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England, Mark
Polvani, Lorenzo

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The Montreal Protocol is delaying the occurrence of the first ice-free Arctic summer

Mark R. England[a,b] and Lorenzo M. Polvani[c,d,1]

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The rapid melting of Arctic sea ice is the largest and clearest signal of anthropogenic climate change. Current projections indicate that the first ice-free Arctic summer will likely occur by mid-century, owing to increasing carbon dioxide concentrations in the atmosphere. However, other powerful greenhouse gases have also contributed to Arctic sea ice loss, notably ozone-depleting substances (ODSs). In the late 1980s, ODSs became strictly regulated by the Montreal Protocol, and their atmospheric concentrations have been declining since the mid-1990s. Here, analyzing new climate model simulations, we demonstrate that the Montreal Protocol, designed to protect the ozone layer, is delaying the first appearance of an ice-free Arctic summer, by up to 15 y, depending on future emissions. We also show that this important climate mitigation stems entirely from the reduced greenhouse gas warming from the regulated ODSs, with the avoided stratospheric ozone losses playing no role. Finally, we estimate that each Gg of averted ODS emissions results in approximately 7 km^2 of avoided Arctic sea ice loss.

Significance

Designed to protect the ozone layer after the discovery of the ozone hole over Antarctica, the Montreal Protocol was signed in 1987 and entered into effect in 1989, when little was known as to the effect of its implementation on the global climate. Since then, it has become clear that the Montreal Protocol is an important mitigation treaty, affecting many aspects of the global climate. Here, we demonstrate that its effect reaches all the way into the Arctic. Specifically, we show that the implementation of the Montreal Protocol has postponed the occurrence of the first ice-free Arctic by as much as 15 y, depending on the details of future emissions.

Arctic | Montreal Protocol | sea-ice | ozone-depleting substances

When will the first ice-free Arctic summer occur? This question has attracted much recent interest from the scientific community (1–5) because of its obvious societal importance. The latest analysis of future projections with state-of-the-art climate models (6) concludes that ice-free Arctic conditions in September will appear by mid-century, roughly corresponding to a 2°C warming of the planet (7–10). The specific date remains somewhat uncertain, however, by approximately two decades, owing to large and irreducible internal climate variability (11–13). In spite of this uncertainty, it is well established that polar warming is mainly caused by anthropogenic emissions (14), primarily greenhouse gases (15). In fact, the connection between carbon dioxide emissions and Arctic sea ice loss is now well established (16).

But recent work has revealed that other greenhouse gases, notably ozone-depleting substances (ODSs), have played an important role in warming the Arctic (17). ODSs are halogenated organic compounds developed in the last century for industrial use as refrigerants and propellants. Their concentrations in the atmosphere grew rapidly in the decades following World War II, leading to the formation of the ozone hole over Antarctica (18, 19), of which the considerable climate impacts over the Southern Hemisphere are now well documented (20, 21). In order to protect the ozone layer, the nations of the world met in Montreal in 1987 and negotiated a treaty to regulate and eventually phase-out the production of ODSs. The resulting *Montreal Protocol* (22), which entered into force in 1989 and has now been ratified by 198 countries, has been very successful: The atmospheric concentrations of the major ODSs have started to decline, the first signs of a healing of the ozone hole have been reported (23), and atmospheric circulation changes caused by this healing have been detected (24, 25).

It is perhaps not as widely appreciated that, in addition to destroying stratospheric ozone, ODSs are long-lived and potent greenhouse gases (26), with global warming potentials that are tens of thousands of times larger than carbon dioxide (27). Furthermore, since ODSs are well-mixed in the troposphere, the surface warming they produce is felt throughout the entire planet, not just at Southern high latitudes. The latest study available reports that the radiative forcing (RF) from halocarbons is 0.38 W/m^2 (28), which amounts to nearly 20% of the RF from carbon dioxide. Had the Montreal Protocol not been signed, the RF from ODSs in the year 2020 would have reached 0.8–0.9 W/m^2, roughly 40% of the RF from carbon dioxide (29).

Because the RF from unregulated ODSs is so large, and because ODSs have been shown to have outsized impacts in the Arctic (17, 30), one is led to ask whether the implementation of the Montreal Protocol might—serendipitously—have had an effect

Author affiliations: [a]Department of Earth and Planerary Sciences, University of California, Santa Cruz, CA 95064; [b]Department of Mathematics and Statistics, University of Exeter, Exeter, EX4 4QF, United Kingdom; [c]Department of Applied Physics and Applied Mathematics, Columbia University, New York, NY 10027; and [d]Lamont Doherty Earth Observatory, Columbia University, New York, NY 10027

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The authors declare no competing interest.

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[1] To whom correspondence may be addressed. Email: polvani@gmail.com.

