Trends in the representation of women amongst geoscience faculty from 1999-2020: the long road towards gender parity

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Abstract

Inequalities persist in the geosciences. White women and people of color remain under-represented at all levels of academic faculty, including positions of power such as departmental and institutional leadership. While the proportion of women among geoscience faculty has been catalogued previously, new programs and initiatives aimed at improving diversity, focused on institutional factors that affect equity in the geosciences, necessitate an updated study and a new metric for quantifying the biases that result in under-representation . We compile a dataset of 2,531 tenured and tenure-track geoscience faculty from 62 universities in the United States to evaluate the proportion of women by rank and discipline. We find that 27% of faculty are women. The fraction of women in the faculty pool decreases with rank, as women comprise 46% of assistant professors, 34% of associate professors, and 19% of full professors. We quantify the attrition of women in terms of a fractionation factor, which describes the rate of loss of women along the tenure track and allows us to move away from the metaphor of the 'leaky pipeline'. Efforts to address inequities in institutional culture and biases in promotion and hiring practices over the past few years may provide insight into the recent positive shifts in fractionation factor. Our results suggest a need for 1:1 hiring between men and women to reach gender parity. Due to significant disparities in race, this work is most applicable to white women, and our use of the gender binary does not represent gender diversity in the geosciences.

Trends in the representation of women among US geoscience faculty from 1999-2020: the long road towards gender parity

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Key Points:

- We compile a dataset of the proportion of women:men in the geosciences from $\sim 2,500$ geoscience faculty. Women make up $\sim 27\%$ of tenured and tenure-track faculty in the institutions considered
- We quantify the attrition of women in the geosciences in terms of a 'fractionation factor' to describe the rate of loss of women along the tenure track and find that the historic disproportionate attrition of women is decreasing.
- We develop a simple model to analyze when gender parity can be reached

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Abstract

Inequalities persist in the geosciences. White women and people of color remain under-represented at all levels of academic faculty, including positions of power such as departmental and institutional leadership. While the proportion of women among geoscience faculty has been catalogued previously, new programs and initiatives aimed at improving diversity, focused on institutional factors that affect equity in the geosciences, necessitate an updated study and a new metric for quantifying the biases that result in under-representation . We compile a dataset of 2,531 tenured and tenure-track geoscience faculty from 62 universities in the United States to evaluate the proportion of women by rank and discipline. We find that 27% of faculty are women. The fraction of women in the faculty pool decreases with rank, as women comprise 46% of assistant professors, 34% of associate professors, and 19% of full professors. We quantify the attrition of women in terms of a fractionation factor, which describes the rate of loss of women along the tenure track and allows us to move away from the metaphor of the 'leaky pipeline'. Efforts to address inequities in institutional culture and biases in promotion and hiring practices over the past few years may provide insight into the recent positive shifts in fractionation factor. Our results suggest a need for 1:1 hiring between men and women to reach gender parity. Due to significant disparities in race, this work is most applicable to white women, and our use of the gender binary does not represent gender diversity in the geosciences.

Plain Language Summary

Both women and people of color are under-represented throughout academic faculty positions in the geosciences, which covers earth, atmospheric, ocean, and planetary sciences. Previous work has shown that women comprise a lower percentage of geoscience faculty. Recently, there have been an increasing number of programs and studies that seek to understand the institutional causes of gender inequities and to find solutions for these inequities. Here, we assess the representation of women in the geoscience faculty and propose a new, quantitative metric that connects with the research on institutional root causes. We gathered a dataset of 2,531 faculty from 62 different universities and quantify the number of women in each discipline, type of institution, and by their rank. Overall 27% of faculty are women, and the percent of women faculty decreases with rank. The typical terminology for this phenomenon is a 'leaky pipeline', but here we suggest the use of what we term a 'fractionation' factor to quantify disproportionate loss of women from the academic field. Importantly, our work is most applicable to white women because of existing disparities in race, and our use of the gender binary does not represent gender diversity in the geosciences.

Introduction

Professorships are a position of power, not only immediately within the academic hierarchy but also more broadly within society. This power dynamic raises the need for the geoscience community to critically examine how social groups are represented in these positions. Women made early contributions to the field, both within the academic system (such as Florence Bascom, who became the second woman to earn a Ph.D in geology in the United States in 1893 and founded the geology department of Bryn Mawr College) and outside of it (such as Eunice Foote, who conducted early experiments demonstrating the greenhouse effect in the 1850s), but in spite of these accomplishments, women were not hired at a wider range of universities until the 1900s. Today, 150 years after the first woman (Hariette Cooke) was hired as a professor with a salary commensurate with the salary of men on the faculty, bias and inequities continue to persist across academic departments, including and in particular within the geosciences ('Geosciences' herein includes the disciplines of Earth, Ocean, Atmosphere, and Planetary Sciences) (Holmes et al., 2008; Wilson, 2016; Bernard & Cooperdock, 2018).

These inequities raise significant concerns for the future of the geosciences, particularly with regards to career advancement of current faculty from marginalized groups, mentoring of students and faculty from marginalized groups, and toxic environments that push faculty from marginalized groups out of their fields (Puritty et al., 2017; Stadmark et al., 2020; Marín-Spiotta et al., 2020). Further, the lack of diversity in the geosciences and the underlying culture of racism and sexism hinder innovation and the dispersal of new ideas (Hofstra et al., 2020). For the sake of science and for future geoscientists and leaders in STEM fields, academic institutions must focus on addressing these inequities.

With respect to gender, an increasing number of Ph.D graduates in the geosciences are women (Bernard & Cooperdock, 2018). In Ocean and Earth Sciences, women have earned more Ph.Ds each year than men since $\sim$ 2007 and $\sim$ 2014, respectively, determined from the Survey of Earned Doctorates reported by NSF (Bernard & Cooperdock, 2018). However, advances in diversity at the student level often don't translate to advances at the faculty level. Previous studies have analyzed the gender diversity among geoscience faculty to show that gender diversity has been increasing, albeit slowly, since 1999 (Wolfe, 1999; de Wet et al., 2002; Holmes & O'Connell, 2003; Holmes et al., 2008; Glass, 2015; Holmes et al., 2015; Wilson, 2016). Recently, programs and initiatives, such as NSF ADVANCE and the Earth Science Women's Network, have been designed to tackle inequities and bias at the institutional level (Holmes, 2015; Adams et al., 2016).

In this study, we quantify the representation of woman geoscience faculty along the tenure-track to consider the institutional factors that may contribute to the lack of representation of women, particularly at high ranks. We compile and analyze a database of Earth, Atmospheric, Ocean, and Planetary Sciences faculty from the 62 colleges and universities in the United States that have granted the most Geosciences PhDs since 1958. Using this database, we determine the current gender makeup of tenure-track geoscience faculty, adding to the temporal trend in gender composition that has been documented since 1999 by past studies (Wolfe, 1999; de Wet et al., 2002; Holmes & O'Connell, 2003; Holmes et al., 2008, 2015; Wilson, 2016). We build upon this previous work by considering the change in representation of women amongst geoscience faculty up to 2020 and considering the role that biases in promotion and hiring and unequal attrition may have in maintaining under-representation of women.

