Potential heat-risk avoidance from nationally determined emission reductions targets in the future

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Abstract

The increasing heat stress from the combined effect of changes such as temperature and humidity in the context of global change receives growing concerns. However, there is limited information for future changes in heat stress, as well as its potential socioeconomic impact, under the intended nationally determined mitigation scenarios. This study established an efficient evaluation method to quantify the benefits from the potential heat stress reduction from a continued intended nationally determined contributions (INDC) mitigation effort. The future heat stress over global land, quantified by the wet bulb globe temperature, was investigated based on the temperature sensitivity approach and multi-model simulations from the latest generation global climate models. The INDC continuous-effort scenario and the delayed-effort scenario, as well as the target-control scenarios of 2\textdegree C warming, were compared. We found that with the delayed mitigation efforts, the increase in frequency, duration, and cumulative intensity of extreme heat stress relative to the INDC continuous-effort scenario in the late 21st century could reach to 113\%, 193\%, and 212\%, respectively. If more ambitious efforts above current INDC pledges were implemented to achieve the 2\textdegree C global temperature goal, the corresponding avoided impact of heat stress frequency, duration, and cumulative intensity in the late 21st century was estimated to be 32\%, 37\%, and 40\%, respectively. Future changes in heat stress in low latitudes, where most developing countries are located, are most sensitive to emission reduction. Our results highlighted the potential avoided heat stress-related impact of global warming from efforts towards climate change mitigation.

1. Introduction

Under the influence of unprecedentedly rapid global warming, the probability of occurrence of heat waves, and their intensity and duration are increasing in many parts of the world (Perkins-Kirkpatrick and Lewis 2020). Heat wave events have a negative impact on socio-economic systems and natural ecosystems, such as threatening human health (Mora et al 2017), reducing labor productivity (Orlov et al 2020), damaging infrastructure, and reducing crop yields (Sun et al 2019). Increasing studies have shown that several variables such as temperature, humidity, and solar radiation affect heat-related diseases and mortality (e.g. Song et al 2017, Buzan and Huber 2020, Raymond et al 2020). In the context of global climate warming, the combined effect of changes in temperature, humidity, etc is posing a major threat to human health (Kjellstrom et al 2016, Mora et al 2017). Quantifying future changes in intensity, frequency, and duration of heat stress is essential for adaptation and mitigation planning.

To actively mitigate climate change, the Paris Agreement adopted at the 21st Conference of the Parties to the United Nations Framework Convention on Climate Change (UNFCCC) proposed two
long-term global temperature control goals: ‘limit global mean temperature increase to well below 2 °C above pre-industrial levels and to pursue efforts to limit it to 1.5 °C.’ (United Nations 2015a, 2015b). To achieve these goals, countries submit greenhouse gas (GHG) emission reduction targets (plans) in the form of intended nationally determined contributions (INDCs). As of 31 October 2021, 194 countries have submitted their respective INDC emission reduction targets, which cover the vast majority of countries and organizations worldwide. INDCs are to represent the potential global GHG emission levels in 2030 and provide the base scenario data for global GHG emissions and future climate change projections. Evaluating climate change through these emission reduction targets can facilitate more effective regional assessments and impact analysis.

In recent years, studies have investigated the changes in heat stress under the scenarios of 2 °C/1.5 °C warming threshold and the implied beneficial for avoiding the increase in heat stress if the warming target is limited to 1.5 °C rather than 2 °C (Dosio et al 2018, Li et al 2018a, Shi et al 2018, 2020, Yin et al 2020, Zhang et al 2020a). However, such studies were based on idealized assumptions to satisfy the 2 °C/1.5 °C temperature control target, which is probably difficult to achieve under the current climate policy (Rogelj et al 2016, Olhoff et al 2019, Zhang et al 2020b, IPCC 2021). Research results based on INDC emission reduction target scenarios are relatively rare and studies mainly focus on the global average temperature response (Rogelj et al 2016, Gütschow et al 2018, Robioui du Pont and Meinshausen 2018, Geiges et al 2020, Liu and Raftery 2021). Few studies have examined regional heat stress response to nationally determined emission reduction, hence the quantitative information for the impact of future mitigation policies on potential heat-related risk is still limited.

Therefore, this study fully took into account national voluntary mitigation efforts involving most countries in the world, and made a large-scale assessment of future heat stress according to the pledged emission reduction scenario of these countries under the framework of the Paris Agreement. This study adopts wet bulb globe temperature (WBGT) to analyze changes in heat stress over global land in the coming decades, and further assess the potential benefits from more ambitious emission reduction policies for the reduction of heat stress, based on a set of outputs from the latest generation global climate models. Data and methods in this study are summarized in sections 2 and 3. We examined future changes in heat stress relative to the present climatology in section 4.1 and compared the difference in heat stress under different emission reduction scenarios in section 4.2. We further investigated the potential impact of future changes in heat stress in the context of socioeconomic scenario in section 4.3.

