Conference demographics and footprint changed by virtual platforms

Matthew Skiles[1], Euijin Yang[1], Orad Reshef[2], Diego Robalino Muñoz[1], Diana Cintron[3], Mary Laura Lind[4], Alexander Rush[5], Patricia Perez Calleja[6], Robert Nerenberg[6], Andrea Armani[7,*], Kasey Faust[1,*], Manish Kumar[1,*]

[1]Department of Civil, Architectural and Environmental Engineering, University of Texas at Austin, Austin, Texas, USA
[2]Department of Physics, University of Ottawa, Ottawa, Ontario, Canada
[3]Department of Chemical Engineering, University of Texas at Austin, Austin, Texas, USA
[4]School for Engineering of Matter, Transport and Energy, Arizona State University, Tempe, Arizona, USA
[5]Department of Computer Science, Cornell University, Ithaca, New York, USA
[6]Department of Civil and Environmental Engineering and Earth Sciences, University of Notre Dame, Notre Dame, Indiana, USA
[7]Department of Chemical Engineering and Material Science, University of Southern California, Los Angeles, California, USA

[*]Corresponding authors, email: armani@usc.edu, faustk@utexas.edu, manish.kumar@utexas.edu

Abstract:

Conferences disseminate research, grow professional networks, and train employees. Unfortunately, they also contribute to climate change and present significant barriers to achieving a socially sustainable work environment. Here, we analyze the recent impact of transforming in-person conferences (IPCs) into virtual conferences (VCs) on improving diversity, equity, and inclusion (DEI) in science and engineering conferences. Factors including cost, gender, career stage, and geographic location were evaluated. VCs demonstrated a clearly discernable and in some case orders of magnitude improvement across nearly all metrics. Based on participant survey results, this improvement may be attributed to a combination of reduced financial and personal-life burdens. However, despite this clear impact, further development of virtual networking features and poster sessions is necessary in order to achieve widespread adoption and acceptance of this new format.

Conferences fulfill a range of needs by facilitating dissemination of ideas, initiating collaborative relationships, and providing education, training, and career opportunities. Traditional in-person conferences (IPCs) have filled this role for centuries[1], and these events cut across all sectors: academia, industry, and government. However, this format has been criticized as outdated and detrimental to the environment[2-4]. More recent, emerging evidence is also connecting this modality to social sustainability issues as well, notably poor retention of a diverse workforce. In this context, the two dominant contributors are the intrinsic power-imbalance in the workplace and an imbalance in home-life responsibilities[5, 6].

Over the past two decades, the creation and sustainment of a diverse, equitable and inclusive (DEI) work environment in the scientific and engineering community has not kept pace with many other fields. In part, this can be attributed to career expectations revolving around conference travel and participation. Participation in conferences can be cost prohibitive for many, as the cumulative expenses can be thousands of dollars per person. International travel creates additional barriers[7] which are exacerbated by the frequent changes in document requirements and lengthy delays in obtaining visas. These financial and documentation barriers can also dissuade scientists that have difficulty securing funding to cover conference costs such as students, postdocs or scientists from historically underrepresented institutions. These factors can also exclude participants from countries that do not have very high research activity, such as nations that are not in the top 10 research countries as defined by the Nature Index (NI)[8], NI>10.

However, even for those researchers who are able to travel, the time away from home necessitated by work-related travel is intrinsically exclusionary to care-givers, who are primarily women[3, 7, 9]. Yet, given how important conference attendance is to career advancement, this community is frequently faced with the decision of choosing between work and family. Lastly, despite conference organizers' attempts to solve accessibility concerns of the disabled community, many conferences still fall short of providing an equitable experience.

The recent surge in virtual events is forcing the scientific community to re-evaluate its long-held position against VCs. The initial anecdotal evidence indicated that VCs enabled a more diverse population to participate. But a quantitative analysis of the impact on DEI challenges has yet to be performed. Such analysis is critical to make decisions regarding the format of future events, potentially resulting in a paradigm shift in the field. Here, we evaluate several metrics, including cost, carbon footprint, impact of conference format, and attendee demographics. We collected historical data from three US-based IPCs of varying sizes and disciplines within STEM. These results were compared to the same three conferences after they transitioned to a VC format in 2020. These scientific conferences were among the first conferences to transition online in response to the COVID 19 pandemic and were chosen to investigate the impact of an abrupt transition from historically IPCs to a new virtual format.

The historically IPCs-turned-VCs analyzed here are the Annual International Conferences on Learning Representations (ICLR), the American Astronomical Society (AAS), and the North American Membrane Society (NAMS) conferences. Also analyzed here are several conference series that were originally designed for the VC environment including the Photonics Online Meetups (POM 1: January 2020, POM 2: June 2020) and the International Water Association Biofilms (IWA) conference. These conferences span five fields of science and engineering and range from small to large scale events. All have international audiences

We focused our analysis on the environmental, social and economic costs of VCs vs IPCs and accompanying demographic impacts (global participation), participation from women, early career researchers and scientists from underrepresented institutions. We also assessed the challenges and benefits of the VC format.