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on the year when the Arctic will first become ice-free in September. This is the question we address in this paper. To answer it, we have performed climate model runs with the so-called "World Avoided" scenarios, in which the concentrations of ODSs, ozone, and other halocarbons evolve as if the Montreal Protocol had not been signed, hence the scenario name (31). Several aspects of the climate system under the World Avoided scenario—the surface temperature, the hydrological cycle, the intensity of tropical cyclones, and even the carbon cycle—have been documented (32–37). But the question of whether the signing of the Montreal Protocol has had an impact on the year of the first ice-free Arctic summer remains unexplored, as all previous studies of the World Avoided scenario were limited to small ensembles of model runs and thus unable to address questions (such as the first year of ice-free Arctic) where internal variability is known to be important (11–13).

We quantify that impact here by contrasting climate model runs under the World Avoided scenario against "Standard" future scenario run, in which the implementation of the Montreal Protocol is accounted for, forced following the Climate Model Intercomparison Project (38), Phase 5 (CMIP5) prescriptions. We have examined two future Representative Concentration Pathways (RCPs), for moderate and high emissions futures, referred to as RCP4.5 and RCP8.5 (39). For each pathway, we have performed and analyzed a 10-member ensemble of climate model runs under World Avoided scenario forcings, over the period 1985 to 2050, and then compared it with a corresponding Standard scenario ensemble of 10 runs (*Methods*). Our model has been very widely used in recent years: It is a CMIP-class atmosphere–ocean–land–sea–ice earth system model (40), whose historical and future simulations have been analyzed in dozens of papers. In particular, its simulation of recent Arctic sea ice climatology, variability, and regional trends have been shown to be very realistic (12, 41, 42), making it an ideal model for the present task.

Climate Forcings in the World Avoided Scenarios

Before considering the evolution of Arctic sea ice, we clarify how the forcings in the World Avoided scenario differ from those in the Standard scenario. This is relatively simple: All forcings in the two scenarios are identical, except for halocarbons and stratospheric ozone. Recall that halocarbons comprise both ODSs and their non-ozone-depleting replacement compounds, referred to here as HFCs (*Methods*). Broadly speaking, ODSs are controlled under the Montreal Protocol. A number of HFCs (transition compounds from chlorine- and bromine-containing ODSs) were added to the Montreal Protocol under the 2016 Kigali Amendment to mitigate their future climate impact. The differences between the World Avoided and Standard scenarios—vis-a-vis ODSs, HFCs, and stratospheric ozone—are shown in Fig. 1. First, note how ODSs concentrations in the Standard scenario (blue curve in Fig. 1*A*), after increasing rapidly in the second half of the 20th century and peaking in the 1990s, decline in the 21st century as a consequence of the Montreal Protocol. In contrast, in the World Avoided scenario, ODSs concentrations increase unabated in the 21st century (red curve, *Methods*). Second, the replacement compounds evolve conversely (Fig. 1*B*): In the Standard scenarios, they grow continuously after the signing of the Montreal Protocol (with some notable difference between the RCP4.5 and RCP8.5 pathways) but are nearly flat in the World Avoided scenario (there would be no replacement gases without the Montreal Protocol). Third, since ODSs are the major cause of ozone depletion, stratospheric ozone in the model needs to be specified consistently with ODSs concentrations (*Methods*). As shown in Fig. 1*C*, in the World Avoided scenario, Arctic polar cap ozone depletion continues and accelerates into the 21st century owing to the unregulated increase of ODSs, whereas the ozone layer recovers—in fact, it super-recovers (43)—in the Standard Scenario.

While the destruction of the ozone layer and the accompanying increase in biologically harmful ultraviolet radiation have received the greatest attention in studies of the World Avoided scenario (32, 44, 45), we here highlight the role of ODSs as powerful greenhouse gases (26, 29, 36). Their RF by 2050, had the Montreal Protocol not been implemented, would have reached 2.2 W/m^2 by the middle of this century, amounting to almost two-thirds of the RF from CO$_2$ in the RCP4.5 pathway (*SI Appendix*, Fig. S1 *A* and *C*). Note that the RF from the replacement gases (*SI Appendix*, Fig. S1*B*), which are absent in the World Avoided scenario, is more than an order of magnitude smaller: less than 0.2 W/m^2 for the stronger RCP8.5 case.