2. Data

The data used in this study include updated national determined emission reduction targets submitted by countries, outputs of CMIP6 global climate models, gridded population and GDP.

2.1. Intended nationally determined contributions (INDC) commitment data

The national INDC reports have been submitted by 194 countries, which together account for more than 99% of global GHG emissions (UNFCCC 2021). These countries include 192 Parties to the Paris Agreement, and Eritrea and Iraq have submitted their first INDCs, but have not yet become the Party to the Paris Agreement. The INDC report of each country may be found at the United Nations Framework Convention on Climate Change (UNFCCC) website (UNFCCC 2021). The INDC commitment data are to represent the potential global GHG emission levels in 2030, which provides the basic information for global GHG emission and future climate change projection. Table S1 (available online at stacks.iop.org/ERL/17/055007/mmedia) shows the updated submissions of INDCs from 1 January 2018 to 31 October 2021, and the archived submissions before December 2017 were shown in the (Wang et al 2018, supplementary material). National emissions targets range from absolute emissions values to relative emissions with respect to the base year level, or the reduction values relative to the base year level.

2.2. Outputs of CMIP6 global climate models

The bias-corrected statistical-downscaled outputs from five global climate models participating in the 6th phase of Coupled Model Intercomparison Project (CMIP6, Eyring et al 2016) were used in this study for characterizing heat stress under the historical period (1981–2014) and the future scenarios (2015–2100, O’Neill et al 2016), for detailed information about this dataset refer to table S3 and Lange (2019).

In addition, the WFDE5 (bias-adjusted ERA5 reanalysis data, Cucchi et al 2020) dataset was applied to evaluate the reliability of the models in the reference period. The spatial resolution of all datasets is 0.5° × 0.5°. In this study, the period of 1981–2010 is considered as the reference period, and the pre-industrial period is defined as 1861–1880. A comparison of global average temperature differences between the future period and multiple possible pre-industrial baseline periods (e.g. 1861–1880 and 1850–1900) shows a statistical similarity (King et al 2017).

2.3. Population and GDP

Historical population and GDP per capita are respectively derived from Gridded Population of the World (GPW) v4 (Center for International Earth Science
Information Network 2018) and Kumm et al (2018), respectively. Future projections of population and GDP under SSPs scenarios are derived from International Institute for Applied Systems Analysis (IIASA, Kc and Lutz 2017) and Organization for Economic Co-operation and Development (OECD, Dellink et al 2017). Due to the Chinese population policy is not taken into account, the part of results about China is replaced by the projection results from Jiang et al (2020) (see text S4) all gridded population and GDP per capita datasets have uniform spatial resolutions of 0.5° × 0.5°.

3. Methods

The key steps of the method (figure 1) to assess future heat risk under the national pledged emission mitigation scenarios include: construction of INDC emission scenarios (section 3.1), analysis of temperature sensitivity to GHG emissions (section 3.2), evaluation of INDC-induced global warming level, using a slicing method to estimate INDC-induced temperature and relative humidity change (section 3.4), quantifying the characteristics of heat stress under scenarios (section 3.5), and assessing the heat-related population exposure (section 3.6).

3.1. Construction of emission scenarios

There are three emission scenarios involved in this study: one is the temperature control scenario of the 2 °C target scenario; the other two are the voluntary emission reduction scenarios related to the INDC (table 1, text S1). The 2 °C target scenario is consistent with previous studies that aim to investigate climate signals in response to 2 °C global warming level (King et al 2017). Considering the probability of achieving 1.5 °C target by the end of the century is very small, 1.5 °C target scenario was not used in this study. In terms of INDC scenarios, this study used the updated INDCs submissions as of 31 October 2021, which is before the opening of 26th session of the Conference of the Parties (COP26) to the UNFCCC and the deadline for updated INDCs submissions. We first analyzed and extracted the emission targets of each country to obtain the temporal trends of the INDC emissions by individual countries before 2030, and then extend the target scenario to 2100. We collected 1153 future emission path simulations (from 56 socio-economic models) from the Intergovernmental Panel on Climate Change (IPCC) scenario database (https://tntcat.iiasa.ac.at/AR5DB/). Considering the difficulty and uncertainty of carbon capture and storage (CCS) in the future, the scenario with CCS > 15 GtCO₂eq yr⁻¹ was omitted, leaving 368 future emission paths (figure 2, grey line). We further filtered 77 emission paths, all of which need to meet the 2030 updated INDC emission level (45–54 GtCO₂eq yr⁻¹), the bolded vertical line; the new committed emission levels were more concentrated at 45–48 GtCO₂eq yr⁻¹, which was lower than the 50–56 GtCO₂eq yr⁻¹ pledged in 2018). Among these extended INDC scenarios, we focused on the ‘continuous action’ scenario and the ‘delayed action’ scenario of the INDC. The INDC ‘delayed action’ scenario assumes that the INDC mitigation actions will be delayed or stagnant after 2030 and return to a ‘no policy’ status, whereas the ‘continu-ous action’ scenario assumes that the INDC pledged mitigation actions will continue after 2030 till the end of the 21st century, and the emissions will decline steadily worldwide, with a relatively constant rate of decarbonization after 2030 at a level similar to pre-2030 action. Based on the assumptions, according to the decarbonization rate of each path, the two types of scenarios could be selected, as shown in green shaded areas in figure 2 for the ‘continuous action’ scenario (70 year average decarbonization rates for 2030–2100, 9.1%–21.6%) and in red shaded areas for the ‘delayed action’ scenario (70 year average decarbonization rates, −8.2% to −4.6%). Then, the cumulative GHG emissions by 2100 (2012–2100) were calculated (table 1, column 7). Please see the supplementary text S1 for detailed information about construction of INDCs emission scenarios.

