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

Meghana Ranganathan[1], Ellen Lalk[1,2], Lyssa M. Freese[1], Mara A. Freilich[1,2], Julia Wilcots[1], Margaret L. Duffy[1], Rohini Shivamoggi[1]

[1]Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA, USA
[2]Woods Hole Oceanographic Institution, Woods Hole, MA, USA

Key Points:

- We compile a dataset of the proportion of women:men in the geosciences by rank, university, and subdiscipline from $\sim 2,500$ geoscience faculty to show that women make up approximately 27% of all tenured and tenure-track faculty amongst 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
- We develop a simple model to analyze when gender parity can be reached

Corresponding author: Meghana Ranganathan, `meghanar@mit.edu`

Abstract

Inequalities persist in the geosciences. Women and people of color remain underrepresented at all levels of the academic faculty, including positions of power. The proportion of women among geoscience faculty has been catalogued in previous studies but there has yet to be research considering the effects of institutional practices on the under-representation of women. Here, we compile a dataset of 2,531 tenured and tenure-track geoscience faculty from 62 universities to evaluate the proportion of women by rank, discipline, and type of institution. 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'. Given 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. Our results support previous work that shows tackling the diversity problem at the student level is insufficient to ensure gender parity at the faculty level. Rather, 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.

Plain Language Summary

Both women and people of color are underrepresented 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, but there is a lack of research into the reasons why women are under-represented. 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 account for institutional reasons why women may leave the academic field. We find that if faculty are hired at a 1:1 gender ratio starting in 2021, there will be gender parity by 2056. 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 her male colleagues, 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 underrepresented groups, mentoring of underrepresented students and faculty, and toxic environments that push underrepresented faculty 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 (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, 2015; Wilson, 2016). It is a consistent trend in these studies that gender diversity is highest amongst junior faculty and steadily drops off with associate professors and, subsequently, full professors.

In this study, we quantify the representation of female 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, based on the significant disparities in race as reported by (Bernard & Cooperdock, 2018), 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.

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. 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 geoscience workforce. Furthermore, the geoscience faculty from these institutions serve in a primary mentorship role for those geoscience trainees, making representation and diversity amongst these faculty particularly important (Hernandez et al., 2020).

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. Only tenure-track faculty hired by these departments were included in the dataset (thus excluding lecturers, or research faculty). 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.

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. 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.

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 (male/female). 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 to widen the scope of gender studies in STEM disciplines. This is discussed in more detail in the Discussion section.

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 of female 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 of female assistant professors is higher than the percentage of female associate professors, which is higher than the percentage of female 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

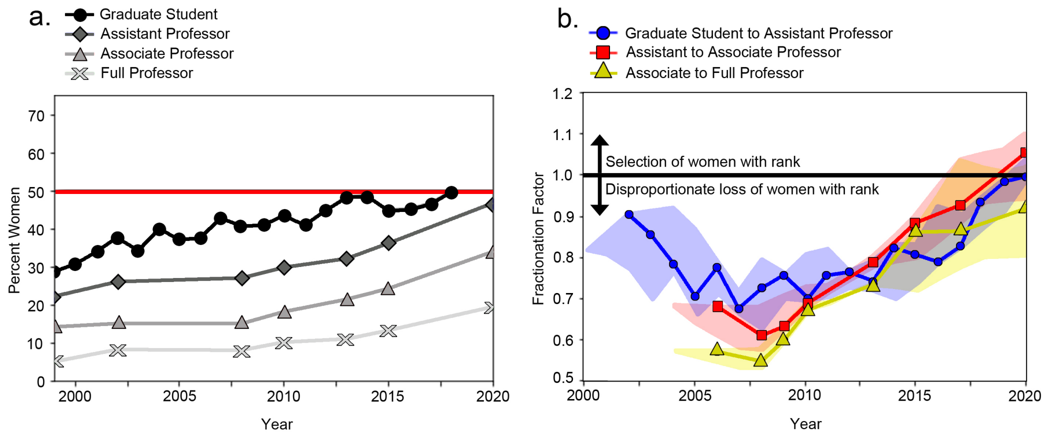

Figure 1. Multi-decadal time-series of gender distribution in faculty by rank (a) Percentage of female faculty by rank for the last 21 years. References: 1999 Data (de Wet et al., 2002), 2002 Data (Holmes & O'Connell, 2003), 2008, 2010, 2013 Data (Wilson, 2016) exact percentages interpreted from a bar chart, 2015 Data (n = 2324) (Holmes et al., 2015), 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

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 underrepresented groups. 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 under-represented 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). 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 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. This framework 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. In this way, the fractionation framework focuses on bias in an institutional sense.

