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Mid- and long-term climate projections for fragmented and delayed-action scenarios

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ABSTRACT

This paper explores the climate consequences of "*delayed near-term action*" and "*staged accession*" scenarios for limiting warming below 2 °C. The stabilization of greenhouse gas concentrations at low levels requires a large-scale transformation of the energy system. Depending on policy choices, there are alternative pathways to reach this objective. An "*optimal*" path, as emerging from energy-economic modeling, implies immediate action with stringent emission reductions, while the currently proposed international policies translate into reduction delays and higher near-term emissions. In our *delayed action* scenarios, low stabilization levels need thus to be reached from comparatively high 2030 emission levels. Negative consequences are higher economic cost as explored in accompanying papers and significantly higher mid-term warming, as indicated by a rate of warming 50% higher by the 2040s. By contrast, both mid- and long-term warming are significantly higher in another class of scenarios of *staged accession* that lets some regions embark on emission reductions, while others follow later, with conservation of carbon-price pathways comparable to the *optimal* scenarios. Not only is mid-term warming higher in *staged accession* cases, but the probability to exceed 2 °C in the 21st century increases by a factor of 1.5.

1. Introduction

Greenhouse-gas emission scenarios are an important tool to provide coherent storylines exploring the options and costs of realizing mid- to long-term climate-change mitigation goals. A prominent method for developing such scenarios is the use of integrated assessment models (IAMs). These models show a large diversity in approaches that lead to differences in coverage of geographical regions, sectors, greenhouse gases and pollutants, as well as structural differences that relate to economic feedback mechanisms.

Many of these models also include simple representations of the physical climate system, to be able to optimize emission pathways for achieving long-term climate goals. This special issue presents the results from the AMPERE project, involving a large number of IAMs aimed at limiting total greenhouse-gas emissions to achieve a set of standardized CO_2 emission budgets. Different models achieve these budgets by means of different time-dependent emission pathways. Given (a) the wide range of approaches for estimating first-order climate-system response

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in IAMs and lack of these in others (e.g. [1]), and (b) the differences in the time-dependent emission pathways produced by the IAMs, the consequences of mitigation policy cases and technological options for long-term climate goals are not immediately clear and comparable across IAMs.

Therefore, in this paper the emission scenarios developed by IAM groups within the AMPERE project are assessed in a common climate-modeling framework. This allows us to provide a context of mid- to long-term projections of greenhouse-gas concentrations and warming for evaluation of the mitigation scenarios.

The AMPERE project has some unique features compared to previous IAM intercomparisons that make it particularly interesting for an in-depth analysis of the climate response to anthropogenic emissions. AMPERE focused on scenario variants that deviate from the idealized assumption of immediate full cooperative action on meeting a stabilization target. First, it explored a *delayed action* situation where moderate levels of mitigation stringency are aimed for in the short term (2030) and the long term target is only adopted thereafter [2]. Secondly, it studied *staged accession* to a global climate regime, where some regions join the global climate mitigation effort at later times than others [3]. The two scenario sets allow to explore strong peak and decline emission scenarios, as well as the loss of mitigation stringency due to *staged accession* of key emitting countries. These types of scenarios are highly policy relevant and at the same time sufficiently different from the standard set of representative concentration pathways (RCPs — see [2]) that have been investigated by a suite of climate models [4,5]. For example, the AMPERE scenarios with moderate near-term mitigation policies lead to a pronounced "emissions gap" over the next two decades compared to immediate and optimal climate policy scenarios, which have been the focus of the vast majority of scenarios in the past. As shown by single-model studies [6–8] and with a large suite of models by Riahi et al. [9] in this special issue, many IAM models suggest that low long-term targets compatible with 2 °C temperature change can still be reached from relatively higher near-term emissions. The transient temperature consequences of this near-term emissions gap have, however, only been explored to a limited degree [6,7]. This is thus a key issue that will be addressed in this paper.

As a further original contribution to the literature, the paper draws on two different approaches to explore the climate outcome of the IAM emission scenarios. One approach uses the simple coupled carbon-cycle/climate model MAGICC6 that generates probabilistic information [10] about the climate response. The second approach uses a step function emulation of CMIP5 [5] general circulation models to deduce the temperature response to the forcing projections generated by MAGICC6. The comparison of the two approaches delivers two insights that are new to the literature. It shows how the climate outcomes from an approximation of the latest round of climate model ensemble runs relate to the temperature estimates from MAGICC6, and to this end the IAMs which often rely on this type of simple climate models to explore climate consequences of mitigation pathways.

The AMPERE project adopted cumulative CO_2 emission budgets as long-term targets (including CO_2 equivalent pricing of non-CO_2 emissions) while earlier studies mostly focused on a variety of greenhouse gas stabilization targets. This leads to a better harmonization of cumulative greenhouse-gas emissions across model scenarios and allows to explore the range of climate outcomes that can emerge from emission budgets.

Drawing from the AMPERE scenario exercises, we will analyze four key variants of "default" mitigation scenarios to explore how sensitive mid- to long-term projections are to:

- An extrapolation of the current level of mitigation ambition over the 21st century, without new policies required, for example, for achieving presently proposed Copenhagen Pledges and emission targets under the Cancun Agreement [3,9].
- Concerted immediate action to meet the long term CO_2 budget in an economically efficient way [3,9]. This and the first scenario serve as benchmark cases.
- Concerted, but weak action broadly consistent with presently proposed Copenhagen Pledges and the Cancun Agreement, leading to relatively high emission levels by 2030 [9].
- Fragmented participation of country groups, including cases of Europe and China taking early mitigation action, followed later by other regions, or not at all [3].

Additional scenario variants [9] represen technology sensitivity cases that assume limited potential for biomass (maximum of 100 EJ/yr), exploring strategies that would avoid large-scale expansion of bioenergy and thus avoid potential competition over land for food and fiber. These sensitivity cases (LimBio) are very relevant also for the emission pathways, since they limit the potential for negative emissions from Bio-CCS that can possibly compensate in the long term for overshoots of near-term emission targets or budgets, thus inhibiting such near-term overshoots.