3.2. Estimation of climate warming response to GHG emissions

The Earth system models (ESMs) considered in this study were comprehensive ESMs with coupled carbon-climate system responses, where terrestrial and ocean carbon-cycle processes were coupled with atmosphere-ocean general circulation models (Gillett et al 2013). Based on the simulation of ESM models, the relationship between climate warming and cumulative GHG emissions could be established. In this study, 78 simulation experiments of climate warming response to GHG emissions (Tokarska et al 2016) were used from the comprehensive ESMs ensemble, including: 23 experiments based on the RCP (Representative Concentration Pathways) 2.6, 29 based on RCP4.5, and 26 based on RCP8.5 (as in table S2 and figure S1). Supplementary figure S1 showed the results of all these simulation experiments. It could be seen that the relationship between cumulative GHG emissions and climate warming does not differ much for different RCP scenarios for different warming level (such as 1.5 °C, 2 °C, 3 °C or 4 °C) and was nearly constant for each RCP pathway, with only a small change when cumulative emissions approached 2000 GtC (Allen et al 2009, Matthews et al 2009). This method has been used as an important tool for climate policy evaluation (Zickfeld et al 2009, Tokarska et al 2016). These 78 simulation experiments involved different levels of temperature sensitivity, from highly sensitive to less sensitive (figure S1), which presented a wide range of temperature responses to emission scenarios for different models.
Based on the temperature sensitivity datasets, we constructed a function of temperature change responses to cumulative GHG emissions (\( \text{CliRe}_{\text{emi}} \)),

\[
\text{CliRe}_{\text{emi}} = \frac{\Delta T}{\Delta I}
\]  

(1)

where \( \Delta I \) represents the cumulative anthropogenic GHG emissions above the current level in 2012, including CO\(_2\) and other non-CO\(_2\) GHG emissions. All non-CO\(_2\) emissions were converted into a unified unit of CO\(_2\) equivalent emissions, according to the global warming potential of each gas.
Figure 2. GHG emissions for INDC scenarios. The 2030 INDC emission targets were calculated based on each country’s pledged data. After 2030, emission scenarios consistent with INDC pledges by 2030 were collected from the UNFCCC database. Emission scenarios with CCS > 15 GtCO$_2$eq yr$^{-1}$ were omitted, leaving 368 future emission paths (grey lines). Various policy assumptions were grouped into different categories. This study focused on the ‘Continuous Action’ (‘pledged’) scenario (in green shaded areas) and the ‘Delayed Action’ scenario (in red shaded areas) of the INDC. Note that, there is a bolded vertical line at the year 2030 that is indicative of the 2030 INDC emissions range of 45–54 GtCO$_2$eq yr$^{-1}$. Actually, the new committed emission levels were more concentrated at 45–48 GtCO$_2$eq yr$^{-1}$, which was lower than the 50–56 GtCO$_2$eq yr$^{-1}$ pledged in 2018. For the bolded vertical line, the lower end of the range aligns with the green shading, and the upper end is a little lower than the red shading, which is because the values of 54.1–54.5 GtCO$_2$eq yr$^{-1}$ (at 2030) were also covered in order to increase the future more possibility of the ‘Delayed Action’ scenario.

\[ \Delta T \text{ is the corresponding change of global temperature, subject to decadal moving average. We estimated the 33rd–66th percentile range of } \text{CliRe}_{\text{emi}} \text{ to be } 1.77 \degree C–2.70 \degree C \text{ per 1000 GtC (when the cumulative emission exceeded 400 GtC, the 400 GtC nearly corresponded to the level of cumulative emission in 2012), and the estimated median ratio to be } 2.12 \degree C \text{ per 1000 GtC, according to all model simulations (supplementary figure S1 showed all simulations).} \]

3.3. Estimation of global warming level under different scenarios

We further extrapolated the global average temperature rise by the end of the 21st century under different scenario of the INDC. The warming above the current level (\(\Delta T_{\text{INDC}}\)) under the INDC scenarios was estimated by the following equation:

\[ \Delta T_{\text{INDC}} = \text{CliRe}_{\text{emi}} \times \Delta I_{\text{INDC}} \] (2)

where \(\Delta I_{\text{INDC}}\) represents cumulative emissions (from year 2012) under the INDC scenarios, which was calculated by summing national INDC emissions for each year.

