1970 and 1989.

Figure 14 shows a slight but significant shift in the most frequent nonscientific terms in these decades compared to the 50s and 60s. The most frequent methods term and the third most frequent term overall (scientific and non) is "model," which doesn't even appear in the top 10 list of the 50s and 60s. In the 70s, "model" and "measurement" appear in titles at the same frequency, but "model" becomes much more frequent in titles in the 1980s, pushing to it to the first. Almost one-third of the occurrences of "model" were contributed by *WRR*. The most frequent types of modeling seen in titles were "flow," "transport," and "stochastic." As computing power became more assessable, scientists were accumulating enough data to develop robust models to predict future outcomes in various locations.

"Measurements" comes in second and implies a higher level of precision of numerical values than mere "observations" could provide, though "observations" still holds strong in the list. Contributed mostly by *JGR: Space Physics*, "observations" was more frequently connected to articles involving massive and expensive equipment: many titles include names of satellite series or space telescopes launched by rockets. The most frequent word seen with "observations" in *JGR: Space Physics* was "plasma," which makes the top 10 scientific word list in these decades as well, as discussed earlier in the previous section.

"Effect(s)" and "analysis" outnumber "study" in these decades compared to previous ones. Perhaps this implies that scientific discovery had become, as "analysis" implies, more of a systematic approach of making sense of numerical data, and as "effects" implies, using the data to understand potential future consequences of events. These terms push down "study" from previous years, the latter implying an archaic practice of memorizing, pouring over sets of numbers and observations, and applying mere human thought to make sense of them. "Data" starts to decrease in frequency compared to previous years; it is mostly contributed by articles in *JGR: Space Physics,* with many articles on geomagnetic and solar data, and *JGR: Solid Earth,* with seismic and gravity data. "Comment" makes its debut on the top 10 list, and "reply" appears again showing growth in the formal commenting process, with *WRR* contributing

the most to the frequency of both words, perhaps indicating an increase in controversial research, opinions, and perhaps increased competition for prestige among researchers.

Years 1990-2009:

Journals (1990-2009): AGU started out the 1990s with 11 journals and grew to 17 by 2009. In 1991, *JGR: Solid Earth and Planets* was split to give Planets its own section (Chapman, 1991). *Geochemistry, Geophysics, Geosystems*, affectionally known as *G-Cubed,* was first published in 2000 as an interdisciplinary electronic-only journal where no issues would be printed on paper: its mission was to take advantage of an online environment where large datasets and other electronic supplements not conducive to printing were provided alongside articles (Langmuir, 1999). 2003 saw the start of *JGR: Earth Surface* to provide a niche journal for the growing community of scientists working on surface processes, also known as geomorphologists (Anderson, 2003). This same year also witnessed the birth of *Space Weather,* which focused on operational space weather forecasting (Robinson, 2003). *Space Weather* was different from the other journals in that it was also published as a quarterly magazine for a broad audience of technicians, engineers, and policy makers. Two years later, in 2005, the seventh section of *JGR*, *JGR*: *Biogeosciences*, was started to handle the growing scientific interest in biological, ecological, and biogeochemical systems interactions (McKnight, 2005). And finally, in 2011, AGU acquired *Journal of Advances in Modeling Earth Systems (JAMES*), which had been publishing articles since 2009 by the Center for Multiscale Modeling of Atmospheric Processes at Colorado State University. *JAMES* was the first AGU journal to be published fully open access.

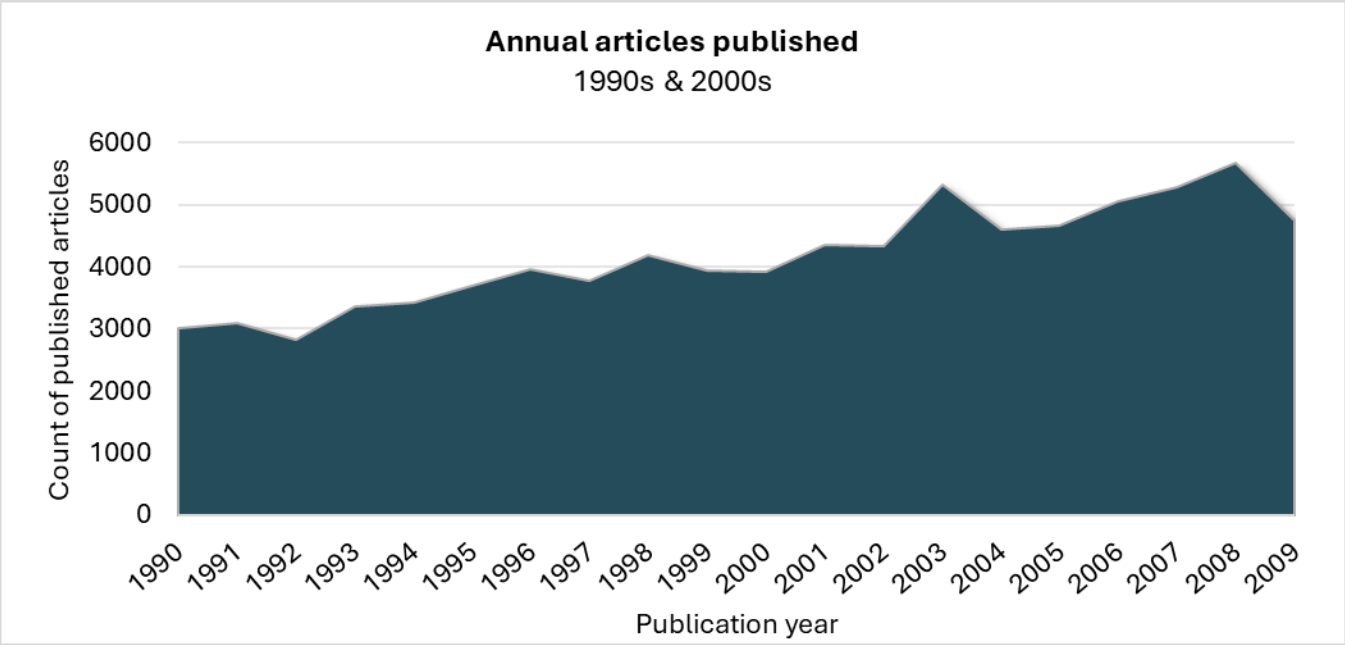

Figure 15: Number of AGU articles published annually between 1990 and 2009.

Published articles (1990-2009): 83,151 were published with Figure 15 showing that the article output continued to climb, ending the aughts, with a 58% increase from 1990. The increase in published articles from 1990 through the early 2000s was fueled by massive growth in *GRL* and, to a lesser extent, *JGR: Atmospheres*. In fact, *GRL*'s peak output was in 2006 with 1700 articles, which was a 170% increase from 1990, and an annual output not surpassed until 2021 with 1864 articles. *JGR: Atmospheres* went

from 349 articles in 1990, peaked at 1140 in 2003 (a level not seen since as of the publication of this article), and closed the aughts at 738. The output of these two journals impelled AGU to publish bimonthly reports of *GRL* in 1992 and *JGR: Atmospheres* in 1996. The decrease in 2009 from 2008 could have been caused by a reduction in spending after the 2008 global financial crisis.