We focus here on the quantitative aspects of gender in hiring and promotion. Because of our focus on academic institutions, we define gender as defined by institutions themselves on public websites. This means that if institutions do not visibly represent their non-binary faculty, then this study will not account for non-binary gender. In the discussion section, we refer to other literature for qualitative aspects of gender experience that are essential for interpreting these findings. Further, there are significant disparities in race that this study does not address. Over approximately the same timeframe of this study (1999-2018), an average of 85% of Ph.Ds were awarded to white students (Bernard & Cooperdock, 2018). Given this, it is nearly certain that a disproporationate majority of the women in our dataset are white women and this study is therefore most applicable to the representation of white women in the geosciences. In the Discussion, we put this work in the context of current programs, initiatives, and studies that aim to understand root causes of and address institutional inequities in geoscience departments.

Methodology

We compiled a dataset of 2,531 tenured and tenure-track faculty from university websites for 62 universities that each granted $> 0.5\%$ of total geoscience doctorates in the United States between 1958 and 2017. In total, these schools granted 79.4% of all geoscience doctorates during that time period (Table S1 of the Supplement) (NSF Survey of Doctorates). These departments likely contribute the greatest number of trainees to the academic geoscience workforce and thus have a significant impact on the diversity and future of geoscience fields. The geoscience faculty from these institutions serve in a primary mentorship role for many geoscience trainees, making representation and diversity amongst these faculty particularly important (Thomas et al., 2007; Hernandez et al., 2020). This study does not consider many Minority-Serving Institutions and other institutions that grant the rest of geoscience doctorates.

To build our database, we count faculty from all departments consisting of majority geoscientists. Their areas of study include earth and planetary science, atmospheric science, geology and geophysics, oceanography and marine science, and geography departments. We focused on faculty that were hired by geoscience departments, excluding faculty with joint appointments in a geoscience department but whose primary appointment is a non-geoscience department. Only tenure-track faculty hired by these departments were included in the dataset (thus excluding lecturers, or research faculty), due to their role as mentors for future generations of geoscientists and institutional decision-makers. However, previous work has considered the representation of women in non-tenure-track positions and has found relatively high percentages of women in these positions (Thompson et al., 2011; Wilson, 2016).

Name, title, and key words relating to geoscience sub-discipline were identified from department directories, and in some cases from the faculty member's group or personal website. Subdisciplines are listed in Table S1, and faculty are counted under as many of these subdisciplines as were identified. Thus, for the purposes of the subdiscipline study, a faculty member may be a part of multiple subdiscipline categories given the overlap between many geoscience subdisciplines and the increasingly interdisciplinary nature of some work. However, faculty members are only counted once for all other studies in this paper. Our dataset cannot account for errors that arise due to out-of-date websites, as we assume webpages reflect the most updated department information. The dataset was last checked on September 7, 2020 and is accurate as of that date.

In this study, gender identity is assigned to faculty members by pronouns used in the faculty directories or on university news sources. This may lead to inaccuracies if faculty members do not identify with a binary gender but nonetheless typically use binary pronouns in a professional context or if faculty members are misgendered by the website. Furthermore, pronouns are not equivalent to gender, and therefore there is potential for error if a faculty member uses she/her or he/his pronouns but does not identify on the gender binary.

We remove all sub-categories within the dataset that represent only a small number of individuals, defined as 25 members, or $< 1\%$ of the full dataset. Thus, we do not assess the gender distribution of several sub-disciplines (e.g. History of Science). For this reason, we also exclude faculty who do not use 'she/her/hers' or 'he/him/his' pronouns. Less than 1% of the faculty in our dataset are identified with non-binary pronouns on academic websites. Based on other survey methodologies in allied fields (Strauss et al., 2020), we expect that the actual number of non-binary faculty may be higher but that non-binary visibility is limited on official websites. In what follows, we only present two genders (man/woman). Consideration of only two genders does not account for or consider the wide diversity of gender that exists, or the historic and systemic biases that result in low numbers of non-binary faculty. Further study and data availability is needed

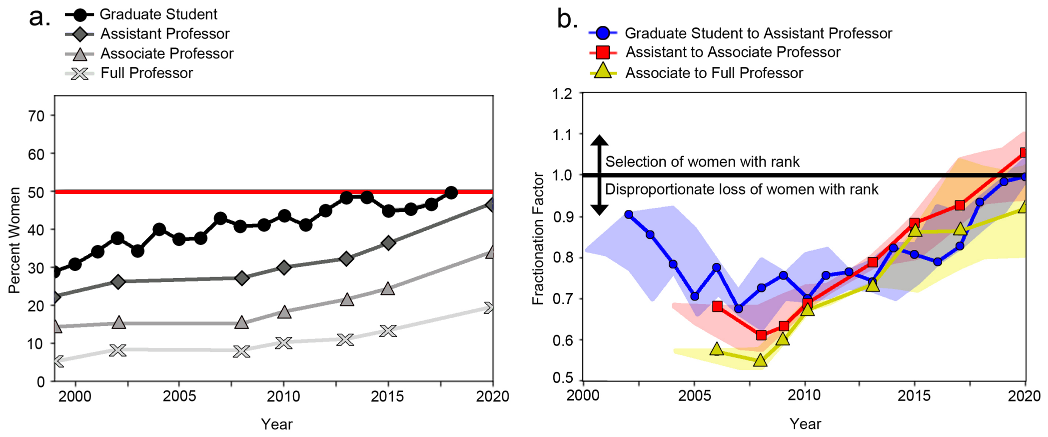

Figure 1. Multi-decadal time-series of gender distribution in faculty by rank (a) Percentage of faculty who are women by rank for the last 21 years. References: 1999 Data (de Wet et al., 2002), 2002 Data (Holmes & O'Connell, 2003), 2008, 2010, 2013 Data (Wilson, 2016) exact percentages interpreted from a bar chart, 2015 Data (n = 2324) (Holmes et al., 2015; Glass, 2015), 2020 Data (This Study). (b) Fractionation factor (see Equation 1) for the three transitions (graduate student to assistant professor, assistant to associate professor, associate to full professor). Shading represent a range in promotion timeline of ±2 years

to widen the scope of gender studies in STEM disciplines. This is discussed in more detail in the Discussion section.

Throughout this study, we use the term under-represented to mean that the numerical representation of a group (women in most cases) is less than that in the US population. This is passive, technical language that does not address the causes of under-representation. Under-representation is a symptom of structural factors. When appropriate when discussing the results we use the terms marginalized or excluded to position this work in its wider structural context (Morris, 2021).