2. Methods

2.1. Multi-gas scenarios

Five of the 12 Integrated Assessment Models included in the AMPERE comparison were able to directly provide all the greenhouse gases and air pollutants (see Table 1) required as input for the coupled carbon-cycle/climate model MAGICC6 (see Section 2.3). For other IAMs, a protocol was developed to supplement scenarios with "missing" emission species or categories, to enable climate projections and intercomparison across all models and scenarios:

- If CO_2 from land use was not reported, the mean across the RCP scenarios [2,11] for each time step was added
- If SOx was not reported, emissions were derived using an average relation between CO_2 emissions from the fossil-fuels & industry sectors and SOx emissions across the "full-gas" models (see Supplementary information)
- For other unreported species and given the weaker correlation with CO_2 emissions compared to SOx, the time series was inserted from the same scenario produced by MESSAGE, for no reason other than the completeness of coverage of AMPERE scenarios by that model
- For any other gas or sector that was not reported, for each time step emissions were derived by interpolation between the lowest and highest RCP emission scenarios RCP3PD and RCP8.5, using CO_2 emissions from energy and industry as interpolation key.

Table 1
Gases (and sectors) reported in the emission scenarios produced by IAMs in this paper.

IAM name	CO_2 fossil fuels & industry	CO_2 land use	CH_4	N_2O	F-gas	SOx	BC OC	CO	NOx
DNE21[a]	×	×	×	×	×	×	×	×	×
GCAM	×	×	×	×	×	×	×	×	×
GEM[a]	×		×	×	×				
IMACLIM	×								
IMAGE	×	×	×	×	×	×	×	×	×
MERGE-ETL	×	×	×	×	×	×			
MESSAGE	×	×	×	×	×	×	×	×	×
POLES	×		×[b]	×	×				
REMIND	×	×	×	×	×	×	×	×	×
WITCH	×	×	×	×	×				
WorldScan[a]	×	×	×	×					

[a] Over 2005–2050.
[b] Excluding land use.

2.2. Harmonization (RCP approach)

As highlighted by Rogelj et al. [12] deviation of simulated present-day emissions from (global) inventories might have a significant effect on future climate projections. To minimize this effect, all AMPERE emission scenarios were harmonized to RCP levels in year 2005 for each species separately. The harmonization factors decline linearly to unity in 2050 to preserve as much as possible the character of most IAM scenarios that aim at a pre-defined radiative forcing level in 2100. The same method was used for the RCPs, see Meinshausen et al. [4] and van Vuuren et al. [2].

2.3. Climate-model projections of concentrations, radiative forcing and warming

We first used a simple coupled carbon-cycle/climate model (MAGICC6 — [13]) for deriving pathways of greenhouse-gas concentrations and radiative forcing for each of the IAM emission scenarios, for all Kyoto[1] greenhouse gases and pollutants, including SOx, Black Carbon, Organic Carbon and co-emitted substances.

The implications for future changes in global-mean surface-air temperature were analyzed for each of the scenarios through two independent methods. In the first method, calculations of concentrations and forcing are integrated in MAGICC6 to drive projections of warming. The model setup allows to derive a best-estimate and probability distribution for each of these variables, by running MAGICC6 600 times with different parameter sets for each emission scenario [15]. Parameter sets were drawn randomly that allow the model to reproduce a series of observed time series of climate variables in terms of the overall median and uncertainty ranges, while the overall probability distribution of climate sensitivity is consistent with IPCC AR4 [10], with a median estimate of 3 °C and a 76% chance of a value between 2 and 4.5 °C.

The results of climate projections in this paper are presented as:

- Single-model/single emission scenario projections: the medians and 66% ranges across the ensemble members of individual IAM scenarios.
- Multi-model/single emission scenario projections: overall-medians and 66% ranges across all ensemble members from all IAM realization of the same emission scenario.

The second method attempts to include global-mean surface-air temperature estimates from global climate models (GCMs) by providing emulations using the step response simple climate model (SCM) of Good et al. [16] as a proxy. This method has shown to give good agreement between the SCM and the GCM for global projections [16]. The advantages of this method lie in its simplicity and the use of GCM data, which allows traceability of the results directly back to the GCMs. The median radiative forcing projections from MAGICC6 were used by the SCM to provide temperature rise emulations for 17 different GCMs that took part in the Couple Model Project Phase 5 (CMIP5) and from which a GCM model average is derived. As explained in the Supplementary information it was not possible to include all CMIP5 GCMs in the emulations. The subset of 17 GCMs used here is somewhat more sensitive to forcing compared to the full CMIP5 means, typically leading to a roughly 0.2 °C higher warming by 2080–2099 for RCP scenarios.

2.4. Integrated assessment model scenarios

As indicated above, the scenarios presented in this paper vary along three key dimensions, i.e. the climate target, the degree of delay in combination with technology constraints and the level of participation.

AMPERE adopted two climate targets that are broadly consistent with achieving atmospheric GHG concentration levels at 450 and 550 ppm CO_2eq. Participating modeling teams were not requested to directly implement GHG stabilization targets corresponding to radiative forcings of 2.6 W/m^2 and 3.7 W/m^2 in 2100, because not all models represent the full basket of greenhouse gases and other radiative agents like aerosols and their associated forcing. To harmonize targets between models and to remove uncertainties in translating forcing levels into GHG emissions, models were constrained by cumulative CO_2 budgets for the 21st century of 1500 $GtCO_2$ and 2400 $GtCO_2$ for the 450 and 550 ppm CO_2eq targets, respectively,[2] given the strong link between long-term cumulative emission budgets and climate projections [15,17]. Although the global budgets apply to CO_2 only, models were asked to apply the emerging CO_2 price to other Kyoto gases represented in the model. Models are given full temporal flexibility for keeping emissions within the respective budgets. This can lead to overshooting the emission budgets followed by compensation later, and hence overshooting of the associated radiative forcing target prior to 2100.

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[1] Carbon Dioxide (CO_2), Methane (CH_4), Nitrous Oxide (N_2O), Fluorinated gases (F-gases: HFCs, PFCs, SF6), and NH_3. As of December 2012 NF_3 is included in the "Kyoto basket" of gases, but not in the models in this study. Current contributions to global warming are insignificant, but considerable emission growth is projected [14] S.A. Montzka, E.J. Dlugokencky, J.H. Butler, Non-CO_2 greenhouse gases and climate change, Nature, 476 (2011) 43–50. Not including this gas in the emission pathways implies implicitly that (future) controls to limit emissions of NF_3 are effective.