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 ($\alpha(\text{Graduate Student,Assistant Professor}) < 1$). 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, $\alpha(\text{Assistant Professor, Associate Professor}) > 1$, 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 dipicted in Figure 1b. The fractionation factors of ≈ 1 may suggest that diversity, equity, and inclusion policies and programs from the last decade or so (such as the ADVANCE program, improved mentoring and support networks, departmental efforts to improve workplace culture (Dutt, 2015; Hallar et al., 2015; Hastings et al., 2015; Holmes, 2015; Adams et al., 2016)) are beginning to improve the outlook for gender diversity in the geosciences.

However, 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.

Further, 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. Furthermore, these results do not mean that diversity initiatives are working for all groups and do not suggest that we should be continuing our past strategies of tackling diversity and inclusion issues. 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 & Cooperdock, 2018)) show that even when things improve for white women, this does not suggest that efforts are working for other minoritized groups.

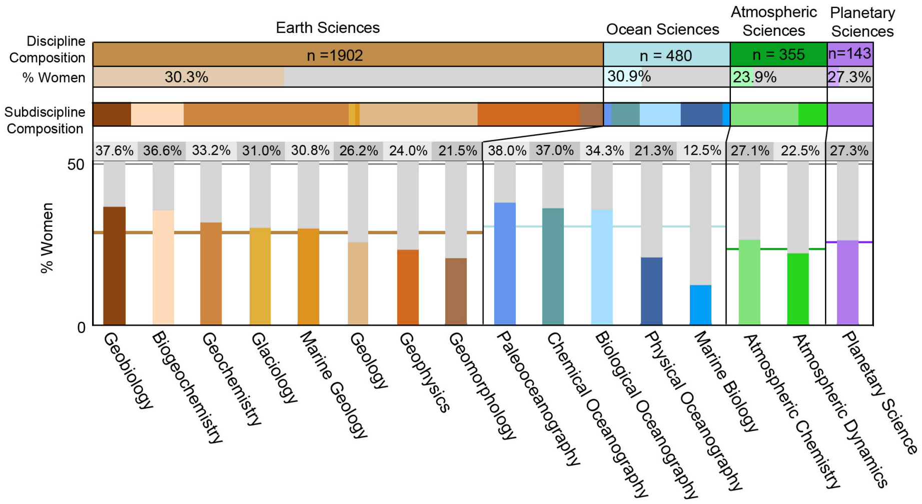

Figure 2. Faculty gender distribution by sub-discipline Gender distribution at the faculty level in order from highest to lowest percent women within each discipline. The black line represents an even gender distribution. Brown, blue, green, and purple lines represent the gender distributions of the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

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 of female faculty range between 23% and 30% of the faculty in each discipline, with atmospheric sciences having the lowest percentage of female faculty ($\sim 23\%$) and ocean sciences having the highest percentage of female faculty ($\sim 30\%$).

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 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 of female 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 of female 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 female, 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 of female 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 of female 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 of female faculty than subdisciplines in the physical sciences (geophysics, physical oceanography, atmospheric dynamics). In particular, atmospheric physics and physical oceanography have the lowest percentage of female 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, many studies have 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, and cultures of sexism all play a role in making academic geoscience careers inacessible to women, people of color, and other underrepresented groups (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. 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 female faculty in the geosciences remains lower than the percentage of male faculty 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 female 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