Results

Women make up approximately 27% of all the tenured and tenure-track faculty in the 62 academic institutions considered. The fraction of women in the faculty pool decreases with rank, as 46% of assistant professors are women, 34% of associate professors are women, and 19% of full professors are women. These statistics are roughly equivalent at the public and private universities considered. At all career stages, these numbers are lower than the US statistics for professors in 2016 across all disciplines, which show that 42% of all the tenured and tenure-track faculty were women, 51% of assistant professors are women, 45% of associate professors were women, 32% of full professors were women (Johnson, 2017). Evaluation of current department leadership (i.e. department heads, department chairs, or equivalent) shows that 21% of leadership positions are held by women. While this is an under-representation of women with respect to the faculty pool, it is roughly equivalent to the percentage of women who are full professors.

We compare our data with results from past studies of the demographics of the geosciences faculty, most of which present results from reports of the geoscience workforce. The percentage woman faculty in major geoscience departments has been steadily increasing for the past twenty years for all ranks (Figure 1). For all timepoints considered

(1999, 2002, 2008, 2010, 2013, 2015 and 2020), the percentage woman assistant professors is higher than the percentage woman associate professors, which is higher than the percentage woman full professors (Figure 1a).

In this study, we discuss the higher rate of attrition of women than men in geosciences using a concept from geochemistry: fractionation. In isotope geochemistry, fractionation factors quantitatively describe processes that affect the relative proportion of isotopes of the same element. Here, we describe fractionation as being the ratio between the percentage of women at one rank of academia (Rank $i+1$) and the percentage of women in the rank below (Rank i) at the time that the women in Rank $i+1$ were at Rank i. Mathematically, if the average time that it takes to get from Rank i to Rank $i+1$ is t_i, then the fractionation factor α is

$$\alpha(R_i, R_{i+1}) = \frac{\text{\% of Women in Rank } i+1}{\text{\% of Women in Rank } i \; t_i \text{ Years Ago}} \tag{1}$$

While this study focuses on the attrition of women, the use of fractionation factors could be applied to other excluded and historically excluded groups (due to race, sexuality, socioeconomic status, or other forms of margainalization). This metric is well suited for this context because it quantifies the proportional loss of women across academic rank. A fractionation factor of 1 means that the proportion of women in one rank is the same as the proportion of women in the rank before. Thus, it would imply no difference in attrition by gender. A fractionation factor of 0, on the other hand, means that none of the women in one rank continued to the next rank, while the same is not true for men.

This framework enables us to add a quantitative approach to considering the attrition of women and to move beyond the common analogy of the 'leaky pipeline'. The 'leaky pipeline' frames the lack of representation of women (and other marginalized groups) in the context of a pipeline which begins at early education and ends at higher levels of academia. The 'leaks' are the attrition of women from the pipeline towards professorships. This metaphor has been criticized for suggesting the existence of only one track through academia and the sciences (Lykkegaard & Ulriksen, 2019). Several alternatives to the 'leaky pipeline' have been proposed to better incorporate and value the variety in pathways taken in modern science careers (e.g. the braided river analogy), as well as to acknowledge the additional barriers faced by marginalized groups (Batchelor et al., 2021). The 'leaky pipeline' also focuses on absolute attrition of women, while failing to consider the unequal attrition between men and women. This may implicitly put the blame on individual women for leaving by not accounting for the structural and institutional factors that certainly contribute to the under-representation of certain groups as seen in data (Marín-Spiotta et al., 2020).

The fractionation factor, on the other hand, quantifies the proportional attrition between identities. This factor focuses not on individual women leaving, but on how the proportions of women compared to men decrease with rank. Thus, fractionation acknowledges that successful careers may exist outside of academia by diverting attention from attrition alone and focusing on bias in attrition, a more useful metric for diversity problems in academia. Furthermore, the fractionation framework quantifies bias that must be a result of institutional and structural factors that cause women to leave academic institutions at a rate higher than men. This puts the onus on institutions, rather than women, to ensure equity in retention.

To study the presence of bias under the fractionation framework, we compare our results with previous studies on the gender diversity of geoscience faculty and NSF data of gender diversity in Ph.D graduates (Figure 1b). We interpolate the data presented in Figure 1a onto the full timespan 1999−2020. For simplicity, we assume that the average length of time between graduating with a Ph.D and becoming an assistant professor is ~ 2 years (the length of a typical post-doc contract), and that the average length of time from assistant professor to associate professor (with tenure) is $\sim$ 7 years, and that promotion from associate professor to full professor is also $\sim$ 7 years. The shading represents the range of possible time to promotion (± 2 years), in particular due to the fact that, on average, women take nearly two years longer to be promoted to full professor, which represents a loss of earnings and influence within academic institutions (Van Miegroet et al., 2019). Up until the last few years ($\sim$ 2017), the percentage of women at the rank of assistant professor has been smaller than the percentage of women graduating with Ph.Ds (α(Graduate Student,Assistant Professor) < 1). Similar trends can be seen between the assistant professor and associate professor level (when one is typically awarded tenure) and between the associate professor and full professor level. Additionally, at all career stages, from 1999-2015, women advanced less often than men do. This suggests that resolving diversity problems in academia must involve approaches beyond outreach and student-focused initiatives.

For the year 2020, there is negligible evidence of differential loss of women at all three stages (fractionation factor ≈ 1). In particular, α(Assistant Professor, Associate Professor) $>$ 1, which is likely a function of the fact that the pool of associate professors are not all exactly 7 years from being assistant professors; error in promotion timeline of +/- 2 years is reasonable and depicted in Figure 1b. Tenure clocks are extended in some cases, such as for new parents. Extensions for childcare features its own equity challenges given that often women still shoulder the burden of childcare. Men are often able to continue to work during this clock extension, while women spend this time as a primary caretaker (Antecol et al., 2018). Further, achieving a fractionation factor of 1 (i.e. parity in attrition) between any two ranks does not imply gender parity in the geoscience faculty. In order to achieve gender parity, hiring must occur at a 1:1 men to women ratio and fractionation between all previous ranks must be 1. Thus, even after fractionation factors reach 1, work still must be done to ensure gender parity in a reasonable timeframe.

Changes in the fractionation factors α(Graduate Student, Assistant Professor) and α(Assistant Professor, Associate Professor) are expected to occur on similar timescales, given the similar pool sizes (ca. 500 individuals). On the other hand, since the full professor pool is 3 times as large as either the assistant or associate professor pools, we would expect a change in α(Associate Professor, Full Professor) of a similar magnitude to take 3 times as long. Factors that contribute to uncertainty in α(Associate Professor, Full Professor) include that criteria for promotion from associate professor to full professor is not uniform across institutions, promotion can be more variable in timing than previous promotions, individuals can go up for promotion again if denied, and not all tenured faculty make it to the full professor rank.

Gender and Discipline

Gender diversity varies between the four major disciplines that make up geosciences: Earth Sciences, Ocean Sciences, Atmospheric Sciences, and Planetary Sciences (Figure 2). The percent woman faculty range between 23% and 30% of the faculty in each discipline, with atmospheric sciences having the lowest percentage woman faculty ($\sim$ 23%) and ocean sciences having the highest percentage woman faculty ($\sim$ 30%). This dataset can only account for geoscience faculty primarily in geoscience departments, and thus does not represent those that are primarily in other departments. We do not expect this to bias the results, as there has been no reason proposed as to why there should be a gender difference in faculty who are hired outside of geoscience departments. We present results for other subdisciplines in Supplement Table S3.