Scientific terms (1990-2009):

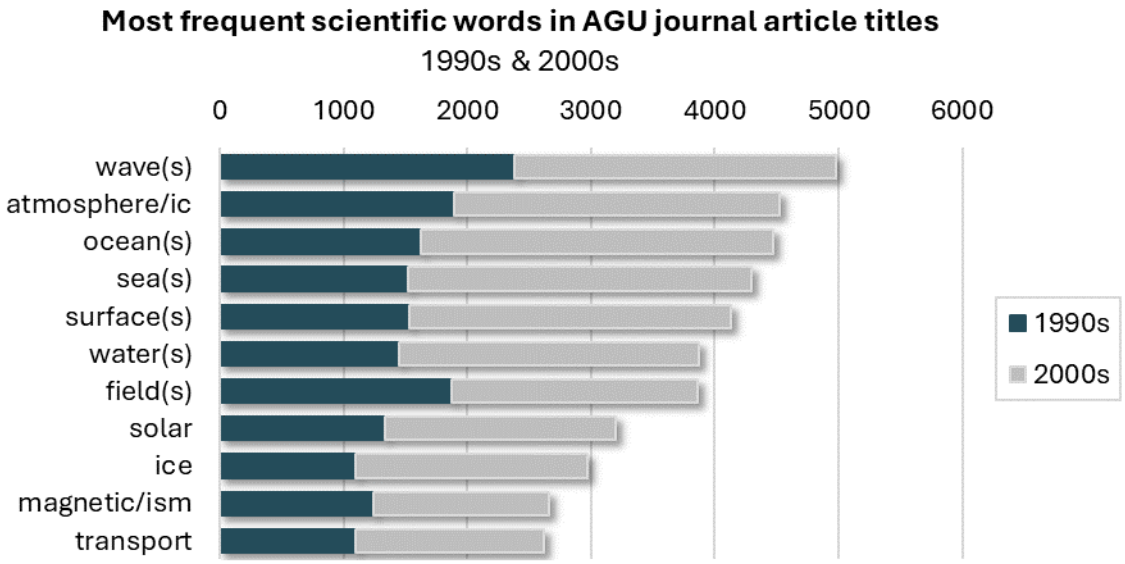

Figure 16: Most frequently occurring scientific terms in titles of AGU articles published between 1990 and 2009.

The most frequent science-related terms in titles in these years, as presented in Figure 16, show exciting movement from previous years. Although “wave” is still at the top, “field” and “solar” drop down the list and “atmosphere/ic” climbs its way to second. “Ionosphere/ic,” “plasma,” “wind,” and “aurora” drop off the list due to the increase in articles (and journals) on oceans and atmospheres.

When we review adjacent terms to “wave(s),” we find that the most frequent association is “micro-”; however, the methodology of creating the top 10 lists does not consider parts of compound words, so the frequency of “microwaves” is not included in the count of “wave.” Nevertheless, “microwave(s)” was the most commonly associated prefix with “wave.” *JGR: Atmospheres* contributed the most titles with “microwave,” which were used to measure atmospheric composition and temperature. *GRL* contributed the most articles with “wave” in the title with many articles on gravity and seismic waves. *JGR: Space Physics* provided the second most articles with “wave,” many about Alfvén and plasma waves. The other frequent words associated with “wave(s)” are shown in Figure 17.

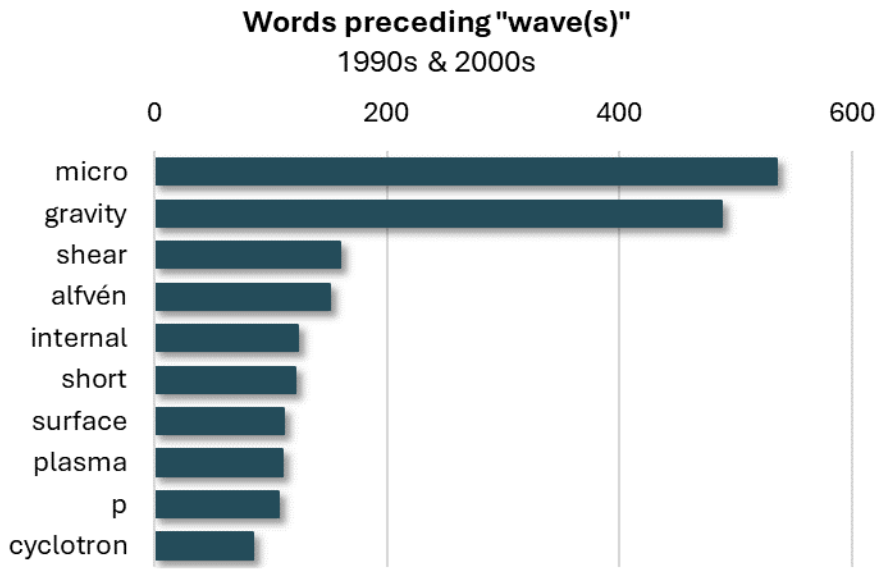

Figure 17: Most frequent words and prefixes preceding "wave(s)" in titles of AGU articles published from 1990–2009.

"Atmosphere/ic" holds strong in these decades, especially as *JGR: Atmospheres* output increases. The journal contributed articles on this topic in aerosols in an era when the scientific community and the public were concerned about ozone depletion, illustrated by policy such as the Montreal Protocol, which phased out the production of ozone-depleting chemicals. Other topics ranged from methane, atmospheric carbon dioxide, atmosphere-ocean circulation, and dust/particles. *GRL* continued with the theme of El Niño and ocean warming as it contributed articles on atmospheric circulation and ocean-atmosphere interactions. Some smaller journals contributed approximately 200 articles each with titles containing "atmosphere/ic": a majority of *JGR: Planets* were on Martian and Venusian atmospheres, while *Global Biogeochemical Cycles* articles focused on atmospheric carbon dioxide, methane, and nitrogen.

A strong interest in the "sea" and "ocean" are apparent in all journals but contributing the most was unsurprisingly *JGR: Oceans* on ocean circulation, variability, and the Pacific. Across all journals with "ocean" in the titles, the most frequent were titles with "Indian Ocean," with some on the Pacific and the Atlantic Oceans. Also frequently seen associated with "ocean" is "Southern" again indicating an increased awareness of El Niño, both within the scientific community and the public at large.

"Surface" makes its debut on the list with *GRL* contributing articles on sea and ocean temperatures and *JGR: Atmospheres* contributing many on "land" and "temperature"; this is as land and ocean warming issues began to take hold in the public. Words directly adjacent to "surface" in titles and their frequencies are shown in Figure 18.