Given the large positive RF from unregulated ODSs, it is not surprising that the surface warming in the World Avoided scenario is considerably larger than that in the Standard scenario

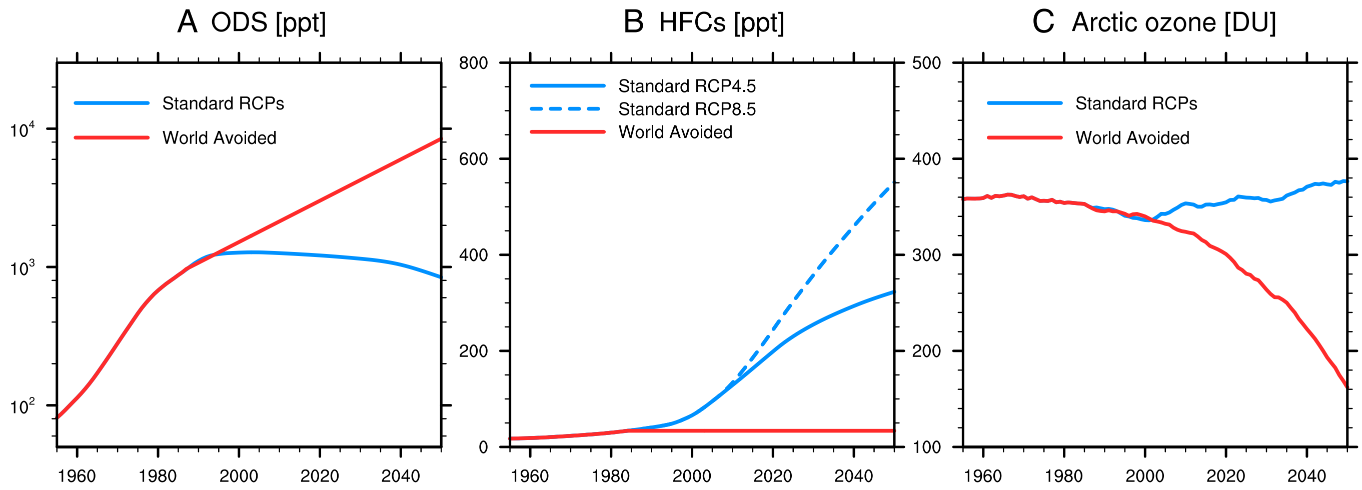

Fig. 1. Forcing differences between the World Avoided and the Standard scenarios. Mixing ratios of (*A*) ODSs, (*B*) replacement compounds (HFCs), and (*C*) levels of Arctic stratospheric ozone (averaged 60–90 N, in Dobson units), from 1955 to 2050, for the Standard (blue) and World Avoided (red) scenarios.

in the 21st century. Under RCP4.5, we find that the global mean surface temperature by 2050 is 0.50°C warmer in the World Avoided than in the Standard scenario (and 0.40°C warmer for the RCP8.5 case, see *SI Appendix*, Fig. S2 *A* and *C*). These values are consistent with, but somewhat smaller than, those of an earlier study with comparable World Avoided forcings (32), who found an additional 1 °C warming by 2050. More importantly, the Arctic polar cap would be almost 1 °C warmer in the World Avoided scenario (0.88 °C and 0.78 °C for RCP4.5 and RCP8.5, respectively, *SI Appendix*, Fig. S2 *B* and *D*).

Delayed Sea Ice Loss Due to the Montreal Protocol

Such a large warming, obviously, impacts the evolution of Arctic sea ice extent (SIE), as shown in Fig. 2. It is well known that Arctic SIE is affected by large internal (i.e., unforced) variability, as seen by the jaggedness of the time series in that figure. This is why we have performed 10-member ensembles of runs, following the recommendation of an earlier study with the same model, which suggested such an ensemble size as nearly optimal for studying the emergence of ice-free Arctic summer conditions (12). In spite of this internal variability, however, the effect of Montreal Protocol in delaying the first year of ice-free Arctic condition is strong enough to be seen in the raw September SIE time series of Fig. 2. It is even clearer in the smoothed version of these time series, shown in *SI Appendix*, Fig. S3. Following the common definition of "ice-free Arctic" as the first year with September SIE < 1 million km^2 (1, 3), we find that each one of the ten members in the World Avoided ensemble becomes ice-free before the corresponding Standard scenario member for the RCP4.5 case (Fig. 2*A*). In fact, all members of the World Avoided ensemble are ice-free before all members of the Standard ensemble. Or, from a different angle, without the Montreal Protocol, ten ice-free summers would have occurred prior to the first ice-free summer in the Standard RCP4.5 scenario, on average, in our simulations. And even for the RCP8.5 case (Fig. 2*B*), the worst-case CO_2 forcing scenario in CMIP5, nine of the ten World Avoided members become ice-free before the corresponding Standard scenario member. These results demonstrate how large the sea ice loss caused by the unregulated growth of ODSs would have been if the Montreal Protocol had not been implemented.