While the fractionation factors calculated for 2020 suggest no inequitable attrition of women overall for the geosciences, this is not the case for certain disciplines. As an example, we discuss the fractionation for the ocean sciences to illustrate the point that

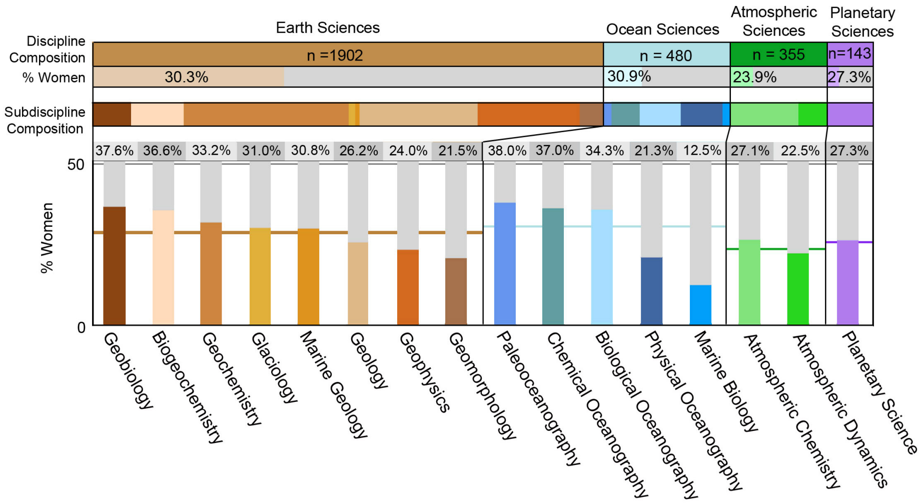

Figure 2. Faculty gender distribution by sub-discipline Gender distribution at the faculty level in order from highest to lowest percent women within each discipline. The black line represents an even gender distribution. Brown, blue, green, and purple lines represent the gender distributions of the major disciplines of earth sciences, ocean sciences, atmopheric sciences, and planetary sciences, respectively

fractionation factors for each discipline do not necessarily mirror the fractionation factors of the geosciences as a field.

In the ocean sciences, gender parity was reached amongst Ph.D graduates around 2006 (Bernard & Cooperdock, 2018). Since then, the percent woman Ph.D graduates in the ocean sciences has wavered between $\sim 50\%$ and $\sim 60\%$. Given that parity was reached in 2006 and most assistant professors are hired $\sim 2-4$ years post-PhD, with full retention the percent woman assistant professors should have reached $\sim 50\%$ at least by 2010. In our 2020 data, we find that in fact $\sim 50\%$ of the ocean sciences assistant professors are women, though we do not have the data to confirm whether gender parity was reached in 2010 or more recently. Further, since the average time to tenure is ~ 7 years, we should have seen gender parity within associate professors by 2017-2018 if there were equal hiring and promotion since 2006, but this is not reflected in the data. In 2020, only $\sim 39\%$ of associate professors in the ocean sciences are women, giving a fractionation factor of ≈ 0.78. These fractionation factors are computed assuming that the assistant professors were all at the beginning of the ~ 7 years in this rank, and that associate professors were all at the beginning of the ~ 7 years in this rank. The attrition continues: only $\sim 22\%$ of full professors in the ocean sciences are women.

We further assess the gender distribution within the sub-disciplines of the major disciplines defined above (earth sciences, ocean sciences, and atmospheric sciences), presented in Figure 2. While some sub-disciplines have a higher percentage woman faculty than others, no sub-discipline has yet achieved gender balance. Geobiology, paleooceanography, and chemical oceanography have the highest representation of women at around 38%. We find low percentages woman faculty in the subdisciplines of marine biology (12.5%), physical oceanography (21.3 %), and geomorphology (21.5%). In the case of marine biology, our dataset may not have enough faculty to fully represent the sub-discipline, since we did not consider marine biologists in biology or zoology departments. Variations in fractionation and gender distribution with sub-discipline suggest that it is insufficient to consider the geosciences as a whole and instead important to consider each discipline individually. Data of both rank and subdiscipline are in Supplement Table S1.

Subdisciplines in the chemical and biological sciences (geochemistry, geobiology, chemical oceanography, biological oceanography, atmospheric chemistry) generally have a higher percentage woman faculty than subdisciplines in the physical sciences (geophysics, physical oceanography, atmospheric dynamics). In particular, atmospheric physics and physical oceanography have the lowest percentage woman faculty (22% and 21% respectively). The higher percentages of women in the biological and chemical sciences as compared to the physical sciences is a well-documented phenomenon across levels of STEM (Ceci et al., 2014), and may be attributed to cultural factors including the myth of 'brilliance' being more prevalent in physics- and math-based disciplines (Leslie et al., 2015).

Data on the gender distribution within geoscience subdisciplines published in 2003, compared to the new data presented here, show that many disciplines have improved with respect to representation of women faculty (Geology from 19% to 26%, Geophysics from 18% to 24%, Oceanography from 28% to 31%, Atmospheric Sciences from 12.5% to 27.3%, and Planetary Sciences from 17% to 27%) (Holmes & O'Connell, 2003). However, the gender distribution in geochemistry faculty has gone roughly unchanged in the past 18 years (from 34.9% to 33.2%). While the comparison with data published in 2003 enables a rough assessment of how subdisciplines might have changed, we cannot make any definitive comparisons because this dataset did not evaluate the same institutions we did and may not have defined the subdisciplines as we have in this study (Holmes & O'Connell, 2003).

Discussion

We do not have sufficient data to determine the cause of the discrepency in attrition between men and women. However, previous work has considered this question, leaving us with hypotheses. Studies have pointed to institutional culture as being a factor in the attrition of women. Policies that lead to inadequate childcare and maternity leave , policies that do not protect women from harassment, the timeline and process of tenure, and cultures of racism and sexism all play a role in making academic geoscience careers inacessible to women, people of color, and other marginalized groups (de Wet et al., 2002; Puritty et al., 2017; Marín-Spiotta et al., 2020; Bocher et al., 2020). To achieve gender parity at all levels of faculty in the geosciences, we need to look beyond recruitment and retention at the student level and consider biased institutional practices (including hiring and promotion processes) and problematic cultures that cause the lack of representation of women faculty in the geosciences.

Lower representation of women - and low fractionation factors - at all levels may point to biases in the hiring and tenure process. We note that the representation of women seen at the assistant professor level is not translated as expected to the associate professor level in many disciplines, as shown above for the ocean sciences. Bias in the tenure process within academia has been found in many previous studies, with respect to race (in particular, anti-Black bias) (Perna et al., 2007) and gender (Box-Steffensmeier et al., 2015), amongst other identities, in many disciplines of STEM. Although this study focuses exclusively on the US, under-representation of women is an issue in other countries as well including throughout much, but not all, of Europe (Piccoli & Guidobaldi, 2021; Giakoumi et al., 2021). In the next section of the discussion, we apply simple models of hiring to further explore the potential for bias in hiring.