[2] A few models do not include emissions from land-use changes. For these models, cumulative fossil-fuel-related CO_2 emission budgets were prescribed as 1400 and 2400, respectively, based on the mean correlation of these budgets of models that do include land-use emissions.

Both sets of scenarios, on *delayed action* and on *staged accession*, ran a no climate policy *baseline* (Base-FullTech-OPT and AM3-Base) that differed only for a few models that did not harmonize final energy in the *staged accession* experiments. Emission results are drawn from the same set of models in the two sets of experiments, with 2 additional models adding to the collection of *staged accession* scenarios. The two sets of experiments included the same climate policy benchmark scenarios with full flexibility of emission reductions and identical targets (450/550-FullTech-OPT and 450/550 immediate action). The *staged accession* experiments also included technology targets until 2020 in these benchmark scenarios, but their impact on climate outcomes is negligible.

The two sets of experiments differed in the type of the scenarios that deviated from the benchmark climate policy cases. The first of these two sets, on *delayed action* (see [9]), explored the consequences of weak near-term climate policies, by considering a combination of different short-term and long-term targets, which divide the century-scale time horizon of the scenarios into two stages. During the first stage up to the year 2030, global emissions are required to follow a trajectory toward a 2030 emission target. After 2030, emissions are constrained further to stay within a cumulative emission budget for the full century (2000–2100) in order to achieve stabilization of greenhouse gas concentrations in the long-term. In this set-up, the amount of cumulative emissions that may be vented to the atmosphere in the second stage (after 2030) will critically depend on the short-term emission pathway to 2030. The distinct separation of the time-frames helped in the AMPERE project to explicitly assess the consequences of actions over the short-term for the attainability and costs of long term objectives [9]. In this paper we focus in addition on the critical question of the climate response of the weak short-term targets.

We distinguish between low and high short-term targets. In our “Low” short-term target, annual greenhouse gas emissions stay close to present levels [18] of around 51 $GtCO_2e$/yr until 2020 and reach 53 $GtCO_2e$/yr by 2030. Emissions in the “High” short-term target are around 55 $GtCO_2e$/yr in 2020, and increase to 61 $GtCO_2e$/yr by 2030. These levels are significantly above the emission levels from optimal policy scenarios that aim at low stabilization levels (e.g., 450 ppm CO_2eq, [19]).

Our second set of experiments, on *staged accession* scenarios [3], considered a *reference climate policy* case where countries are locked into their current level of action throughout the 21st century. The 2020 emission targets are mostly based on the unconditional Copenhagen Pledges of countries [3,20]. Post-2020, regions are assumed to continue with emission reductions that sustain their average emission intensity improvements at a rate that is roughly consistent with their pre-2020 action. The reference policy was used to formulate a *staged accession* scenario in which only the EU took more ambitious climate action early on, while the others followed the *reference policy* until 2030. After 2030, both the EU and the rest of the world transitioned to the carbon price trajectory that emerges in the 450 ppm benchmark policy until 2050. However, due to the excess emissions in the first half of the century, this carbon pricing policy will no longer achieve the concentration target in the benchmark. Thus, the *staged accession* scenarios allow to study the risk of not achieving the climate target due to delayed action early in the century.

3. Results

Although the impacts of climate change are driven by regional and local patterns, many of these roughly scale with global-mean indicators like greenhouse-gas concentrations and warming. This is one reason why long-term climate goals in both the scientific literature [21] and the policy debate [22] are often framed in terms of global-mean values. In this section we analyze the emission scenarios in terms of several global-mean climate indicators. For the figures presented in this paper, the ranges reflect the differences in IAM emission results, combined with our estimates of uncertainty in carbon-cycle and climate parameters.

3.1. CO_2 concentration

CO_2 emissions are a prime output variable of all IAMs and the resulting elevated atmospheric CO_2 concentration is the major determinant of projected global warming, certainly on the long-term. Elevated CO_2 concentrations also affect the environment directly, for example by driving ocean acidification (threatening e.g. coral reefs, shellfish and some plankton species [23]) and CO_2-fertilization of terrestrial vegetation. Due to the long residence time of CO_2 in the atmosphere, concentrations by 2100 are a good indicator to compare overall impacts between scenarios over the 21st century, as well as post-2100 commitment.

In the *baseline* scenarios (Fig. 1a), CO_2 concentrations increase from present-day values around 400 ppm to a range of about 800–1100 ppm by 2100. The average value across the models is 900 ppm. Although the *reference policy* pathway, representing an extrapolation of current climate policies, brings down CO_2 concentrations considerably, by 2100 these are still much higher than today and increasing. The graph also shows the emission profiles resulting from the 450 and 550 ppm CO_2eq mitigation scenarios. The scenarios lead to much lower CO_2 concentration, as well as declining concentrations by the end of the century.

A typical feature of the *staged accession* scenarios (Fig. 1b) is that these lead to concentrations that stay significantly higher than the *immediate action*, or optimal scenarios. The lower long-term target of 450 ppm is more sensitive in this respect and *staged accession* leads to median concentrations higher by as much as a standard deviation distance above the median of the *immediate action* realizations and close to the 550 scenarios until the 2050s.

Given that the optimal 450 scenarios achieve a lower emissions and concentration level in the early decades of the 21st century than other scenarios, the 450 *delayed action* scenarios are obviously also more sensitive than the 550 scenarios to emission levels being too high around 2030 (Fig. 1c & d). However, post-2030 mitigation measures seem effective in bringing down concentrations to levels close to the optimal scenarios by 2100.

Limiting the potential for global net-negative emissions provided by combining modern-biomass energy systems with carbon capture and storage requires earlier CO_2 emission reductions, hence leads to lower CO_2 concentrations in early decades. Even in these scenarios, however, end-of-century concentrations converge with the optimal scenario, although the rate of decline is lower by that time.