To better illustrate the considerable delay caused by the Montreal Protocol on September sea ice loss over the Arctic, in Fig. 3, we present the ensemble-mean September sea ice concentrations at 2020, 2030, and 2040 under the World

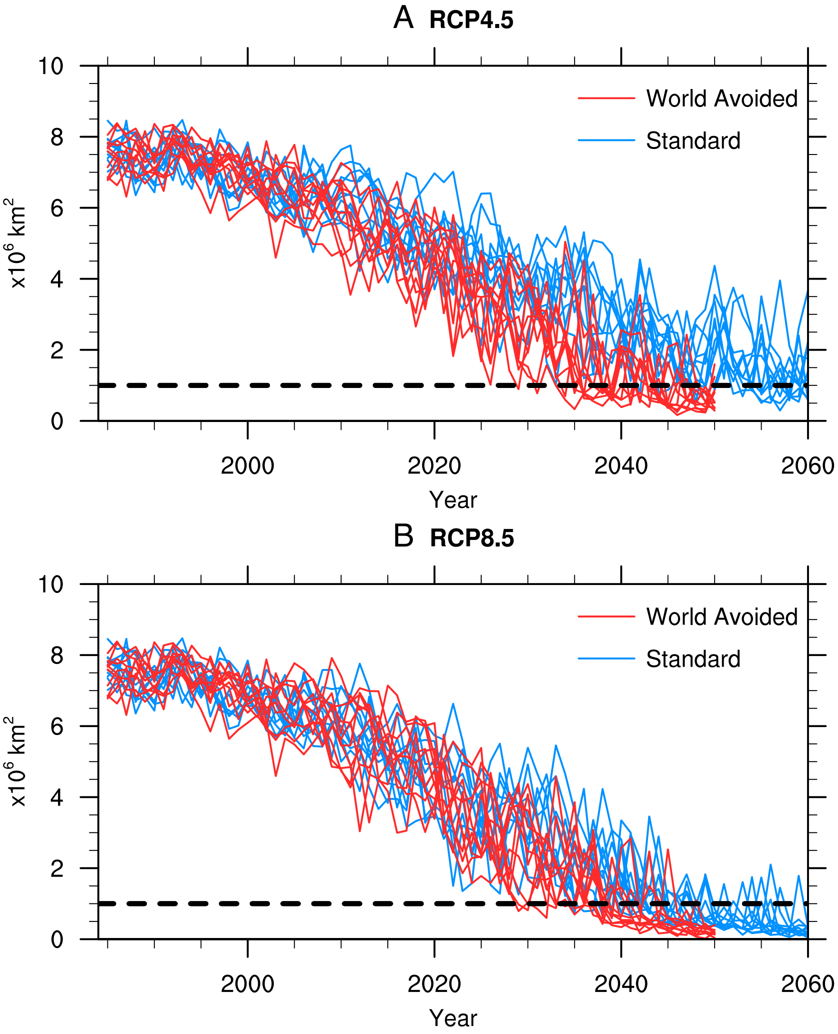

Fig. 2. Time series of September sea ice extent for the World Avoided (red) and the Standard (blue) scenario for (*A*) the RCP4.5 pathway and (*B*) the RCP8.5 pathway. Each ensemble comprises 10 members. The dashed horizontal black line marks the value 1 × 10^6 km^2, when the Arctic is considered to be functionally ice-free.