What will it take to reach gender parity?

Given that the proportion of women at all levels has been increasing, a natural question is how long we have to wait for academic spaces to reach gender parity. Based on the observation that the percentage of faculty that are women remains lower than that of men at all ranks, the rate of hiring must be at least 1:1 - one woman professor hired per man. Here we consider two questions: (1) what is the current rate of hiring, (2) if we begin hiring at 1:1 starting in 2020, how long will it take to reach gender parity?

There is no database available of hiring rates and the diversity of applicant pools and hires amongst geoscience faculty. Further, it is difficult to gather this data from webpages given that faculty webpages do not consistently state in what year each faculty member was hired. Therefore, we use a simple model to estimate the percentage of women hired as assistant professors in the geosciences each year. We assume that the number of assistant professors in our dataset has been constant with time (i.e. from 1999-2020, there have always been 505 assistant professors in the geosciences) and that the average assistant professor remains in the position for 7 years, compatible with the model developed above. From these assumptions, we compute the number of woman assistant professors in year i (f_i) as

$$f_i = f_{i-1} - h_{i-7} + h_i \tag{2}$$

where h_i represents the number of women hired this year and h_{i-7} represents the women hired seven years ago (who are now leaving the assistant professor pool due to promotions, or contract terminations). We interpolate the data from Figure 1a onto each year from 1999-2020 and use Equation 2 to compute h_i. From 1999-2020, we estimate the percentage of women hired each year to vary between $\sim 23\%$ (in the early 2000s) to $\sim 56\%$ (in 2016) (Figure 3b). 2016 is the only year in which the percentage of women hired equals or exceeds 50% according to this model. In all other years, including between 2017 and 2020, women are less than 50% of the hires to geoscience assistant professors. The estimate for 2020 is $\sim 42\%$ of hires are women. These estimates match up with the data shown in Figure 1a, since women make up approximately 46% of the assistant professors in 2020 and in the ~ 6 years leading up to 2020, we estimate the hiring rate of women to fluctuate between 42% and 56%. If the number of assistant professors has been increasing, then the estimated percent of hires that are women is overestimated in this simple model.

Based on these assumptions, our analysis suggests that hiring rates have been in the 1:1 range since 2016. Given this result, we consider if the geosciences were to continue hiring 1:1 on average from 2020, how long would it take to reach gender parity? To estimate the answer to this question, we build a simple model in which we consider the faculty pool to be in steady state (the number of faculty hired = number of faculty who retire each year). We assume a promotion timeline of 7 years as an assistant professor, 7 years as an associate professor, and a 35 year career (assuming a retirement age of ~ 65). Given these assumptions and the current number of faculty in each rank, we use a flux into and out of the faculty pool of 70 people per year. If hiring is in line with the approximate 50/50 gender split of women at the PhD level and in the general population starting in the 2021 hiring cycle and there is no bias in hiring and promotion, we may expect the assistant and associate professor pools could reach gender parity by 2028 and 2035, respectively. However, due to the long residence time of full professors, the full professor pool and the total faculty pool would not reach equal (binary) gender representation before 2056 (Figure 3). Assuming a 35 year career, this would be approximately when current graduate students are nearing retirement.

This model is a simplified representation of the complex hiring practices and rentention in academia. We note, however, that this model can be thought of as a 'best case' scenario, given that professors often do not retire at age 65, and the full professor pool is about three times greater than either the assistant or the associate professor pool. Furthermore, this model does not account for bias in retention. As shown above, bias in retention has been decreasing in the last ~ 10 years, and while these results may not have

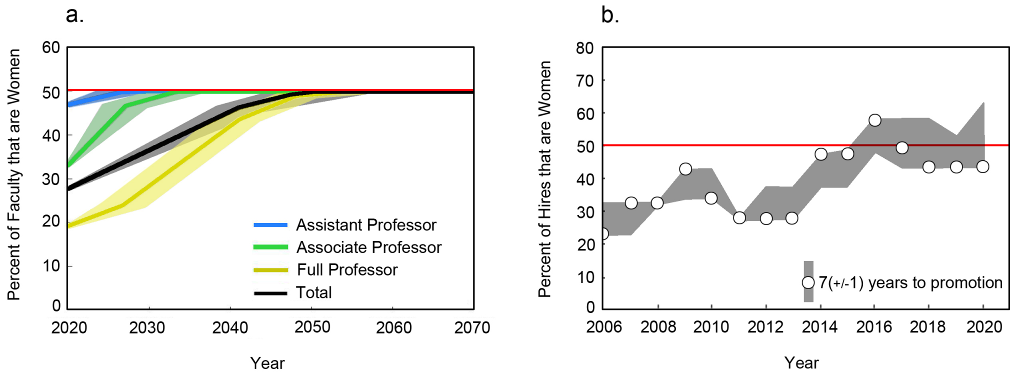

Figure 3. Estimated gender distribution over time (a) Model outlook on faculty gender composition by rank. If faculty are hired at a 1:1 gender ratio, and assuming there is equal retention between men and women, we should expect gender parity by 2055.(b) Estimated percent of hires that are women by year, computed from Equation 2. This shows that we have been hiring at a 1:1 ratio since 2015, assuming a range of 6-8 years for promotion.

the longevity to establish a clear trend, they do suggest that current initiatives may be working to improve gender equity. However, assessment is required to determine how current programs and efforts work and who they are working for. This model does emphasize a need to ensure continued hiring at 1:1 ratio; because women are currently underrepresented relative to men, without at least a 1:1 hiring strategy, we will never reach gender parity. Furthermore, this demonstrates the need for a continued study in the demographics of geoscience faculty to establish long-term trends.

Equity Initiatives and Systemic Change

The fractionation framework focuses on quantifying attrition and cannot propose causes for biases and inequities or solutions to those inequities. Recent research has considered the causes for inequities, including hierarchical cultures that enable harassment and bias (Marín-Spiotta et al., 2020) and hampers belonging (Cheryan et al., 2017), racism and sexism within academia (Bocher et al., 2020; Dutt, 2020; Ramos & Yi, 2020), inaccessibility of fieldwork (Morales et al., 2020), among other factors. Some factors are not specific to hiring, but relate to bias in other aspects of academic careers that are considered heavily in hiring such as publishing, grant awards, and speaking invitations (Bornmann et al., 2007; Ford et al., 2018; Pico et al., 2020). Many studies focus on the need for institutional change (Ahmed, 2012), and the fractionation factor provides a quantitative metric that can be used to assess institutional change. These quantitative studies are important because perceptions of composition of the faculty are biased, with studies showing that men are more likely than women to believe that representation is equal between men and women (Popp et al., 2019; Giakoumi et al., 2021).