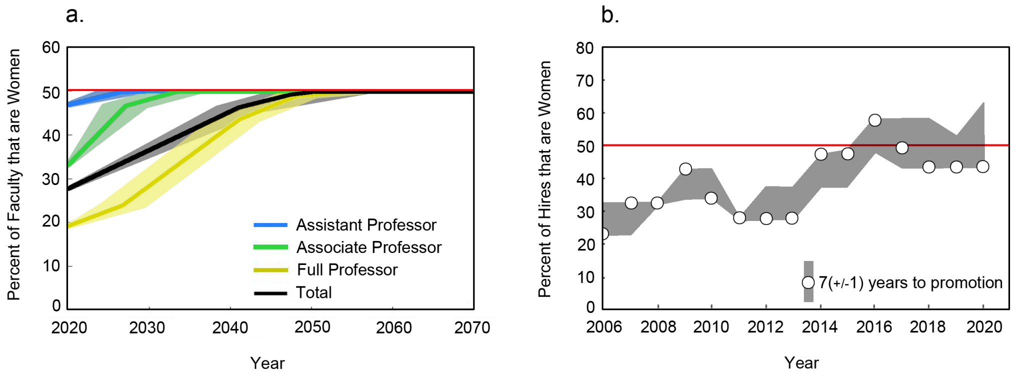

Figure 3. Estimated gender distribution over time (a) Model outlook on faculty gender composition by rank. If faculty are hired at a 1:1 gender ratio, and assuming there is equal retention between men and women, we should expect gender parity by 2055.(b) Estimated percent of hires that are women by year, 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.

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 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 the proportion of female faculty is currently lower than the proportion of male faculty, 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.

Moving beyond gender and the gender binary

In this study, we consider only two genders: male and female. 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 is a 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.

(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 marginalized 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 a significant underrepresentation 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 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 work 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 are underrepresented 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. Here, we reframe this phenomenon in which fewer underrepresented groups are seen at higher levels of the academic hierarchy in terms of a fractionation factor, which 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.

These results suggest that tenure and promotion processes within geoscience departments may have institutional inequities and implicit biases that result in a disproportionate attrition of women. Further, an implication for the results presented in this study is that outreach and recruitment at the student level is insufficient to improve the gender diversity and inclusivity of the geosciences at the higher ranks of academia, since many disparities worsen during the tenure-track.

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. 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.

Extensive studies have been done on the retention and loss of women in academia. These studies have suggested that combating internal biases, improving family leave and childcare opportunities, adjusting the timeline and process of tenure, and improving the internal cultures of geoscience departments may be positive steps towards achieving equality and equity (de Wet et al., 2002; Marín-Spiotta et al., 2020; Bocher et al., 2020). However, many of the existing programs and studies focus on the retention and recruitment of white women, 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. 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 bias and inequities that continue to persist.

Acknowledgments

We credit Marianna Linz, Kristin Bergmann, David McGee, Christine Y. Chen for helpful conversations and feedback. No funding was provided for this work.

The data that support the findings of this study and the code used to generate the figures are openly available at `https://github.com/lfreese/female_geosci`.

The authors declare that they have no known conflicts of interest.

References

Adams, A., Steiner, A., & Wiedinmyer, C. (2016). The Earth Science Women's Network (ESWN): Community-Driven Mentoring for Women in the Atmospheric Sciences. *Bulletin of the American Meteorological Society*(March), 345–354. doi: 10.1175/BAMS-D-15-00040.1

Bacon-Bercey, J. (1978). Statistics on Black Meteorologists in Six Organizational Units of the Federal Government. *Bulletin of the American Meteorological Society*, *59*(5), 576–580. doi: 10.1175/1520-0477(1978)059⟨0576:sobmis⟩2.0.co;2

Bernard, R. E., & Cooperdock, E. H. (2018). No progress on diversity in 40 years. *Nature Geoscience*, *11*(5), 292–295. Retrieved from `http://dx.doi.org/`

10.1038/s41561-018-0116-6 doi: 10.1038/s41561-018-0116-6

Bocher, M., Ulvrova, M., Arnould, M., Coltice, N., Mallard, C., Gerault, M., & Adenis, A. (2020). Drawing everyday sexism in academia: Observations and analysis of a community-based initiative. *Advances in Geosciences*, *53*, 15–31. doi: 10.5194/adgeo-53-15-2020

Box-Steffensmeier, J. M., Cunha, R. C., Varbanov, R. A., Hoh, Y. S., Knisley, M. L., & Holmes, M. A. (2015). Survival analysis of faculty retention and promotion in the social sciences by gender. *PLoS ONE*, *10*(11), 1–22. doi: 10.1371/journal.pone.0143093

Brunsma, D. L., Embrick, D. G., & Shin, J. H. (2017, jan). Graduate Students of Color. *Sociology of Race and Ethnicity*, *3*(1), 1–13. Retrieved from http://journals.sagepub.com/doi/10.1177/2332649216681565 doi: 10.1177/2332649216681565

Ceci, S. J., Ginther, D. K., Kahn, S., & Williams, W. M. (2014). Women in academic science: A changing landscape. *Psychological Science in the Public Interest, Supplement*, *15*(3), 75–141. doi: 10.1177/1529100614541236