RESULTS

Demographic Impact The elimination of the travel and cost burdens realized with the VC format resulted in a large increase in attendance at all events (**Figure 1**). The increase in attendance was particularly pronounced for international attendees. We propose that this trend may be related to the substantial decrease in costs as compared to IPCs as described below.

The cost of attending IPCs for international attendees was dominated by airfare (**Figure 1 and Table S1, S2**). When compared to US attendees, the average researcher from Africa, Asia, Europe, the Middle East, and Oceania paid between 90% to 210% more to attend NAMS IPCs (**Table S3**). When placed in financial context, the cost of attendance for scientists from Africa to past ICLR (2018-2019), AAS (2016-2019), and NAMS (2015-2019) IPCs was on average between 80% to 250% of their country's annual per capita gross domestic product (GDP), compared to approximately 3% of per capita GDP for US participants (**Figure 1c and Table S4**). Cost of attendance for participants from Asia to past ICLR (2018-2019), AAS (2016-2019), and NAMS (2015-2019) IPCs was approximately 15% of their country's per capita GDP (**Figure 1c and Table S4**). However, it is important to note that many conferences not included in this analysis have registration fees in excess of $700. For these events, registration fees can begin to compete with airfare as a significant contributing financial consideration.

The 2020 ICLR, AAS and NAMS VC delegations were more geographically diverse, likely due to the elimination of these travel and registration costs as seen from responses to our surveys (Supplementary Information, SI). Notably, the audiences were approximately 40% to 120% larger than the historical average for IPCs (**Table S5**). Attendance by scientists from NI>10 countries increased significantly from the historical average at ICLR, AAS, and NAMS IPCs to the 2020 ICLR, AAS, and NAMS VCs (**Figure 1d and Table S6**). The increased representation was more comparable to delegations seen at conferences originally designed for the virtual environment; specifically, 31% to 38% of attendees at the POM 1, POM 2, and IWA VCs were from NI>10 countries (**Figure S1**).

In this context, the environmental impact of international conferences can also be considered. In a collection of decarbonization pathways designed to limit global warming to 1.5° C with a small overshoot, the median global per capita carbon budget for the entire year of 2030 was 3.26 tonnes of CO_2 equivalents (CO_2e)[10]. The carbon footprint for a single international attendee to the 2019 ICLR, AAS, or NAMS IPCs approached this value. Conversely, the cumulative footprints of the more than 7000 attendees to 2020 ICLR, AAS, and NAMS VCs (1.07 tonnes CO_2e) was comparable to the average footprint of a single attendee (combined average of domestic and international) to one of the analyzed 2019 IPCs as shown in **Figure S2** and **Table S7,** and discussed further in the SI.

Participation of Women The VC format also eliminated travel burdens that can act as a barrier to attendance for certain sociodemographic groups. This impact is likely reflected in changes in the gender makeup of VC delegations (**Table S8)** and supported by survey responses to a follow up survey sent separately to men and women attendees of NAMS 2020 (**Table S9**). Attendance by women increased between 60% to 260% at ICLR, AAS, and NAMS VCs compared to the IPC baselines (**Figure 2 and Table S10**). On average, women made up larger fractions of the conference delegations at 2020 VCs as compared to IPCs (**Figure 2g and Table S11**). The increase in the number of female attendees is particularly significant considering that women make-up smaller portions of STEM fields compared to men. For example, women comprise only 33% to 34% of STEM researchers in the countries that made up the delegations for historical ICLR, AAS, and NAMS IPCs (**Table S12, S13, S14**). Survey responses confirmed that the elimination of the travel requirement realized with VCs partially explain trends in attendance by gender. For example, about half (47%) of the 2020 NAMS VC survey respondents that did not plan on attending the originally scheduled 2020 NAMS IPC indicated that the primary reason for attending the VC was convenience (**Figure S3**).

Abstract submittals to the 2020 NAMS conference from before and after the decision to switch from an in-person to a virtual format also indicated an increase in interest and participation from female researchers for the VC. Approximately a quarter (26%) of abstracts submitted to the 2020 NAMS IPC were from female researchers, which was aligned with historical average attendance by women to 2015-2019 NAMS IPCs (**Figure S4**). After it was announced that the 2020 NAMS conference would be held online, 37% of submitted abstracts came from female scientists (**Figure S4**). The 2020 ICLR VC also saw an increase in attendance from gender queer and transexual scientists. On average, 2018-2019 ICLR IPCs were attended by 1 gender queer scientist and 0 transgender scientists. The 2020 ICLR VC was attended by 8 gender queer scientists and 2 transgender scientists (**Figure 2a**). However, it should be noted that this increase in reported attendance by LGBTQ scientists could be the result of an increased willingness to identify as LGBTQ.