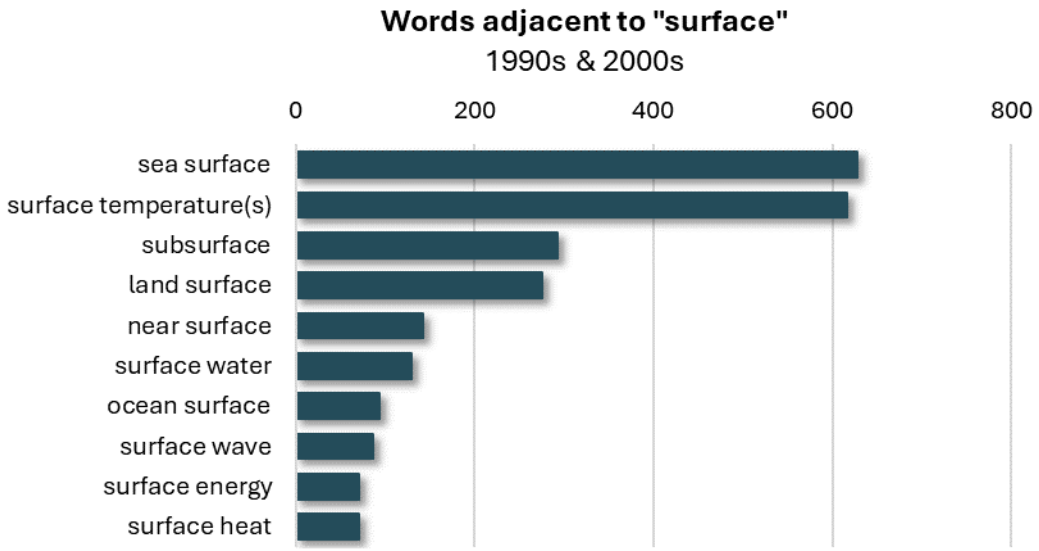

Figure 18: Most frequent words, prefixes, and suffixes adjacent to "surface(s)" in titles of AGU articles published from 1990-2009.

"Water" sits mid-list with unsurprising help from *WRR* (37% of the occurrences) and titles are dominated by articles on groundwater. Other water-adjacent words are shown in Figure 19.

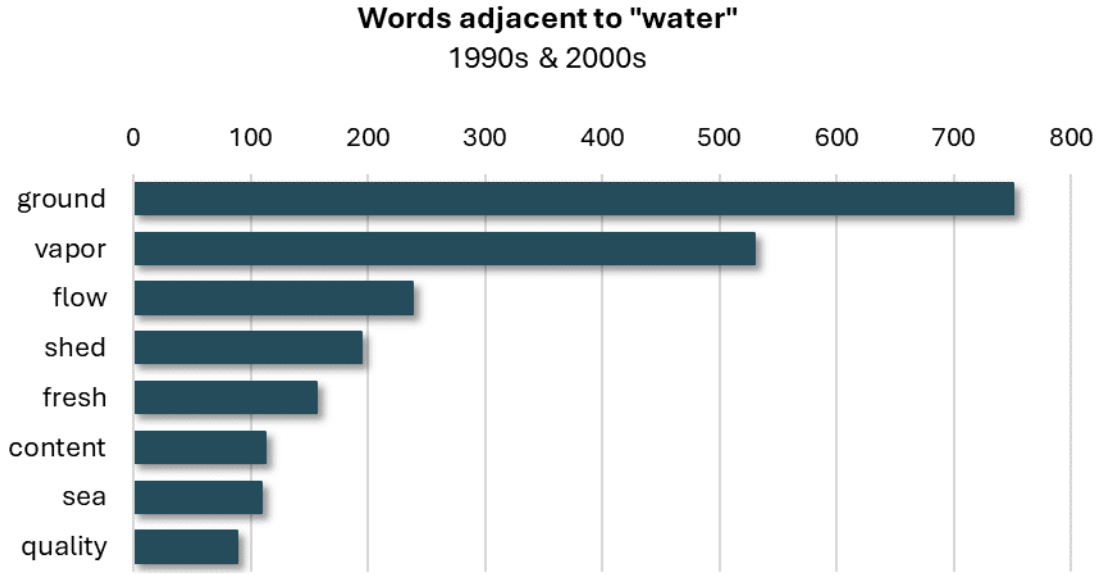

Figure 19: Most frequent words, prefixes, and suffixes adjacent to "water" in titles of AGU articles published from 1990-2009.

We can't talk about sea, oceans, and El Niño without talking about warming and "ice," which appears on the top 10 list on research observing *less* ice, a harbinger of the humanity-threatening topic of global warming. However, the frequency of "ice cores" in titles also suggests an interest in using ice samples to uncover stories of recent and distant pasts.

“Magnetic” is also tenacious in the list but drops in frequency compared to earlier years: *JGR: Space Physics* contributes almost half of the word’s frequency with articles on the effects of solar wind on both interplanetary and Earth’s magnetic fields.

Nonscientific terms (1990-2009):

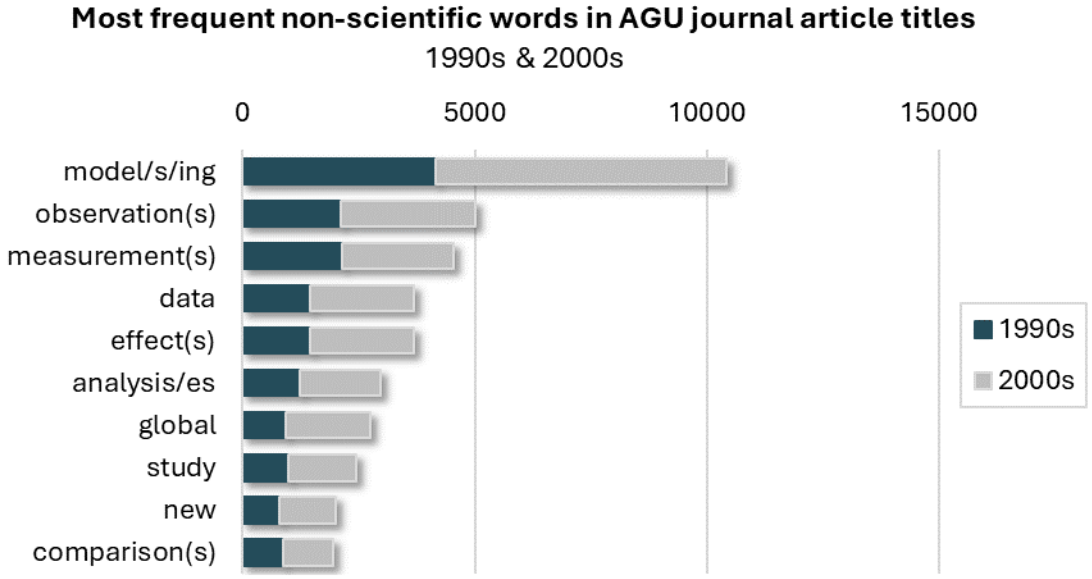

Figure 20: Most frequently occurring nonscientific terms in titles of AGU articles published between 1990 and 2009.

The top three nonscientific terms from the previous two decades held steady (Figure 20). *JGR: Atmospheres* contributed most heavily to the frequency of “model” with articles on climate. *GRL* contributed most to “observations” with articles on satellite observations, with many on observations of planets and their moons. “Measurements” appears due to its frequency *in JGR: Atmospheres* articles with many on aerosols and ozone. “Data” climbs up one spot from the previous years with many articles contributed by *JGR: Atmospheres* and *GRL* on satellite data and seismic data. Articles with “effect(s)” appears in 5% of all titles across all journals, many on the consequences of human activity, pollutants, and seasonal variations in weather, signaling the deeper work of disentangling the anthropogenic from natural causes of observed phenomena, a topic fraught with political and for many readers, interpersonal, debate.