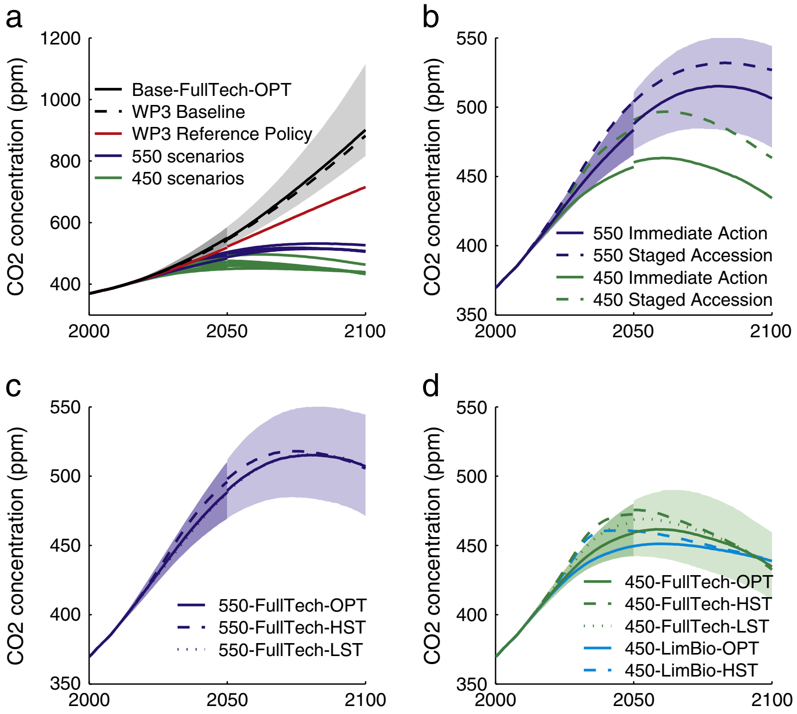

Fig. 1. CO_2 concentration projections resulting from IAM emission scenarios as calculated with MAGICC6. Panel a) Baselines and weak policy scenarios as well as all scenarios shown in the other panels for illustration; panel b) staged accession mitigation scenarios; panel c) 550 ppm CO_2eq with delayed-action variants; and panel d) 450 ppm CO_2eq with delayed-action variants. Lines indicate median estimates across all MAGICC6 ensemble members for all IAM realizations of the same scenario. Shaded area shows 66% uncertainty range around the median over all available models for only one scenario per panel, including both uncertainty resulting from carbon-cycle/climate modeling (MAGICC6) and energy-economic modeling (IAMs). Results through 2050 include more IAM realizations per scenario than results post-2050, which results in discontinuities of statistics in 2050. Note different y-axis in panel a).

3.2. CO_2eq concentration

The climate response is determined not only by CO_2, but also by non-CO_2 greenhouse gases and air pollutants, including those that lead to aerosols like sulfate and black carbon. In the climate model MAGICC6 emissions of CO_2 and all other greenhouse gases from the IAMs give rise to separately calculated changes in concentrations of these greenhouse gases. In addition, IAM-provided emissions of air pollutants either (a) influence atmospheric chemistry that leads to tropospheric-ozone formation and changes in the lifetime – and hence concentration – of methane, or (b) lead to tropospheric aerosols like sulfates, black carbon and organic carbon, with a cooling or warming effect on climate. The total effect of anthropogenic emissions on the climate is expressed here as CO_2-equivalent concentrations, i.e. the CO_2 concentration that at a given moment in time would result in the same radiative forcing as that of all greenhouse-gases and aerosols in the model combined. Since non-CO_2 species generally have much shorter residence times than CO_2, peak value of CO_2eq concentration over the 21st century is a relevant indicator in addition to the level by 2100.

At present, the CO_2 and CO_2-equivalent concentrations are about equal, due to mutually compensating effects of non-CO_2 greenhouse gases and (cooling) aerosols. In the *baseline* scenarios (Fig. 2a), equivalent-CO_2 concentrations increase to roughly 1100 ppm by 2100, about 200 ppm higher than CO_2 concentrations. This is caused by an increase of the atmospheric concentration of non-CO_2 greenhouse gases (CH_4 and N_2O) in the atmosphere, and at the same time, a decline in the net negative forcing caused by aerosols. The latter is largely due to assumed gradually more far-reaching clean-air policies.

In the *reference policy* pathway and low-emission scenarios, the CO_2-equivalent concentrations add roughly 100, respectively 50 ppm to the CO_2 concentrations by 2100, due to strong reduction measures in non-CO_2 greenhouse gases (and the more potent forcing of CO_2 at lower concentration levels). There is no significant difference between the amount non-CO_2 forcings add around 2100 compared to the time of peaking (2060 for 450 and 2080 for 550 scenarios)

Note the high peak in concentrations in Fig. 2d for the LimBio-HST scenario is an artifact of sampling: starting from the high 2030 emission levels, only three models were able to realize a 450 ppm consistent CO_2 budget with limitations on Biomass-CCS, which by coincidence have much higher non-CO_2 emissions that lead to a high and early peak. This atypical behavior explained by limited sample size does not occur for the CO_2 concentration pathways of the LimBio cases in Fig. 1d.

3.3. Surface-air temperature change

The increase in global-mean surface-air temperature is most often linked to overviews of impacts, such as provided by IPCC's 4th assessment report, as well as long-term policy

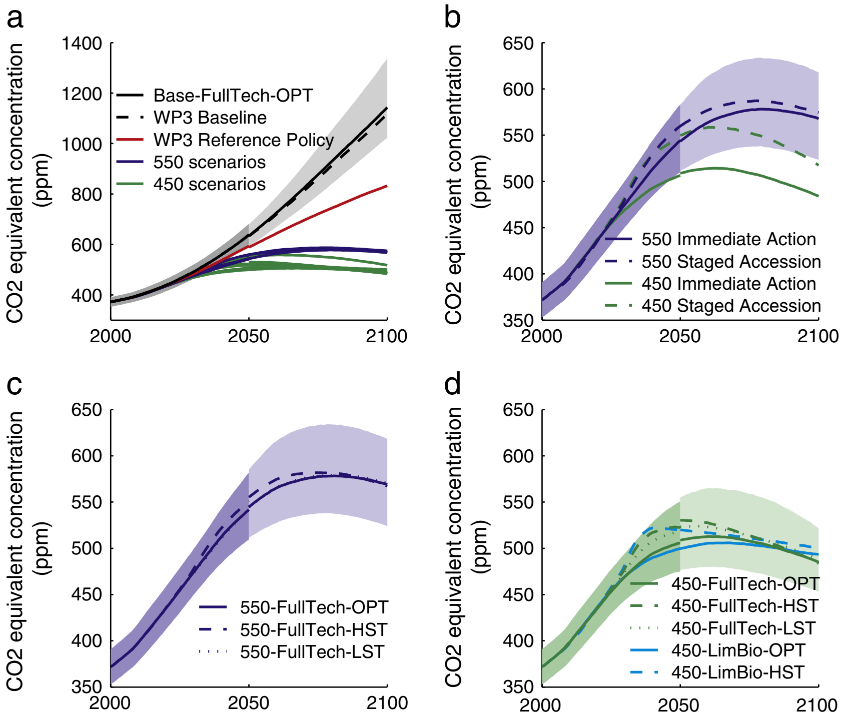

Fig. 2. As in Fig. 1 for CO_2-equivalent concentration projections resulting from IAM emission scenarios as calculated with MAGICC6. Note different y-axis in panel a).

targets, such as the 2 °C and 1.5 °C goals mentioned in the Cancun Agreements [22]. In addition to long-term temperature levels, it can be useful to look at the peak warming level during the 21st century. The reason is that it is not well known whether temporarily exceeding temperature targets would lead to (irreversible) impacts or feedbacks, which implies there is a risk of this being the case.