Participation of Students and Postdoctoral Researchers High costs characteristic to IPCs can also be exclusionary to certain sociodemographic groups that may face challenges securing funding for travel, such as students and postdoctoral researchers. Cost of attendance to historical NAMS IPCs was on average $1612 for students and $2142 for postdocs. The shift to a virtual environment resulted in a significant growth in this population of attendees (**Figure 3a-c and Table S15**). Additionally, on average, for all conferences evaluated, the VC delegations had higher proportions of students (29% to 42%) and postdoctoral researchers (5% to 11%) compared to historical IPCs (**Figure 3d and Table S16, S17**). Additionally, the audiences of conferences designed for the virtual environment (POM 1, POM 2, and IWA) were all comprised of over 45% students and post-doctoral scholars, demonstrating the impact that virtual events can have on the careers of emerging scholars (**Figure S5)**. The AAS conference surprisingly did not show much change in conference composition as seen from surveys (32% completion) (**Figure S6**). The role of cost on attendance was evident in survey responses, as 33% of respondents to NAMS surveys indicated that they were not planning on attending the scheduled 2020 NAMS IPC prior to the decision to move online (**Figure S7**). Of the respondents that were not planning on attending, 34% indicated that cost was the primary motivation for attending the 2020 NAMS VC (**Figure S3**).

Participation of Historically Underrepresented Institutions A unique and particularly challenging subset of researchers to engage are those from Primarily Undergraduate Institutions (PUIs) and High Research Activity (R2) Universities (as distinct from the Very High Research Activity Category – R1). Attendance from both groups increased at VCs. At the 2020 NAMS VC, attendance by researchers from PUIs and R2 Universities increased from the IPC baseline by 157% and 45%, respectively. Similarly, attendance at the 2020 AAS VC from PUIs and R2

Universities increased by 72% and 106%, respectively (**Figure 3e and Table S18**). Increasing participation of researchers from these historically excluded institutions will enhance their educational experiences and provide more research opportunities. Additionally, attending technical events will provide students with mentoring and networking opportunities, potentially increasing the likelihood that they pursue graduate degrees.

Effect of Time Zones and Conference Format While VCs may eliminate many barriers to participation, the impact on international attendances seen in this work was strongly dependent on the VC format (**Figure S8 and Table S19)** with the primary variations being synchronous, asynchronous, or blended (both options available) content delivery. The 2020 NAMS VC was organized around synchronous live talks. Consequently, attendance from regions where the conference was held during normal work hours was significantly higher than in other regions. As a result, attendance from Europe and the Middle East increased by 102% and 76%, respectively, when compared to the 2015-2019 NAMS IPC average. Conversely, for Asia, where the 2020 NAMS VC was held around or past midnight local time, attendance decreased by 62%. In the case of the 2020 AAS VC which was also synchronous, attendance increased for all regions compared to AAS IPCs (60% to 700% increase), and the largest percent increases came from Europe, Oceania, and Other Americas. Therefore, the dependence on working hours was not universally observed. However, it is important to note that some regions had very small participant numbers which could influence the analysis.

The 2020 ICLR VC was asynchronous, with only a few live events and most talks pre-recorded and released for consumption at the attendee's leisure. A live Q&A session was held for each keynote speaker after the video had been available for some time, thus affording the opportunity to interact with the speaker. As a result of this format, attendance at the 2020 ICLR VC increased for all regions (57% to 1700% increase), when compared to the 2018-2019 ICLR IPC average. Additionally, unlike the AAS and NAMS conferences, over 50 people attended the 2020 ICLR VC from every region in the world, increasing confidence in the analysis. Based on these results, it is clear that to take full advantage of the virtual format and to make these events effective at disseminating science, it is necessary to offer content asynchronously or using a blended format. A similar blended approach was used by the IWA VC. At IWA, pre-recorded presentations were released at a specified time and presenters were available to answer questions during and after the video presentation.

Initial Attendee Perceptions of Virtual Conferences The VC format, in general, was well received by attendees and helped to shift negative perceptions to more positive views towards this format. No major alterations in the type of content presented was observed between IPCs and VCs, as discussed in the SI. Attendees to 2020 VCs indicated via pre-conference surveys that they were initially skeptical about the efficacy of VC components, but overall felt that the format could possibly improve IPCs in some ways. When asked what they foresaw as the biggest challenge with the virtual format, networking and social interaction was the most common response for NAMS surveys (42% of respondents) and POM 2 surveys (25% of respondents) (**Figure S9**). Aversion to engaging with the virtual format was lowest among students, as indicated by the fact that only 25% of graduate students and no undergraduate students who submitted abstracts to the 2020 NAMS IPC elected to withdraw from the conference once it was moved online. Conversely, 37% of industry personnel and 39% of postdoctoral researchers who applied to the 2020 NAMS IPC elected not to attend the 2020 NAMS VC (**Figure S11**). NAMS survey respondents indicated that they were looking forward to some aspects of the virtual format, particularly the opportunity to seamlessly transition between sessions and quickly access the internet to research unfamiliar concepts that arose during the conference.