“Analysis” is contributed mostly by *JGR: Atmospheres* and *WRR*; in *JGR: Atmospheres*, it is most frequently seen with “data” and “ozone.” *WRR* contributed the occurrences of “analysis” with topics such as flow analysis, rainfall, stream and river discharge and recharge, and nitrogen runoff. *GRL* contributed 15% of its frequency (compared to 23% in *JGR: Atmospheres* and 18% in *WRR*), perhaps because the word represents too detailed a method for a short-format journal.

“Global” makes its debut on the list and compliments the new globally focused journal *Global Biogeochemical Cycles* and reflects increasingly advanced and accessible technology that could collect massive amounts of data to construct complex models. Words seen directly following the word “global” in titles are shown in Figure 21.

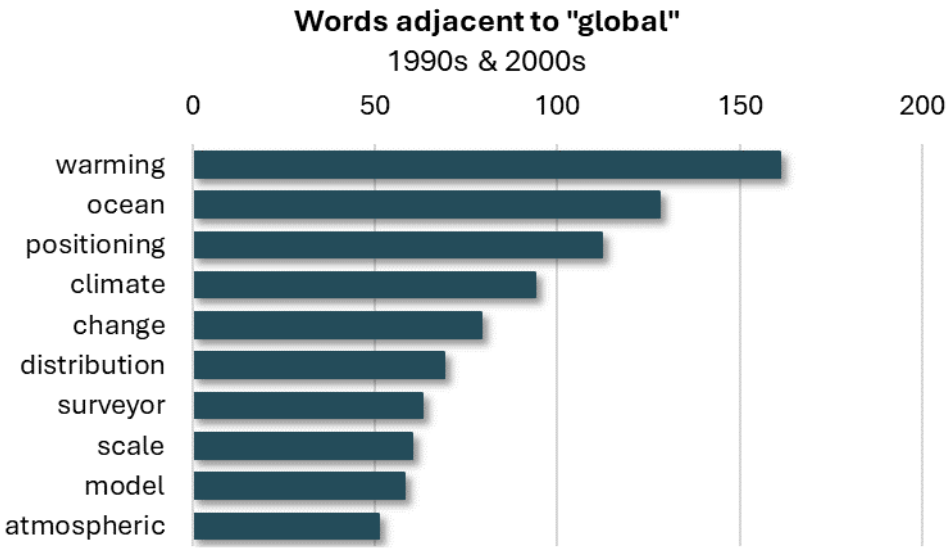

Figure 21: Most frequent words and prefixes preceding "global" in titles of AGU articles published from 1990-2009.

We have a notable return of “study,” most often occurring in *JGR: Atmospheres* and most frequently used in “case study” and “regional study”; that there was a need to declare that the article not about global, broadly applicable phenomenon suggests that results reported in articles by default should be broadly applicable.

Years 2010-2022

Journals (2010-2022): Between 2010 and 2022, AGU launched six new open access journals whose topics reflected increased attention on the interactions between humans and Earth systems. In 2013, *Earth’s Future* was launched to publish work on the effects that a changing climate has on current and future human systems. In 2016, *Earth and Space Science* was launched as a broad-topic journal encouraging articles on methodology, instrumentation, and data-gathering processes (Hanson, 2014). In 2017, *GeoHealth* launched as both a journal and an AGU section on the intersection of geosciences and human and environmental health (McEntee, 2016). In 2018, *AGU Advances* was founded to add a highly selective journal to the AGU umbrella that covered the breadth of Earth and space science research and issues (McEntee, 2018). In 2020, *Perspectives of Earth and Space Scientists* started as a homage to AGU’s centennial anniversary to share the personal stories behind scientific discoveries, advances, and events in the Earth and space sciences. First focusing on authors who were honored as AGU Fellows, *Perspectives* has expanded to include personal reflections from across the full spectrum of Earth and space scientists (Wysession, 2022). And finally, in 2021, *Community Science* was launched as a place to share results and case studies on transdisciplinary research that includes social and public health conducted in partnership with communities intended to address community challenges.

Published articles (2010-2022): 82,615 were published in these years with Figure 22 showing the continued growth of articles for the most recent years considered in this study. By 2003, article output across all AGU journals had already reached more than 5000 a year, hovering there a few years afterwards and by 2010, AGU journals consistently published at least 5000 articles annually. In 2016,

more than 6000 articles were published, a number that has maintained itself every year since. By 2022, the total number of articles published in the previous 10 years has almost outpaced the total number of articles published in the 20 years prior (~83,000) with six more years to go in the decade.

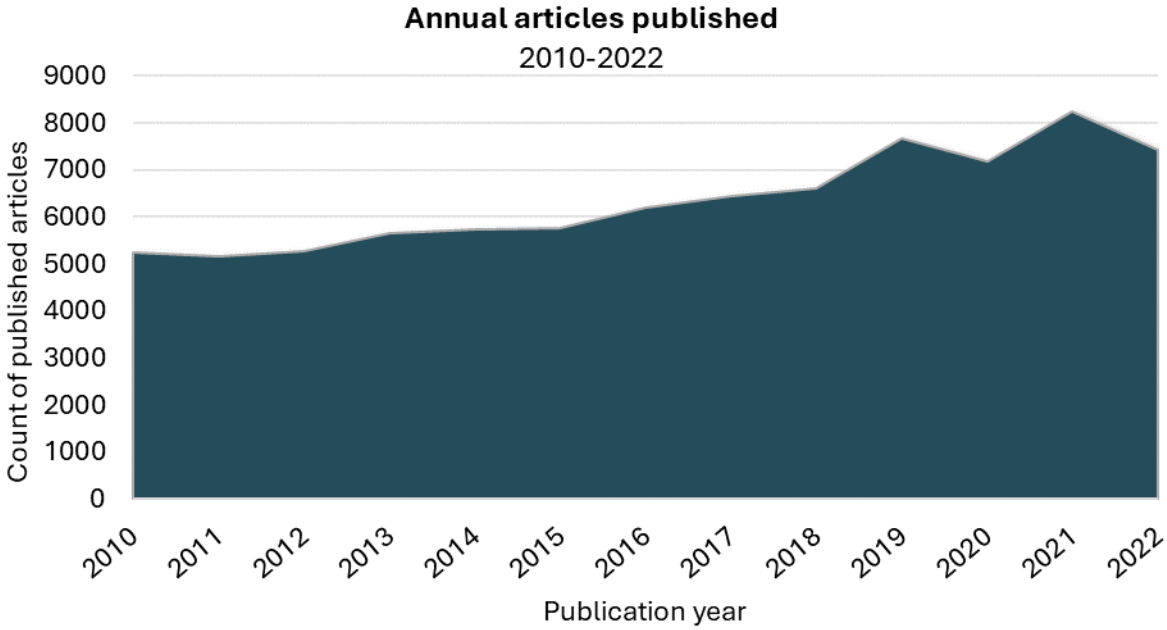

Figure 22: Number of AGU articles published annually between 2010 and 2022.