Both the *baseline* and *reference policy* scenarios lead to much higher warming than the 2 °C limit (Fig. 3). It is also important to note that in these scenarios global mean temperature would still be increasing by 2100. By contrast, the 550 scenarios lead to stabilizing of temperatures by 2100 — most likely above 2 °C, while the 450 scenarios on average peak around 2 °C and embark on a gradual decline by the 2070s. The scenarios that impose limited potential for global net-negative CO_2 emissions through biomass-energy combined with carbon capture and storage form an exception here (see further).

Again, the mitigation scenarios that assume a *staged accession* or *delayed action* resulting in high short-term emission levels make a larger difference for the 450 ppm long-term target. Warming is structurally higher for the 450 *staged accession* variant (Fig. 3b) and is also higher throughout the whole 21st century for the high short-term emission level *delayed action* variant (Fig. 3d) compared to the *immediate action* and *optimal* scenarios, leading to warming above, rather than below 2 °C.

While Fig. 3 shows for each scenario the median projections and spread of results across all IAMs, individual IAMs produced a diverse set of time-dependent emission pathways, even for the *delayed action* scenarios that were designed to constrain the IAMs to comparable emission budgets. As an illustration of the diversity across IAMs, Fig. 4 shows individual median warming projections for each individual IAM emission scenario for the optimal 450 and 550 ppm CO_2eq scenarios.

For both scenarios, nearly all individual IAM results show comparable behavior, with median warming pathways staying within the overall 66% uncertainty range. The GCAM model results deviate from the results of other models as they have a distinct pattern of rapid increases before a peak warming around the 2070s, followed by a rapid decline. This is driven by the model's relatively large potential for net-negative global CO_2 emissions (and thus the large potential for delaying emission reduction in the short-term), reaching 4 times the all-model average by 2100. As a result, the GCAM result for the 450 scenario venture deeply into “550 territory”, in the sense that peak warming in the 450 scenario exceeds peak warming in a 550 realization of most other IAMs.

A further observation is that not all individual IAM scenarios lead to stabilization in the 550 case and a warming decline in the 450 case. For IMACLIM and POLES the decline in CO_2 concentrations by 2100 (not shown) that appears in the overall median (Fig. 1c and d) is absent, or too small to lead to the warming stabilization, or decline seen for other IAMs.

To further explore uncertainties related to climate-system response, we compare in Fig. 5 the MAGICC6 results with our second method of deriving projections of surface-air temperature change resulting from our emission scenarios. The results need to be interpreted with care. The GCM step response functions generally lead to stronger warming, which can largely be explained by the GCMs represented in the step-response method, which form a subset of the full CMIP5 collection (see Supplementary information).

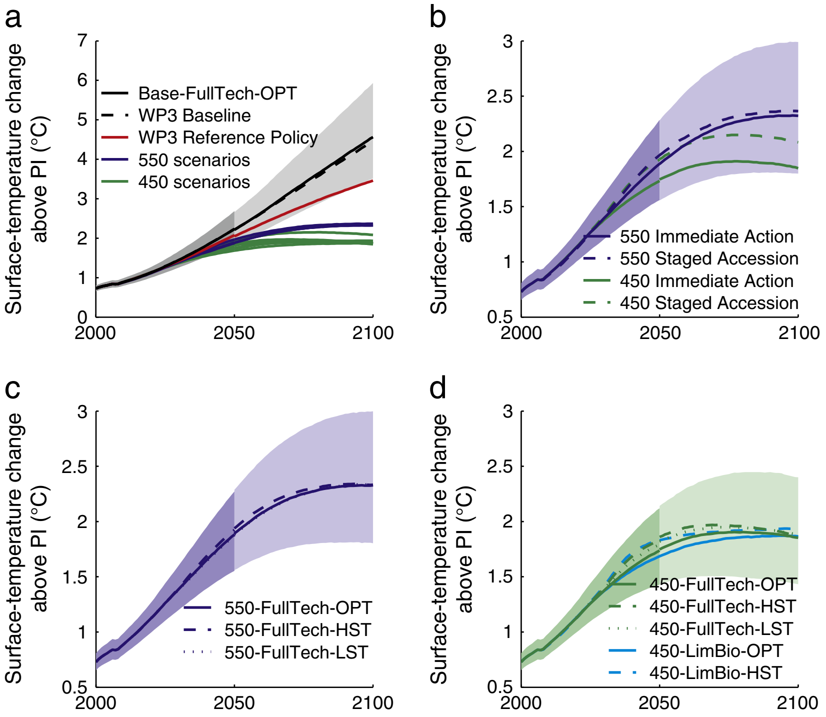

Fig. 3. As in Fig. 1 for projections of global-mean surface-air temperature change relative to pre-industrial resulting from IAM emission scenarios as calculated with MAGICC6. Note different y-axis in panel a).

3.4. Rate of warming

For human and natural systems to adapt to global warming, also the rate of temperature increase can be a crucial factor. In the past, different rates of maximum temperature increase have been suggested as a guardrail to prevent 'unacceptable' climate impacts (in the order of 0.1–0.2 °C per decade, for instance [24]). Fig. 6 shows the rate of warming defined by linear trends over 21 years centered around the year in question, expressed in temperature change per decade. This is very close to the change between the average temperatures over the 10 years following the year in question and the 10 years preceding that year.