The fractionation factors of ≈ 1 may suggest that recent gender equity policies and programs are beginning to improve the outlook for gender representation in the geosciences. The National Science Foundation (NSF)'s ADVANCE program, has funded programs across the United States and has produced research with demonstrated impacts on the recruitment and retention of women in the sciences (Holmes, 2015). Other funded programs, such as the NSF Aspire project, which developed a model that helps institutions understand the causes of inequities and develop solutions (Griffin, 2020), and Atmospheric Science Collaborations and Enriching Networks (ASCENT), a series of workshops for women in atmospheric sciences (Hallar et al., 2015), have tackled similar problems. Organizations such as the Earth Science Women's Network (Adams et al., 2016), Society for Women in Marine Science, GeoLatinas, and the Association for Women Geoscientists provide mentorship and networking opportunities for women in the geosciences.

Progress has not always been consistent. A detailed study of the career trajectories of men and women graduates in physical oceanography from the six largest oceanographic institutions from 1980-2009 revealed inconsistent progress with more equal hiring of women and men into tenure track positions in the period 1980-1996 than in the period 1996-2009 (Thompson et al., 2011). This strongly suggests that the representation of women at higher ranks is not solely due representation among graduate students, but instead to factors at play during hiring and promotion. It is important to continue monitoring faculty diversity and differential attrition with respect to both race and gender to ensure that any progress is maintained.

Research into practices that alleviate bias and inequity have proposed ways institutions and individuals may contribute to resolving inequitable cultures and institutional practices, including ways to reframe diversity conversations (Keisling et al., 2020), promoting inclusivity in fieldwork (Carabajal & Atchison, 2020), and creating specific policies within institutions (National Academy of Sciences, National Academy of Engineering, 2007a; Dutt, 2015). Many of these practices have been shown in programs, such as ADVANCEGeo, a geoscience focused grant from the NSF ADVANCE Program, to be effective at improving retention (Holmes et al., 2015). The National Academy of Sciences, National Academy of Engineering, and Institute of Medicine outlined the systemic inequities that lay at the foundation of academic institutions and presented recommendations in line with the studies cited here, including addressing inequities in hiring and promotion, ensuring equity of faculty search processes, and reviewing tenure practices (National Academy of Sciences, National Academy of Engineering, 2007b). Further, there are several edited volumes and special issues summarizing lessons learned from programs such as NSF ADVANCE, including suggestions for structural change (Rosser & Chameau, 2006; Stewart & Valian, 2018; Furst-Holloway & Miner, 2019; Laursen & Austin, 2020).

Many of these programs are created and sustained by women and people of color. While these programs are creating positive change, they are also putting an undue burden on those most at risk from institutional bias (Harris, 2013). Furthermore, these results do not mean that diversity initiatives are working for all groups. Those most affected by the problem may have clearer ideas about solutions. Men and women have systematically different perceptions of the most effective responses to gender bias (Giakoumi et al., 2021). Some solutions that are designed to alleviate inequities faced by women, such as parental leave, may not have the intended effect depending on the implementation (Antecol et al., 2018). There is also overwhleming evidence that programs intended to alleviate gender bias primarily benefit white women, revealing the need for intersectional approaches. Affirmative action is one example of a structural program that predominantly benefited white women rather than people of color. White women are not consistently in solidarity with women of color. For example, white women have been leading voices in dismantling affirmative action over the past few decades (Hall, 2016). This study focuses on women and does not have the data to discuss race, ability, gender identity, or sexual orientation, among other factors. Furthermore, given the racial makeup of the geosciences (Bernard & Cooperdock, 2018), this data likely reflects progression for white women only. Current studies (e.g. Bernard and Cooperdock (2018)) show that even when the representation of white women increases, this does not suggest that institutions have becomes unbiased nor that equity with respect to race or other marginalization has improved.

Moving beyond gender and the gender binary

In this study, we consider only two genders: man and woman. The gender binary does not accurately and completely represent gender diversity due to the exclusion of those outside of the binary. Studies, most notably (Rasmussen et al., 2019) and (Strauss et al., 2020), have discussed the harm that the continued exclusion of non-binary scientists from studies of gender inequities does to those who identify outside of the gender binary, including the psychological harm that comes from misgendering and the harm that comes from overlooking the ways in which non-binary scientists are discriminated. Focusing on the gender binary neglects the complex ways in which institutional gender-based discrimination operates. Based on the data presented here showing that fewer than 25 geoscience faculty at the 62 institutions we studied use non-binary pronouns on institutional websites, this study suggests that there may be significant lack of representation of non-binary geoscientists or that non-binary geoscientists do not feel safe or comfortable presenting as such within their department or both. Either of these interpretations implies systematic discrimination against scientists who identify outside of the gender binary and a culture in geosciences that is not inclusive to all gender identities, concerns which are supported by (Rasmussen et al., 2019) and (Strauss et al., 2020).

More studies need to be done to understand the full diversity of gender identity in the geosciences. (Rasmussen et al., 2019) and (Strauss et al., 2020) recommend broadening studies of gender diversity and gender-based inequities beyond simply quantitative studies, as these often exclude scientists outside of the binary. In addition to the need for further qualitative work on gender, our results support the necessity for organizations to lead formal, inclusive data-gathering that is done in conjunction with social scientists and in which gender is identified based on self-identification (Rasmussen et al., 2019; Strauss et al., 2020).

This study focuses on the inequities with respect to gender, which is information that is readily available and collectable. However, as we look towards advancing the inclusivity and diversity of the geosciences, we must ensure that systems to address inequities are focused on more than one group. There are dramatic inequities with regard to race in the geosciences, including lasting marginalization of Black, Indigenous, and Latinx scientists (Bernard & Cooperdock, 2018). Studies have shown that there are further inequities rooted in cultural and systematic problems with respect to mentoring, education, service burden, and many other factors (Thomas et al., 2007; Zambrana et al., 2015; Brunsma et al., 2017; Jimenez et al., 2019; Dutt, 2020). As early as 1978, June Bacon-Bercy pointed out that for the representation of Black meteorologists to reach population parity, the rates of Black students earning bachelors degrees would need to increase dramatically, emphasizing our social obligation to take action to overcome discrimination and marginalization (Bacon-Bercey, 1978). Certainly these inequities affect the faculty body of, and the practice of, the geosciences.

Further, considering gender alone ignores the ways in which marginalized identities intersect. People who experience multiple types of marginalization have experience and outcomes that cannot by understood as the result of discrete forms of discrimination (Crenshaw, 1989). For example, in the New Zealand professoriate, Maori and Pacific women have lower salaries than non-Maori and Pacific men while there is no significant salary difference for Maori and Pacific men (McAllister et al., 2020). Survey results show that women of color in astronomy experience higher rates of sexual harrassment than white women do and that more women of color than white women in STEM report feeling unsafe on campus because of their gender (Clancy et al., 2017; National Academies of Sciences, Engineering, and Medicine, Policy and Global Affairs, Committee on Women in Science, Engineering, and Medicine, 2018). The disparities in representation of women of color are almost surely much larger than those presented in this study. Recent studies have begun to build an intersectional framework to address the ways in which race, class, gender, ability, and other marginalized identities interact with each other in the context of STEM (Metcalf et al., 2018) and a desired direction for future research and interventions is to engage with intersectional frameworks to provide a complete understanding of the ways in which institutional inequities persist.