Then, the warming level above the preindustrial level was estimated based on the sum of the INDC warming above the current level (\(\Delta T_{\text{INDC}}\)) and the current warming above the preindustrial level. The current warming in 2012 was estimated to be about 0.85 ± 0.14 \degree C (Hartmann et al 2013).

In addition, the assessment results from recent related studies were also comprehensively evaluated, such as Liu and Raftery (2021), Olhoff et al (2019) and Rogelj et al (2016). Supplementary text S2 described the specific results of each study. Based on the results, this study presented the estimation of the average global warming response under the Continuous Action and Delayed Action scenarios of the INDC (table 1, the 7th column). Our estimation of the average global warming response in the late 21st century under the ‘continuous action’ scenarios of the INDC is \(\sim 2.6 \degree C \text{ (2.3 } \degree C–3.1 \degree C)\). For the ‘delayed action’ scenarios, it is \(\sim 4.3 \degree C \text{ (3.7 } \degree C–5.3 \degree C)\). Note that, part of scenarios considered CCS in the future, but only available until the mid to late 21st century with CCS > 5 GtCO$_2$ yr$^{-1}$, and there will be a \(\sim 0.2 \degree C\) reduction of temperature (table 1, the 8th and 9th column).

3.4. Estimation of regional temperature and humidity change under different scenarios

In CMIP experiments, there was no specially experimental design for the INDC ‘continuous action’ and ‘delayed action’ scenarios, but for SSP scenarios. Therefore, we used slicing method (sometimes referred to as time sampling method) to identify INDC-reduced climate signals (James et al 2017, King et al 2017). This method uses existing climate model experiments, and achieved by identifying the time that each degree of warming is reached and examining regional climate changes which occur at that
Table 1. Basic information of INDC emission scenarios.

| Scenarios                  | Description                                                                 | Global emission peaking year | Modelling group                                                                 | 70 year average global decarbonization rate (2030–2100) (GtCO₂eq yr⁻¹) | Cumulative carbon emissions (2012–2100) (GtCO₂eq yr⁻¹) | Global mean warming above the preindustrial level | CCS (Gt CO₂ yr⁻¹) | Starting year with CCS > 5 | Temperature change with CCS |
|----------------------------|-----------------------------------------------------------------------------|-------------------------------|--------------------------------------------------------------------------------|----------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------|-------------------------------------------------|---------------------|--------------------------|-----------------------------|
| INDC continued-action (pledged) scenario (in green, figure 2) | Assume that the INDC emission reduction rates promised by countries are continued until the end of the century | 2030s                         | GCAM 3.0—AMPERE2-450-NoCCS-OPT  IMAGE 2.4—EMF27-550-EERE  IMAGE 2.4—EMF27-550-NoCCS  MESSAGE V.1—EMF22 3.7 NTE  REMIND 1.5—AMPERE2-550-EERE-OPT  REMIND 1.5—AMPERE2-550-NoCCS-OPT  WITCH_AMPERE—AMPERE2-550-LowEI-OPT  WITCH_EMF22—EMF22 3.7 NTE w Delay  WITCH_EMF27—EMF27-550-Conv  WITCH_EMF27—EMF27-550-EERE  WITCH_EMF27—EMF27-550-FullTech  WITCH_EMF27—EMF27-550-LimBio  WITCH_EMF27—EMF27-550-LimSW  WITCH_EMF27—EMF27-550-LimTech  WITCH_EMF27—EMF27-550-LowEI  WITCH_EMF27—EMF27-550-NoCCS  WITCH_EMF27—EMF27-550-NucOff  WITCH_ROSE—ROSE 550 HI Fos  WITCH_ROSE—ROSE 550 SL Gr | 9.1%–21.6% (24 models)                                                                 | 2659–3136                                                                 | 2.3 °C–3.1 °C (33%–66%) | 0.40 (in 2100)          | No                          | ~0.2 °C reduction            |
Table 1. (Continued.)