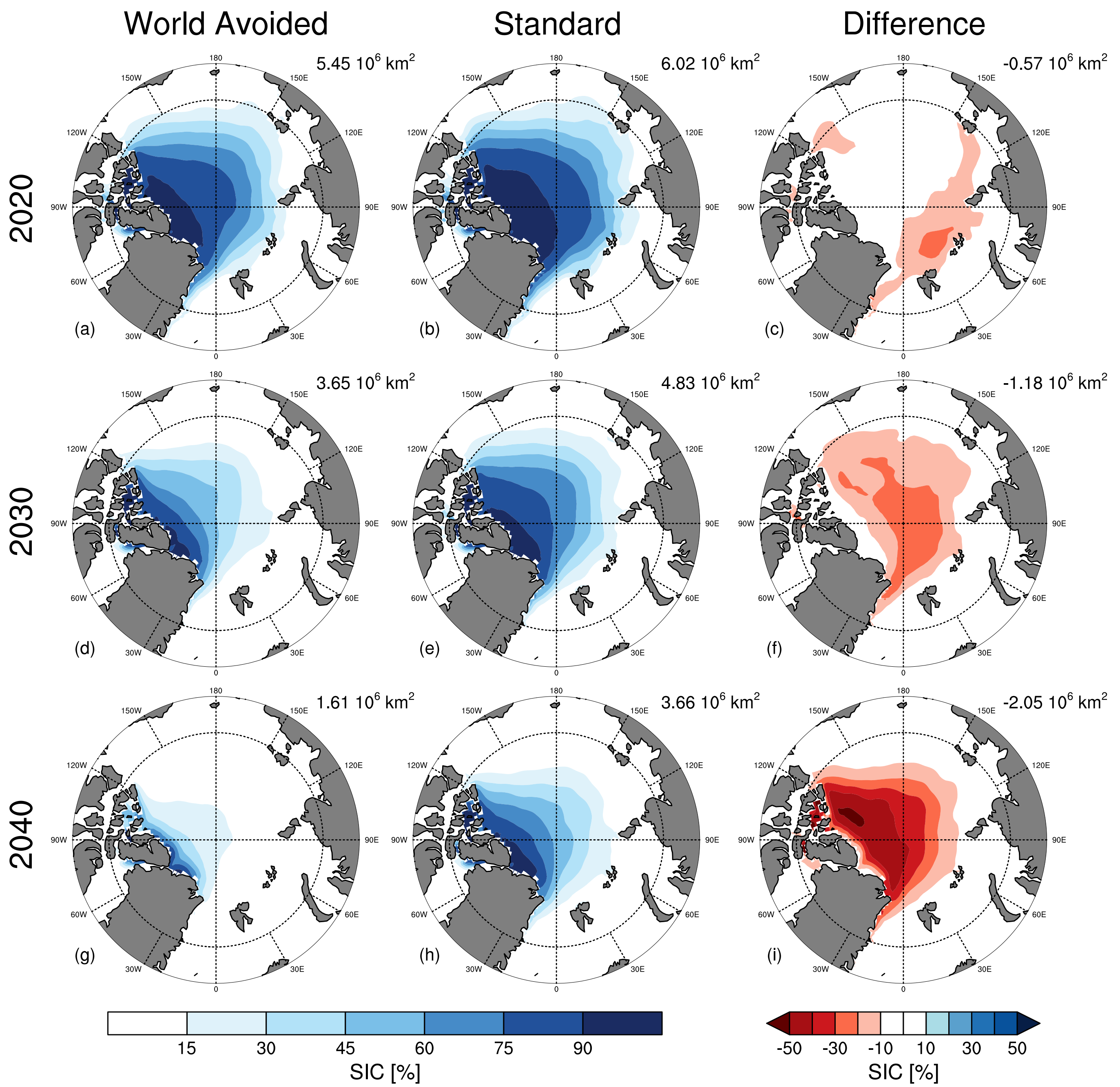

Fig. 3. Ensemble mean September sea ice concentration (in %) for the World Avoided (*Left*) and Standard scenarios (*Middle*) and their difference (*Right*), under the RCP4.5 pathway. Each panel shows the average of a 5-y period centered on 2020 (*Top*), 2030 (*Middle*), and 2040 (*Bottom*). Top right numbers in each panel show SIE in km^2.

Avoided and the Standard scenarios (and their difference), for the RCP4.5 case. Note that by 2020, the Montreal Protocol is retarding sea ice loss by more than half a million km^2, with that number rising to over one million by 2030, and to over two million by 2040. Even in the high-emission RCP8.5 scenario (46), the delay in SIE loss is over one million km^2 by 2030 and not far from two million km^2 by 2040 (*SI Appendix*, Fig. S4).

To put this in the context of CO$_2$ emissions, it is useful to recall that 1 metric ton of carbon dioxide emitted into the atmosphere results in approximately 3 m^2 of sea ice loss, according to a recent estimate (16). Using an emulator to convert concentrations into emissions (*Methods*), we estimate that each metric ton of avoided CFC-11-equivalent emissions corresponds to 7,000 m^2 of avoided Arctic sea ice loss. This much larger impact of ODS compared to CO$_2$ is not unexpected, given their very large global warming potential. Nonetheless, such a large mitigating impact of the Montreal Protocol on Arctic sea ice loss is remarkable if one keeps in mind that the protocol was aimed at preventing ozone depletion in the Antarctic stratosphere, and little was known of its effect on Arctic sea ice when the protocol was signed.

Finally, to accurately quantify the delay in ice-free summer Arctic conditions resulting from the implementation of the Montreal Protocol, we have constructed 10,000-member synthetic probability distribution functions (PDFs) of the year of first ice-free September conditions from the original 10-member ensembles using bootstrapping with replacement (*Methods*). For the RCP4.5 case, the World Avoided and Standard scenario PDFs are separated by almost 15 y (Fig. 4*A*). The number is smaller (7.4 y) for the RCP8.5 case, but nonetheless highly statistically significant, as the two PDFs are still very well separated (Fig. 4*B*). Note, furthermore, that in the Standard scenario, the date of the first ice-free summer differs by nearly a decade between the RCP4.5 and RCP8.5 pathways, whereas in the World Avoided scenario, that date is not statistically different between the two pathways (*SI Appendix*, Table S1). The fact that the projections of summer ice-free Arctic are essentially insensitive to the pathway in the absence of the Montreal Protocol again highlights the potent greenhouse effect of ODSs, which overwhelms the differences between the RCP4.5 and RCP8.5 pathways in the first half of the 21st century.