Implications

This study quantifies the gender diversity of tenured and tenure-track faculty in the geosciences using information from 62 colleges and universities in the United States. We determine that women remain under-represented in the faculty body of geoscience departments ($\sim 27\%$ of all faculty) and the disparity increases with increasing rank in academia and varies with geoscience discipline. We reframe this phenomenon in which under-representation increases at higher levels of the academic hierarchy in terms of a fractionation factor, which here quantifies the inequitable attrition of women. We show significant attrition of women across the geosciences, though this has decreased in recent years when considering the geosciences as a whole. Additionally, we show that continued hiring at a 1:1 ratio is necessary to ensure reaching gender parity across all ranks of professorship. These results suggest that despite a number of initiatives, tenure and promotion processes within geoscience departments may still have institutional inequities and implicit biases that result in a disproportionate attrition of women.

While gender diversity has improved at the assistant professor and associate professor stage, the representation of women at the full professor rank is increasing far more slowly, at least partially because faculty stay in the full professor stage for many decades. Full professorships bring with them a significant amount of power and influence, both over internal policies within departments and institutions and also within society. The expertise of full professors tends to be most valued due to their rank and full professors are generally influential in hiring decisions. Further, this has implications for the gender pay gap, since salaries increase with rank and thus women on average make less than men in academia (Newman, 2014). Thus, under-representation at this stage may perpetuate inequities. Accelerating change at higher ranks and otherwise ameliorating the present gendered power differentials is critical to ensuring a just future for the geosciences.

Importantly, the fractionation factor pushes for accountability within institutions and systems for the biases and cultures that lead to higher fractionation of women into other paths of work. As addressed in the discussion section, there are a number of programs and implementation strategies focused on institutional and cultural changes that are needed alongside a continued 1:1 ratio hiring to ensure recruitment and retention of women (Holmes, 2015; Bocher et al., 2020; Carabajal & Atchison, 2020; Griffin, 2020; Marín-Spiotta et al., 2020). However, many of the existing programs and studies focus on the retention and recruitment of white women (Liu et al., 2019), and moving forward an intersectional lens must be put on diversity programs to ensure that racial diversity, diversity with respect to ability, sexual orientation, among others, are incorporated. Investing in programs dedicated to fixing institutional sexism, racism, and inequities, such as those funded by NSF ADVANCE, is critical if we are to adequately consider the institutional barriers that uniquely exist for those with intersectional identities. Continued research on the role that biases and systemic inequities have in hiring and retention processes is needed, and as programs are instituted to combat these inequities, assessments of their success and failure is important.

Our methods of data collection are neither exhaustive across the field, inclusive of intersectional identities, nor sustainable. Institutions, associations, and foundations should continue to improve data collection and transparency so that work like this can be expanded on to include an intersectional and gender inclusive lens (Langin, 2020) and hold the field accountable to the biases and inequities that continue to persist.

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Supporting Information for "Gender Diversity Among Tenured and Tenure-Track Geoscience Faculty"

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Contents of this file

Introduction

Text S1: Institutional Factors. We consider the effect that gender proportions at one level of the academic hierarchy may have on the gender proportions of another level. We compare the gender composition of the faculty during the 2019-2020 academic year to the gender composition of graduate students obtained from the NSF graduate student survey for 2018 and 2019. At a given institution, there is a weak correlation between the percent of faculty who are female and the percent of graduate students who are female (Figure S1). While no causative statements can be made based on this correlation, it appears that institutions with a higher percentage of female professors are not more likely to have a higher percentage of female graduate students at an instant in time. This may be either because the assumption that diversity attracts diversity is not always applicable or may be because the typical percentages of female faculty are not high enough to attract more female students.

For nearly every institution we considered, there are more women at the graduate student level than at the faculty level. The percentage of graduate students ranges from $\sim 30\%$ to $\sim 60\%$, while the percentage of female professors ranges from $\sim 0\%$ to $\sim 40\%$. The proportions of female faculty do not differ significantly between private and public institutions.

There are also more women graduate students at a given institution than women postdocs. Additionally, there are more women postdocs than women faculty at any given institution on average. This suggests a systematic attrition of women at each stage of the academic process (from graduate student to postdoctoral associate to tenure-track faculty member). There is a strong correlation between the number of women postdocs and the number of women graduate students at a given institution. This may result from graduate students becoming postdocs at the same institution or with other institutional factors related to support for early career women.

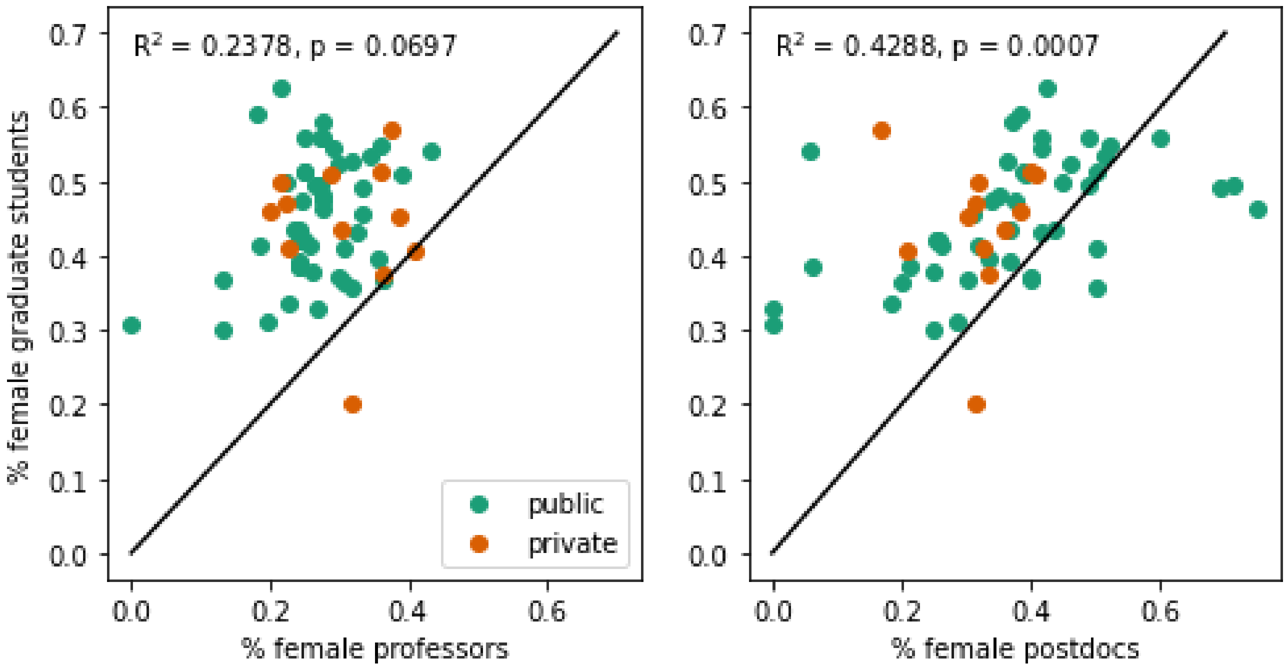

Figure S1. **Correlations between academic ranks** Comparison of percent female faculty in 2020 with percent female graduate students in 2017 and 2018 from the graduate student survey at each institution we consider. The color of the data point shows whether an institution is public or private.