Scientific terms (2010-2022):

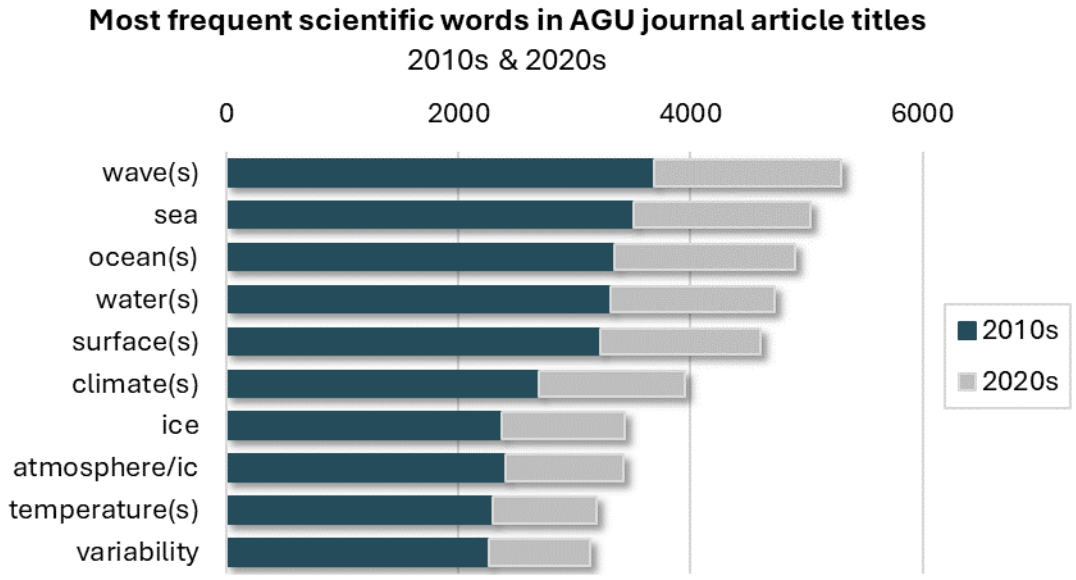

Figure 23: Most frequently occurring scientific terms in the titles of AGU articles published between 2010 and 2022.

Figure 23 indicates that space physics and climate science were dominant forces in AGU journals over these 13 years with “wave” topping the list again. *GRL* contributed approximately one-third of the word’s frequency with articles primarily on gravity waves but also on seismic waves and earthquakes, radiation and electrons, and ocean waves. *JGR: Space Physics* contributes equally to the word’s frequency with articles on electrons and ions, solar wind, ultra-low-frequency waves, and plasma. Figure 24 shows the words preceding “wave(s)” in titles in these years.

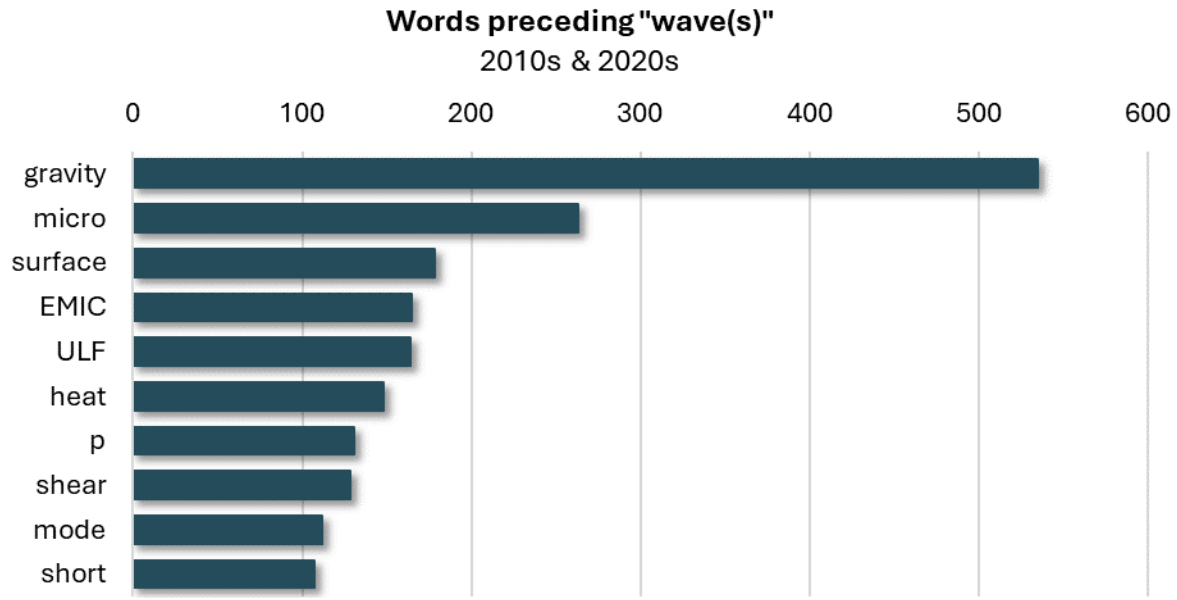

Figure 24: Most frequent words and prefixes preceding "wave(s)" in titles of AGU articles published from 2010–2022.

“Gravity” waves dominate the list of wave-associated words, many about atmospheric composition, ocean activity, ocean and atmospheric temperature, and tsunamis. “Microwaves” appear as a far-away second, with many articles on using microwaves with satellites to study the composition of the atmosphere, ice, and bodies of water.

Returning to the overall top 10 list, we see that water-related terms dominate with “sea,” “ocean” and “water” in the second, third, and fourth positions, respectively. “Sea” appears most frequently as an adjective in phrases such as “sea ice,” “sea surface,” “sea-level rise” and “air-sea exchange”. The frequency of “sea” was mostly contributed by *GRL* (43% of all titles with the word were in GRL), but only 5% of GRL titles contained the word “sea.” *JGR: Oceans* contributed 28% of the frequency of “sea,” with many articles on sea ice and the Arctic, but a whopping 18% of *JGR: Ocean’s* titles contained the term. Fourteen percent of *Paleoceanography and Paleoclimatology* article titles contained the word “sea,” many on sea surface temperature and chemical composition of sites in named seas.

“Ocean” appears mostly with names of specific oceans with the Southern and Indian Oceans being the most frequent, followed by the Arctic, Pacific, and Atlantic in descending order of frequency. “Ocean” also appears frequently in phrases like “global ocean,” “upper ocean,” and “deep ocean.” Ocean” frequency is heavily contributed by *GRL* titles, but also by those of *JGR: Oceans* and *Global Biogeochemical Cycles*. In *GRL*, articles on the El Niño effect dominated, as climate change and warming oceans were “immediate impacts” topics deserving expedited publication that the journal is

known for. In *JGR: Oceans*, many articles with “ocean” in the title were on the Arctic and ice, while those in *GBC* focused on climate.

In fourth place is “water,” *with GRL* and *WRR* contributing the most to its frequency namely with articles on water vapor, watersheds, and freshwater topics. By far the most common water-related word was “groundwater,” with a wide array of topics including flow, quality, effects of climate change, and pollutants. Other words accompanying “water” are shown in Figure 25.