| Scenarios (Continued.) | Description | Global emission peaking year | Modelling group | 70 year average global decarbonization rate (2030–2100) (GtCO₂ eq yr⁻¹) | Cumulative carbon emissions (2012–2100) (GtCO₂ eq yr⁻¹) | Global mean warming above the preindustrial level | CCS (Gt CO₂ yr⁻¹) | Starting year with CCS > 5 | Temperature change with CCS |
|-------------------------|-------------|-------------------------------|-----------------|-----------------------------------------------|--------------------------------------------------|-----------------------------------------------|--------------------|----------------------------|-----------------------------|
| INDC delayed-action scenario | Assume that the INDC emission reductions promised by countries are not implemented well after 2030, and emissions follow along the no-policy path (Business As Usual scenario) | — | EC-IAM 2012—EMF27-Base-Conv | −4.6% to −8.2% (11 models) | 5582–6291 | 3.7 °C–5.3 °C (33%–66%) | 0 | No | No |
|                         |             |                               | EC-IAM 2012—EMF27-Base-FullTech |                        |                    |                                              | 0 | No |
|                         |             |                               | EC-IAM 2012—EMF27-Base-LimBio |                        |                    |                                              | 0 | No |
|                         |             |                               | EC-IAM 2012—EMF27-Base-LimSW |                        |                    |                                              | 0 | No |
|                         |             |                               | EC-IAM 2012—EMF27-Base-LimTech |                        |                    |                                              | 0 | No |
|                         |             |                               | EC-IAM 2012—EMF27-Base-NucOff |                        |                    |                                              | 0 | No |
| IMAGE 2.4—AME Reference |             | IMAGE 2.4—EMF27-Base-EERE |                        |                    |                                              | 0 | No |
| IMAGE 2.4—EMF27-Base-LowEI |             | SGM_EMF22—EMF22 Reference |                        |                    |                                              | 0.016 (in 2070) | No |
| TIAM-World_2007_version—EMF22 Reference |             | TIAM-World_2007_version—EMF22 Reference |                        |                    |                                              | 0.001 (in 2040) | No |
date. It is computationally cheap, and removes model variability due to temperature sensitivity to GHGs, which reduces the range of projections for some temperature-related variables (James et al. 2017). This method follows the experience of simulation: when the same climate model simulates climate change in different emission scenarios (for example, SSP2-4.5, SSP5-8.5), the corresponding spatial patterns of climate are roughly consistent when these scenarios reach the same warming range (Stocker et al 2013, Vautard et al 2014, King et al 2017). Therefore, we assume that when the same climate model simulates climate change under either INDC scenarios or SSP scenarios, the corresponding spatial patterns of climate are roughly the same when the INDC scenario and the SSP scenario reach the same warming range (such as 2 °C, 2.6 °C, 4.3 °C). The plausibility of this assumption has been verified in previous studies (Li et al 2018b, Zhang and Zhou 2020). In practice, following the suggestion of King et al (2017), we defined the 2 °C target scenario as all years within decades in the SSP3-7.0 and SSP5-8.5 simulations (2015–2100) when decadal-average temperatures are between 1.8 °C–2.2 °C warmer above the preindustrial baseline. Correspondingly, the world consistent with the ‘continuous action’ scenario and the ‘delayed action’ scenario of the INDC was defined in the same way but for decadal-averaged temperatures at 2.3 °C–3.1 °C and 3.7 °C–5.3 °C above the preindustrial baseline, respectively (figure S2).

3.5. Quantification of heat-stress characteristics

We characterized heat stress at present and under future scenarios based on the key indicators of heat stress. The WBGT, an index originally proposed by Yaglou and Minard (1957) for measuring heat stress and further standardized by International Organization for Standardization (Parsons 2006), was adopted in this study for characterizing heat stress (text S3). Following previous studies (Willett and Sherwood 2012, Fischer and Knutti 2013, Lee and Min 2018), daily maximum WBGT could be estimated as follows:

\[
\text{WBGT} (°C) = 0.567T_{\text{max}} + 0.393e + 3.94
\]  

(3)

\[T_{\text{max}}\] is the daily maximum temperature (°C), \(e\) is the daily mean vapor pressure (hPa), which can be derived from daily mean temperature \((T_{\text{mean}}, \°C)\) and relative humidity (RH, %):

\[
e = \frac{\text{RH}}{100} \times 6.105 \times \exp \left( \frac{17.27T_{\text{mean}}}{237.7 + T_{\text{mean}}} \right).
\]

(4)

A heat wave event was defined when daily maximum WBGT exceeded the annual 95th percentile threshold in the reference period baseline (1981–2010) for at least consecutive 3 d. We assessed heat wave events, including the frequency (the sum of heat wave days in a given year), duration (the maximum length of heat wave days in a given year), and cumulative intensity (the sum of differences between real WBGT and the 95th threshold in heat wave days in a given year).