Clancy, K. B., Lee, K. M., Rodgers, E. M., & Richey, C. (2017). Double jeopardy in astronomy and planetary science: Women of color face greater risks of gendered and racial harassment. *Journal of Geophysical Research: Planets*, *122*(7), 1610–1623. doi: 10.1002/2017JE005256

Crenshaw, K. (1989). Demarginalizing the Intersection of Race and Sex: A Black Feminist Critique of Antidiscrimination Doctrine, Feminist Theory and Antiracist Politics. *University of Chicago Legal Forum*, *1989*(1), 139–167.

de Wet, C. B., Ashley, G. M., & Kegel, D. P. (2002). Biological clocks and tenure timetables: Restructuring the academic timeline. *GSA Today*, *12*(11), 24. doi: 10.1130/1052-5173(2002)012⟨0024:BCATTR⟩2.0.CO;2

Dutt, K. (2015). Institutional Transformation: the Lamont-Doherty Earth Observatory Experience. In *Women in the geosciences: Practical, positive practices toward parity* (pp. 51–66). doi: 10.1002/9781119067573

Dutt, K. (2020). Race and racism in the geosciences. *Nature Geoscience*, *13*(1), 2–3. Retrieved from http://dx.doi.org/10.1038/s41561-019-0519-z doi: 10.1038/s41561-019-0519-z

Hallar, A., Avallone, L., Thiry, H., & Edwards, L. (2015). ASCENT, a Discipline-Specific Model to Support the Retention and Advancement of Women in Science. In *Women in the geosciences: Practical, positive practices toward parity* (pp. 135–148). Retrieved from http://www.eiu.edu/wism/about{_}biographies.php

Hastings, M., Wiedinmyer, C., & Kontak, R. (2015). Facilitating Career Advancement for Women in the Geosciences Through the Earth Science Women's Network (ESWN). In *Women in the geosciences: Practical, positive practices toward parity* (pp. 149–159).

Hernandez, P. R., Adams, A. S., Barnes, R. T., Bloodhart, B., Burt, M., Clinton, S. M., . . . Fischer, E. V. (2020). Inspiration, inoculation, and introductions are all critical to successful mentorship for undergraduate women pursuing geoscience careers. *Communications Earth & Environment*, *1*(1), 1–9. Retrieved from http://dx.doi.org/10.1038/s43247-020-0005-y doi: 10.1038/s43247-020-0005-y

Hofstra, B., Kulkarni, V. V., Galvez, S. M. N., He, B., Jurafsky, D., & McFarland, D. A. (2020). The diversity–innovation paradox in science. *Proceedings of the National Academy of Sciences of the United States of America*, *117*(17), 9284–9291. doi: 10.1073/pnas.1915378117

Holmes, M. A. (2015). Best Practices to Achieve Gender Parity: Lessons Learned from NSF's ADVANCE and Similar Programs. In *Women in the geosciences: Practical, positive practices toward parity* (pp. 33–35).

Holmes, M. A., OConell, S., & Dutt, K. (2015). *Women in the Geosciences.*

Holmes, M. A., & O'Connell, S. (2003). Where are the Women Geoscientists? *Report on the workshop: Where are the women geoscience professors?*, 1–44.

Holmes, M. A., O'Connell, S., Frey, C., & Ongley, L. (2008). Gender imbalance in US geoscience academia. *Nature Geoscience*, *1*(2), 79–83. doi: 10.1038/ngeo113

Jimenez, M. F., Laverty, T. M., Bombaci, S. P., Wilkins, K., Bennett, D. E., & Pejchar, L. (2019). Underrepresented faculty play a disproportionate role in advancing diversity and inclusion. *Nature Ecology and Evolution*, *3*(7), 1030–1033. Retrieved from `http://dx.doi.org/10.1038/s41559-019-0911-5` doi: 10.1038/s41559-019-0911-5

Johnson, H. L. (2017). Pipelines, Pathways, and Institutional Leadership. *American Council on Education*. Retrieved from `https://vtechworks.lib.vt.edu/handle/10919/84062`

Langin, K. (2020). *Lgbtq researchers say they want to be counted.* American Association for the Advancement of Science.