Part of the success realized by VCs is related to the wide range of currently available virtual environments for hosting oral sessions. Oral sessions at analyzed conferences were either livestreamed via webinar (synchronous format) (**Figure S12**) or pre-recorded and released at a specified time (asynchronous format). They were popular among attendees, with 43% of NAMS survey respondents and 74% of POM 2 survey respondents indicating that they preferred the virtual format for oral sessions over the in-person format (**Figure S13 and S14**). Some presentations and Q&A sessions were recorded and made available indefinitely, eliciting persistent viewing after the conference ended. The ICLR platform drew 652,087 total pageviews during the scheduled conference days, and then views increased again by 74% (481,092 additional views) in the three months following the conference, indicating a significant increase in exposure for presenters and sponsors compared to the in-person format (**Figure S15**).

Analyzed VCs had poster authors publish their posters via twitter, using a web-based iPoster sharing platform, or by uploading a 5-minute pre-recorded presentation to the conference website. The poster presentations had high view counts (NAMS iPosters had on average 142 views) (**Figure S16**), but presenters could not tell how many attendees were viewing their posters and features for communicating with poster viewers were not effective. In contrast, Twitter-based poster sessions are increasing in frequency and allow asynchronous communication. However, Twitter is not available in every country, limiting access. Consequently, virtual posters were less popular, with 85% of NAMS survey respondents and 43% of POM 2 survey respondents indicating that they preferred in-person poster sessions to virtual poster sessions (**S13 and S14**).

Analyzed VCs attempted to facilitate networking by employing a variety of social media, messaging, video chat, and virtual reality features (**Table S20**). However, survey respondents indicated that the interactions felt inauthentic and contrived. As a result, 75% of POM 2 survey respondents and 96% of NAMS survey respondents indicated that they preferred in-person networking to virtual networking (**Figure S13 and S14**). In response to this feedback, VCs that occurred later in 2020 and in early 2021 took advantage of improvements in virtual networking technology. These features included robust central chat and discussion board features, as well as Gather.town, an app that allowed participants to navigate a virtual room with an avatar and video chat with other avatars in close proximity. The January 2021 POM used Gather.town to hold a virtual job fair and poster session among other networking events. Gather.town was also used at the 2020 IWA VC and was popular with attendees, as all 56 survey respondents indicated that they would like the Gather.town Interactive Lounge feature to be included in future IWA VCs.

DISCUSSION

Our findings reveal that VCs reduce the environmental impact of conferences, the financial burden, and the social cost. In the VC format, researchers are much more likely to be able to overcome economic and travel related barriers that are intrinsic to IPCs and that ultimately discourage participation from institutions and countries with limited resources, women, disabled scientists, and early career researchers and practitioners (e.g., students, postdocs). These factors are discussed further in the SI. Thus, virtual formats can provide an excellent avenue to address DEI challenges stemming from barriers to participation and representation at IPCs and other professional events. However, despite these clear benefits, the difficulties networking in a virtual environment are routinely emphasized as a limitation.

Seventy-five percent of POM 2 survey respondents and 96% of NAMS survey respondents indicated that they preferred in-person networking to virtual networking (**Figure S13 and S14**). Analyzed VCs experimented with incorporating social media and organizing virtual breakout rooms to facilitate networking with some success. However, survey respondents indicated that the interactions felt inauthentic and contrived. Therefore, while virtual networking technology has improved considerably, there is substantial need for further development of these features as well as research into their efficacy.

One approach to overcome this challenge and increase in-person interaction without increasing cost or travel was piloted during POM 1 by creating locally organized viewing and networking sites (POM-hubs). This “conference within a conference” approach allowed for reduced cost and travel, increased local and regional networking, and created an international conference. Notably, approximately half of the POM 1 attendees participated in the conference from a local hub-site.[1] This hybrid hub approach pioneered by POM 1[1] is a promising solution to this challenge that warrants further study. A hybrid format could allow communities to realize many of the advantages identified by this analysis of COVID VCs, while still offering the option of a traditional IPC experience. It would be ideal for post-pandemic conferences to utilize the ~~rich~~ knowledge gained on the benefits of expanding inclusion using virtual tools. The resultant conferences could facilitate networking and effective dissemination of scientific knowledge to diverse audiences in an environmentally sustainable manner, moving toward more equitable environments and opportunities. Innovative VC strategies and platforms used to administer oral and poster sessions and virtual networking are further discussed in the SI along with additional discussion on organization recommendations.