One may wonder if the destruction of the ozone layer in the World Avoided, including over the Arctic, as a consequence of the increasing concentration of unregulated ODSs in that scenario, plays some role in delaying the occurrence of an ice-free Arctic summer. Recall that, in addition to shielding the earth's surface from ultraviolet radiation, ozone absorbs radiation in several infrared bands (47) and therefore also acts as a greenhouse gas. Stratospheric ozone depletion would thus provide a negative RF which would cool the surface (36) and, as a consequence, oppose a fraction of the sea ice loss caused by the unregulated ODSs. To examine the impact of stratospheric ozone depletion, we have performed an additional 10-member ensemble of World Avoided model runs, identical to those under the RCP4.5 pathway except for stratospheric ozone concentrations, which are unchanged from the Standard simulations, and hence feature a recovery as opposed to drastic depletion of stratospheric ozone over the Arctic (as shown in the blue line in Fig. 1*C*). Contrasting these additional runs with those in which ozone depletion occurs, we are able to disentangle the role of ODSs as greenhouse gases or as ozone-depleting agents and to separately quantify the effect of ozone loss in the World Avoided scenario. As shown in *SI Appendix*, Fig. S5, the World Avoided time series of Arctic SIE are not sensitive to ozone depletion. The reason for this is that the cooling from ozone depletion only becomes substantial after 2030, by which time Arctic SIE is already close to being ice-free in September. As a consequence, the destruction of the ozone layer has no discernible impact on the date of the first ice-free summer (as one can see in *SI Appendix*, Fig. S6). In practice, of course, these considerations are somewhat academic, as severe stratospheric ozone depletion would be unavoidable in a future with no Montreal Protocol, given the very high concentrations of ODSs.

One might also wonder to what degree the results we have presented here are altered by the recent signing of the Kigali Amendment to the Montreal Protocol, which aims at reducing the use of HFCs in the coming decades. Since it only became effective in 2019, the Kigali Amendment was not incorporated in either the pathways we have used here (39) or the more recent pathways (48). While the potential global reduction in global warming from the Kigali Amendment is estimated to be between 0.3 and 0.5 °C by the end of this century, only a small fraction of it —less than 0.05 °C—would be realized by 2035 (figures

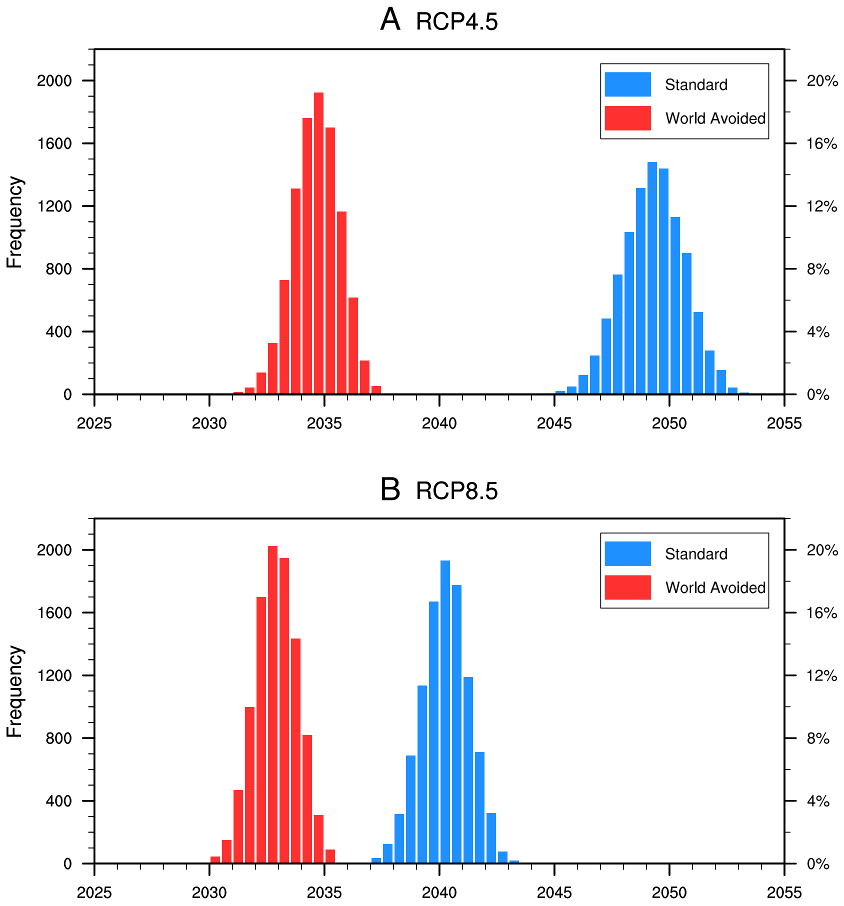

Fig. 4. Synthetic PDFs, obtained by bootstrapping with replacement, of the first year for which the Arctic is ice-free in September for (*A*) the RCP4.5 and (*B*) the RCP8.5 pathway. Blue for the Standard scenario, red for the World Avoided scenario.