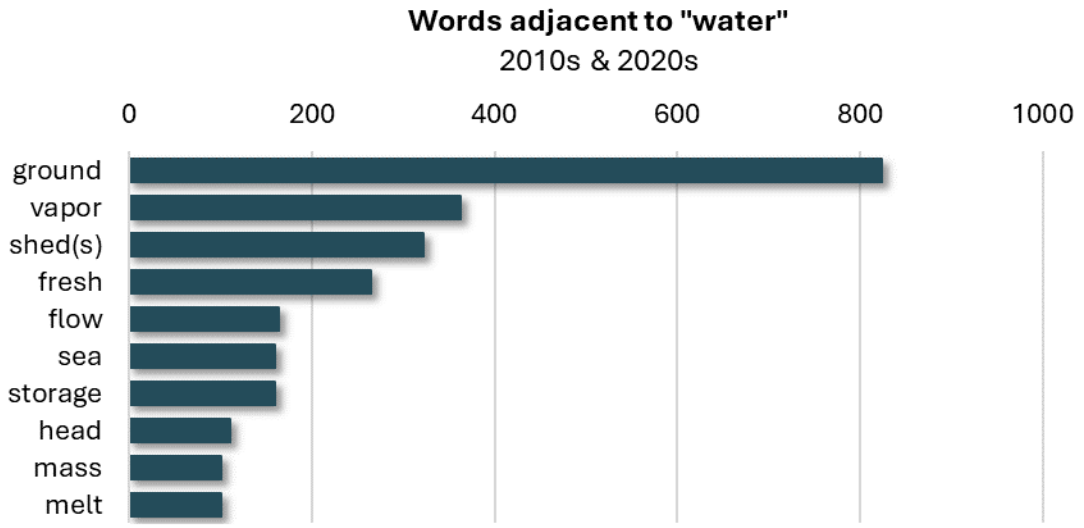

Figure 25: Most frequent words, prefixes, and suffixes adjacent to "water" in titles of AGU articles published from 2010–2022.

“Surface” holds fifth in the top 10 list, as it had in previous years. Many articles with this word in the title were on bodies of water and temperatures at the surface. The journal with the highest proportion of articles with “surface” in the title was *JGR: Oceans,* with 45% of titles containing the word, many on ocean circulation and currents, temperatures, and chemical composition. The most frequent words adjacent to “surface” during these years are shown in Figure 26.

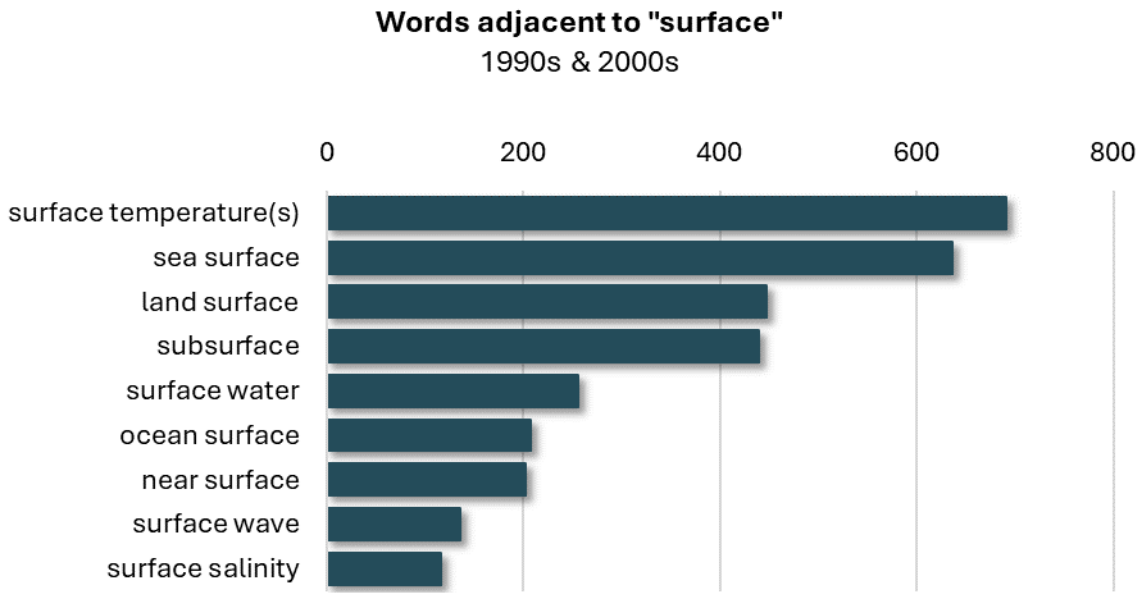

Figure 26: Most frequent words, prefixes, and suffixes adjacent to "surface" in titles of AGU articles published from 2010–2022.

With a strong societal focus on climate in recent years, it is not surprising that “climate” appears in the top 10 list; in fact, it might be surprising that “climate” doesn’t sit higher than sixth. However, words more frequent than “climate” provide specific indications of climate change especially in bodies of water (sea, ocean, water, surface). “Ice,” appearing in seventh, is also a bellwether of short- and long-term temperature variability, the latter term also appearing in the list in 10th. “Atmosphere/ic” drops to eighth from second in the previous years perhaps indicating, based on the words more frequently seen than “atmosphere/ic,” a stronger scientific need to understand the roles of oceans in the Earth system.

Nonscientific terms (2010-2022):

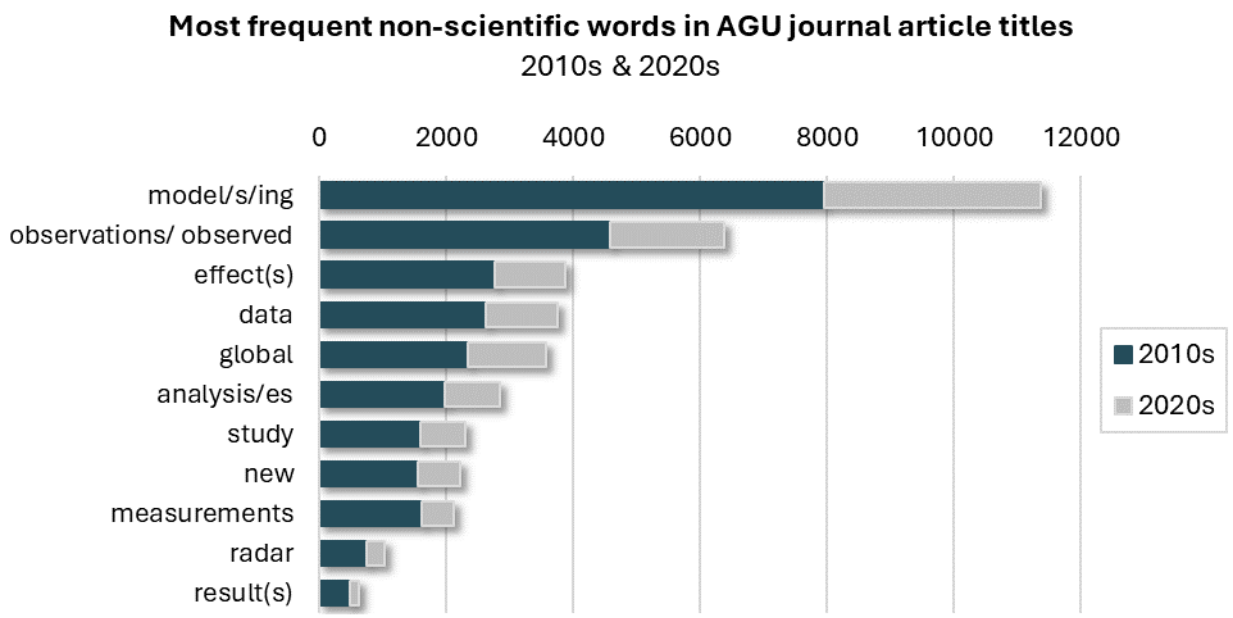

Figure 27: Most frequently occurring nonscientific terms in the titles of AGU articles published between 2010 and 2022.