Our study is characterized by one important limitation. While nearly all interactions made the abrupt shift from in-person to virtual, our analysis is focused on STEM subjects. In some ways, the demographic and financial sensitivities of this population are distinct from other academic communities or an industry or government audience. However, they do share several similarities, particularly for global industry consortiums. Notably, all groups are sensitive to international politics and visa policies, fluctuations in currencies and the financial markets, and gender inequities. However, the attendees at scientific events tend to be highly educated (BS degree or higher in a STEM field) and speak English as a primary or secondary language. These limits do not adversely affect our conclusions, as we are focusing on STEM. However, to extend our conclusions outside of higher education and STEM fields specifically, a broader population analysis should be performed with appropriate benchmarking. Such an analysis will require engaging conference organizers in other areas including humanities, commerce, business as well as related industry, nonprofits, and government organizations.

In addition to extending the analysis outside of STEM, the present research findings motivate several new areas of investigation. A few examples include: (1) developing strategies for improving virtual networking, (2) role of organization type on the impact of travel (small vs. large business, domestic vs. global), (3) policy development by technical/scientific societies, funding agencies, and universities, and (4) longitudinal study tracking travel and career progression. These topics are discussed further in the SI. In this context, we consider the present conclusions to be a significant first step in understanding the positive impact of VCs, paving the way for future policy decisions and reducing DEI challenges in the workplace.

METHODS

Data

Registration, digital platform and survey data were collected from three IPCs-turned-VCs and are presented in **Table S21**. The three analyzed IPCs-turned-VCs include the Annual ICLR (~2300 historical average attendees), the AAS Summer Meeting (~700 historical average attendees), and the NAMS Annual Conference (~450 historical average attendees). Complementing this is data from the POMs (~1000 attendees) and the IWA conference (~350 attendees), conference series that were specifically designed for the virtual ecosystem. These conferences represent varying fields and community sizes and allow for comparisons across a range of STEM backgrounds. Data for IPCs-turned-VCs were collected for 2020 VCs and for historical IPCs. POM and IWA data provided a control for an always VC, while the baseline data for historically IPCs allowed for the elimination of effects from other variables, facilitating direct analysis of the impact that virtual components had on conference performance.

Specific data collected include registration and abstract information, spanning information such as the number and type of participants (e.g., students, industry personnel), geographic participation, institution, and gender. For IPCs-turned-VCs, this data was collected for registrations accrued before and after moving online. Carbon footprint and cost of attendance were estimated based on attendee work locations and conference destinations. Descriptive statistics[11] and thematic mapping[12] were applied to understand changing sociodemographics realized in the shift to a virtual format. Additional data collected on webinar attendance and virtual platform activity were used to assess the efficacy with which the VCs distributed content to attendees. Qualitative data was collected by asking participants to fill out polls as well as pre-and-post conference surveys designed to interrogate the participant experience and field suggestions for improvement. Surveys were also used to investigate the impact of travel burden and cost barriers for female versus male NAMS attendees. Survey questions included multiple choice and open-ended questions about specific conference components and the participant experience. The surveys were produced by the authors for the conferences that they organized. Survey and polling questions underwent IRB review receiving and exempt status (Protocol 2020-05-0026) at the University of Texas at Austin.

Sociodemographic data was provided by conference organizers and filled in as necessary. Attendee countries were manually categorized by region for analysis. Job type data (i.e. Graduate Student, Industry Personnel) was provided by conference organizers via registration or survey data. Data that included specific job titles (i.e. Operations Director, Research Scientist) for attendees were categorized manually by job type. Gender data was provided by organizers for some conferences via voluntary surveys. Gender data for the NAMS conference was manually assigned based on author familiarity with the participants and through internet search of attendee names. The Gender API[13] was also employed to assign gender to attendee names for NAMS and AAS conference attendees. Due to confidence in the accuracy of manually assigned names for NAMS attendees, discrepancies in the genders assigned to NAMS attendees by the manual process and the Gender API indicated that the Gender API was less accurate than the manual process (**Table S8**). Consequently, the Gender API was only applied to assign gender to AAS participants. Attendee academic institutions were manually categorized according to databases of institution types. Minority Serving Institutions were defined according to the 2007 U.S. Department of Education database[14]. High Research Institutions (R2) were defined as any institution that was included in the 2018 Carnegie Classification of R2 Universities[15]. Primarily Undergraduate Institutions (PUI) were defined as any university that awarded 20 or fewer PhD degrees in NSF-supported fields during the combined previous two academic years[16] as reported by the U.S. National Science Foundation (NSF) records on PhD degrees for major science and engineering fields awarded by universities during 2017 and 2018[17, 18]. Non-research-intensive countries were defined as countries that were not in the top 10 countries for scientific research as defined by the Nature Index that measured top countries in terms of contributions to papers published in 82 leading journals during 2019 (NI>10)[19].

Travel Distance

Attendee travel distance, carbon footprint, and cost were calculated via python scripts using attendee origin location data provided by conference organizers. NAMS and AAS registrant origin locations were provided by organizers via registration data as a list of attendees with attendee-specific locations. If location for an attendee was not included, origin location was determined via internet search of the attendee name. ICLR and POM registrant origin location data was provided by conference organizers and comprised a list of countries in attendance and the number of attendees from each country. While the sample size of data for single ICLR conferences varied by data type (i.e. origin country, gender, job title), origin country was the largest dataset for all ICLR conferences, and was thus assumed to be the true size of the conference delegations.