Both *baselines* and *reference policy* scenarios lead to decadal warming rates in the order of 0.3 to even 0.5 °C/decade throughout the century. While the optimal 450 scenarios lead to maximum rates of warming close to 0.2 °C and rapidly reducing these, the optimal 550 scenario leads to a warming structurally faster than the 450 scenario by some 0.05 °C/decade, which implies a structurally larger challenge to adaptation in the 550 scenarios. The warming rates estimated by the step function emulations are close to those projected by MAGICC6, as shown in

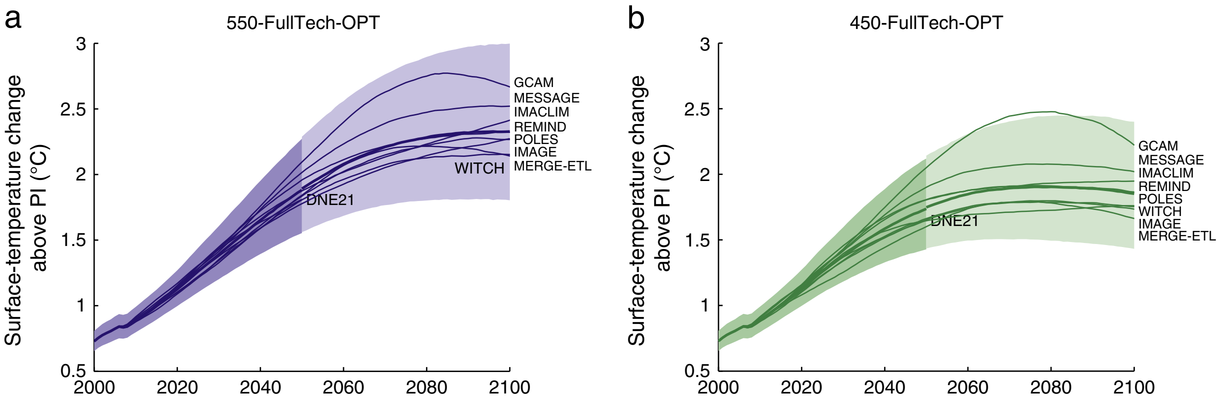

Fig. 4. Median projections of global-mean surface-air temperature change relative to pre-industrial resulting from individual IAM emission scenarios as calculated with MAGICC6 for the optimal 550 (a) and 450 (b) scenarios. The bold line indicates the overall median across all MAGICC6 ensemble members for all available IAM emission realizations of a particular scenario and the shaded area the 66% uncertainty range (comparable to the lines in other figures in this paper).

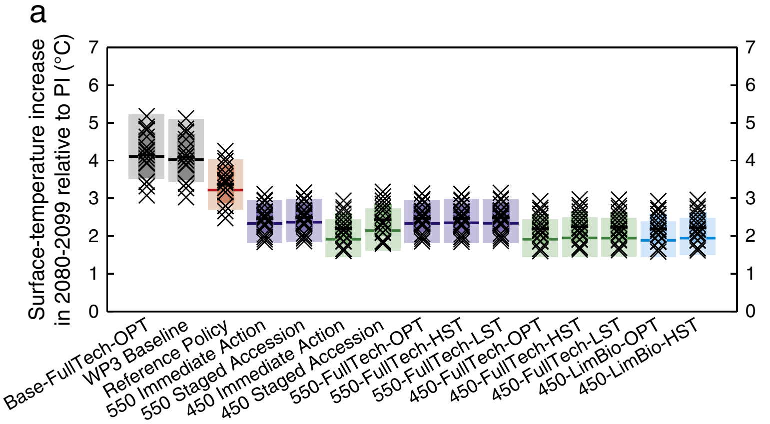

Fig. 5. Projections of global-mean surface-air temperature change in 2080–2099 relative to 1986–2005 from GCM emulations. The mean projections across all IAM realizations per scenario for each individual GCM emulation are indicated by crosses. The mean across all GCM emulations per scenario is indicated by horizontal black bars, while dark shaded areas indicate one standard deviation below and above the mean. Results from MAGICC6 are represented by colored bars (median) and wider light shaded areas (66% uncertainty range).

Table 2, confirming that the transient-warming response is comparable between the methods. However, the step-function method seems somewhat more sensitive to near-term changes in radiative forcing, so that *staged accession* carries a larger 'climate penalty' – in terms of higher near-term warming – compared to *immediate action* scenarios.

Interestingly, while for the overall temperature change so far we only observed relatively small differences between the variants consistent with 450 and 550 ppm CO_2eq, for the decadal rate significant differences can be observed. The effect of *staged accession* and *delayed action* is very strong around 2040, leading to a rate of warming higher by 50% for the 450 scenarios. This difference is driven primarily by higher CH_4 emissions around 2030 (as the climate policies would still have to be introduced). The impact is also noticeable for the limited biomass-CCS scenario.

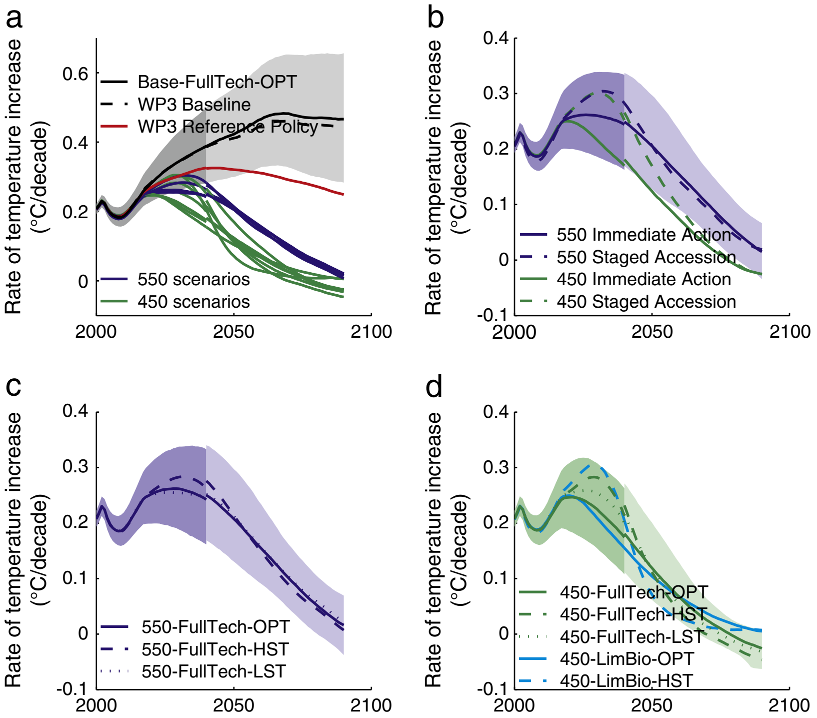

Fig. 6. As in Fig. 1 for projections of rate of change in global-mean surface-air temperature resulting from IAM emission scenarios as calculated with MAGICC6. Note different y-axis in panel a).