Turning to methods- and content-related words, Figure 27 shows "model" again at the top of the chart, occurring almost twice the frequency than second-place "observations." *WRR* contributed the most to the frequency of "model" appearing in 25% of *WRR*'s titles. A sampling of WRR titles with "model/s/ing" indicates topics such as water and heat transport, subsurface flow modeling, flood risk assessment, sediment resource reduction, and general articles on using models in water research and "geostatistics." In the same years, almost 50% of articles in the modeling journal *JAMES* contained the word "model" in their titles. A sampling of JAMES articles with "model/s/ing" in the titles indicates diverse topics such as ocean-wave-atmosphere models, global maize yield, global precipitation, vegetation, and polar cloud models.

The ever-present "observations" made it to the list again through major contributions from *JGR: Space Physics* on topics such as satellite and spacecraft observations, including many observations from the Van Allen Probes.

"Effect(s)" appears in the list and is contributed mostly by *GRL* and *JGR: Atmospheres*, as the highest volume journals, but only 4% and 6%, respectively, of their titles contained this word. "Effects" expresses the so-what of the observed phenomena, perhaps a turning away from the causes of an event and focusing instead on the potential consequences—immediate and future—of observed events and human activity. The journals with the highest proportion of "effect" in their titles are *WRR* and *JGR: Biogeosciences* with 7% of both journals' titles containing the word.

In the era of "big data," that "data" appears on this list is expected. A third of the frequency of "data" was contributed by *GRL*, and many titles mention "data assimilation" or another method used to come to the conclusions purported in the paper. It's no surprise that with the proliferation of data and ease of capturing data in the 21st century that what's done with data—analysis—also appears on the top 10 list. *JGR: Atmospheres* contributed the most titles with "analysis/es," but 6% of titles, the highest seen for

this word, contained “analysis/es” each in *Earth and Space Science*, *Radio Science*, and *Water Resources Research*.

Terms over all time

We now turn from a detailed analysis to a general overview including 1) the top 5 most frequent scientific terms by decade shown in Figure 28 and 2) the number of journals and articles published each year of this analysis in Figure 29.

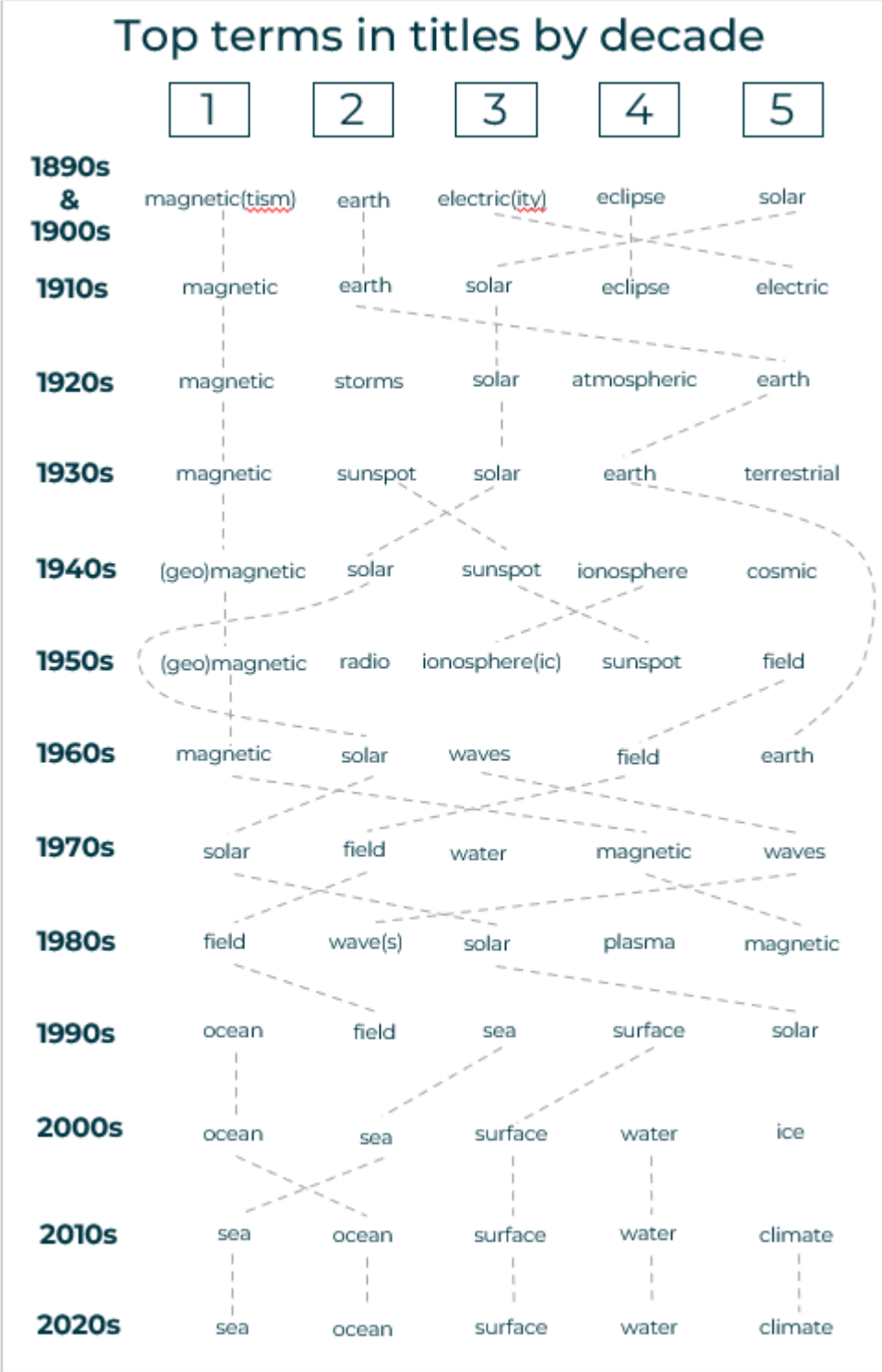

Figure 28: The five most common scientific terms in the titles of AGU journal articles by decade of publication. Straight dotted lines indicate recurring terms in consecutive decades; curved dotted lines indicate recurring terms in nonconsecutive decades. Terms displayed as multiple versions with the same root (e.g., "ionosphere(ic)") indicate that both words appeared in the top five terms of that decade and were combined. Terms not displayed as multiple versions (e.g., "atmosphere") did not have terms with identical roots in the top five and were not combined. The design was inspired by Monastersky & Van Noorden, 2019.