Leslie, S.-J., Cimpian, A., Meyer, M., & Freeland, E. (2015). Expectations of brilliance underlie gender distributions across academic disciplines. *Science*, *347*(6219). doi: 10.4135/9781483392240.n8

Lykkegaard, E., & Ulriksen, L. (2019). In and out of the STEM pipeline–a longitudinal study of a misleading metaphor. *International Journal of Science Education*, *41*(12), 1600–1625. doi: 10.1080/09500693.2019.1622054

Marín-Spiotta, E., Barnes, R. T., Berhe, A. A., Hastings, M. G., Mattheis, A., Schneider, B., & Williams, B. M. (2020). Hostile climates are barriers to diversifying the geosciences. *Advances in Geosciences*, *53*, 117–127. Retrieved from `https://adgeo.copernicus.org/articles/53/117/2020/` doi: 10.5194/adgeo-53-117-2020

McAllister, T. G., Naepi, S., Wilson, E., Hikuroa, D., & Walker, L. A. (2020, aug). Under-represented and overlooked: Māori and Pasifika scientists in Aotearoa New Zealand's universities and crown-research institutes. *Journal of the Royal Society of New Zealand*, 1–16. Retrieved from `https://www.tandfonline.com/doi/full/10.1080/03036758.2020.1796103` doi: 10.1080/03036758.2020.1796103

Metcalf, H., Russell, D., & Hill, C. (2018). Broadening the Science of Broadening Participation in STEM Through Critical Mixed Methodologies and Intersectionality Frameworks. *American Behavioral Scientist*, *62*(5), 580–599. doi: 10.1177/0002764218768872

National Academies of Sciences, Engineering, and Medicine, Policy and Global Affairs, Committee on Women in Science, Engineering, and Medicine, C. o. t. I. o. S. H. i. A. (2018). *Sexual Harassment of Women* (P. A. Johnson, S. E. Widnall, & F. F. Benya, Eds.). Washington, D.C.: National Academies Press. Retrieved from `https://www.nap.edu/catalog/24994` doi: 10.17226/24994

Perna, L. W., Gerald, D., Baum, E., & Milem, J. (2007). The status of equity for black faculty and administrators in public higher education in the south. *Research in Higher Education*, *48*(2), 193–228. doi: 10.1007/s11162-006-9041-4

Puritty, C., Strickland, L. R., Alia, E., Blonder, B., Klein, E., Kohl, M. T., ... Gerber, L. R. (2017). Without inclusion, diversity initiatives may not be enough. *Science*, *357*(6356), 1101–1102. doi: 10.1126/science.aai9054

Rasmussen, K. C., Maier, E., Strauss, B. E., Durbin, M., Riesbeck, L., Wallach, A., ... Erena, A. (2019). The Nonbinary Fraction: Looking towards the future of gender equity in astronomy. *arXiv*, *3*, 1–15.

Stadmark, J., Jesus-Rydin, C., & Conley, D. J. (2020). Success in grant applications for women and men. *Advances in Geosciences*, *53*, 107–115. Retrieved from `https://adgeo.copernicus.org/articles/53/107/2020/` doi: 10.5194/adgeo-53-107-2020

Strauss, B. E., Borges, S. R., Faridani, T., Grier, J. A., Kiihne, A., Maier, E. R., ... Zamloot, V. (2020). Nonbinary Systems: Looking Towards the Future of Gender Equity in Planetary Science. , 1–8. Retrieved from http://arxiv.org/abs/2009.08247

Thomas, K. M., Willis, L. A., & Davis, J. (2007, apr). Mentoring minority graduate students: issues and strategies for institutions, faculty, and students. *Equal Opportunities International*, *26*(3), 178–192. Retrieved from https://www.emerald.com/insight/content/doi/10.1108/02610150710735471/full/html doi: 10.1108/02610150710735471

Van Miegroet, H., Glass, C., Callister, R. R., & Sullivan, K. (2019). Unclogging the pipeline: advancement to full professor in academic STEM. *Equality, Diversity and Inclusion*, *38*(2), 246–264. doi: 10.1108/EDI-09-2017-0180

Wilson, C. (2016). *Status of Geoscience Workforce.* Retrieved from http://www.americangeosciences.org/workforce/reports/status-report-2014

Wolfe, C. J. (1999). Number of women faculty in the geosciences increasing, but slowly. *Eos*, *80*(12), 1997–2000. doi: 10.1029/99EO00090

Zambrana, R. E., Ray, R., Espino, M. M., Castro, C., Douthirt Cohen, B., & Eliason, J. (2015). "Don't Leave Us Behind": The Importance of Mentoring for Underrepresented Minority Faculty. *American Educational Research Journal*, *52*(1), 40–72. doi: 10.3102/0002831214563063