Conference city and attendee origin coordinates were determined by querying the Google Maps API[20] with the location names. If a city-specific attendee origin was not recognized by the API, the attendee origin was set to the attendee's origin country name. Google Maps API queries of only country name return coordinates for the geographical center of the country. Travel distance between attendee origin and conference location were calculated as the great circle distance (great_circle python package).

Carbon Footprint of Attendance

The carbon footprint of conference attendees was calculated for all IPCs-turned-VCs as the cumulative emissions associated with the flight and hotel stay. The air travel carbon footprint was calculated according to the methodology for the myclimate air travel emissions calculator[21]. The myclimate calculator computes air travel footprint by adding 95 km to the great circle distance to account for flightpath inefficiencies and calculating greenhouse gas (GHG) emissions associated with the fuel burn and life cycle footprint of the airplane and associated aviation infrastructure. The GHG emissions are then converted to CO_2e. It was assumed that all conference attendees flew economy class. If city-specific attendee origin data was available and the attendee was local (<= 100 km from the conference city) it was assumed that the attendee did not fly to the conference city, and their travel CO_2e was set to 0. If registrant origin coordinates were not found, the attendee travel distance and travel footprint were set to the average for that conference.

The carbon footprint per night for the attendee hotel stay was determined using the Hotel Carbon Measurement Initiative (HCMI) rooms footprint per occupied room from the Hotel Sustainability Benchmarking Tool published by the Cornell Center of Hospitality Research[22]. The tool provides city-specific and country-specific footprint data. If data was not available in the Hotel Sustainability Benchmarking Tool for the conference city, then the footprint per night was set to the country average in the tool. If no data was available for the country in which the conference was held, the footprint was set to the value that was closest to the conference location geographically. Student hotel footprint calculations were adjusted to assume shared hotel rooms, i.e. footprint per night was divided by two. If attendee specific job title (student vs. non-student) information was not available, percent students as defined by the voluntary survey data was multiplied by the number of attendees from each country to estimate the number of students from each country. When computing total hotel footprint, it was assumed that attendees stayed for all but one night of the conference (i.e. for a four-day conference, nightly hotel footprint was multiplied by 3). If the attendee was local, the hotel footprint was set to 0. If the attendee origin was not near the conference city and their job title (student vs. non-student) was not known, the attendee hotel footprint was set to the conference average.

Cost of Attendance

Cost of attendance for individual attendees was computed for historically IPCs-turned-VCs by calculating their cost of travel based on air travel distance and summing with the estimated cost of the hotel, food, and conference registration fees. Travel cost was calculated as the one-way air travel distance multiplied by the cost distance for air travel defined in [23], and doubled to represent the cost of a round trip flight. If the registrant was local, their travel cost was set to 0. If the registrant origin was not known, the travel cost was set to the average conference travel distance and converted to cost using[23]. To account for a potential overestimate of travel cost, a sensitivity analysis where the one-way flight cost is multiplied by 1.5 instead of 2 was conducted and is presented in **Table S1**.

NAMS hotel cost was taken from NAMS records. 2020 ICLR hotel cost was set to the average of hotel options provided by the ICLR website. For 2018-2019 ICLR and all AAS conferences, the cost of U.S. hotels was set to the U.S. General Services Administration lodging max per diem for the conference city. For 2018-2019 ICLR the cost of all hotels outside of the United States was set to the U.S. State Department lodging max per diem for the conference city. Nightly hotel costs were divided by two for students to assume shared rooms. If attendee specific job title (student vs. non-student) information was not available, percent students as defined by the voluntary survey data was multiplied by the number of attendees from each country to estimate the number of students from each country. ICLR 2020 student hotel cost data was taken from “double room rate” and ICLR 2020 non-student hotel cost data was taken from the “single room rate” cost on the ICLR website. When computing total hotel cost, it was assumed that attendees stayed for all but one night of the conference (i.e. for a four-day conference, nightly hotel cost was multiplied by 3). If the attendee was local, the hotel cost was set to 0. If the attendee was not local, but their job title (student vs. non-student) was not known, the hotel cost was set to the conference average.

Food cost for conferences held in U.S. cities was taken from U.S. General Services Administration city-specific per diem rates for breakfast, lunch, and dinner. For NAMS, one dinner is subtracted from the total cost to account for the banquet dinner provided by NAMS. Food cost for conference cities outside of the U.S. was taken from U.S. State Department city-specific Meals and Incidental Expenses (M & EI) per diem. Attendees were assumed to stay for all but one night of the conference. If the attendee was local, food cost was set to 0. If the attendee origin was not known, the food cost was set to the conference average.

Registration costs for historical NAMS IPCs was set to the recorded registration fee per registrant. Fees for the sponsor and exhibitor registration types, where sponsors made their contributions via the registration fee, at historical NAMS conferences were set to conference average of that year (these registration types are excluded from the average).