We further examined differences in heat stress between scenarios. Referring to previous studies that investigated the benefits of achieving 1.5 °C target rather than 2 °C target (e.g. Dosio et al 2018, Li et al 2018a), we estimated the impact on heat stress avoided by achieving 2 °C target instead of the ‘continuous action’ of INDC, which are defined as 100% \((C_{\text{continuous}} - C_2 °C)/C_{\text{continuous}}\), where \(C_{\text{continuous}}\) and \(C_2 °C\) were changes of heat stress indicators relative to the reference period under the ‘continuous action’ scenario and 2 °C target scenario, respectively. The additional impact on heat stress by delaying the action of INDC rather than continuous action could be estimated similarly, as 100% \((C_{\text{delayed}} - C_{\text{continuous}})/C_{\text{continuous}}\), where \(C_{\text{delayed}}\) was changes of heat stress indicators under the ‘delayed action’ scenario. Here, considering that the INDC ‘continued action’ scenario is the closest to the current climate policy, this study focuses on the INDC ‘continued action’ scenario when comparing the differences between the scenarios, to reflect the gap from the worst ‘delayed action’ scenario to the current ‘continued action’ scenario, and the further gap from the current ‘continued action’ scenario to the ideal ‘2-degree’ scenario.

Moreover, we characterized subregional features of heat stress following the definition of IPCC SREX (Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation) report (tables 2, S4 and figure S3). In some cases, we focus on the nine key regions where potentially the densest population distributed in the future, as suggested by Schwingshackl et al (2021), that is, EAS, SAS, SEA, WAF, EAF, CAM, ENA, CEU, and MED.

3.6. Evaluation of the heat-related population exposure

To further quantify the impact of heat-related extreme events, we analyzed population exposure to heat stress among different regions under future scenarios. Population exposure was defined as the product of population and heat stress frequency at each grid cell, and the regional aggregated population exposure can be derived. This approach is suggested by Jones et al (2015) and applied in many recent studies (e.g. Chen et al 2020, Wang et al 2021). We paired the ‘2 °C target’ with SSP1, ‘continuous action’ with SSP2, and ‘delayed action’ with SSP3. The combination of ‘2 °C target’ and SSP1 (sustainability pathway) represents the most sustainable future projection. By contrast, the combination of ‘delayed action’ and SSP3 (regional rivalry pathway) represents the worst projected climatic and socioeconomic conditions.
**Table 2. Regions analyzed in this study.**

| Label | Name                          | Label | Name                          | Label | Name                          |
|-------|-------------------------------|-------|-------------------------------|-------|-------------------------------|
| ALA   | Alaska                        | ENA   | Eastern North America         | SAU   | Southern Australia/New Zealand|
| AMZ   | Amazon                        | MED   | Southern Europe/the Mediterranean | SSA   | South-Eastern South America  |
| CAM   | Central America               | NAS   | Northern Asia                 | SEA   | Southeast Asia                |
| CAS   | Central Asia                  | NAU   | Northern Australia            | TIB   | Tibetan Plateau               |
| CEU   | Central Europe                | NER   | Northeast Brazil              | WAF   | West Africa                   |
| CGI   | Eastern Canada/Greenland/Iceland | NEU | Northern Europe               | WAS   | West Asia                     |
| CNA   | Central North America         | SAF   | Southern Africa               | WSA   | West Coast South America      |
| EAF   | Easter Africa                 | SAH   | Sahara                        | WNA   | Western North America         |
| EAS   | Eastern Asia                  | SAS   | Southern Asia                 |       |                               |

Whereas the combination of ‘continuous action’ and SSP2 (middle pathway) reflects an intermediate pathway between the above two extreme assumptions.

**4. Results and discussion**

**4.1. Future changes in heat stress**

Before analyze future changes, we first evaluate models’ performance in simulating the spatial pattern of heat stress. Our results indicate that the multi-model mean considerably reproduced the spatial pattern of annual mean and extreme WBGT in the reference period (figure S4); the multi-model ensemble mean can capture the spatial pattern of heat stress frequency, duration, and cumulative intensity, despite biases in detail is observed (figure S5 and table S5).

The increments relative to the reference period in global averaged heat stress frequency, duration, and cumulative under the 2°C target scenario, the ‘continuous action’ scenario, and the ‘delayed action’ scenario are displayed in table 3. Our results indicate heat stress frequency, duration, and cumulative intensity are projected to increase to several times of the reference period even in the case of the lowest 2°C target scenario. The increment of global averaged frequency, duration, and cumulative intensity of heat stress is respectively 3.3 (4.8), 1.9 (3.0), and 3.8 (6.2) times of that in the reference period under the 2°C target scenario (the ‘continuous action’ scenario). Under the worst-case ‘delayed action’ scenario, the results are respectively 10.0, 8.5, and 18.9 times of that in the reference period.