Table 2
Maximum decadal rate of warming over 2020–2080 (°C/decade).

IAM scenario	MAGICC6	GCM step-response functions
Base-FullTech-OPT	0.50	0.48
WP3 baseline	0.48	0.45
Reference policy	0.33	0.34
550 immediate action	0.31	0.29
550 staged accession	0.31	0.33
450 immediate action	0.26	0.25
450 staged accession	0.28	0.30
550-FullTech-OPT	0.28	0.29
550-FullTech-HST	0.30	0.30
550-FullTech-LST	0.27	0.29
450-FullTech-OPT	0.26	0.24
450-FullTech-HST	0.30	0.28
450-FullTech-LST	0.27	0.26

3.5. Warming limits: Probability to exceed 2 °C within 21st century

Given the prominence that the long-term goals of 1.5 an 2 °C have achieved in the policy debate it is important to note again the large uncertainties involved in calculating back these goals to emission trajectories (e.g. [25]). Fig. 7 shows the probability of exceeding 2 °C over time as calculated with MAGICC6.

For *baselines* and *reference policy* scenario, warming is likely (>66% probability) to exceed 2 °C by 2050 and very likely (>90%) by 2060. The 550 scenarios manage to postpone the moment 2 °C is likely to be exceeded by only a decade. By contrast, the 450 scenarios are not likely to exceed 2 °C at any time. However, the 450 *staged accession* scenario leads to a peak probability to exceed 2 °C of 66%, which is 1.5 times more likely than for the 450 *immediate action* scenario. Although the limited biomass-CCS scenarios reach probabilities comparable to the other 450 scenarios, they do not peak and keep increasing through 2100.

The 550 scenarios are likely to exceed 2 °C and have a lower probability of 40–50% to exceed 2.5 °C by 2100 (not shown). Even a level as high as 3 °C, however, is still likely to be exceeded for the *reference scenario* and very likely for the *baselines*.

It is important to note that although the mean of the *optimal* 450 scenarios across all IAMs is not likely to exceed 2 °C, the probability to exceed 2 °C is still roughly 45%, which means there is only a 55% probability to hold warming below 2 °C. This is only a median likelihood, or a chance of “as likely above as below” to stay below the 2 °C long-term goal. For a “likely” chance to hold warming below 2 °C, the probability should be 66% or higher, i.e. the probability to exceed 2 °C should be lower than 33%. Here again the diversity among IAM emission pathways is important to emphasize. Fig. 8a shows 2 °C exceeding probabilities for the 450 *immediate action* scenario for individual IAMs. Of the 8 models that covered the whole of the 21st century, five achieved an exceeding probability around 33%, while all four mid-term IAMs that estimate emissions to 2050 only show behavior typical of the five low-exceeding longer-term probability scenarios. This implies that the majority of IAM scenarios provide *optimal* 450 pathways with a likely chance of holding warming below 2 °C. Fig. 8b shows that *staged accession* has the largest impact on exactly these scenarios, by increasing the probability to exceed 2 °C up to 3 times. On the other hand, these estimates are sensitive to the probability distribution of climate sensitivity in the MAGICC6 setup. The greenhouse-gas concentration region around which exceeding probability is most sensitive to small changes in concentrations might well shift for a different estimate of the climate sensitivity's most likely value and other characteristics like skewness and width of the distribution [26].

4. Discussion

In all mitigation scenarios assessed in this paper, mitigation efforts are effective in reducing concentrations, radiative forcing and warming in the mid- and long-term. The scenario variants that assume higher 2030 emission levels than the *optimal* scenarios carry some level of climate “penalty” in terms of higher mid- to long-term warming, with the largest effect on the 450 ppm CO_2eq scenarios. The 450 scenarios have a reasonable probability of larger than 50% to limit warming to 2 °C over the 21st century and are generally on a downward temperature trajectory by 2100. By contrast, the optimal 550 ppm CO_2eq scenarios reach emission levels by 2030 that are not very different from the weak policy/delay scenarios. We find thus that the delay scenarios, which approximate the policy stringency from the present international negotiations (pledges) to be rather consistent with a 550 ppm CO_2e target. These scenarios are all associated with a probability of around 80% to exceed 2 °C within the 21st century, and all reach a much higher median estimate of warming of roughly 2.5 °C above pre-industrial by 2100. In addition, our *reference policy* scenario that is also linked to current policies leads to a median warming estimate of over 3 °C by 2100. We thus find the currently proposed stringency of emission reductions to be incompatible with the long-term objective of keeping global warming below the stated objective of 2 °C.

Within the range of 450 scenario variants, we observe several key differences that root back in the scenario design and the main research questions that they aim to address. Conclusions for the *delayed action* scenarios differ thus from the ones that we can draw from the *staged accession* scenarios. The *delayed action* scenarios aim at exploring implications of different 2030 emission levels to reach specific long-term targets. By definition, all scenarios are thus constrained with the same 21st century CO_2 emission budget to reach comparable level of concentrations, radiative forcing and warming in the long term by 2100. In this set-up, the 2030 emission target represents a perturbation of the transient pathway towards a long-term objective. Our conclusions from the “delayed action” scenarios focus thus on the transient effects and implied mid-term climate “penalties” that may arise due to suboptimal timing of policies. Given the pre-defined emission budgets, emissions by 2030 at a level of the high targets (HST) need to be compensated by more rapid and deeper emission reductions after 2030 compared to scenarios intersecting lower 2030 levels. While Riahi et al. [9] in this issue find that this has significant adverse effects for costs and feasibility of the transformation, we find in addition also that the *delayed action* scenarios carry a penalty on mid-term climate change, which is expressed most starkly by an up to 50% higher rate of warming around the 2040s, compared to the optimal scenarios. Earlier single-model studies showed a comparable