Hypothetical registration fees for a 2020 NAMS IPC were assigned to attendees to the 2020 NAMS VC. 2020 NAMS attendees with Registrant Type "Student" were assigned a hypothetical 2020 NAMS IPC registration fee equal to the average fee for students at the 2015-2019 NAMS IPCs (average based on Title Category, with "Unknown/Other" title category excluded from the average). 2020 NAMS VC attendees with Registrant Type "Professional/Academic" were assigned a registration fee equal to the average fee for non-students at the 2015-2019 NAMS IPCs (average based on Title Category, "Unknown/Other" excluded).

Student and non-student registration fees for 2018-2019 ICLR IPCs were set to early registration fees from the conference website. The registration fees for the 2020 ICLR VC were set to the 2018-2019 ICLR IPC average fees. As attendee specific job title (student vs. non-student) information was not available, percent students as defined by the voluntary survey data was multiplied by the number of attendees from each country to estimate the number of students from each country (i.e. Total student registration fees by country = % students from job title data * total attendees from country * student registration fee).

Registration fees for 2016-2019 AAS IPCs were set to the early registration fees for "Full Member / Educator / International Affiliate", "Graduate Student Member", "Undergraduate Student Member", "Emeritus Member", and "Amateur Affiliate" from the 2020 Winter Meeting website. As attendee specific job title information was not available, percentages on attendee job title as defined by the voluntary survey data was multiplied by the number of attendees to estimate the number of each job type in attendance. The total registration fee for each conference was calculated accordingly. The total registration fees were then divided by the number of attendees and the average registration fee was assigned to each registrant.

VC registration fees for ICLR and NAMS were set to $50 for students and $100 for non-students. VC registration fees for AAS were set to the full meeting fees for "Full Member / LAD Member", "Graduate Student", "Undergraduate Student / High School Student", "Emeritus Member", and "Amateur Affiliate" from the 2020 VC website.

World Map Figures

Attendee origin coordinates and conference city coordinates were converted to great circle distance paths and saved in .kml files using the lxml and geographiclib.geodesic python packages. World maps were plotted using Tableau and MapBox.

Global Annual per Capita Carbon Budget for 2030 and 2050

Median global carbon budget calculated in terms of Kyoto GHG as CO_2e for 2030 and 2050 were taken from a set of decarbonization pathways as outlined in the Intergovernmental Panel on Climate Change report on Mitigation Pathways Compatible with 1.5° C in the Context of Sustainable Development[10]. The global carbon budget was divided by the medium variant of global population projections for 2030 and 2050 produced by the United Nations Department of Economic and Social Affairs[24].

Car Travel Footprint

Car travel footprint per mile was taken from U.S. EPA estimates for average passenger vehicles[25].

Virtual Conference Carbon Footprint

VC footprints were estimated based on emissions for YouTube video streaming multiplied by the projected duration of conference webinar and video streaming by attendees[4].

Regional Average Cost/Regional Per Capita GDP

Country specific GDP per capita was defined as the 2019 GDP per capita in the attendee country's national currency converted to USD and divided by the total country population as calculated in the World Economic Outlook Database[26]. Total representative GDP per capita for conference attendees from each region was calculated as the sum of GDP per capita for all the countries in each region multiplied by the number of conference attendees from each country in the region. Total cost of attendance for each region was calculated as the sum of the cost of attendance for all the participants from each region. The regional average cost divided by the regional per capita GDP was calculated by dividing the total cost of attendance for all the attendees from each region by the total representative GDP for the attendees from each region.

Gender Makeup of STEM Researchers from Conference Attendee's Countries

Country-specific percent women data is taken from "Female researchers as a percentage of total researchers (Full-Time Equivalents) – Natural sciences and engineering (sub-total)" published by[27] with the exception of the US which is not included in that dataset. US percent women is derived from women as a percent of MS and PhD graduates employed in Science and Engineering occupations[28]. Overall percent women in STEM for the countries represented in the conference delegations was calculated with percent values from each country represented at the conference, weighted by the number of attendees from each country.

Data availability

The data that support the plots within this paper and other findings of this study have been deposited on Github[29] (DOI: doi.org/10.5281/zenodo.5567764). Source data files for main text figures are also available.

Code availability

The custom code used to process and analyze the data for this study has been deposited on Github[29] (DOI: doi.org/10.5281/zenodo.5567764).

Additional information

Correspondence and requests for materials should be addressed to M.K.

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Contributions

M.K., K.F and M.S. conceived the idea. M.K and M.S. collected data. M.S. and E.Y. analyzed data. O.R., M.L.L, P.P.C, R.N., A.R., and A.A. provided access to data and provided insights on data. M.K., K.F., A.A. and M.S. wrote the manuscript.

Competing interests

The authors the following competing interests: M.K. and M.L.L. were organizers of NAMS. A.R. was an organizer of ICLR. P.P.C. and R.N. were organizers of IWA. A.A. and O.R. were organizers of POM.