The maps of changes in the frequency, duration, and cumulative intensity under various future scenarios relative to the reference period are displayed in figure 3. The most important feature of changes in heat stress indicators in terms of the spatial pattern is a ‘single-peaked’ zonal distribution, that is, the strongest growth in extreme heat stress occurs in low-latitudes. The increment of heat stress frequency, duration, and cumulative intensity averaged between 10°N and 10°S is 2.2, 1.9, and 1.5 times of that averaged over global land, respectively. The Indonesian archipelago, the Amazon basin and the Congo River basin, located near the equator, are projected to experience the most prominent increases in heat stress. The reason for this spatial pattern can be explained as: the magnitude of the annual variability of WBGT in low latitudes is relatively small, and a slight increment in mean value of WBGT may lead to plenty of days exceeding the threshold defined in our study. Our results suggest that people living in parts of Sub-Saharan Africa, Amazon, and Southeast Asia will experience the most pronounced increase in heat stress in the world. It is worth noting that countries with low GDP per capita (a common measure of the level of socioeconomic development) are mostly located in those regions (figure S6), people who live in those regions may be lack reliable countermeasures (e.g. use of air conditioners) against rapidly increasing risk from heat stress. This phenomenon corroborates previous work finding inequality in people impacted by climate change related to wealth (King and Harrington 2018, Diffenbaugh and Burke 2019, Alizadeh et al 2022).

The regionally averaged increments of heat stress indicators in SEA, WAF, EAF, and CAM are much greater than the corresponding global averaged levels (figure 4). For example, the increase in the heat stress frequency, duration, and cumulative intensity in SEA are respectively 2.3, 2.0, and 1.8 times the global averaged level under the ‘delayed action’ scenario. The increments of heat stress indicators in SAS are slightly higher than the global averaged level. Although the increments of heat stress indicators in CEU, ENA, EAS, and MED is visibly below the global average
Table 3. Future changes in global averaged heat stress frequency, duration, and cumulative intensity relative to the reference period. Multi-model means and inter-model spreads are displayed.

| Indicators (unit)         | '2 °C target' | 'Continuous action' | 'Delayed action' |
|--------------------------|---------------|---------------------|------------------|
| Frequency (days)         | 36.6 (27.9–45.4) | 10.2 (7.9–12.6)     | 56.3 (38.8–73.9) |
| Duration (days)          | 53.4 (42.4–64.3) | 16.2 (12.6–19.9)    | 93.5 (64.4–122.5) |
| Cumulative intensity (°C) | 111.8 (102.2–121.4) | 47.1 (38.4–55.8)    | 284.7 (233.3–346.2) |

Figure 3. Spatial distribution of changes in heat stress indicators relative to reference period under future climate scenarios. (a)–(c) Frequency; (d)–(f) duration; (g)–(i) cumulative intensity. (a), (d), (g) 2 °C target scenario; (b), (e), (h) continuous action scenario; (c), (f), (i) delayed action scenario. Zonal averages are displayed on the right side of the maps.

Figure 4. Regional average changes in heat stress indicators in the nine major regions and global land relative to reference period under future climate scenarios. Error bars display the standard deviations of inter-model spread.

level, the absolute value of heat stress indicators (frequency exceeds 50 d and duration exceeds 20 d) in those regions is still enough to pose a considerable threat to human’s habitat under the ‘delayed action’ scenario.

4.2. Differences in heat stress across scenarios

Based on the multi-model mean results, the global average avoided impact of more ambitious mitigation action to achieve the 2 °C target scenario instead of the ‘continuous action’ is estimated to be 32%, 37%, and 40%, in terms of heat stress frequency, duration, and cumulative intensity, respectively; correspondingly, the additional impact under the ‘delayed action’ scenario rather than the ‘continuous action’ scenario is estimated to be 113%, 193%, and 212%, respectively (figure 5). For specific regions, the values may be significantly higher than those of global average, for example, the regional averaged avoided impact (i.e. the 2 °C target scenario versus the ‘continuous action’ scenario) in AMZ (Amazon) is 36%, 43%, and 48%, in terms of heat stress frequency, duration, and cumulative intensity, respectively; correspondingly, the additional impact is estimated to be 123%, 238%, and 286%. The results show that there are greater differences between different scenarios for heat stress duration and cumulative intensity than for heat stress frequency. The avoid impact and additional impact is generally more remarkable in low-latitudes (e.g. CAM, AMZ, WAF, SEA). Results in figure 3 indicate the spatial pattern of changes in a given indicator under different scenarios is similar, although the magnitudes vary, which is in line with Seneviratne and Hauser (2020). Thus, the additional
Figure 5. Regional average changes in heat stress indicators in 26 regions (cf. table 2) and global land relative to INDC pledged scenario. Error bars display the standard deviations of inter-model spread.

impact is also greater in regions with greater avoided impact (figure 5).

4.3. Heat exposure under socioeconomic scenarios
We first consider the combination of fixed population counts (i.e. the reference period) and heat stress frequency under different future scenarios (figures 6(a)–(c) and S5). SAS, EAS, and SEA are projected to be the regions with the highest population exposure to heat stress under all future scenarios. If we take demographic changes into account, the results of population exposure will vary (figures 6(d)–(f) and S7–S8). Due to dramatic population growth in sub-Saharan Africa, population exposures in WAF and EAF are projected to be comparable with those in densely populated Asia. It is noticed that the regions with high population exposure usually tend to be characterized by relatively lower GDP per capita, indicating a serious challenge for these regions adapting to increased risk of heat stress in the future. If the global sustainable development goals are well realized, which are consistent with the combination of ‘2 °C target’-SSP1, can be achieved, the projected heat-related population exposure (GDP per capita) is lowest (highest). In the contrast, a world following a regional rivalry pathway of development, which is consistent with the combination of ‘delayed action’-SSP3, is projected to suffer the highest heat-related population exposure and lowest GDP per capita, especially in developing countries, which is mostly distributed in hot low-latitudes.