2–20 of ref. 27). This number constitutes a tiny fraction of (less than 2%) of the warming in our model by that date so that the mitigating effect of the Kigali agreement, which is substantial by 2100, is unlikely to impact the date of the first ice-free Arctic in September, which is projected to occur much earlier.

In summary, our findings reveal an important, largely unforeseen, benefit from the implementation of the Montreal Protocol. Ostensibly designed to protect the stratospheric ozone layer, especially over the Antarctic continent where the ozone hole had formed, the regulation and phase-out of ODSs are causing a substantial delay in the occurrence of the first ice-free Arctic summer. If indeed future emission comparable to those in the RCP8.5 scenario appear increasingly implausible, as has been suggested (46), from the RCP4.5 results obtained here we conclude that the Montreal Protocol will result in postponing the ice-free Arctic summer conditions by at least a decade, possibly more.

While the uncertainty in future emission scenarios cannot be narrowed at this stage, we note that an earlier study (36) of the World Avoided scenario, with a different model but similar unregulated ODS growth, found a larger avoided Arctic warming than the one reported here: Our estimate, therefore, might be on the conservative side. In addition, we emphasize that the 3.5% annual growth rate of ODSs used to simulate World Avoided scenario in this study is at the lower end of the plausible 3% to 7% range suggested by reference (29). From our modeling results, we estimate that if ODSs had increased at a sustained rate of 7% annually, the first ice-free Arctic summer conditions would have occurred as early as the present year. Of course, further studies with additional models are needed to corroborate our findings. But, in the meantime, they provide new evidence that the Montreal Protocol, in addition to saving the ozone layer, has proven to be a very important mitigation treaty for Arctic climate.

Materials and Methods

Ozone-Depleting Substances and Other Halogenated Compounds. ODSs are organic compounds of fluorine, chlorine, and bromine that contribute to the destruction of the ozone layer and are regulated under the Montreal Protocol. In our model, see below, the following ODSs are included: CFC-11, CFC-12, CFC-113, CFC-114, CFC-115, CCl_4, CH_3CCl_3, HCFC-22, HCFC-141B, HCFC-142B, Halon-1211, Halon-1301, Halon-2402, CH_3Br, and CH_3Cl. In addition to these ODSs, the following additional halogenated gases (referred to as "replacement compounds" or "HFCs" for short) are also included in our model runs: HFC-23, HFC-32, HFC43_10, HFC-125, HFC-134a, HFC-143a, HFC-227ea, HFC-245fa, CF_4, and SF_6. These halocarbons originally fell into the "basket of gases" of Annex A to the Kyoto Protocol but, following the Kigali Amendment which became effective in 2019, are now also regulated by the Montreal Protocol. Since the Standard RCP4.5 and RCP8.5 scenarios were designed more than a decade ago (39), the future concentration of HFCs in those scenarios does not include the corrections that follow from the Kigali Amendment.

Model Description. The climate model we have used here is the coupled atmosphere–ocean–land–sea–ice earth system model used for the Community Earth System Model (CESM) Large Ensemble (LENS) project (40). It has been fully documented (49) and is often referred to as CESM1(CAM5): We have here used the same identical version but have performed and analyzed new runs with different forcings (see below). Unless otherwise noted, all forcings for the historical and future simulations are as specified by the CMIP5 protocol (39). Well-mixed greenhouse gases are specified from monthly mean files, with a single value applied at all levels, longitudes, and latitudes: They comprise CO_2, CH_4, N2O, CFC-12, and CFC-11*. The latter incorporates all halogenated compounds other than CFC-12, the concentrations of each being combined into a weighted average, and the weights being the efficiency of each compound relative to CFC-11, as listed in Table 8.A.1 of ref. 50. To illustrate the time series ODSs in our model with a single curve (as in Fig. 1*A*), we combine them all into a single quantity which we call CFC-11-equivalent, computed in a manner similar to CFC-11*. Finally, the ozone concentrations are specified from a monthly file, which depends on the scenarios, as described below.

Model Simulations. We here analyze five 10-member ensembles of model runs, all starting at 1985 and ending at 2050.

The first two ensembles are standard CMIP5 historical and scenario model simulations, performed under the auspices of the LENS project, one with RP4.5 forcings (51) and the other with RCP8.5 forcings (40). We have randomly selected 10 members from the available output. We refer to these as the Standard scenario ensembles. Both ensembles are identically forced over the period 1985 to 2005 and with the respective CMIP5 scenario forcings over the period 2005 to 2050.