Fig 1 | VCs increase overall attendance and geographical diversity while reducing costs. (**a**) The delegation for the 2019 ICLR IPC located in the US was global but concentrated in the United States (n=2584). (**b**) The delegation for the 2020 ICLR, which was originally scheduled to occur in Ethiopia but transitioned online, was larger (n=4980) and more geographically diverse. (**c**) Regional average cost of attendance to IPCs as a percent of attendee country's GDP per capita for ICLR (n=2), AAS (n=4), and NAMS (n=4) conferences was significantly higher for African participants, and very low for US participants. *Error bars are not included for AAS Middle East because n<3. (**d**) The delegations for 2020 ICLR (n=1), AAS (n=1), and NAMS (n=1) VCs generally represented more countries that were not in the top ten research countries as defined by the Nature Index[19] (NI>10) and included a higher number of attendees from those countries compared to the average delegations from IPCs. (**e**) Average registration, food, hotel, and travel costs for a single attendee to past ICLR (n=2), AAS (n=4), and NAMS (n=4) IPCs totaled thousands of USD, compared to less than 200 USD for 2020 ICLR (n=1), AAS (n=1), and NAMS (n=1) VCs. Error bars are the propagated uncertainty for Food, Registration, Hotel, and Travel costs. *Error bars in all panels are defined as standard deviation and are not included for ICLR IPC data because n<3.

Fig. 2 | VCs increase gender diversity. (**a**) The 2020 ICLR VC (n=1) was attended by more scientists of all genders compared to the 2018-2019 ICLR IPCs (n=2). (**b**) A positive percent change in attendance for all genders was observed between the 2018-2019 ICLR IPCs and the 2020 ICLR VC, with the highest percent increase in attendance observed for Gender Queer scientists and scientists that identified as a gender that was not included in the survey. (**c**) The 2020 AAS VC (n=1) was attended by more male and female scientists compared to the 2016-2019 AAS IPCs (n=4). (**d**) A positive percent change in attendance for males and females was observed between the 2016-2019 AAS IPCs and the 2020 AAS VC, with a larger percent increase for female scientists. (**e**) The 2020 NAMS VC (n=1) was attended by more male and female scientists compared to the 2015-2019 NAMS IPCs (n=4). (**f**) A positive percent change in attendance for males and females was observed between the 2015-2019 NAMS IPCs and the 2020 NAMS VC, with a larger percent increase for female scientists. (**g**) The female fractions of the delegations at the ICLR (n=1), AAS (n=1), and NAMS (n=1) VCs were larger than at historical ICLR (n=2), AAS (n=4), and NAMS (n=4) IPCs and were more comparable to the delegation-specific STEM average, with female fractions in STEM calculated as a weighted average of females in STEM for the origin countries of conference attendees[27, 28]. For panels **a** and **b**: Female=Red, Gender Queer=Orange, Male=Yellow, Other=Green, Prefer not to answer=Blue, Trans=Black. For panels **c**, **d**, **e**, and **f**: Female=Red, Male=Yellow, Unknown=Purple. For panel **g**: STEM Average=dark grey, IPC Average=light gray, 2020 VCs=magenta *Error bars in all panels are defined as standard deviation and are not included for ICLR IPC data because n<3.

Fig. 3 | VCs increase participation by early career scientists (students and postdocs) and from non-research-intensive institutions. (**a**) The 2020 NAMS VC (n=1) was attended by substantially more students and postdoctoral researchers than the 2015-2019 NAMS IPCs (n=4), while attendance by other job types remained fairly constant. (**b**) A positive percent change in attendance for all categories was observed between 2015-2019 NAMS IPCs and the 2020 NAMS VC, and percent increase in attendance by students and postdoctoral researchers was very high. *Error bar for Undergrad Student is too large to be included. (**c**) Students and postdoctoral researchers made up a larger percentage and industry personnel and academic scientists represented smaller fractions of both the 2020 ICLR VC delegation (n=1) compared to the 2019 ICLR IPC (n=1) and the 2020 NAMS VC delegation (n=1) compared to the 2015-2019 NAMS IPCs (n=4). (**d**) On average, postdoctoral researchers and students made up smaller fractions of the delegations at historical IPCs (total n=6: ICLR (n=1), AAS (n=1), and NAMS (n=4)) compared to the fractions they represented at analyzed 2020 VCs (total n=6: ICLR (n=1), AAS (n=1), NAMS (n=1), POM (n=2), and IWA (n=1)). (**e**) A positive percent change in attendance by persons from PUIs and R2 Universities was observed at the 2020 NAMS (n=1) and AAS (n=1) VCs compared to the 2015-2019 NAMS IPCs (n=4) and 2016-2019 AAS IPCs (n=4), while attendance from minority serving institutions decreased, but this is likely a result of small sample sizes (attendees from minority serving institutions<10). *Error bars in all panels are defined as standard deviation.

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