The above results emphasize that most people who live in middle and low latitudes are at risk of being severely threatened by dangerous heat stress. On the one hand, strengthening current mitigation action is critical to the people’s health in these regions, where economically underdeveloped, densely populated, and vulnerable to heat stress. On the other hand, while focusing on economic development, it is more imperative to strengthen the ability to cope with extreme heat risks, such as advanced cooling facilities equipped, medical treatment for heat illnesses to improve, as well as the future adjustment of outdoor labor hours.

4.4. Comparison with the results considering only temperature
Most previous studies on heat stress only considered the role of temperature (e.g., Zhang and Wang 2019, Shi et al 2020), in recent years, increasing efforts have been paid to investigate heat stress based on heat–humidity indicator (Buzan and Huber 2020, Li et al 2020). In this study, we adopt WBGT, a heat–humidity indicator, instead of surface air temperature alone, to characterize the potential heat-related impact associated with nationally determined emission reductions under the Paris Agreement. However, the role of humidity in shaping heat stress intensity has not been quantified. Therefore, we perform the same analysis presented in figure 3, but replacing the WBGT by daily maximum temperature (figure S9), and display the difference between the two results in figure 7. Our results clearly show that the role of humidity remarkably enhances heat stress in low latitudes, which is in line with Chen et al (2019). The following explanations can be regarded
as possible mechanisms for this phenomenon: WBGT increases nonlinearly with both temperature and relative humidity, and a slight increase in either temperature or relative humidity may lead to a substantial increase in WBGT, especially when the temperature is at a large value (Luo and Lau 2019); the projected decrease in relative humidity over lands in mid-high latitudes is more pronounced than that in low-latitudes, which would partly cancel the effect of increasing temperature (Brouillet and Joussaume 2019, Coffel et al 2019).

5. Conclusion
In this study, we quantified the benefits from the potential heat stress reduction by implementing the national pledged INDC mitigation effort, based on the simulations of the latest generation of global climate models. We used WBGT than temperature itself to characterize heat stress. We found that the frequency, duration, and cumulative intensity of extreme heat stress under INDC scenarios were projected to greatly exceed those under the 2°C target scenario. If more effective mitigation action based on current policies to be implemented to achieve the 2°C global temperature control goal, 32%, 37%, and 40% of increment of heat stress frequency, duration, and cumulative intensity were expected to be avoided by the end of 21st century, respectively. However, if the INDC mitigation action will not be kept implementing in the post-2030s, the additional increase in heat stress frequency, duration, and cumulative intensity...
is projected to be respectively 113%, 193%, and 212% by the end of the 21st century, relative to those under the ‘continuous action’ scenario of INDC. Our results further indicate that the greatest increase in heat stress frequency, duration, and cumulative intensity occur low latitudes, where most developing countries are located. Under this worst-case scenario, most people in middle and low latitudes would be severely threatened by dangerous heat stress.

When further considering future changes in the socioeconomic impact of heat stress, this study revealed that the negative impact of heat stress would be avoided to the greatest extent possible by achieving a sustainable development pathway. Countries should focus on the development of science, technology, and education to achieve long-term, technology-oriented development that effectively reduces income inequality between and within countries, and move towards an environmentally friendly society by prioritizing the use of clean energy in their future development.

This study was not aimed at the commonly used scenario (SSP emission scenario). In contrast to the traditional CMIP-like studies, we do not pre-set idealized emission scenarios, but timely tracked the latest national emission reduction pledges submitted by countries to UNFCCC as of 31 October 2021, and further updated the overall global emission pledged scenarios. We presented a new assessment in heat stress characteristics based on the updated national self-determined emission reduction, which are the current national mitigation commitments negotiated by governments. Our results promptly established a timely linkage between emission reduction and regional heat-related risk avoidance. We explore a method to quickly evaluate the effects of emission reduction policies and judge the adequacy of reduction effort for people’s comfortable lives. This is also a concern of many governments, enterprises, scientific community and the public.

In this study, we investigate heat stress based on the relative thresholds that indicate extreme cases in present climatology. However, the uniformly determined thresholds for classifying heat stress intensity levels do not yet accurately reflect the specific impact of heat stress on the population due to the differentiating factors such as age, gender, health status, clothing, labor intensity, and individual tolerability. Further studies could incorporate the vulnerability of different populations to heat stress to conduct more elaborate projections for heat-related impacts and risks.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Conflict of interest

The authors declare that they have no competing interest.

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