Table S1. Universities and Departments Studied

University	Department
Arizona State University	School of Earth and Space Exploration
Brown University	Department of Earth, Environmental, and Planetary Sciences
California Institute of Technology	Division of Geological and Planetary Sciences
College of William & Mary	Department of Geology
Colorado School of Mines	Department of Geology and Geological Engineering
	Department of Geophysics
Colorado State University	Department of Atmospheric Science
	Department of Geosciences
Columbia University	Department of Earth and Environmental Sciences
Cornell University	Department of Earth and Atmospheric Sciences
Florida State University	Department of Earth, Ocean, and Atmospheric Science
Georgia Institute of Technology	School of Earth and Atmospheric Sciences
Harvard University	Department of Earth and Planetary Sciences
Indiana University, Bloomington	Department of Earth and Atmospheric Sciences
Johns Hopkins University	Department of Earth and Planetary Sciences
Louisiana State University	Department of Geology and Geophysics
	Department of Oceanography & Coastal Sciences
Massachusetts Institute of Technology	Department of Earth, Atmospheric and Planetary Sciences
North Carolina State University	Department of Marine, Earth, and Atmospheric Sciences
Ohio State University	School of Earth Sciences
	Department of Geography
Oregon State University	College of Earth, Ocean, and Atmospheric Sciences
Pennsylvania State University	Department of Meteorology and Atmospheric Science
	Department of Geosciences
Princeton University	Program in Atmospheric and Oceanic Sciences
	Department of Geosciences
Purdue University	Department of Earth, Atmospheric, and Planetary Sciences
Rice University	Department of Earth, Environmental and Planetary Sciences
Rutgers University	Department of Earth and Planetary Sciences
Stanford University	Department of Earth System Science
	Department of Geological Sciences
	Department of Geophysics
Stony Brook University	Department of Geosciences
	School of Marine and Atmospheric Sciences
Texas A&M University	Department of Atmospheric Sciences
	Department of Geography
	Department of Geology and Geophysics
	Department of Oceanography

Table S1. Universities and Departments Studied

University	Department
University of Alaska, Fairbanks	Department of Geosciences
University of Albany, SUNY	Department of Atmospheric and Environmental Sciences
University of Arizona	Department of Geosciences
	Department of Hydrology and Atmospheric Sciences
University of California, Berkeley	Department of Earth and Planetary Science
University of California, Davis	Department Of Earth And Planetary Sciences
	Department of Land, Air, Water Resources
University of California, Los Angeles	Department of Atmospheric and Oceanic Sciences
	Department of Earth, Planetary, and Space Sciences
University of California, Santa Barbara	Department of Earth Science
	Department of Geography
University of California, Santa Cruz	Earth and Planetary Sciences
University of California, San Diego	Scripps Institution of Oceanography
University of Chicago	Department of the Geophysical Sciences
University of Colorado, Boulder	Department of Atmospheric and Oceanic Sciences
	Department of Geological Sciences
University of Delaware	Department of Earth Sciences
	Department of Geography and Spatial Sciences
	School of Marine Science & Policy
University of Hawaii, Manoa	Department of Earth Sciences
	Department of Oceanography
University of Houston	Department of Earth and Atmospheric Sciences
University of Illinois, Urbana-Champaign	Department of Atmospheric Science
	Department of Geography and Geographic Information Scie
	Department of Geology
University of Iowa	Department of Earth and Environmental Sciences
University of Kansas	Department of Geography & Atmospheric Science
	Department of Geology
University of Maryland, College Park	Department of Atmospheric and Oceanic Science
	Department of Geology
University of Miami	Rosenstiel School of Marine and Atmospheric Science
University of Michigan	Department of Climate and Space Sciences and Engineerin
	Department of Earth and Environmental Sciences
University of Minnesota, Twin Cities	Department of Earth and Environmental Sciences
	Department of Soil, Water, and Climate
University of Nevada, Reno	Department of Geography
	Department of Geological Sciences and Engineering
University of North Carolina, Chapel Hill	Department of Geography
	Department of Geological Sciences
University of Oklahoma, Norman	School of Geosciences
	School of Meteorology
University of Rhode Island	Department of Geosciences
	Graduate School of Oceanography

Table S1. Universities and Departments Studied

University	Department
University of Southern California	Department of Earth Sciences
University of South Carolina	School of Earth, Ocean, and Environment
University of South Florida	School of Geosciences
University of Texas, Austin	Jackson School of Geosciences
University of Texas, Dallas	Department of Geosciences
University of Utah	Department of Atmospheric Sciences
	Department of Geology and Geophysics
University of Washington	Department of Atmospheric Sciences
	Department of Earth and Space Sciences
	Department of Oceanography
University of Wisconsin, Madison	Department of Atmospheric and Oceanic Sciences
	Department of Geosciences University of Wyoming
	Department of Geology and Geophysics
Virginia Polytechnic Institute and State University	Department of Geography
	Department of Geosciences
Yale University	Department of Earth and Planetary Sciences

Table S2. Percentage of Women by Rank and Subdiscipline

Subdiscipline	Assistant Professor	Associate Professor	Full Professor
Geobiology	54	50	27
Biogeochemistry	59	45	25
Geochemistry	58	40	22
Glaciology	40	42	20
Marine Geology	0	66	27
Geology	46	30	19
Geophysics	37	30	18
Geomorphology	33	31	11
Total Earth Science	*51*	*38*	*21*
Paleoceanography	71	12	38
Chemical Oceanography	55	45	25
Biological Oceanography	48	55	26
Physical Oceanography	37	29	15
Marine Biology	75	0	22
Total Ocean Science	*50*	*40*	*22*
Atmospheric Chemistry	25	41	22
Atmospheric Dynamics	40	30	14
Total Atmospheric Science	*38*	*33*	*17*
Planetary Science	*46*	*40*	*17*

Table S3. Percentage of Women by Rank and Subdiscipline for Subdisciplines Not Presented in the Main Text

Subdiscipline (# Faculty)	**Assistant Professor**	**Associate Professor**	**Full Professor**
Climate Dynamics (172)	48	27	13
Ecology (191)	52	51	25
Education (15)	100	100	10
GIS/Engineering (61)	37	30	14
Hydrology (167)	48	31	20
Impacts (108)	51	37	30
Land Surface Processes (12)	33	0	25
Paleobiology (20)	33	33	27
Paleontology (51)	60	12	13
Resource Management (34)	71	27	25
Sustainability (35)	50	14	25