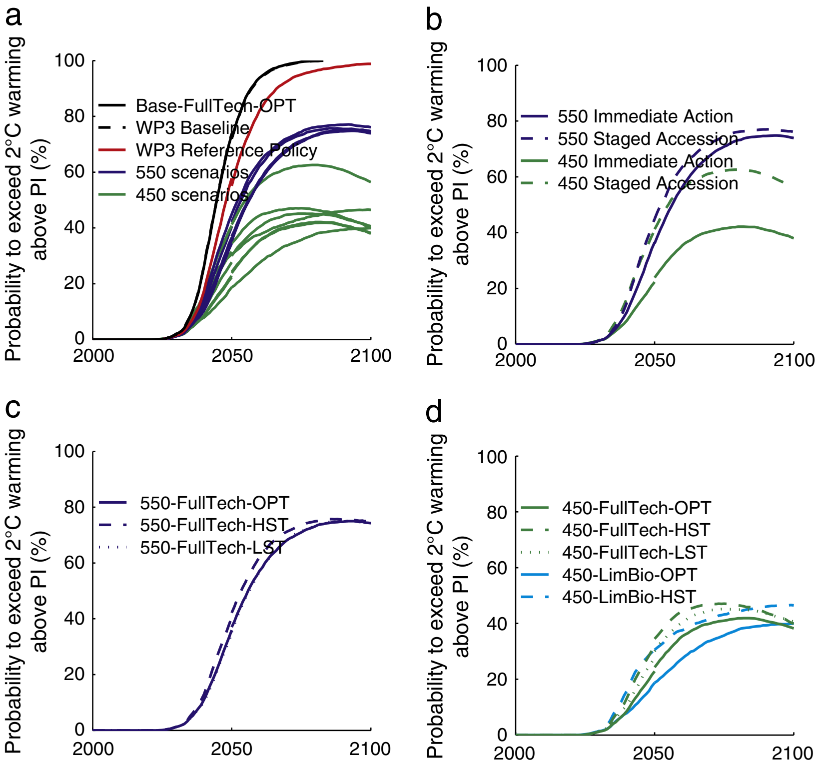

Fig. 7. As in Fig. 1 for estimates of the probability for global-mean surface-air temperature change to exceed 2 °C above pre-industrial resulting from IAM emission scenarios as calculated with MAGICC6.

effect of delayed emission reductions on mid-term warming [6]. A higher mid-term rate of warming may pose a challenge for the required adaptation needs and under inadequate adaptation would increase damage costs from climate change. Overshoot is also a problem for CO_2 concentration, which, for example, in the *staged-accession* scenarios approaches 500 ppm for multiple decades, before dropping almost down to 450 ppm by the end of the century. Ocean acidification has been projected to lead to coral reefs stopping to grow above around 450 ppm CO_2 and even start to dissolve above around 550 ppm, so that an overshoot of CO_2 concentration brings the risk of severe damage to coral reefs, irrespective of the effects of warming that lead to more frequent coral-bleaching events [27,28].

In contrast to our *delayed action* scenarios, our second type of scenarios on *staged accession* did not constrain the long-term emissions and instead explored the consequences

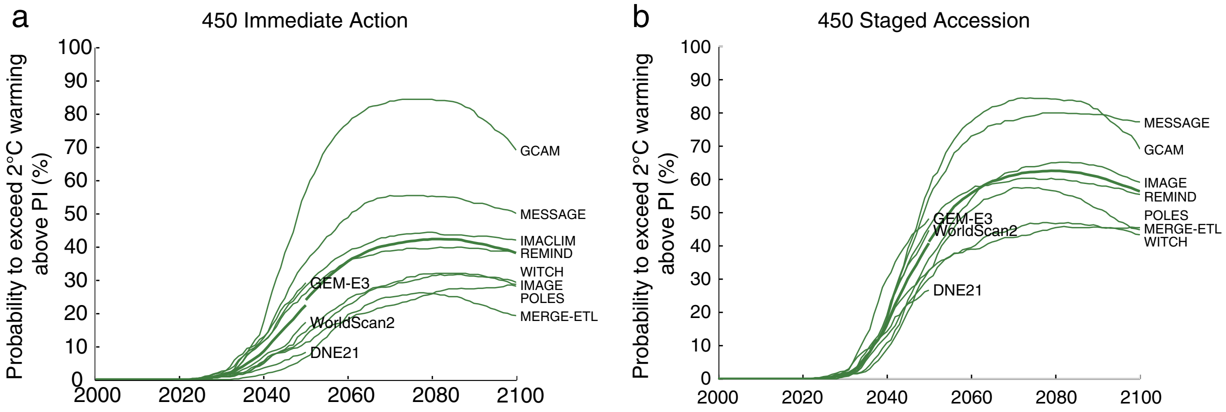

Fig. 8. Estimates of the probability for global-mean surface-air temperature change to exceed 2 °C above pre-industrial resulting from individual IAM emission scenarios as calculated with MAGICC6 for the 450 immediate action (a) and 450 staged accession (b) scenarios. The bold line indicates the overall median across all MAGICC6 ensemble members for all IAM emission realizations.

of maintaining a mitigation cost trajectory of the optimal pathway, starting from a 2030 emission level considerably higher. Hence, the "penalty" on energy-economics in these scenarios is limited and the emphasis is shifted instead towards a penalty on climate. Note however, that these scenarios by no means represent a weak climate policy case: still strong mitigation efforts result from a carbon price signal that does not adapt to the fact of delay, but is motivated by ambitious climate policy objectives. Nonetheless, in these *staged accession* cases, both mid- and long-term climate projections are affected significantly compared to the *immediate action* 450 scenarios, with a "best-guess" (median) warming peak of 2.2 °C, rather than 1.9 °C above pre-industrial, a 50% higher rate of warming around the 2040s, and a probability to exceed 2 °C over the 21st century about 50% higher (increasing on average from roughly 45% to 65%).

5. Conclusions

Peak and decline behavior is a prominent feature of stringent mitigation pathways. Here, we applied two methods of projecting future warming; one method using a Monte-Carlo simulation of carbon cycle and simple climate model and a second method of emulating the response of complex General Circulation climate Models. Both methods show clearly that near- and long-term warming are significantly increased by *delayed action* to reduce greenhouse-gas emissions compared to *immediate action*. Estimates of the probability that warming exceeds 2 °C above pre-industrial respond strongly to peak and decline pathways.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.techfore.2013.09.013.

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