The remaining ensembles were performed by the authors specifically for this study. Two of them are meant to be directly compared to the Standard scenario ensembles and are forced following the RCP4.5 and the RCP8.5 pathways, respectively, but with World Avoided forcings (see below): We refer to these as the World Avoided ensembles. Each run in the World Avoided ensemble is initialized and forced identically to the companion member in its corresponding Standard ensemble, except for halocarbons and ozone as detailed below.

The fifth ensemble, which we refer to as the "World Avoided fixed-ozone" ensemble, is nearly identical to the World Avoided scenario ensemble under the RCP4.5 pathway, except that stratospheric ozone is unchanged from the Standard scenario. While the forcing in this ensemble is chemically inconsistent, this ensemble allows us to distinguish the impact of ozone depletion from the impact of ODSs in the World Avoided.

Model Forcings. First, except for halocarbons and ozone, all natural and anthropogenic forcings are identical between the Standard and World Avoided scenarios. Second, halocarbons in the Standard scenarios follow the CMIP5 specifications. In the World Avoided scenario, halocarbons are specified thusly: ODSs grow at a rate of 3.5% per year from 1985, as in previous studies with the CESM model (32, 34, 35), while non-ozone-depleting halocarbons are kept constant at 1985 concentrations (Fig. 1 *A* and *B*).

Third, the ozone forcing is constructed as follows. We start by separating, column-wise, tropospheric from stratospheric ozone using the threshold value of 150 ppbv (52). In both the Standard and World Avoided scenarios, tropospheric ozone is identical, and specified as per the CESM Large Ensemble Project (40). The differences in ozone between the Standard and World Avoided scenarios only concern *stratospheric* ozone.

In the Standard scenario, stratospheric ozone follows a depletion-and-recovery trajectory, as specified by the CMIP5 protocol. For the World Avoided scenario, stratospheric ozone needs to be precomputed, consistently with ODSs concentrations. We do this by carrying out a small, three-member ensemble of RCP4.5 simulations of the CESM Whole Atmospheric Chemistry Climate Model, Version 4 (53), in which stratospheric ozone chemistry is interactive, so that ozone is computed from ODSs concentrations. The same model was used to compute ozone for the Standard scenario (40). We force these three simulations with World Avoided ODSs emissions, from 1985 to 2070, and average the resulting stratospheric ozone from these three runs to minimize interannual stratospheric variability, as in ref. 40; we then use this average to force the CESM1(CAM5) model.

We specify the same stratospheric ozone in RCP4.5 and RCP8.5. We do this for two reasons. First, in the Standard scenario, the Large Ensemble project used the same stratospheric ozone for both pathways, and we need to be consistent with that choice. Second, and most importantly, the differences in stratospheric ozone between the two pathways–in the Standard scenario–are small at 2050 and only emerge toward the very end of the 21st century. This is clearly seen, e.g., in figure 11 of ref. 43. The same applies, *a fortiori*, in the World Avoided scenario, where ODSs completely overwhelm any small pathway differences induced by different CO_2 concentrations.

CFC-11-Equivalent Emissions. Since our climate model is forced by prescribing the atmospheric concentration of well-mixed greenhouse gases (CO_2, CH_4, N_2O, and ODSs), we employ the FaiR emulator (54) to estimate the corresponding emissions. We run version 2 of the FaiR model with the same atmospheric concentrations used to force the CESM model from 1985 to 2050, and it returns the corresponding emissions over that period. We do this separately for all the ODSs included in the CESM forcing and then combine them all into the quantity CFC-11-equivalent, using the same method used to compute CFC-11* (as detailed above). Then, comparing sea ice loss in our to the cumulative CFC-11-equivalent over the period from 1985 to 2030 (i.e., just prior to the first ice-free Arctic summer in our model), we estimate the area of sea ice loss associated with each Gg of CFC-11-equivalent emissions. We find that 1 metric ton of CFC-11-equivalent results in $7 \pm 3 \times 10^3$ m^2 of sea ice loss, with the uncertainty computed as 95% CI for the mean of the 10-member ensemble of CESM runs.

Analysis. The Arctic is defined as polar cap region 60–90 N. Sea ice extent (SIE) is defined as the total area covered by sea ice concentrations (SIC) greater than 15% in the Northern Hemisphere. We have checked that our key results are not altered if we use sea ice area (total area covered by sea ice), in lieu SIE.

To determine whether our ten-member ensembles are large enough to robustly detect differences between the World Avoided and Standard scenarios, we employ a standard bootstrapping technique, commonly used in climate science, which consists of the following. For each of the ten-member ensemble, we create a synthetic probability distribution function (PDF) of the date of the first ice-free Arctic summer by resampling—with replacement—from that ensemble 10,000 times. Note that the spread between the synthetic PDFs is indicative of the uncertainty in the response to the shared climate forcing and not to the uncertainty due to internal climate variability.

Data, Materials, and Software Availability. The model output needed to reproduce the results of this study can be found at 10.5281/zenodo.7872631 (55).

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