With *Terrestrial Magnetism* starting in 1896, the first 16 years of titles are represented on the top line with mostly terms related to the journal's title. "Magnetic" and "geomagnetic" were strong for the first seven decades, dropping to fourth in the 70s. "Solar" appears throughout the beginning of the century, replaced briefly in the 50s by its sister term "sunspot," and ascends to first in the 70s, not dropping off until the 2000s. "Atmospheric" appears in the 1920s for only one decade despite the journal title change to *Terrestrial Magnetism and Atmospheric Electricity* in 1899. "Radio" also appears for a single decade in the 50s even before AGU acquired the journal *Radio Science* in 1966. In fact, "radio" does not appear in the top 10 list of the 50s and 60s (see section "Scientific terms (1950-1969)") since it wasn't frequent enough in the 60s to be a top word in titles of the 50s *and* 60s. "Waves" appears in the 60s, 70s, and 80s, as its frequency among multiple contexts (radio waves, seismic waves, water waves, etc.) is a reminder of the strong underpinning that basic physics has within the Earth and planetary sciences. "Field" appears in the 60s and works its way up to top spot in the 80s but drops out in the 2000s. Water-related words (water, sea, ocean, ice) initiate their dominance in the top five starting in the 1990s as a rapidly changing climate becomes a concern for scientists and the public.

The trends in scientific topics published in AGU journals would not be possible without the growth in journals, which reflected diversifying topics within—and supported increasing interdisciplinarity across—the geosciences. We first see this diversification in the 70s with the appearance of "water" in the top 5 and top 10 scientific terms, and it certainly correlates with the growth in journal titles and article volume from 1896 to 2022, as shown in Figure 29.

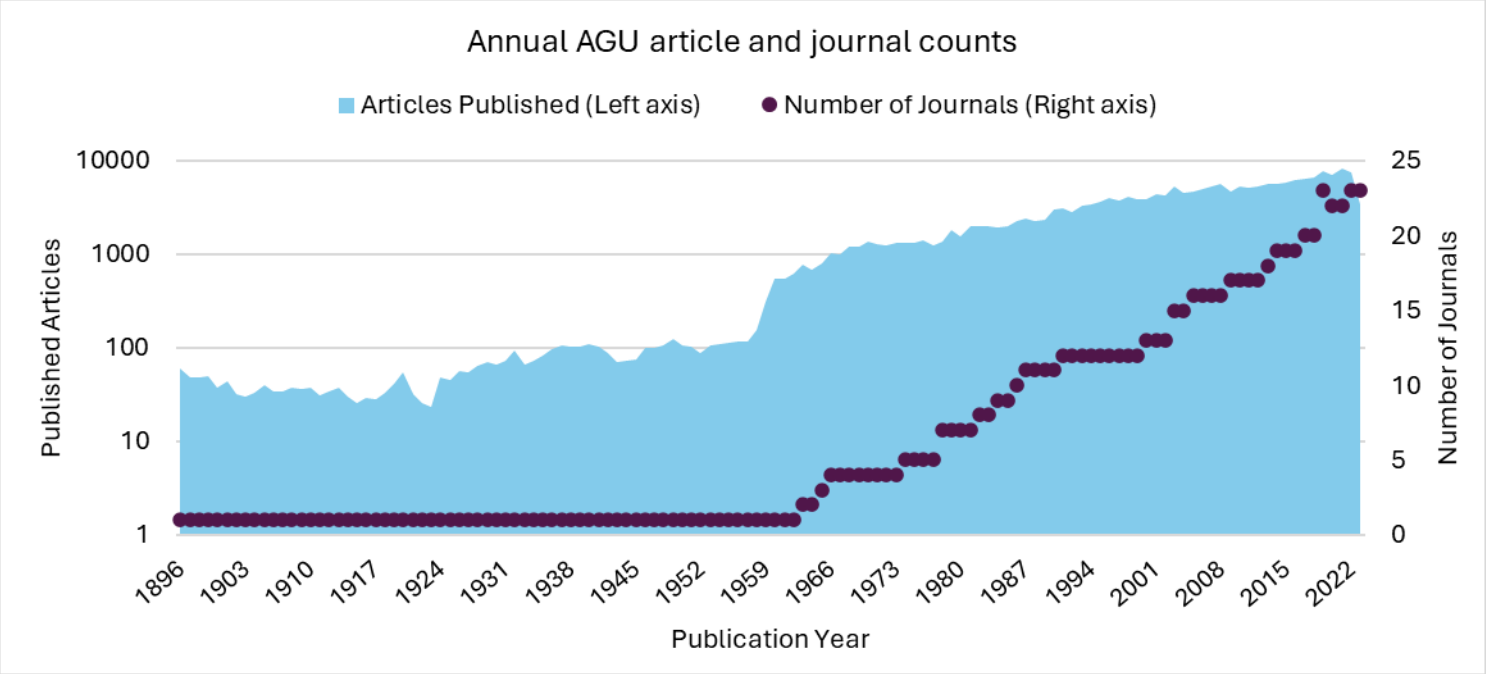

Figure 29: The number of AGU articles published annually (solid fill, left axis, log-axis) and the number of journals (dark circles, right axis).

Conclusion

Combing through article titles shows us that the journal receptacle was more than just a prestigious way to share groundbreaking scientific results. Articles were used for sharing observations, personal reactions to relevant scientific discoveries, repartees with fellow scientists, and some came with an undertow of words of warning. Through article titles, we can reaffirm that AGU journals were built on scientists studying Earth's magnetism and incrementally developing their understanding of the component parts of Earth's atmosphere. Article titles remind us that scientific interests were both limited by and made possible through the technology of the time. The turn of the 19th century when AGU's first journal was founded was a productive era for science—the discovery of the electron came one year after the *Journal of Terrestrial Magnetism* was started. Weather balloons were invented in the 1890s and allowed for an increase in studies on the Earth's atmosphere. In 1908, George Ellery Hale reported that sunspots were highly magnetic, paving the way for a better understanding of the effect of the sun on Earth's magnetic field. The sun could not be disentangled from the study of the Earth, so AGU's journals grew out toward the physics of space and down to the physics of the Earth with their first two sections of *JGR*—space physics and solid earth. The increasing understanding that the oceans reflect Earth's past and present, and that oceans research could be a harbinger of Earth's future propelled geophysicists toward studying oceans and other aqueous environments. Increasingly sophisticated technology allowed for a deeper and whole scale understanding of the Earth's atmosphere and beyond. Basic research—why things are the way they are—gives way to human societies' actions and the effects those actions have on our world and beyond. We cannot study the atmosphere or the ocean without studying the effects of our actions on the environment. The need to understand the cause and effect of observed phenomena—science—is apparent throughout the history of AGU journal titles and tells the story of research progress in geophysics over the past 130 years.

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